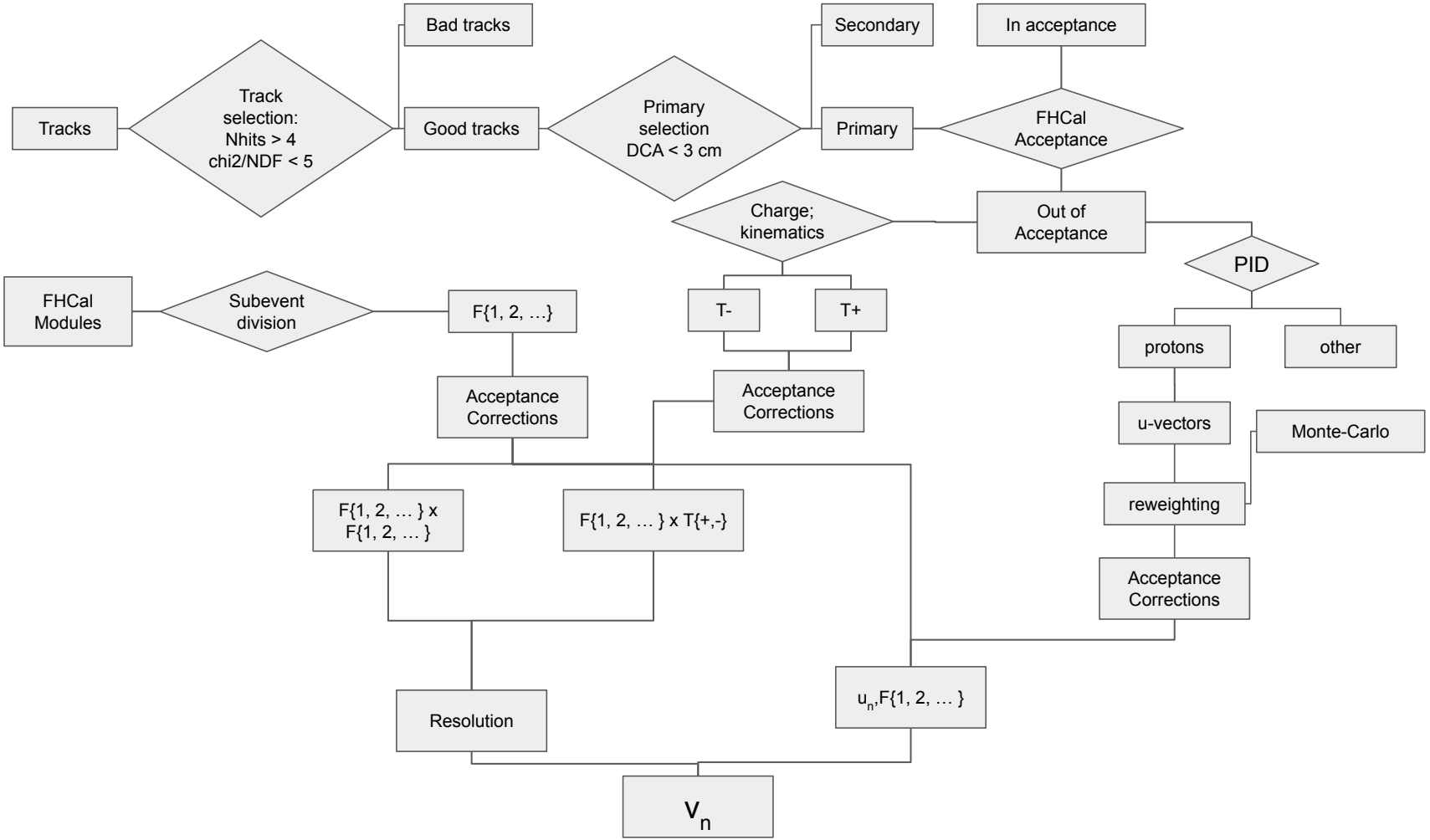
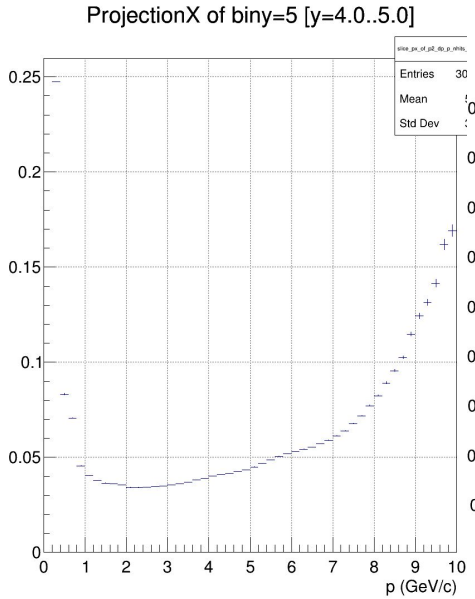
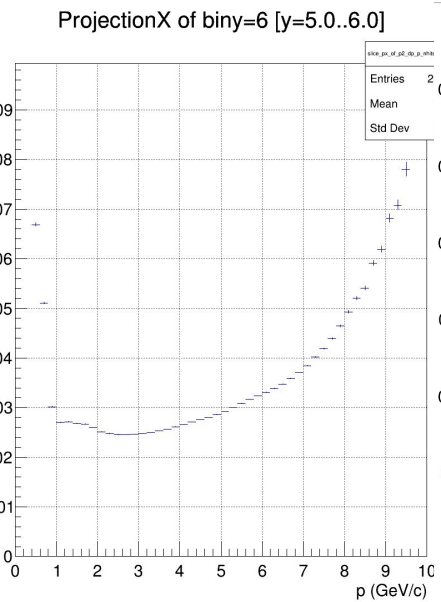
Elliptic Flow in BM@N

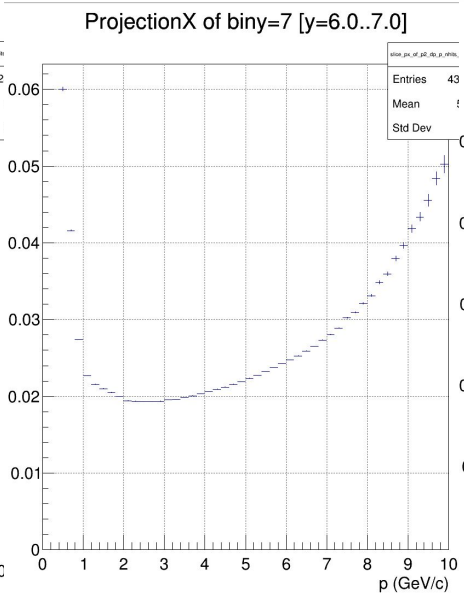
M.Mamaev

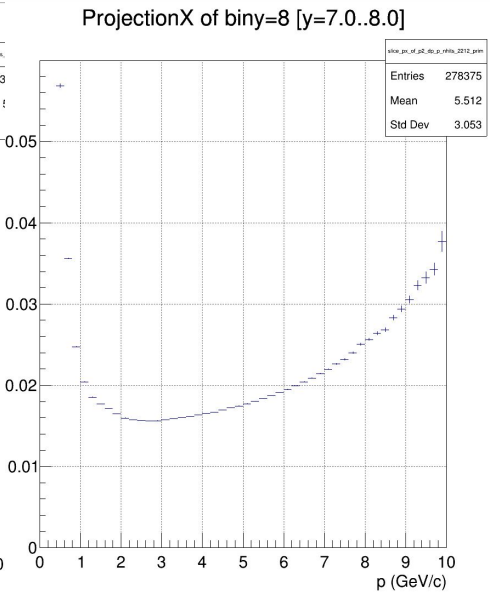

Tracks
Track selection: Nhits > 4 chi2/NDF < 5
Bad tracks
Good tracks
Primary selection DCA < 3 cm
Secondary
Primary
In acceptance
FHCal Acceptance
Out of Acceptance
Charge; kinematics
PID
protons
other
T-
T+
Acceptance Corrections
u-vectors
Monte-Carlo
reweighting
Acceptance Corrections
FHCal Modules
Subevent division
F{1, 2, …}
Acceptance Corrections
F{1, 2, … } x F{1, 2, … }
F{1, 2, … } x T{+,-}
Resolution
u_n,F{1, 2, … }
V_n

Momentum resolution dependence on nhits

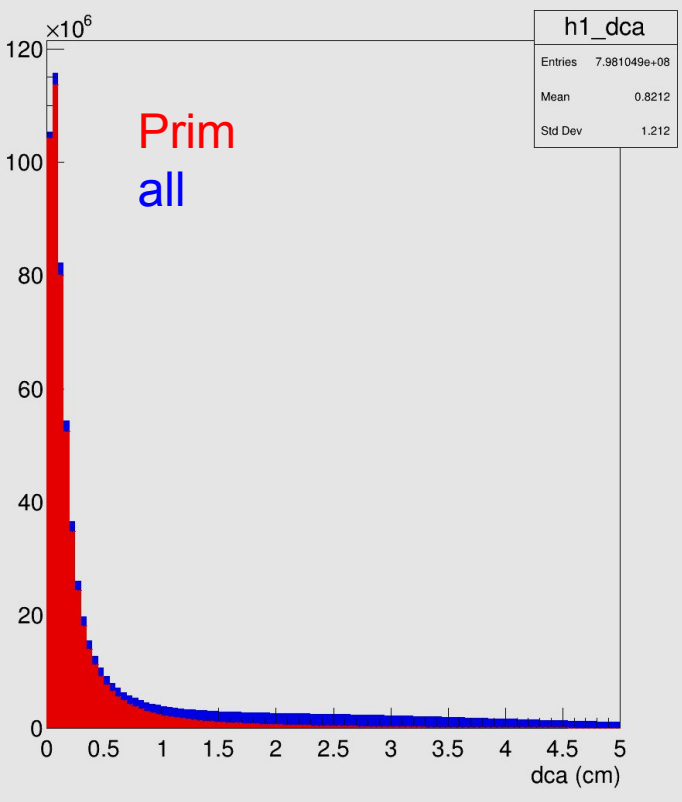


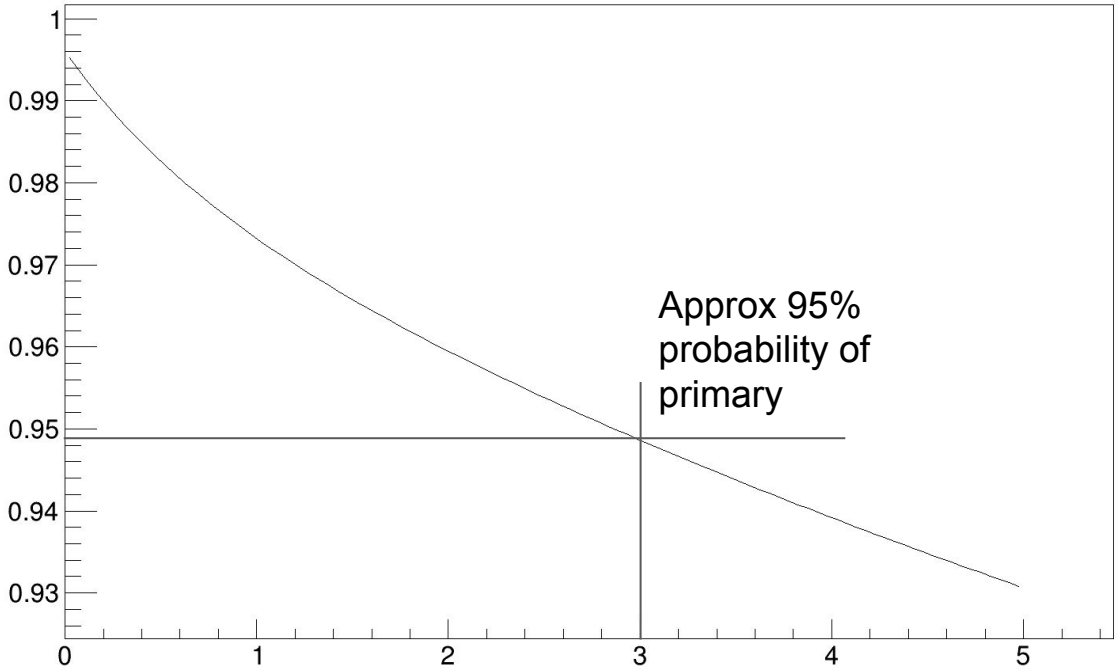




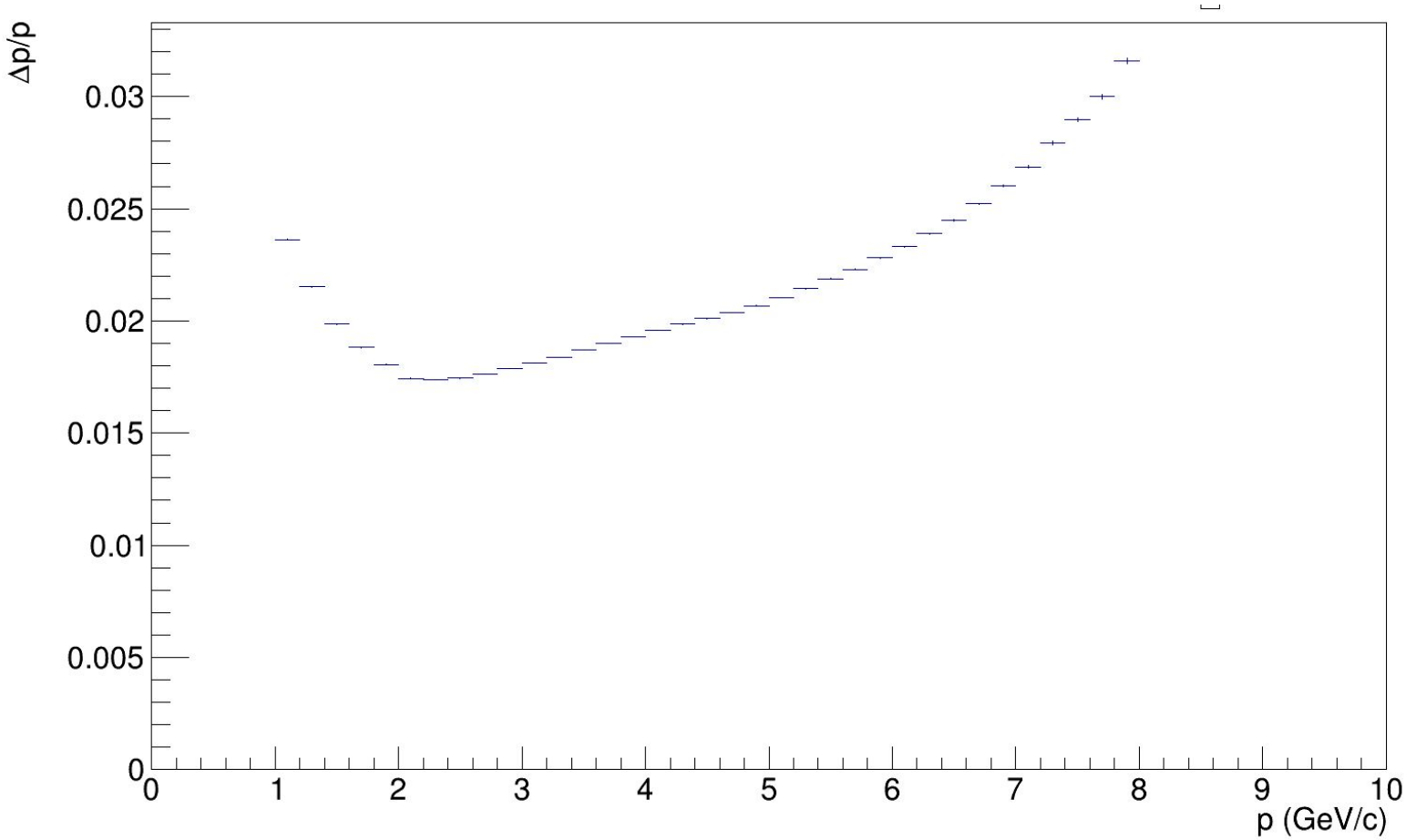


DCA selection

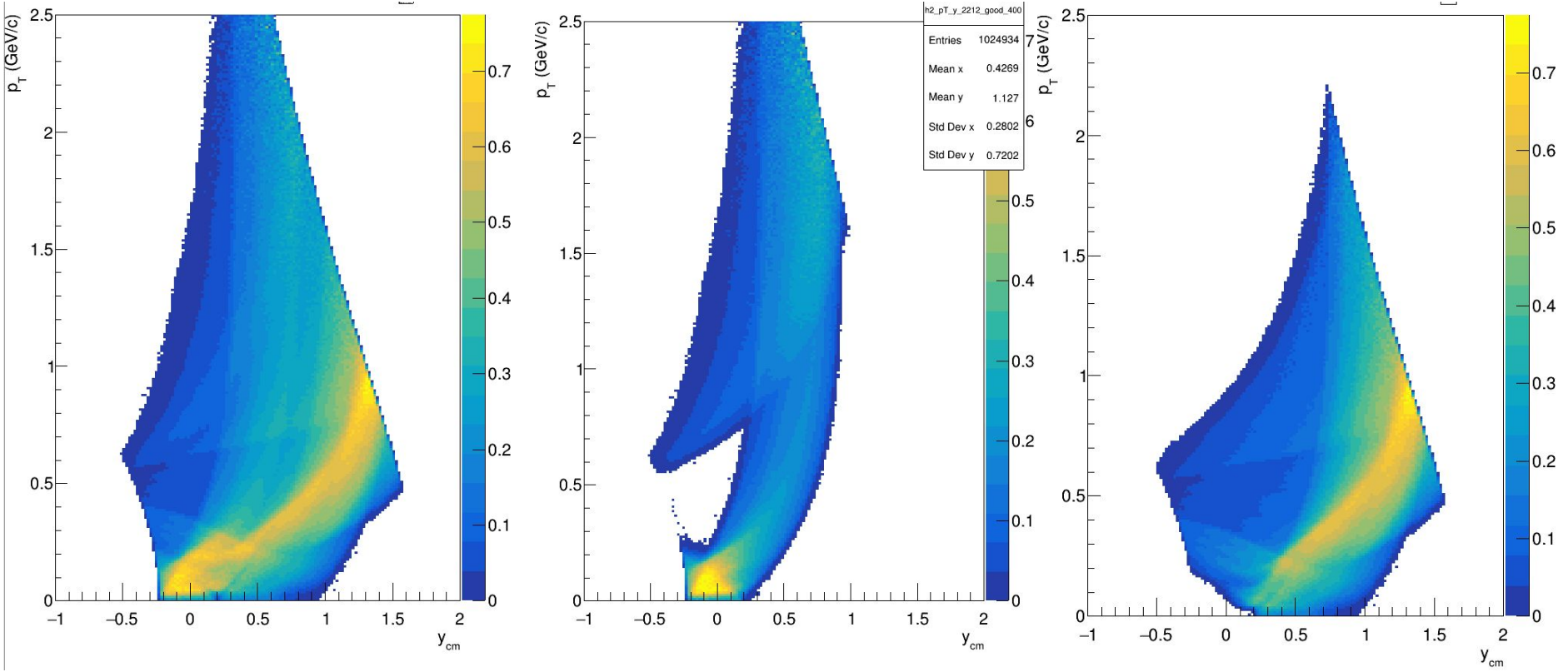




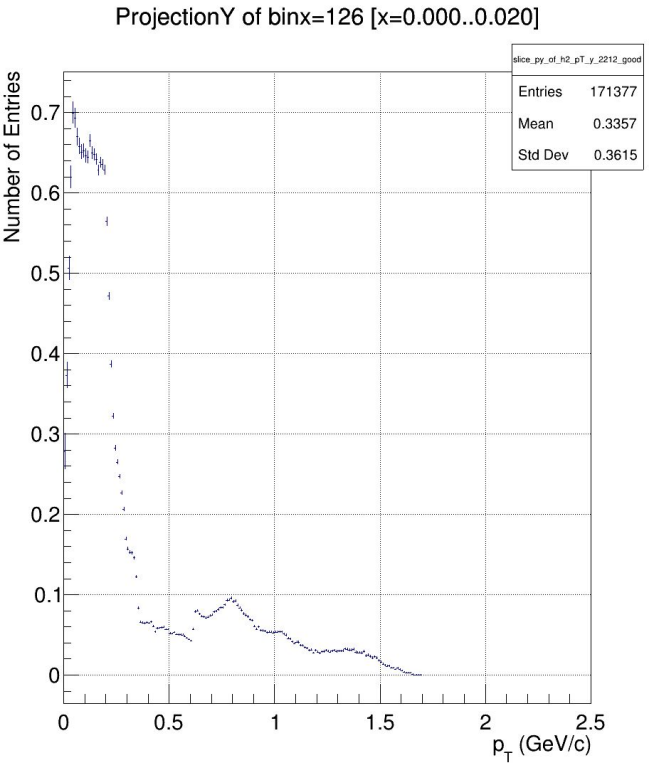
Total momentum resolution for good protons

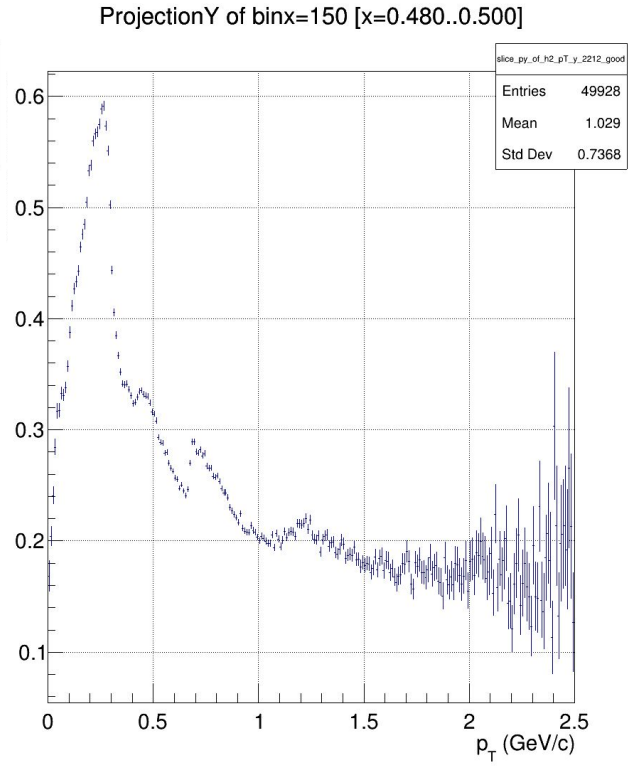


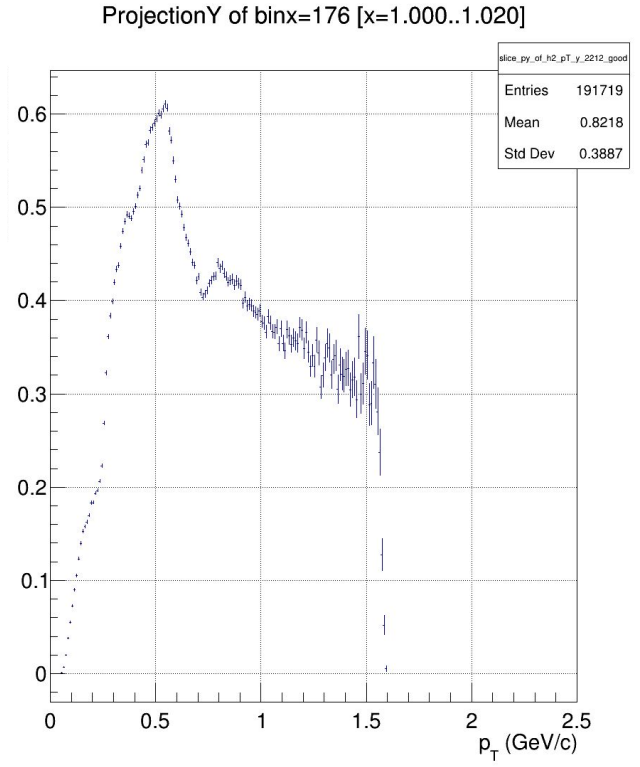
Efficiency plots

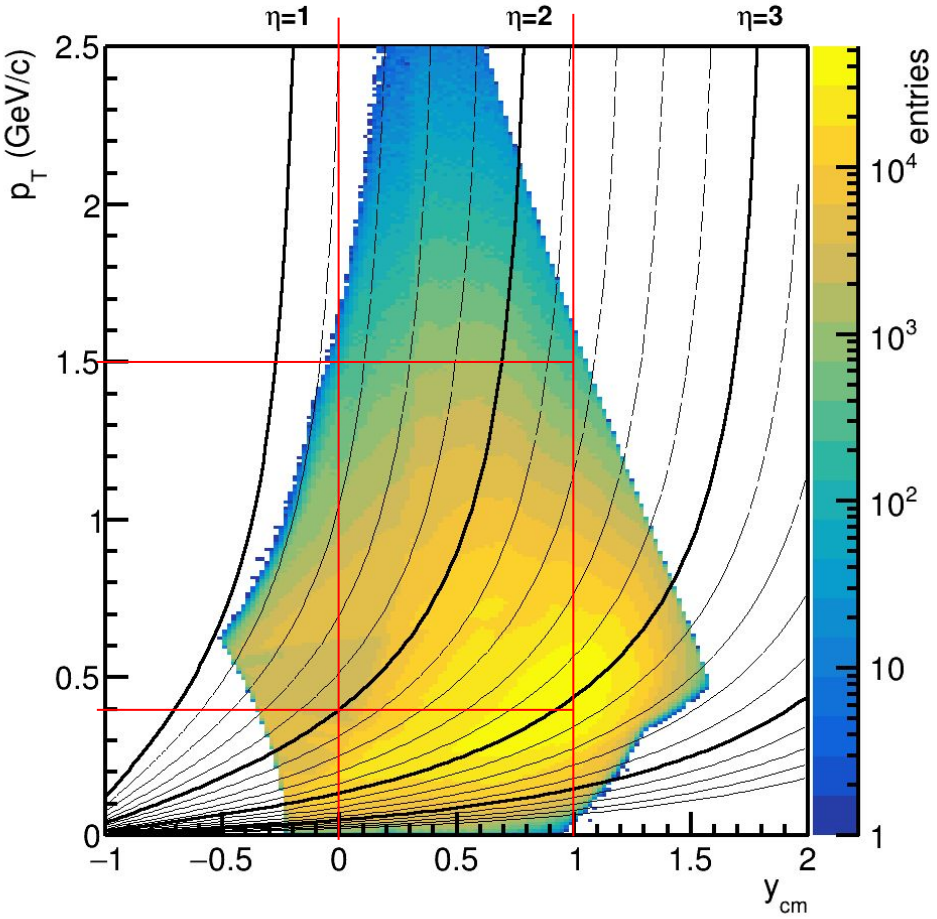


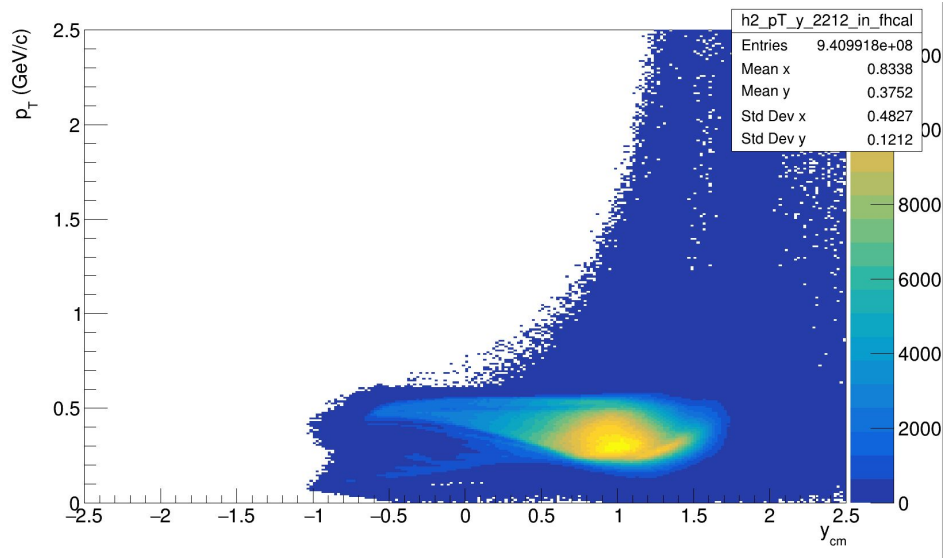
Efficiency projection on pT-axis

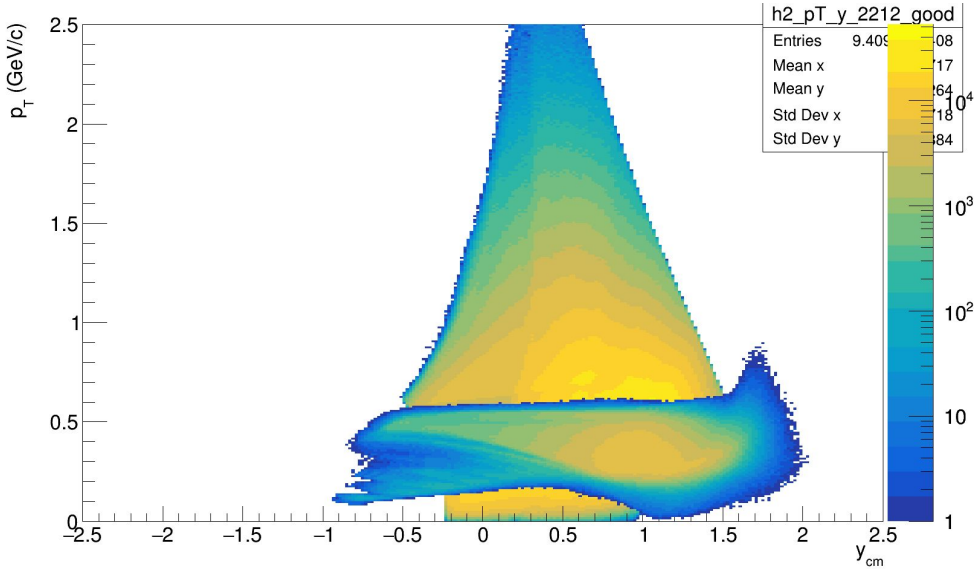


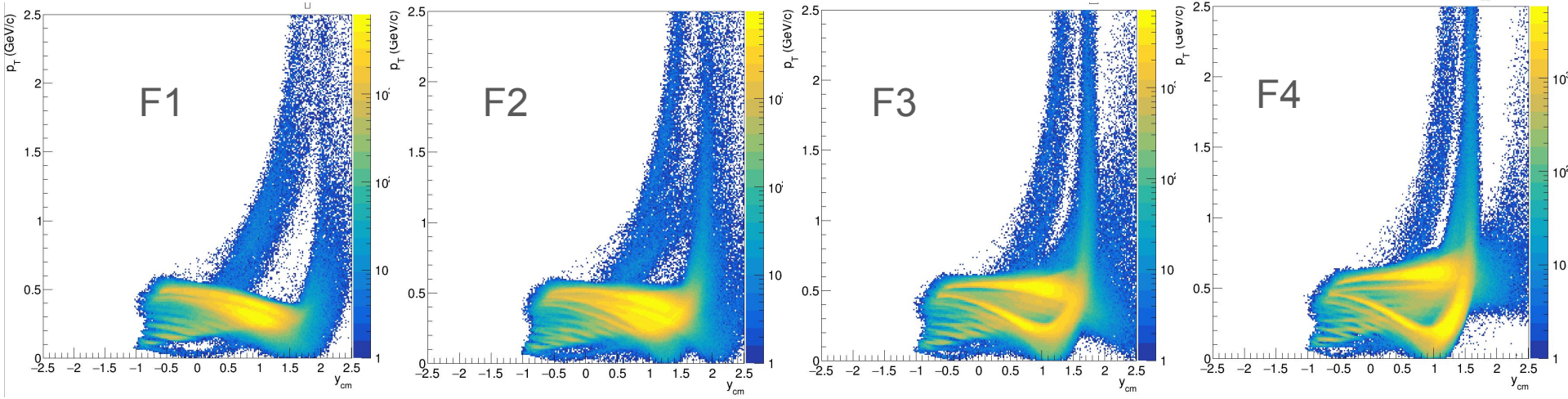


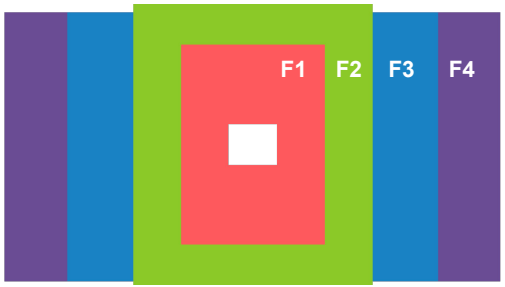


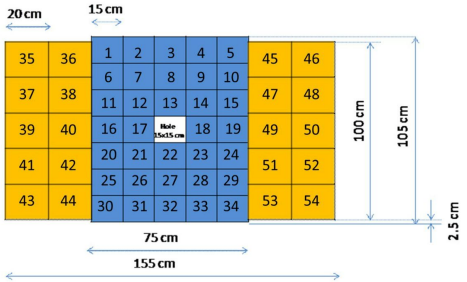

η=1
η=2
η=3
p_T (GeV/c)
2.5
2
1.5
1
0.5
0
−1
−0.5
0
0.5
1
1.5
2
y_cm
entries
10^4
10^3
10^2
10
1

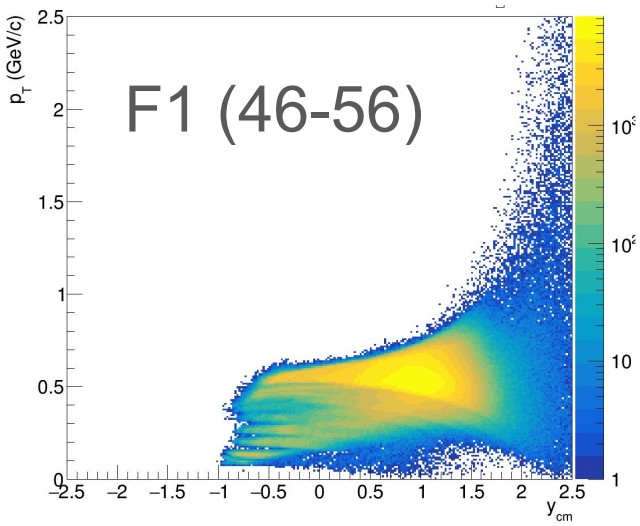

h2_pT_y_2212_in_fhcal
Entries 9.409918e+08
Mean x 0.8338
Mean y 0.3752
Std Dev x 0.4827
Std Dev y 0.1212
p_T (GeV/c)
y_cm

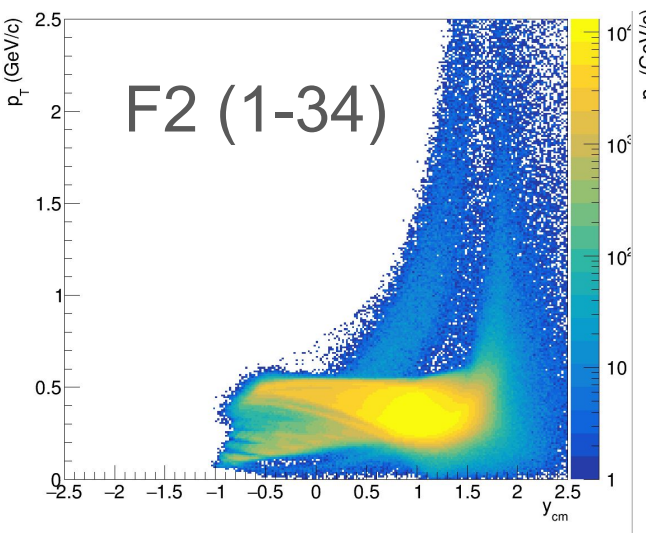

h2_pT_y_2212_good
Entries 9.409
Mean x
Mean y
Std Dev x
Std Dev y
p_T (GeV/c)
y_cm

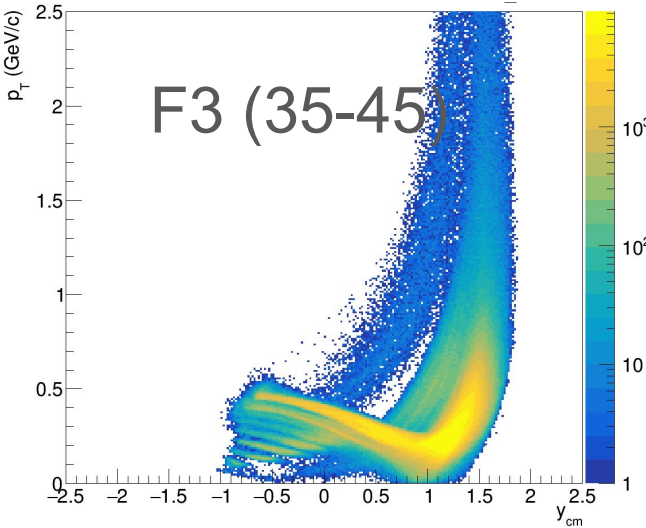

F1
F2
F3
F4
p_T (GeV/c)
y_{cm}

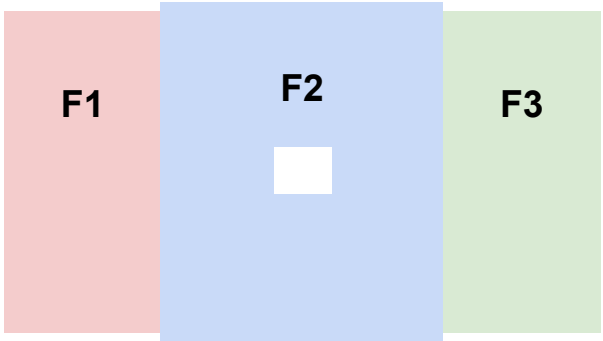

F1
F2
F3
F4

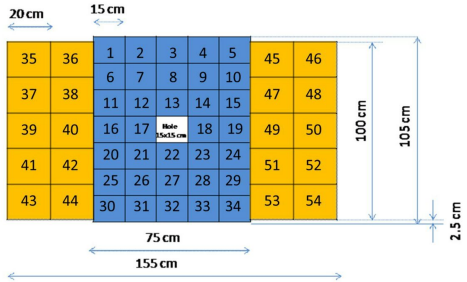

20 cm
15 cm
100 cm
105 cm
2.5 cm
75 cm
155 cm


F1 (46-56)
p_T (GeV/c)
y_{cm}

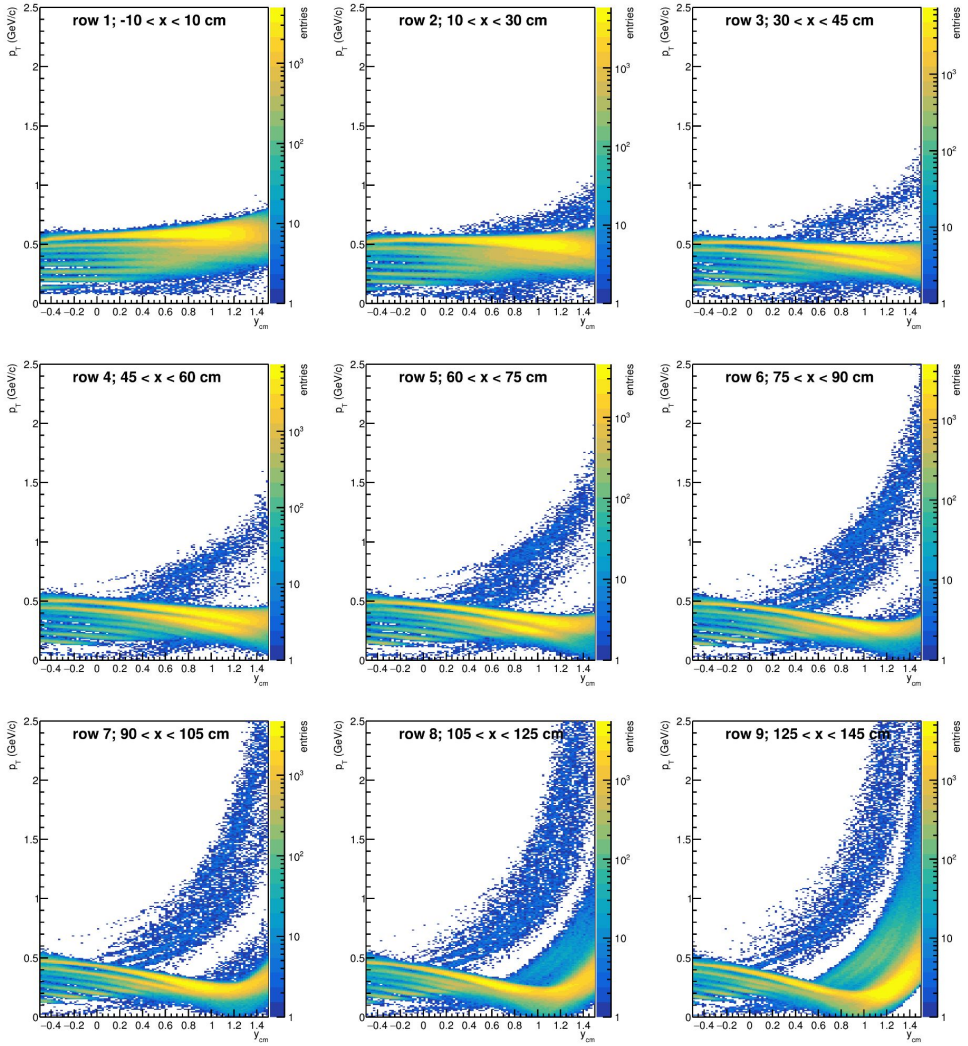

F2 (1-34)
p_T (GeV/c)
y_{cm}

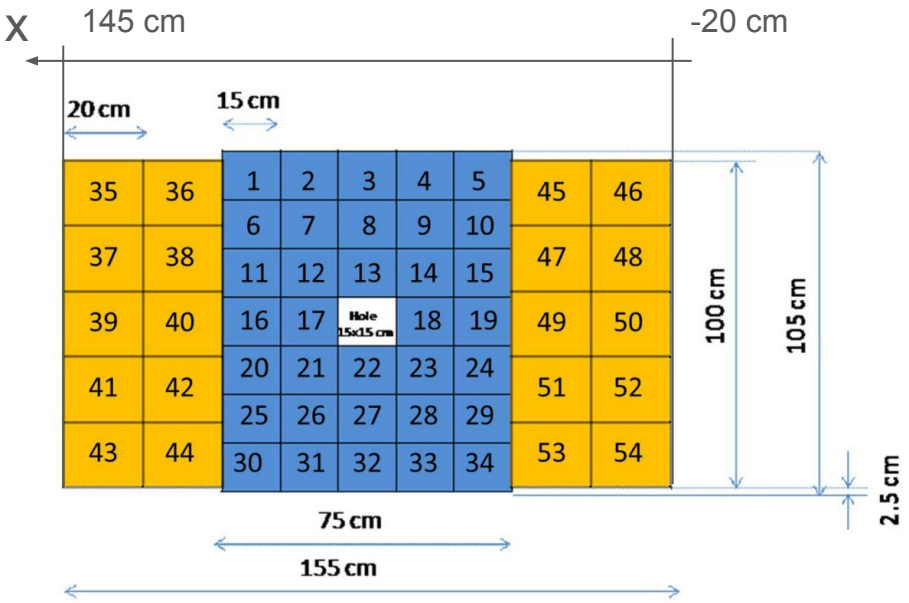

F3 (35-45)
p_T (GeV/c)
y_{cm}


F1
F2
F3

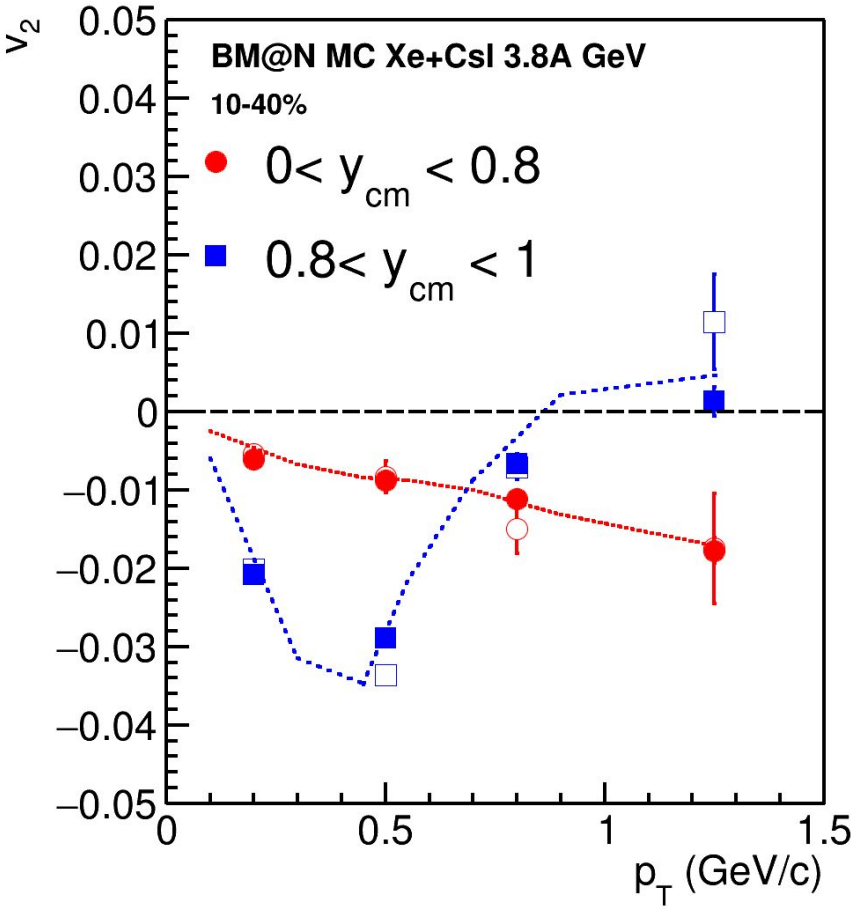

20 cm
15 cm
100 cm
105 cm
2.5 cm
75 cm
155 cm

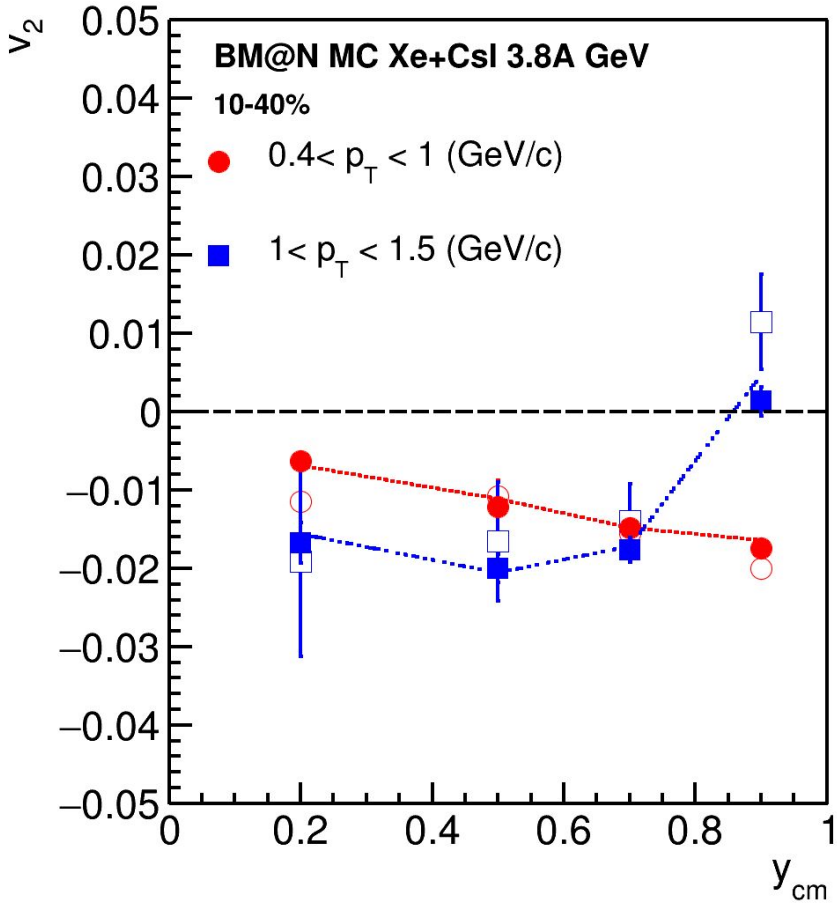



row 1; -10 < x < 10 cm
row 2; 10 < x < 30 cm
row 3; 30 < x < 45 cm
row 4; 45 < x < 60 cm
row 5; 60 < x < 75 cm
row 6; 75 < x < 90 cm
row 7; 90 < x < 105 cm
row 8; 105 < x < 125 cm
row 9; 125 < x < 145 cm
p_T (GeV/c)
y_cm
entries

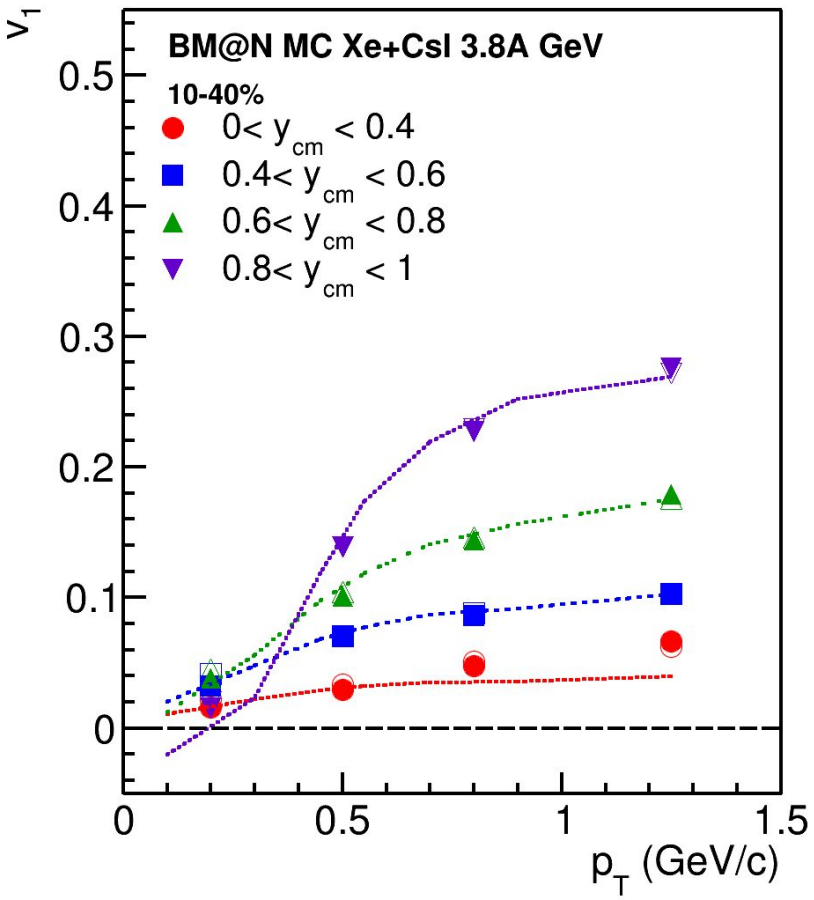

x
145 cm
-20 cm
20 cm
15 cm
35 36 1 2 3 4 5 45 46
37 38 6 7 8 9 10 47 48
39 40 11 12 13 14 15 49 50
41 42 16 17 Hole 15x15 cm 18 19 51 52
43 44 20 21 22 23 24 53 54
25 26 27 28 29
30 31 32 33 34
100 cm
105 cm
2.5 cm
75 cm
155 cm

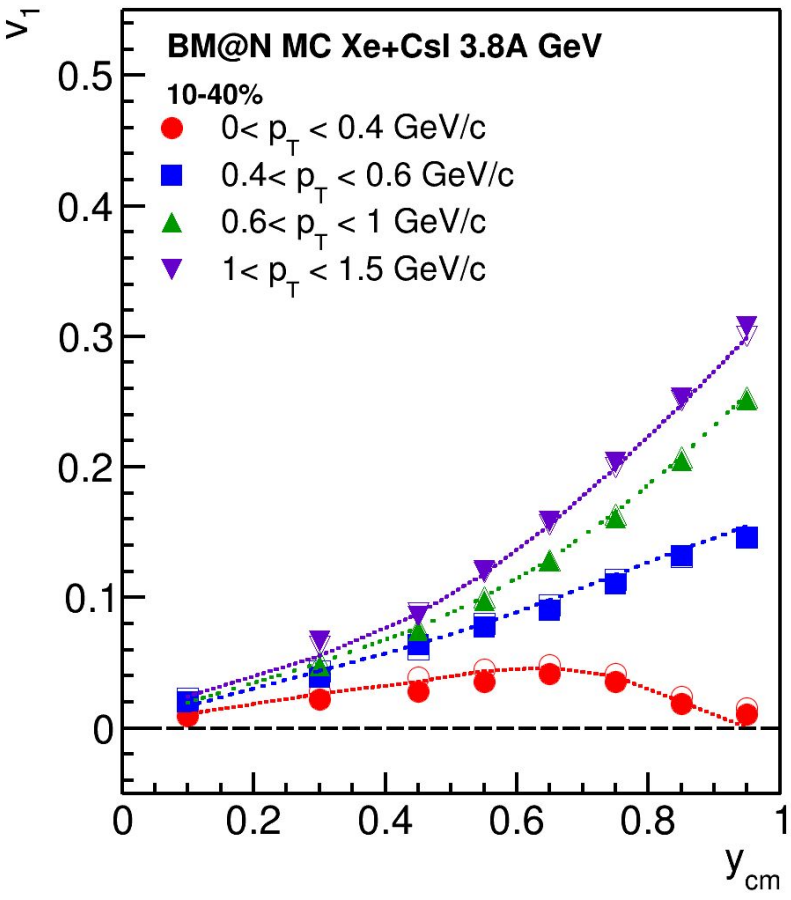
v_2 of protons wrt Reaction Plane (PCA h4)

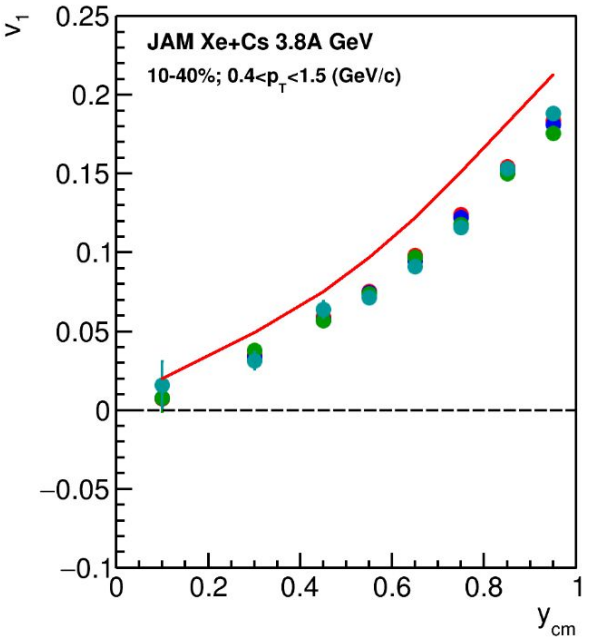


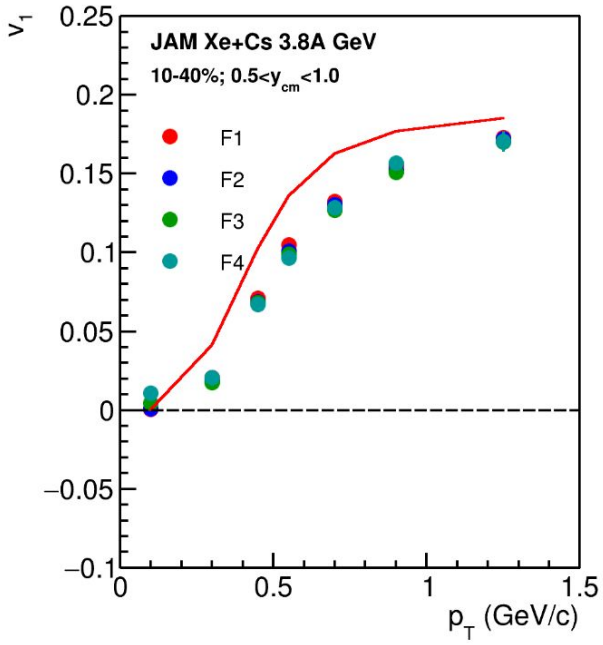


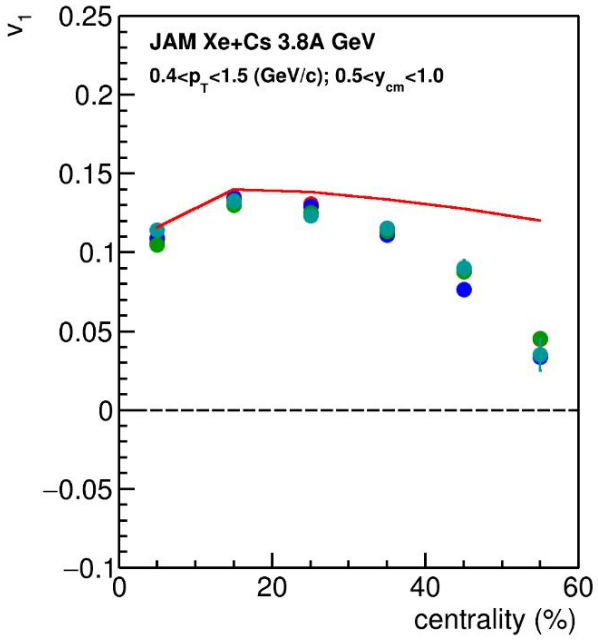
v_1 of protons wrt Reaction Plane (PCA h4)

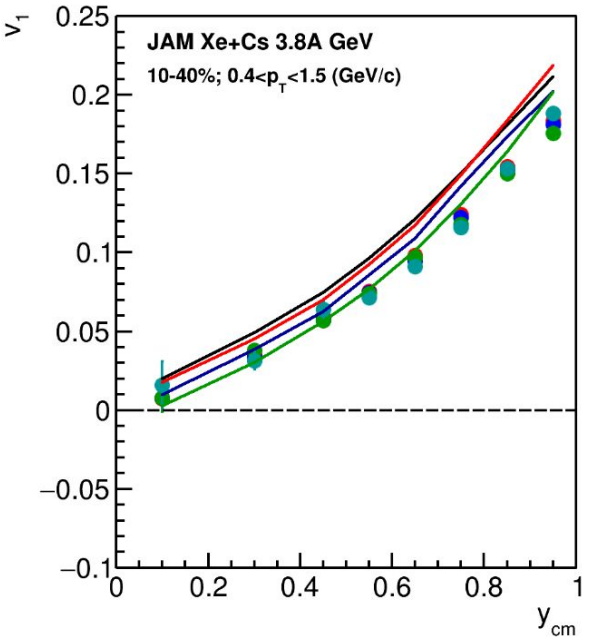


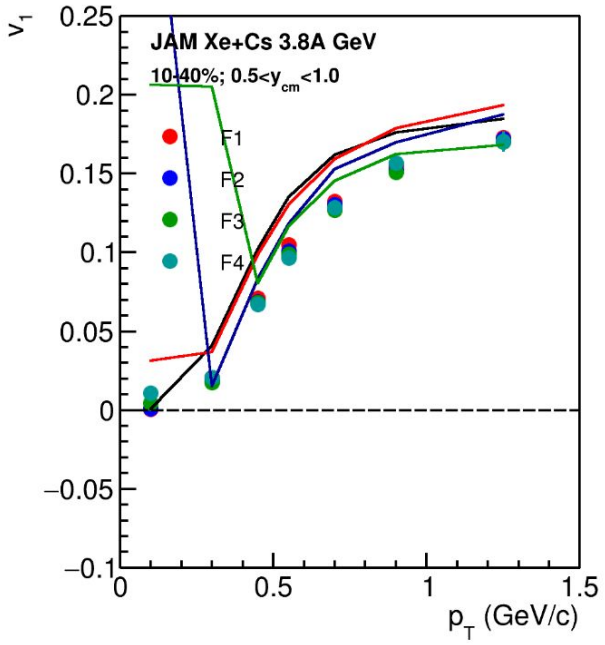


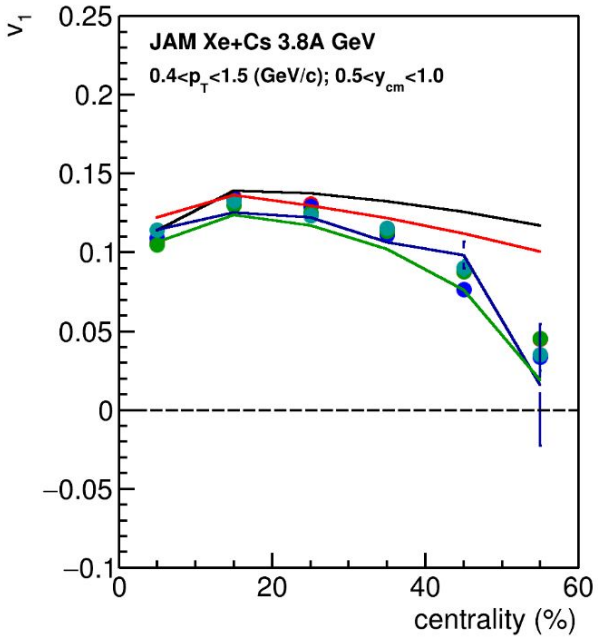

JAM Xe+Cs 3.8A GeV
10-40%; 0.4<p_T<1.5 (GeV/c)
v_1
y_cm

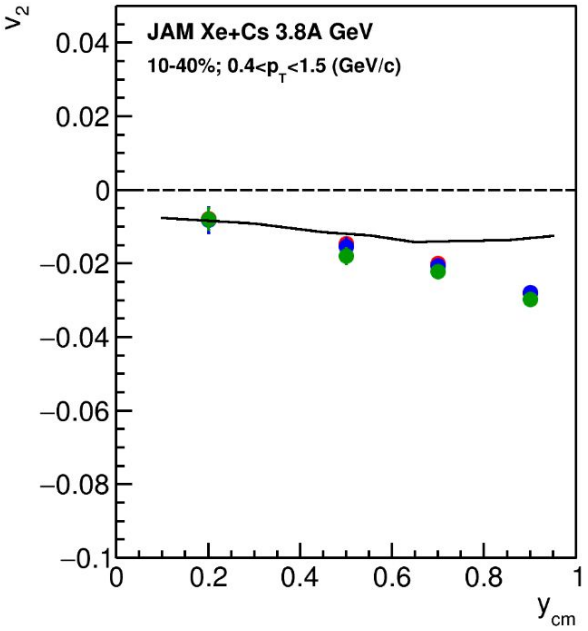

JAM Xe+Cs 3.8A GeV
10-40%; 0.5<y_cm<1.0
F1
F2
F3
F4
v_1
p_T (GeV/c)

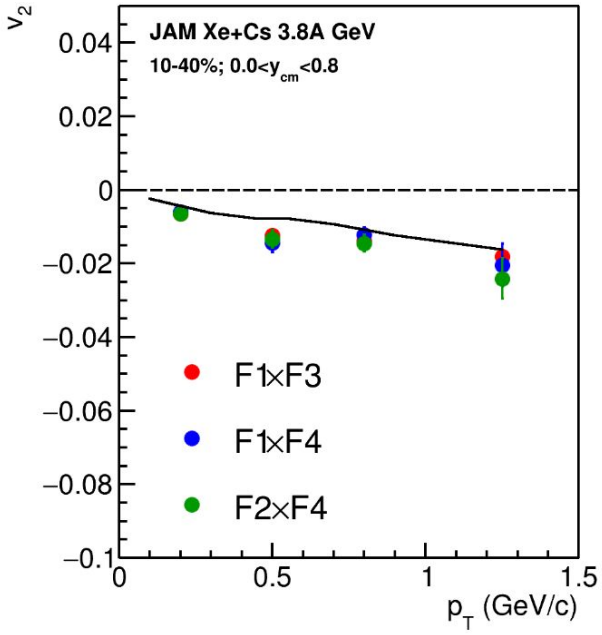

JAM Xe+Cs 3.8A GeV
0.4<p_T<1.5 (GeV/c); 0.5<y_cm<1.0
v_1
centrality (%)

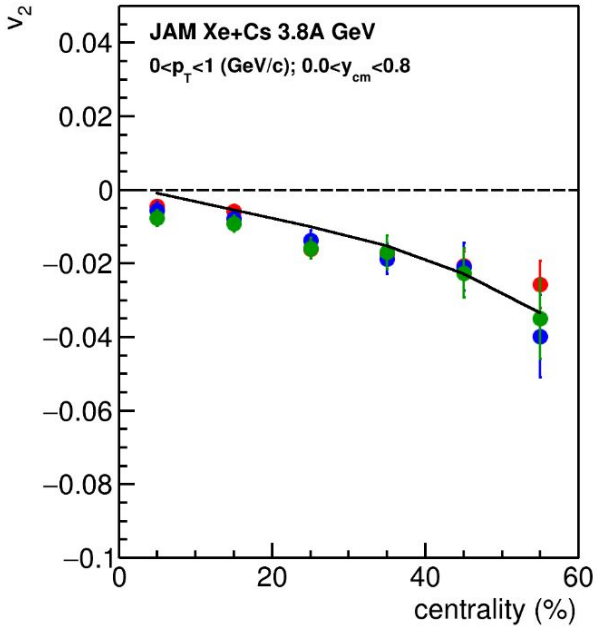

JAM Xe+Cs 3.8A GeV
10-40%; 0.4<p_T<1.5 (GeV/c)
v_1
y_cm

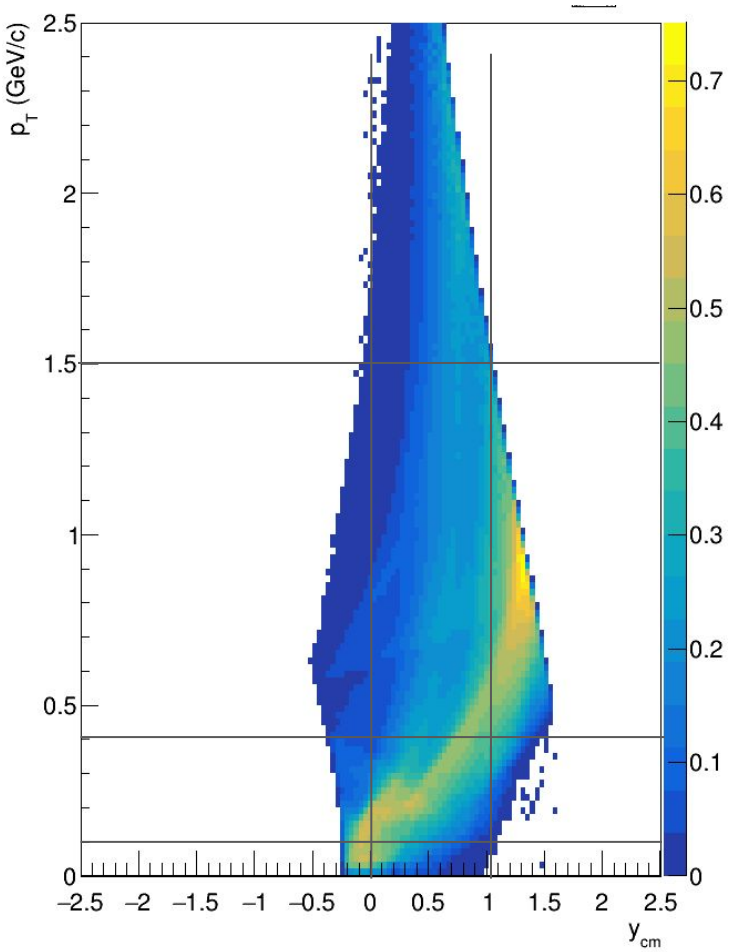

JAM Xe+Cs 3.8A GeV
10-40%; 0.5<y_cm<1.0
F1
F2
F3
F4
v_1
p_T (GeV/c)


JAM Xe+Cs 3.8A GeV
0.4<p_T<1.5 (GeV/c); 0.5<y_cm<1.0
v_1
centrality (%)

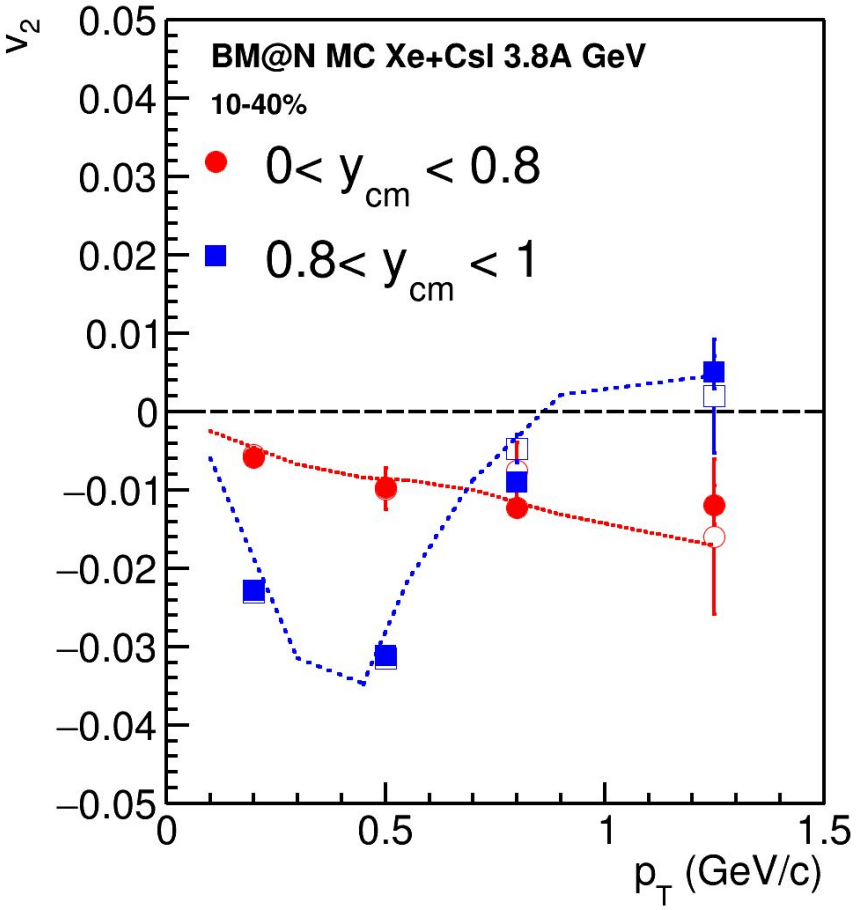

JAM Xe+Cs 3.8A GeV
10-40%; 0.4<p_T<1.5 (GeV/c)
v_2
y_cm

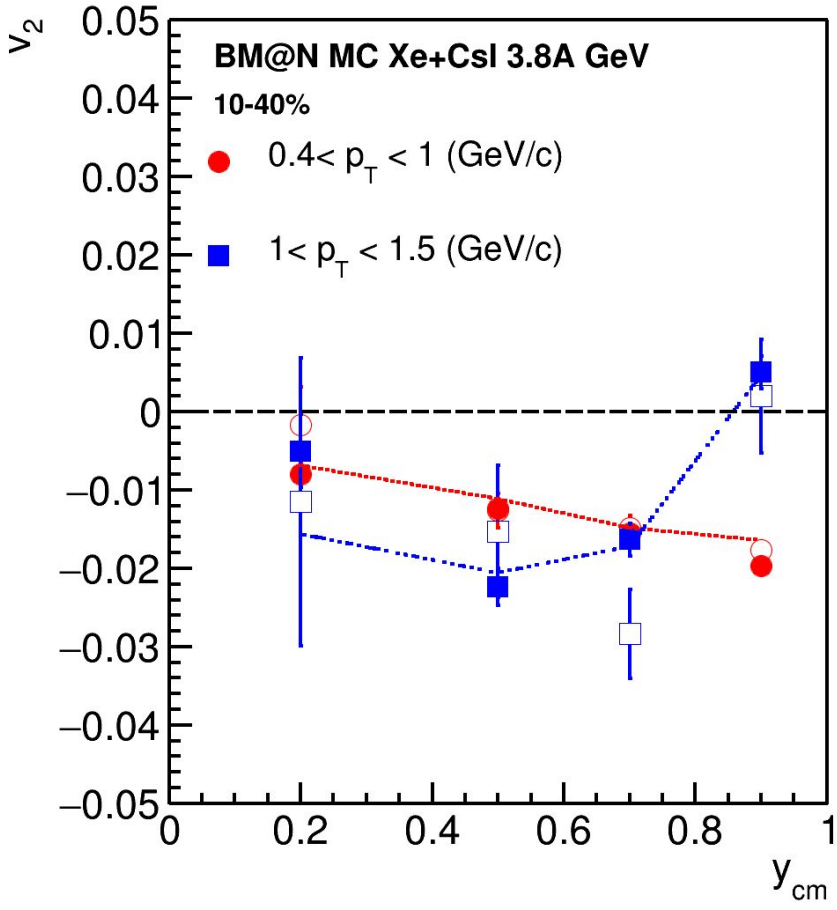

JAM Xe+Cs 3.8A GeV
10-40%; 0.0<y_cm<0.8
F1×F3
F1×F4
F2×F4
v_2
p_T (GeV/c)


JAM Xe+Cs 3.8A GeV
0<p_T<1 (GeV/c); 0.0<y_cm<0.8
v_2
centrality (%)

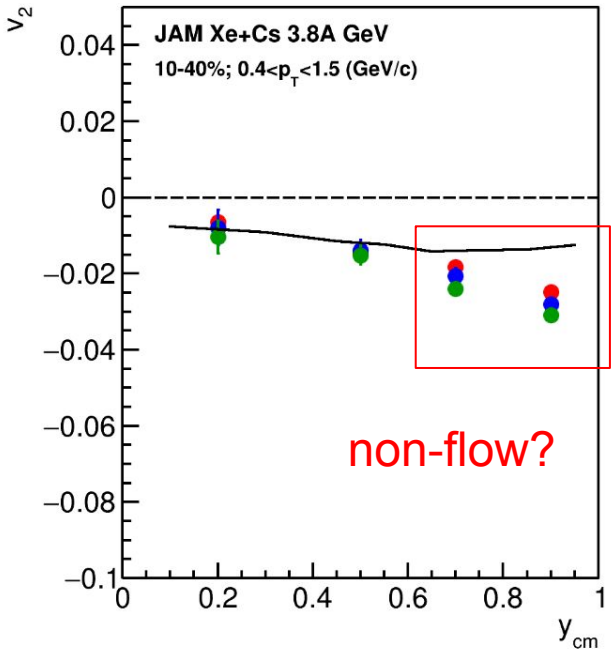

p_T (GeV/c)
2.5
2
1.5
1
0.5
0
−2.5 −2 −1.5 −1 −0.5 0 0.5 1 1.5 2 2.5
y_{cm}
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

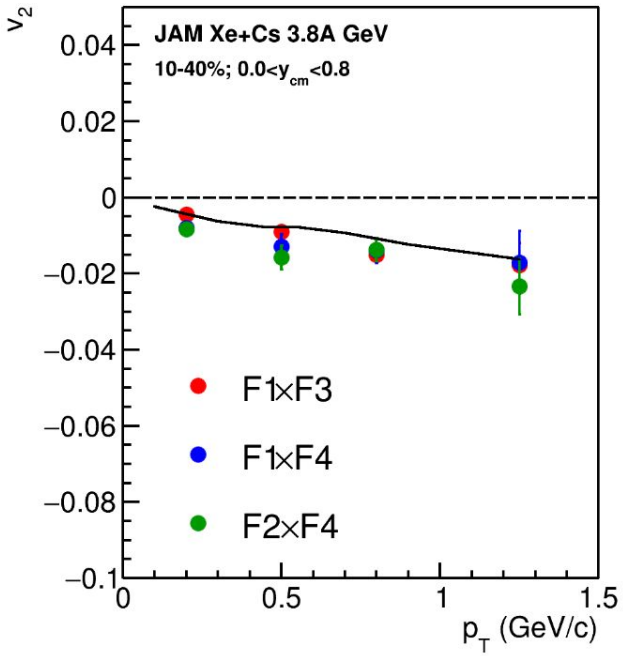
v_2 of protons wrt Reaction Plane (PCA h4)

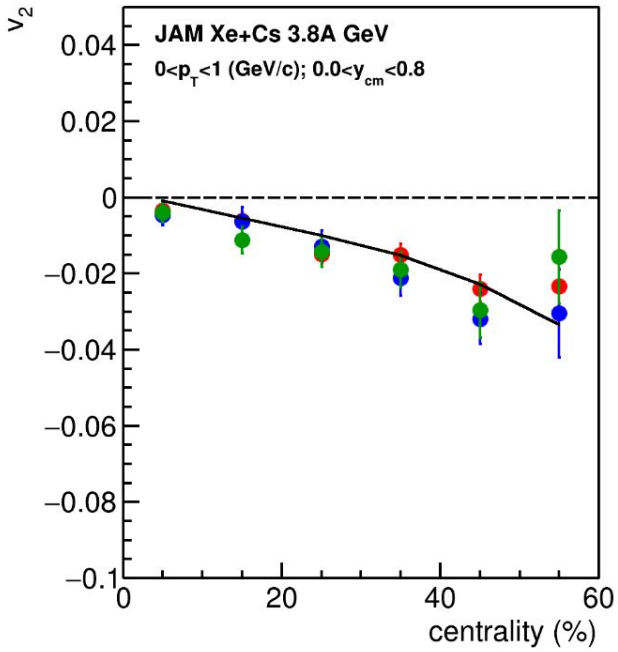




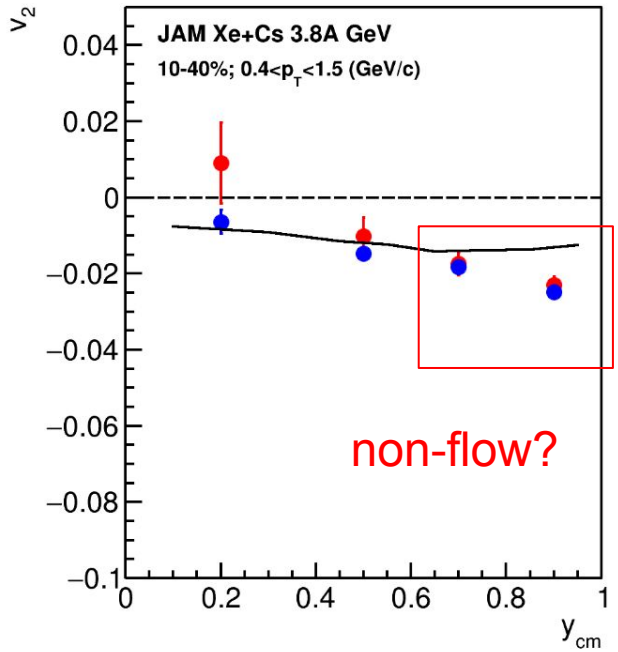
v_2 of protons wrt FHCal symmetry planes (PCA h4)

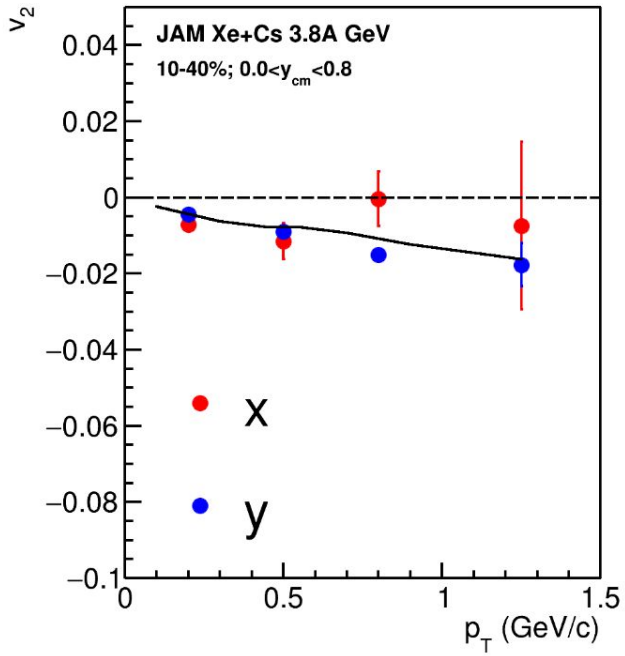


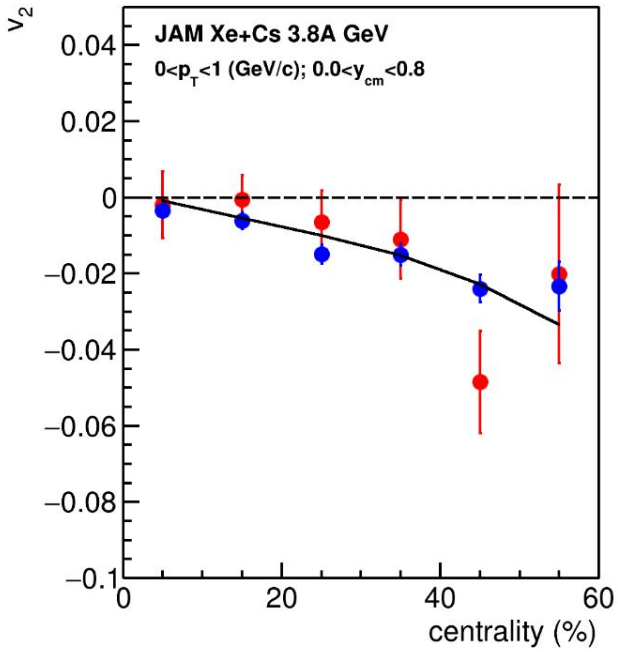




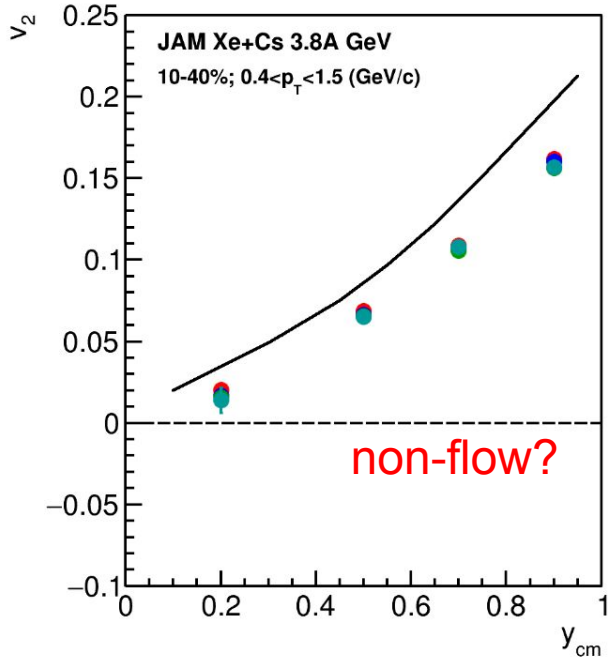
v_2 of protons with different components (PCA h4)

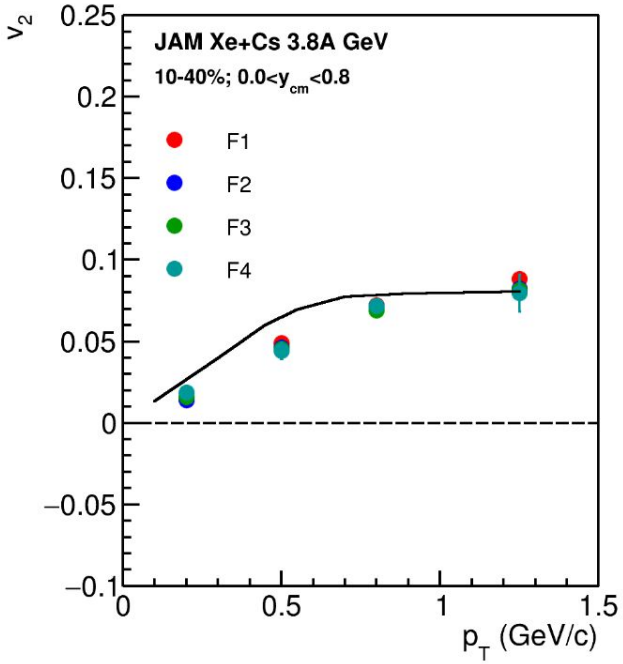


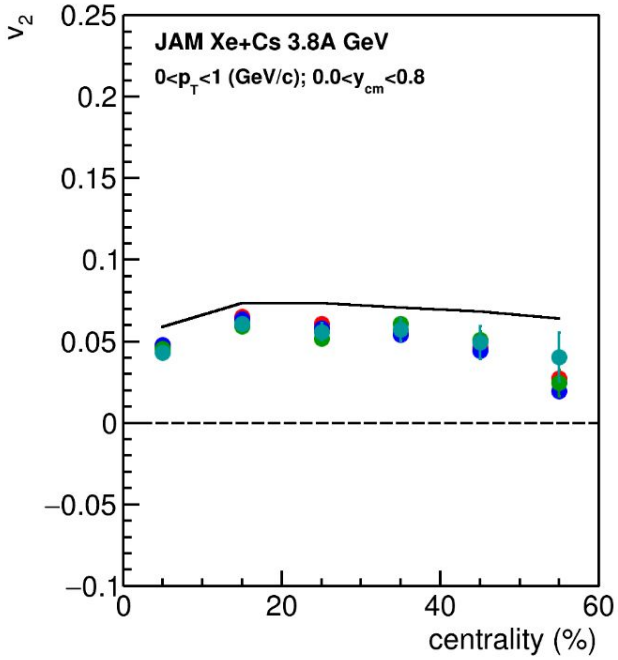




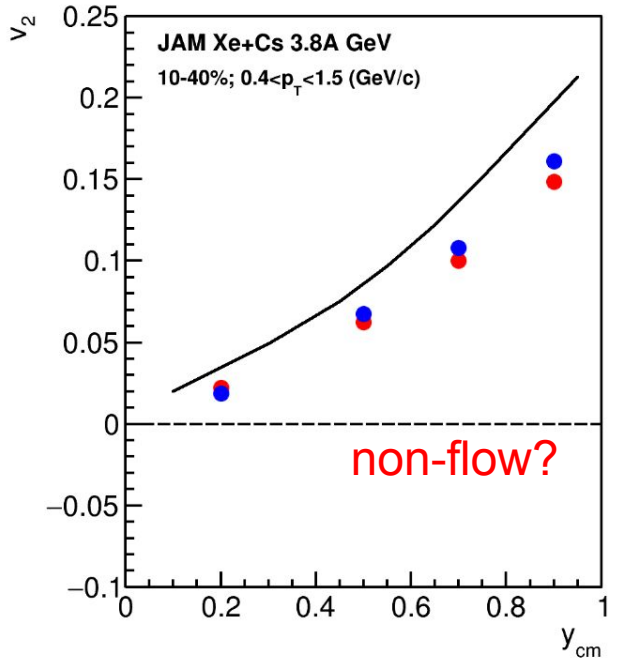
v_2 of protons wrt FHCal symmetry planes (PCA h4)

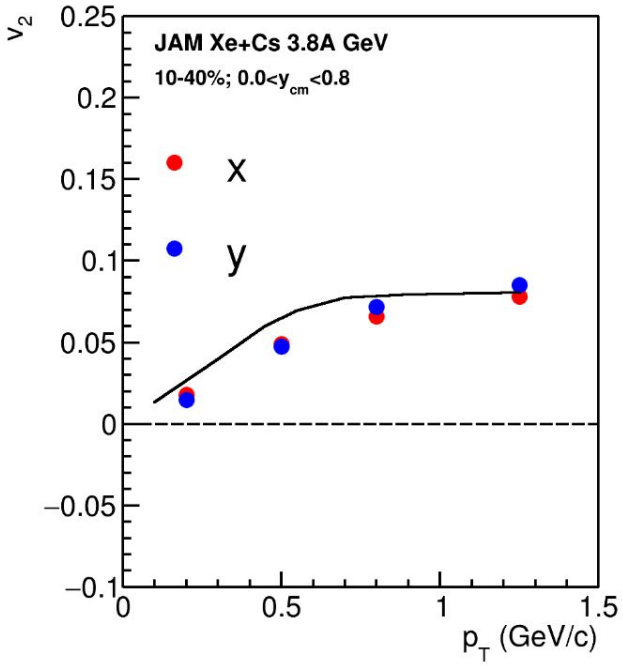


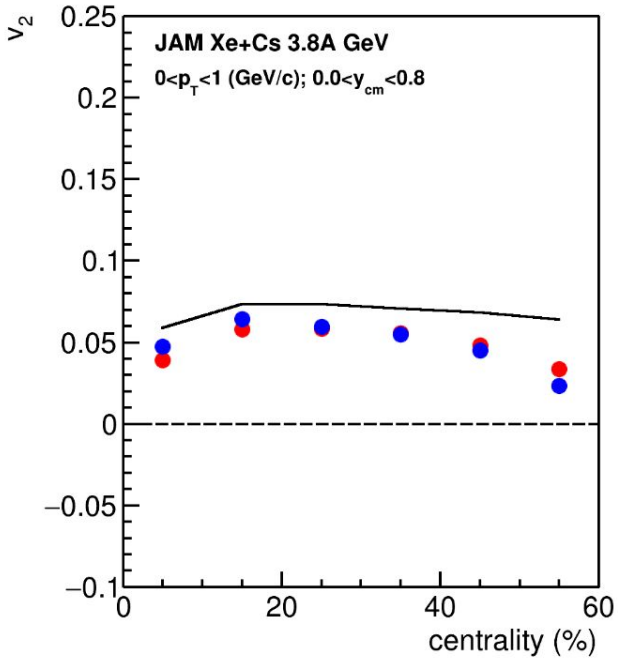


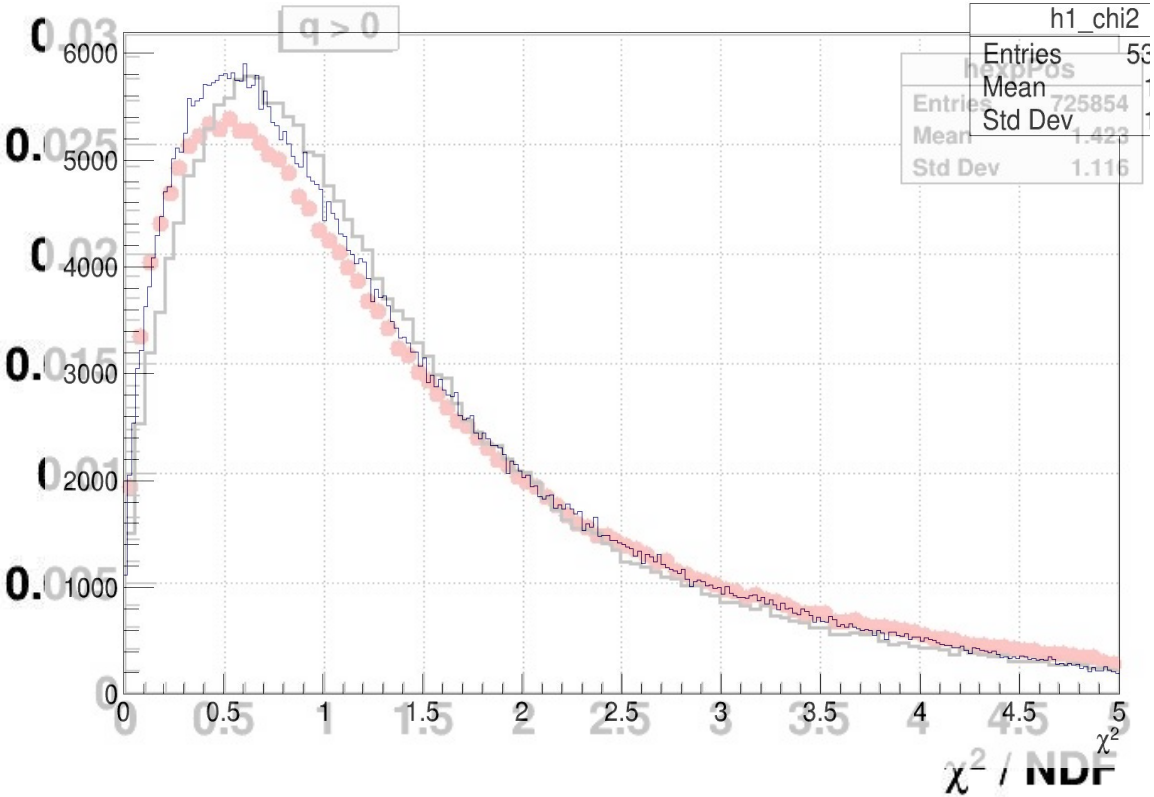


v_2 of protons wrt FHCal symmetry planes (PCA h4)

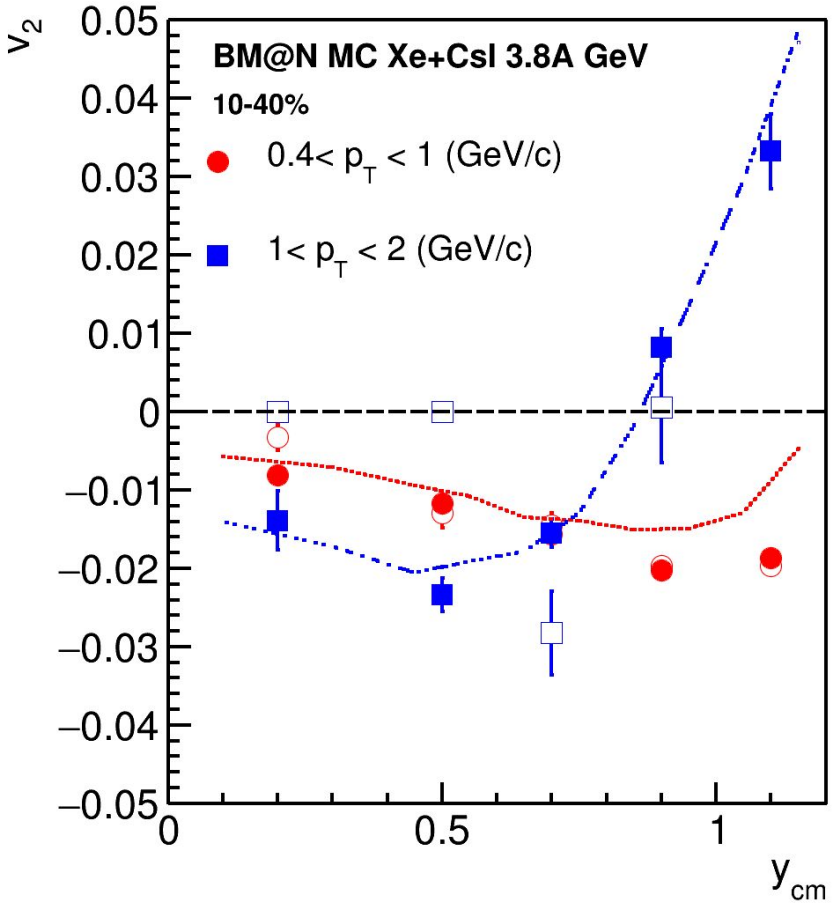


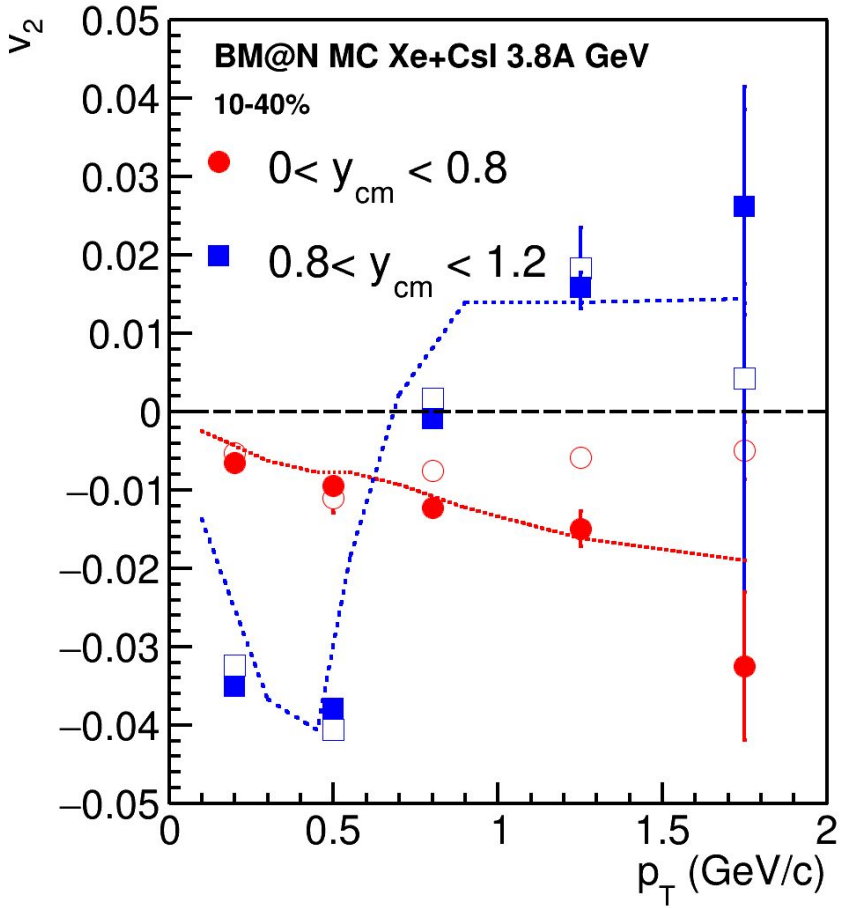




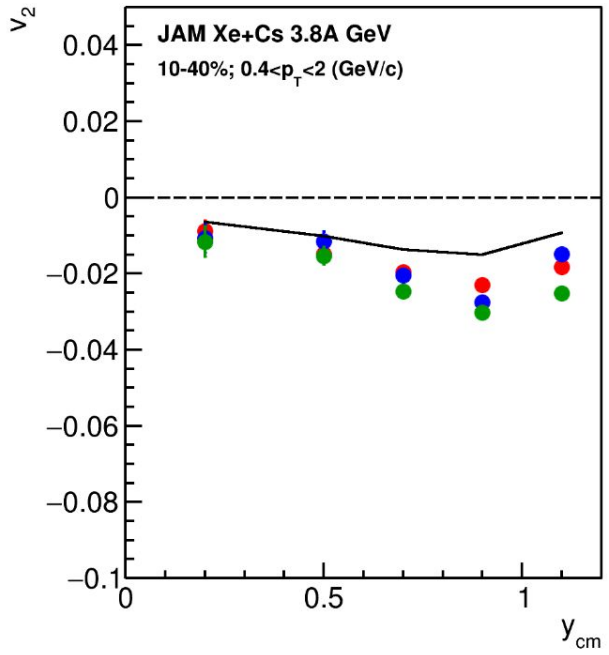

q > 0
h1_chi2
Entries
Mean
Std Dev
hExpPos
Entries 725854
Mean 1.423
Std Dev 1.116
6000
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
χ²
χ² / NDF

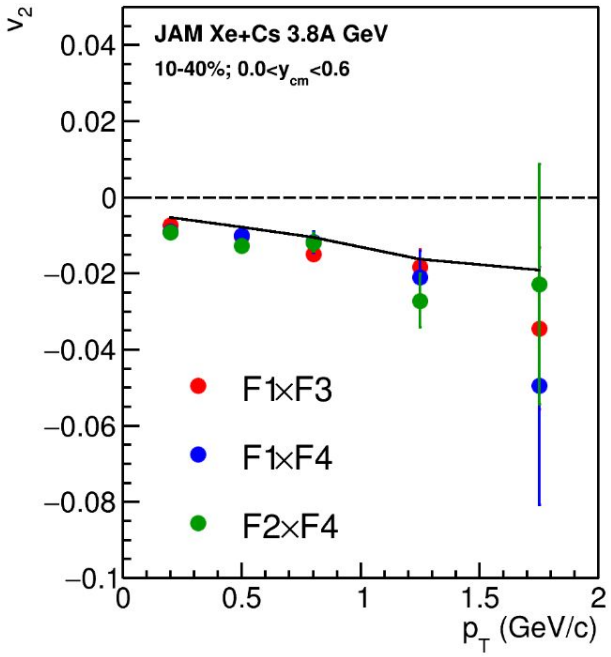
v_2 of protons wrt Reaction Plane

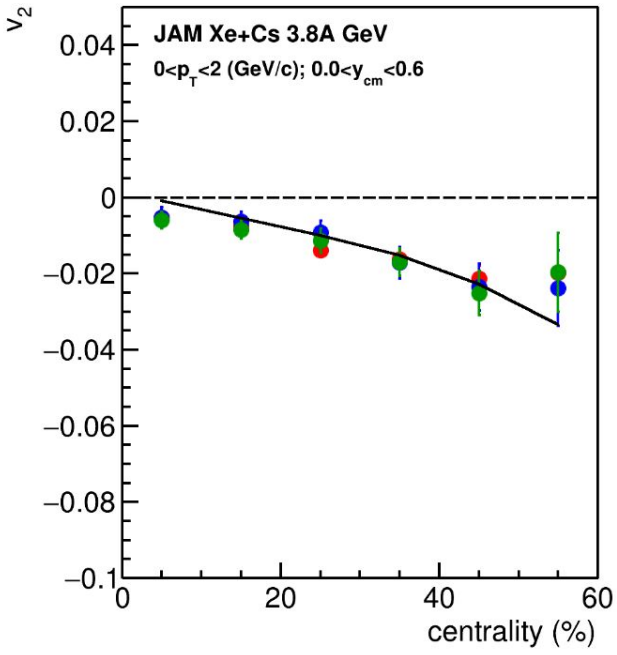




v_2 of protons wrt FHCal symmetry planes

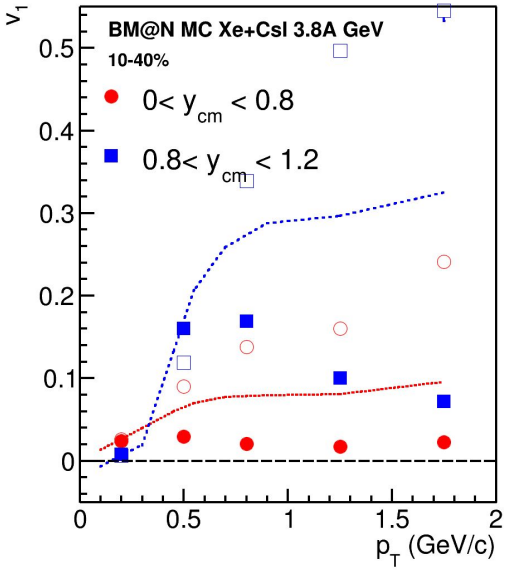




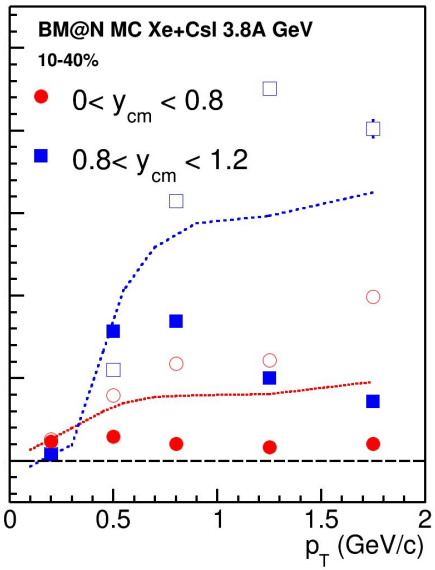


Correction comparison: v1

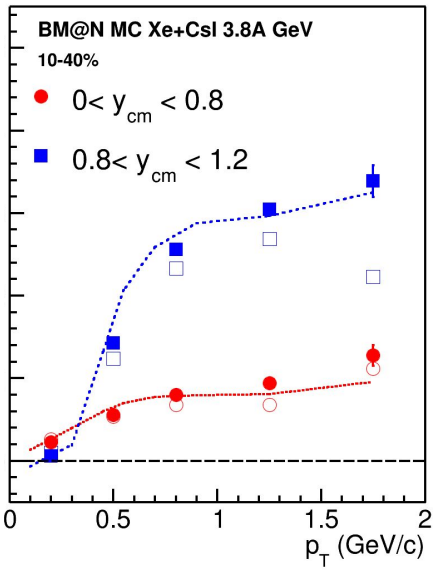
plain



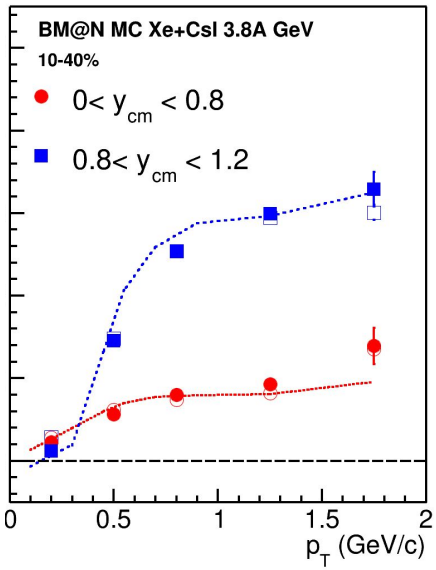
recentered



twist+resc.

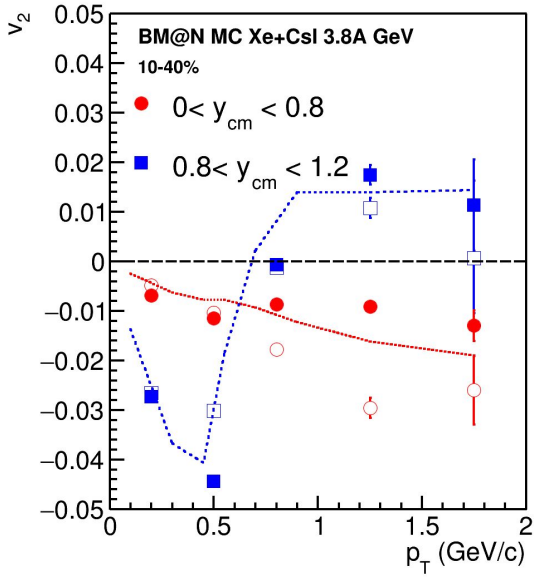


pca (2 harm)

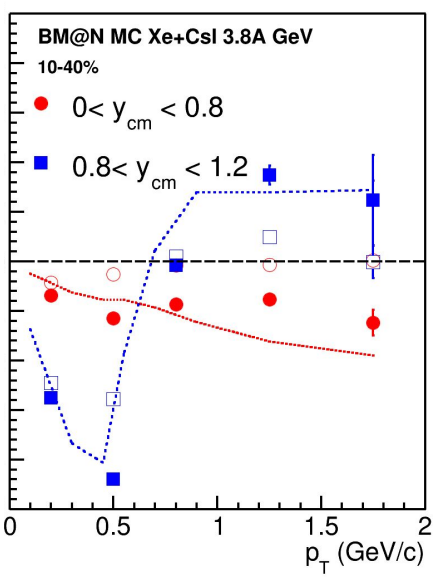


Correction comparison: v2

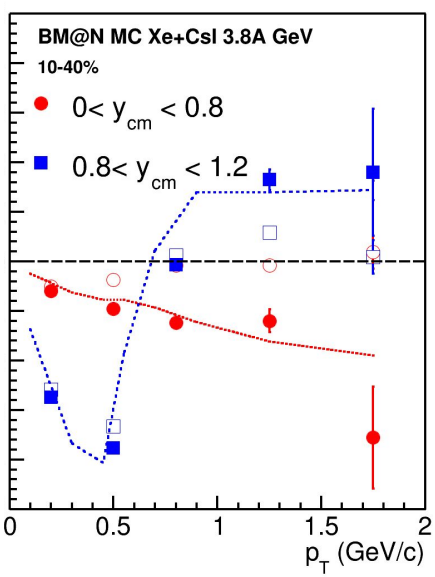
plain



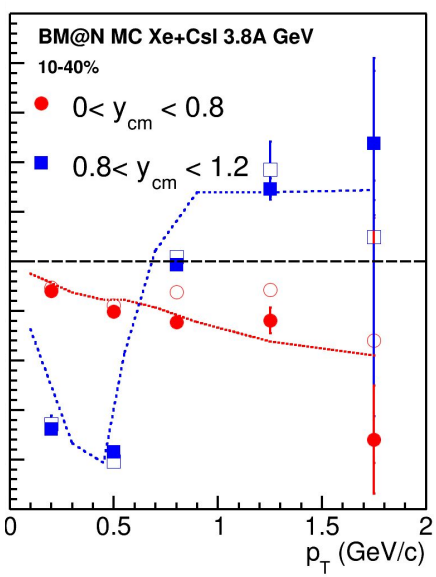
recentered



twist+resc.

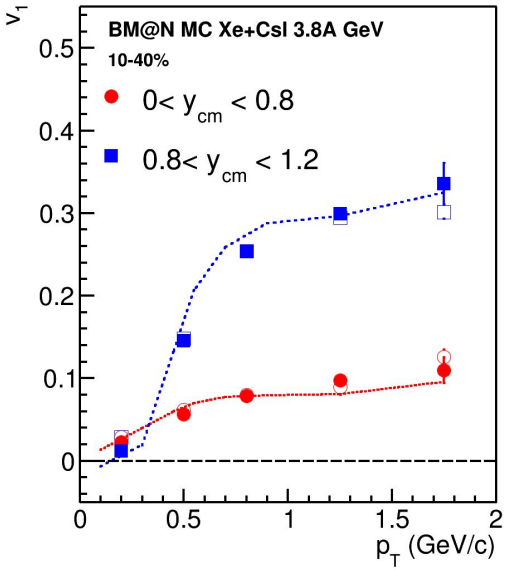


pca (2 harm)

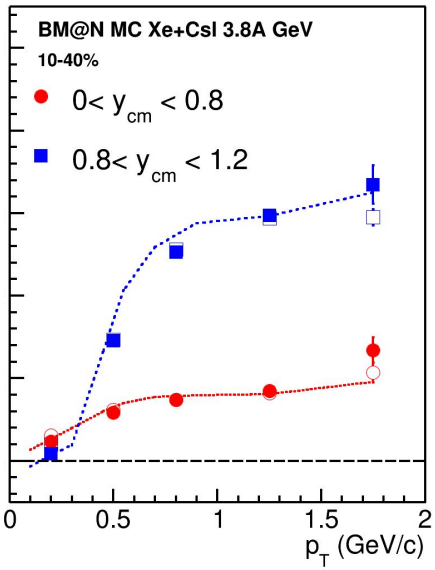


Correction comparison: v1

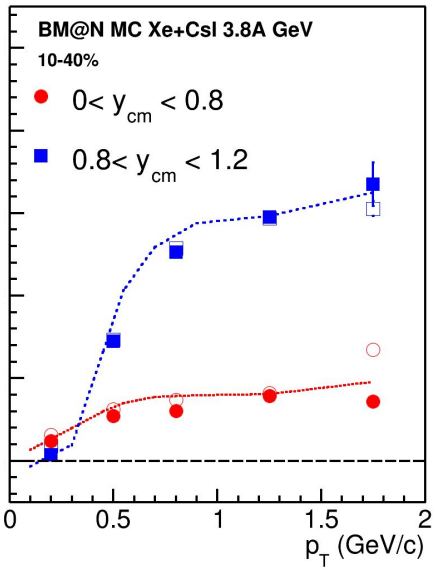
2 harm



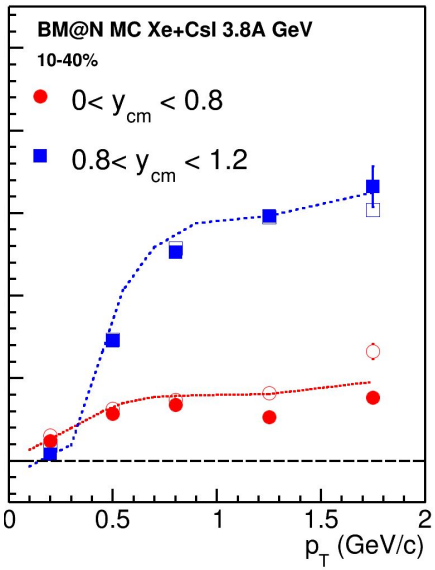
4 harm



8 harm

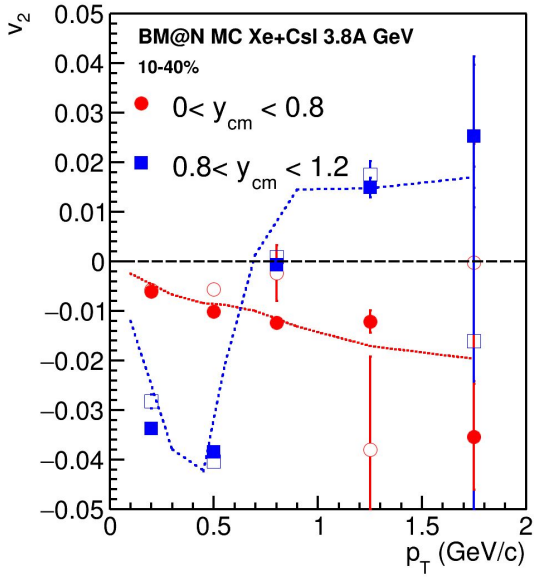


16 harm

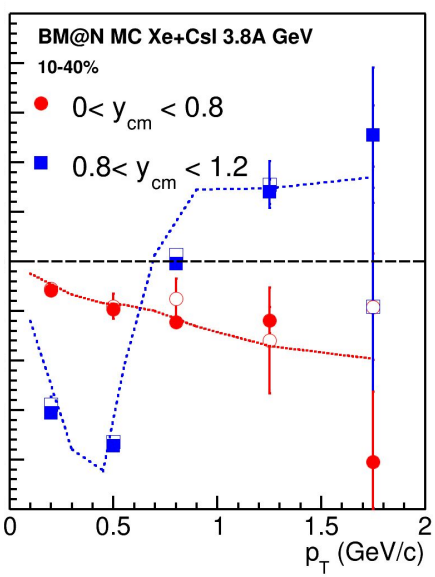


Correction comparison: v2

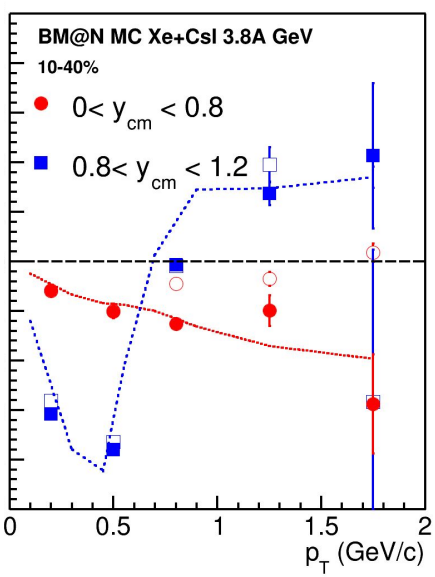
2 harm



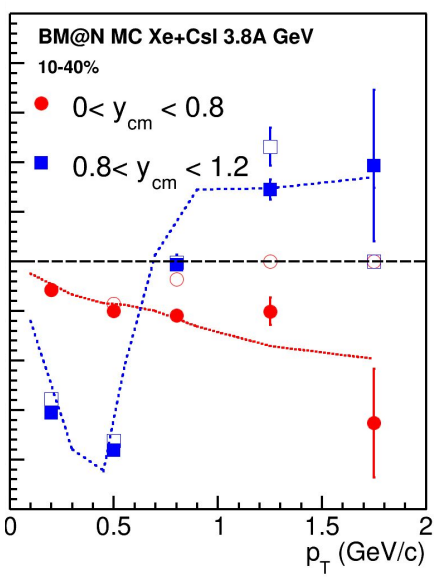
4 harm



8 harm

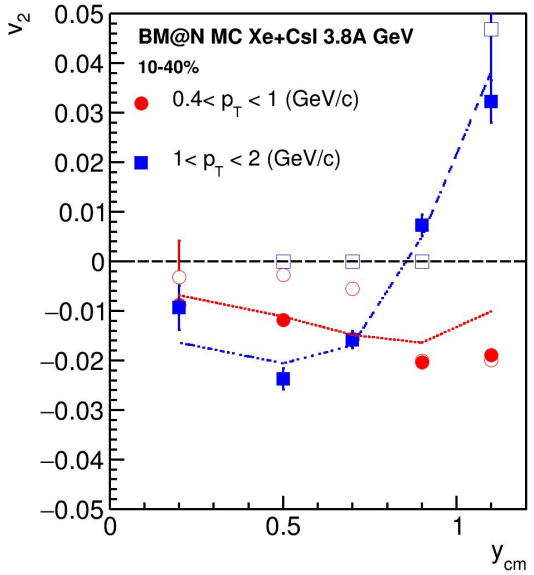


16 harm



Correction comparison: v2

2 harm



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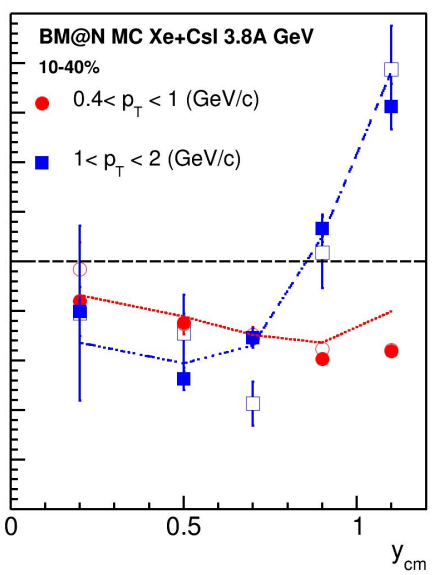
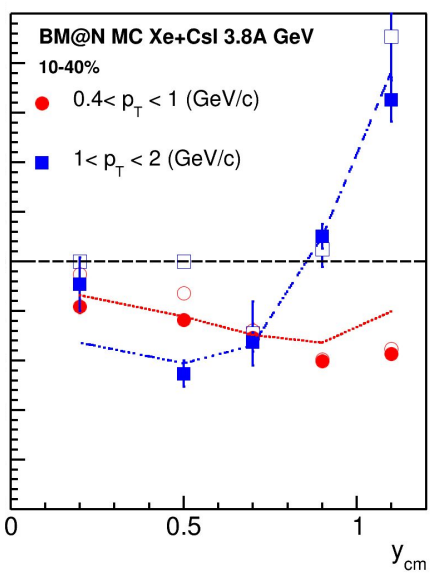
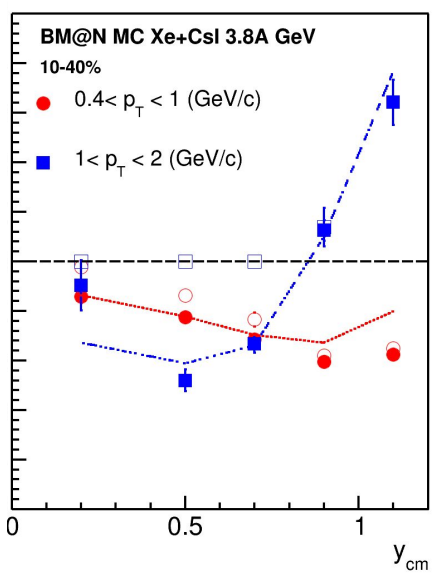
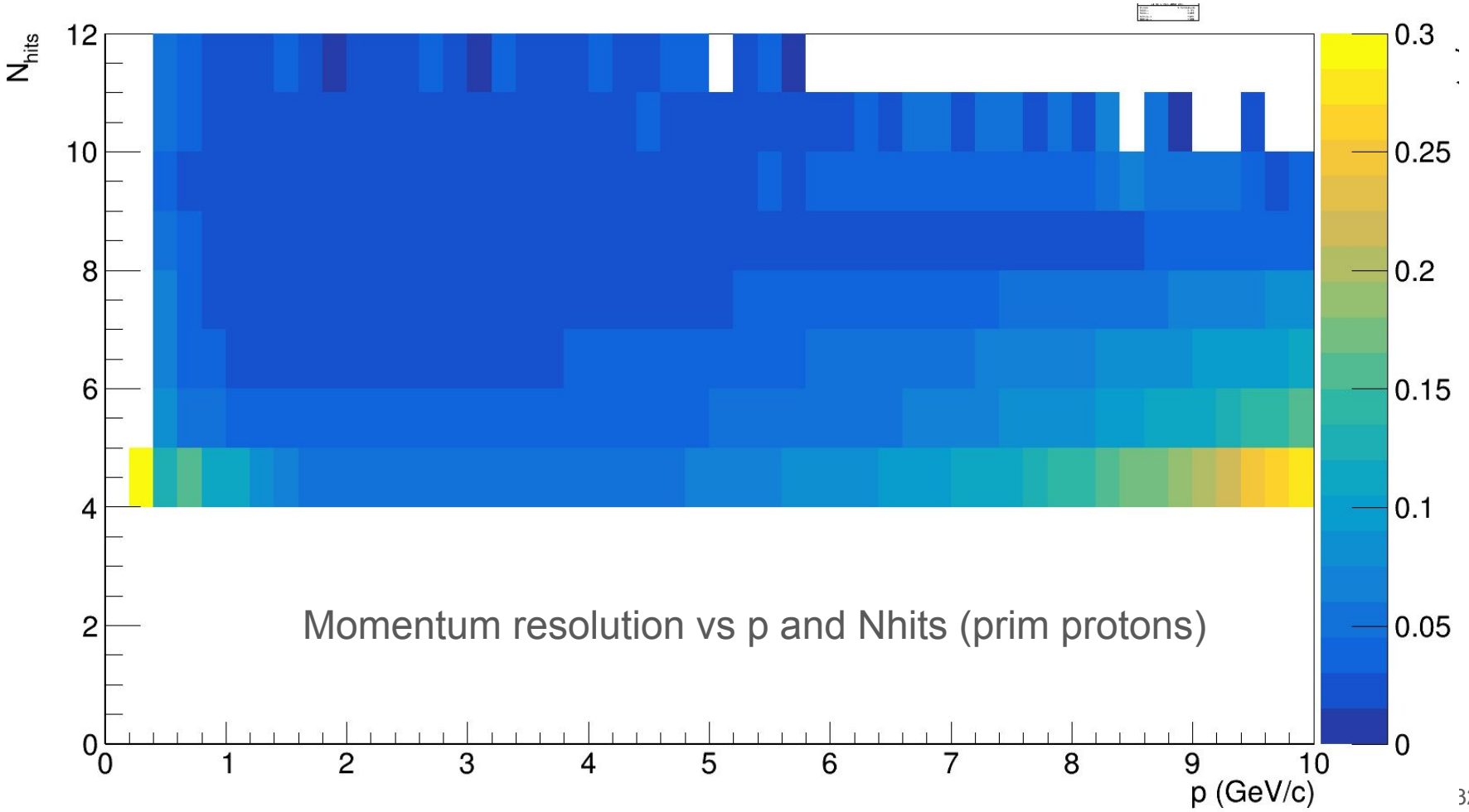


8 harm

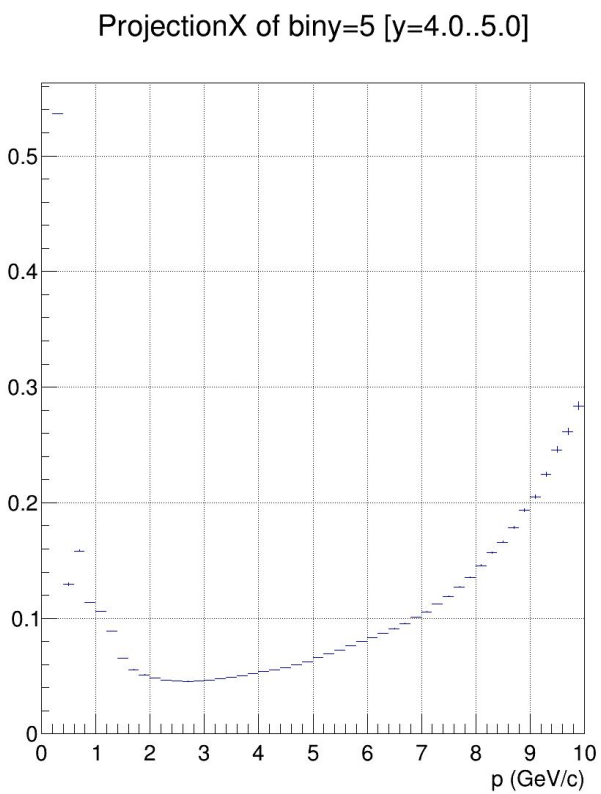


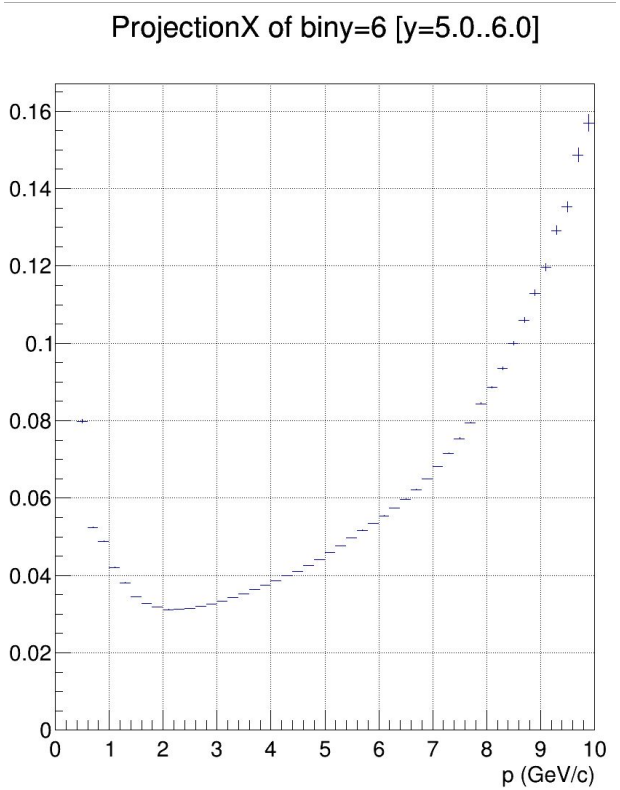
16 harm

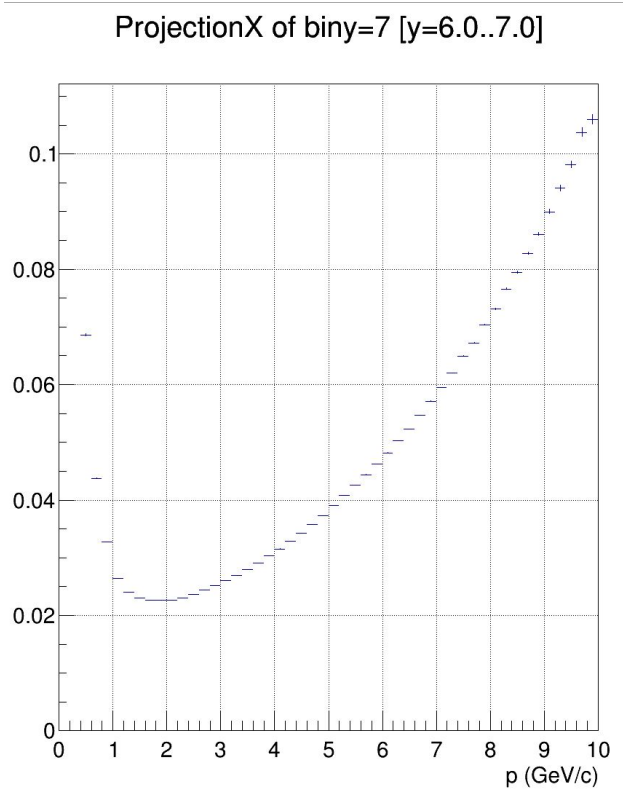



N_{hits}
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
p (GeV/c)
0.3
0.25
0.2
0.15
0.1
0.05
0
Momentum resolution vs p and Nhits (prim protons)

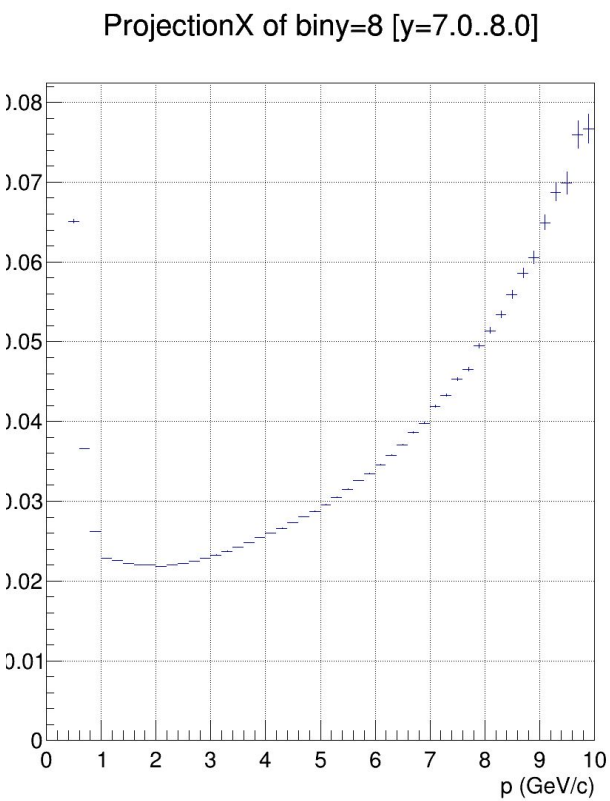
Momentum resolution vs momentum (primary protons in TOF acceptance)

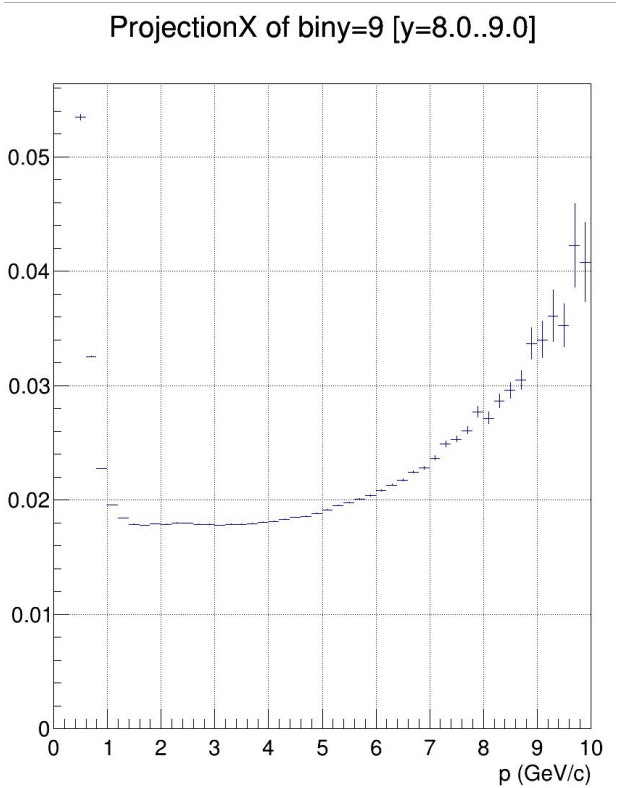


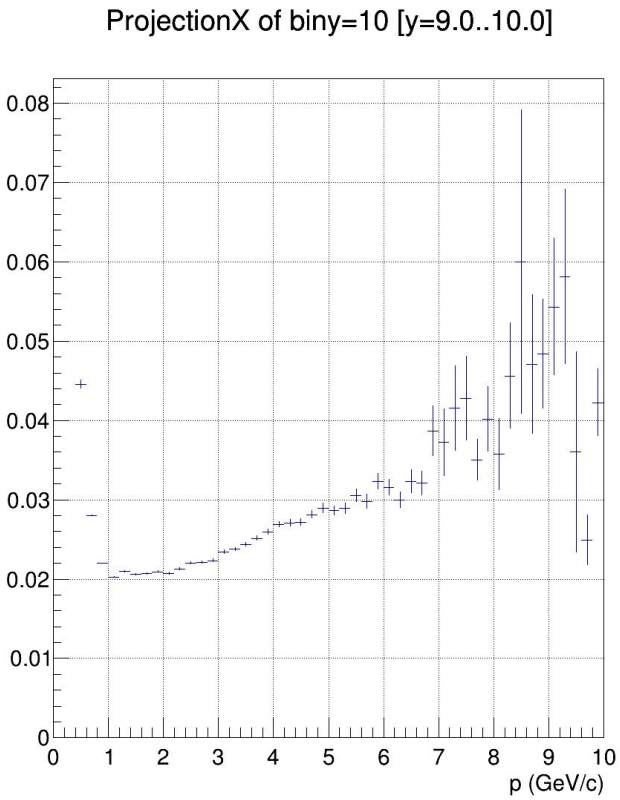




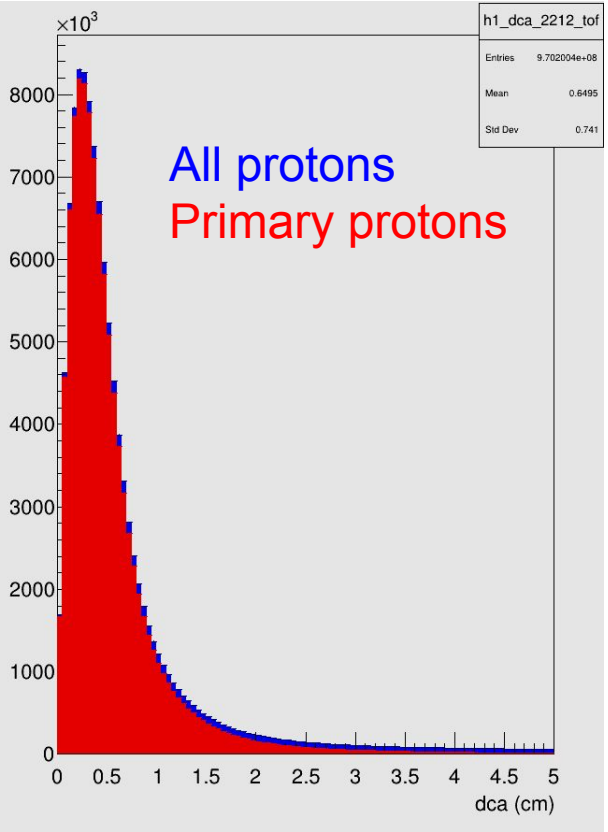
Momentum resolution vs momentum (primary protons in TOF acceptance)

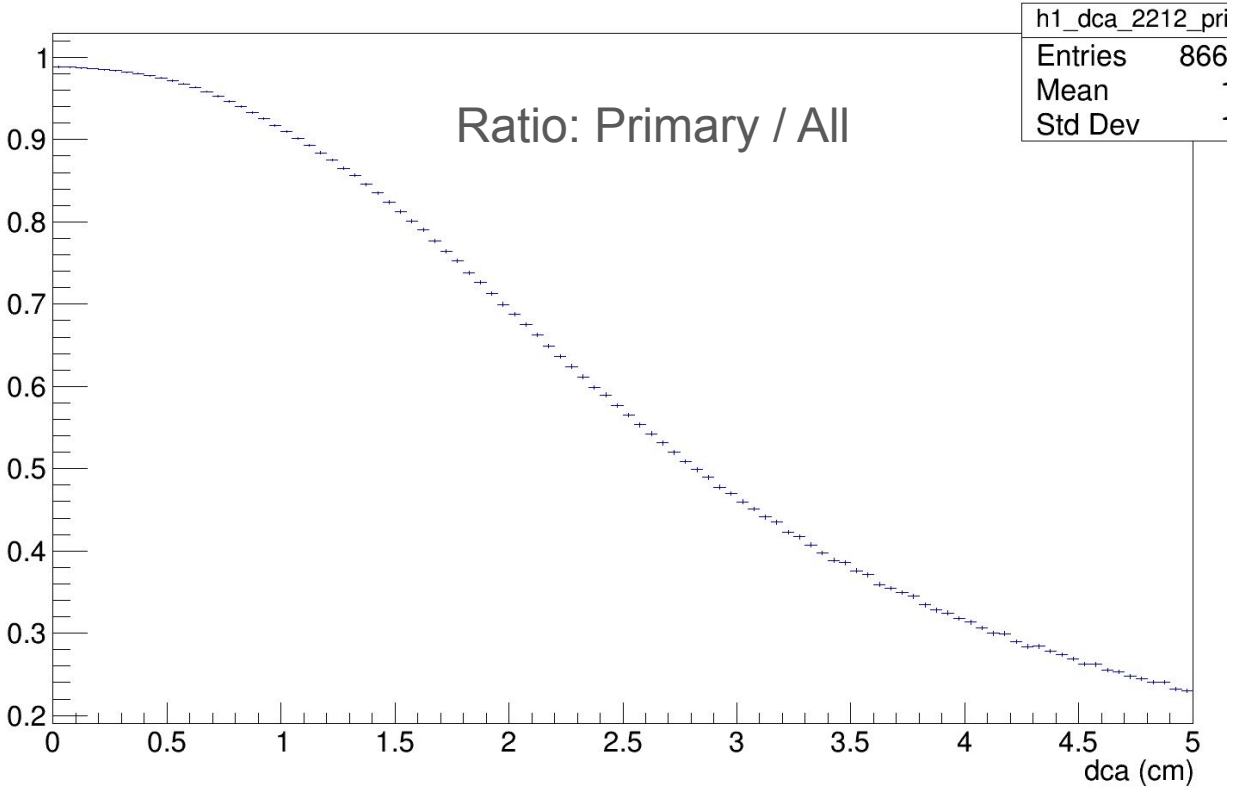




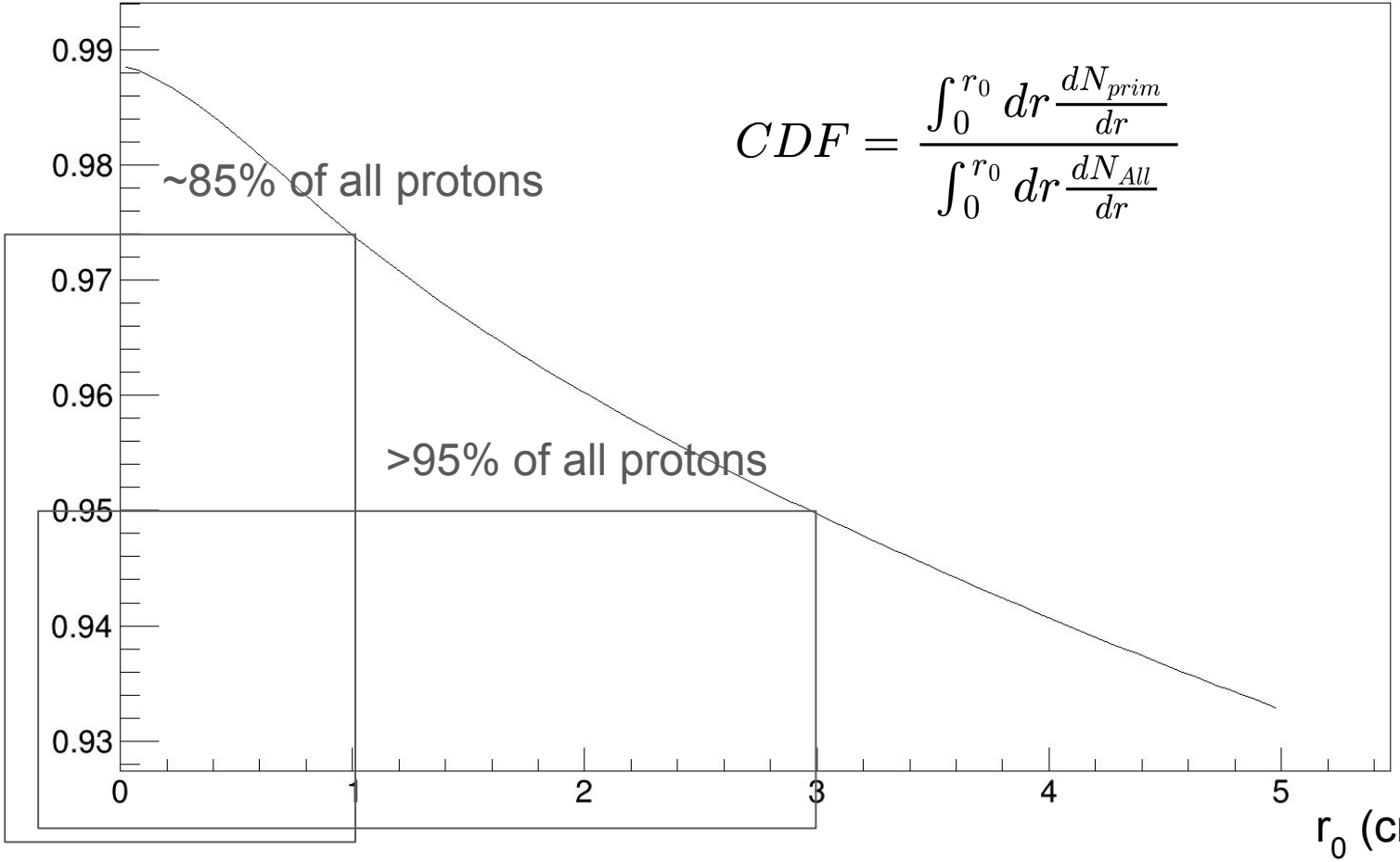


DCA distribution for protons in TOF





CDF for proton DCA (prim / all)

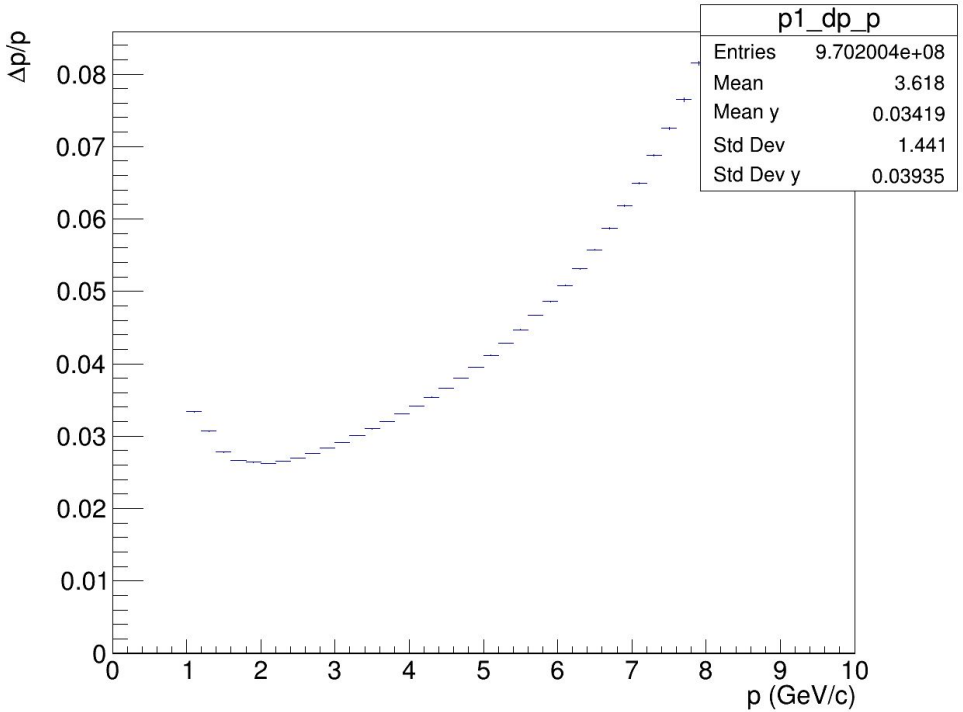


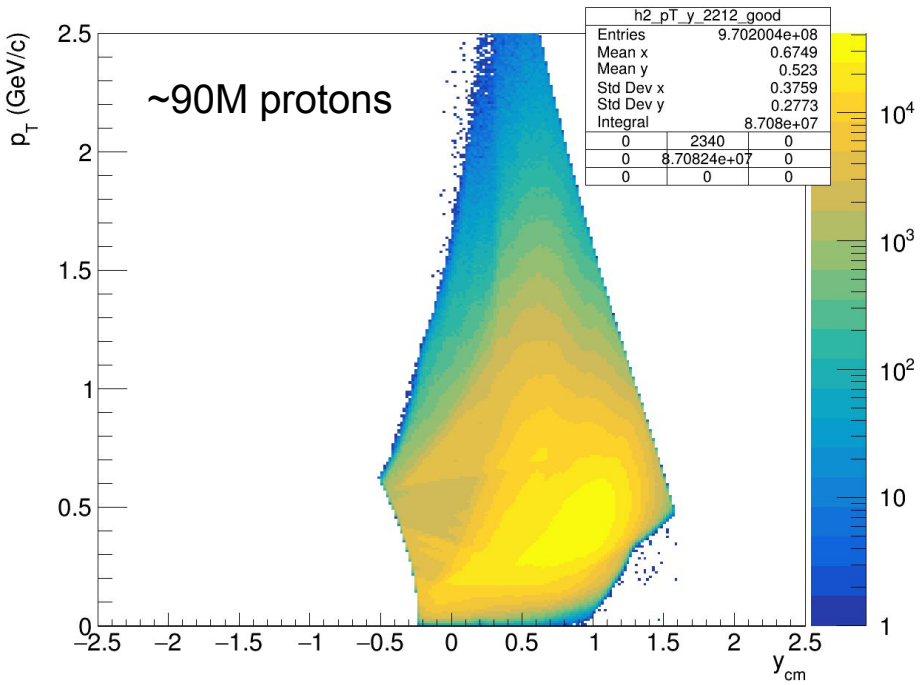
$$CDF = \frac{\int_0^{r_0} dr \frac{dN_{prim}}{dr}}{\int_0^{r_0} dr \frac{dN_{All}}{dr}}$$

Preliminary cuts on tracks

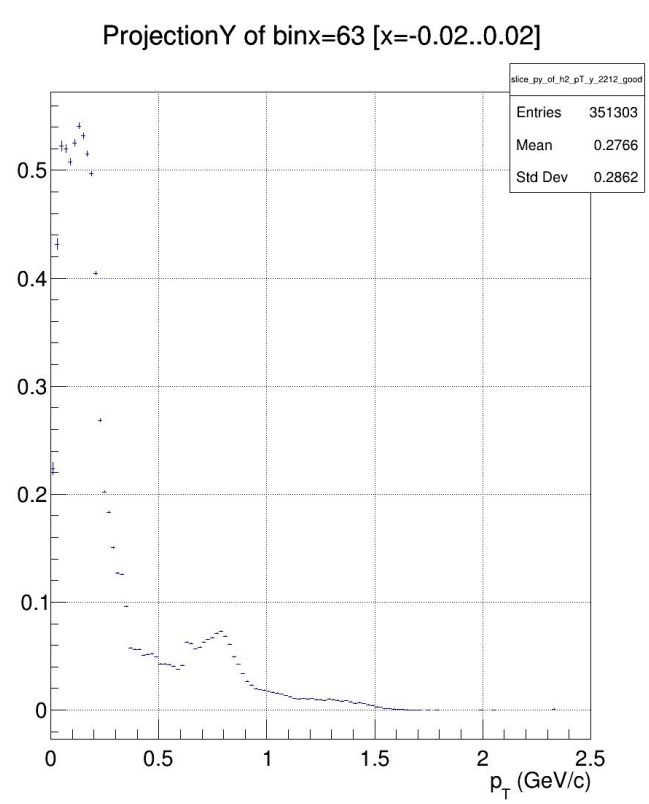
- p/q: [1.0, 8.0] GeV/c
- R_{dca}<3 cm (95% probability of proton being primary)
- Track not in X_{fhcal}: [-30, 160] cm, Y_{fhcal}:[-60; 60] cm (to reject autocorrelations)

Result after applying track-cuts





Efficiency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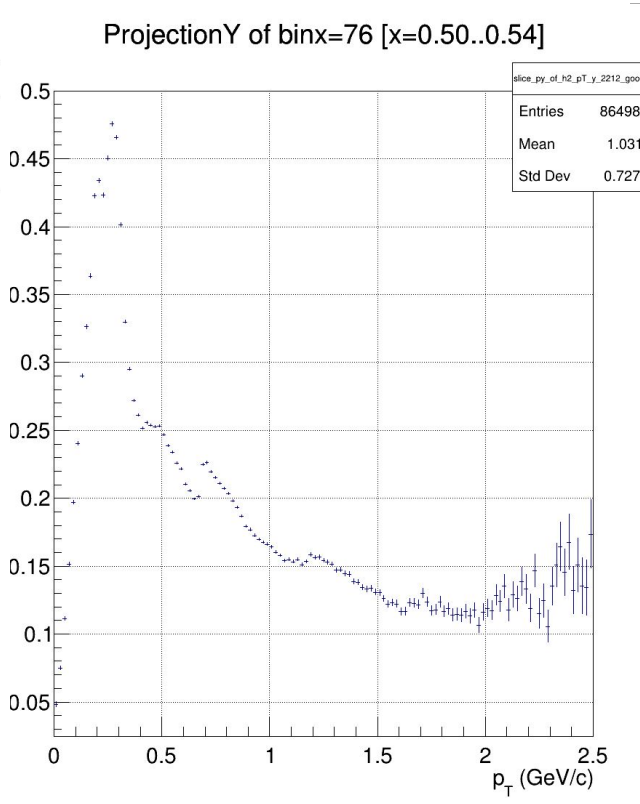
Entries 351303
Mean 0.2766
Std Dev 0.2862
p_T (GeV/c)


ProjectionY of binx=76 [x=0.50..0.54]
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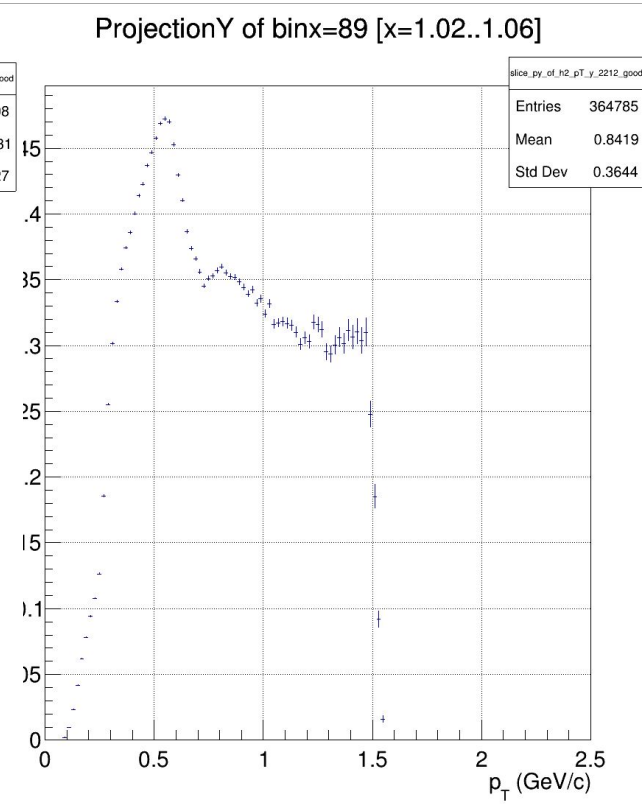
Mean 1.031
Std Dev 0.727
p_T (GeV/c)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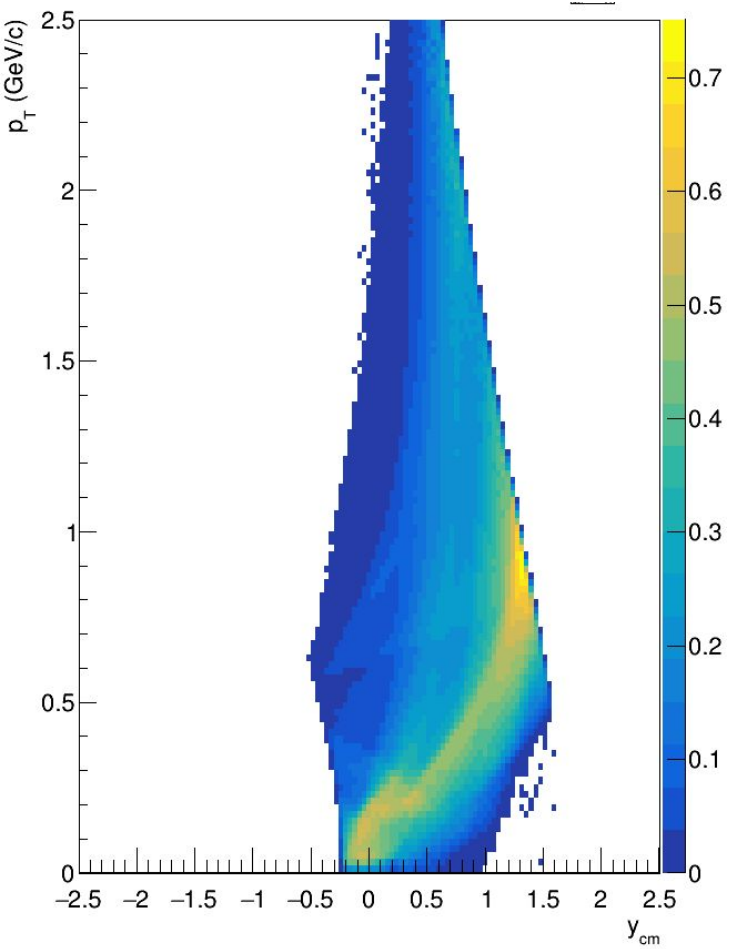
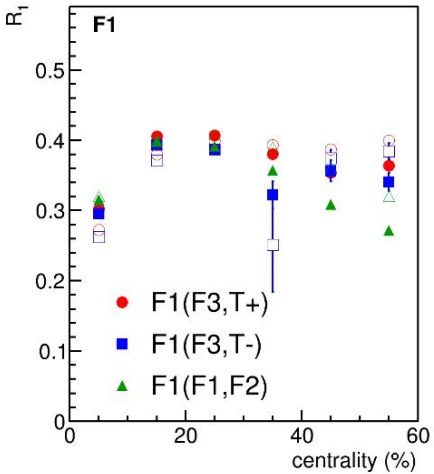
Mean 0.8419
Std Dev 0.3644
p_T (GeV/c)

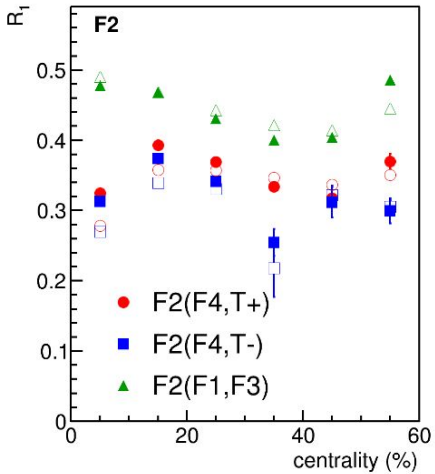
2D efficiency

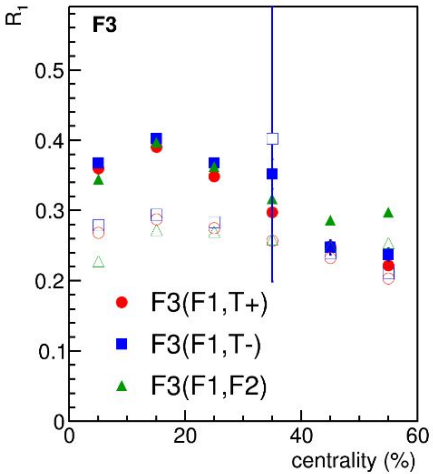


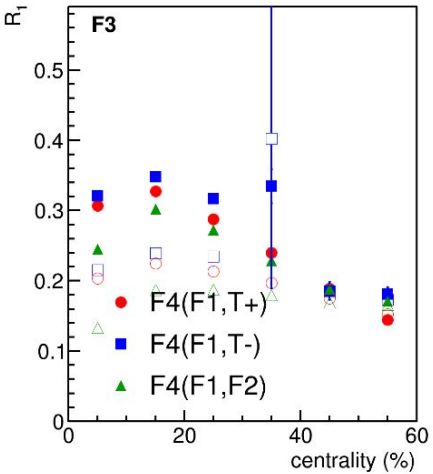
R_1 correction factor for F{1,...,4} (Monte-Carlo)

$x_2X_1X_1$
$x_2Y_1Y_1$
$y_2X_1Y_1$
$y_2Y_1X_1$

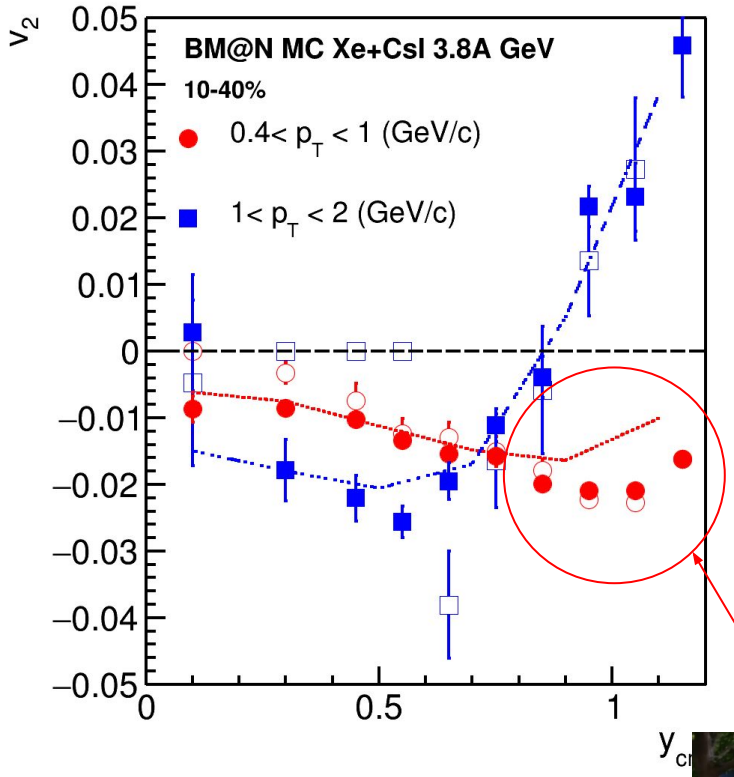


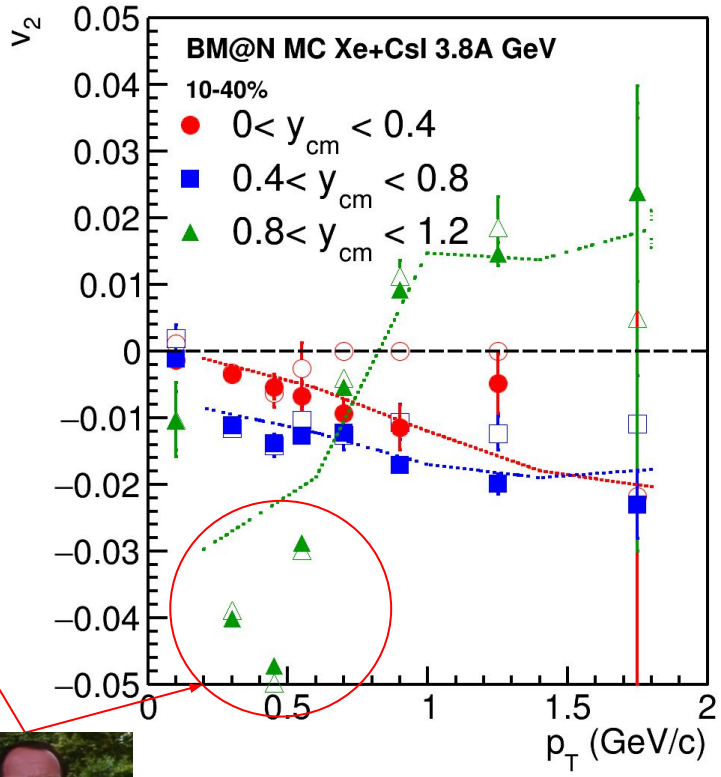






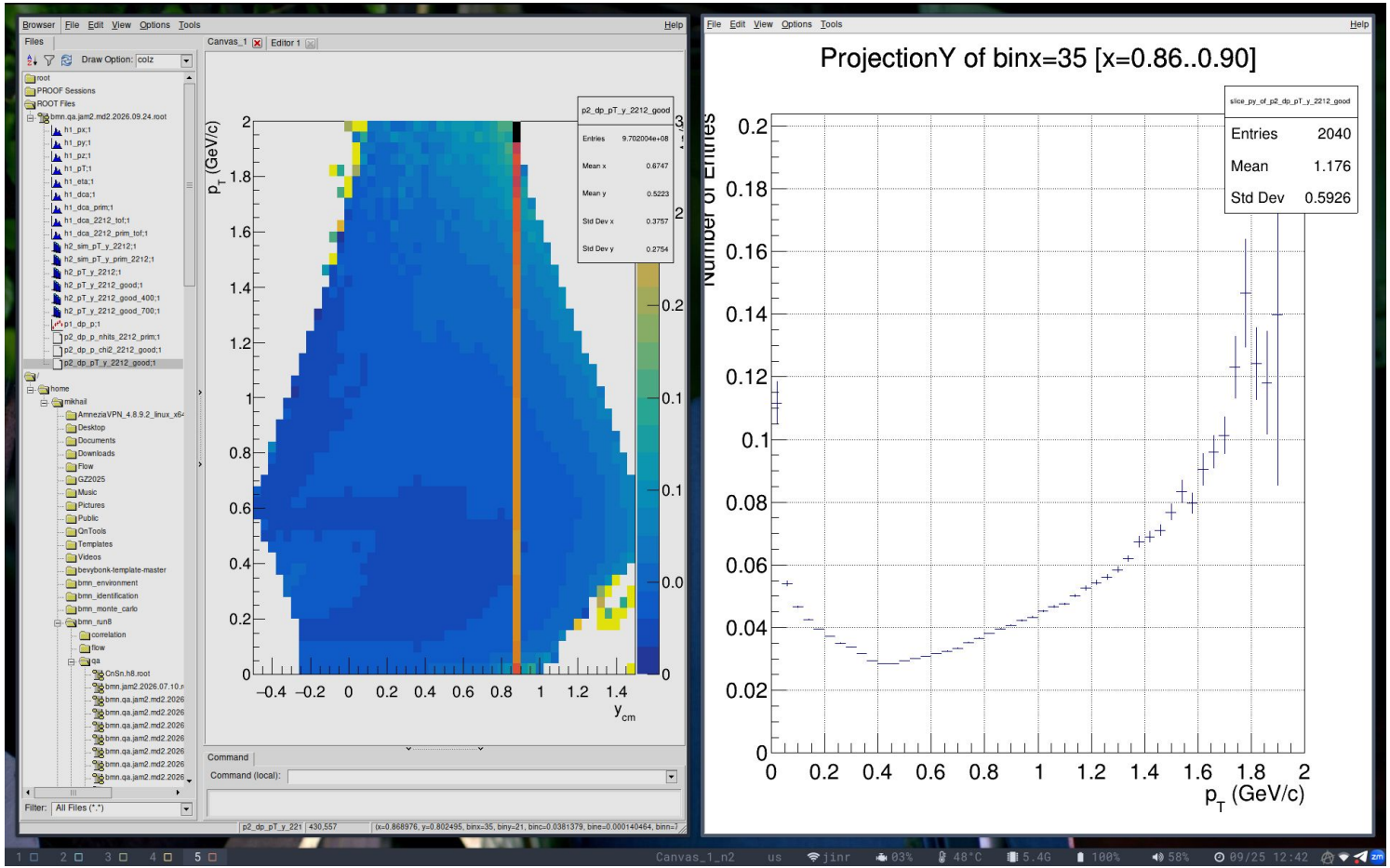
v_2 wrt Reaction Plane (Monte-Carlo)



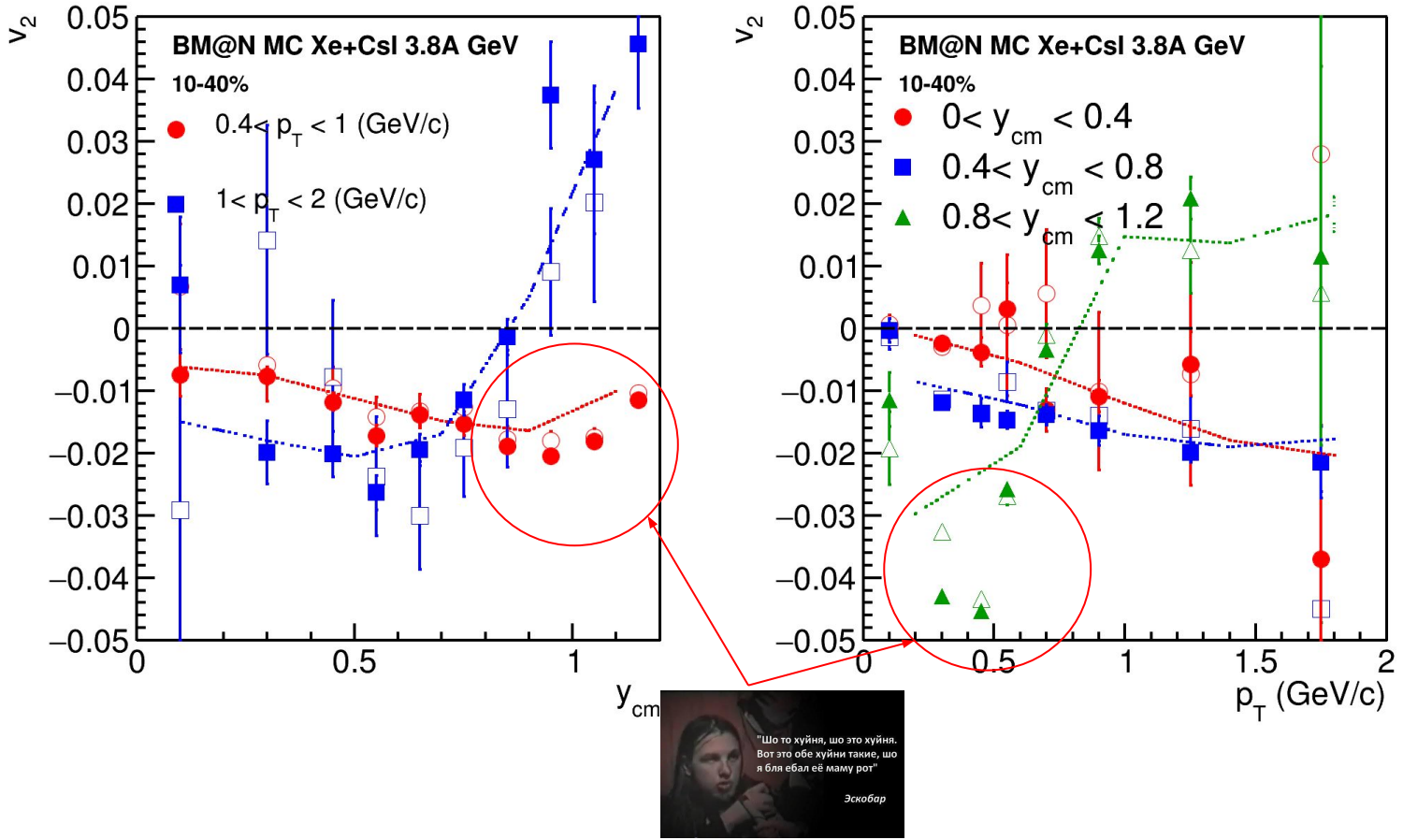


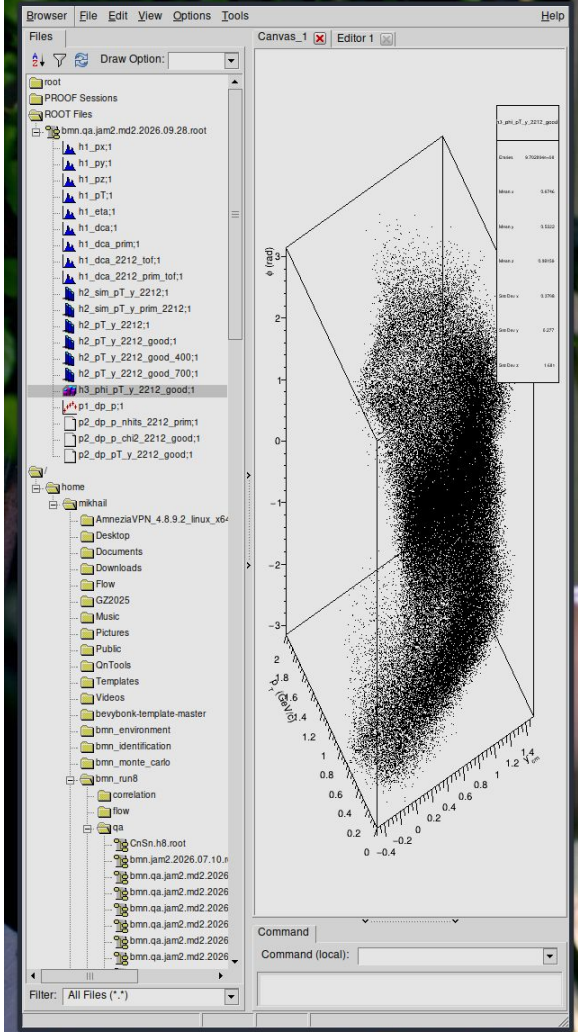


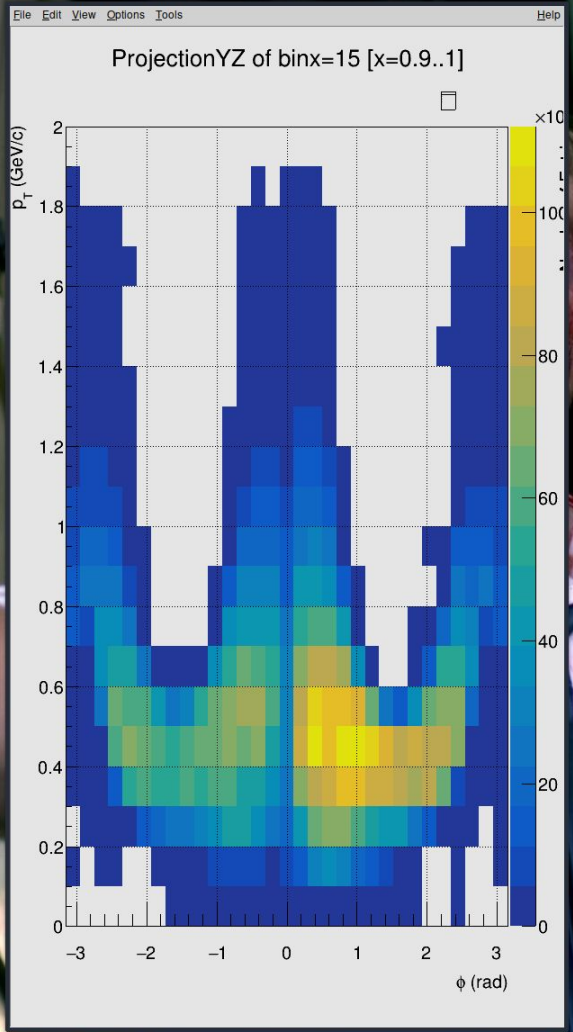
Momentum resolution vs pT in bin of y

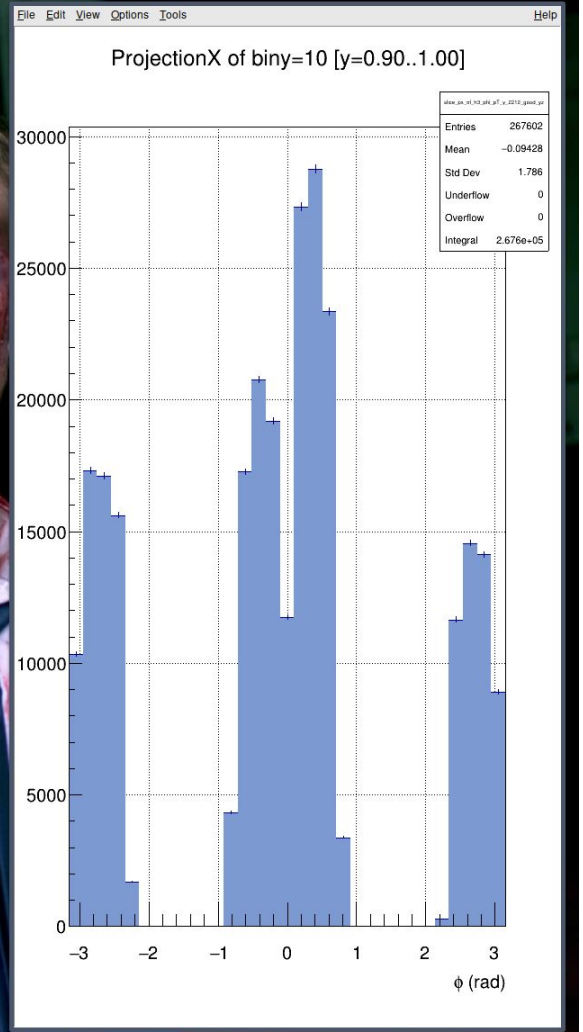


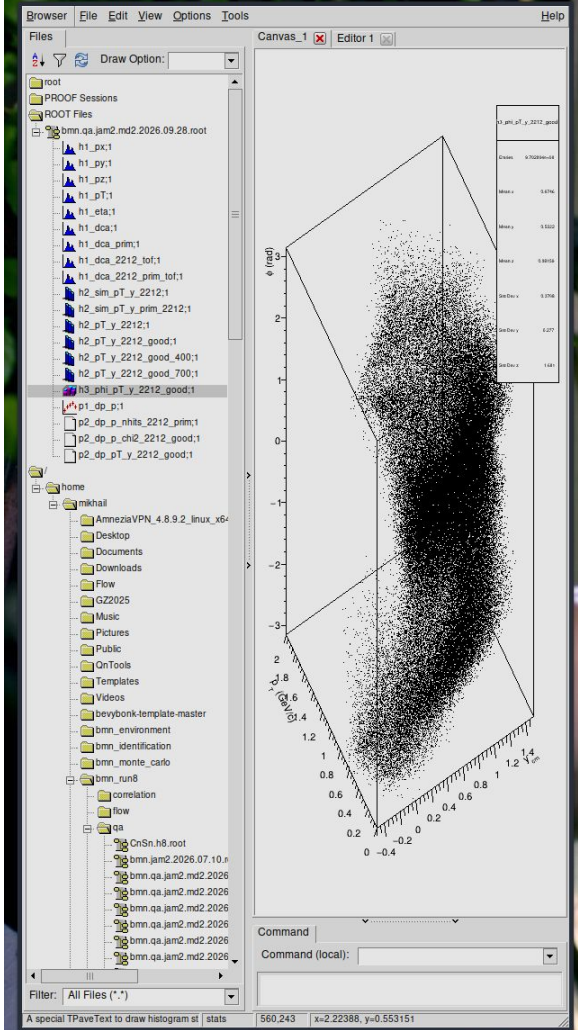
v_2 wrt Reaction Plane (Monte-Carlo, true momenta)

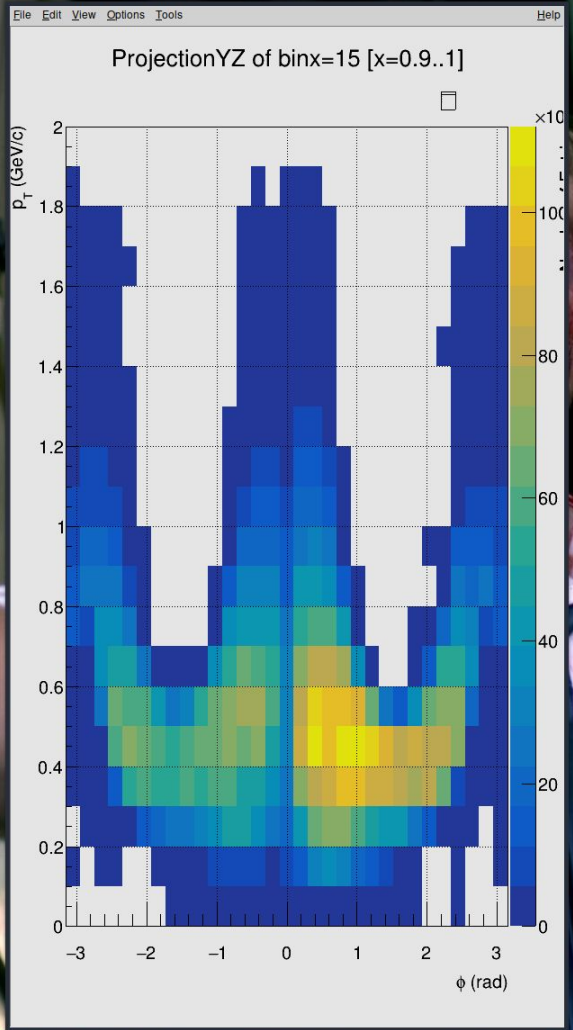


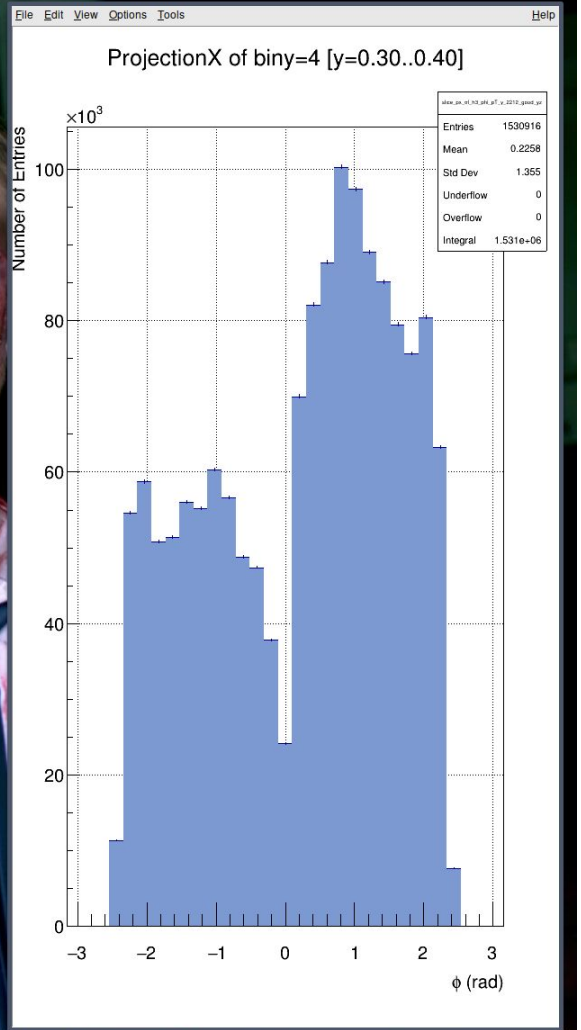

Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.28.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h3_phi_pT_y_2212_good;1
p1_dp_p;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dp_pT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Flow
GZ2025
Music
Pictures
Public
QnTools
Templates
Videos
bevybonk-template-master
bmn_environment
bmn_identification
bmn_monte_carlo
bmn_run8
correlation
flow
qa
CnSn.h8.root
Filter: All Files (*.*)
Canvas_1
Editor 1
Command
Command (local):

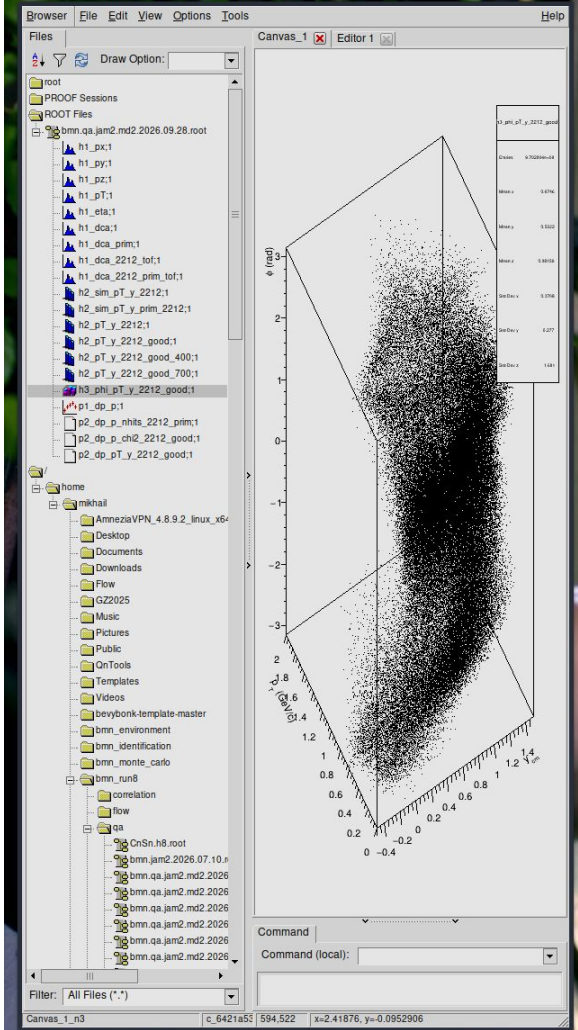

File Edit View Options Tools Help
ProjectionYZ of binx=15 [x=0.9..1]
p_T (GeV/c)
ϕ (rad)

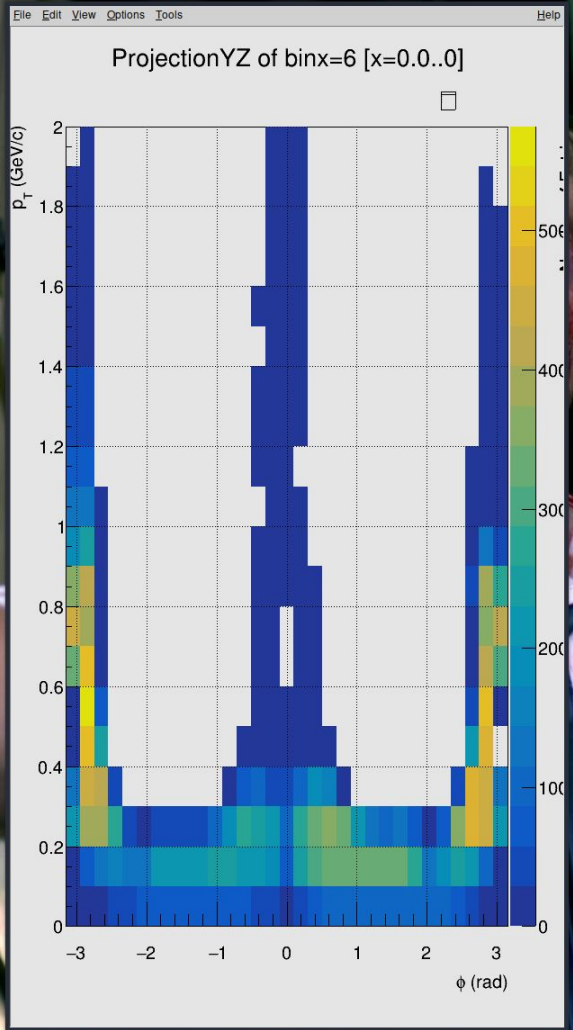

File Edit View Options Tools Help
ProjectionX of biny=10 [y=0.90..1.00]
Entries 267602
Mean −0.09428
Std Dev 1.786
Underflow 0
Overflow 0
Integral 2.676e+05
ϕ (rad)

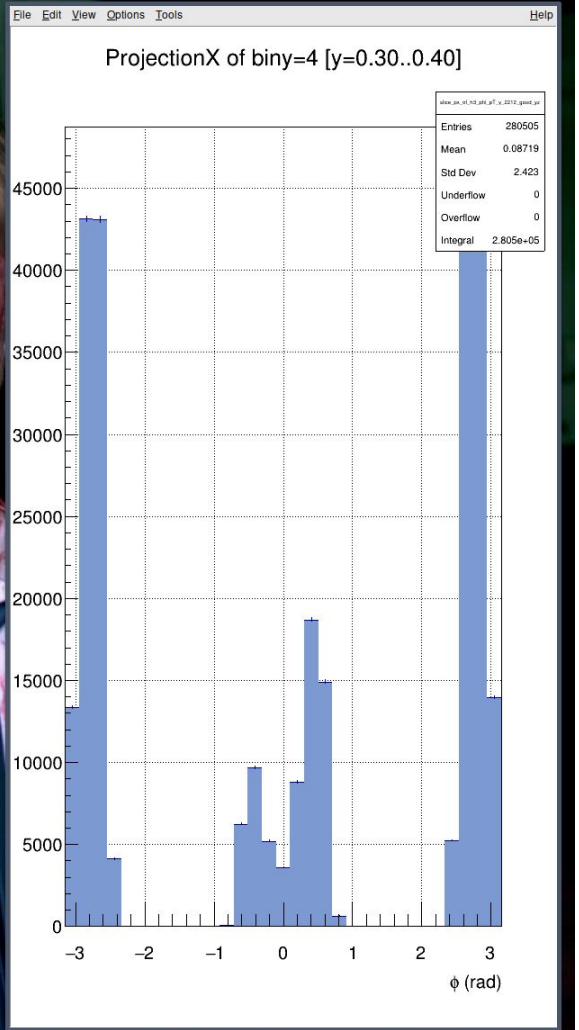

Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.28.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h3_phi_pT_y_2212_good;1
p1_dp_p;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dp_pT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Flow
GZ2025
Music
Pictures
Public
QnTools
Templates
Videos
bevybonk-template-master
bmn_environment
bmn_identification
bmn_monte_carlo
bmn_run8
correlation
flow
qa
CnSn.h8.root
Canvas_1
Editor 1
Command
Command (local):
Filter: All Files (*.*)
A special TPaveText to draw histogram st
stats
560,243
x=2.22388, y=0.553151

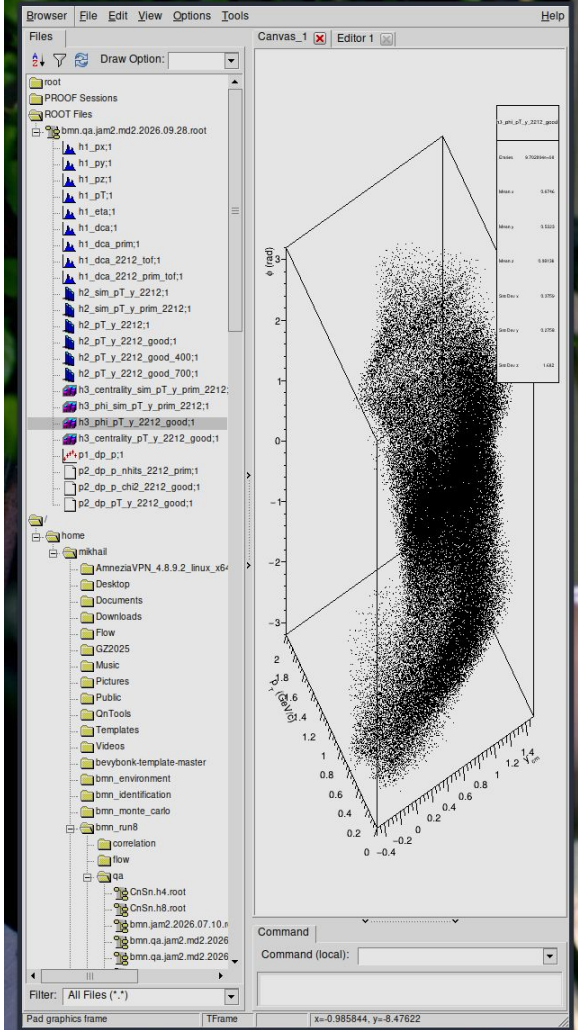

File Edit View Options Tools Help
ProjectionYZ of binx=15 [x=0.9..1]
p_T (GeV/c)
ϕ (rad)

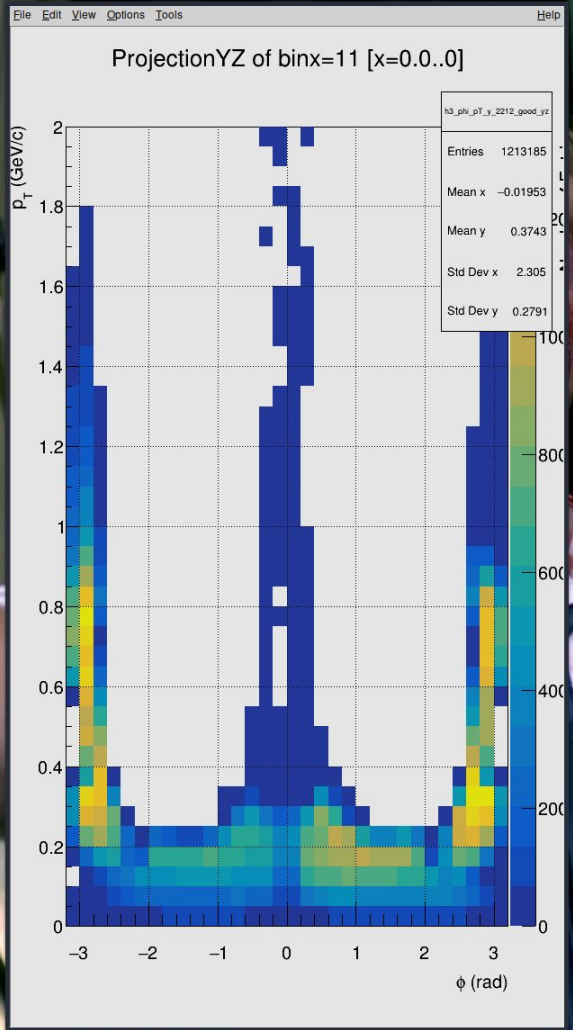

File Edit View Options Tools Help
ProjectionX of biny=4 [y=0.30..0.40]
Number of Entries
Entries 1530916
Mean 0.2258
Std Dev 1.355
Underflow 0
Overflow 0
Integral 1.531e+06
ϕ (rad)

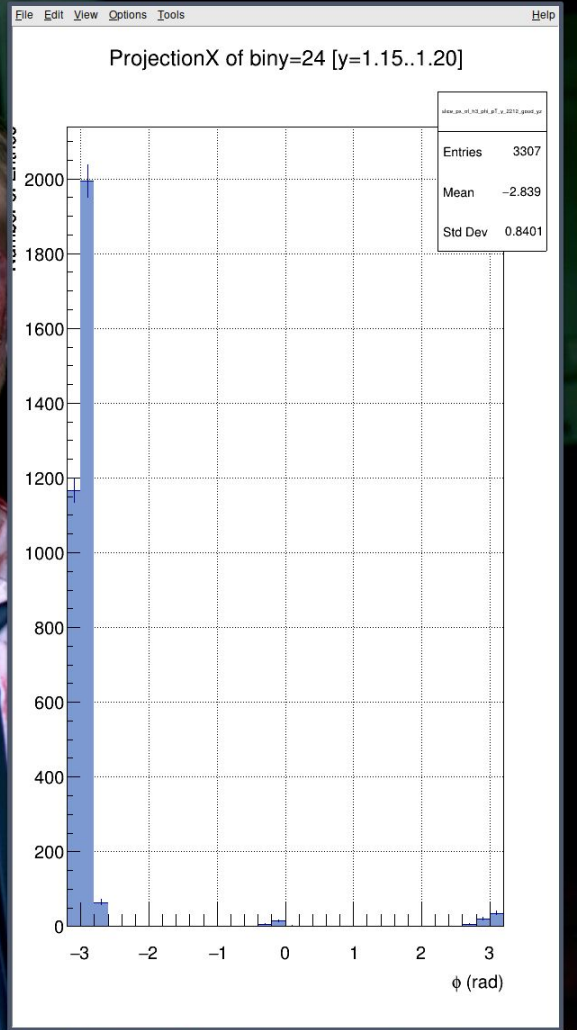

Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.28.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h3_phi_pT_y_2212_good;1
p1_dp_p;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dp_pT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Flow
GZ2025
Music
Pictures
Public
QnTools
Templates
Videos
bevybonk-template-master
bmn_environment
bmn_identification
bmn_monte_carlo
bmn_run8
correlation
flow
qa
CnSn.h8.root
Filter: All Files (*.*)
Canvas_1
Editor 1
Command
Command (local):
Canvas_1_n3
594,522
x=2.41876, y=-0.0952906

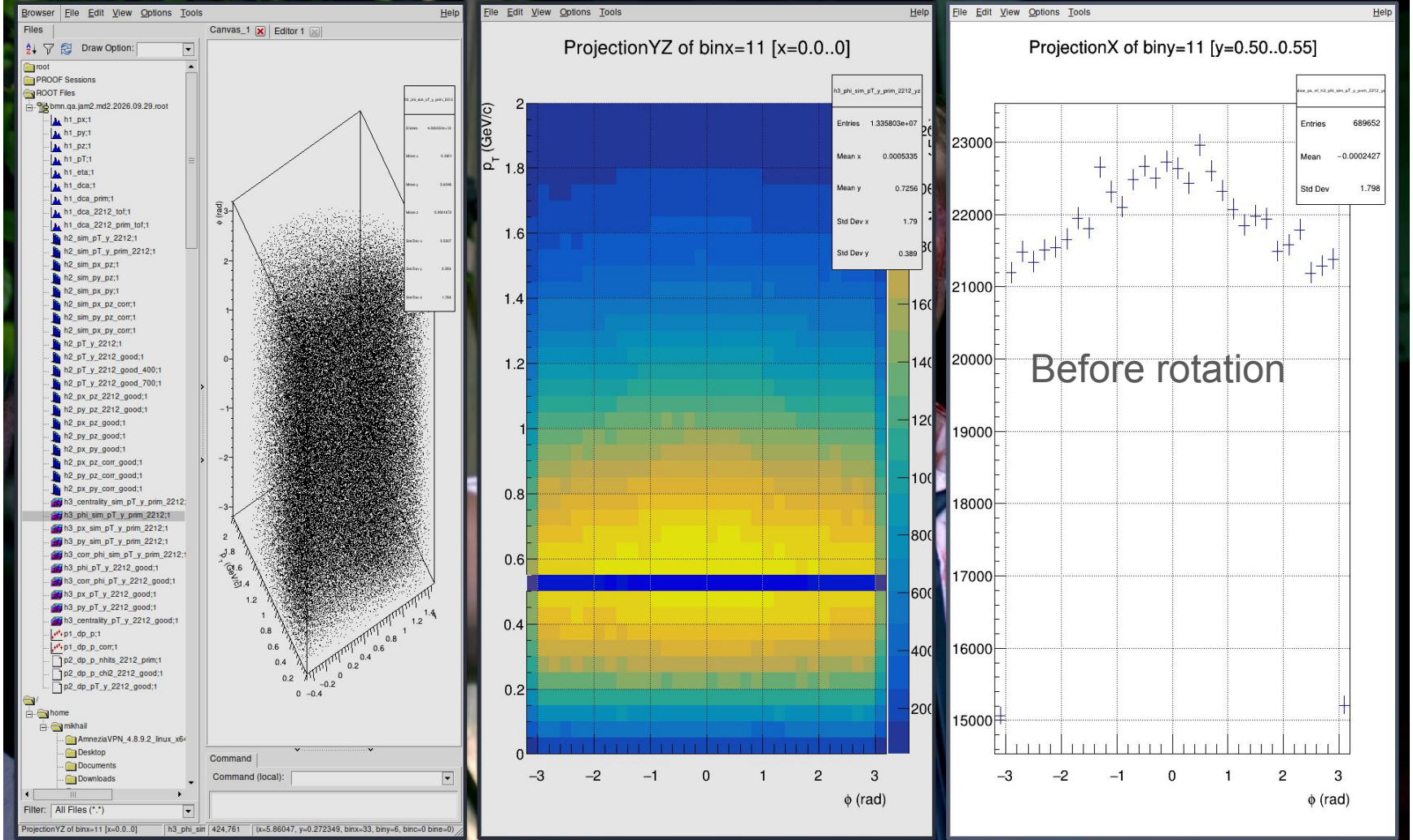

File Edit View Options Tools Help
ProjectionYZ of binx=6 [x=0.0..0]
p_T (GeV/c)
ϕ (rad)

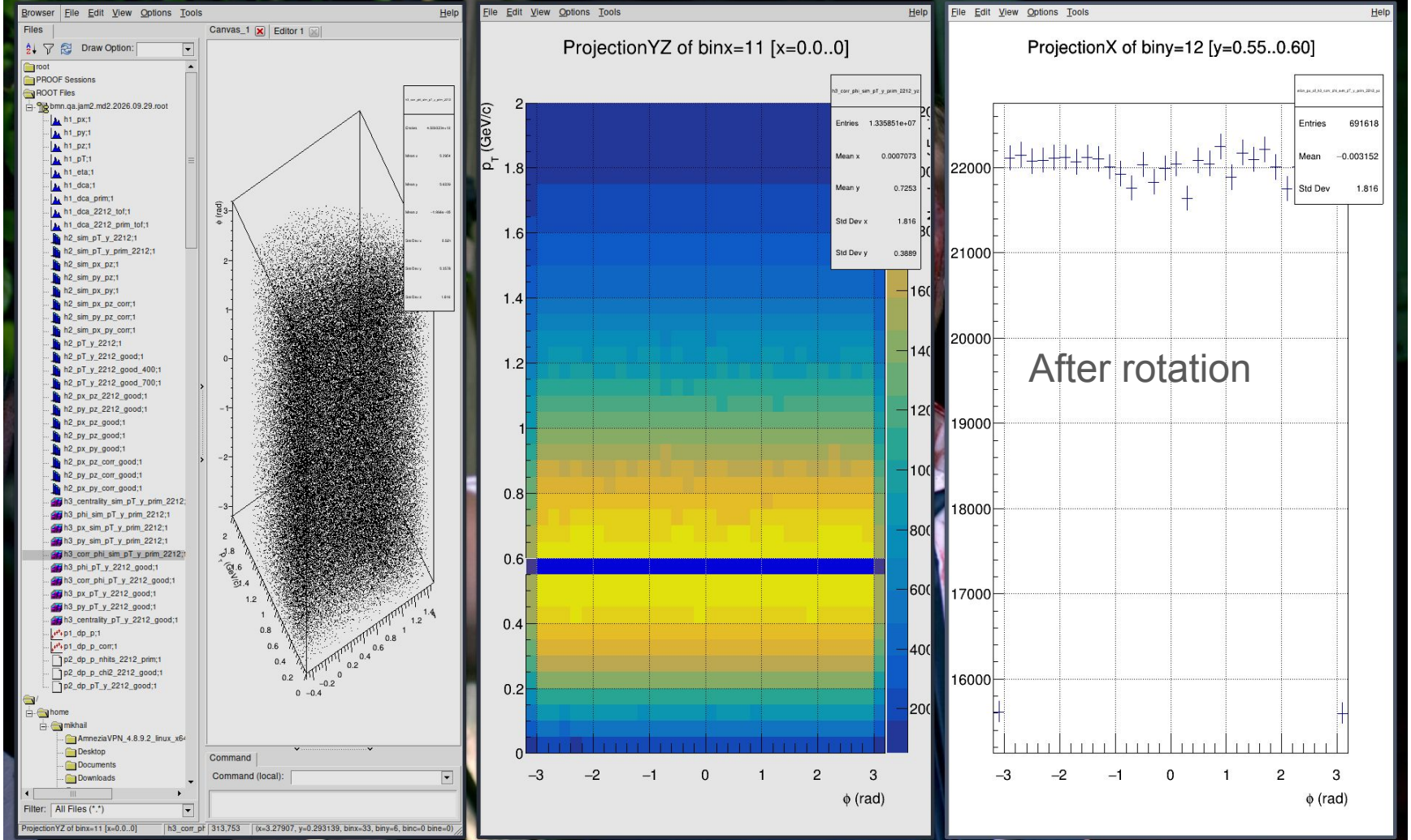

File Edit View Options Tools Help
ProjectionX of biny=4 [y=0.30..0.40]
Entries 280505
Mean 0.08719
Std Dev 2.423
Underflow 0
Overflow 0
Integral 2.805e+05
ϕ (rad)


Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.28.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h3_centrality_sim_pT_y_prim_2212;
h3_phi_sim_pT_y_prim_2212;1
h3_phi_pT_y_2212_good;1
h3_centrality_pT_y_2212_good;1
p1_dp_p;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dp_pT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Flow
GZ2025
Music
Pictures
Public
QnTools
Templates
Videos
bevybonk-template-master
bmn_environment
bmn_identification
bmn_monte_carlo
bmn_run8
correlation
flow
qa
CnSn.h4.root
CnSn.h8.root
bmn.jam2.2026.07.10.x
bmn.qa.jam2.md2.2026
bmn.qa.jam2.md2.2026
Filter: All Files (*.*)
Canvas_1
Editor 1
Command
Command (local):
Pad graphics frame
TFrame
x=-0.985844, y=-8.47622

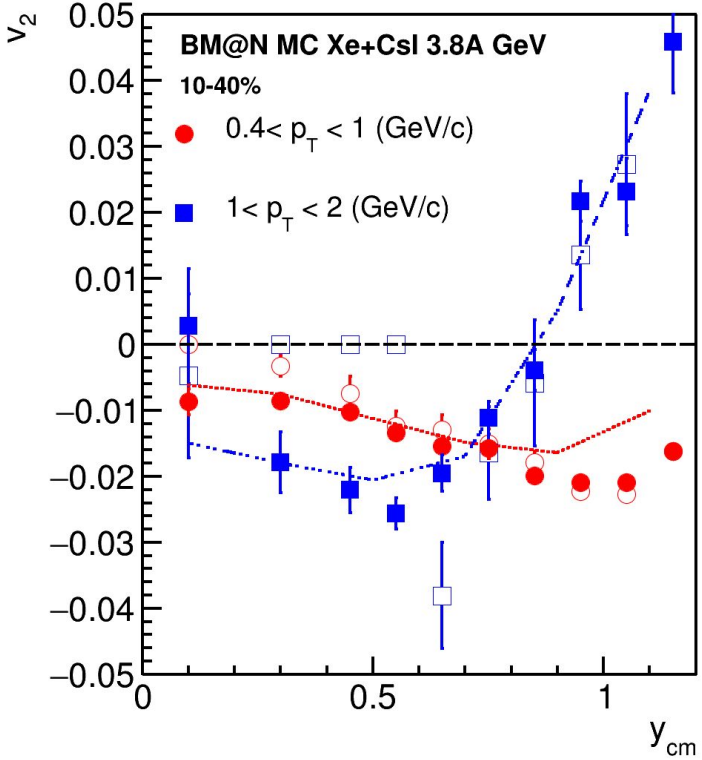

File Edit View Options Tools Help
ProjectionYZ of binx=11 [x=0.0..0]
h3_phi_pT_y_2212_good_yz
Entries 1213185
Mean x −0.01953
Mean y 0.3743
Std Dev x 2.305
Std Dev y 0.2791
p_T (GeV/c)
ϕ (rad)


File Edit View Options Tools Help
ProjectionX of biny=24 [y=1.15..1.20]
Entries 3307
Mean −2.839
Std Dev 0.8401
ϕ (rad)

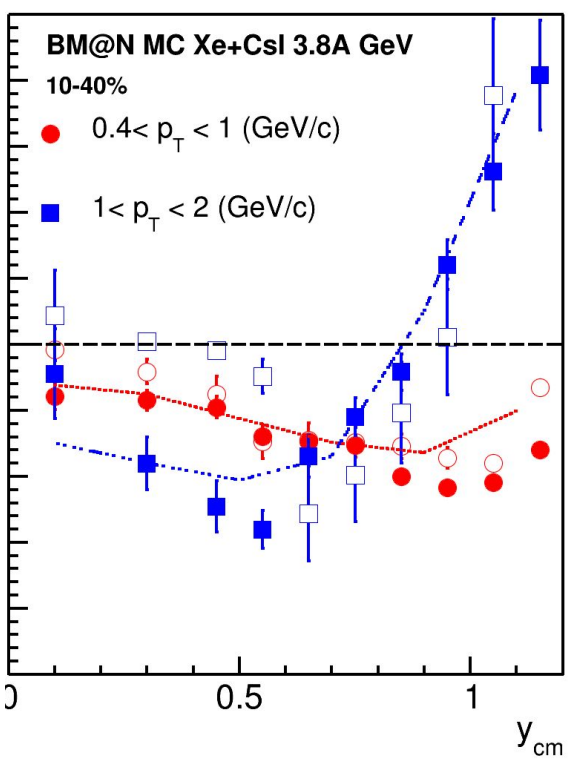

Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.29.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_sim_px_pz;1
h2_sim_py_pz;1
h2_sim_px_py;1
h2_sim_px_pz_corr;1
h2_sim_py_pz_corr;1
h2_sim_px_py_corr;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h2_px_pz_2212_good;1
h2_py_pz_2212_good;1
h2_px_pz_good;1
h2_py_pz_good;1
h2_px_py_good;1
h2_px_pz_corr_good;1
h2_py_pz_corr_good;1
h2_px_py_corr_good;1
h3_centrality_sim_pT_y_prim_2212;
h3_phi_sim_pT_y_prim_2212;1
h3_px_sim_pT_y_prim_2212;1
h3_py_sim_pT_y_prim_2212;1
h3_corr_phi_sim_pT_y_prim_2212;1
h3_phi_pT_y_2212_good;1
h3_corr_phi_pT_y_2212_good;1
h3_px_pT_y_2212_good;1
h3_py_pT_y_2212_good;1
h3_centrality_pT_y_2212_good;1
p1_dp_p;1
p1_dp_p_corr;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dp_pT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Filter: All Files (*.*)
Canvas_1
Editor 1
Command
Command (local):
ProjectionYZ of binx=11 [x=0.0..0]
h3_phi_sim
424,761
(x=5.86047, y=0.272349, binx=33, biny=6, binz=0 bine=0)
File Edit View Options Tools Help
ProjectionYZ of binx=11 [x=0.0..0]
Entries 1.335803e+07
Mean x 0.0005335
Mean y 0.7256
Std Dev x 1.79
Std Dev y 0.389
p_T (GeV/c)
ϕ (rad)
File Edit View Options Tools Help
ProjectionX of biny=11 [y=0.50..0.55]
Entries 689652
Mean −0.0002427
Std Dev 1.798
Before rotation
ϕ (rad)
1 2 3 4 5
Canvas_1_n3
us
jinr
04%
44°C
9.4G
70%
58%
09/30 14:00


Browser File Edit View Options Tools Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
bmn.qa.jam2.md2.2026.09.29.root
h1_px;1
h1_py;1
h1_pz;1
h1_pT;1
h1_eta;1
h1_dca;1
h1_dca_prim;1
h1_dca_2212_tof;1
h1_dca_2212_prim_tof;1
h2_sim_pT_y_2212;1
h2_sim_pT_y_prim_2212;1
h2_sim_px_pz;1
h2_sim_py_pz;1
h2_sim_px_py;1
h2_sim_px_pz_corr;1
h2_sim_py_pz_corr;1
h2_sim_px_py_corr;1
h2_pT_y_2212;1
h2_pT_y_2212_good;1
h2_pT_y_2212_good_400;1
h2_pT_y_2212_good_700;1
h2_px_pz_2212_good;1
h2_py_pz_2212_good;1
h2_px_pz_good;1
h2_py_pz_good;1
h2_px_py_good;1
h2_px_pz_corr_good;1
h2_py_pz_corr_good;1
h2_px_py_corr_good;1
h3_centrality_sim_pT_y_prim_2212;
h3_phi_sim_pT_y_prim_2212;1
h3_px_sim_pT_y_prim_2212;1
h3_py_sim_pT_y_prim_2212;1
h3_corr_phi_sim_pT_y_prim_2212;
h3_phi_pT_y_2212_good;1
h3_corr_phi_pT_y_2212_good;1
h3_px_pT_y_2212_good;1
h3_py_pT_y_2212_good;1
h3_centrality_pT_y_2212_good;1
p1_dp_p;1
p1_dp_p_corr;1
p2_dp_p_nhits_2212_prim;1
p2_dp_p_chi2_2212_good;1
p2_dpT_y_2212_good;1
home
mikhail
AmneziaVPN_4.8.9.2_linux_x64
Desktop
Documents
Downloads
Filter: All Files (*.*)
Canvas_1
Editor 1
Command
Command (local):
ProjectionYZ of binx=11 [x=0.0..0]
h3_corr_pT
313,753
(x=3.27907, y=0.293139, binx=33, biny=6, binc=0 bine=0)
File Edit View Options Tools Help
ProjectionYZ of binx=11 [x=0.0..0]
Entries 1.335851e+07
Mean x 0.0007073
Mean y 0.7253
Std Dev x 1.816
Std Dev y 0.3889
p_T (GeV/c)
ϕ (rad)
File Edit View Options Tools Help
ProjectionX of biny=12 [y=0.55..0.60]
Entries 691618
Mean −0.003152
Std Dev 1.816
After rotation
ϕ (rad)

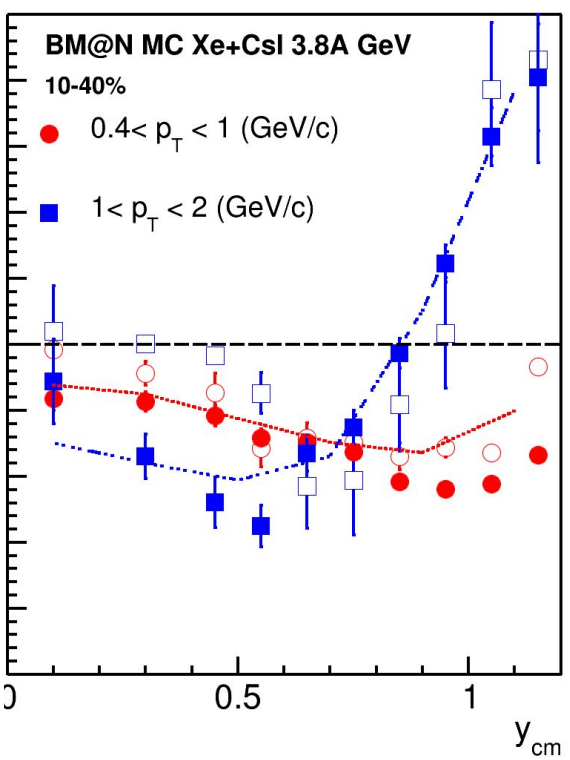
original



Cov from true momentum



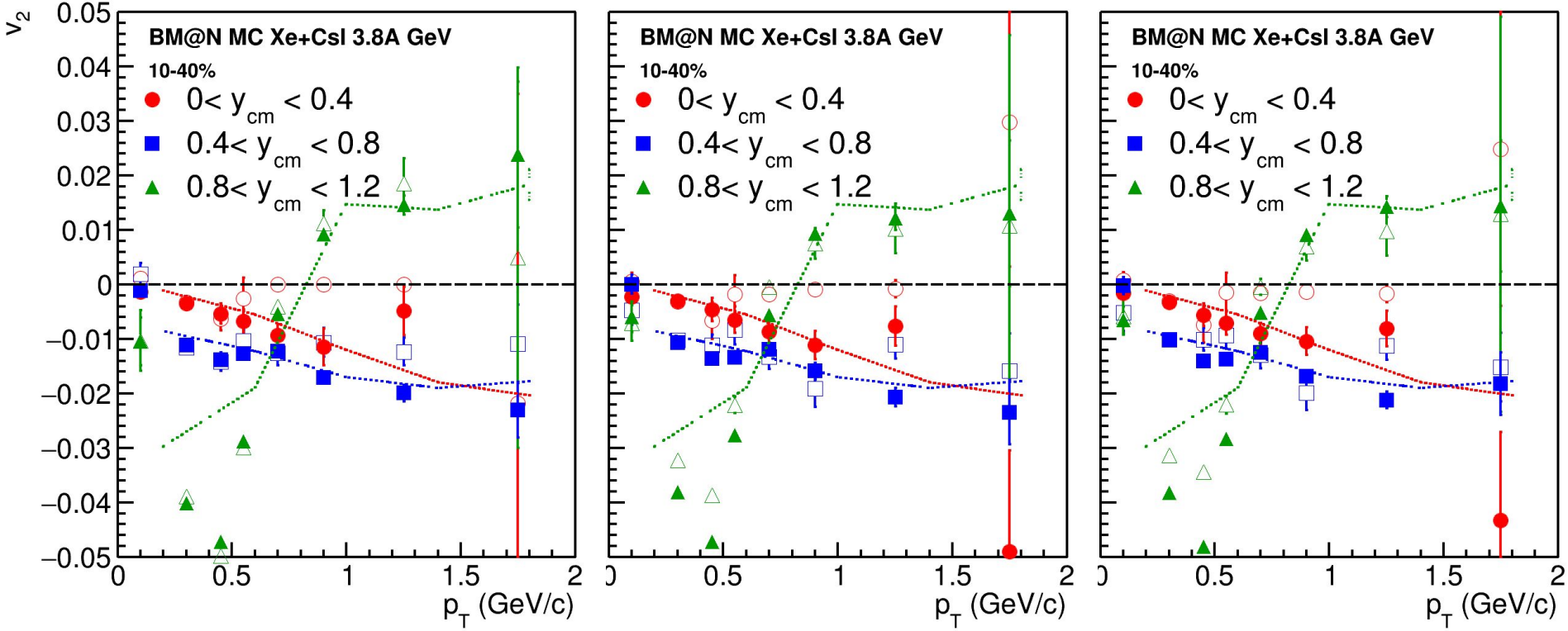
Cov from rec momentum



original

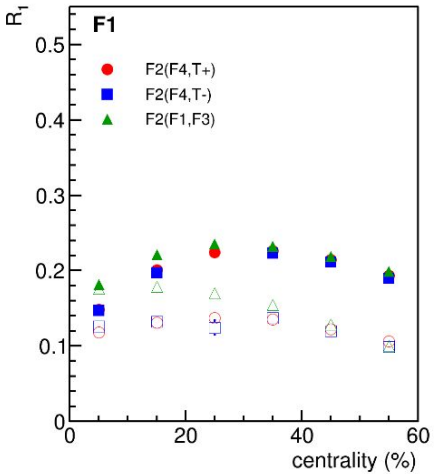
Cov from true momentum

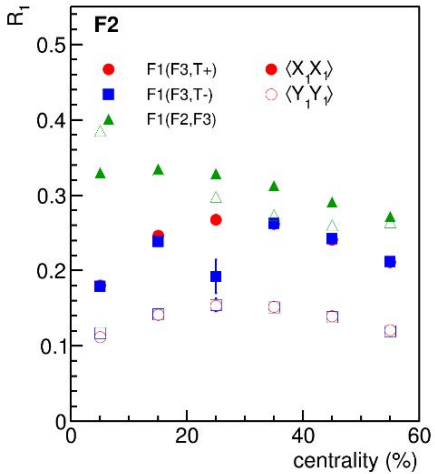
Cov from rec momentum

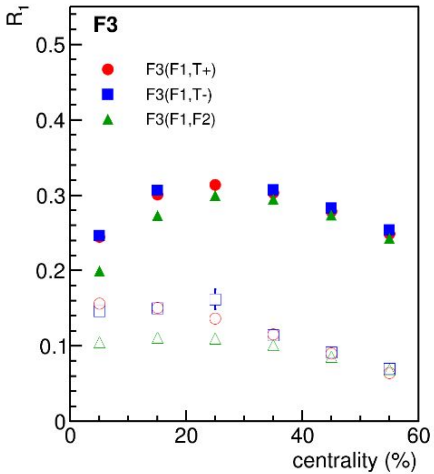


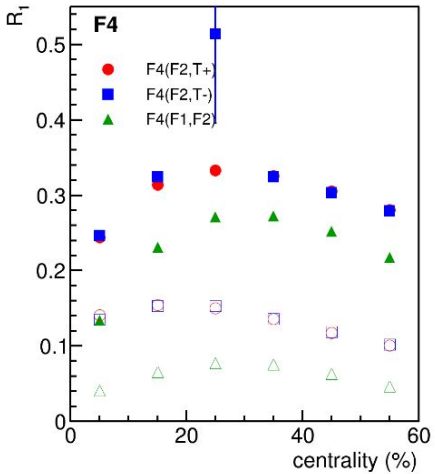
R_1 correction factor for F{1,...,4}

$x_2X_1X_1$
$x_2Y_1Y_1$
$y_2X_1Y_1$
$y_2Y_1X_1$

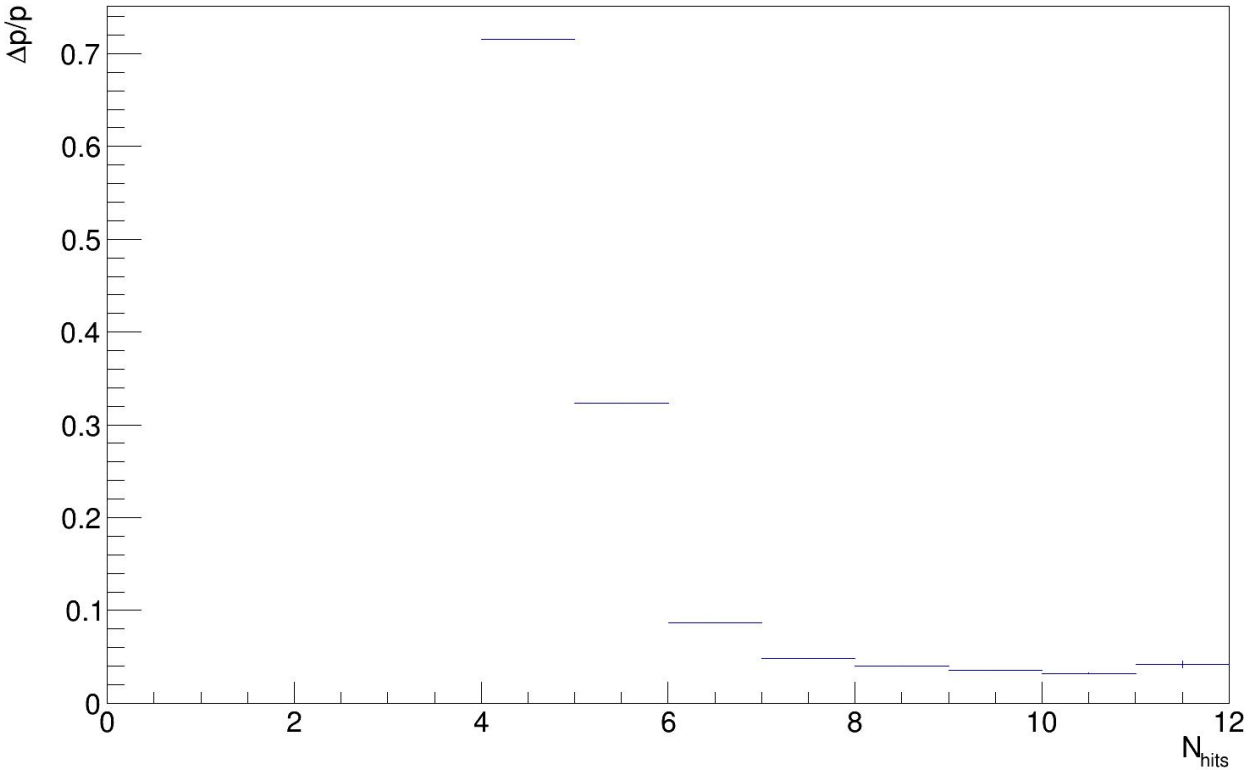




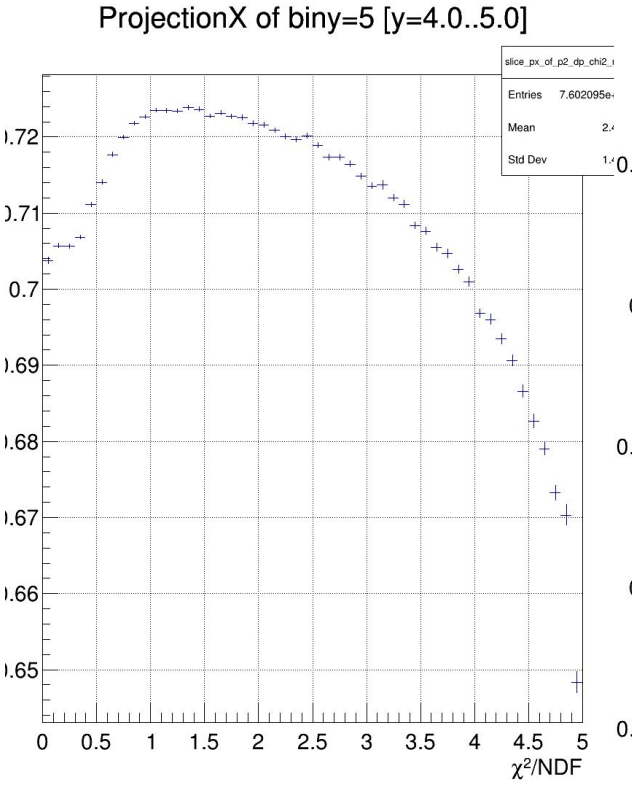


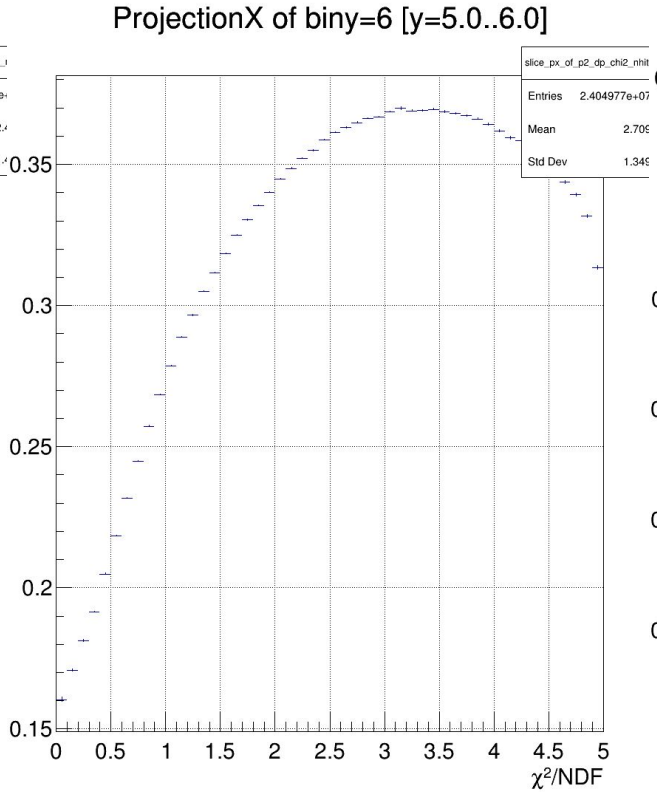


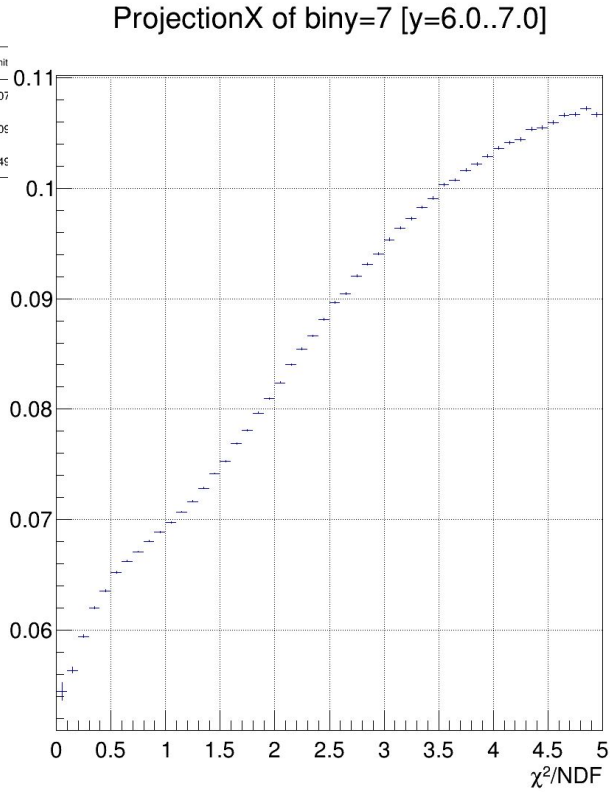
Momentum resolution vs nhits in CT



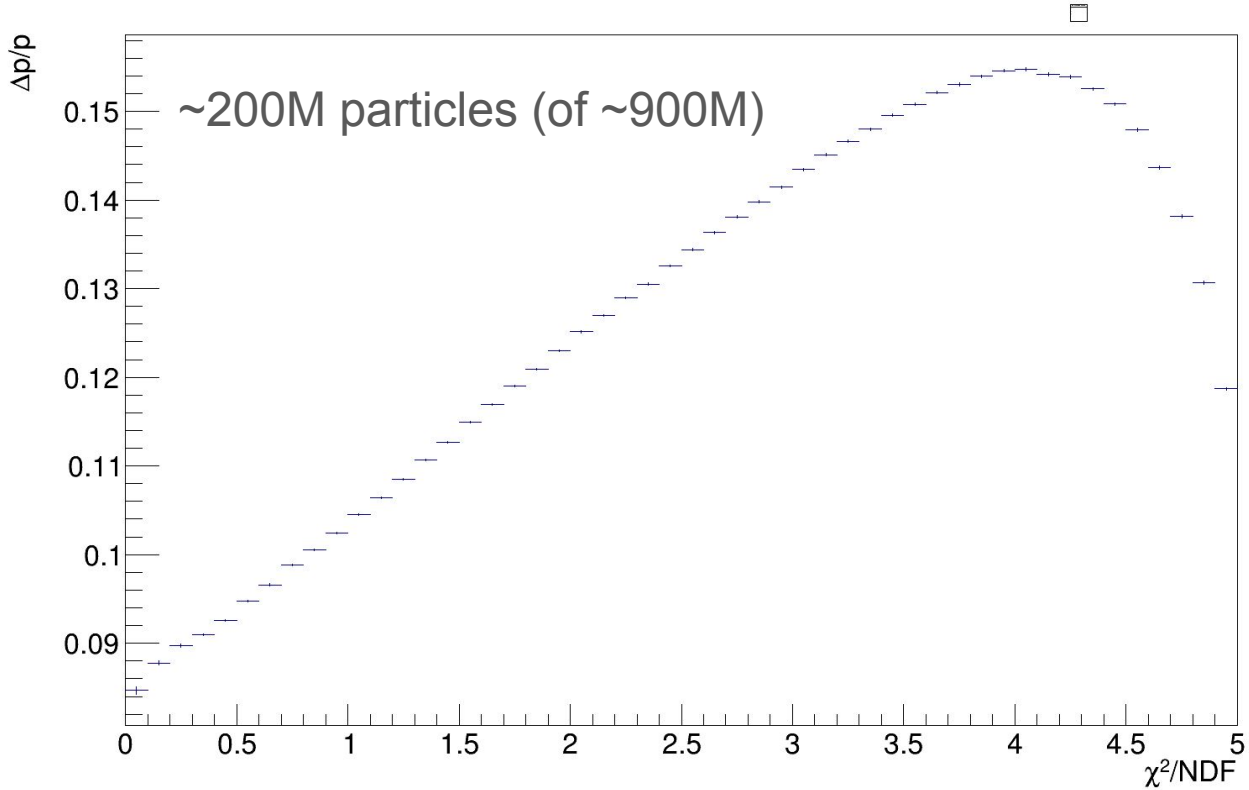
Momentum resolution vs chi2/NDF (nhits =4, 5, 6)



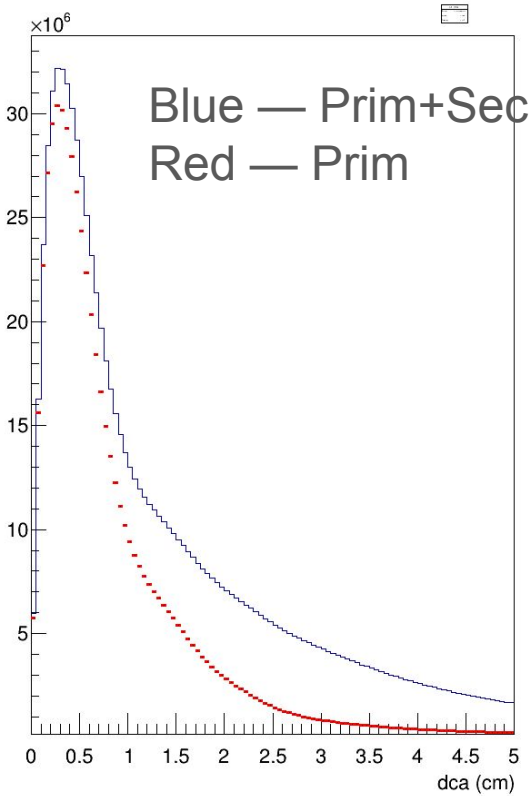


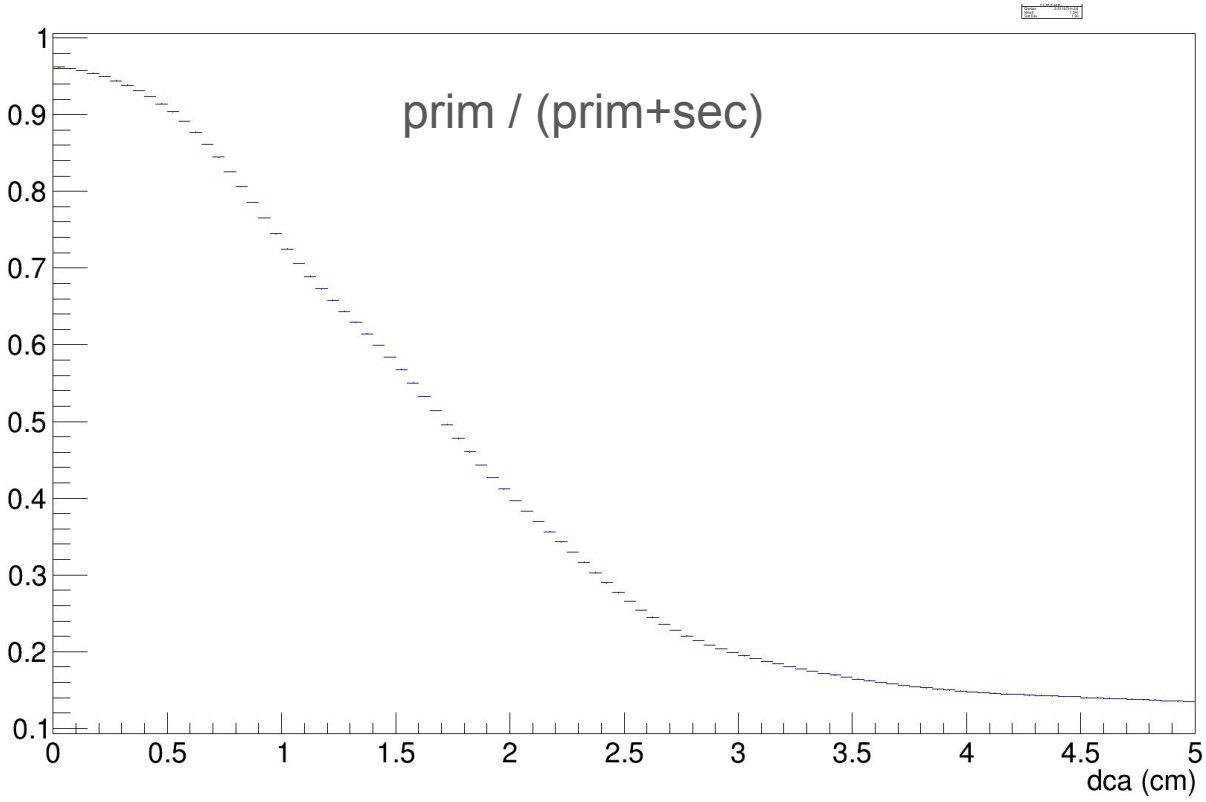


Momentum resolution vs chi2/NDF (nhits > 5)

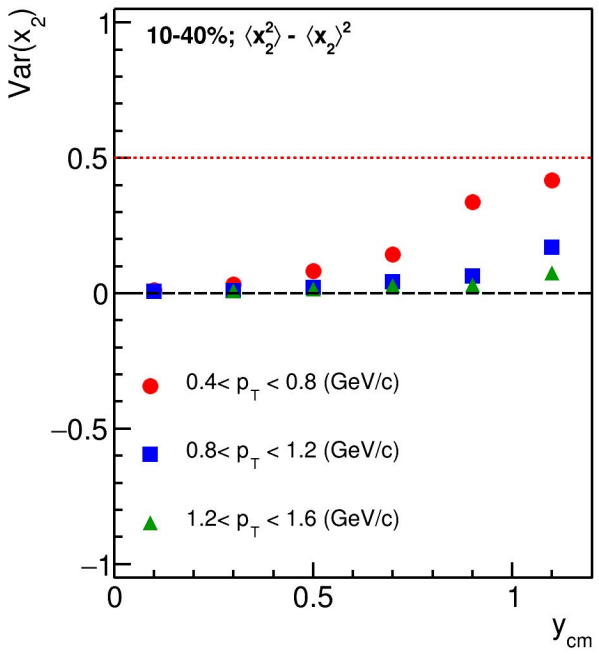


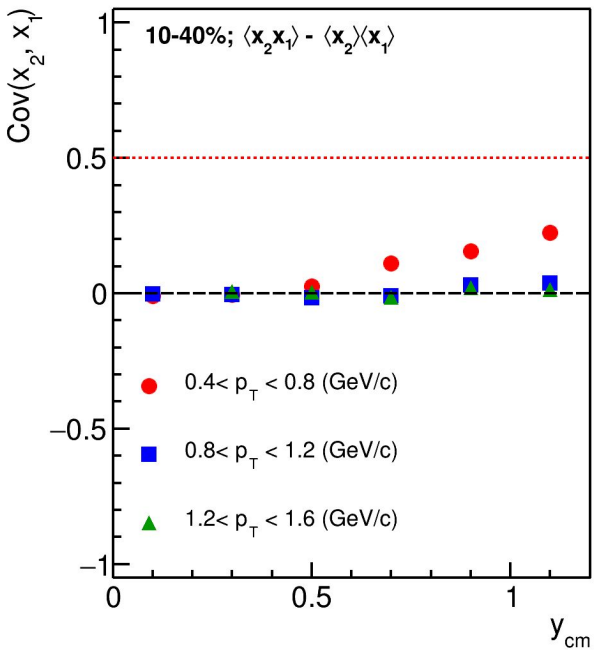
DCA-R comparison between prim and non-prim

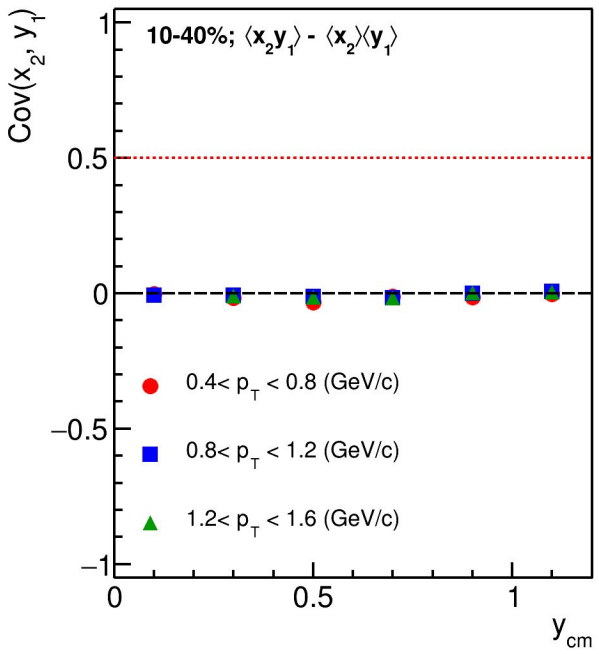




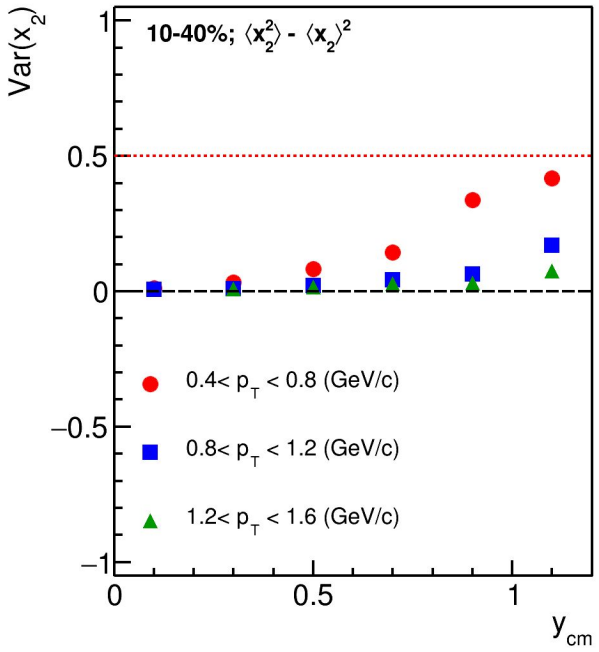
Covariances for x_2 as a function of y_{cm} (n=1, 2)

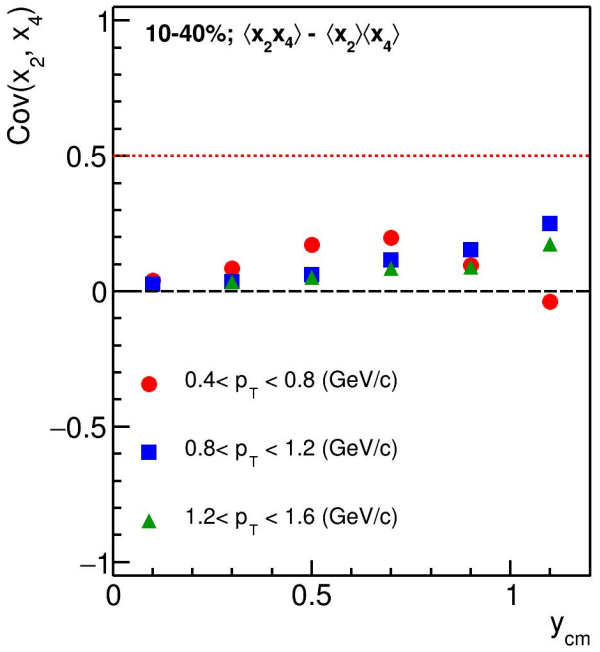


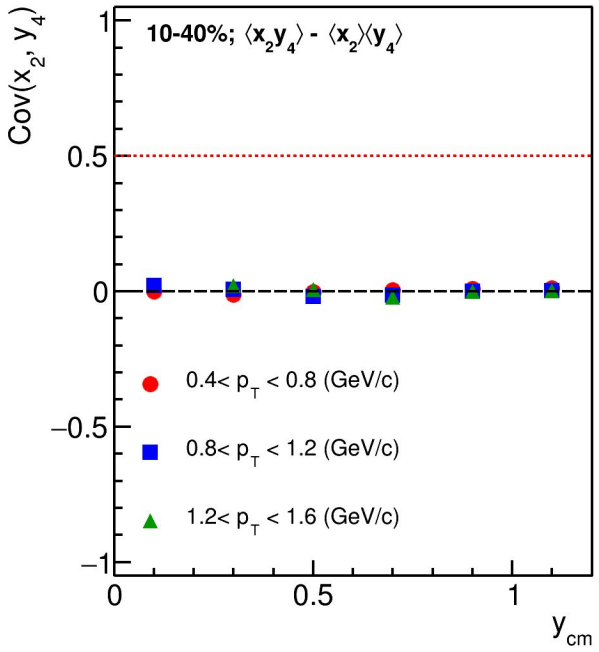




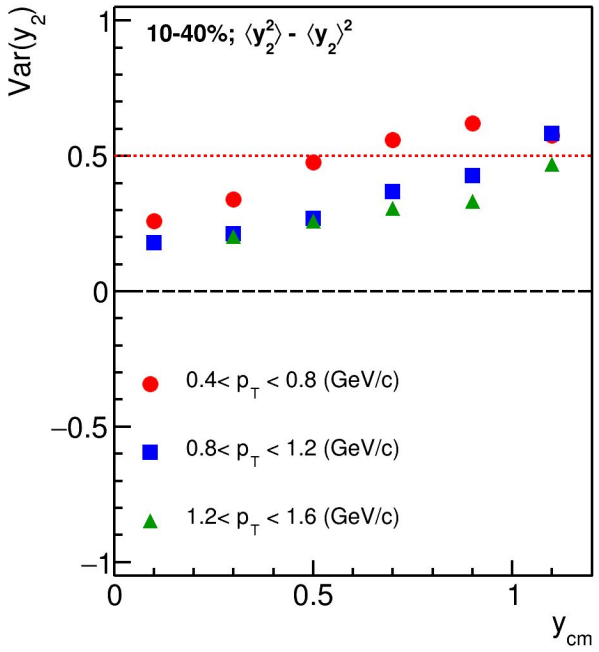
Covariances for x_2 as a function of y_{cm} (n=2, 4)

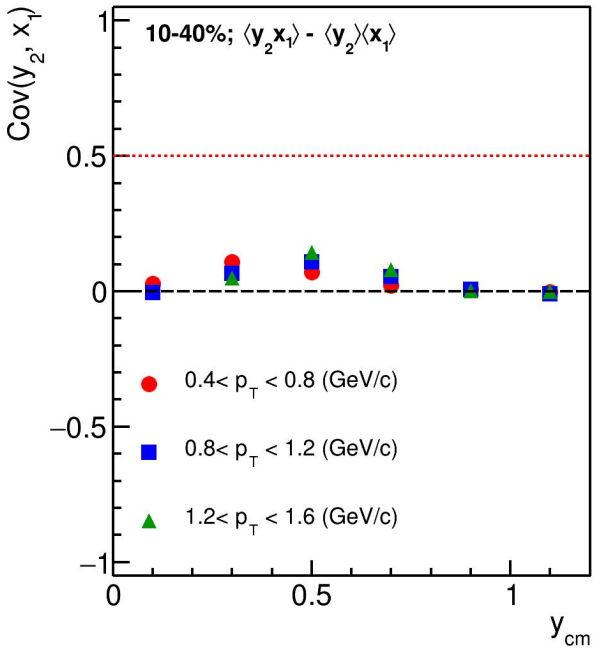


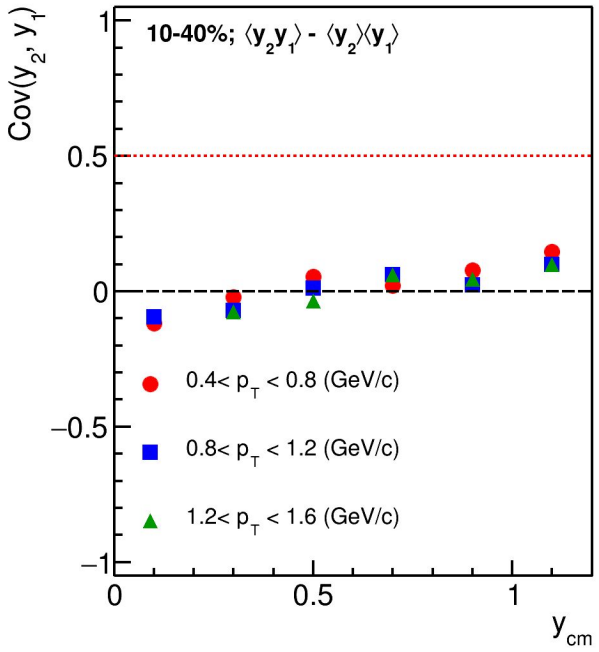




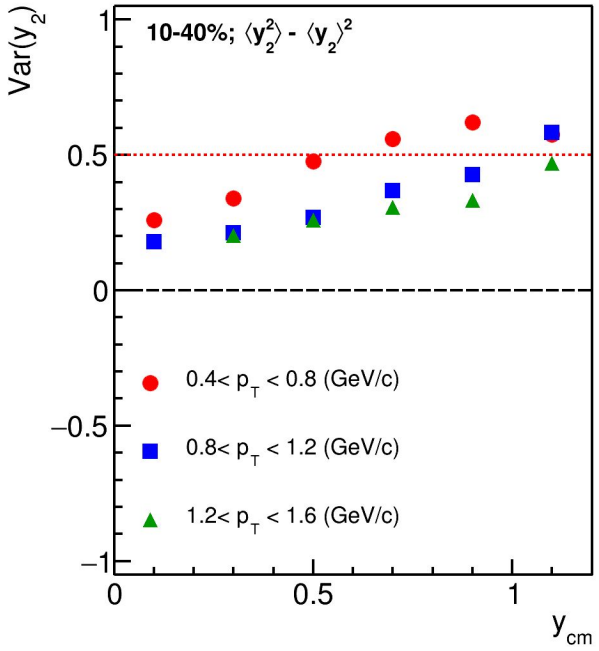
Covariances for y_2 as a function of y_{cm} (n=1, 2)

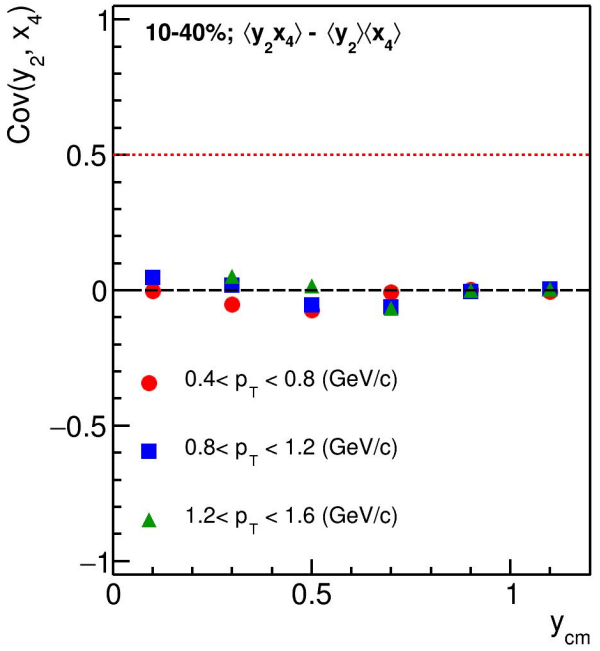


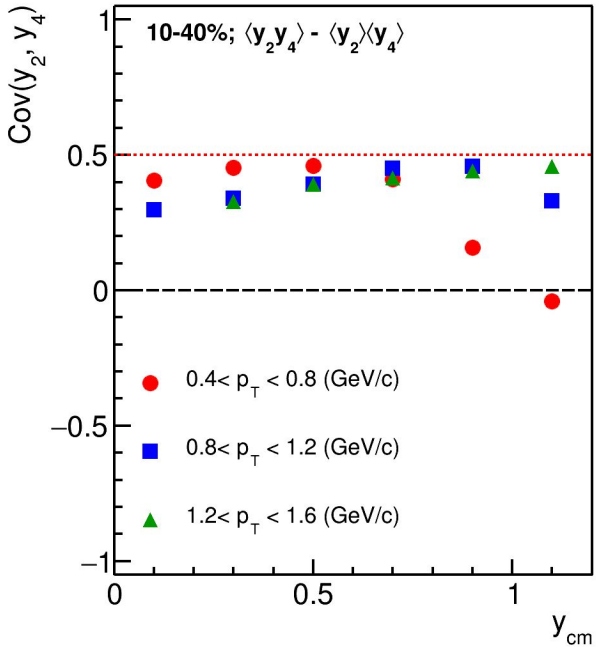




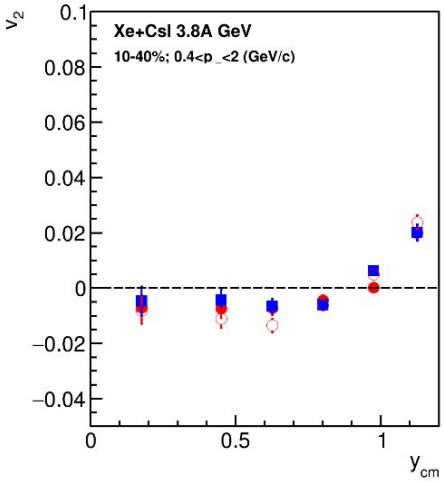
Covariances for y_2 as a function of y_{cm} (n=2, 4)

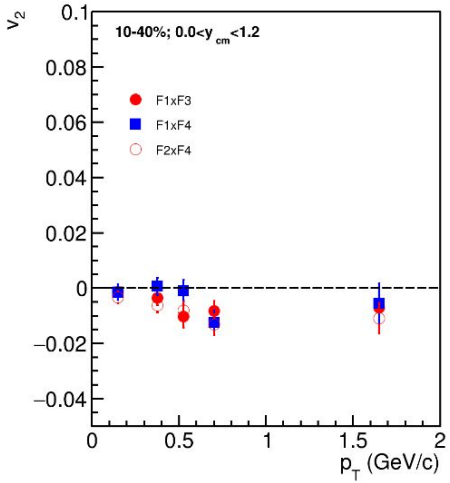


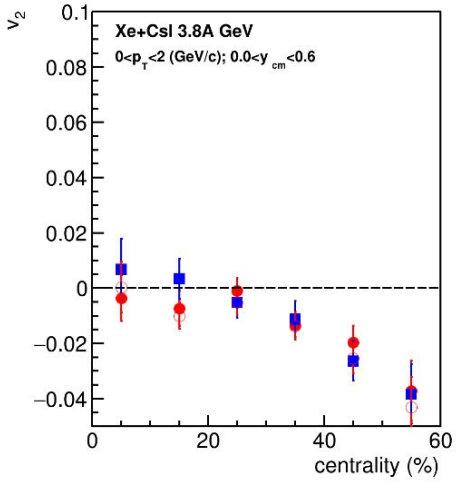


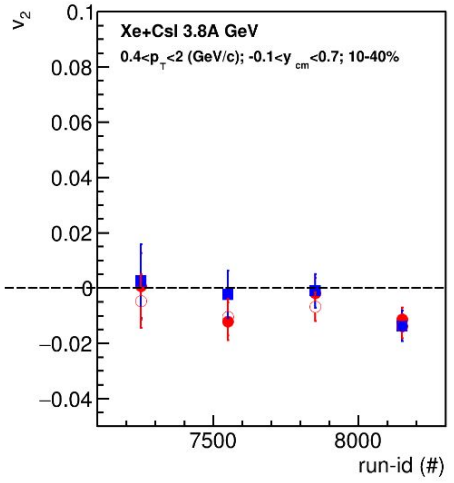


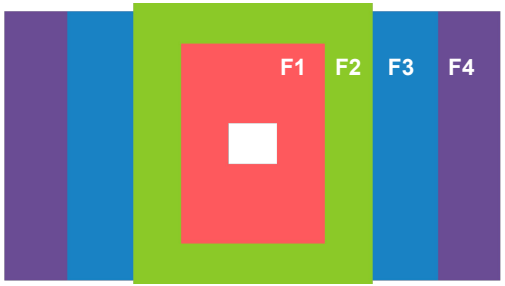
v_2 wrt different planes (PCA with 1-4 harmonics)





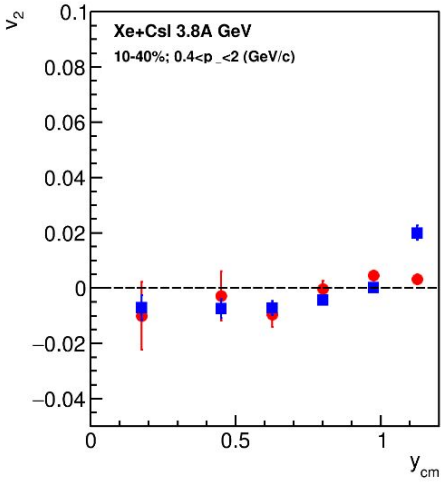


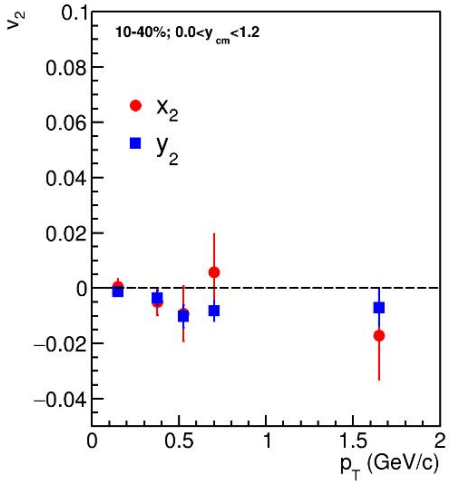


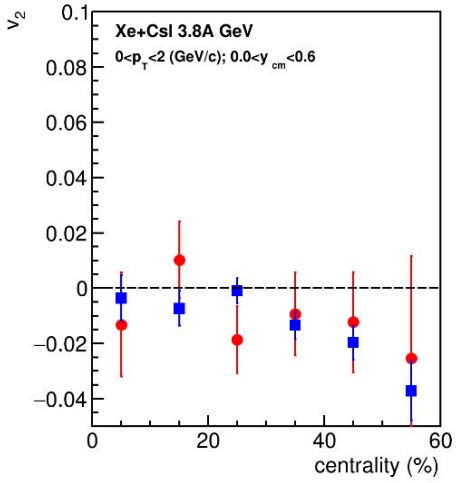


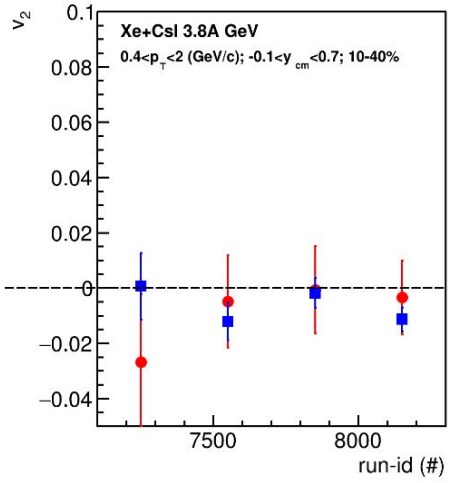
$$v_2 = \frac{4\langle x_2^i X_1^j X_1^k \rangle}{R_1^j R_1^k}$$

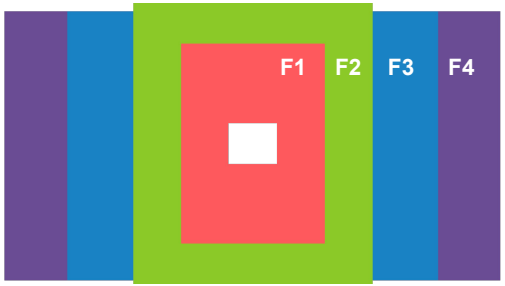
v_2 with different components (PCA with 1-4 harmonics)



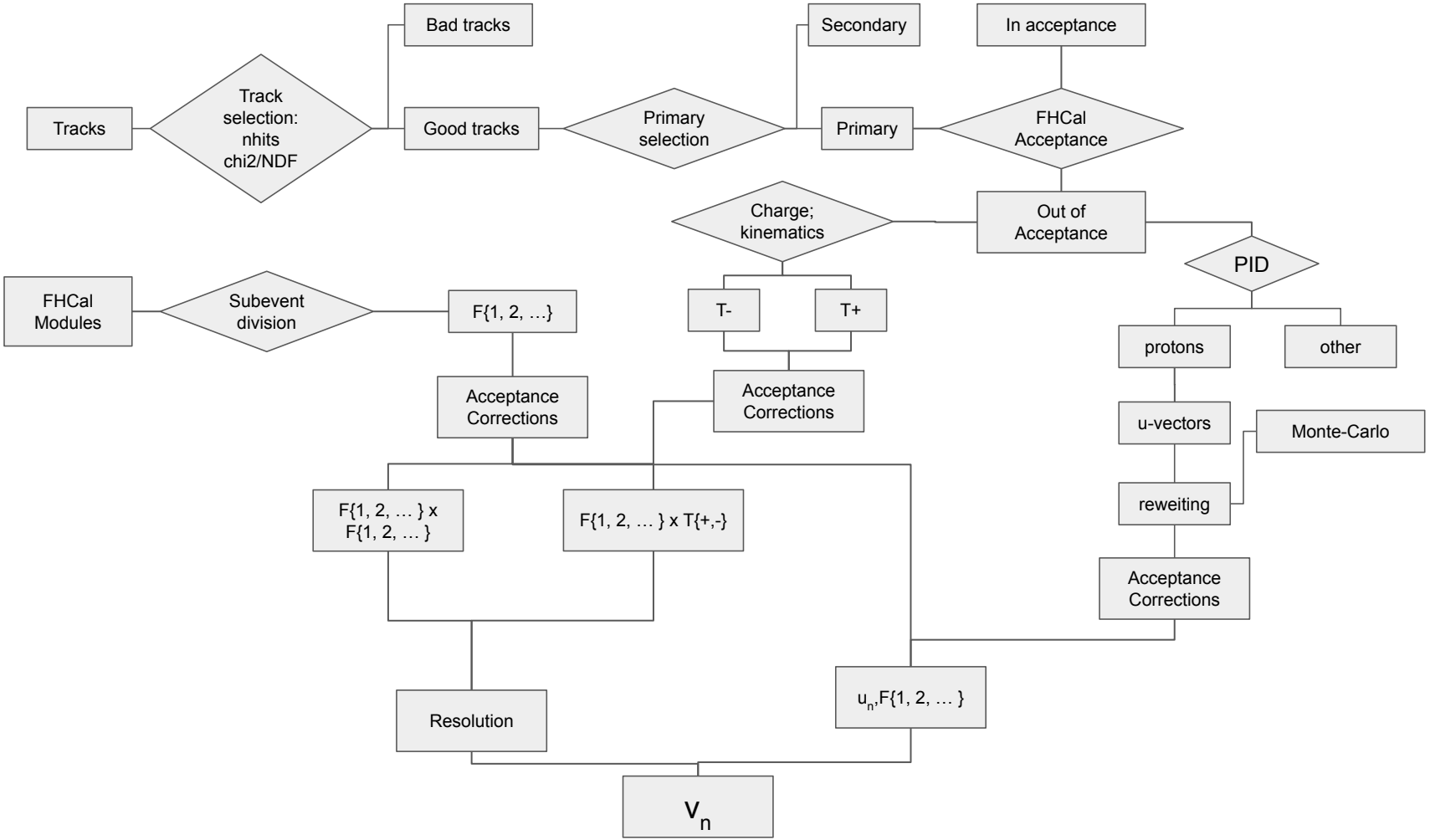




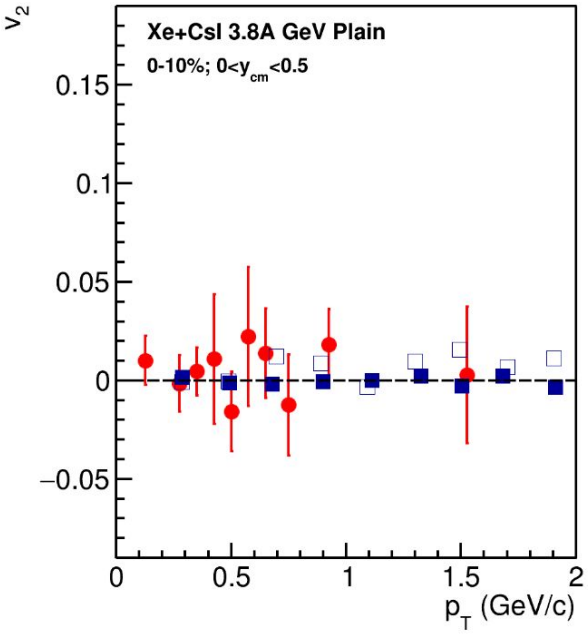


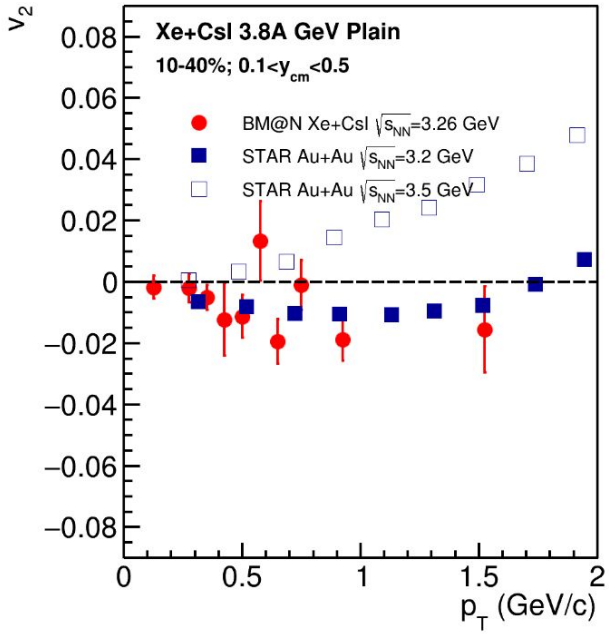


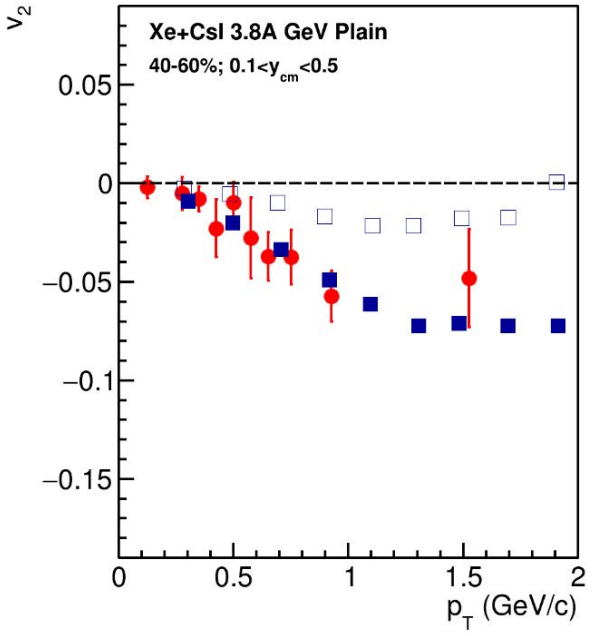
$$v_2 = \frac{4\langle x_2^i X_1^j X_1^k \rangle}{R_1^j R_1^k}$$


Tracks
Track selection: nhits chi2/NDF
Bad tracks
Good tracks
Primary selection
Secondary
Primary
FHCal Acceptance
In acceptance
Out of Acceptance
Charge; kinematics
T-
T+
PID
protons
other
u-vectors
Monte-Carlo
reweiting
Acceptance Corrections
Acceptance Corrections
FHCal Modules
Subevent division
F{1, 2, …}
Acceptance Corrections
F{1, 2, … } x F{1, 2, … }
F{1, 2, … } x T{+,-}
Resolution
u_n,F{1, 2, … }
V_n

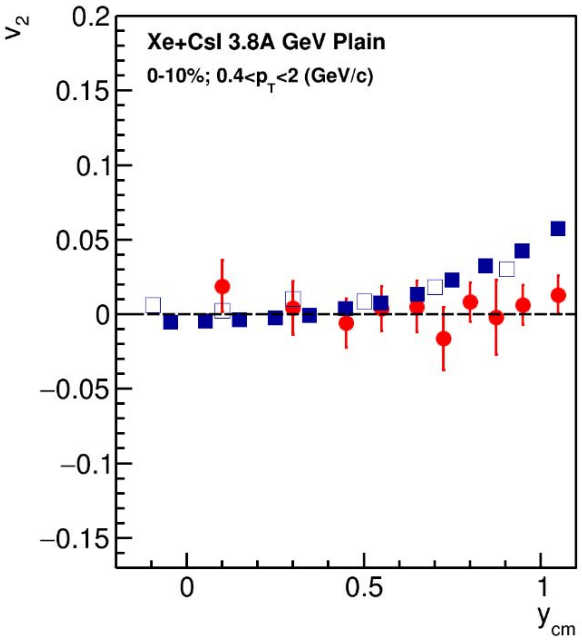
v_2 comparison with STAR: pT (PCA 1-4)

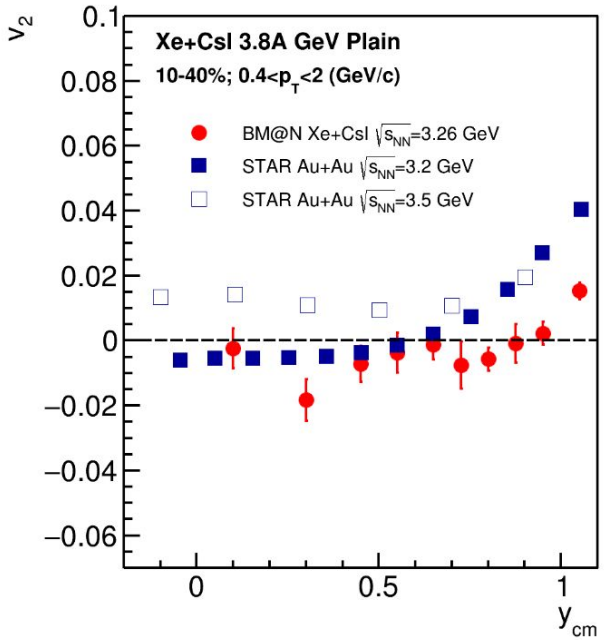


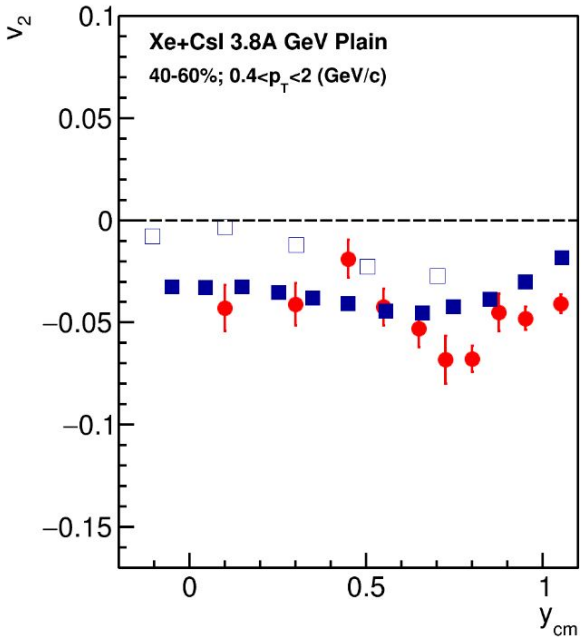


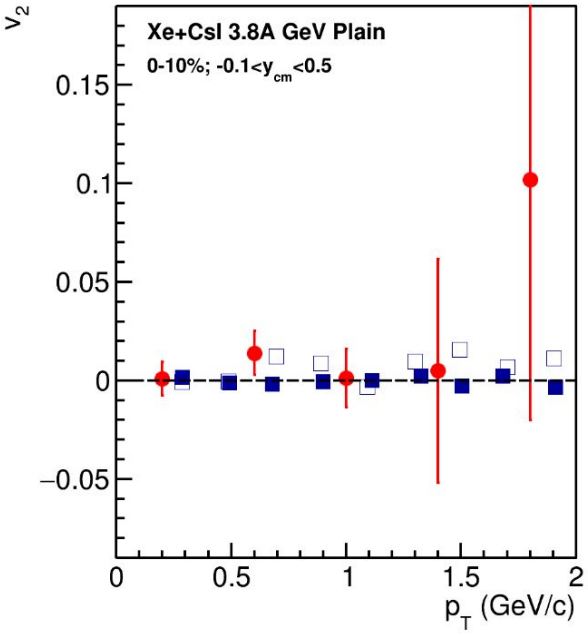


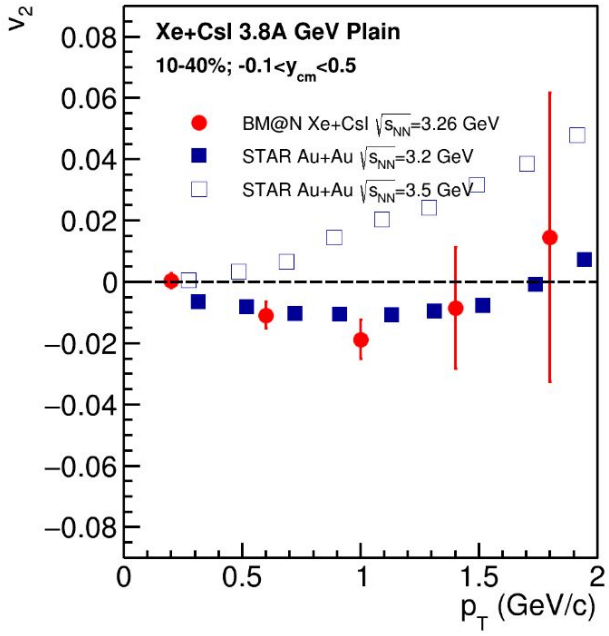
v_2 comparison with STAR: ycm (PCA 1-4)

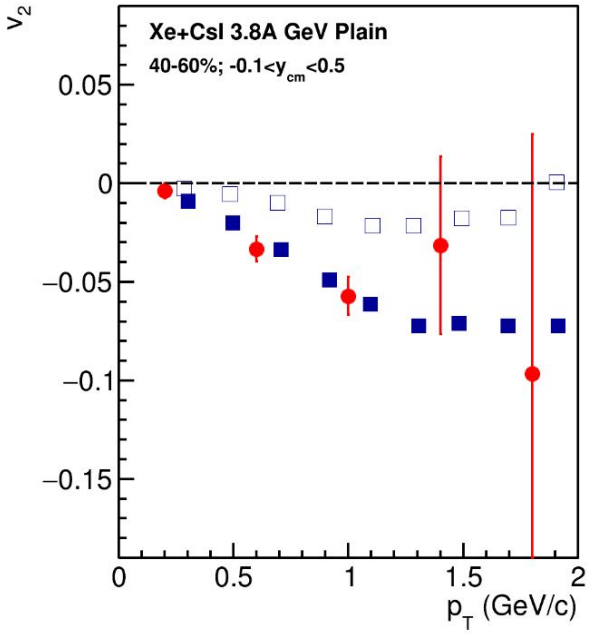


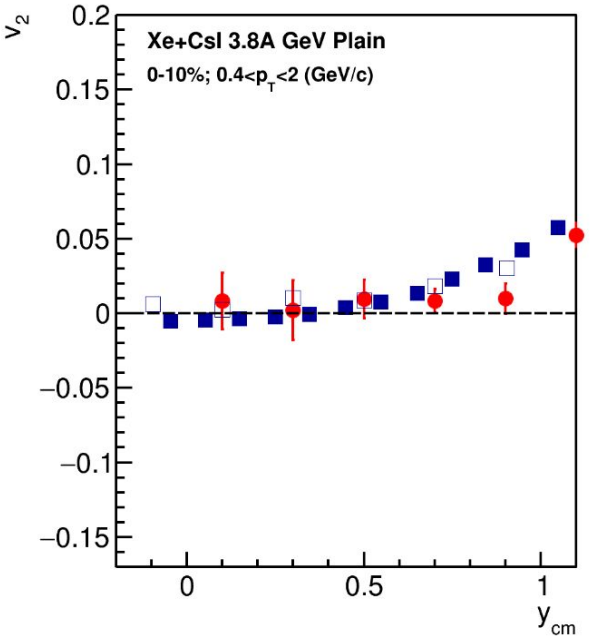


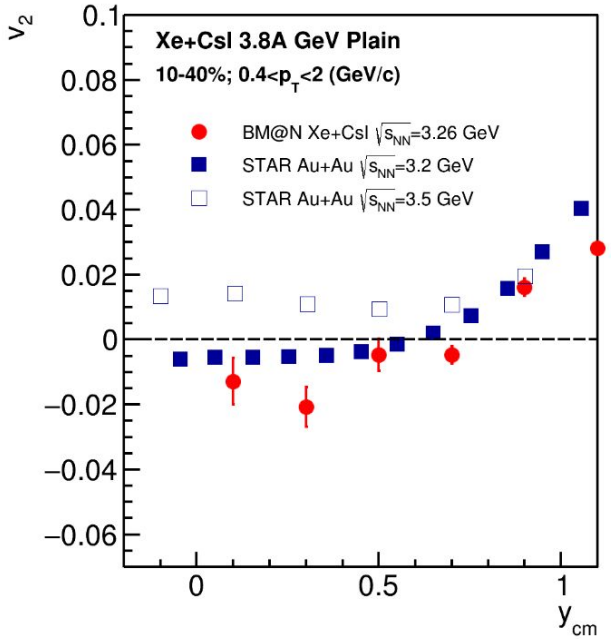


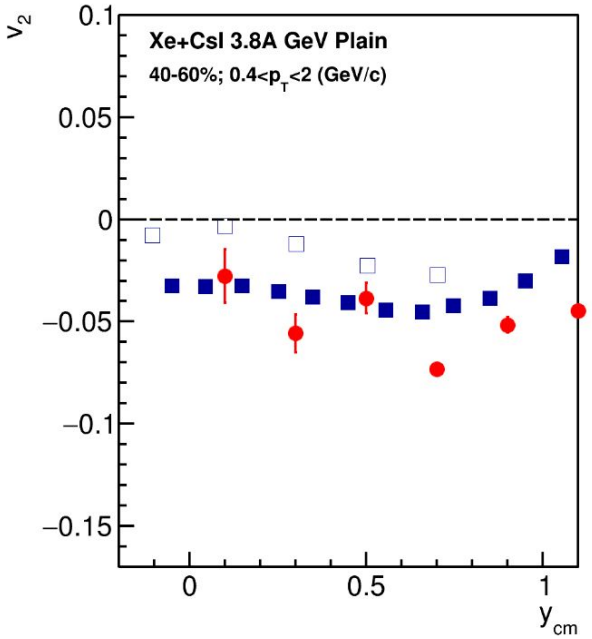

Xe+CsI 3.8A GeV Plain
0-10%; -0.1<y_cm<0.5
v2
pT (GeV/c)


Xe+CsI 3.8A GeV Plain
10-40%; -0.1<y_cm<0.5
BM@N Xe+CsI √sNN=3.26 GeV
STAR Au+Au √sNN=3.2 GeV
STAR Au+Au √sNN=3.5 GeV
v2
pT (GeV/c)

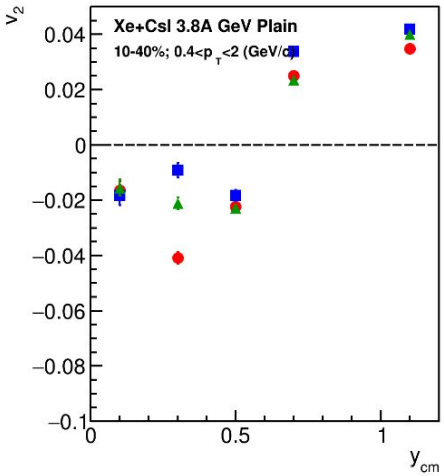

Xe+CsI 3.8A GeV Plain
40-60%; -0.1<y_cm<0.5
v2
pT (GeV/c)

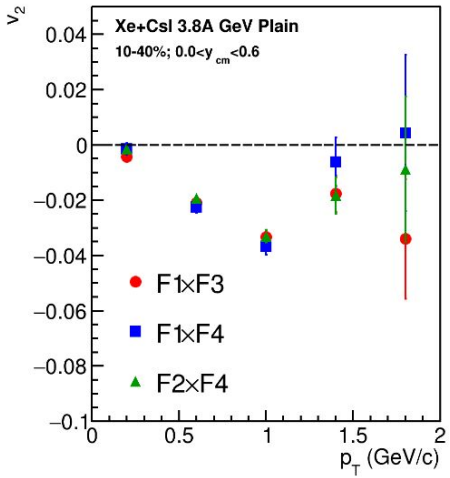

Xe+CsI 3.8A GeV Plain
0-10%; 0.4<p_T<2 (GeV/c)
v_2
y_cm

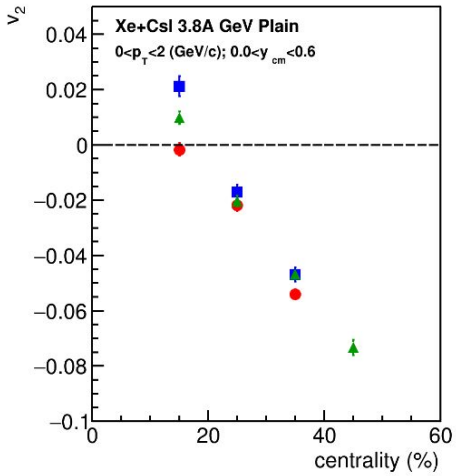

Xe+CsI 3.8A GeV Plain
10-40%; 0.4<p_T<2 (GeV/c)
BM@N Xe+CsI √s_NN=3.26 GeV
STAR Au+Au √s_NN=3.2 GeV
STAR Au+Au √s_NN=3.5 GeV
v_2
y_cm

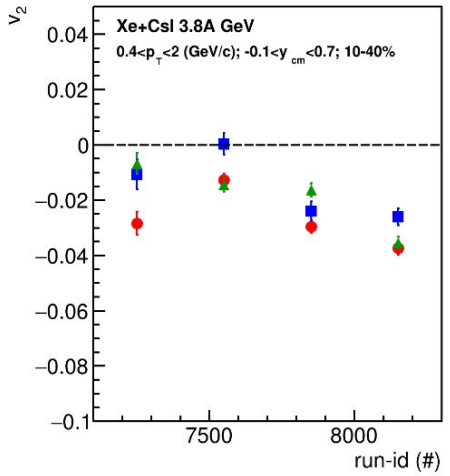

Xe+CsI 3.8A GeV Plain
40-60%; 0.4<p_T<2 (GeV/c)
v_2
y_cm

Proton v_2: pT, y, centrality and run-Id (de-bugged FHCal numeration)

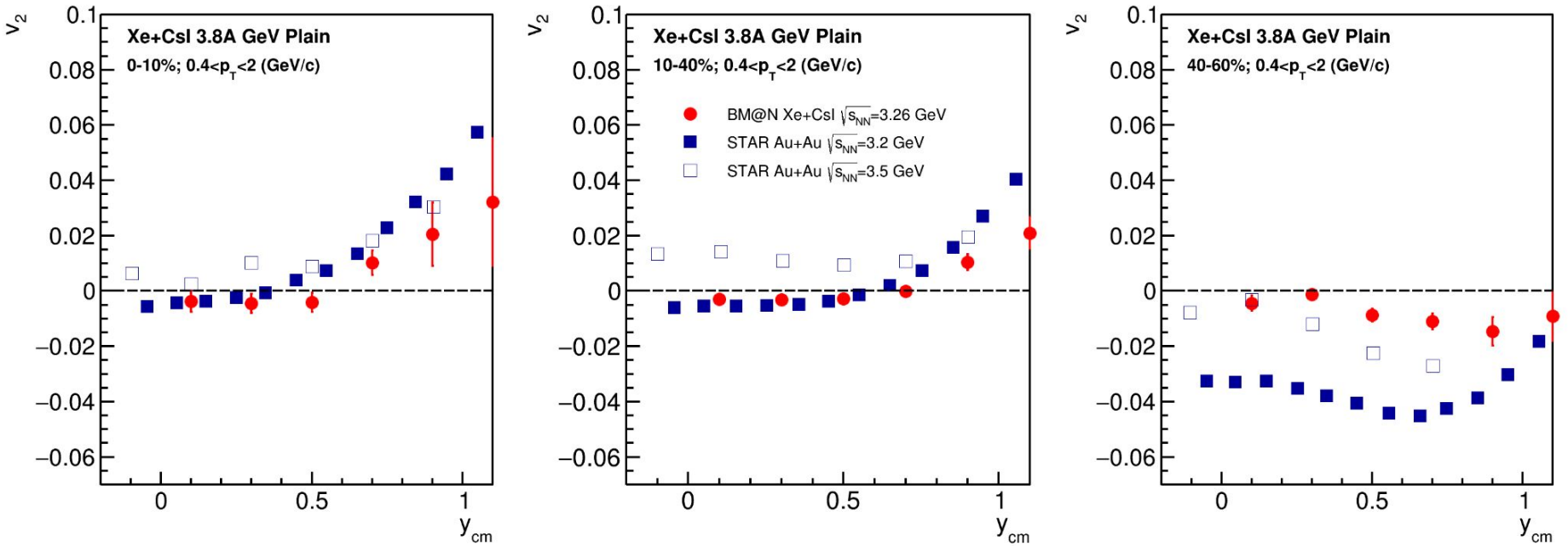




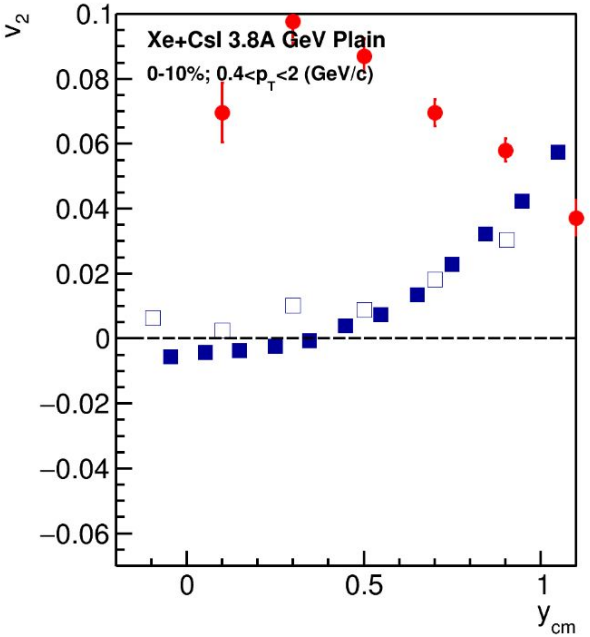


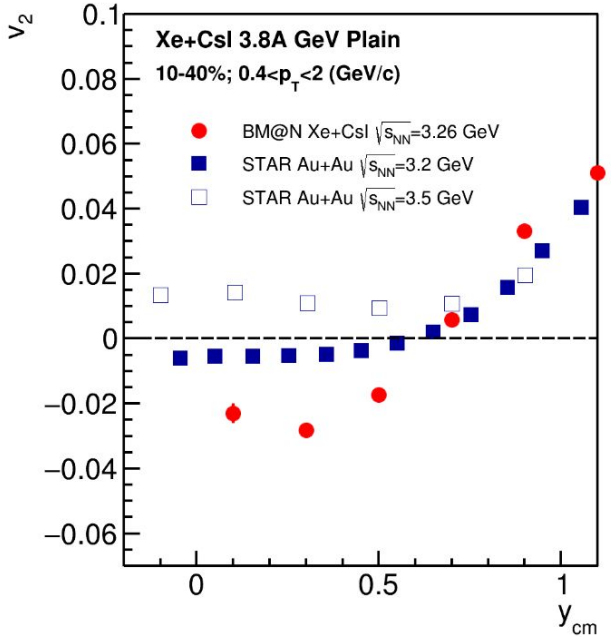


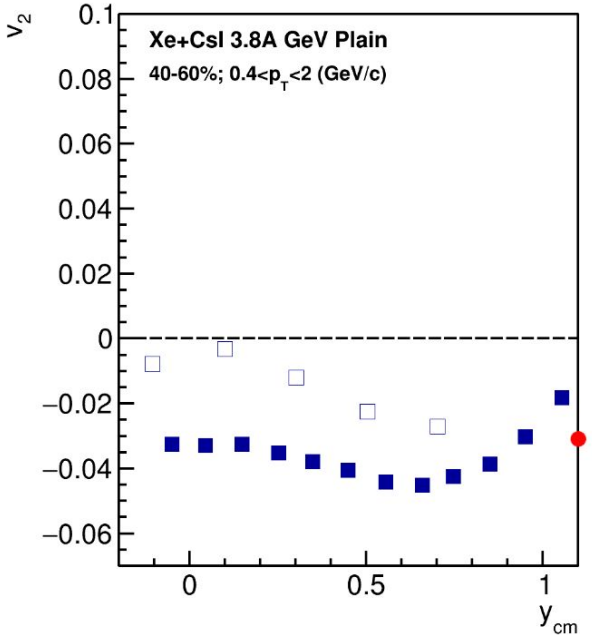
OLD: Proton v_2



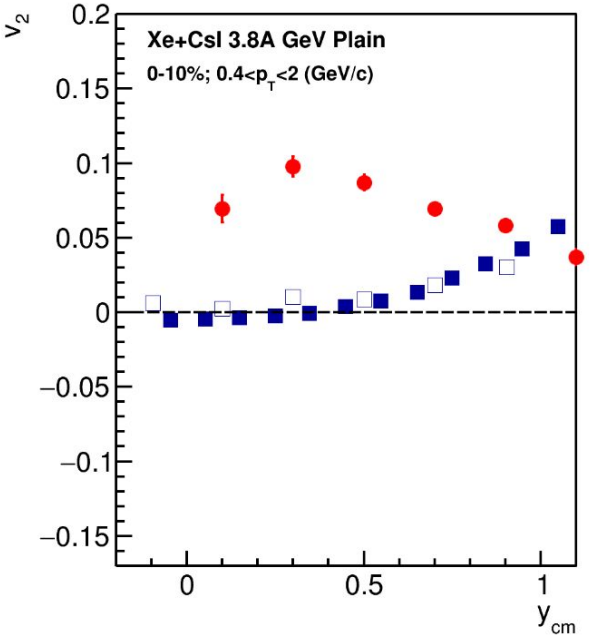
UPD: Proton v_2

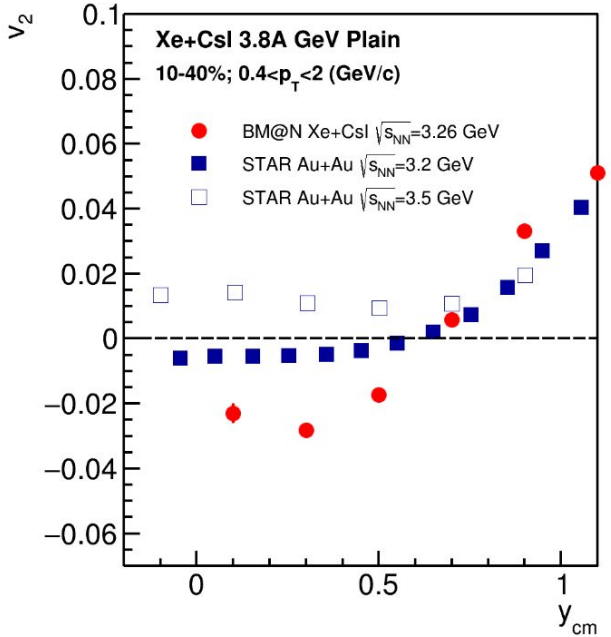


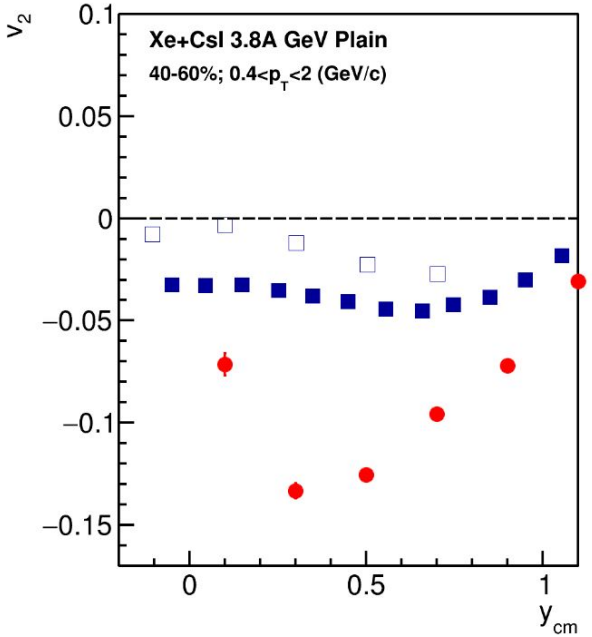




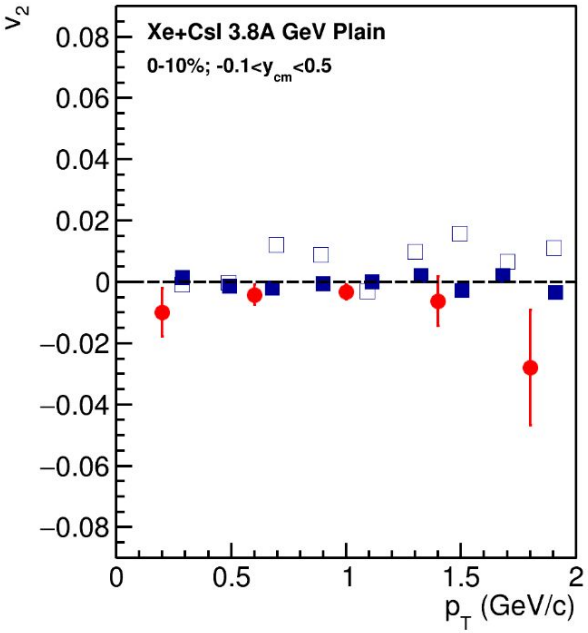
UPD: Proton v_2 after track reweighting

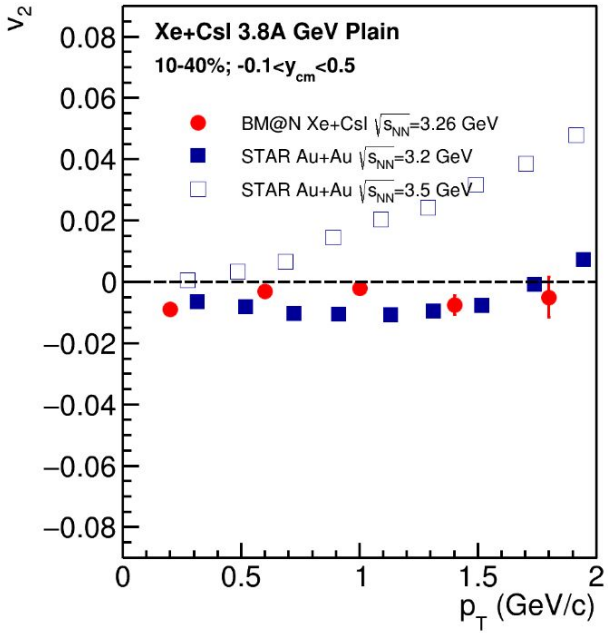


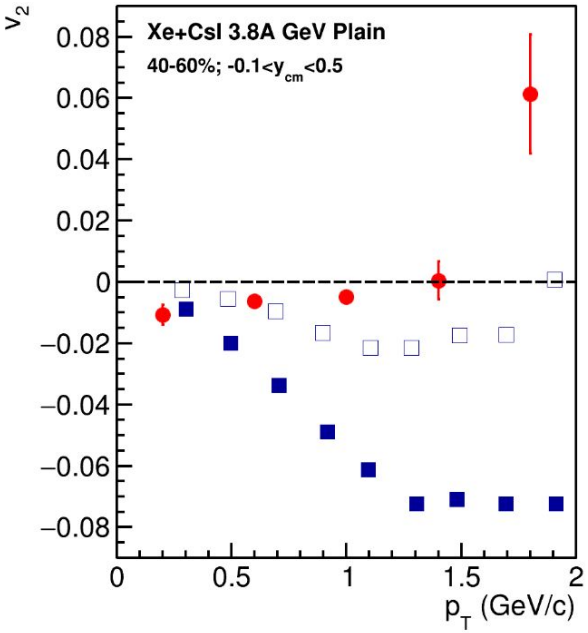




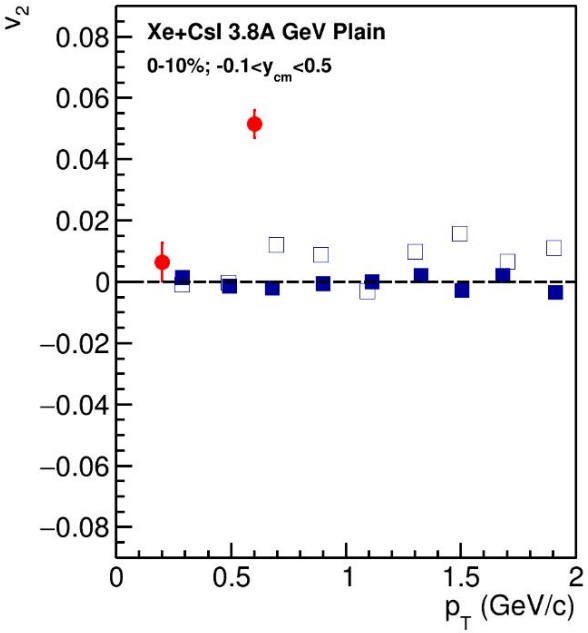
OLD: Proton v_2

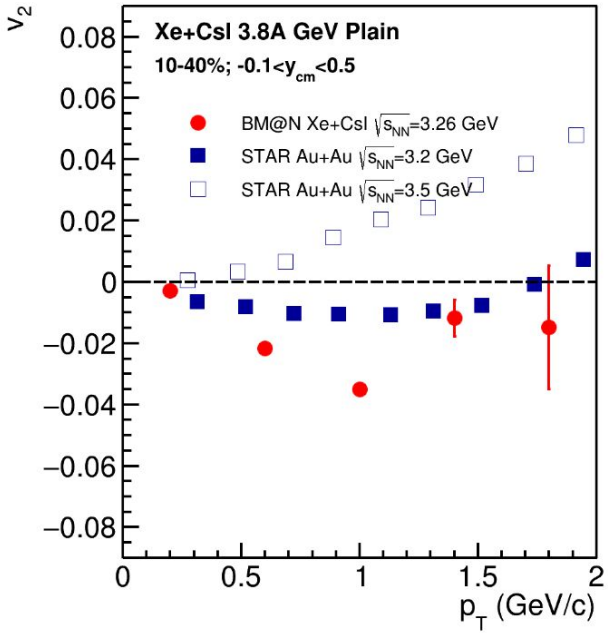


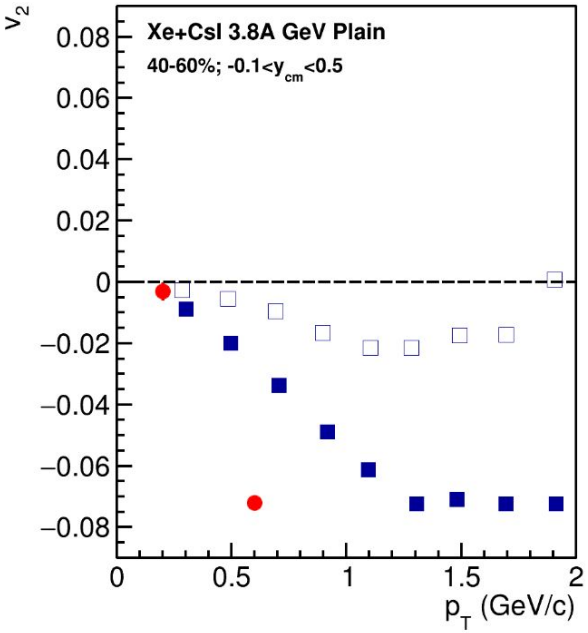




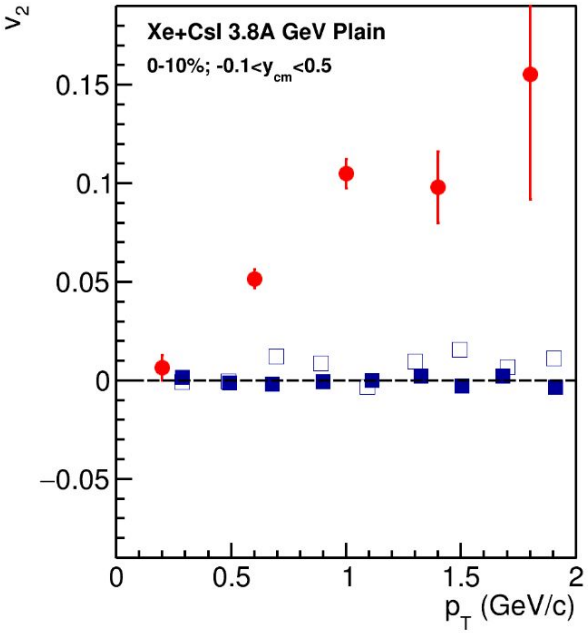
UPD: Proton v_2

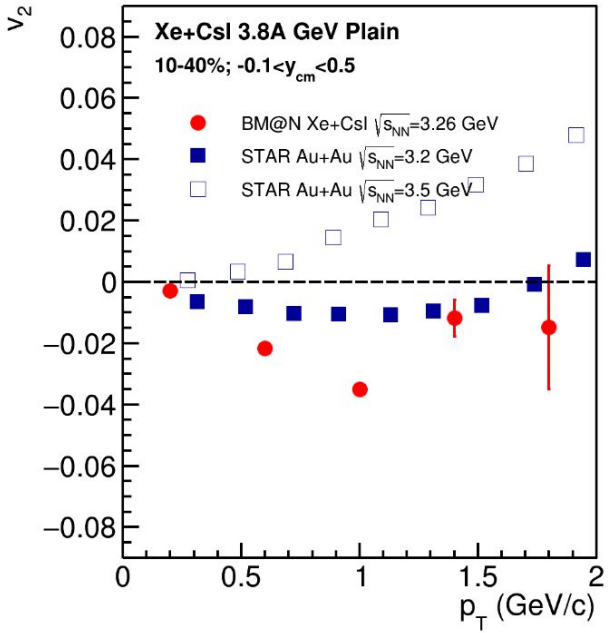


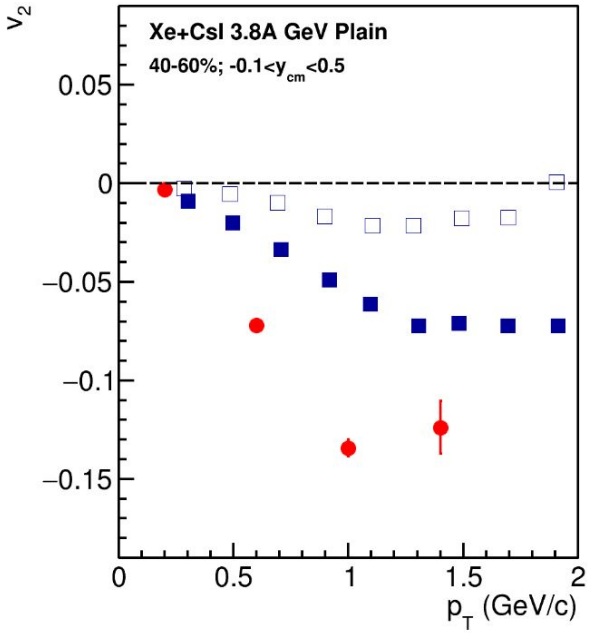




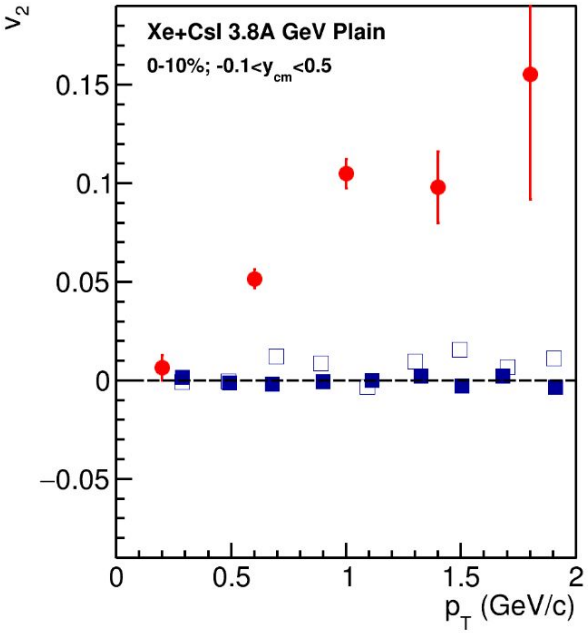
UPD: Proton v_2

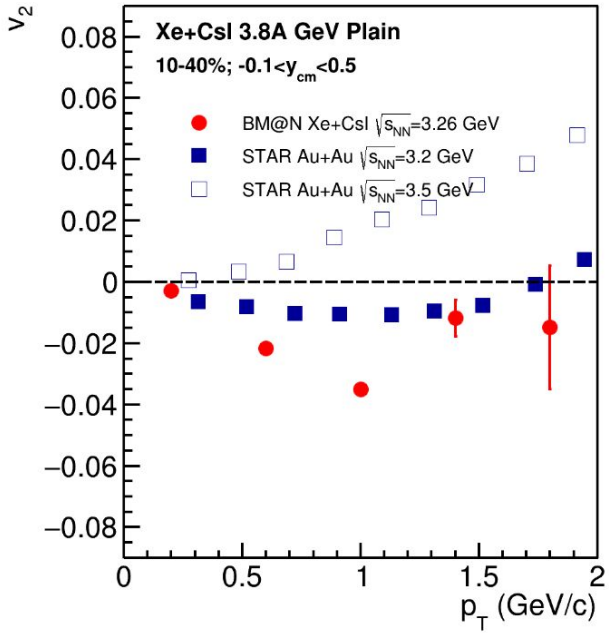


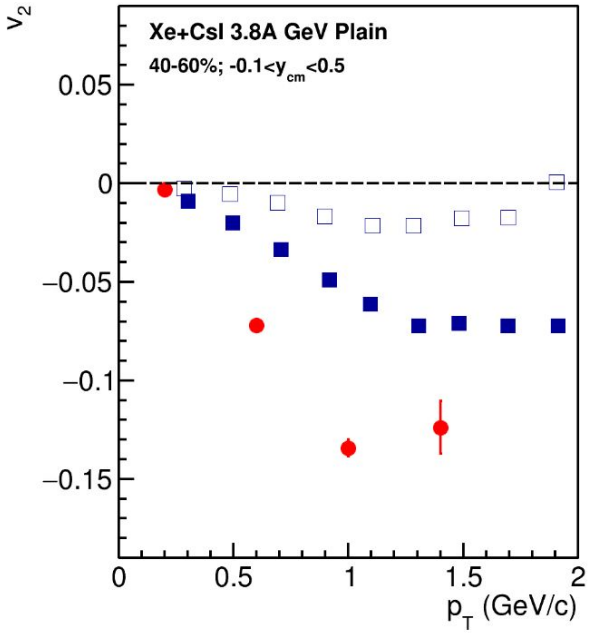




UPD: Proton v_2





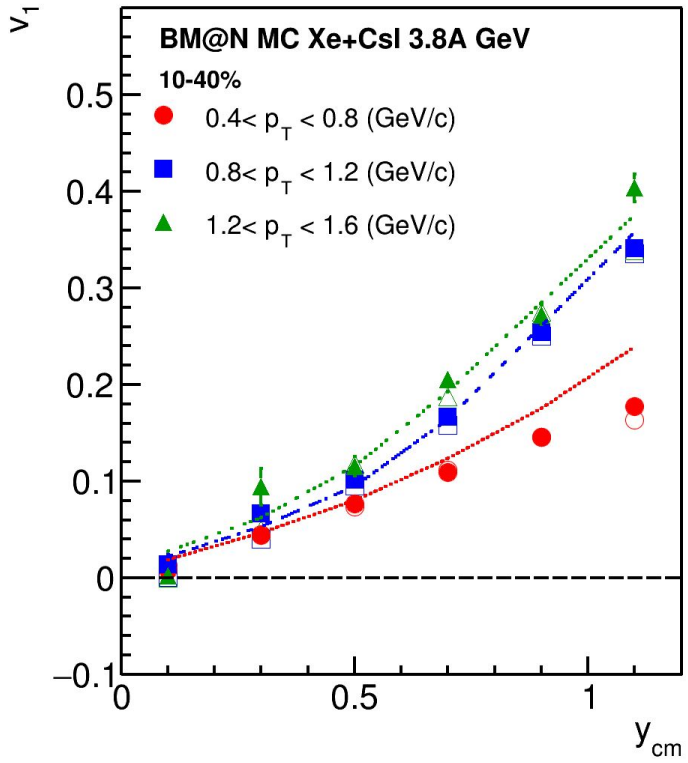


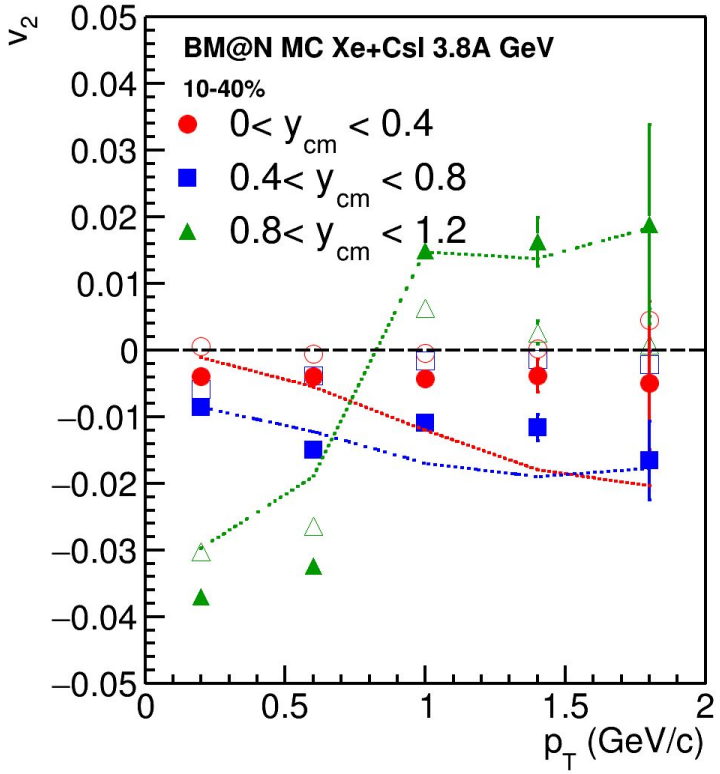
Analysis setup

- JAM MD2 + coalescence for Xe+Cs at E_{kin}=3.8A GeV as an input
- Full reconstruction
- Event selection:
  - N tracks for VTX > 2
- Track selection (as in data)
  - Nhits > 5
  - Chi2/NDF for CT-track < 5
  - R_{dca}<5
- Identification via associated MC-track + hit in any of the TOF

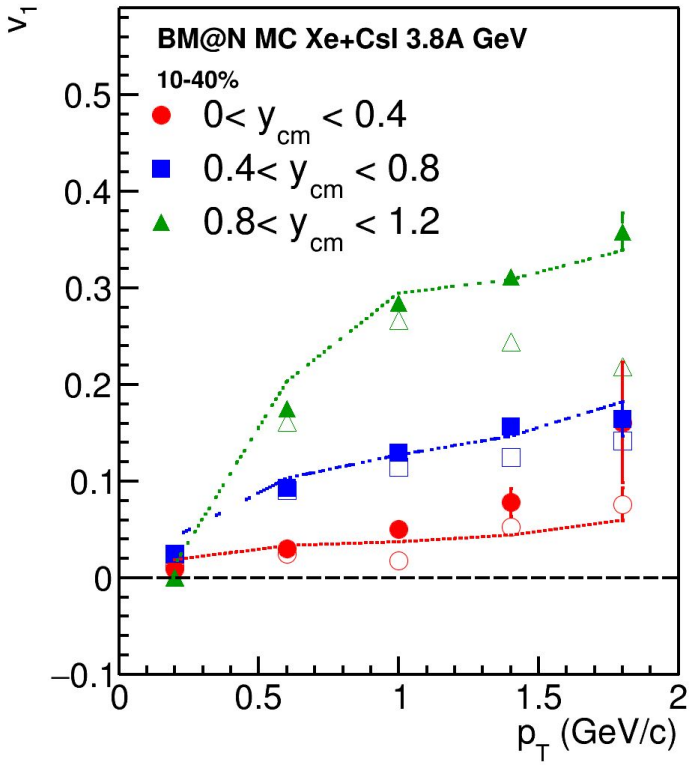
Issue in question:

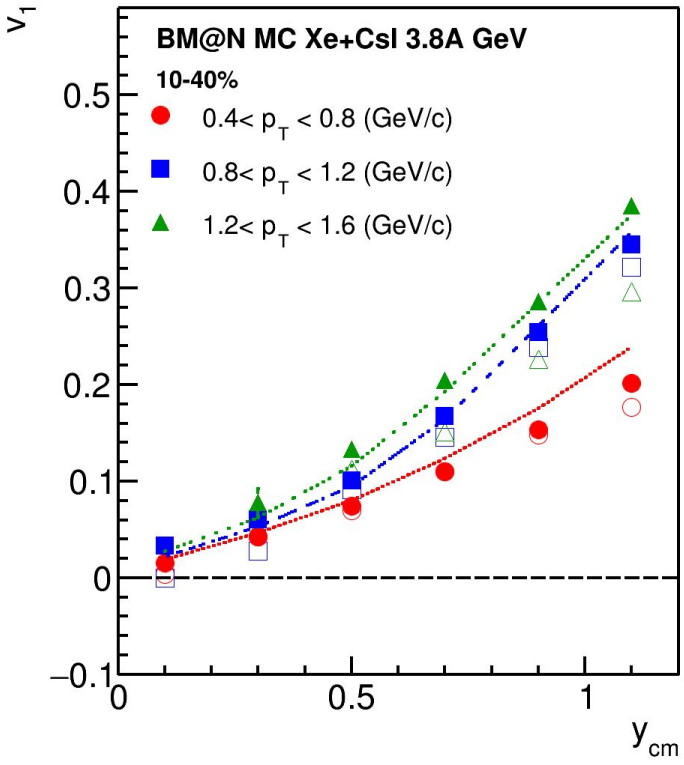
Previously even v_2 was in agreement, check the article in Particles



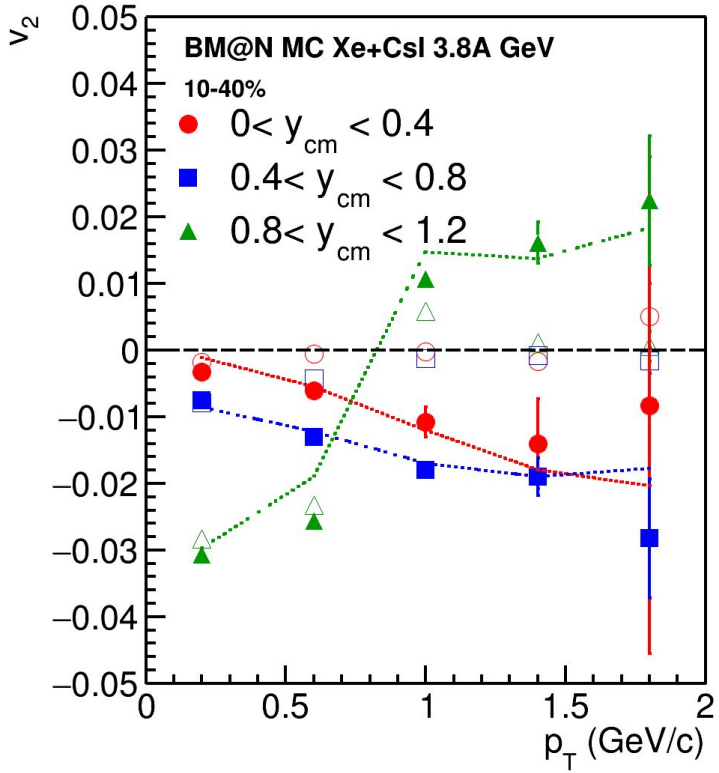


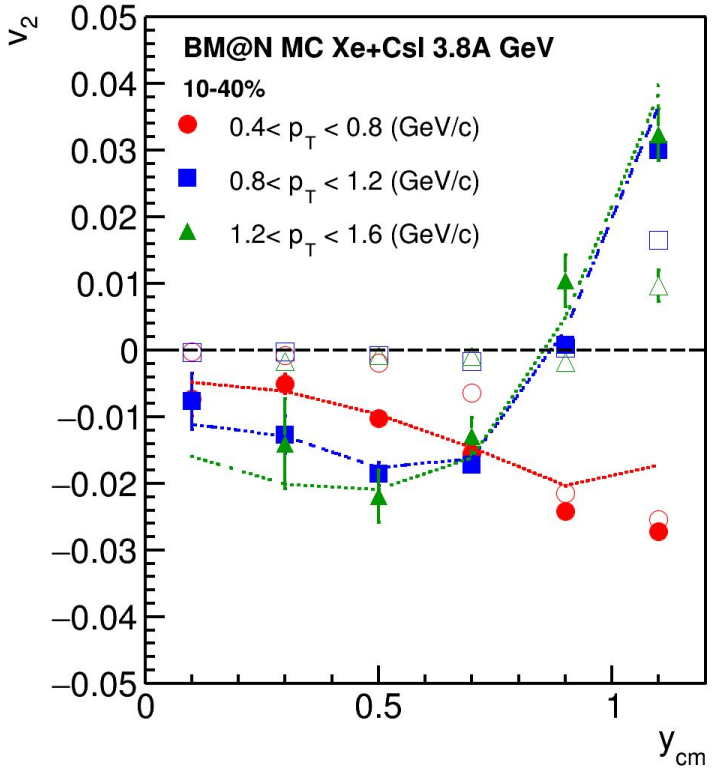
Issue fixed: Tw+Resc Qn-Tools like: v1



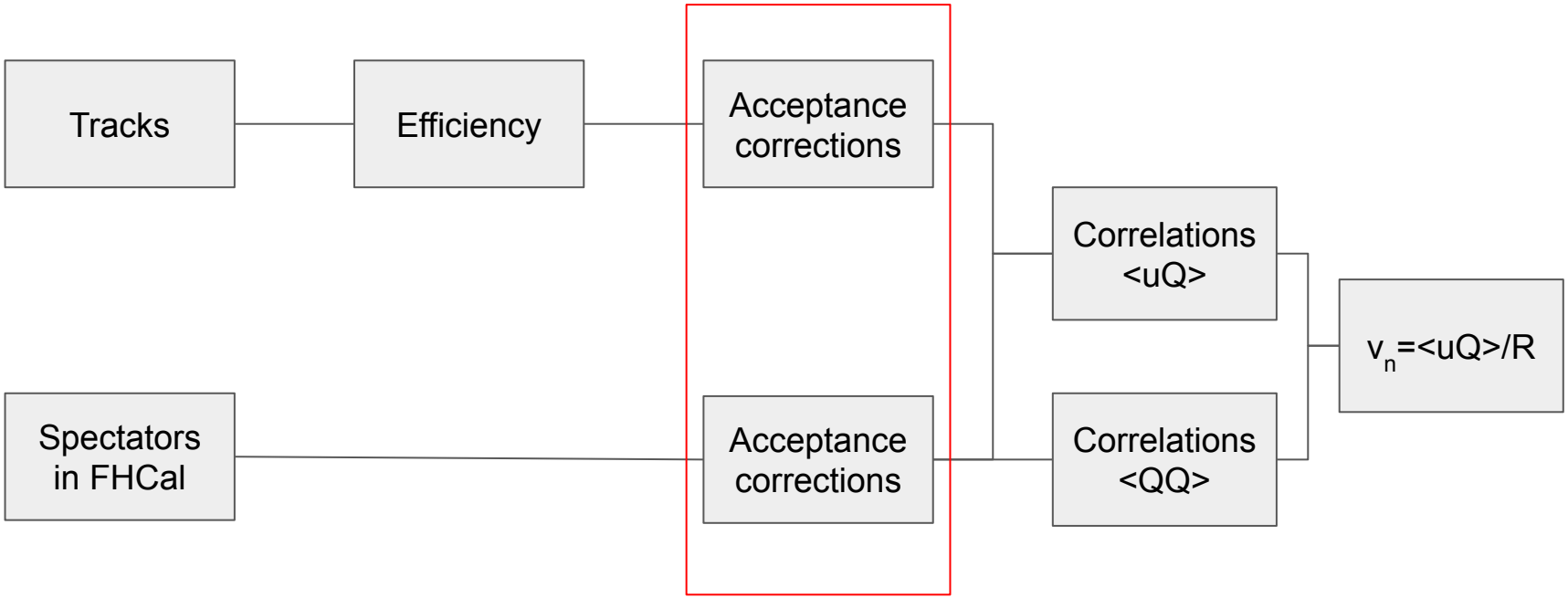


Issue fixed: Tw+Resc Qn-Tools like: v2





Basic flow measurements scheme



Recentering, twist and rescaling corrections

Twist and rescaling:

Given u_n= [cos nφ, sin nφ]

$$C = \begin{bmatrix} 1 + c_{2n} & s_{2n} \\ s_{2n} & 1 - c_{2n} \end{bmatrix}$$ mixing matrix for double harm.

$$u'_n = C^{-1}(u_n - r_n)$$ Recentering, twist and rescaling

$$r = \begin{bmatrix} c_n \\ s_n \end{bmatrix}$$ recentering vector

In QnTools there are no u_n-vectors, for all vectors sum is calculated according to:

$$\vec{q}_n = \frac{\sum_k w_k \vec{u}_n}{\sum_k w_k}$$ In each event

$$\begin{bmatrix} c_n \\ s_n \end{bmatrix} = \frac{1}{M} \sum_{m=1}^{M} \vec{q}_n^{\,m}$$ Sum over events

Then recentering, twist and rescaling is applied event-by-event to each q_n. But:

$$\begin{bmatrix} c_n \\ s_n \end{bmatrix} = \frac{\sum_{m=1}^{M} \sum_k w_k \vec{u}_n}{\sum_{m=1}^{M} \sum_k w_k}$$ ←this value bias flow,

not this→ $$\begin{bmatrix} c_n \\ s_n \end{bmatrix} = \frac{1}{M} \sum_{m=1}^{M} \frac{\sum_k w_k \vec{u}_n}{\sum_k w_k}$$

The subtle difference in calculating corrections

$$\begin{bmatrix} c_n \\ s_n \end{bmatrix} = \frac{\sum_{m=1}^{M} \sum_k w_k \vec{u}_n}{\sum_{m=1}^{M} \sum_k w_k}$$ ←this value bias flow,

not this→ $$\begin{bmatrix} c_n \\ s_n \end{bmatrix} = \frac{1}{M} \sum_{m=1}^{M} \frac{\sum_k w_k \vec{u}_n}{\sum_k w_k}$$

- Averaging over all particles in all events — characteristic of a detector
- Correcting particle distribution: moves the fourier moments to zero
- Work for all multiplicities

- Averaging in a single event and then averaging over all events
- Correcting event-by-event distribution of q_n
- Probably should work the same for large number of particles in one event (>1000)

After correction x and y components should give the same result (by design)

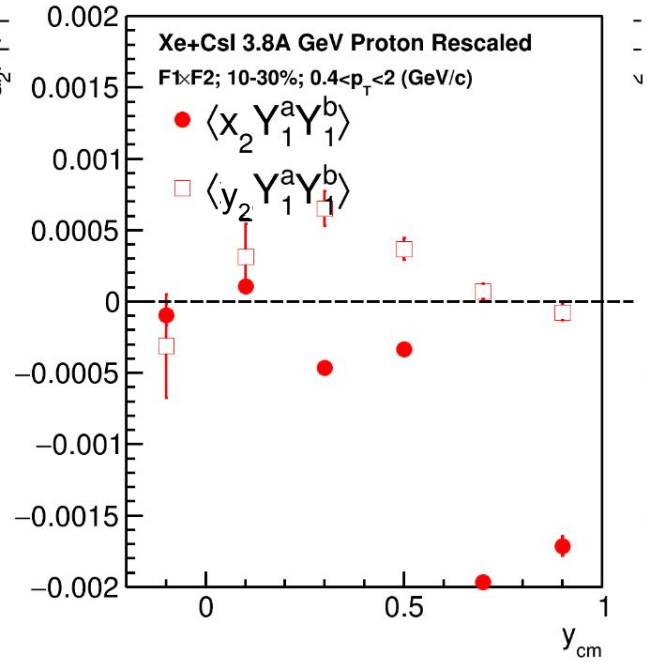
$$r = \begin{bmatrix} c_n \\ s_n \end{bmatrix}$$ recentering vector

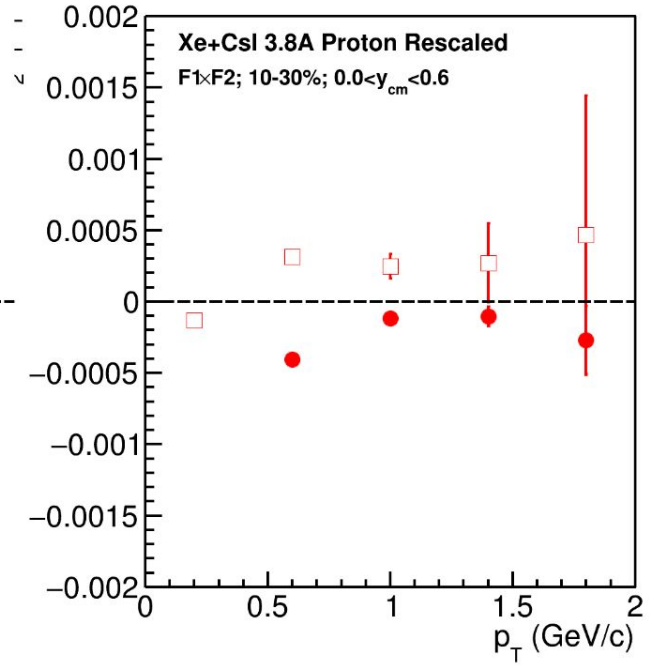
$$C = \begin{bmatrix} 1 + c_{2n} & s_{2n} \\ s_{2n} & 1 - c_{2n} \end{bmatrix}$$ mixing matrix for double harm.

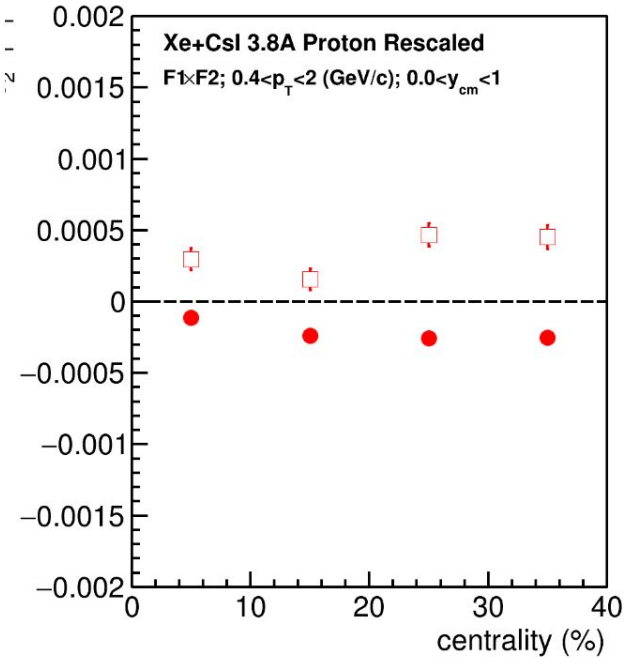
Removes the constant: shifts mean to zero

Untangles and then equalizes cos/sin

Example from the data: u_2 F F correlation



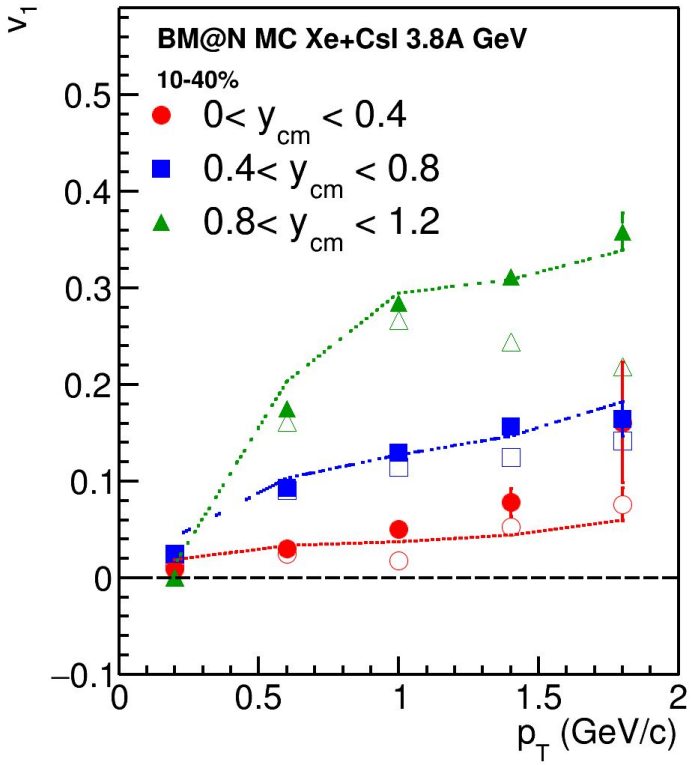




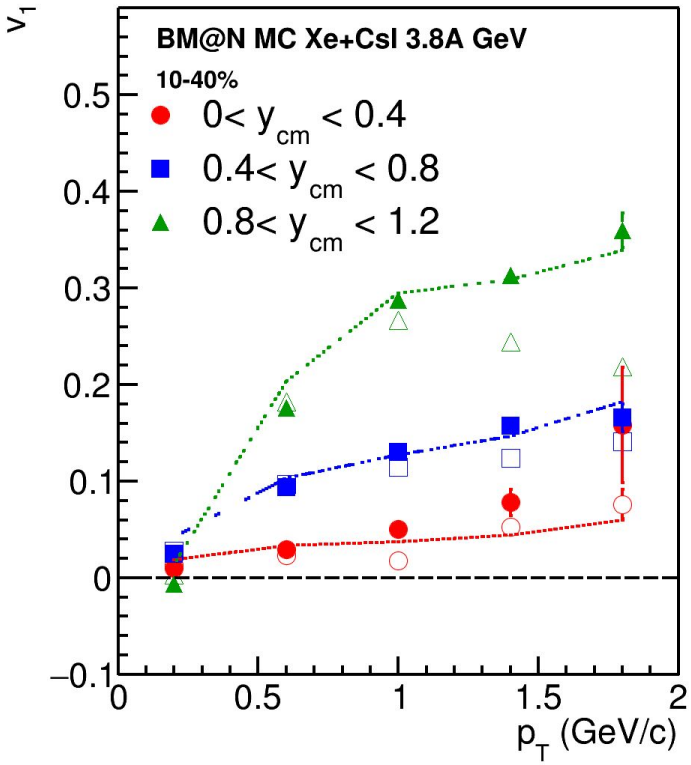
Still large contribution from uncorrected
$\langle x_2 \rangle \langle Y_1 Y_1 \rangle$ and $\langle y_2 \rangle \langle Y_1 Y_1 \rangle$

Correction comparison: v1

QnTools-like Rec+Tw+Resc

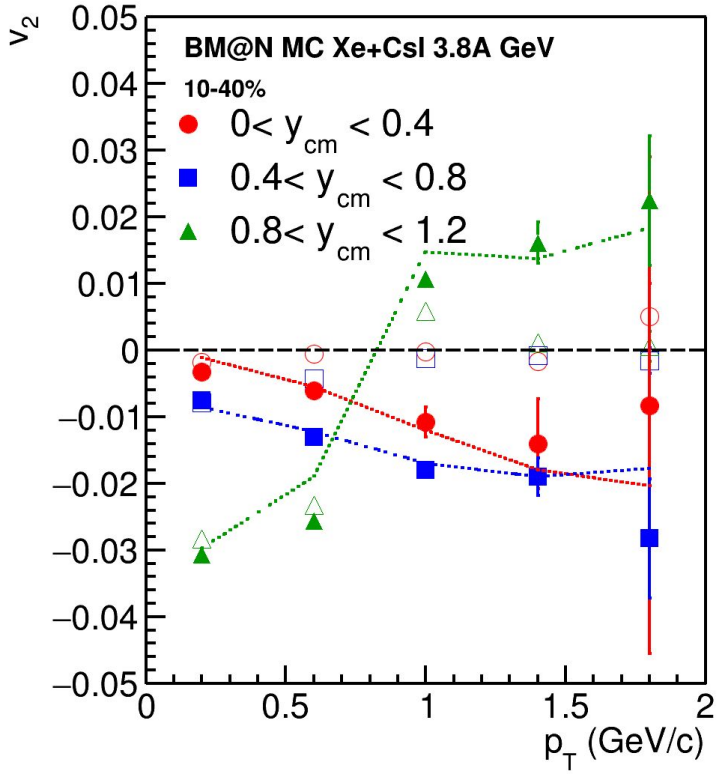


Corrected rec+tw+resc

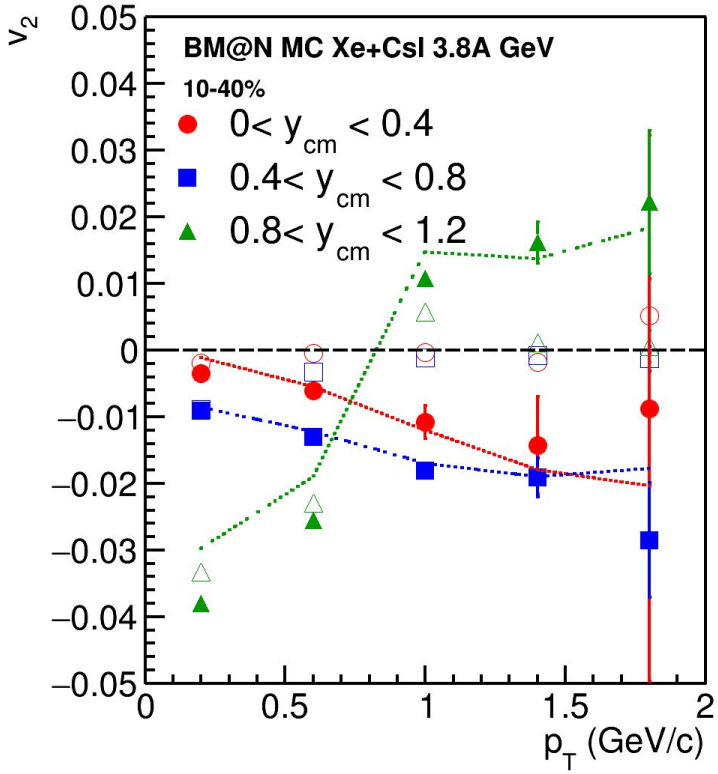


Correction comparison: v2

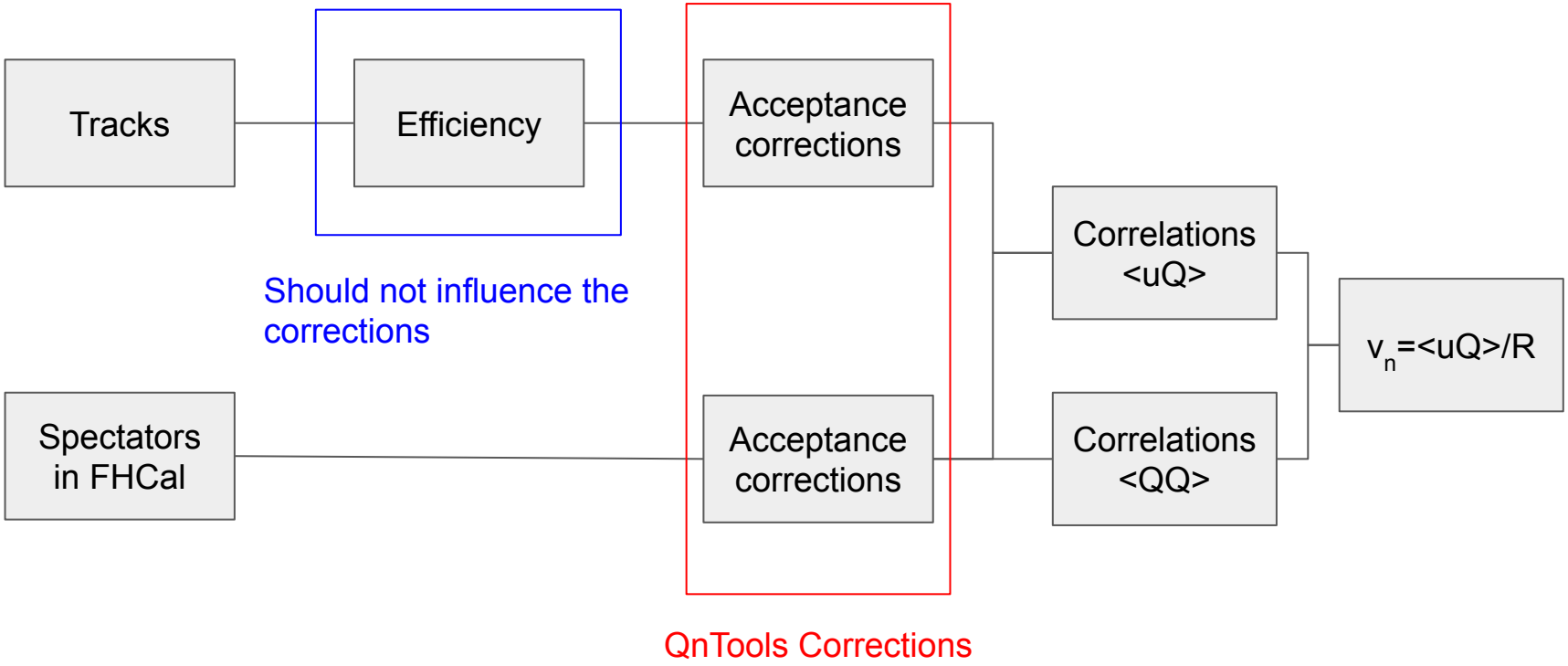
QnTools-like Rec+Tw+Resc



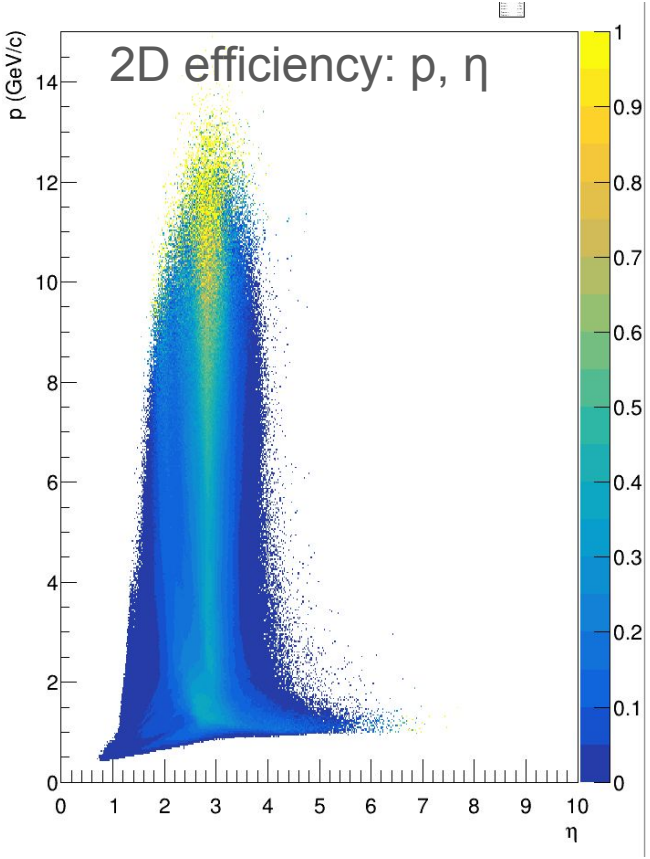
Corrected rec+tw+resc



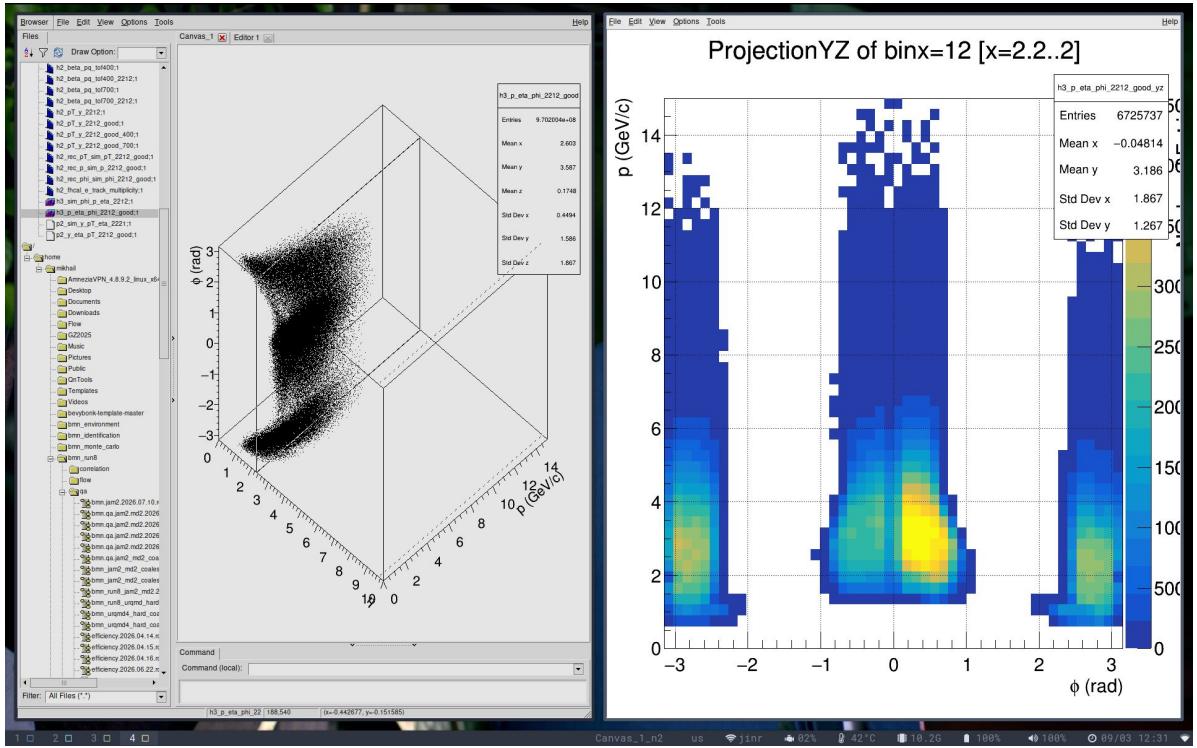
Basic flow measurements scheme



Efficiencies used

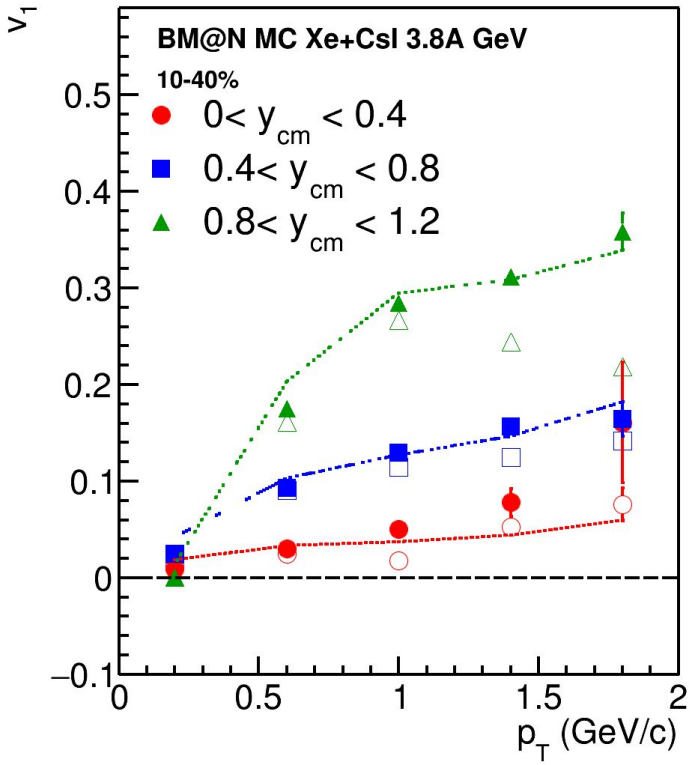


3D efficiency: p, η, φ

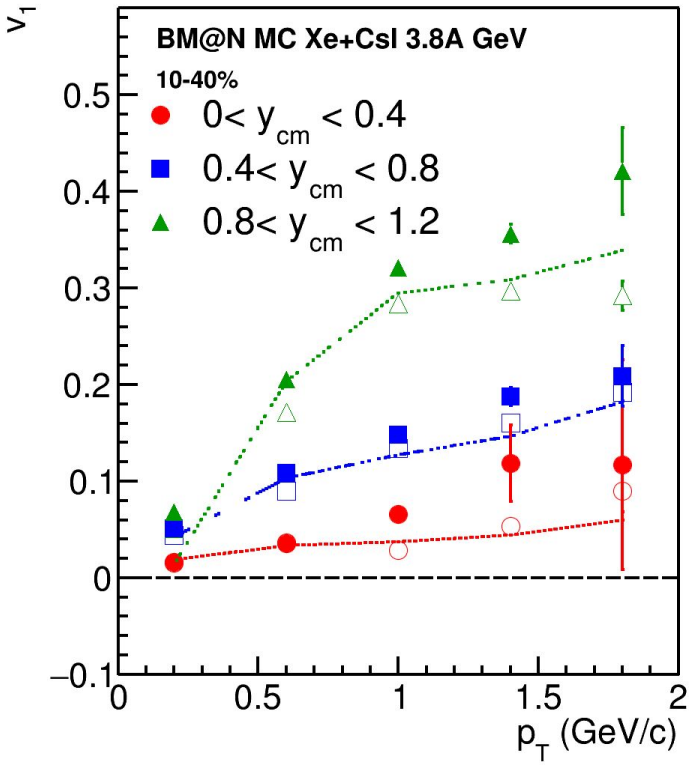


Efficiency comparison, QnTools Tw+Resc: v1

2D efficiency: p, η

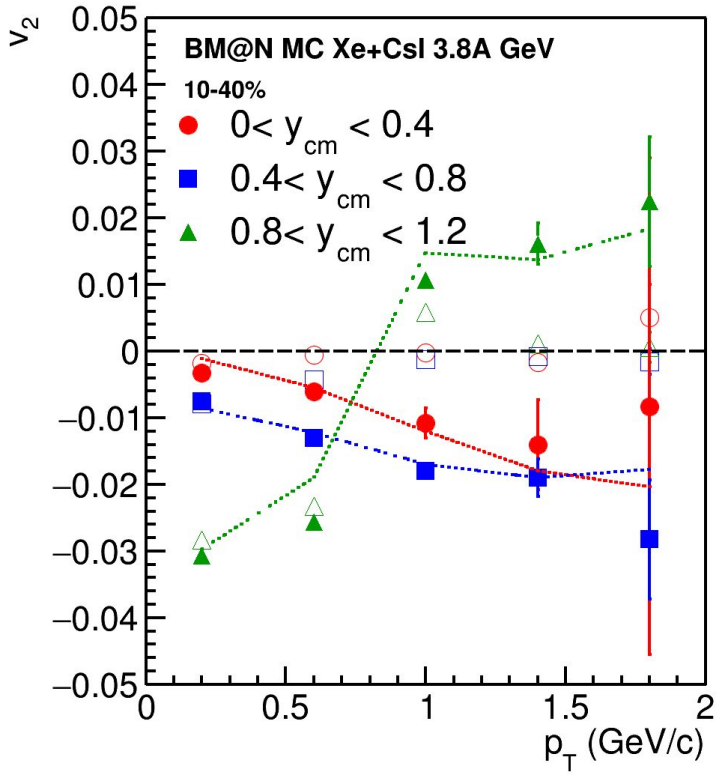


3D efficiency: p, η, φ

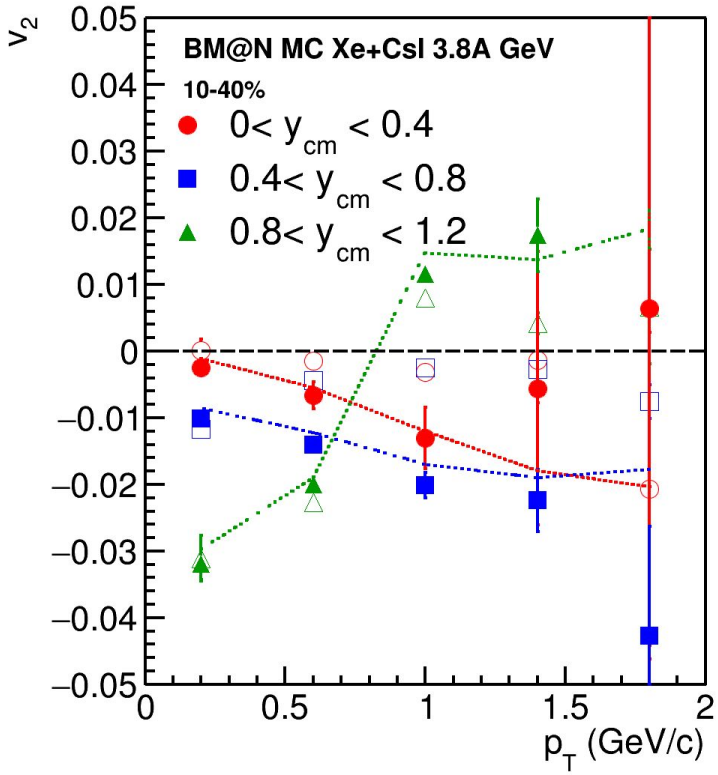


Efficiency comparison, QnTools Tw+Resc: v2

2D efficiency: p, η

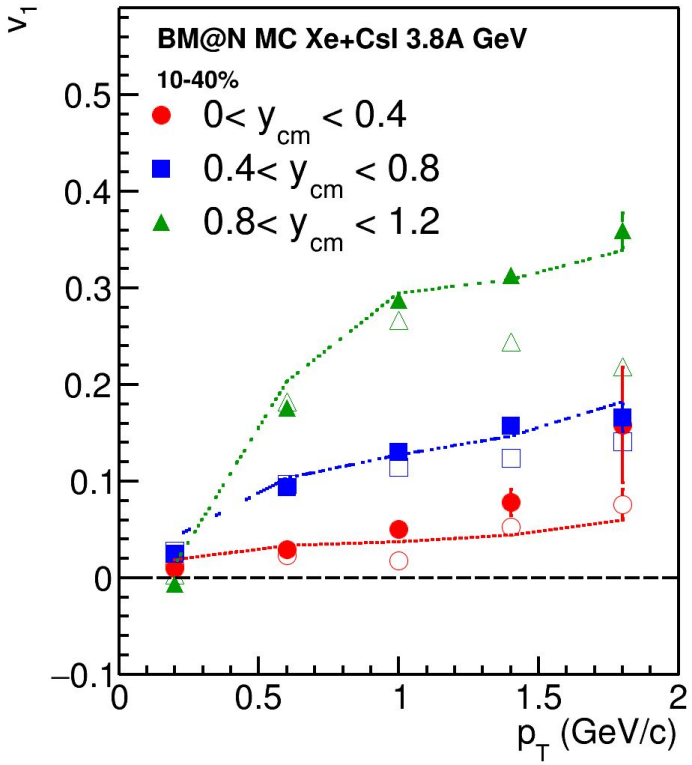


3D efficiency: p, η, φ

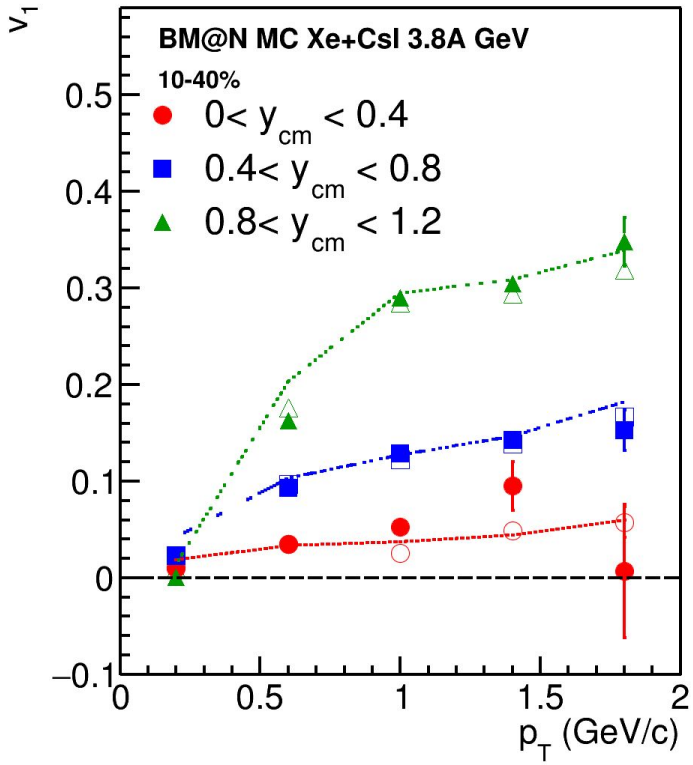


Efficiency comparison, corrected Tw+Resc: v1

2D efficiency: p, η

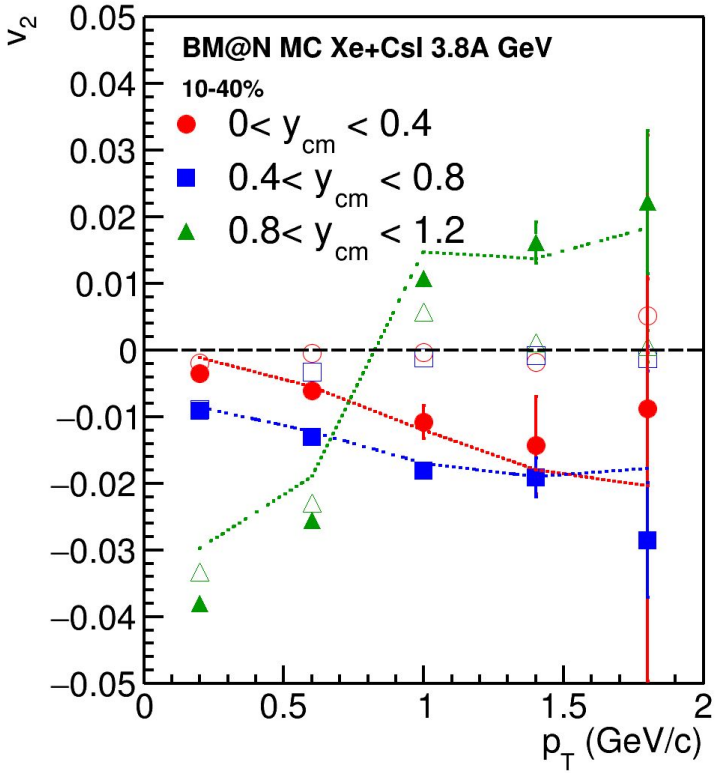


3D efficiency: p, η, φ

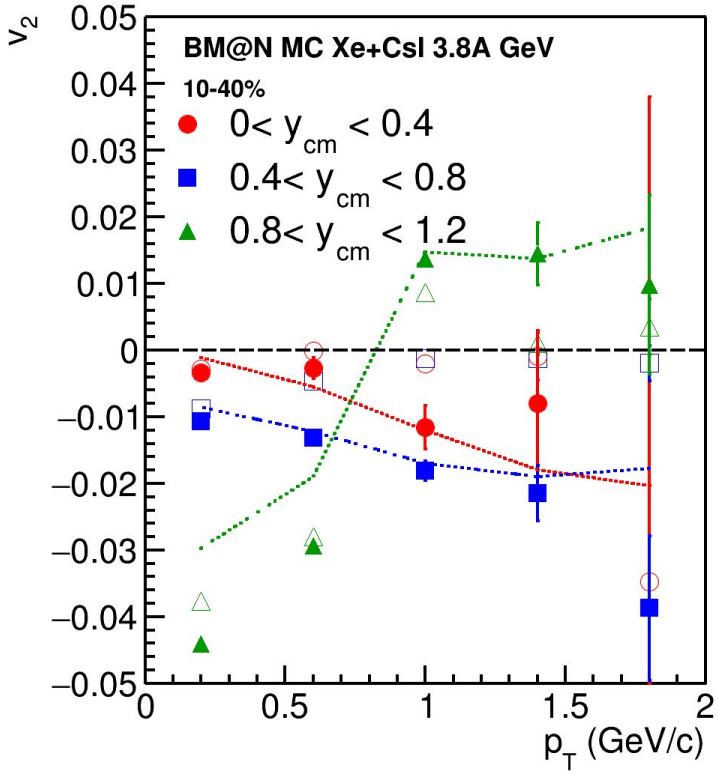


Efficiency comparison, corrected Tw+Resc: v2

2D efficiency: p, η

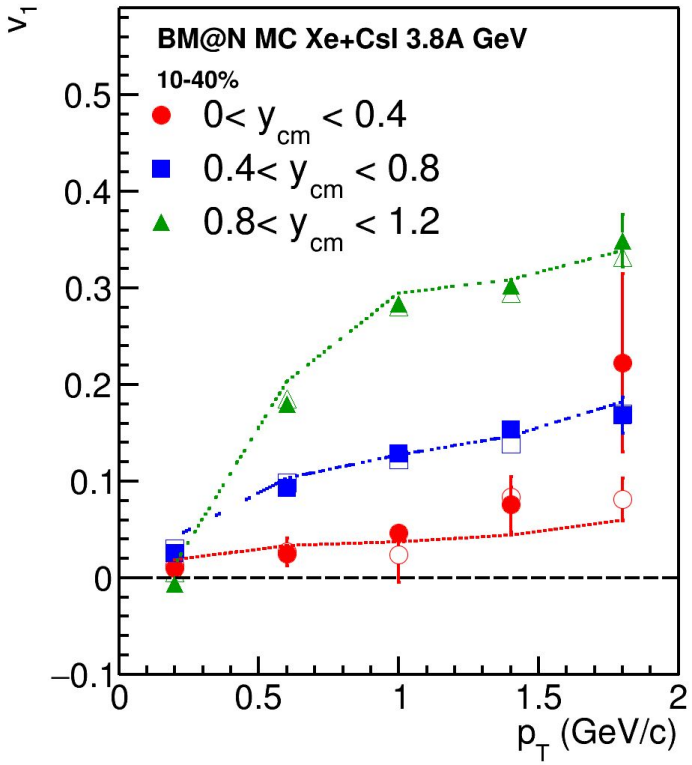


3D efficiency: p, η, φ

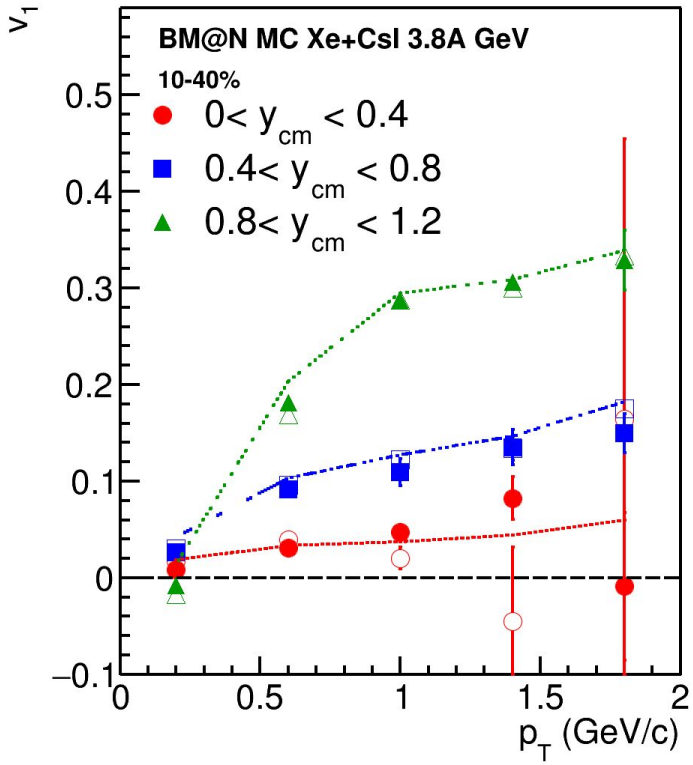


Efficiency comparison, corrected PCA: v1

2D efficiency: p, η

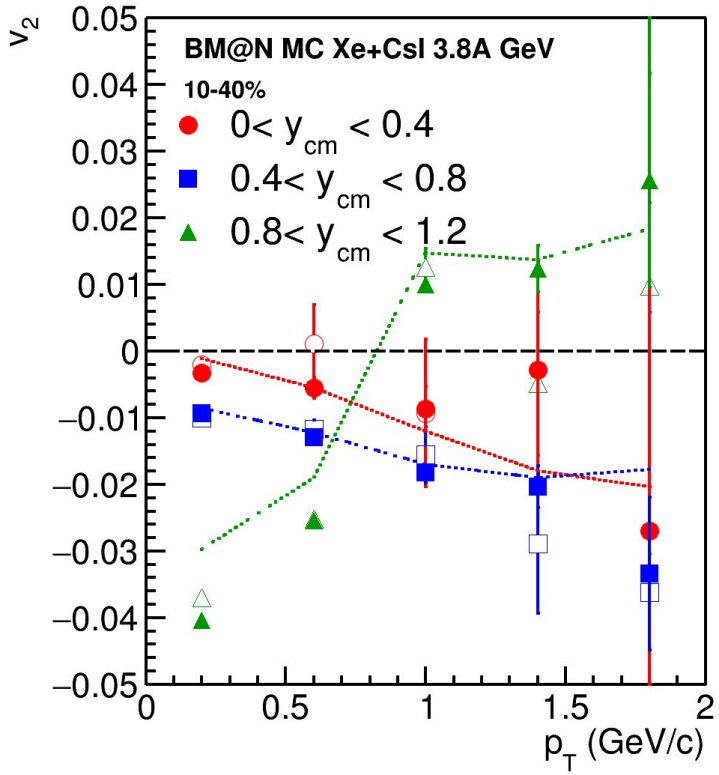


3D efficiency: p, η, φ

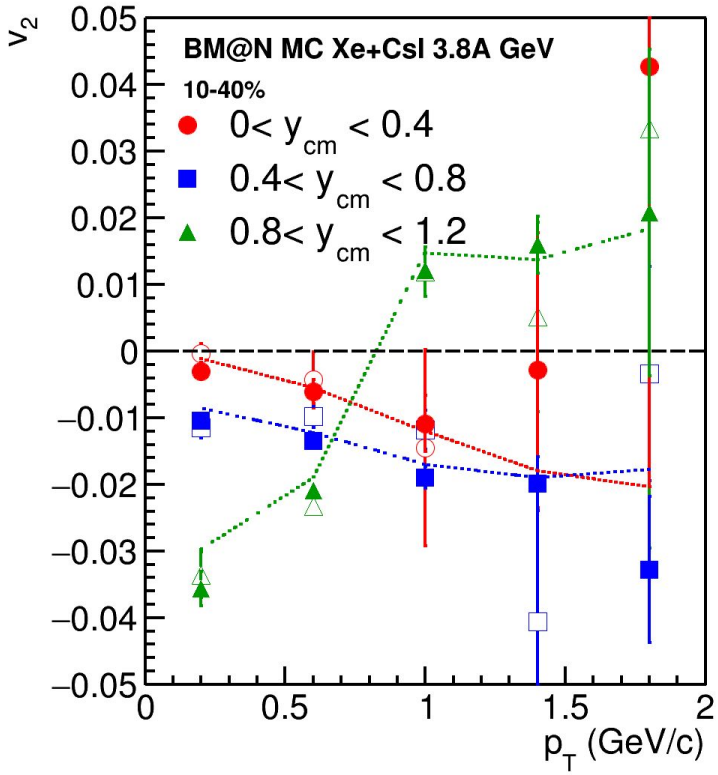


Efficiency comparison, corrected PCA: v2

2D efficiency: p, η



3D efficiency: p, η, φ

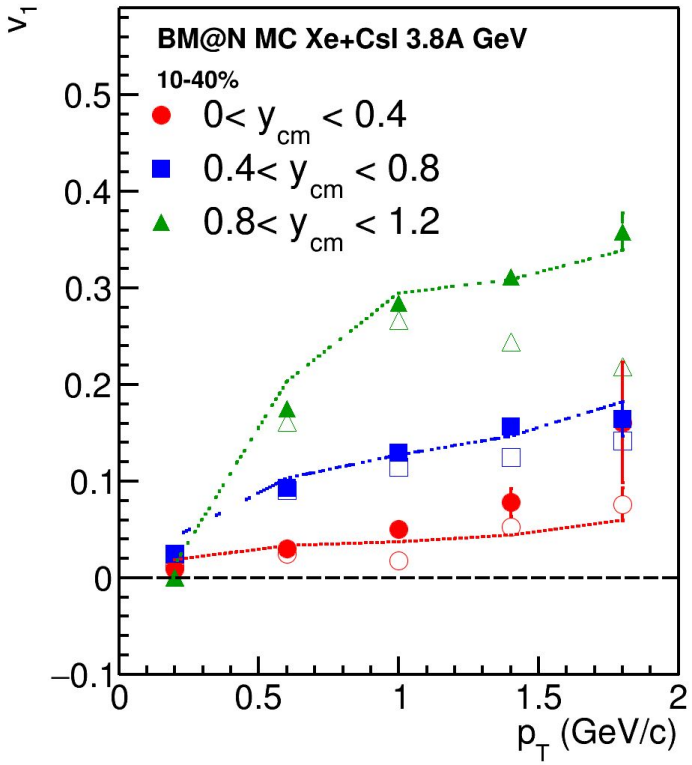


Directed by

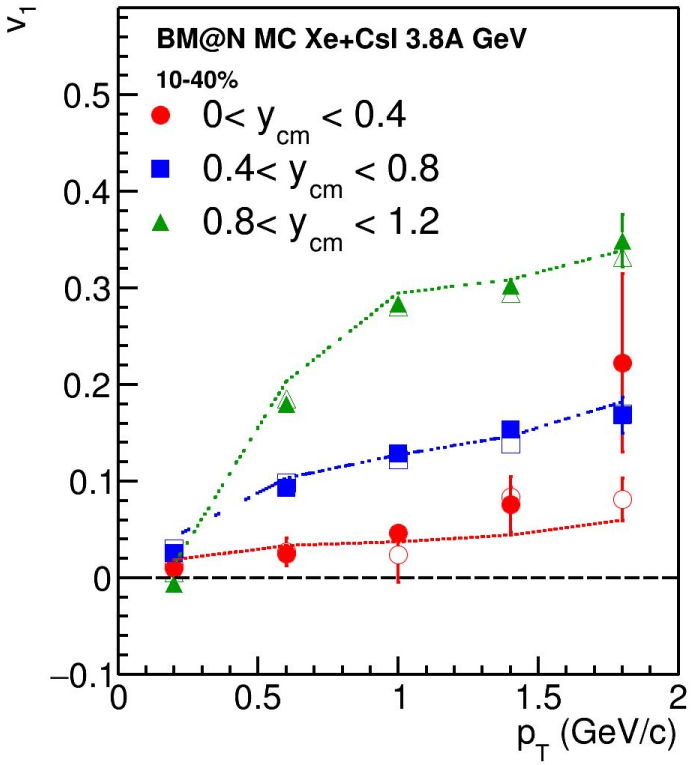
ROBERT B. WEIDE

Correction comparison: v1

Rec+Tw+Resc

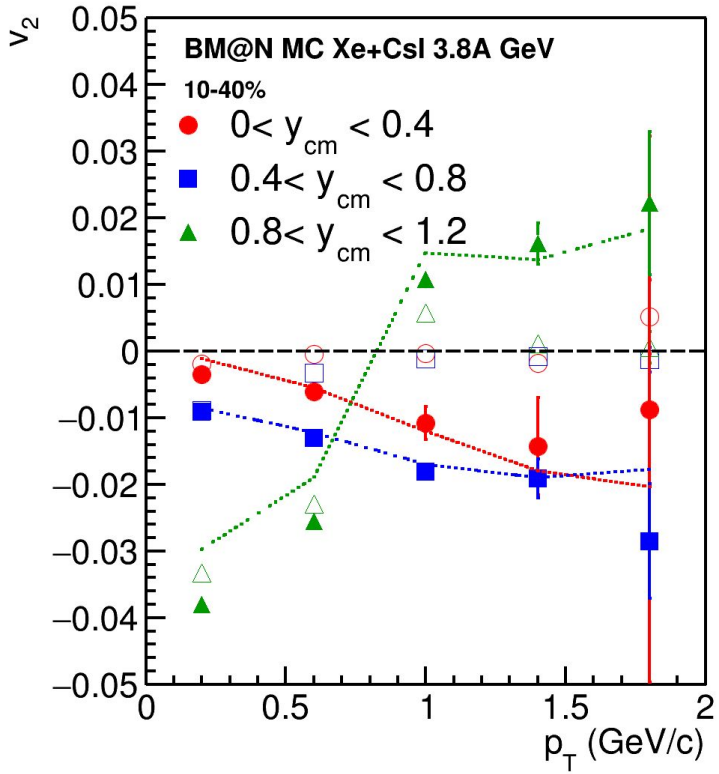


PCA

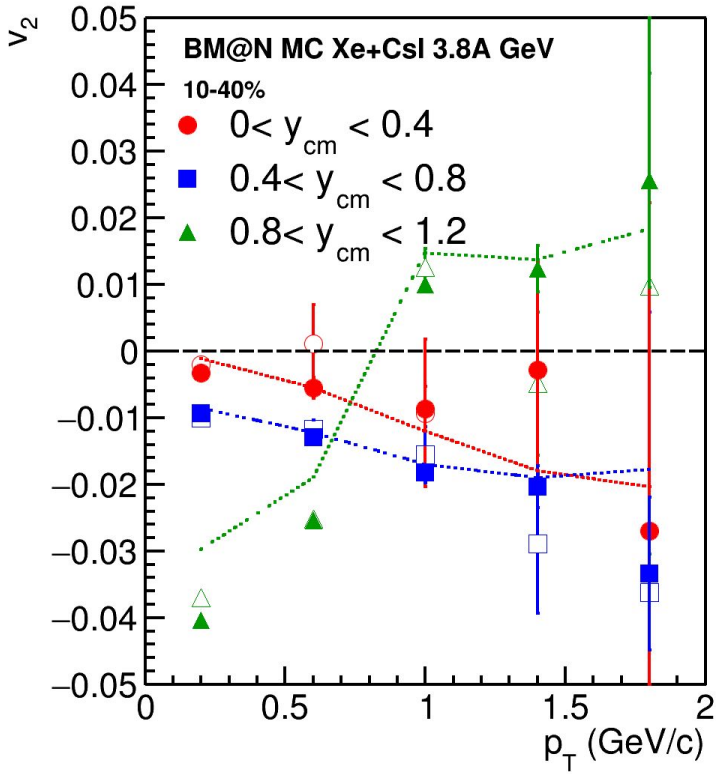


Correction comparison: v2

Rec+Tw+Resc

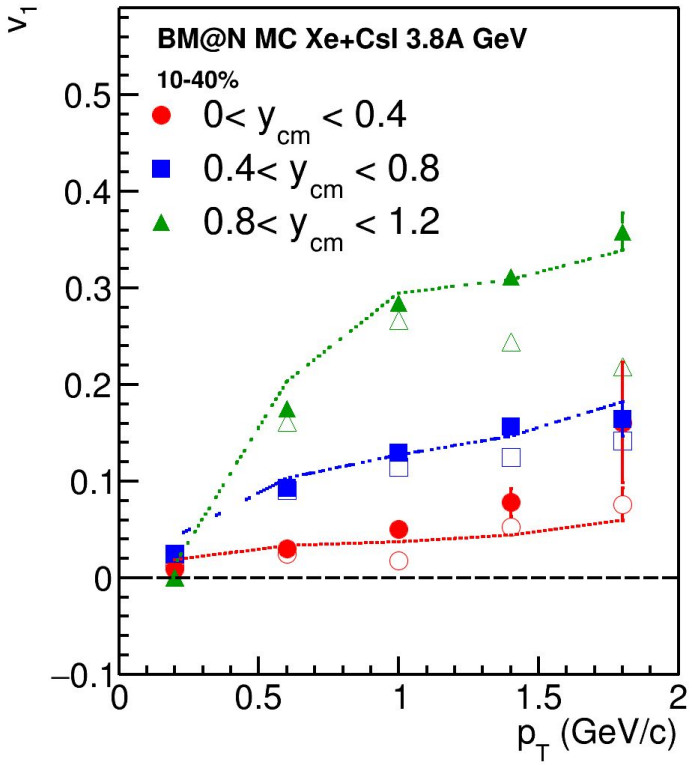


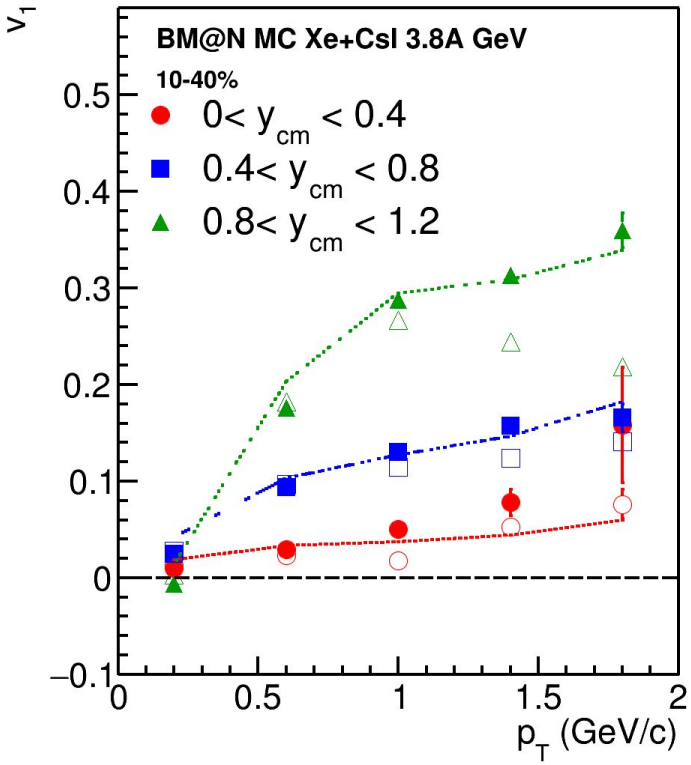
PCA



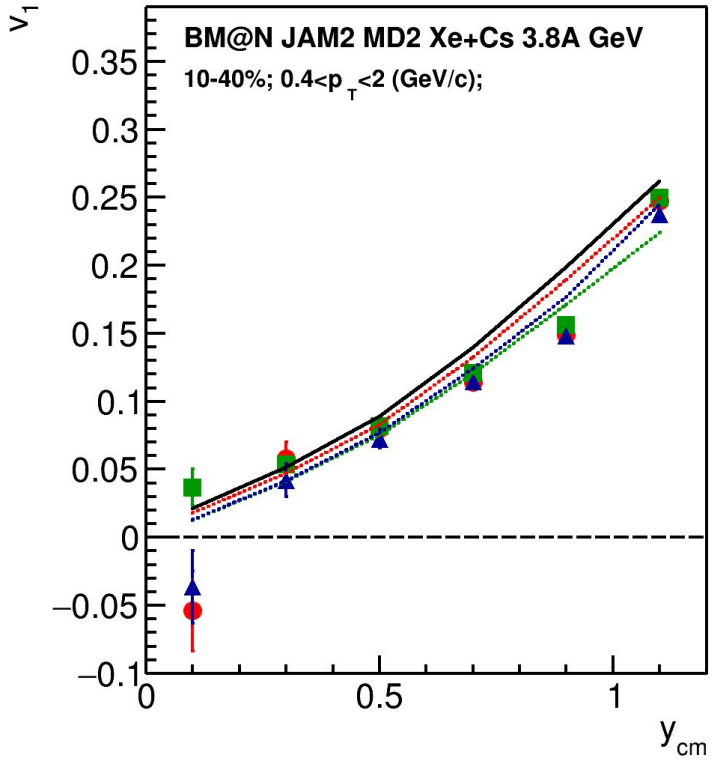
Efficiency comparison: Tw+Resc + v1

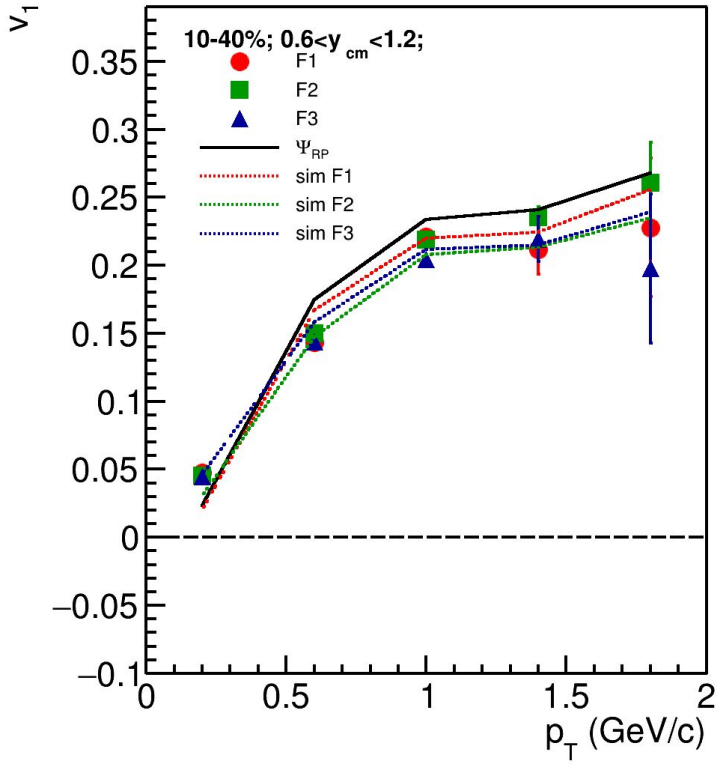
Corrected rec+tw+resc



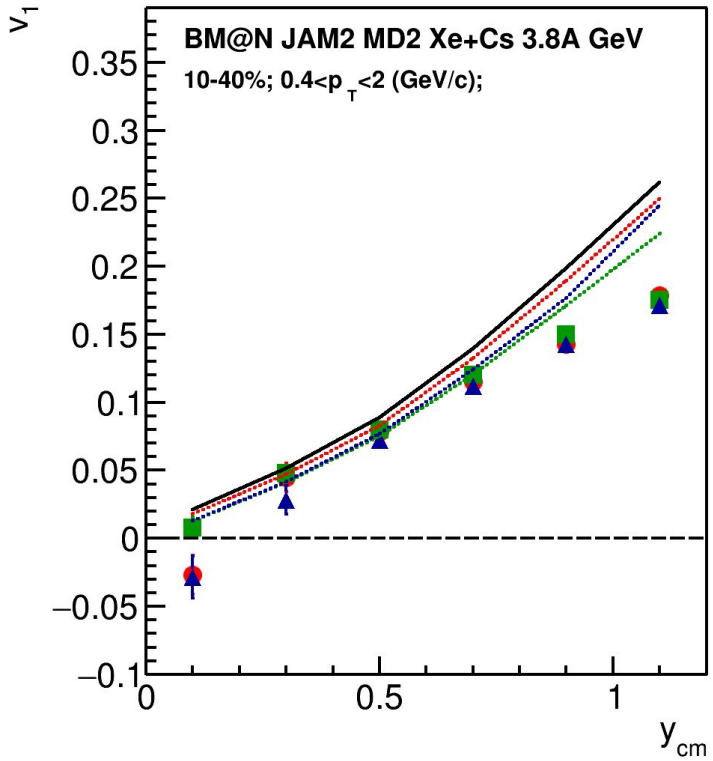


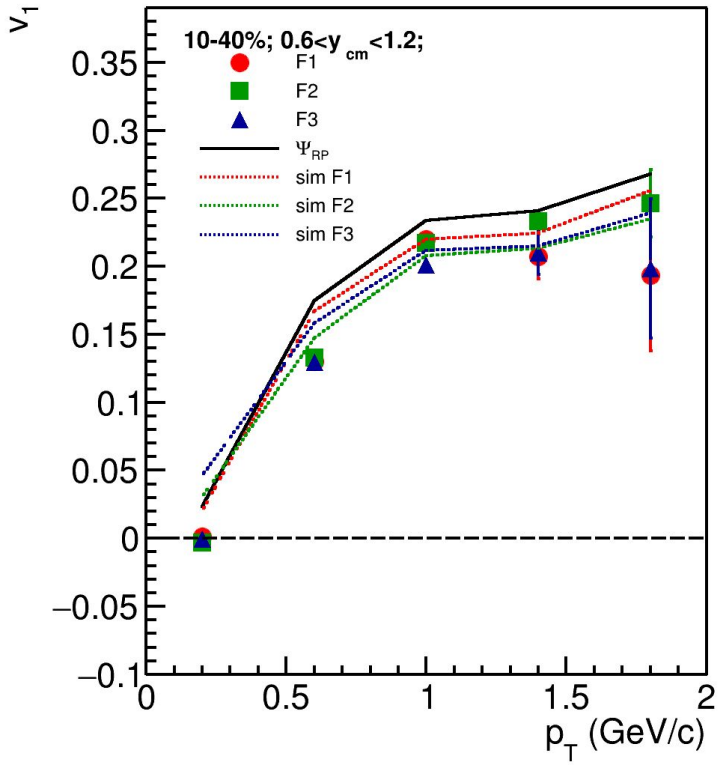
Upd: v1 vs pT and y for MC simulation (η<3.0)



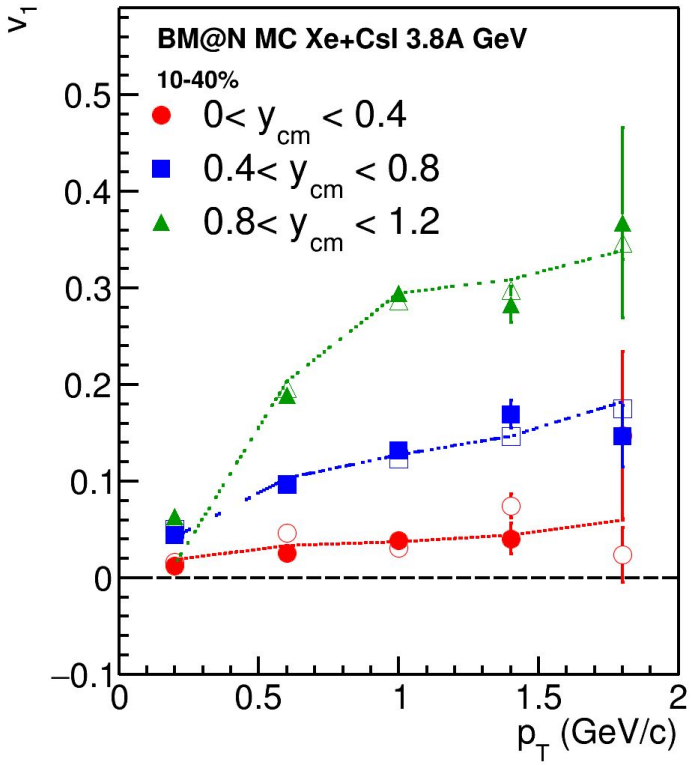


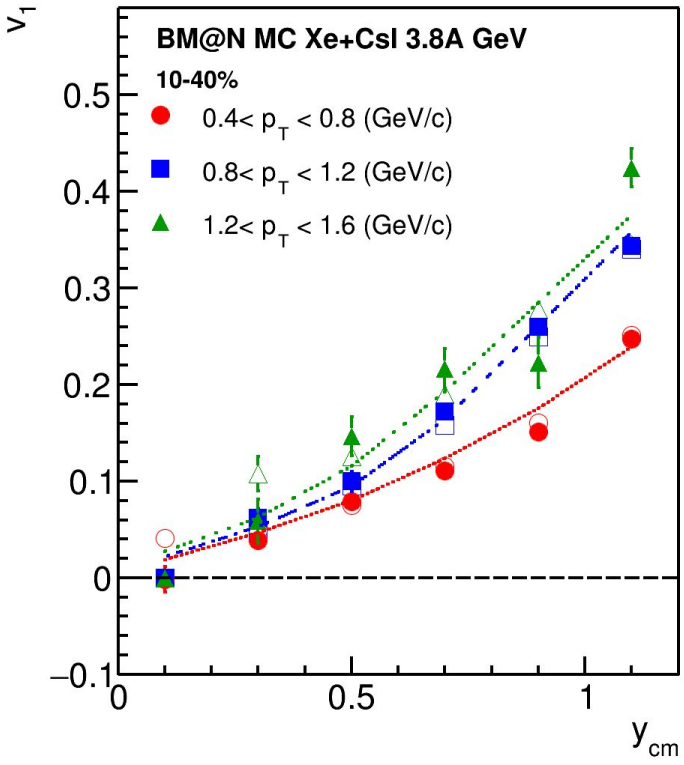
Old: v1 vs pT and y for MC simulation (tr not pointing to FHCAl)



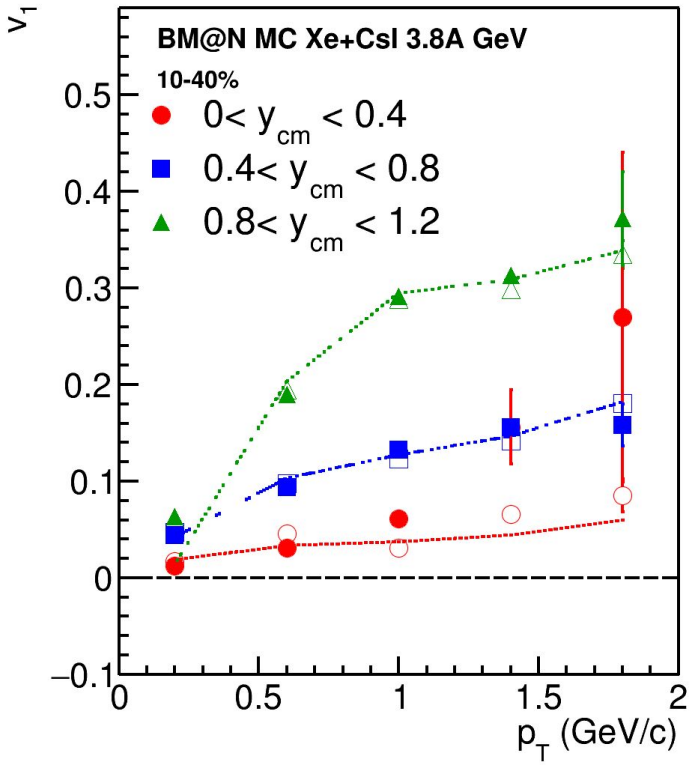


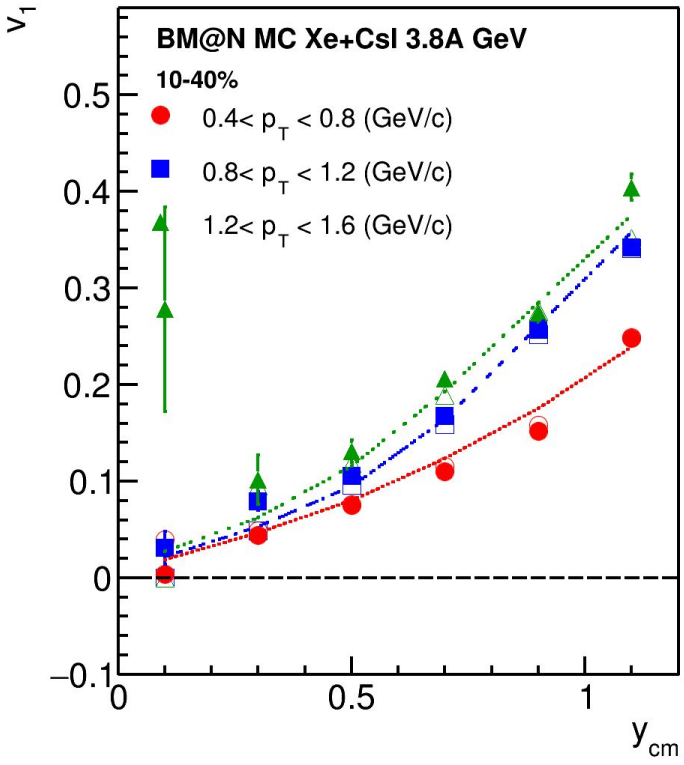
PCA 5 harmonics: v1



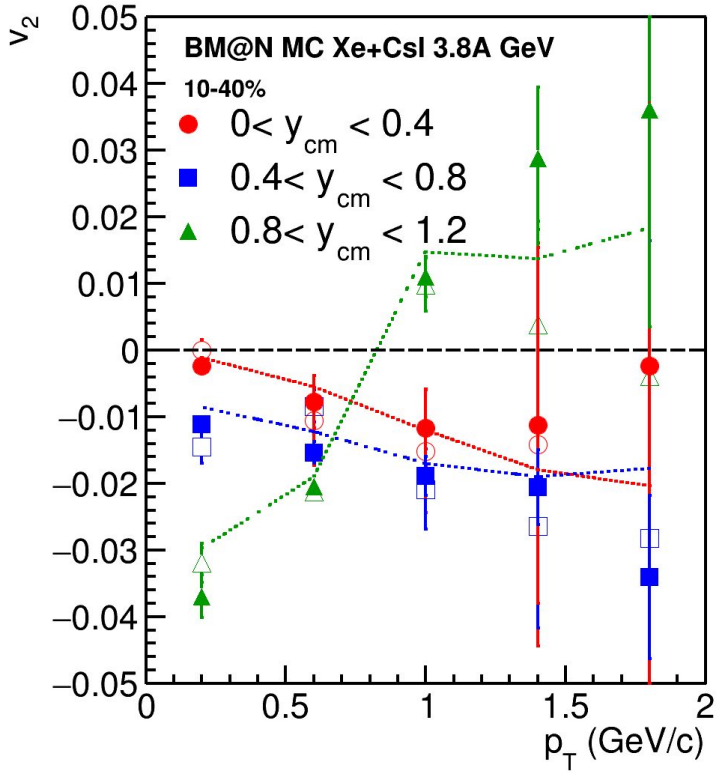


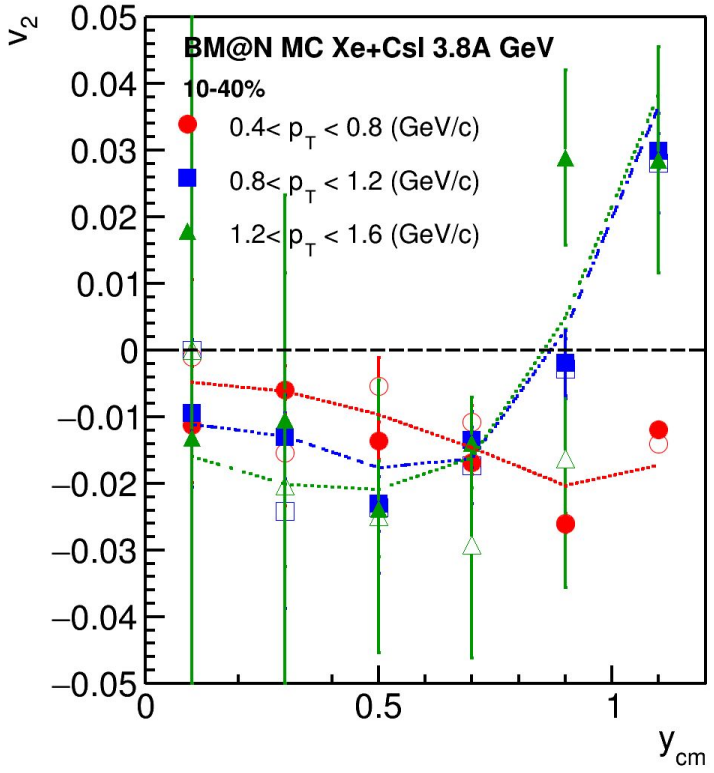
PCA 2 harmonics: v1



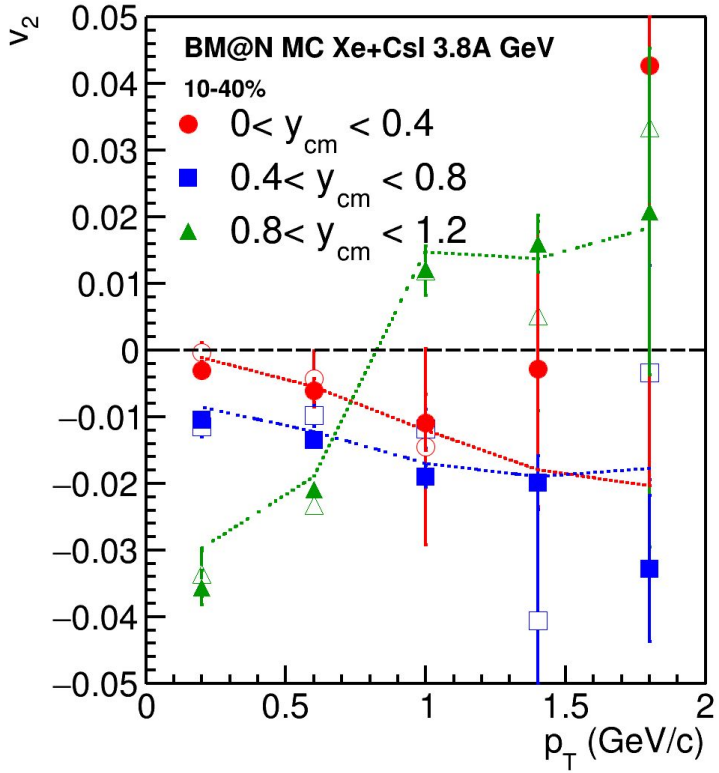


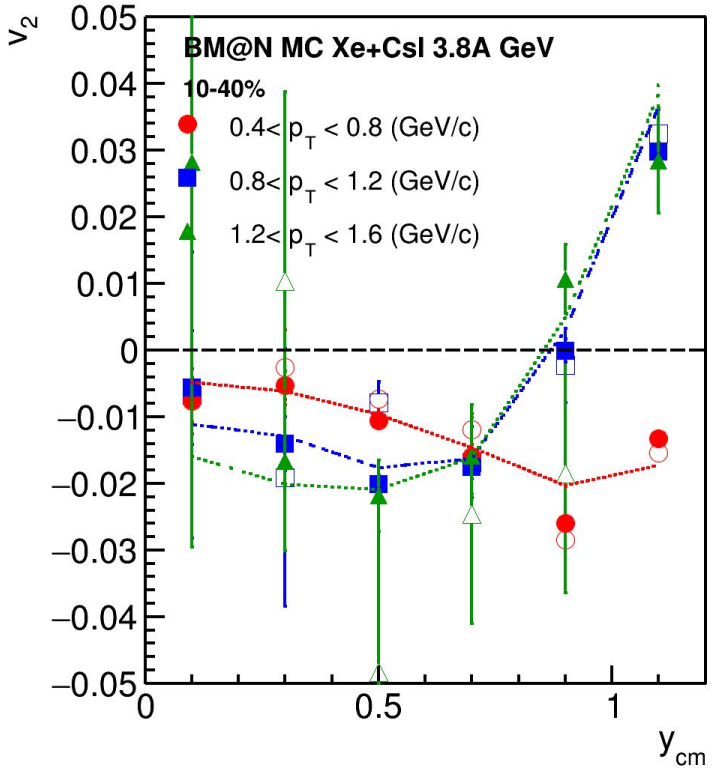
PCA 5 harmonics: v2



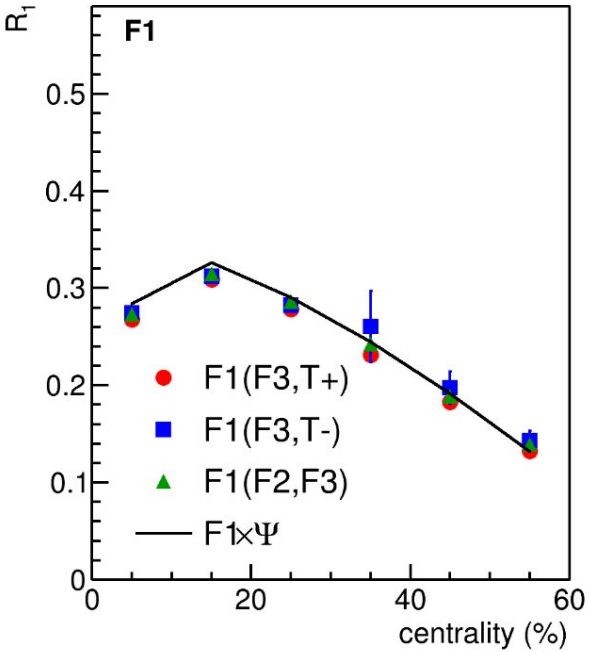


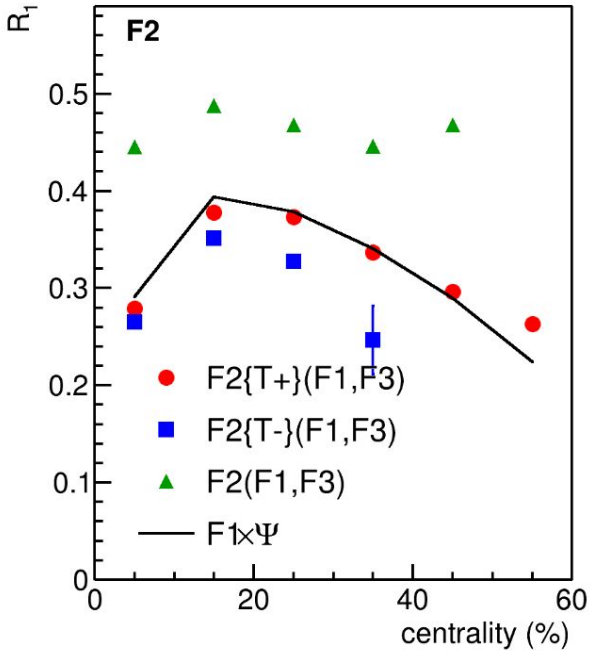
PCA 2 harmonics: v2

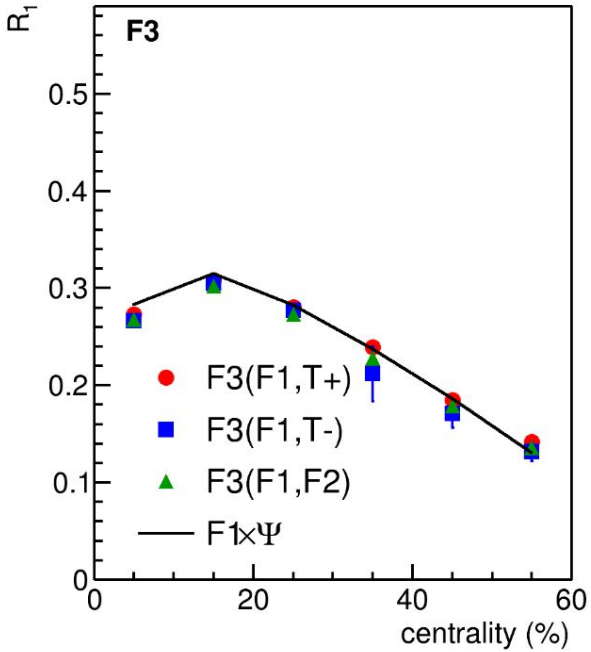




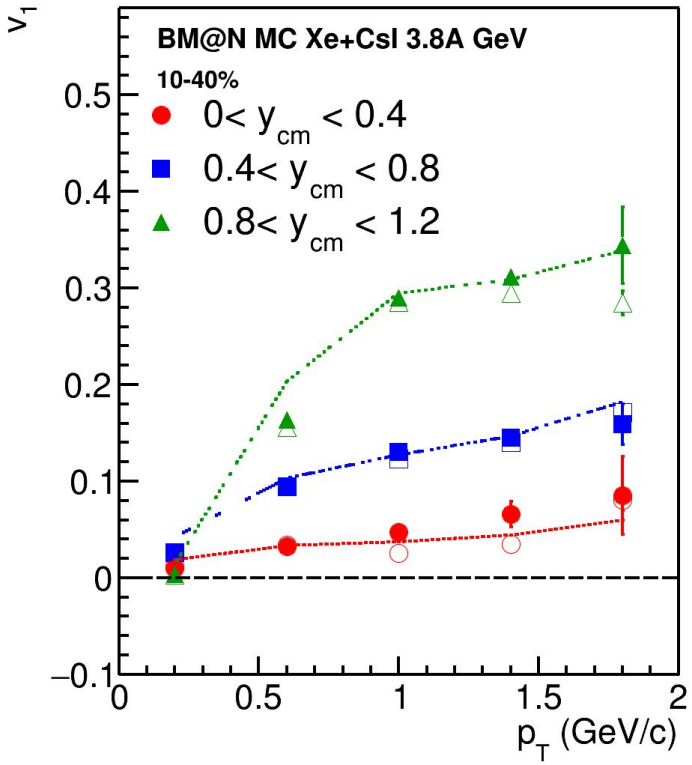
R1 vs centrality for MC simulation (Tw+Resc)

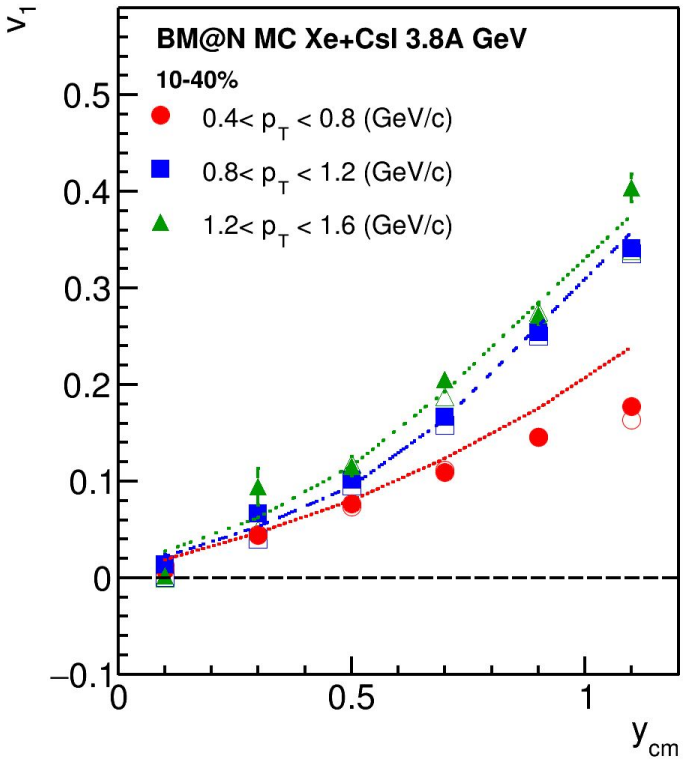




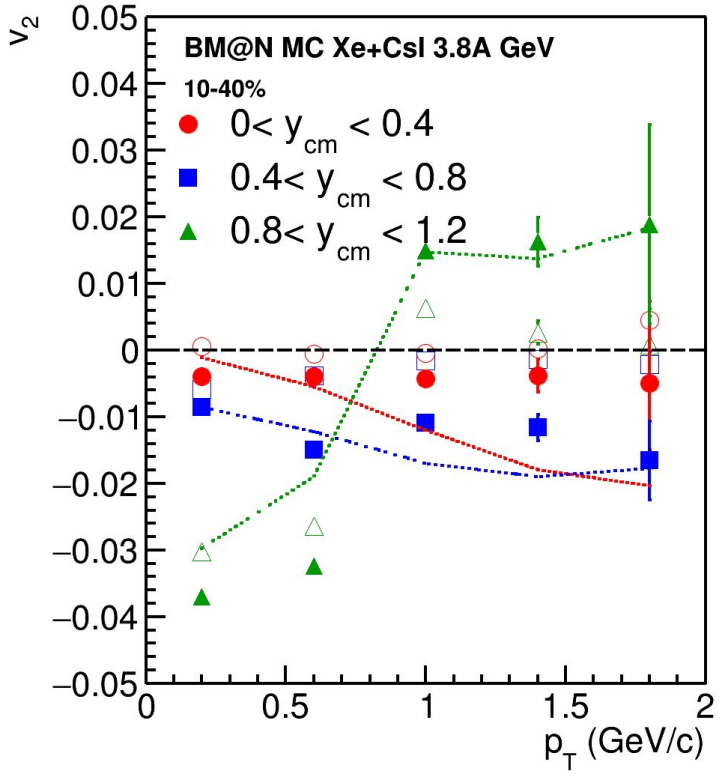


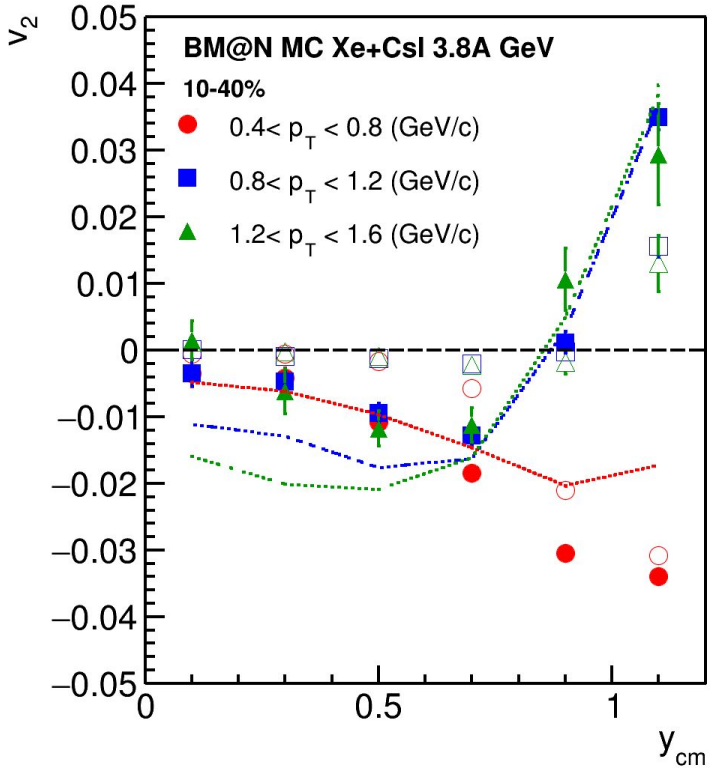
Twist+Rescaling performance on v1



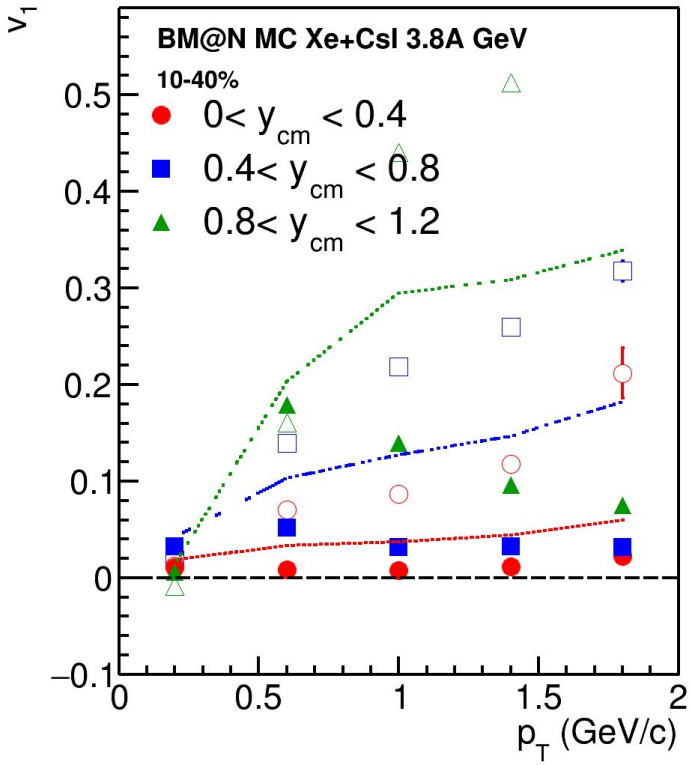


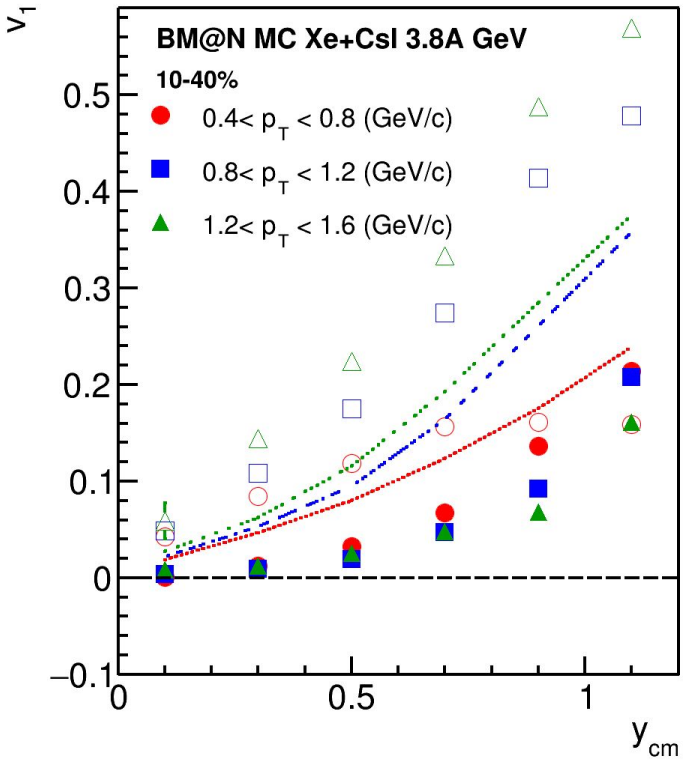
Twist+Rescaling performance on v2



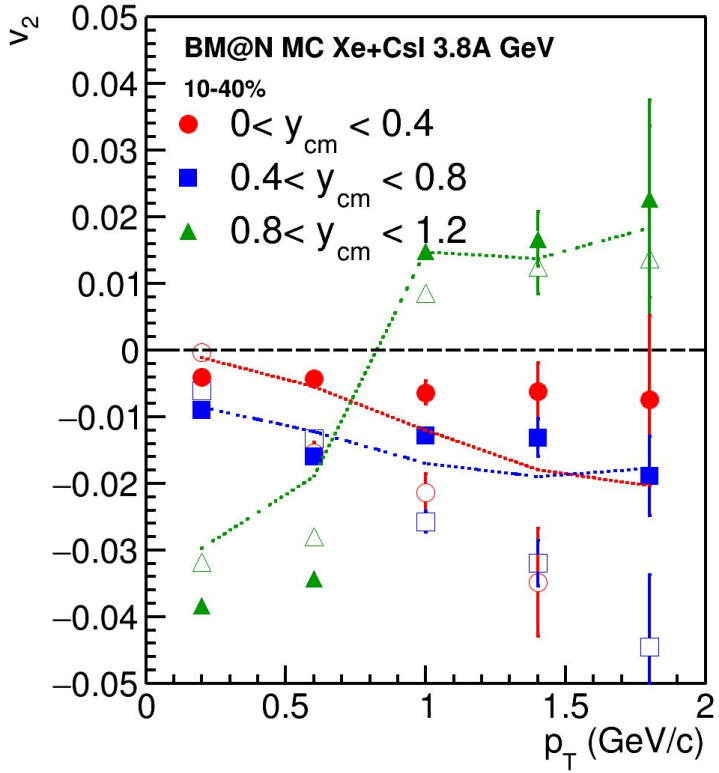


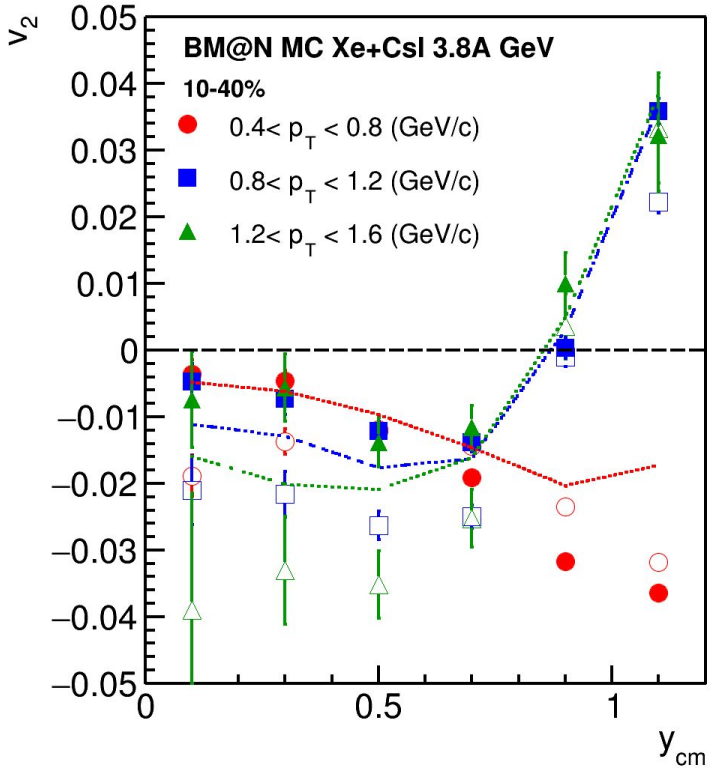
v1 for protons without corrections on u





v2 for protons without corrections on u





The role of detector acceptance in the flow measurements

$$v_n = \frac{1}{2\pi} \int d\varphi d\Psi A(\varphi) \left(1 + 2 \sum_{n=1}^{\infty} v_n (\cos n\varphi \cos n\Psi + \sin n\varphi \sin n\Psi) \right) \cos n\varphi \cos n\Psi$$

detector acceptance/ efficiency

distribution due to physics

In the ideal case scenario A(φ) = 1 / 2π, probability to measure any φ is the same

In the real world probability to measure different φ varies with φ:

$$A(\varphi) = \frac{1}{2\pi} \left[1 + 2 \sum_{m=1}^{\infty} (c_m \cos m\varphi + s_m \sin m\varphi) \right]$$

Interaction of the sine and cosine with acceptance

$$x_n = A(\varphi)\cos n\varphi = \frac{1}{2\pi}\left[1 + 2\sum_{m=1}^{\infty}(c_m \cos m\varphi + s_m \sin m\varphi)\right]\cos n\varphi =$$

$$\frac{1}{2\pi}\left[c_n + (1 + c_{2n})\cos n\varphi + s_{2n}\sin n\varphi + \sum_{k=1;k\neq n}^{\infty}((c_{k+n} + c_{k-n})\cos k\varphi + (s_{k+n} + s_{k-n})\sin k\varphi)\right]$$

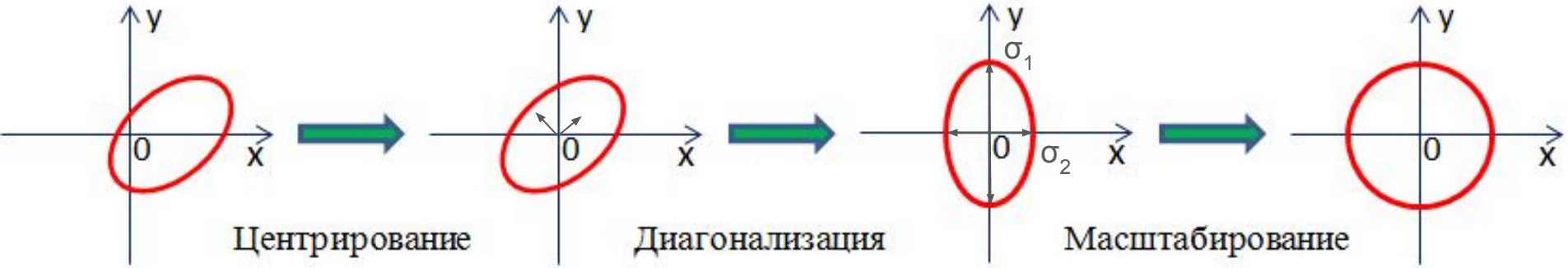
$$y_n = A(\varphi)\sin n\varphi = \frac{1}{2\pi}\left[1 + 2\sum_{m=1}^{\infty}(c_m \cos m\varphi + s_m \sin m\varphi)\right]\sin n\varphi =$$

$$\frac{1}{2\pi}\left[s_n + s_{2n}\cos n\varphi + (1 - c_{2n})\sin n\varphi + \sum_{k=1;k\neq n}^{\infty}((s_{k+n} - s_{k-n})\cos k\varphi + (c_{k-n} - c_{k+n})\sin k\varphi)\right]$$

The same goes with Q_n-vectors. In attempt to measure v_n we get:

$v_n = p_0 + p_1 v_1 + p_2 v_2 + \ldots + p_n v_n + \ldots$

Rescentering, Twist and Rescaling procedure



One of the ways to calculate the corrections is via the covariance matrix:

$$\vec{u}_n = (x_n, y_n) = (\cos n\varphi, \sin n\varphi)$$

$$\Sigma = \begin{bmatrix} cov(x_n, x_n) & cov(y_n, x_n) \\ cov(x_n, y_n) & cov(y_n, y_n) \end{bmatrix} = \begin{bmatrix} \vec{w}_1 \\ \vec{w}_2 \end{bmatrix}^T \times \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \times \begin{bmatrix} \vec{w}_1 \\ \vec{w}_2 \end{bmatrix}$$

Limitations of the twist+rescaling

$$\vec{u}_n = (x_n, y_n) = (\cos n\varphi, \sin n\varphi)$$

$$\Sigma = \begin{bmatrix} cov(x_n, x_n) & cov(y_n, x_n) \\ cov(x_n, y_n) & cov(y_n, y_n) \end{bmatrix} = \begin{bmatrix} \vec{w}_1 \\ \vec{w}_2 \end{bmatrix}^T \times \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \times \begin{bmatrix} \vec{w}_1 \\ \vec{w}_2 \end{bmatrix}$$

Before the correction:
$v_n = p_0 + p_1 v_1 + p_2 v_2 + \ldots + p_n v_n + \ldots$

With the correction we might untangle sine and cosine of the same harmonic:
$v_n = 0 + p_1 v_1 + p_2 v_2 + \ldots + 1 \times v_n + \ldots$

This works if the v_n >> rest (for v_1 for example)
But for v_2 the rest sum might be still larger

Proposed correction

Why stop on the harmonic n, when we can build the covariance matrix for arbitrary number of harmonics:

$$\Sigma = \begin{bmatrix} cov(x_1,x_1) & cov(y_1,x_1) & cov(x_2,x_1) & \dots & cov(y_n,x_1) \\ cov(x_1,y_1) & cov(y_1,y_1) & cov(x_2,y_1) & \dots & cov(y_n,y_1) \\ \dots & & & & \\ cov(x_1,y_n) & cov(y_1,y_n) & cov(x_2,y_n) & \dots & cov(y_n,y_n) \end{bmatrix} = \begin{bmatrix} \vec{w}_1 \\ \dots \\ \vec{w}_{2n} \end{bmatrix}^T \begin{bmatrix} \sigma_1 & 0 & \dots & 0 \\ 0 & \sigma_2 & \dots & 0 \\ \dots & & & \\ 0 & 0 & \dots & \sigma_{2n} \end{bmatrix} \begin{bmatrix} \vec{w}_1 \\ \dots \\ \vec{w}_{2n} \end{bmatrix}$$

Directions that are really measured

Amplitude of changes in this directions

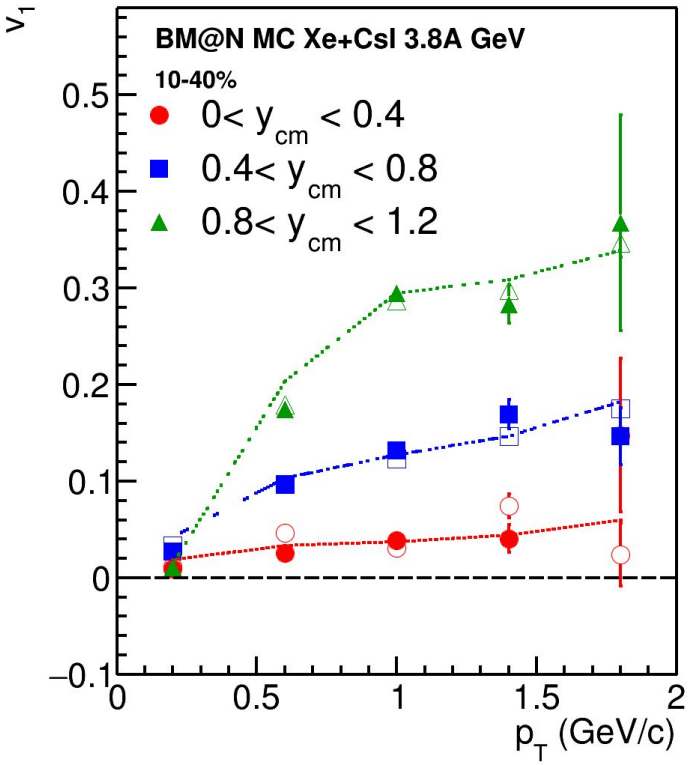
Before the correction:

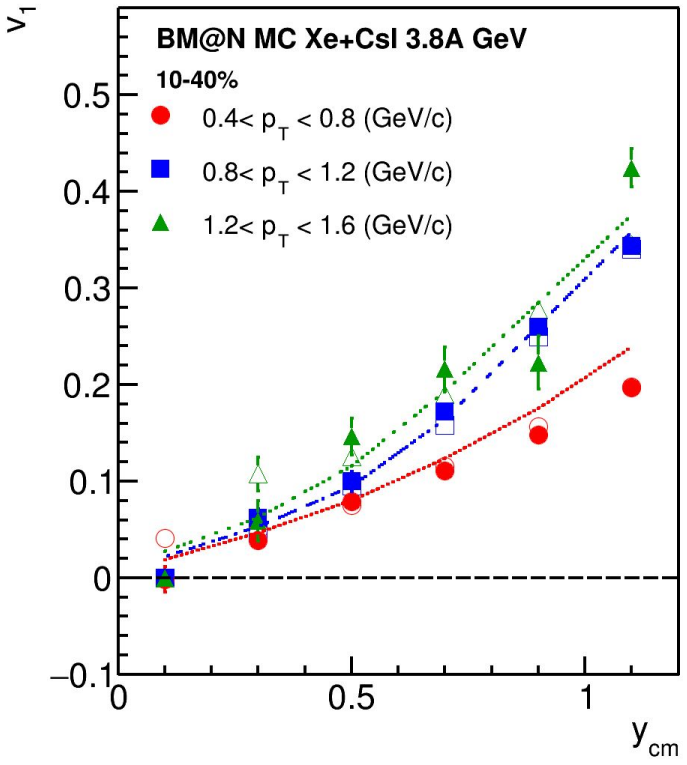
$v_n = p_0 + p_1 v_1 + p_2 v_2 + \dots + p_n v_n + \dots$

Now, applying the correction we get:

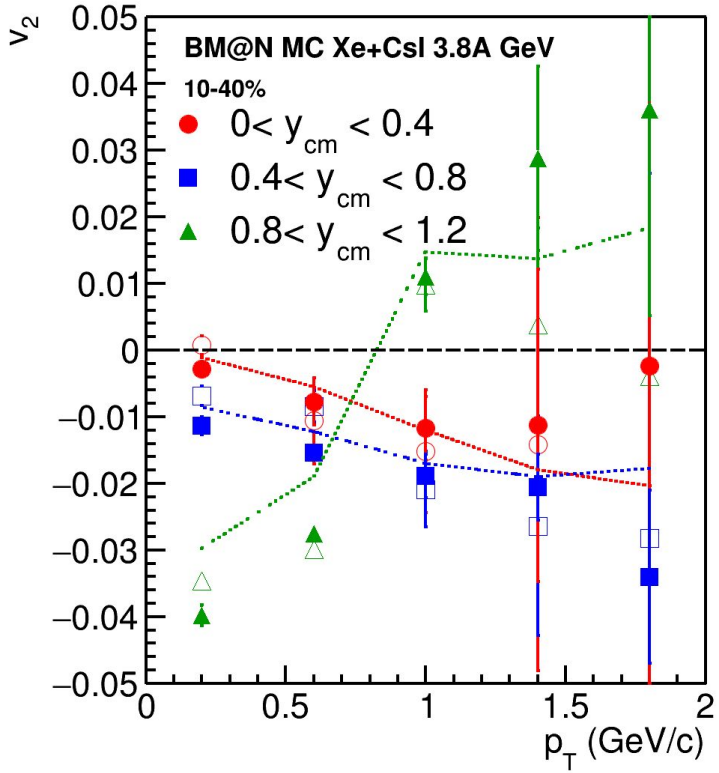
$v_n = v_n + \dots$

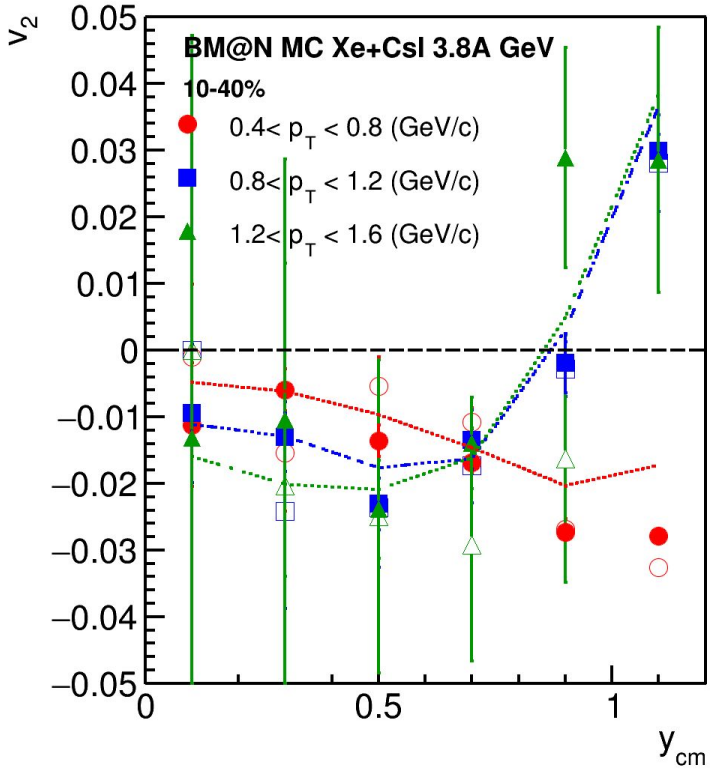
PCA performance on v1



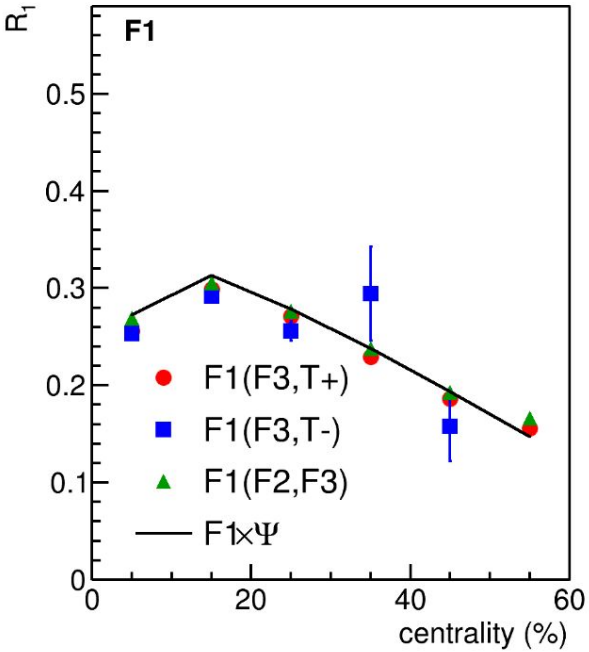


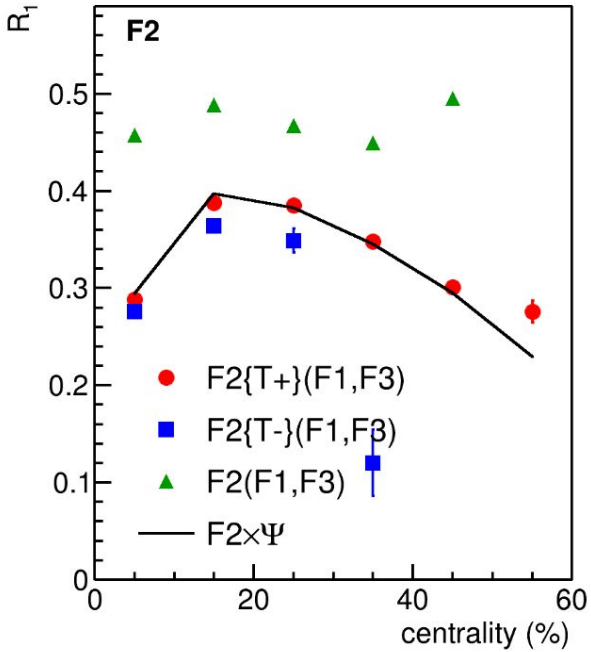
PCA performance on v2

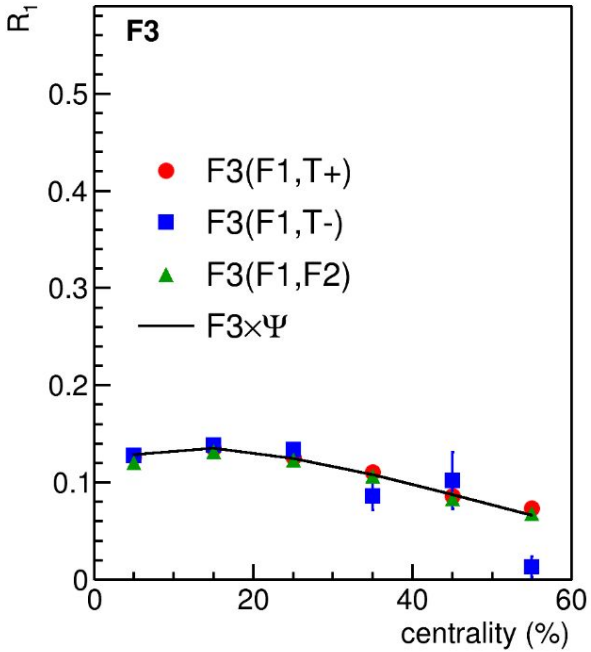




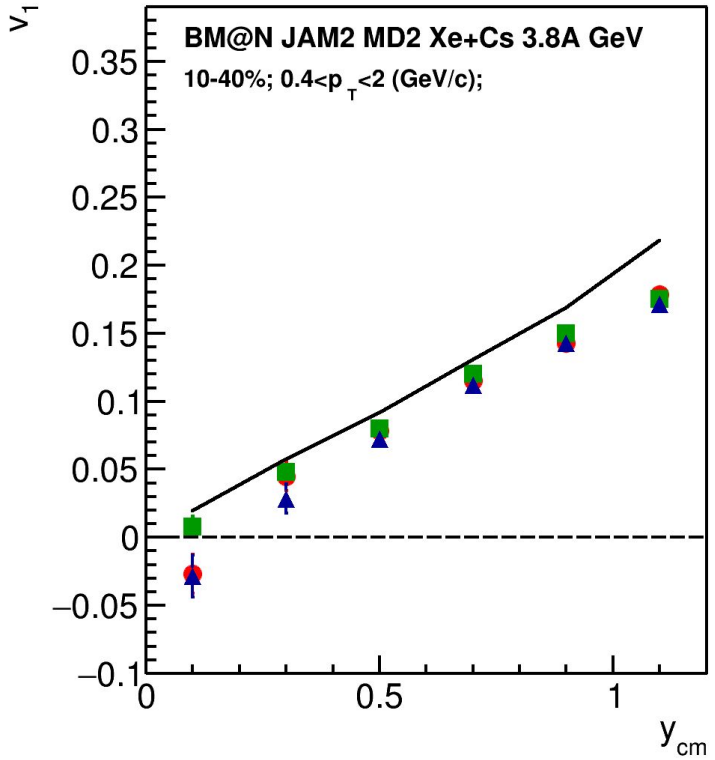
R1 vs centrality for MC simulation (PCA)

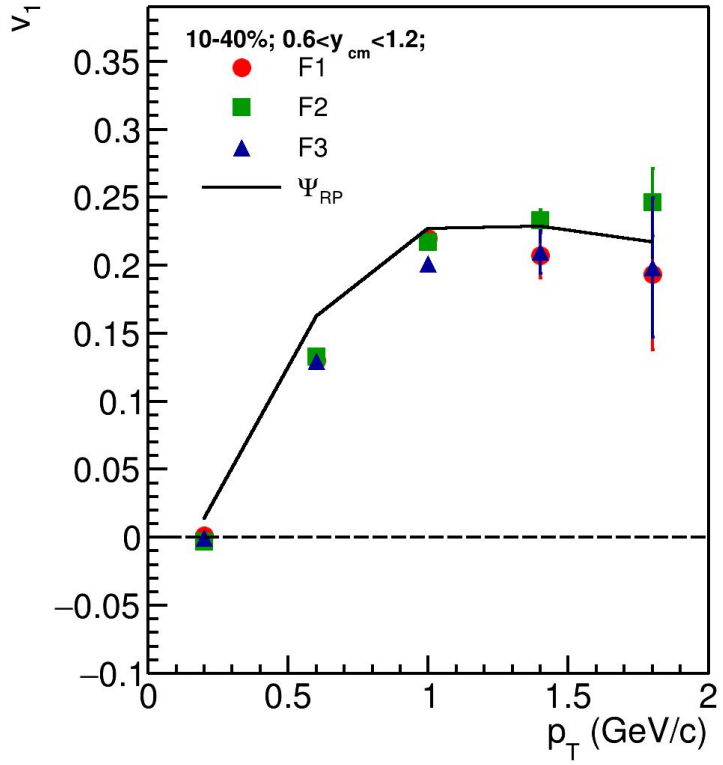




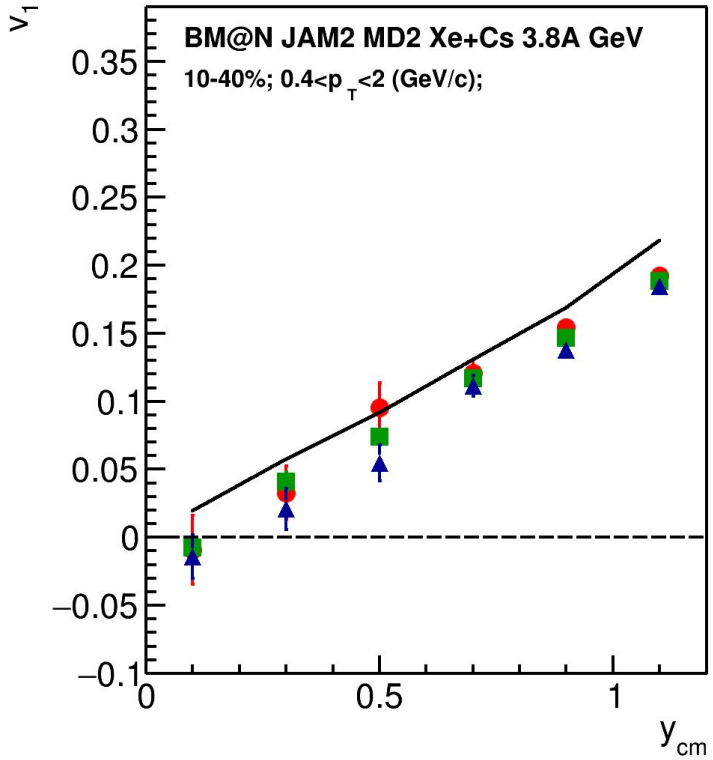


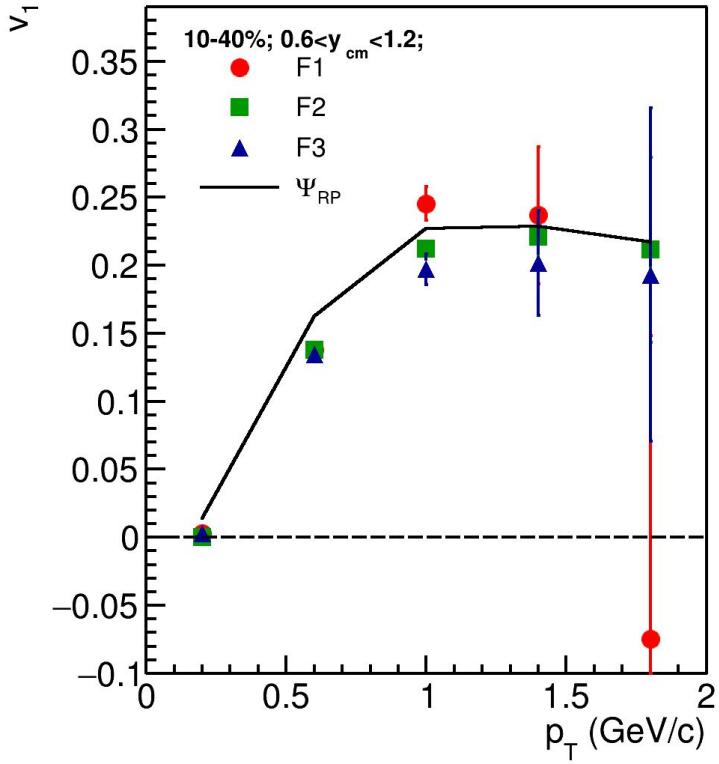
v1 vs pT and y for MC simulation (Tw+Resc)



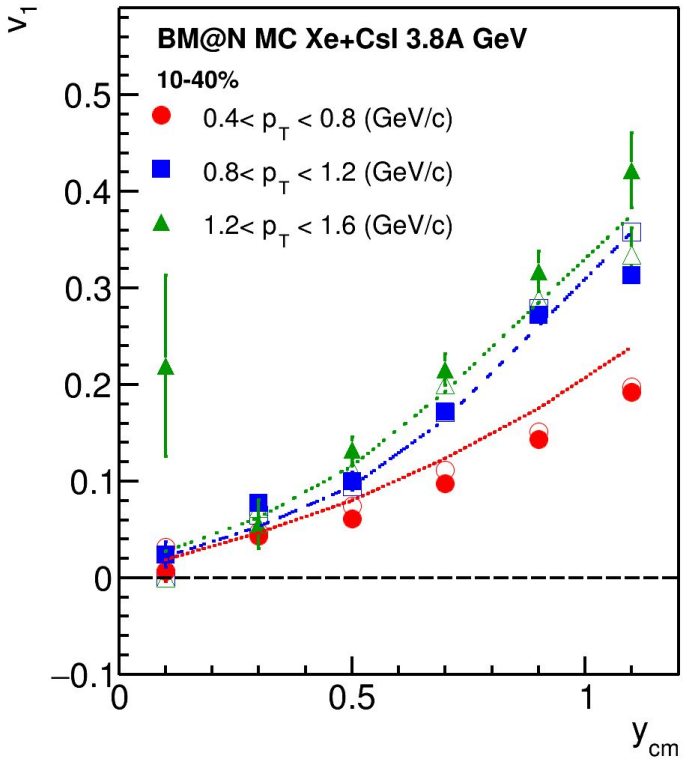


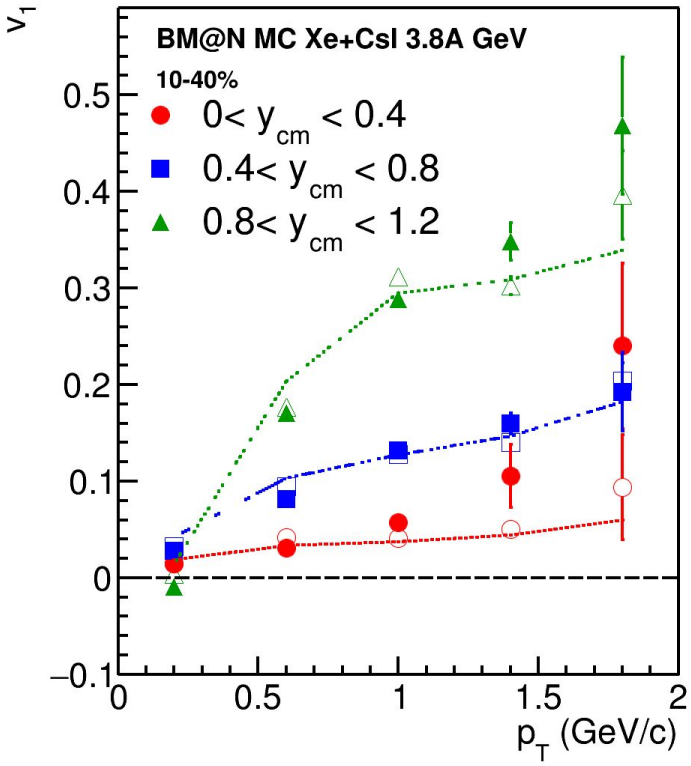
v1 vs pT and y for MC simulation (PCA)



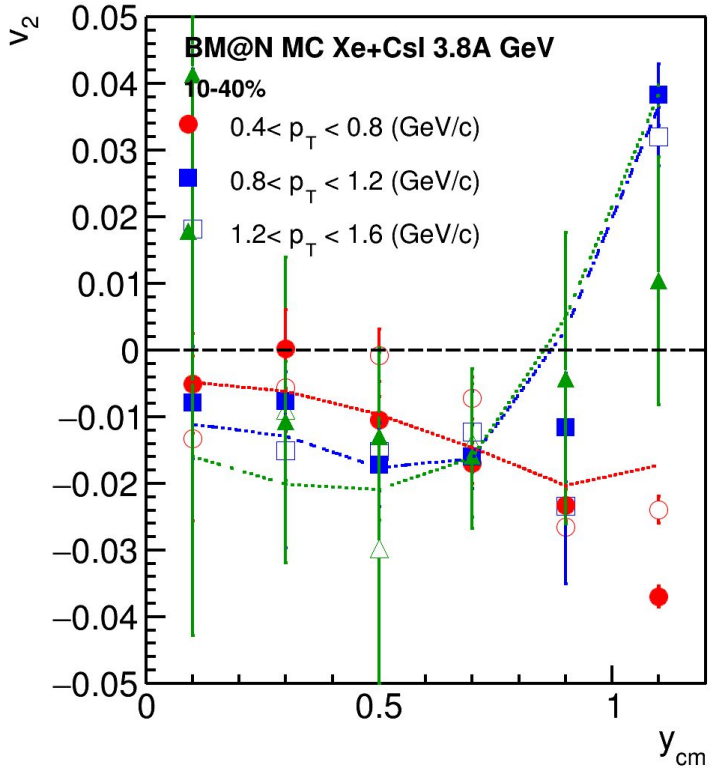


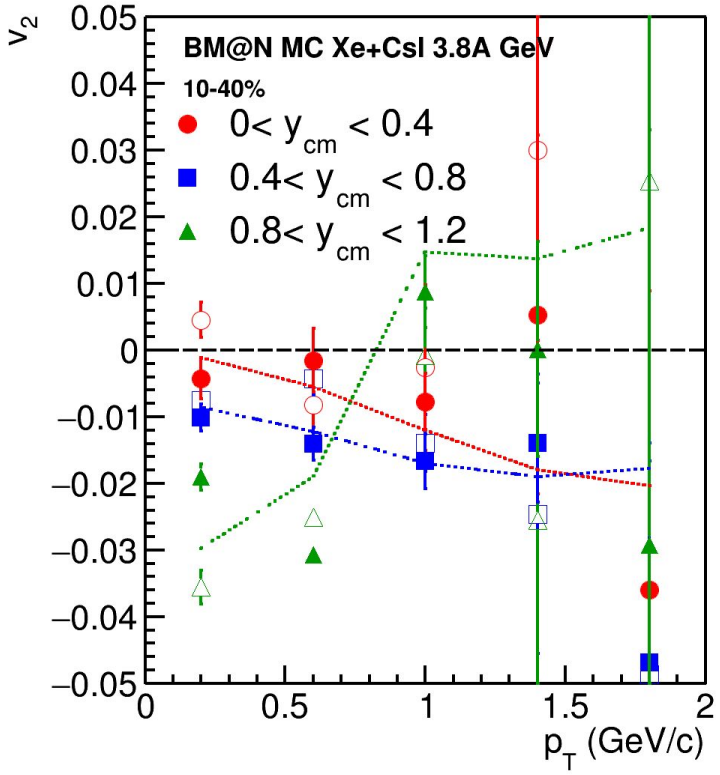
New correction performance on v1





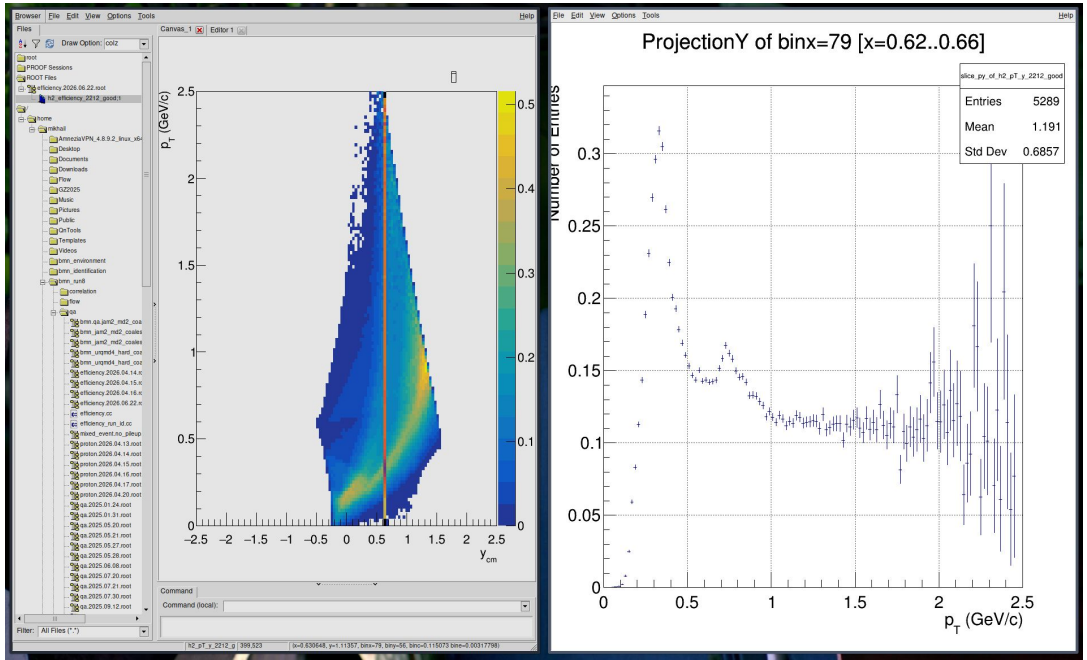
New correction performance on v2



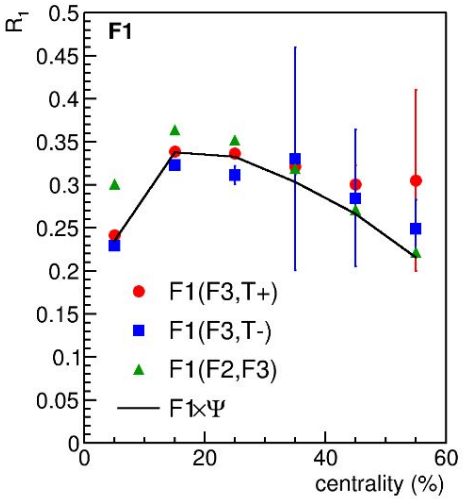


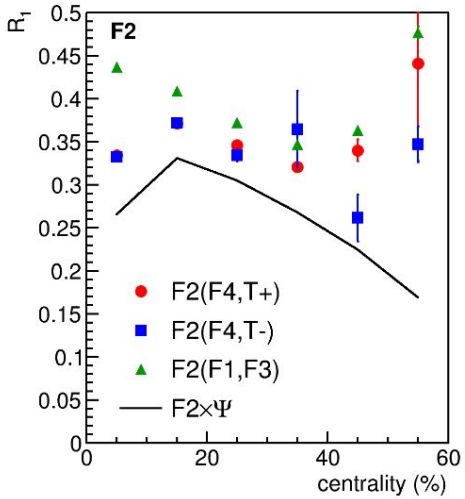
BM@N Monte-Carlo simulation

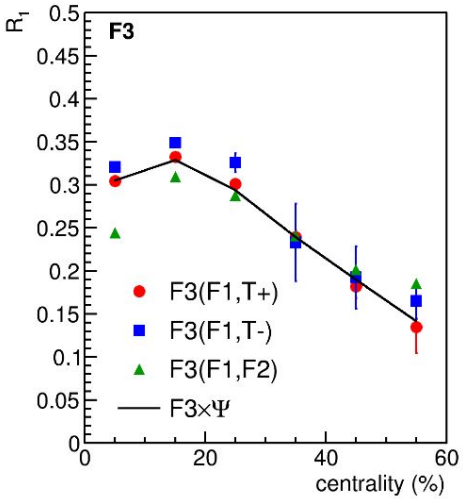
- JAM v2 with MD2 EOS + coalescence was used to generate Xe^{124}+Cs^{133} collisions at E_{kin}=3.8A GeV
- Approximately 3M of events were put through the realistic chain of simulation
- Same track selection criteria as in data
- Identification via the PDG and Mother-Id of associated model particle + hit in either of TOF400 or TOF700

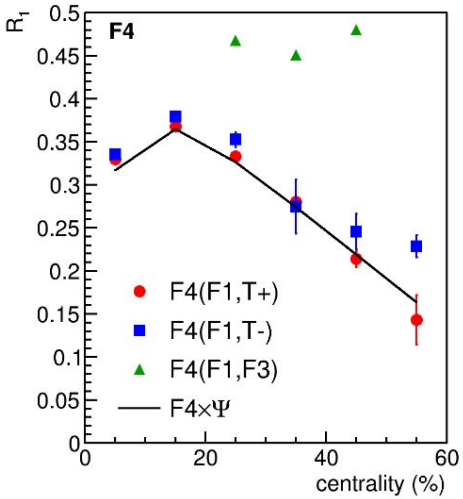


R1 vs centrality for MC simulation

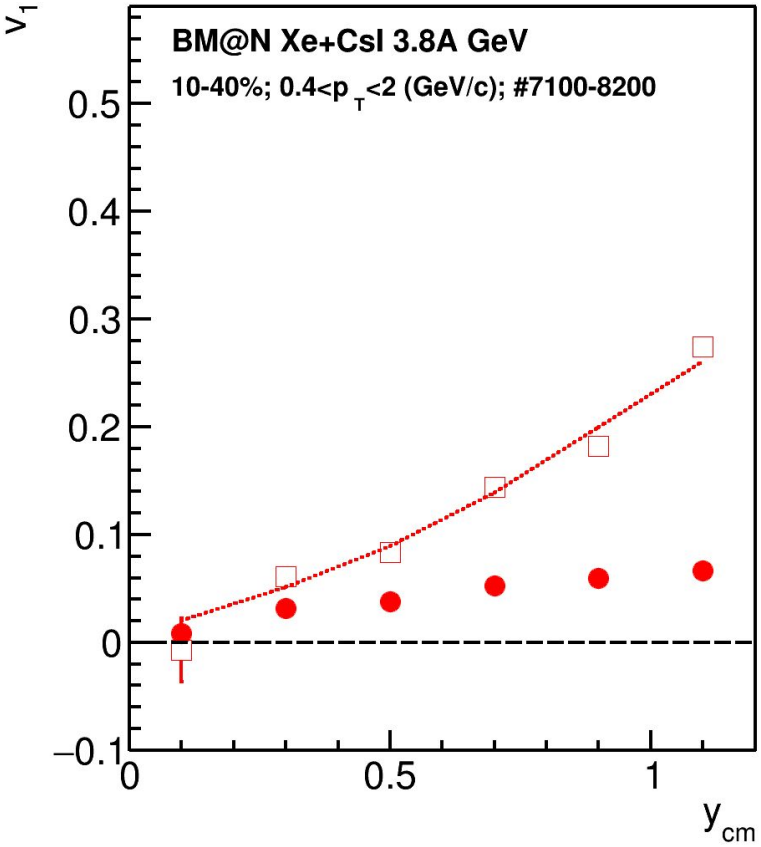


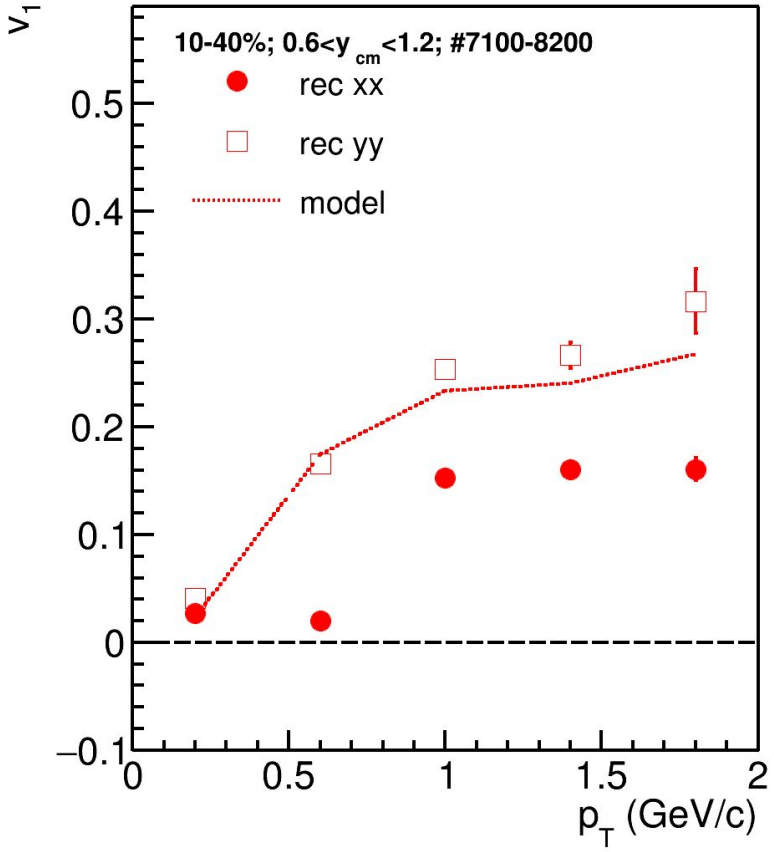




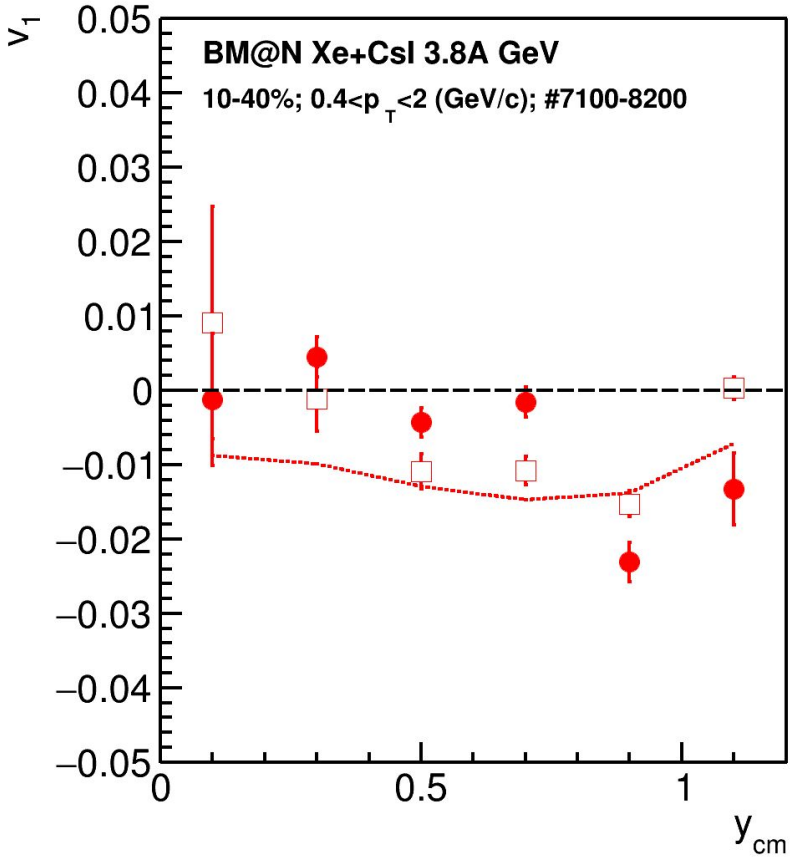


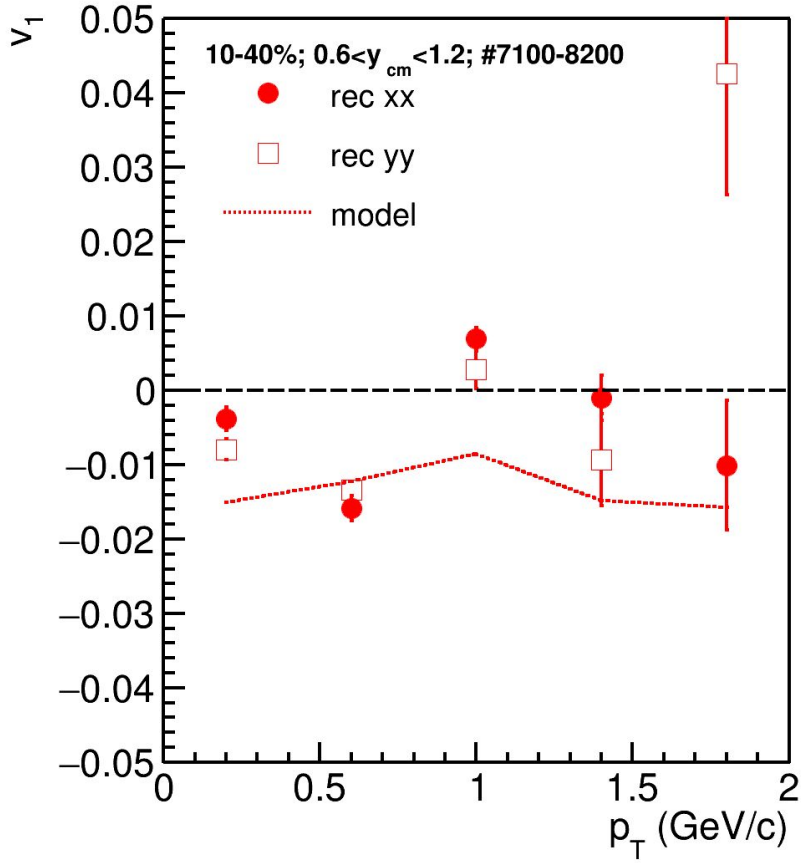
Comparison of v1 wrt RP for reconstructed and model



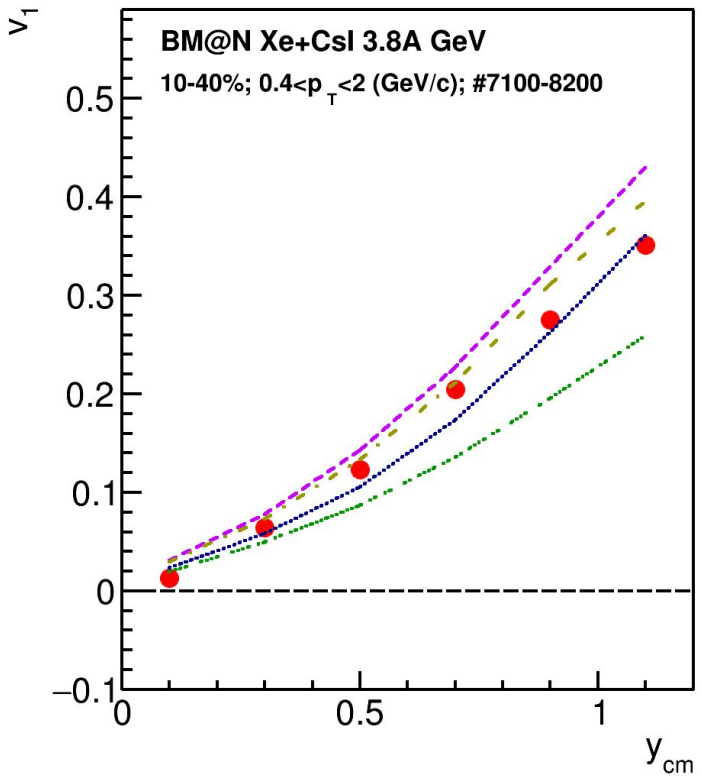


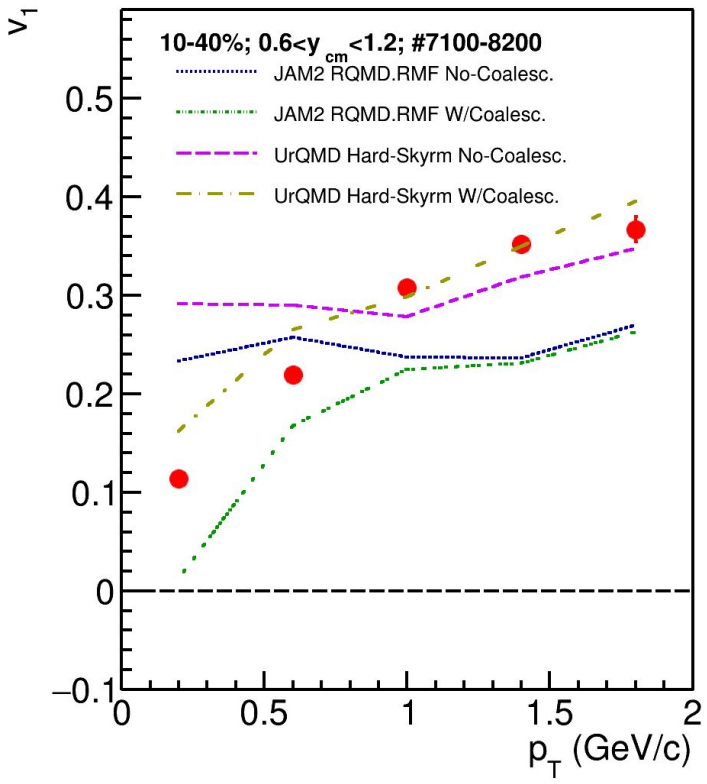
Comparison of v2 wrt RP for reconstructed and model



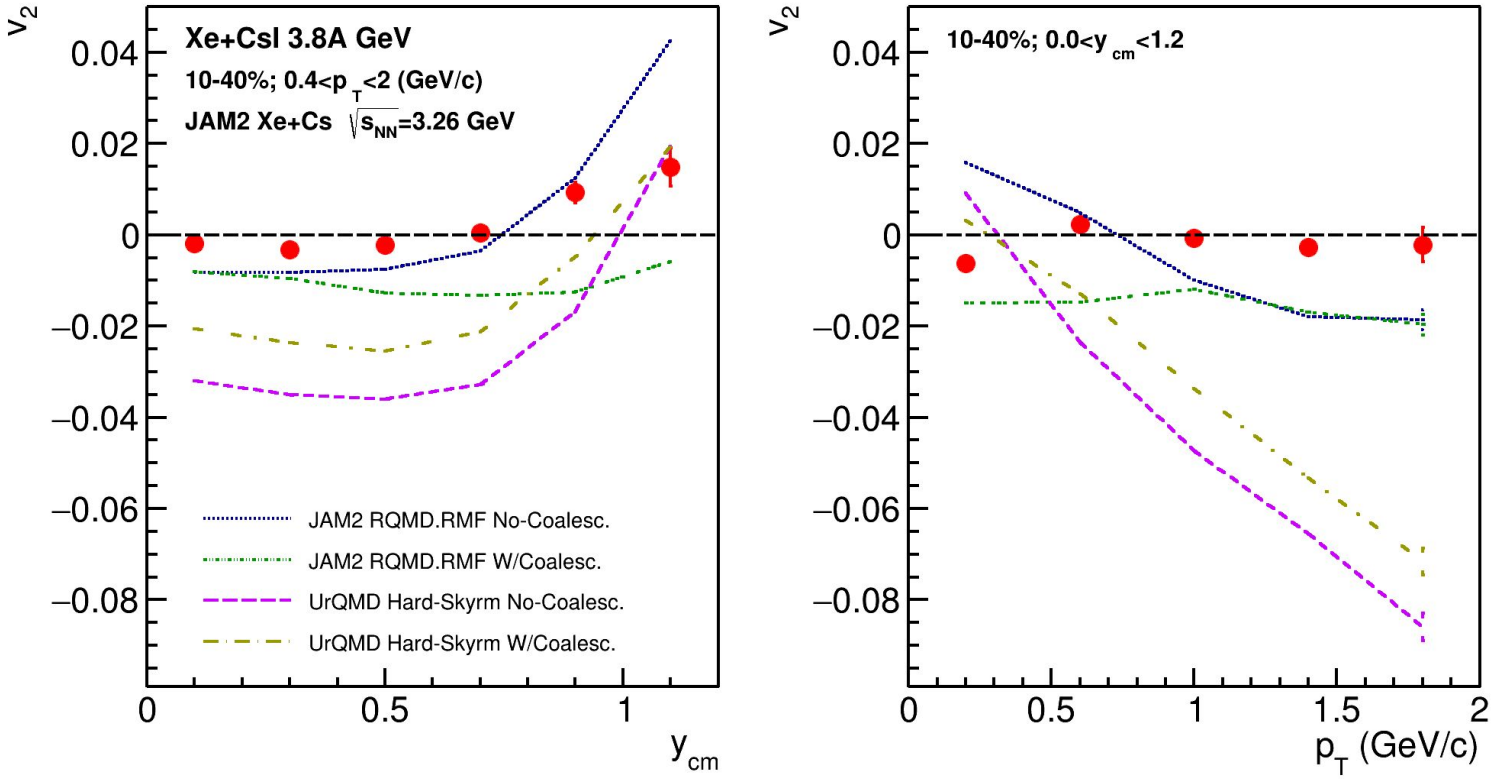


BM@N v_1 of p vs model calculations

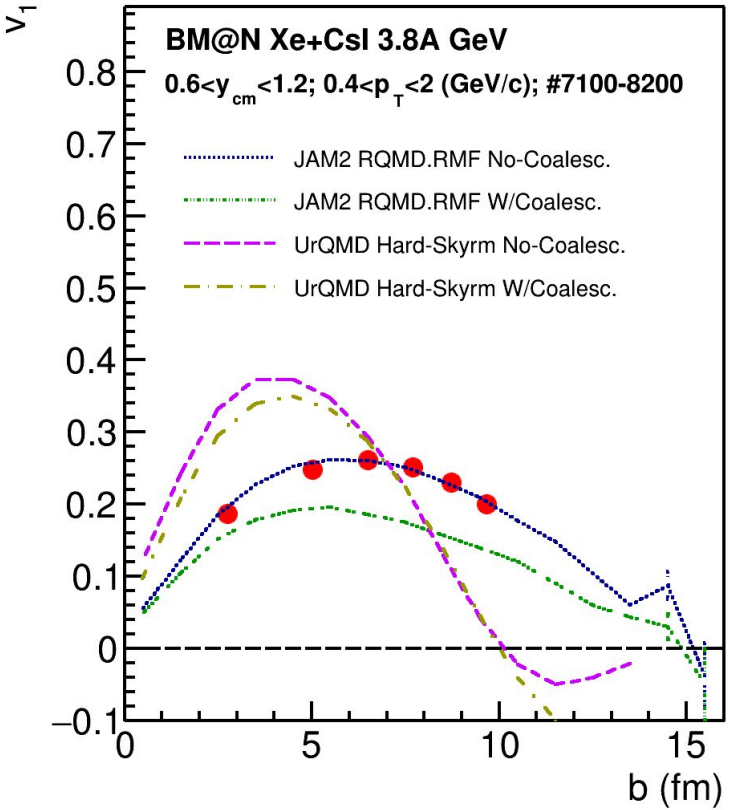


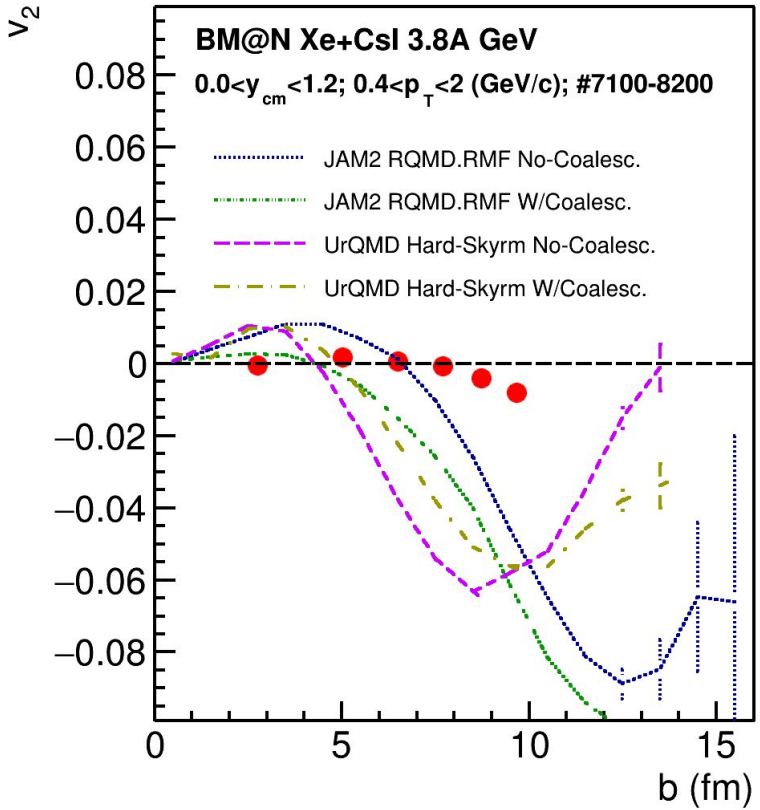


BM@N v_2 of p vs model calculations

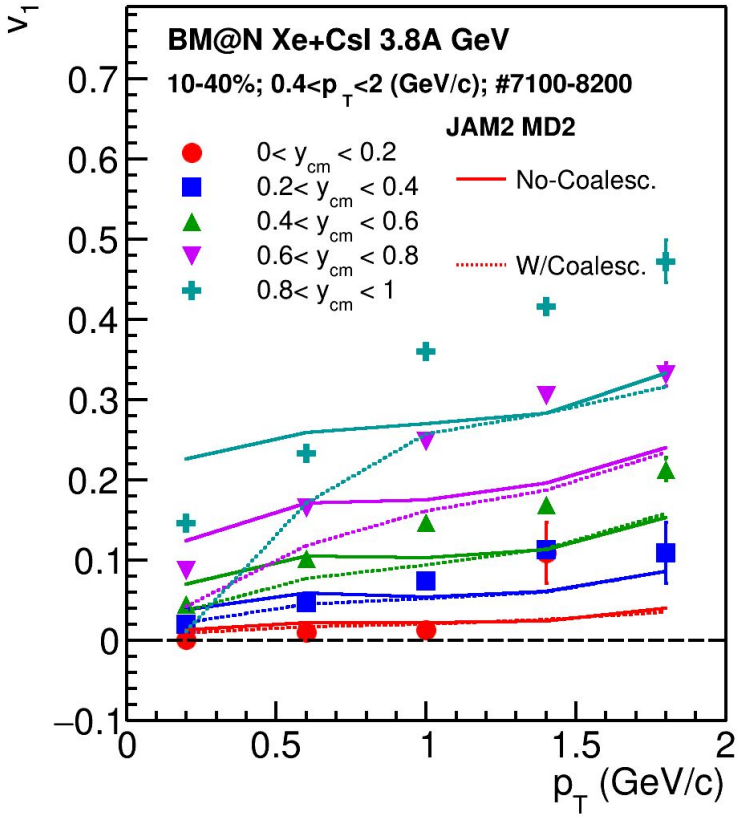


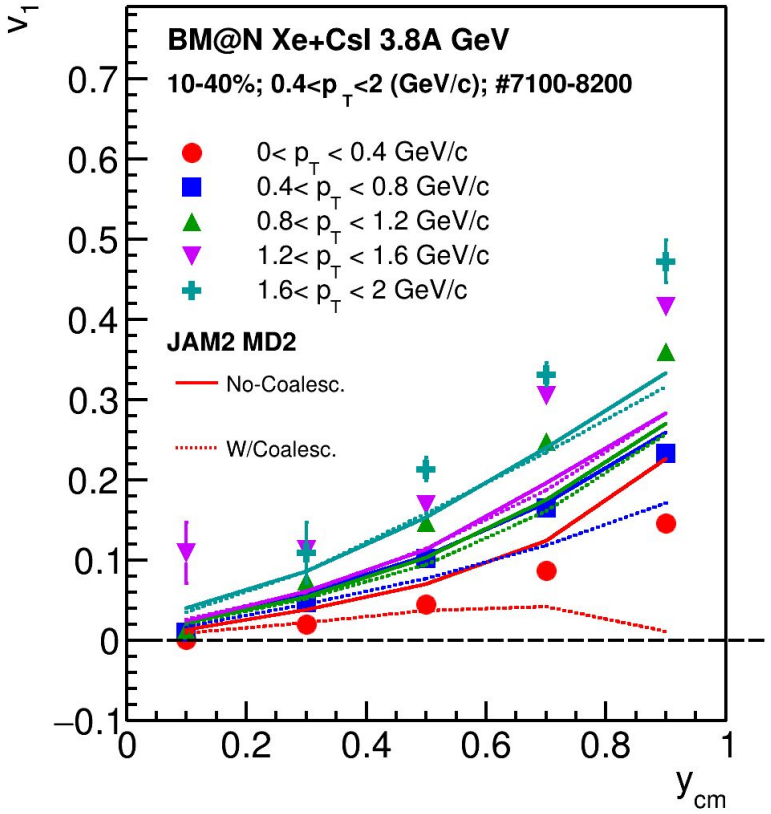
BM@N v_1, v_2 of p vs model calculations



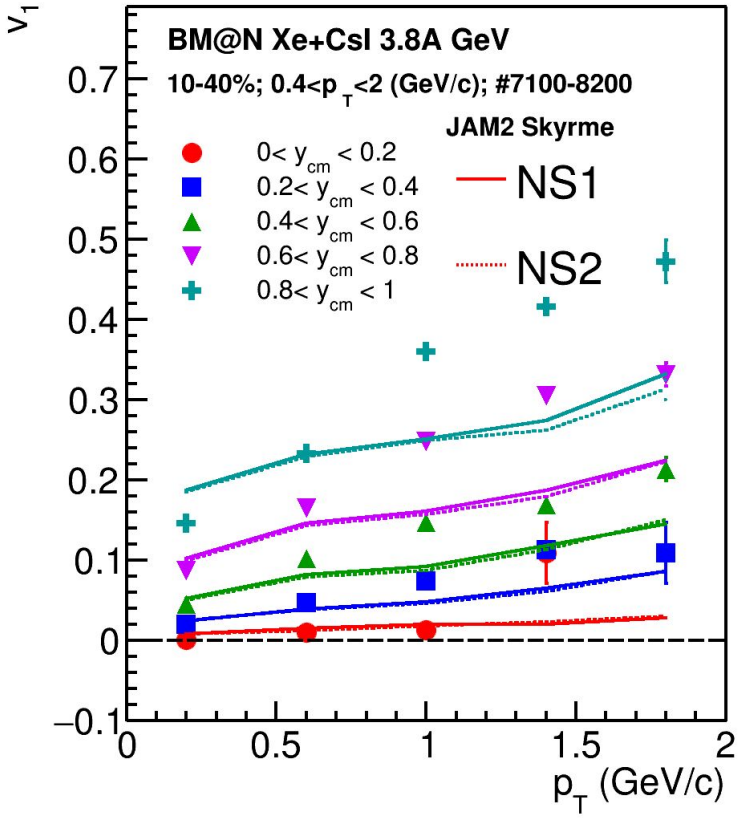


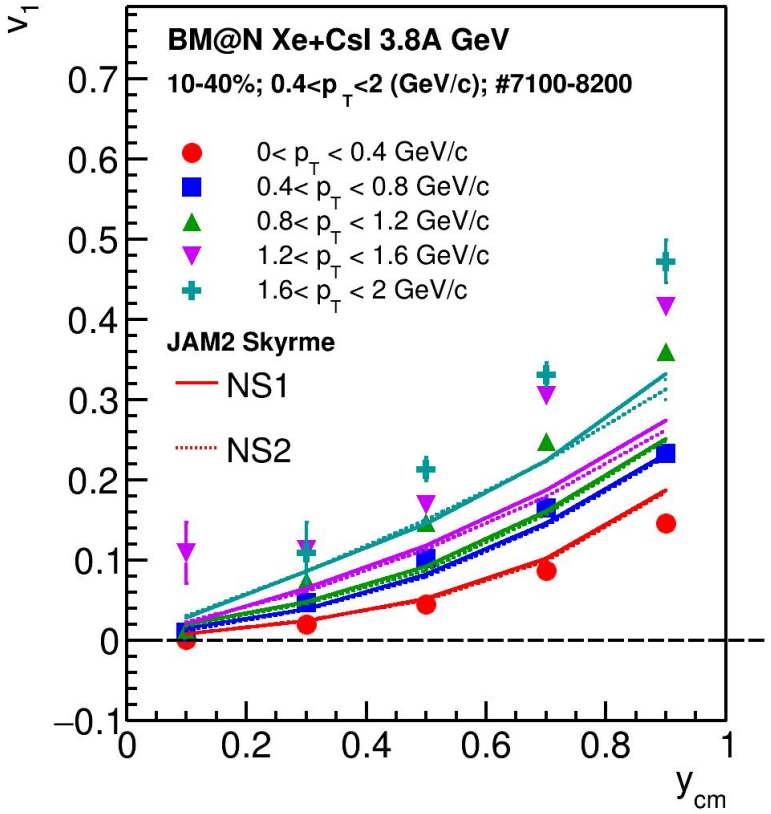
BM@N v_1 of p vs JAM MD2 with vs no coalescence



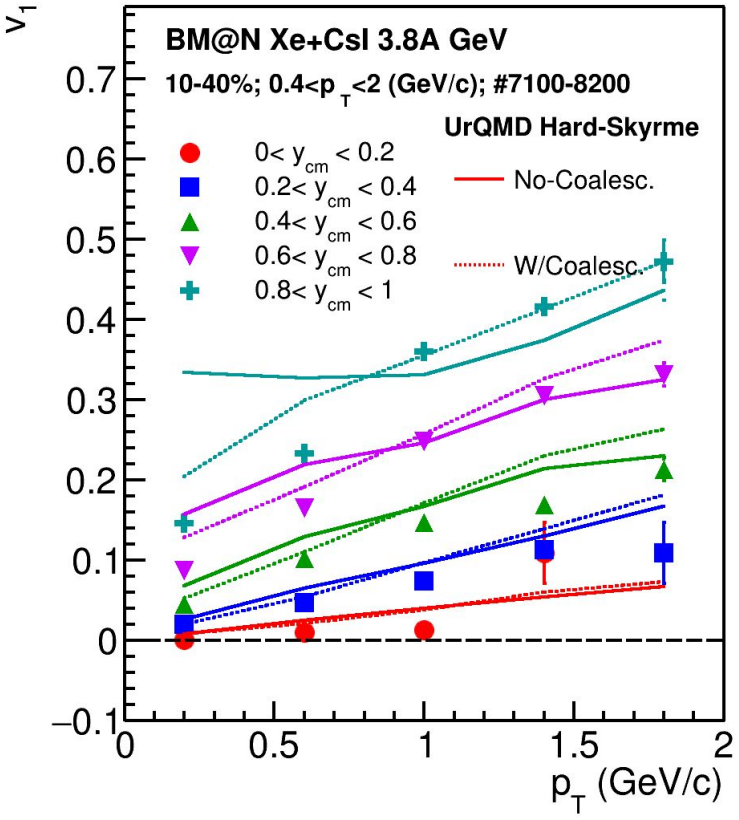


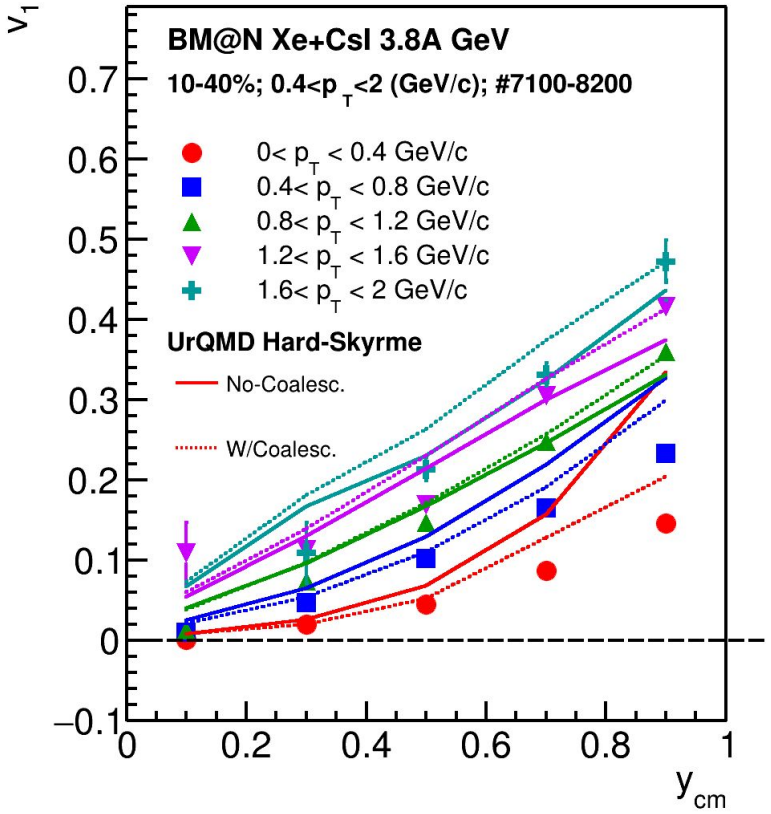
BM@N v_1 of p vs JAM Skyrme (no coalescence)



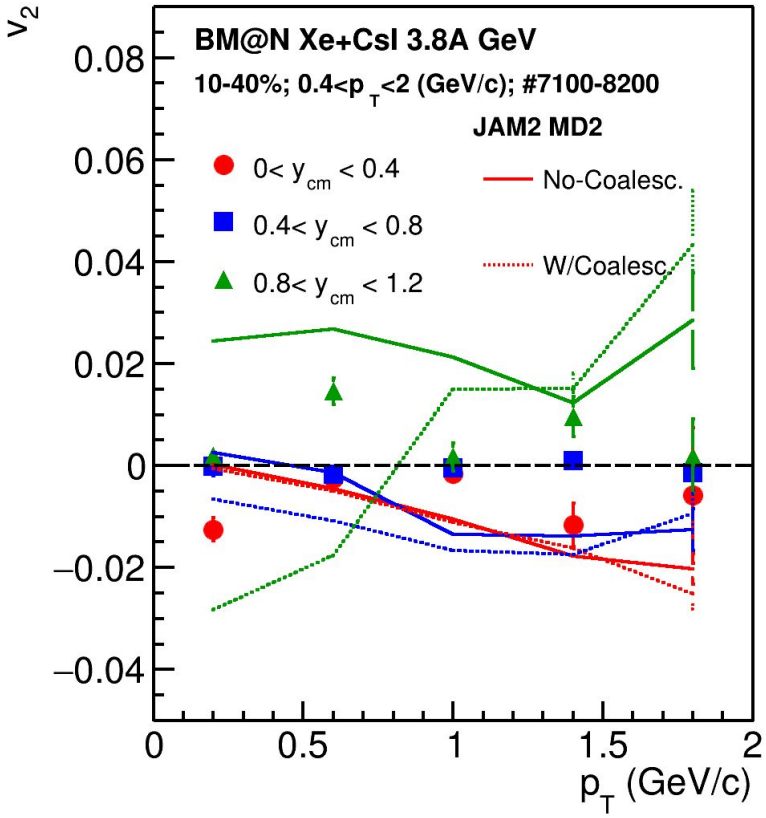


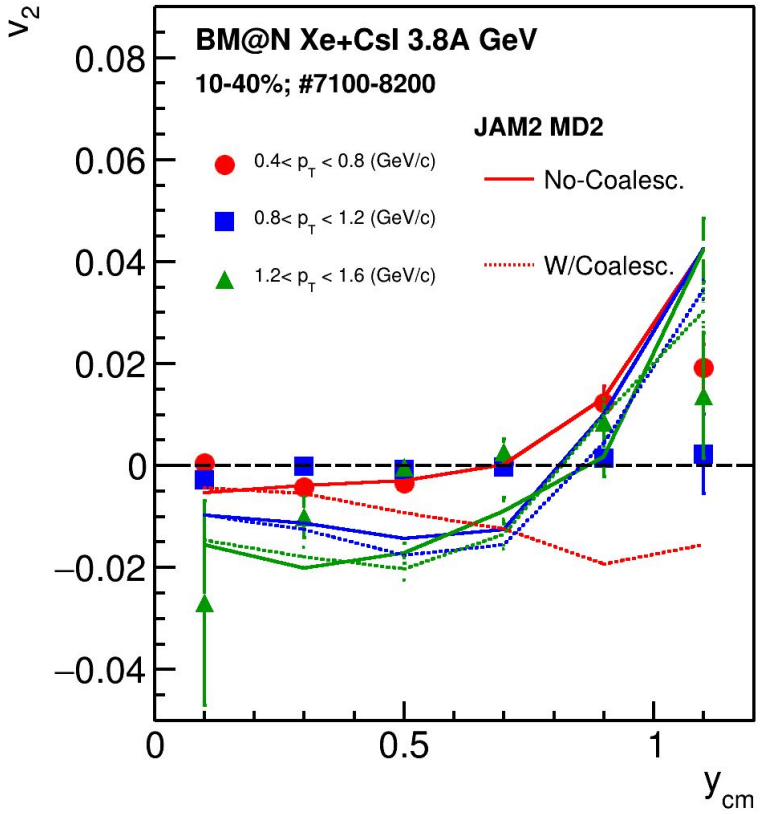
BM@N v_1 of p vs UrQMD hard-skyrme with vs no coalescence



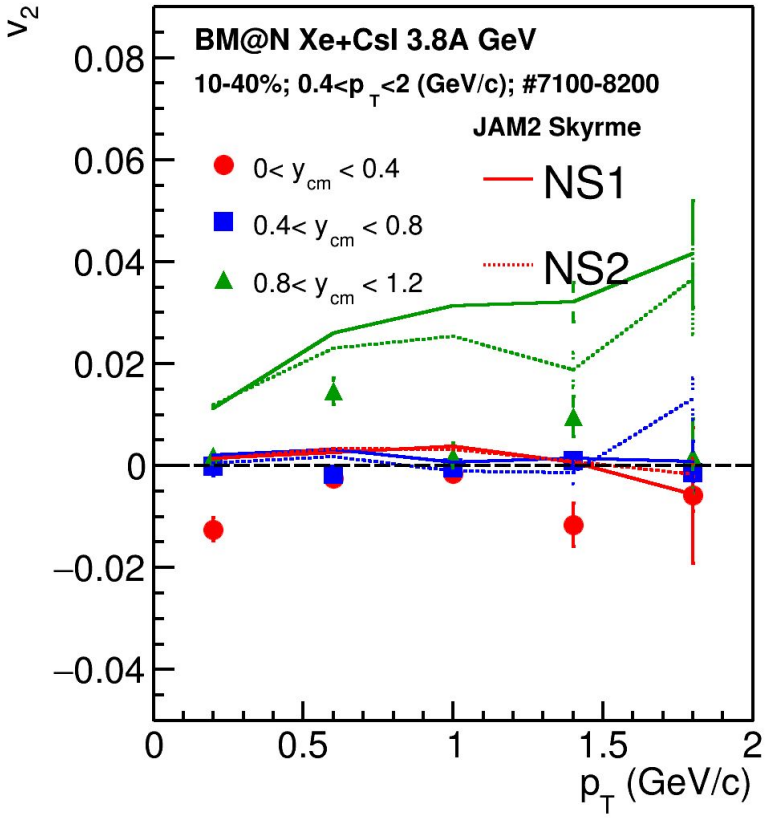


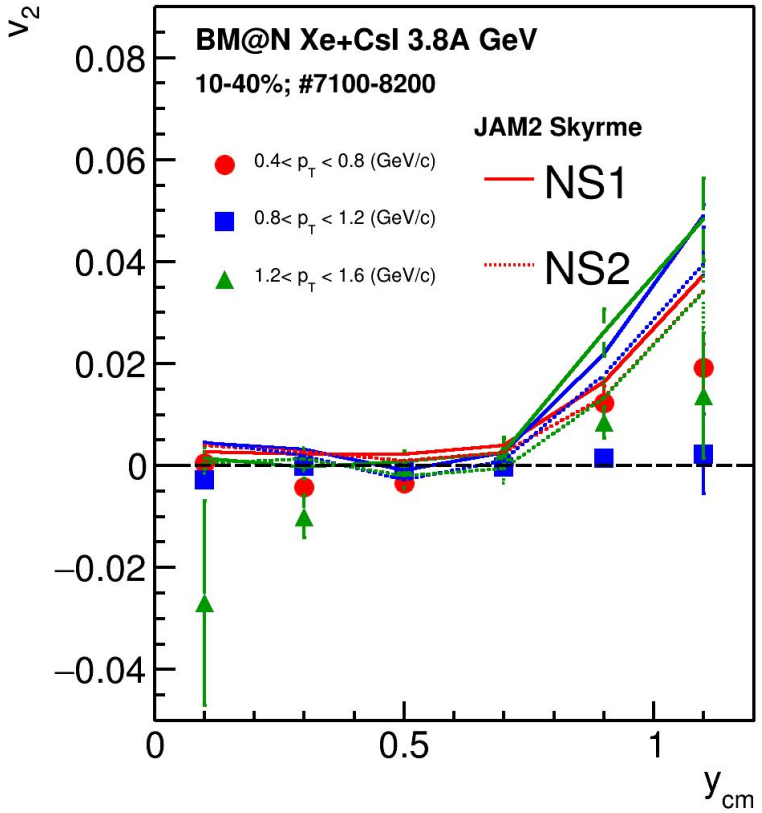
BM@N v_2 of p vs JAM MD2 with vs no coalescence



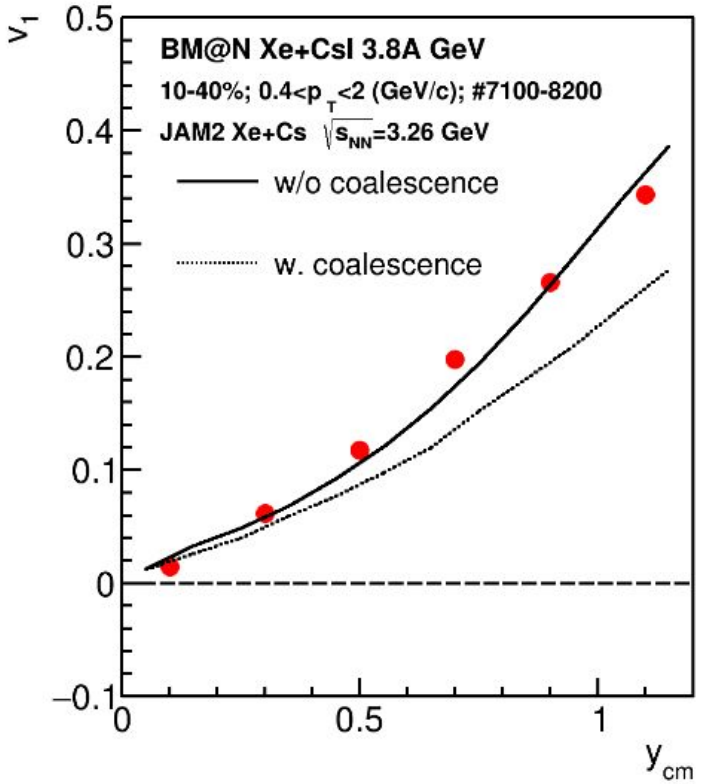


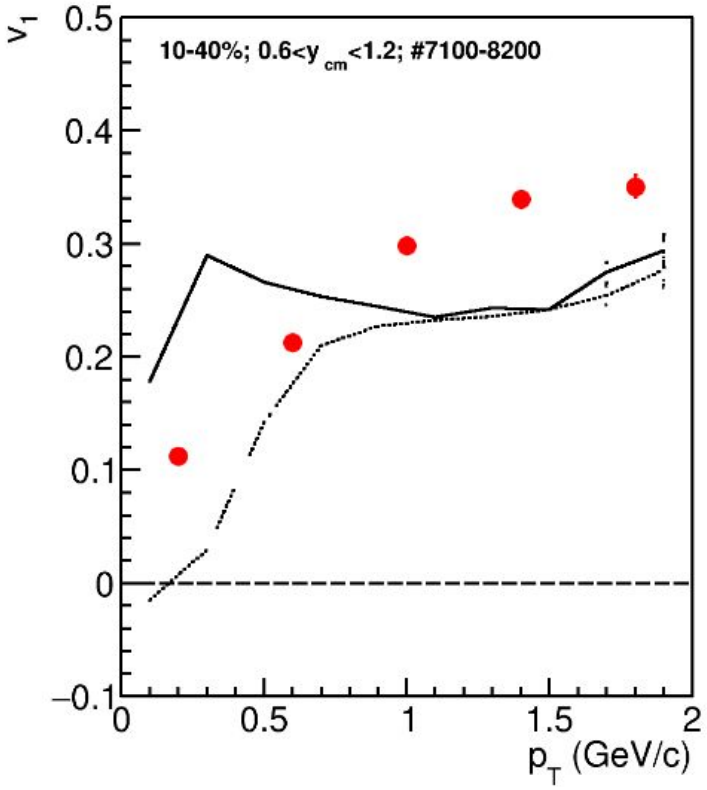
BM@N v_2 of p vs JAM Skyrme (no coalescence)



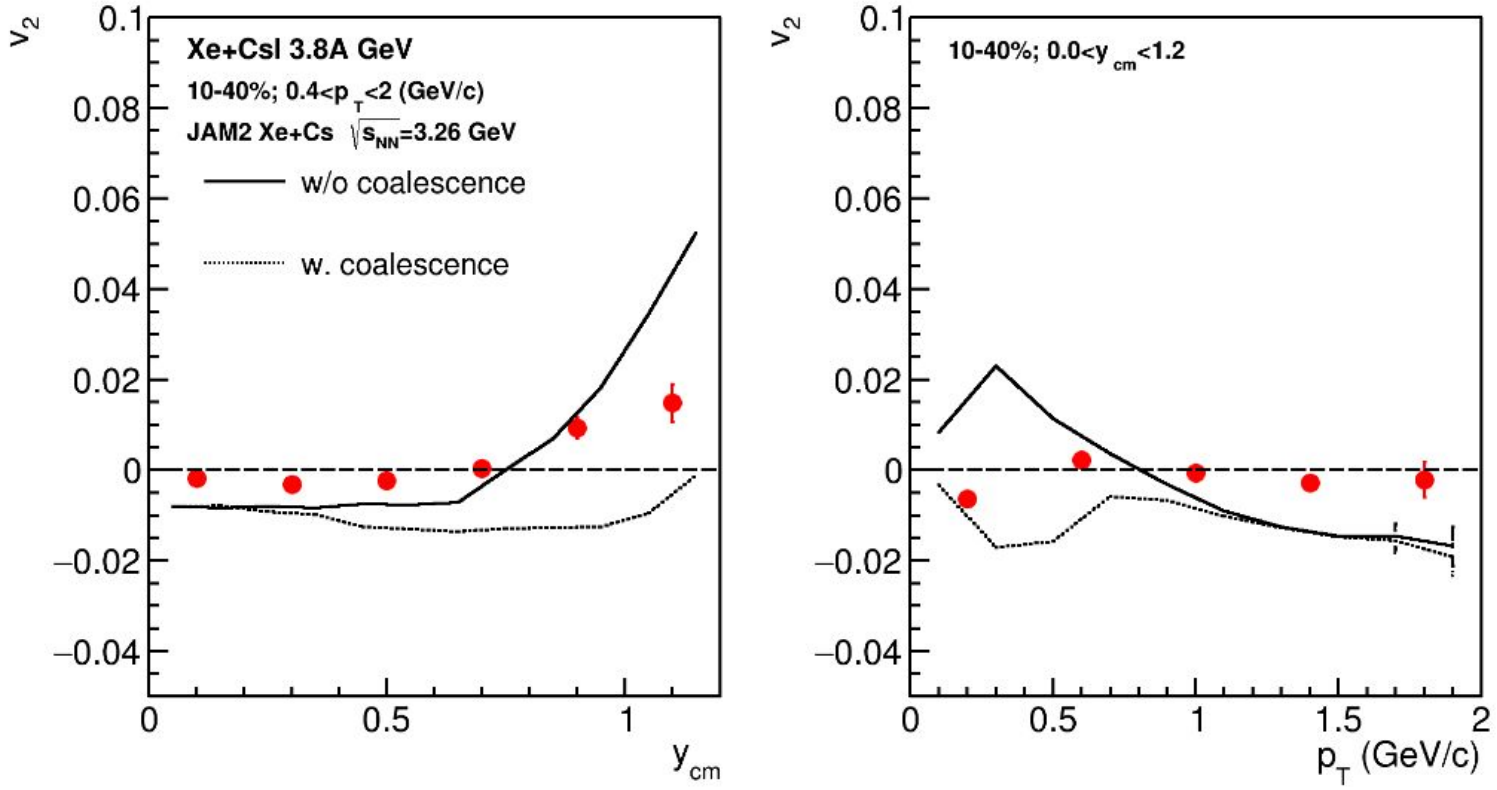


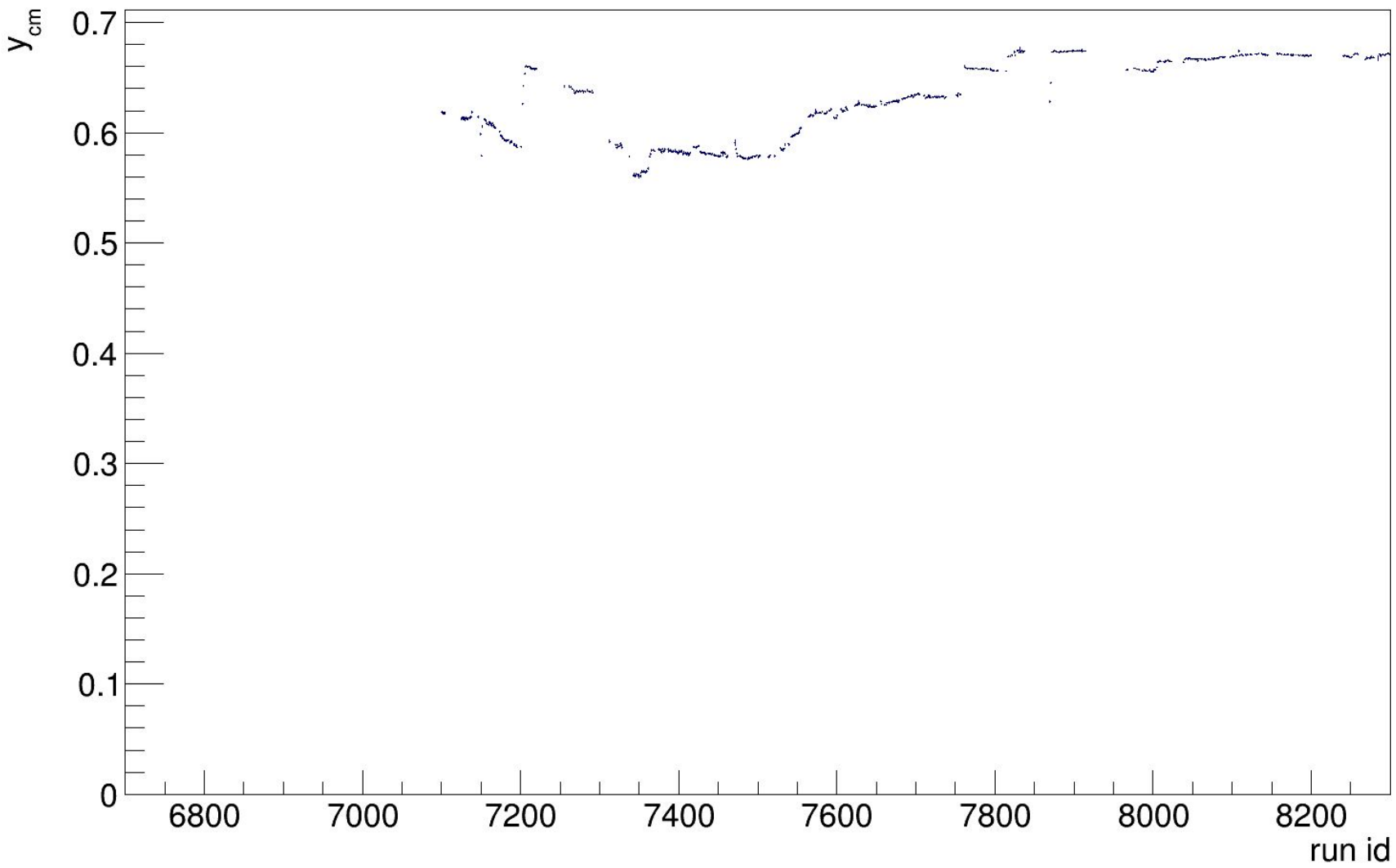
BM@N v_1 of p vs JAM MD2 calculations





BM@N v_2 of p vs JAM MD2 calculations




y_{cm}
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
6800
7000
7200
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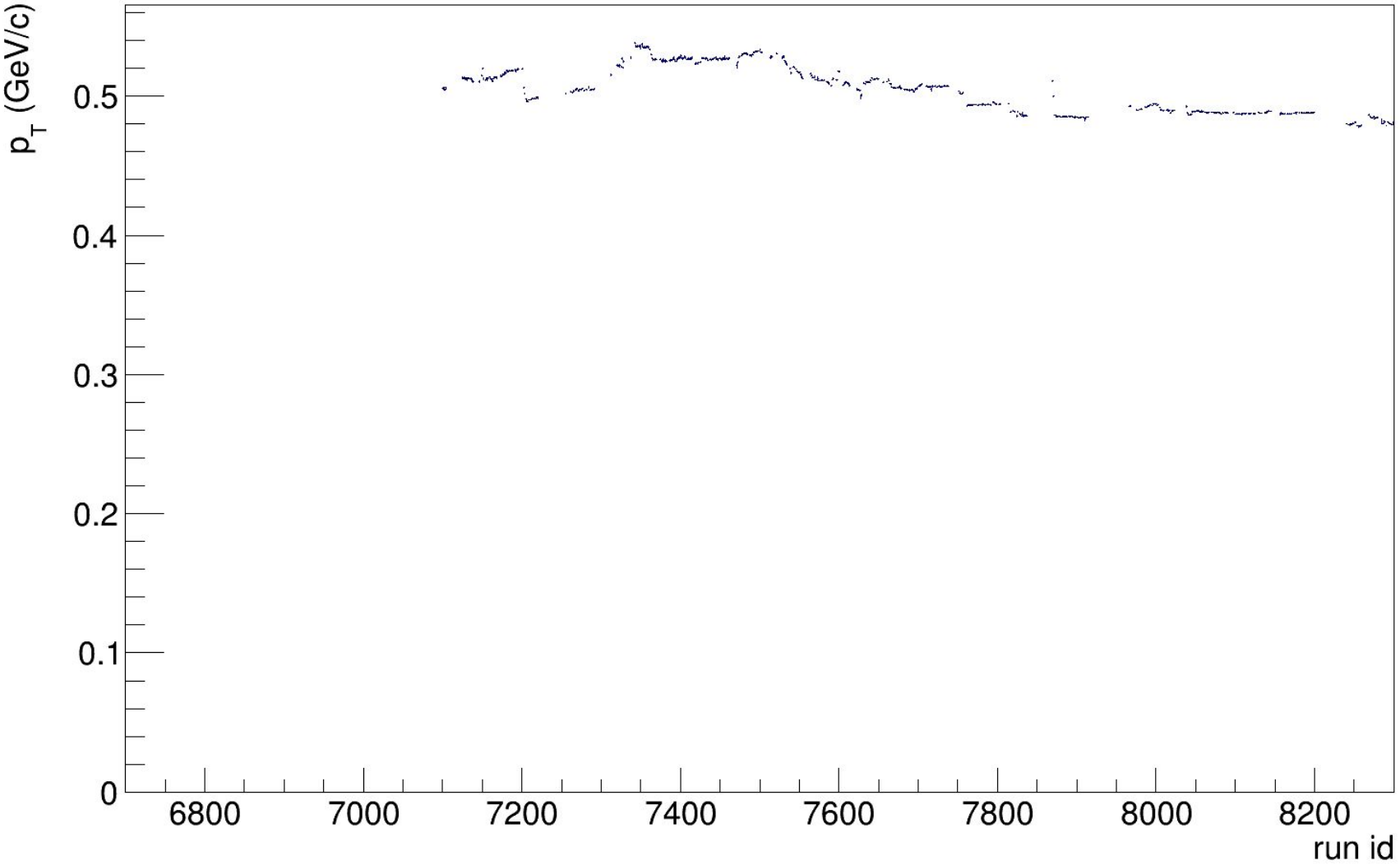
7600
7800
8000
8200
run id


p_T (GeV/c)
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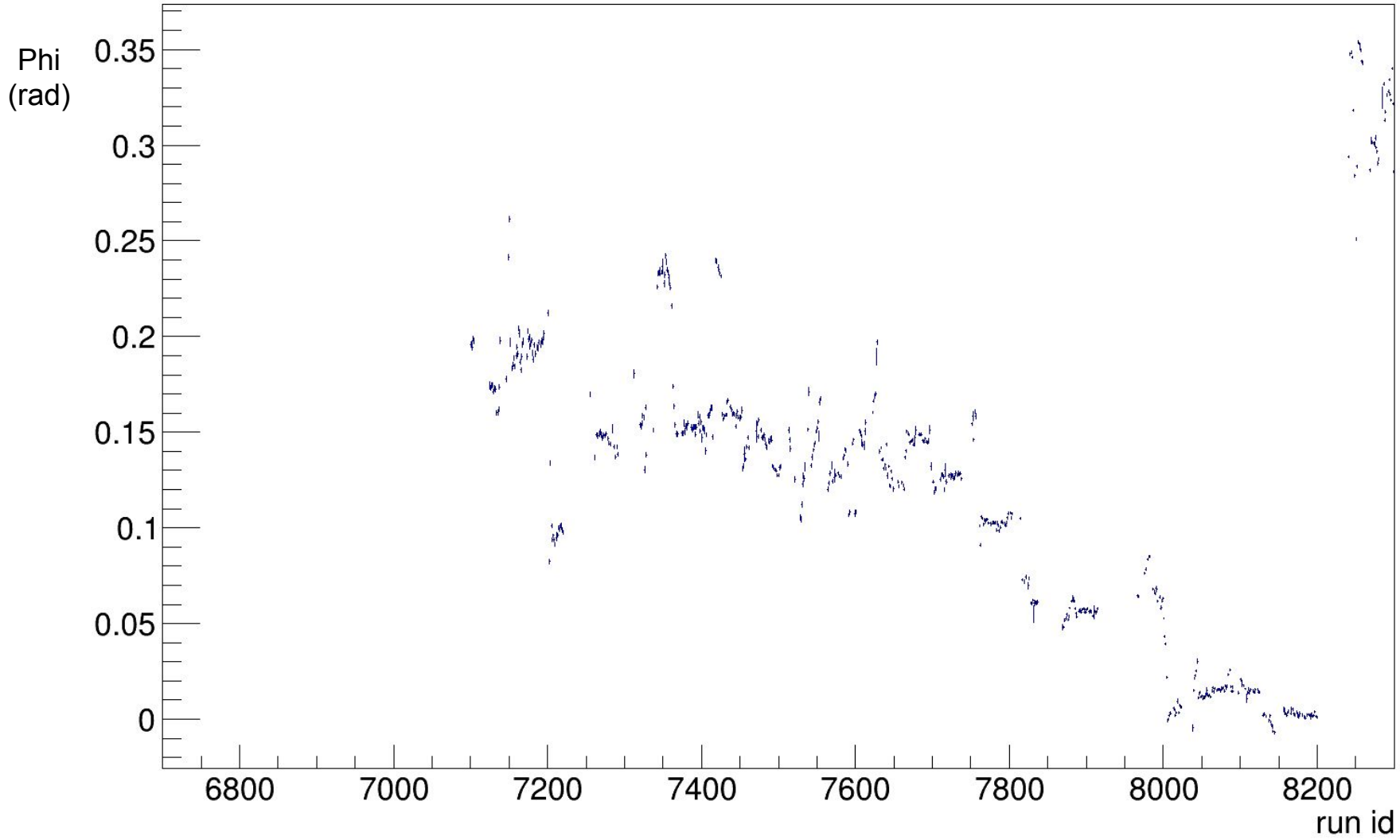
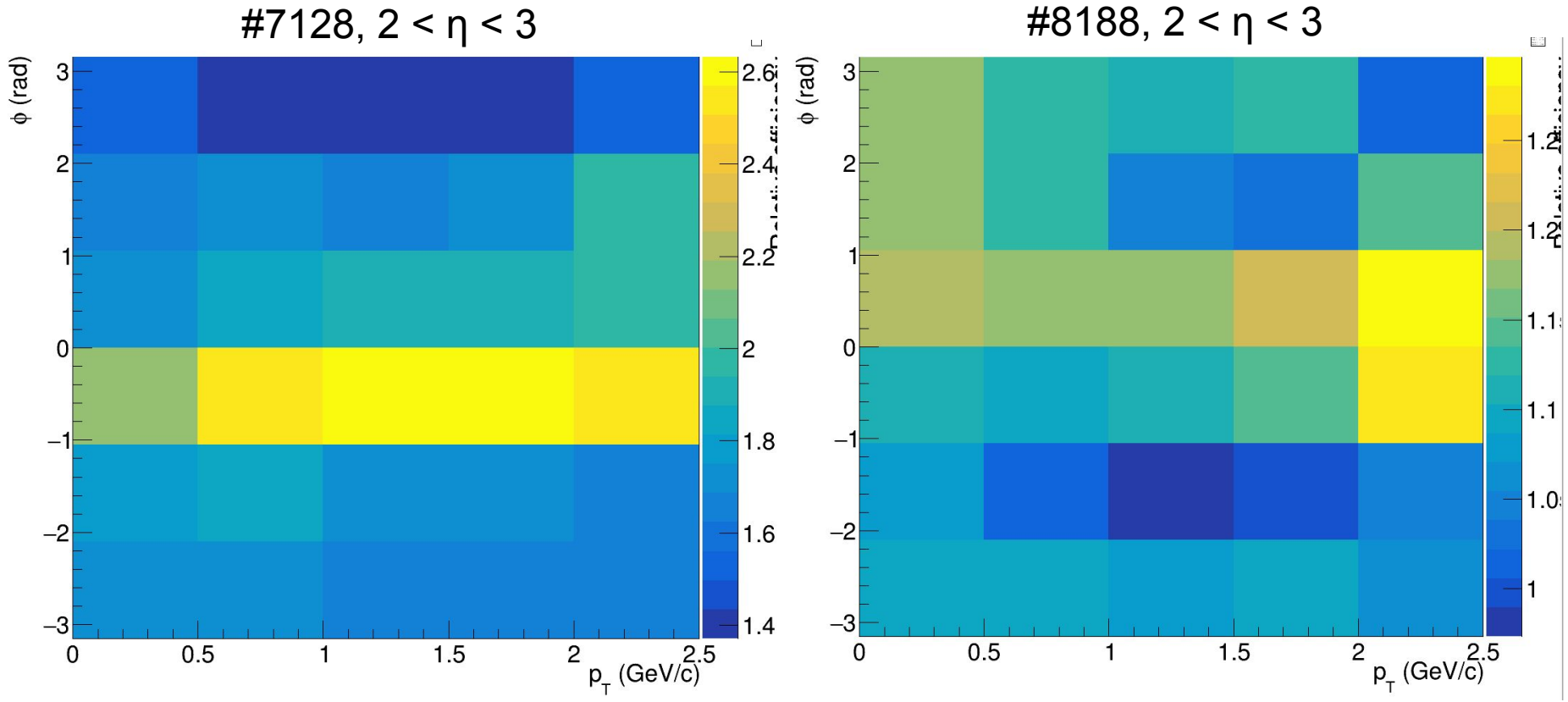
0.4
0.3
0.2
0.1
0
6800
7000
7200
7400
7600
7800
8000
8200
run id

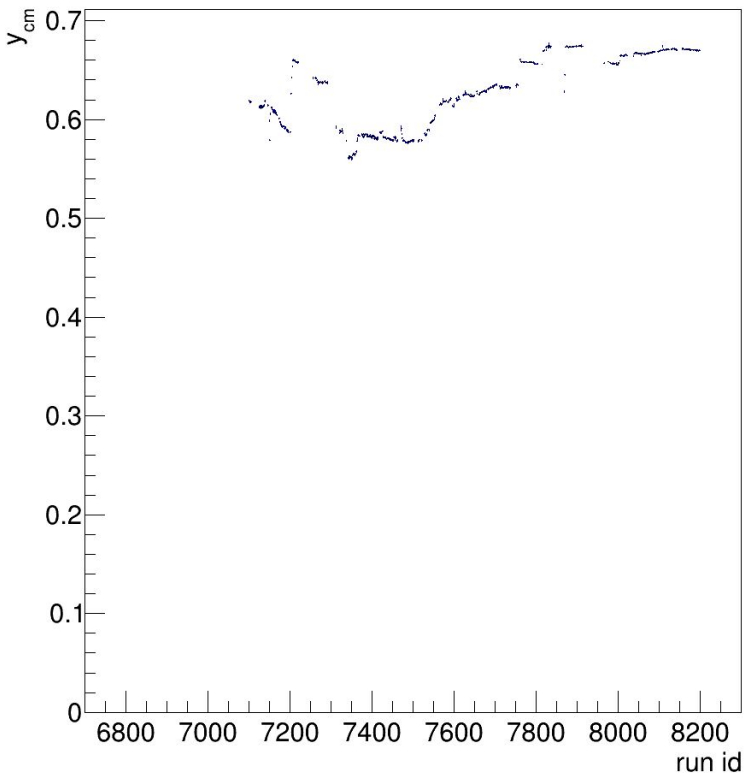

Phi
(rad)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
6800
7000
7200
7400
7600
7800
8000
8200
run id

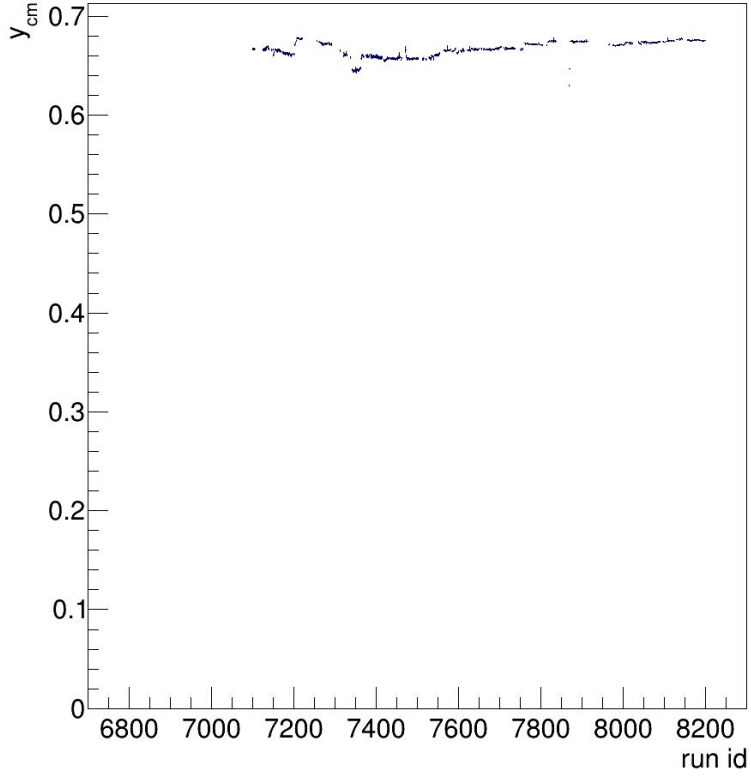
Relative run-by-run efficiency (target run 7500)



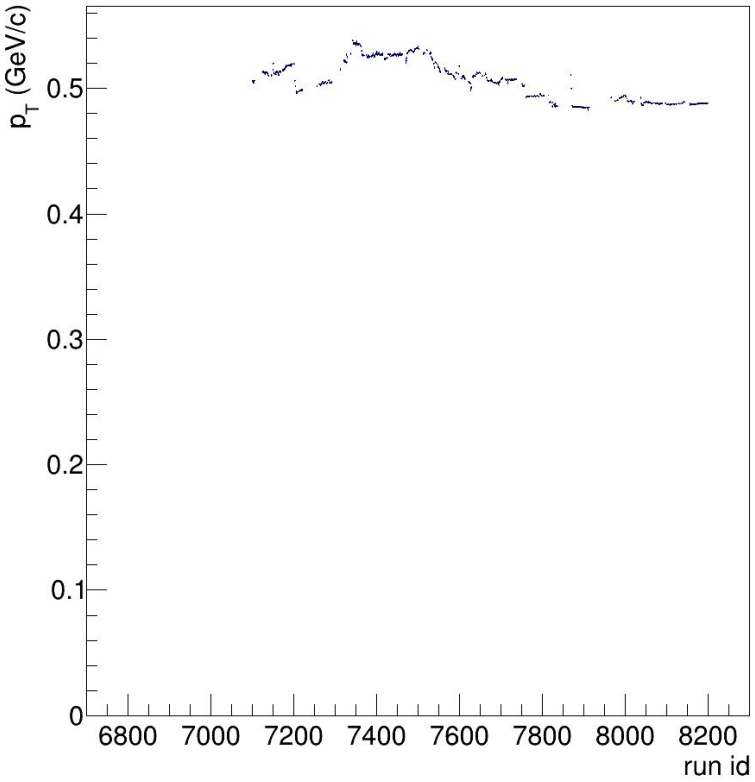
4D-efficiency was built: η, p_T, ϕ, run-id. E = $N_{curr}/N_{target\ run\text{-}id}$

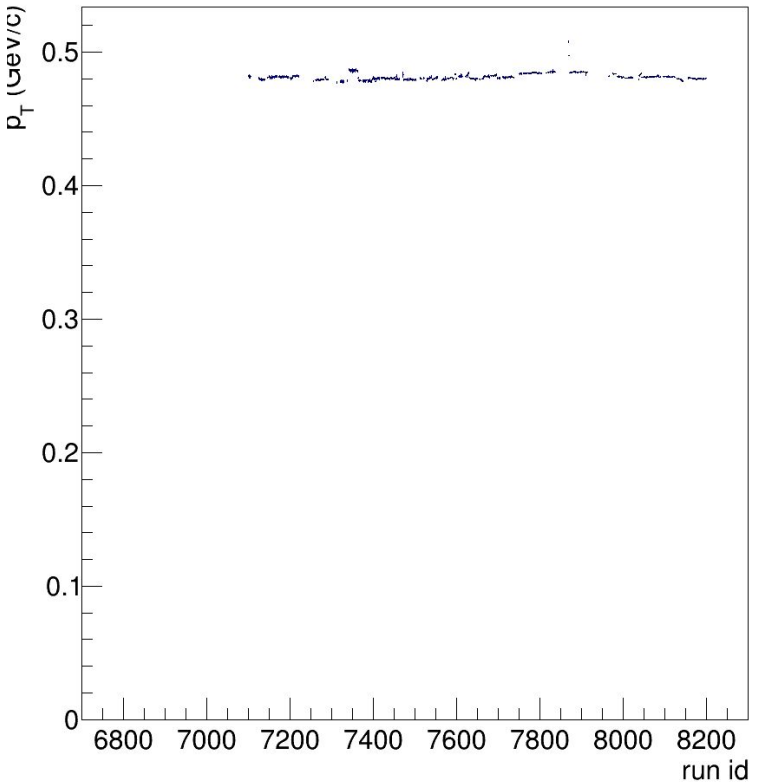
Proton y-distribution before/after reweighting



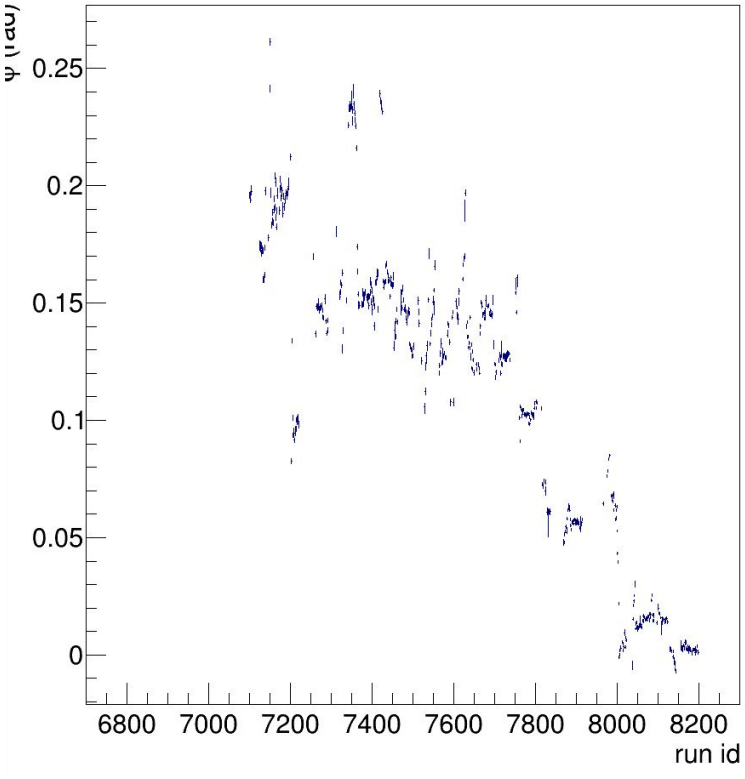


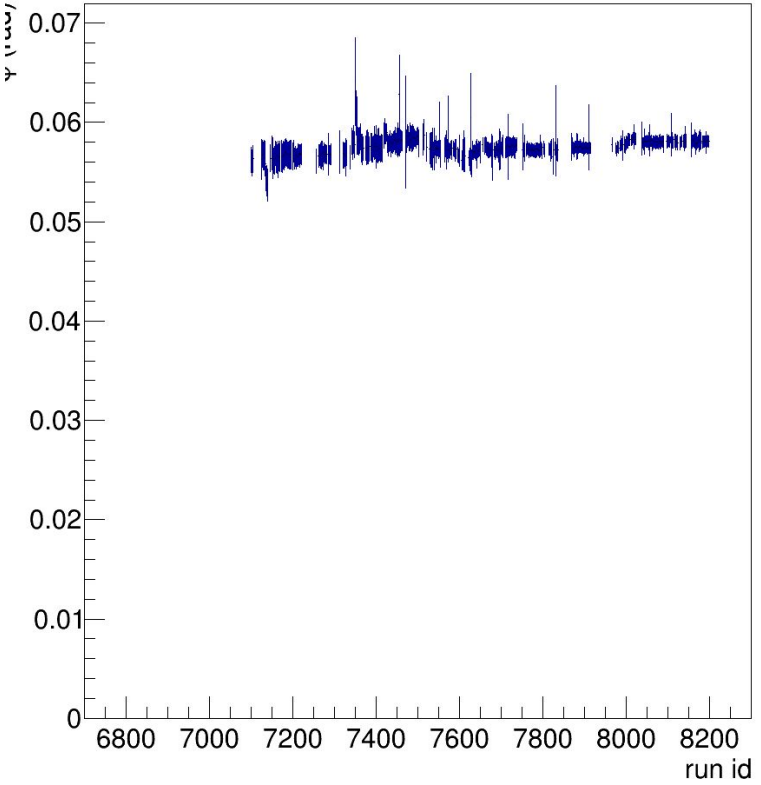
Proton p_T-distribution before/after reweighting



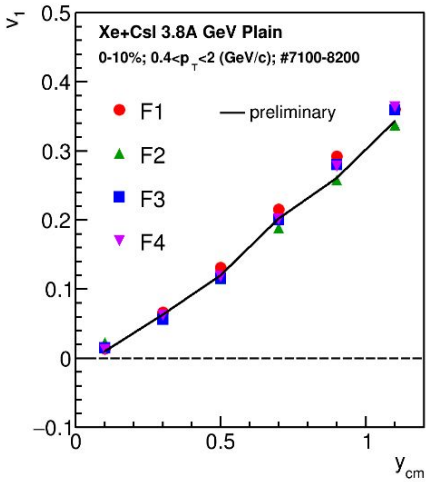


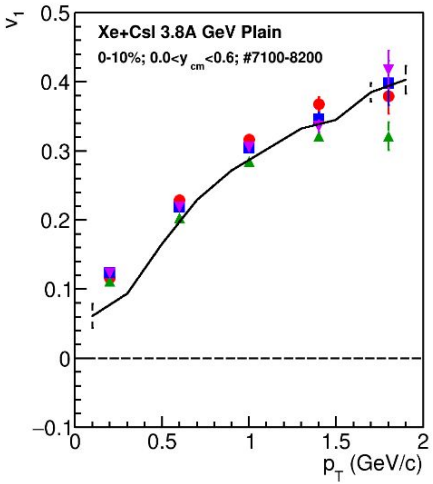
Proton p_T-distribution before/after reweighting

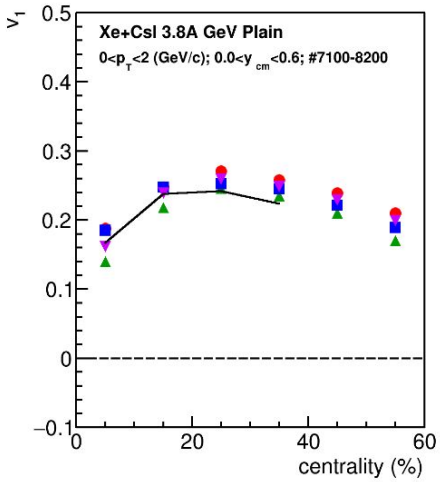


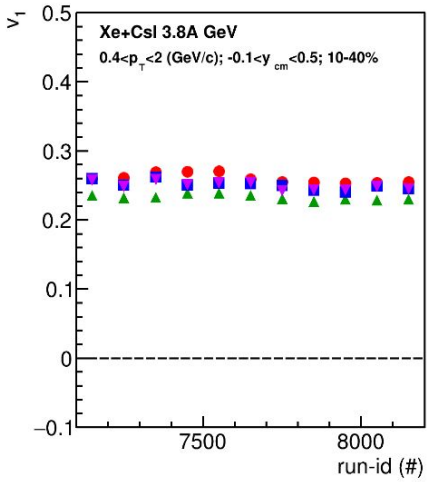


Proton v_1 after track reweighting

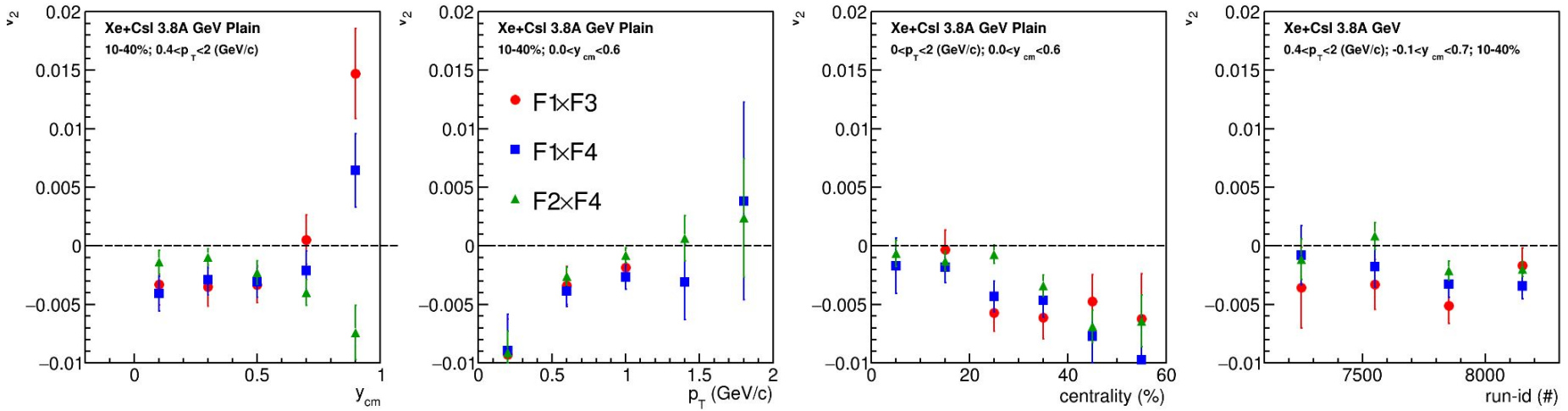




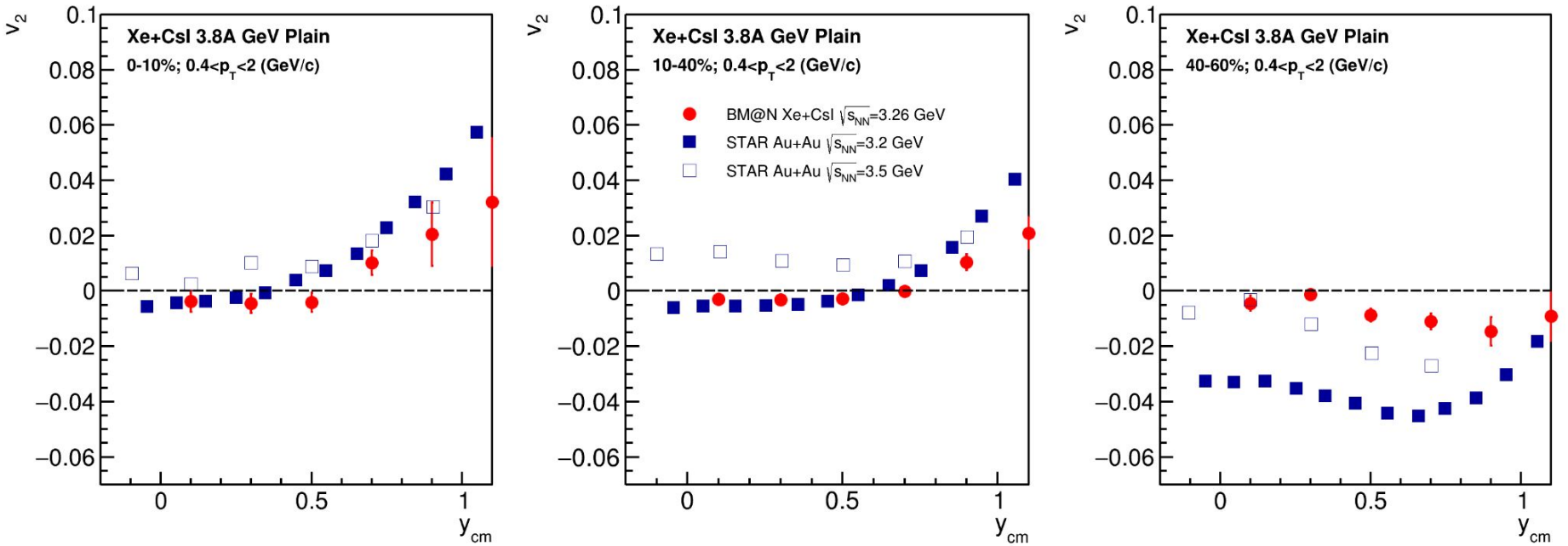




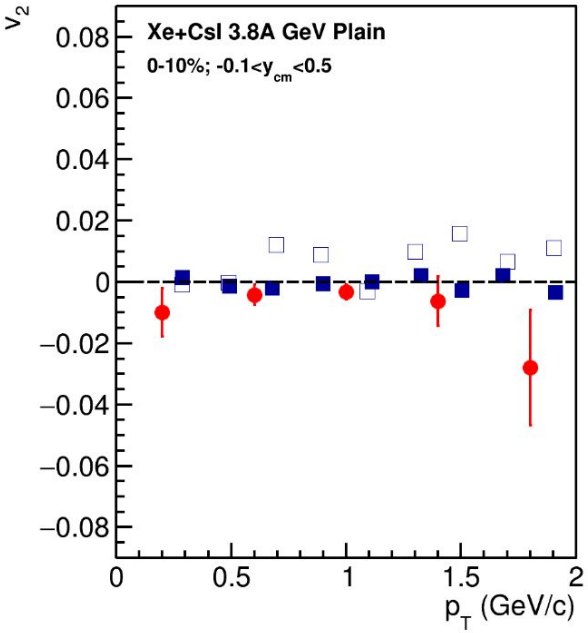
Proton v_2 after track reweighting

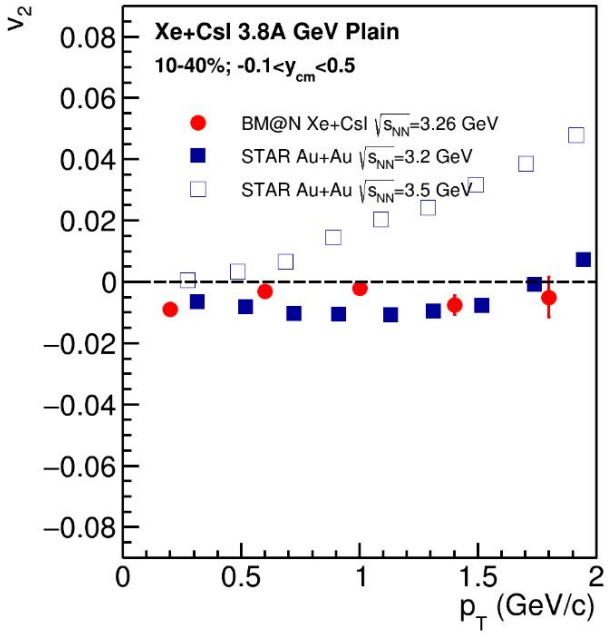


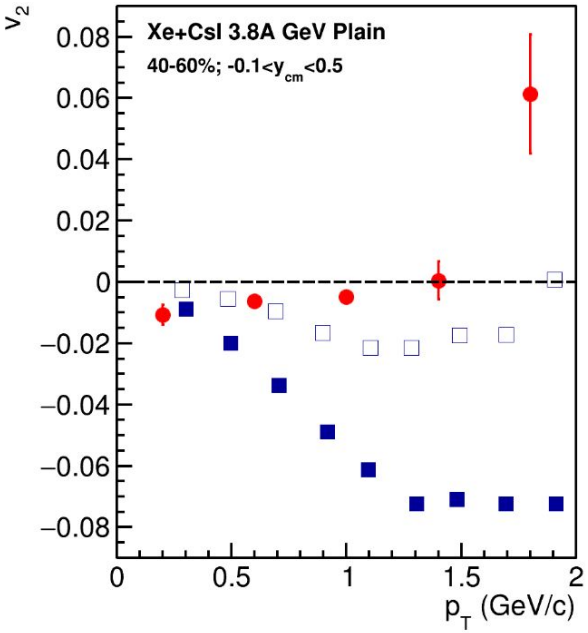
Proton v_2 after track reweighting



Proton v_2 after track reweighting

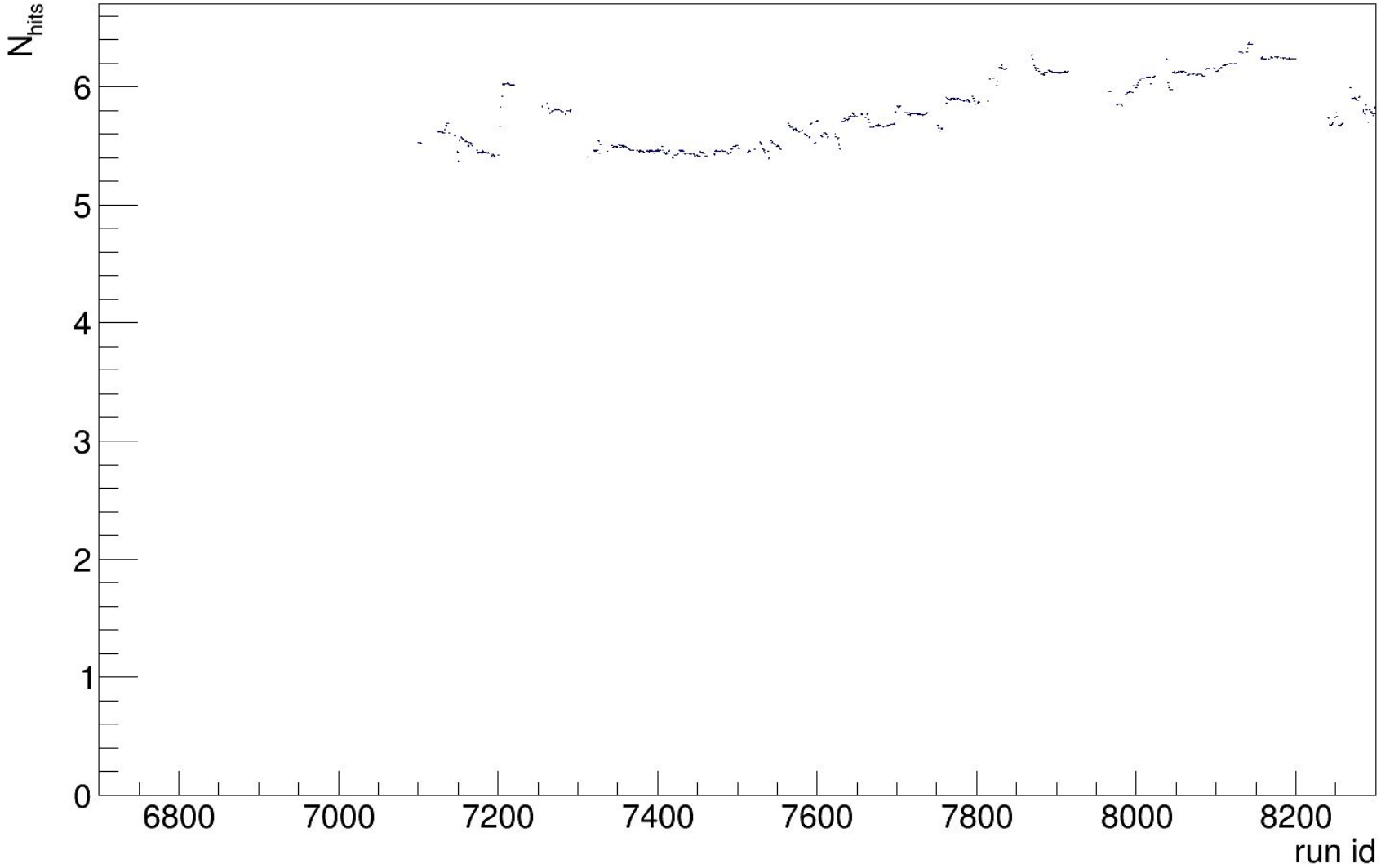


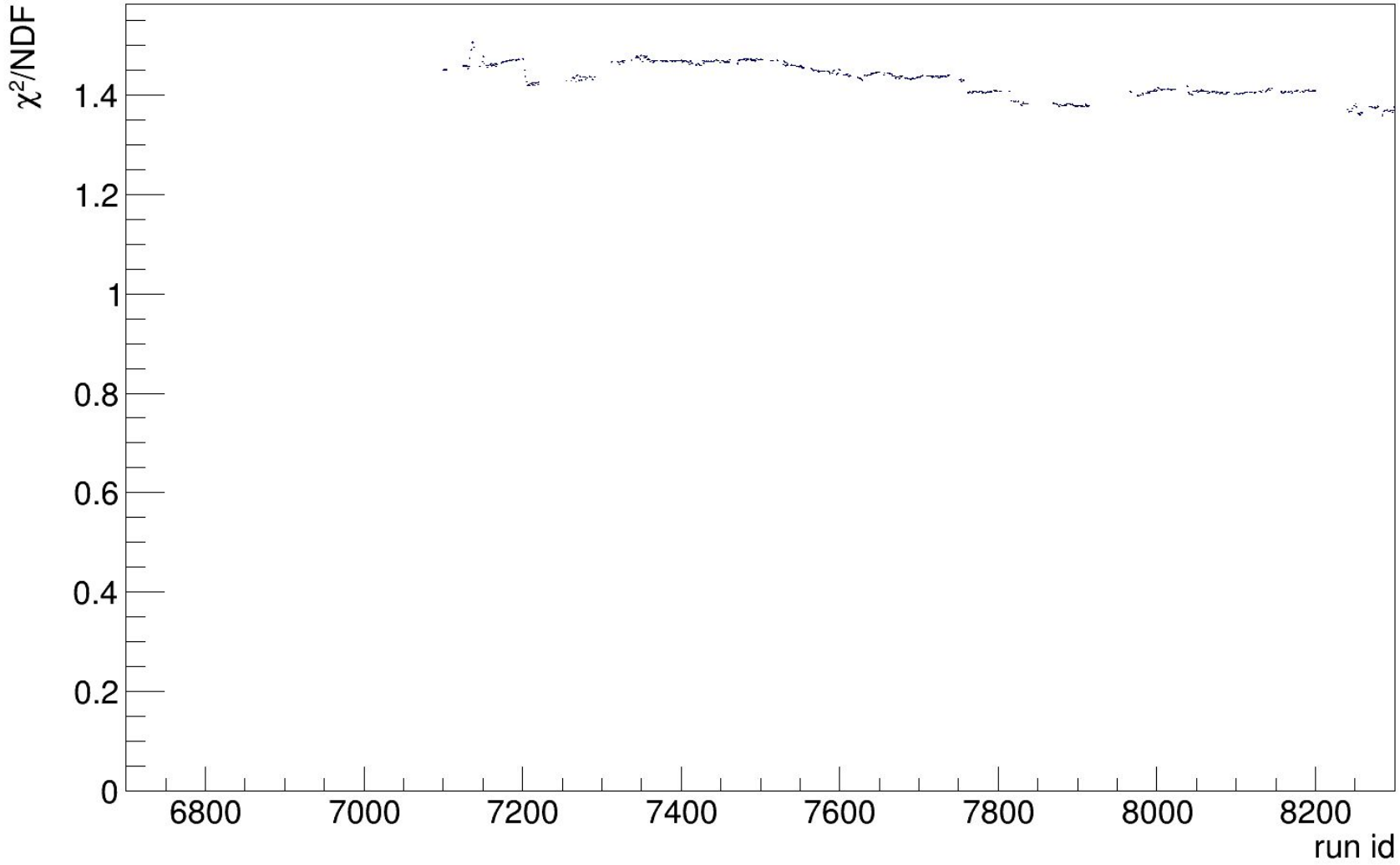


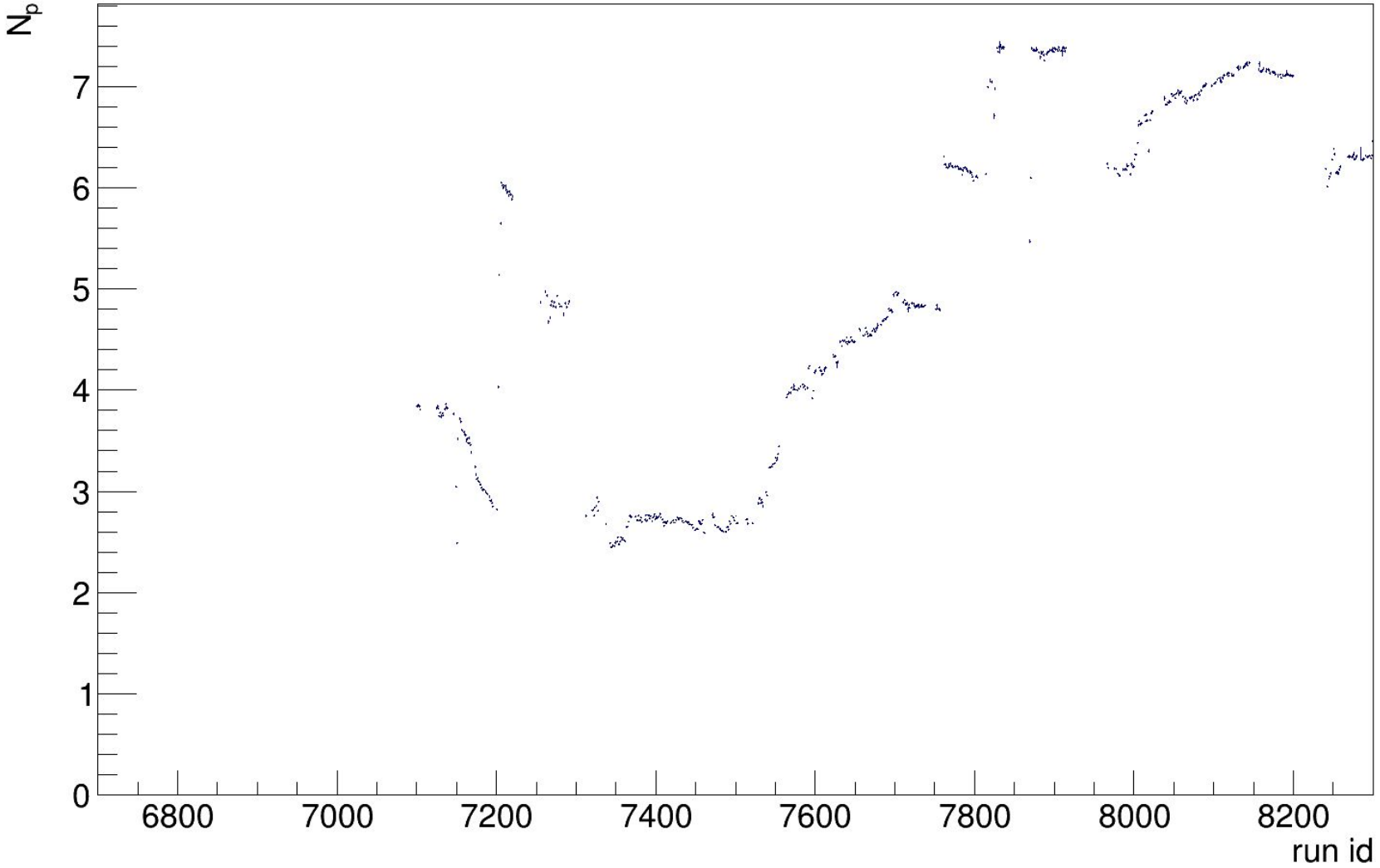


Todo list:

- ❏ Corrections: my recentering, my twist and rescaling, my decomposition steps
- ❏ <Nhits> vs run-id
- ❏ <chi2/NDF> vs run-id
- ❏ <DCA> vs run-id
- ❏ Run-id dependency of vtx for central events
- ❏ $\langle F^i F^j \rangle$ as a function of centrality and run-id for midcentral events and for different run-id's
- ❏ Run-id QA for only physical data
- ❏ <beta> vs p/q
- ❏ Run-id dependence for each matrix element (visualize corrections)
- ❏ TOF vs T0 width
- ❏ TOF vs RPC width
- ❏ TOF QA strip-by-strip run-by-run
- ❏ Why 2 GeV/c cut for time-shifts
- ❏ p_T-y distributions for negatively charged particles and for identified as pions


N_{hits}
0
1
2
3
4
5
6
6800
7000
7200
7400
7600
7800
8000
8200
run id


χ²/NDF
1.4
1.2
1
0.8
0.6
0.4
0.2
0
6800
7000
7200
7400
7600
7800
8000
8200
run id


N_p
0
1
2
3
4
5
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7
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7200
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7800
8000
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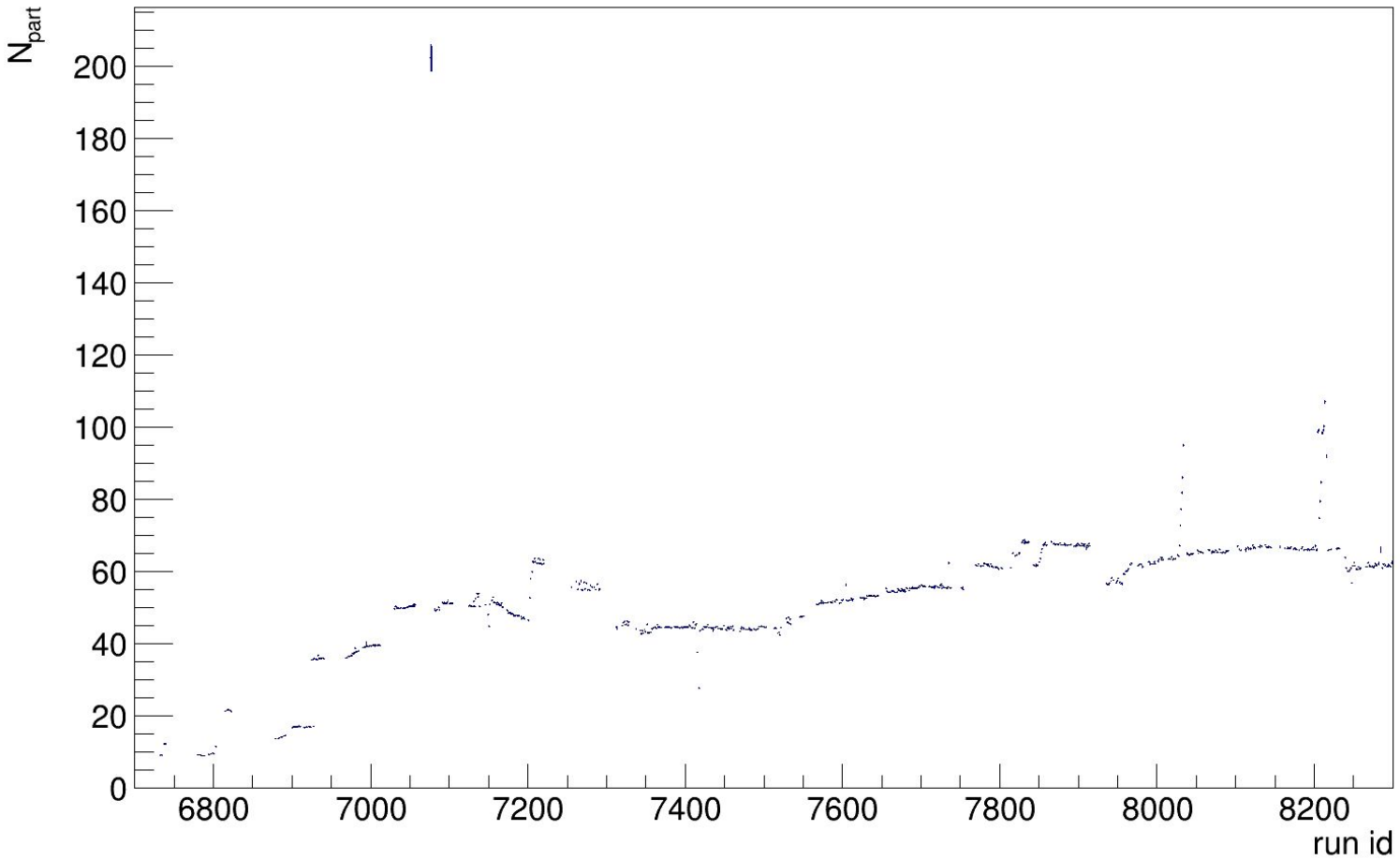
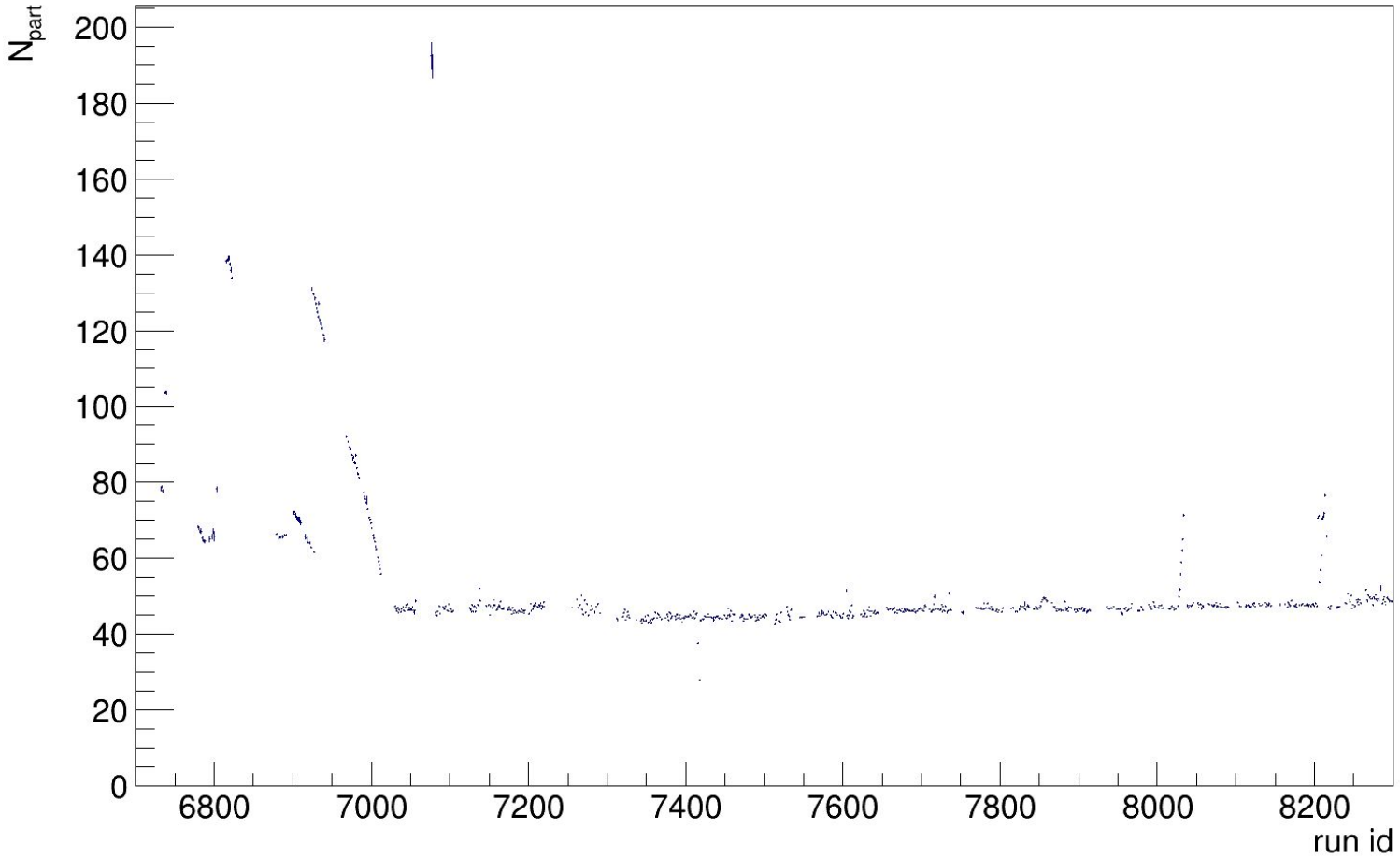
run id

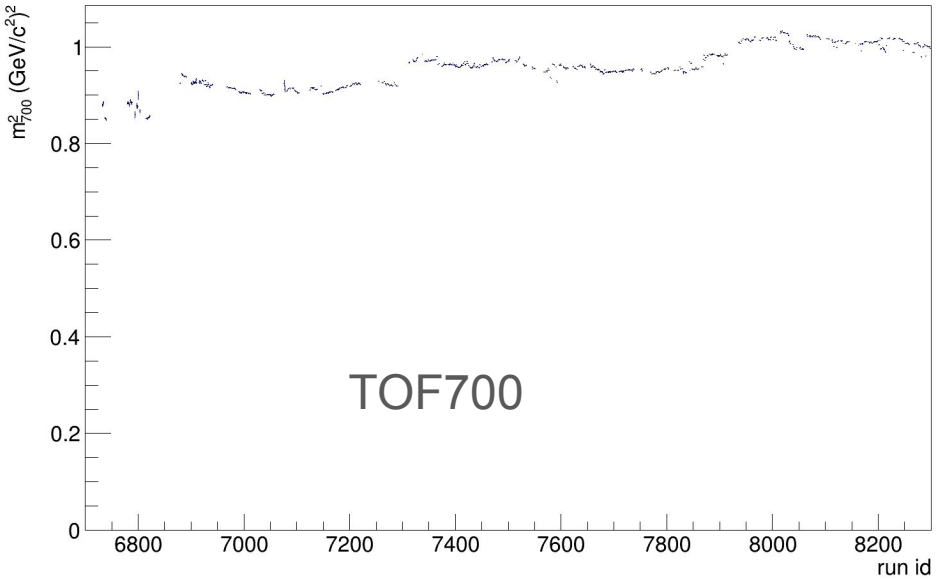
Charged particles multiplicity vs run-id

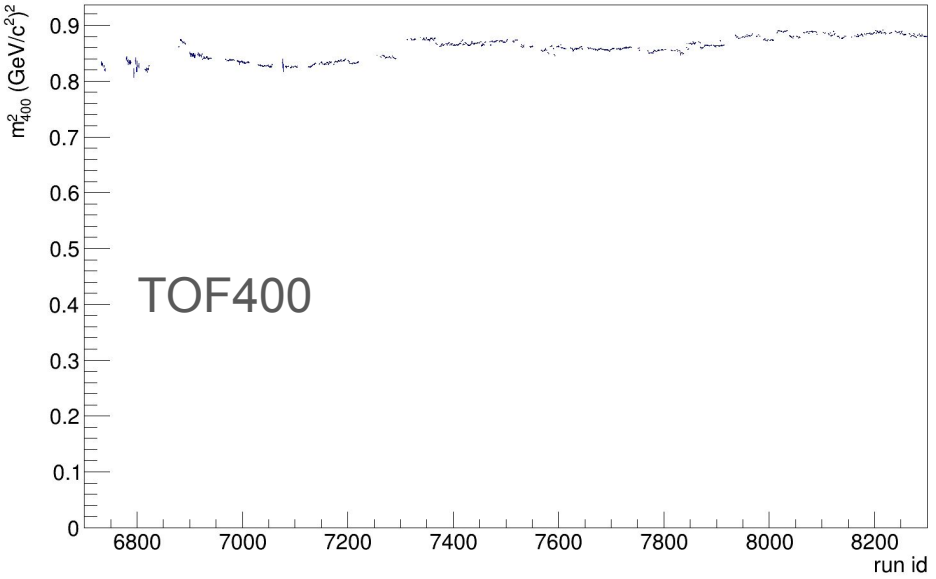


Normalized multiplicity

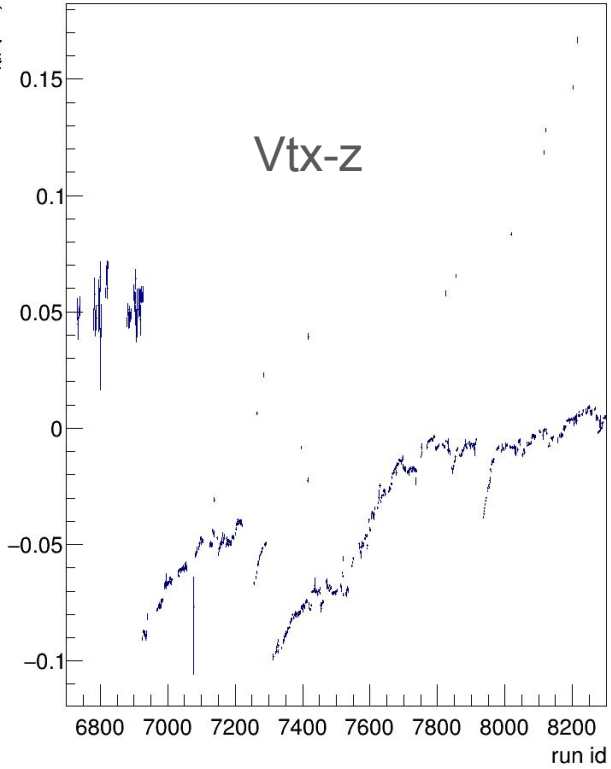


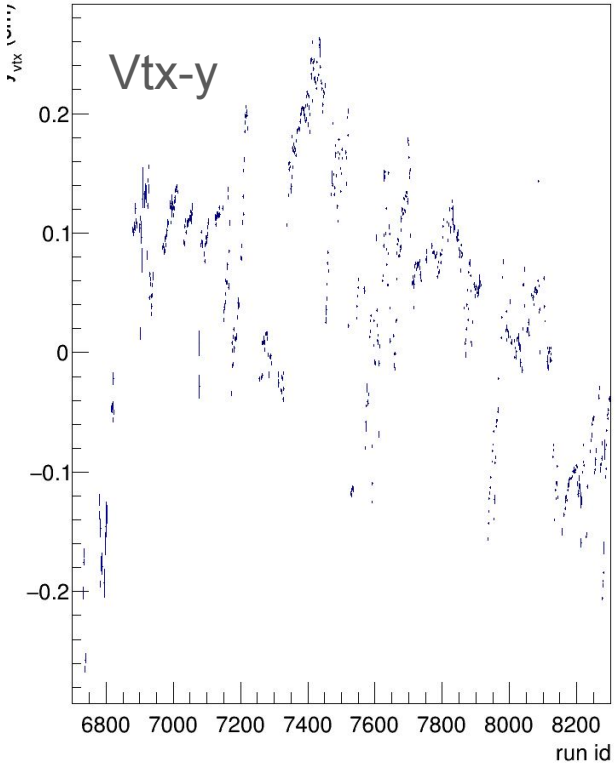
Squared mass of protons with TOF400 and TOF700

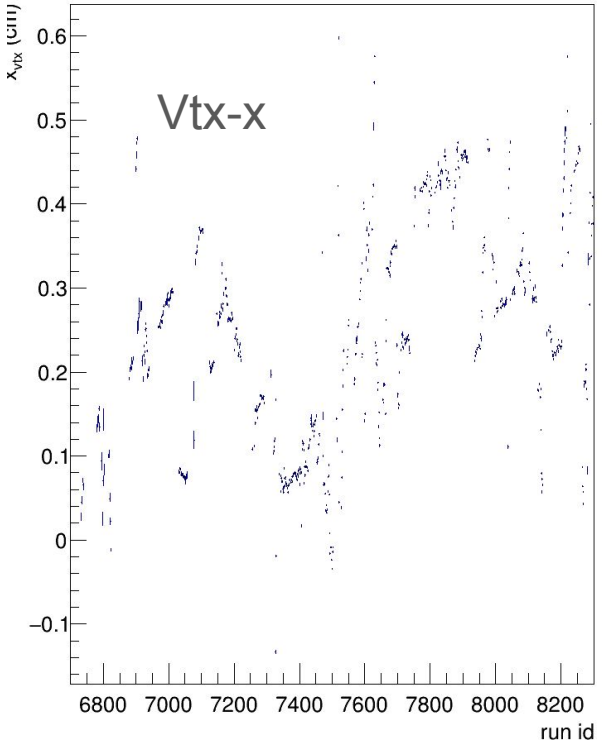




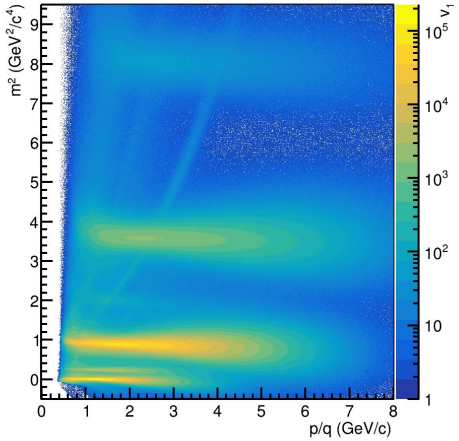
Vertex position



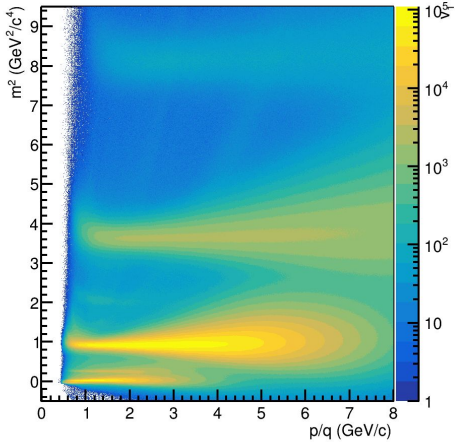




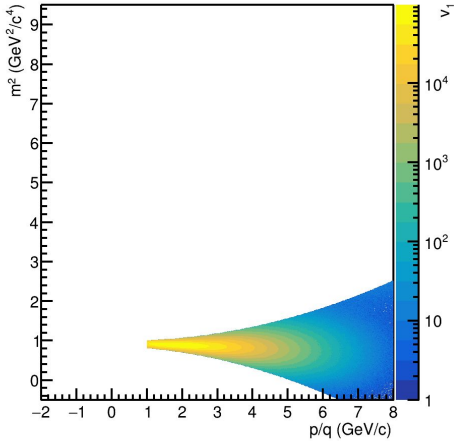
TOF-400



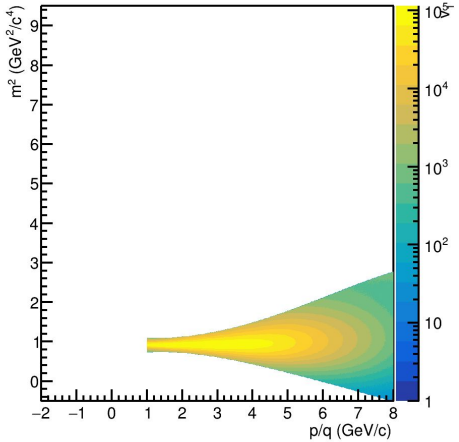
TOF-700



TOF-400



TOF-700



New FHCal-subevents layout

$$A(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{m=1}^{\infty}(c_m \cos m\varphi + s_m \sin m\varphi)\right]$$

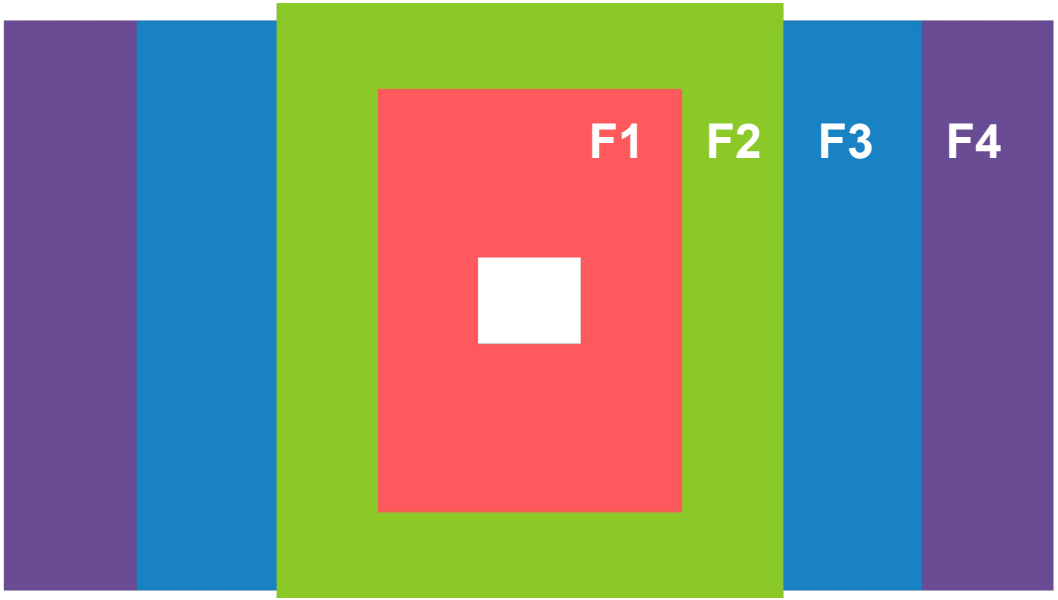
Acceptance function acts as a weight A(φ) u_n and the measured vector x is:

$$x = Mu + c$$

$$u = [x_1, y_1, x_2, y_2]^T$$

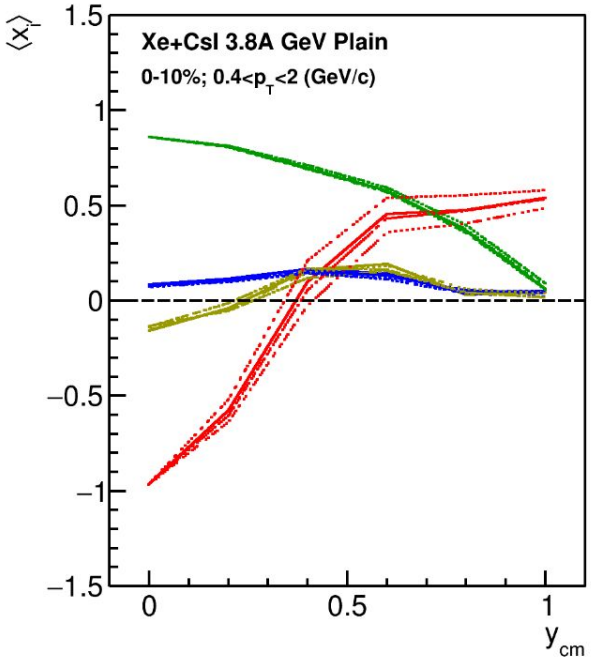
$$c = [c_1, s_1, c_2, s_2]^T$$

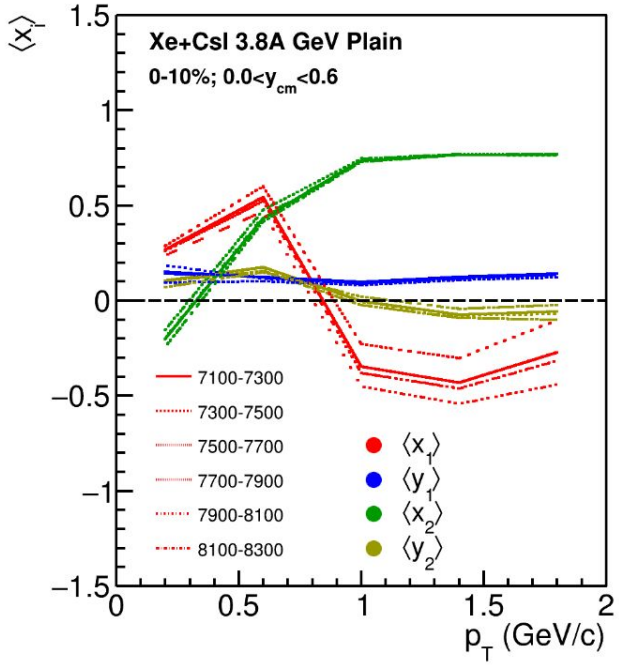
$$M = \begin{bmatrix} 1+c_2 & s_2 & c_1+c_3 & s_1+s_3 \\ s_2 & 1-c_2 & s_3-s_1 & c_1-c_3 \\ c_1+c_3 & s_3-s_1 & 1+c_4 & s_4 \\ s_1+s_3 & c_1-c_3 & s_4 & 1-c_4 \end{bmatrix}$$

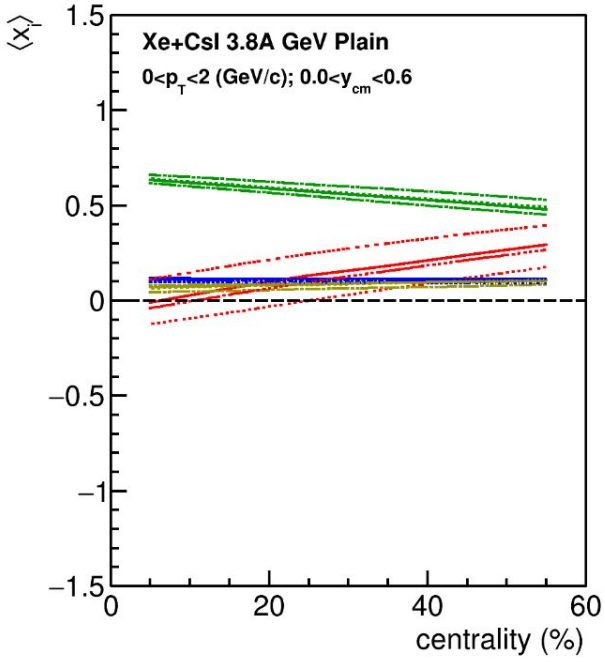


$$u = M^{-1}(x - c)$$

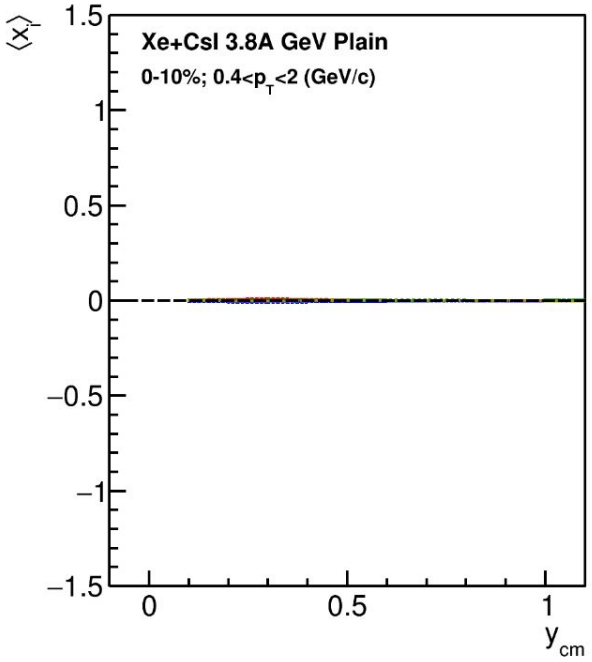
Acceptance Fourier-moments for protons

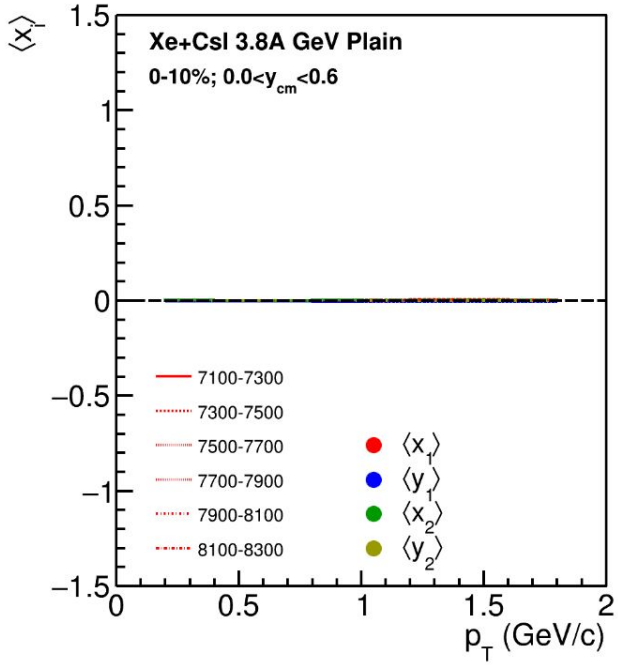


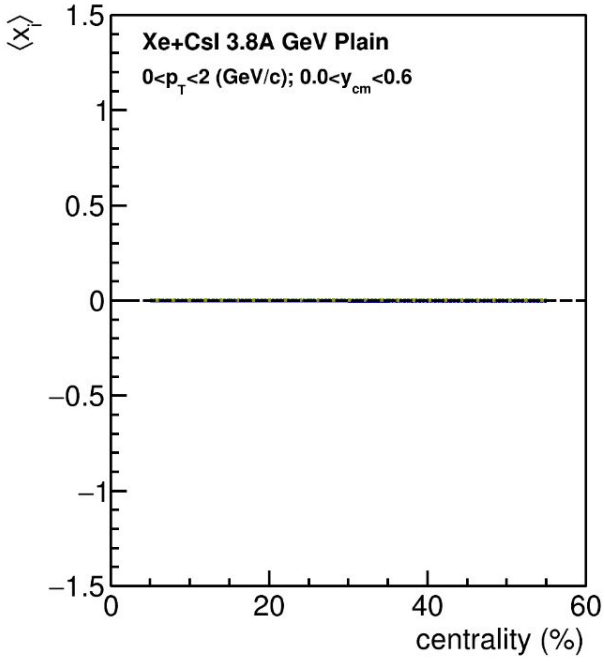




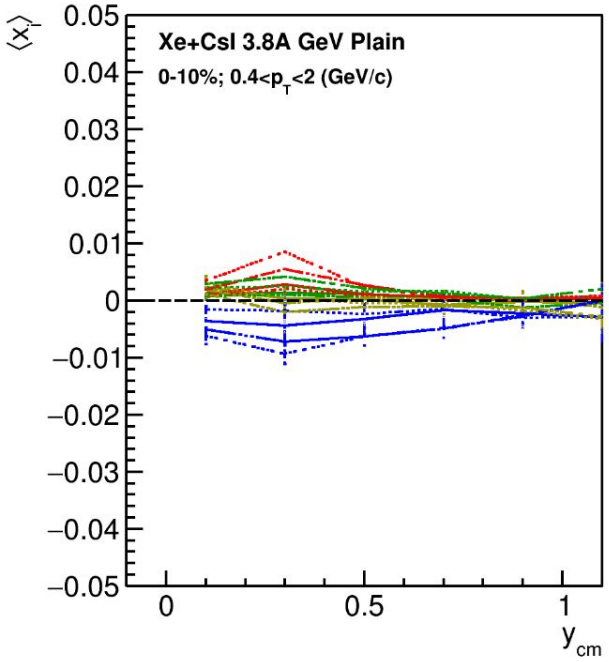
Acceptance Fourier-moments for protons (corrected)

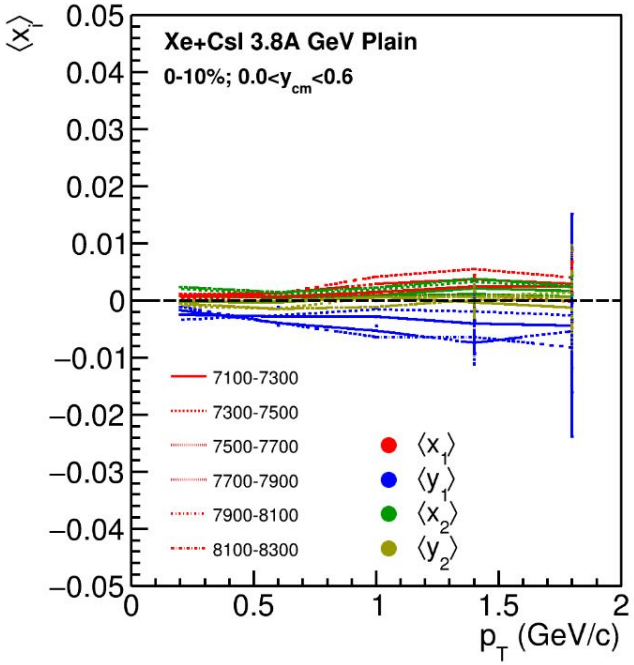


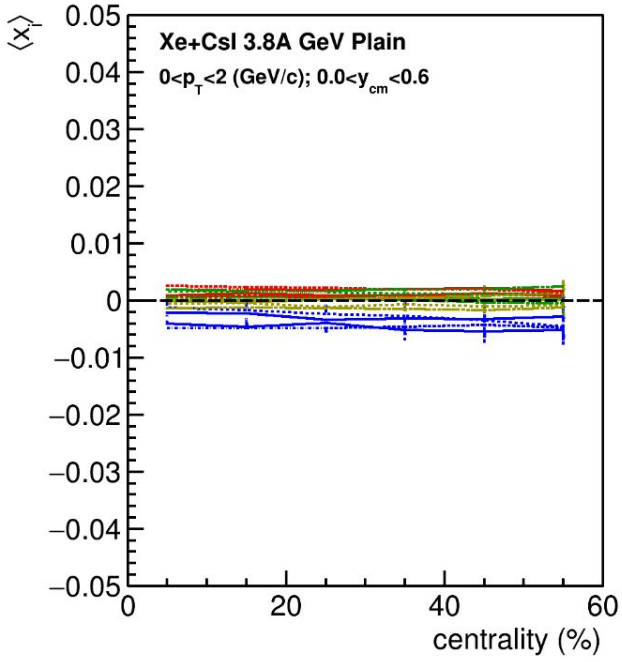




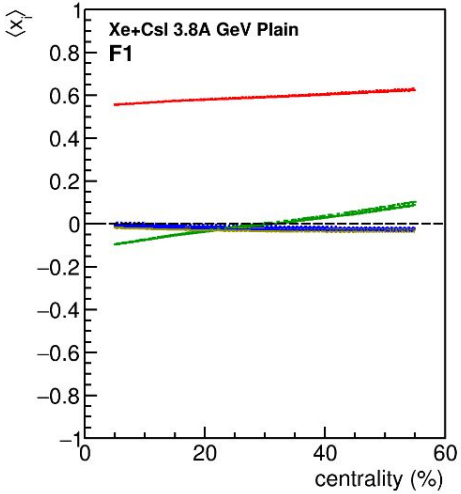
Acceptance Fourier-moments for protons (corrected & zoomed)

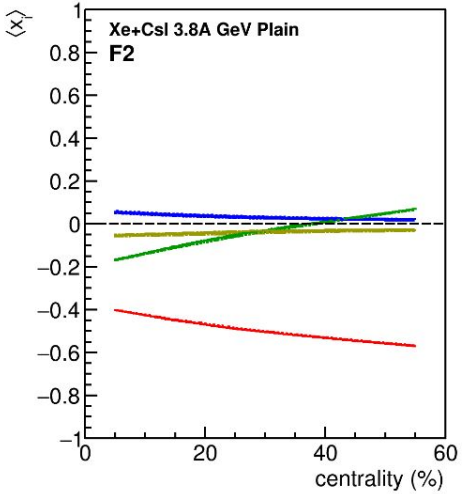


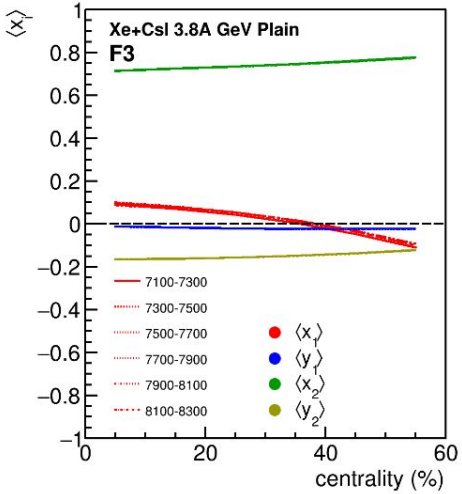


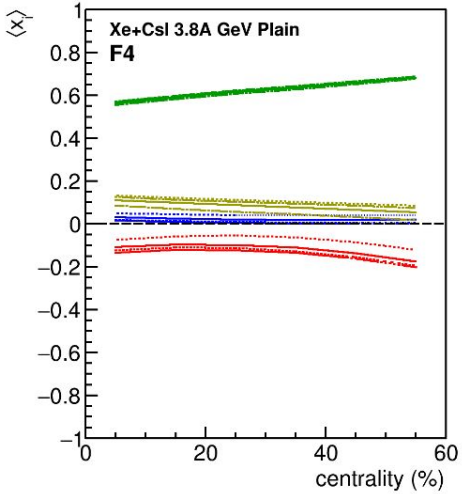


Acceptance Fourier-moments for FHCal

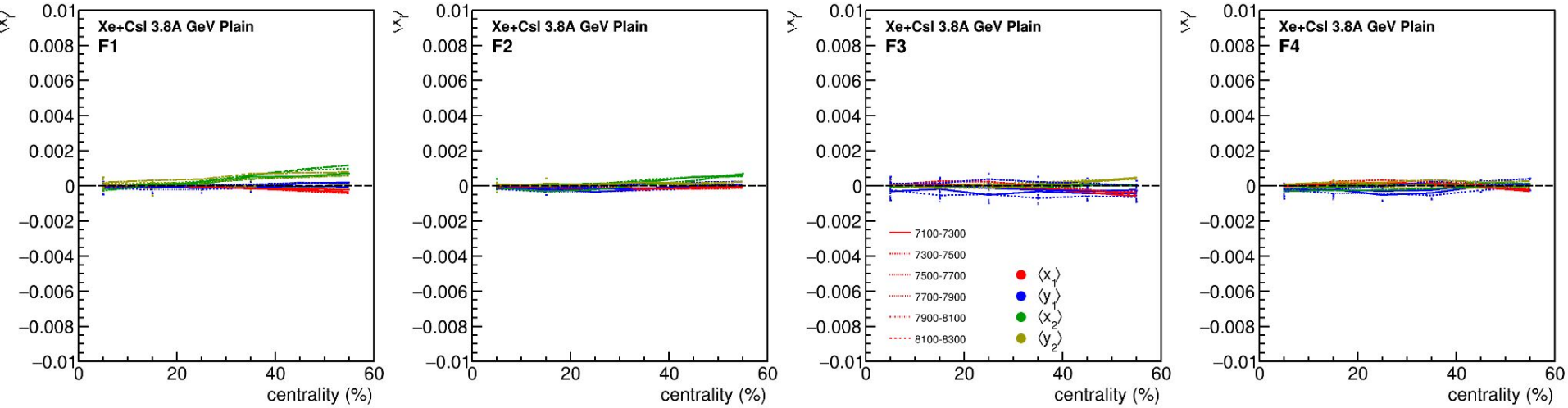




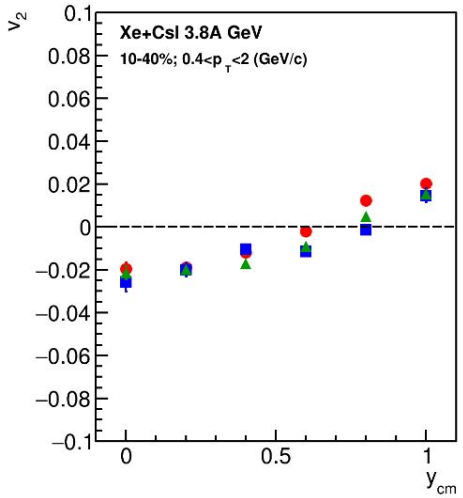


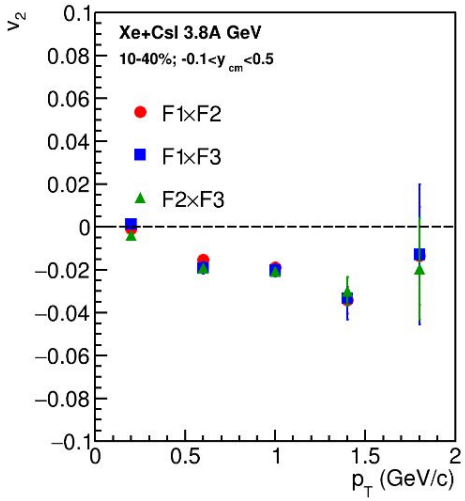


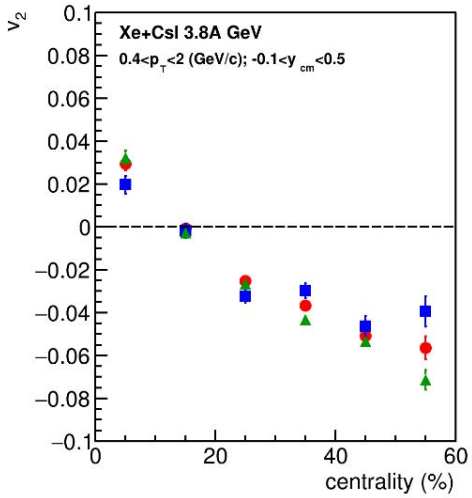
Acceptance Fourier-moments for FHCal

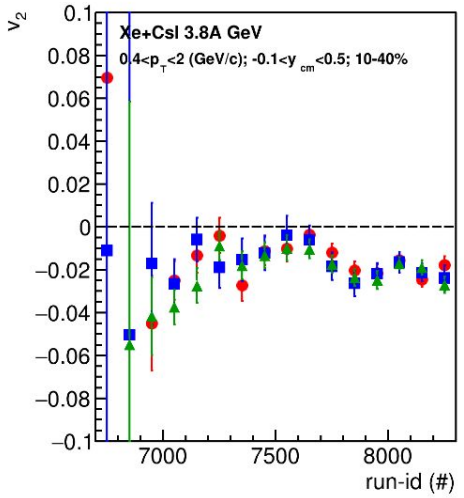


Result with only recentering applied

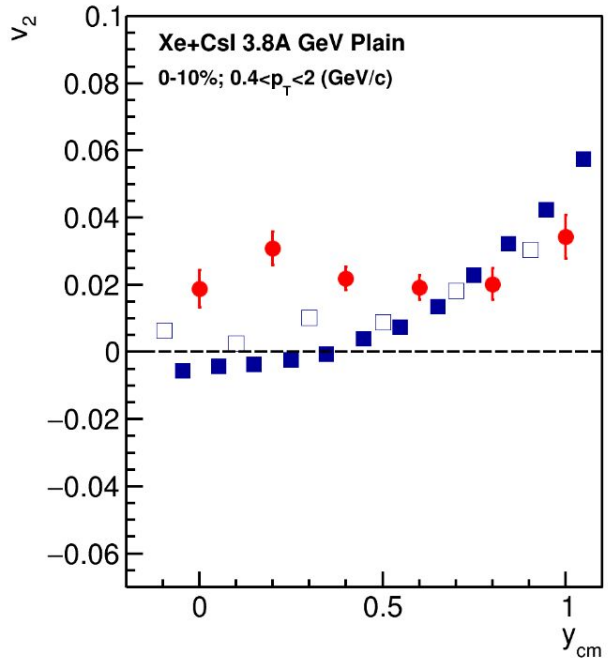


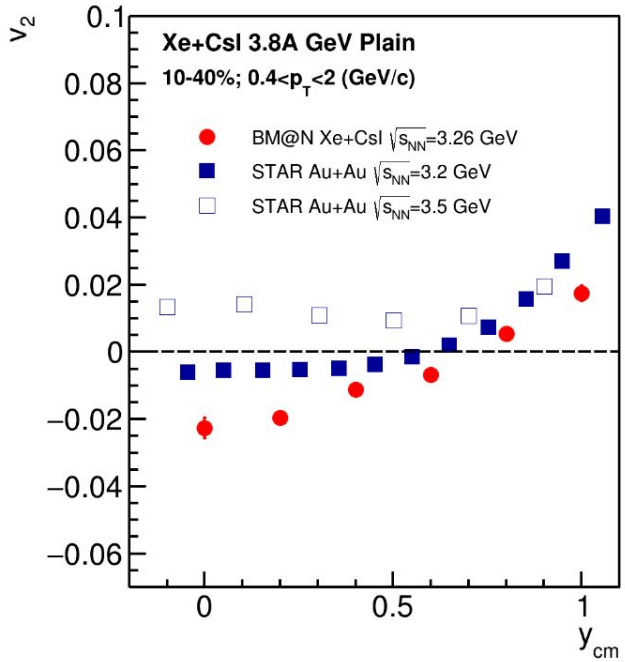


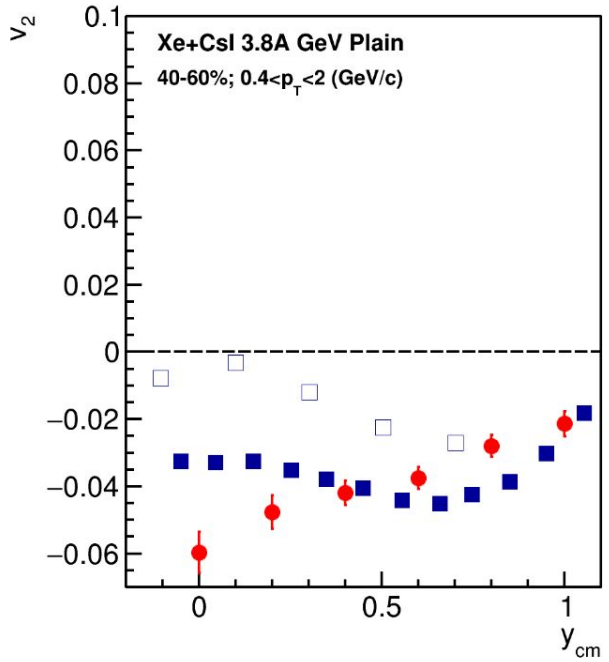




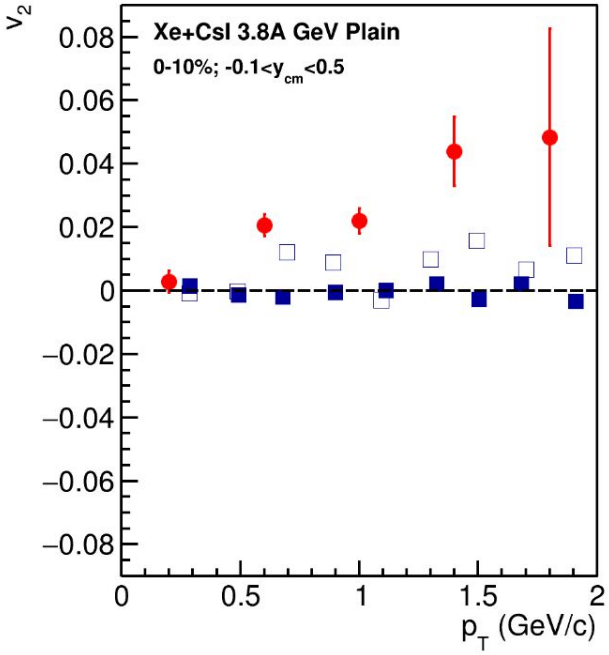
Result with only recentering applied: y-dep vs STAR

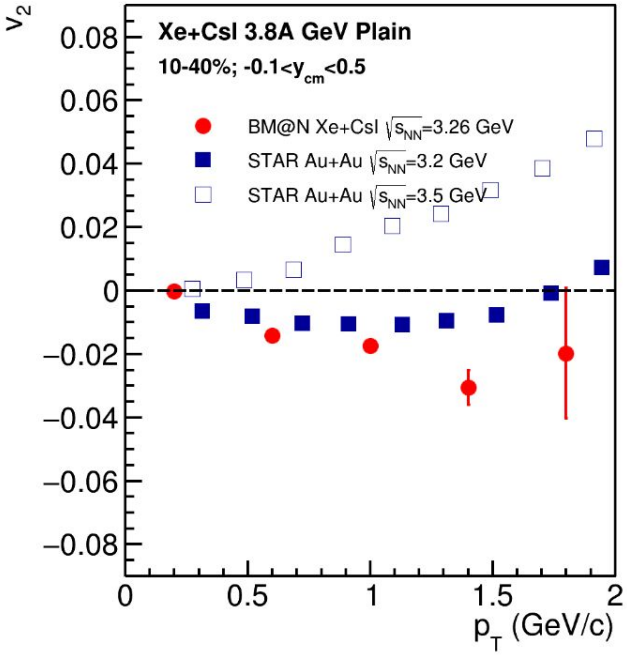


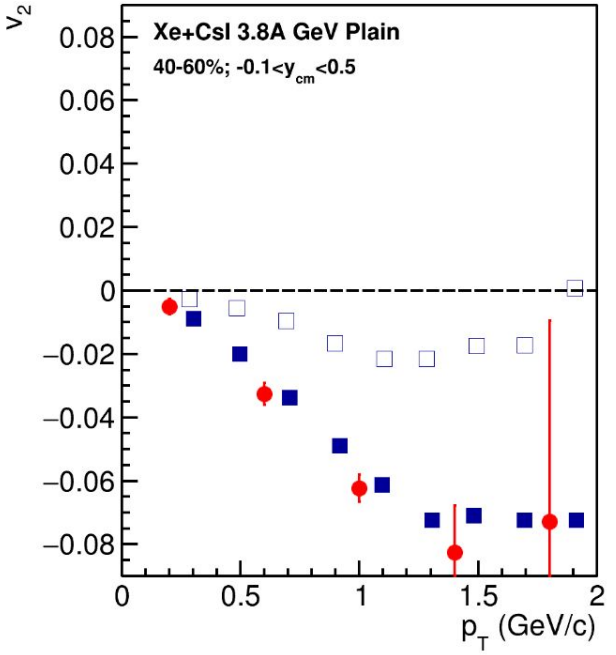




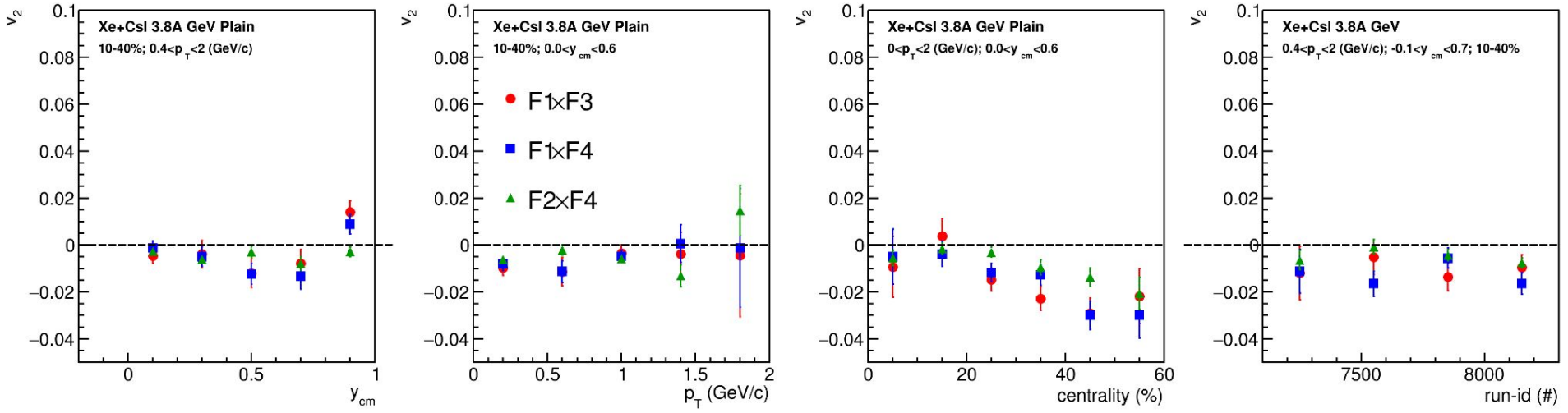
Result with only recentering applied: pT-dep vs STAR



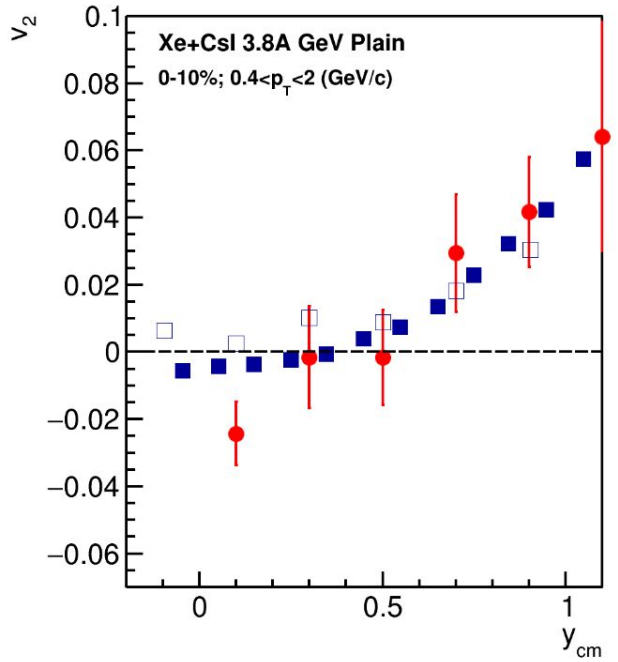


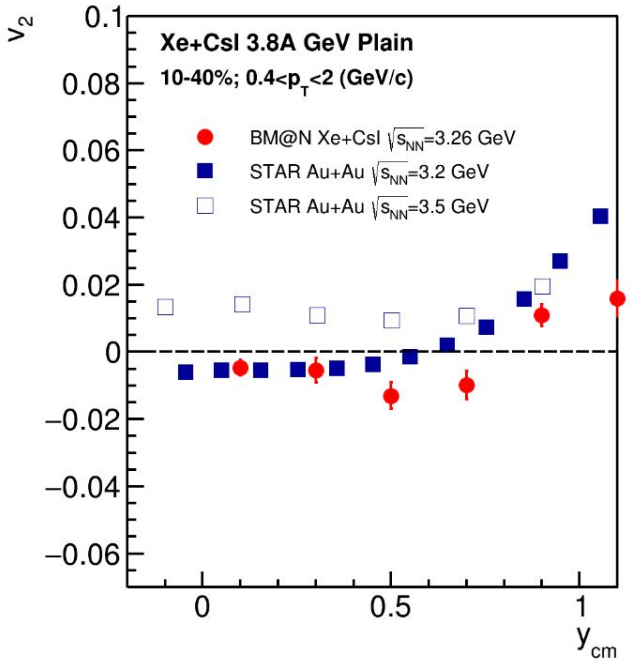


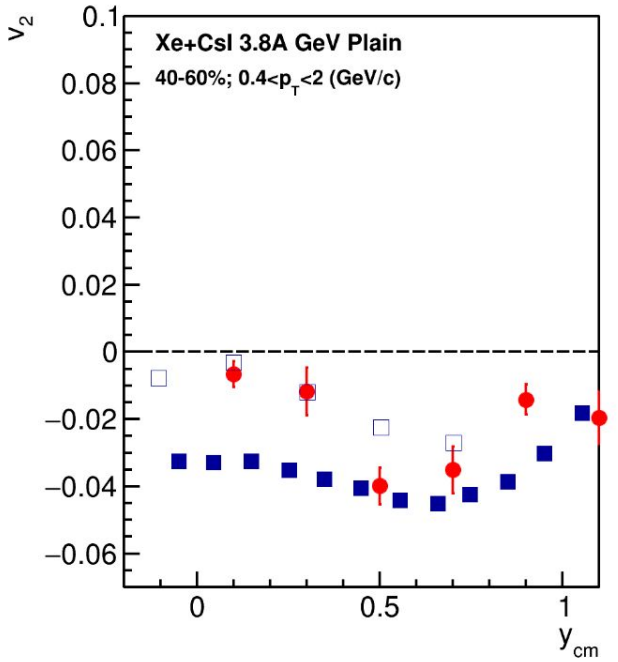
Result with decomposition applied



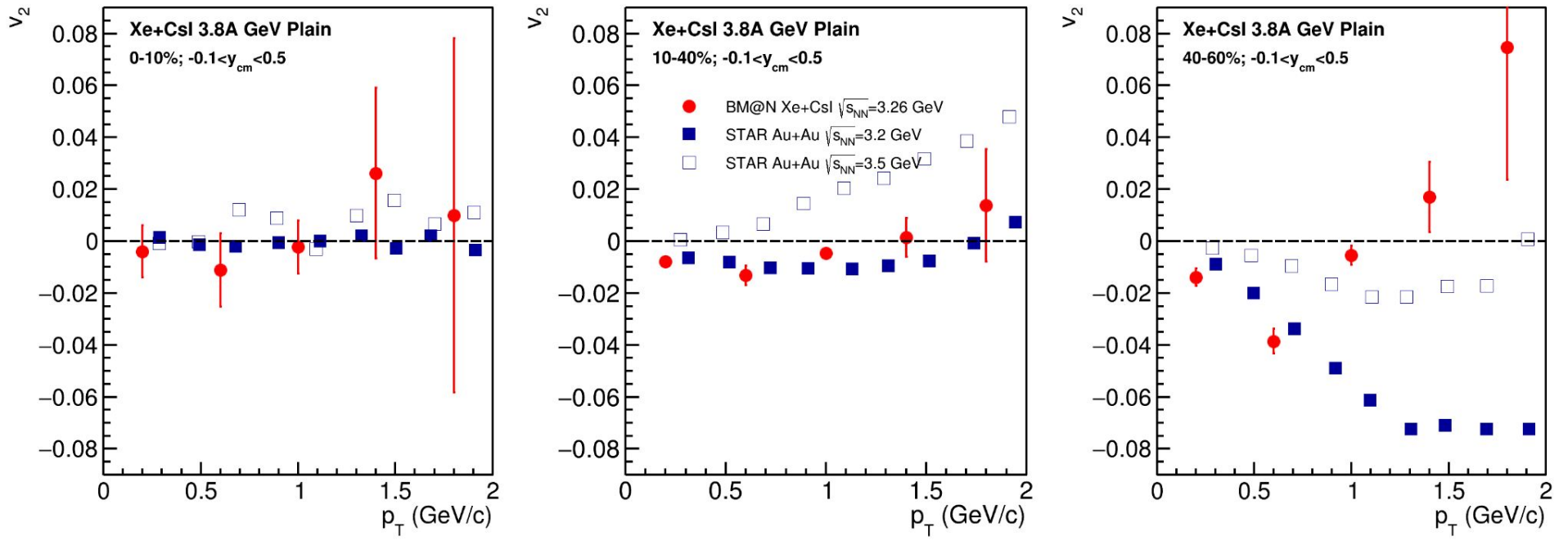
Result with full decomposition: y-dep vs STAR



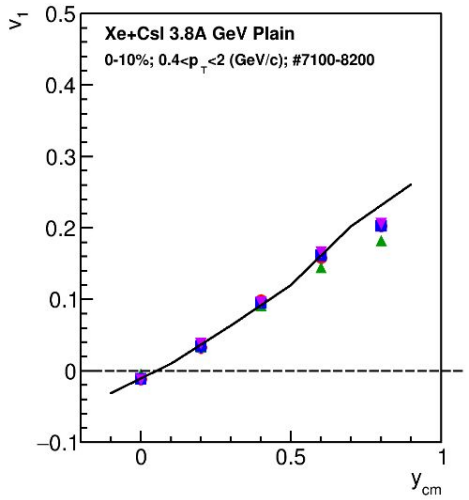


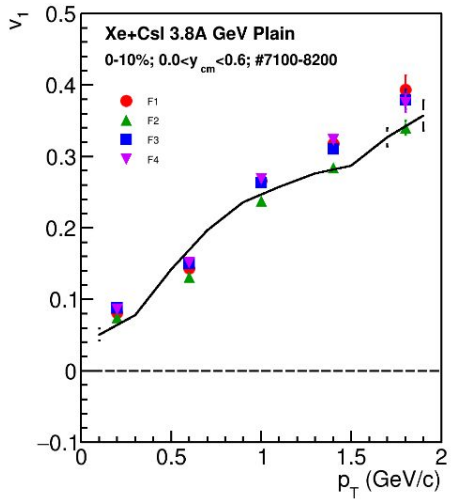


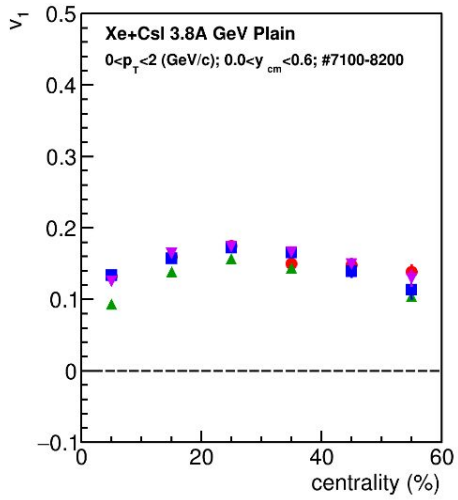
Result with full decomposition: pT-dep vs STAR

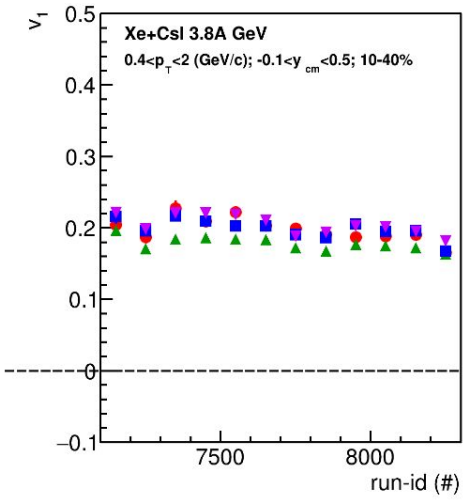


Additional check: comparison with v_1-preliminary



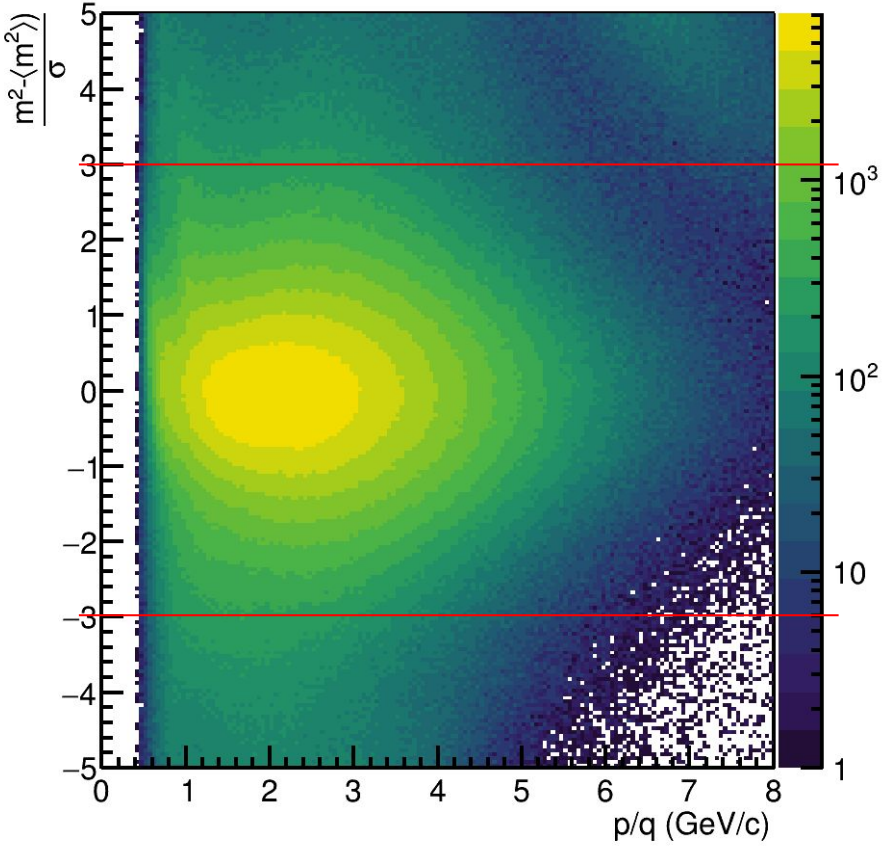




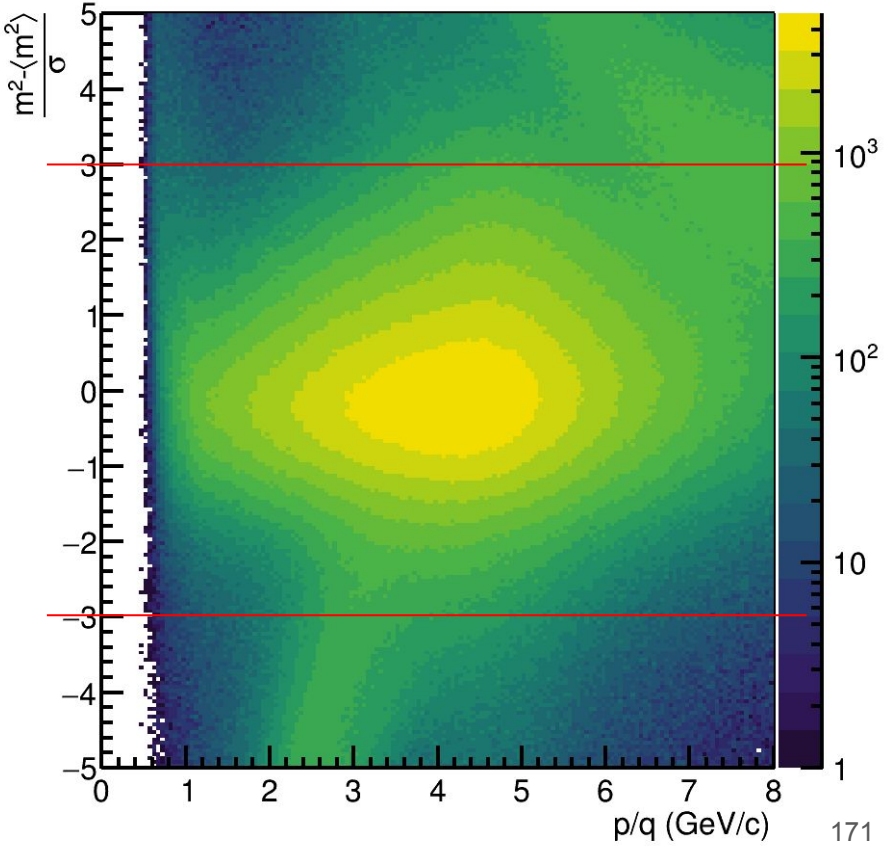


Proton N-sigma distributions

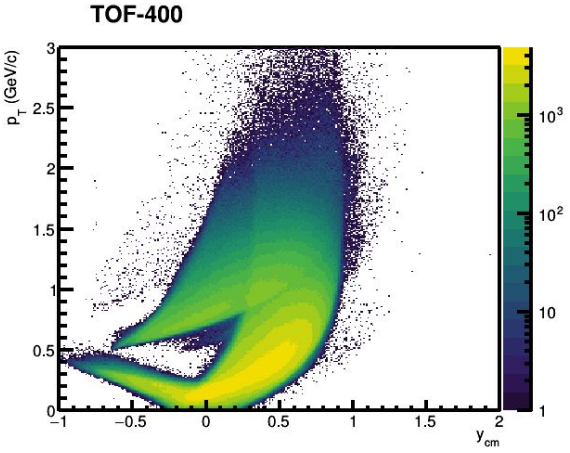
TOF-400

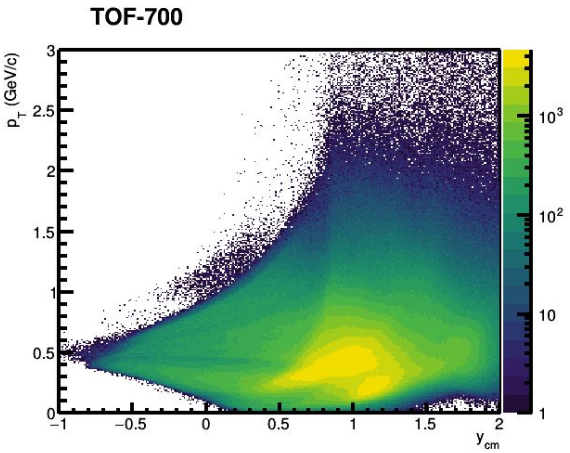


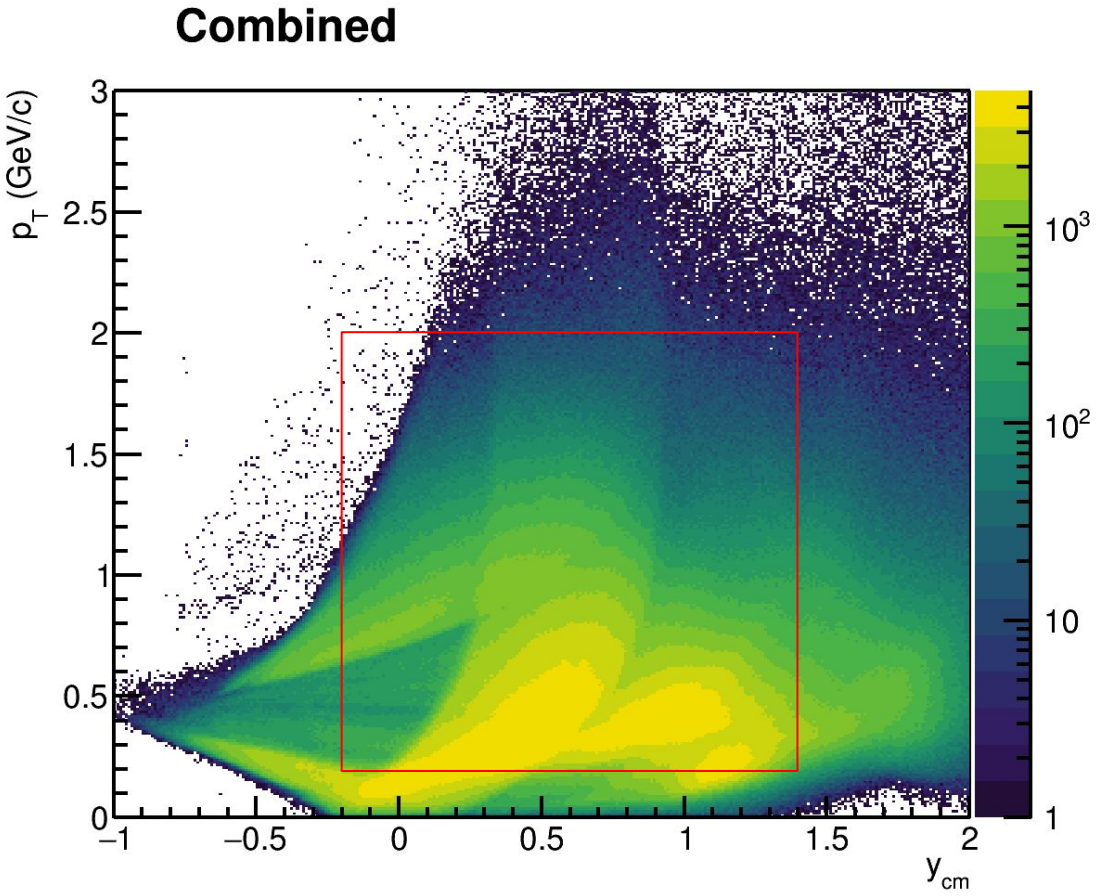
TOF-700



Proton p_T-y acceptance







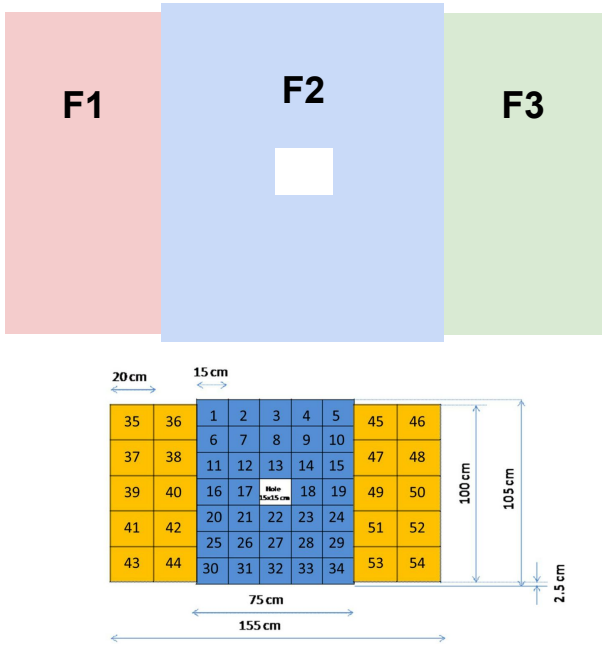
Further notations

In the case of azimuthal isotropy of detector acceptance and no magnetic field:

$$\langle x_2 \rangle = 0 \quad \langle Y_1 \rangle = 0$$

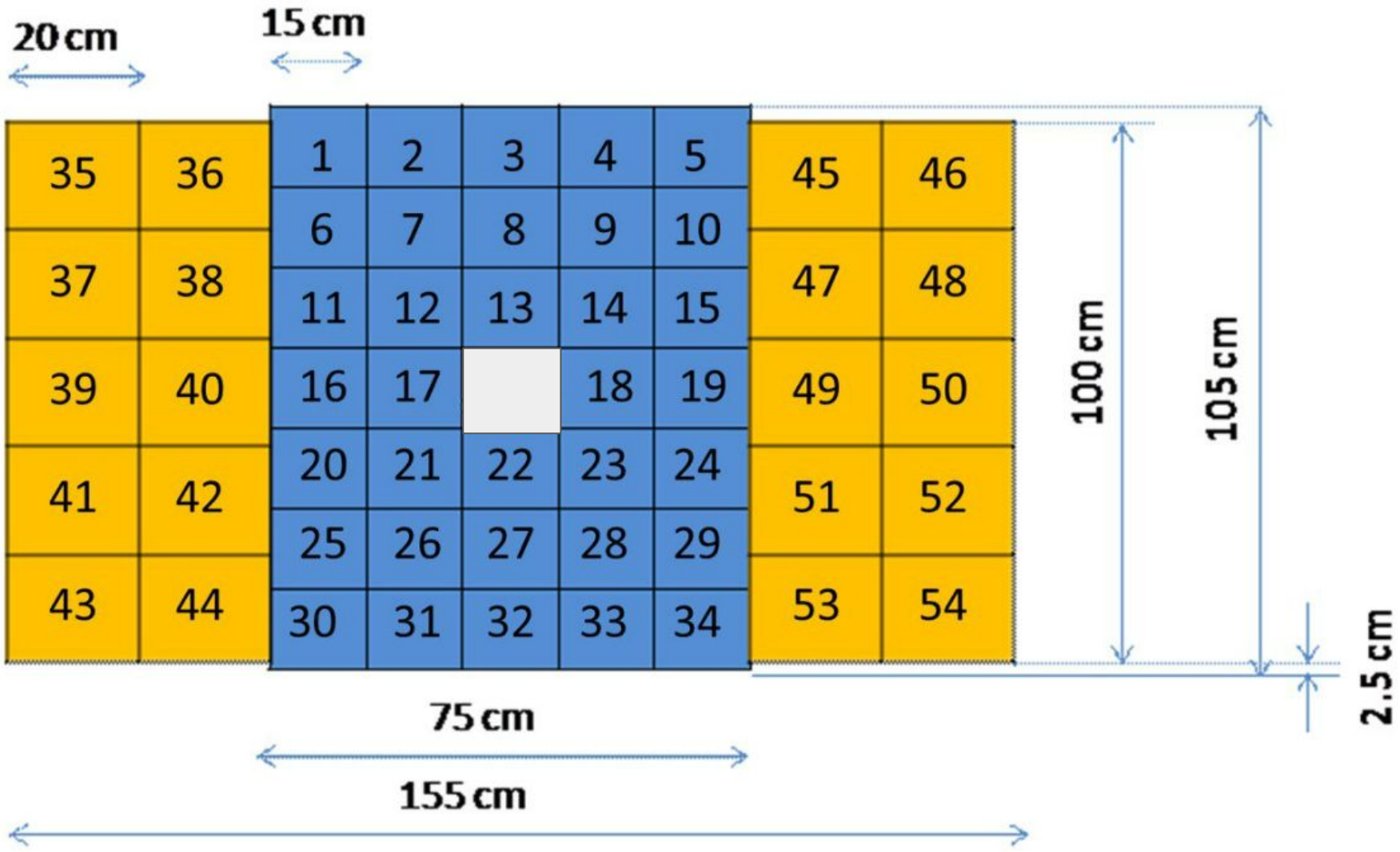
$$v_2 = 2\frac{\langle x_2 Y_1^a Y_1^b \rangle}{\langle Y_1^a Y_1^b \rangle}$$

v_2 is the resolution-corrected cumulant of u_2 and two Q_1-vectors



$$cum(x_2, Y_1^a, Y_1^b) = \langle x_2 Y_1^a Y_1^b \rangle - \langle x_2 \rangle \langle Y_1^a Y_1^b \rangle - \langle x_2 Y_1^a \rangle \langle Y_1^b \rangle - \langle x_2 Y_1^b \rangle \langle Y_1^a \rangle + 2\langle x_2 \rangle \langle Y_1^a \rangle \langle Y_1^b \rangle$$

$$v_2 = 2\frac{cum(x_2, Y_1^a, Y_1^b)}{\langle Y_1^a Y_1^b \rangle}$$


20 cm
15 cm
35
36
37
38
39
40
41
42
43
44
1
2
3
4
5
6
7
8
9
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11
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26
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28
29
30
31
32
33
34
45
46
47
48
49
50
51
52
53
54
100 cm
105 cm
2,5 cm
75 cm
155 cm

New FHCal-subevents layout

$$A(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{m=1}^{\infty}(c_m \cos m\varphi + s_m \sin m\varphi)\right]$$

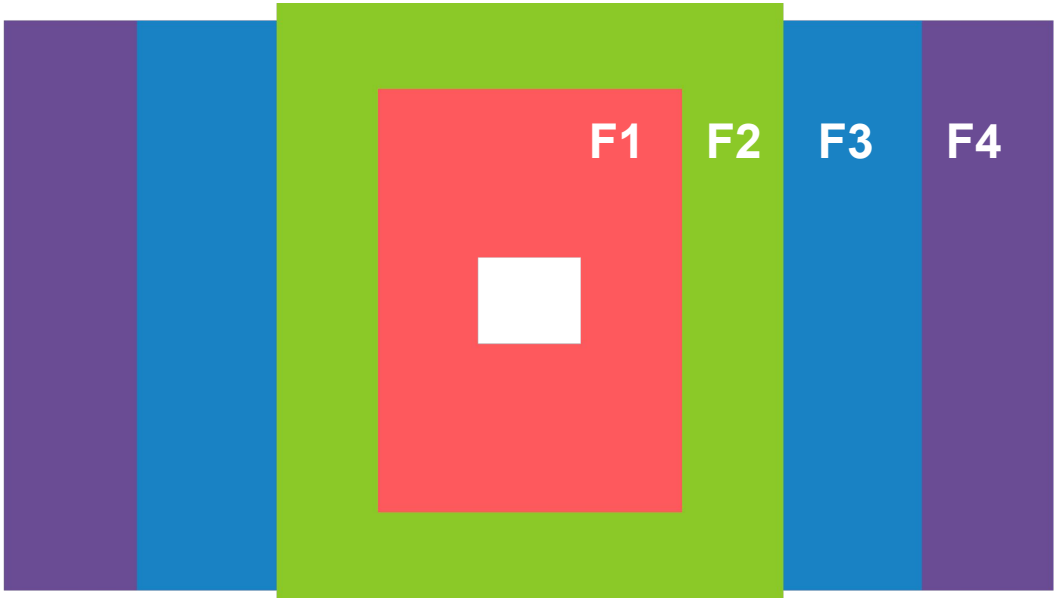
Acceptance function acts as a weight A(φ) u_n and the measured vector x is:

$$x = Mu + c$$

$$u = [x_1, y_1, x_2, y_2]^T$$

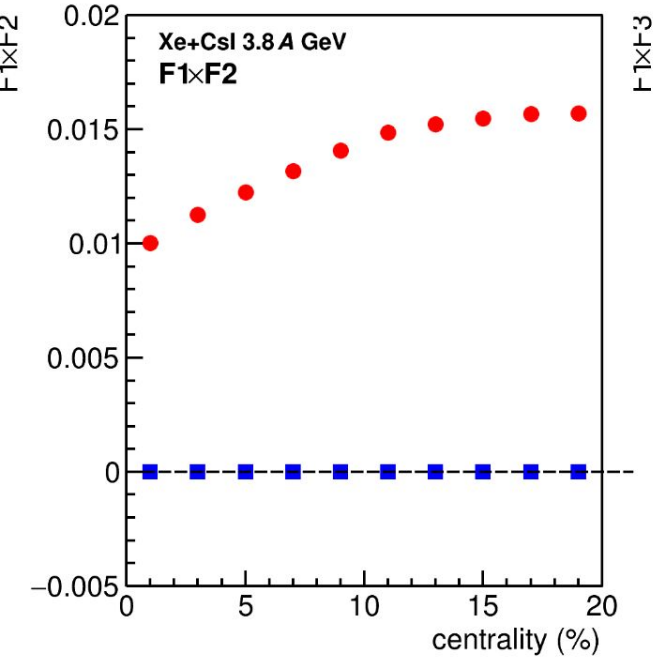
$$c = [c_1, s_1, c_2, s_2]^T$$

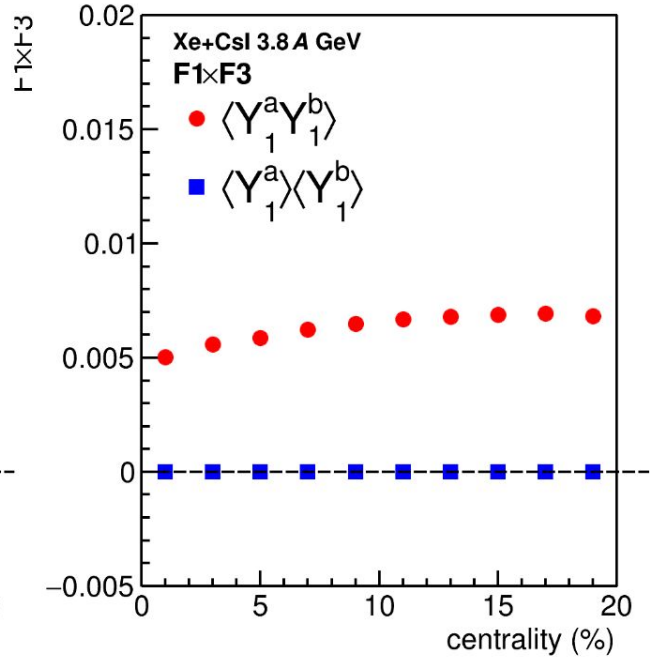
$$M = \begin{bmatrix} 1+c_2 & s_2 & c_1+c_3 & s_1+s_3 \\ s_2 & 1-c_2 & s_3-s_1 & c_1-c_3 \\ c_1+c_3 & s_3-s_1 & 1+c_4 & s_4 \\ s_1+s_3 & c_1-c_3 & s_4 & 1-c_4 \end{bmatrix}$$

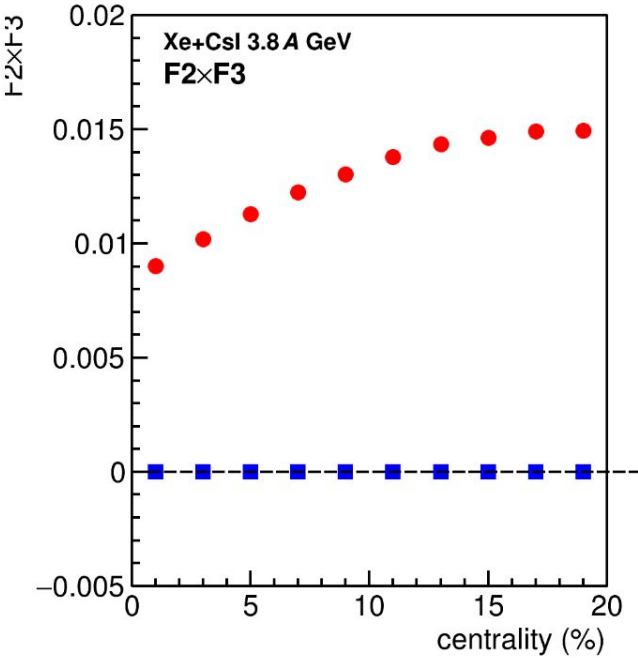


$$u = M^{-1}(x - c)$$

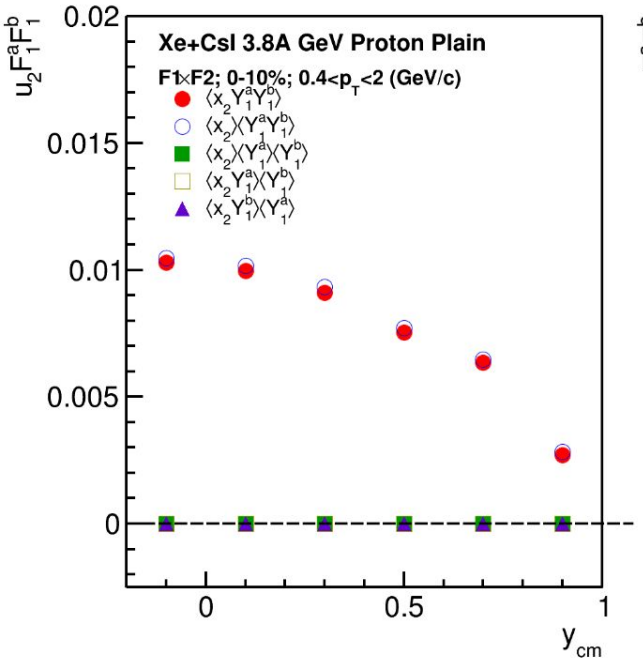
Correlation of recentered Q_1-vectors from FHCal

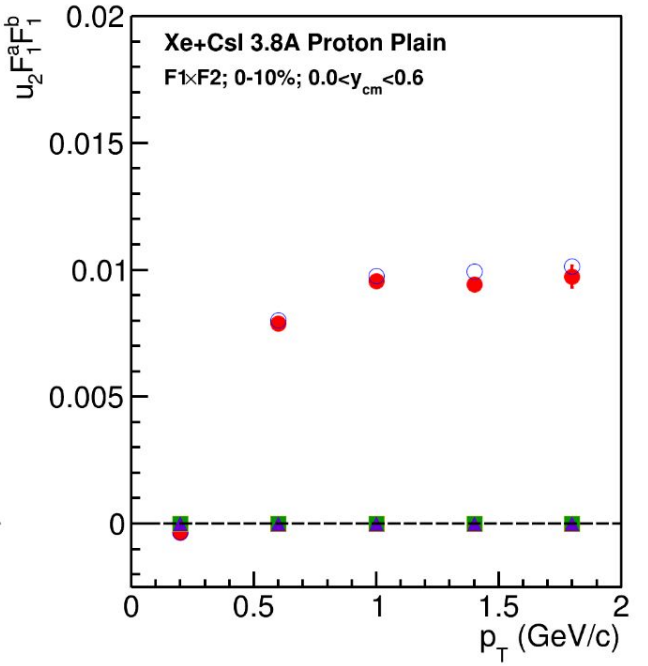


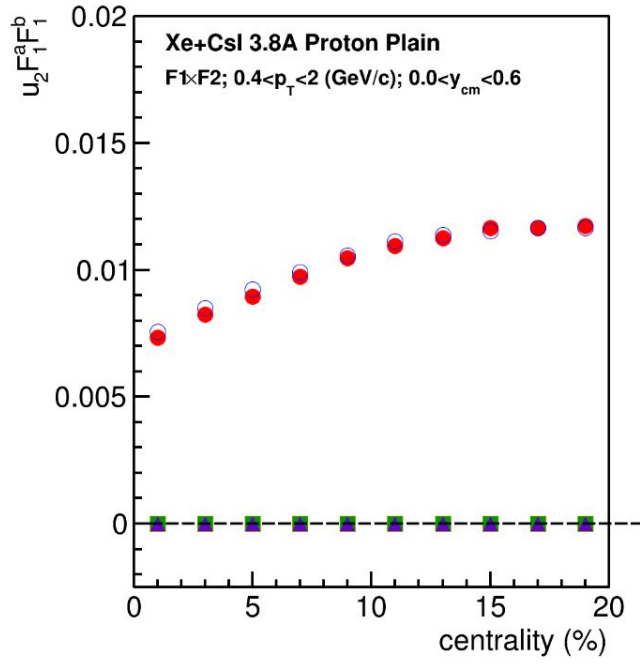




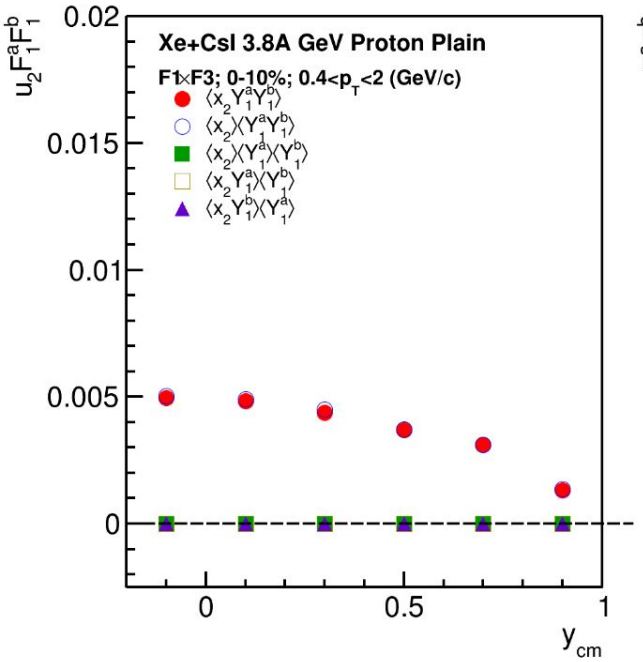
Plain protons with recentered F1 and F2

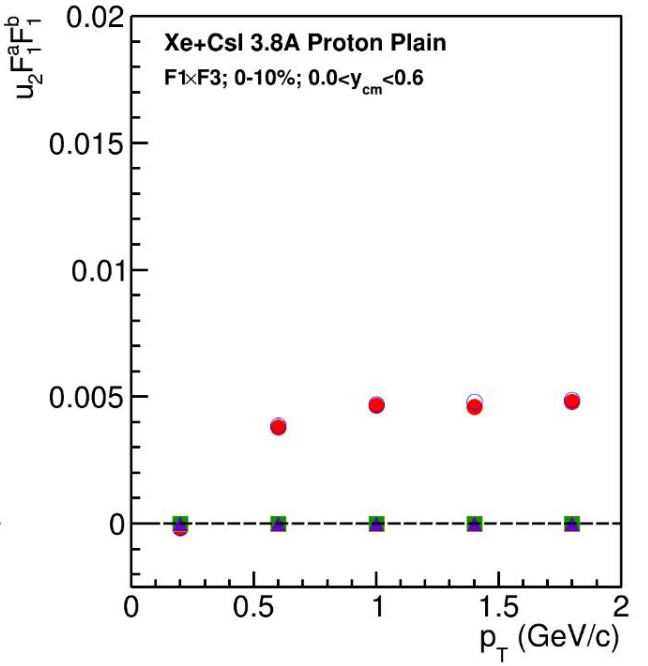


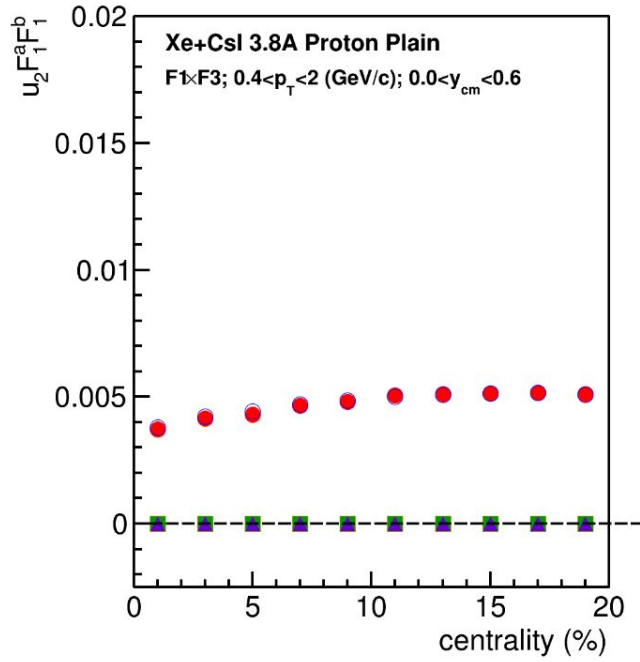




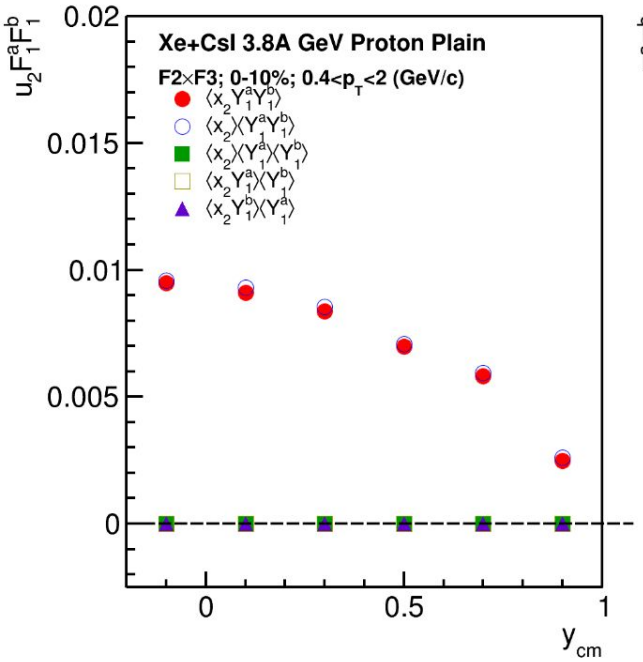
Plain protons with recentered F1 and F3

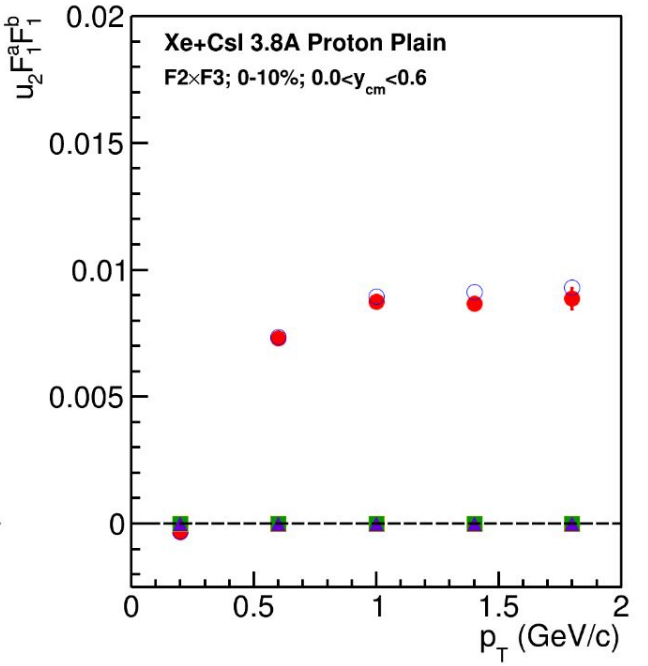


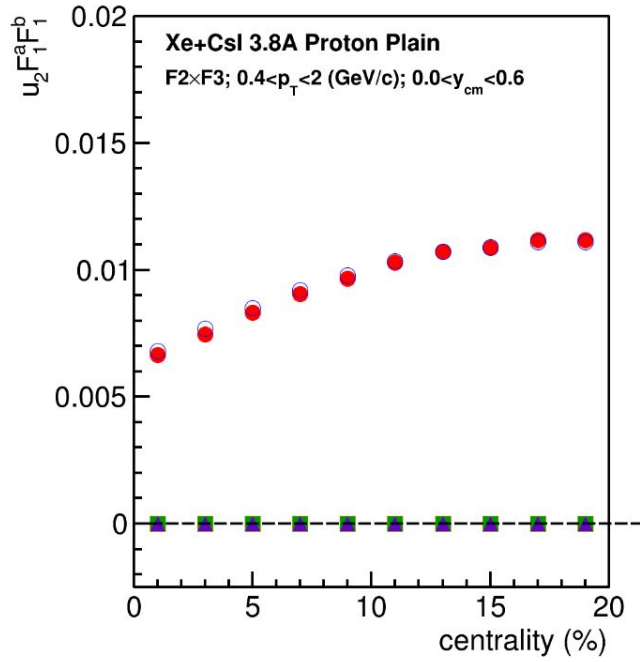




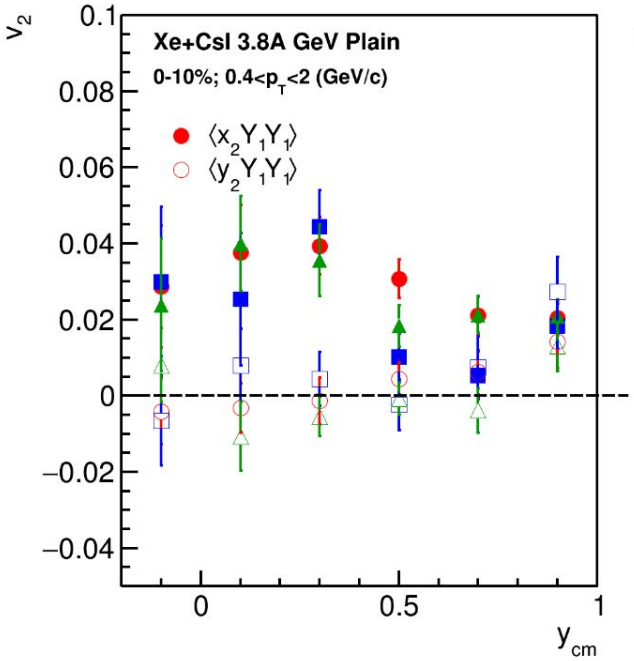
Plain protons with recentered F2 and F3

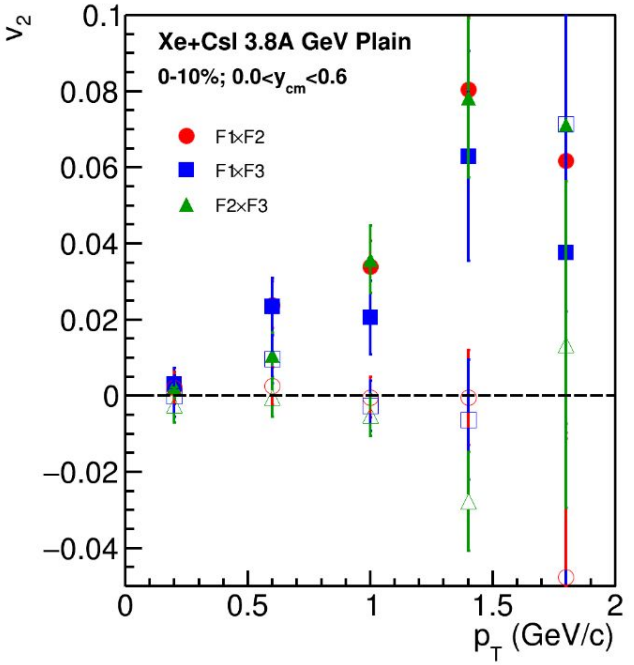


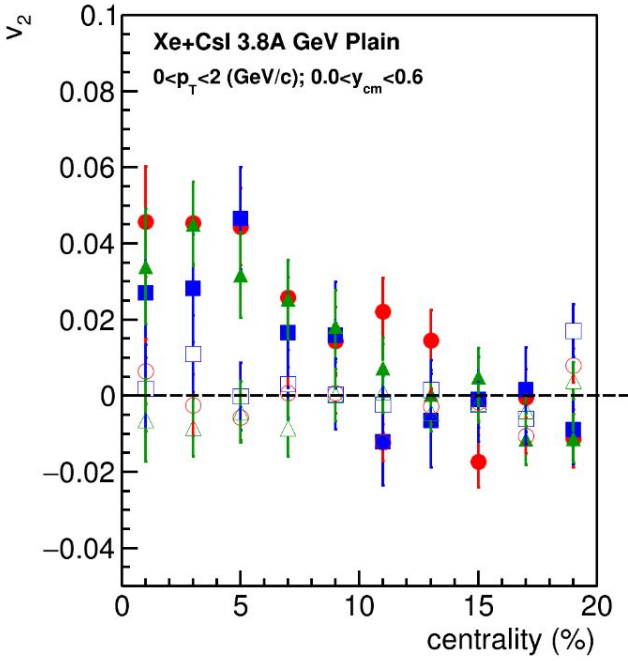




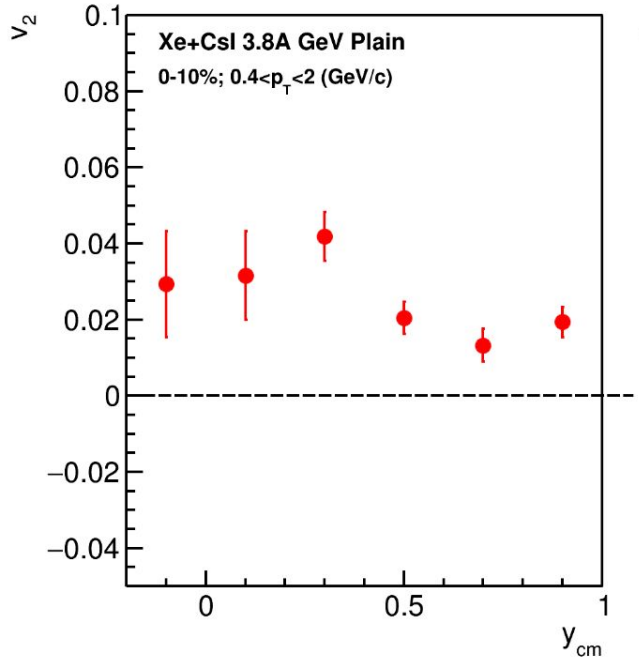
Plain proton v_2 wrt different symmetry planes

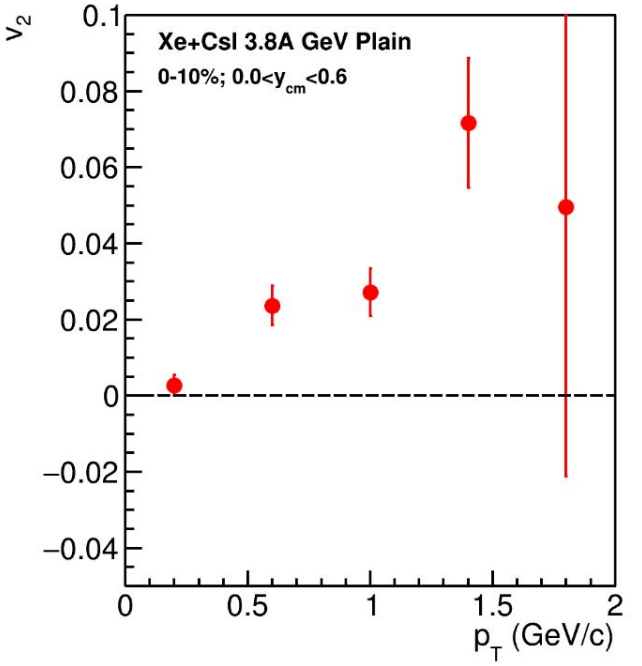


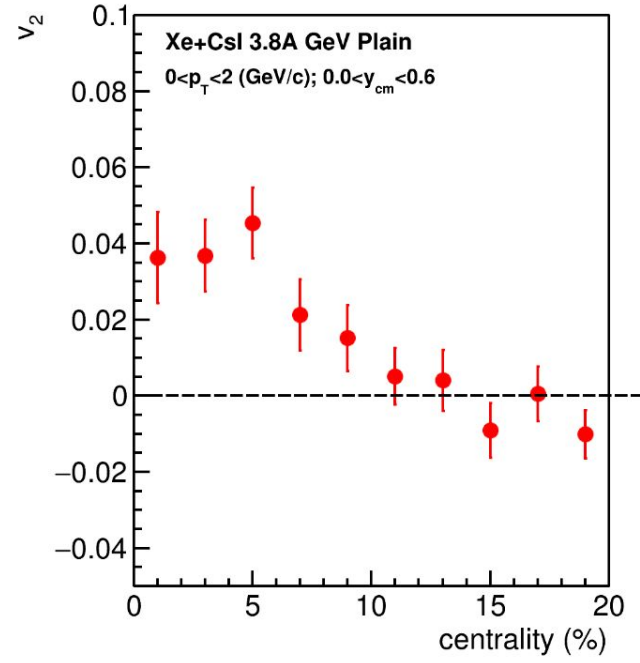




Plain protons with plain F2 and F3

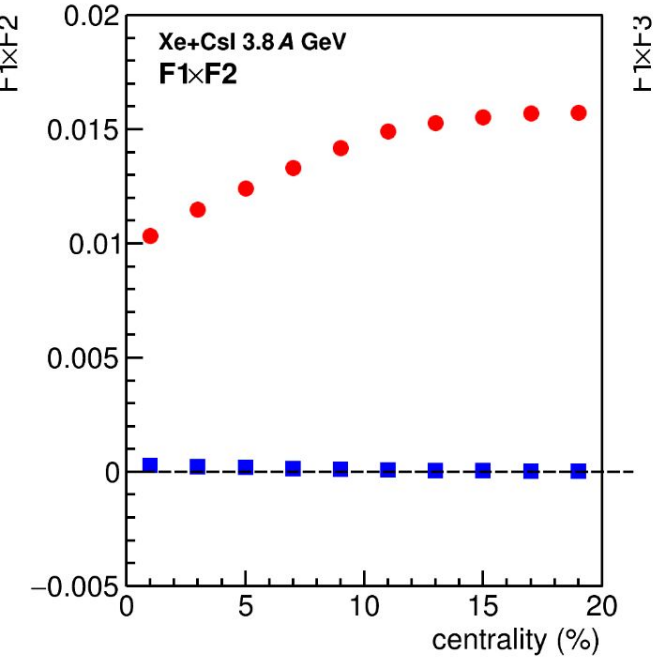


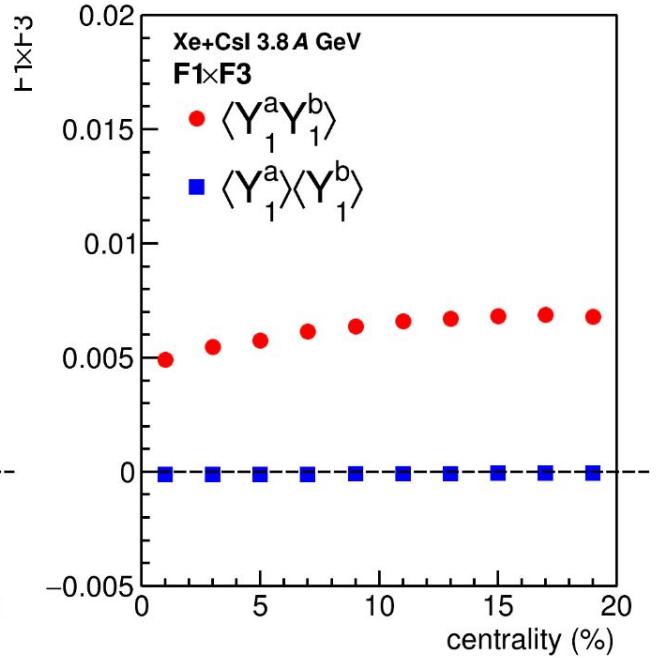


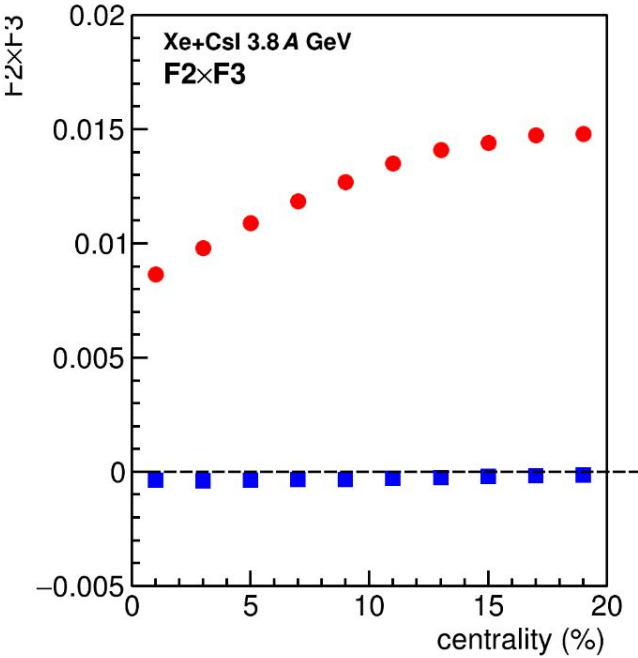


Plain Q1-vectors

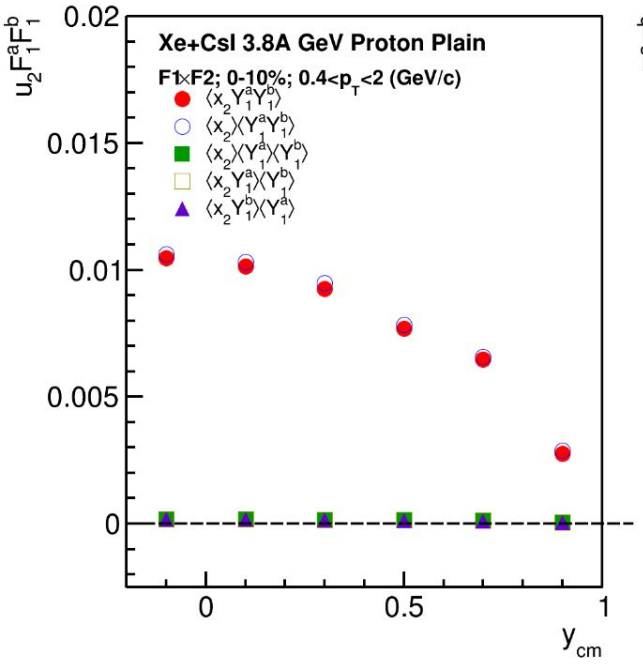
Correlation of plain Q_1-vectors from FHCal

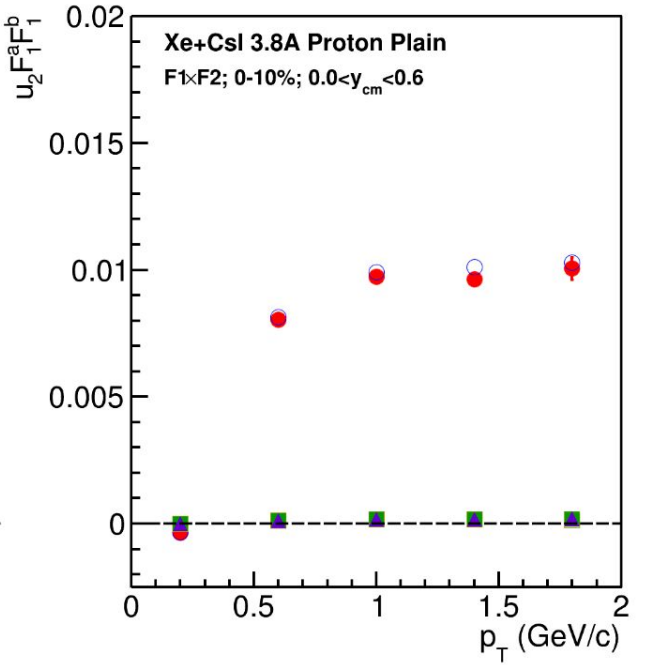


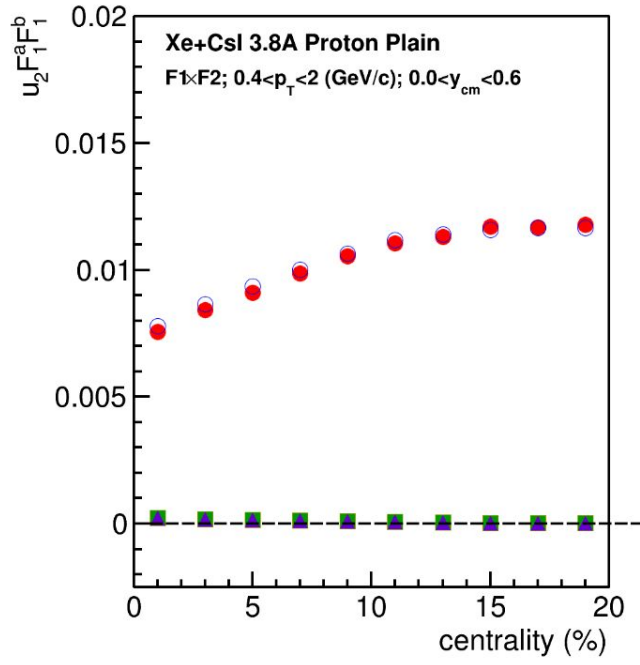




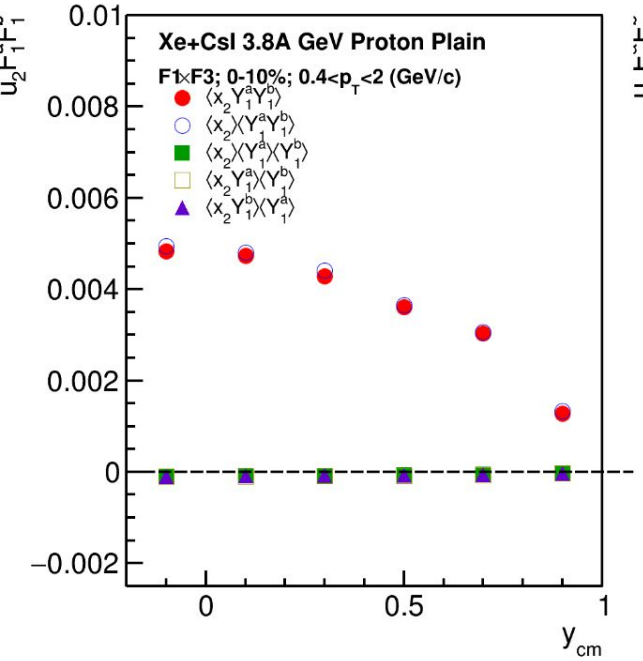
Plain protons with plain F1 and F2

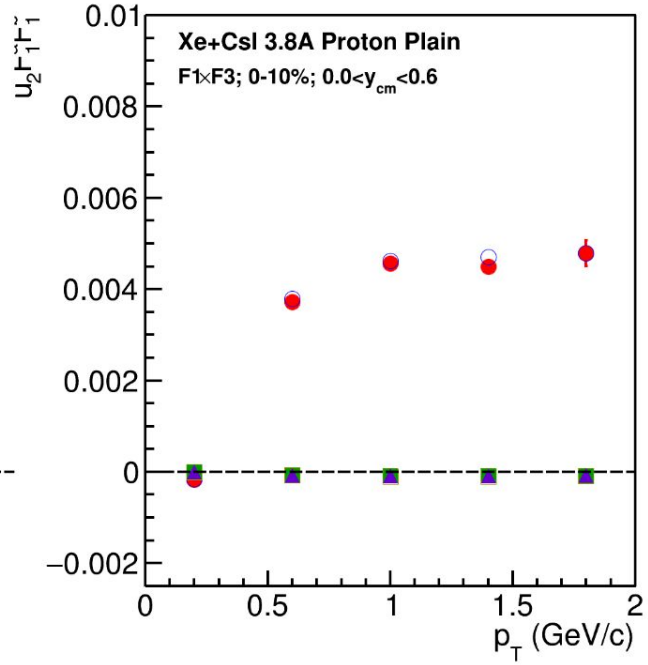


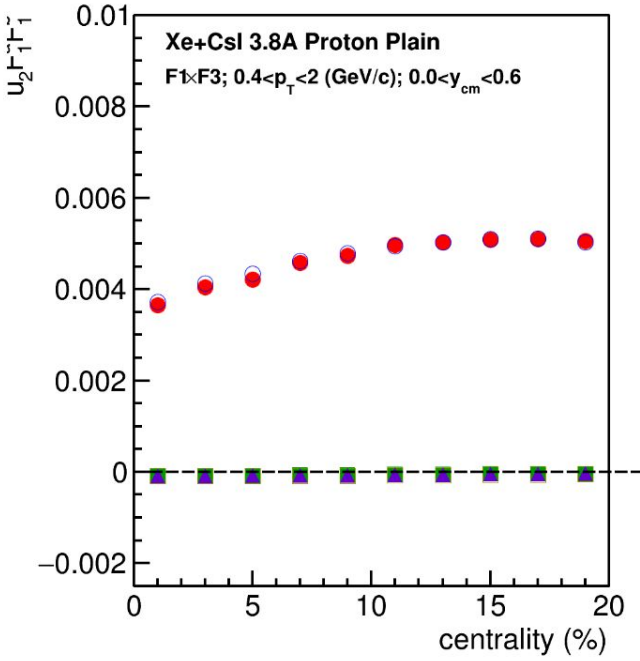




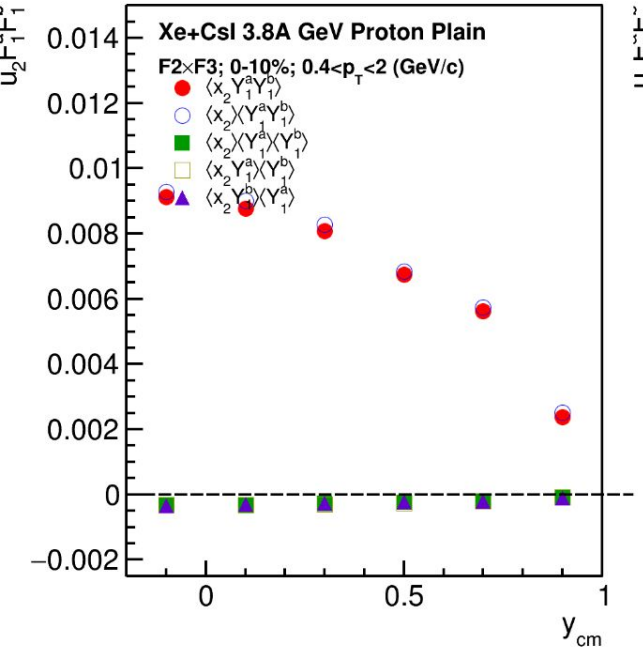
Plain protons with plain F1 and F3

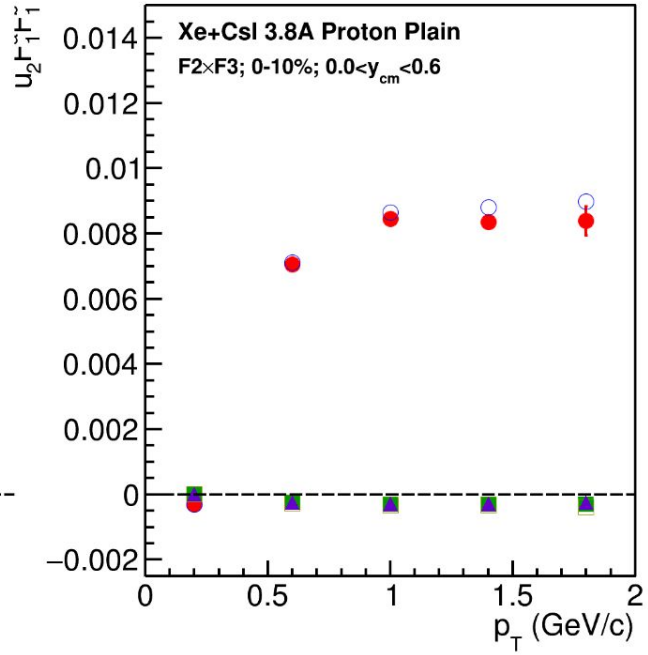


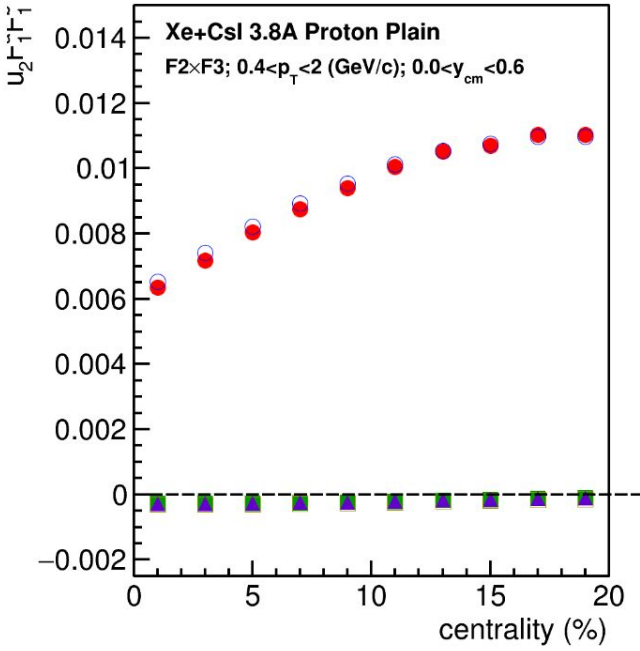




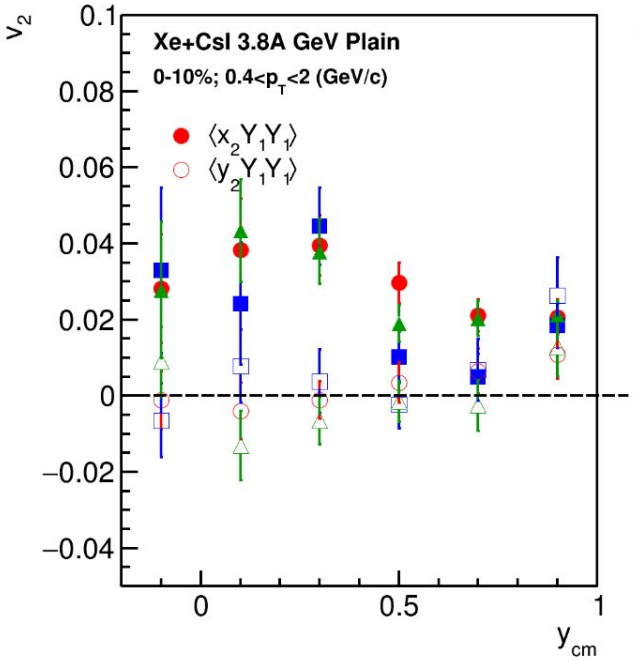
Plain protons with plain F2 and F3

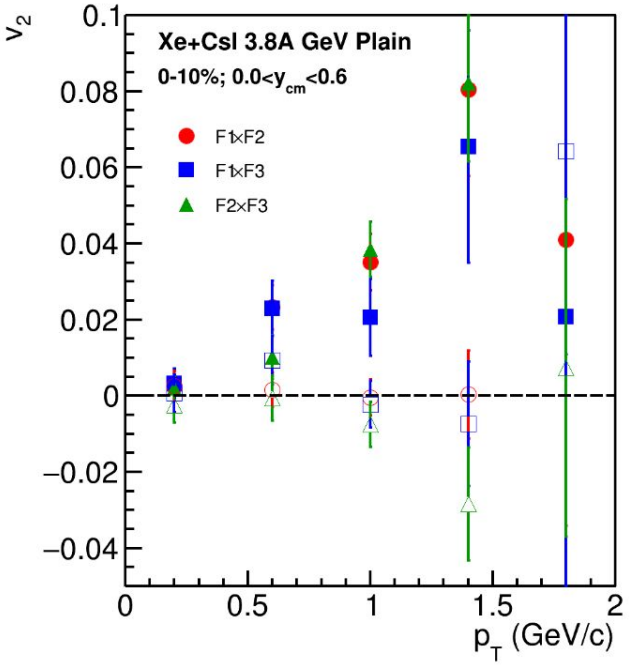


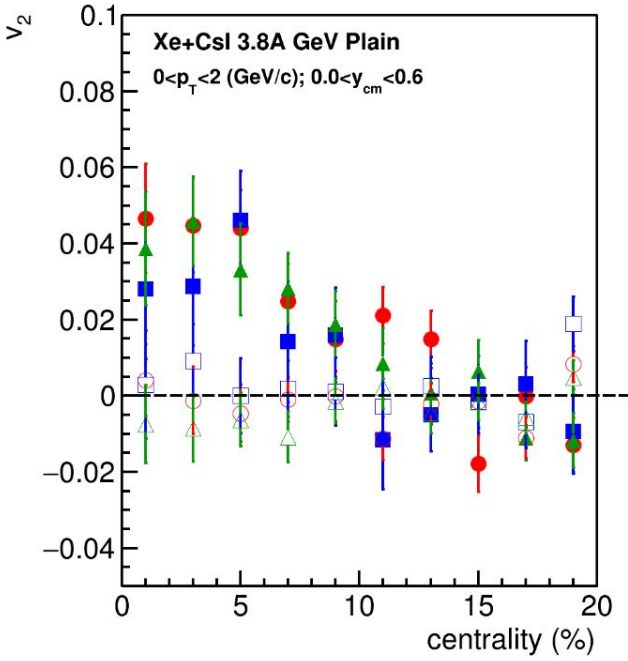




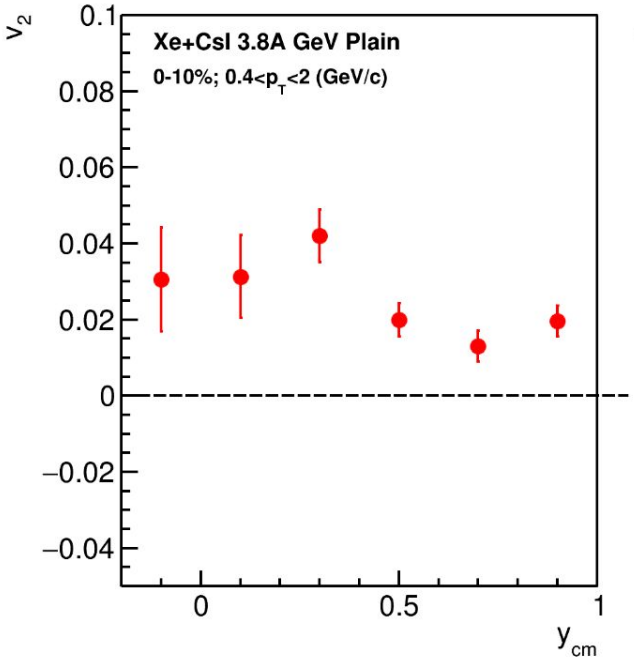
Plain proton v_2 wrt different symmetry planes

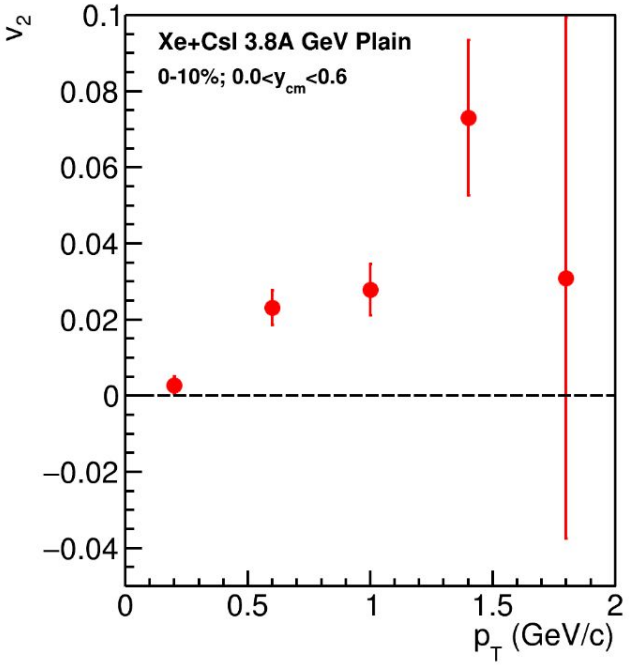


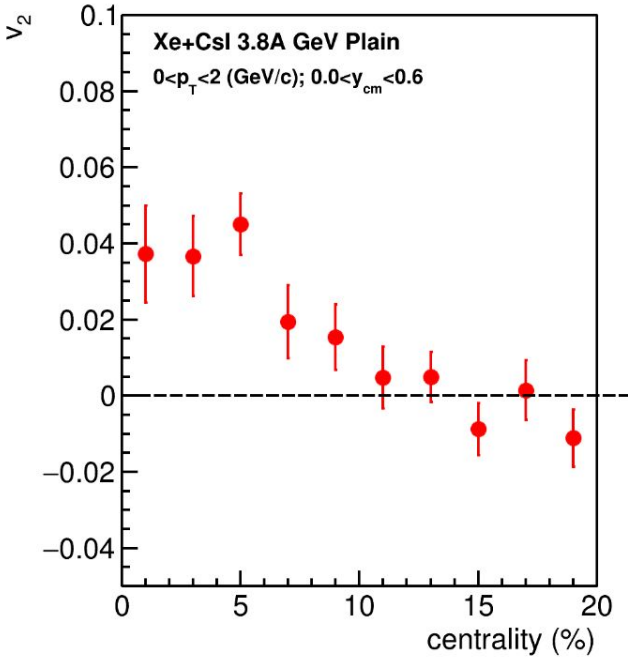




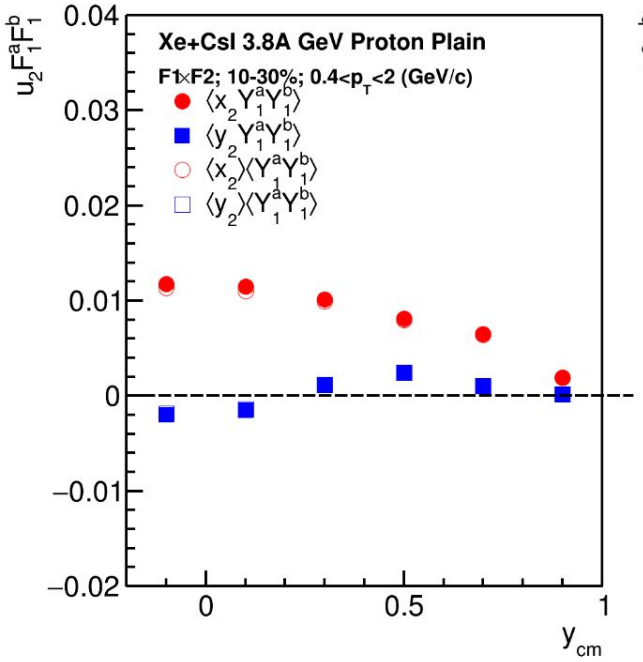
Plain protons with plain F2 and F3

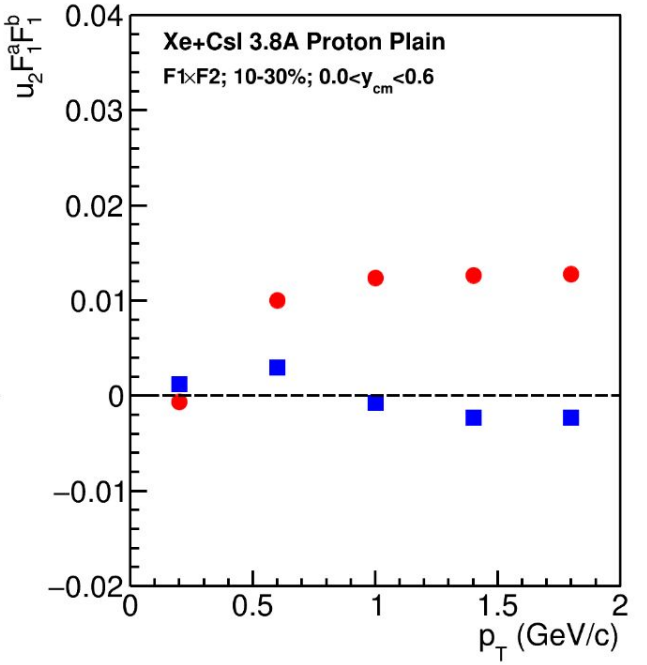


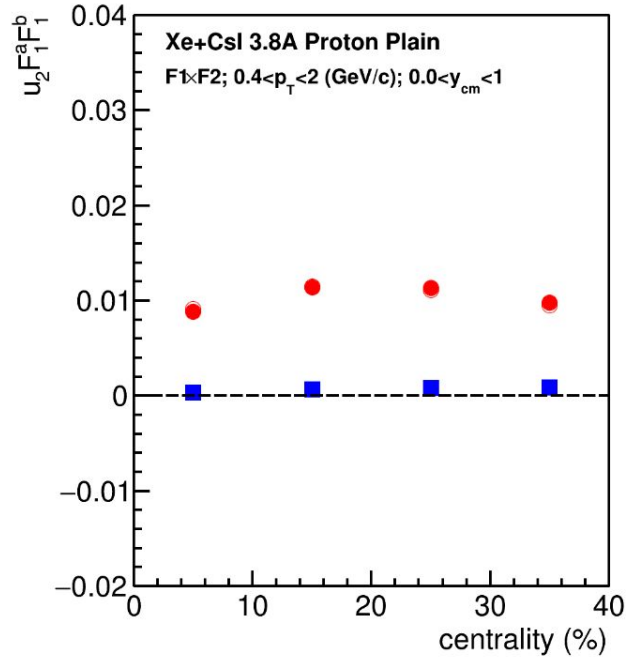




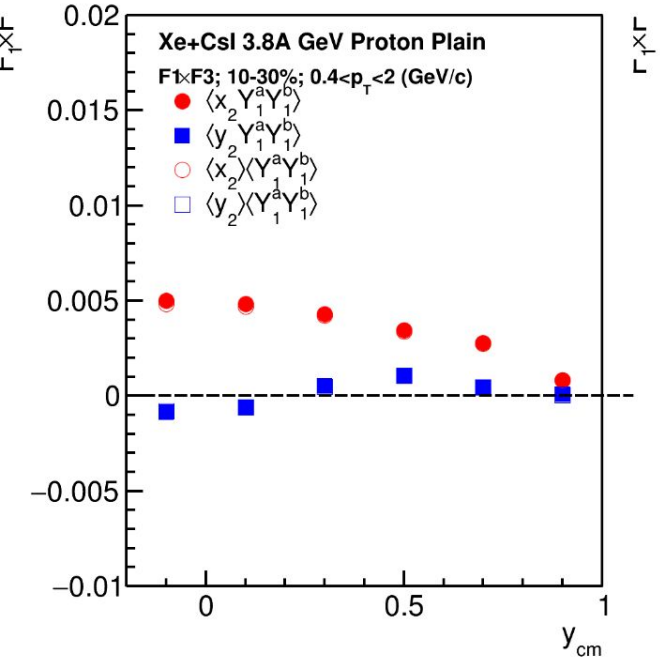
plain u_2-vector with rec.-corr. F1 and F2

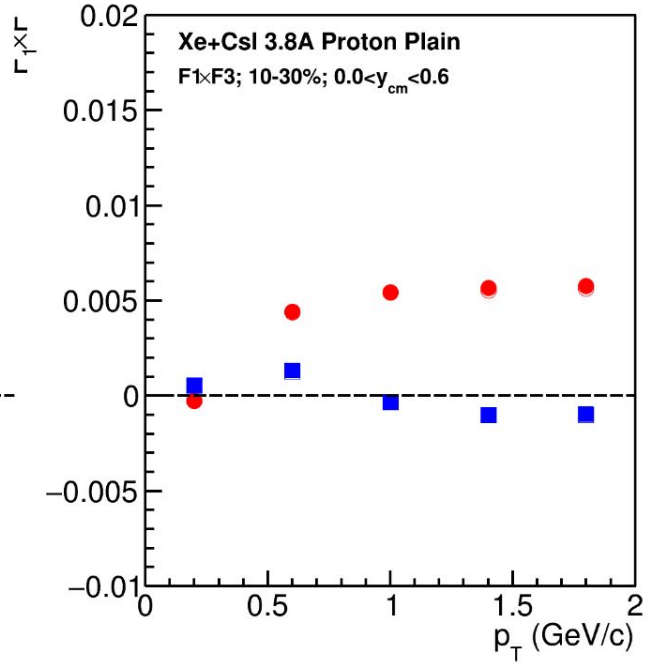


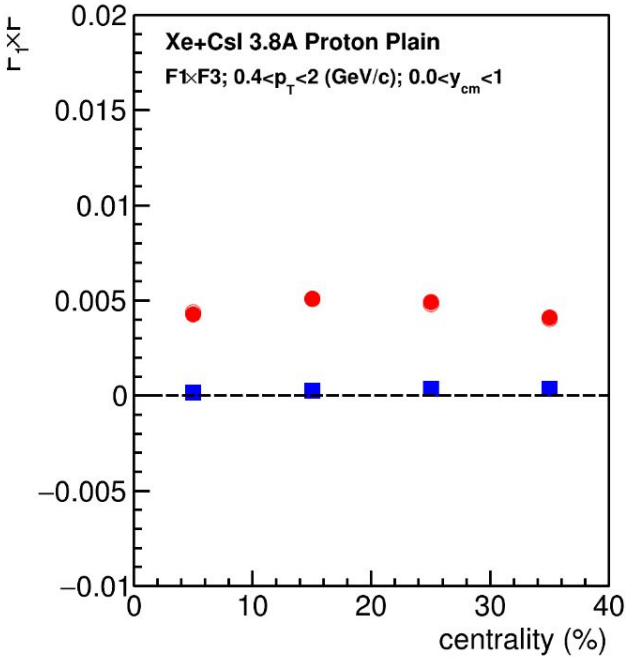




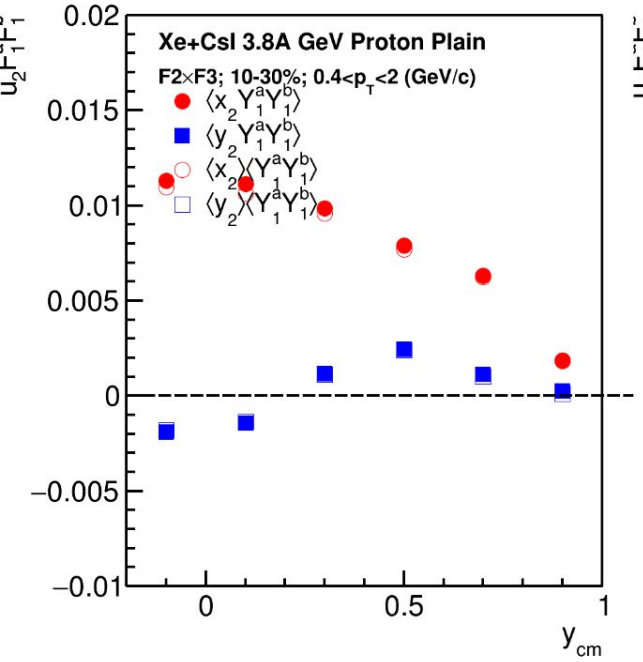
plain u_2-vector with rec.-corr. F1 and F3

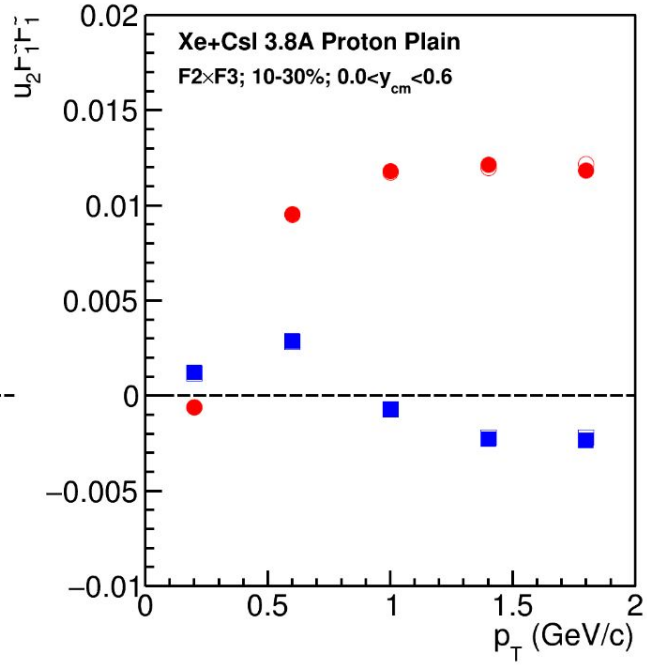


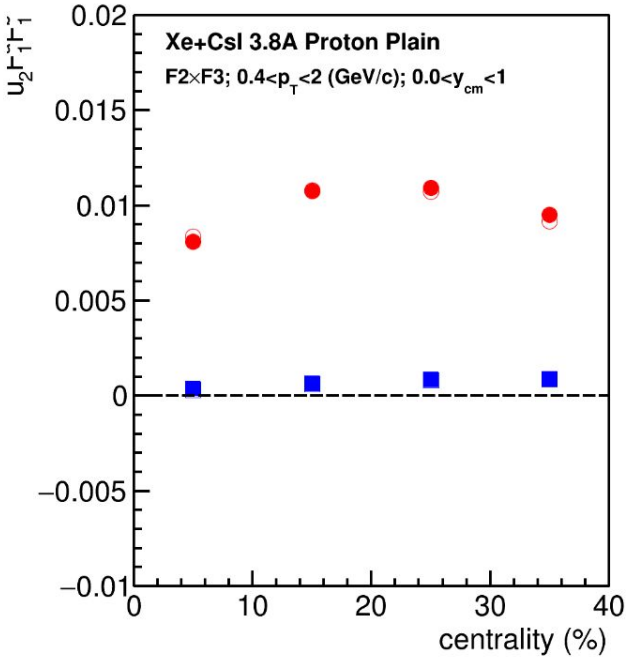




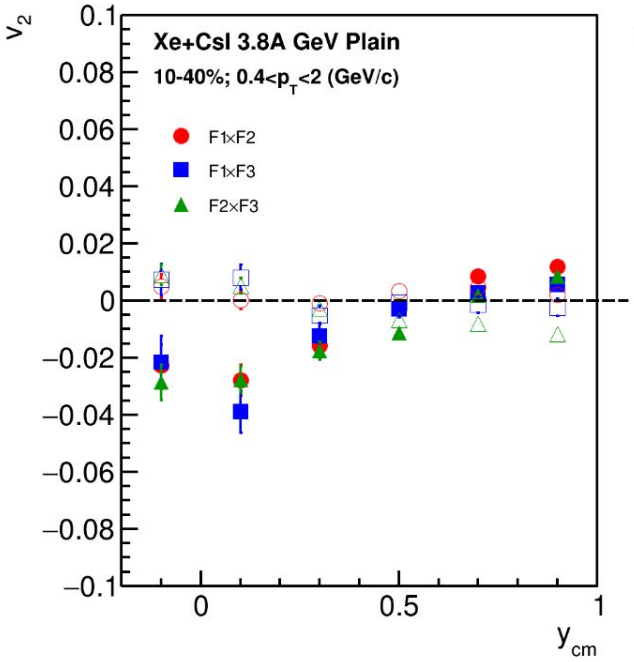
plain u_2-vector with rec.-corr. F2 and F3

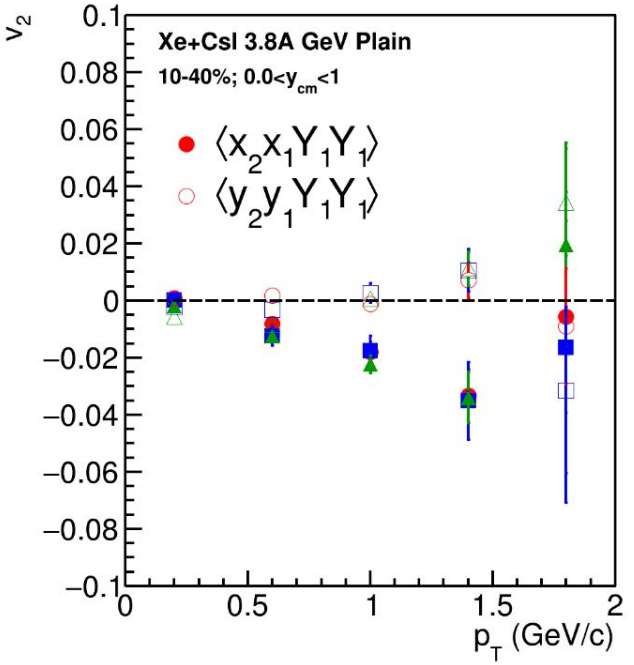


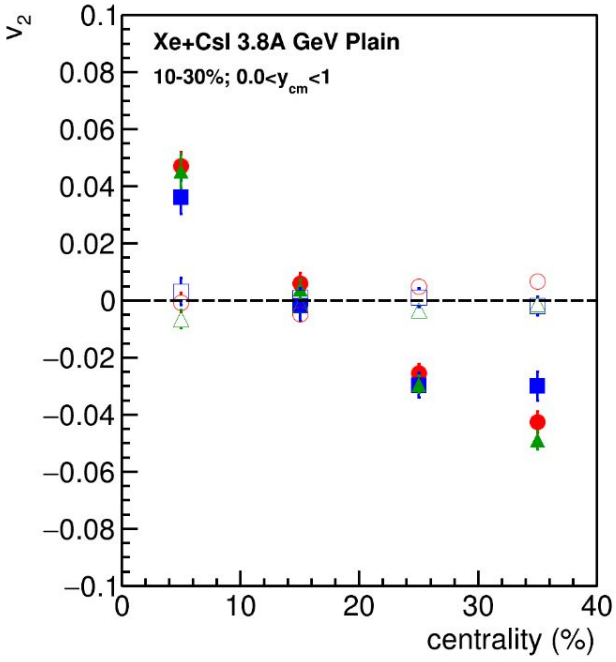




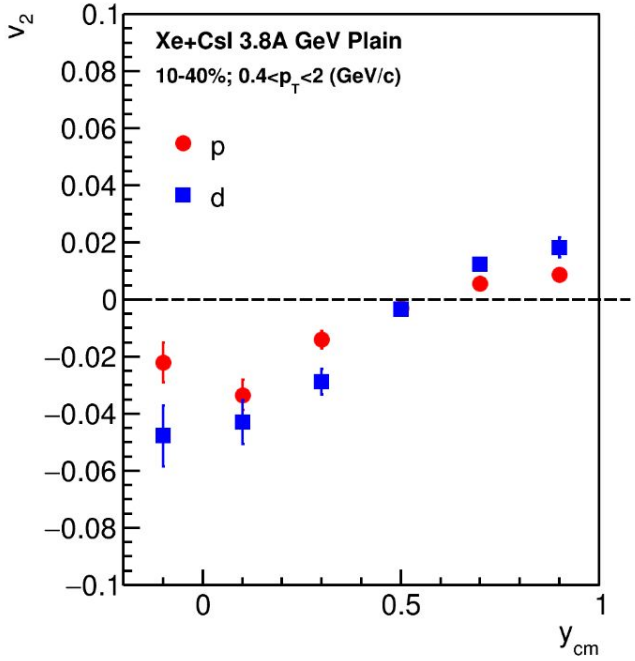
v_2 as a function of y_{cm}, p_T and centrality

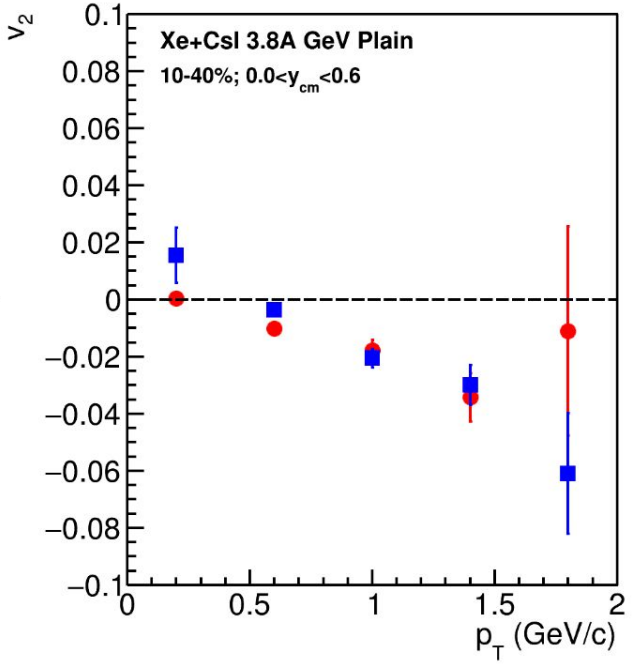


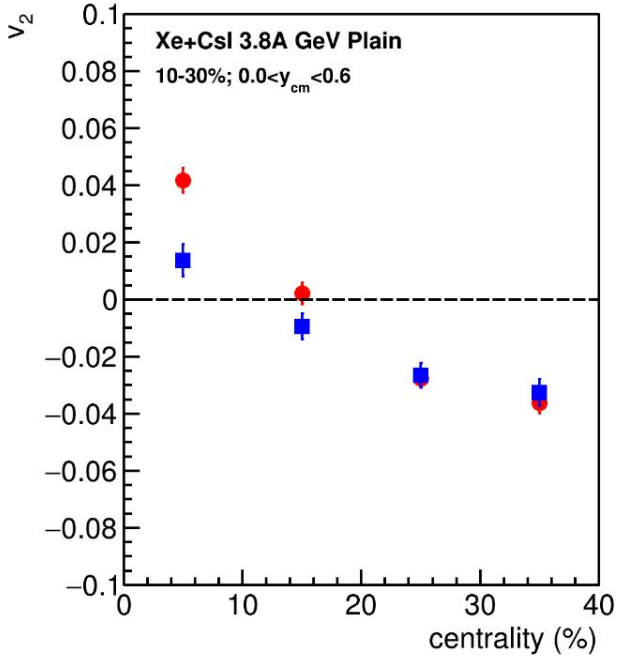




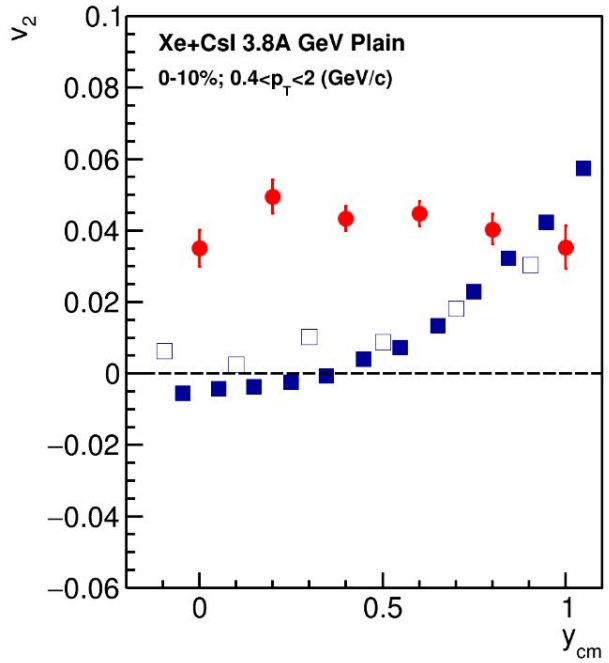
Proton v_2 vs deuteron v_2

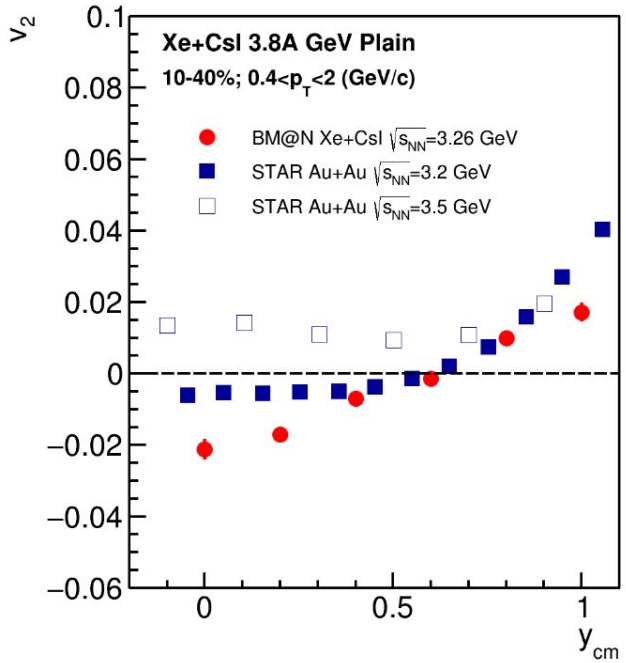


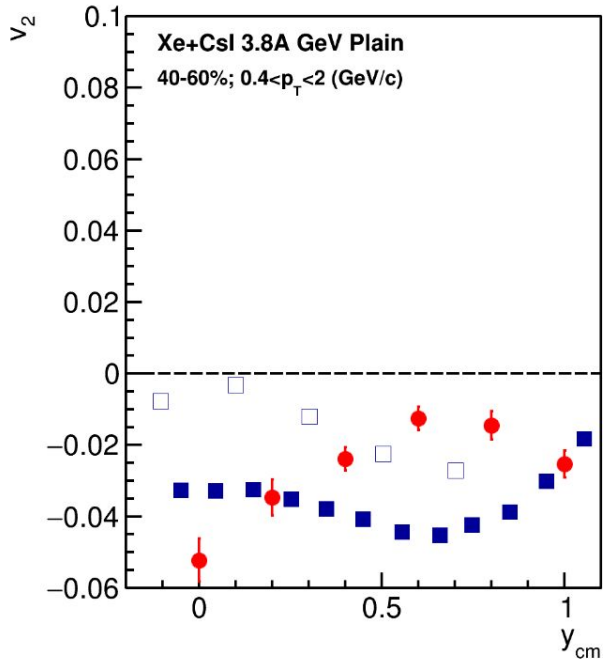




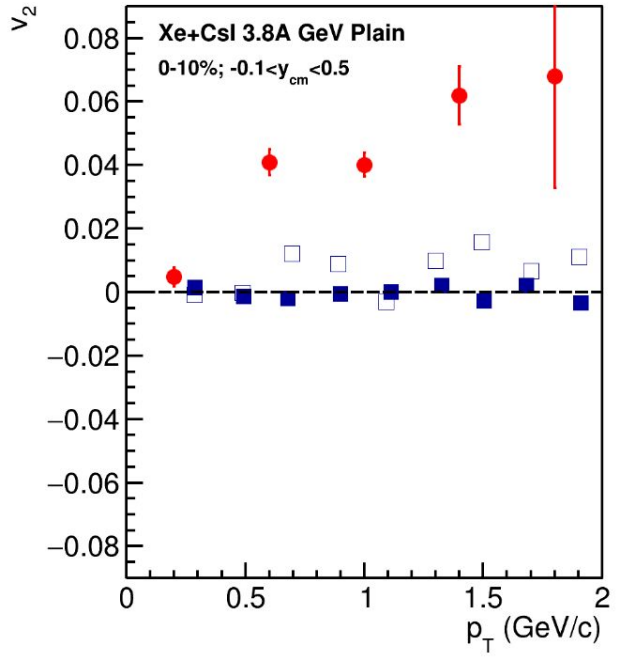
Comparison with STAR-FXT: y-dependence

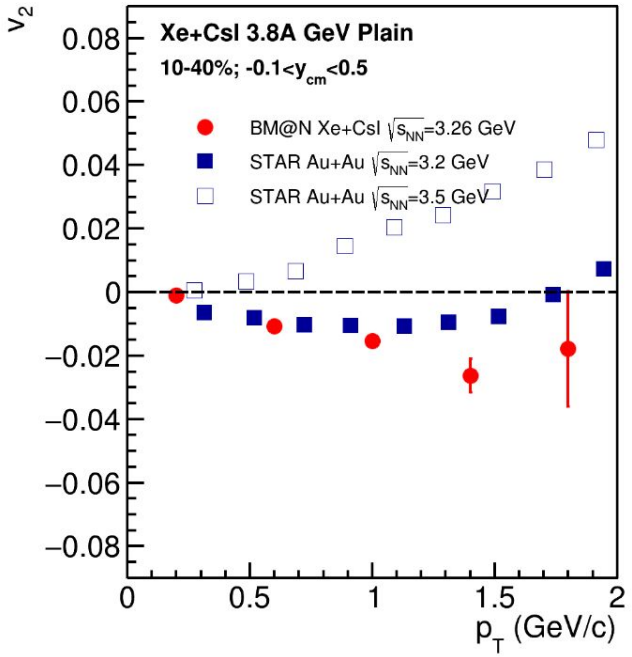


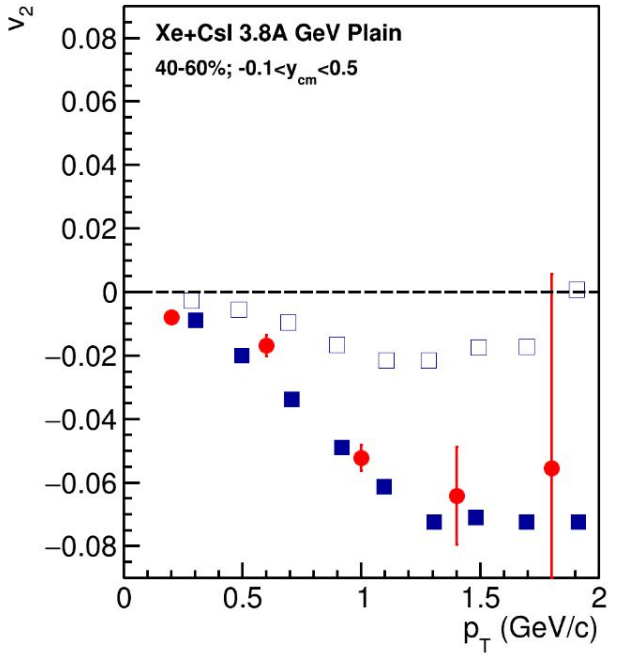


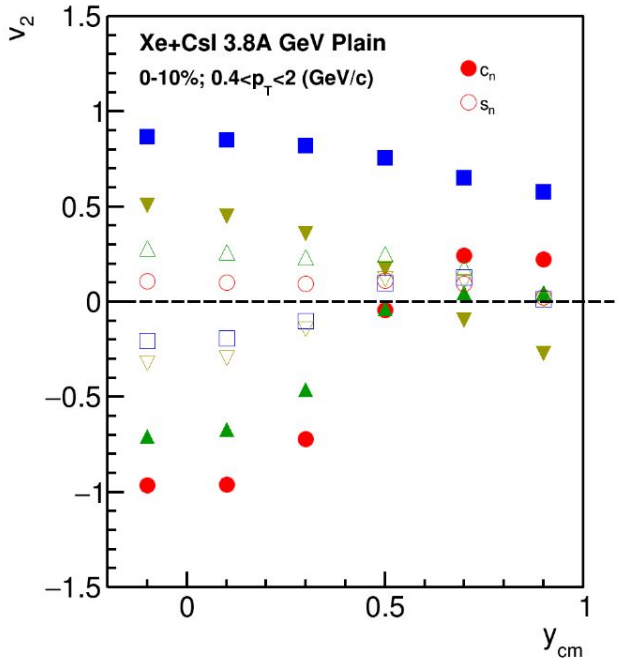


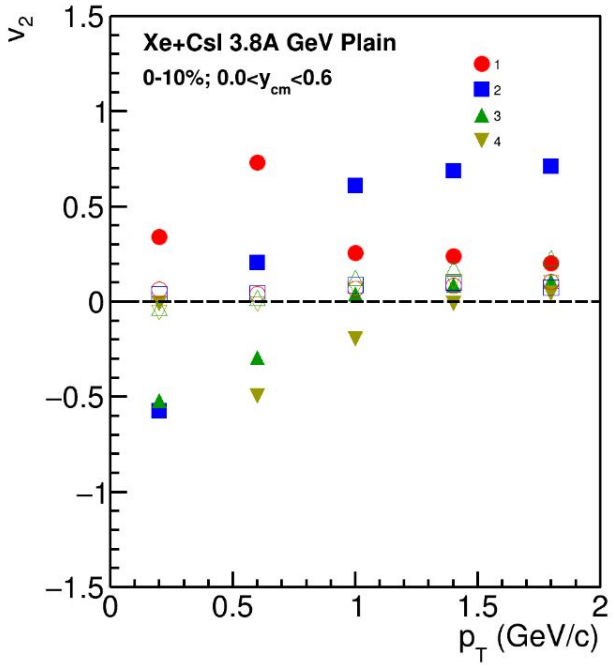
Comparison with STAR-FXT: y-dependence

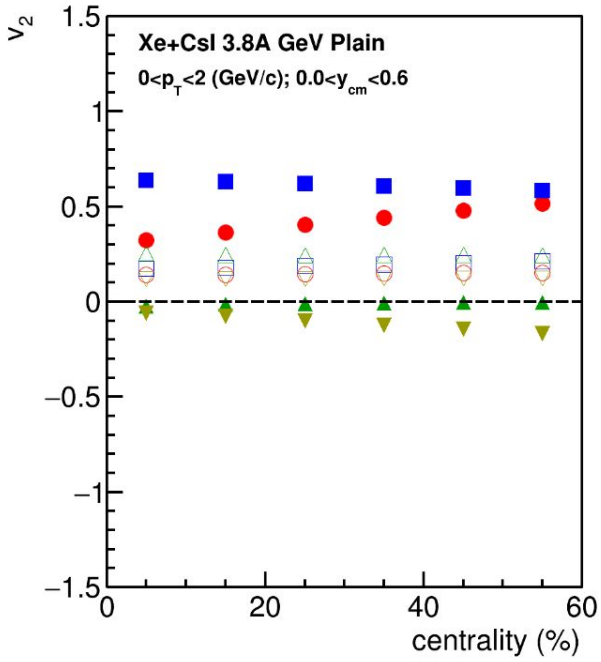


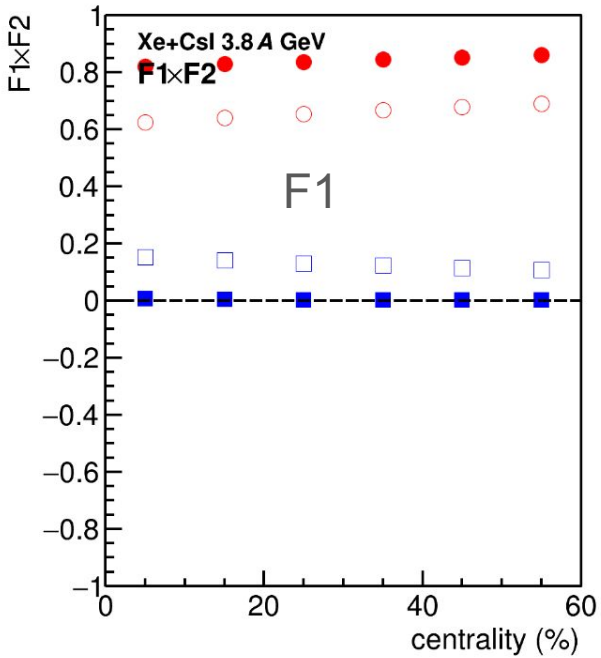


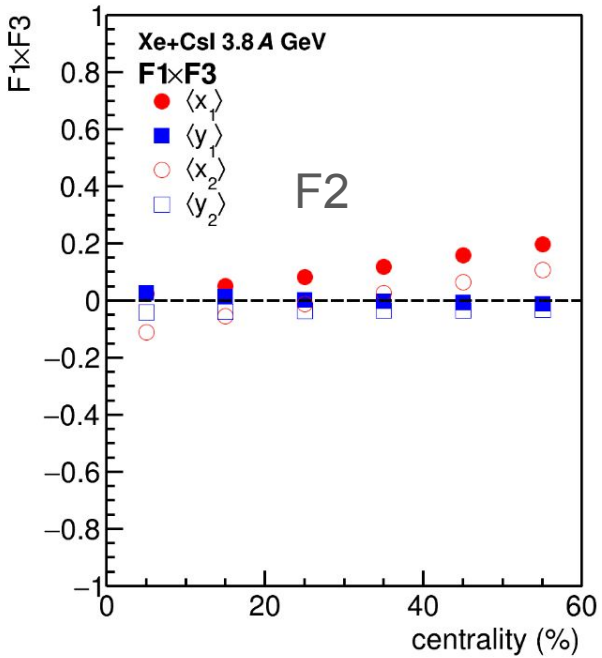


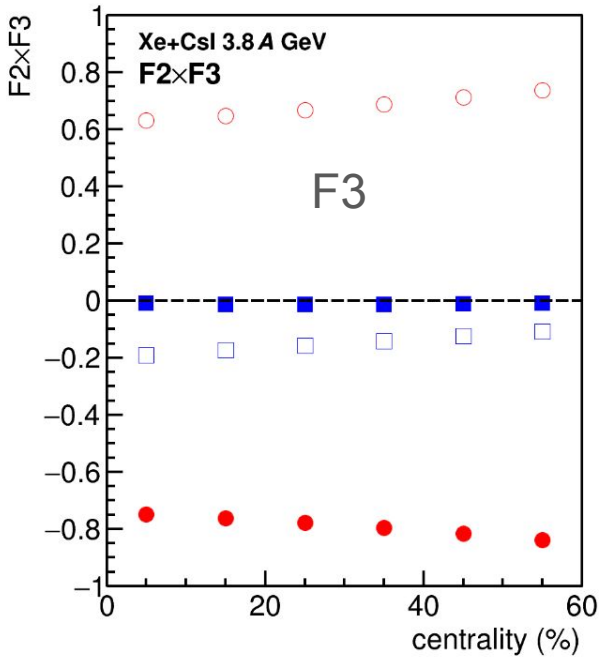

Xe+CsI 3.8A GeV Plain
0-10%; 0.4<p_T<2 (GeV/c)
c_n
s_n
v_2
y_cm

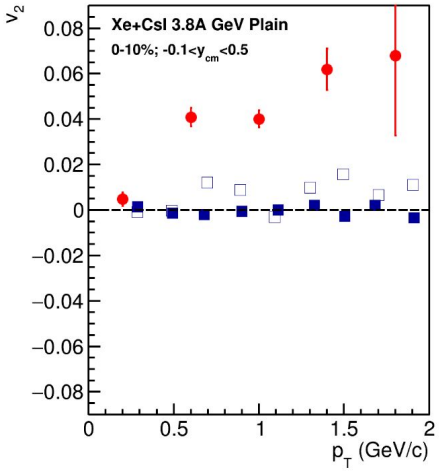

Xe+CsI 3.8A GeV Plain
0-10%; 0.0<y_cm<0.6
1
2
3
4
v_2
p_T (GeV/c)

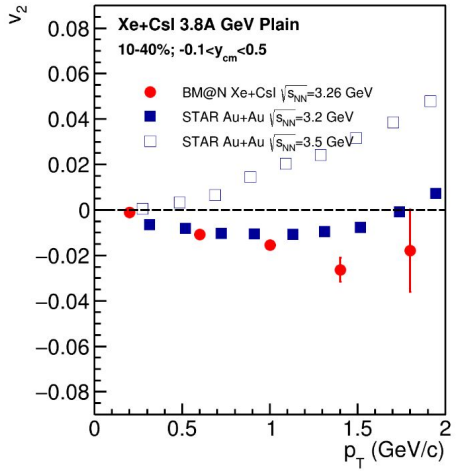

Xe+CsI 3.8A GeV Plain
0<p_T<2 (GeV/c); 0.0<y_cm<0.6
v_2
centrality (%)

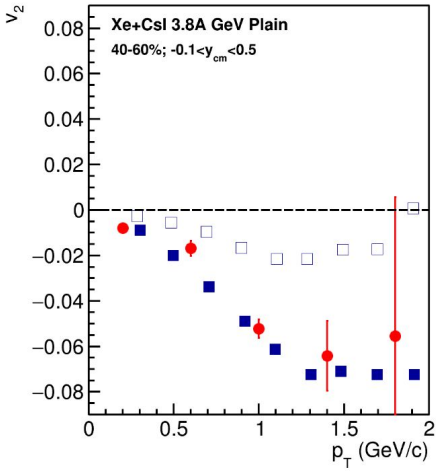

Xe+CsI 3.8 A GeV
F1×F2
F1
F1×F2
centrality (%)

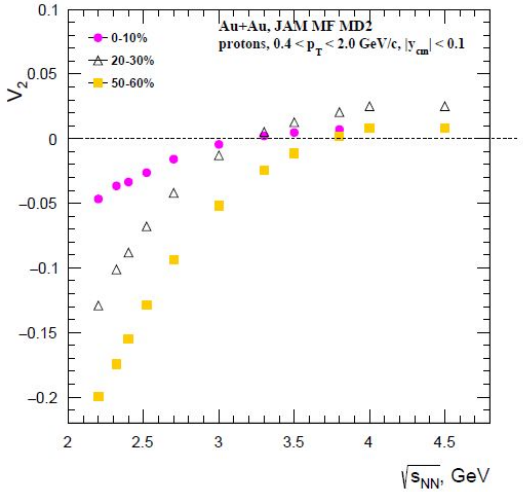

Xe+CsI 3.8 A GeV
F1×F3
⟨x1⟩
⟨y1⟩
⟨x2⟩
⟨y2⟩
F2
F1×F3
centrality (%)

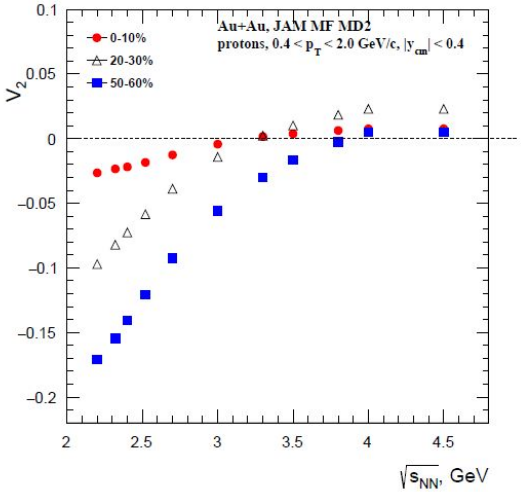

Xe+CsI 3.8 A GeV
F2×F3
F3
F2×F3
centrality (%)


Xe+CsI 3.8A GeV Plain
0-10%; -0.1<y_cm<0.5
v2
p_T (GeV/c)


Xe+CsI 3.8A GeV Plain
10-40%; -0.1<y_cm<0.5
BM@N Xe+CsI √s_NN=3.26 GeV
STAR Au+Au √s_NN=3.2 GeV
STAR Au+Au √s_NN=3.5 GeV
v2
p_T (GeV/c)

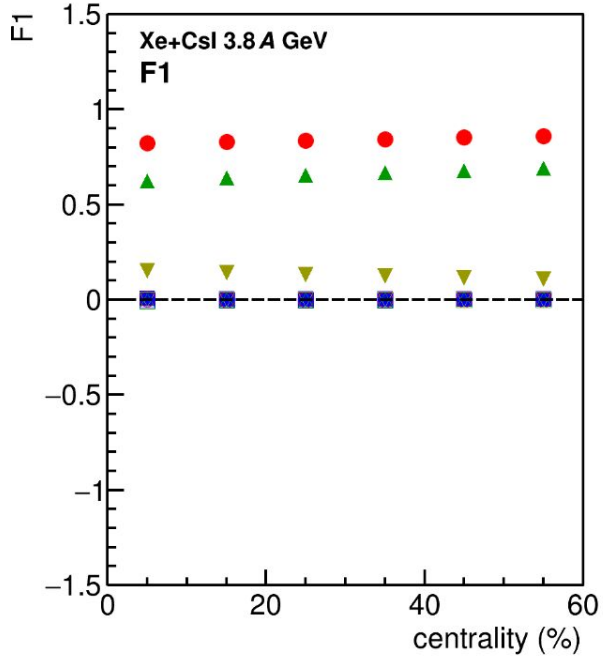

Xe+CsI 3.8A GeV Plain
40-60%; -0.1<y_cm<0.5
v2
p_T (GeV/c)

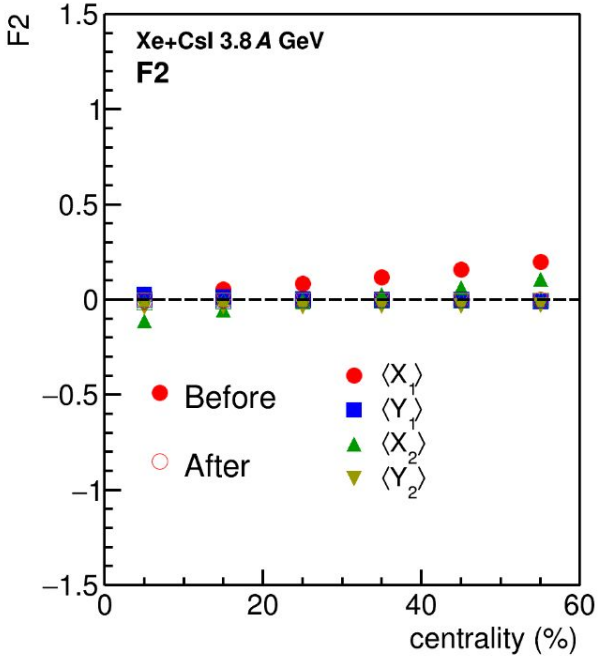

Au+Au, JAM MF MD2
protons, 0.4 < p_T < 2.0 GeV/c, |y_cm| < 0.1
0-10%
20-30%
50-60%
V2
√s_NN, GeV

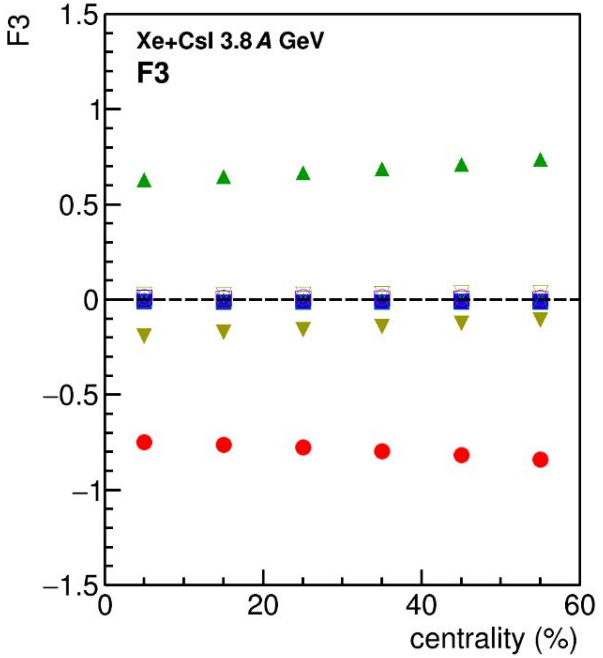

Au+Au, JAM MF MD2
protons, 0.4 < p_T < 2.0 GeV/c, |y_cm| < 0.4
0-10%
20-30%
50-60%
V2
√s_NN, GeV

Decomposition correction

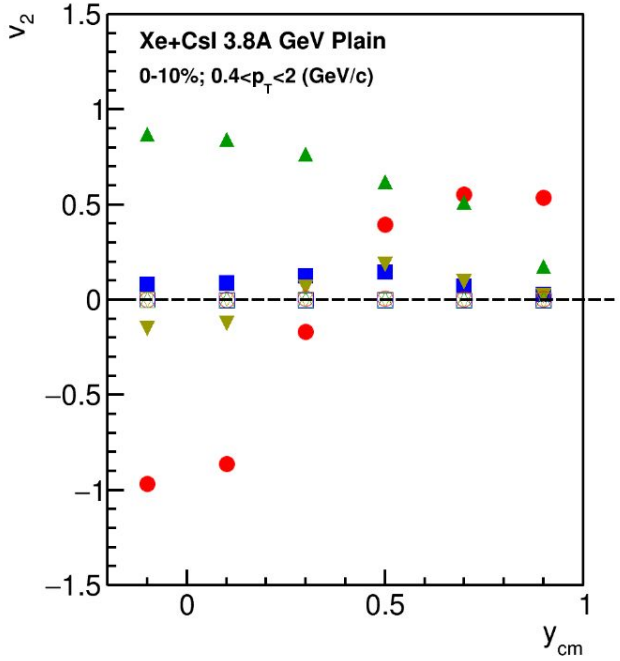
Average of FHCal $Q_{1,2}$-vector components

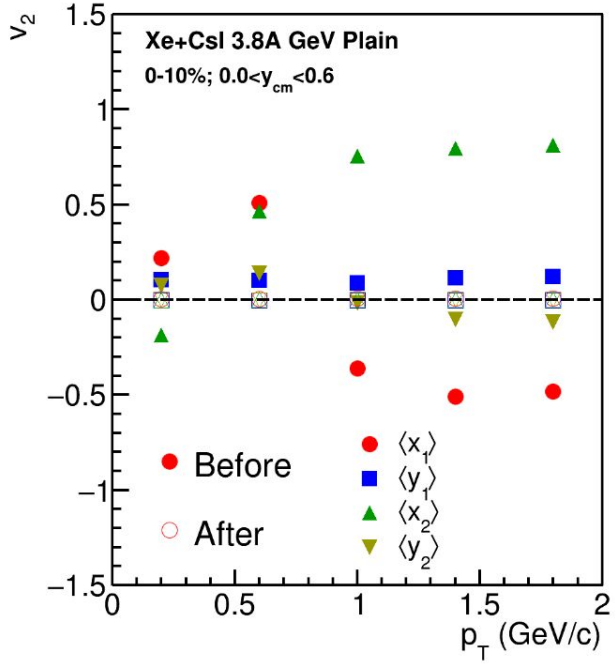


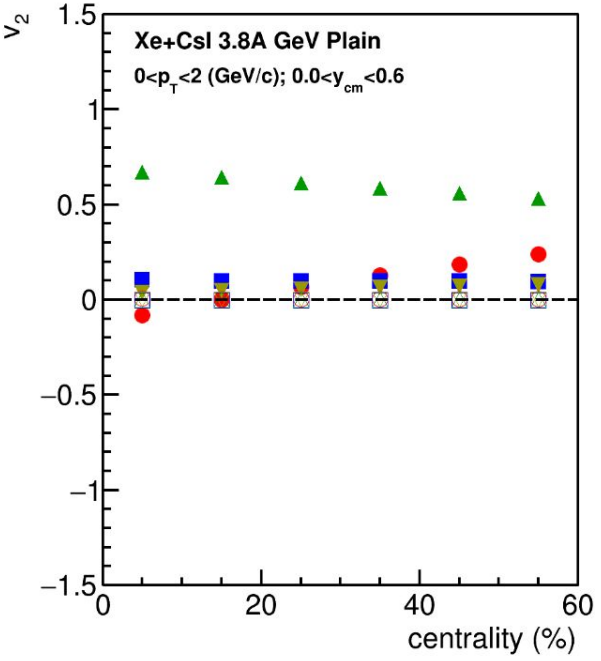




Average of proton $u_{1,2}$-vector components







The core idea of correction

In the case of ideal detector acceptance, distribution is described as:

$$\rho(\varphi - \Psi) = \frac{1}{2\pi}(1 + 2\sum_{n} v_n \cos n(\varphi - \Psi))$$

In the case of azimuthal acceptance non-uniformity this transforms into:

$$P(\varphi - \Psi) = \frac{1}{2\pi}\left(1 + 2\sum_{m}(c_m \cos m\varphi + s_m \sin m\varphi)\right) \times \left(1 + 2\sum_{n} v_n \cos n(\varphi - \Psi)\right)$$

Q_n-vector components in the case of ideal detector acceptance:

$$X_n^{\rho} \equiv \langle x_n \rangle_{\rho}(\Psi) = \int d\varphi \frac{1}{2\pi}(1 + \sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi)) \cos n\varphi = V_n \cos n\Psi$$

$$Y_n^{\rho} \equiv \langle y_n \rangle_{\rho}(\Psi) = \int d\varphi \frac{1}{2\pi}(1 + \sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi)) \sin n\varphi = V_n \sin n\Psi$$

In the case of azimuthal non-uniformity:

$$X_n^{P} = \int d\varphi P(\varphi - \Psi) \cos n\varphi = X_n^{\rho} + \sum_{m=1}^{\infty}(c_m X_{n+m}^{\rho} + c_m X_{m-n}^{\rho} + s_m Y_{m+n}^{\rho} + s_m Y_{m-n}^{\rho})$$

$$Y_n^{P} = \int d\varphi P(\varphi - \Psi) \sin n\varphi = Y_n^{\rho} + \sum_{m=1}^{\infty}(c_m Y_{m+n}^{\rho} - c_m Y_{m-n}^{\rho} - s_m X_{m+n}^{\rho} + s_m X_{m-n}^{\rho})$$

Acceptance decomposition

$$\langle x_n \rangle = \int d\varphi \frac{1}{2\pi} \left(1 + 2\sum_m (c_m \cos m\varphi + s_m \sin m\varphi)\right) \cos n\varphi = c_n$$

$$\langle y_n \rangle = \int d\varphi \frac{1}{2\pi} \left(1 + 2\sum_m (c_m \cos m\varphi + s_m \sin m\varphi)\right) \sin n\varphi = s_n$$

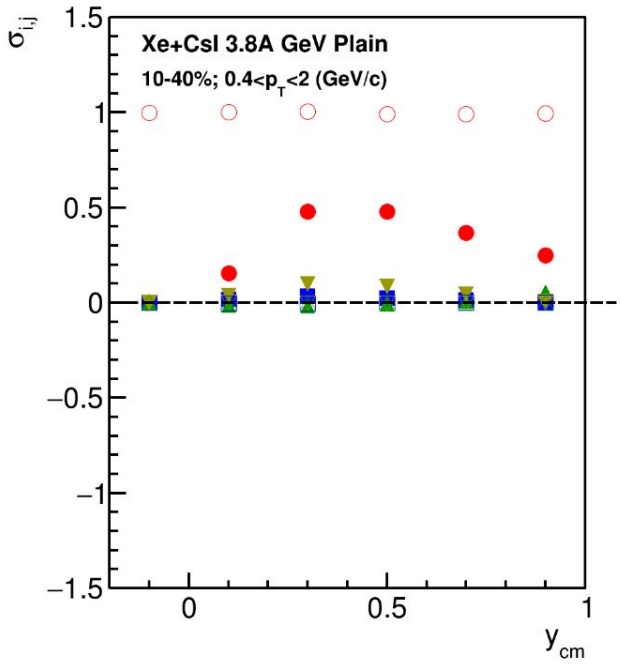
$$cov(x_n x_l) = \langle x_n x_l \rangle - c_n c_l$$

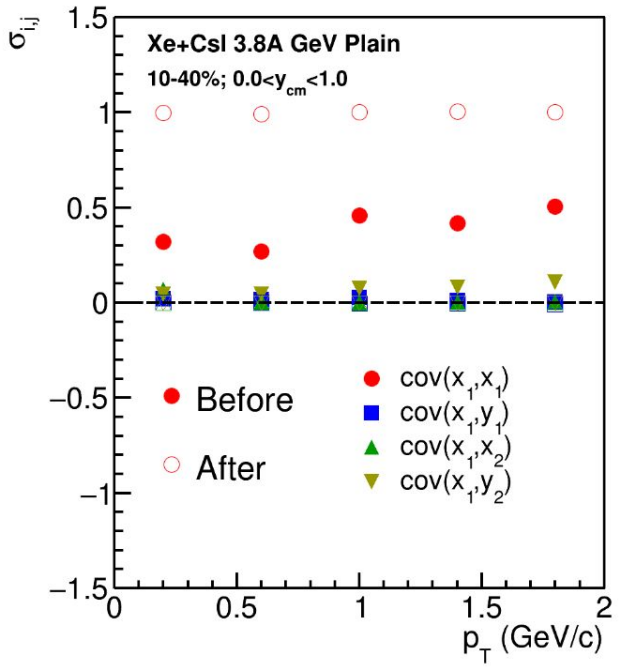
First, for vector s = [X_1, Y_1, X_2, Y_2] we bild covariation matrix M, where $M_{i,j}$ = cov(s_i, s_j). Then we apply the whitening procedure:

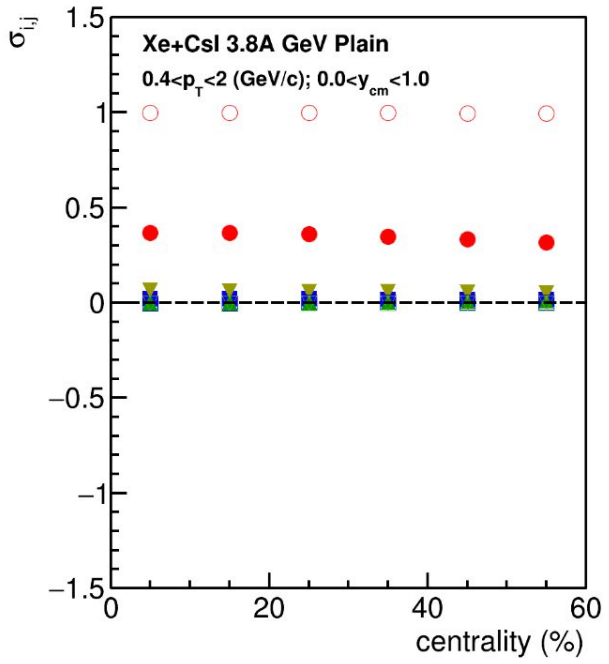
x = $M^{-1/2}$s
After this procedure: cov(x_i, x_i) = 1, cov(x_i, x_j)$_{i!=j}$=0
This supposed to decompose acceptance so that:

$$x = [\cos\varphi, \sin\varphi, \cos 2\varphi, \sin 2\varphi]$$

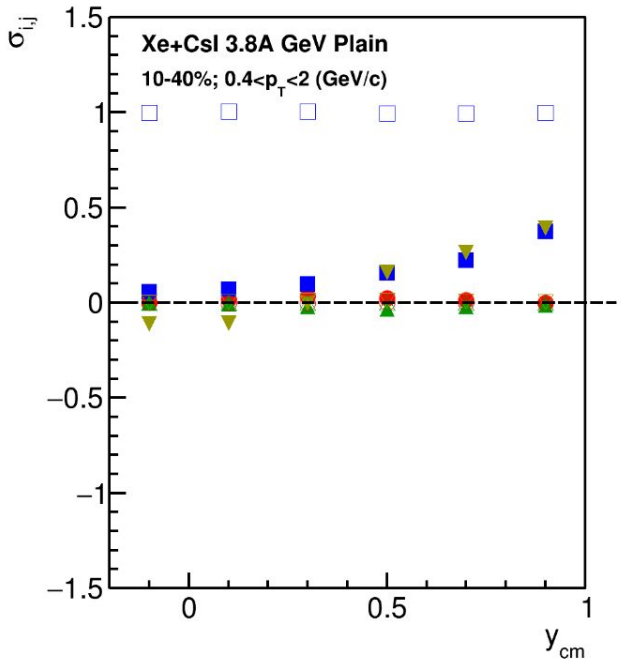
Cov(x_1, x_n/y_n) for protons before/after whitening:

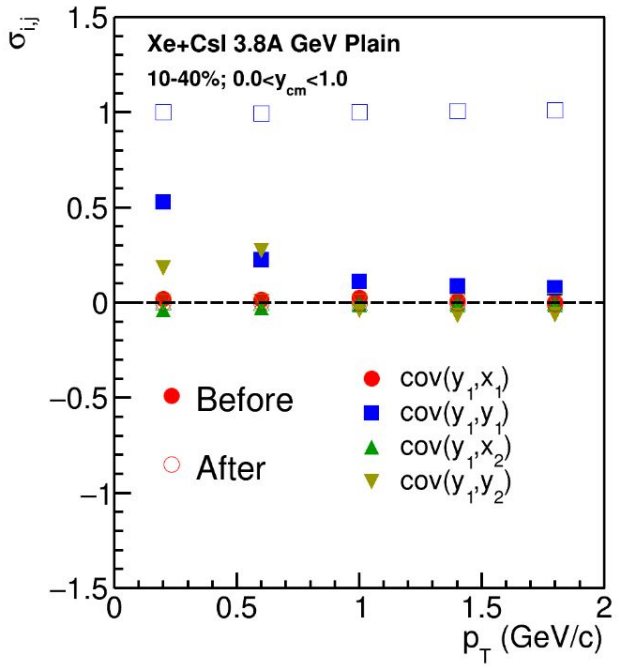


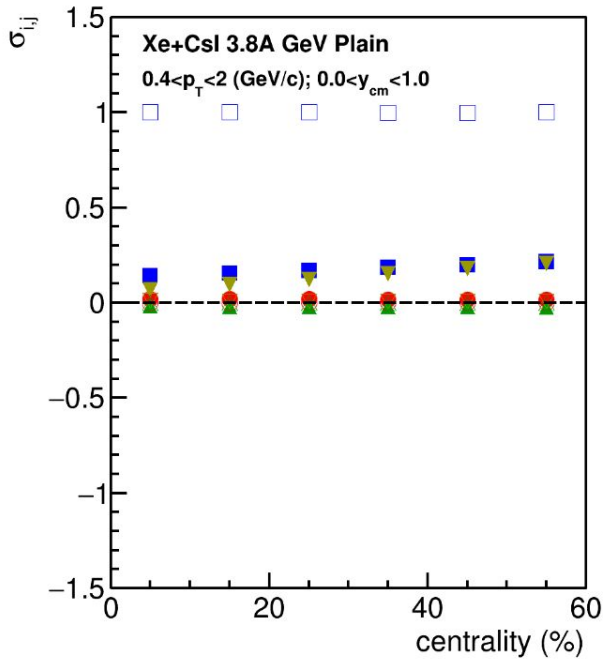




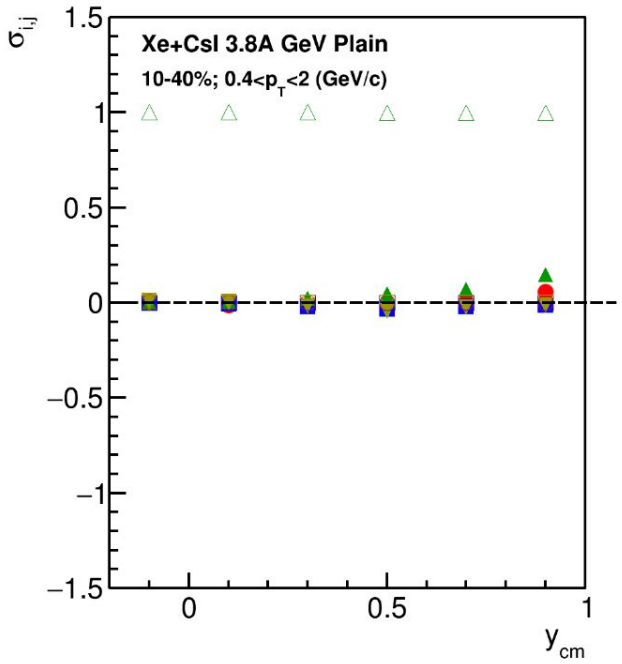
Cov(y_1, x_n/y_n) for protons before/after whitening:

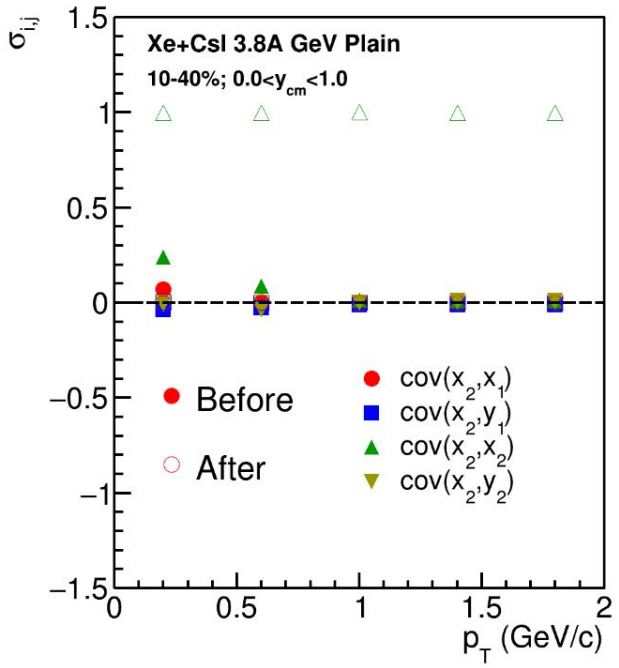


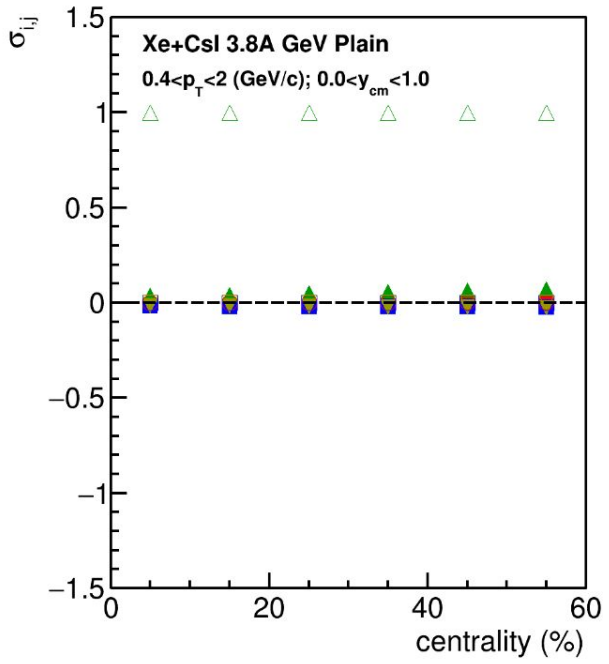




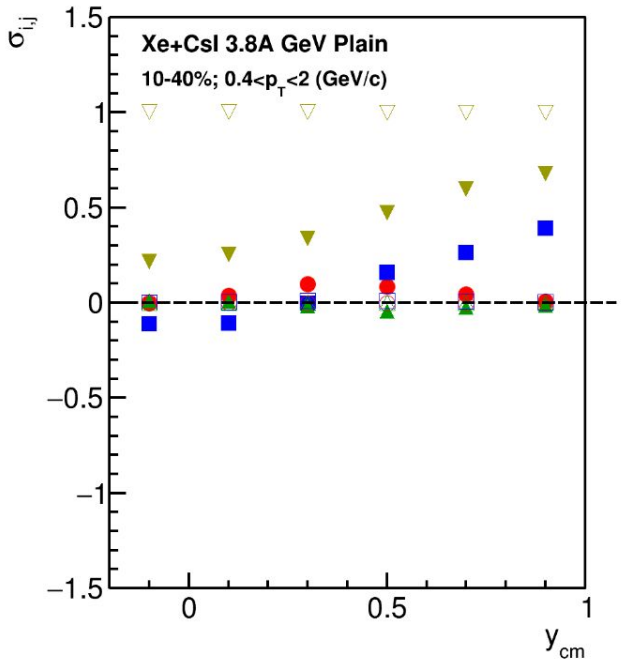
Cov(x_2, x_n/y_n) for protons before/after whitening:

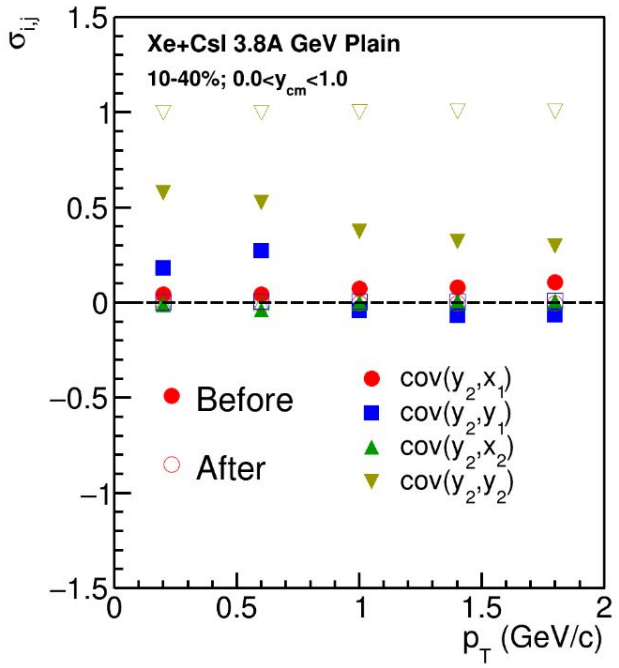


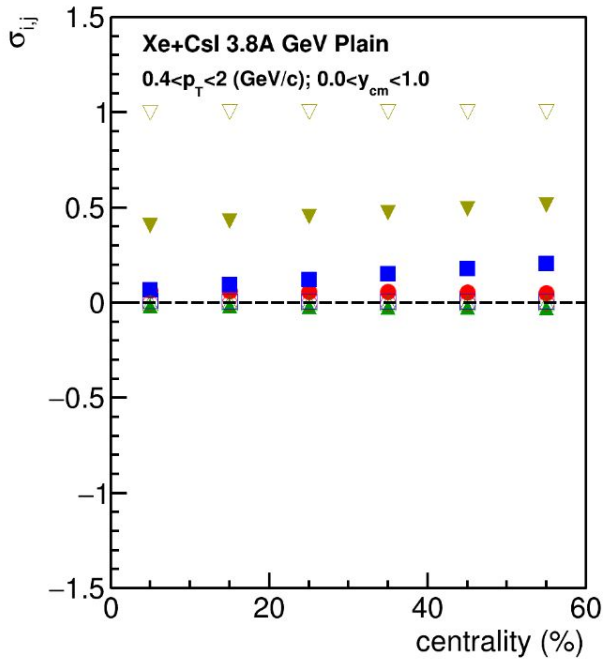




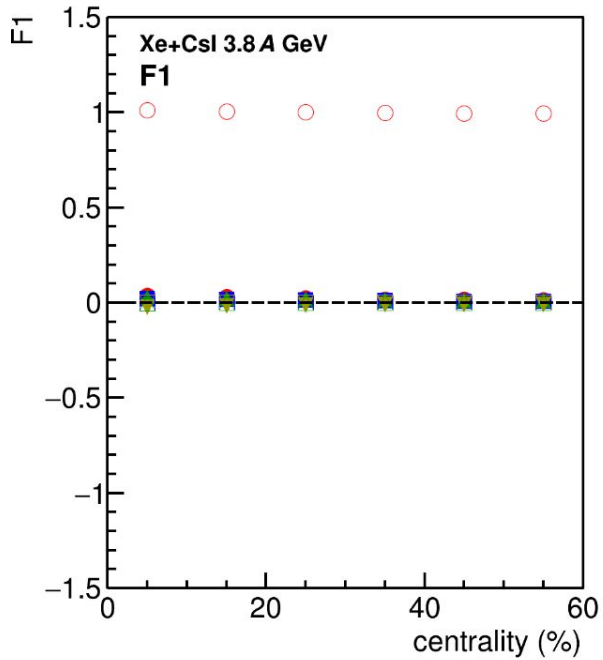
Cov(y_2, x_n/y_n) for protons before/after whitening:

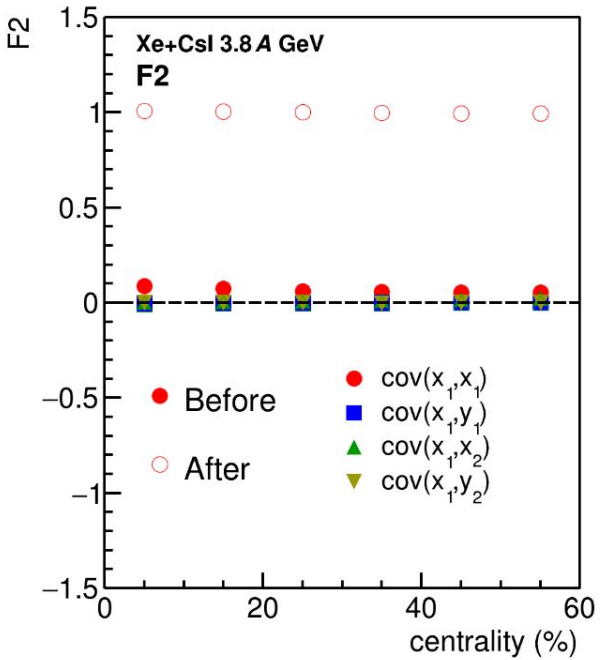


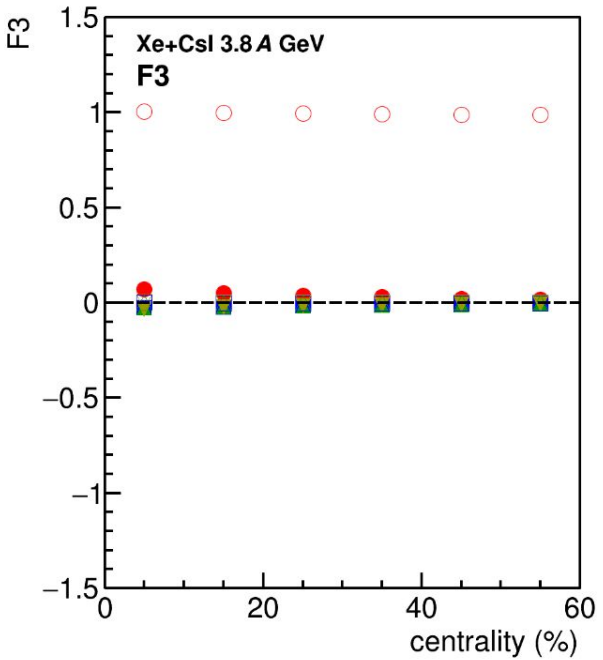




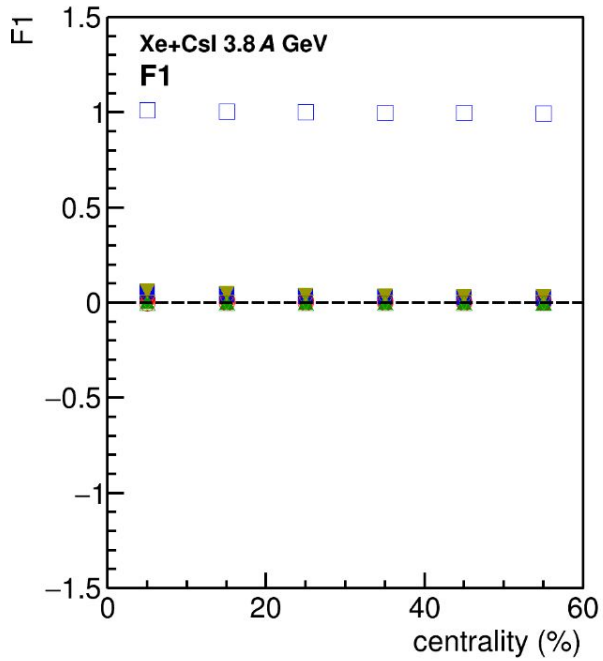
Cov(x_1, x_n/y_n) for FHCal before/after whitening:

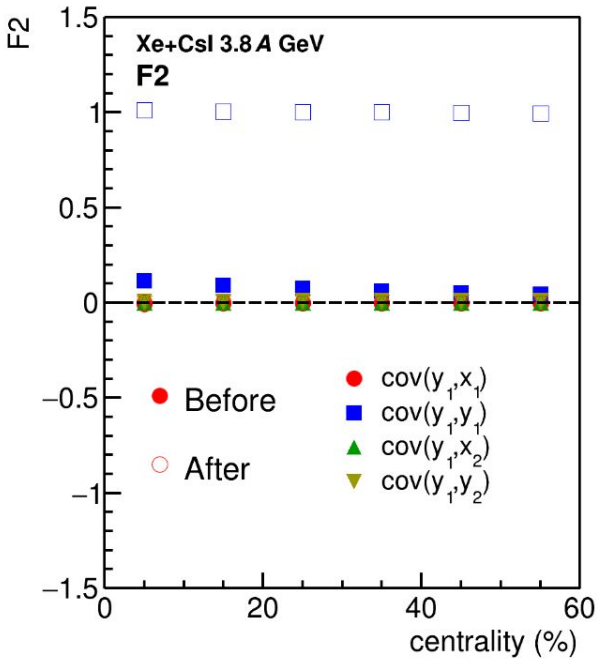


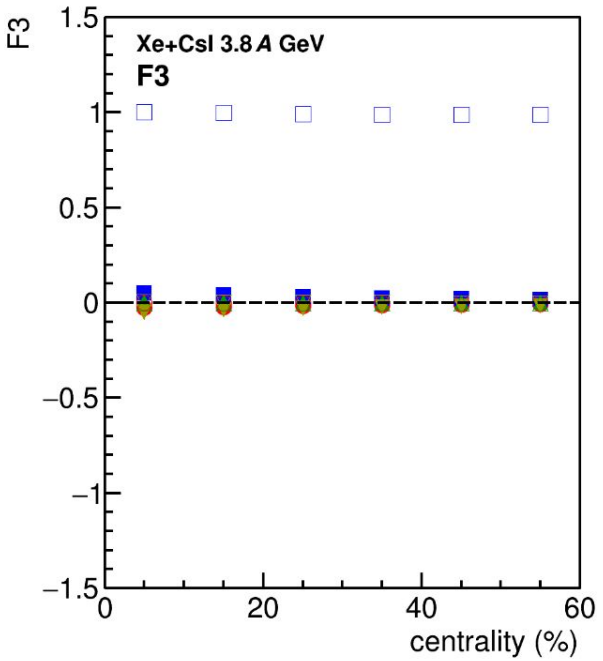




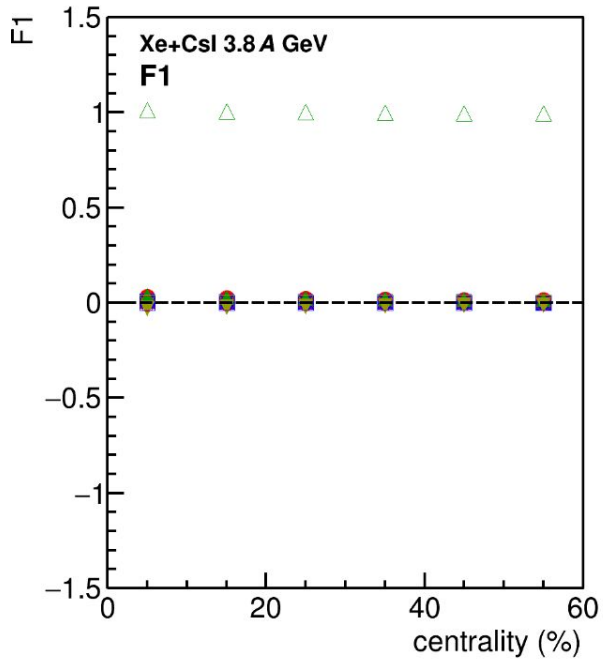
Cov(y_1, x_n/y_n) for protons before/after whitening:

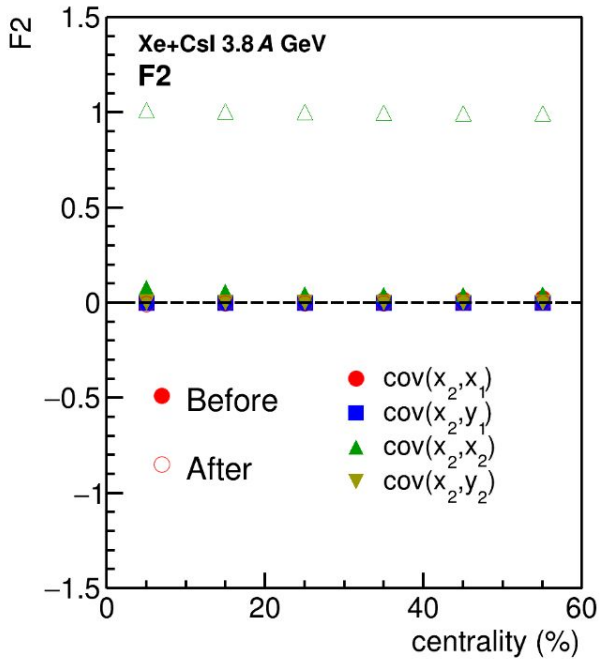


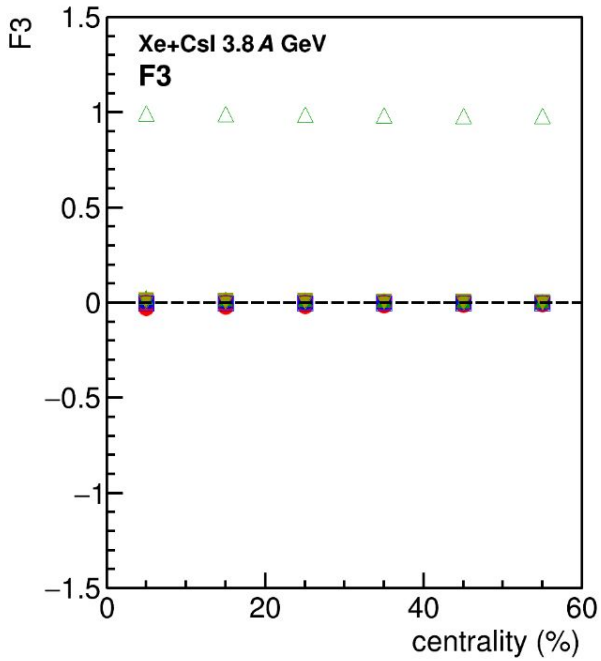




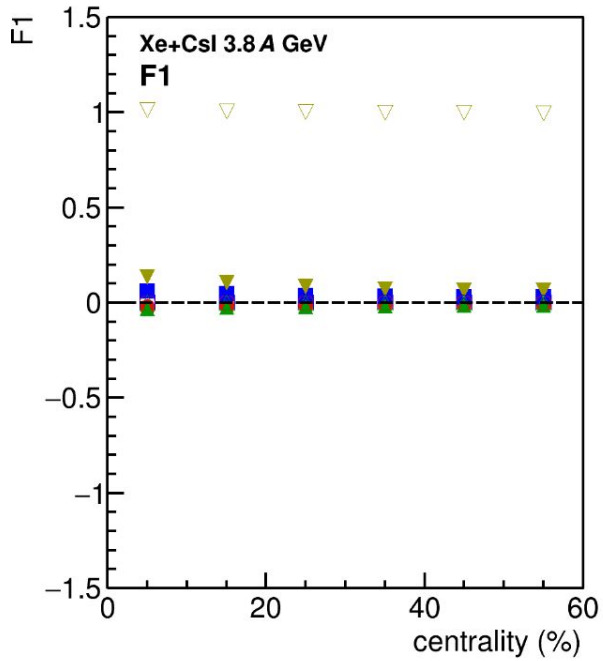
Cov(x_2, x_n/y_n) for protons before/after whitening:

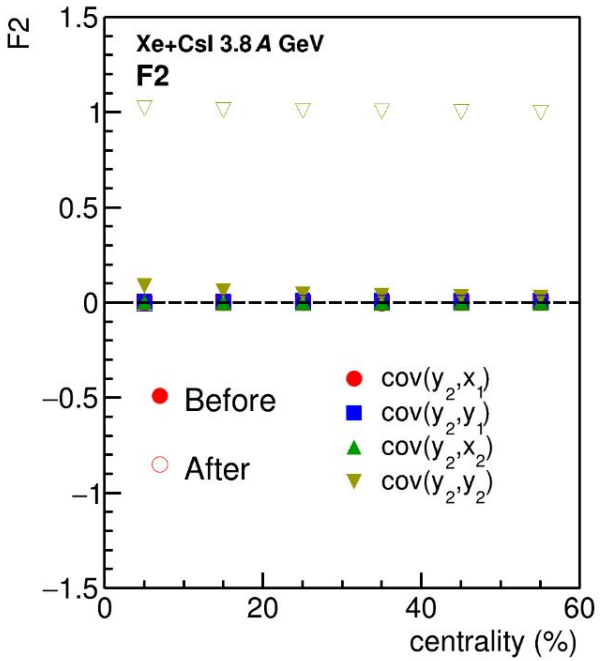


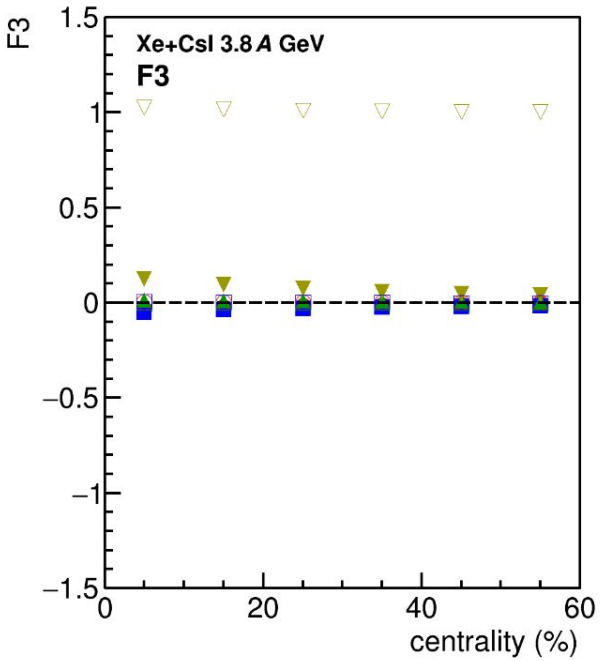




Cov(y_2, x_n/y_n) for protons before/after whitening:

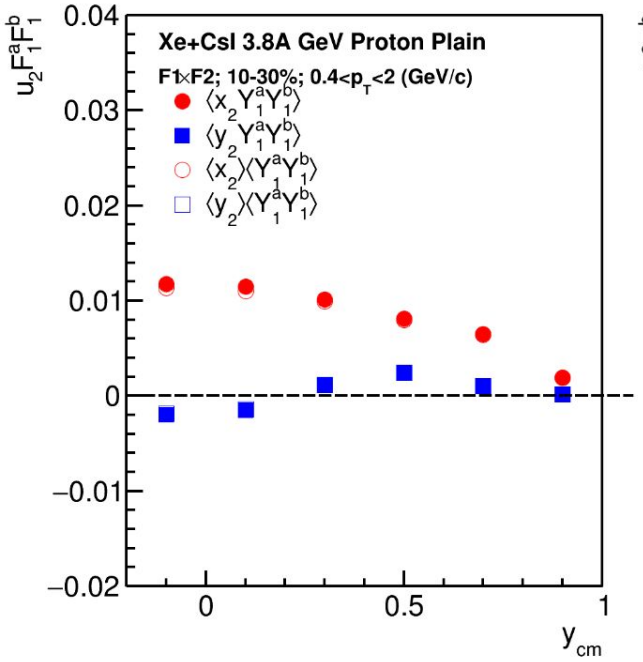


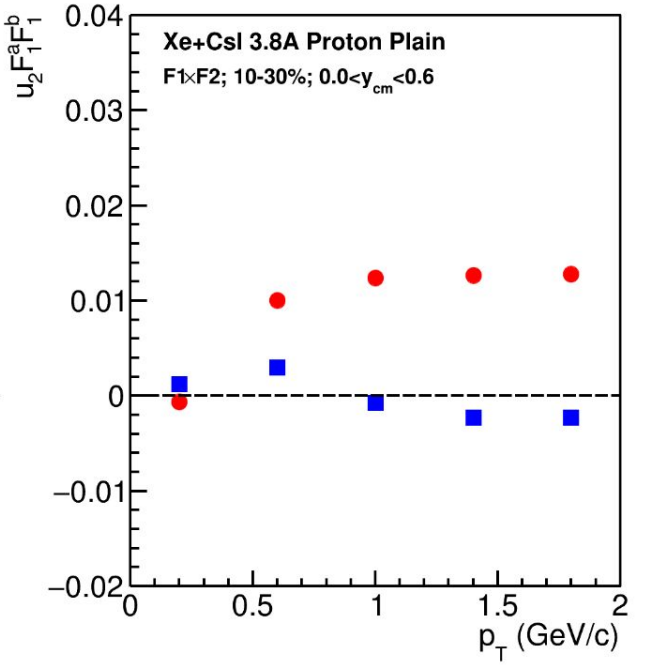


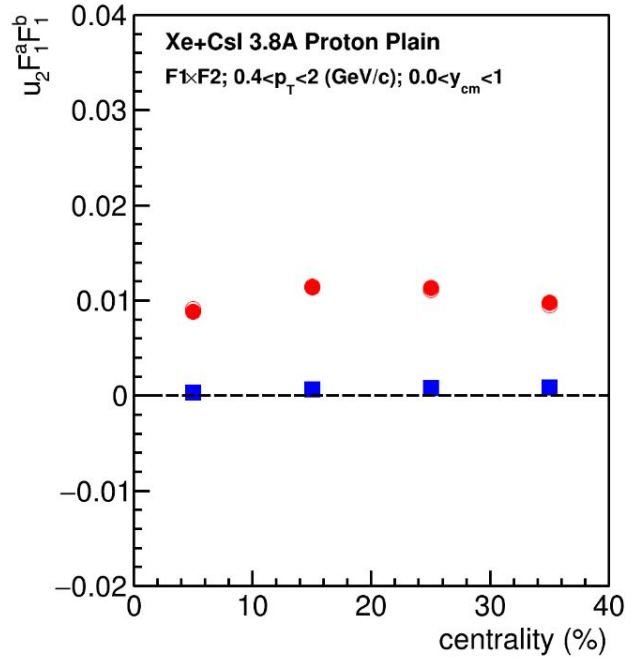


Xe+CsI at 3.8A GeV

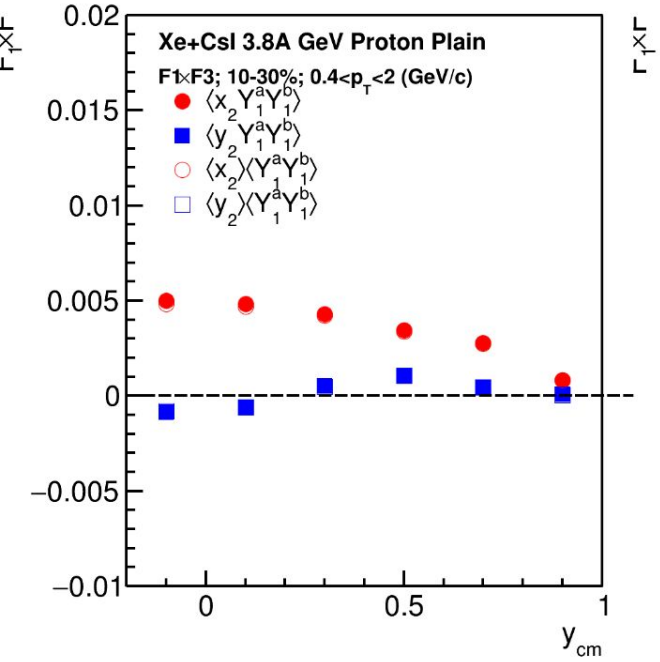
Protons x Rec. F1 x Rec. F2

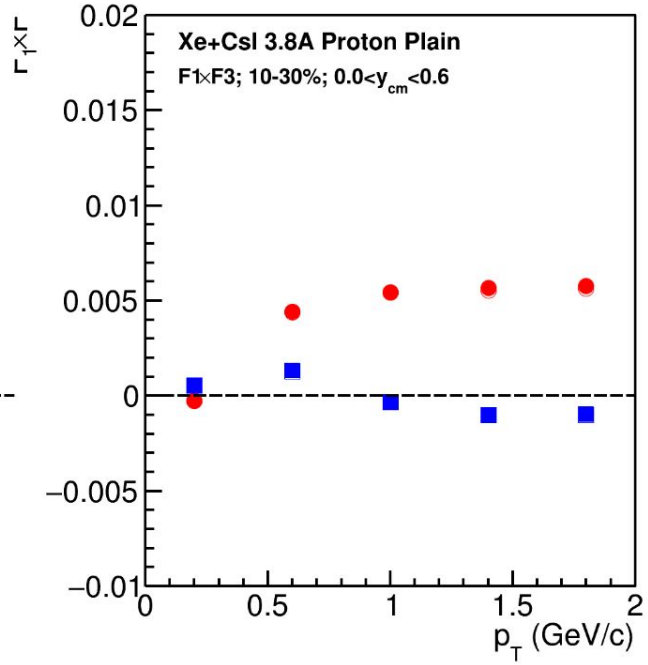


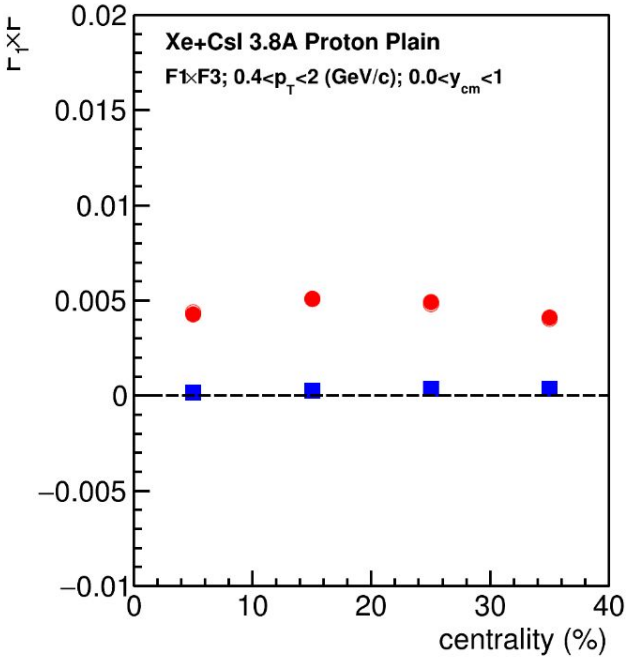




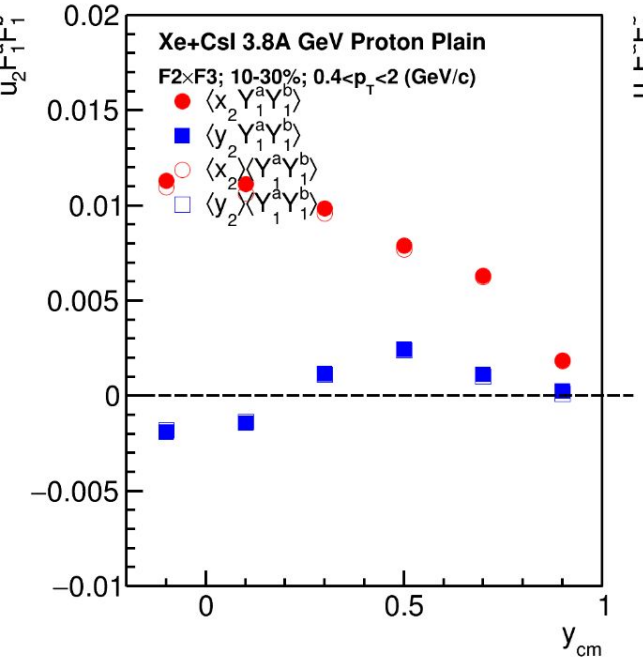
Protons x Rec. F1 x Rec. F3

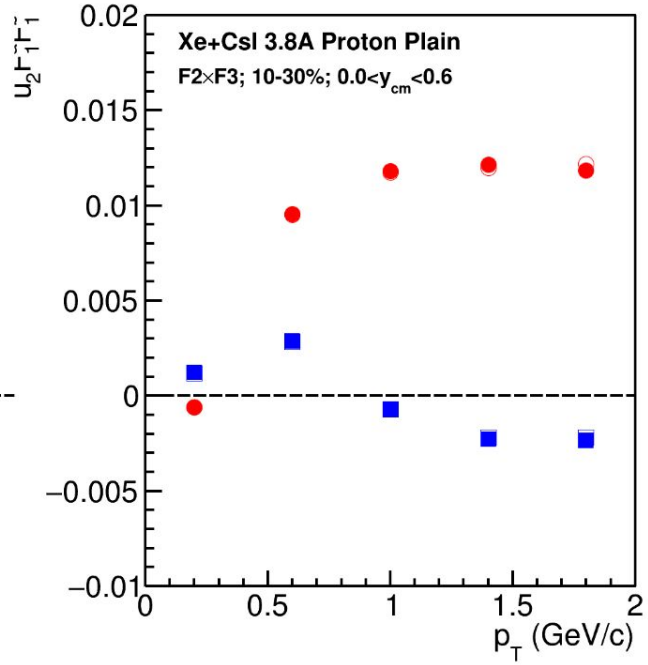


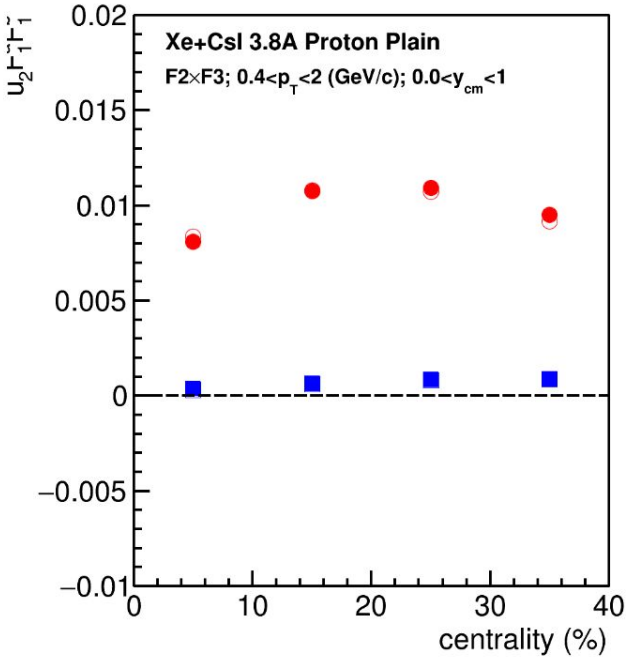




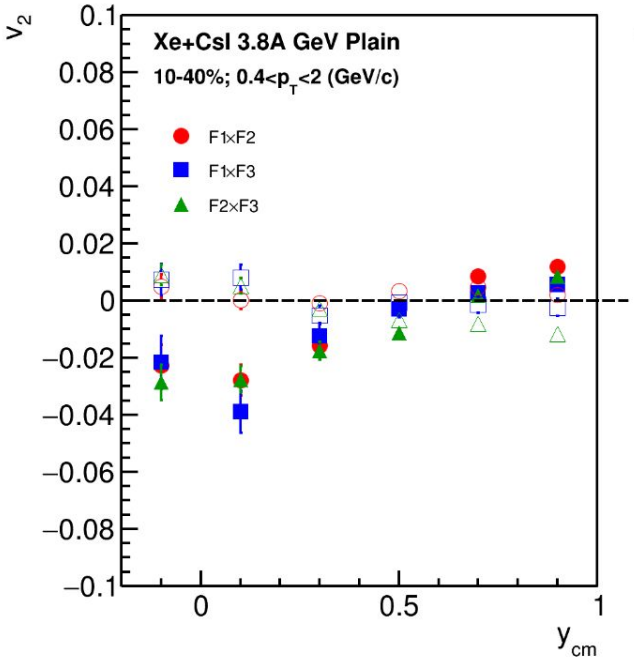
Protons x Rec. F2 x Rec. F3

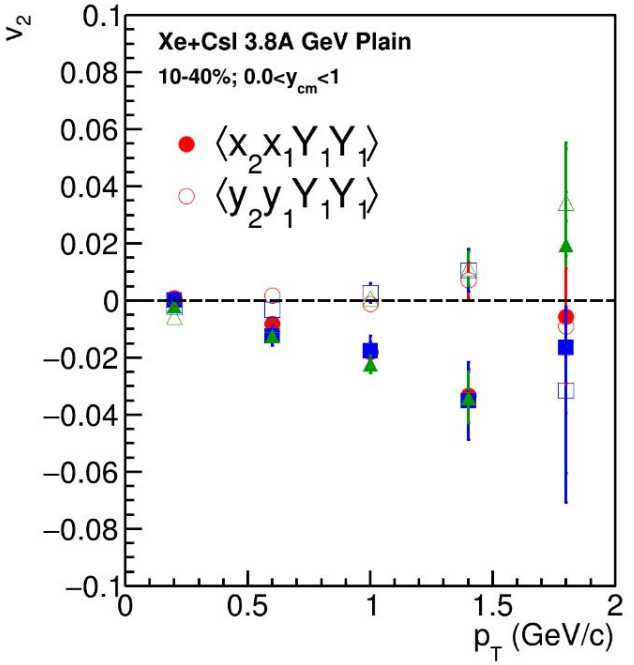


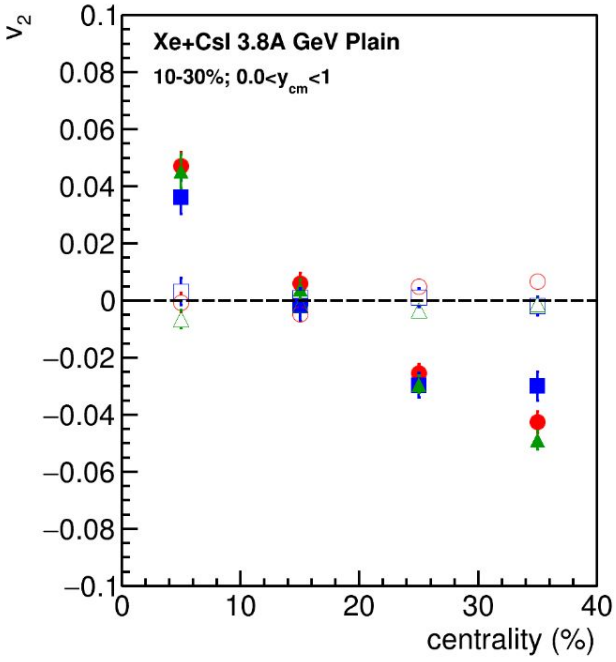




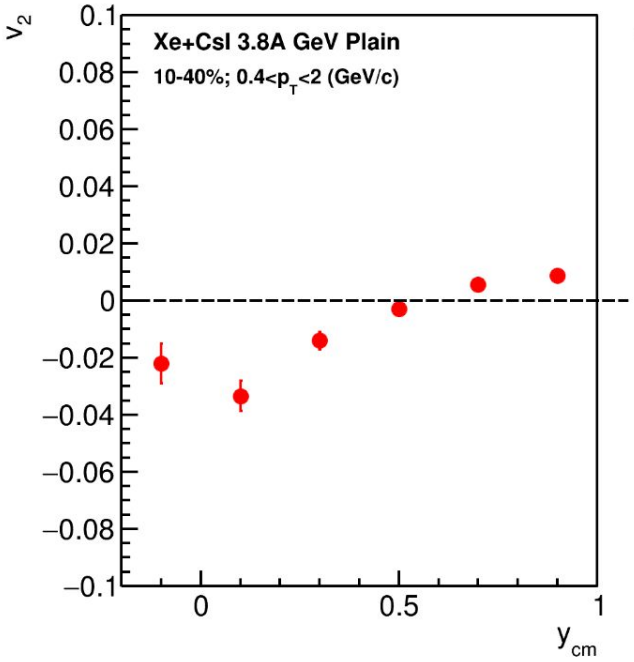
Corrected proton v_2

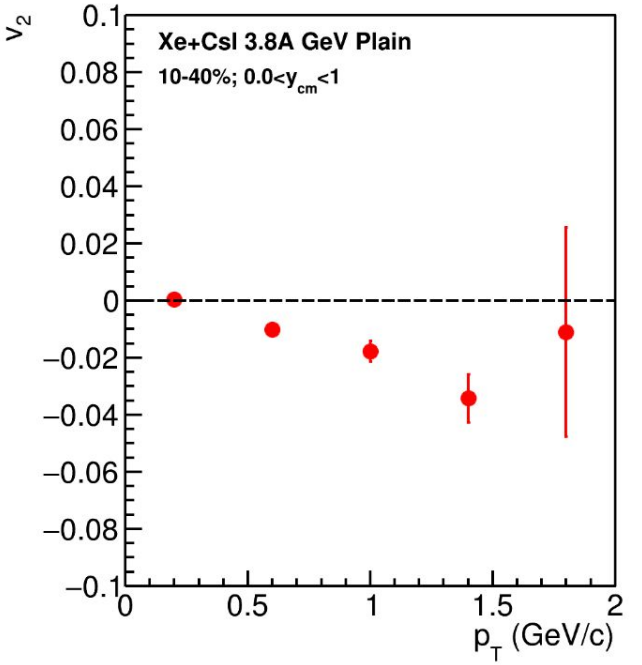


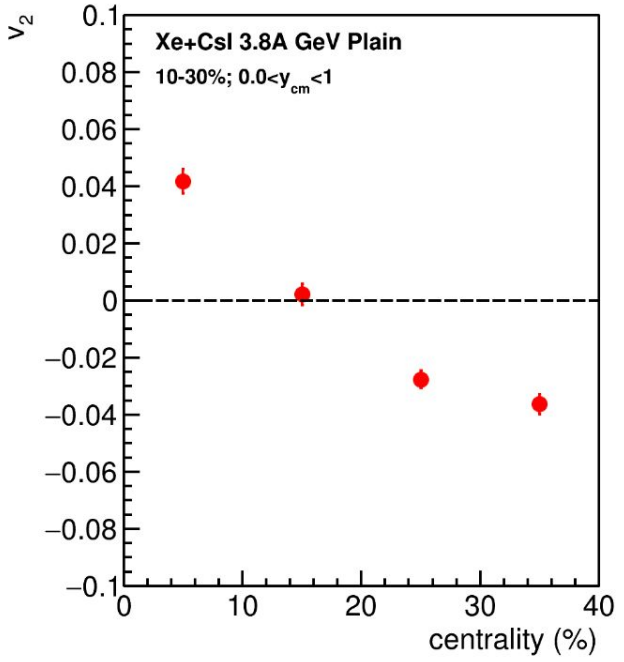




Corrected proton v_2

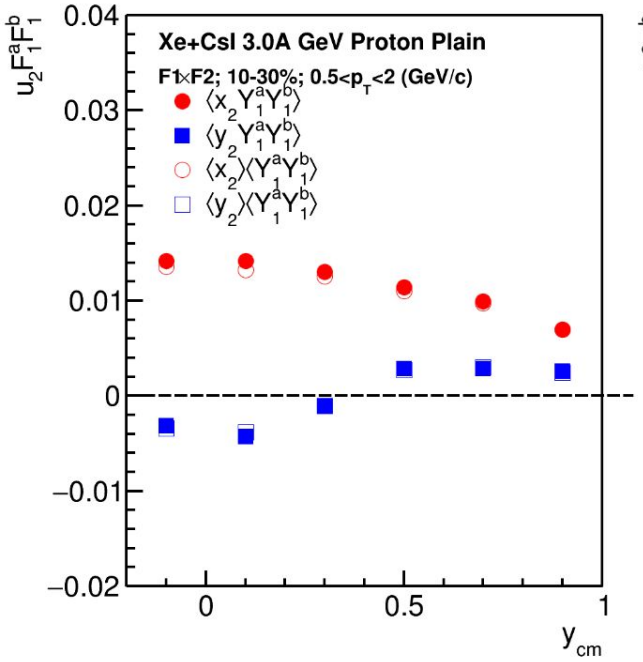


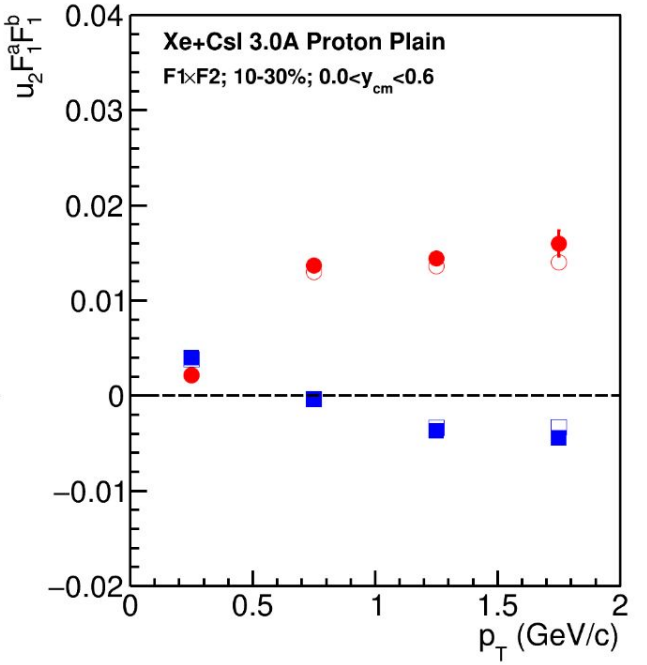


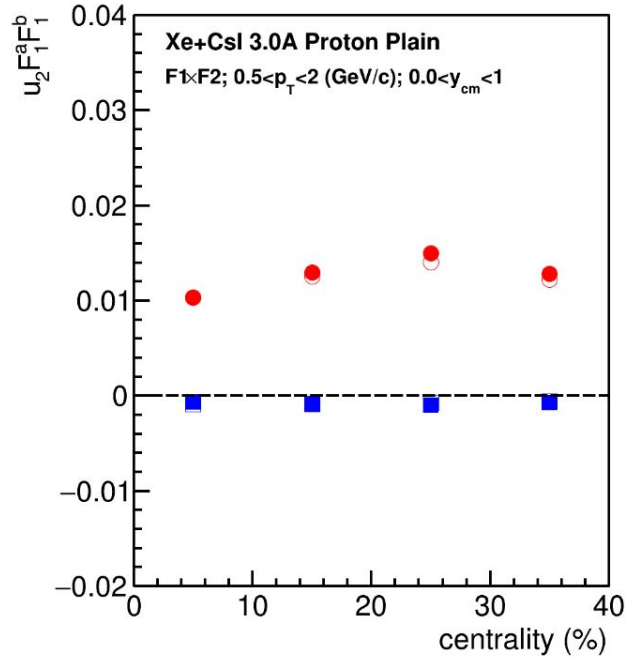


Xe+CsI at 3.0A GeV

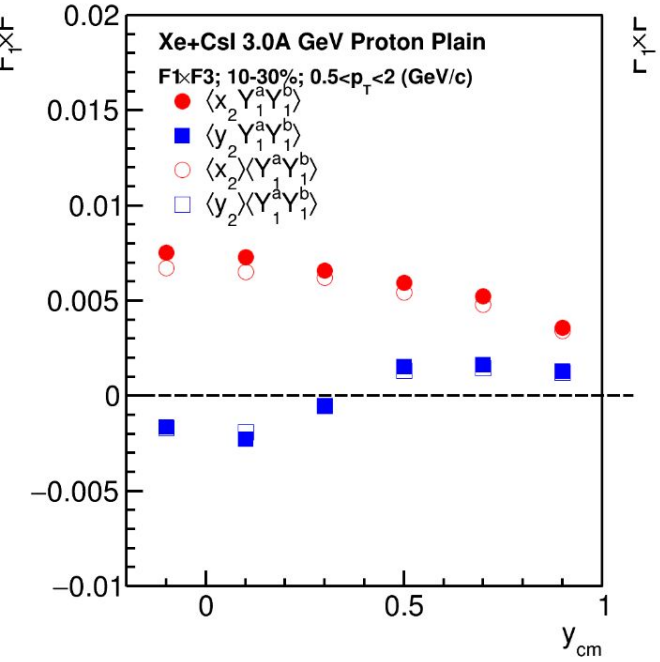
Protons x Rec. F1 x Rec. F2

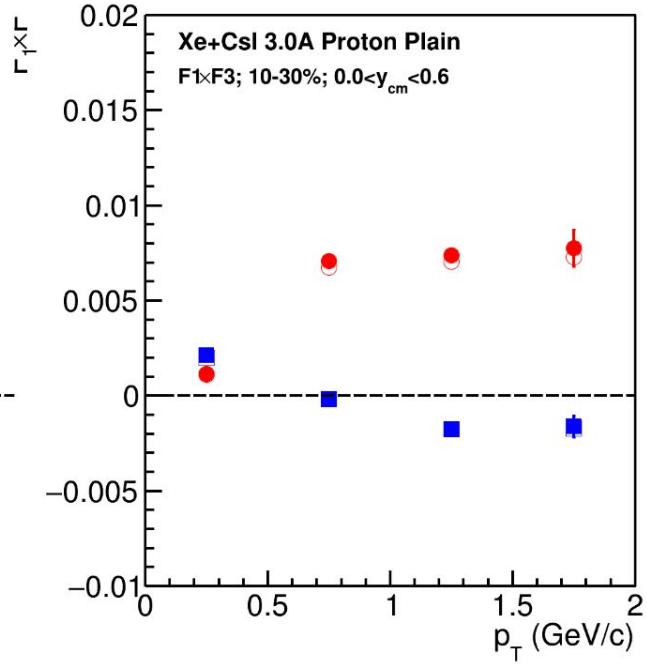


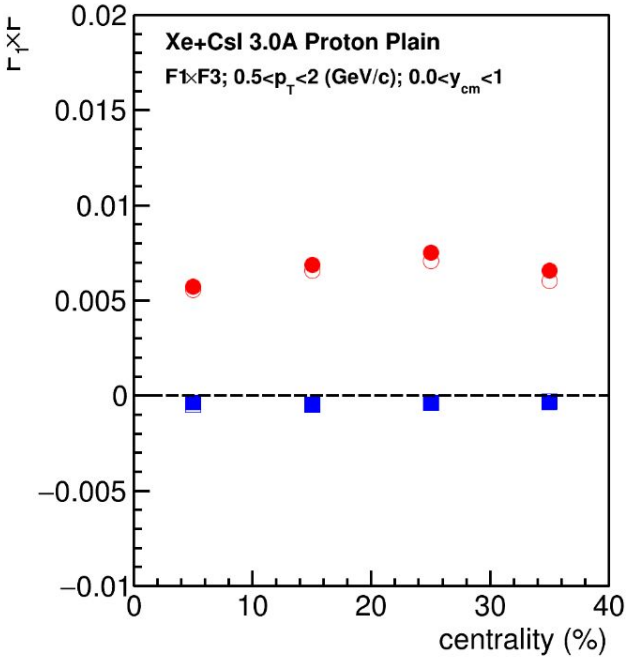




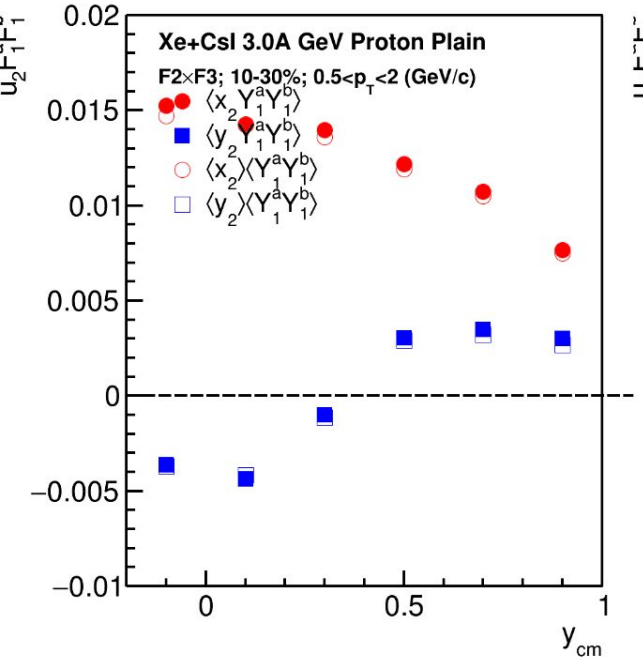
Protons x Rec. F1 x Rec. F3

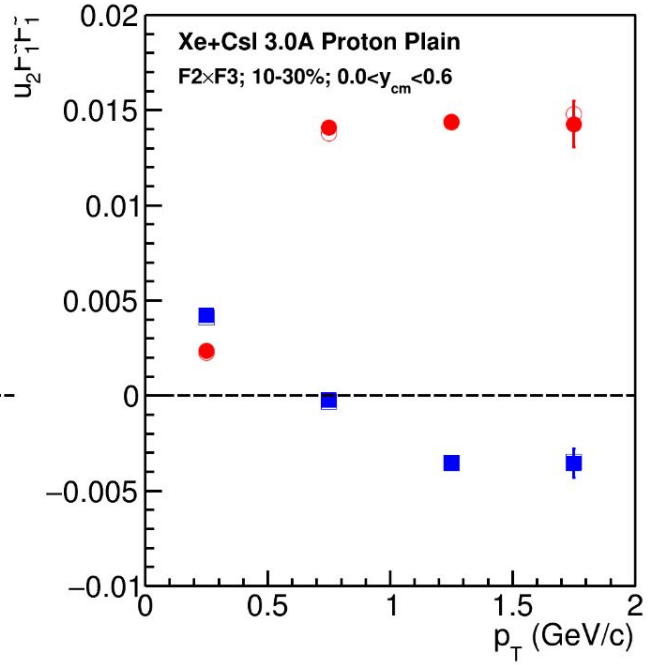


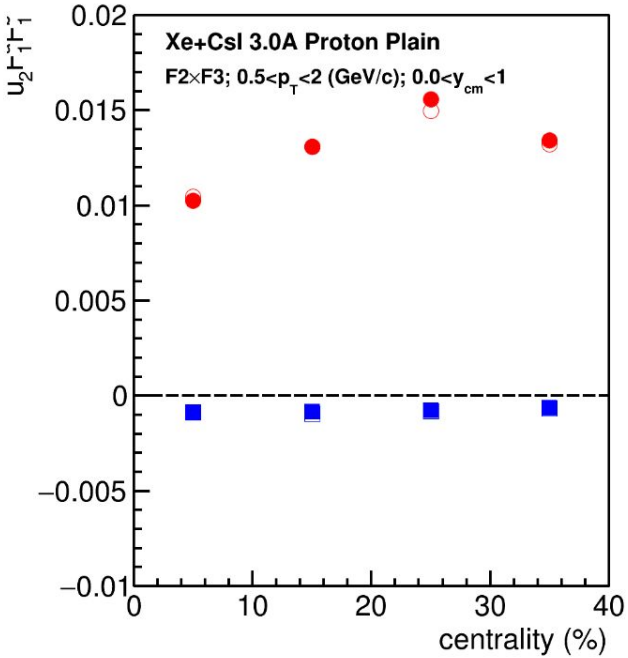




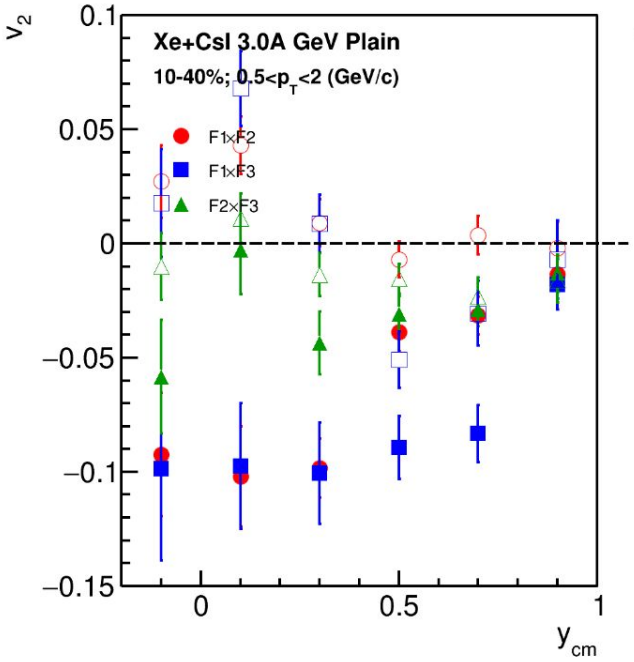
Protons x Rec. F2 x Rec. F2

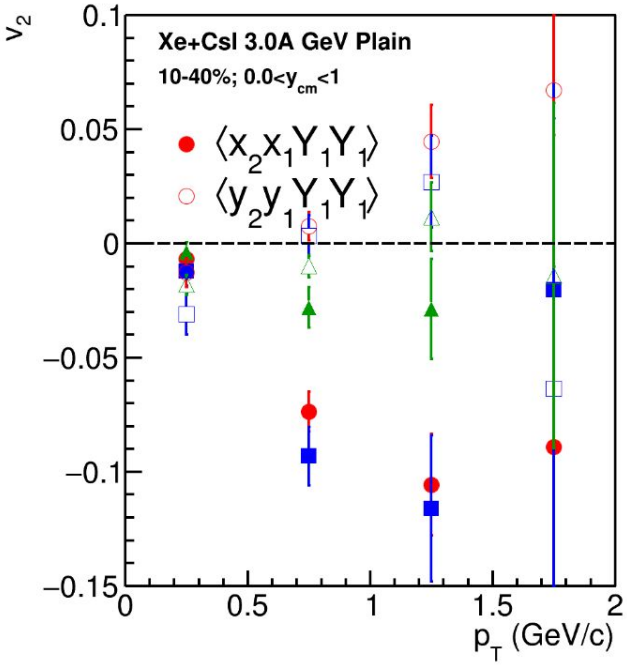


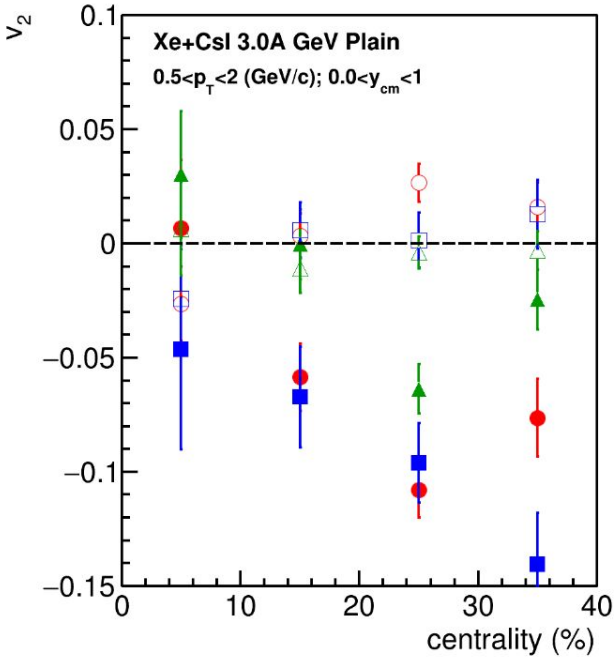




Protons x Rec. F2 x Rec. F2



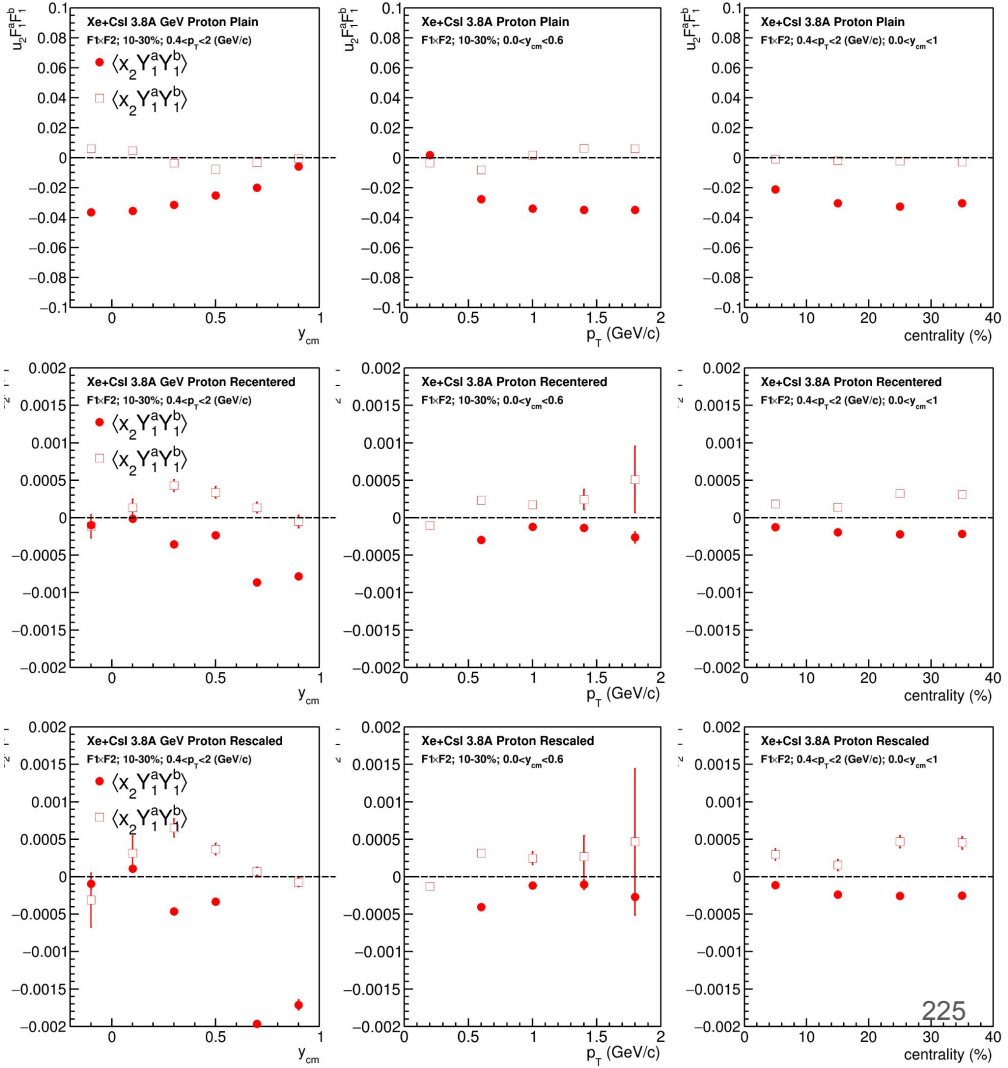




Correlation with F1 and F2

Checking the corrections on u-vector, FHCal vectors are Rescaled-corrected

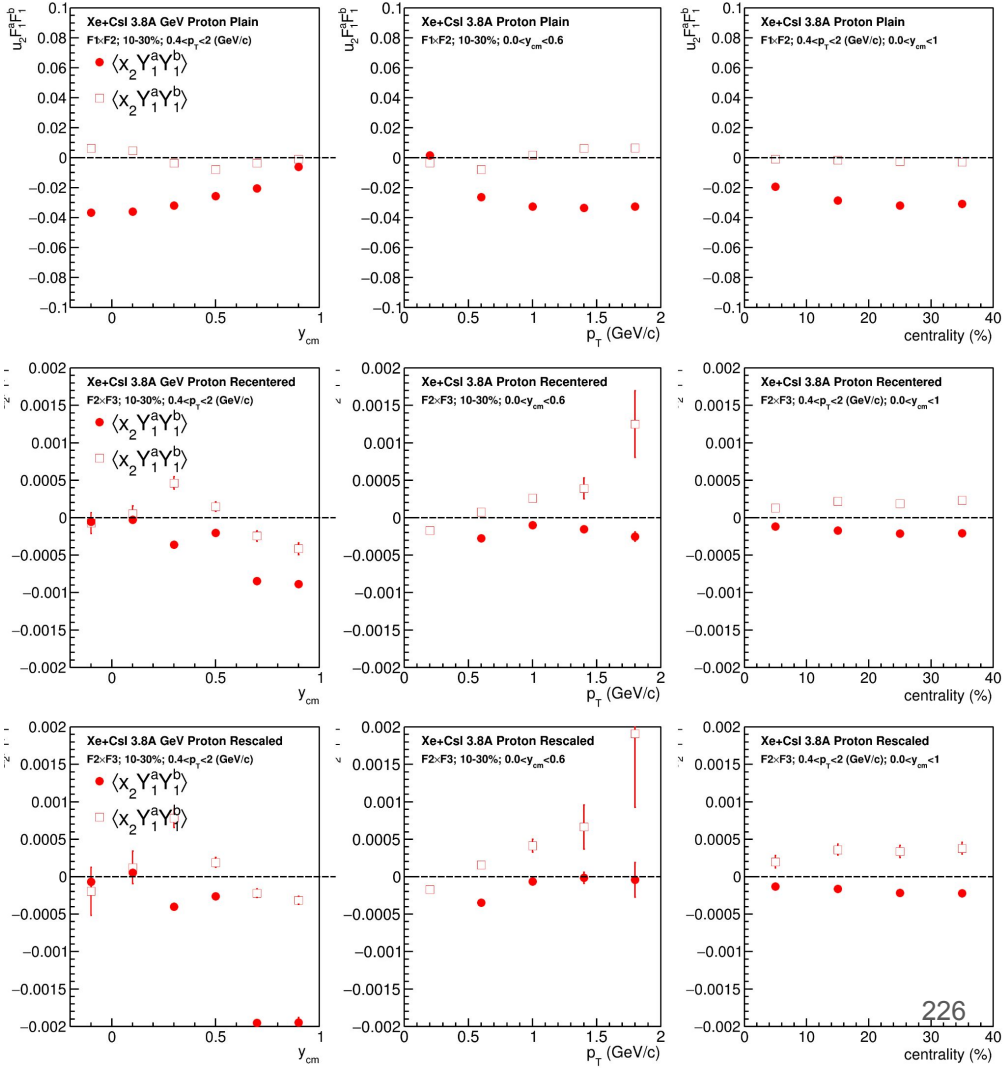
- After applying recentering on u-vector, correlation drops 10 times



Correlation with F2 and F3

Checking the corrections on u-vector, FHCal vectors are Rescaled-corrected

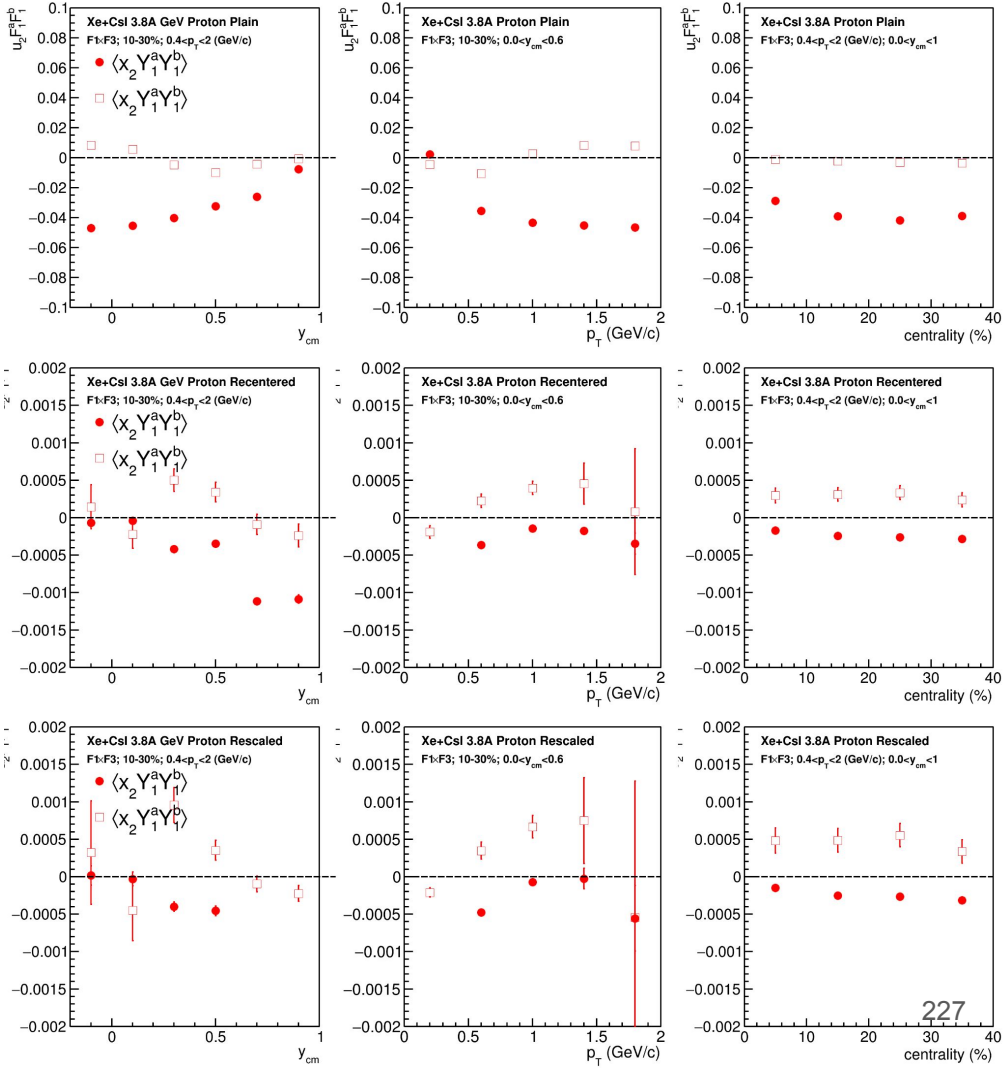
- After applying recentering on u-vector, correlation drops 10 times



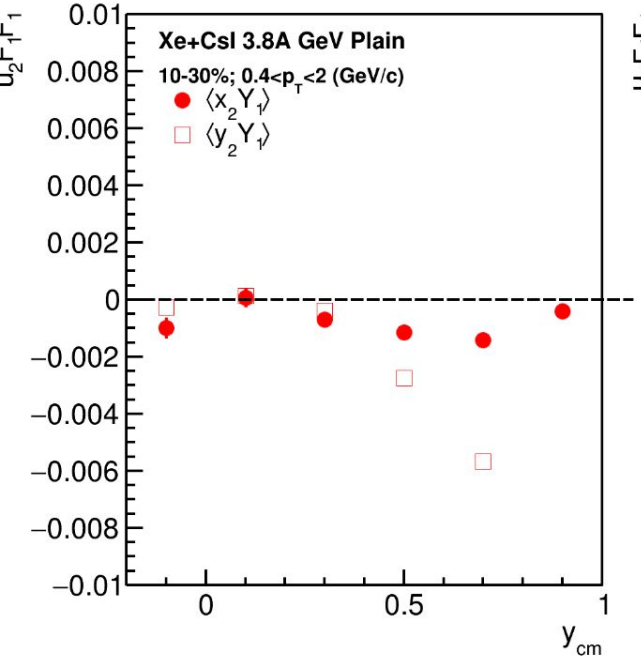
Correlation with F1 and F3

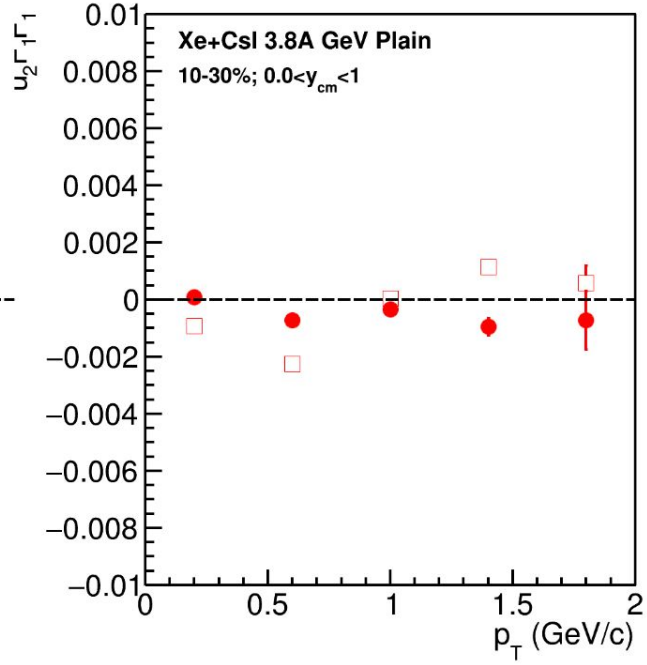
Checking the corrections on u-vector, FHCal vectors are Rescaled-corrected

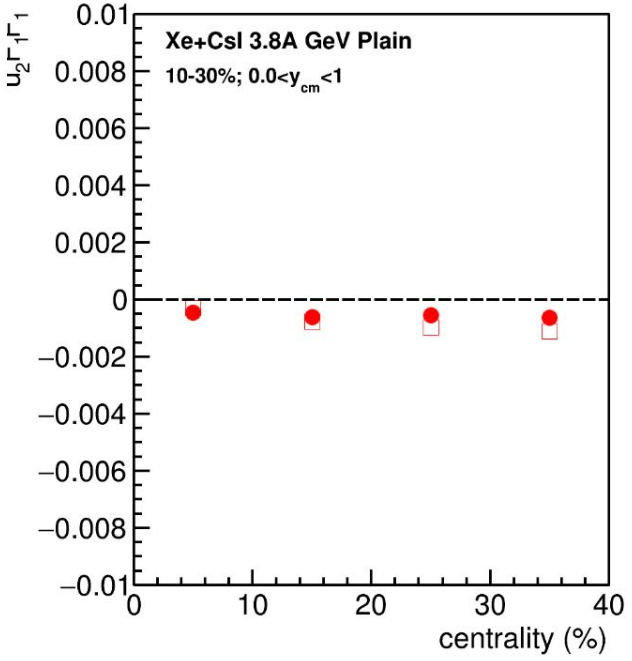
- After applying recentering on u-vector, correlation drops 10 times



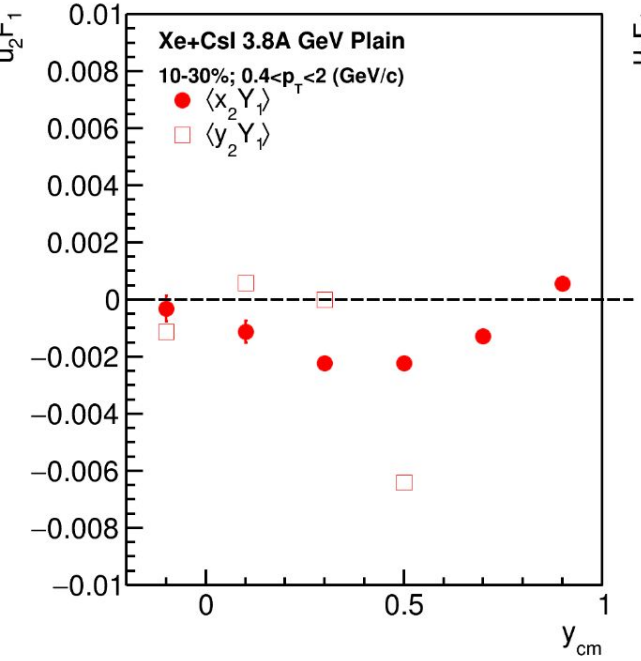
Plain proton with single F1

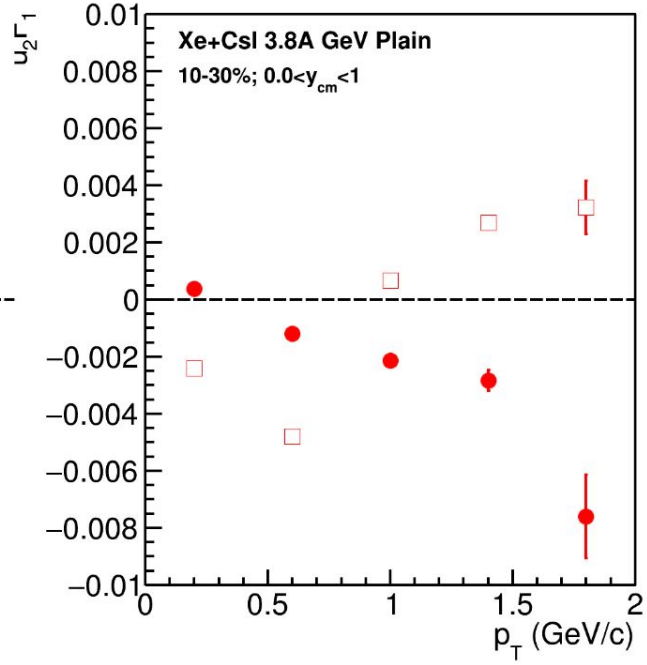


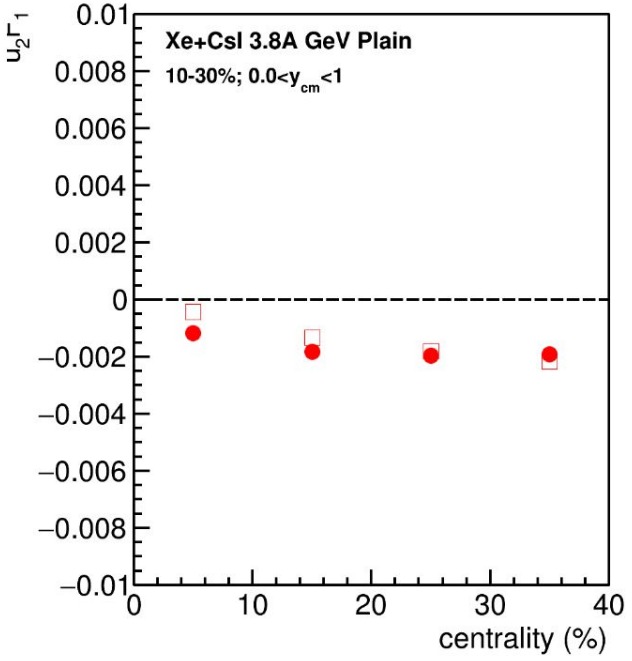




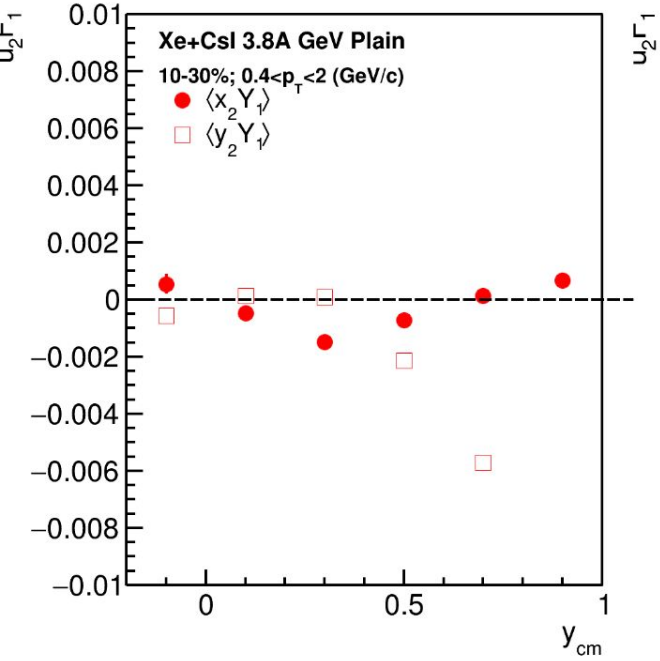
Plain proton with single F2

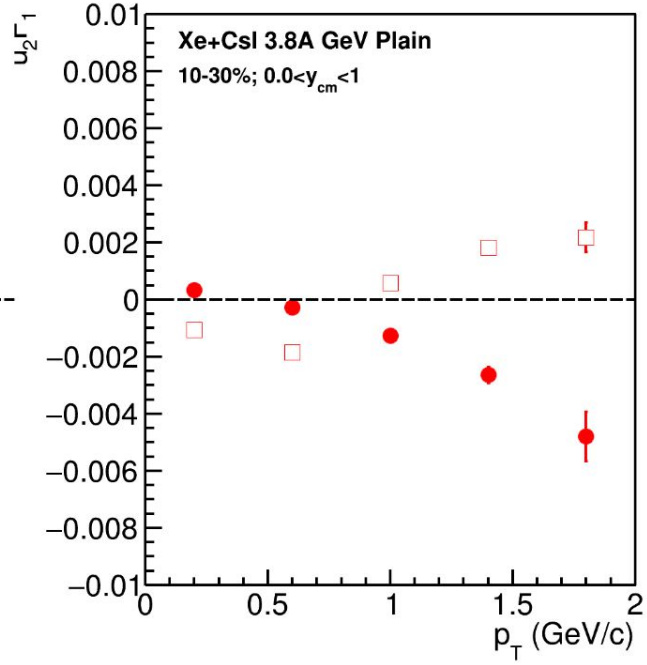


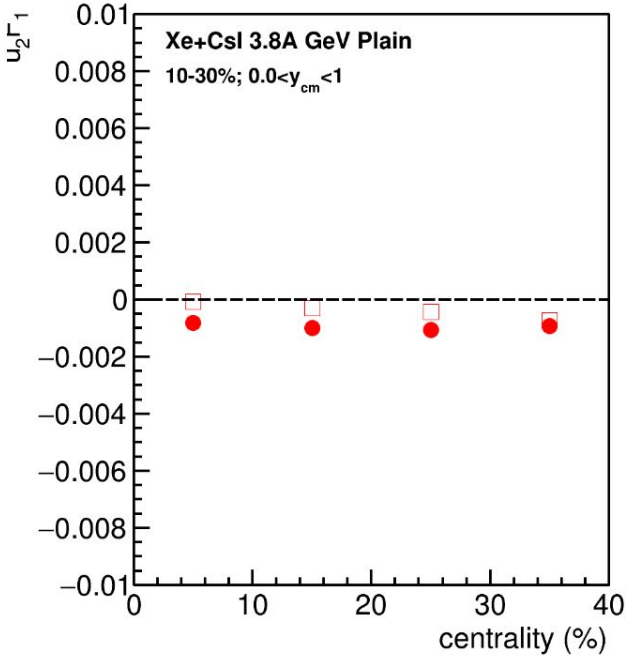




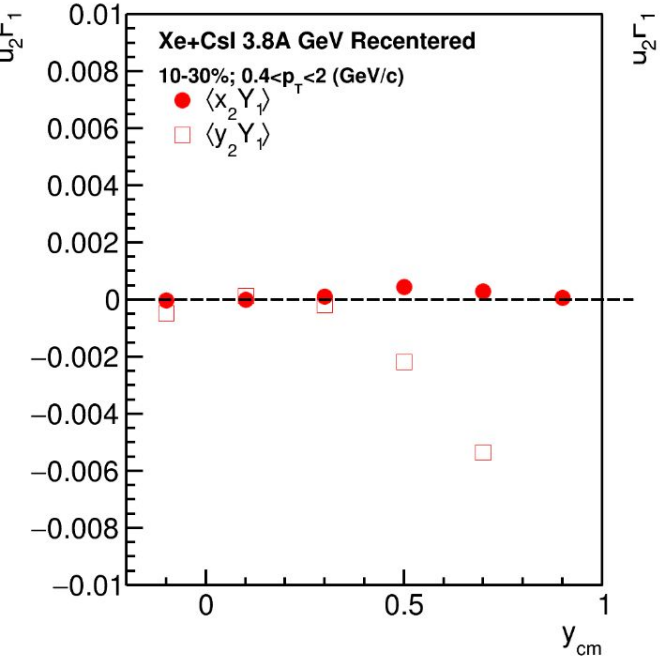
Plain proton with single F3

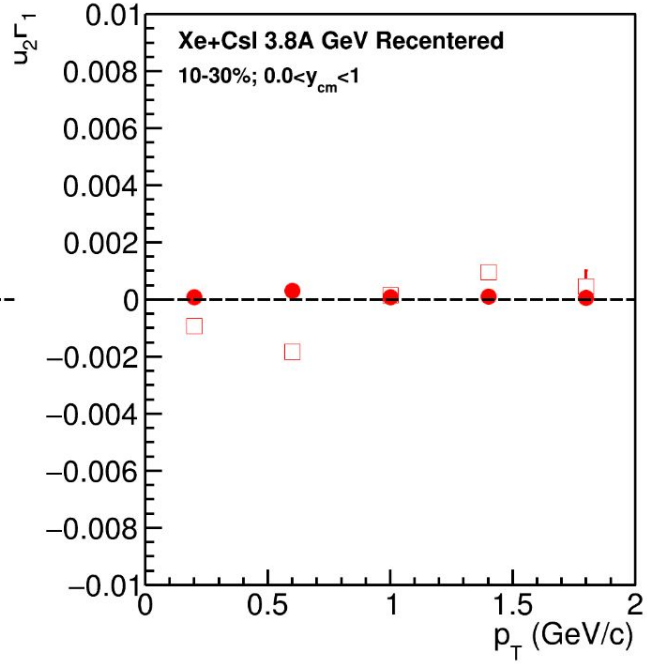


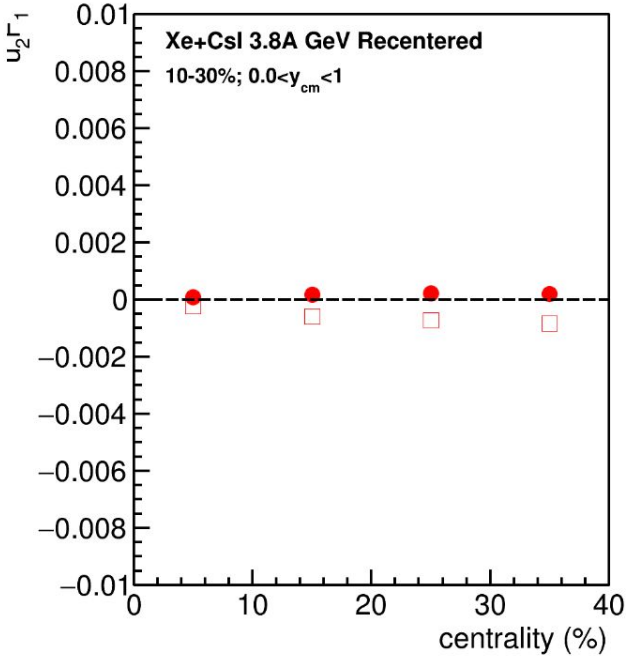




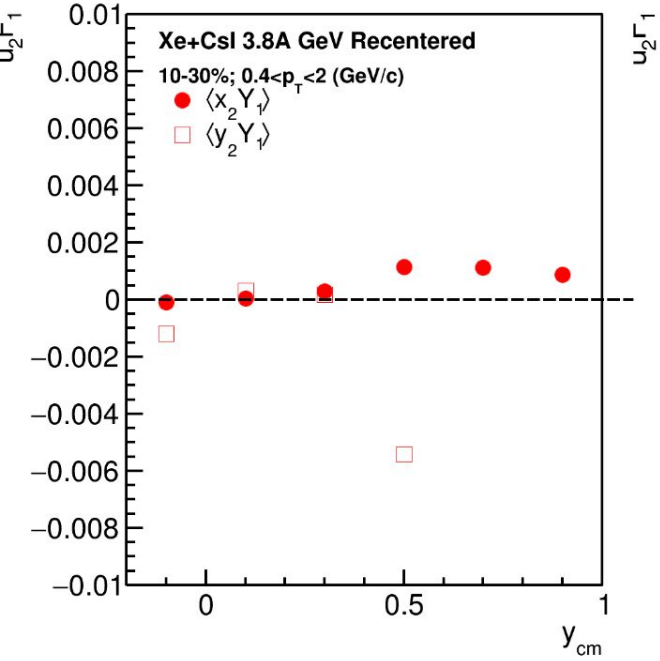
Recentered proton with single F1

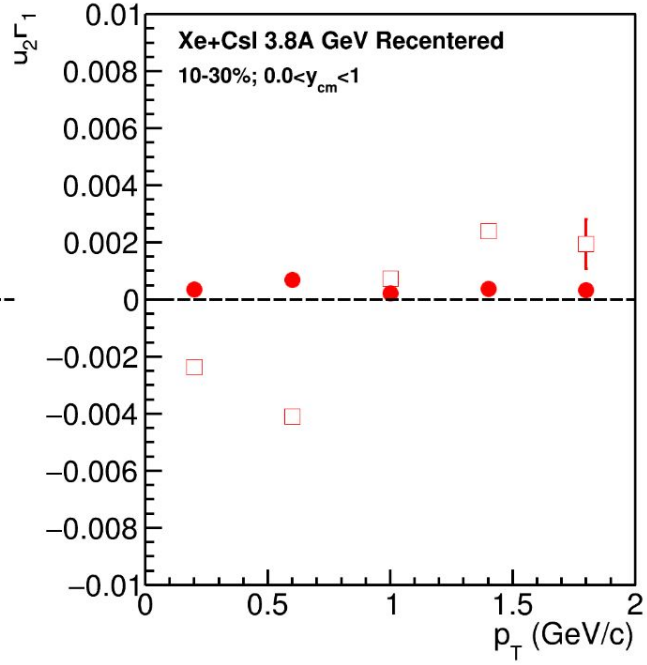


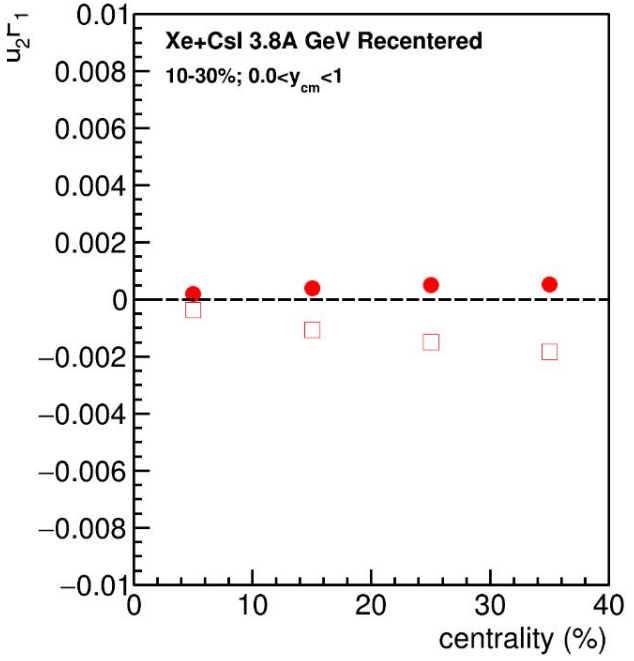




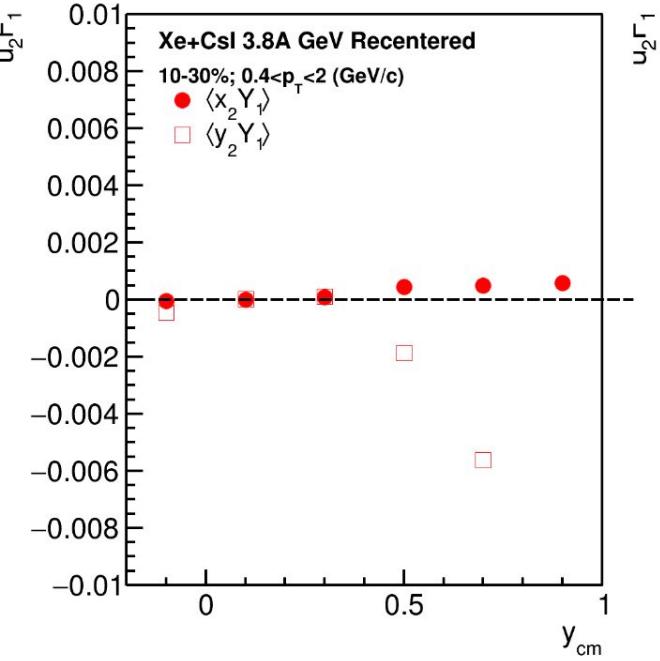
Recentered proton with single F2

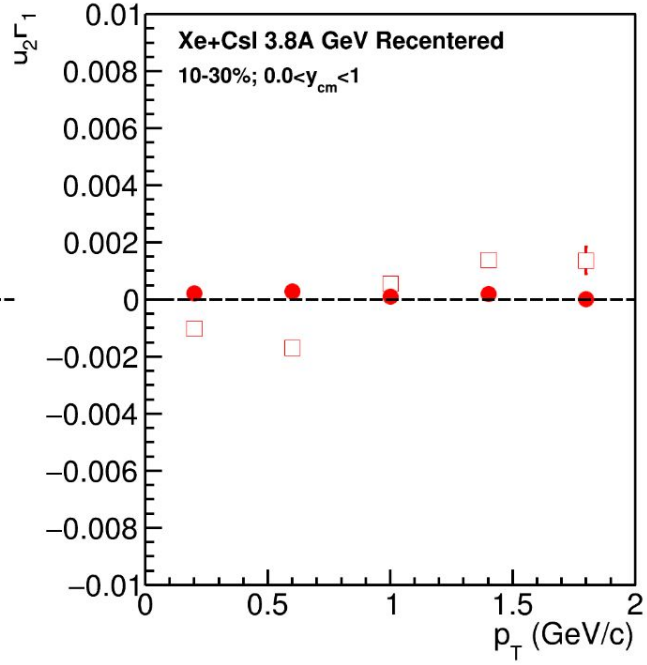


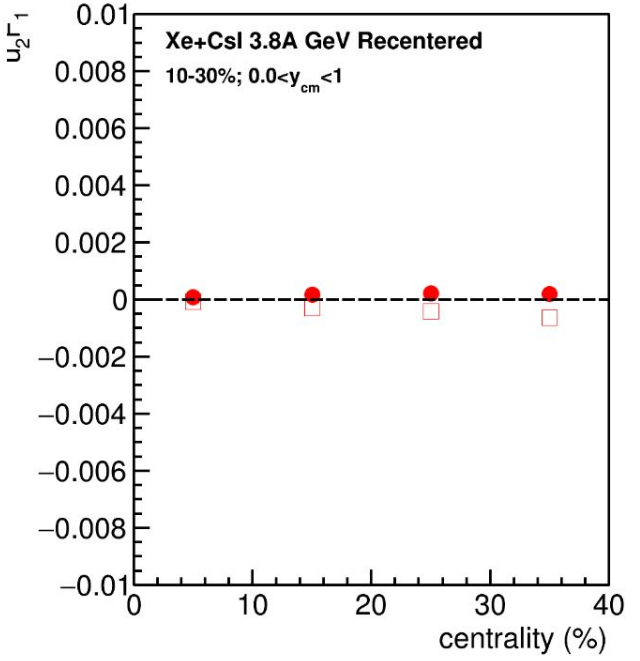




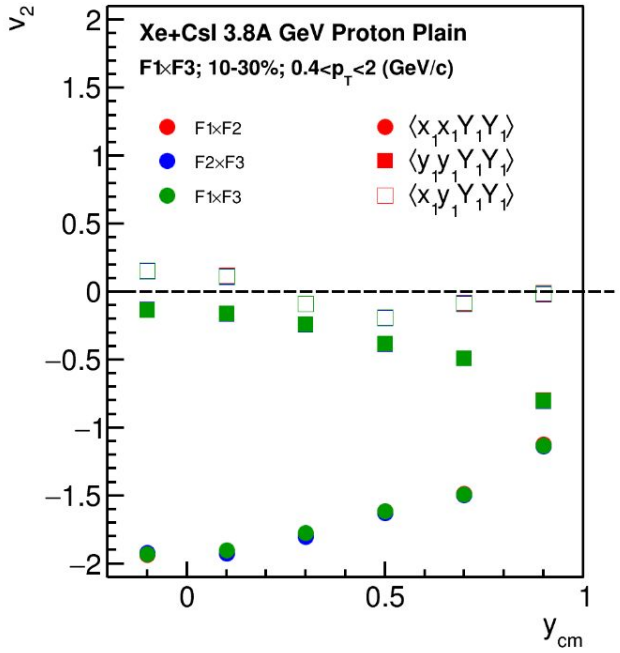
Recentered proton with single F3

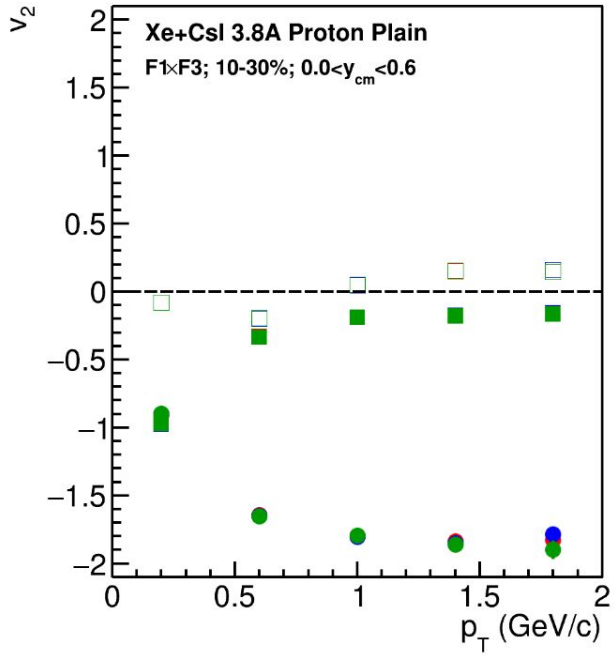


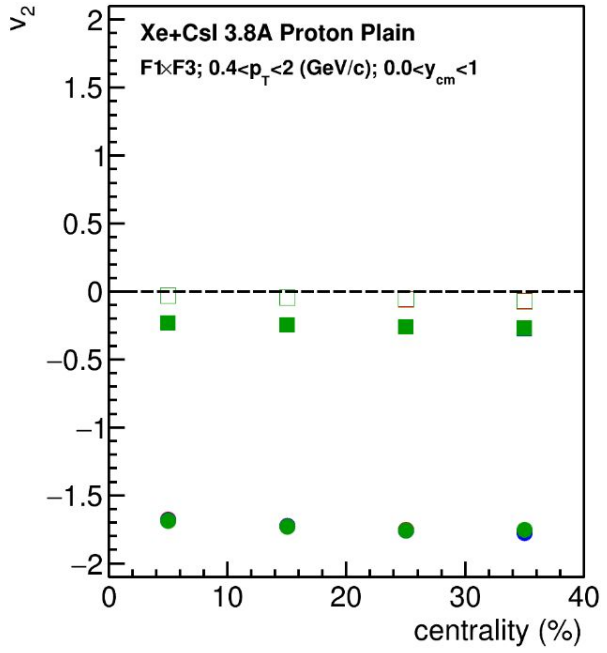




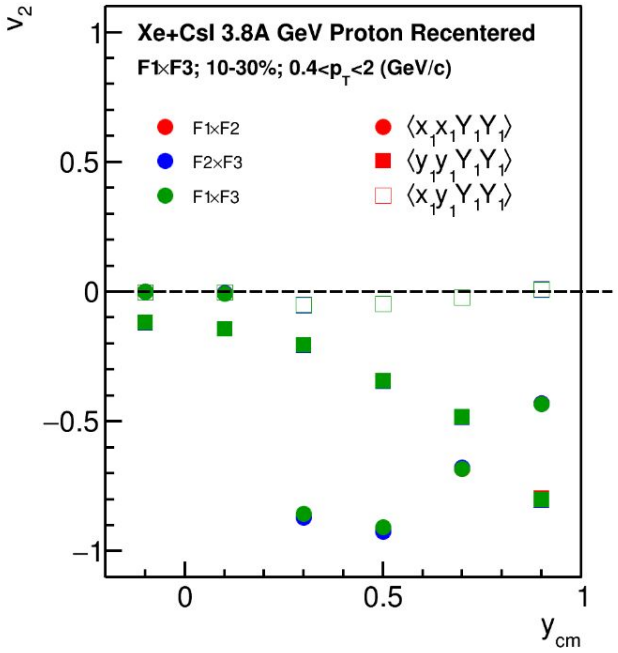
Plain double proton

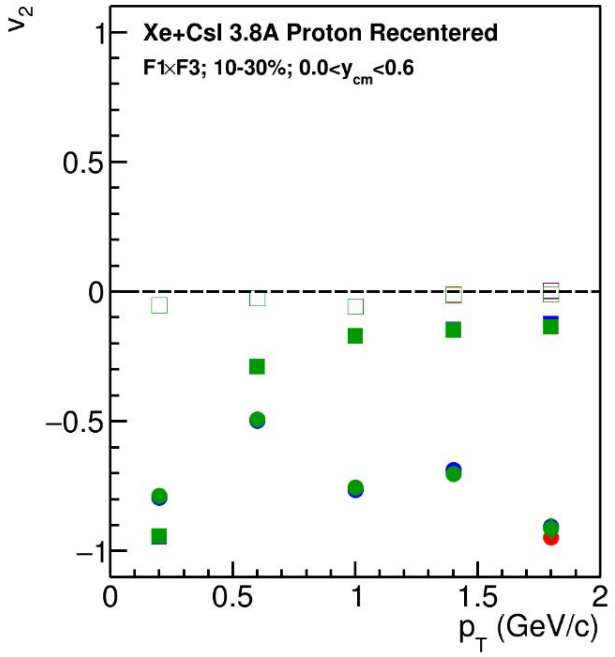


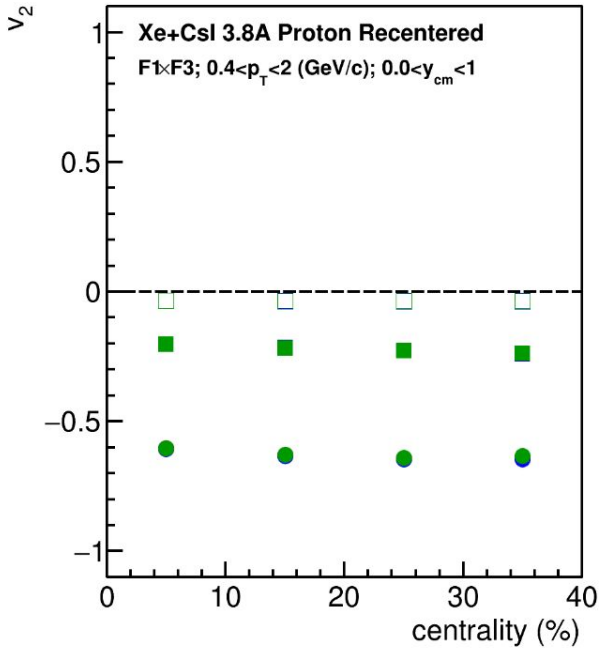




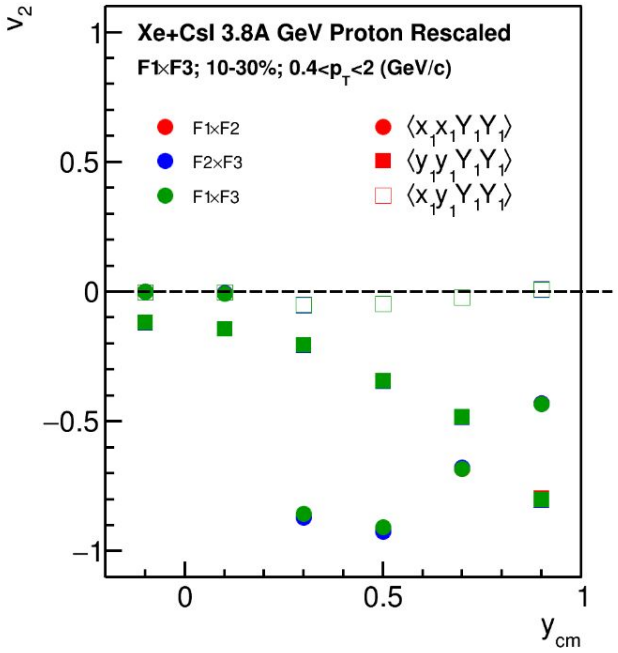
Recentered double

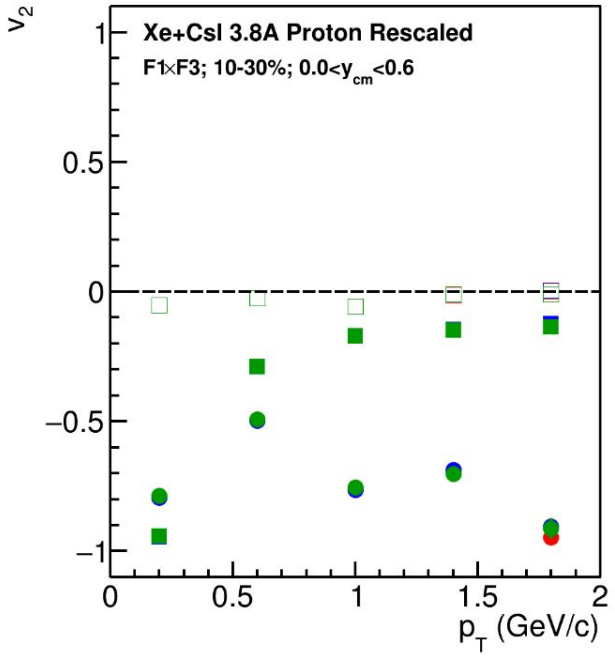


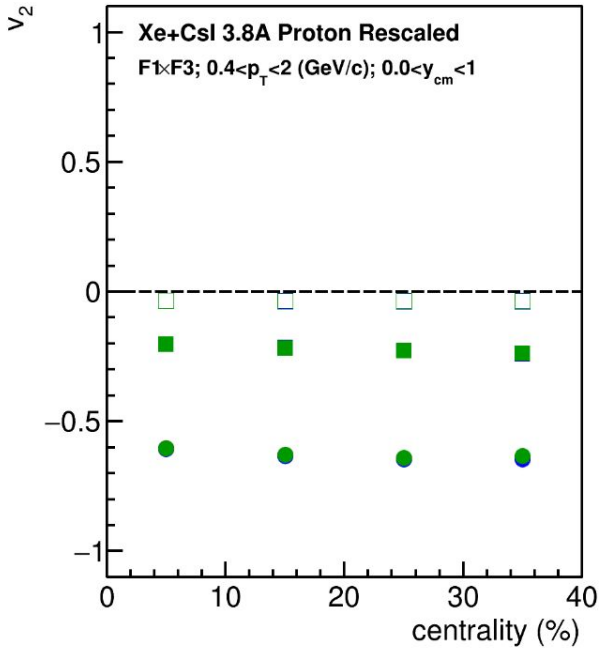




Rescaled double proton

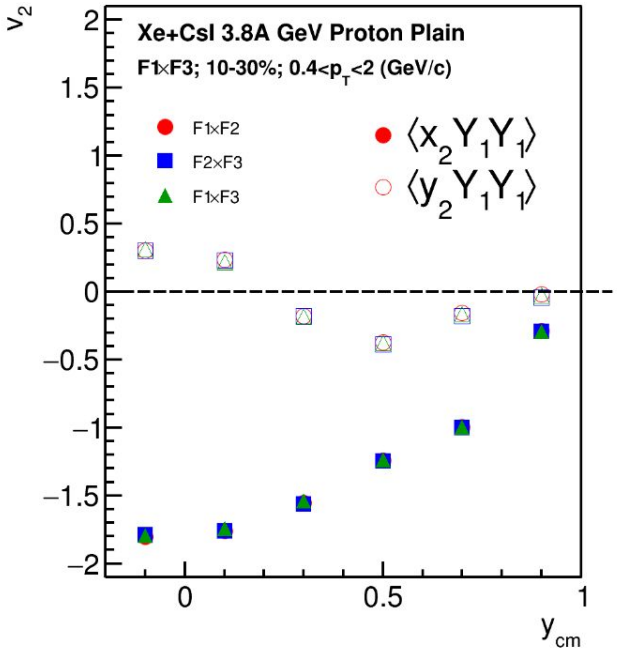


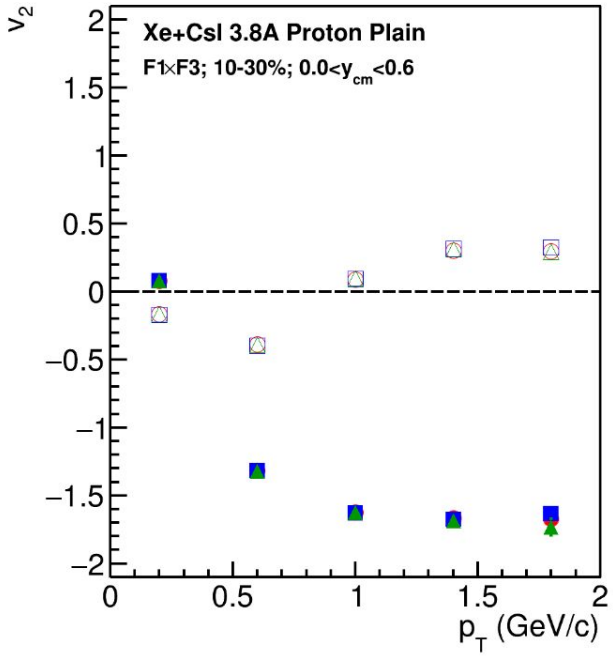


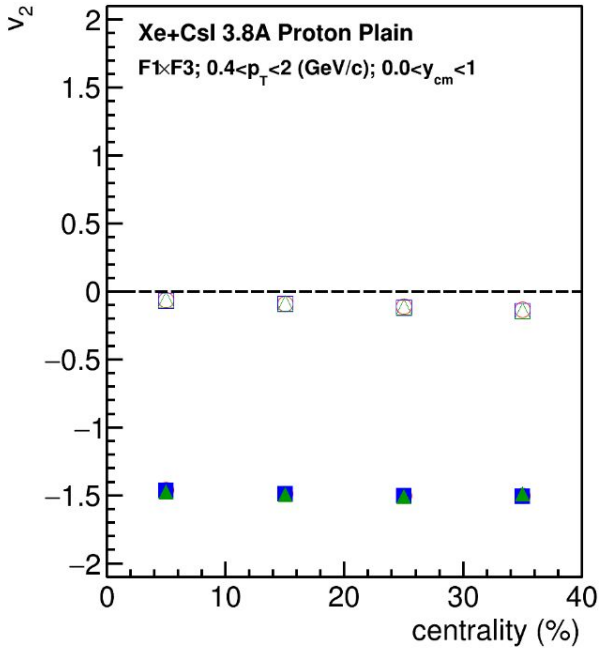


Correlations with recentered F-vectors

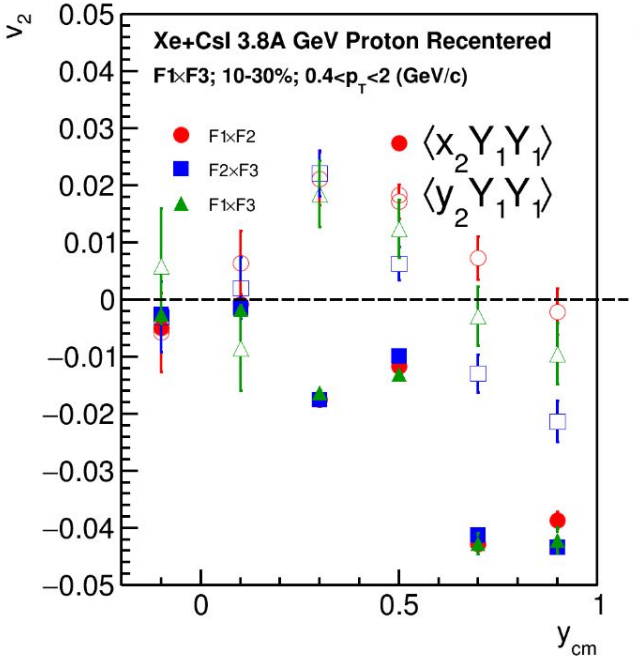
Plain proton v_2

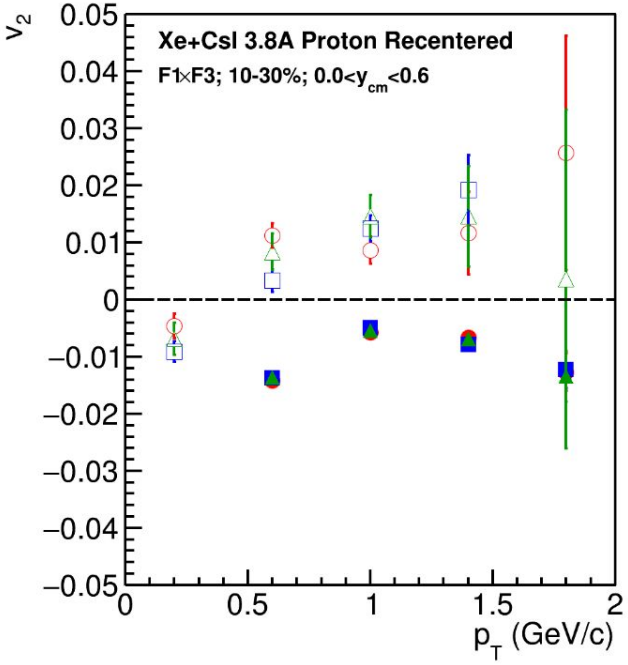


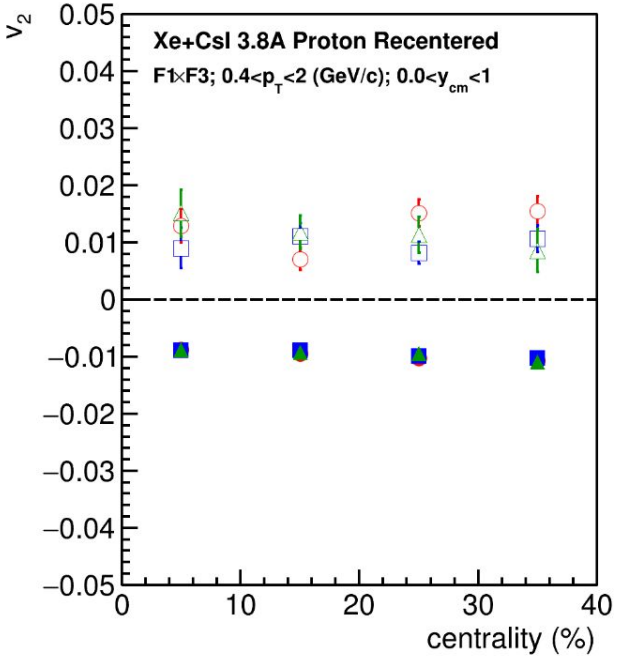




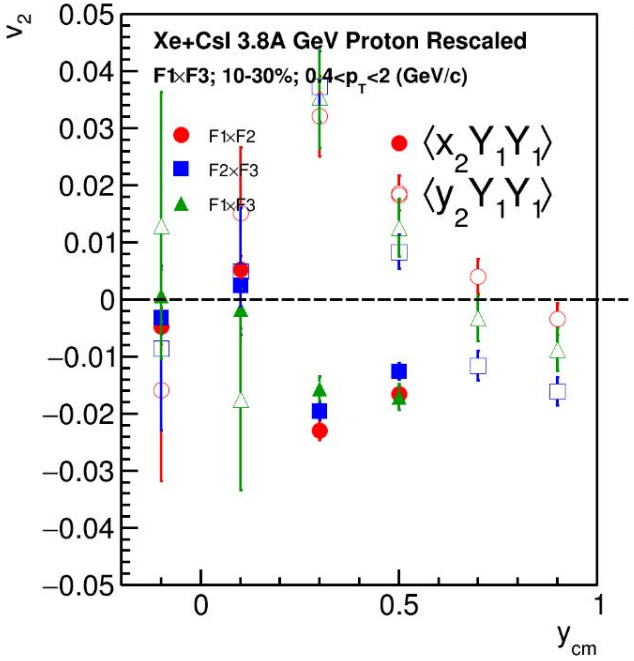
Recentered proton v_2

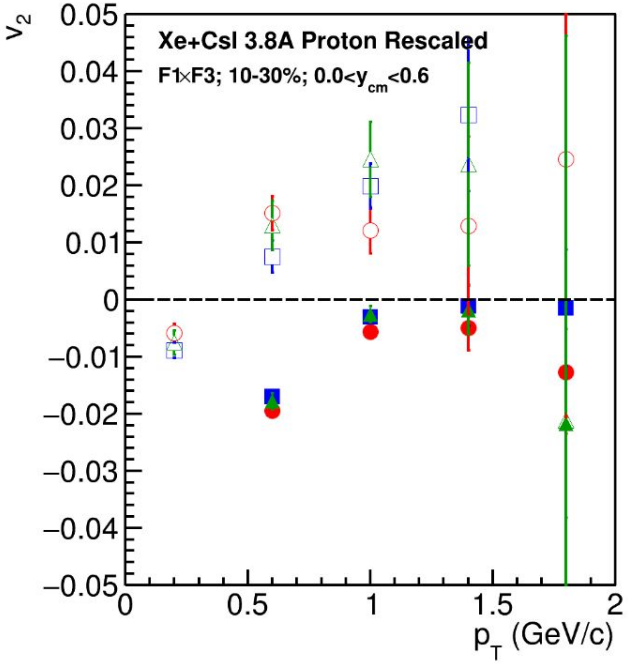


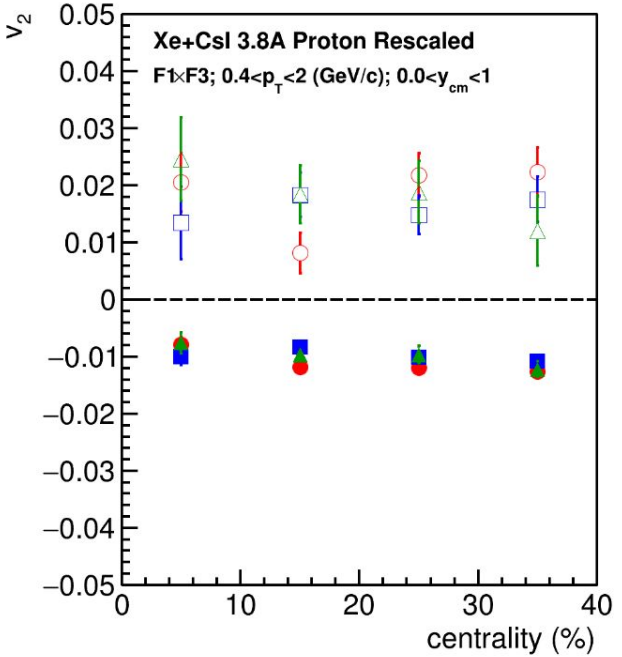




Rescaled proton v_2

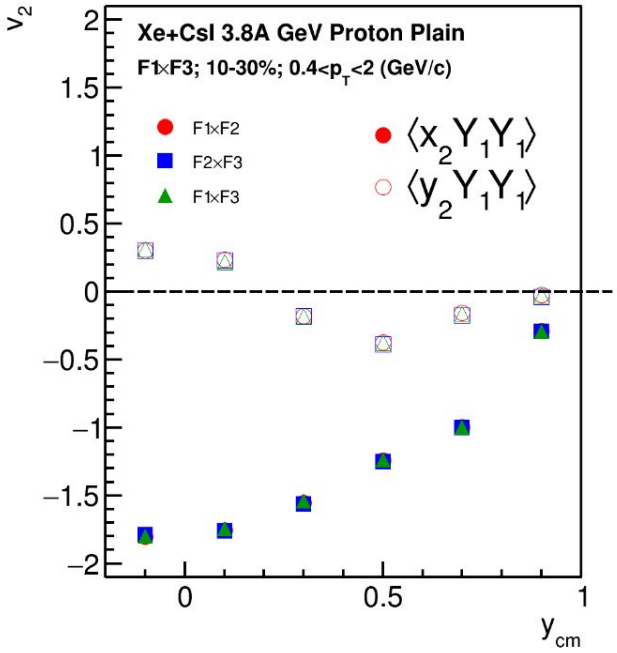


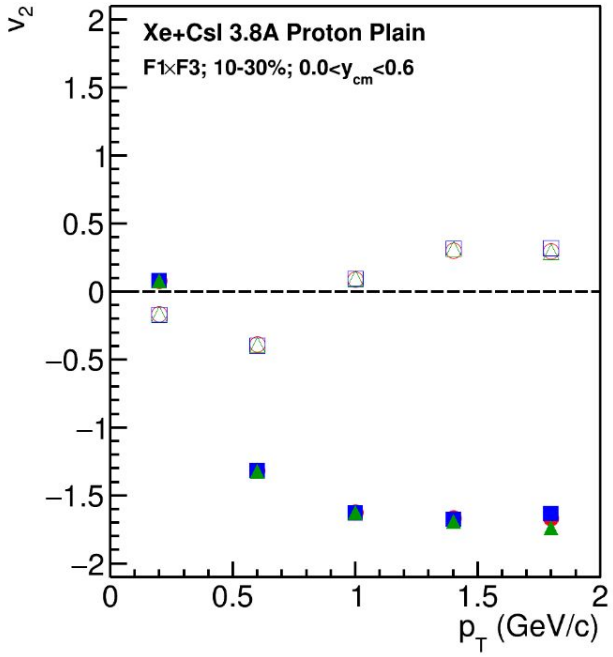


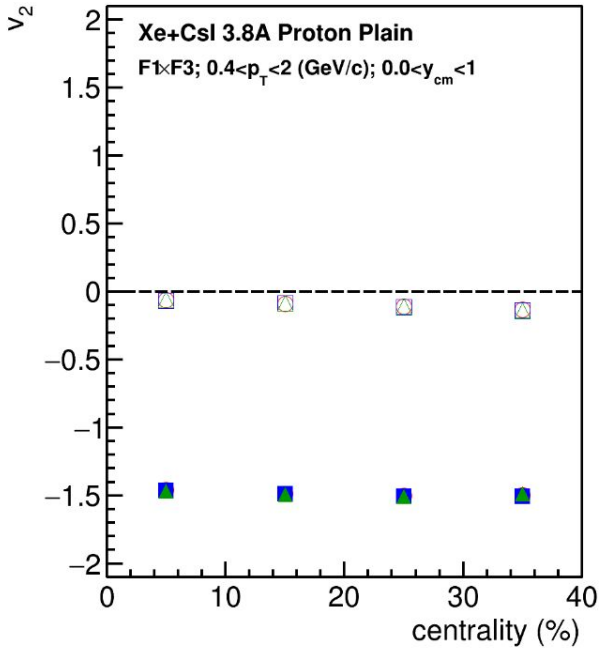


Correlations with rescaled F-vectors

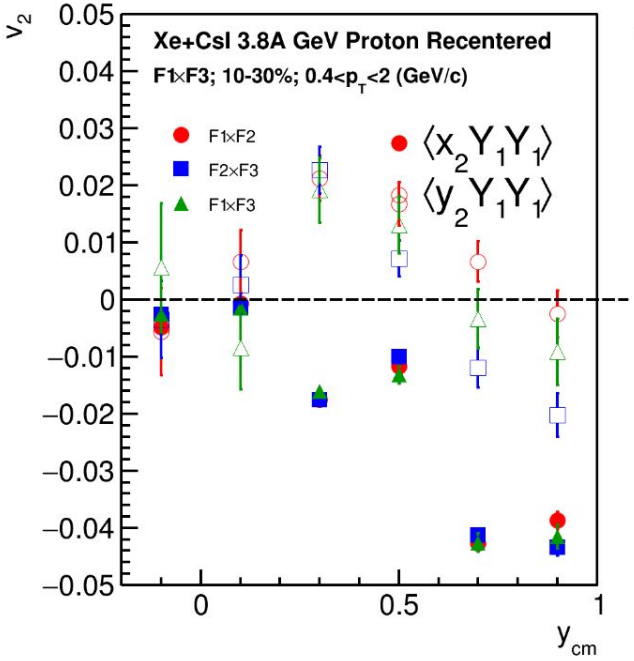
Plain proton v_2

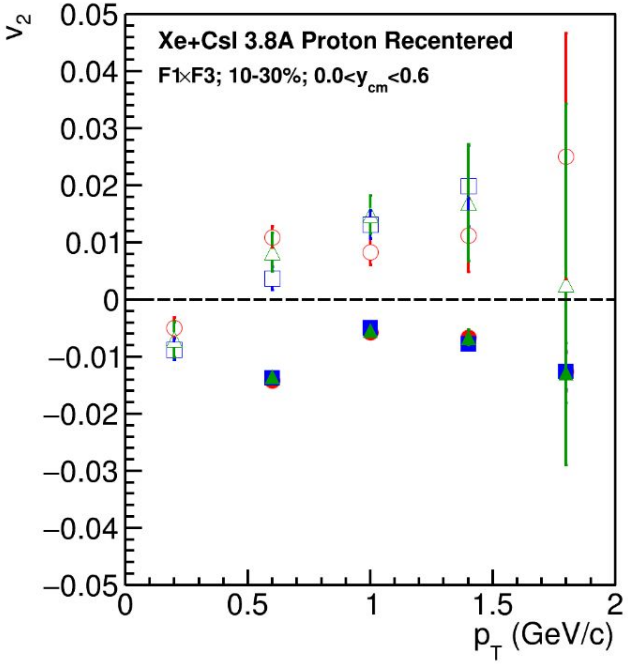


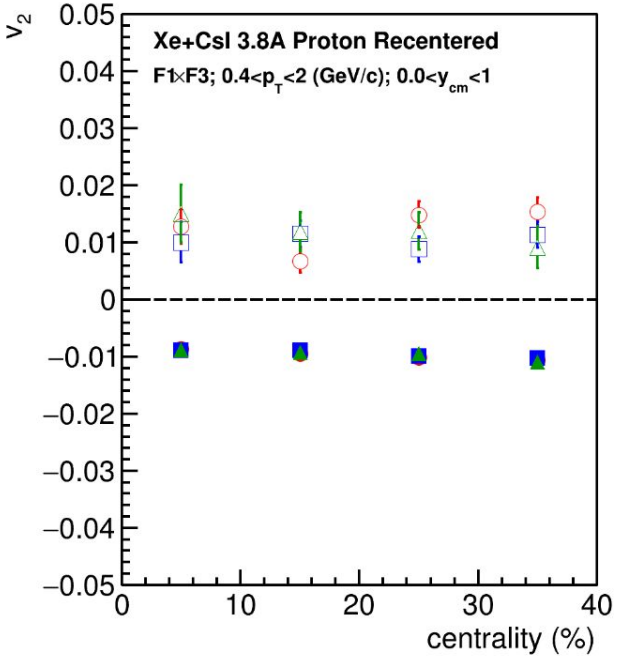




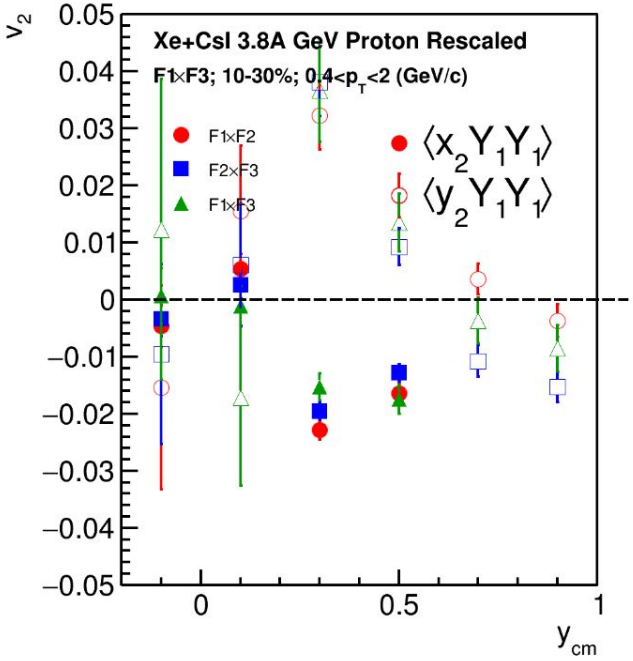
Recentered proton v_2

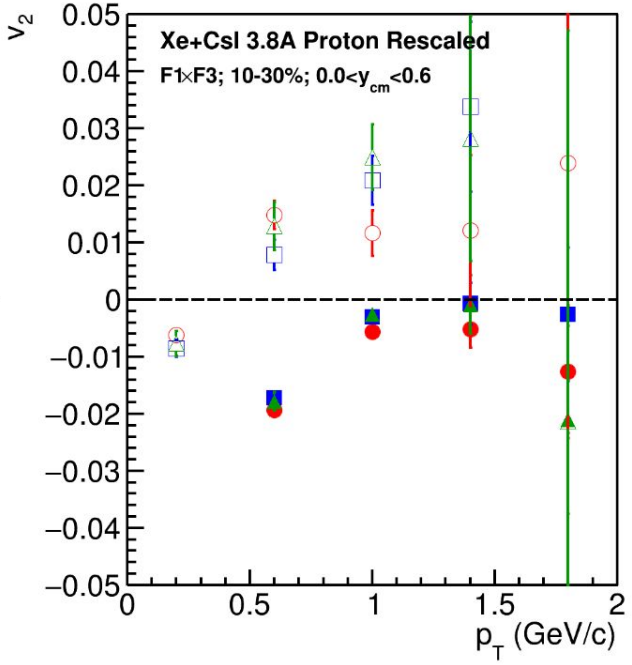


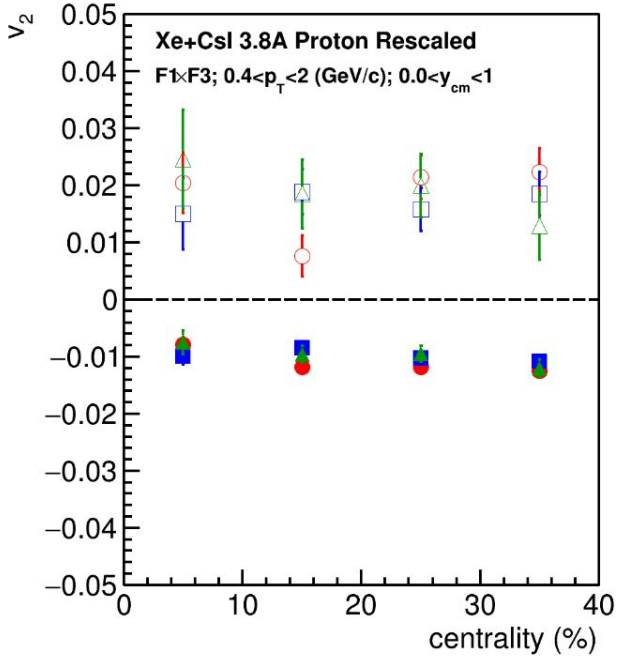




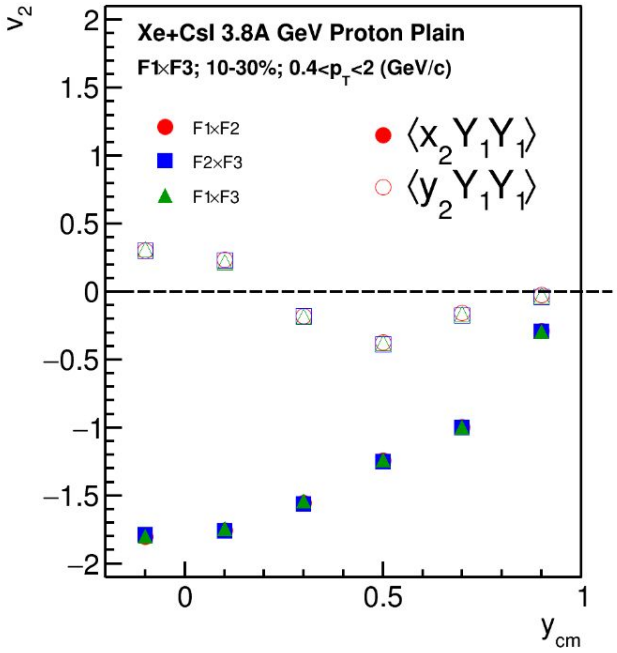
Rescaled proton v_2

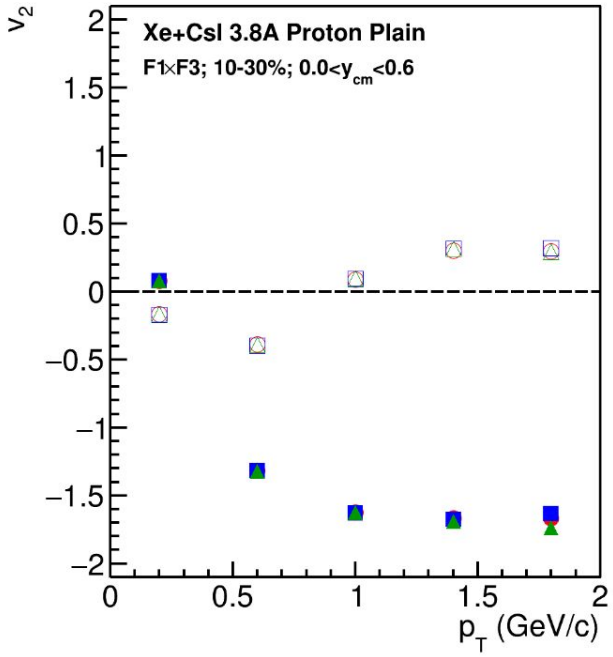


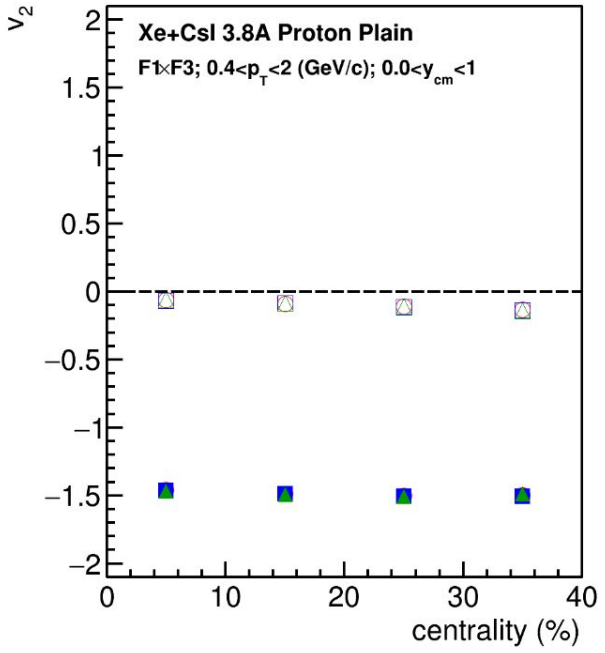




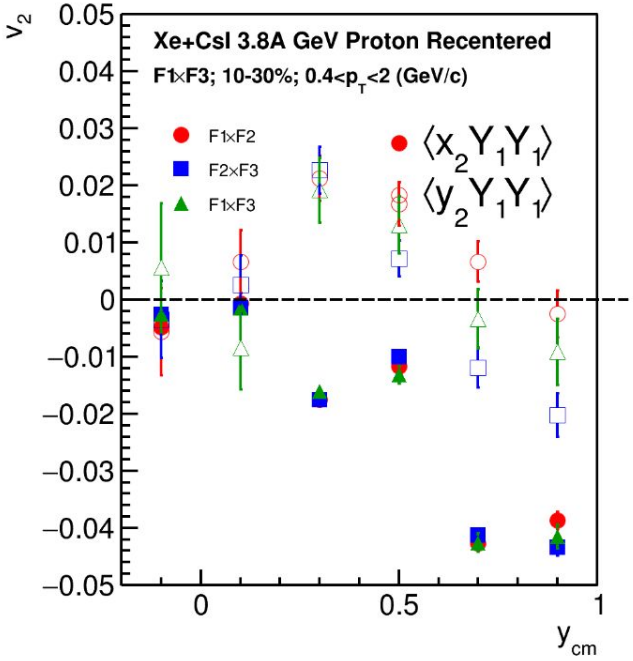
Plain proton v_2

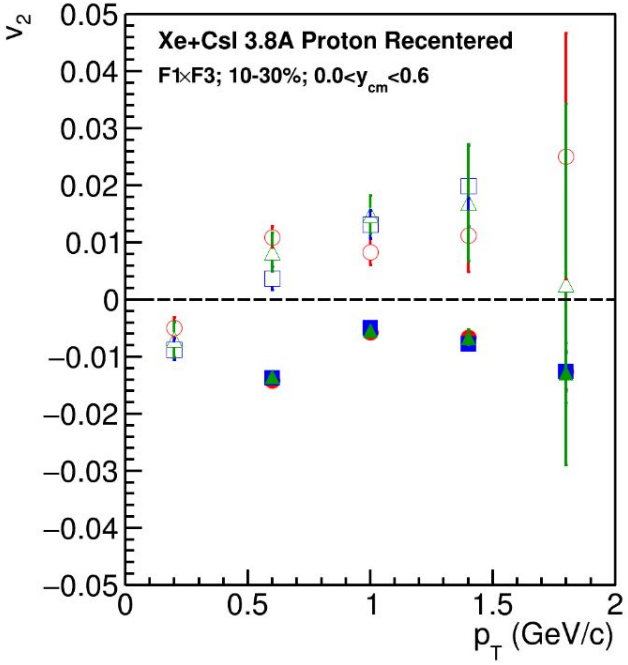


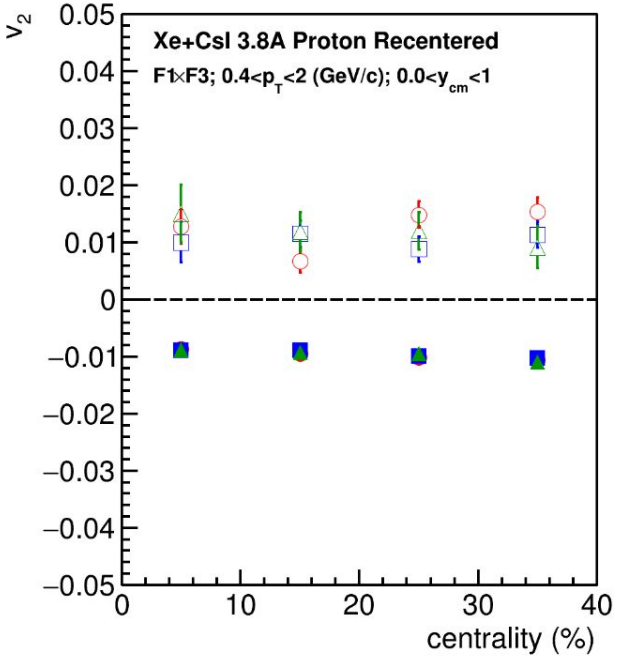




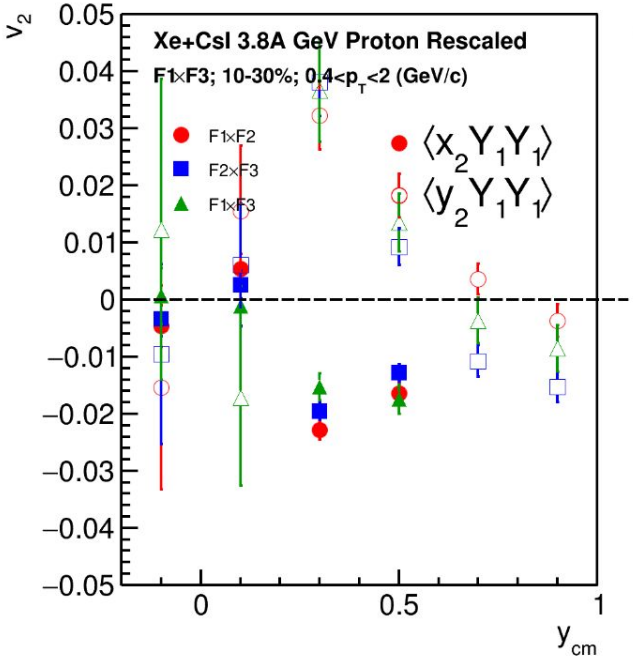
Recentered proton v_2

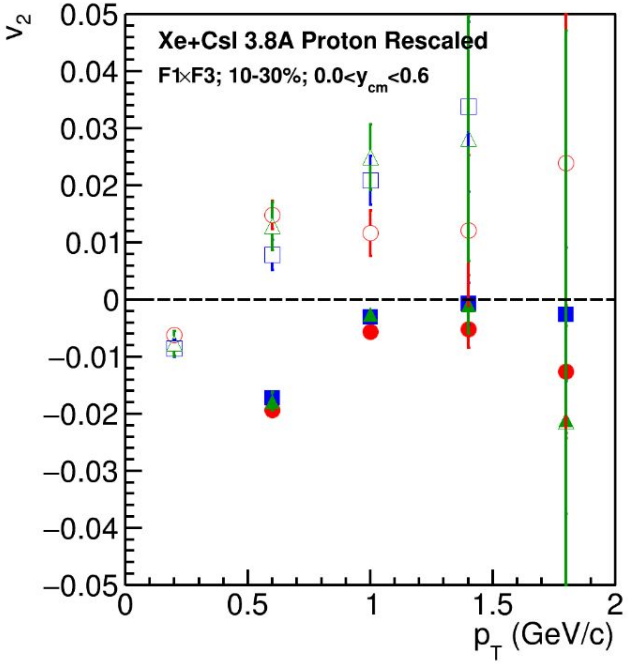


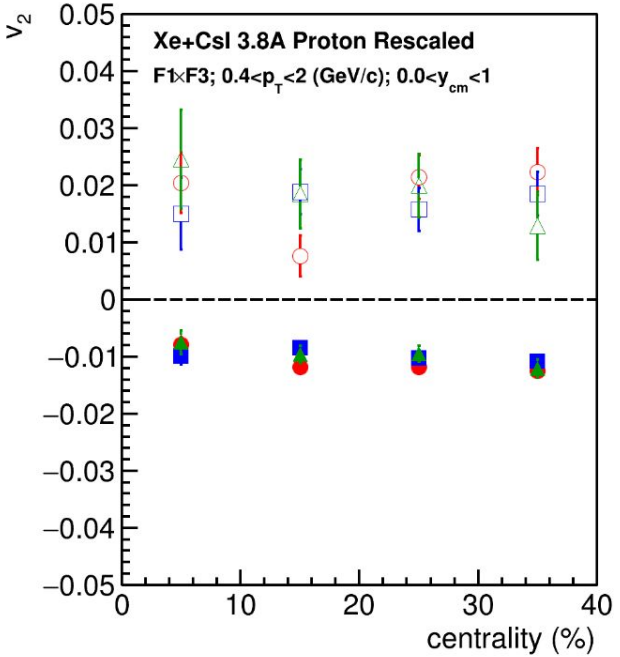




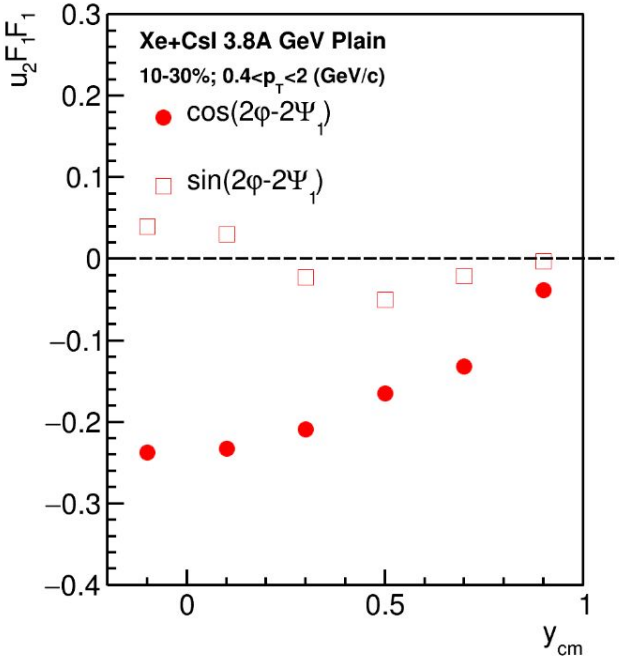
Rescaled proton v_2

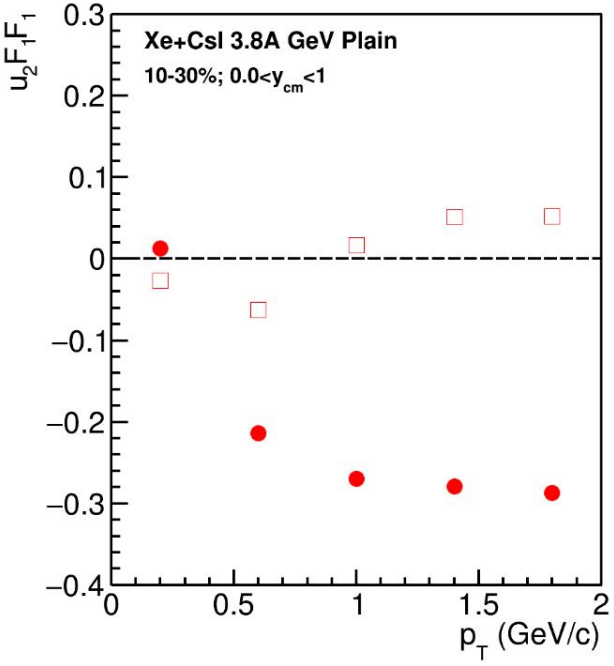


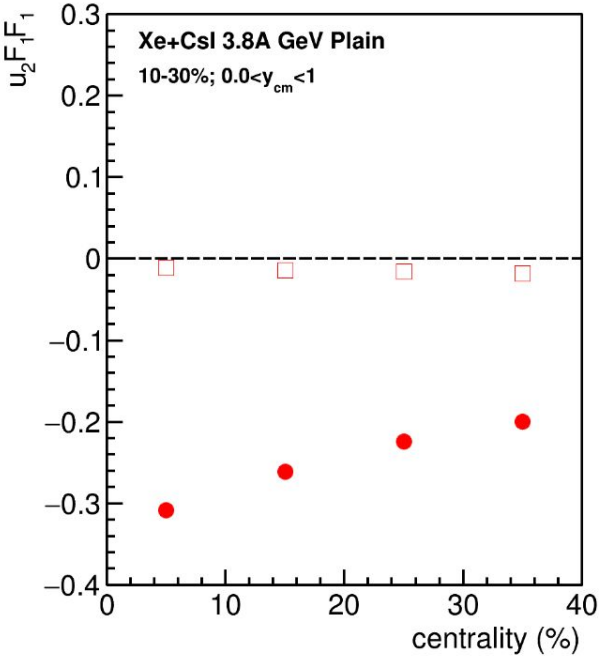




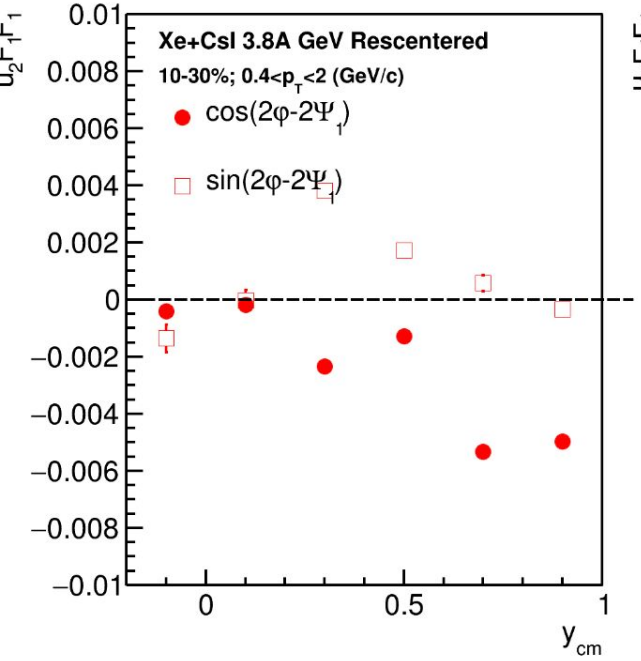
Plain proton correlation with F1

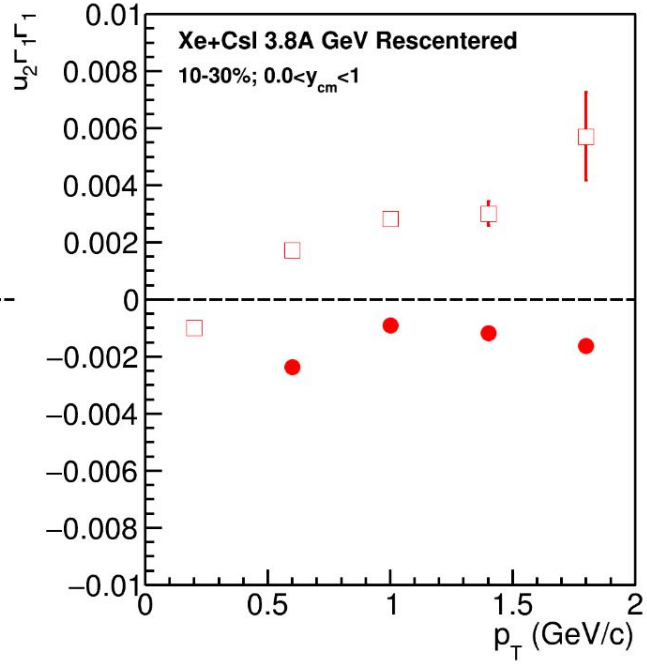


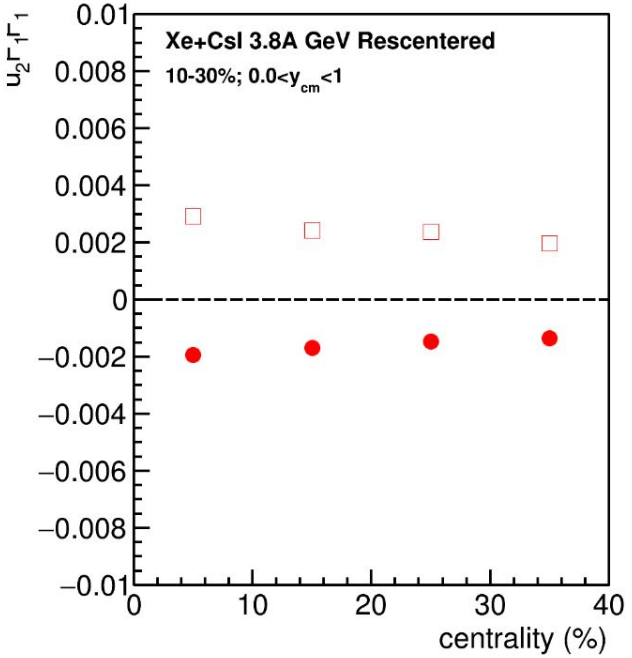




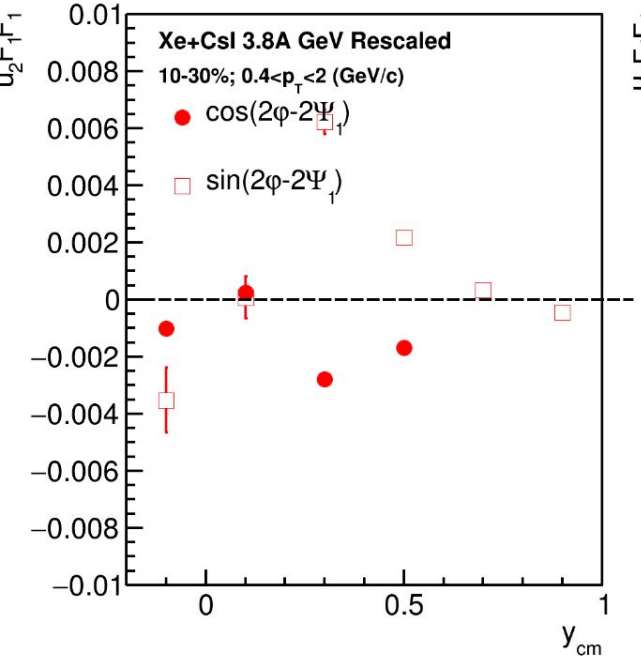
Recentered proton correlation with F1

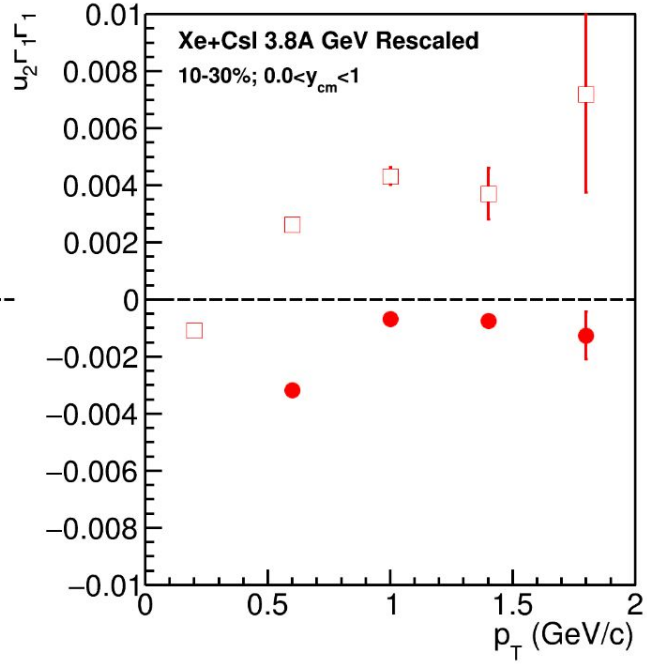


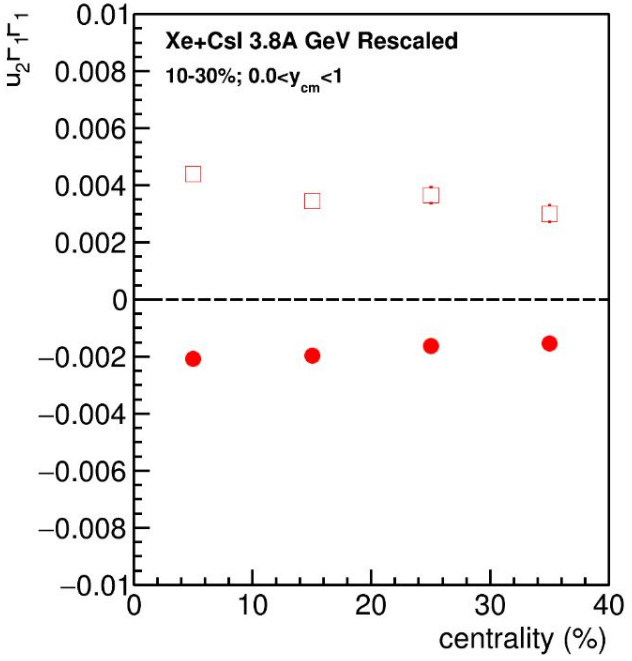




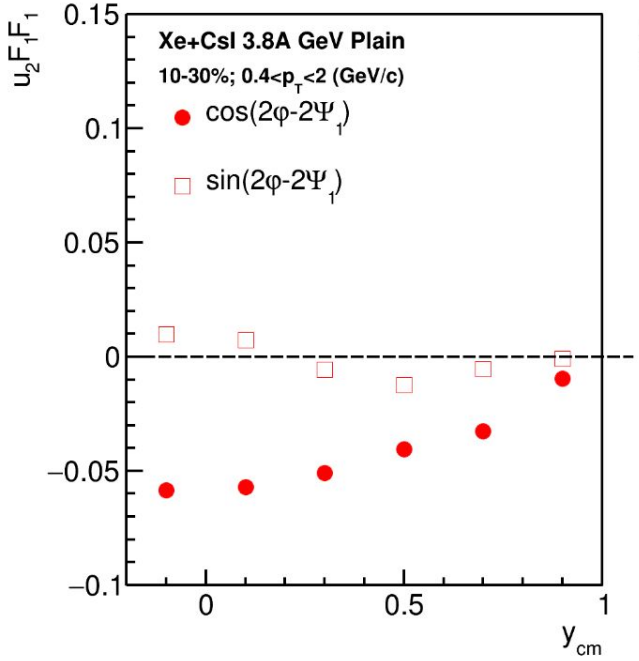
Rescaled proton correlation with F1

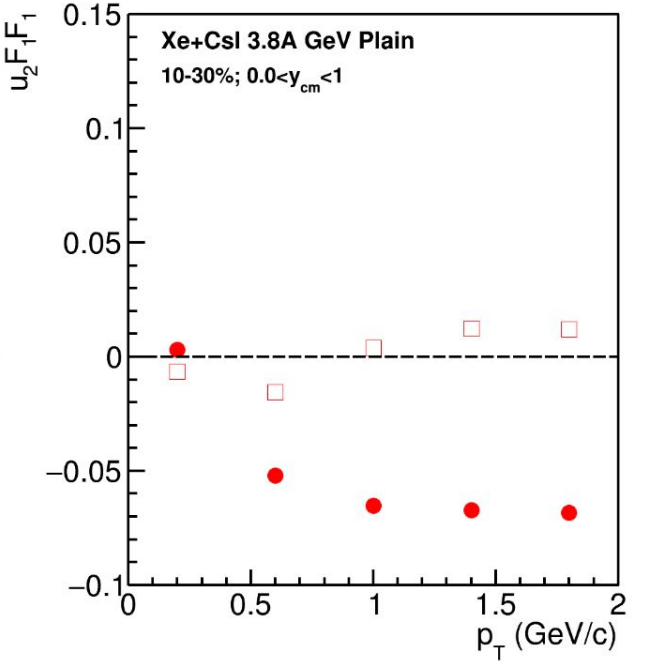


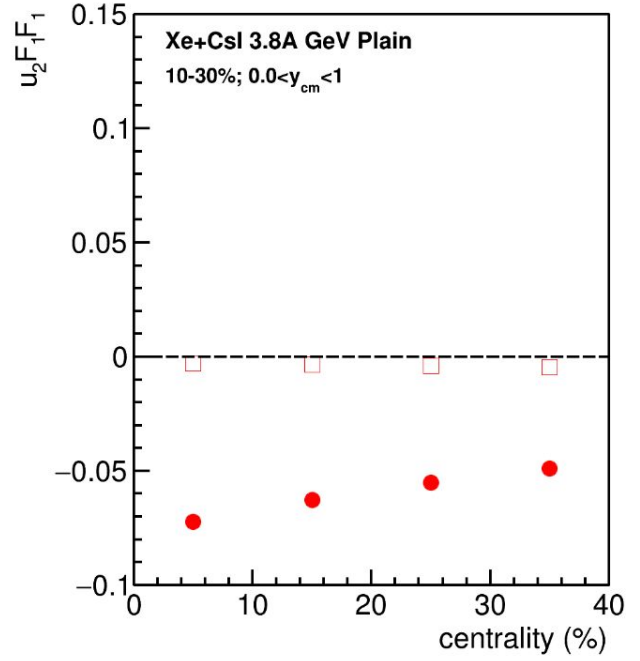




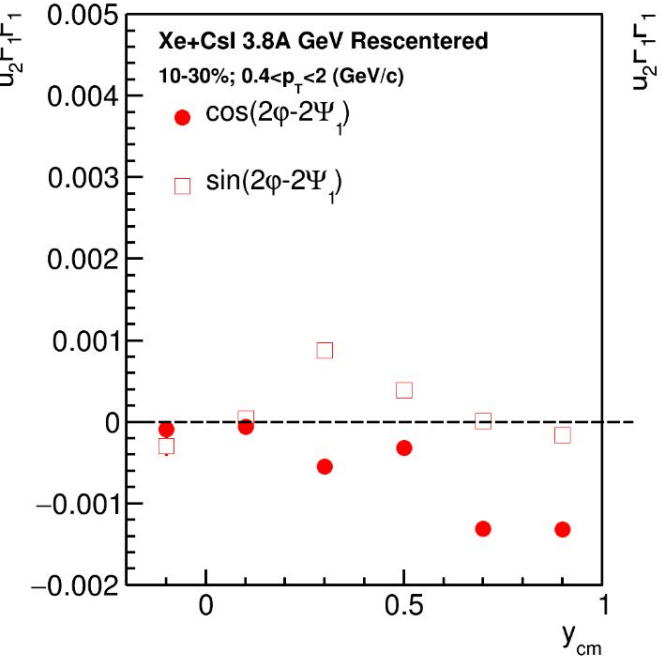
Plain proton correlation with F2

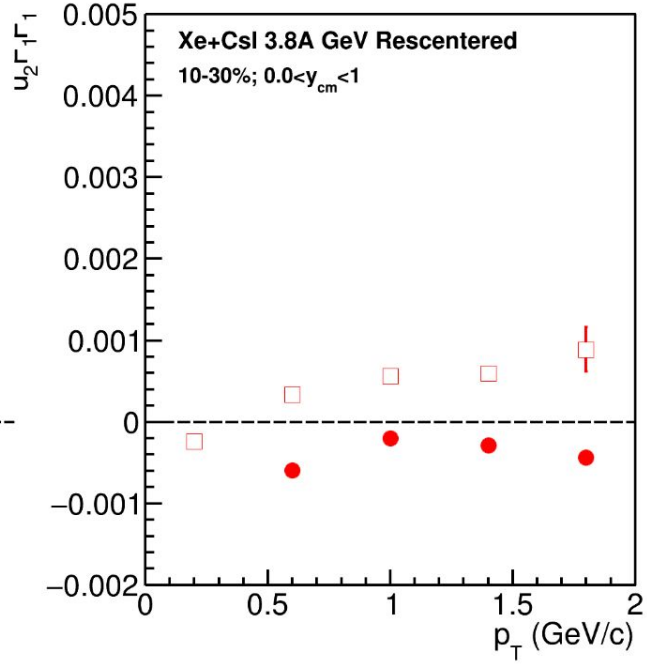


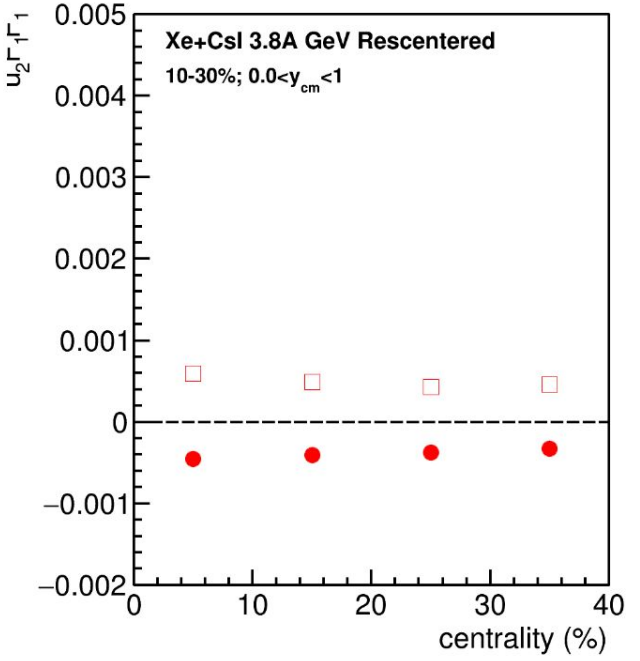




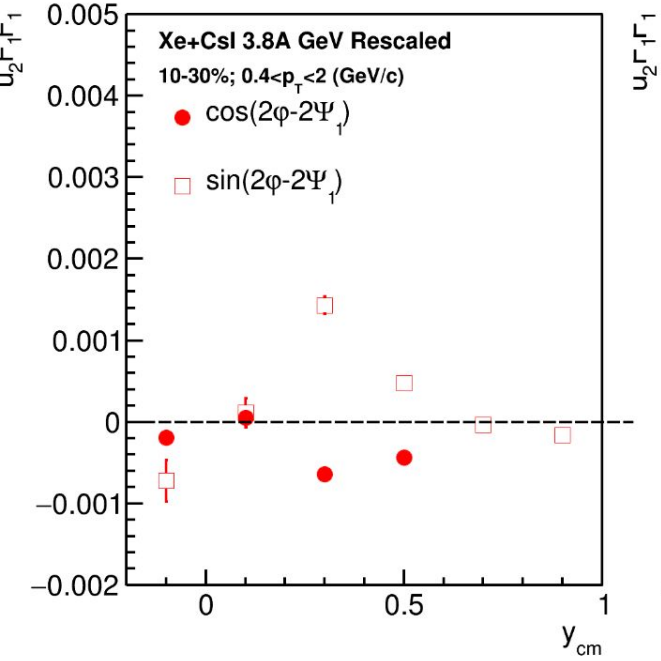
Recentered proton correlation with F2

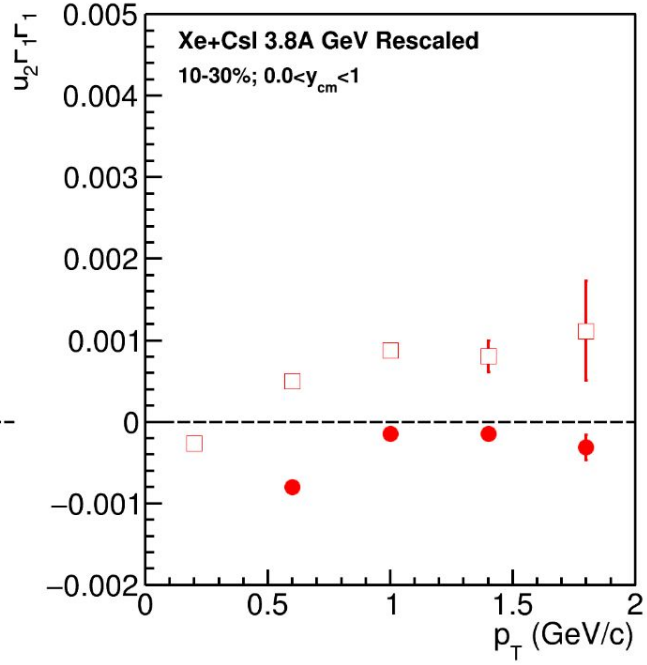


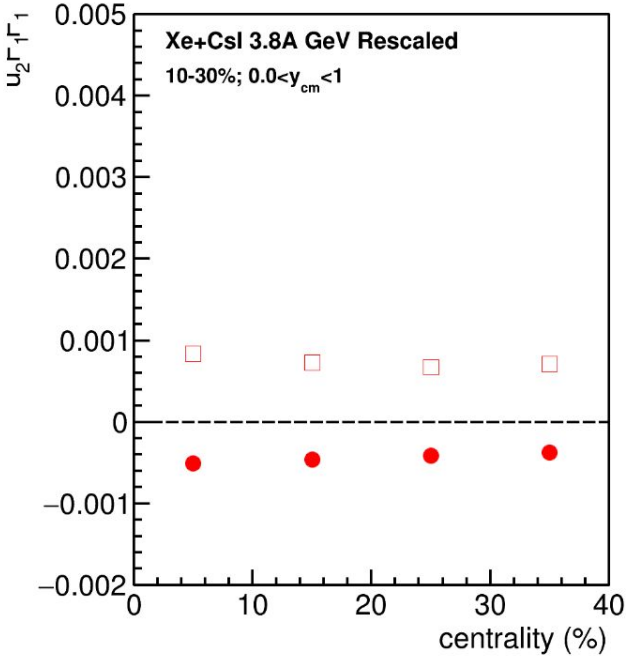




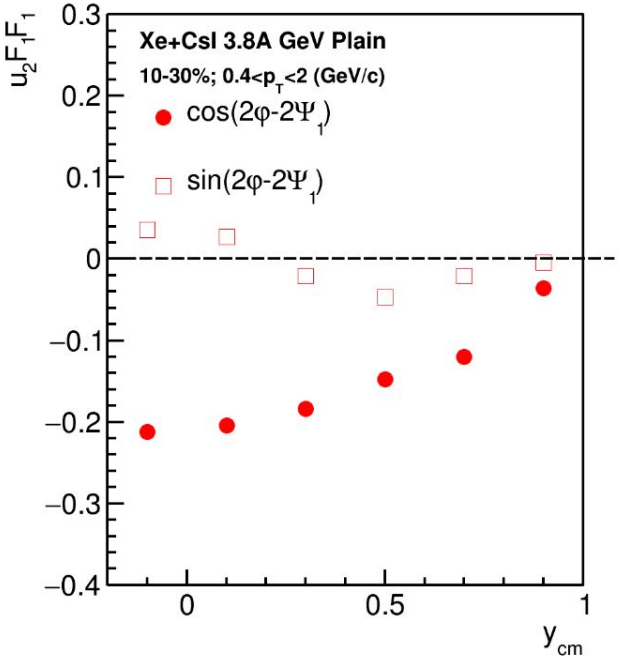
Rescaled proton correlation with F2

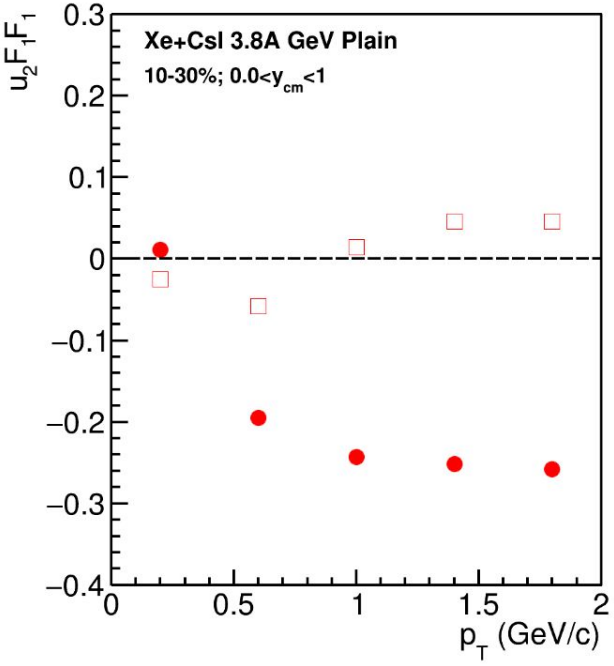


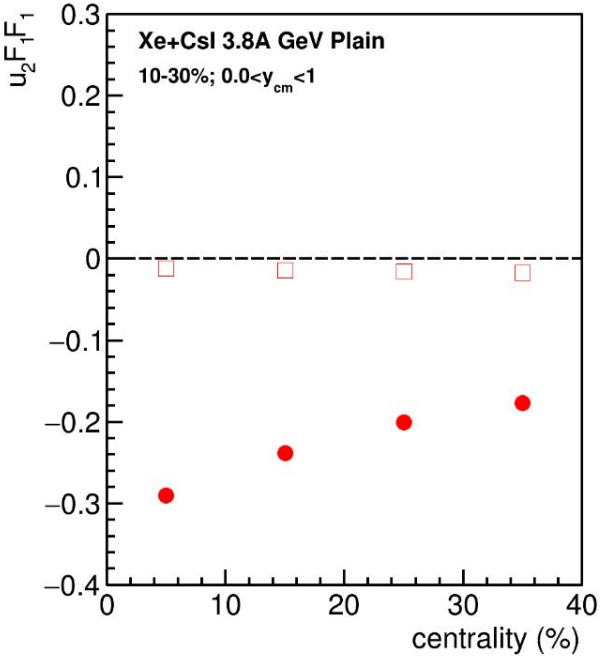




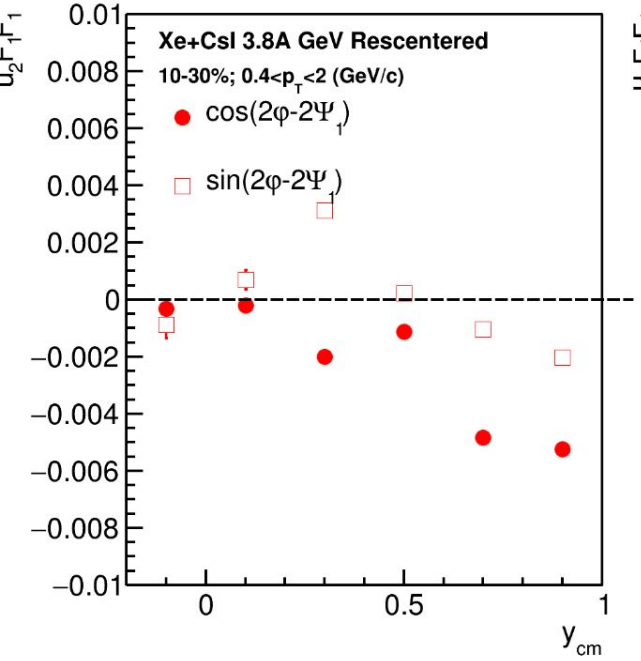
Plain proton correlation with F3

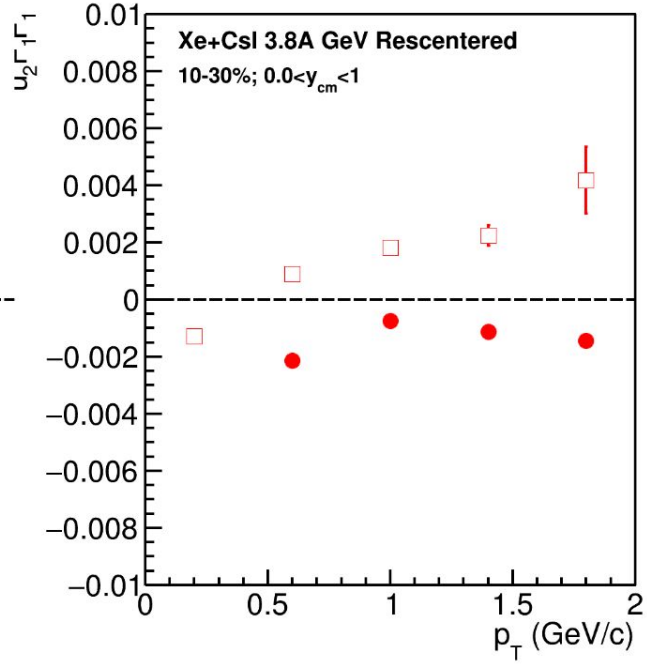


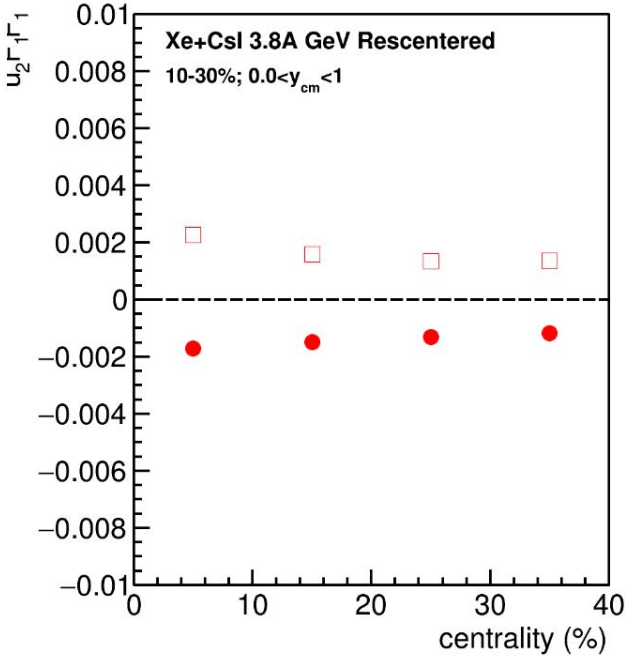




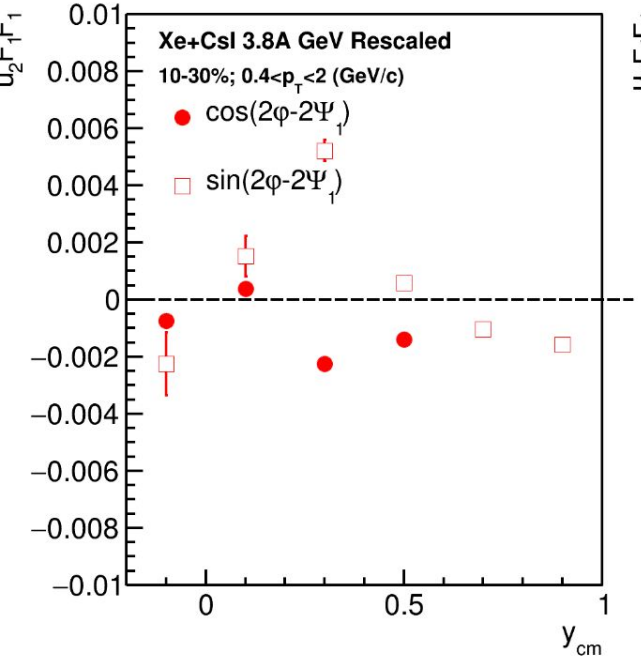
Recentered proton correlation with F3

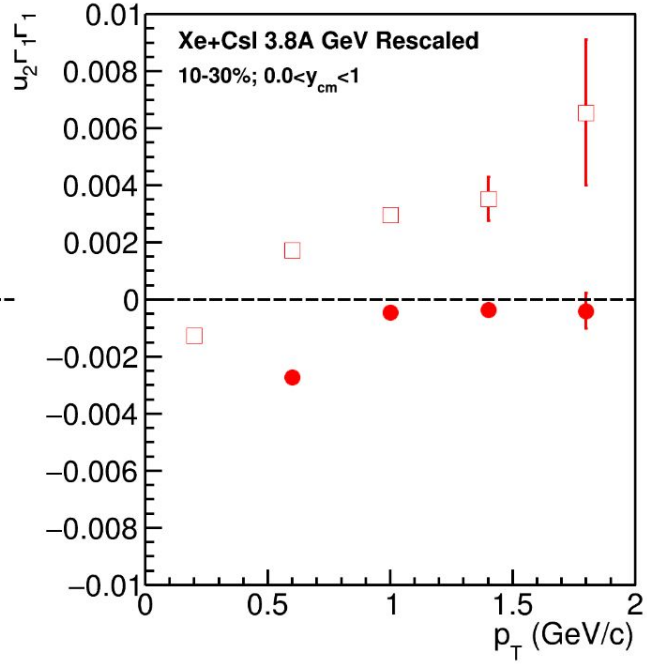


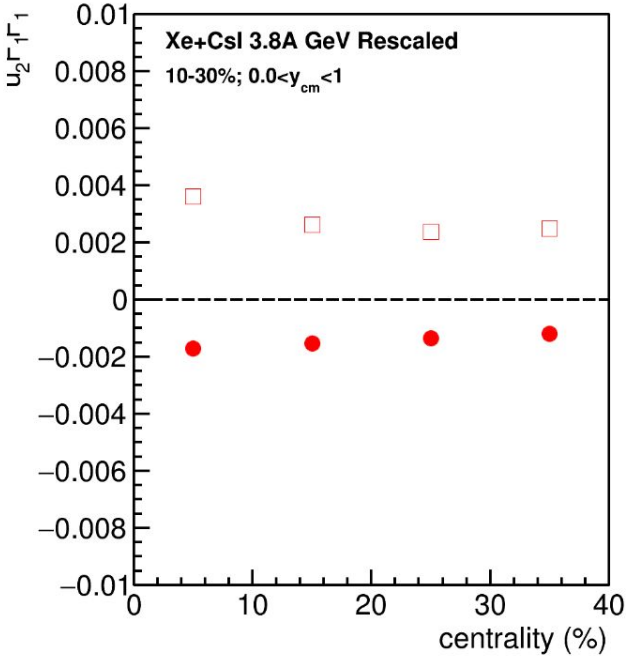




Rescaled proton correlation with F3

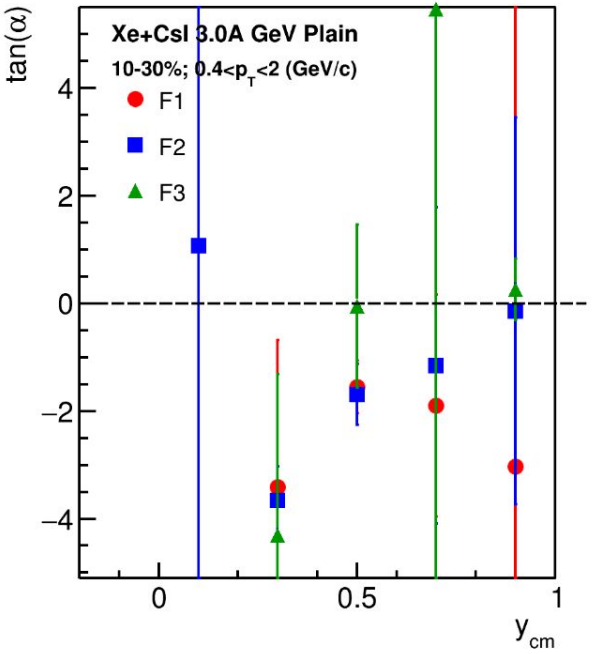


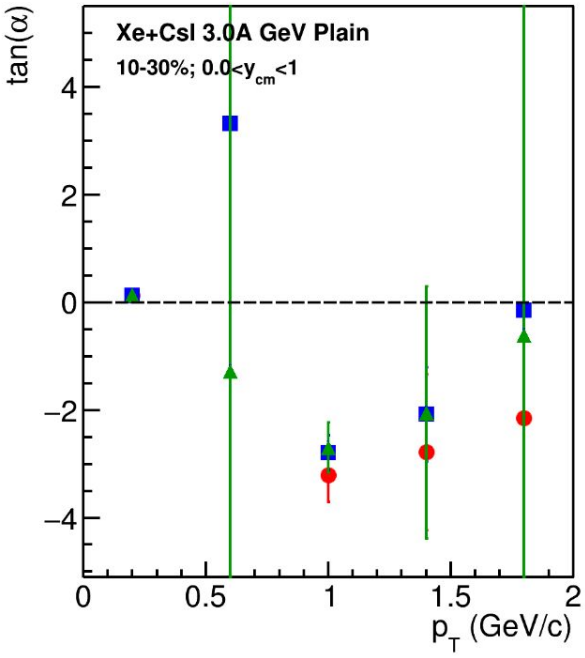


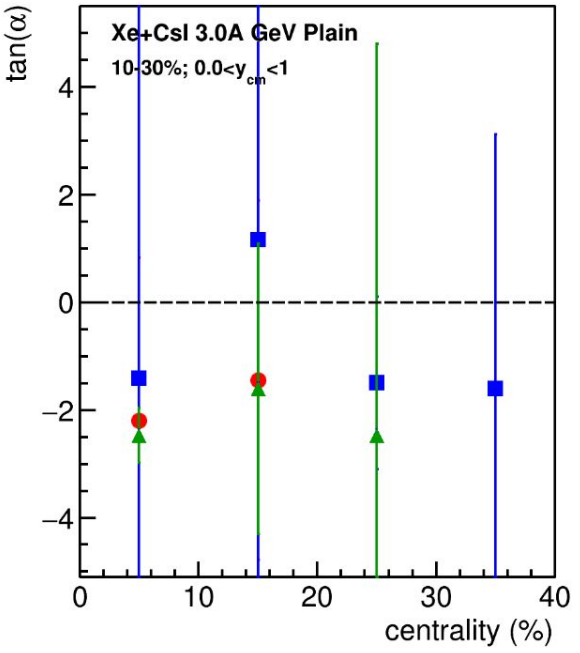


Calculating the effective rotation angle

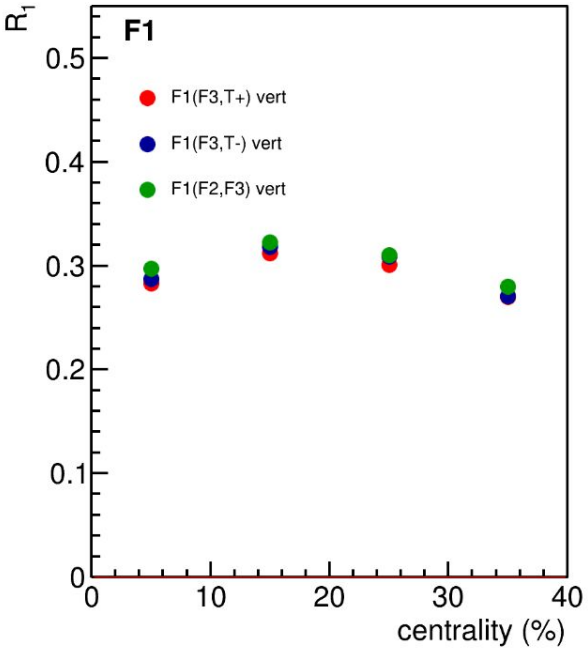
α ~ 31.717474

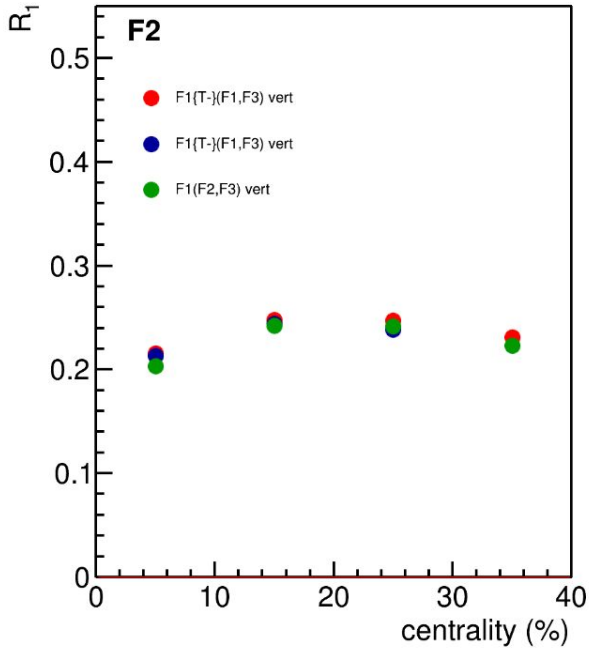


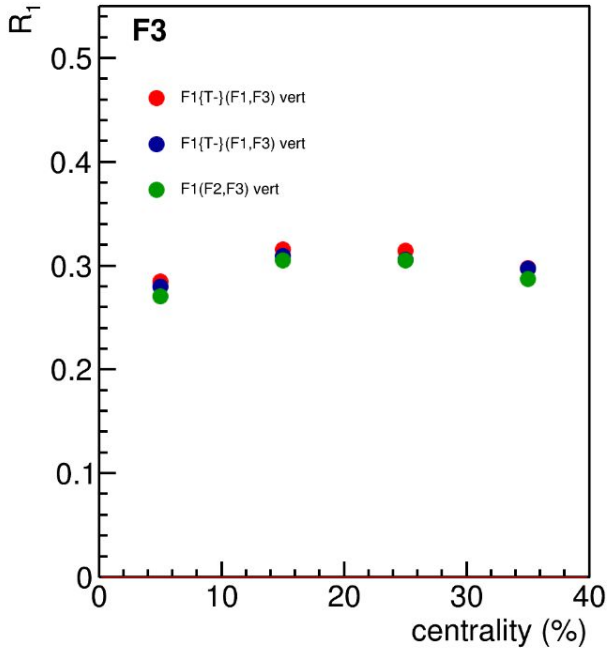




Symmetry plane resolution in Xe+Cs(I) collisions







All the estimations for symmetry plane resolutions are in a good agreement