Elliptic Flow in BM@N

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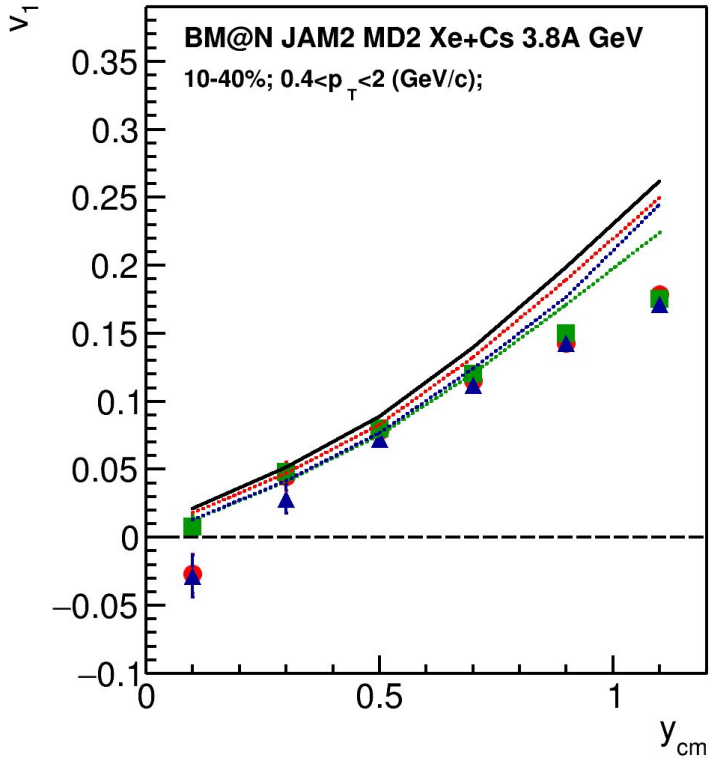
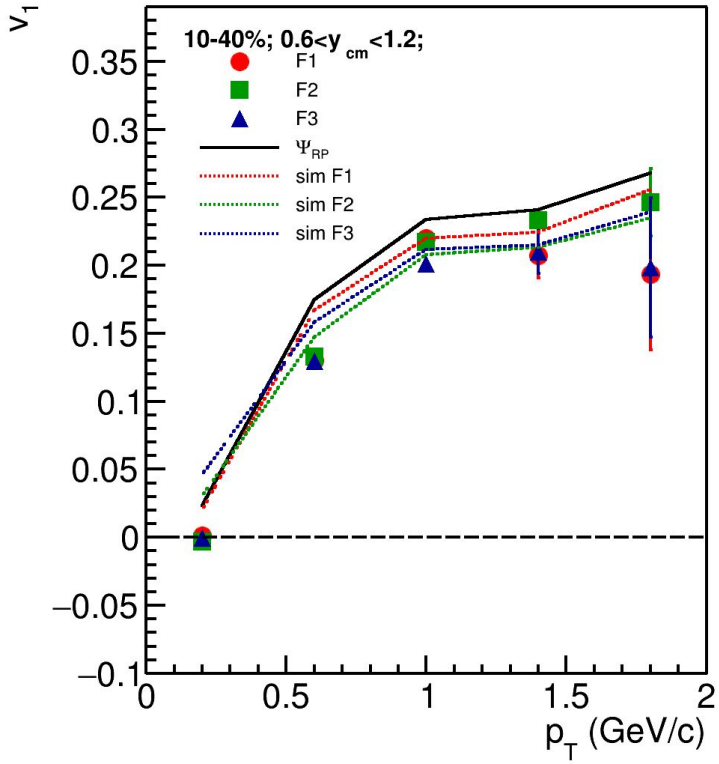
Analysis setup

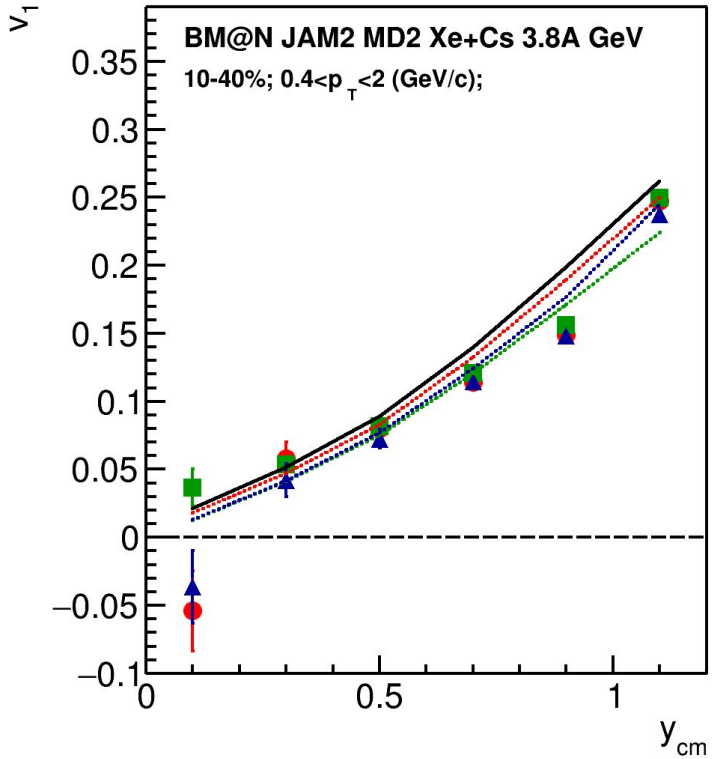
- JAM MD2 + coalescence for Xe+Cs at E_{kin}=3.8A GeV as an input
- Full reconstruction
- Event selection:
  - N tracks for VTX > 2
- Track selection (as in data)
  - Nhits > 5
  - Chi2/NDF for CT-track < 5
  - R_{dca}<5
- Identification via associated MC-track + hit in any of the TOF

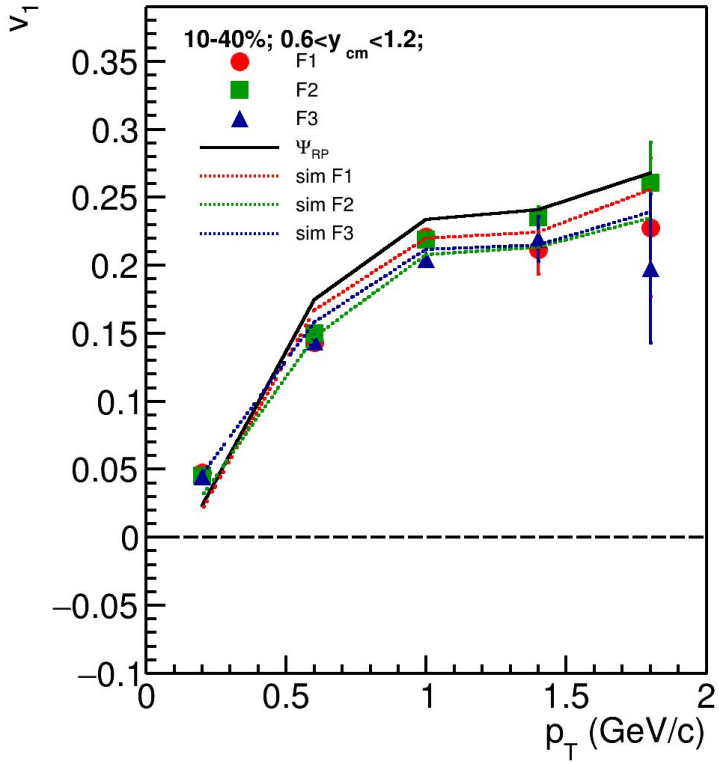
Old: v1 vs pT and y for MC simulation (tr not pointing to FHCAl)



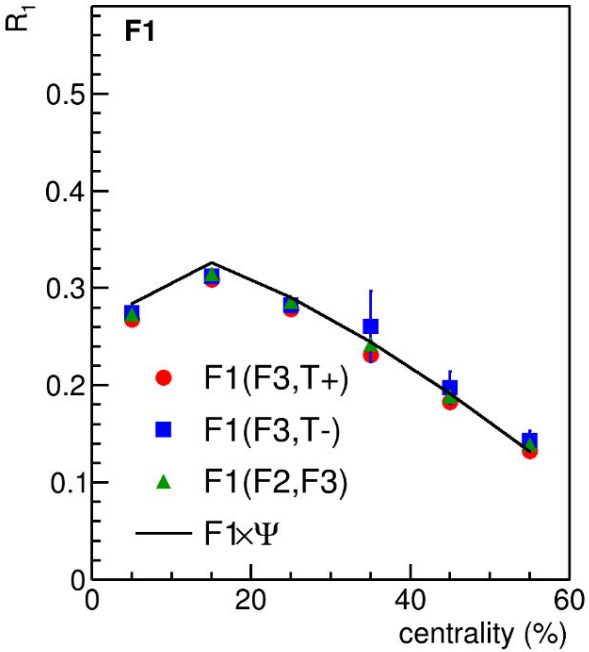


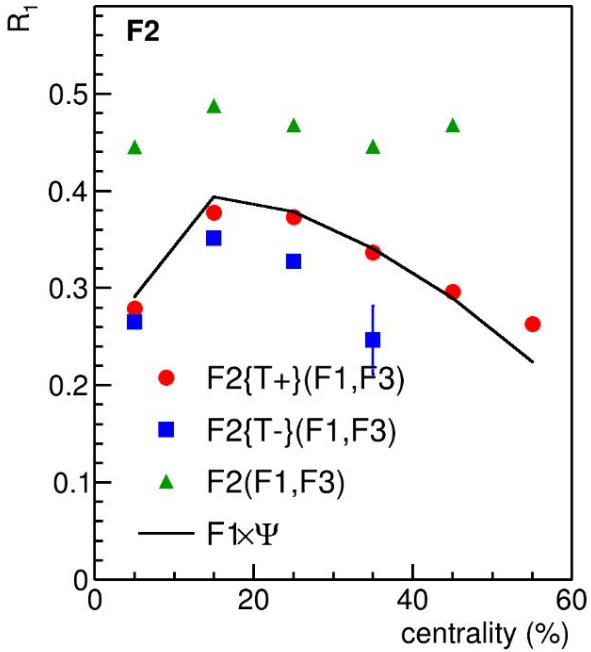
Upd: v1 vs pT and y for MC simulation (η<3.0)

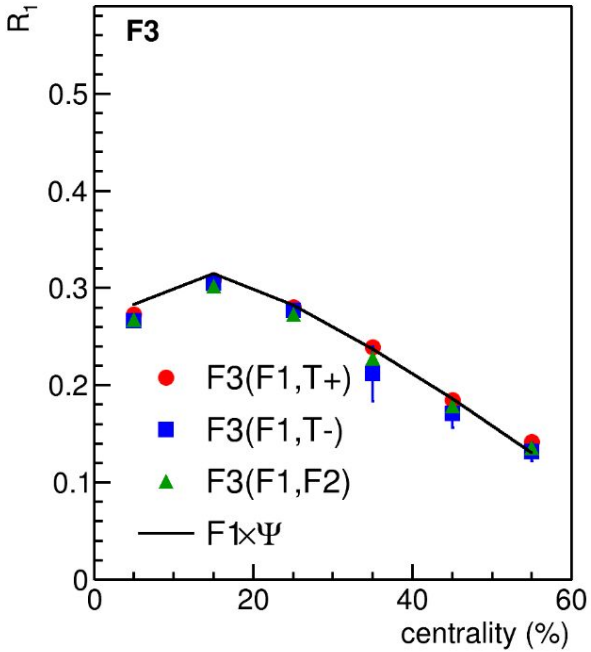




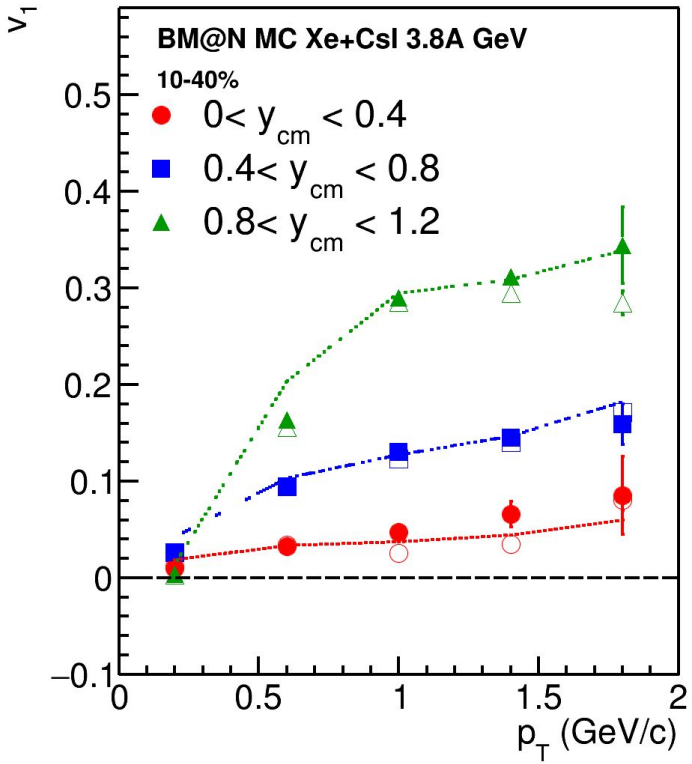
R1 vs centrality for MC simulation (Tw+Resc)

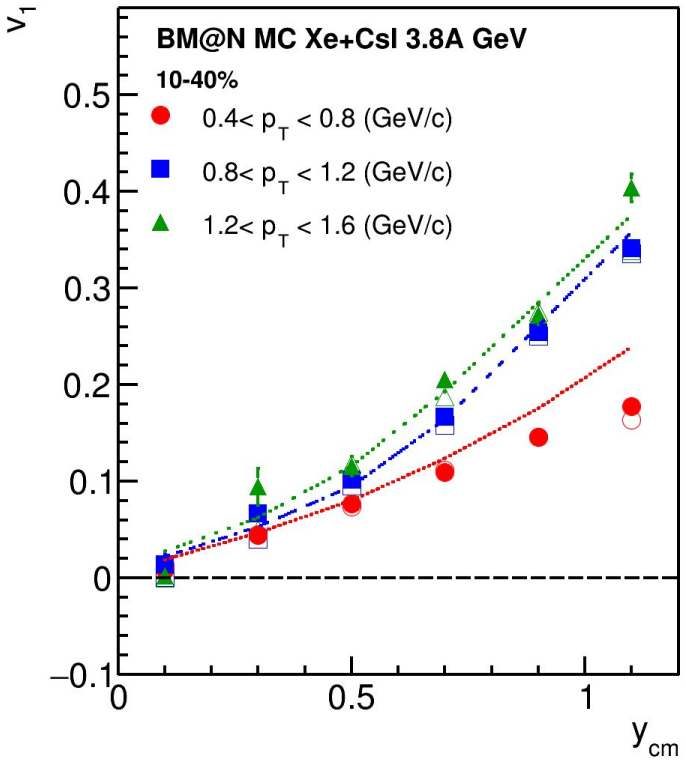




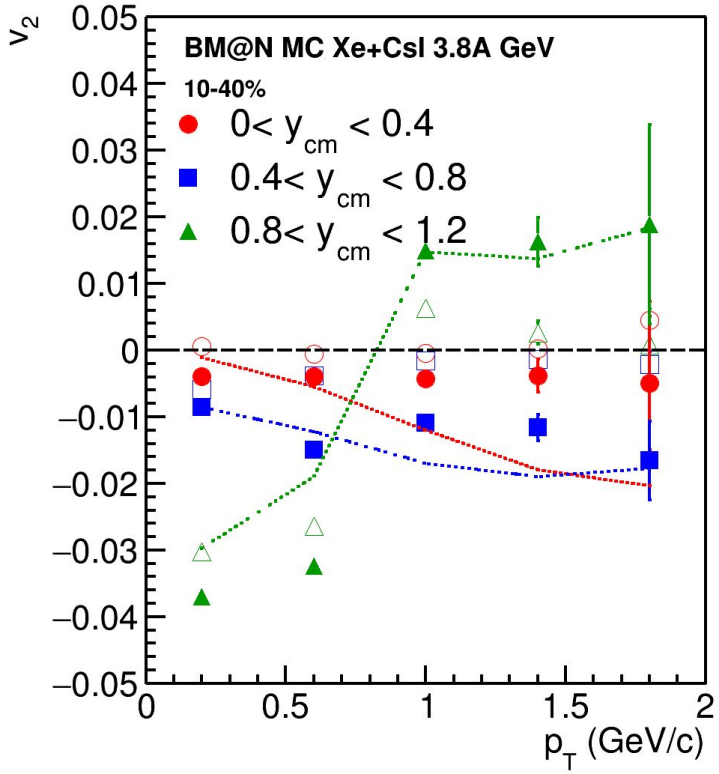


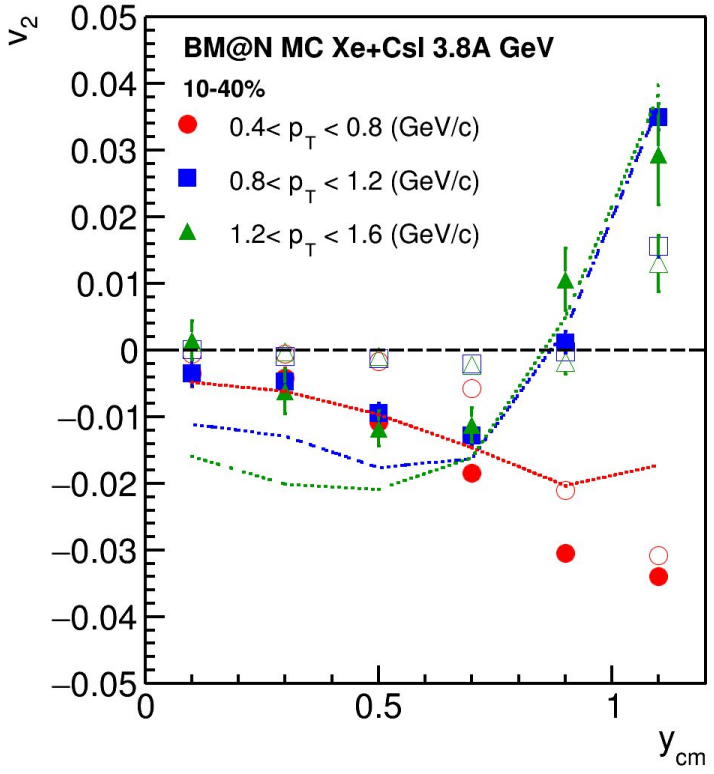
Twist+Rescaling performance on v1



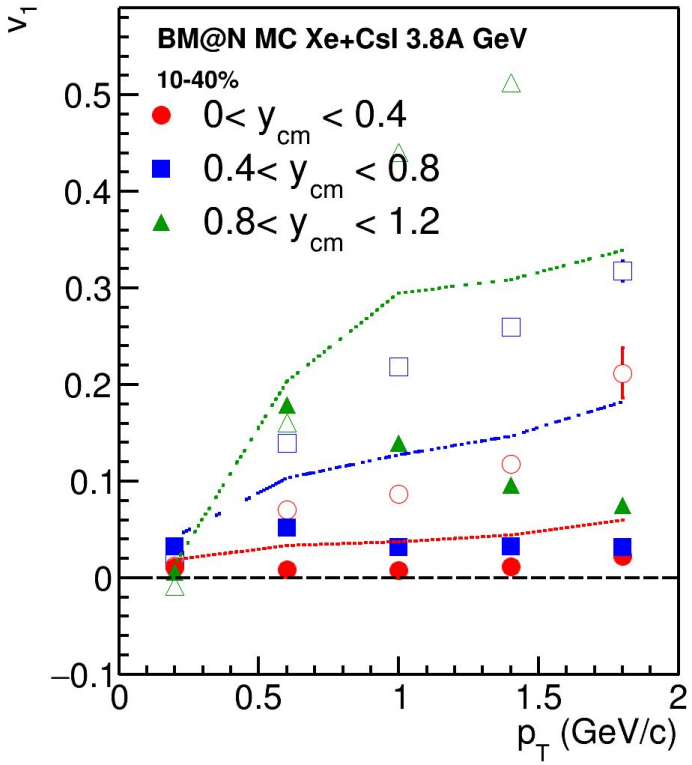


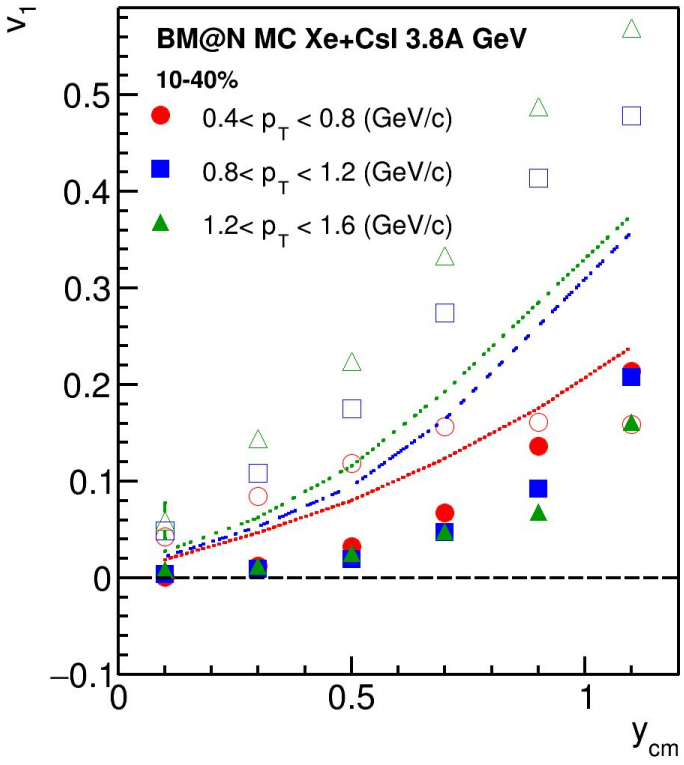
Twist+Rescaling performance on v2



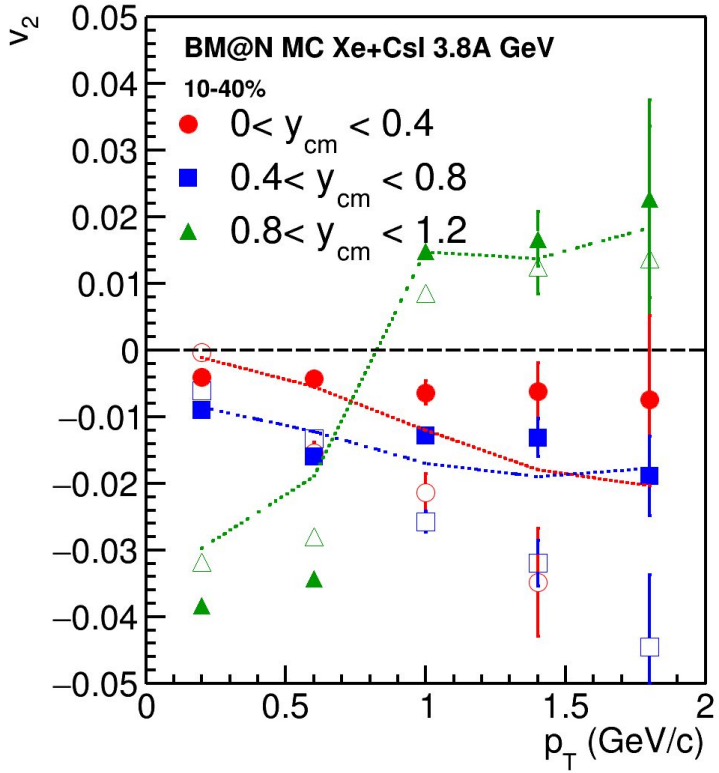


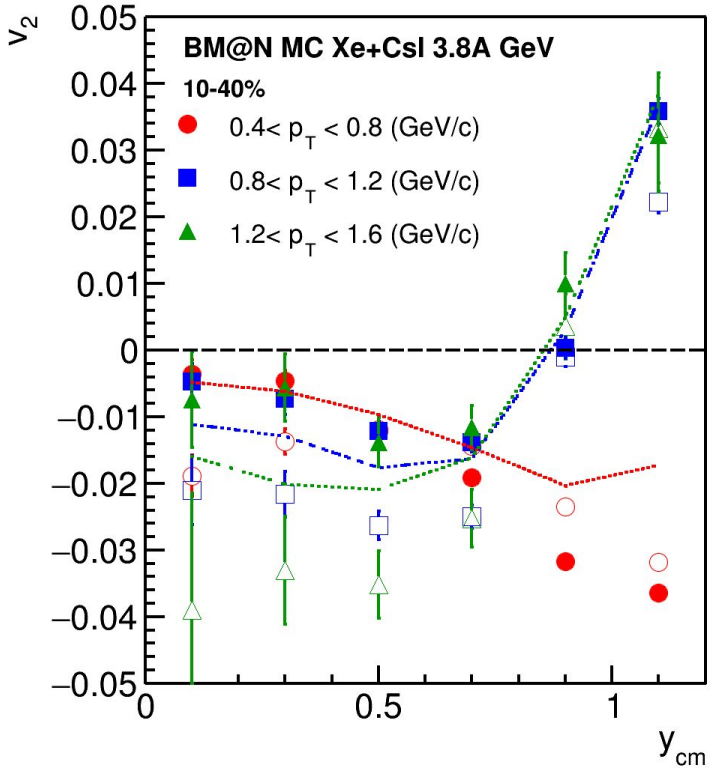
v1 for protons without corrections on u





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

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

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

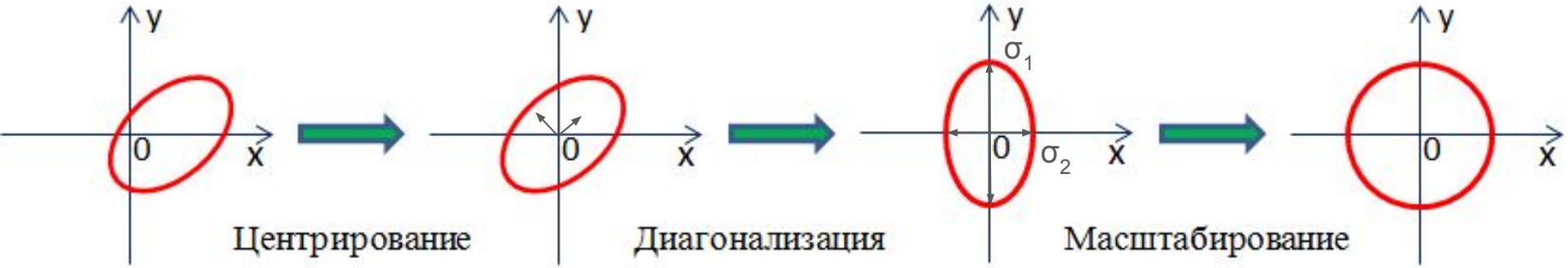
$$y_n = A(\varphi)\sin n\varphi = \frac{1}{2\pi}\left[1 + 2\sum_{m=1}^{\infty}(c_m \cos m\varphi + s_m \sin m\varphi)\right]\sin n\varphi =$$

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

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

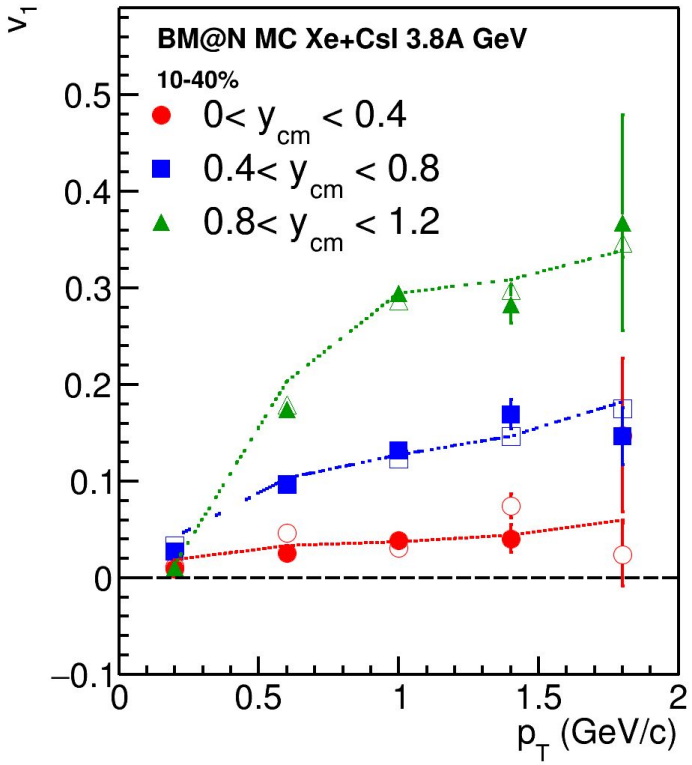
Before the correction:

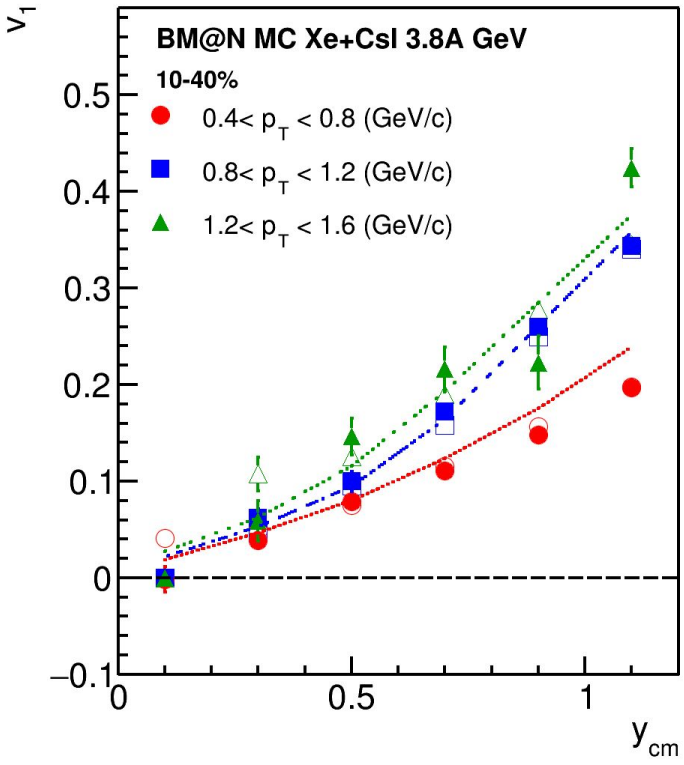
$v_n = p_0 + p_1 v_1 + p_2 v_2 + \dots + p_n v_n + \dots$

Now, applying the correction we get:

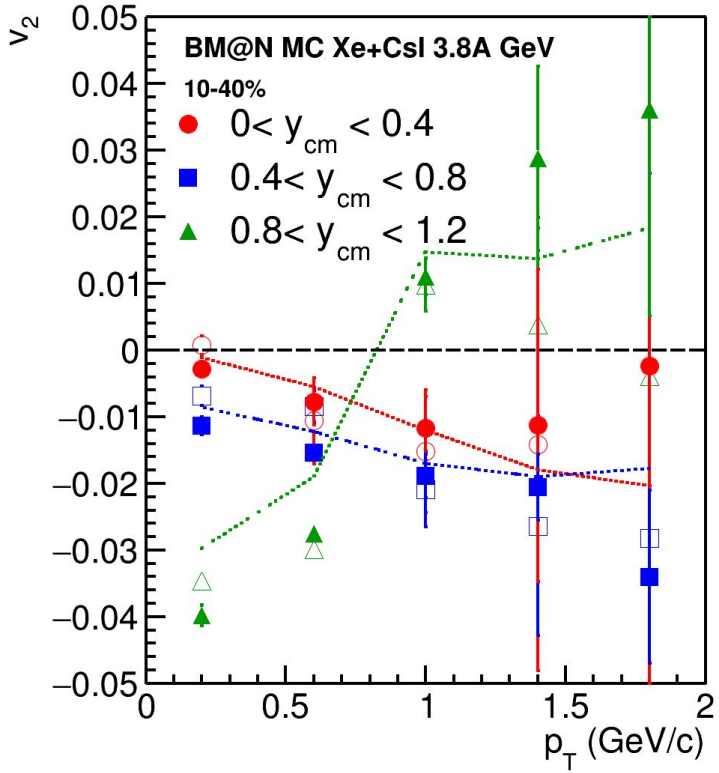
$v_n = v_n + \dots$

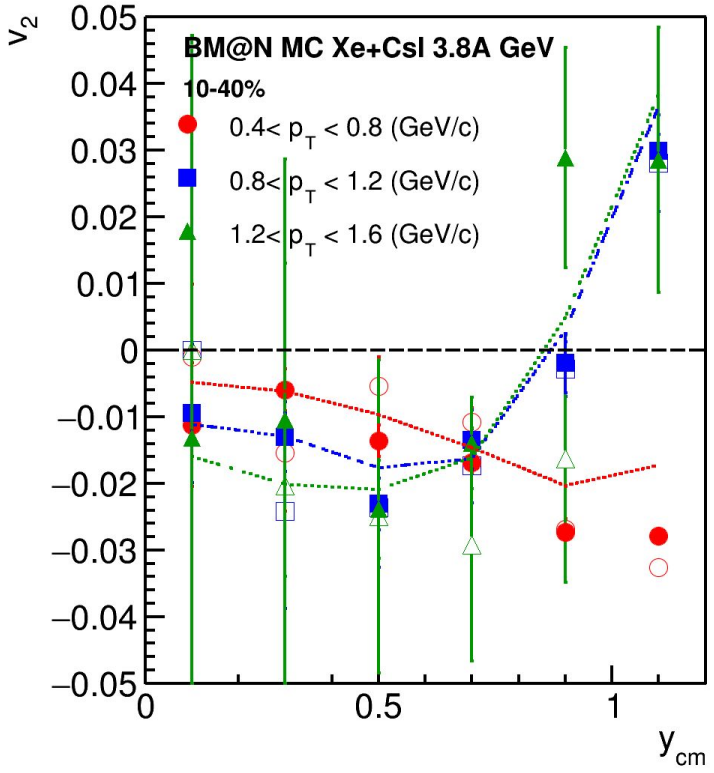
PCA performance on v1



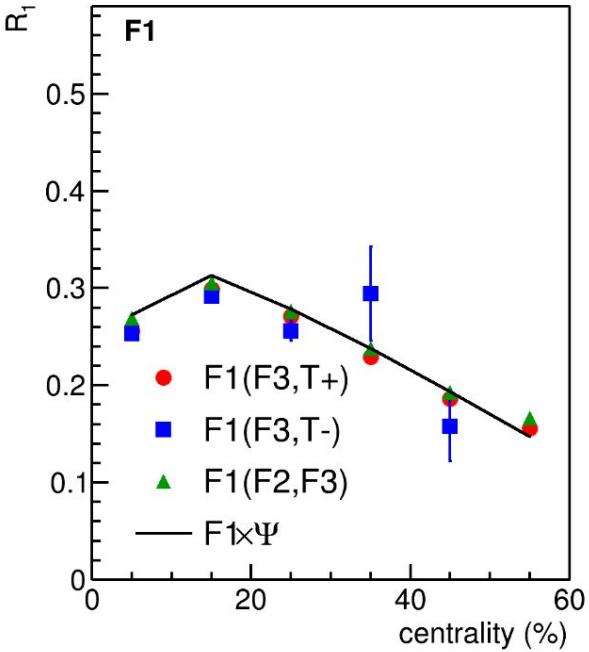


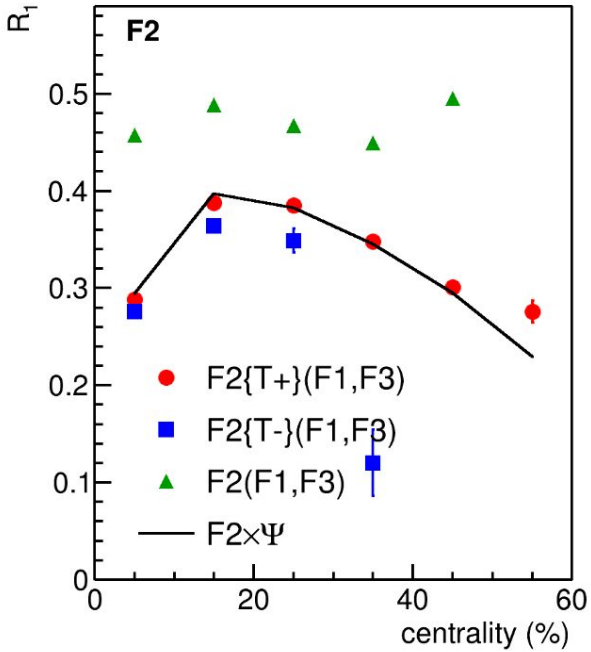
PCA performance on v2

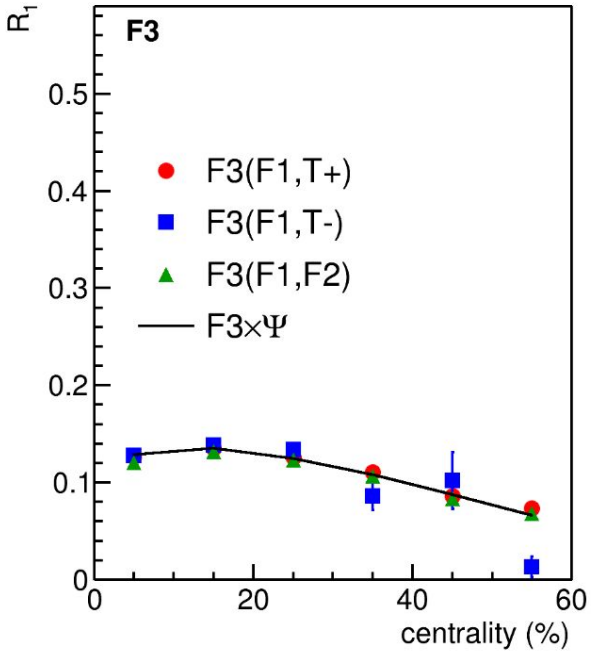




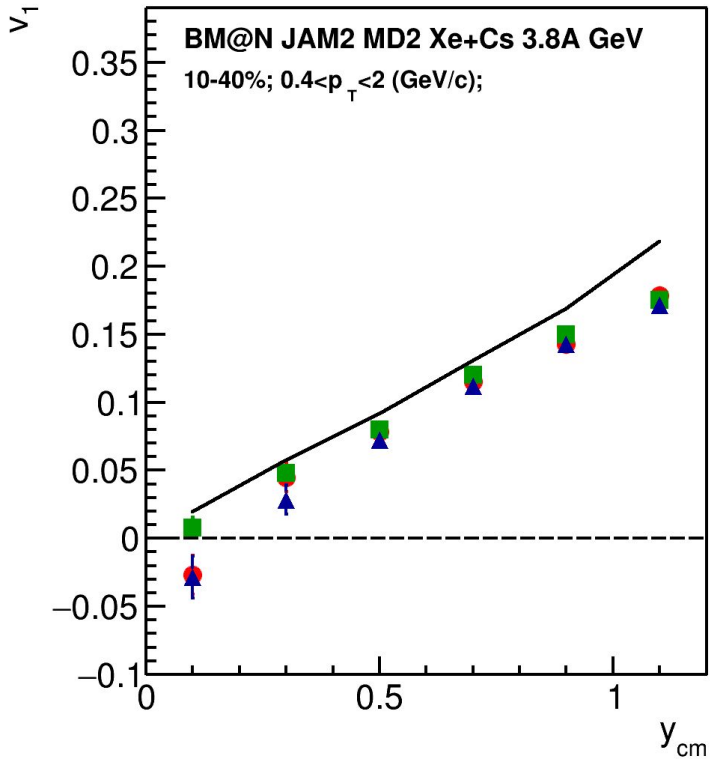
R1 vs centrality for MC simulation (PCA)

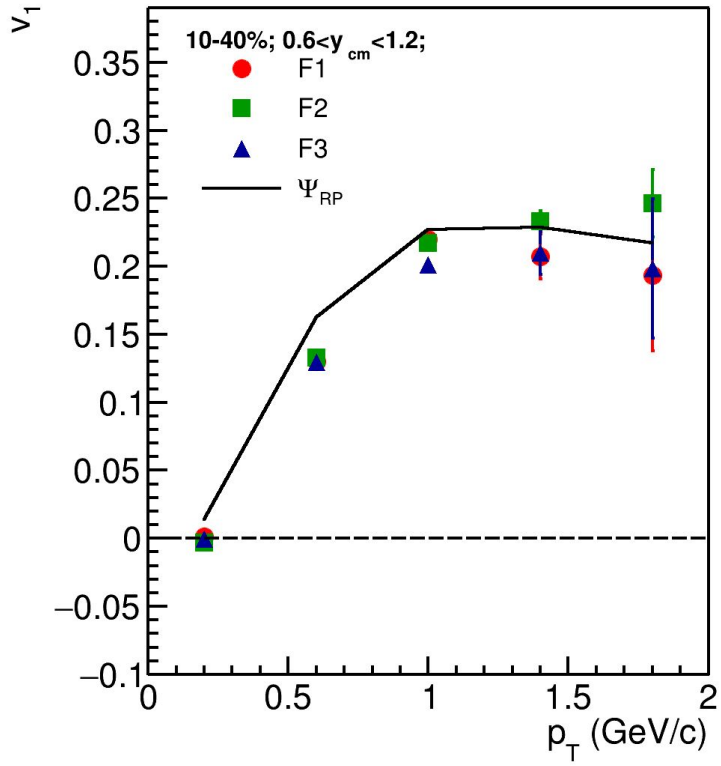




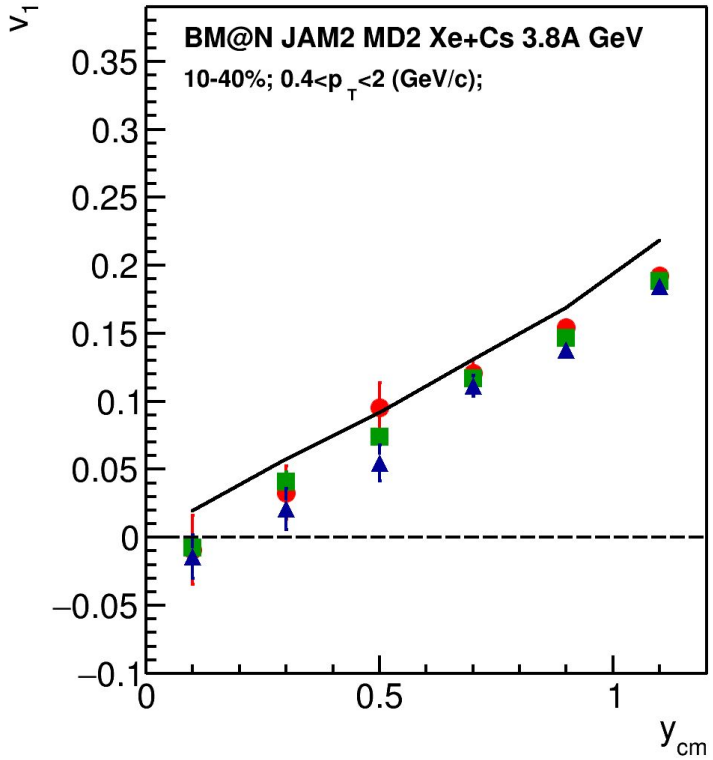


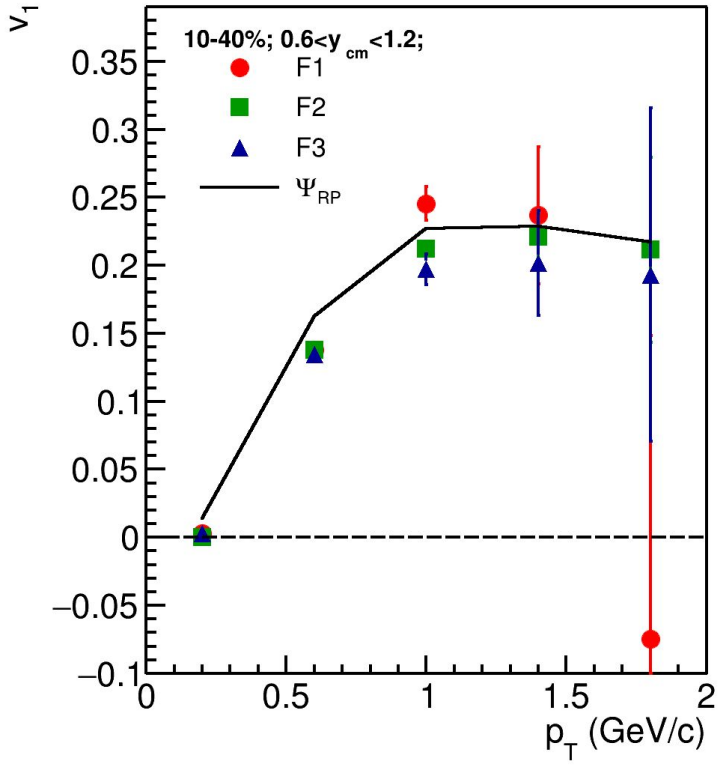
v1 vs pT and y for MC simulation (Tw+Resc)



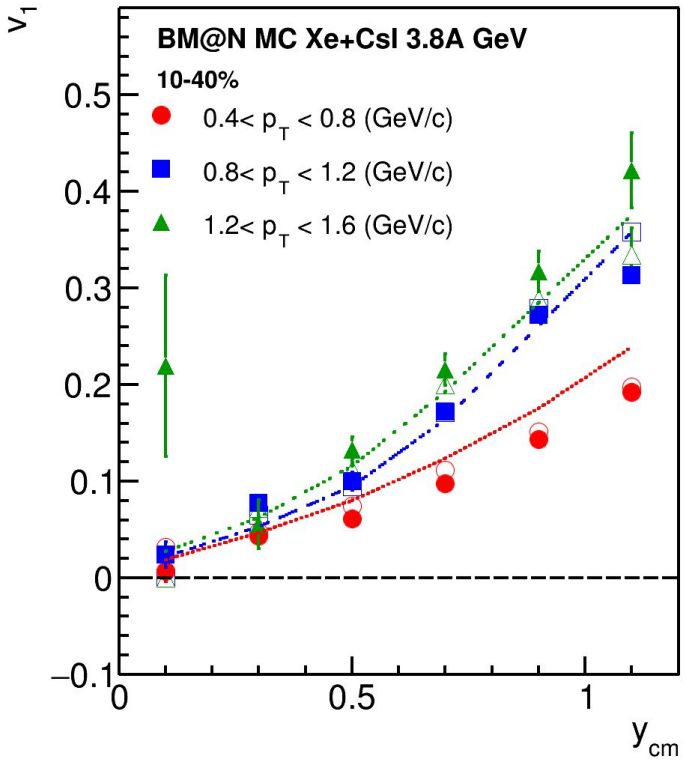


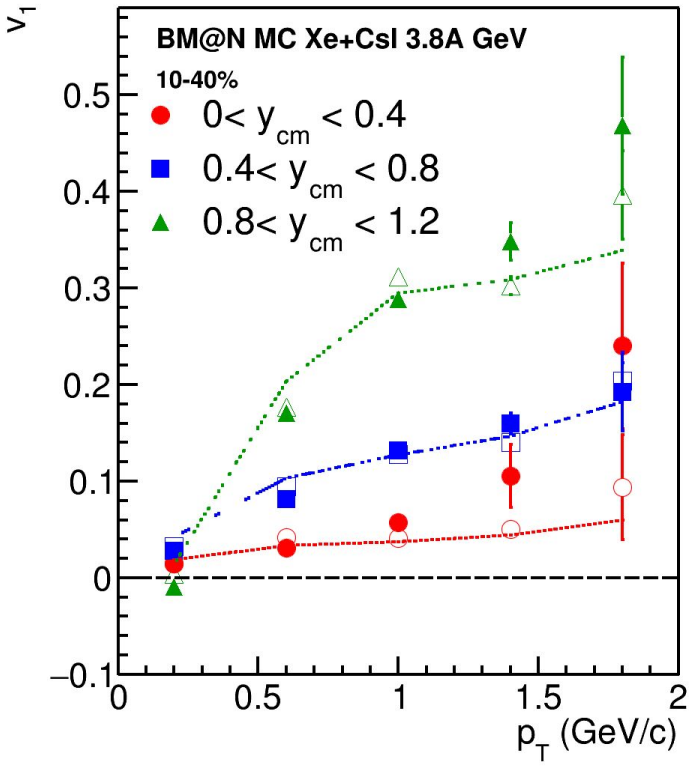
v1 vs pT and y for MC simulation (PCA)



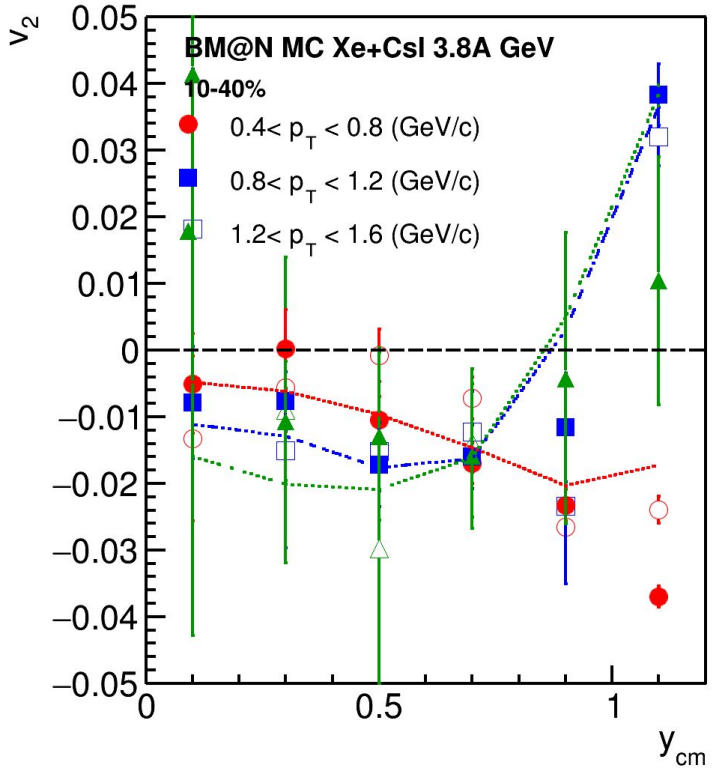


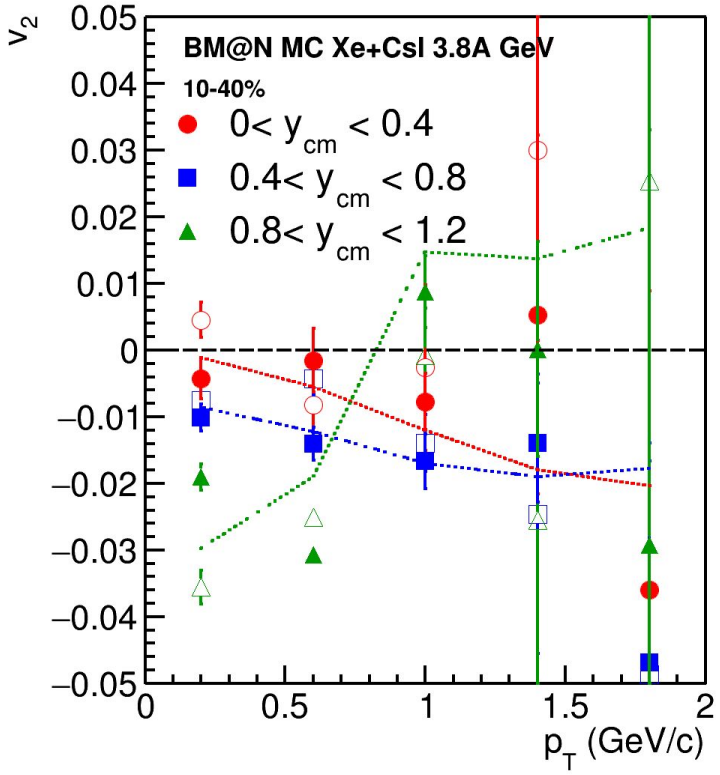
New correction performance on v1





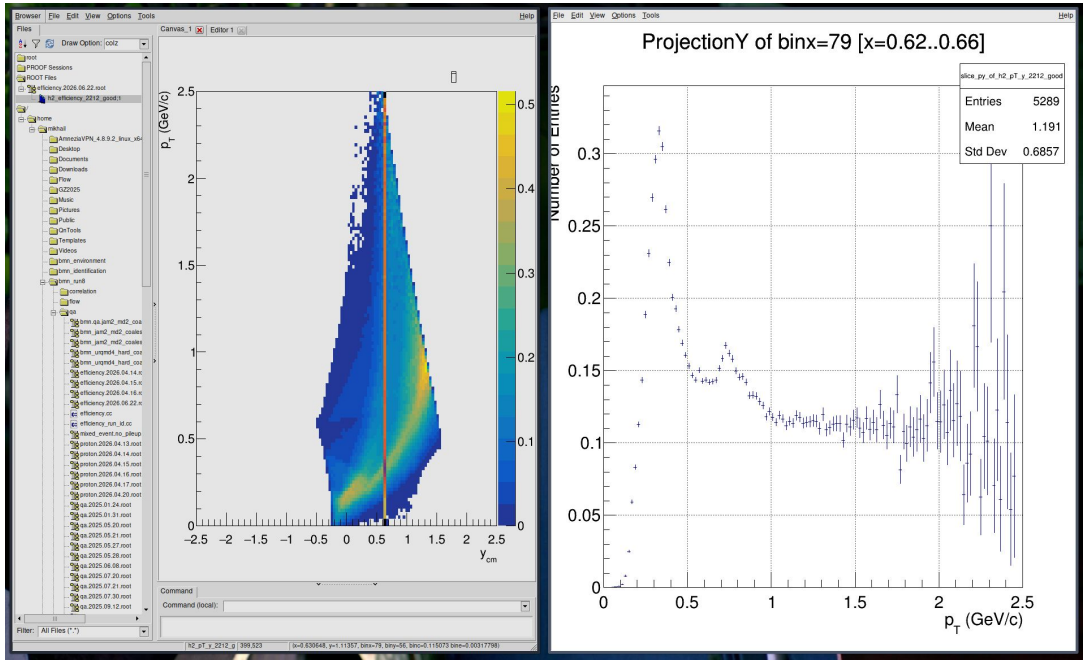
New correction performance on v2



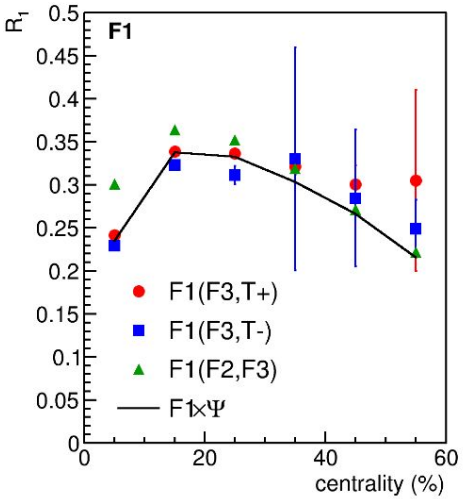


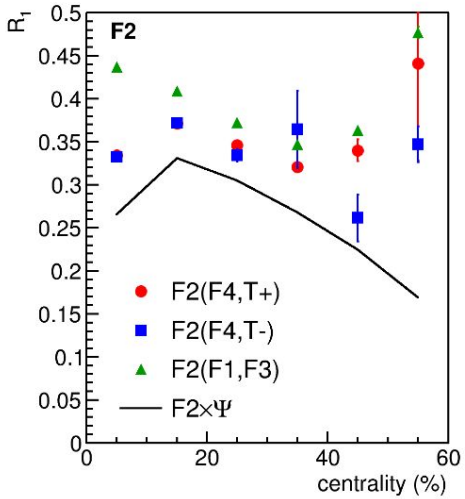
BM@N Monte-Carlo simulation

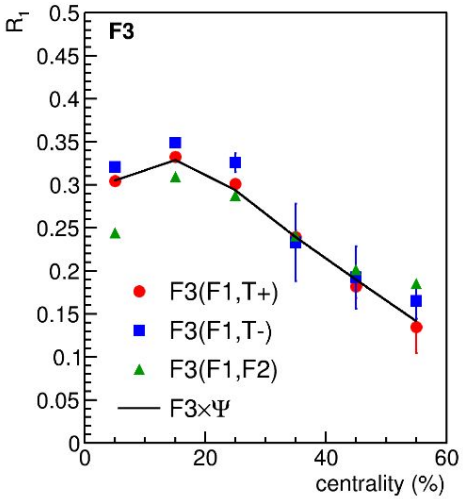
- JAM v2 with MD2 EOS + coalescence was used to generate Xe^{124}+Cs^{133} collisions at E_{kin}=3.8A GeV
- Approximately 3M of events were put through the realistic chain of simulation
- Same track selection criteria as in data
- Identification via the PDG and Mother-Id of associated model particle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

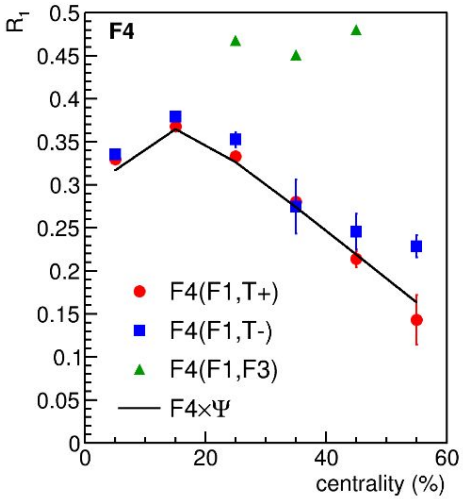


R1 vs centrality for MC simulation

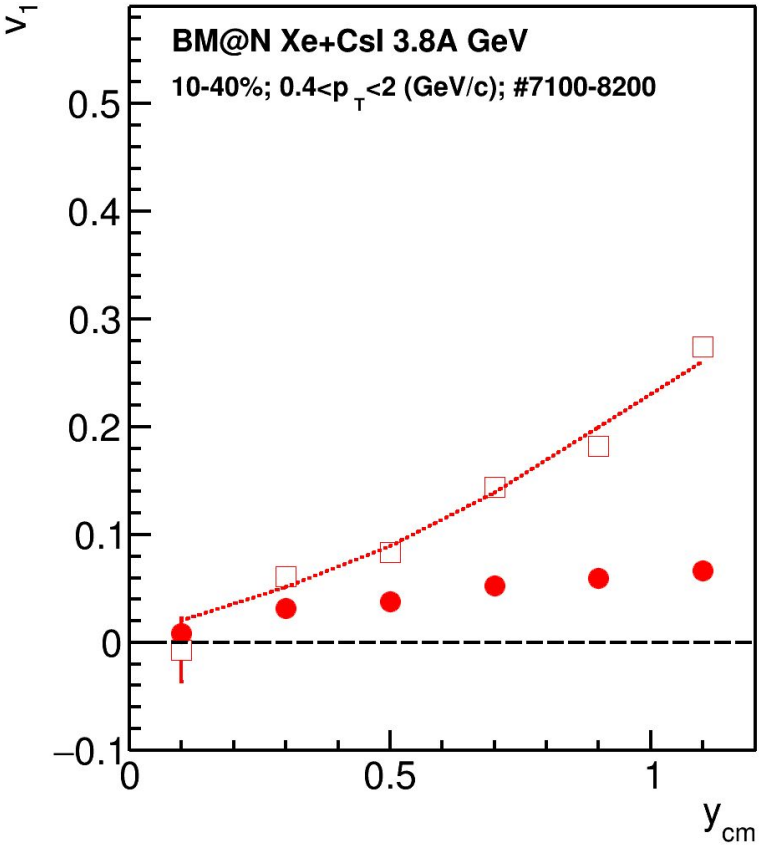


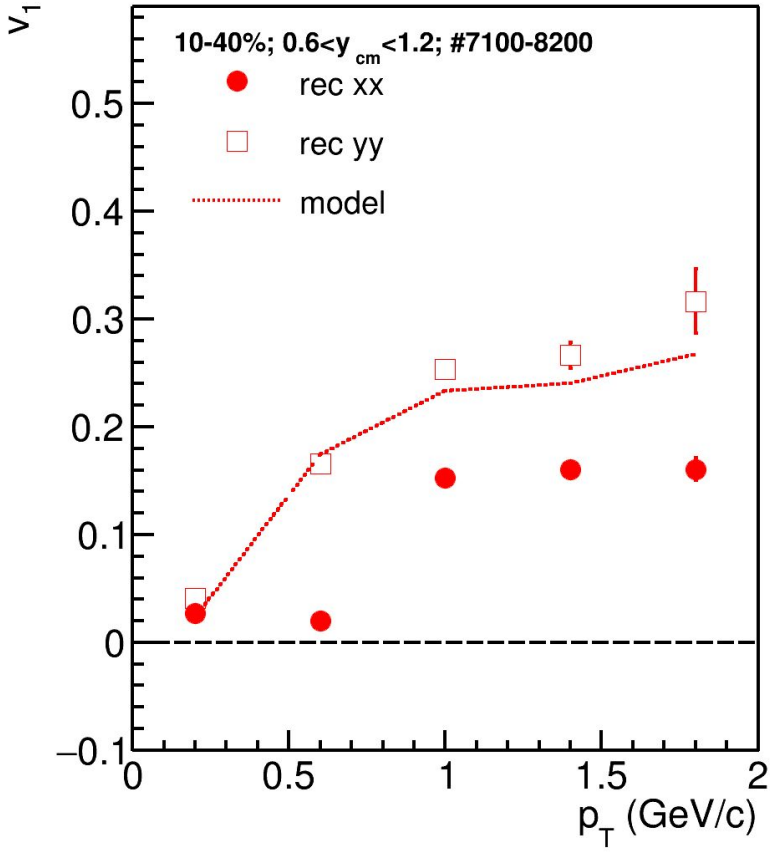




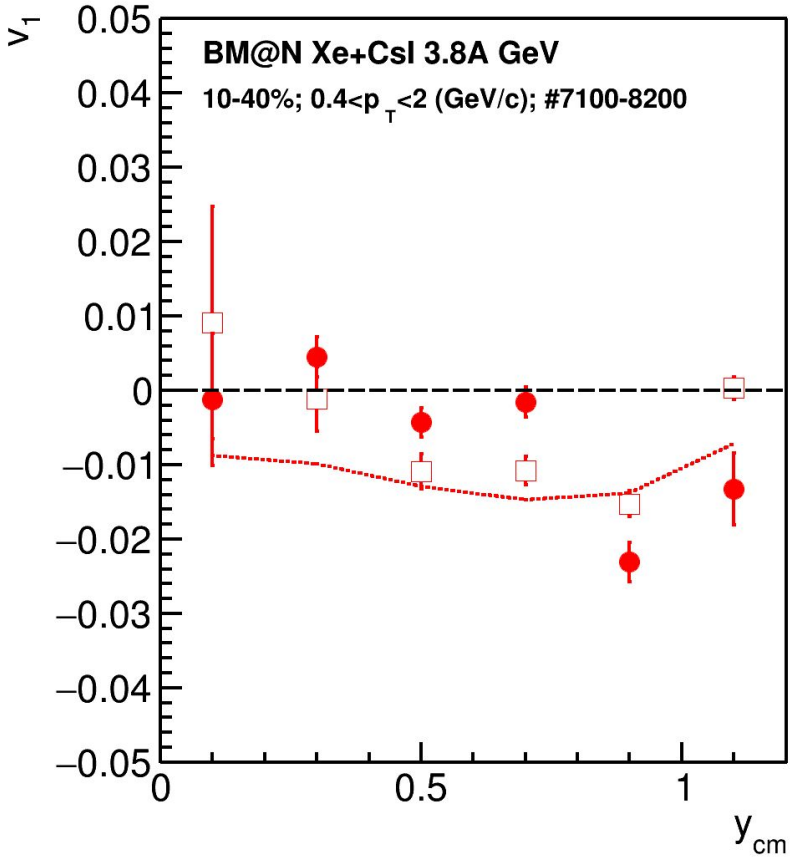


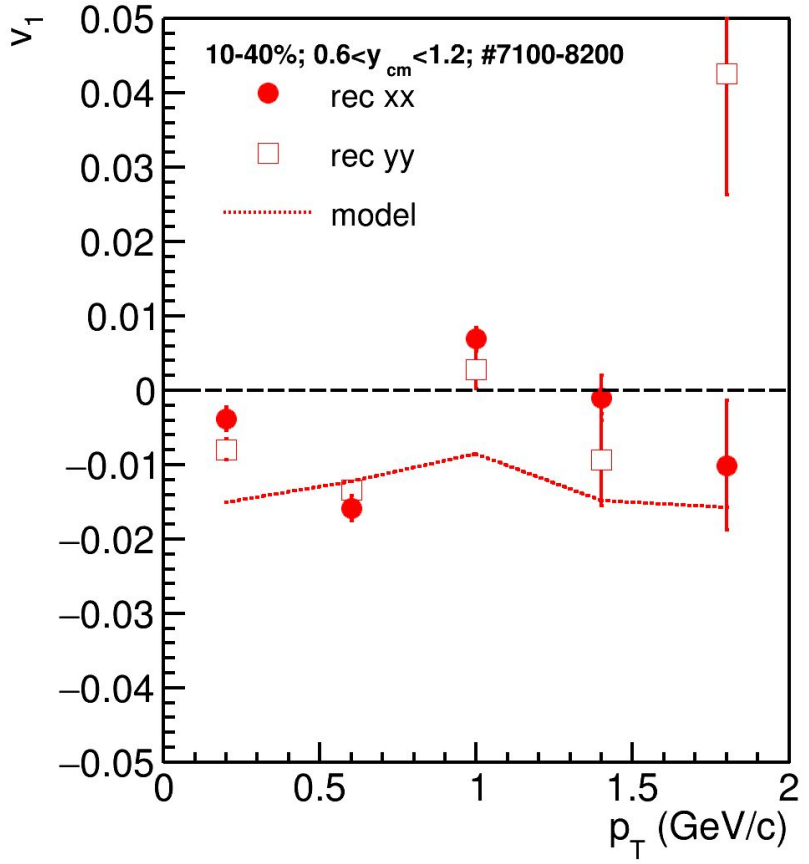
Comparison of v1 wrt RP for reconstructed and model



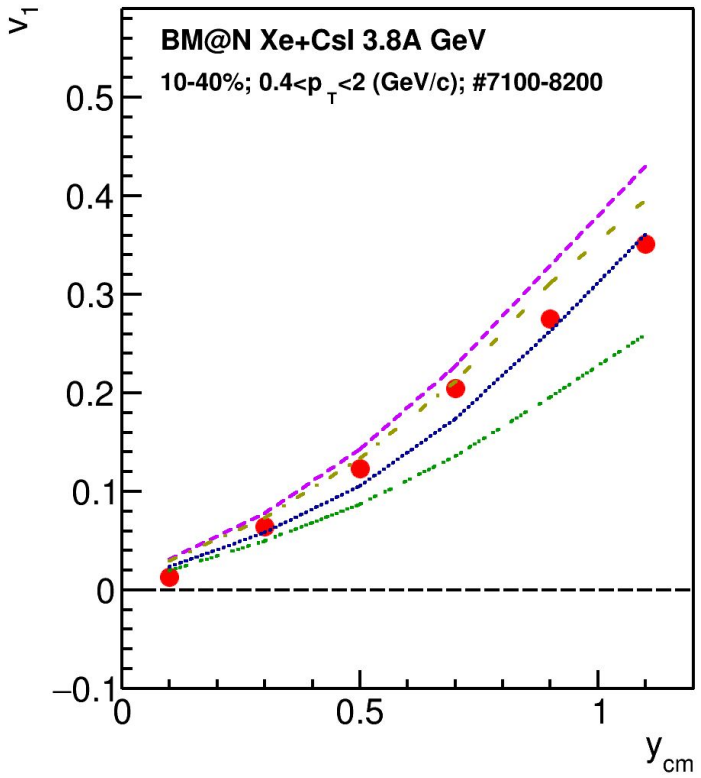


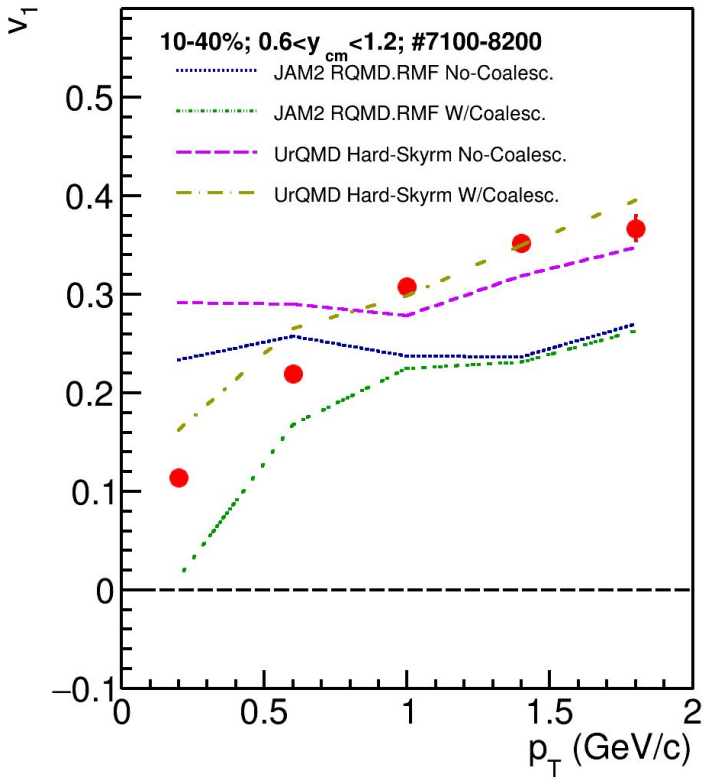
Comparison of v2 wrt RP for reconstructed and model



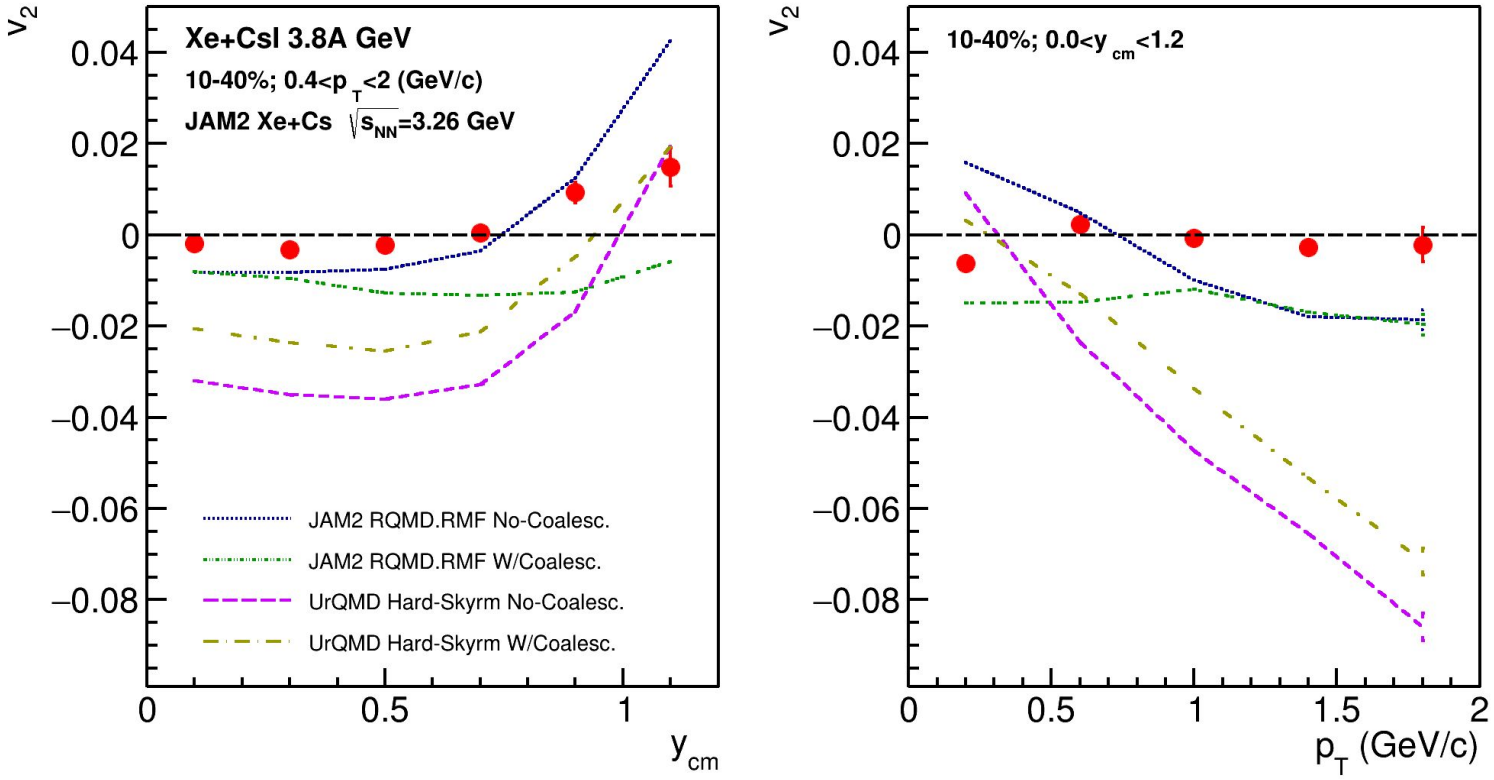


BM@N v_1 of p vs model calculations

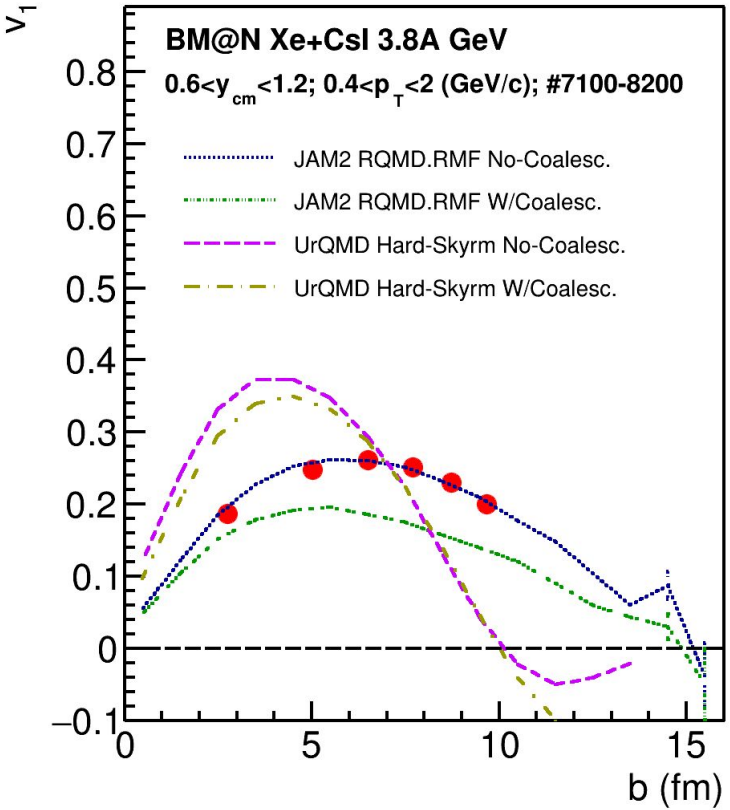


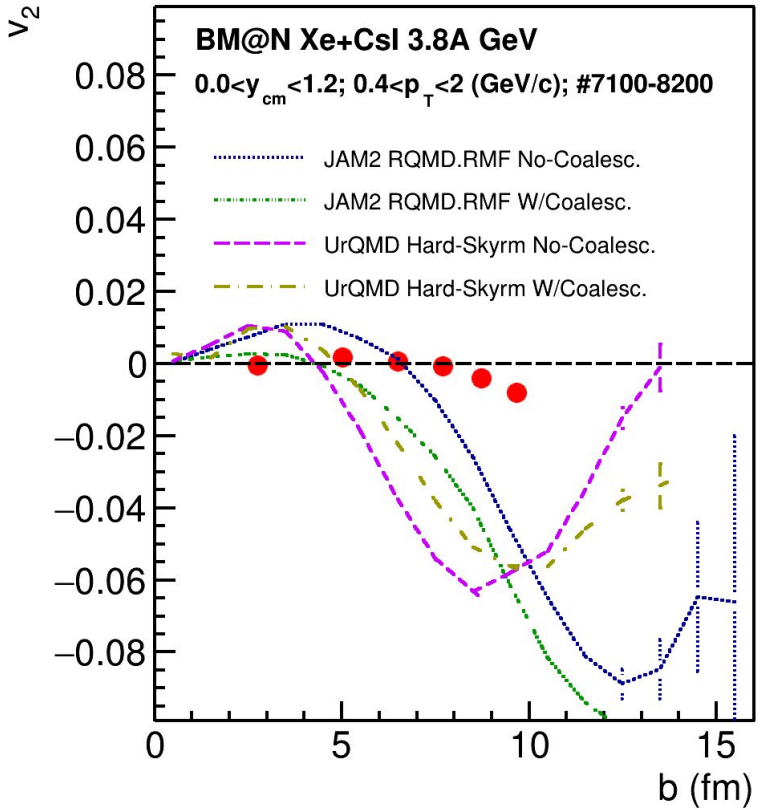


BM@N v_2 of p vs model calculations

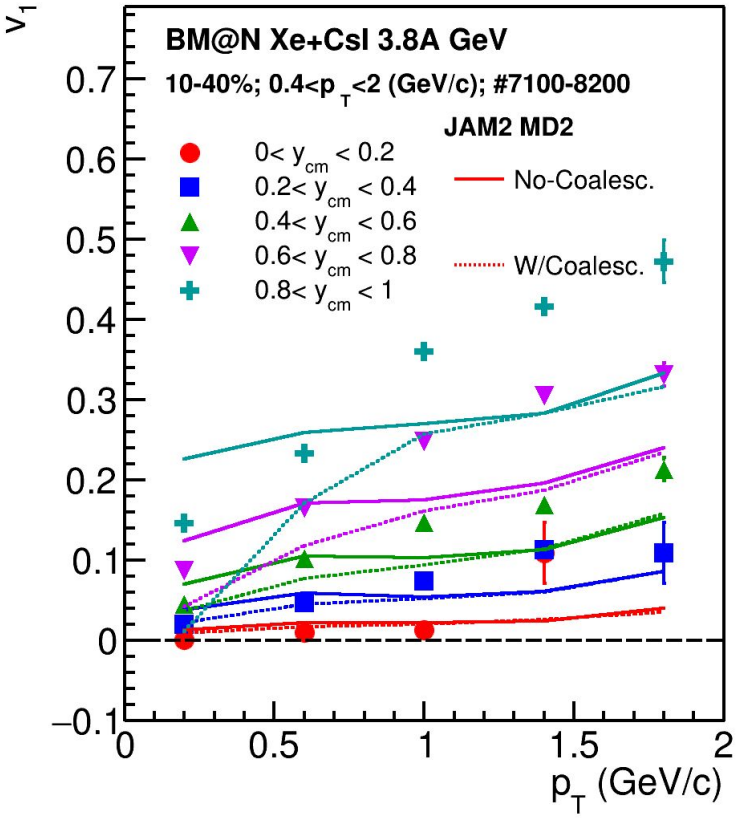


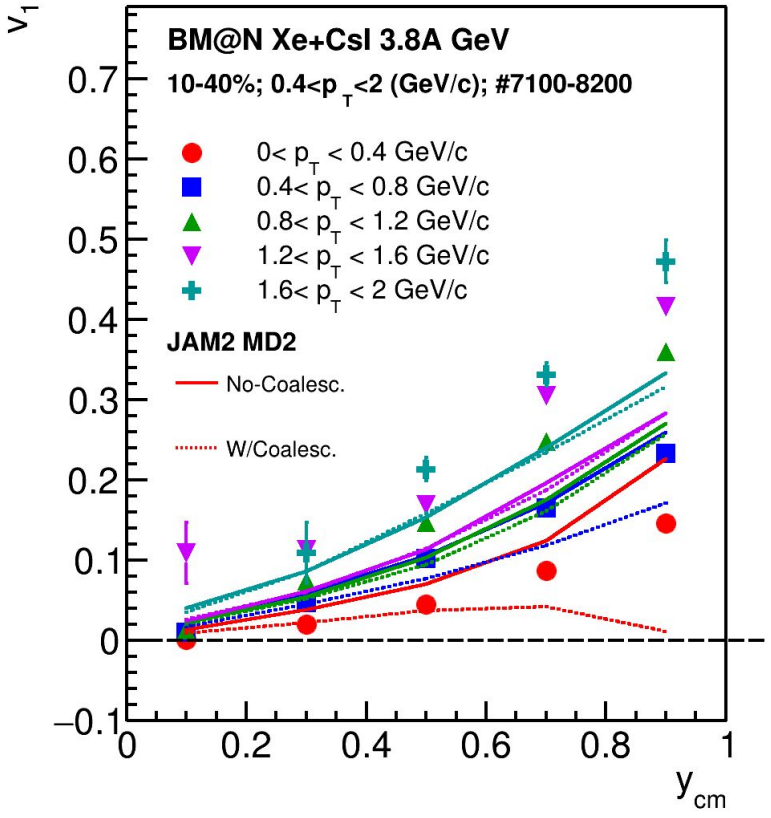
BM@N v_1, v_2 of p vs model calculations



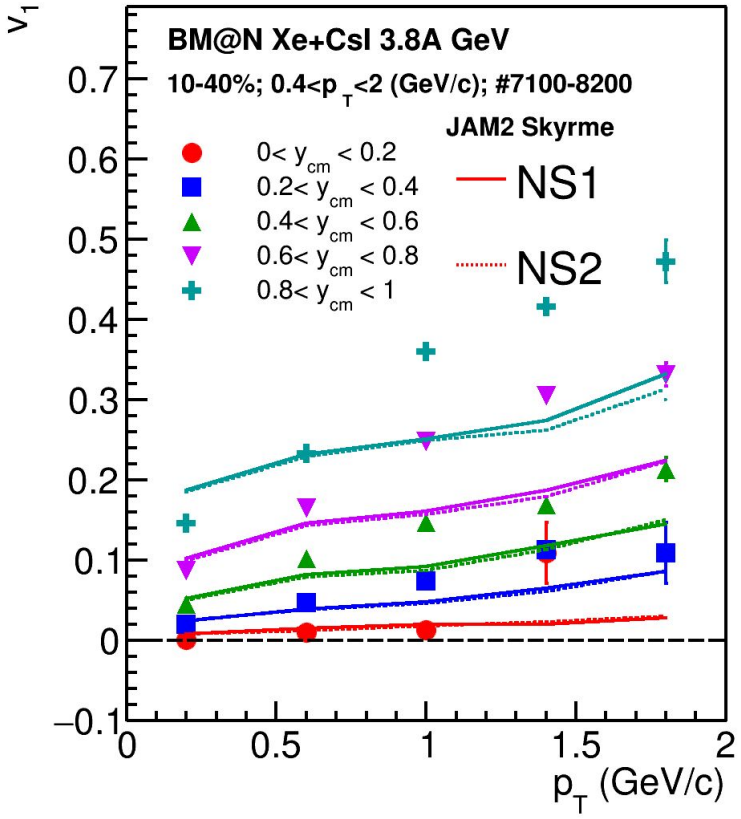


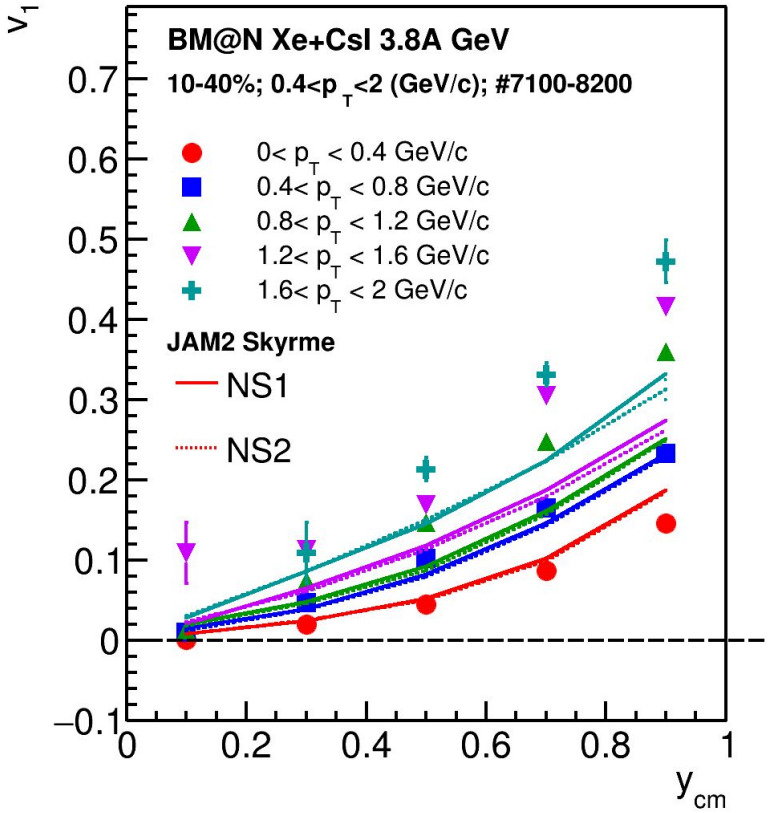
BM@N v_1 of p vs JAM MD2 with vs no coalescence



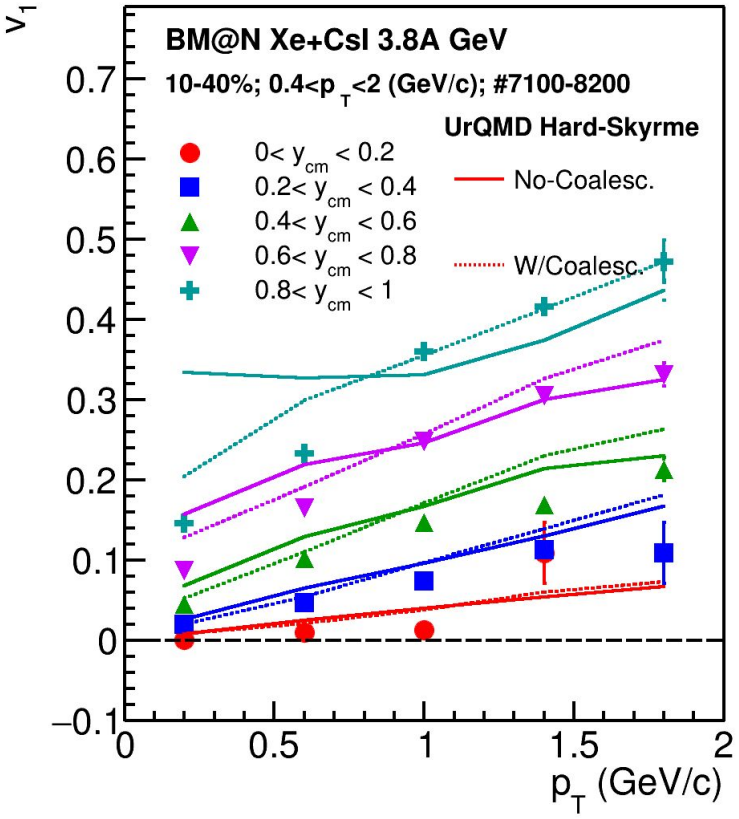


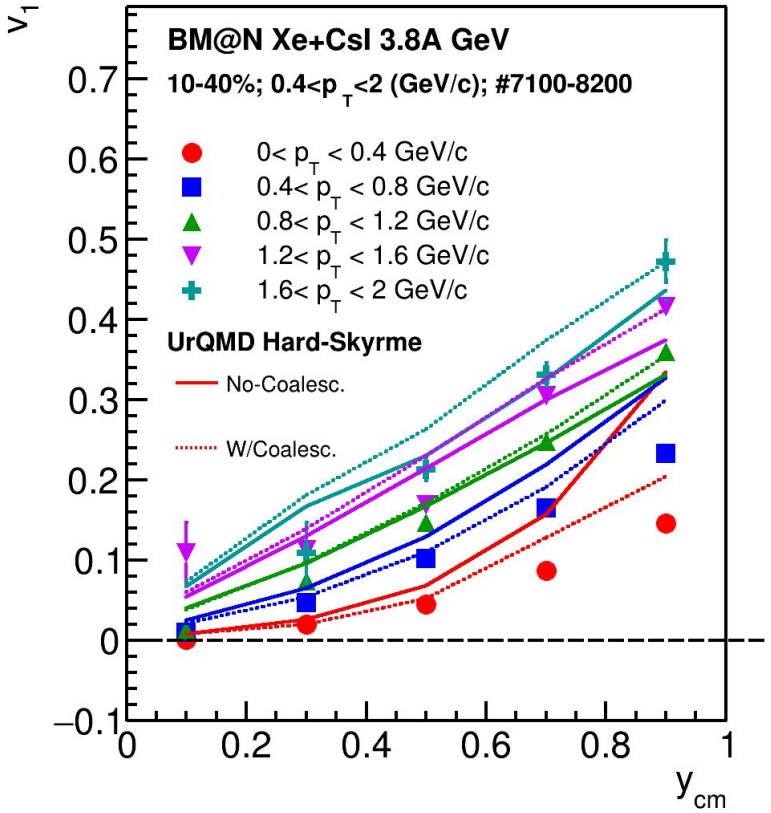
BM@N v_1 of p vs JAM Skyrme (no coalescence)



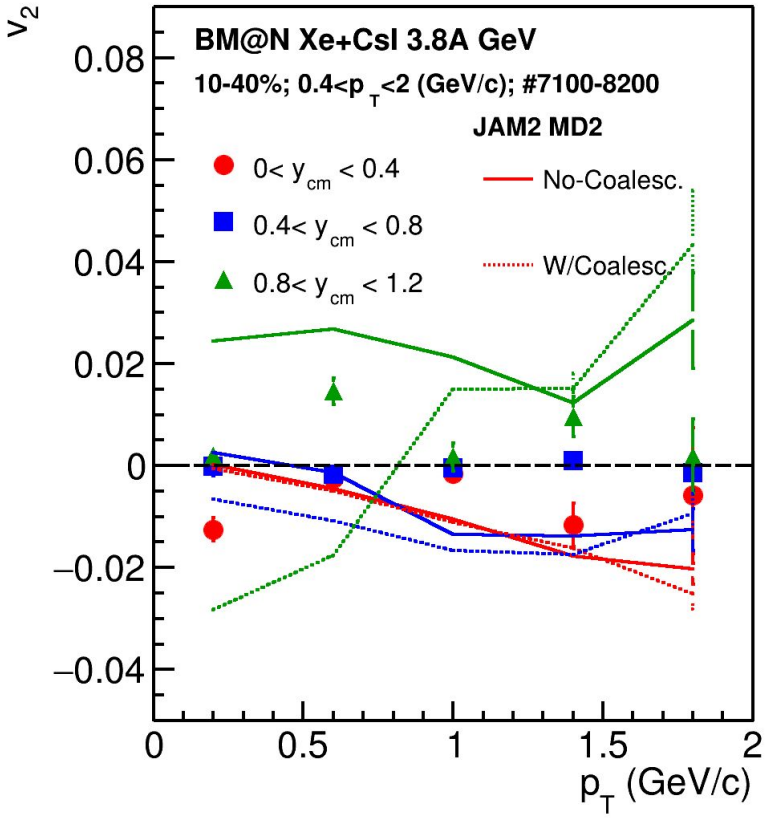


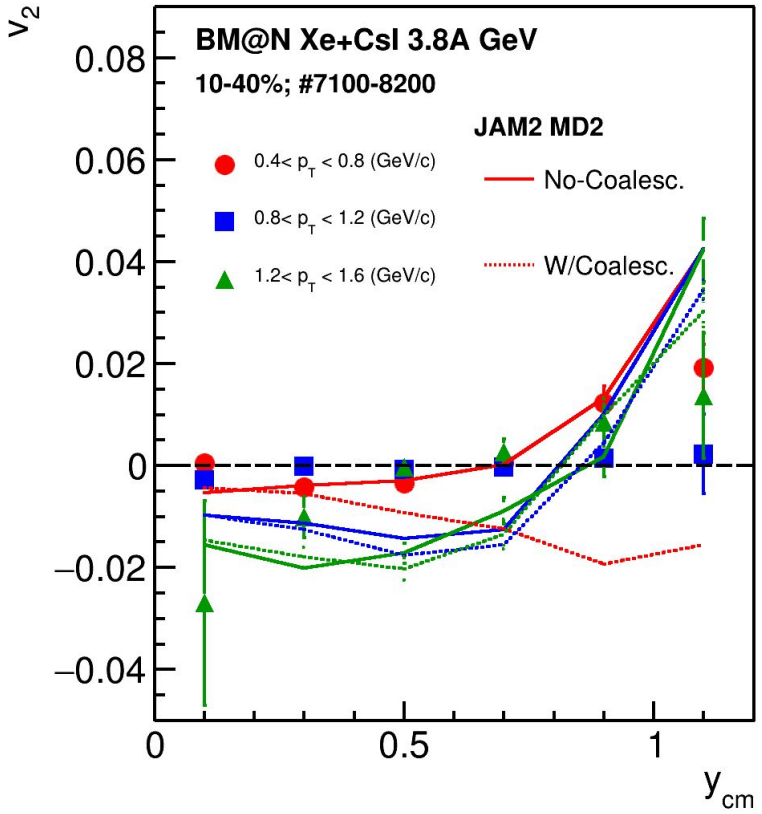
BM@N v_1 of p vs UrQMD hard-skyrme with vs no coalescence



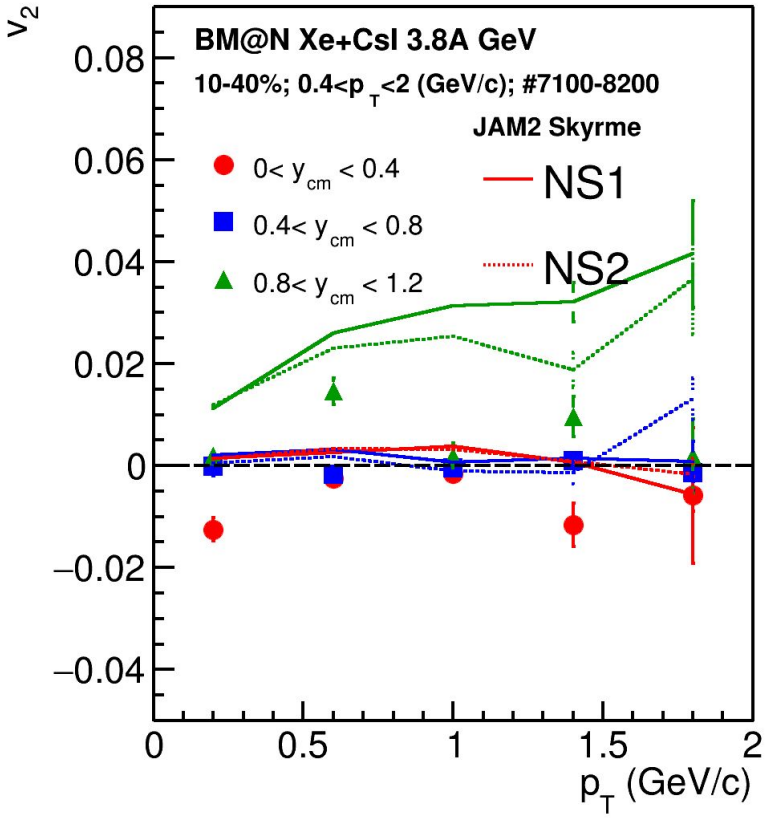


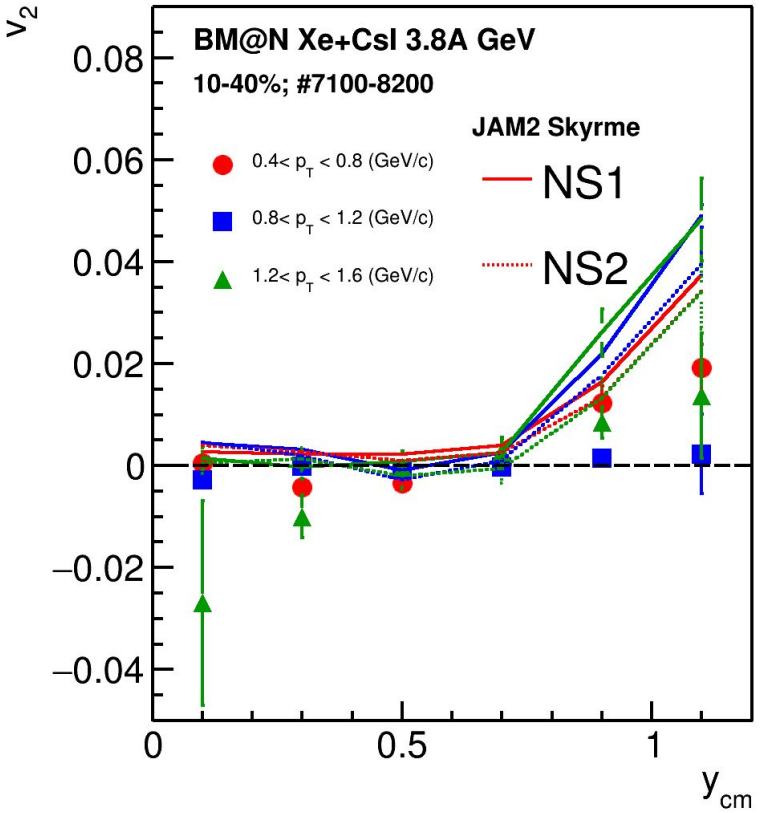
BM@N v_2 of p vs JAM MD2 with vs no coalescence



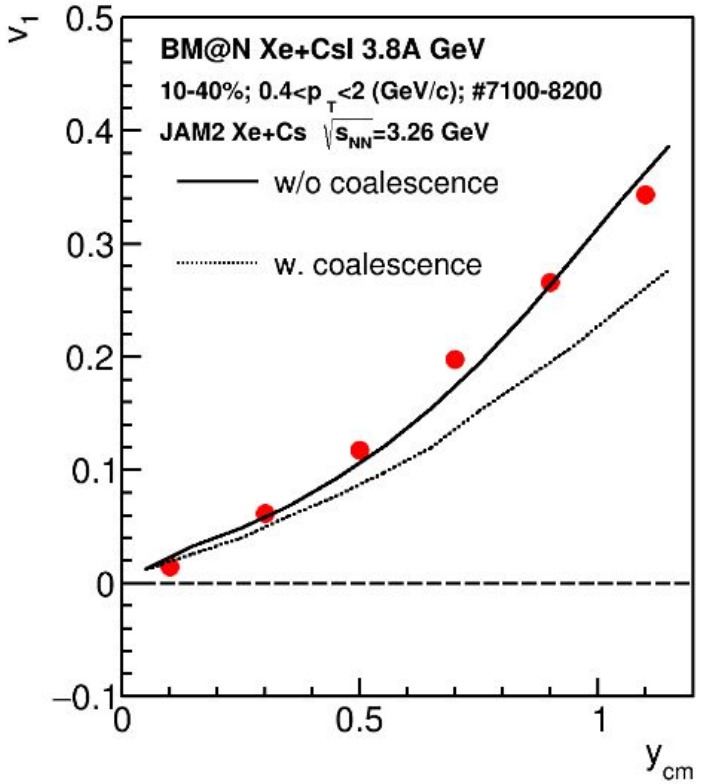


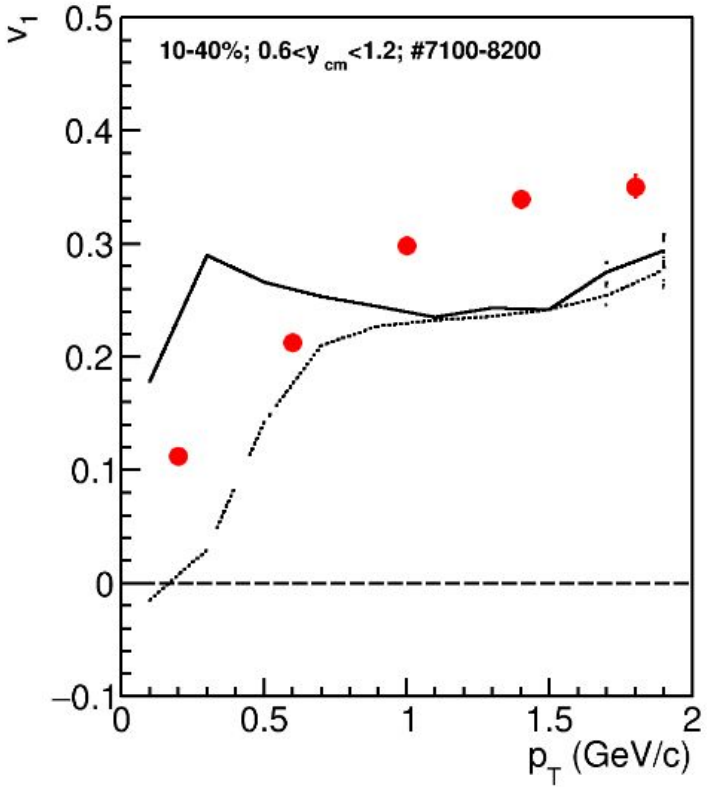
BM@N v_2 of p vs JAM Skyrme (no coalescence)



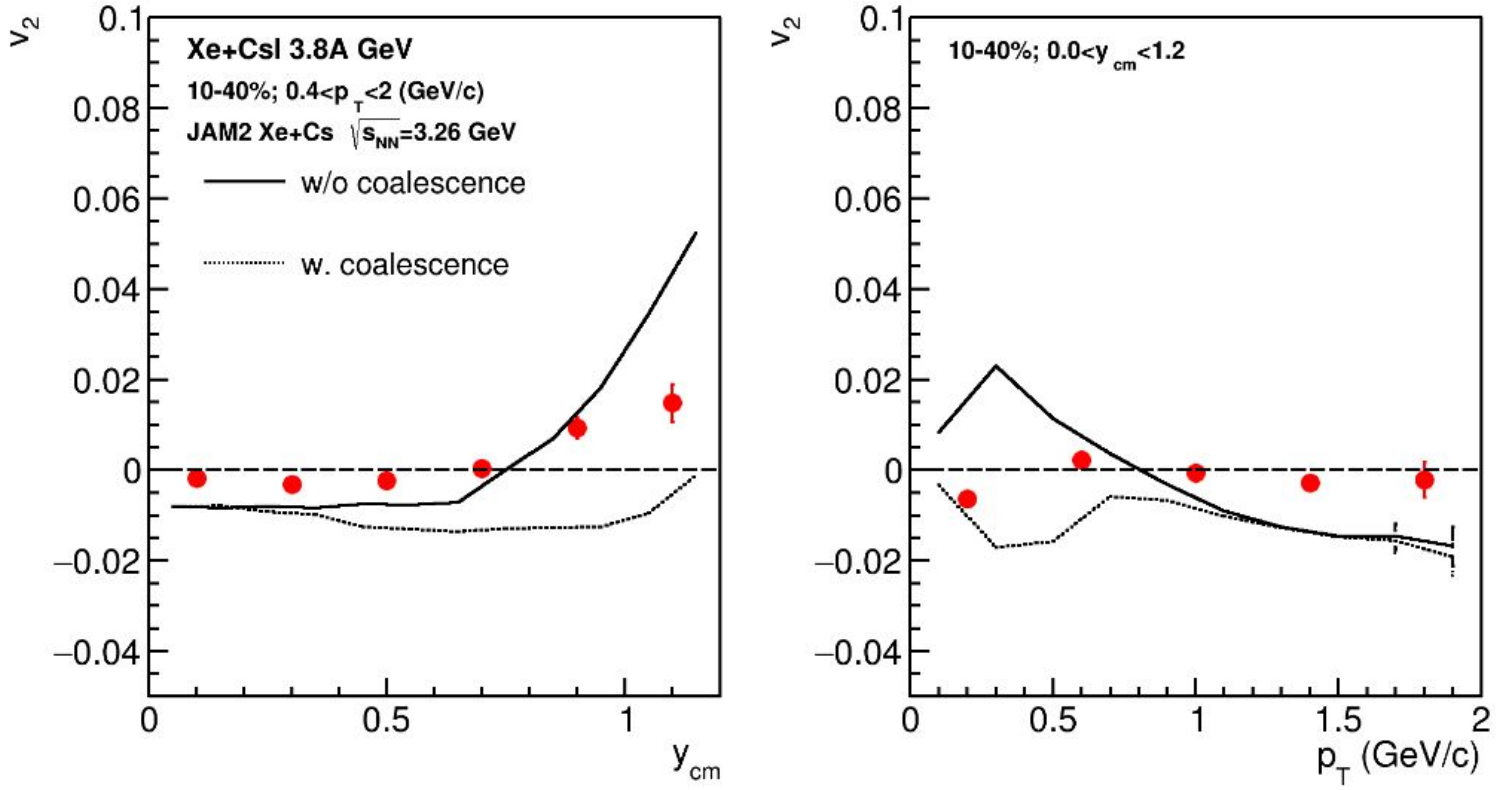


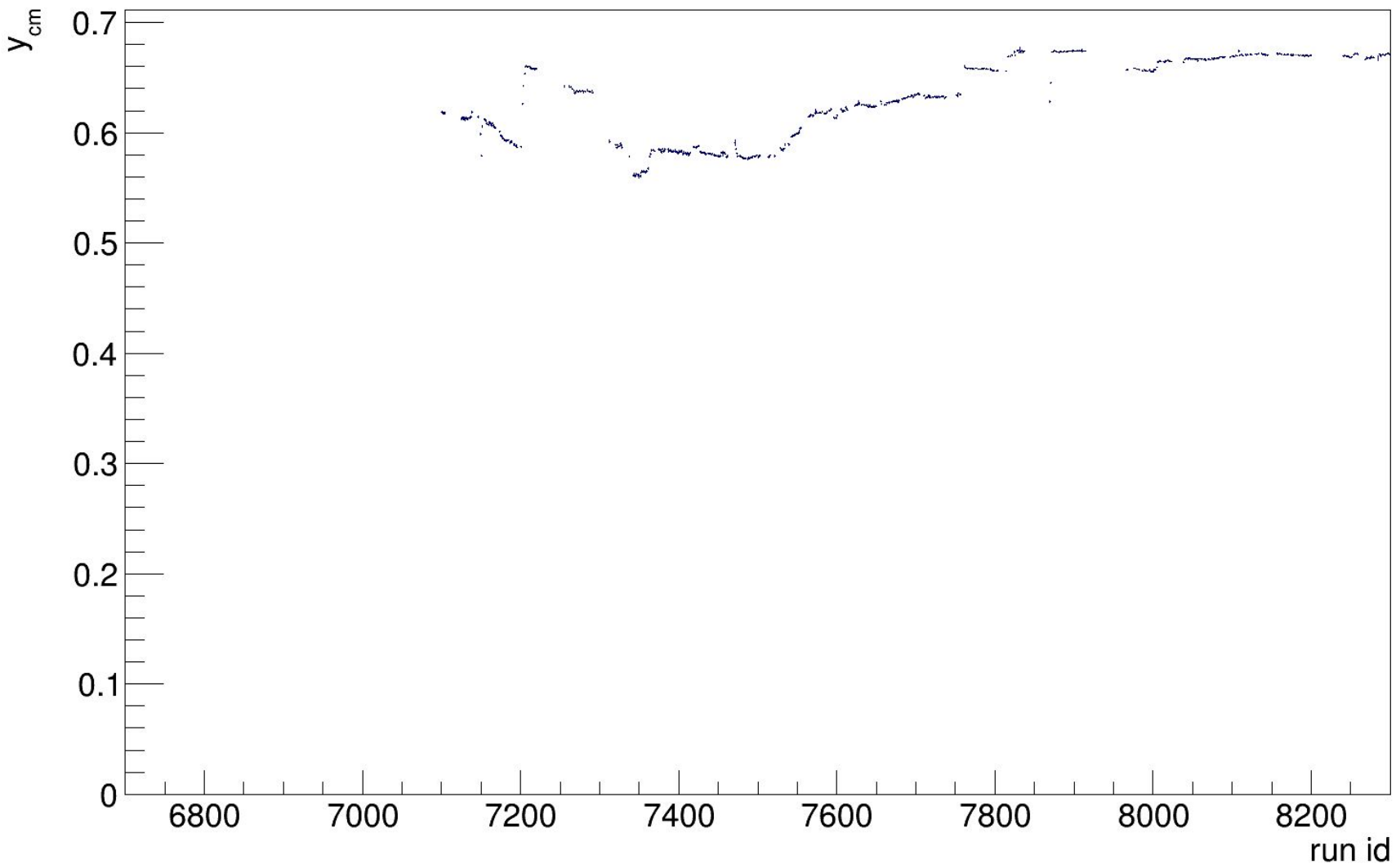
BM@N v_1 of p vs JAM MD2 calculations





BM@N v_2 of p vs JAM MD2 calculations




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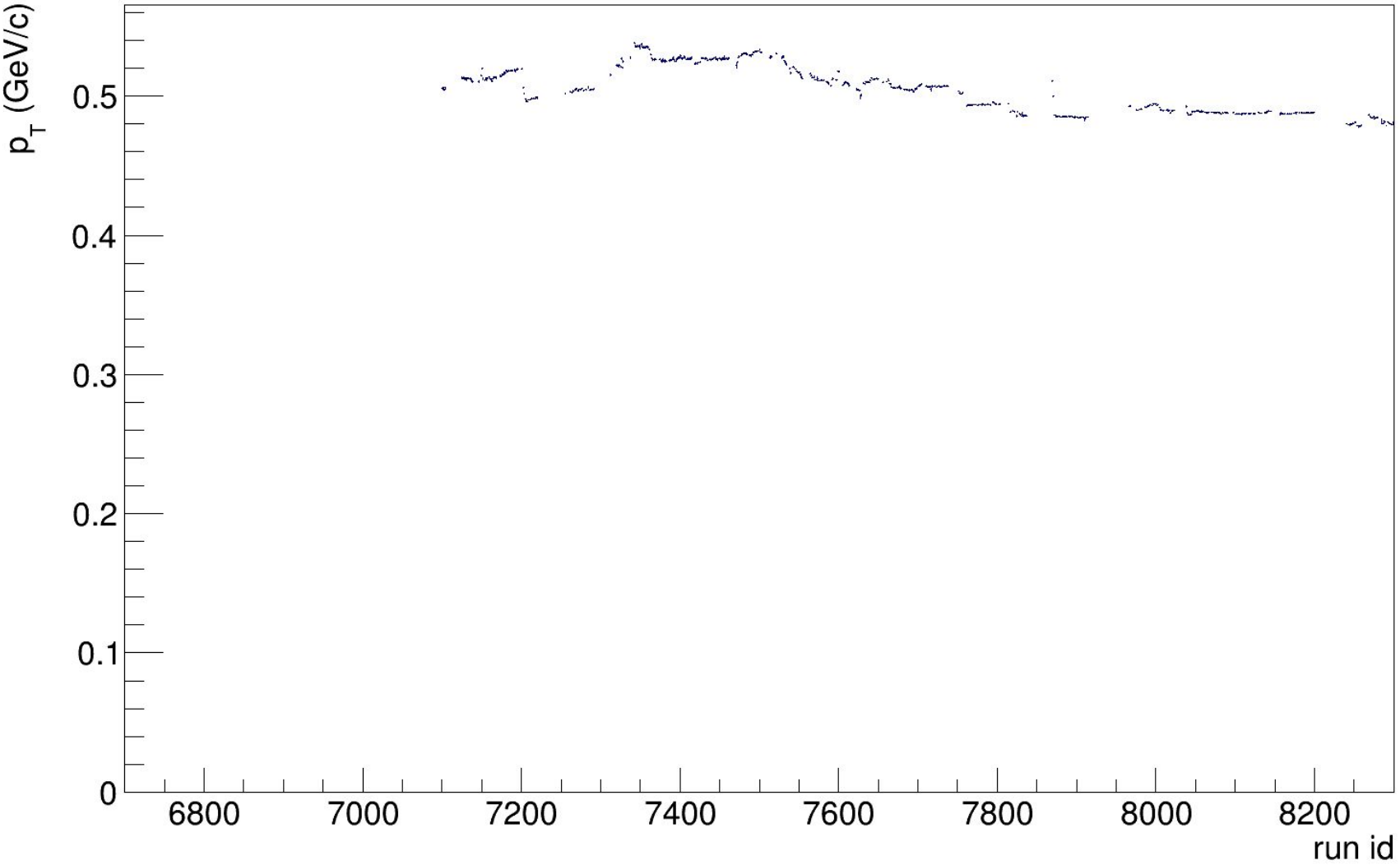
7600
7800
8000
8200
run id


p_T (GeV/c)
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0.2
0.1
0
6800
7000
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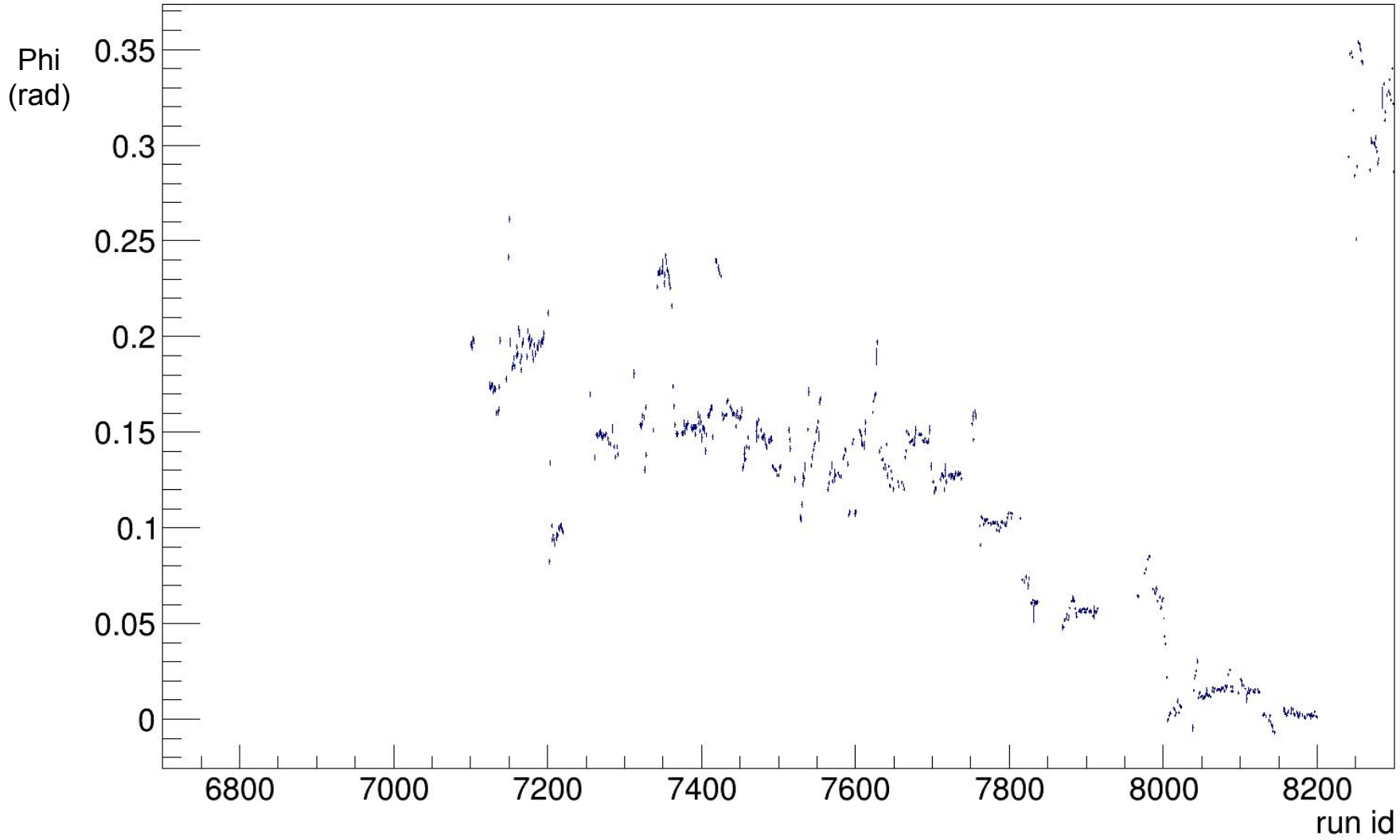
8000
8200
run id


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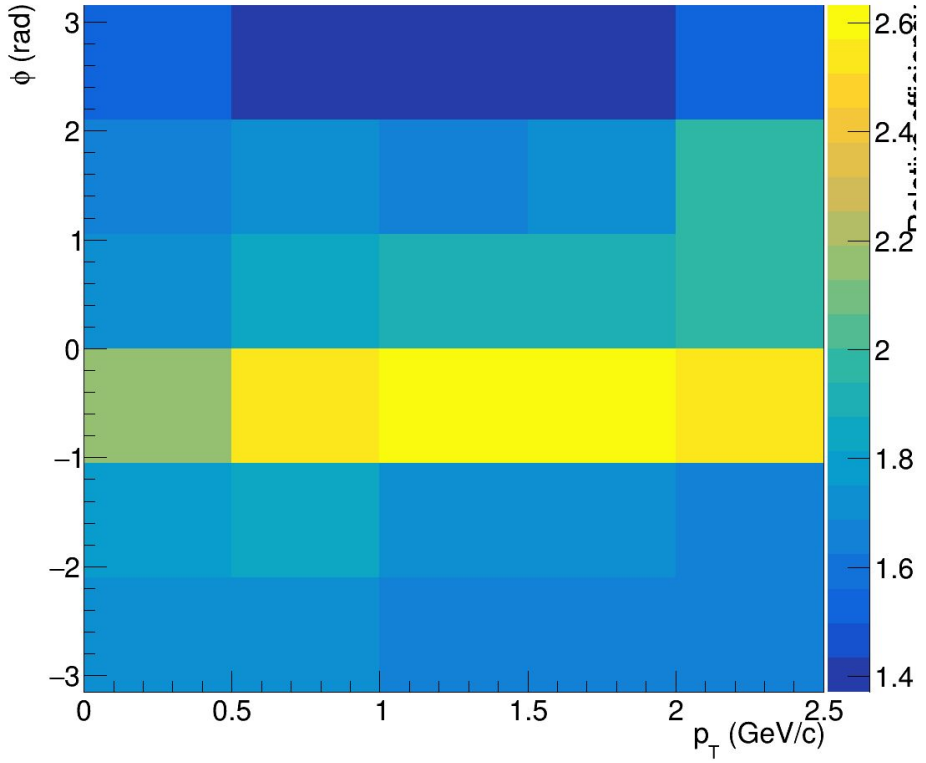
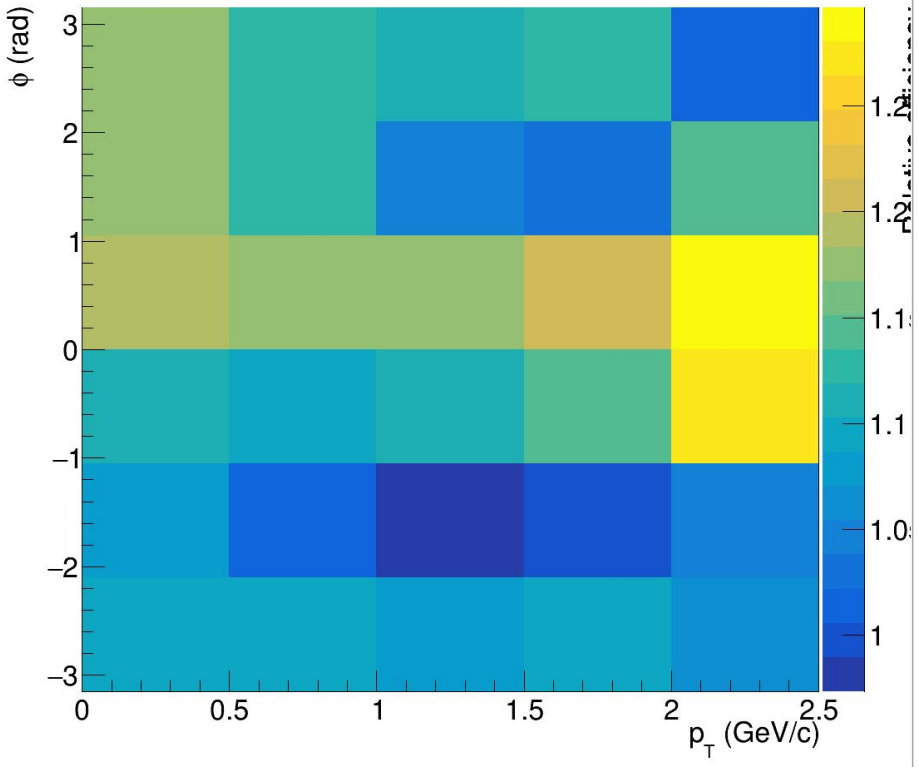
0.3
0.25
0.2
0.15
0.1
0.05
0
6800
7000
7200
7400
7600
7800
8000
8200
run id

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

#7128, 2 < η < 3

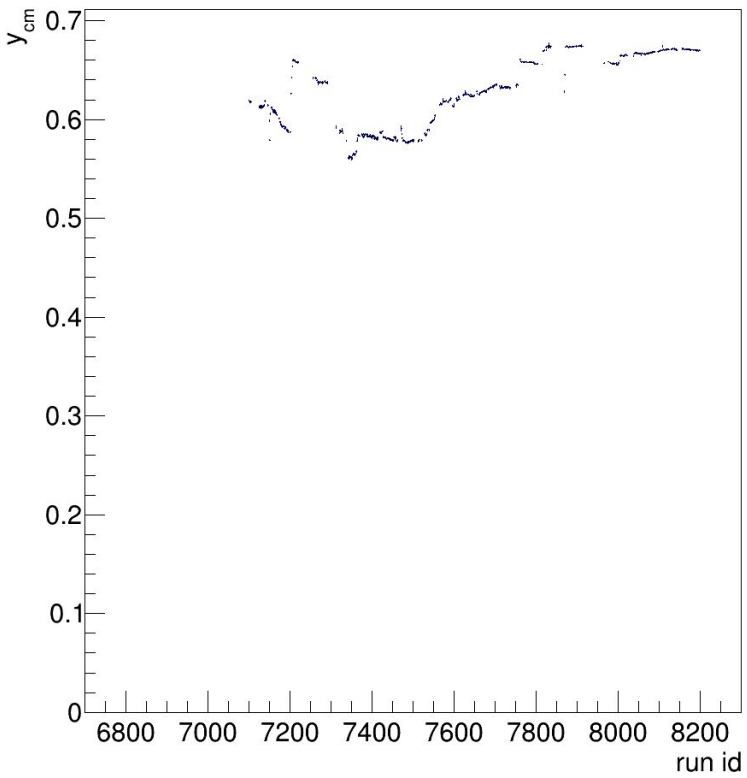


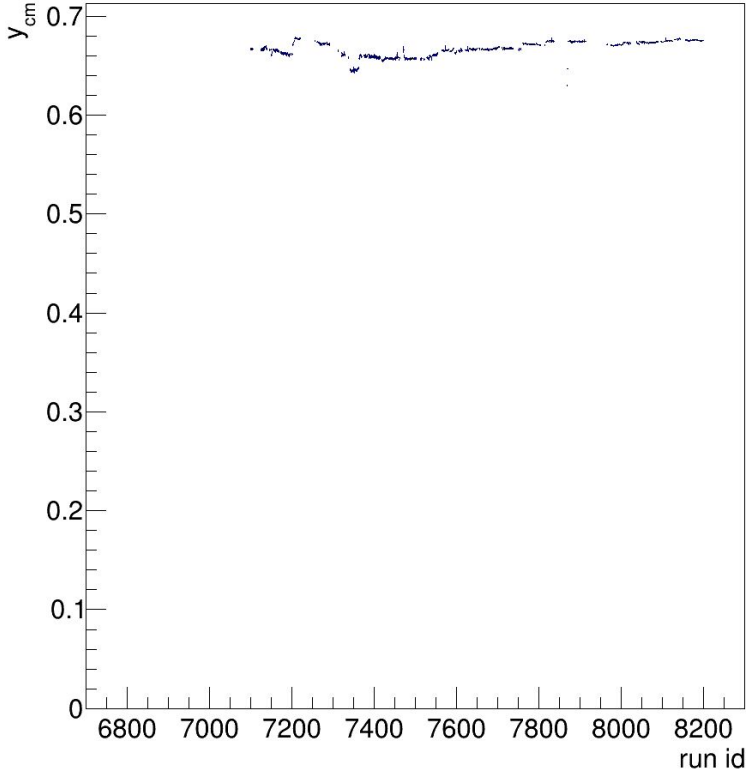
#8188, 2 < η < 3



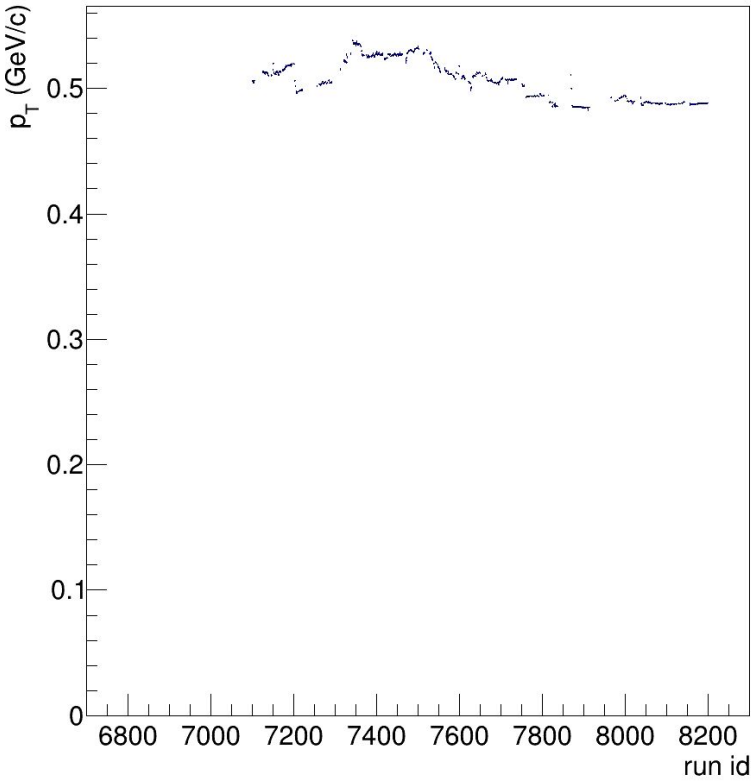
4D-efficiency was built: η, p_T, ϕ, run-id. $E = N_{curr}/N_{target\ run\text{-}id}$

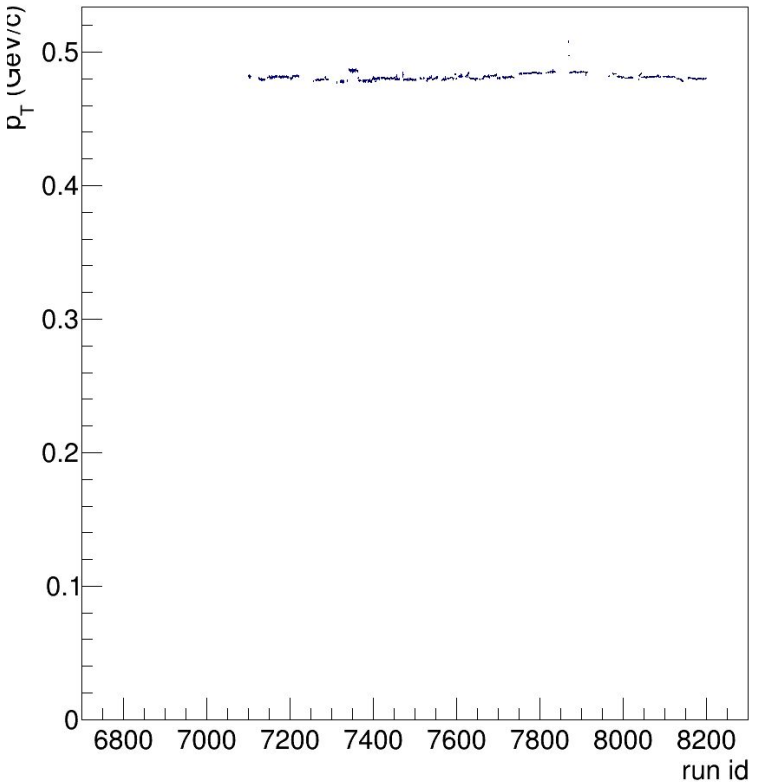
Proton y-distribution before/after reweighting



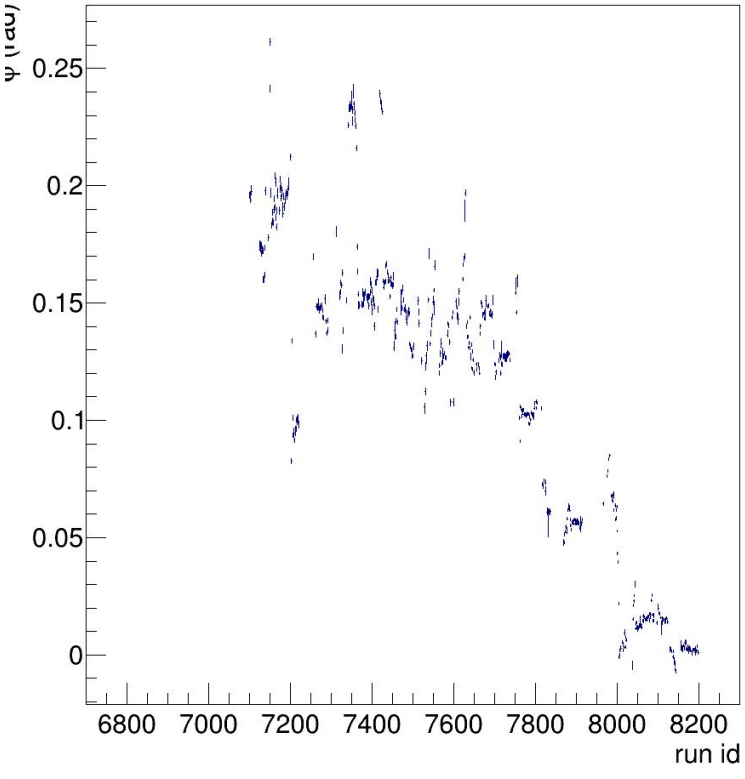


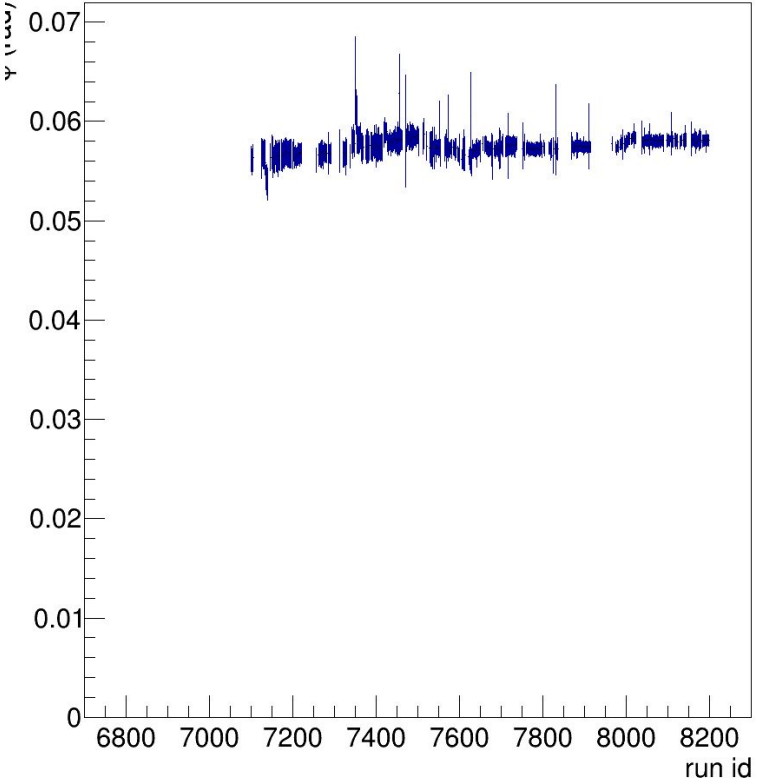
Proton p_T-distribution before/after reweighting



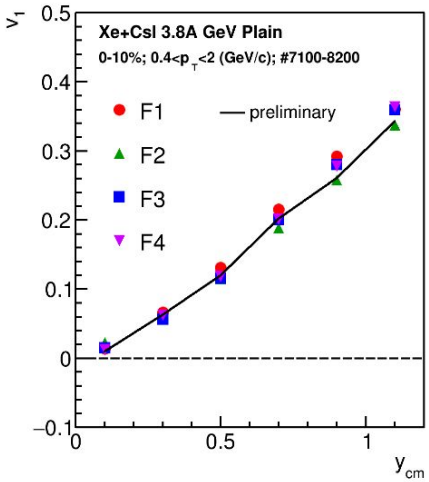


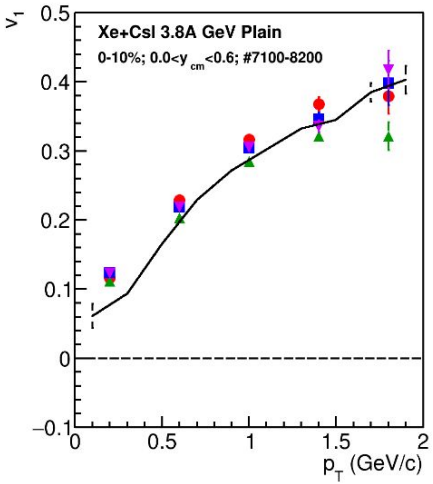
Proton p_T-distribution before/after reweighting

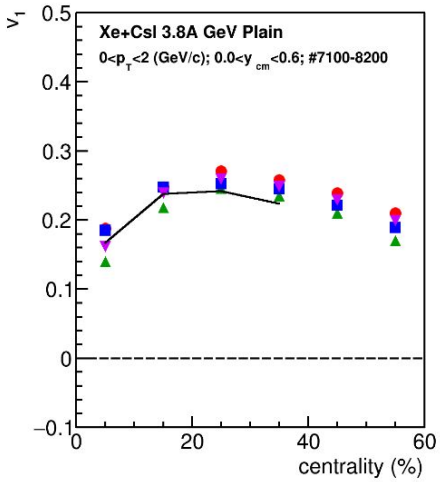


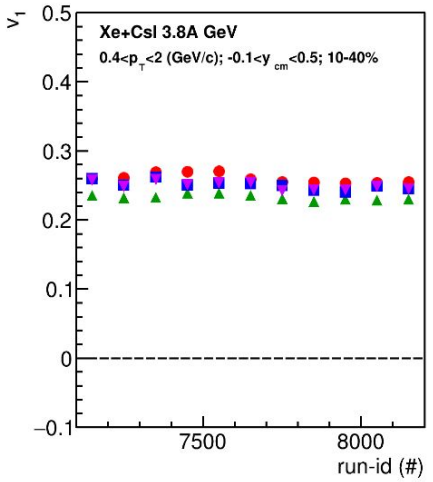


Proton v_1 after track reweighting

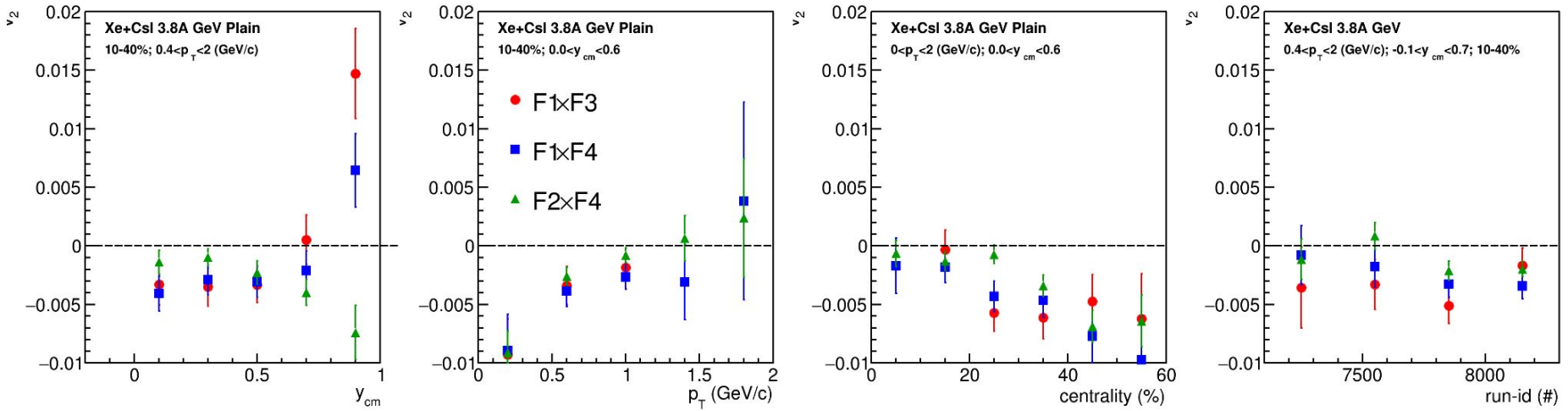




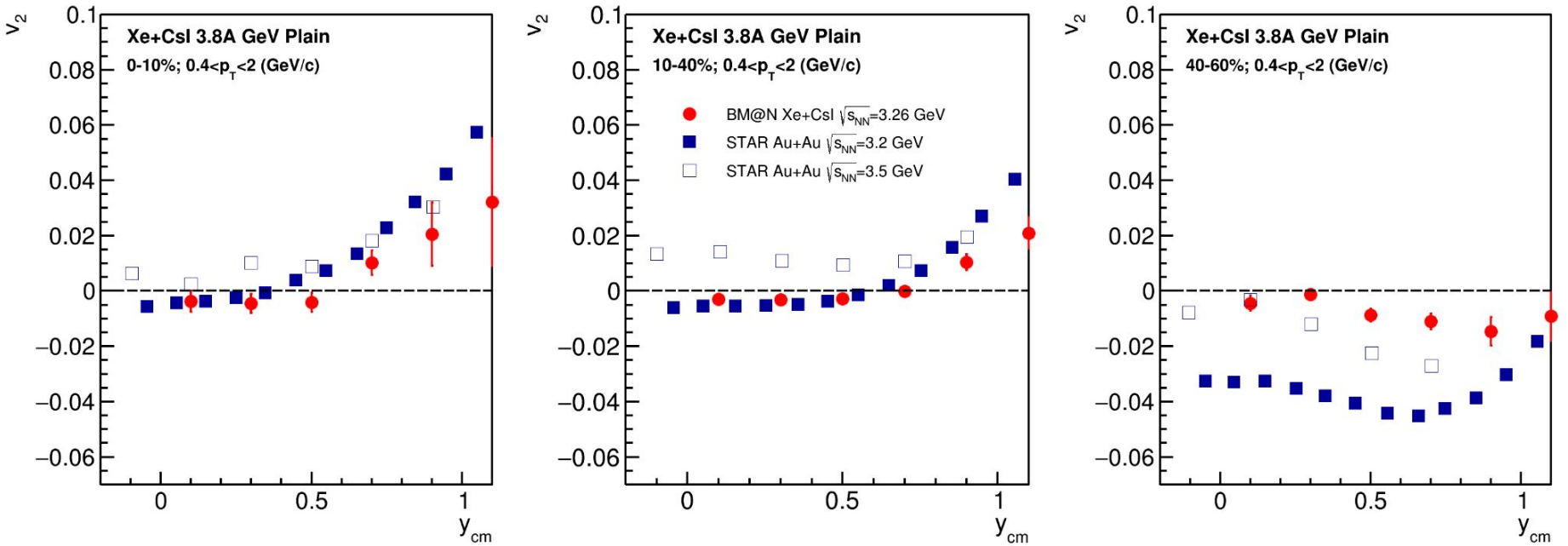




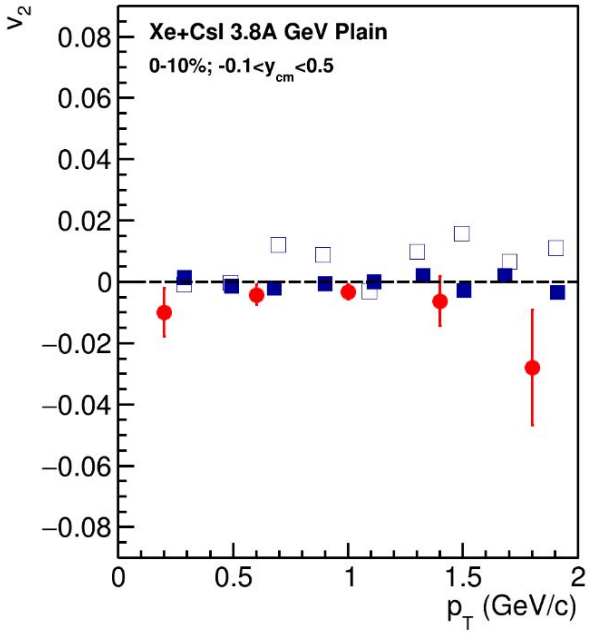
Proton v_2 after track reweighting

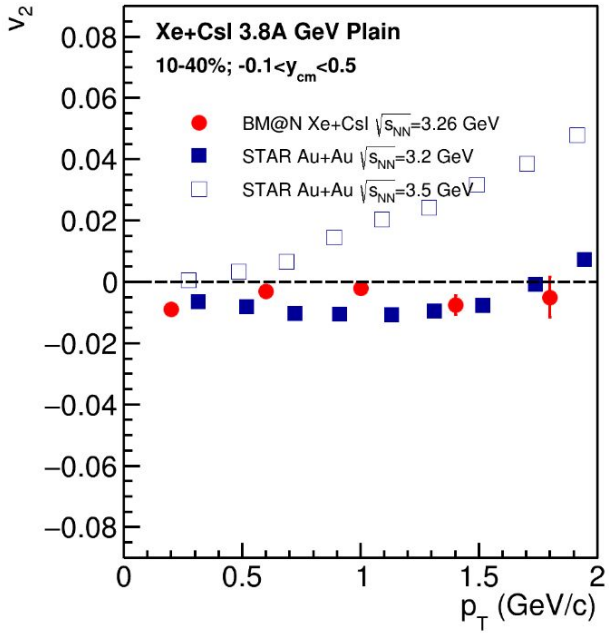


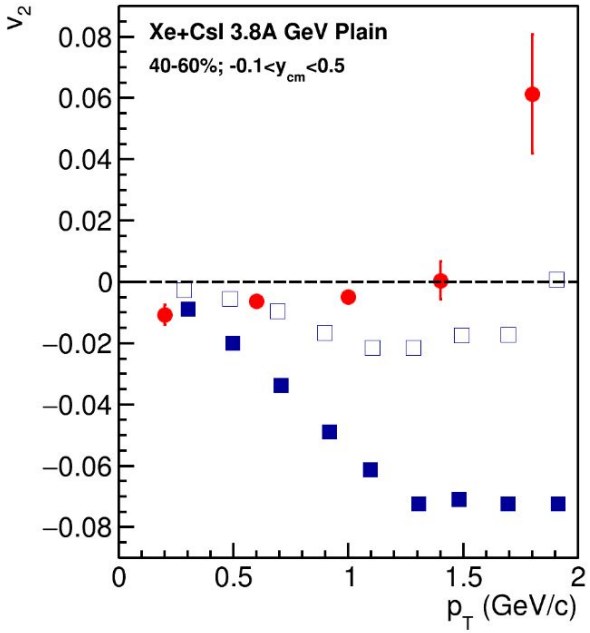
Proton v_2 after track reweighting



Proton v_2 after track reweighting

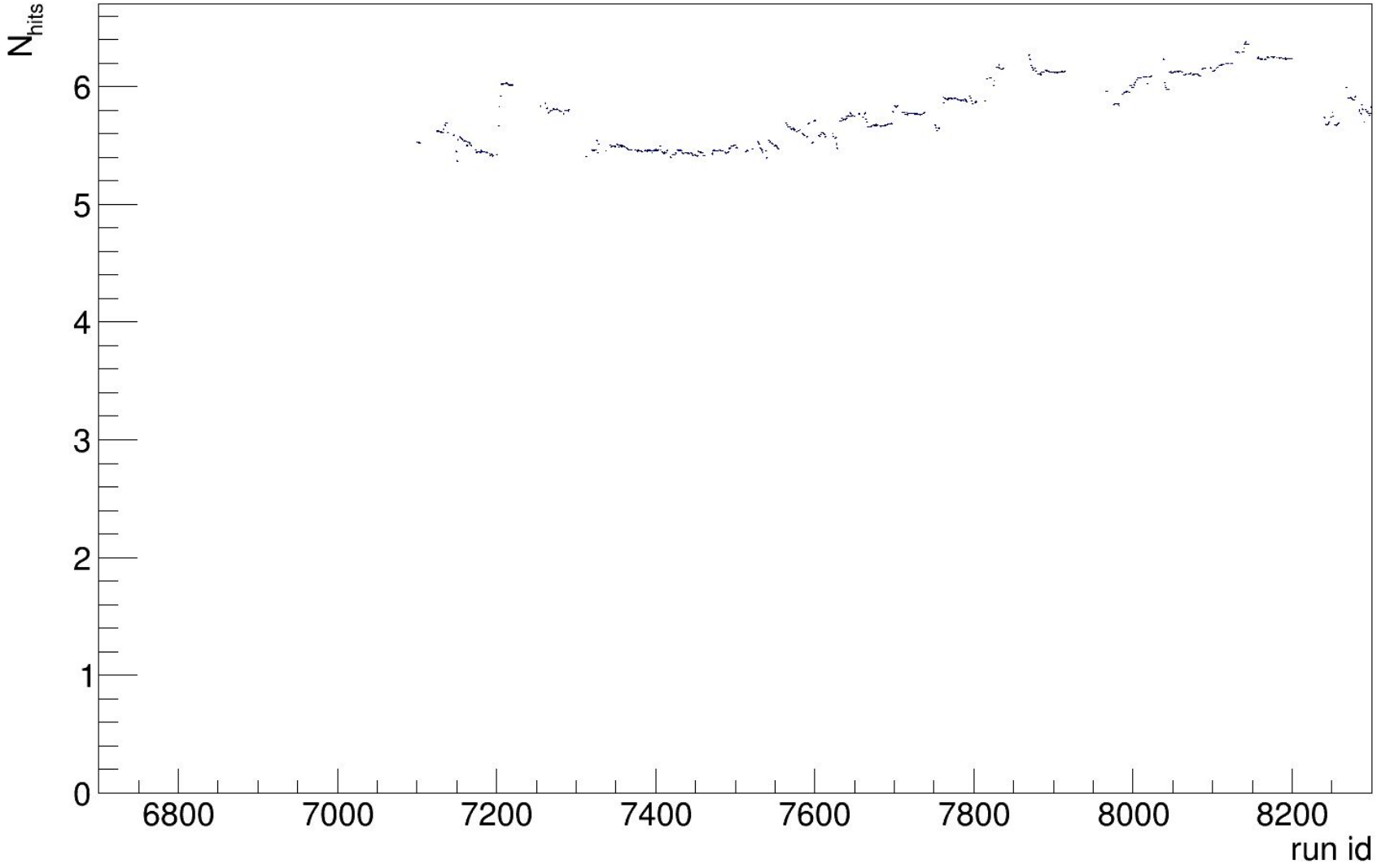


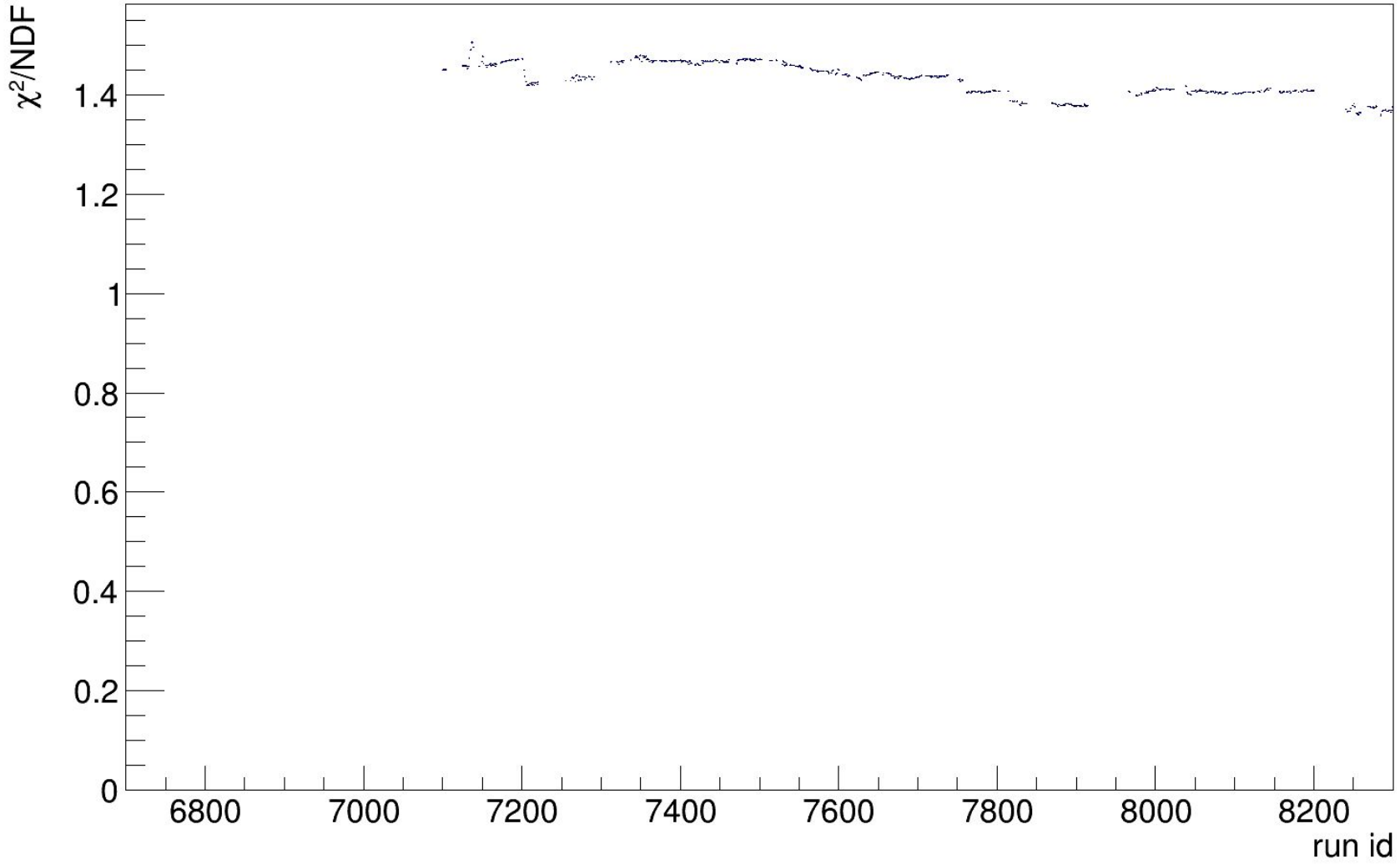


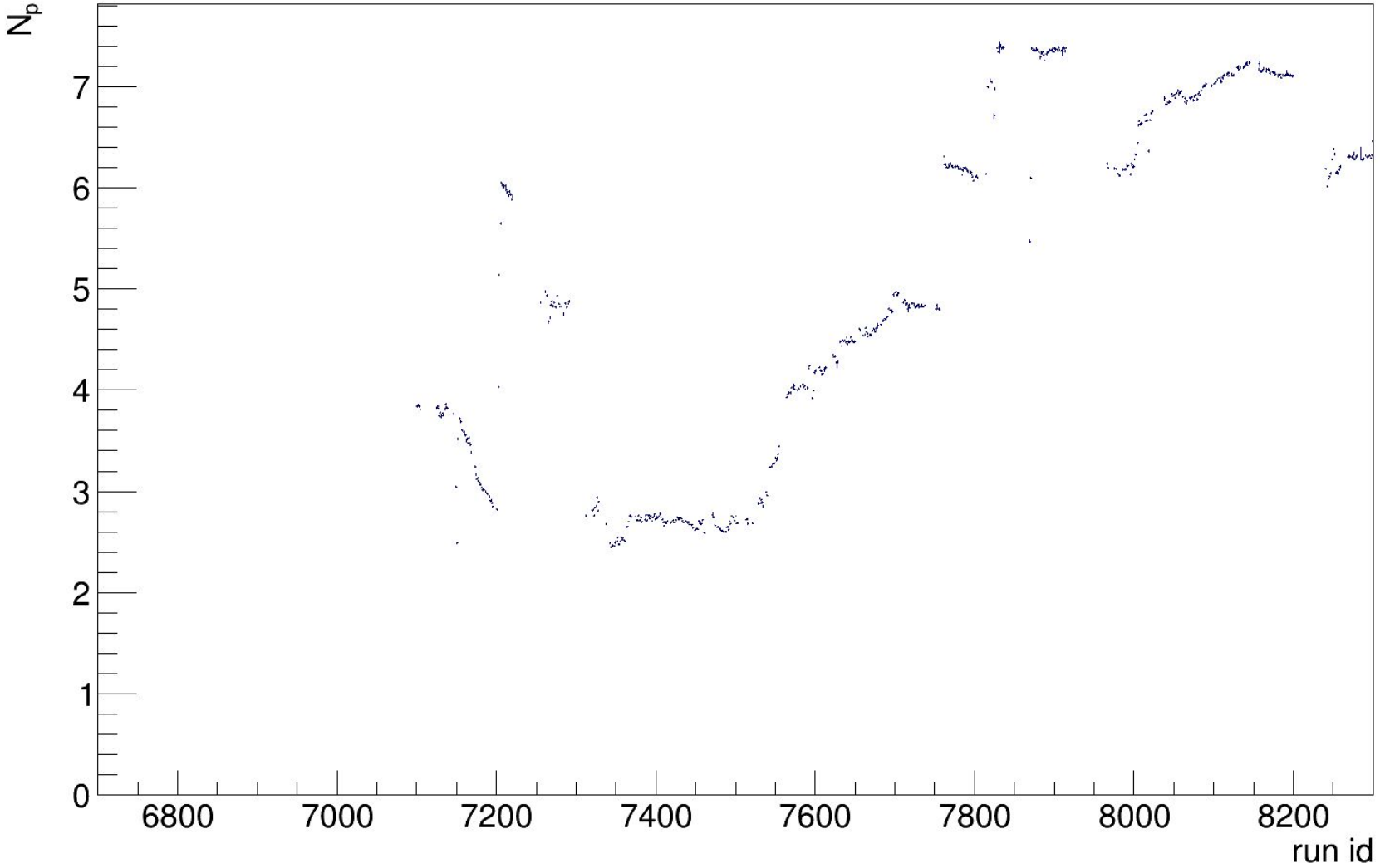


Todo list:

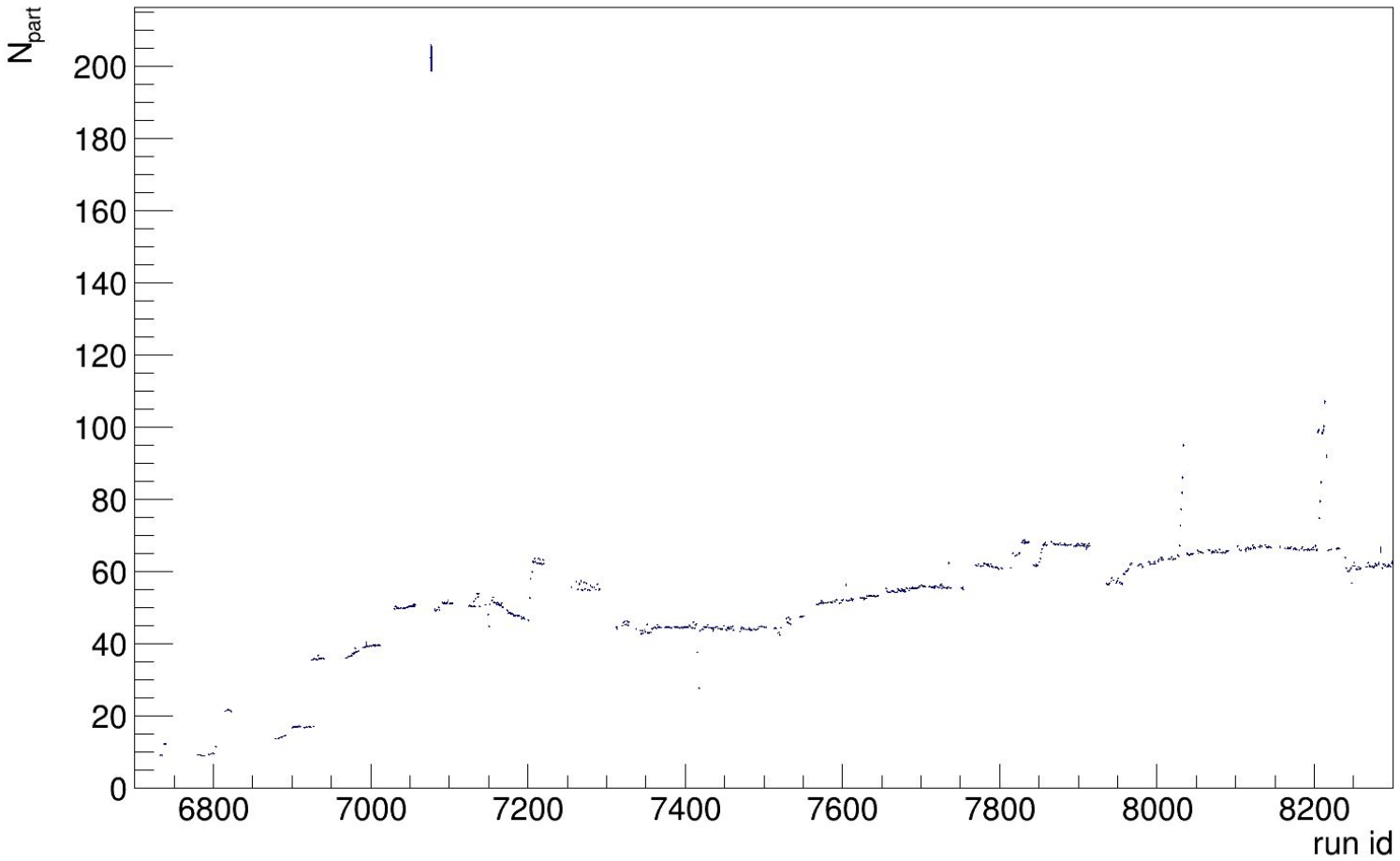
- ❏ Corrections: my recentering, my twist and rescaling, my decomposition steps
- ❏ <Nhits> vs run-id
- ❏ <chi2/NDF> vs run-id
- ❏ <DCA> vs run-id
- ❏ Run-id dependency of vtx for central events
- ❏ $\langle F^i F^j \rangle$ as a function of centrality and run-id for midcentral events and for different 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

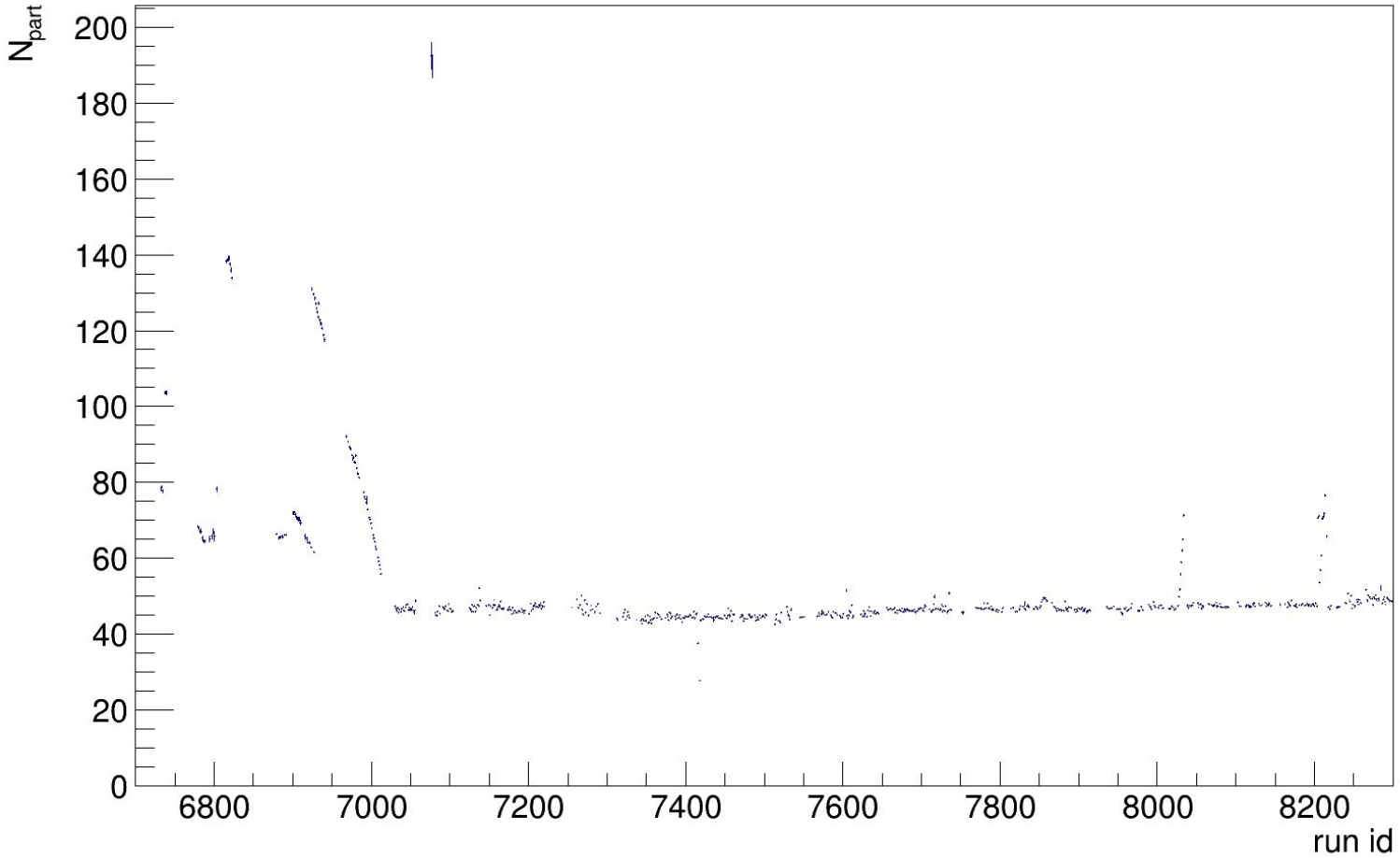

χ²/NDF
1.4
1.2
1
0.8
0.6
0.4
0.2
0
6800
7000
7200
7400
7600
7800
8000
8200
run id


N_p
0
1
2
3
4
5
6
7
6800
7000
7200
7400
7600
7800
8000
8200
run id

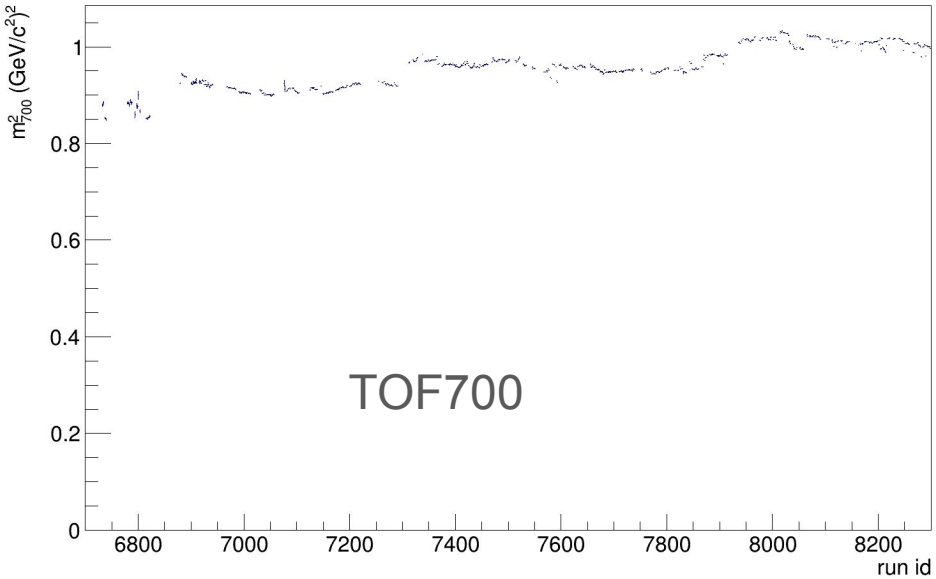
Charged particles multiplicity vs run-id

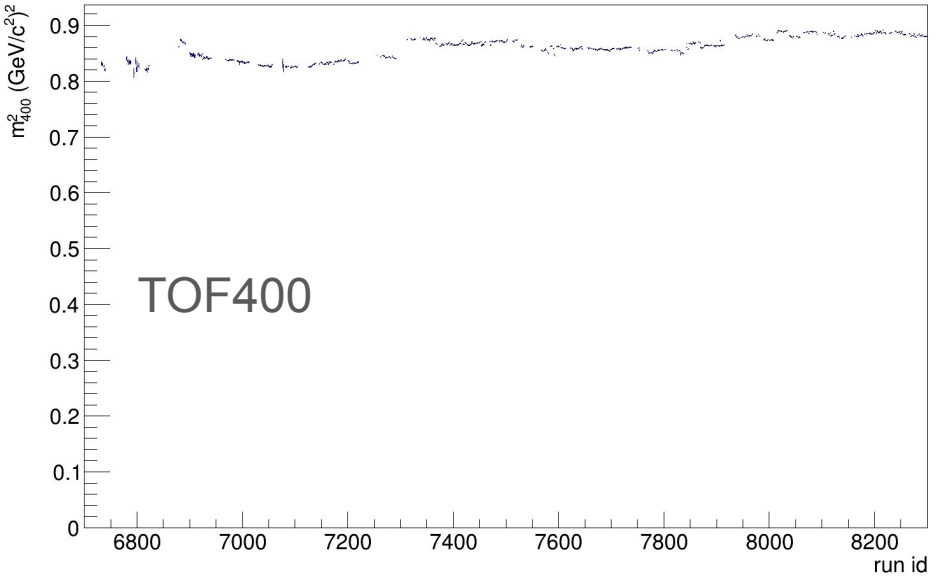


Normalized multiplicity

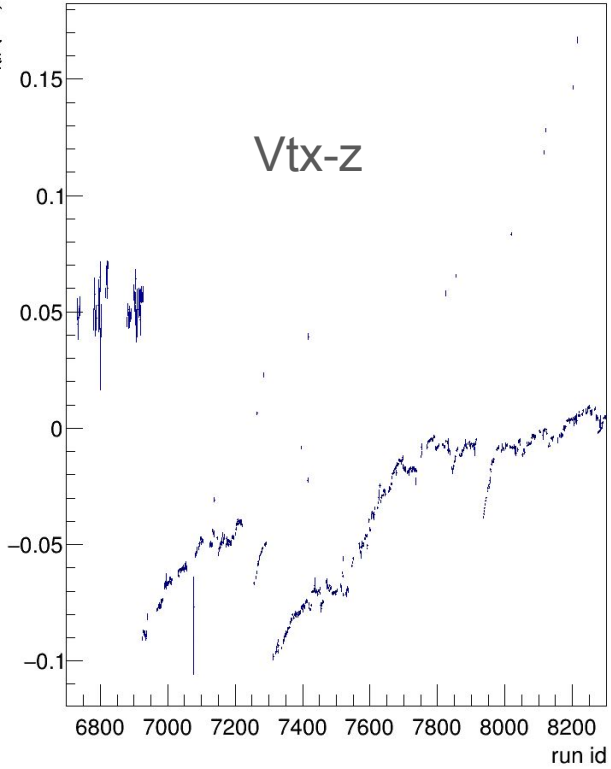


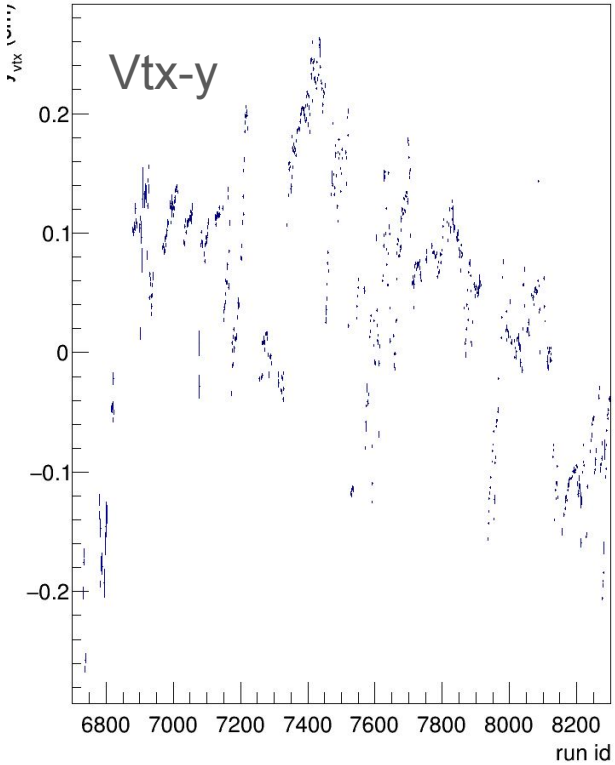
Squared mass of protons with TOF400 and TOF700

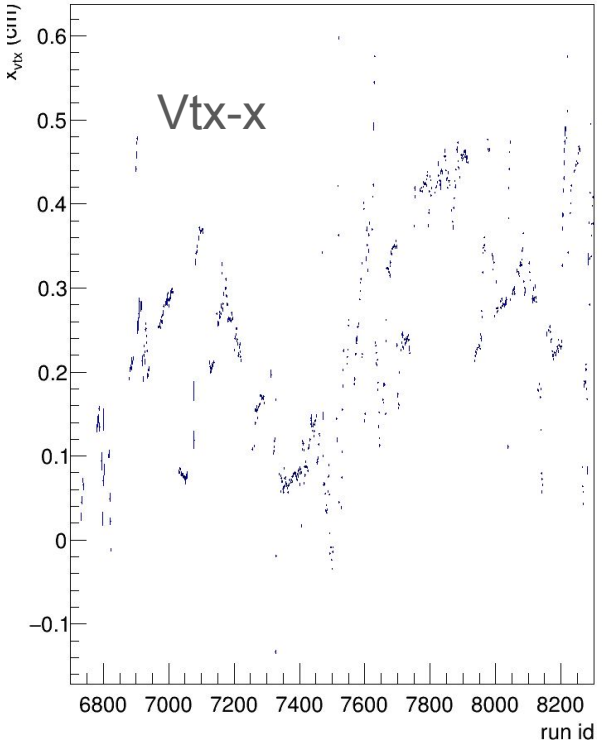




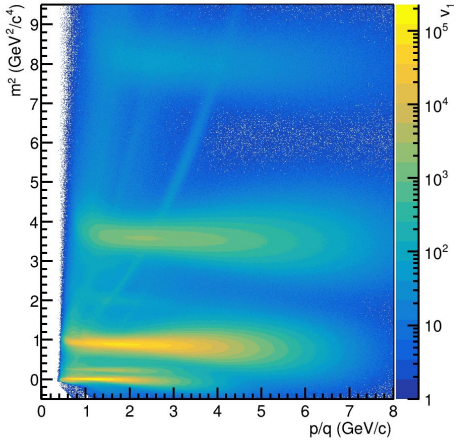
Vertex position



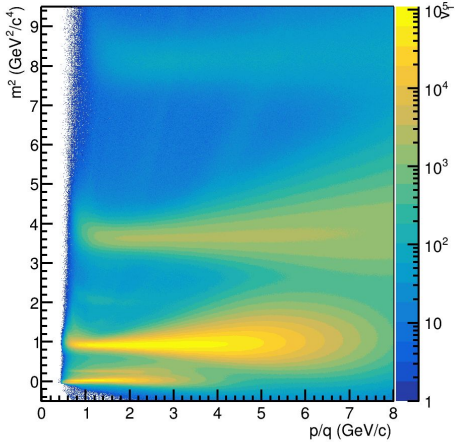




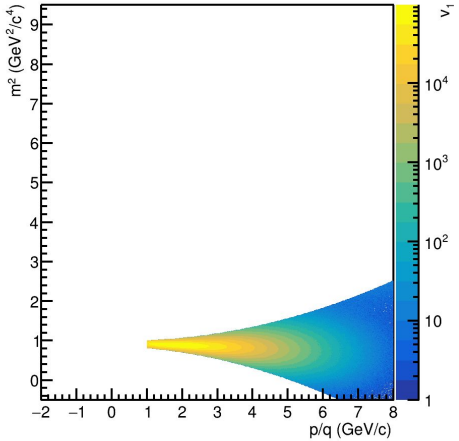
TOF-400



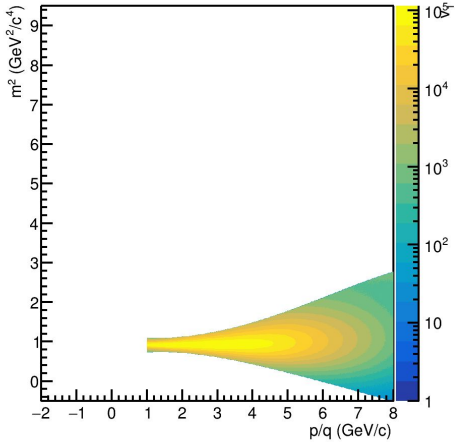
TOF-700



TOF-400



TOF-700



New FHCal-subevents layout

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

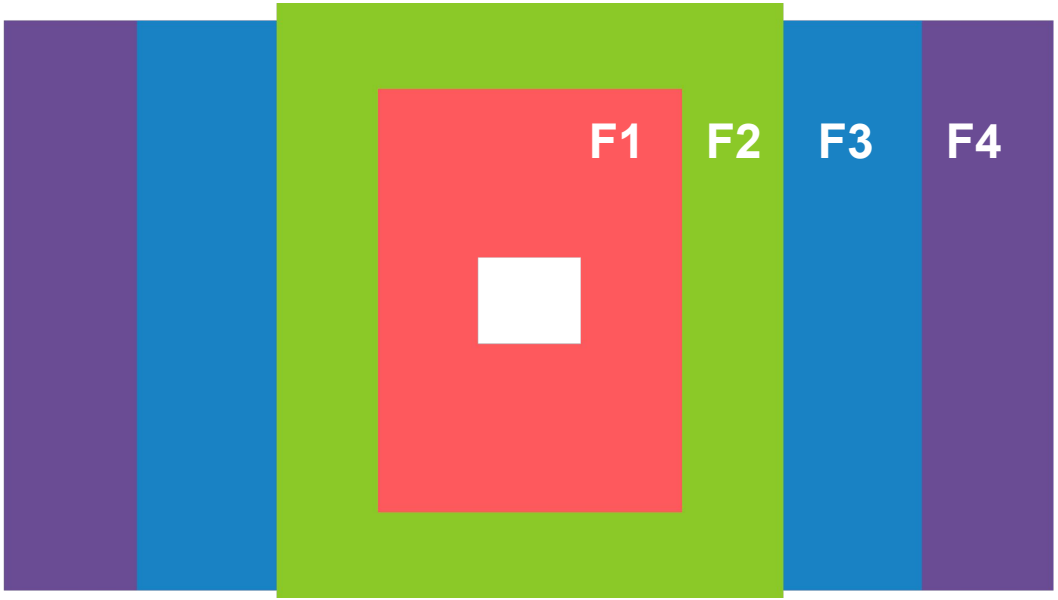
Acceptance function acts as a weight A(φ) u_n and the measured vector x is:

$$x = Mu + c$$

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

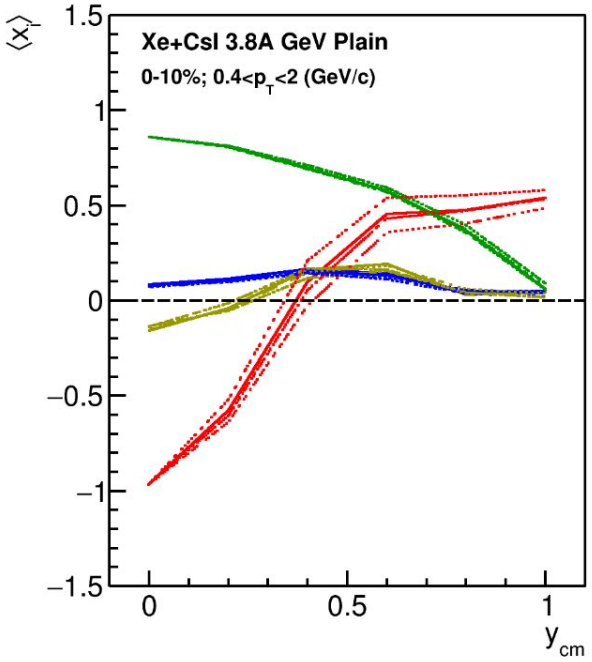
$$c = [c_1, s_1, c_2, s_2]^T$$

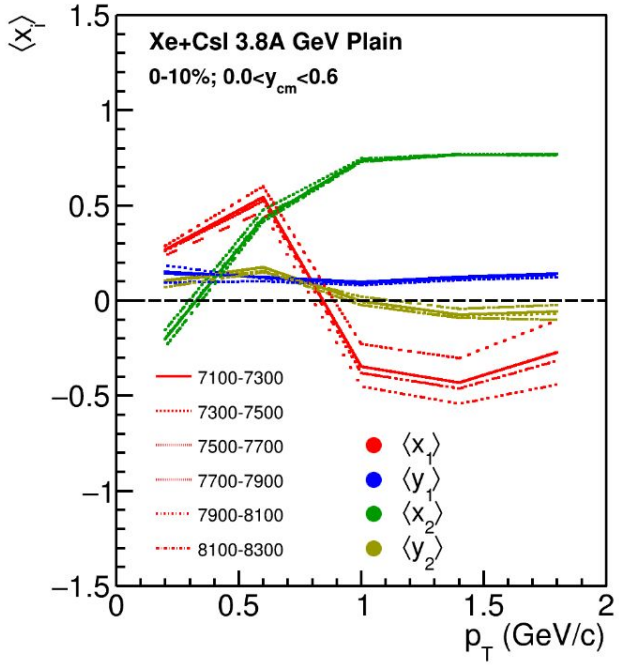
$$M = \begin{bmatrix} 1+c_2 & s_2 & c_1+c_3 & s_1+s_3 \\ s_2 & 1-c_2 & s_3-s_1 & c_1-c_3 \\ c_1+c_3 & s_3-s_1 & 1+c_4 & s_4 \\ s_1+s_3 & c_1-c_3 & s_4 & 1-c_4 \end{bmatrix}$$

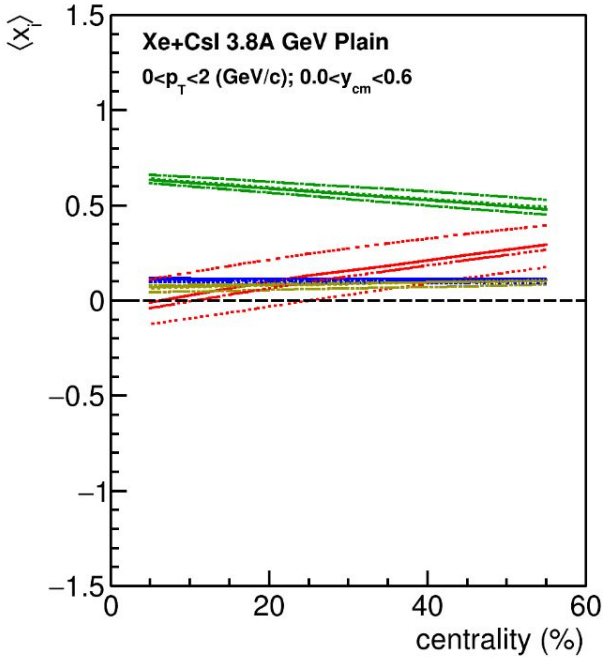


$$u = M^{-1}(x - c)$$

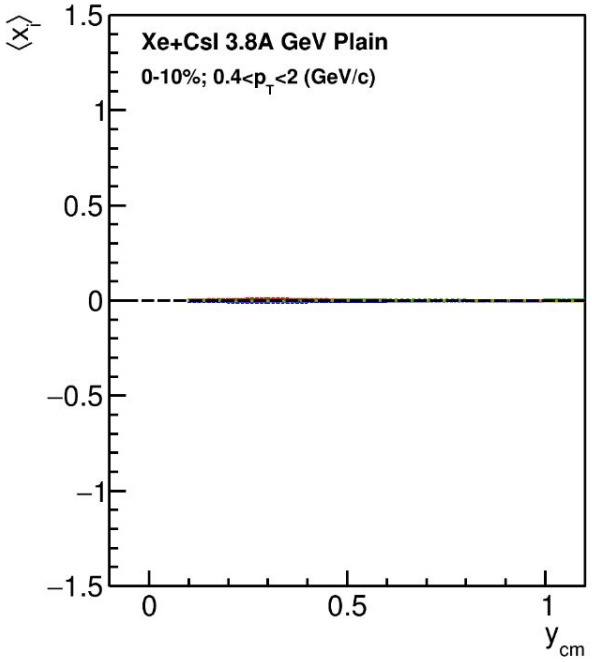
Acceptance Fourier-moments for protons

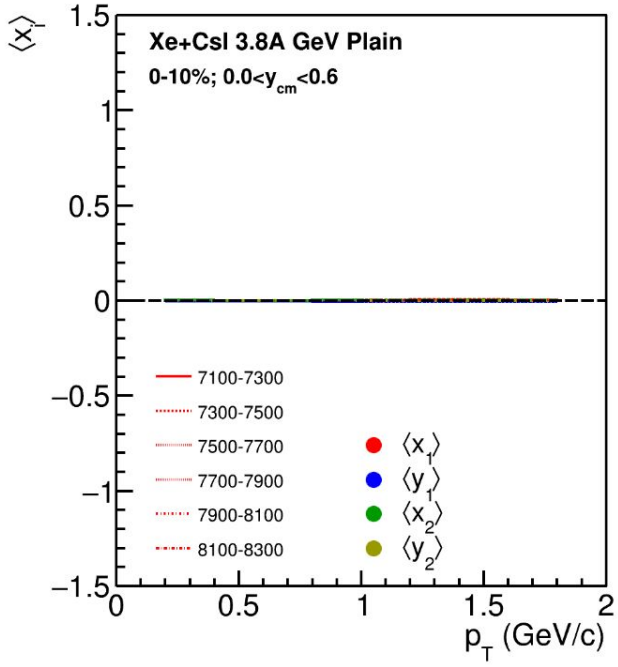


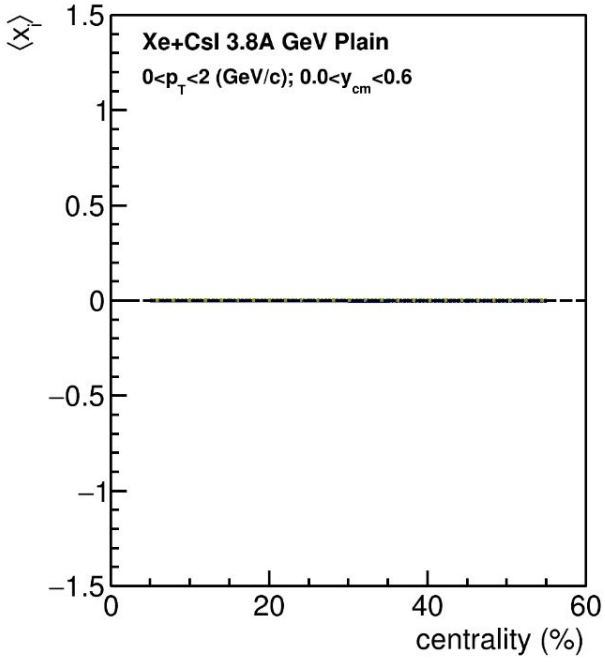




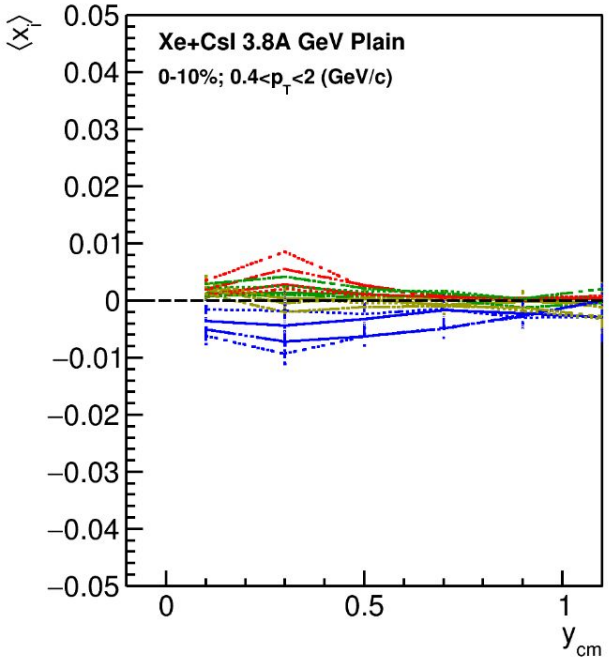
Acceptance Fourier-moments for protons (corrected)

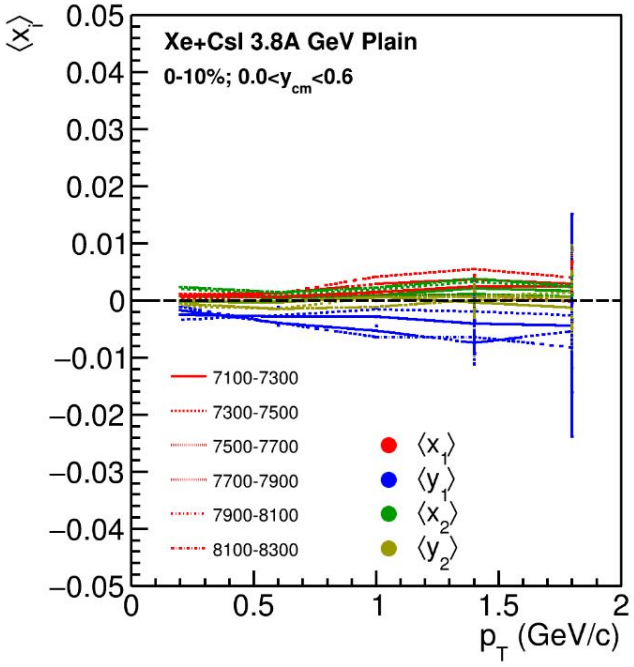


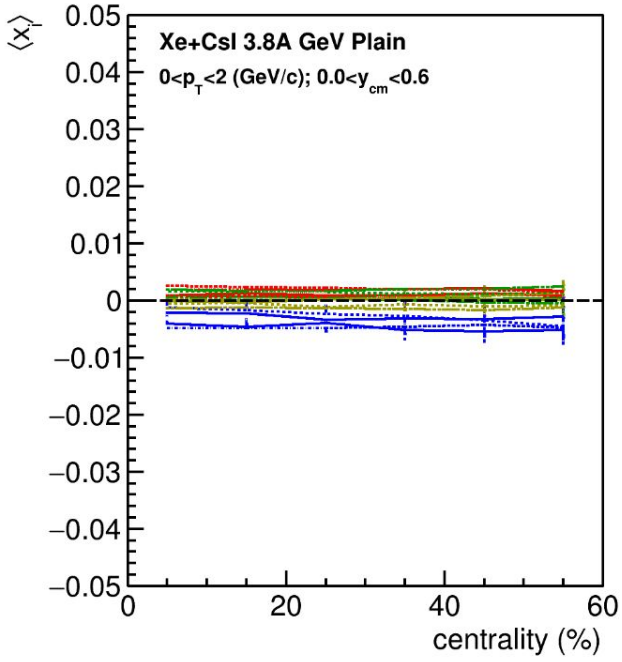




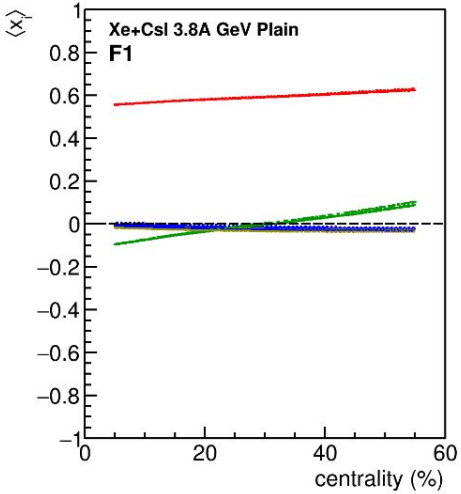
Acceptance Fourier-moments for protons (corrected & zoomed)

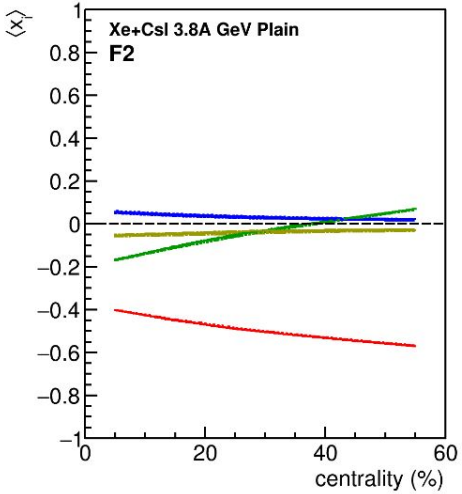


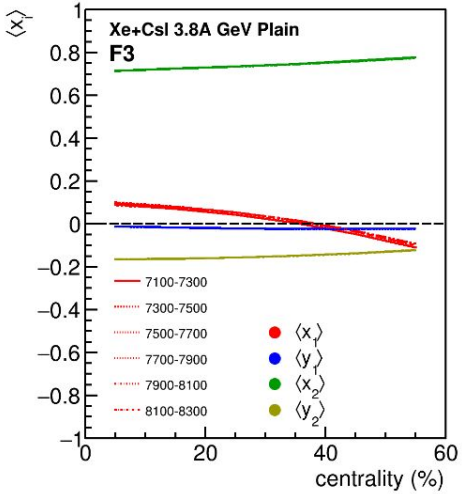


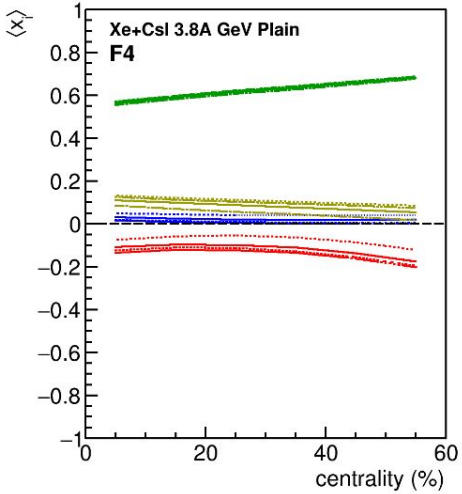


Acceptance Fourier-moments for FHCal

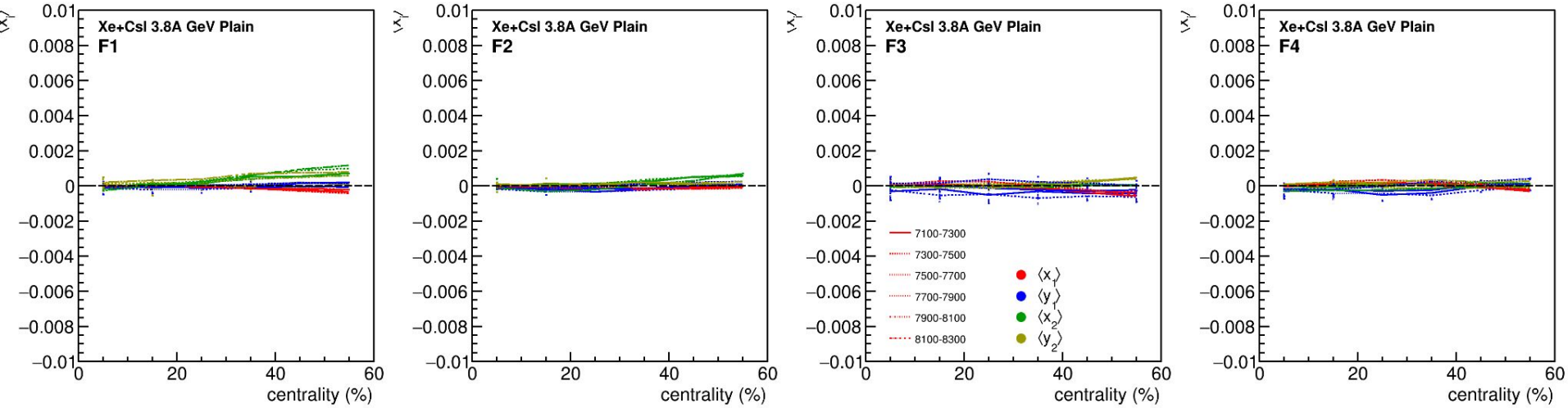




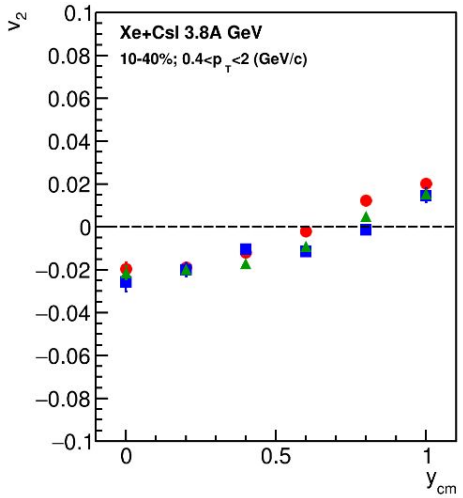


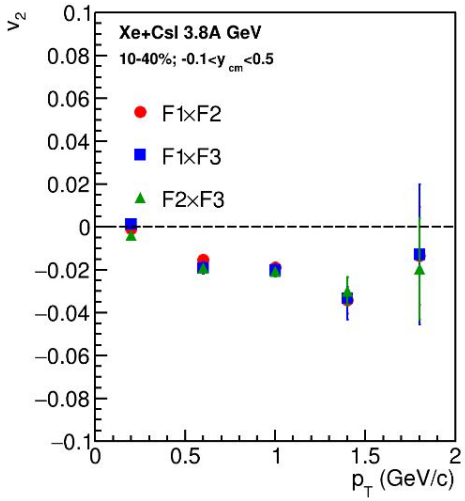


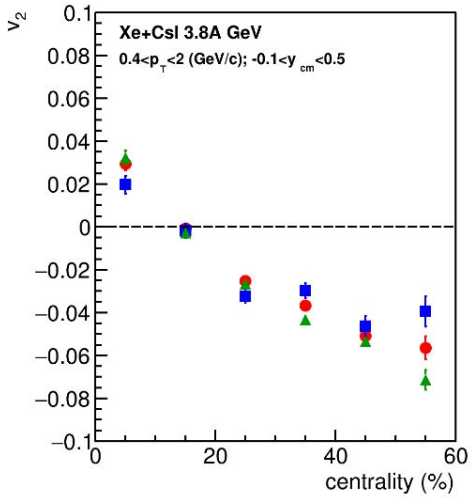
Acceptance Fourier-moments for FHCal

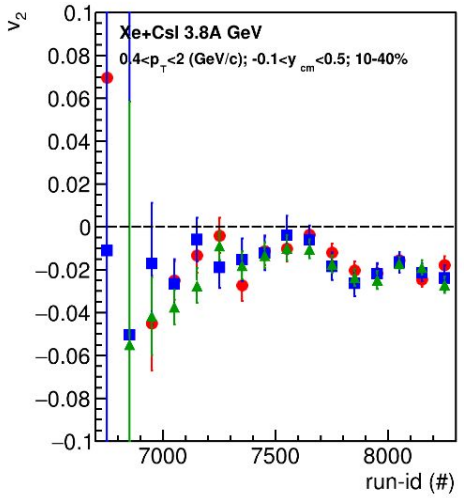


Result with only recentering applied

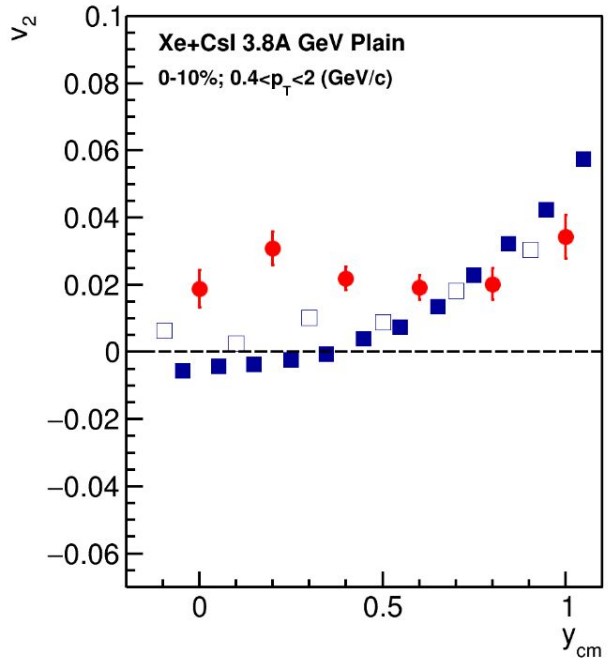


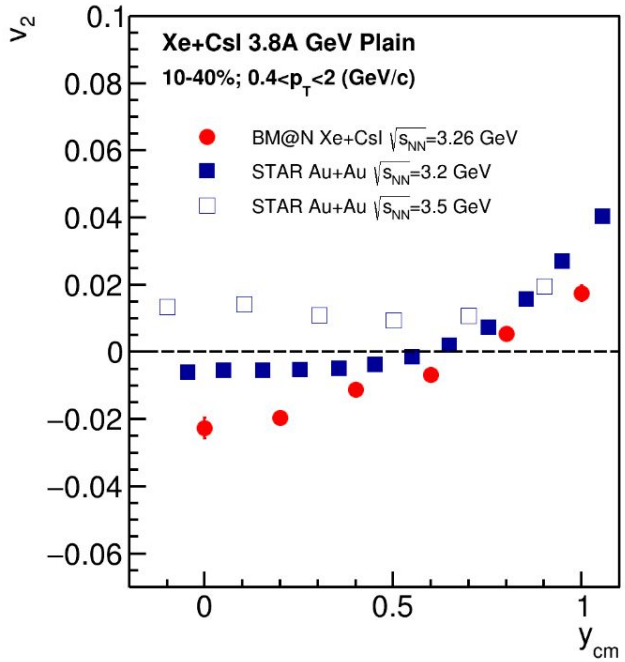


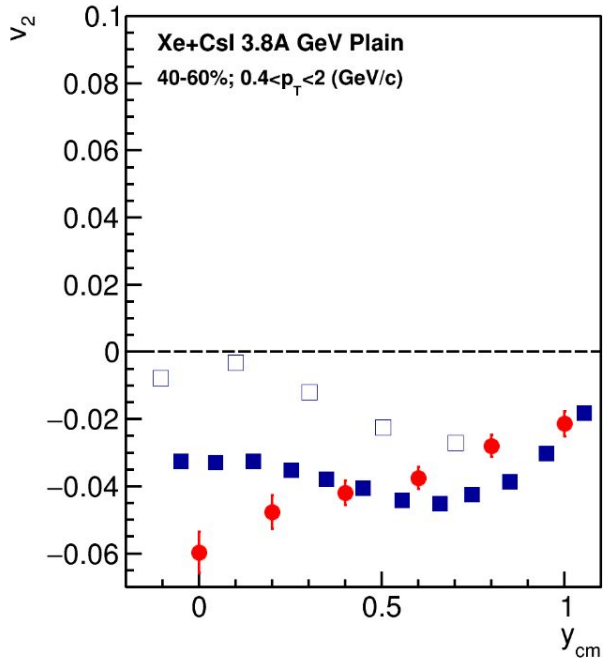




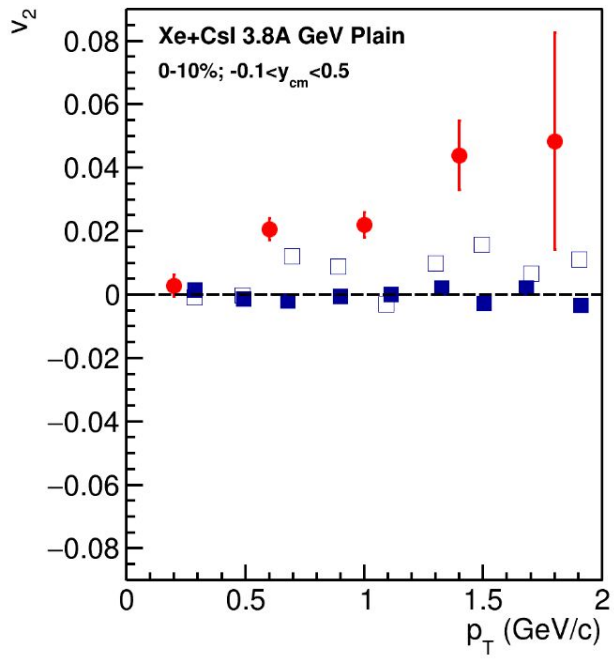
Result with only recentering applied: y-dep vs STAR

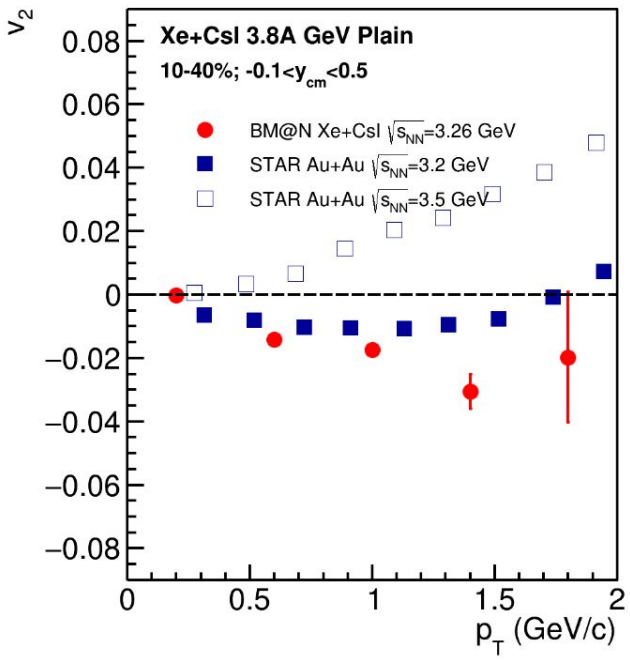


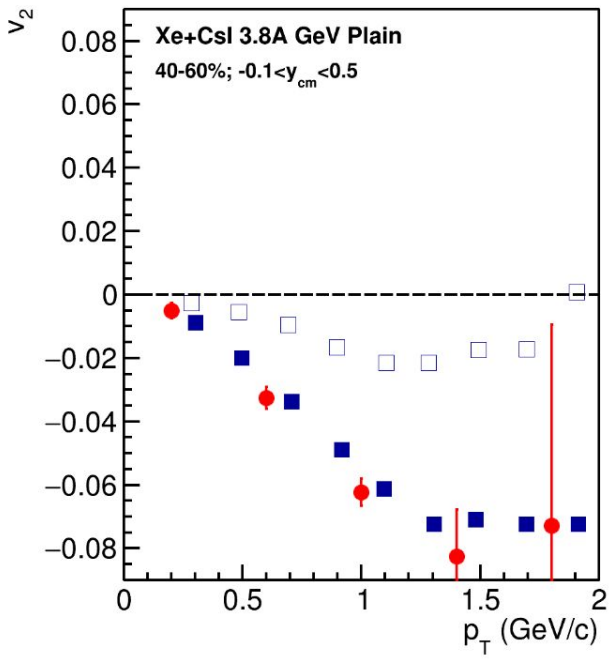




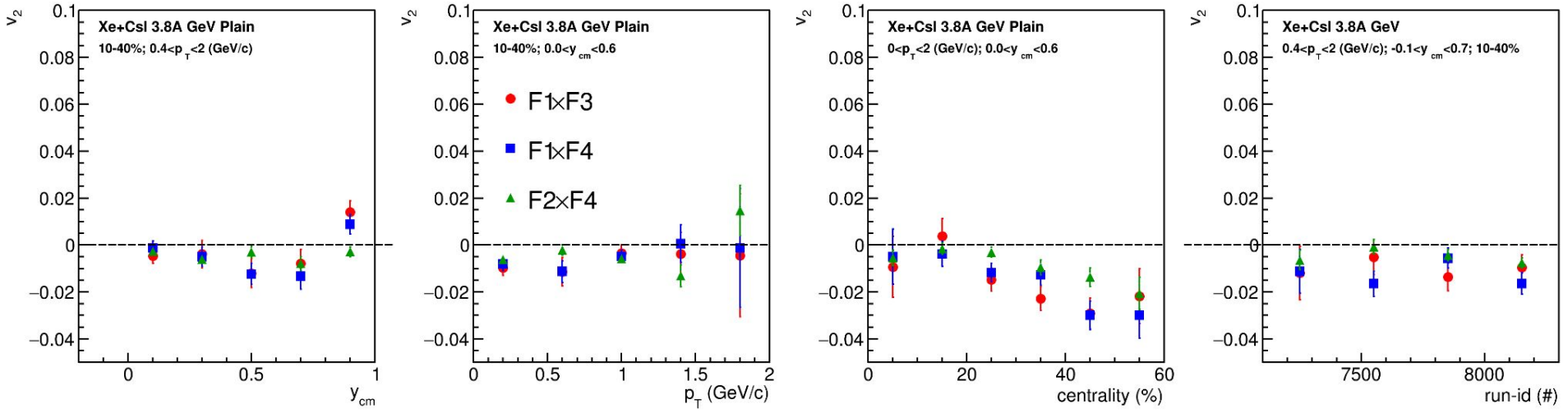
Result with only recentering applied: pT-dep vs STAR



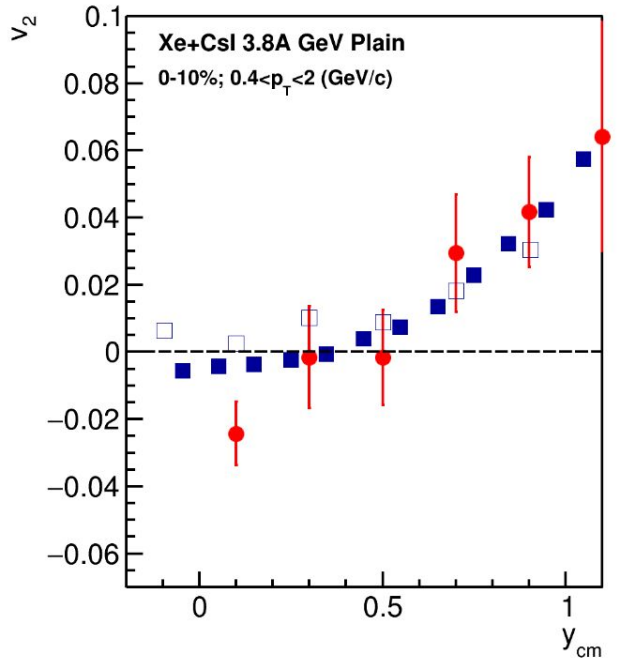


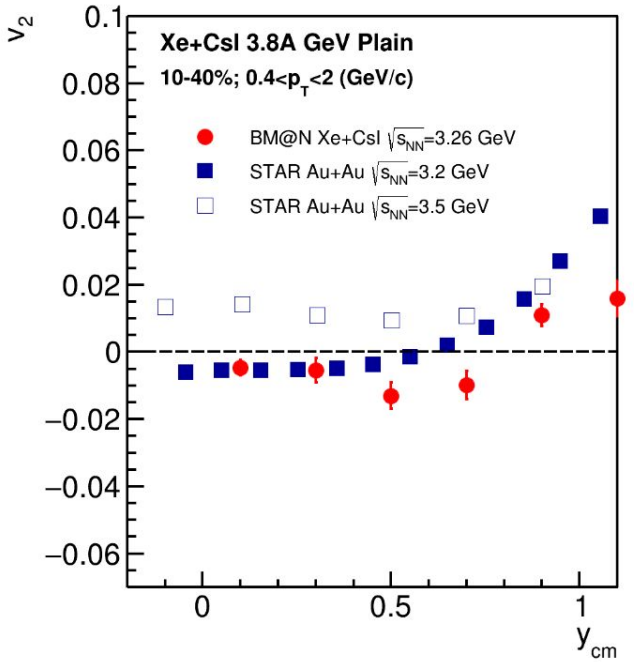


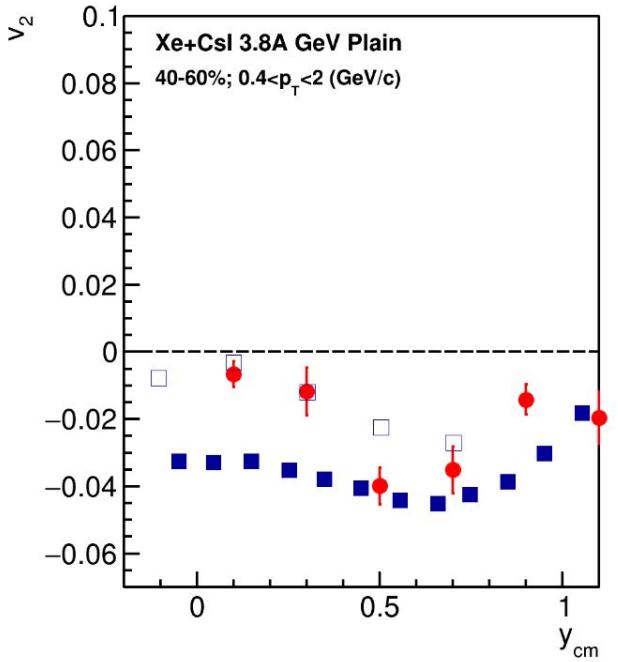
Result with decomposition applied



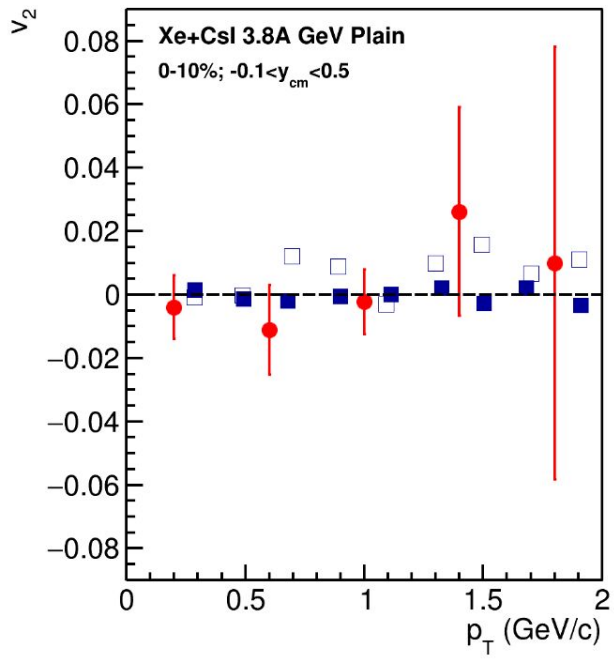
Result with full decomposition: y-dep vs STAR

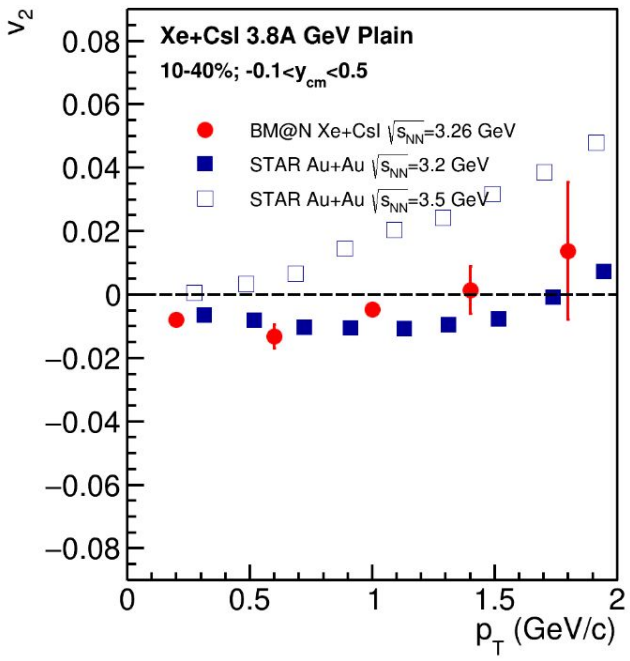


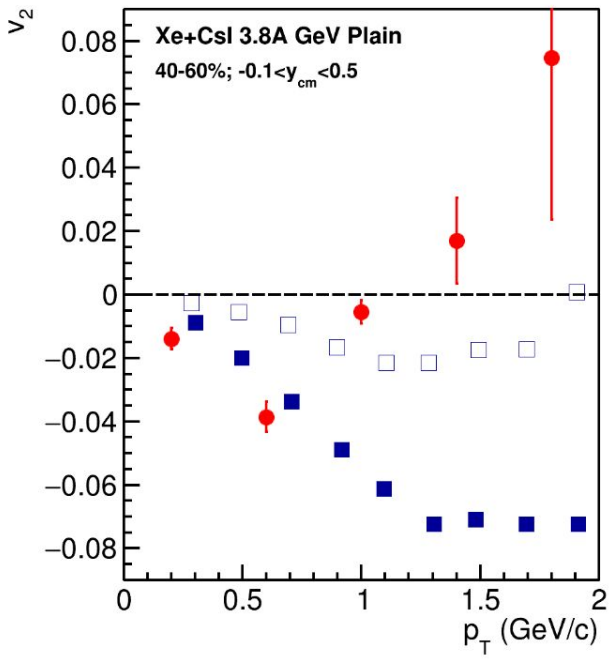




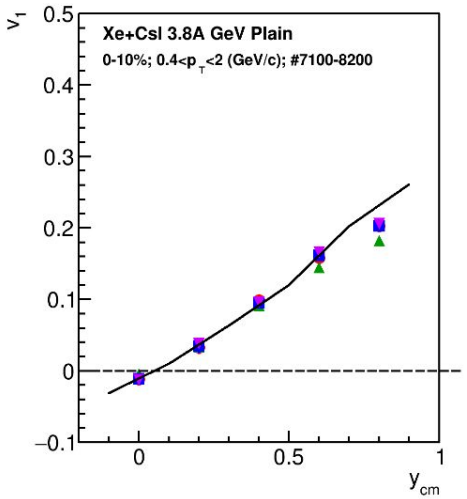
Result with full decomposition: pT-dep vs STAR

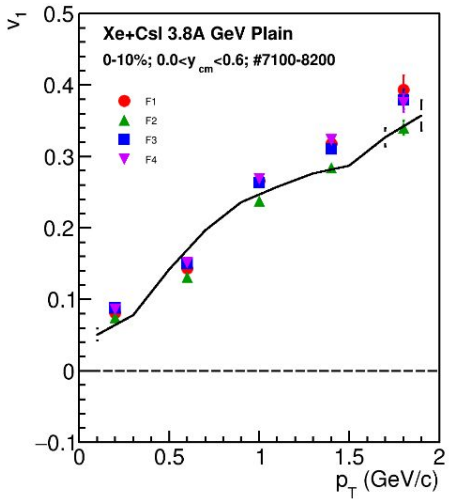


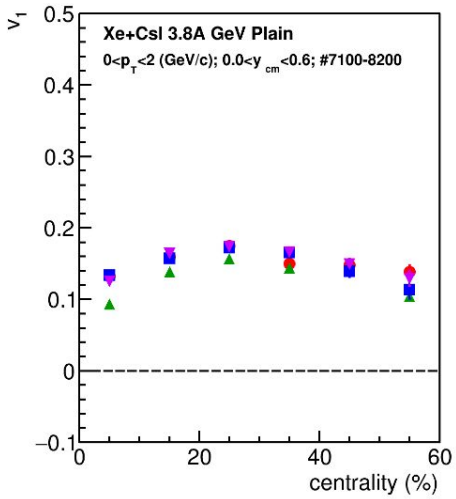


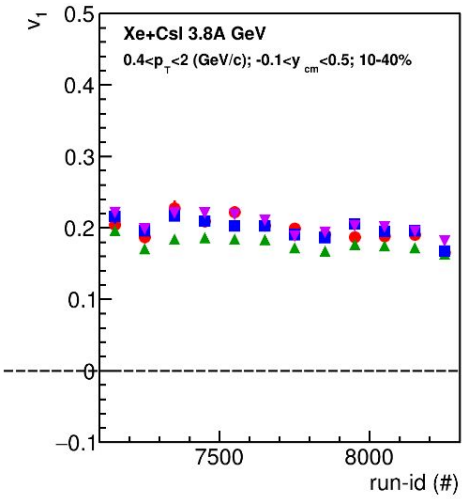


Additional check: comparison with v_1-preliminary



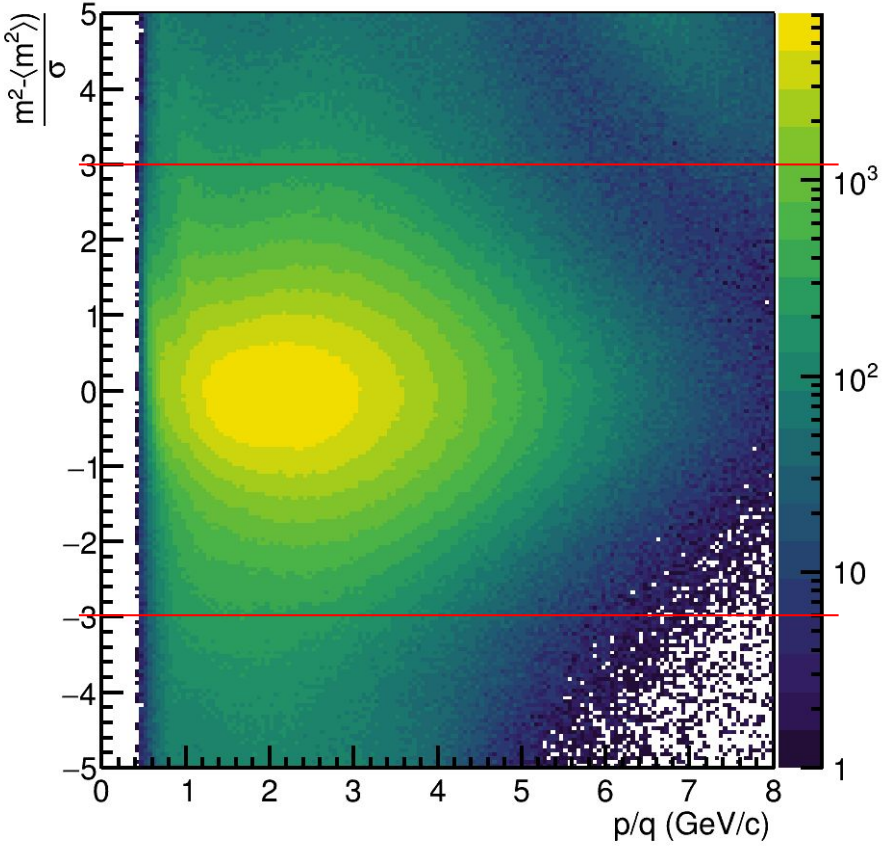




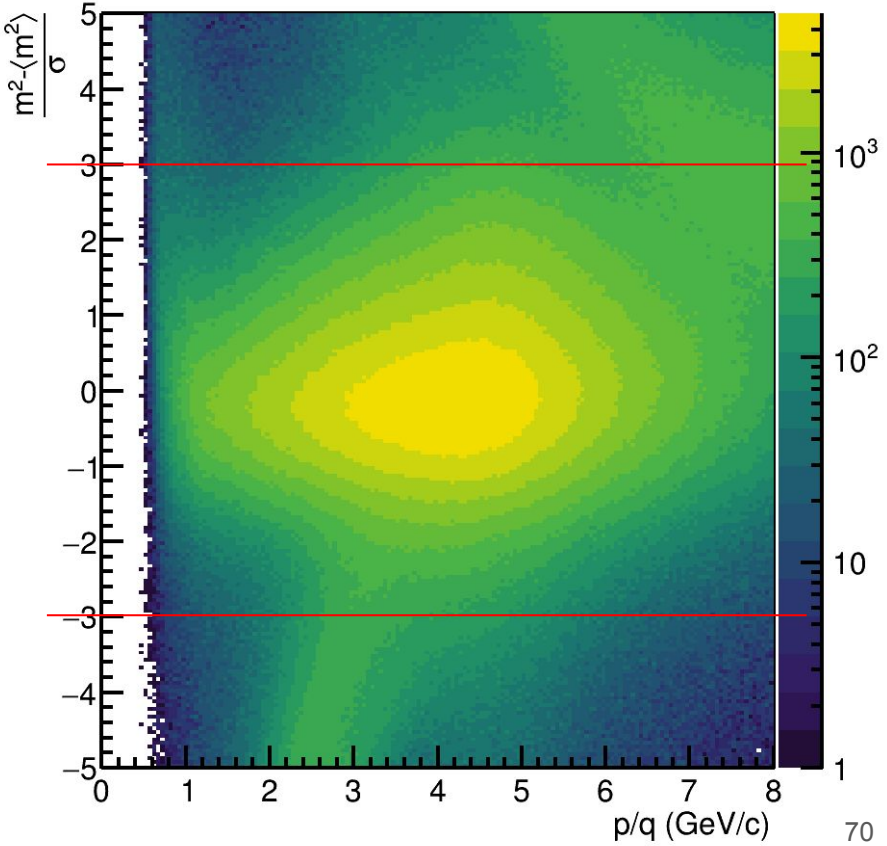


Proton N-sigma distributions

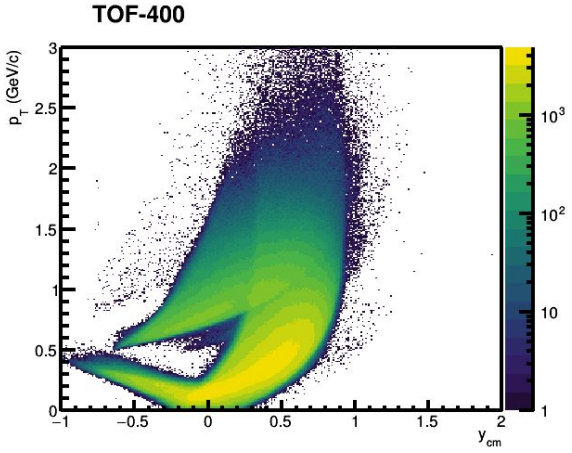
TOF-400

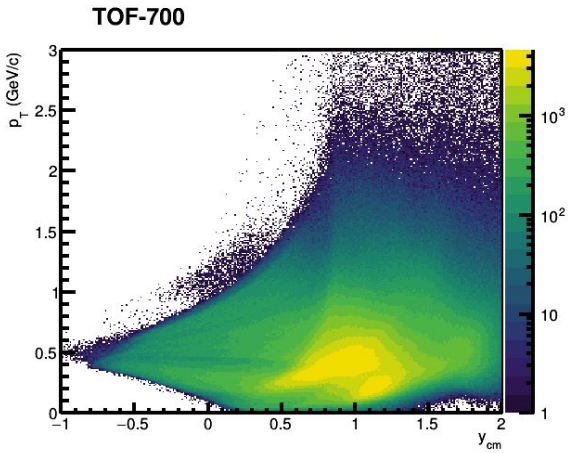


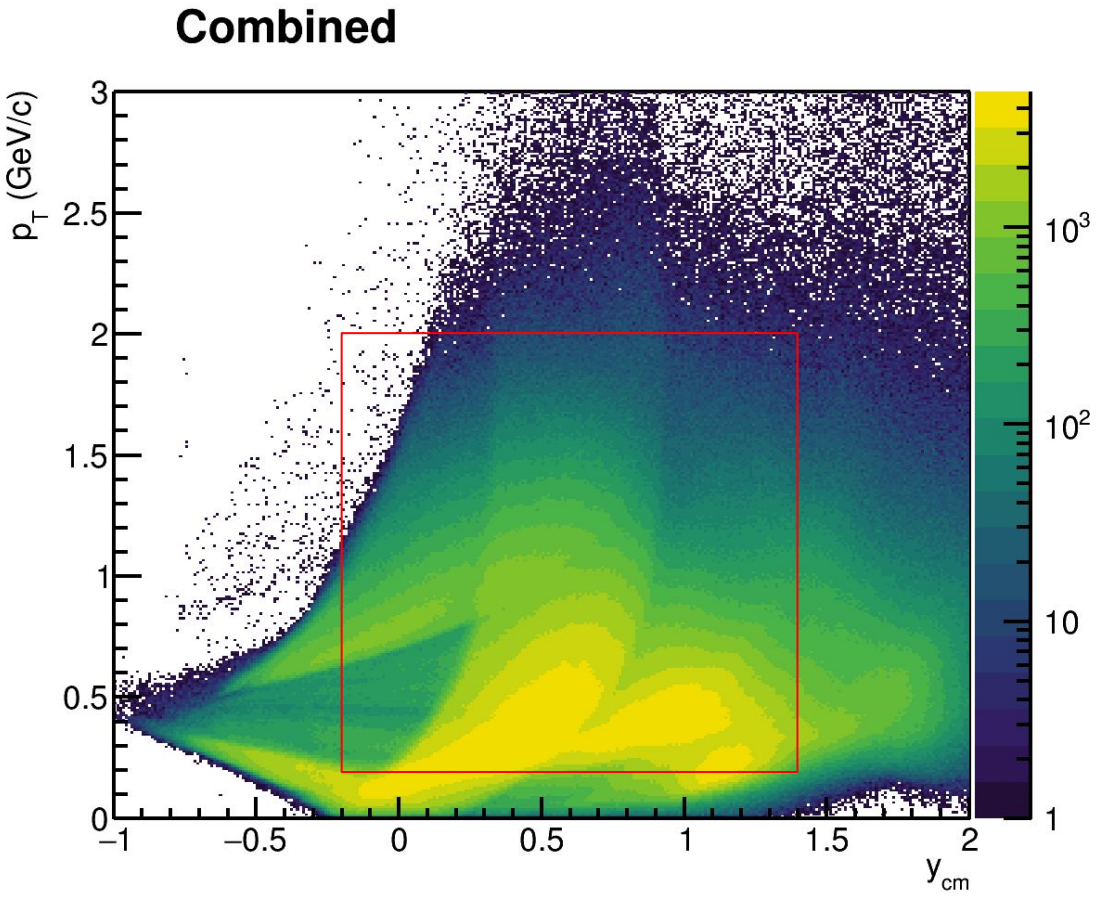
TOF-700



Proton p_T-y acceptance







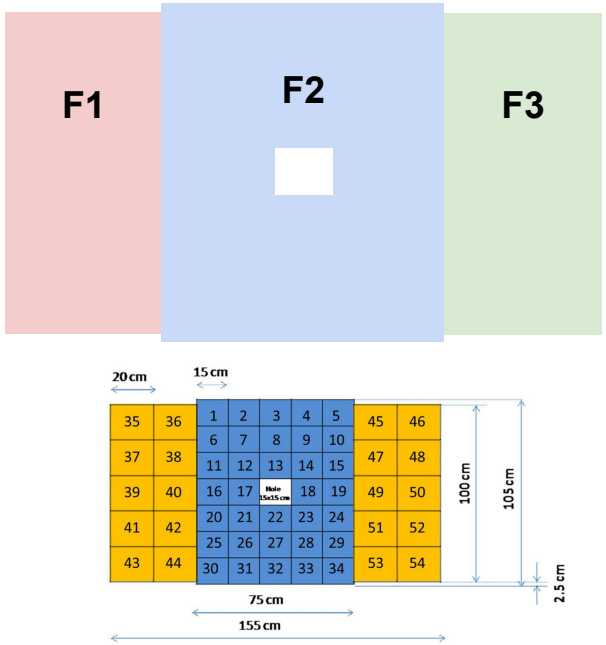
Further notations

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

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

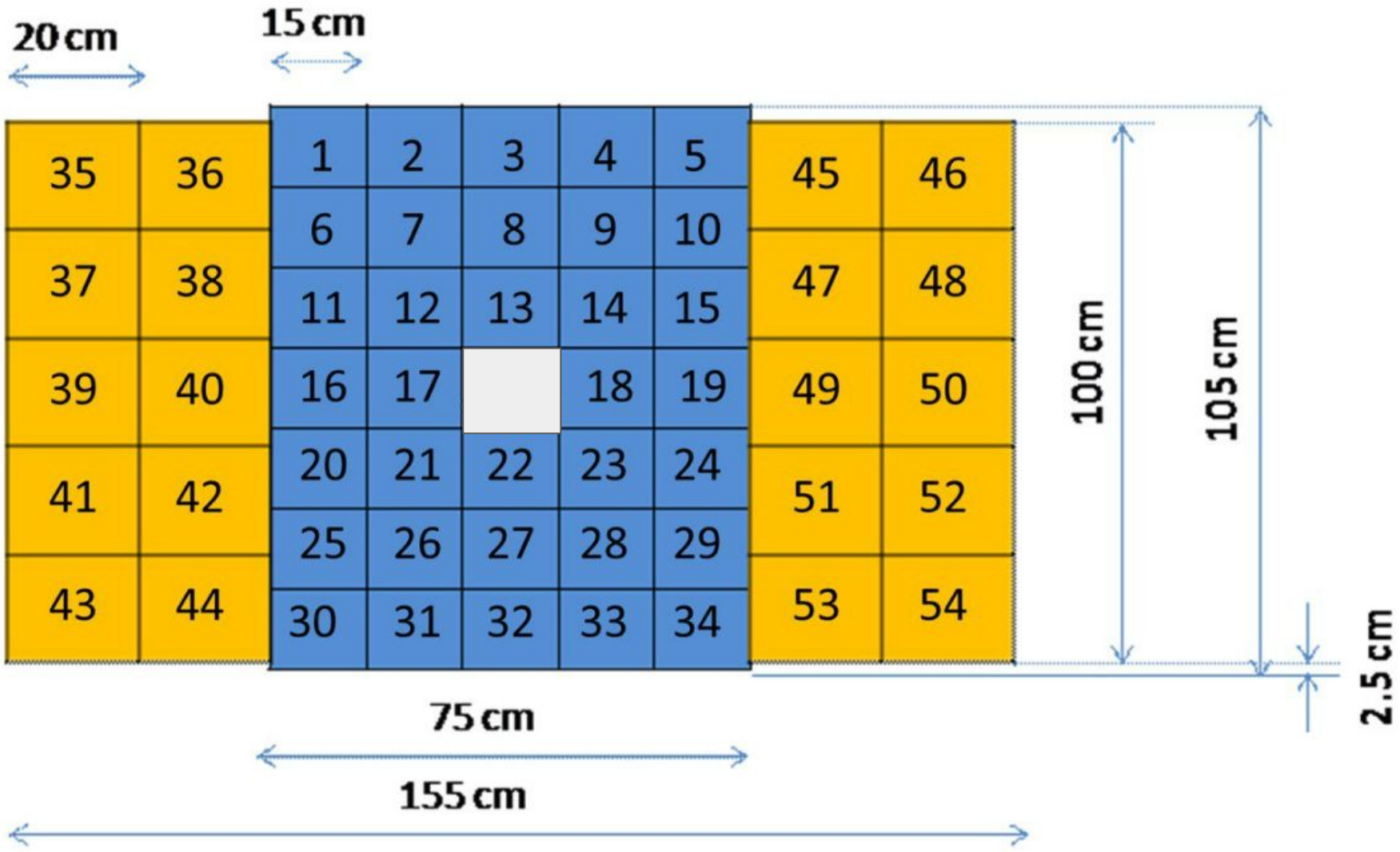
$$v_2 = 2\frac{\langle x_2 Y_1^a Y_1^b \rangle}{\langle Y_1^a Y_1^b \rangle}$$

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
10
11
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14
15
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19
20
21
22
23
24
25
26
27
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

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

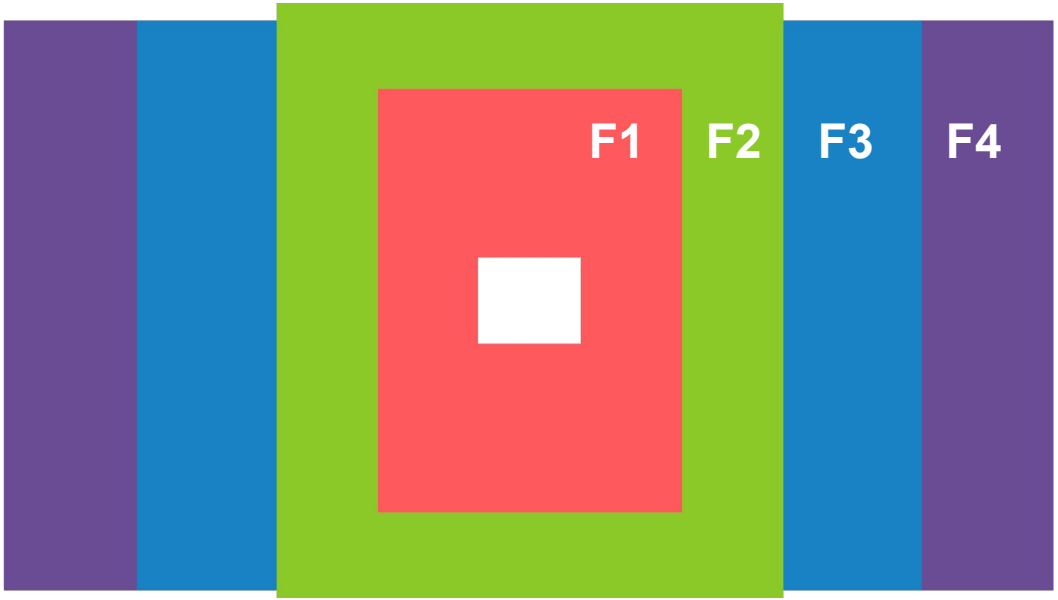
Acceptance function acts as a weight A(φ) u_n and the measured vector x is:

$$x = Mu + c$$

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

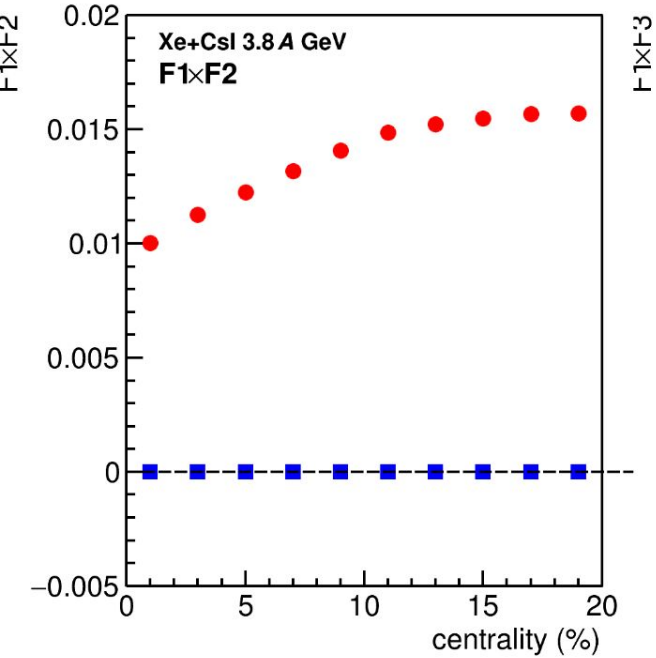
$$c = [c_1, s_1, c_2, s_2]^T$$

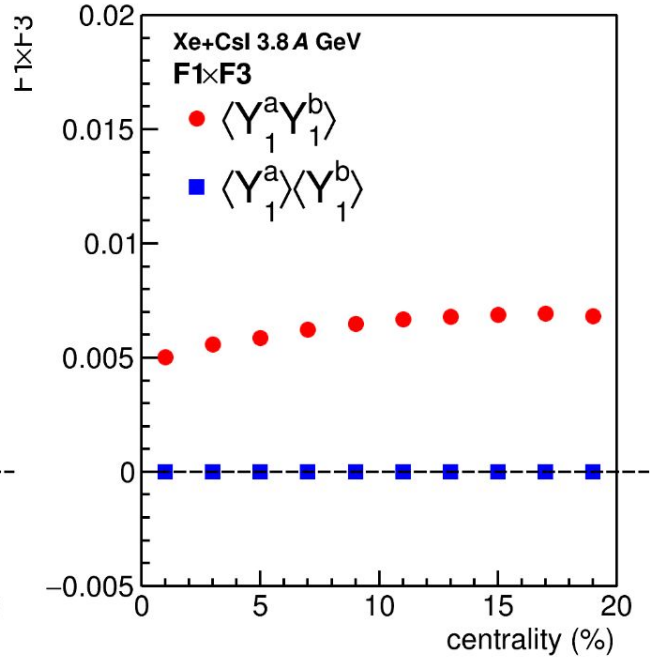
$$M = \begin{bmatrix} 1+c_2 & s_2 & c_1+c_3 & s_1+s_3 \\ s_2 & 1-c_2 & s_3-s_1 & c_1-c_3 \\ c_1+c_3 & s_3-s_1 & 1+c_4 & s_4 \\ s_1+s_3 & c_1-c_3 & s_4 & 1-c_4 \end{bmatrix}$$

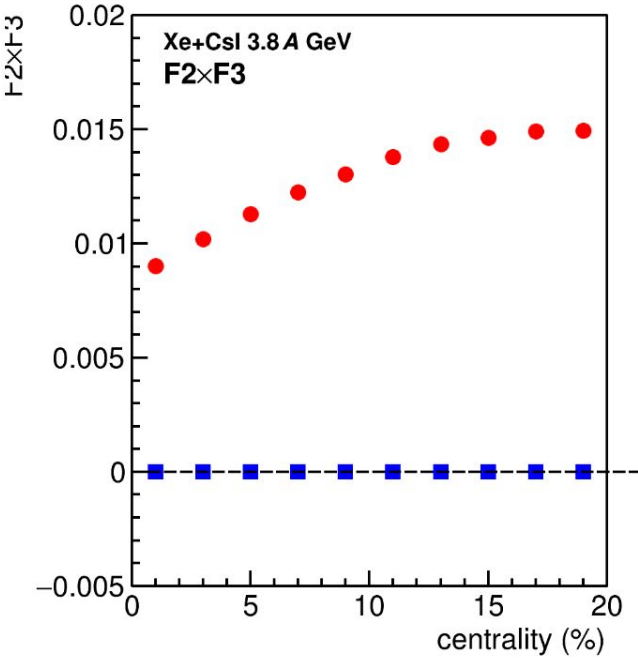


$$u = M^{-1}(x - c)$$

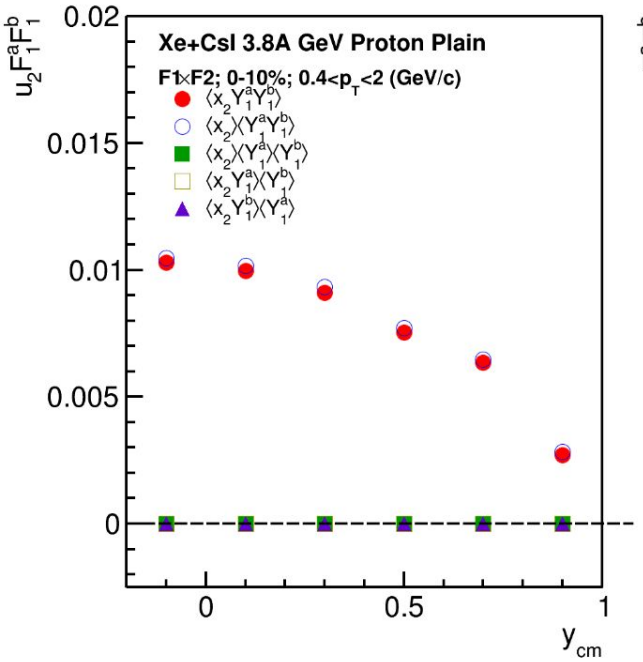
Correlation of recentered Q_1-vectors from FHCal

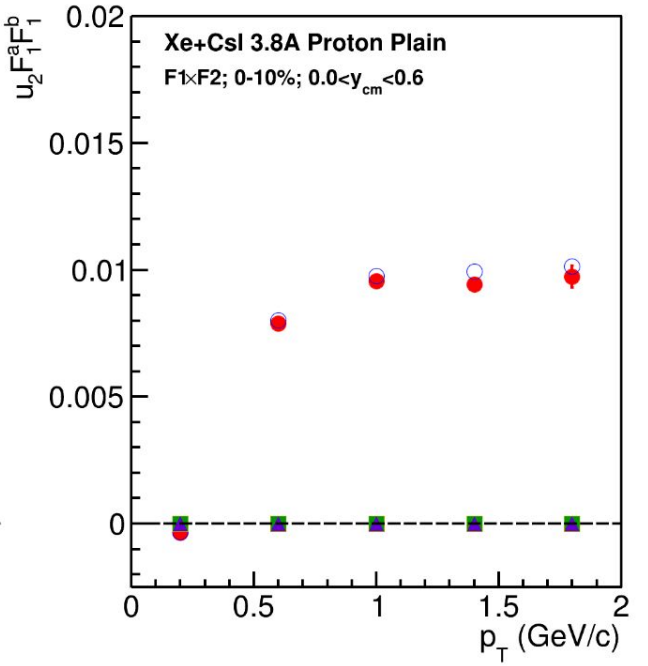


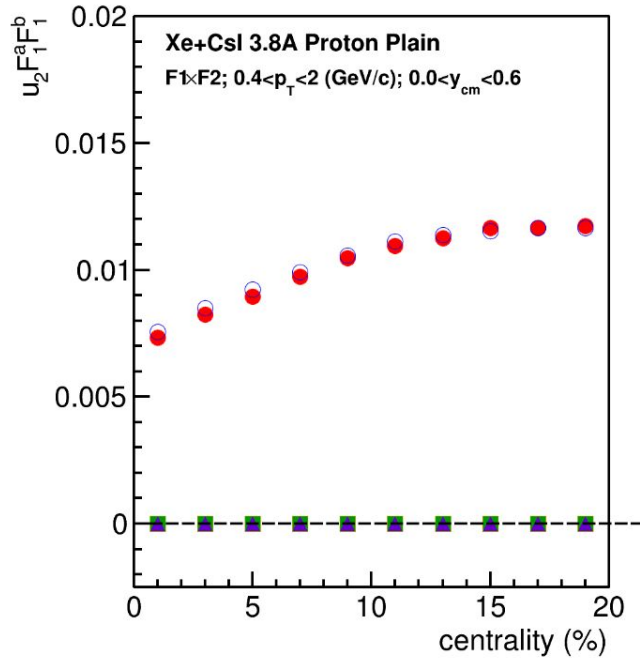




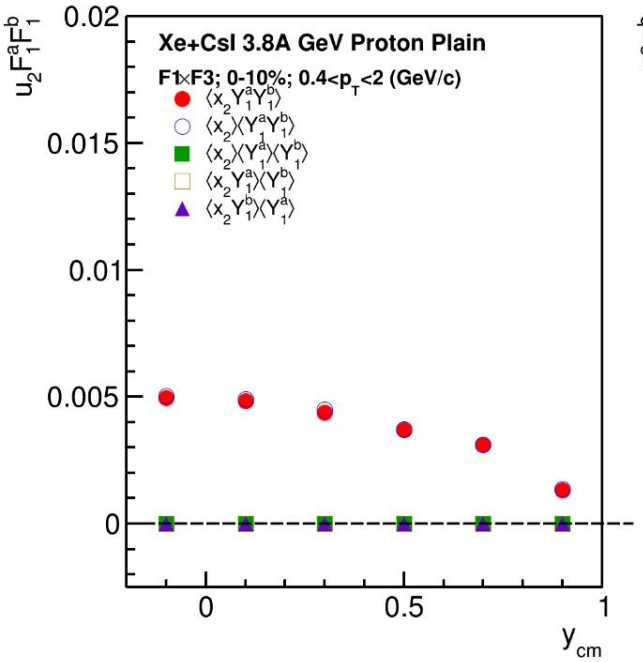
Plain protons with recentered F1 and F2

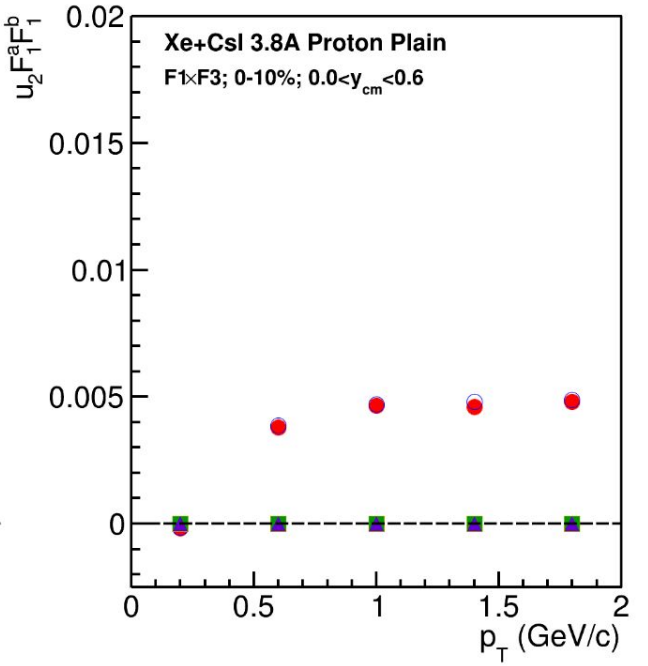


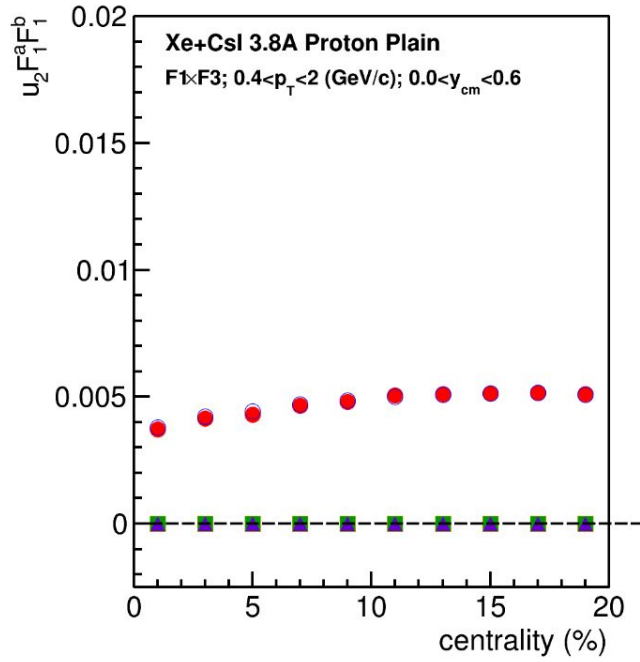




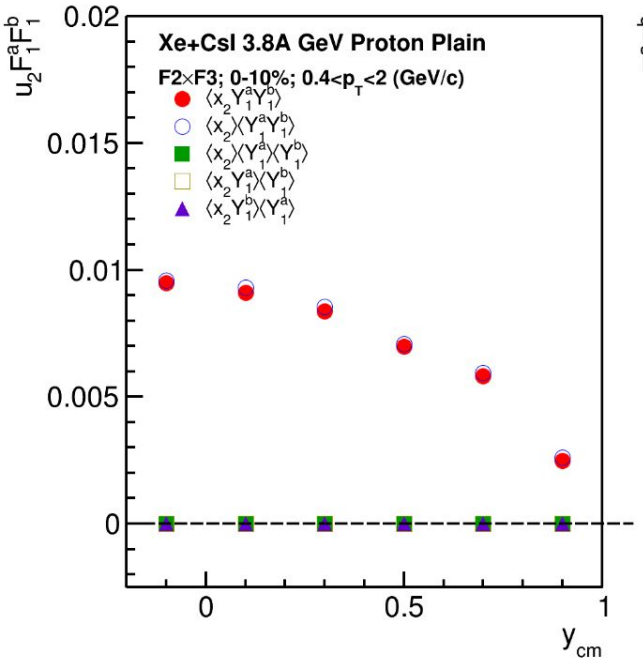
Plain protons with recentered F1 and F3

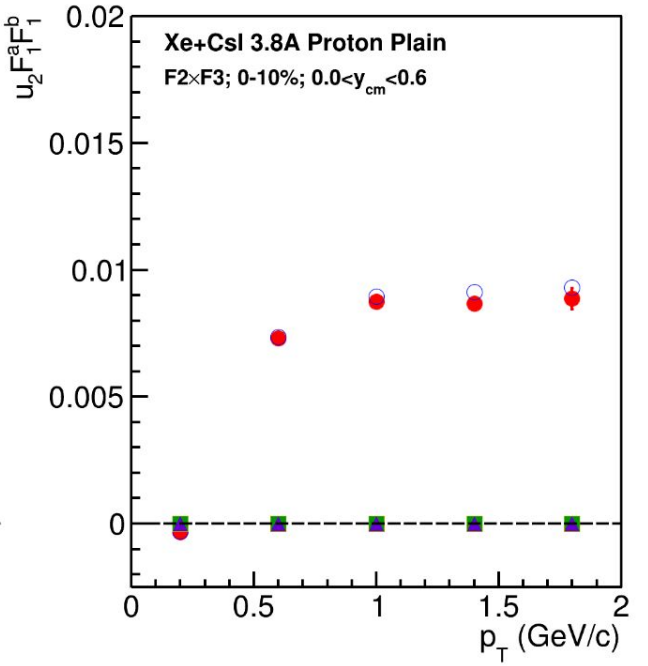


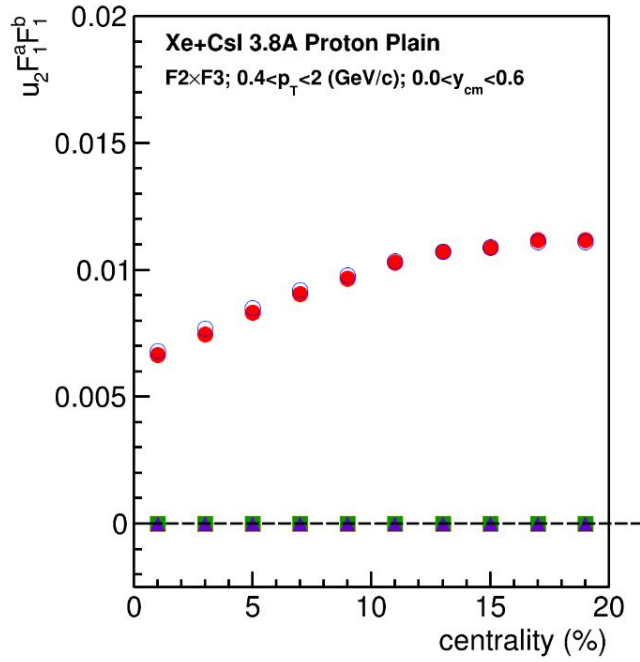




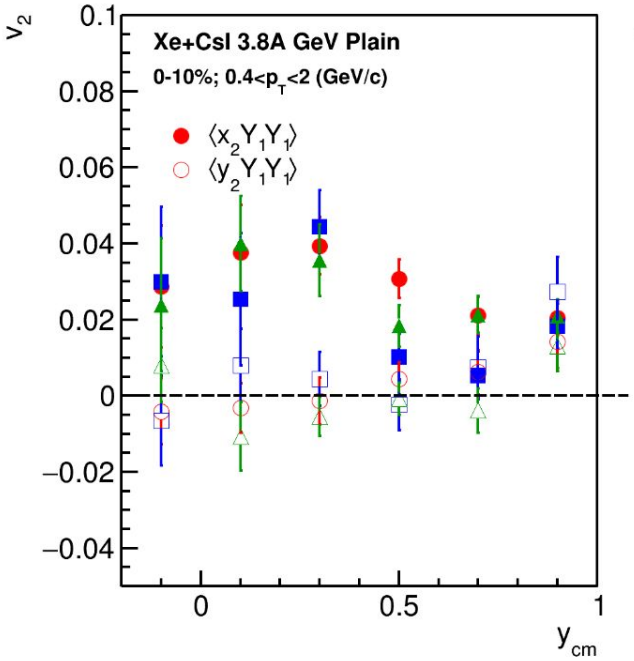
Plain protons with recentered F2 and F3

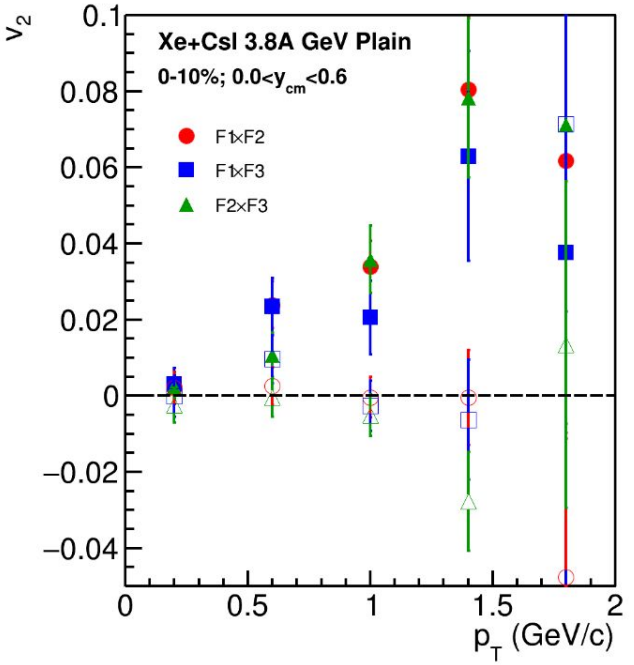


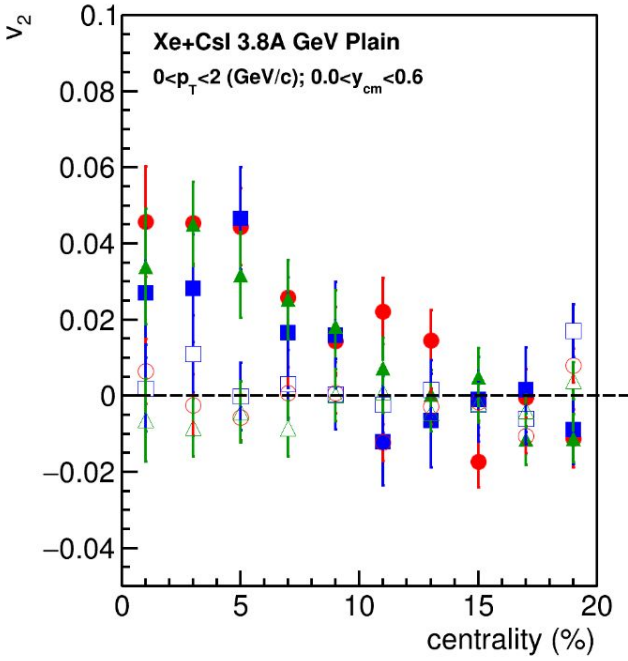




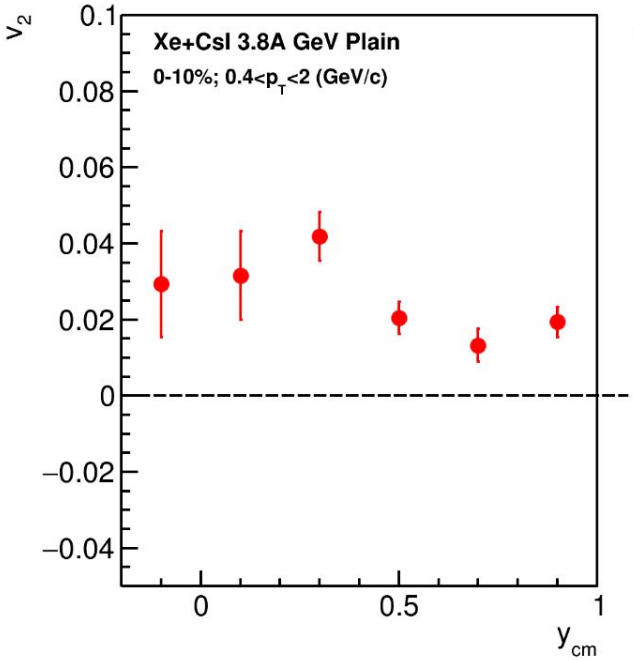
Plain proton v_2 wrt different symmetry planes

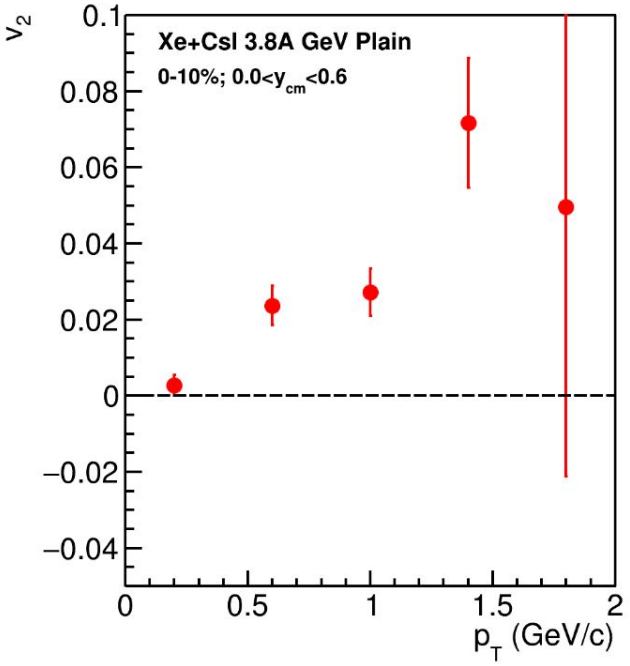


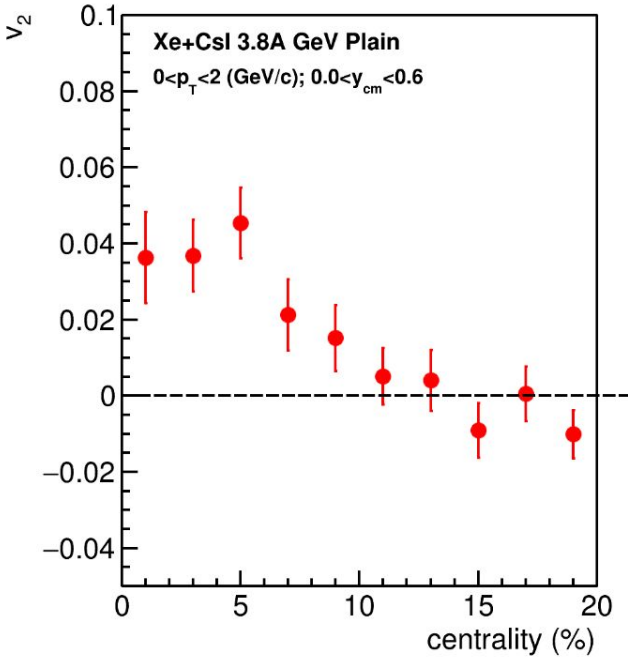




Plain protons with plain F2 and F3

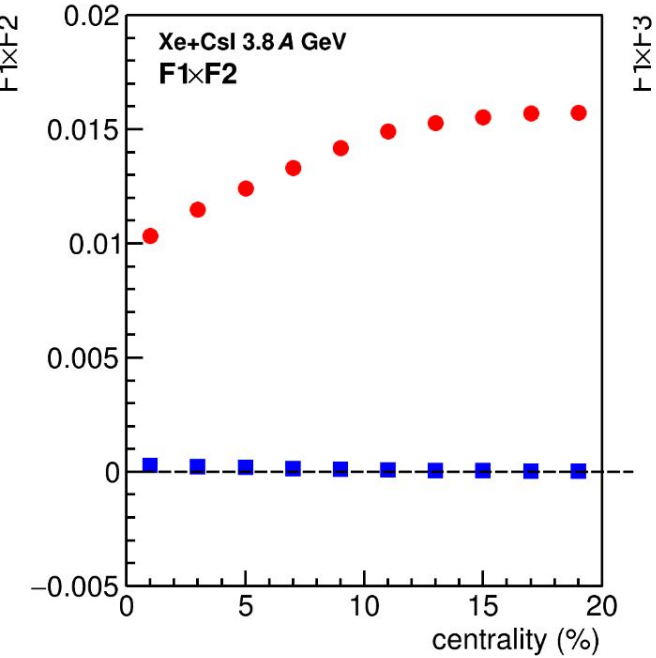


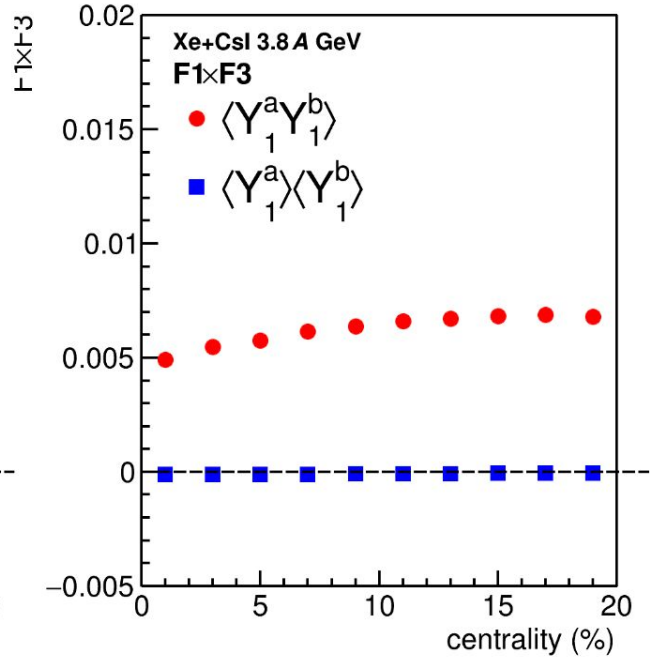


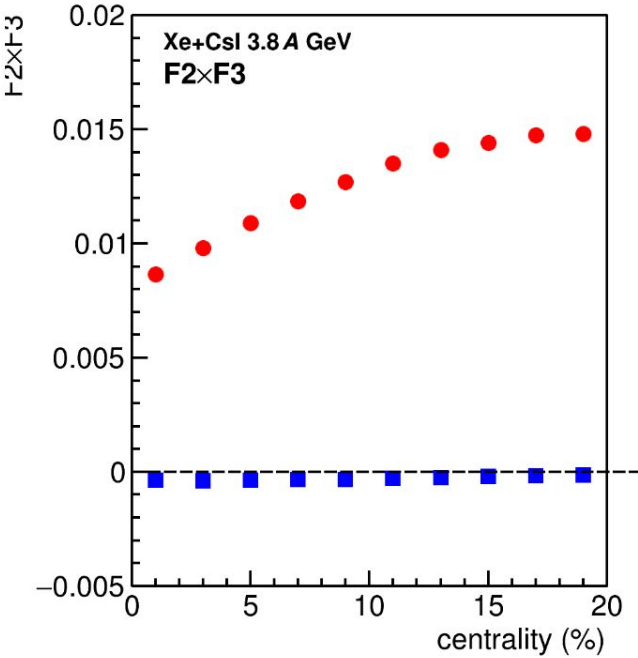


Plain Q1-vectors

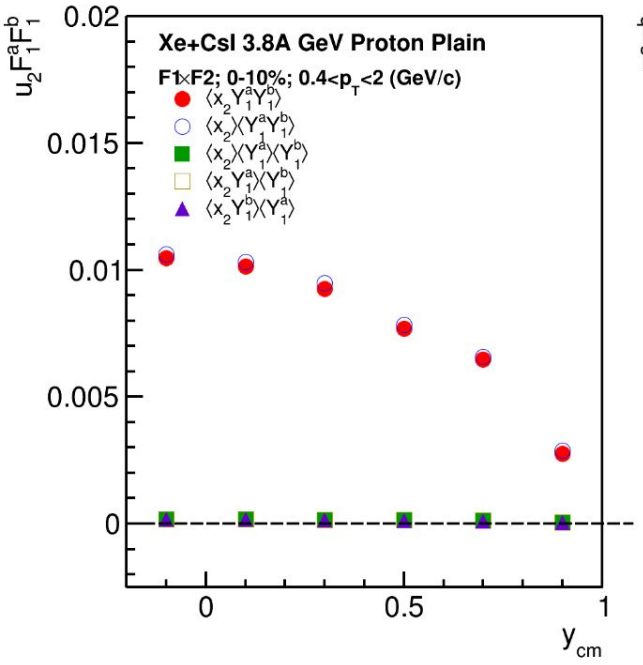
Correlation of plain Q_1-vectors from FHCal

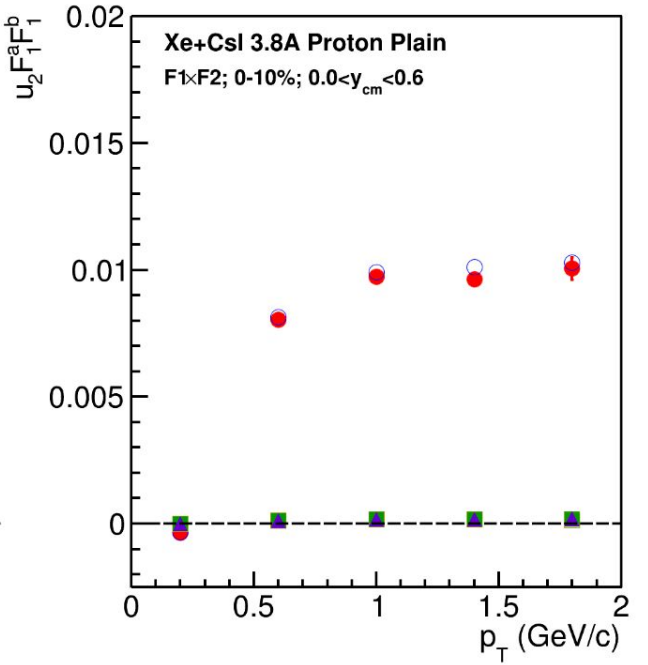


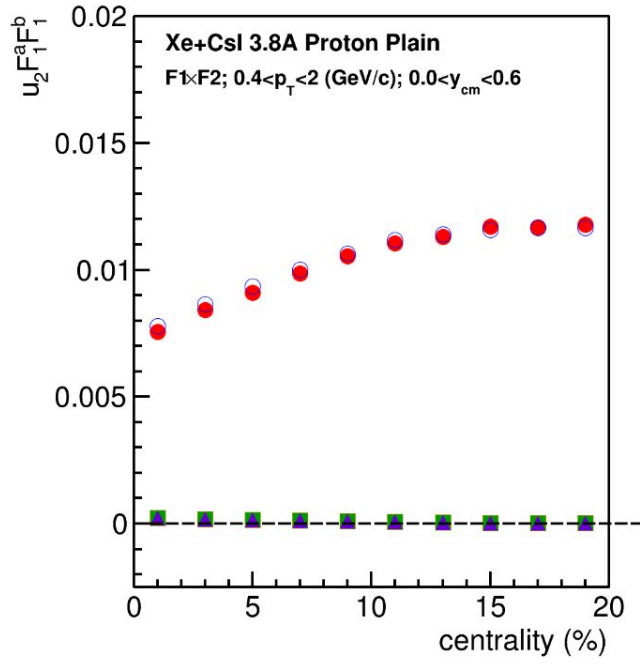




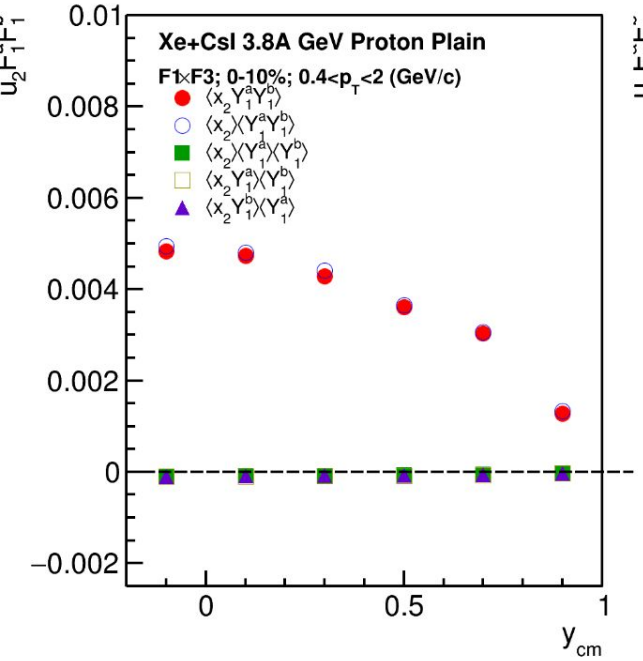
Plain protons with plain F1 and F2

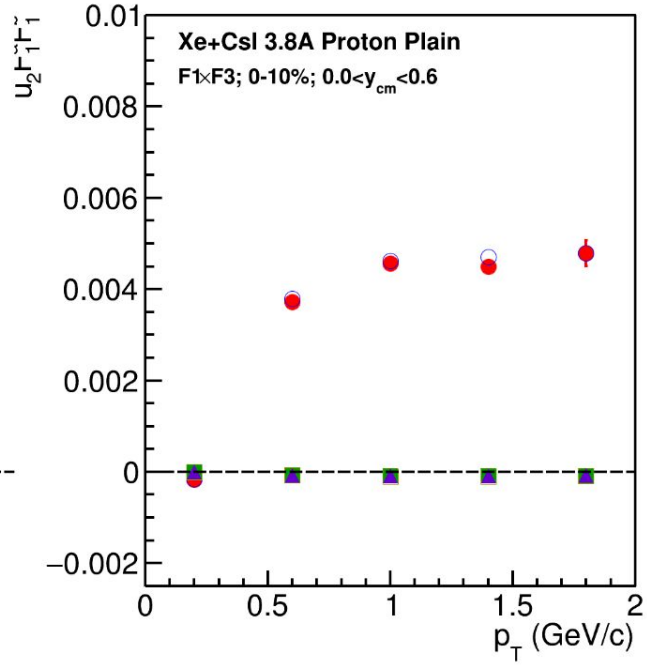


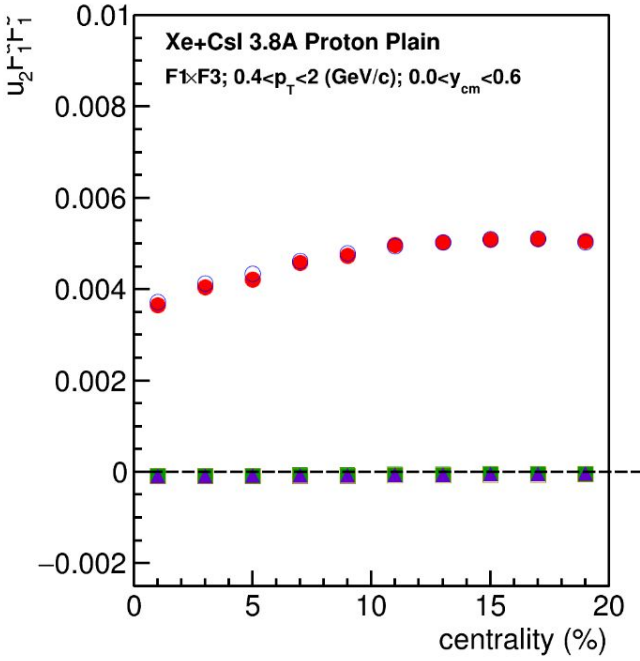




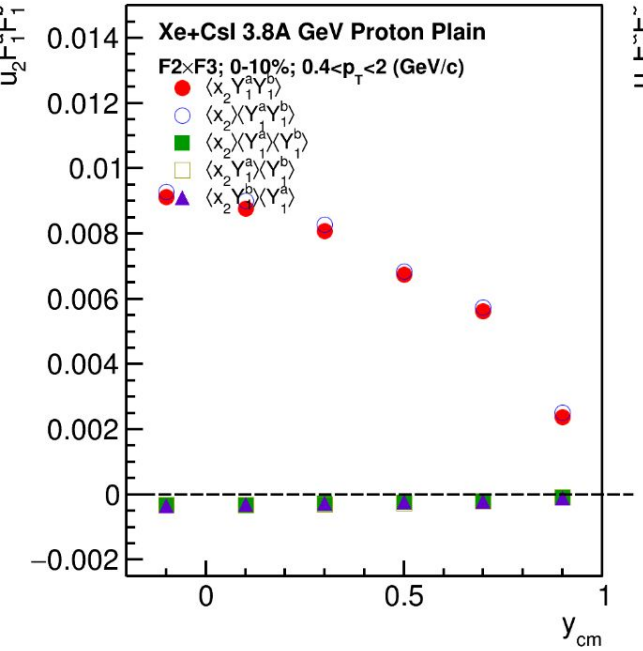
Plain protons with plain F1 and F3

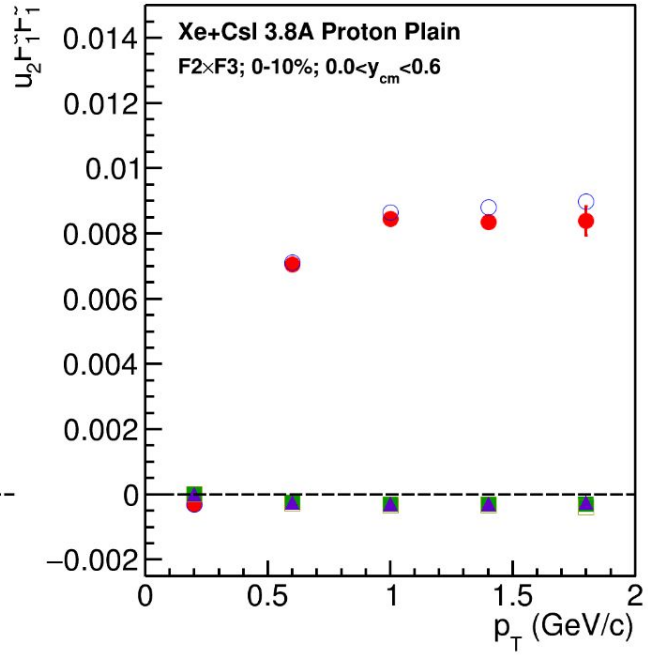


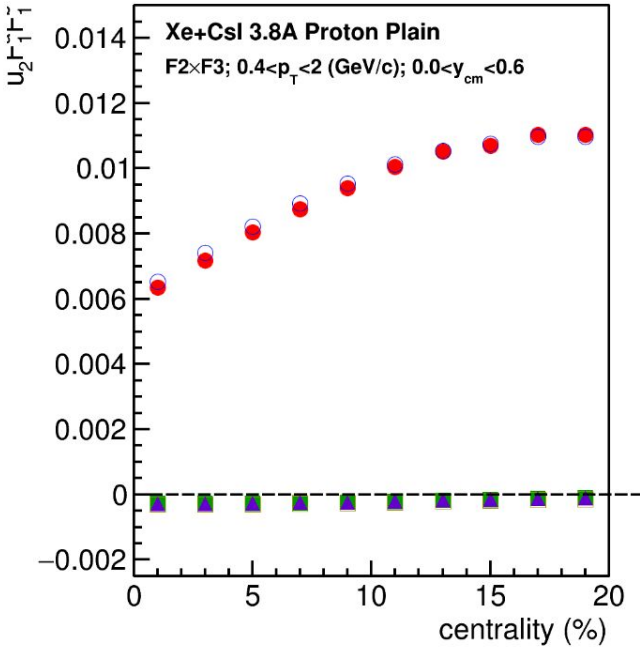




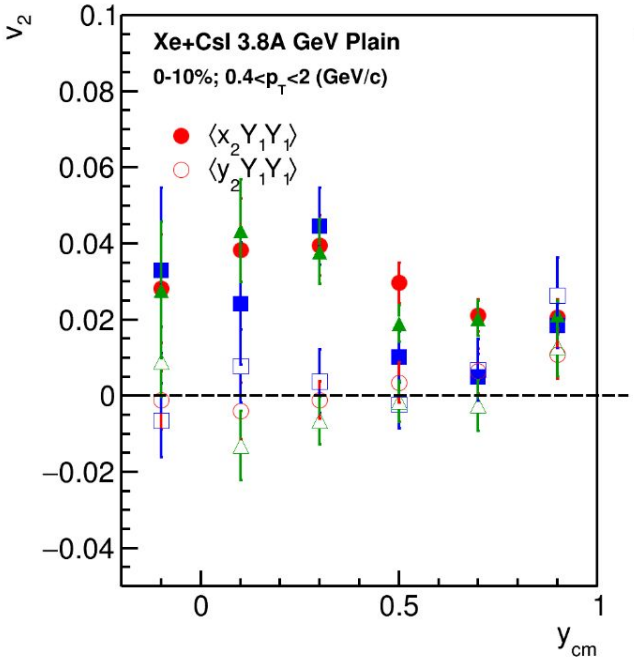
Plain protons with plain F2 and F3

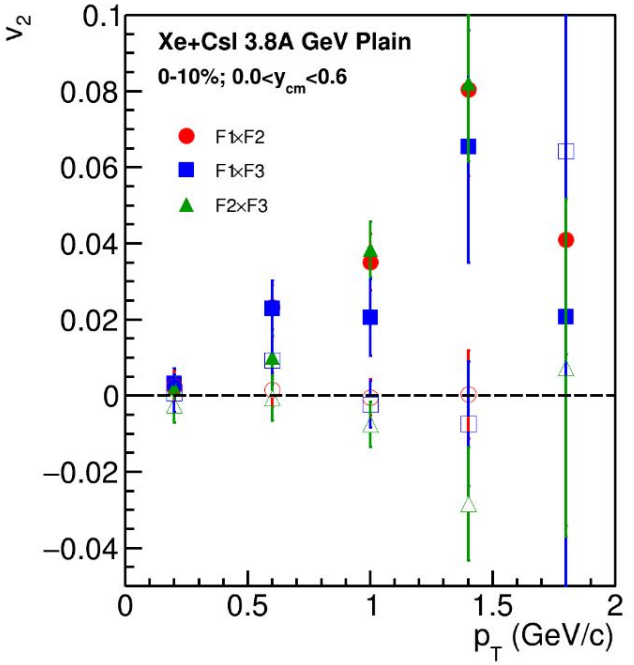


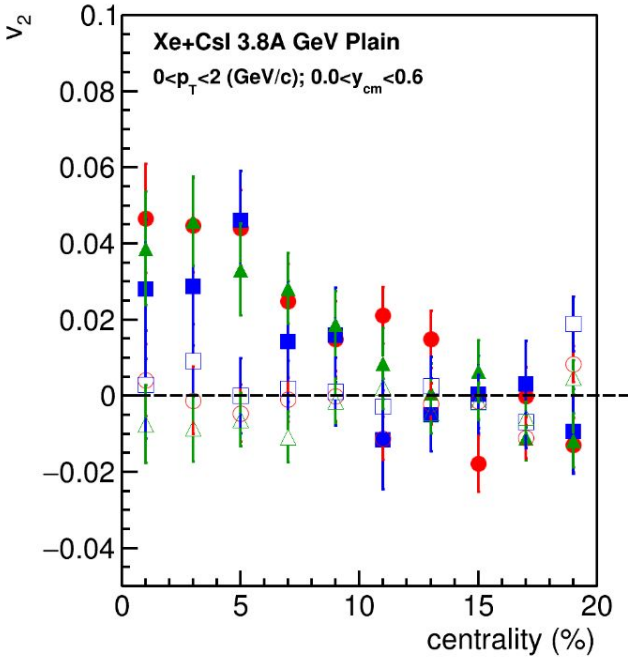




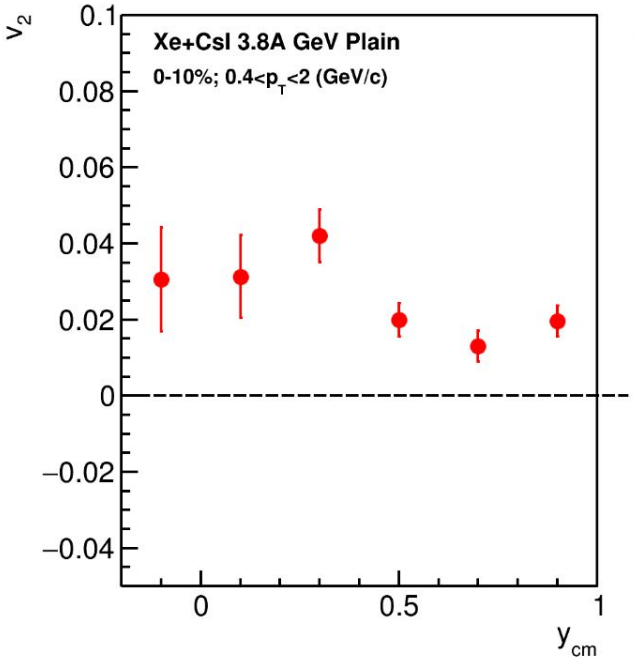
Plain proton v_2 wrt different symmetry planes

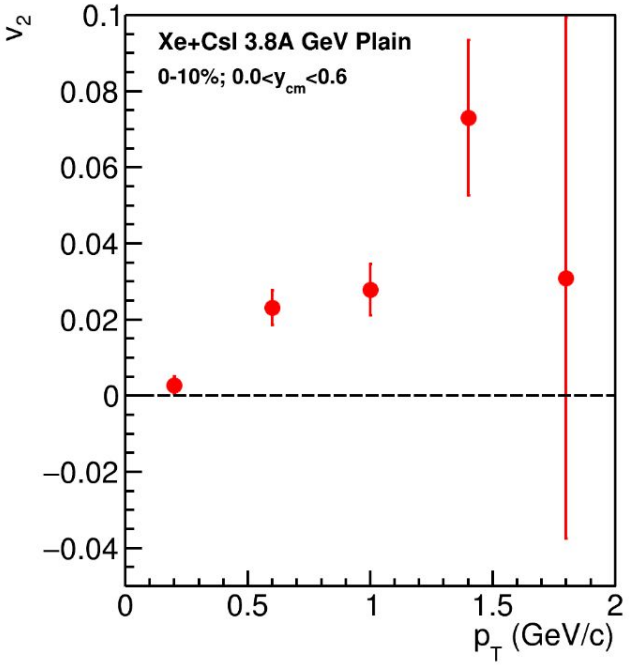


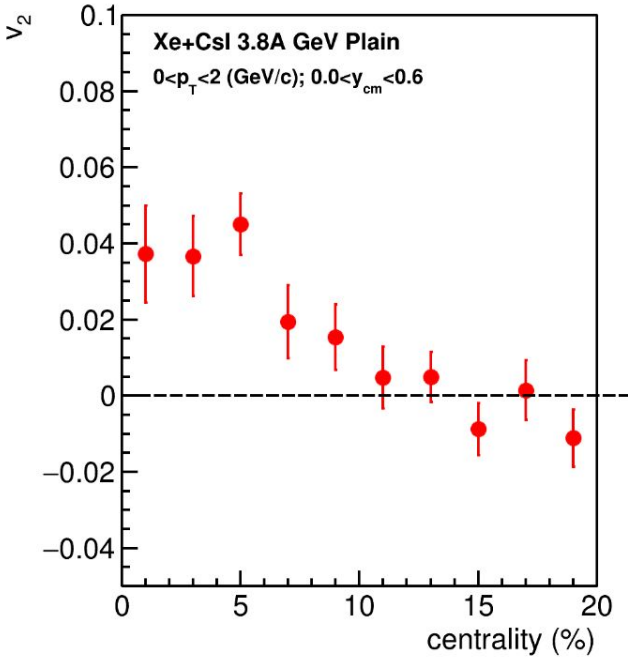




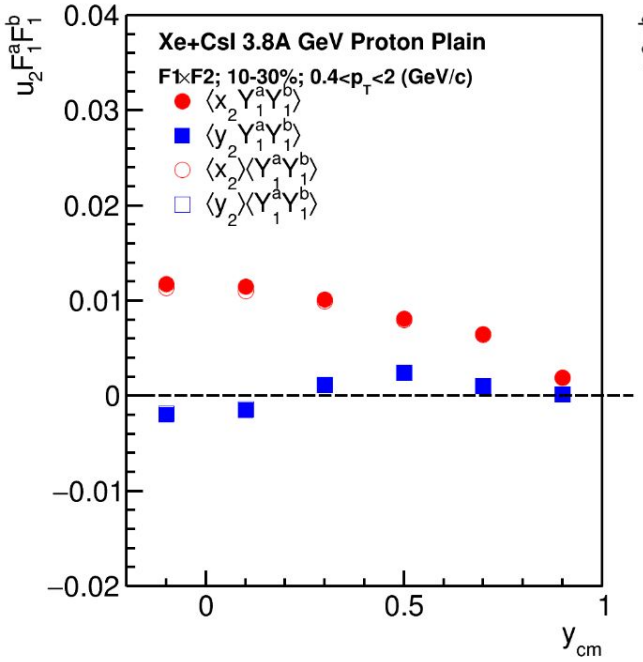
Plain protons with plain F2 and F3

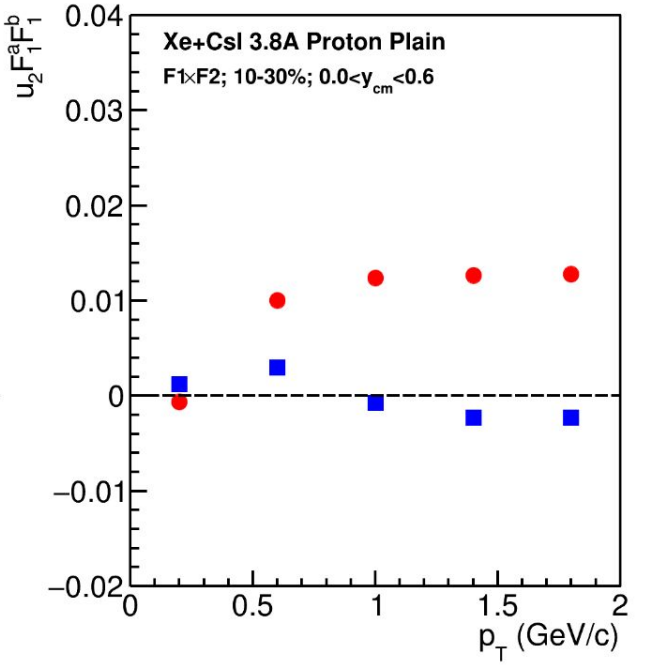


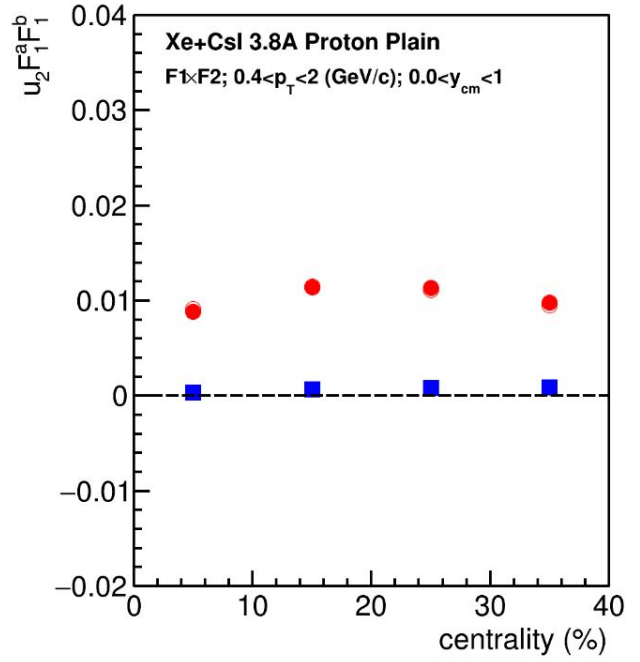




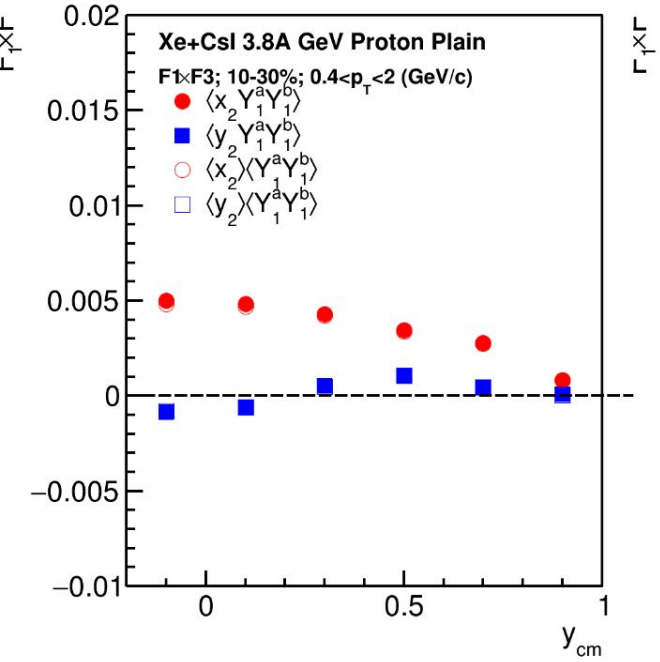
plain u_2-vector with rec.-corr. F1 and F2

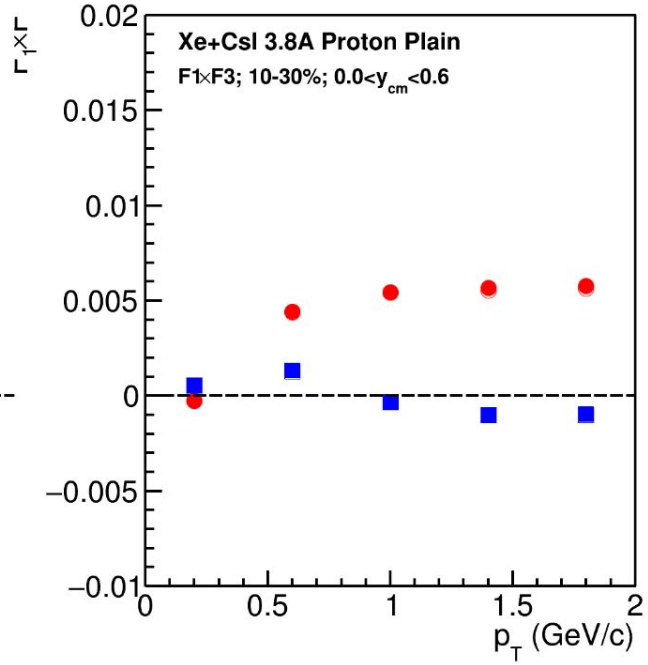


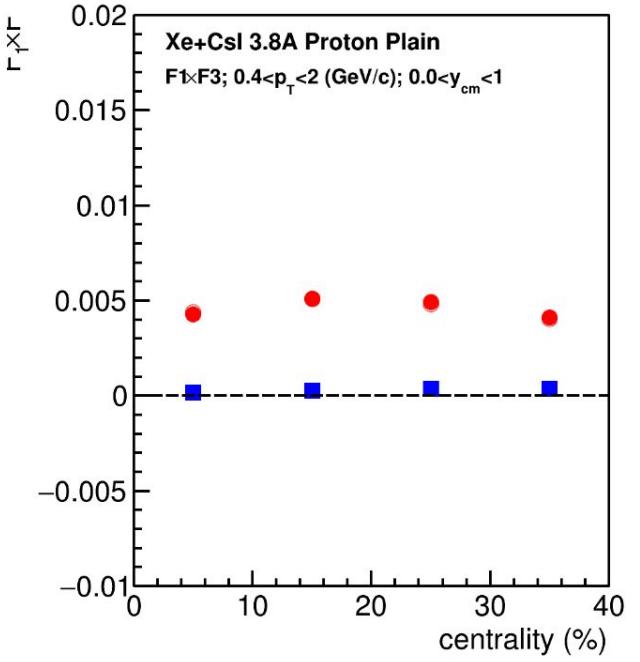




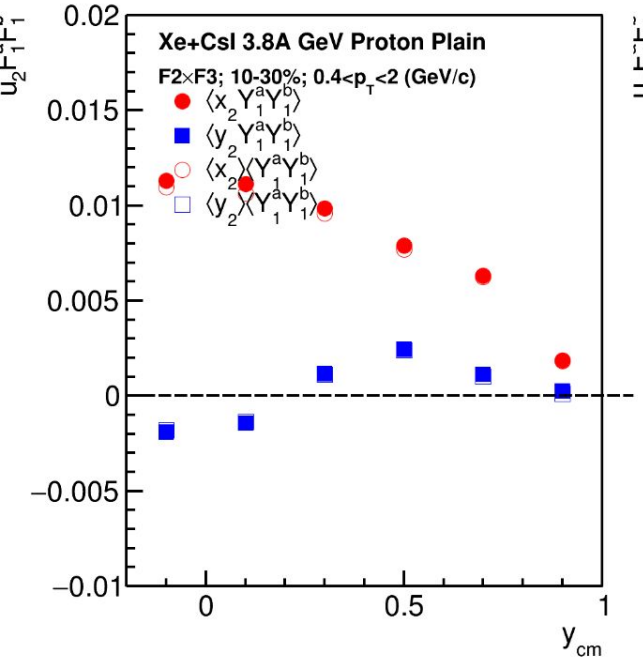
plain u_2-vector with rec.-corr. F1 and F3

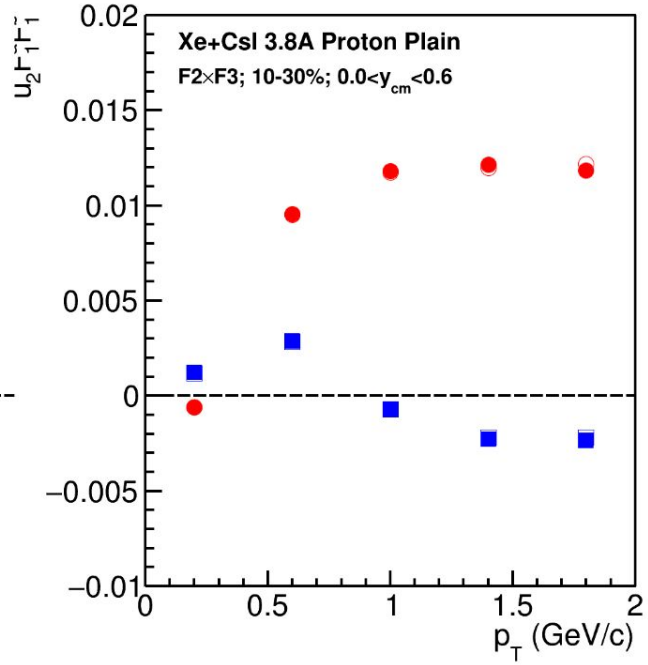


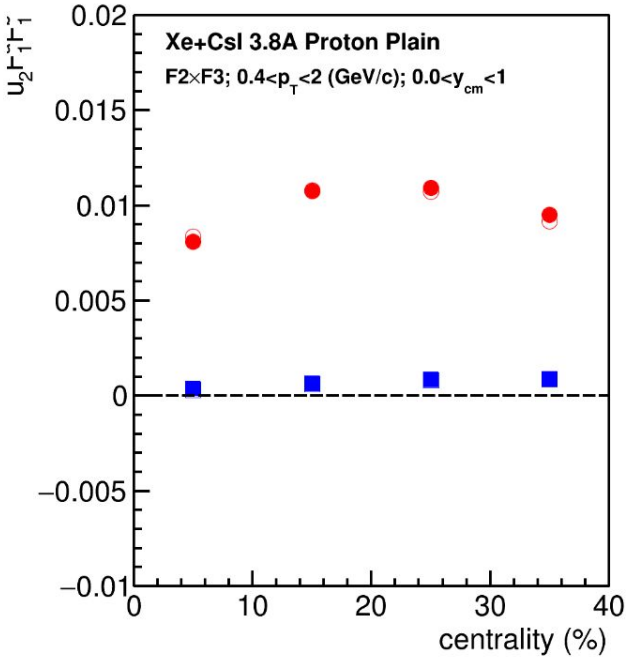




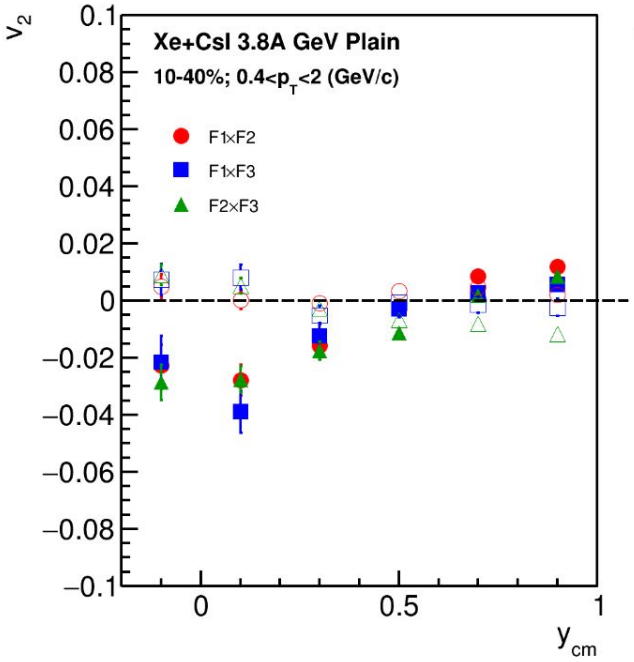
plain u_2-vector with rec.-corr. F2 and F3

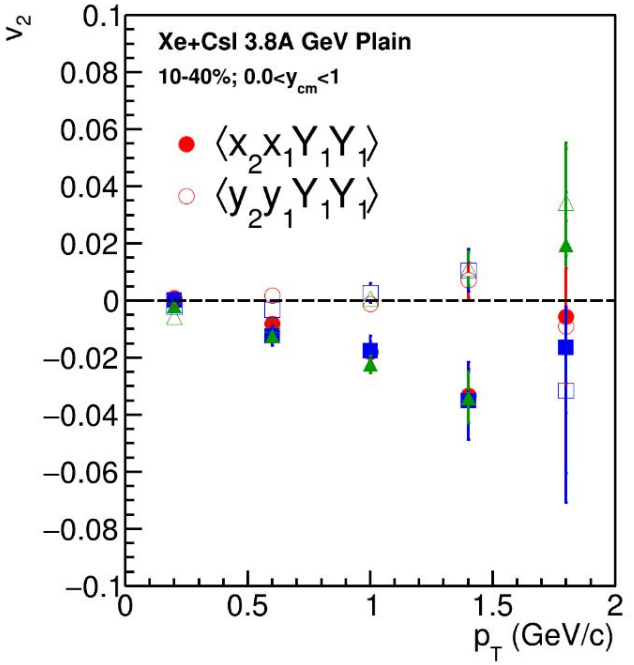


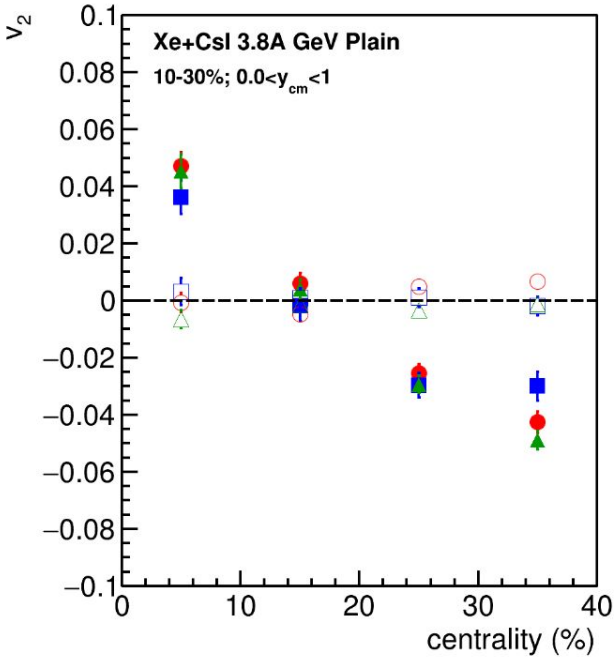




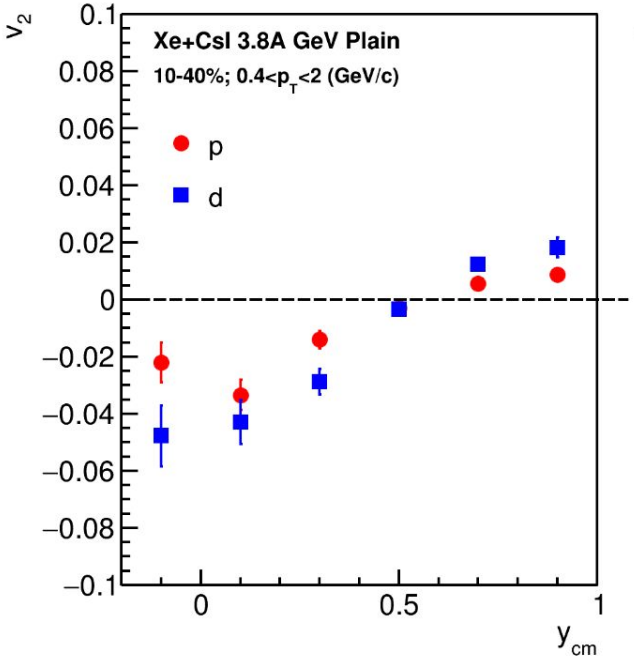
v_2 as a function of y_{cm}, p_T and centrality

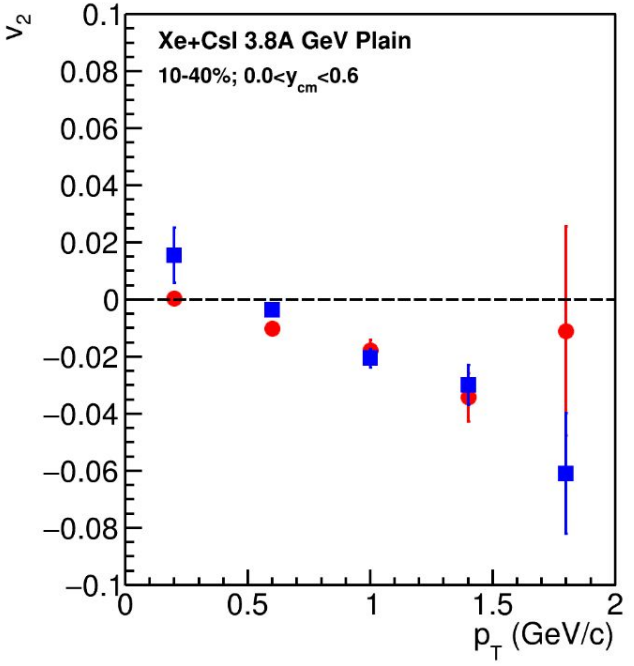


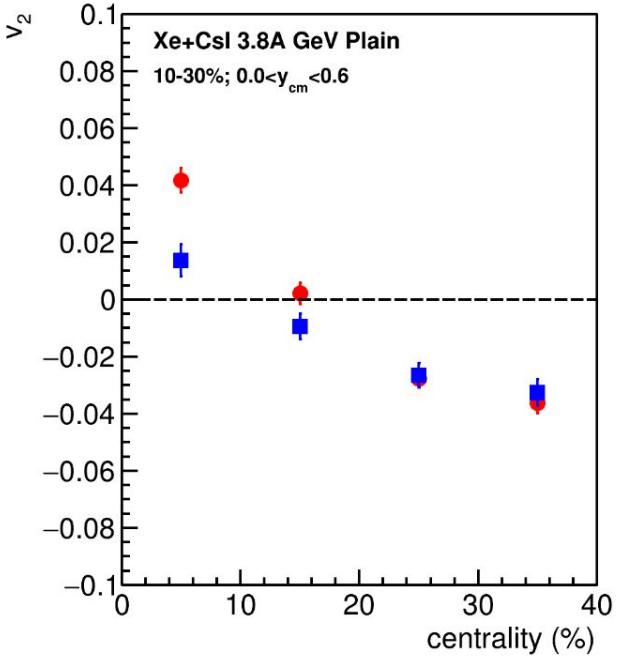




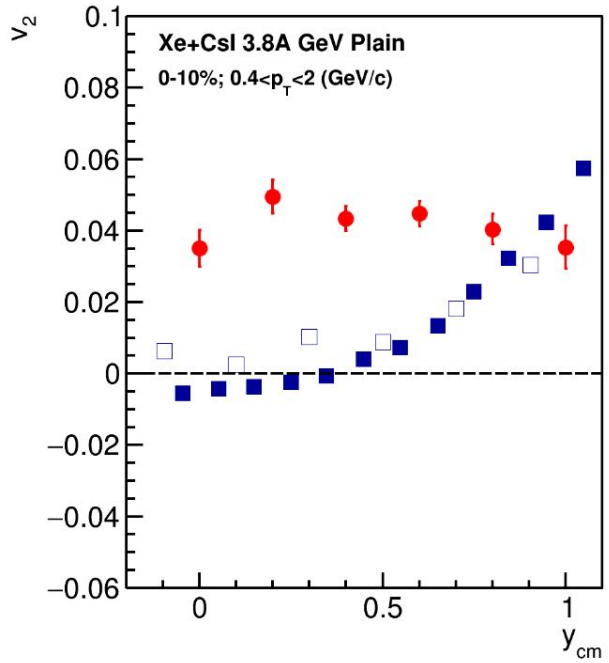
Proton v_2 vs deuteron v_2

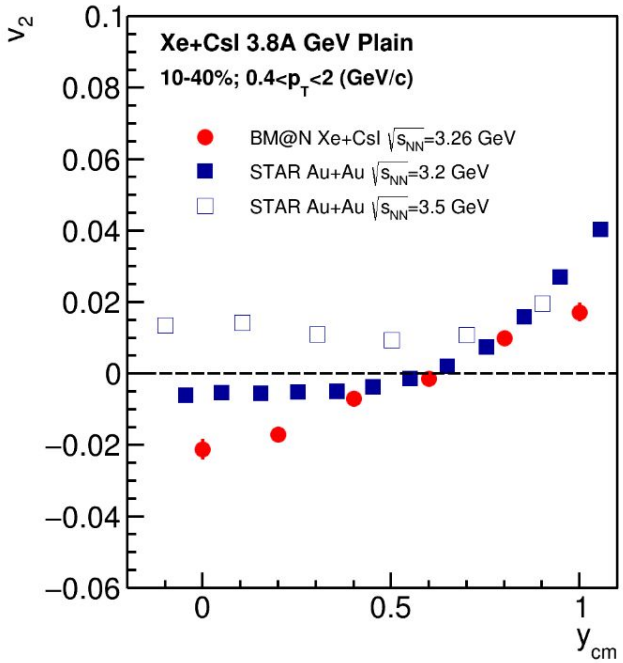


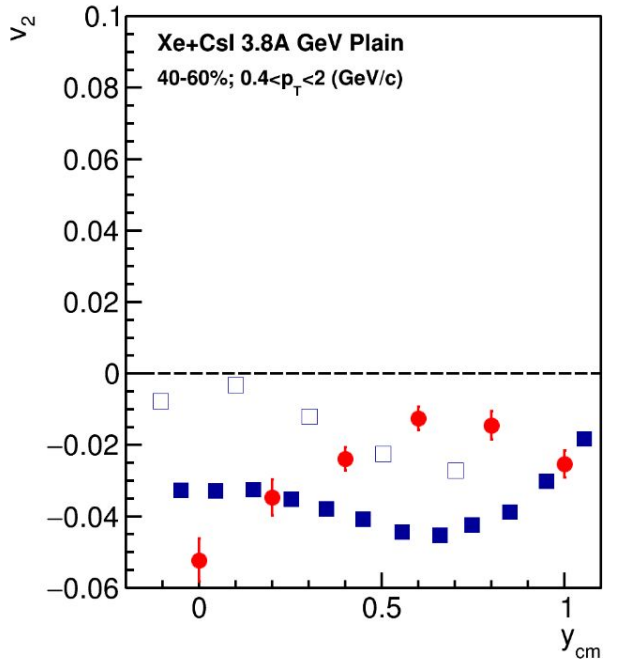




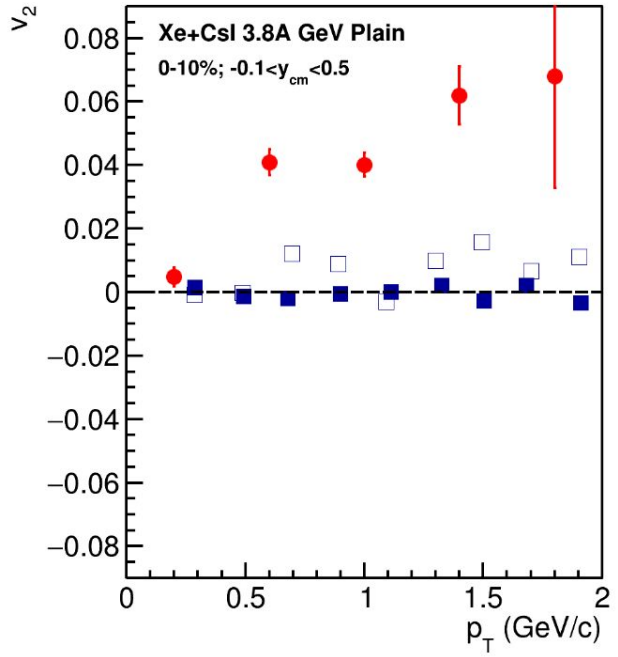
Comparison with STAR-FXT: y-dependence

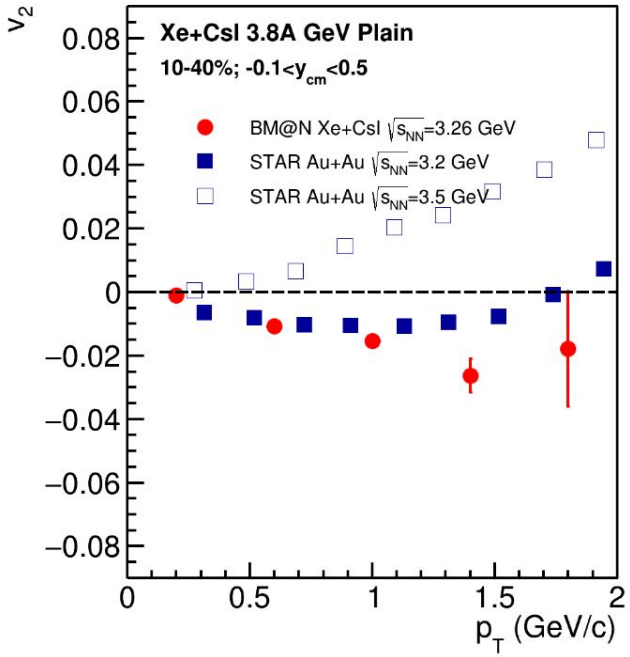


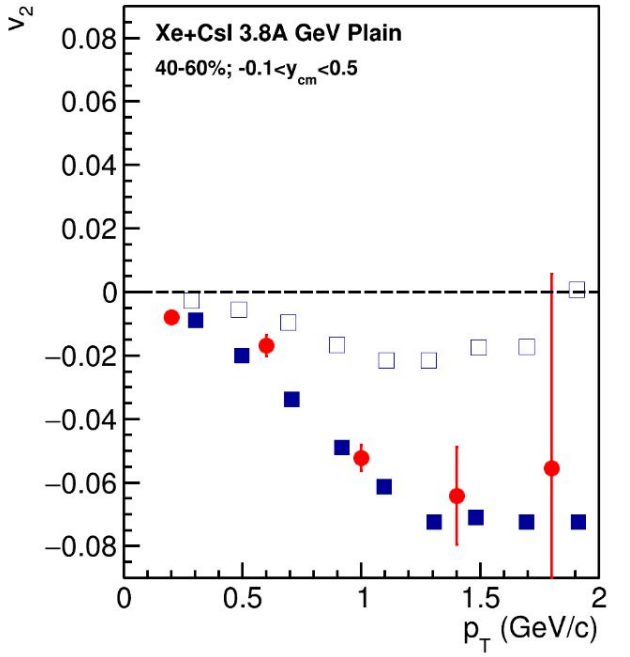


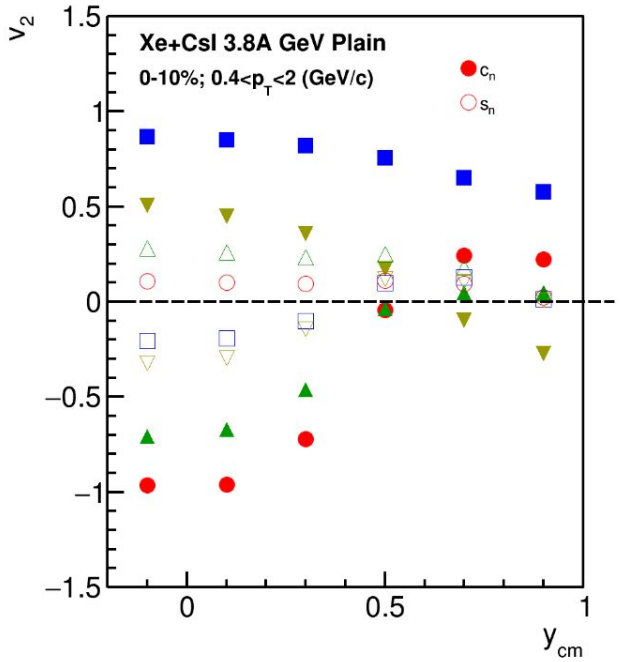


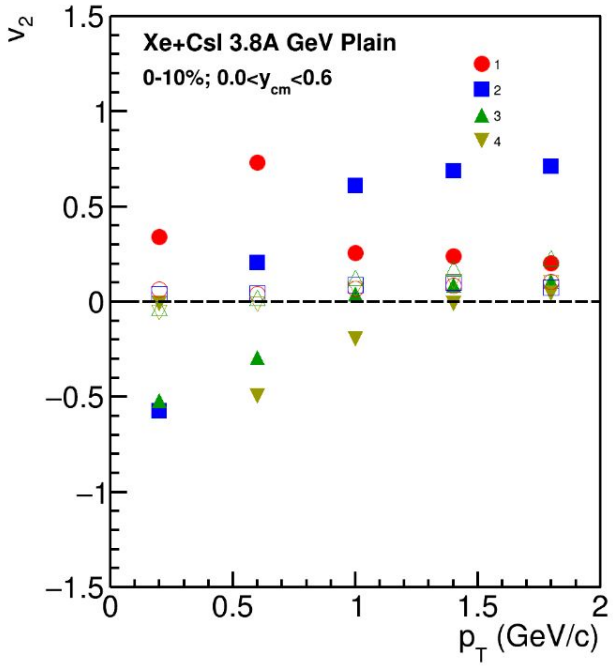
Comparison with STAR-FXT: y-dependence

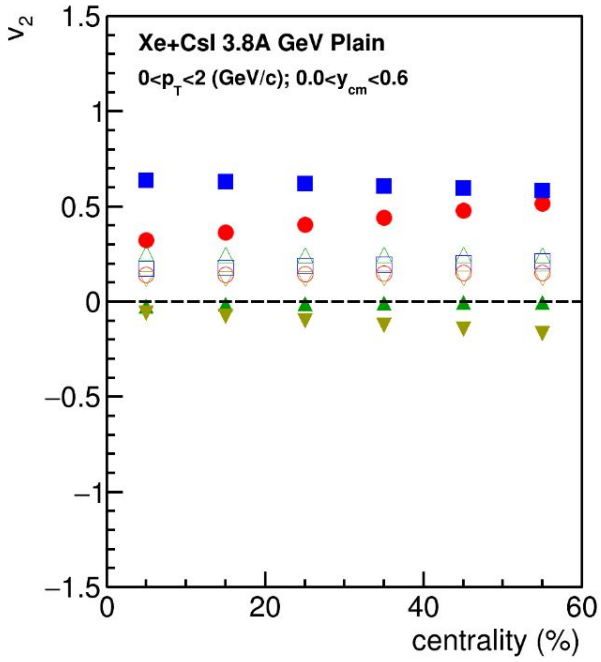


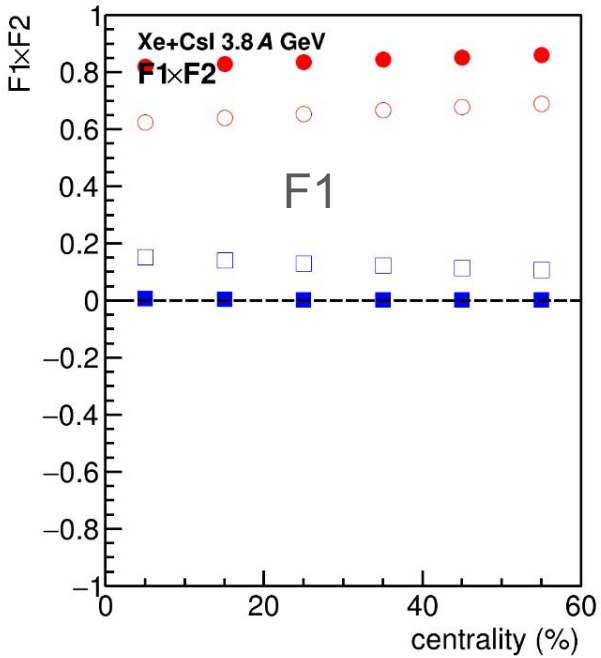


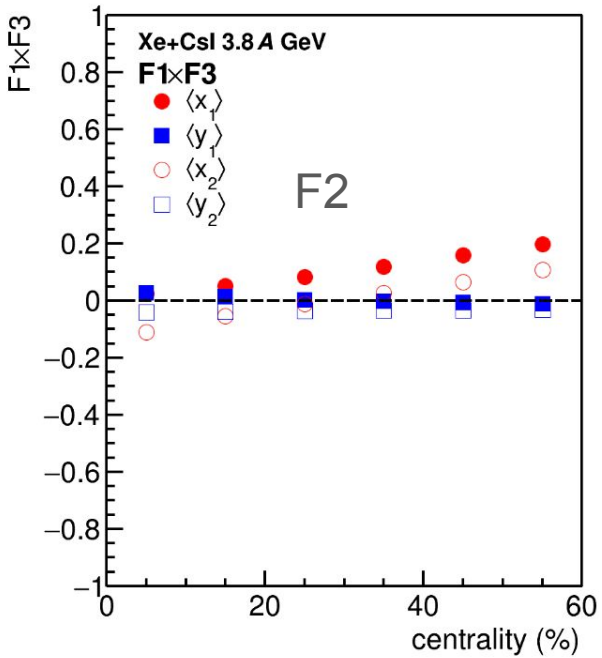


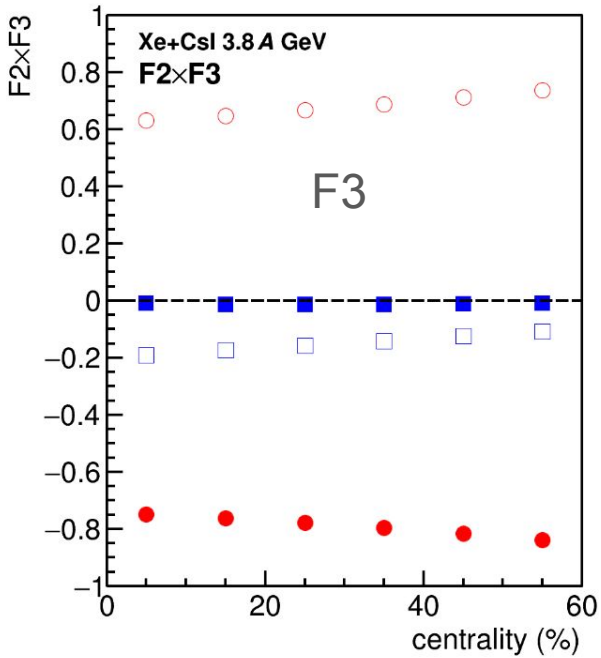

Xe+CsI 3.8A GeV Plain
0-10%; 0.4<p_T<2 (GeV/c)
c_n
s_n
v_2
y_cm

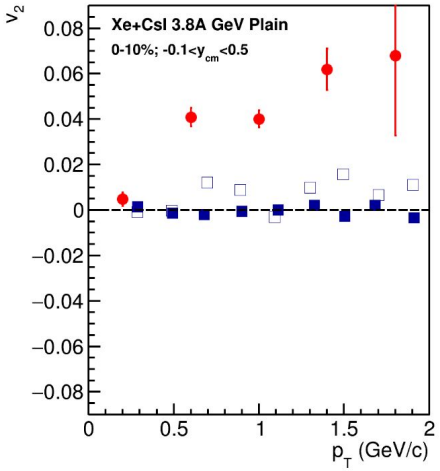

Xe+CsI 3.8A GeV Plain
0-10%; 0.0<y_cm<0.6
1
2
3
4
v_2
p_T (GeV/c)

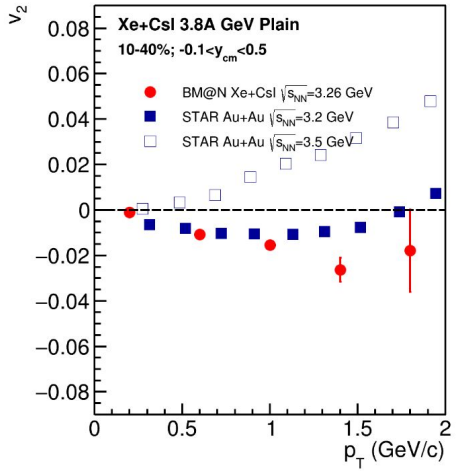

Xe+CsI 3.8A GeV Plain
0<p_T<2 (GeV/c); 0.0<y_cm<0.6
v_2
centrality (%)

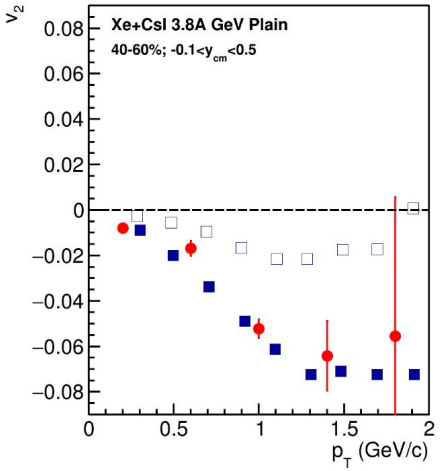

Xe+CsI 3.8 A GeV
F1×F2
F1
F1×F2
centrality (%)


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)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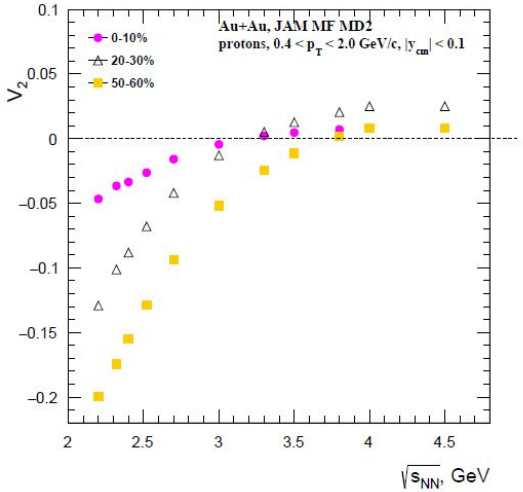
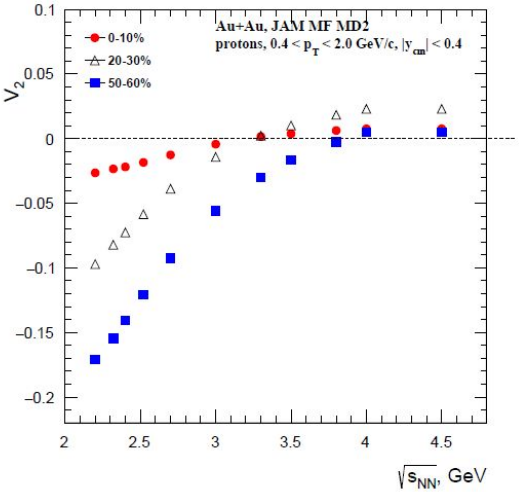
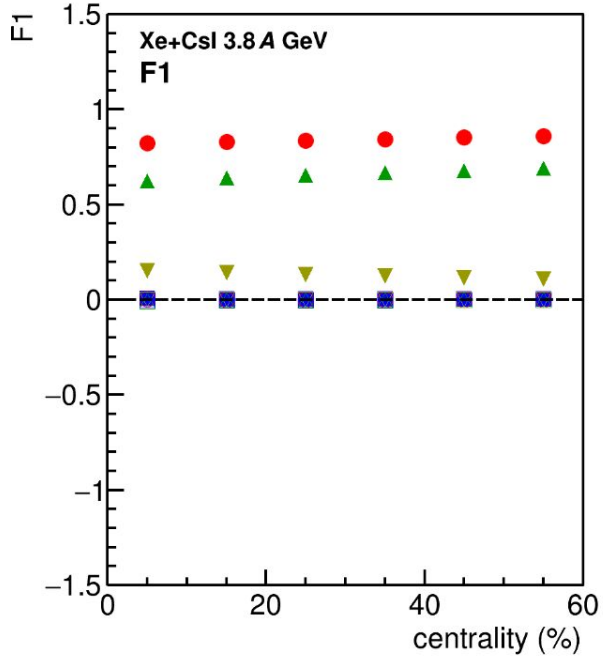
40-60%; -0.1<y_cm<0.5
v2
p_T (GeV/c)

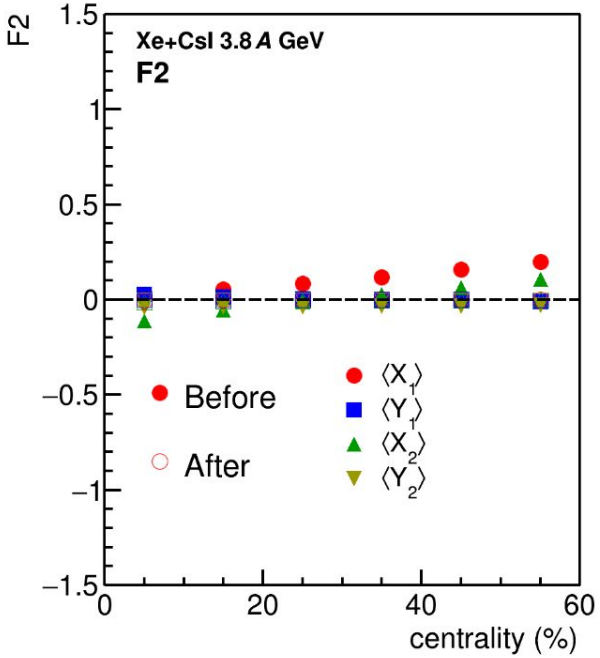

Au+Au, JAM MF MD2
protons, 0.4 < p_T < 2.0 GeV/c, |y_cm| < 0.1
0-10%
20-30%
50-60%
V2
√s_NN, GeV

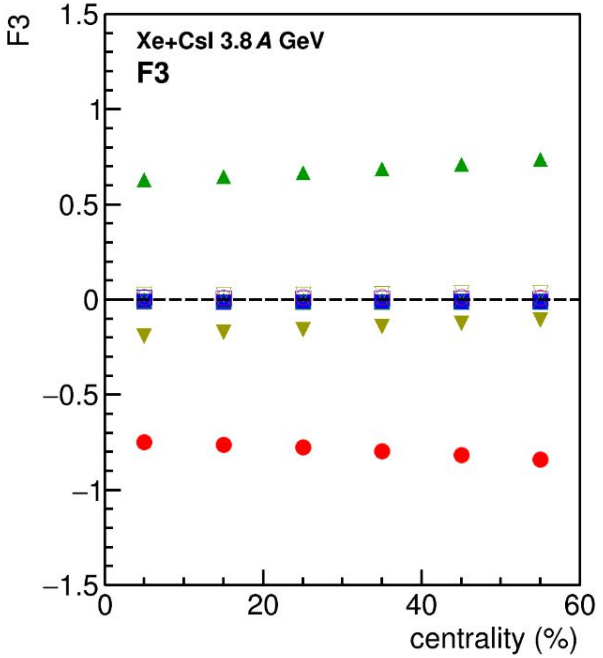

Au+Au, JAM MF MD2
protons, 0.4 < p_T < 2.0 GeV/c, |y_cm| < 0.4
0-10%
20-30%
50-60%
V2
√s_NN, GeV

Decomposition correction

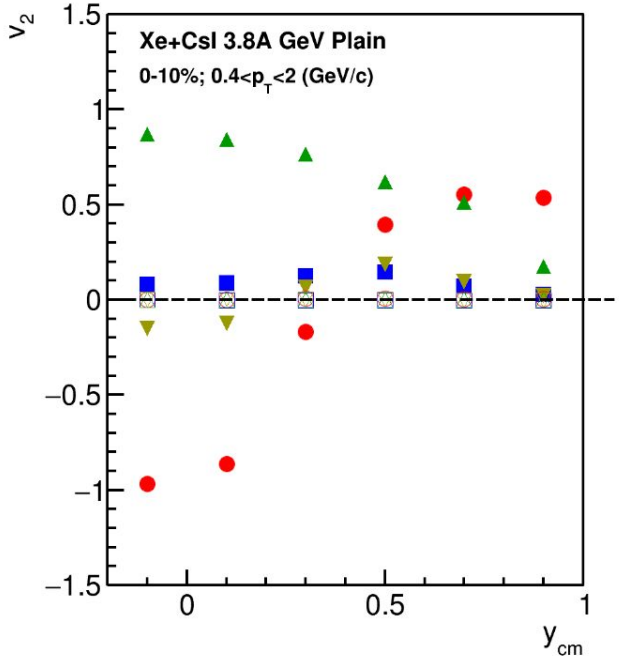
Average of FHCal $Q_{1,2}$-vector components

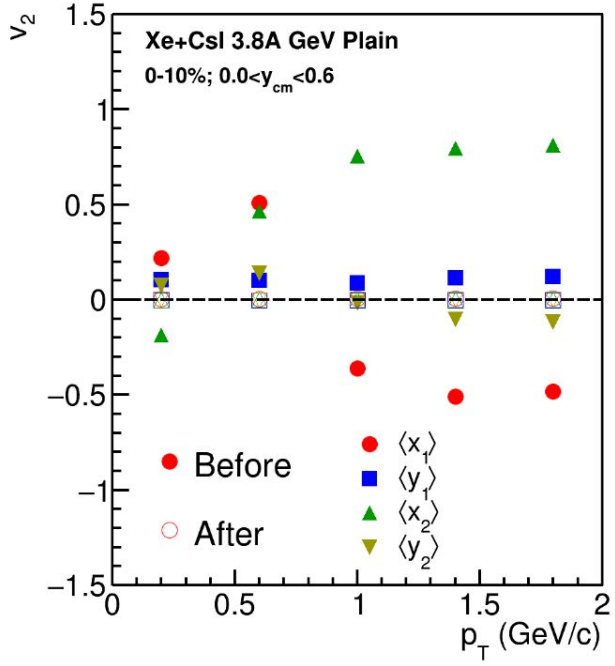


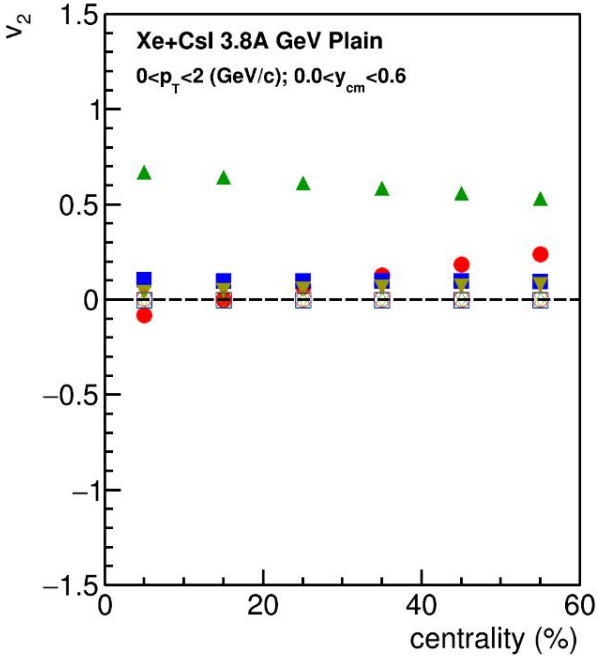




Average of proton $u_{1,2}$-vector components







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

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

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

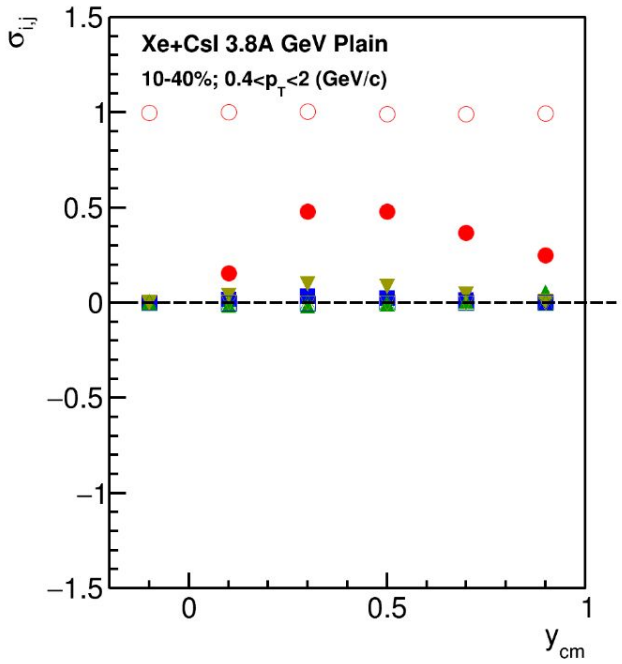
$$cov(x_n x_l) = \langle x_n x_l \rangle - c_n c_l$$

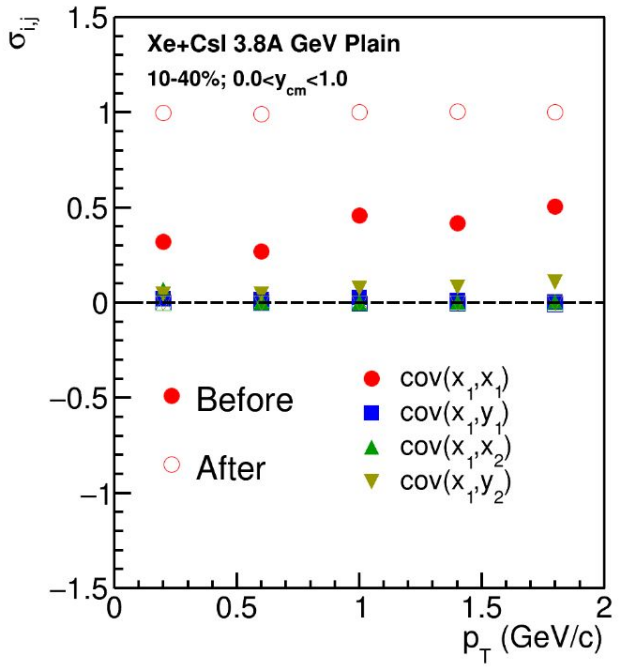
First, for vector s = [X_1, Y_1, X_2, Y_2] we bild covariation matrix M, where $M_{i,j}$ = cov(s_i, s_j). Then we apply the whitening procedure:

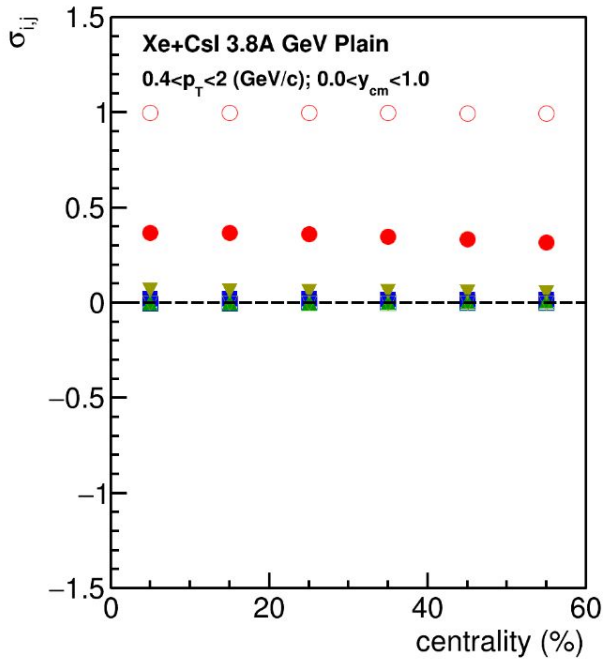
x = $M^{-1/2}$s
After this procedure: cov(x_i, x_i) = 1, cov(x_i, x_j)$_{i!=j}$=0
This supposed to decompose acceptance so that:

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

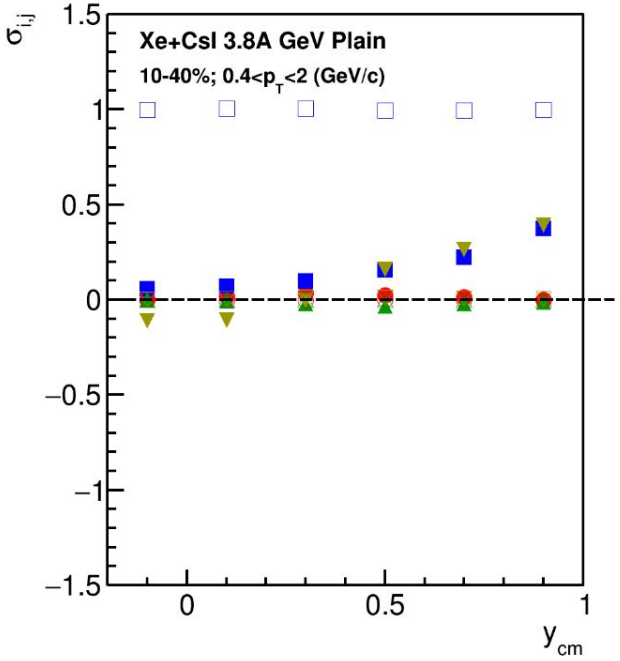
Cov(x_1, x_n/y_n) for protons before/after whitening:

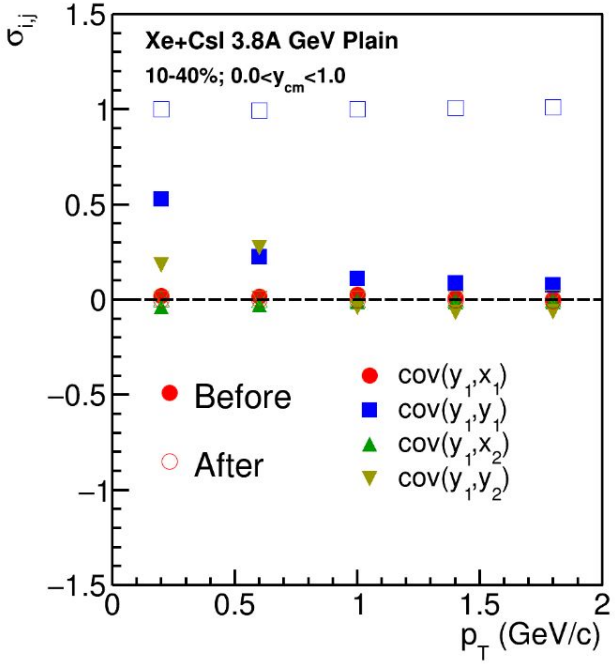


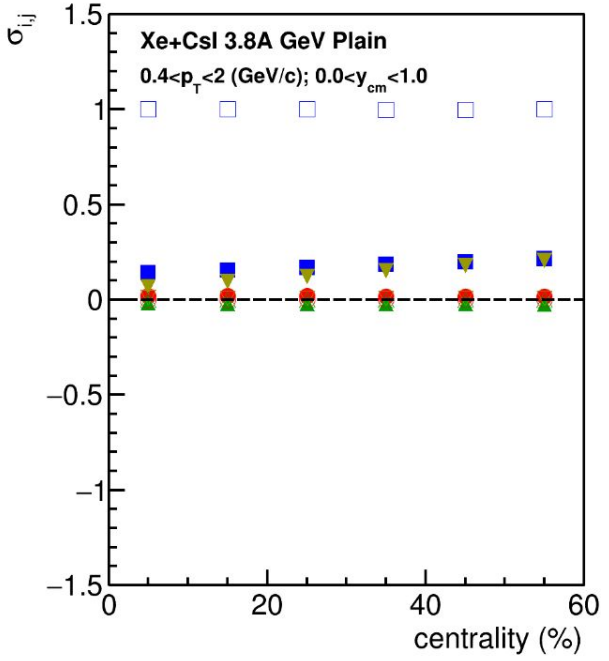




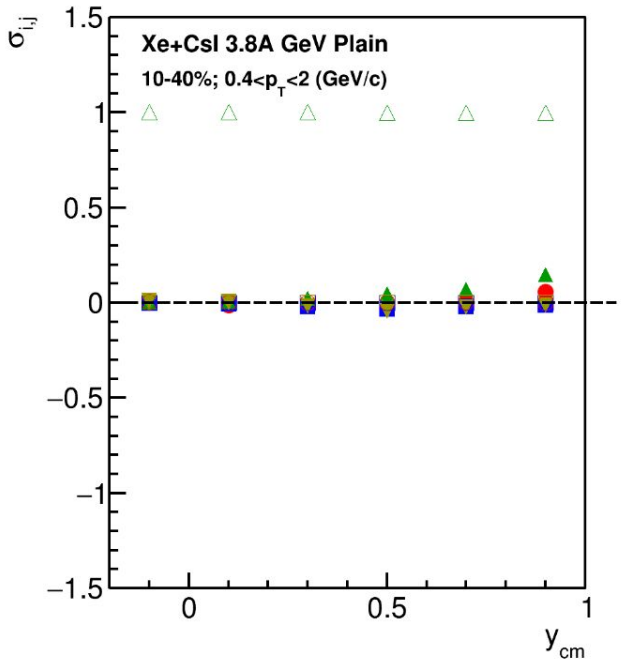
$Cov(y_1, x_n/y_n)$ for protons before/after whitening:

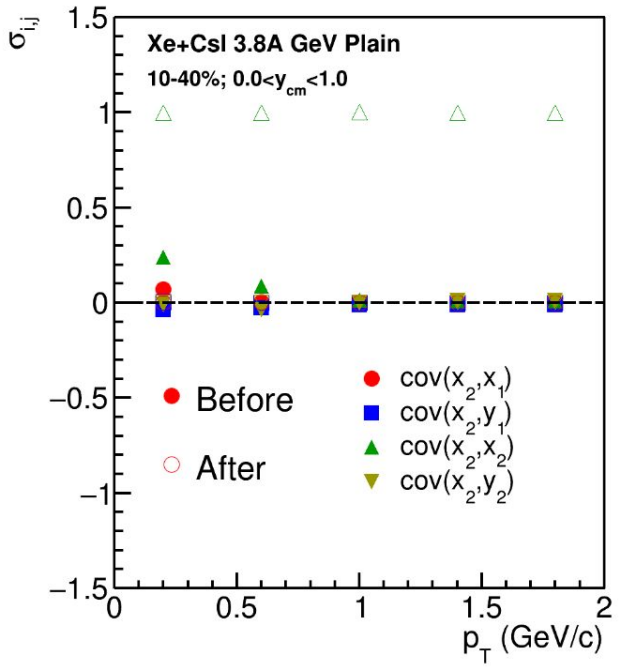


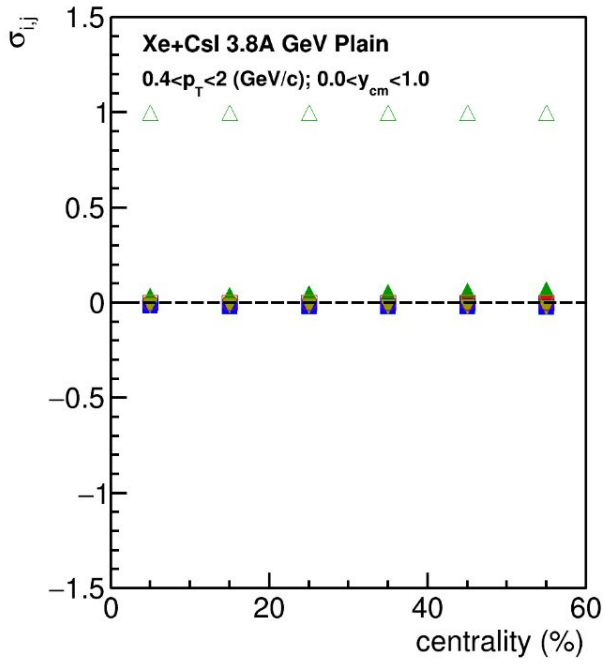




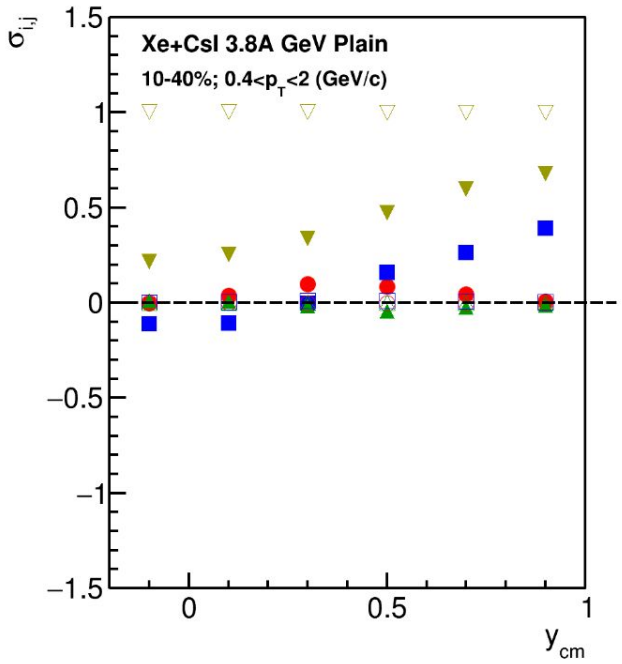
Cov(x_2, x_n/y_n) for protons before/after whitening:

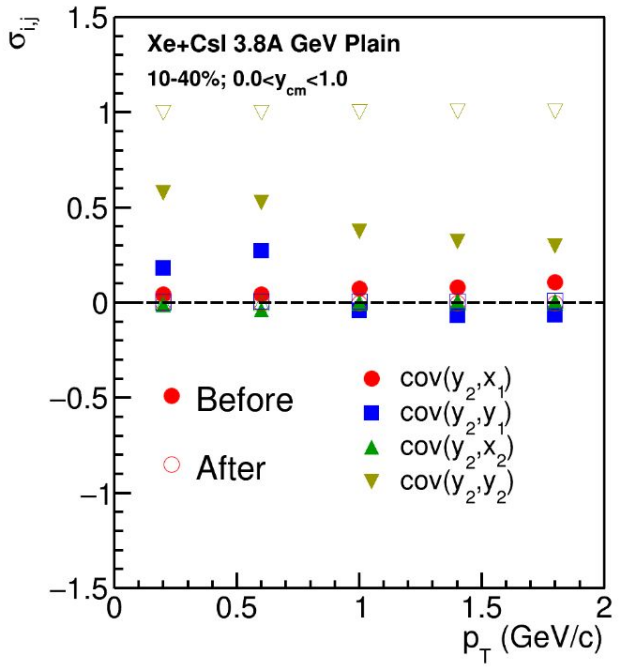


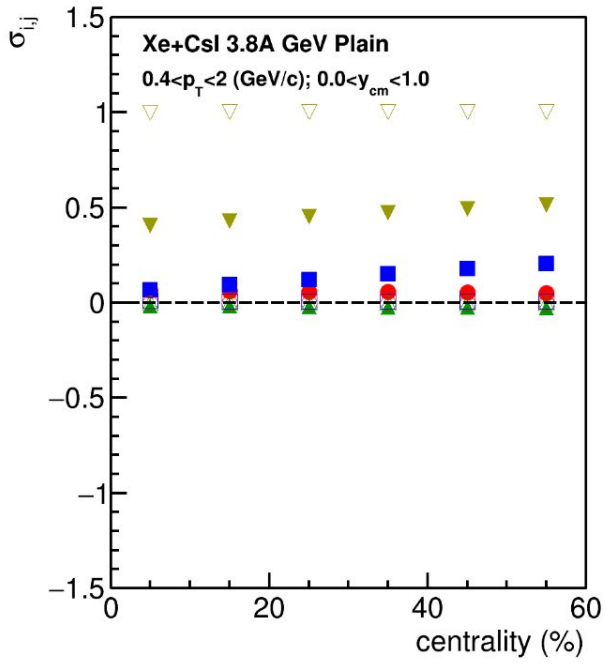




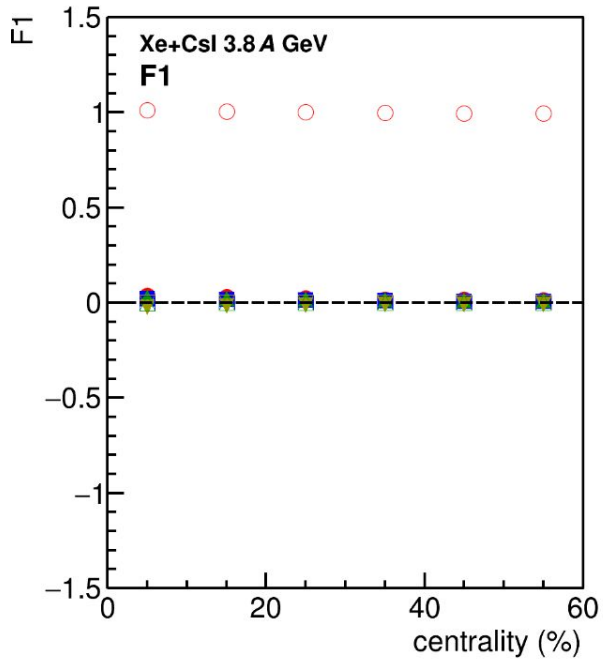
Cov(y_2, x_n/y_n) for protons before/after whitening:

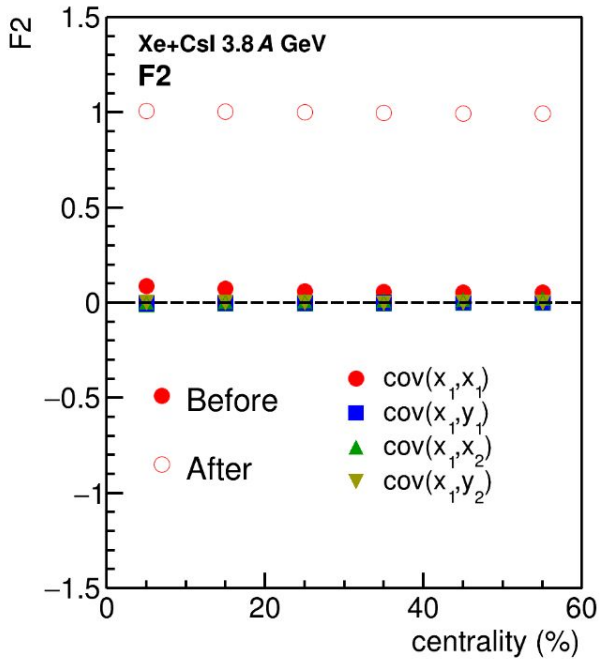


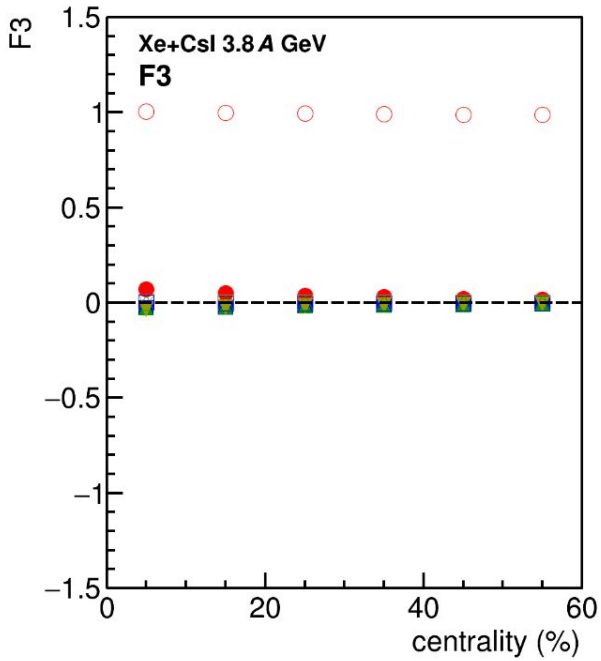




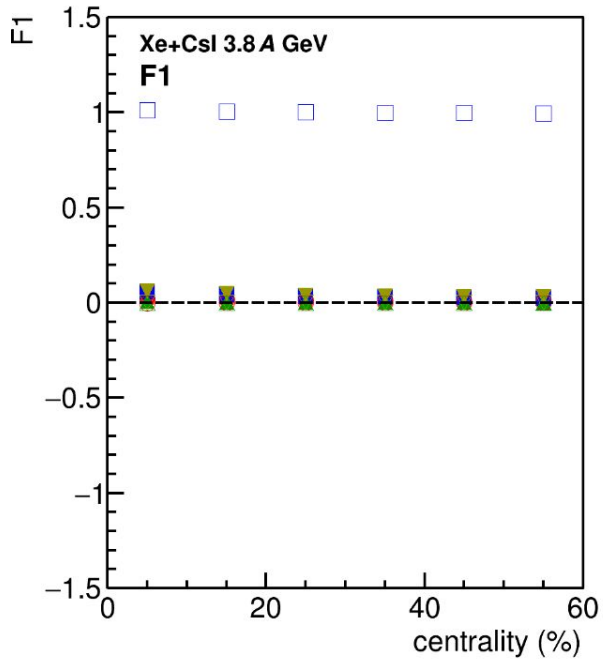
Cov(x_1, x_n/y_n) for FHCal before/after whitening:

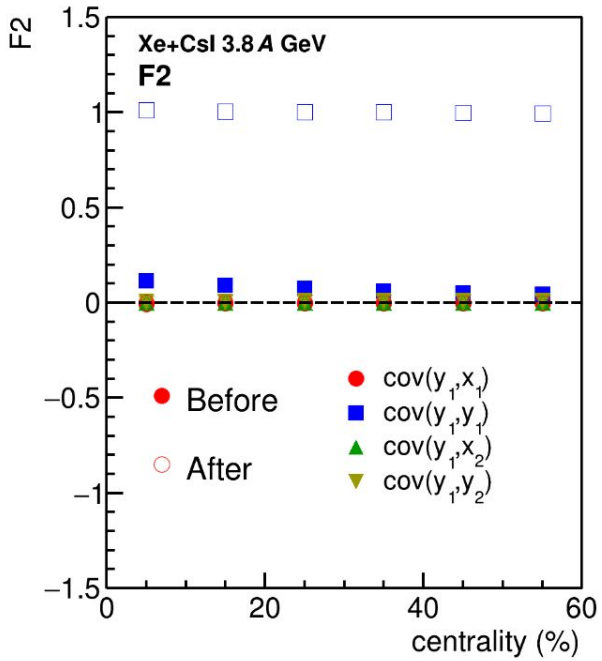


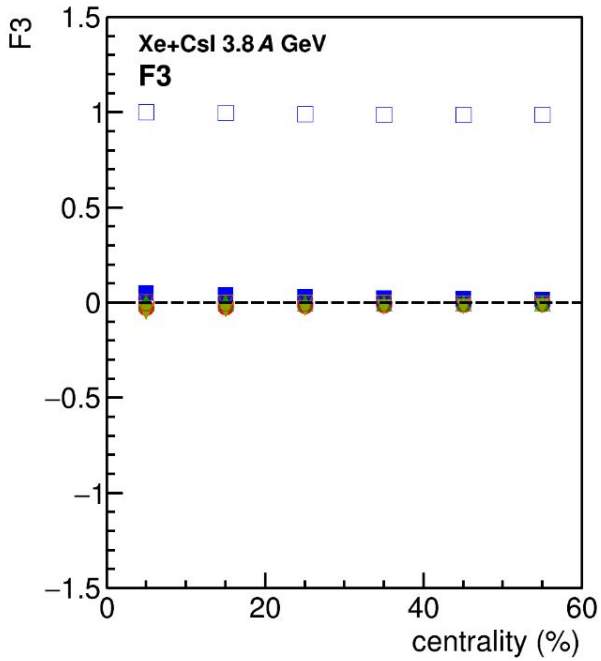




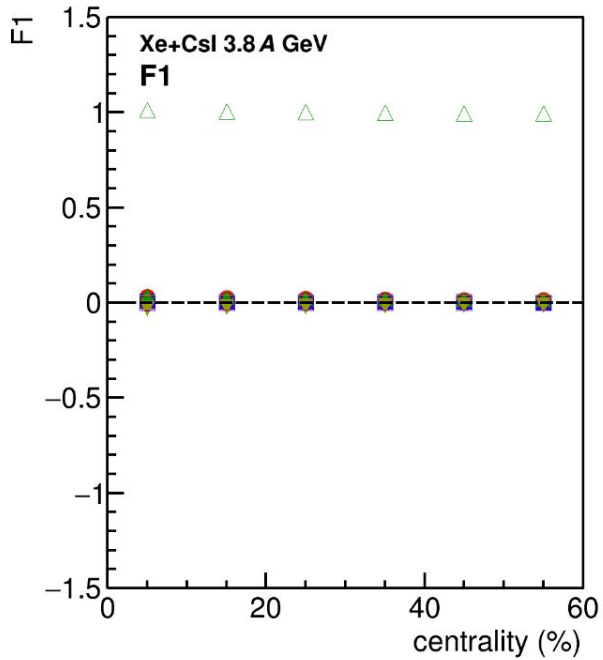
$Cov(y_1, x_n/y_n)$ for protons before/after whitening:

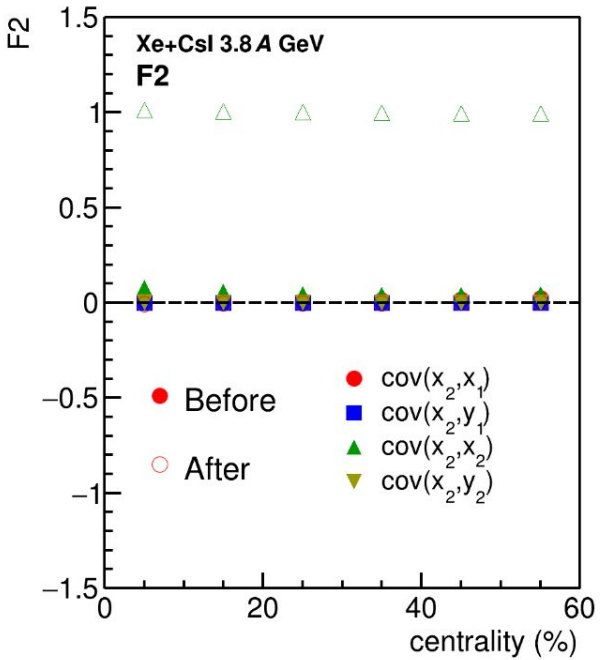


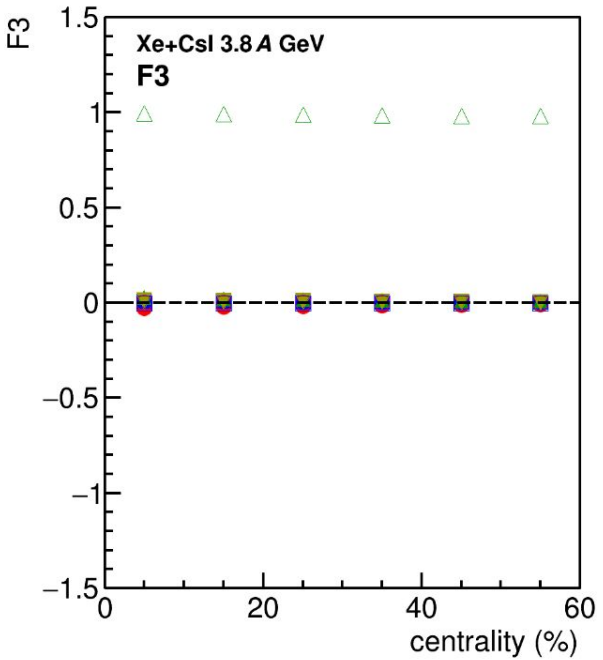




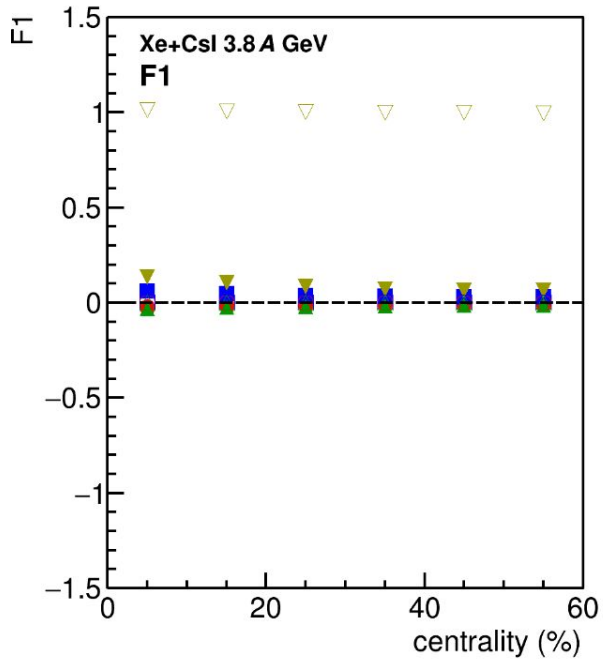
Cov(x_2, x_n/y_n) for protons before/after whitening:

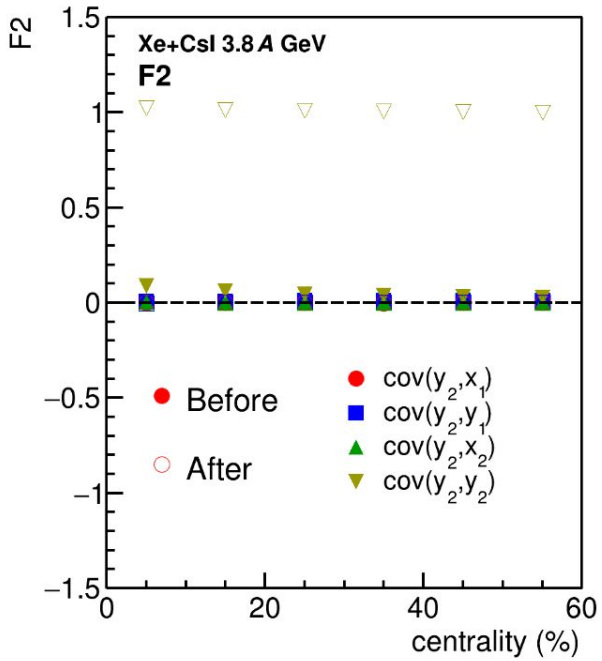


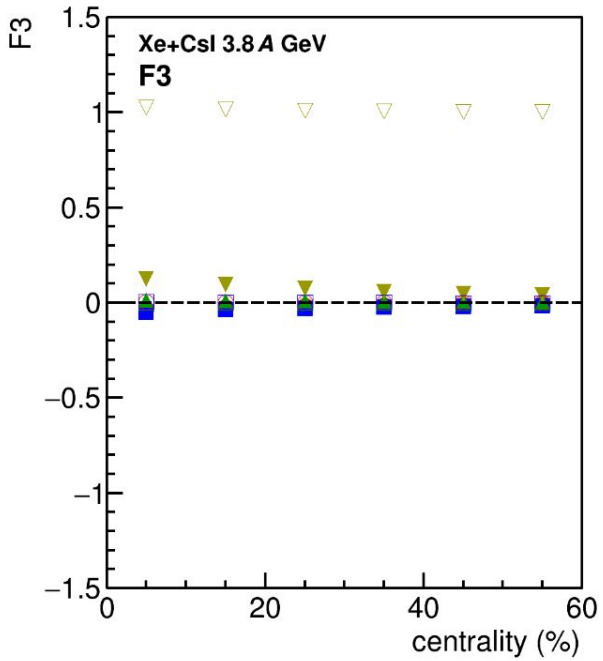




$Cov(y_2, x_n/y_n)$ for protons before/after whitening:

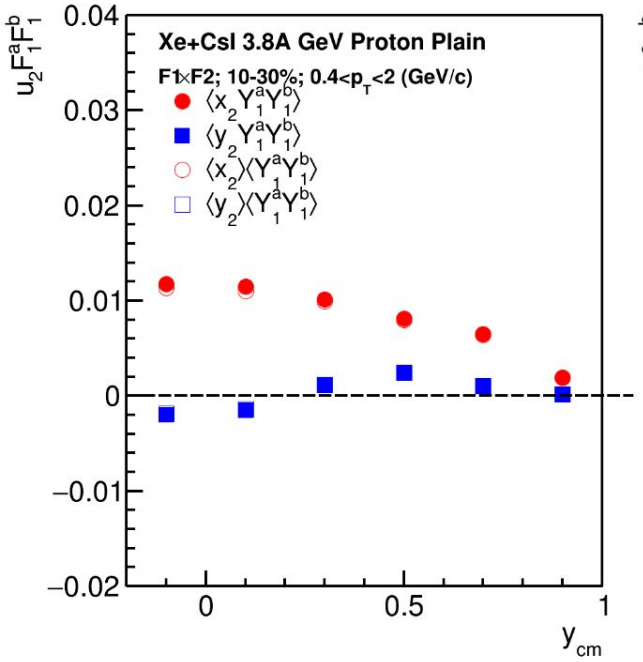


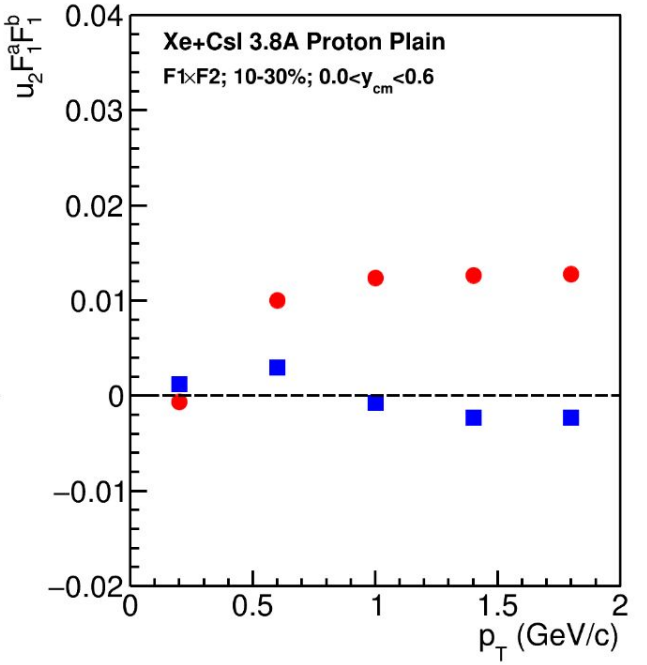


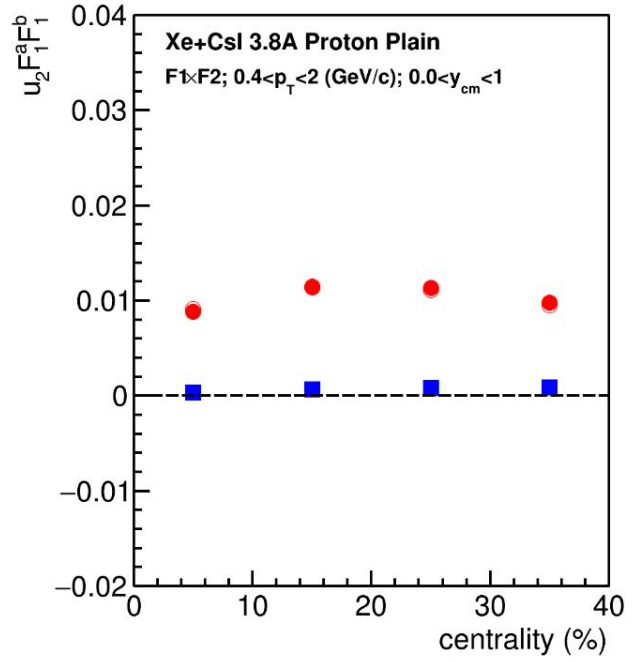


Xe+CsI at 3.8A GeV

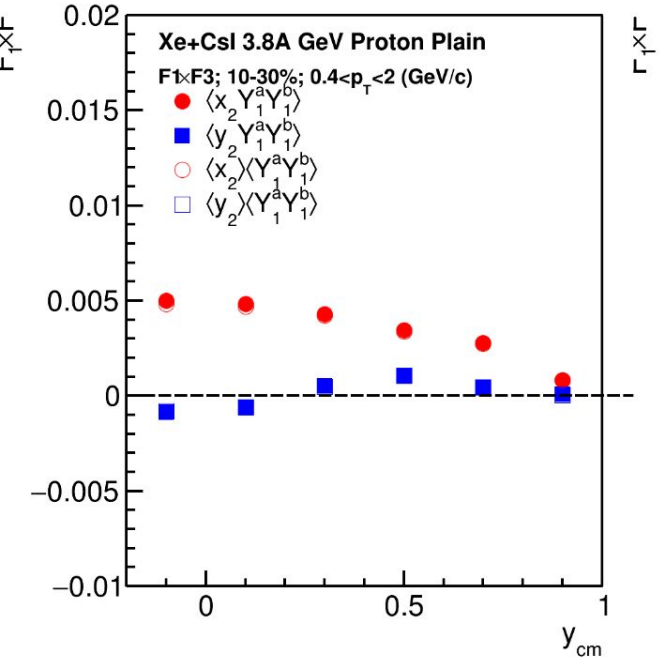
Protons x Rec. F1 x Rec. F2

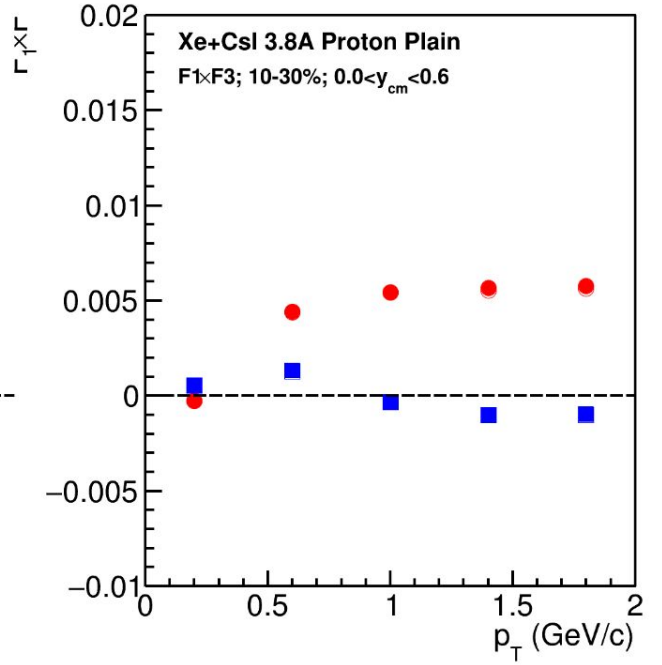


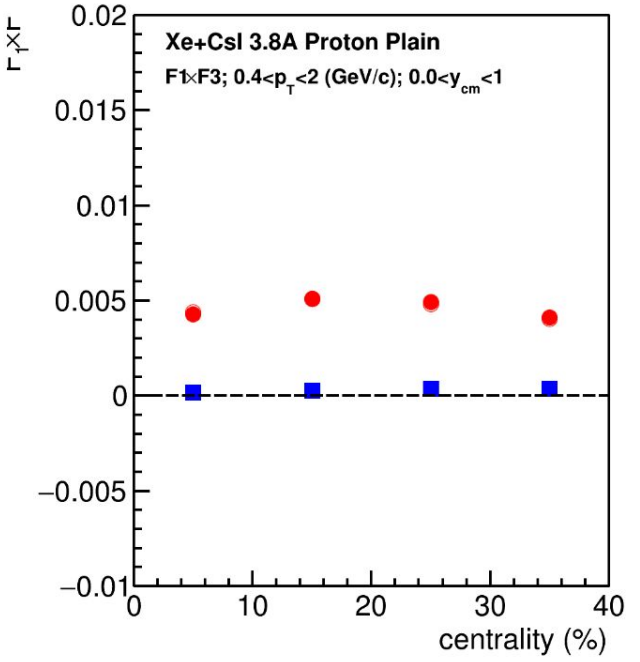




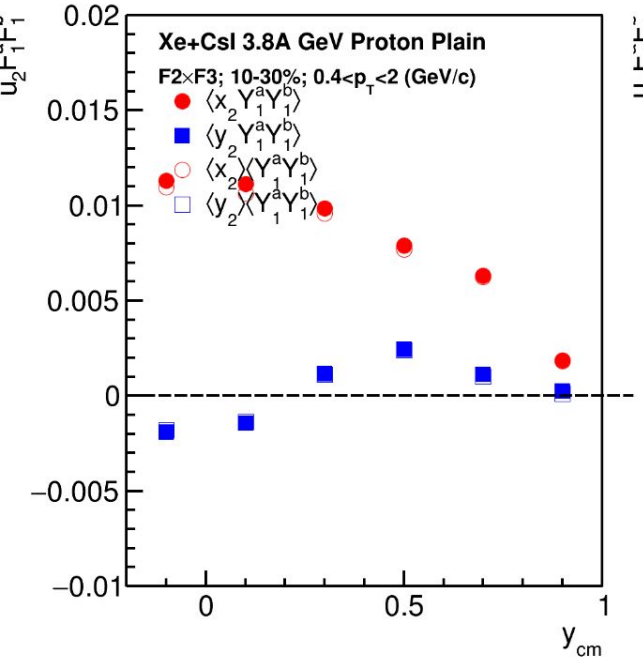
Protons x Rec. F1 x Rec. F3

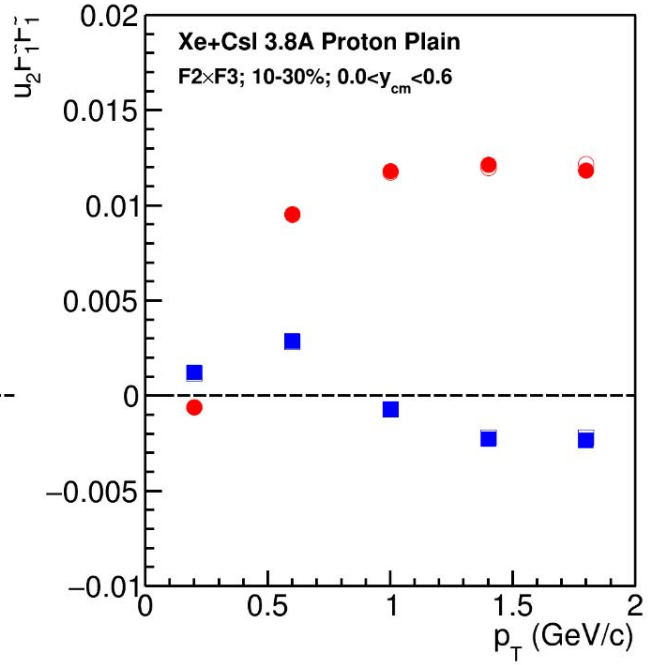


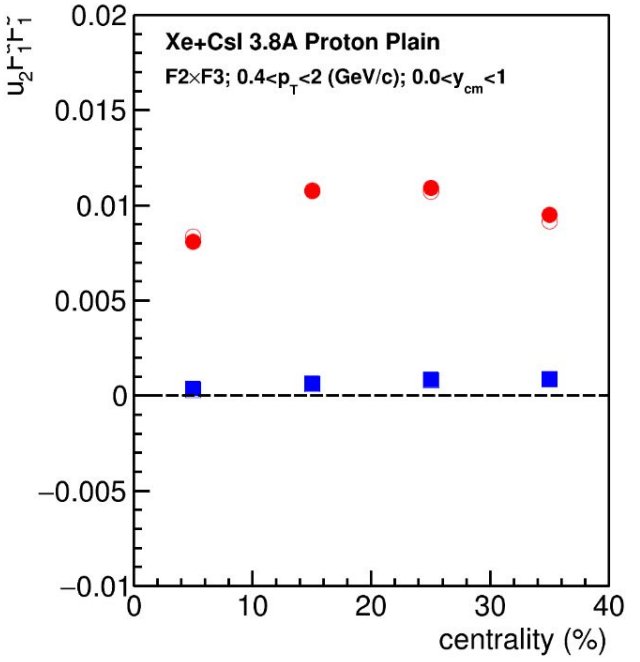




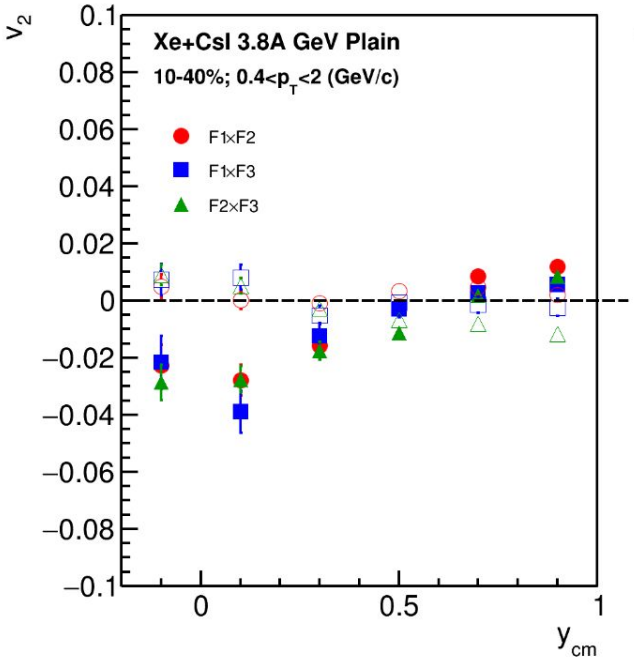
Protons x Rec. F2 x Rec. F3

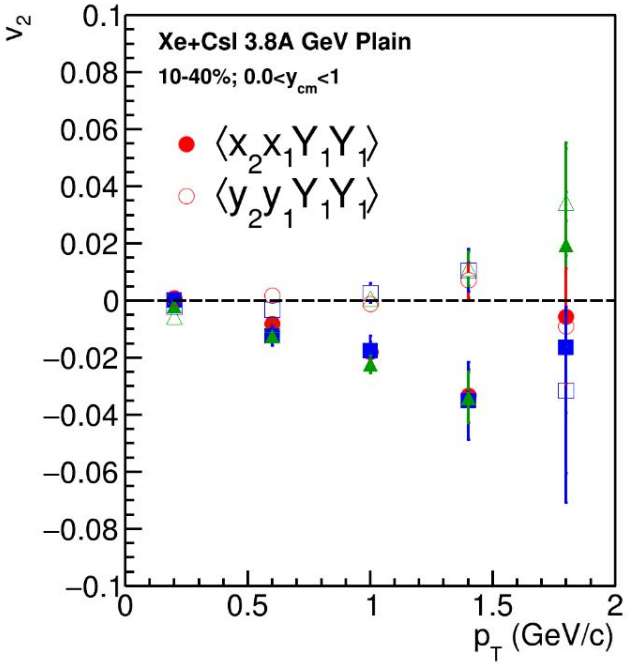


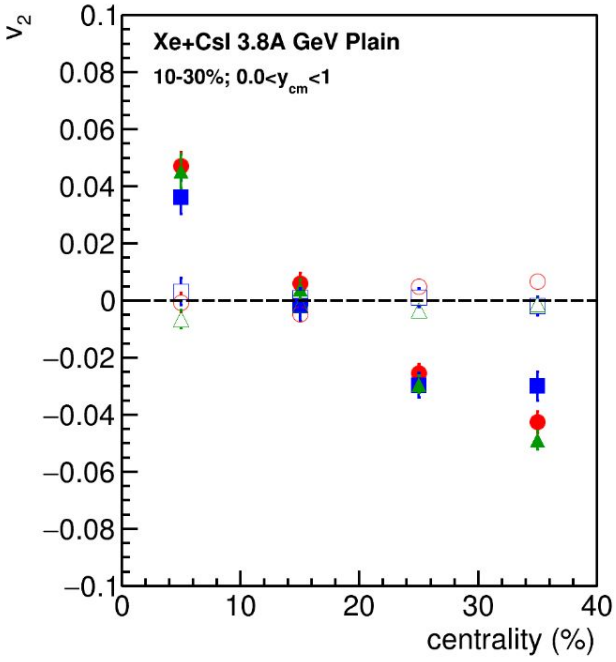




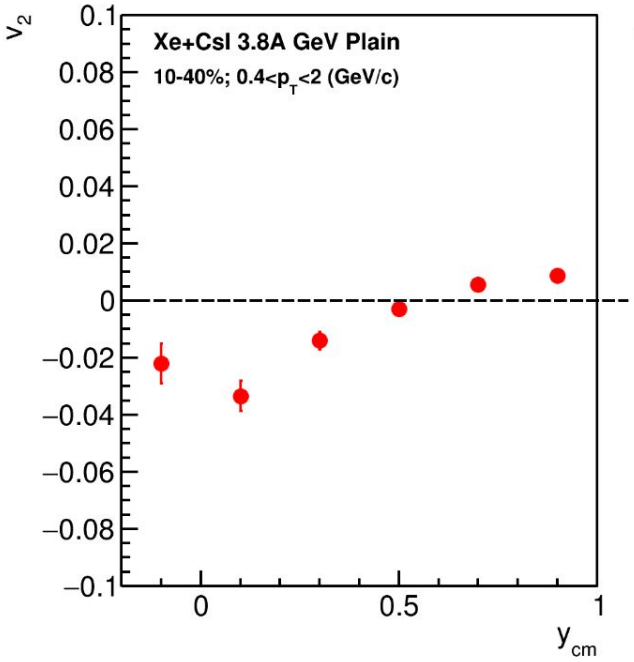
Corrected proton v_2

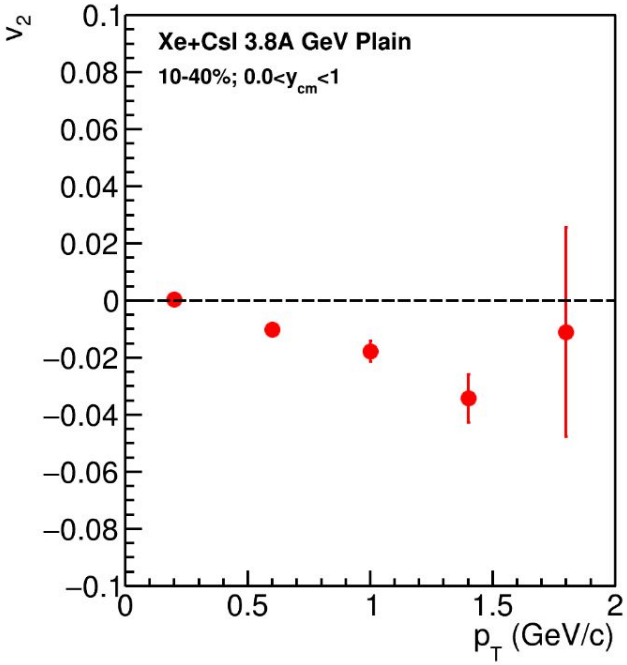


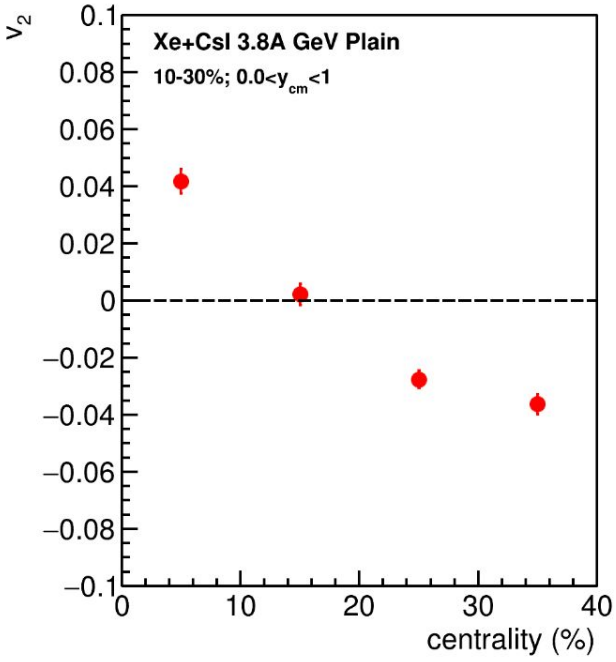




Corrected proton v_2

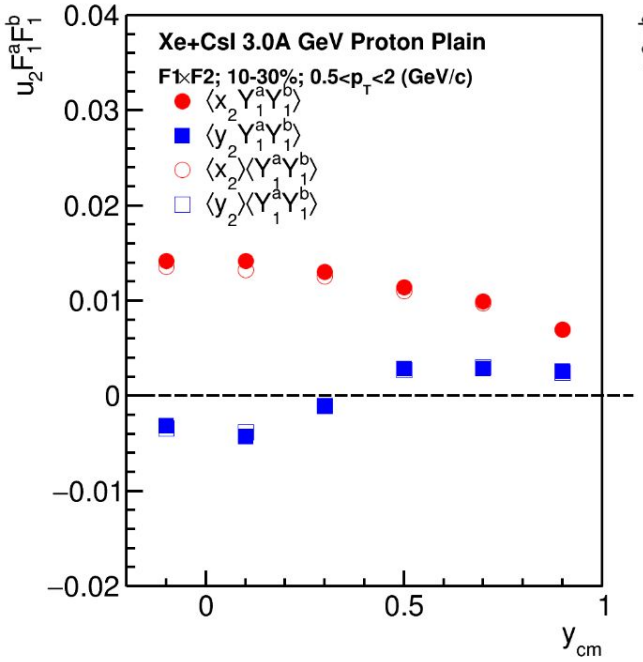


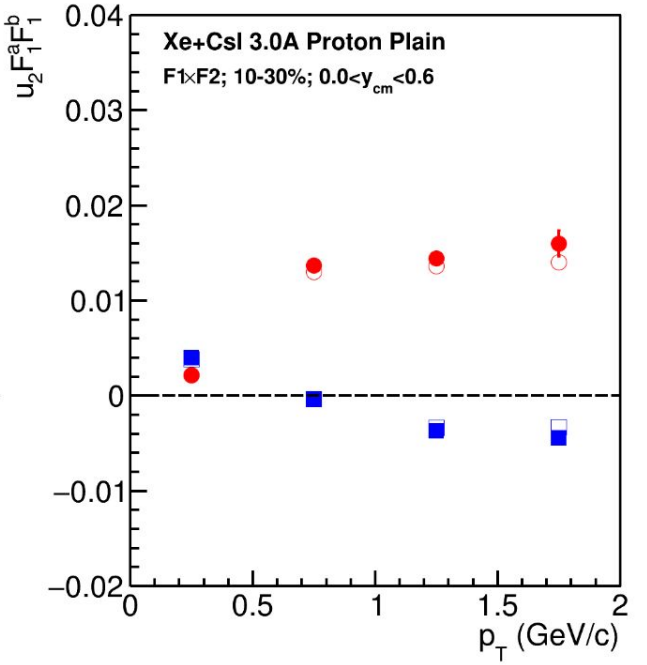


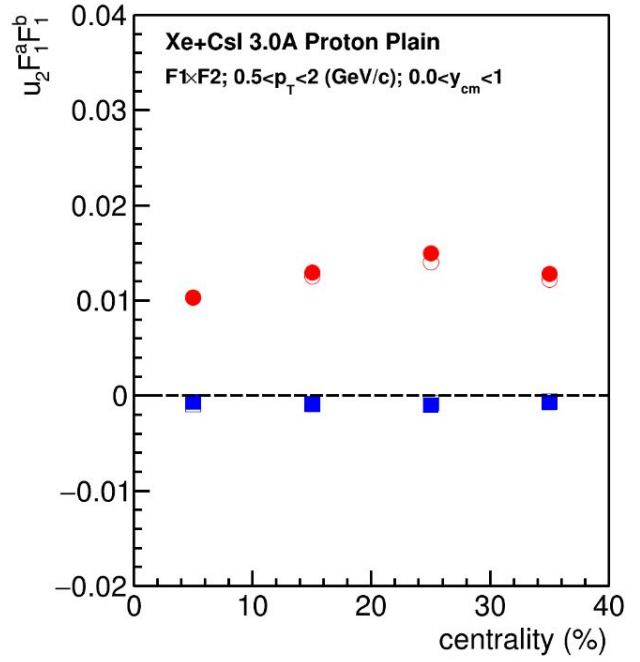


Xe+CsI at 3.0A GeV

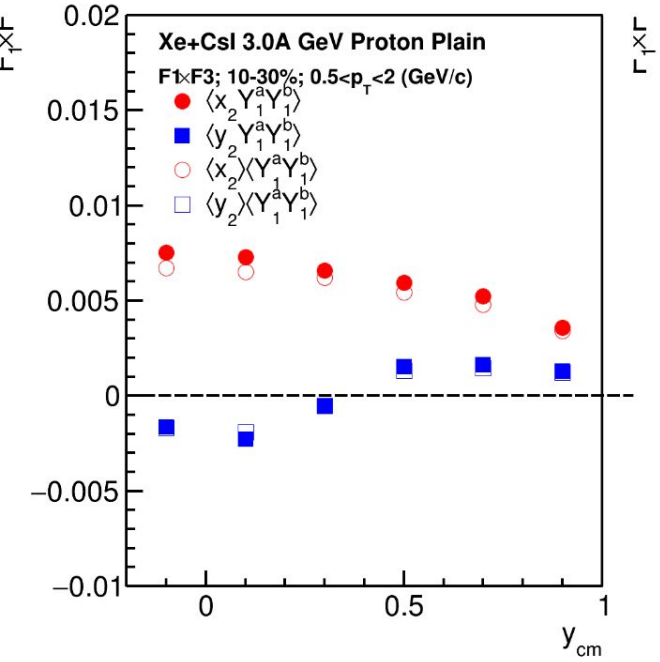
Protons x Rec. F1 x Rec. F2

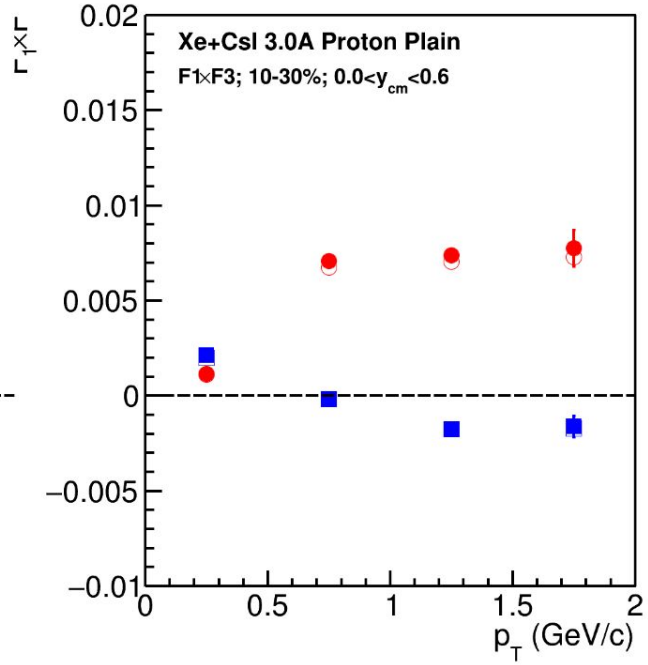


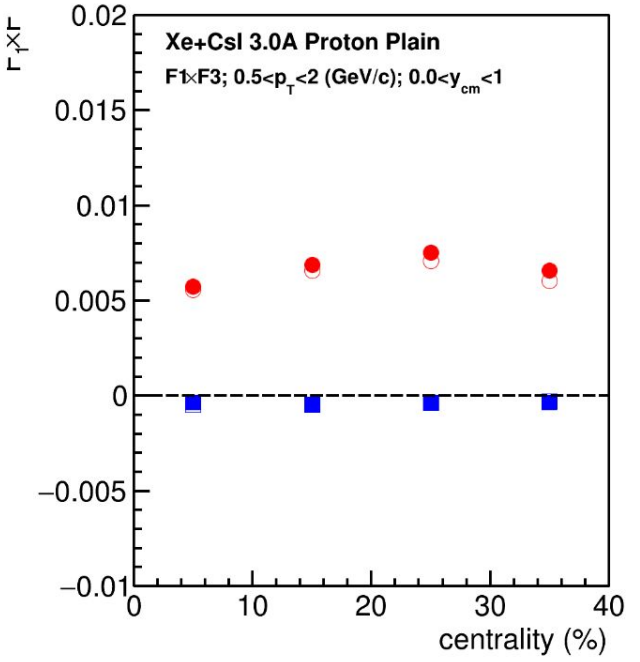




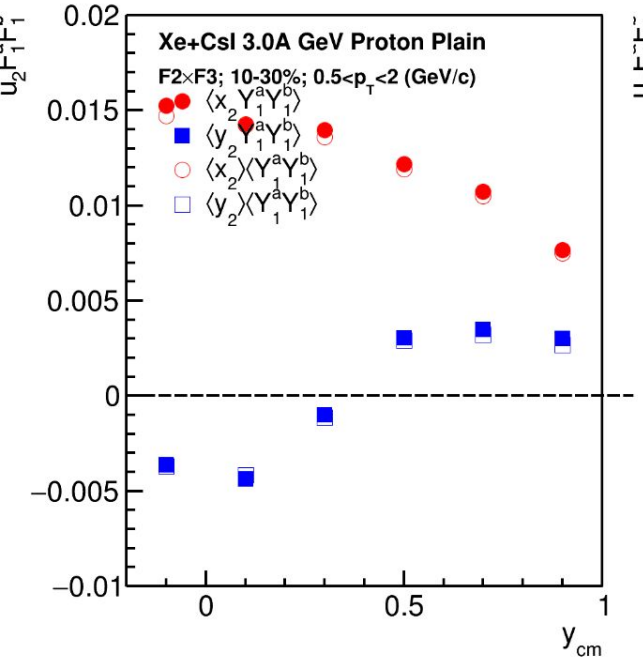
Protons x Rec. F1 x Rec. F3

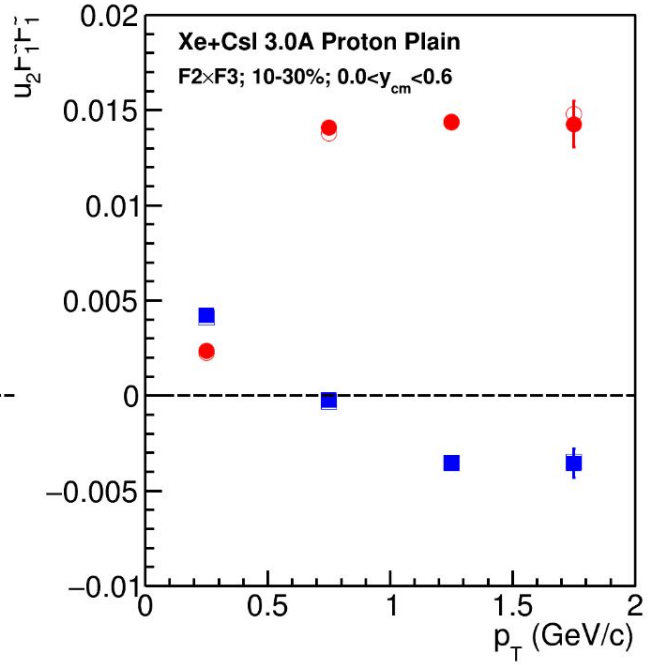


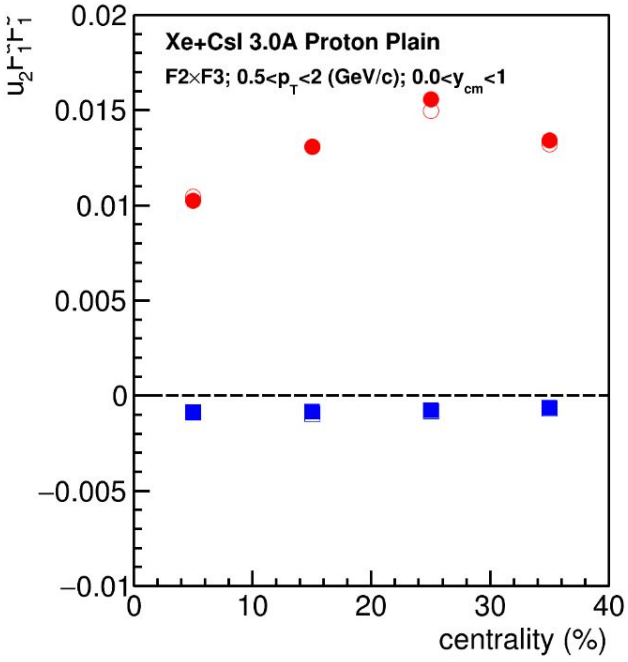




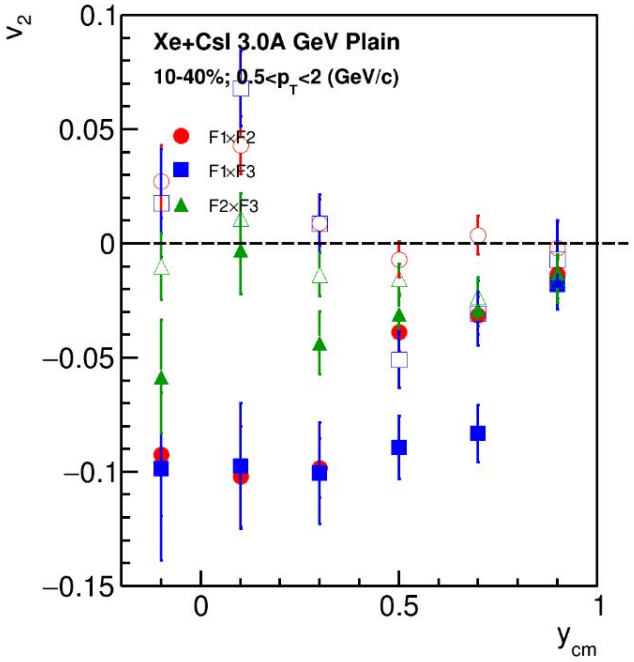
Protons x Rec. F2 x Rec. F2

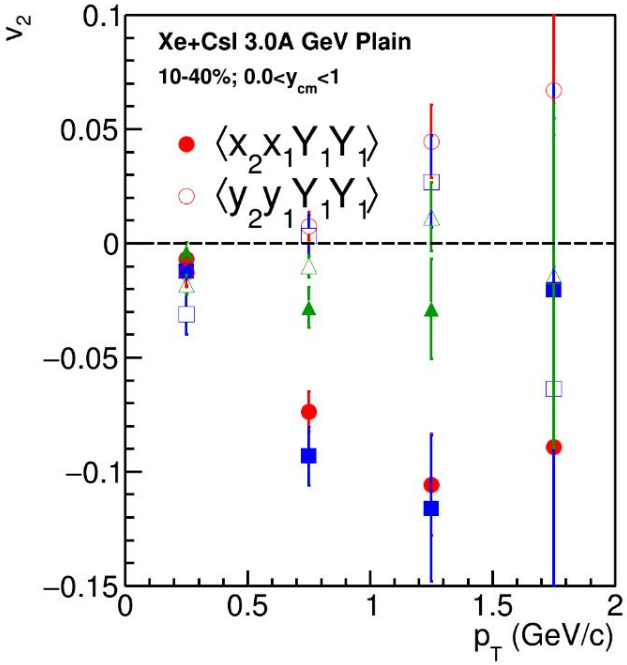


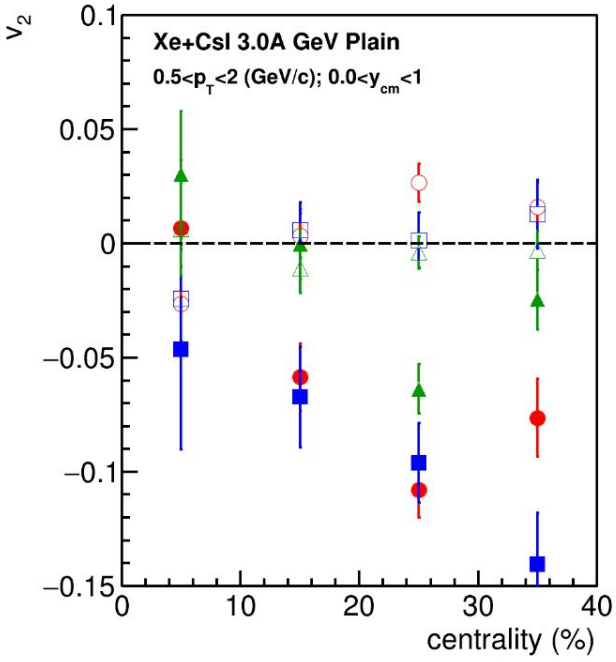




Protons x Rec. F2 x Rec. F2



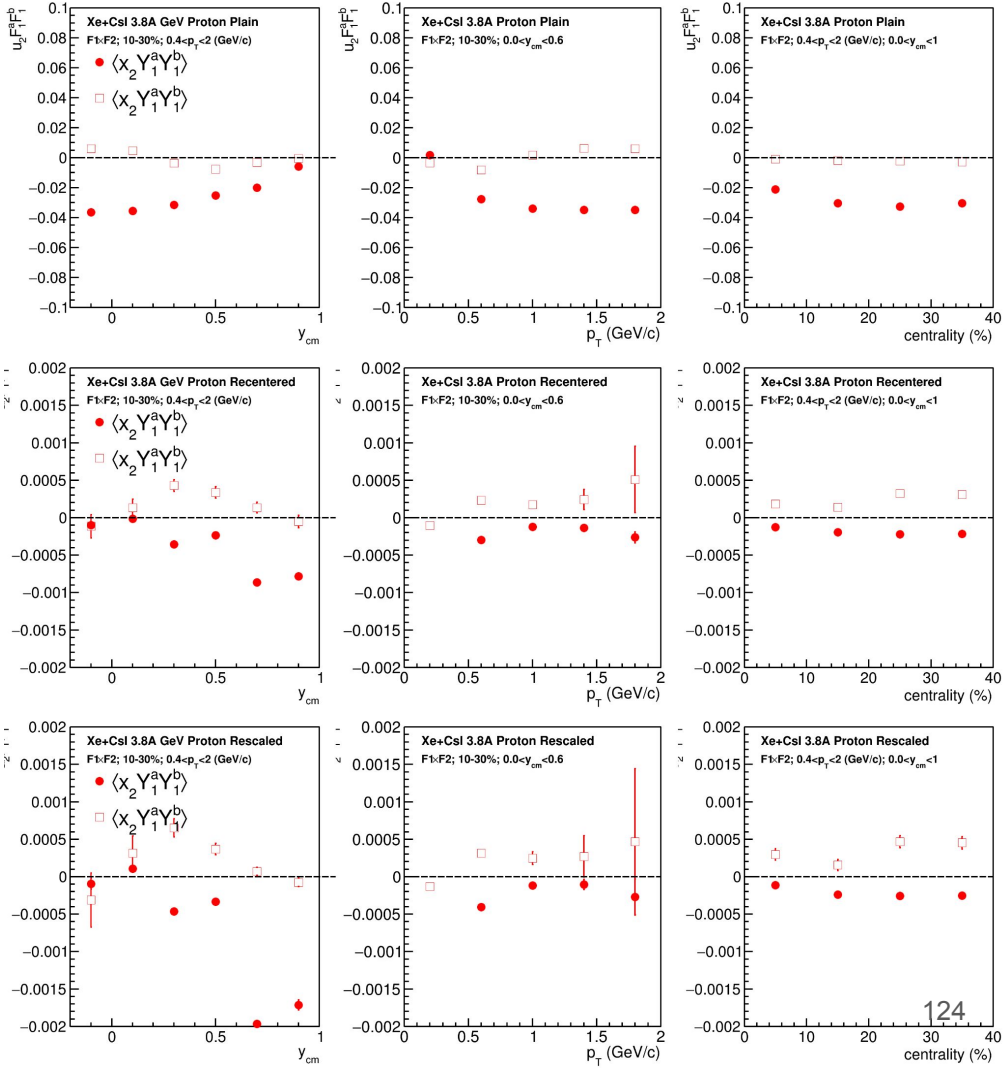




Correlation with F1 and F2

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

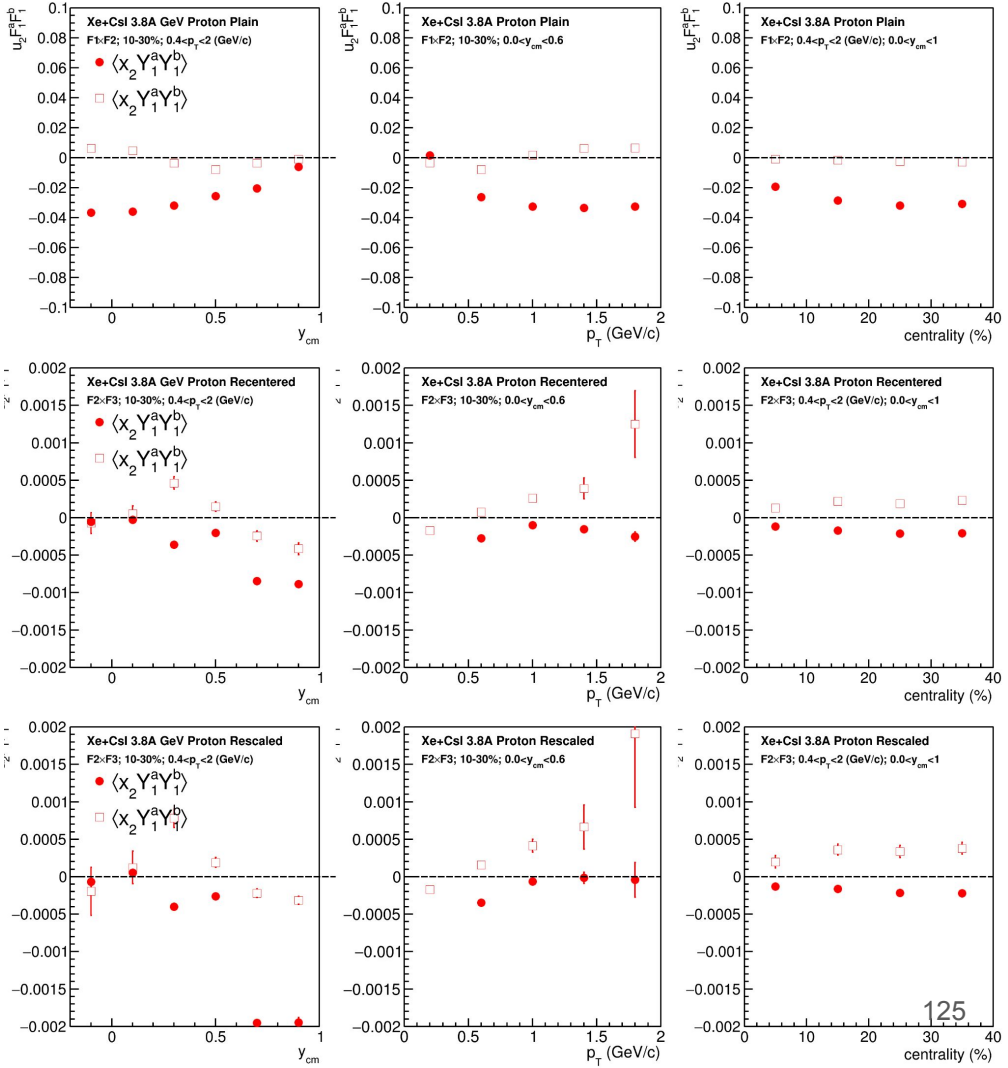
- After applying recentering on u-vector, correlation drops 10 times



Correlation with F2 and F3

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

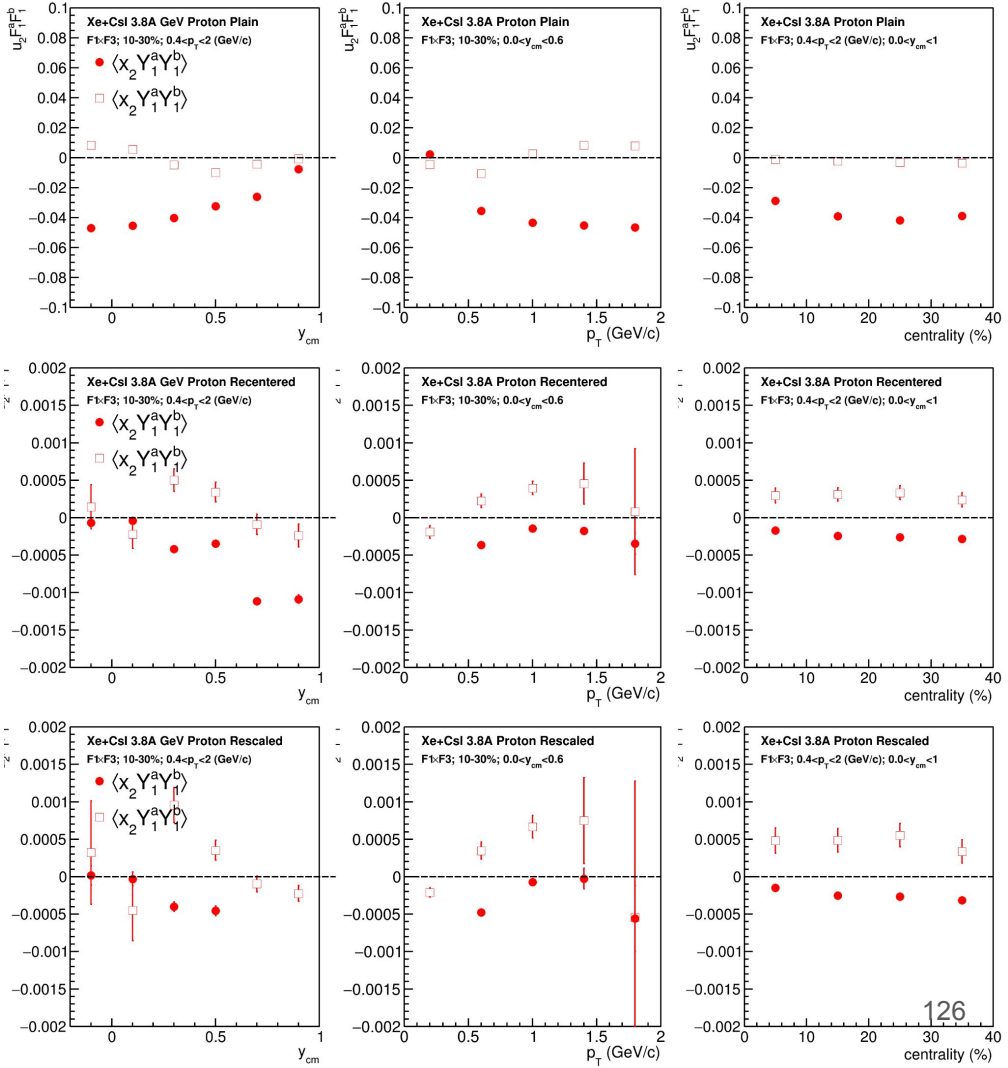
- After applying recentering on u-vector, correlation drops 10 times



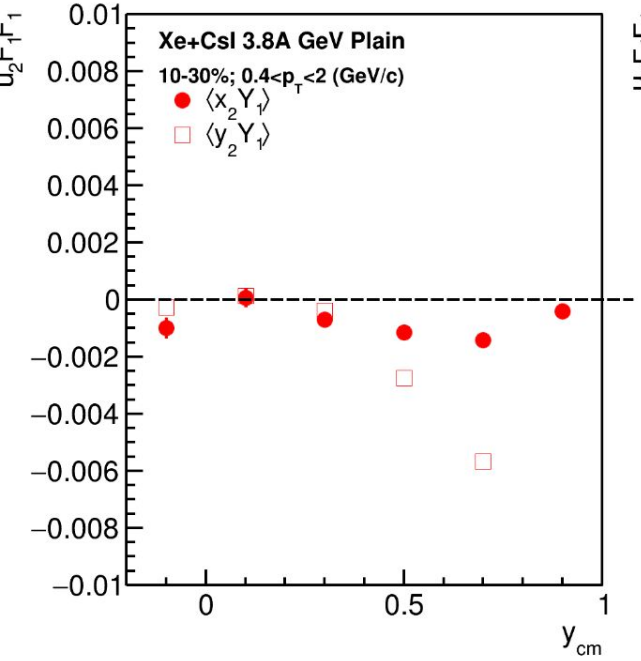
Correlation with F1 and F3

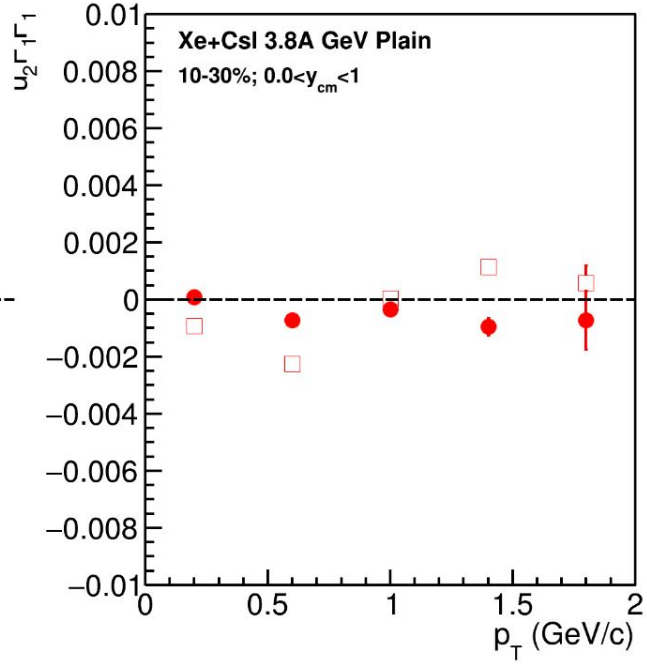
Checking the corrections on u-vector, FHCal vectors are Rescaled-corrected

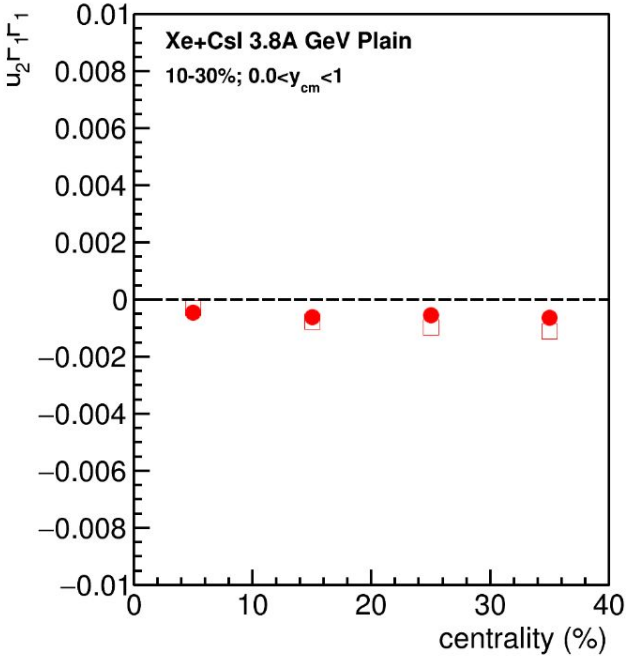
- After applying recentering on u-vector, correlation drops 10 times



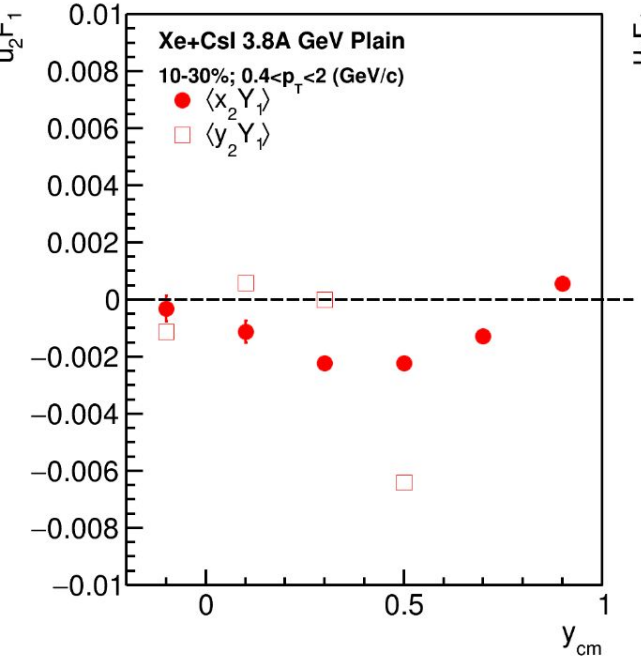
Plain proton with single F1

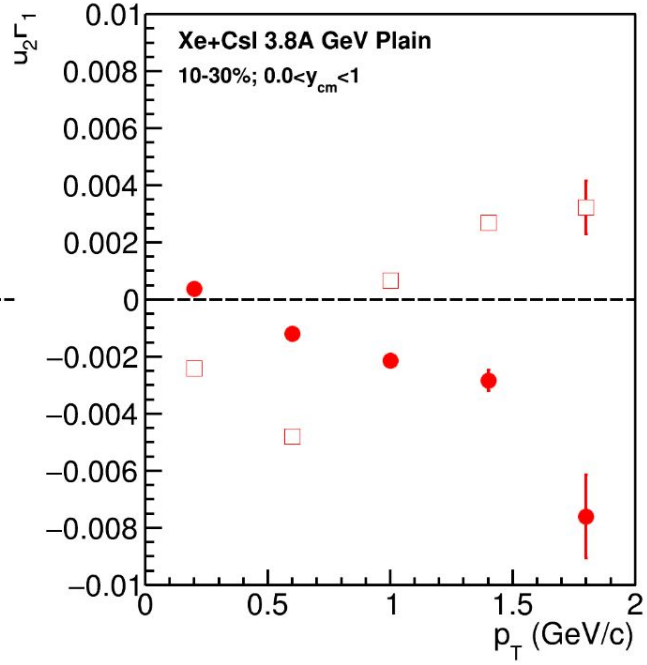


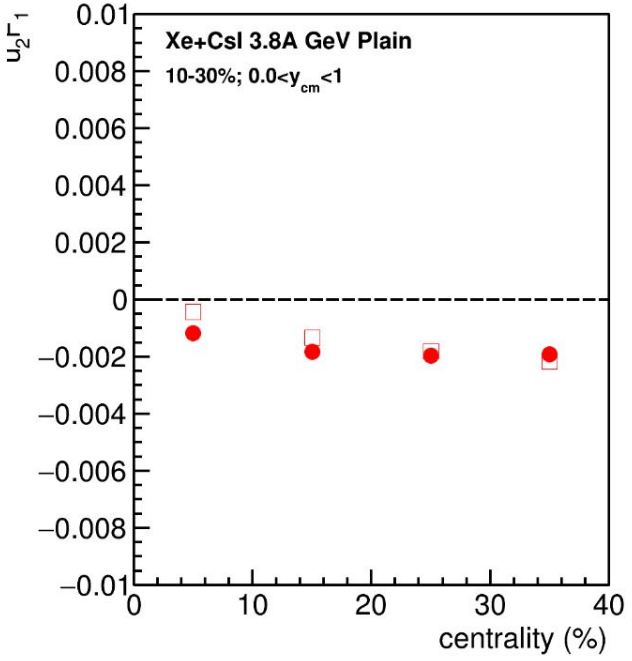




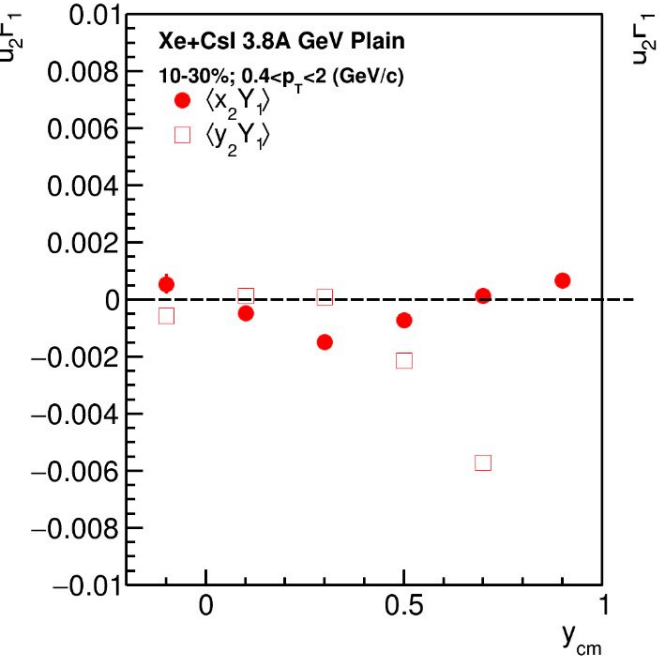
Plain proton with single F2

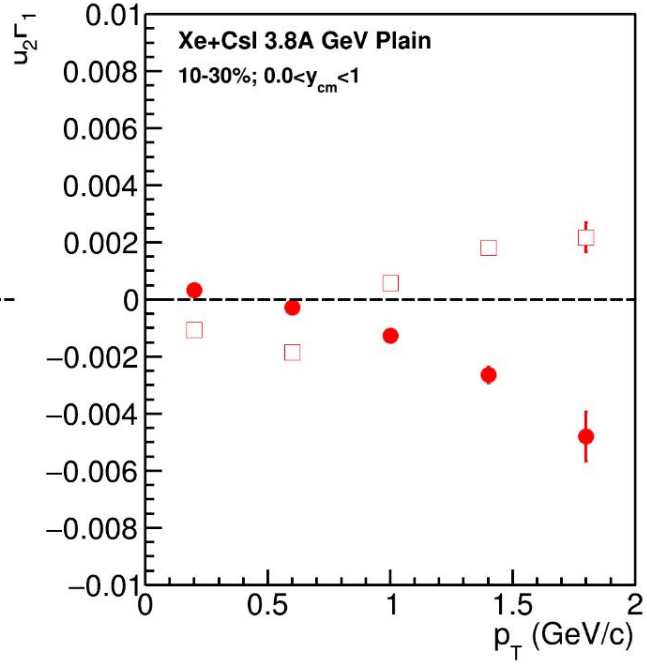


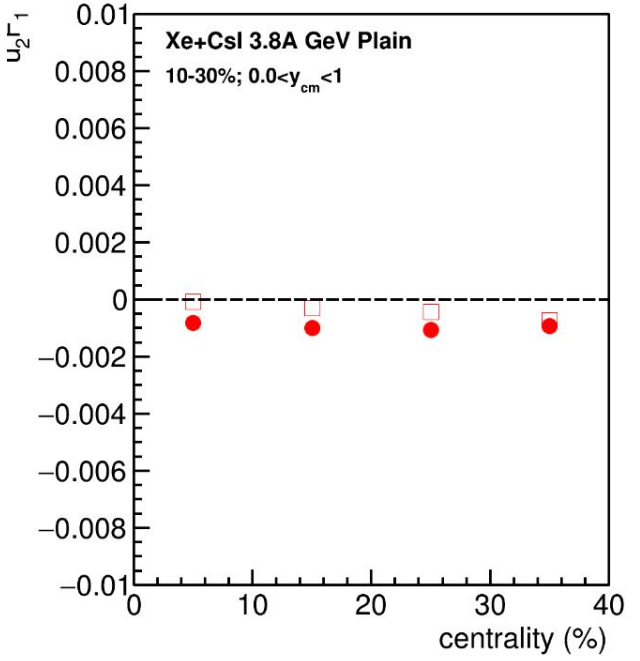




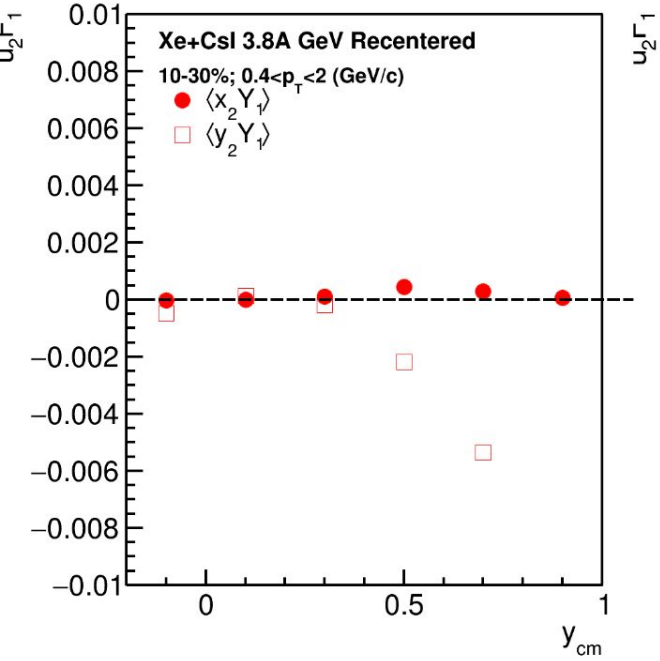
Plain proton with single F3

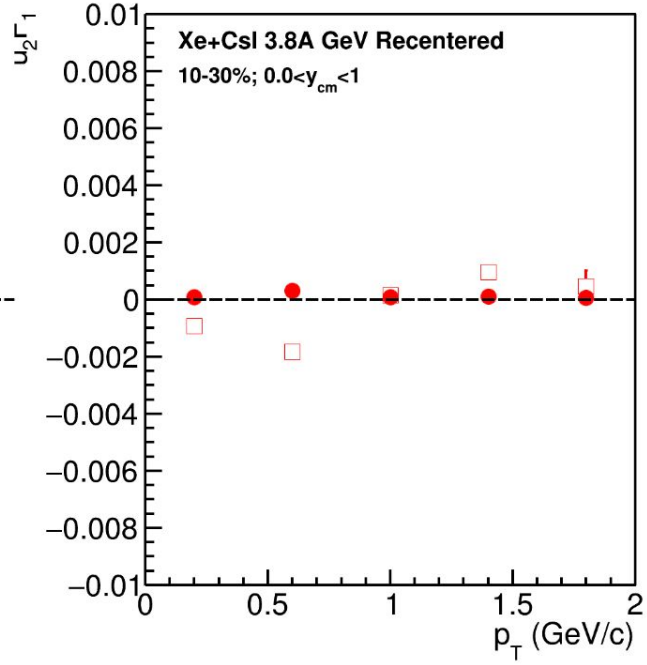


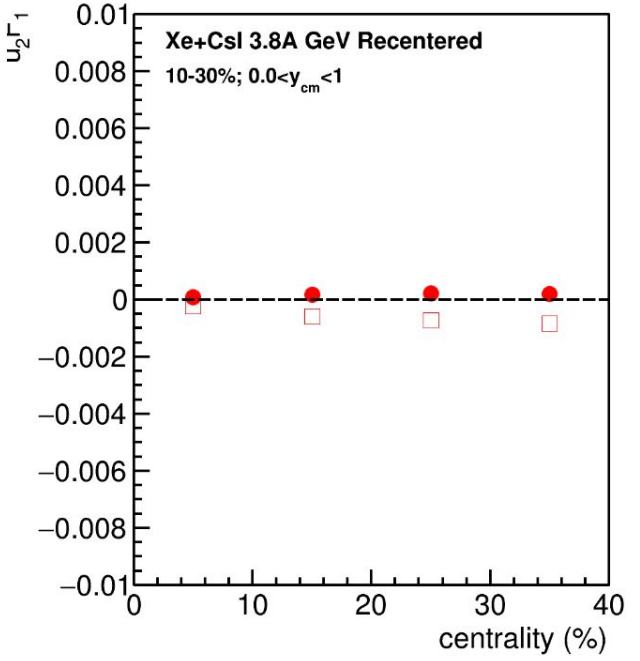




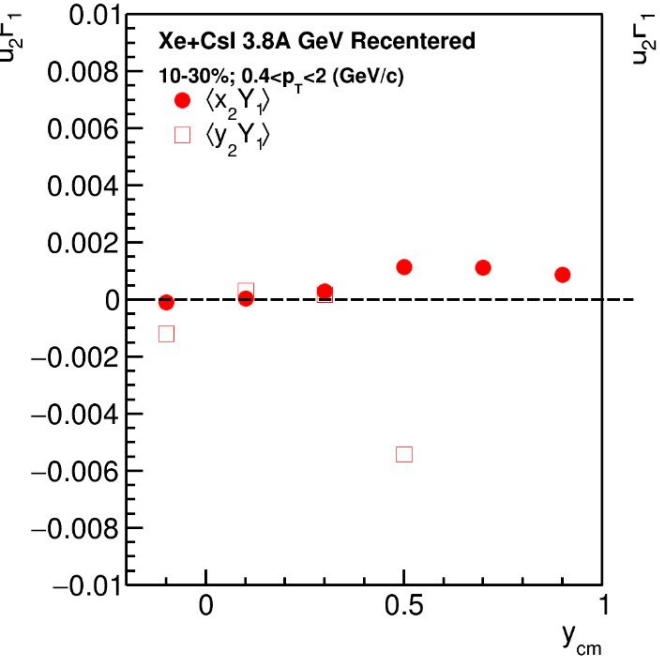
Recentered proton with single F1

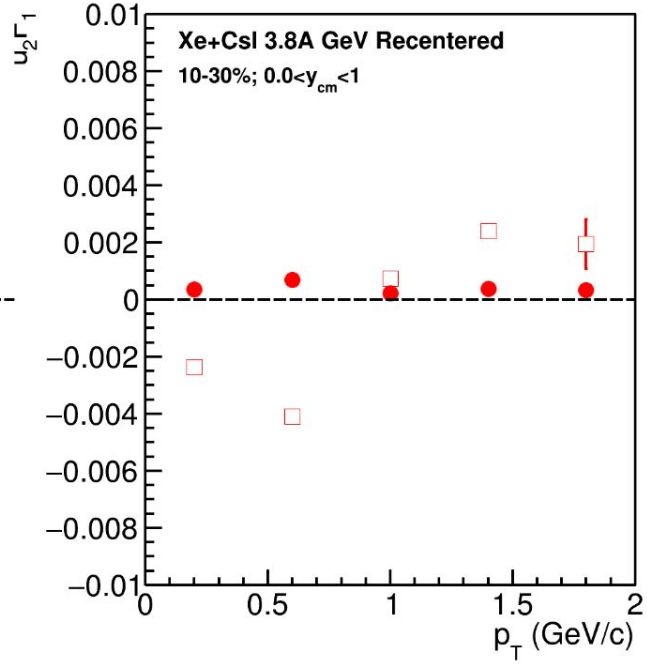


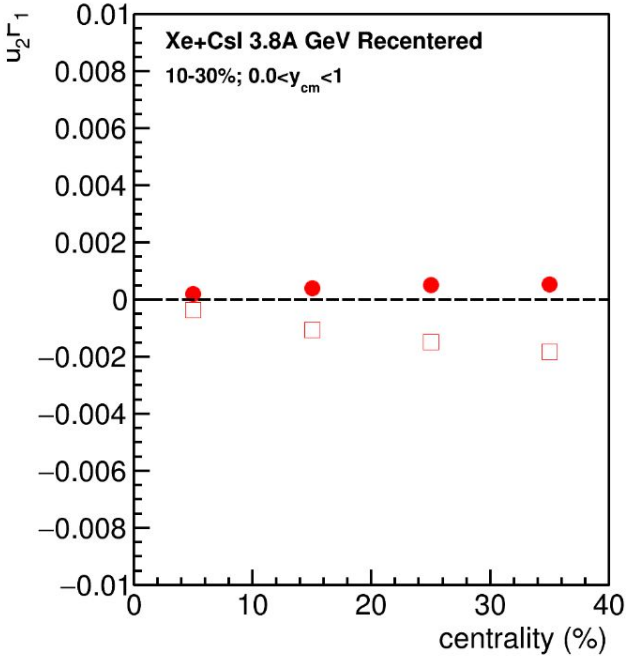




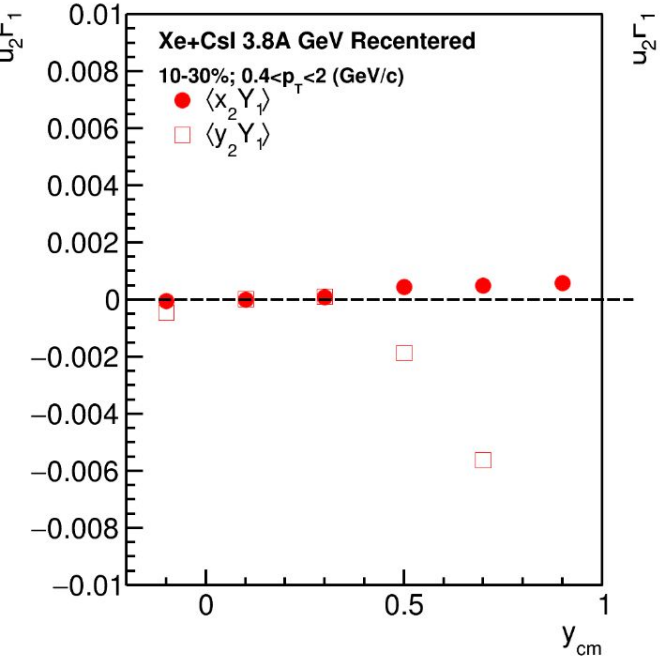
Recentered proton with single F2

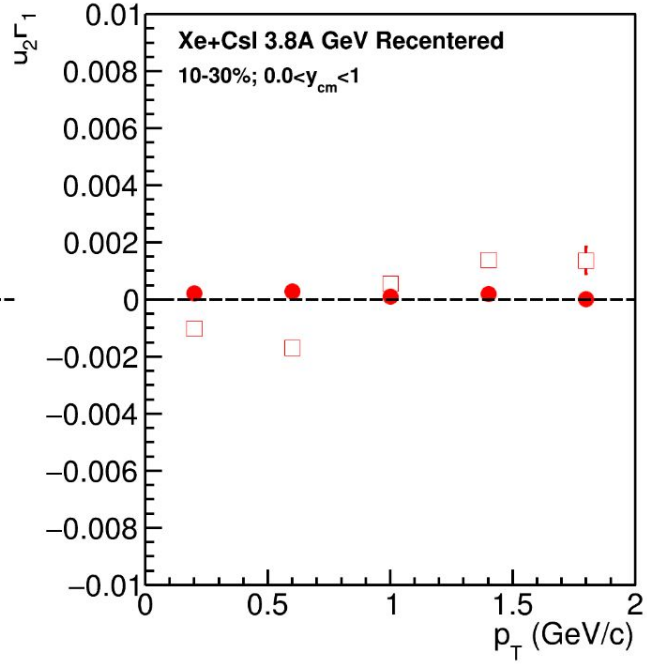


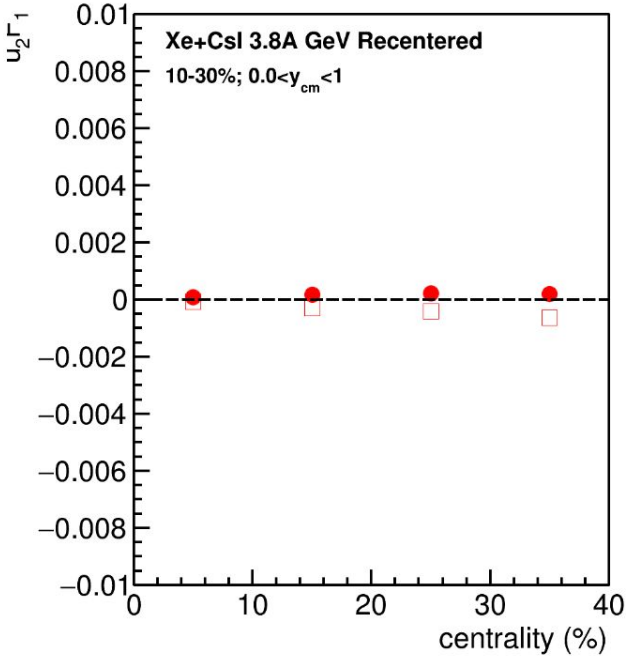




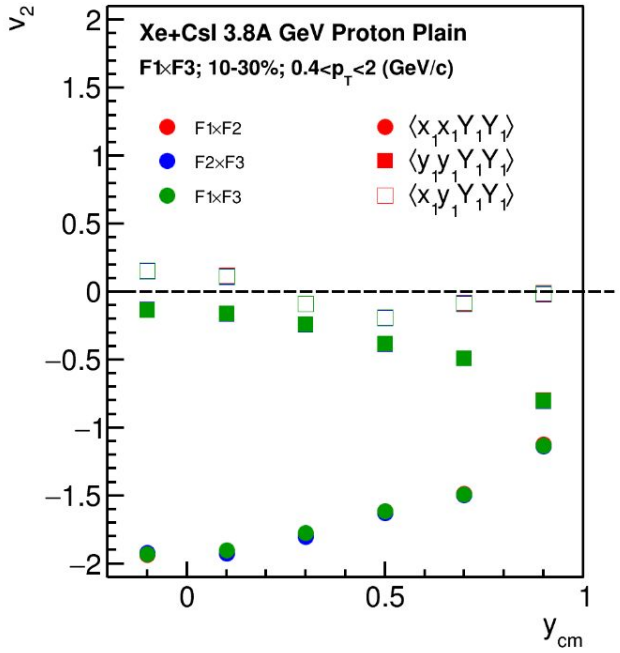
Recentered proton with single F3

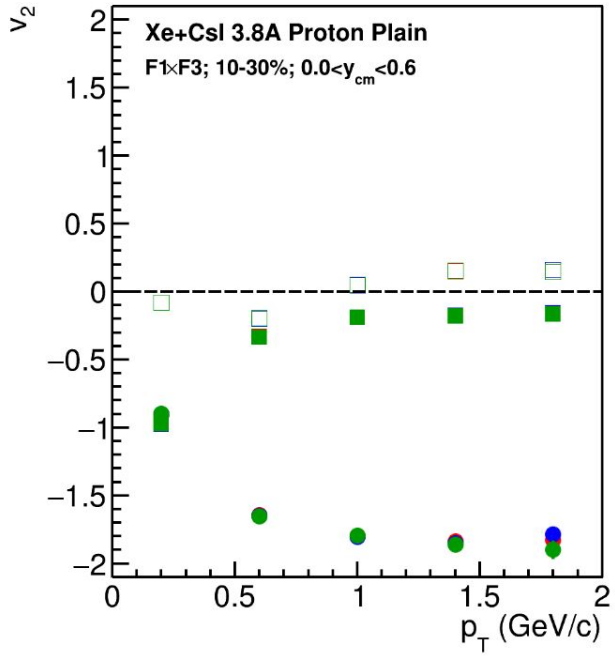


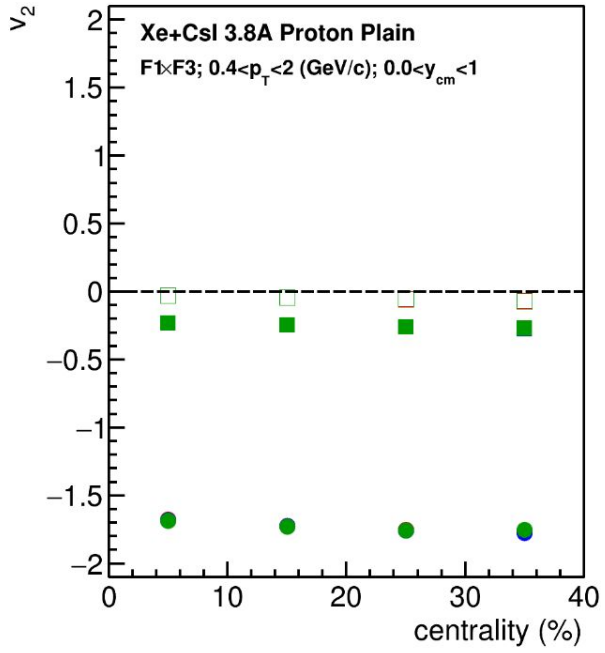




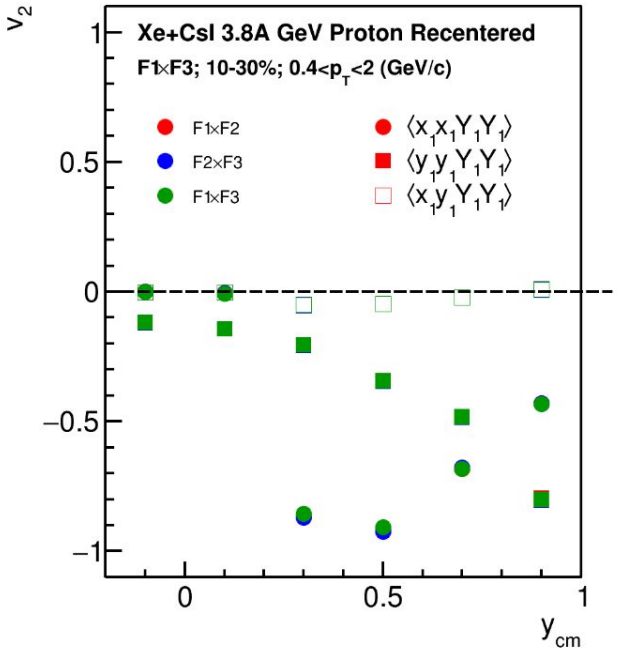
Plain double proton

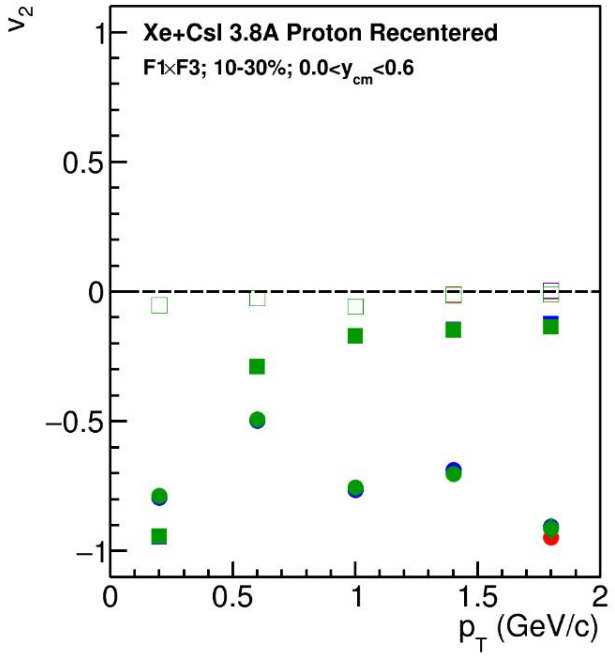


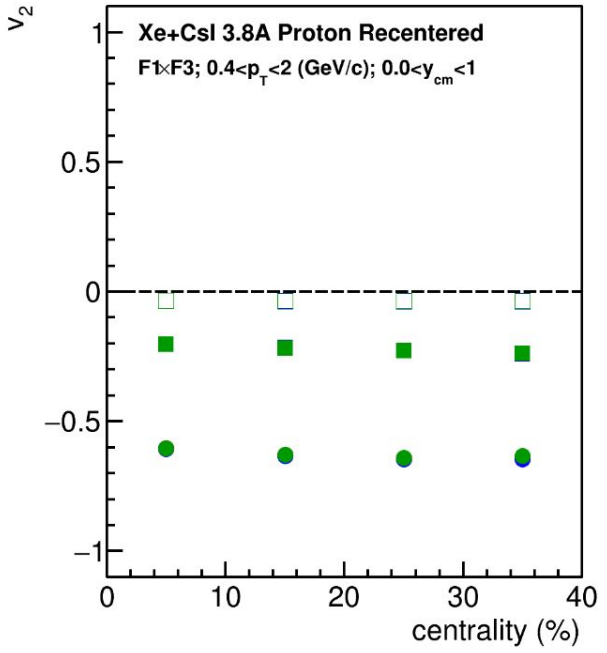




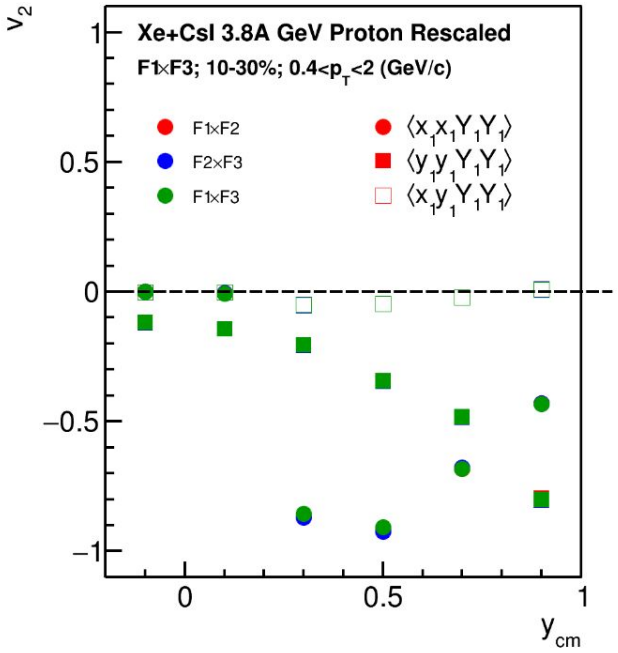
Recentered double

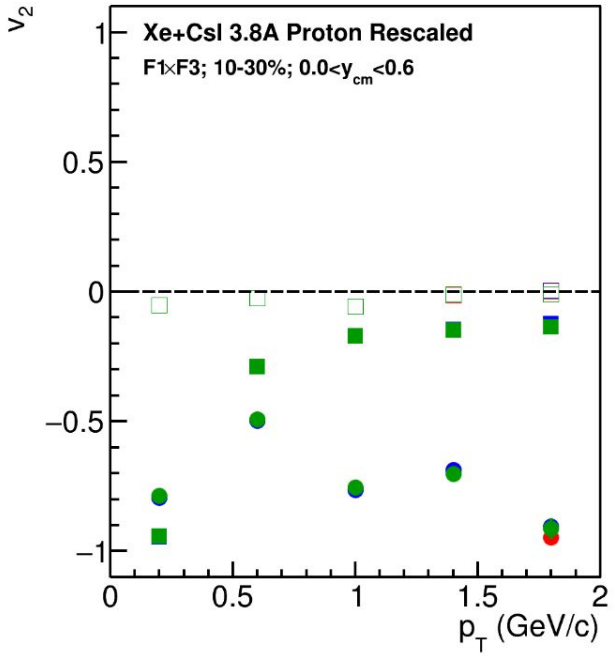


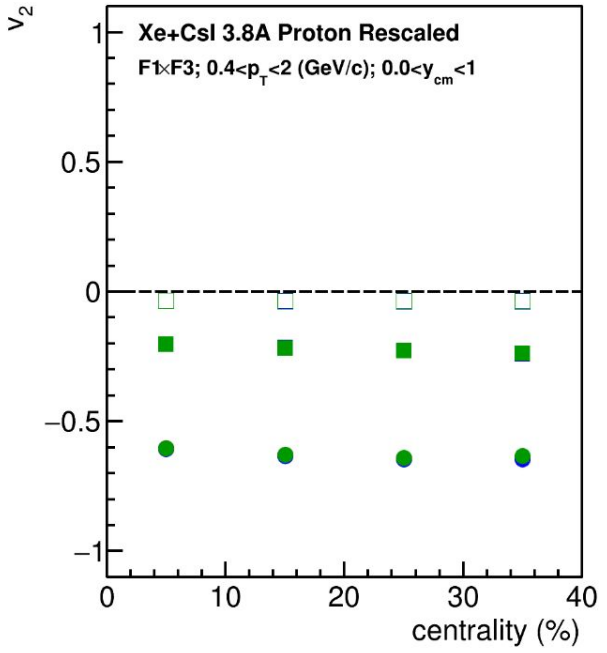




Rescaled double proton

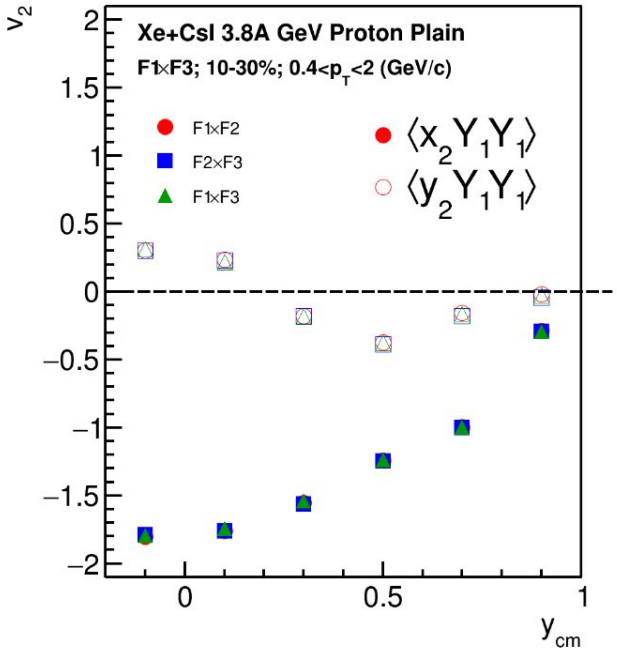


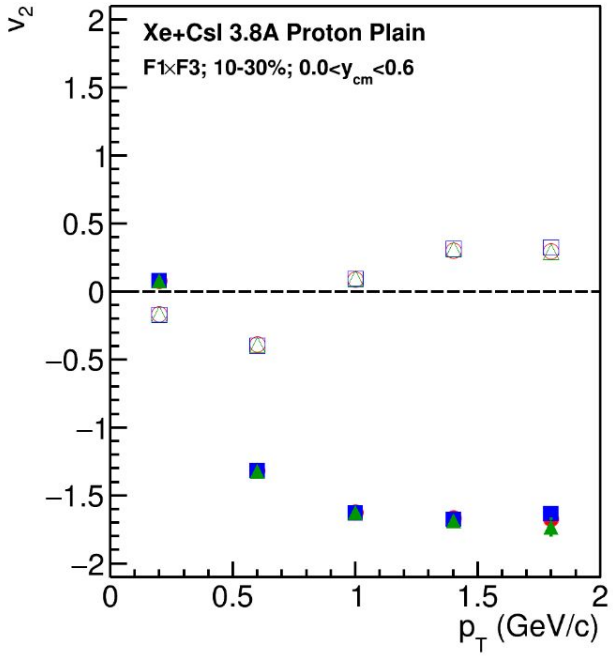


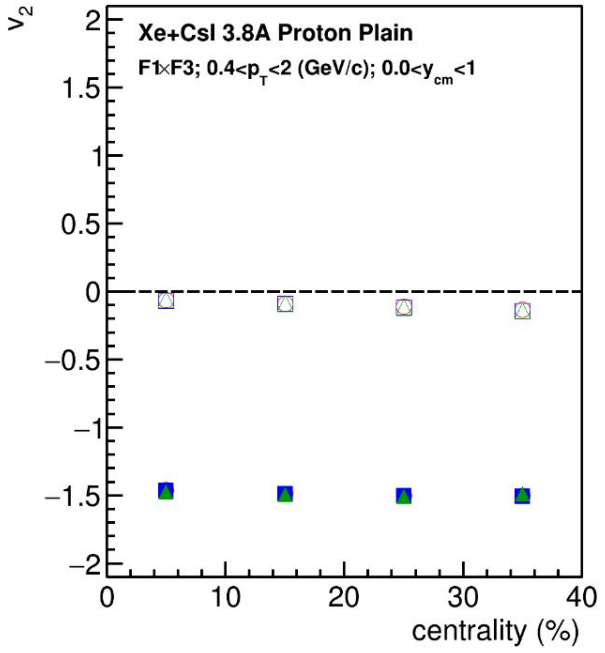


Correlations with recentered F-vectors

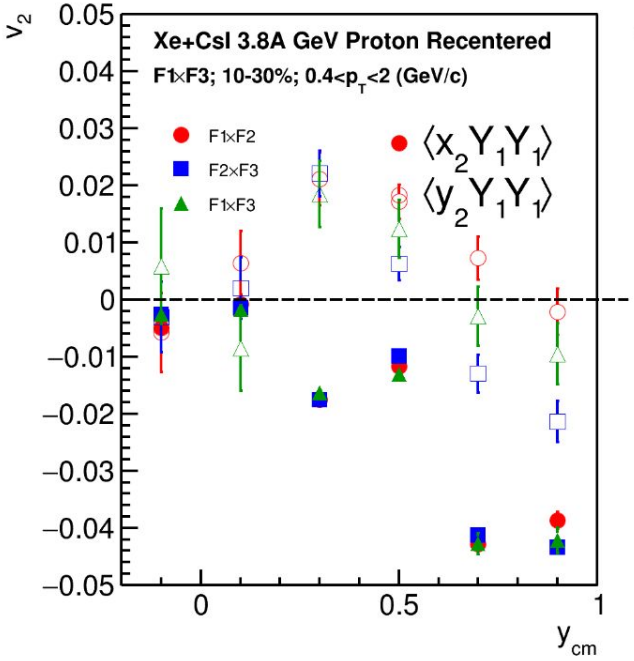
Plain proton v_2

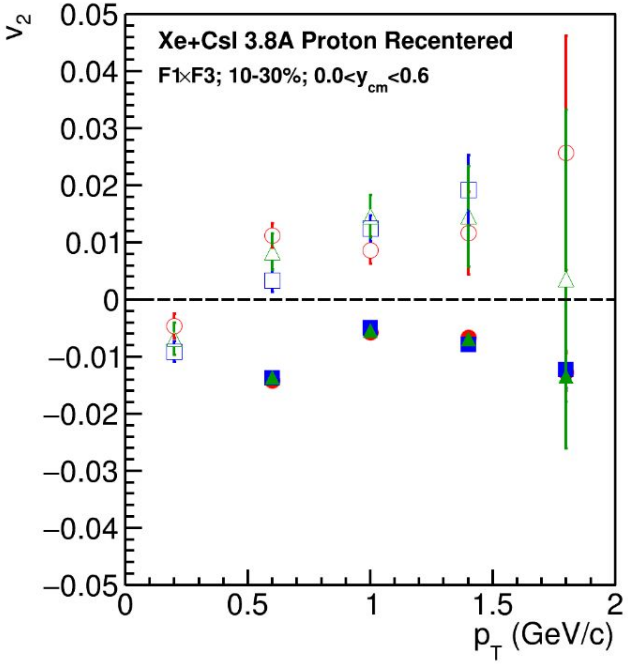


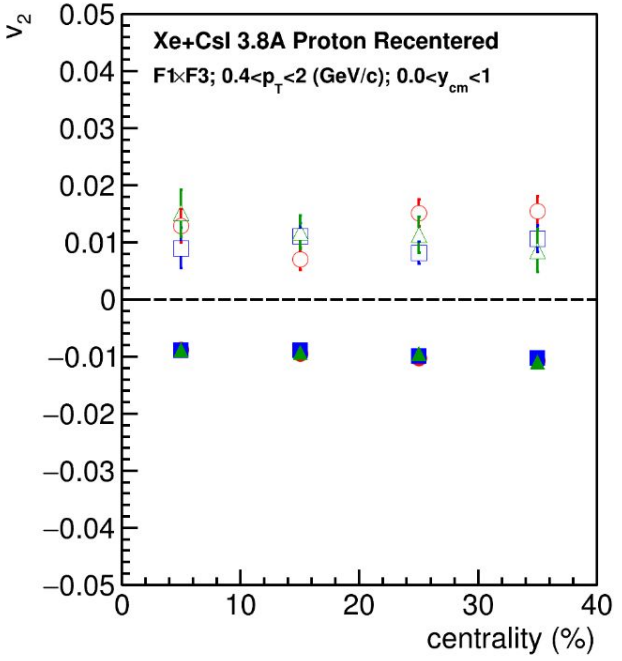




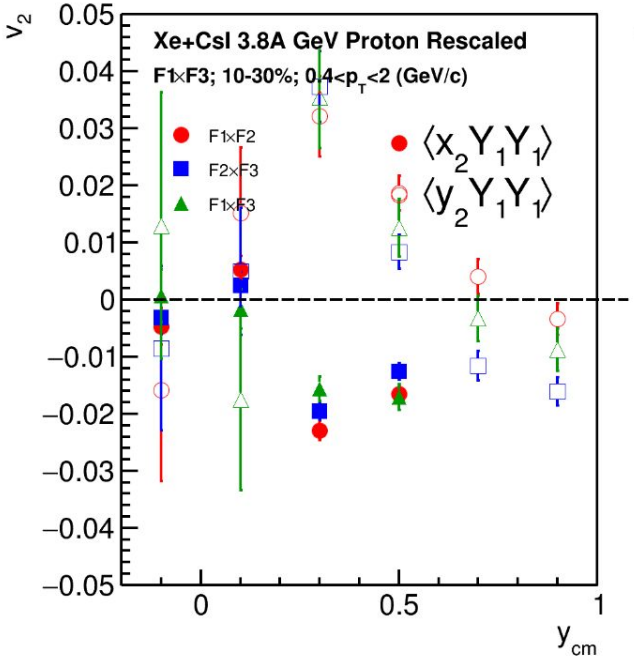
Recentered proton v_2

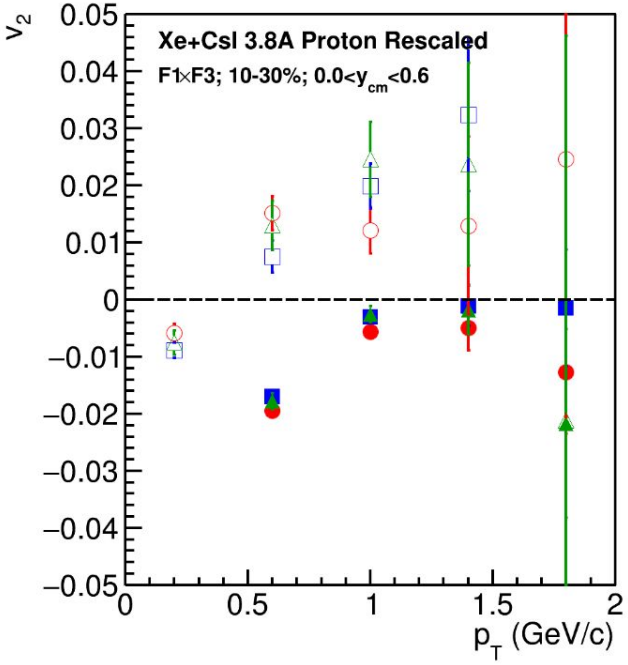


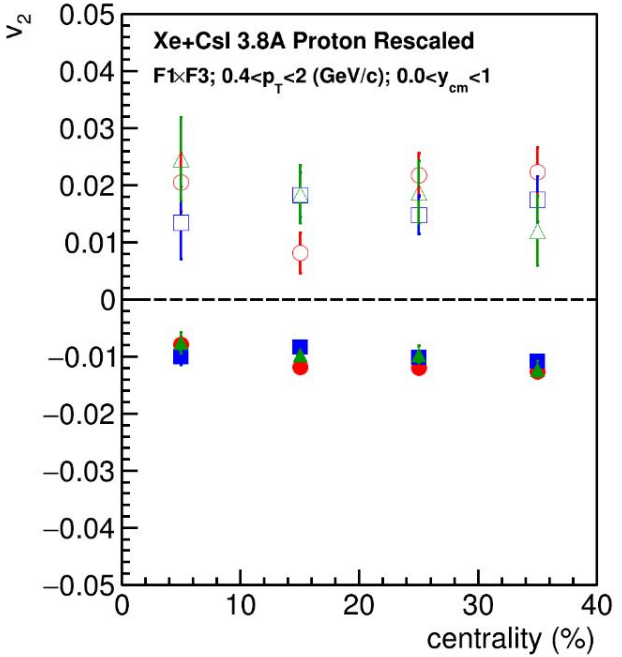




Rescaled proton v_2

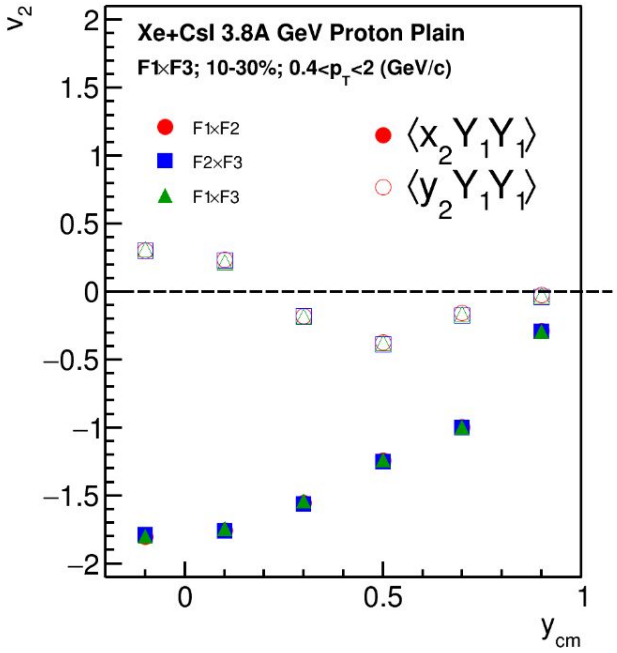


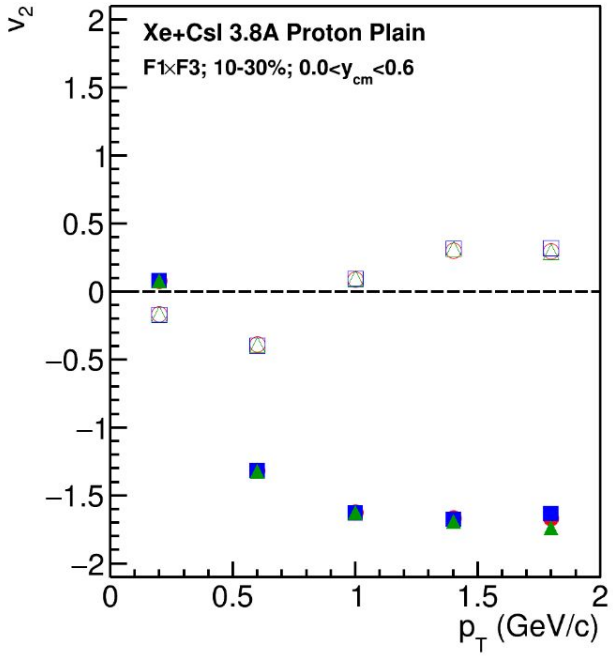


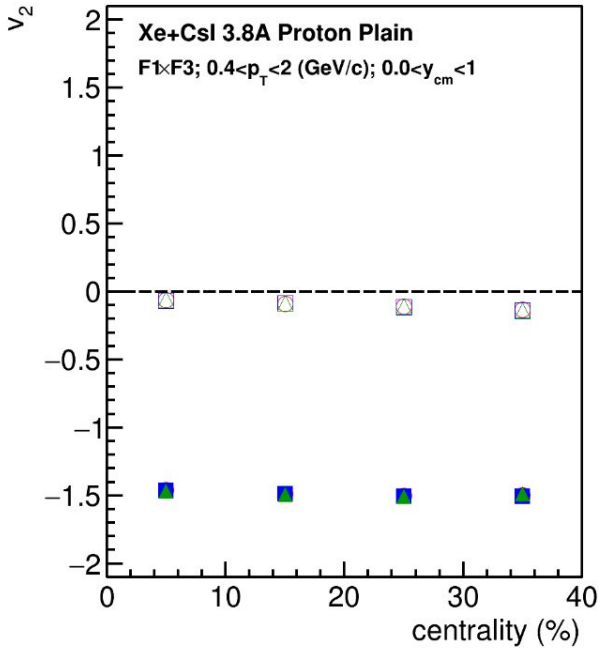


Correlations with rescaled F-vectors

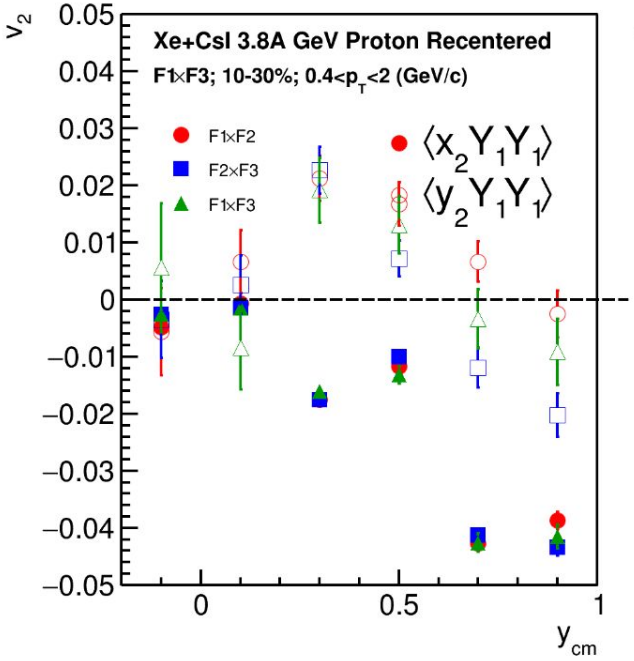
Plain proton v_2

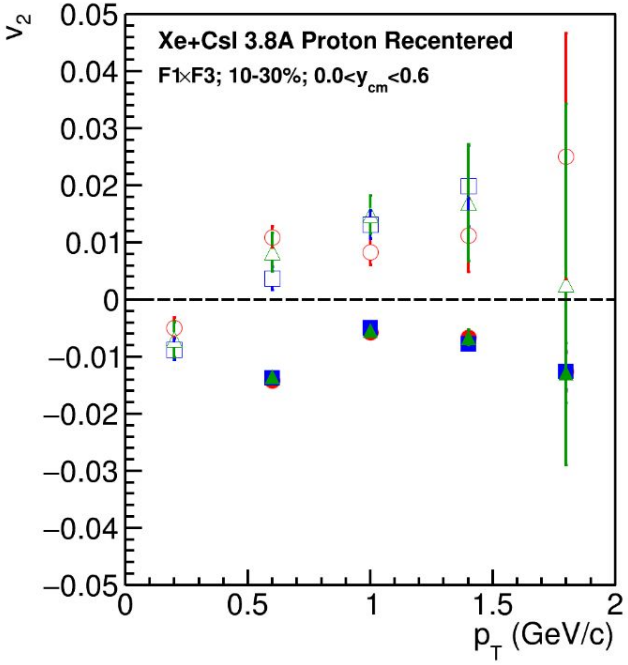


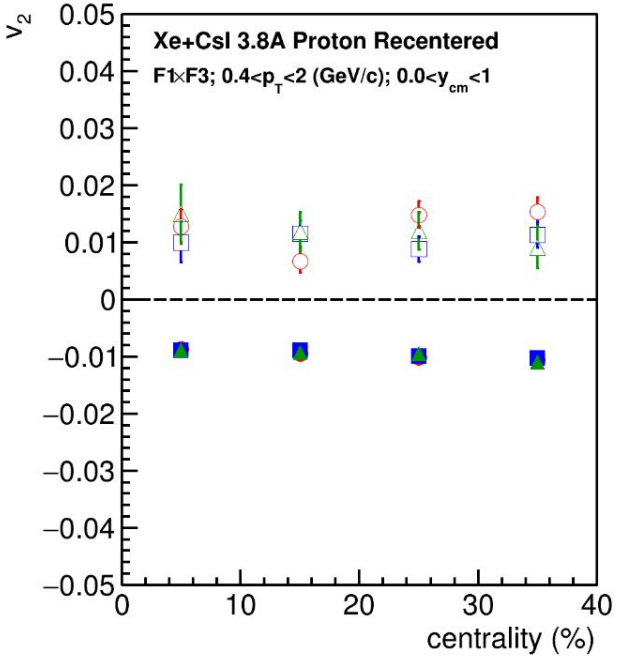




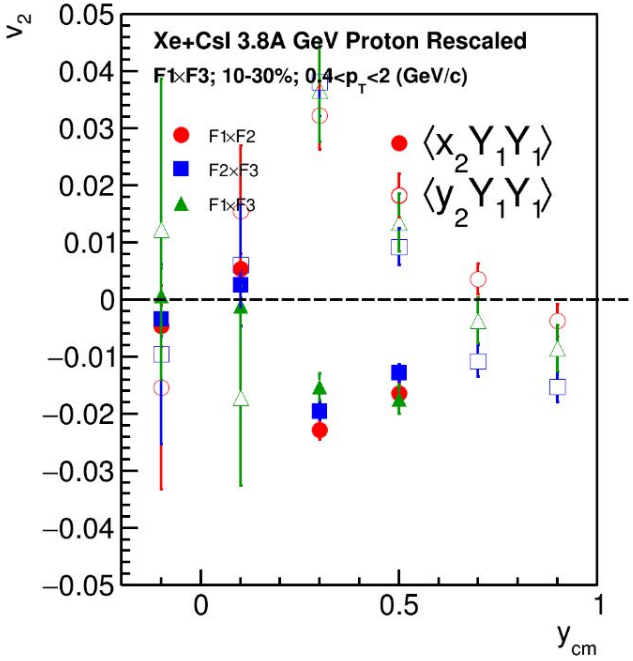
Recentered proton v_2

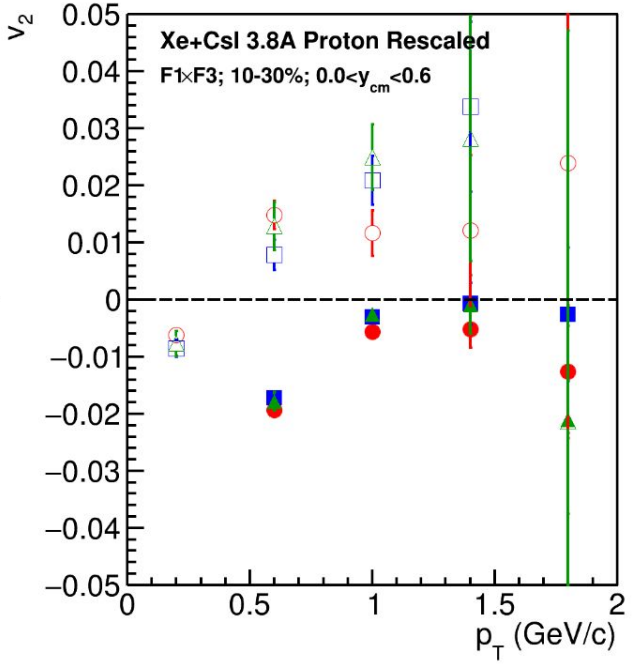


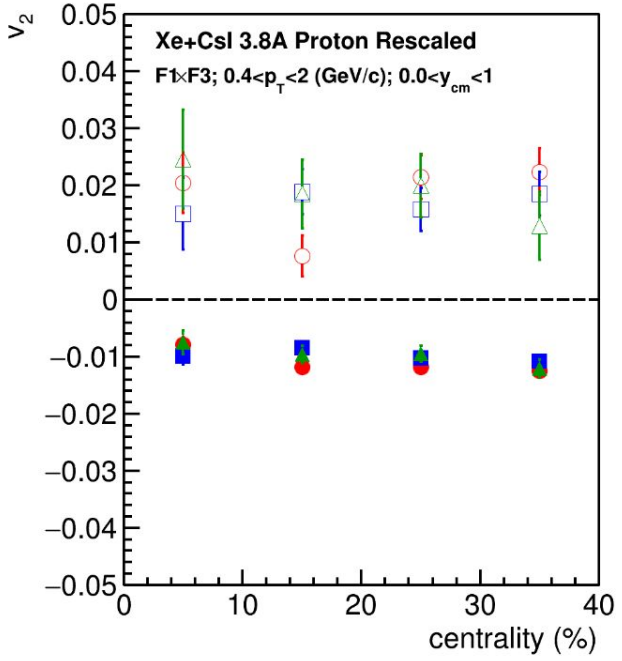




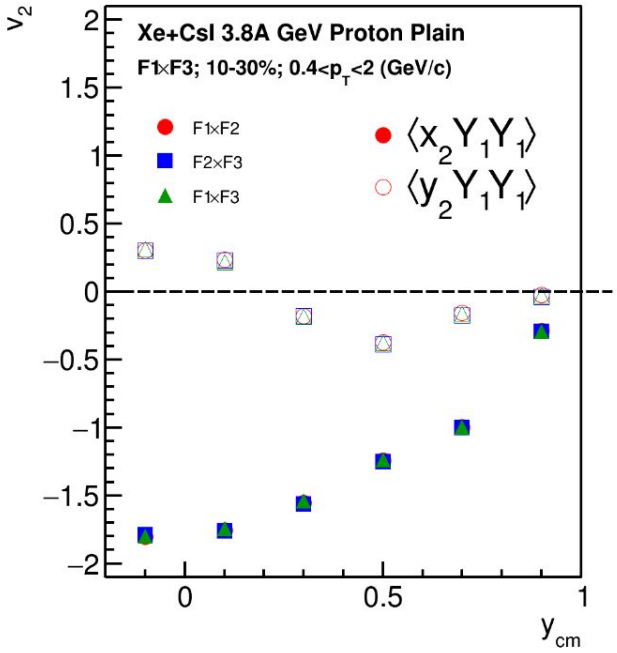
Rescaled proton v_2

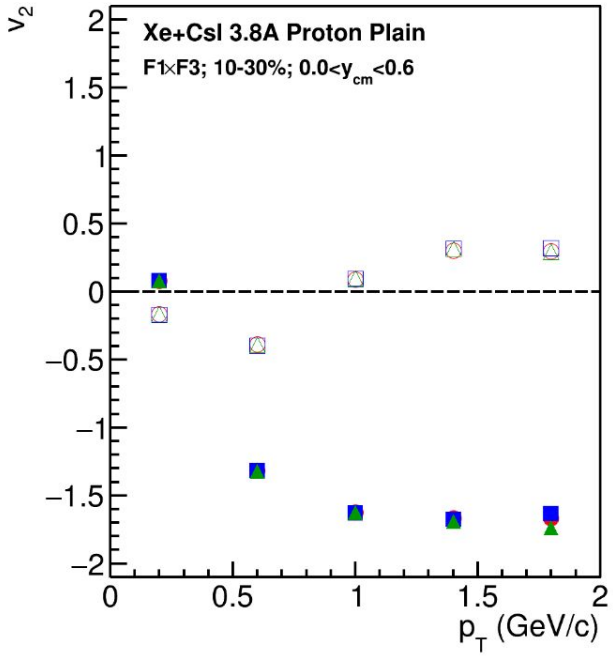


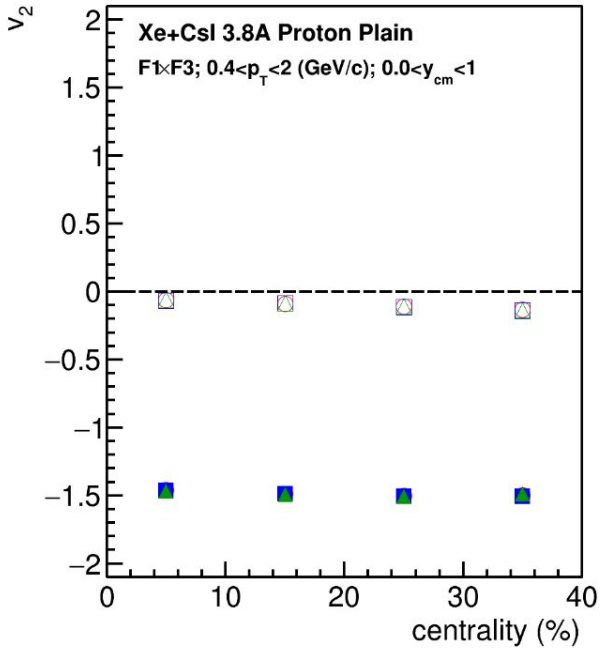




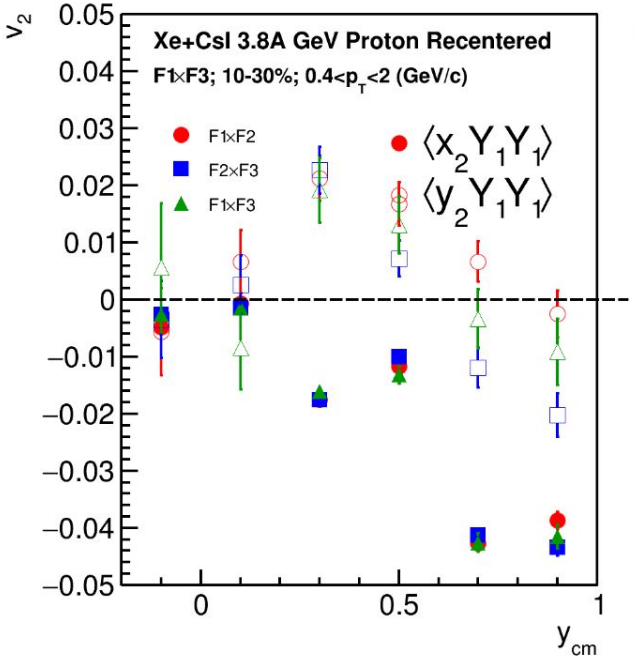
Plain proton v_2

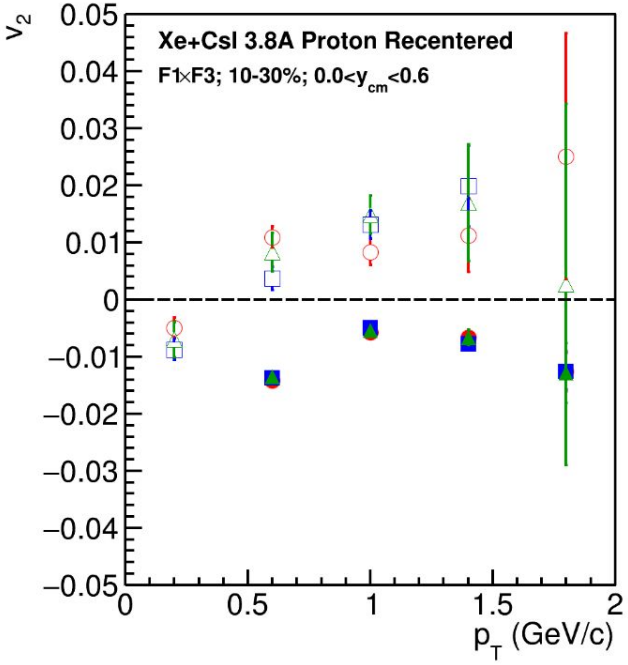


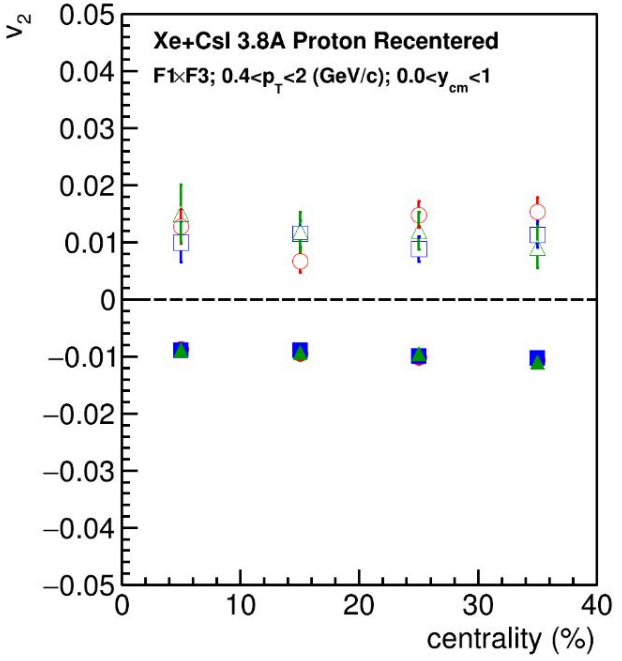




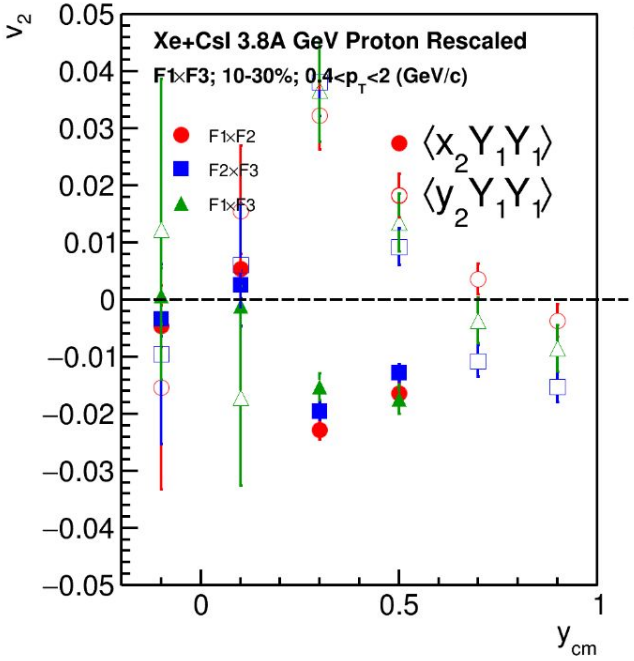
Recentered proton v_2

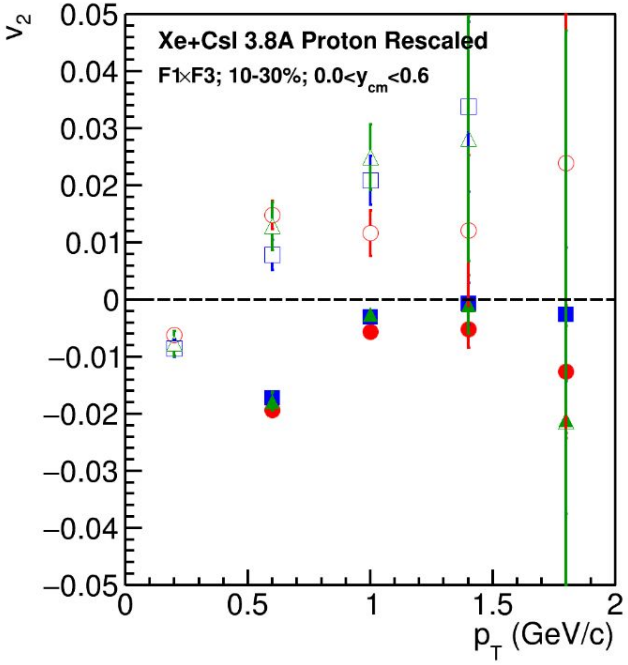


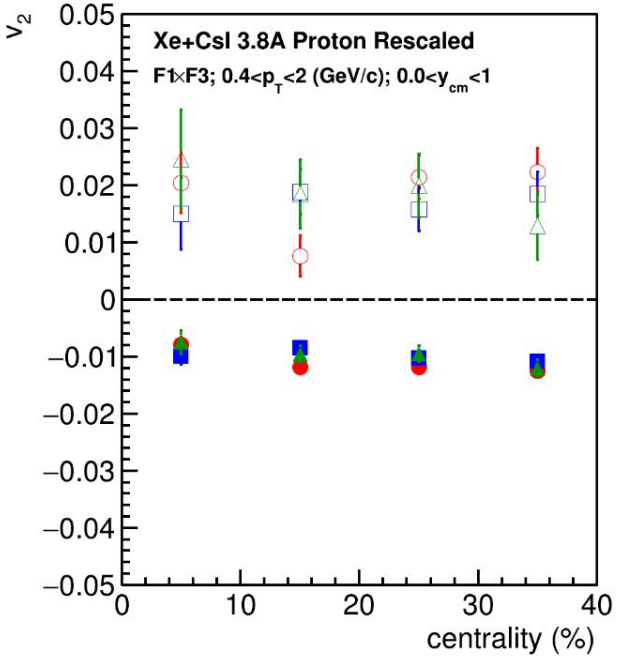




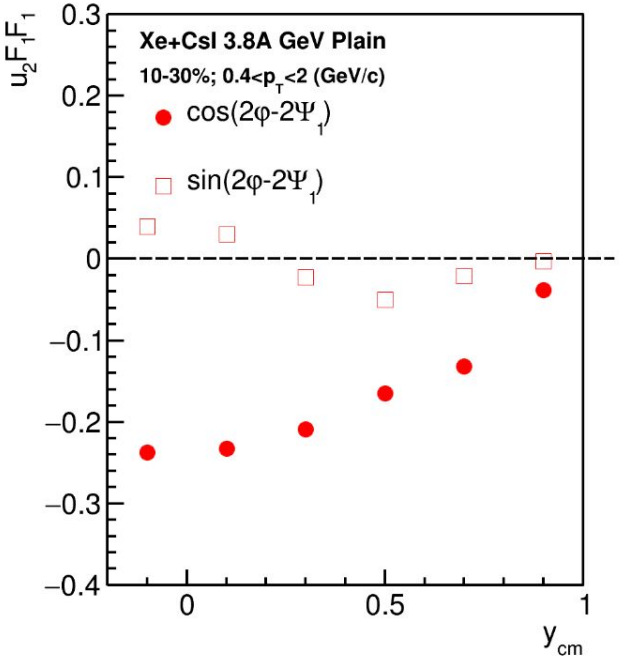
Rescaled proton v_2

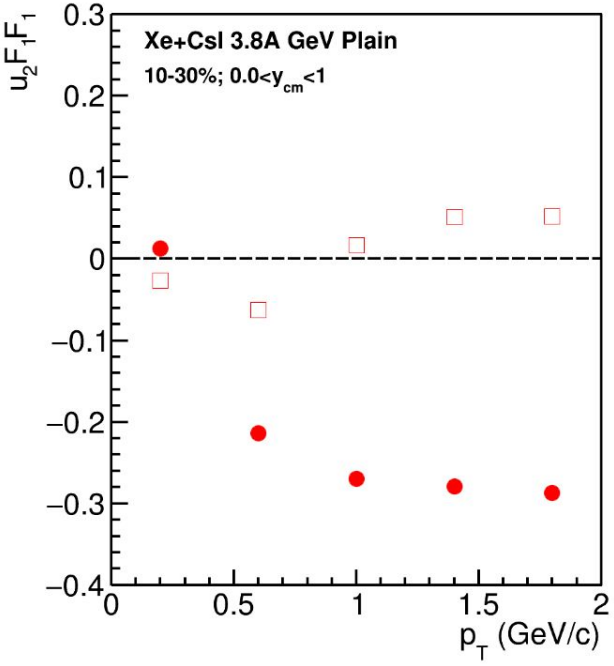


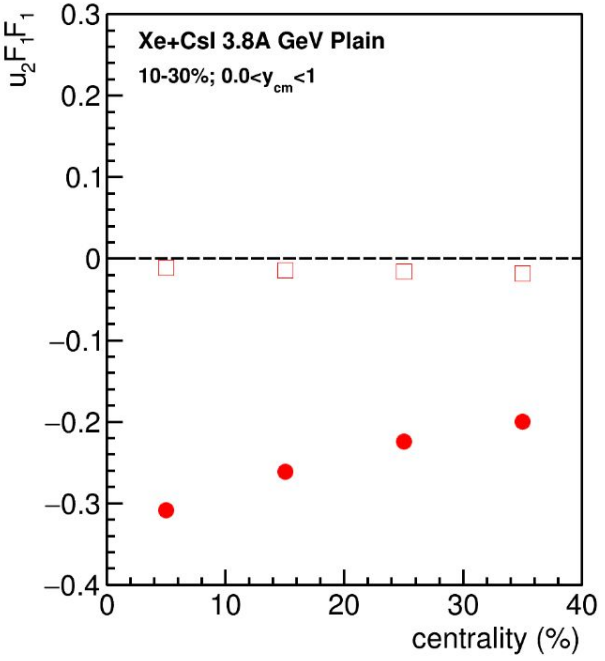




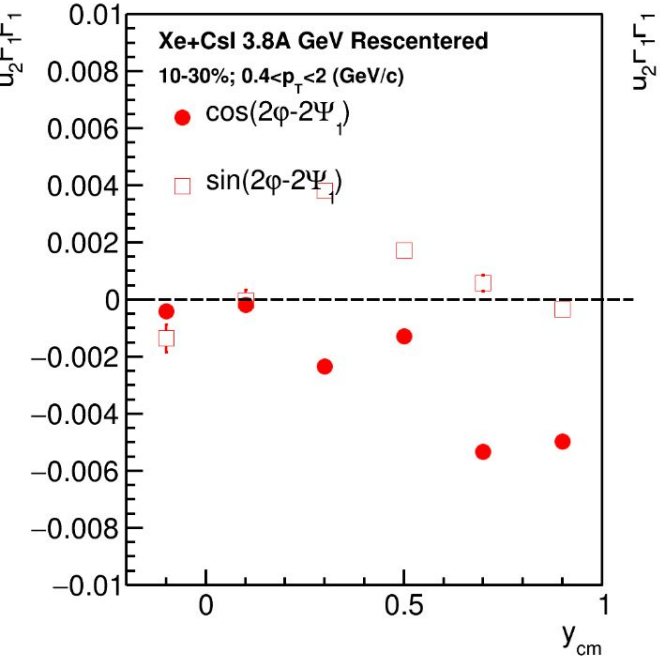
Plain proton correlation with F1

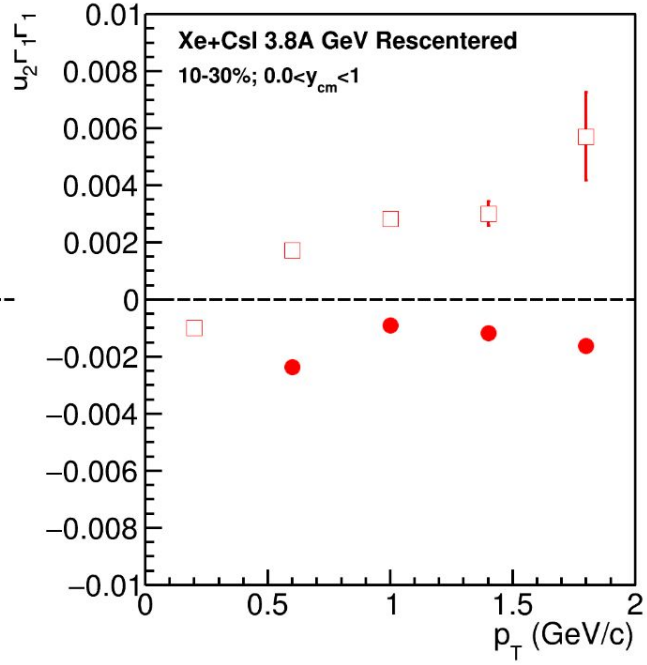


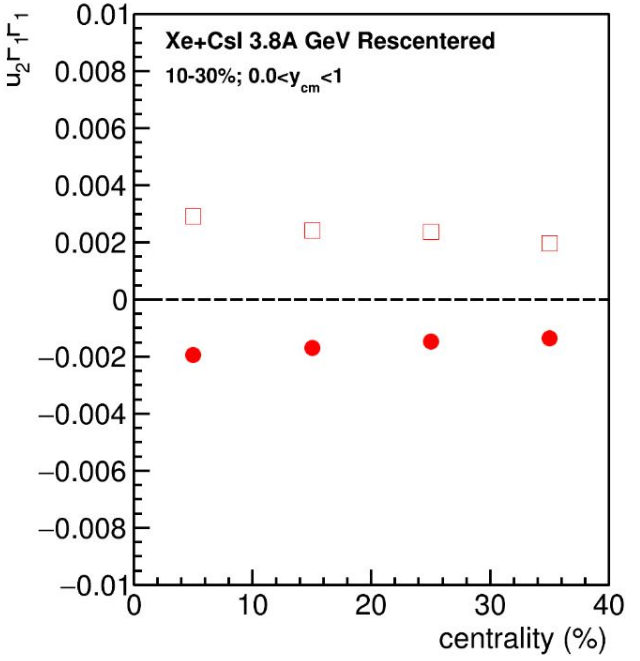




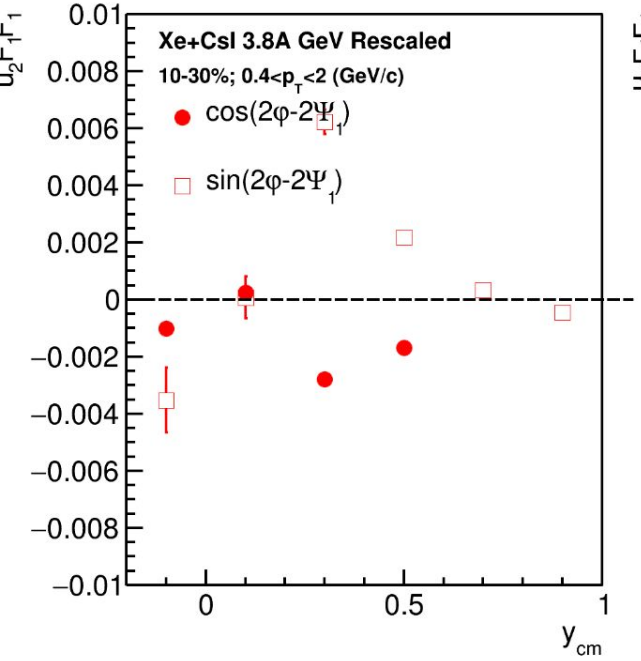
Recentered proton correlation with F1

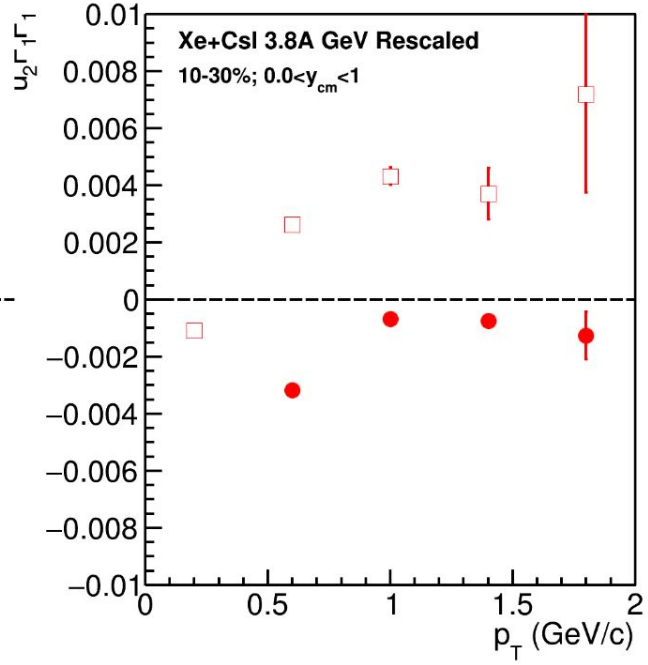


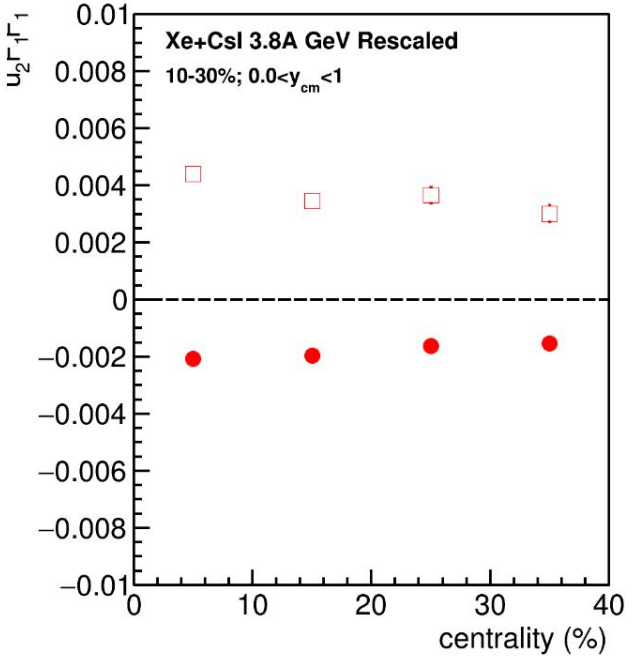




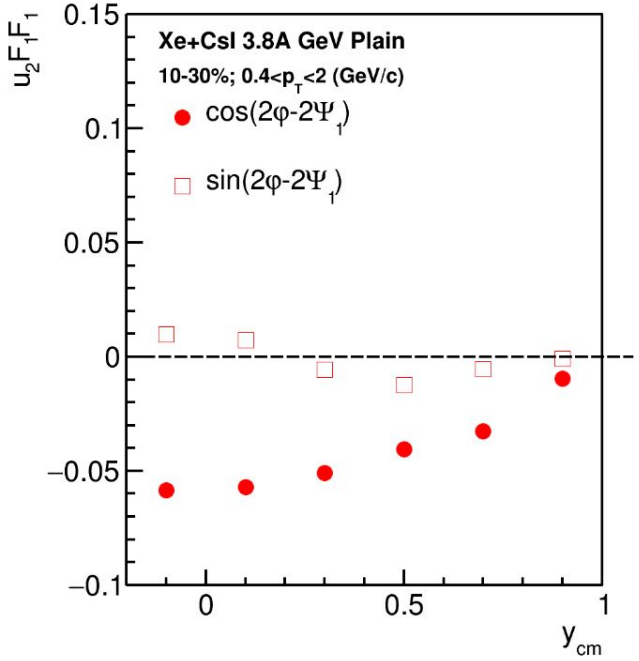
Rescaled proton correlation with F1

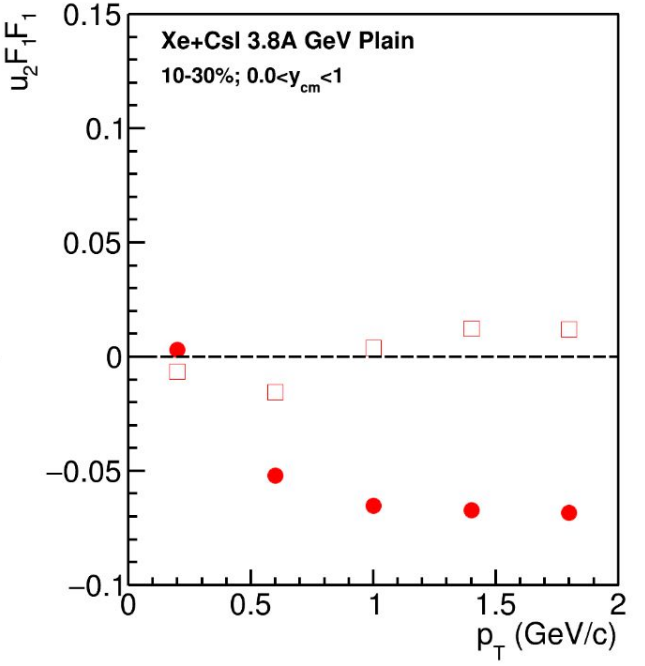


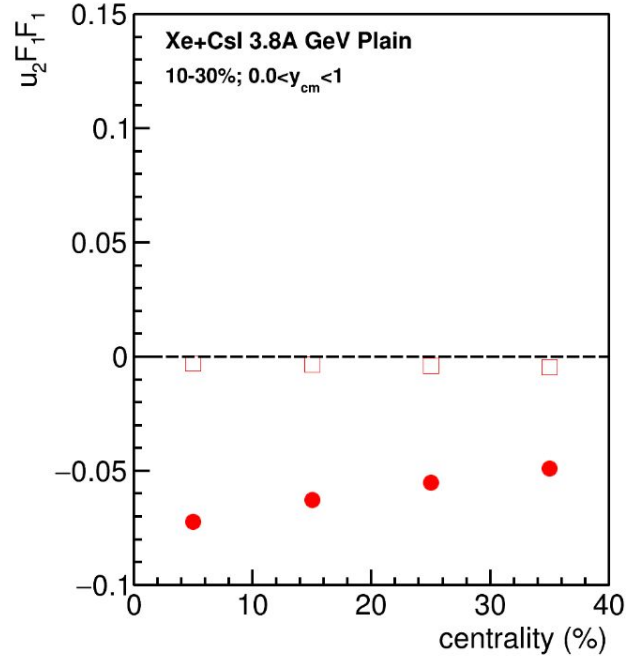




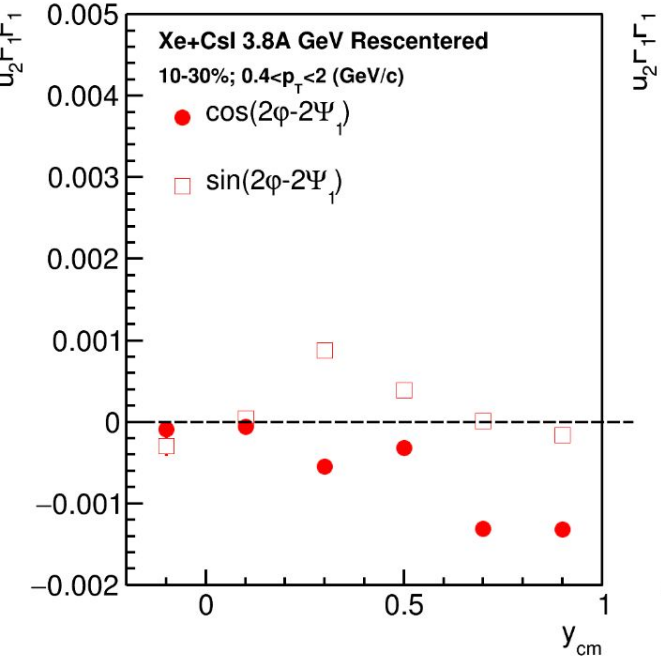
Plain proton correlation with F2

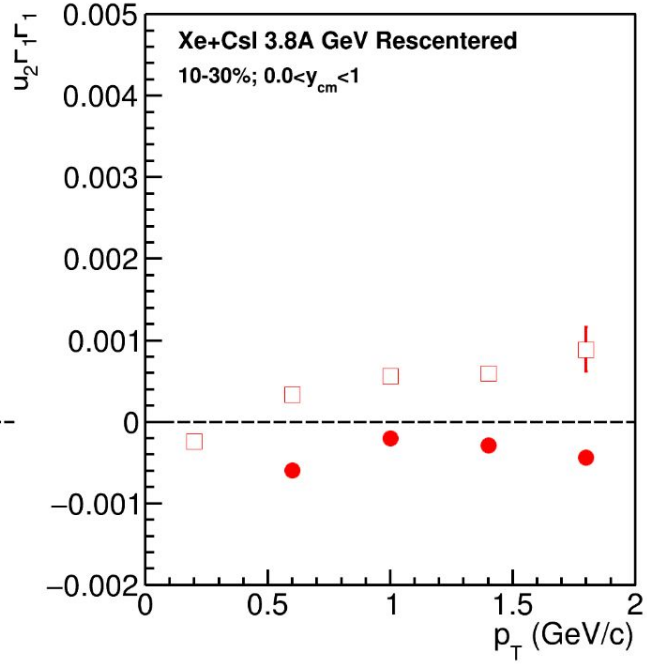


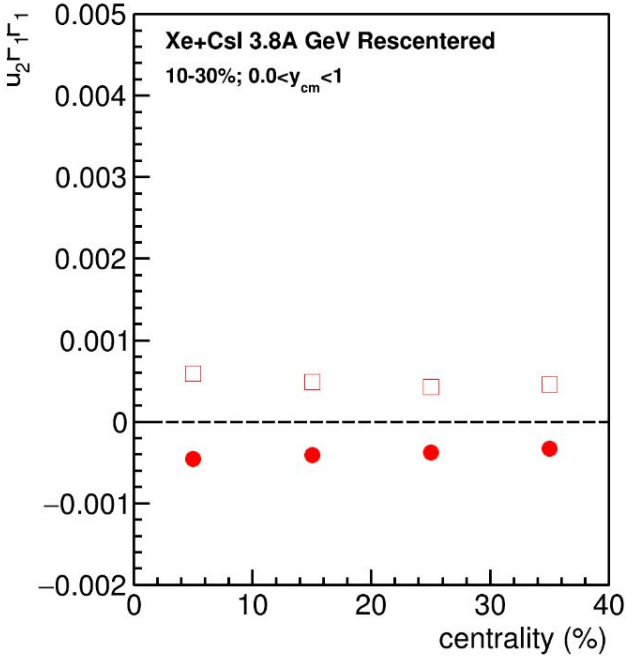




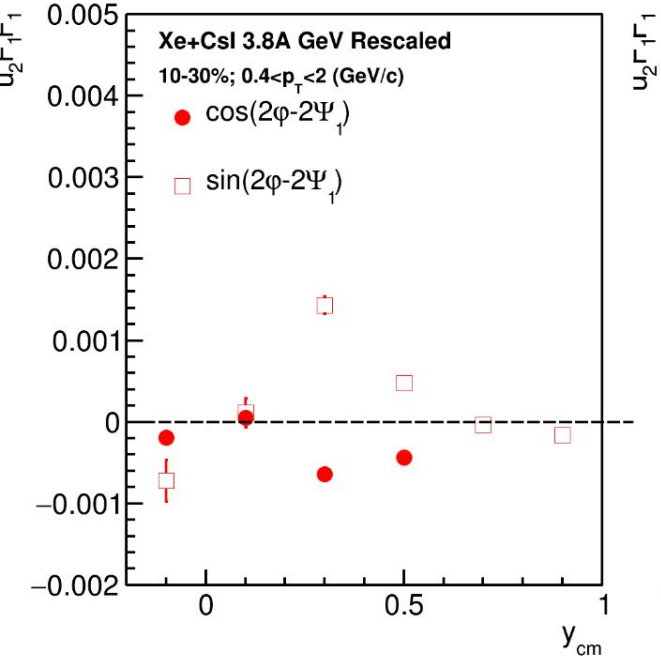
Recentered proton correlation with F2

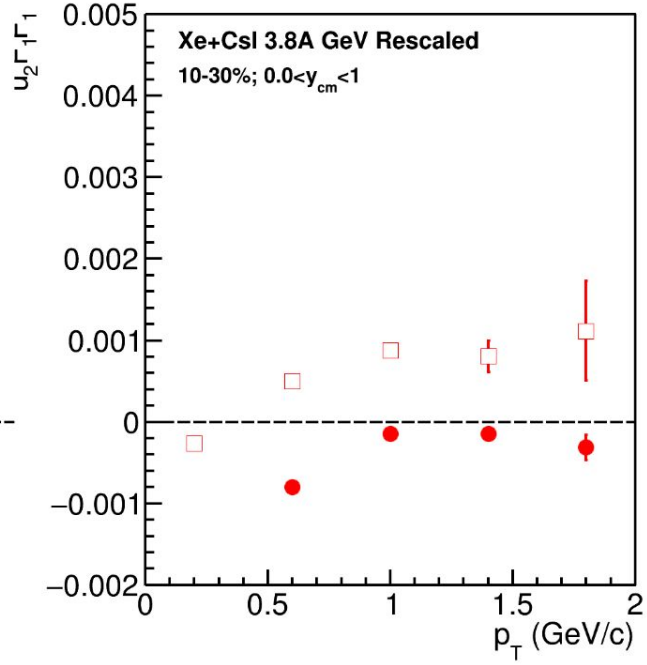


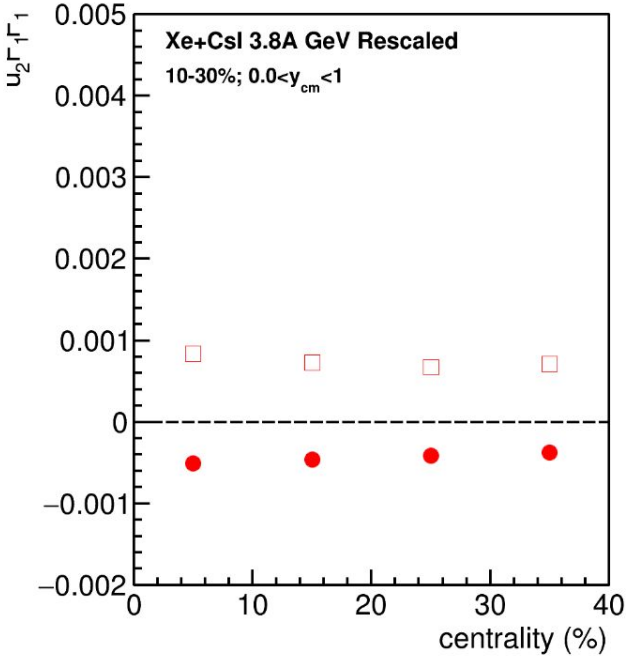




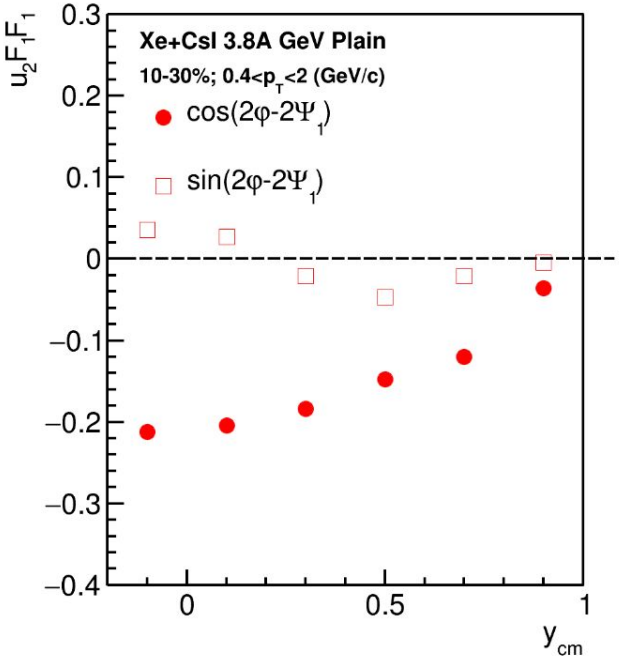
Rescaled proton correlation with F2

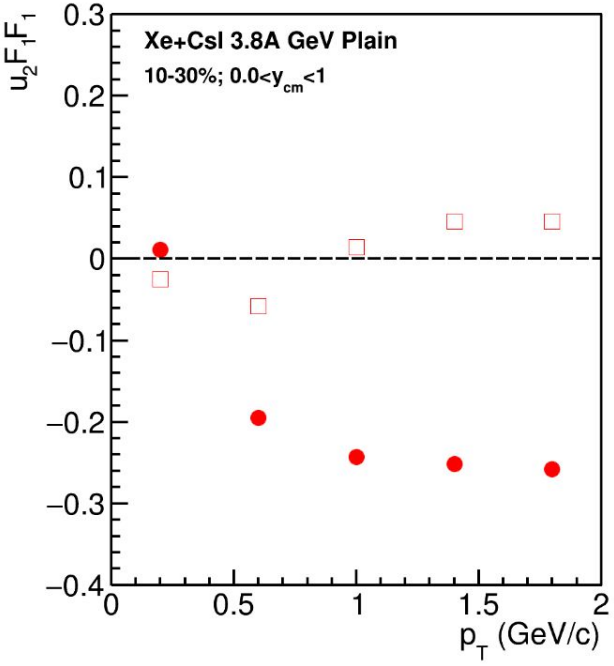


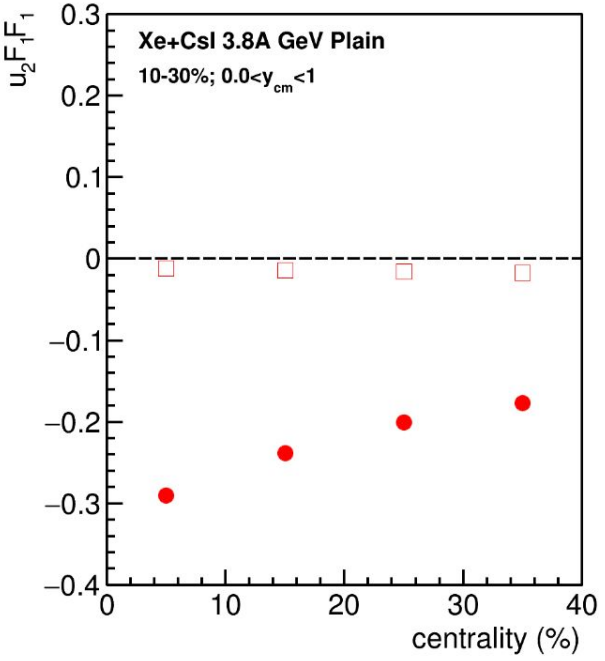




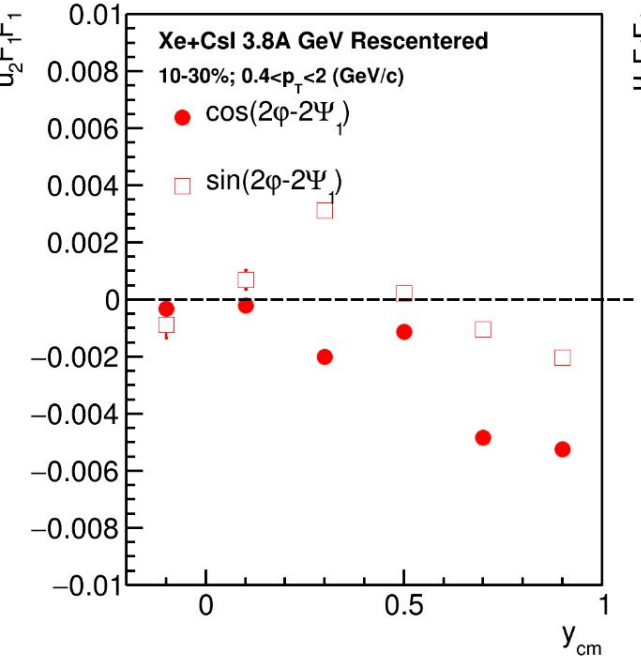
Plain proton correlation with F3

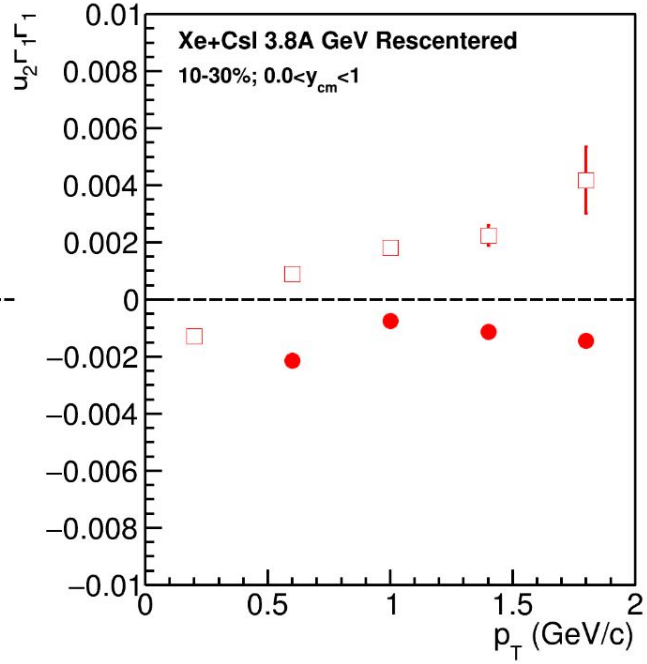


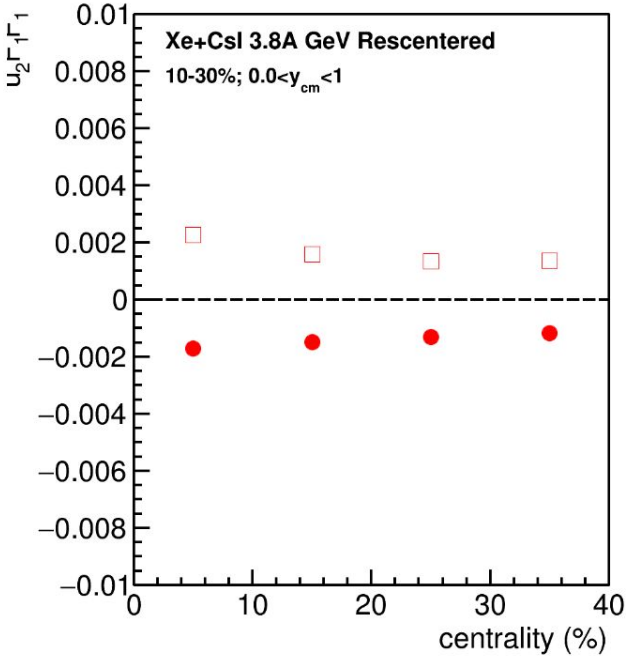




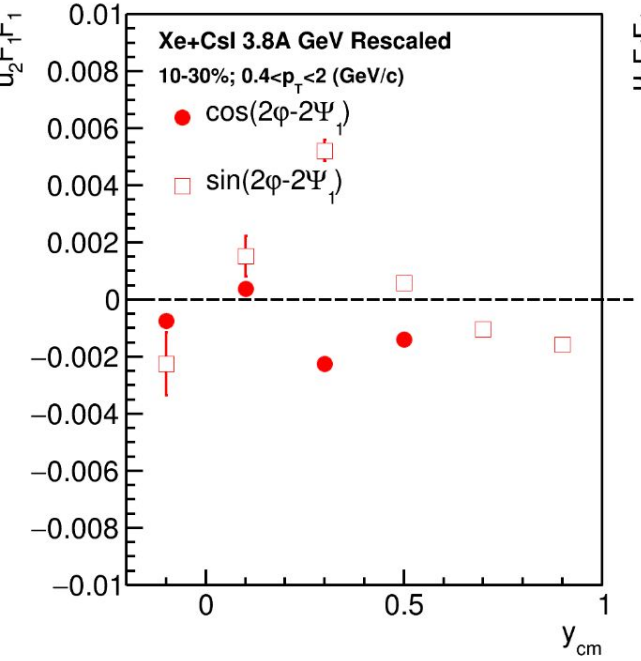
Recentered proton correlation with F3

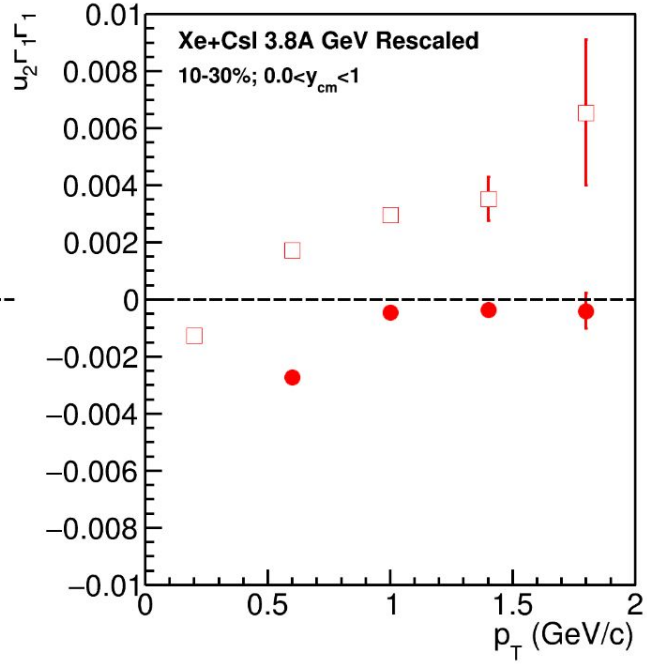


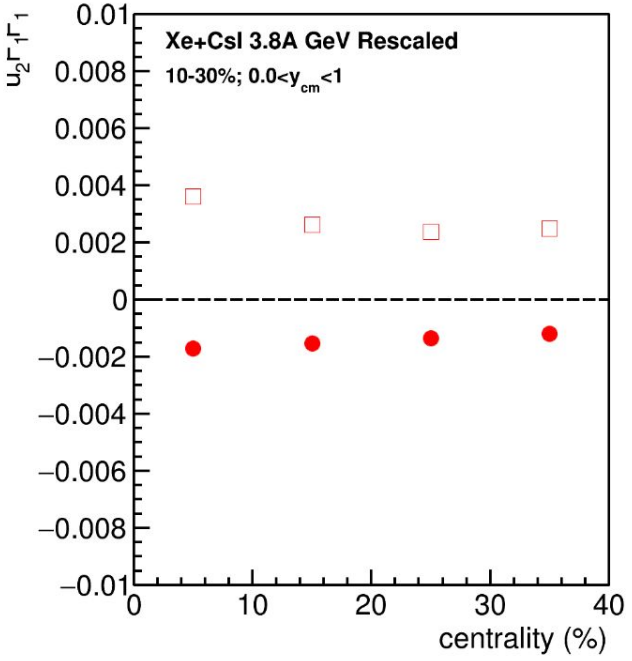




Rescaled proton correlation with F3

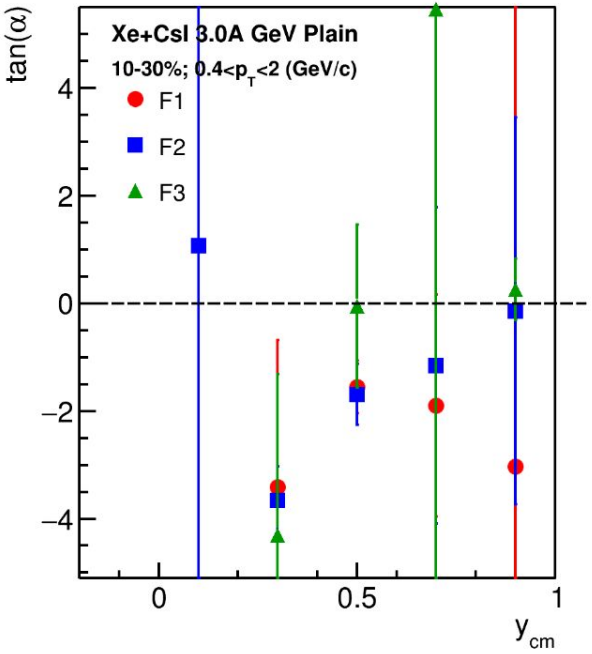


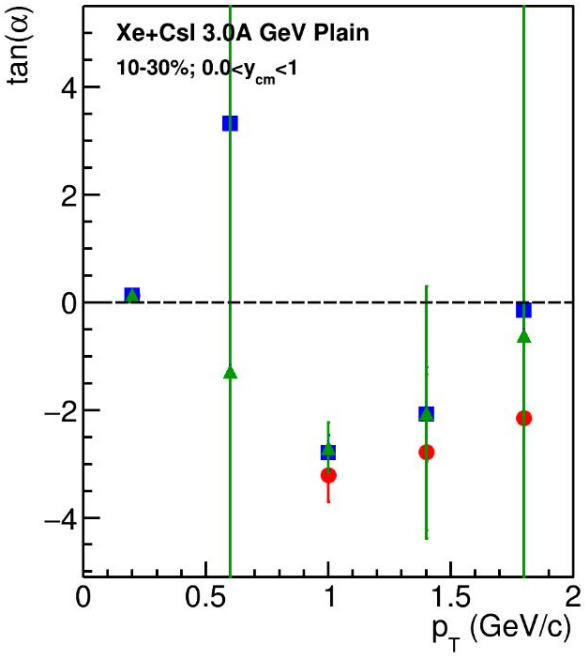


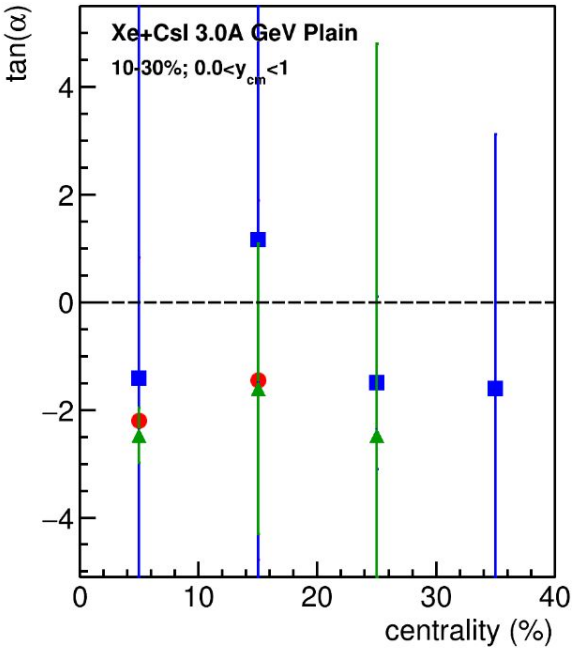


Calculating the effective rotation angle

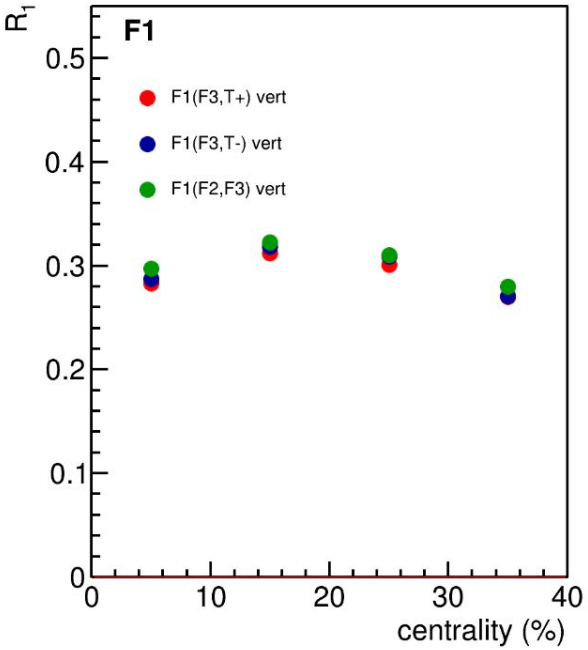
α ~ 31.717474

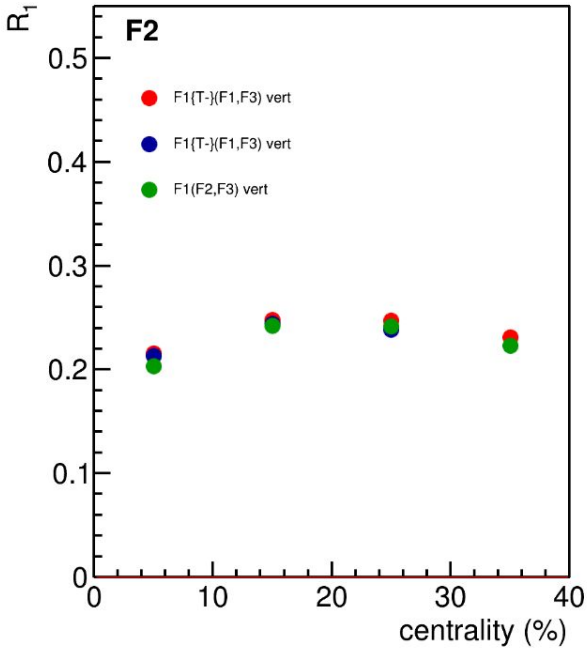


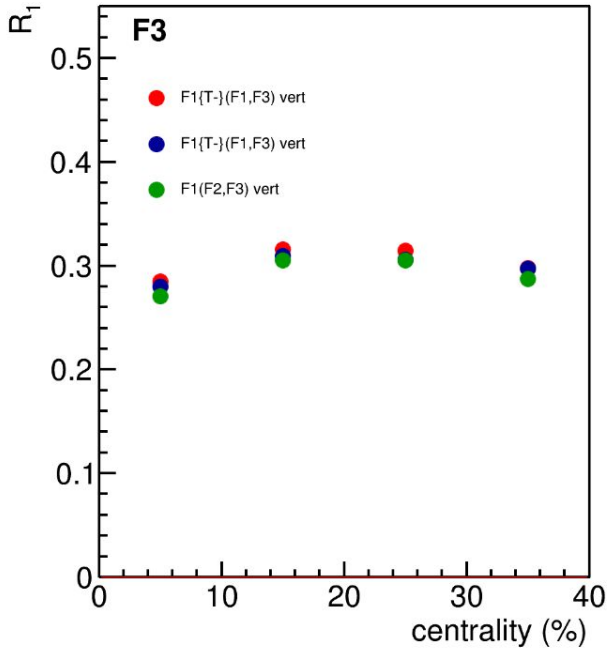




Symmetry plane resolution in Xe+Cs(I) collisions







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