Performance studies towards flow measurements in BM@N

Mikhail Mamaev (MEPhI, INR RAS)
Petr Parfenov (MEPhI, INR DVA)
Arkady Taranenko (MEPhI, JINR)

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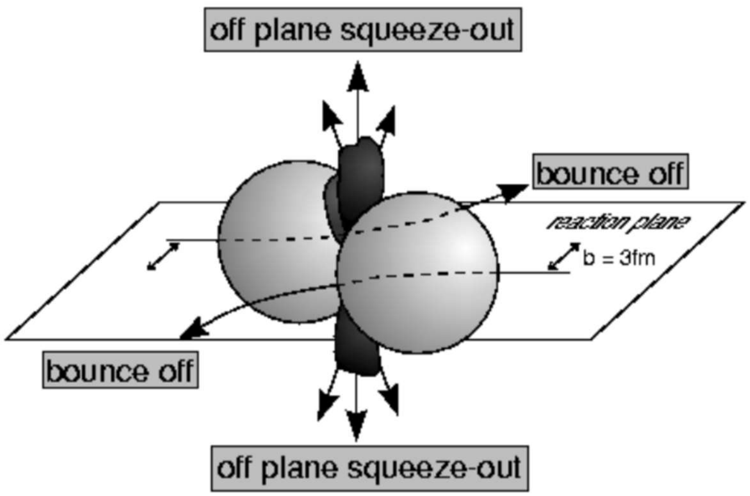
BM@N collaboration meeting, 16/05/2023

Anisotropic flow & spectators



The azimuthal angle distribution is decomposed in a Fourier series relative to reaction plane angle:

$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP}))$$

Anisotropic flow:

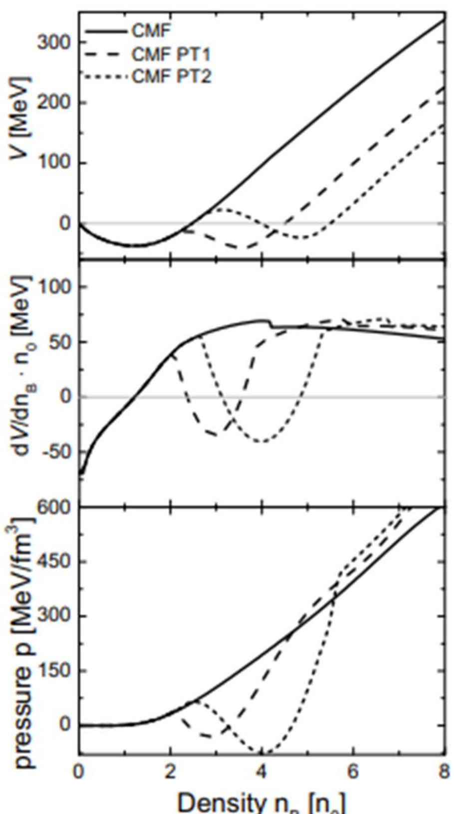
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right] \rangle$$

Anisotropic flow is sensitive to:

- Time of the interaction between overlap region and spectators
- Compressibility of the created matter

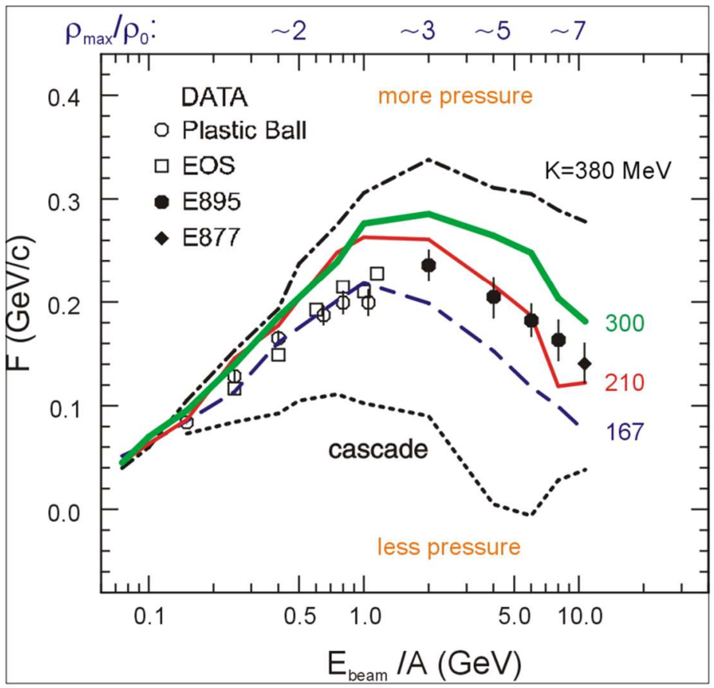
v_n as a function of collision energy

P. DANIELEWICZ, R. LACEY, W. LYNCH
10.1126/science.1078070

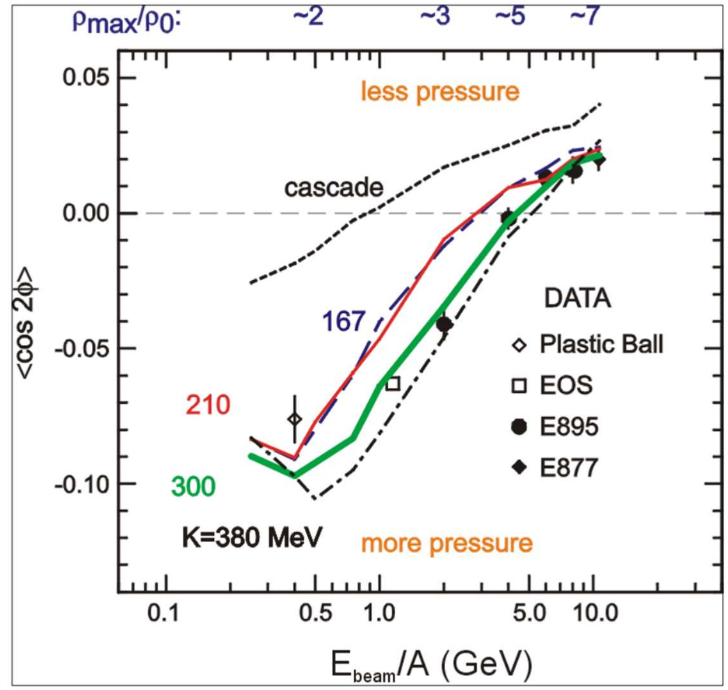


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests softer EOS



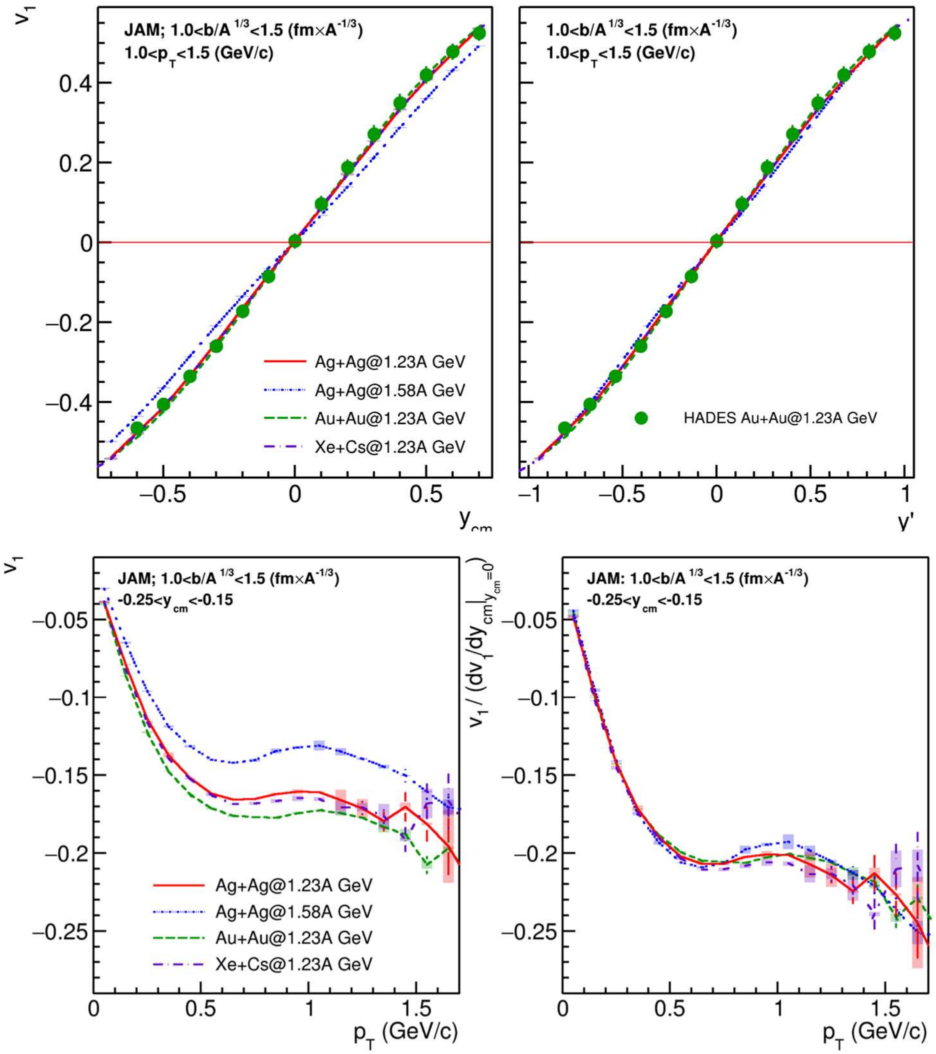
v_2 suggests harder EOS



Describing the high-density matter using the mean field
Flow measurements constrain the mean field

Discrepancy is probably due to non-flow correlations

HADES: dv_1/dy scaling with collision energy and system size

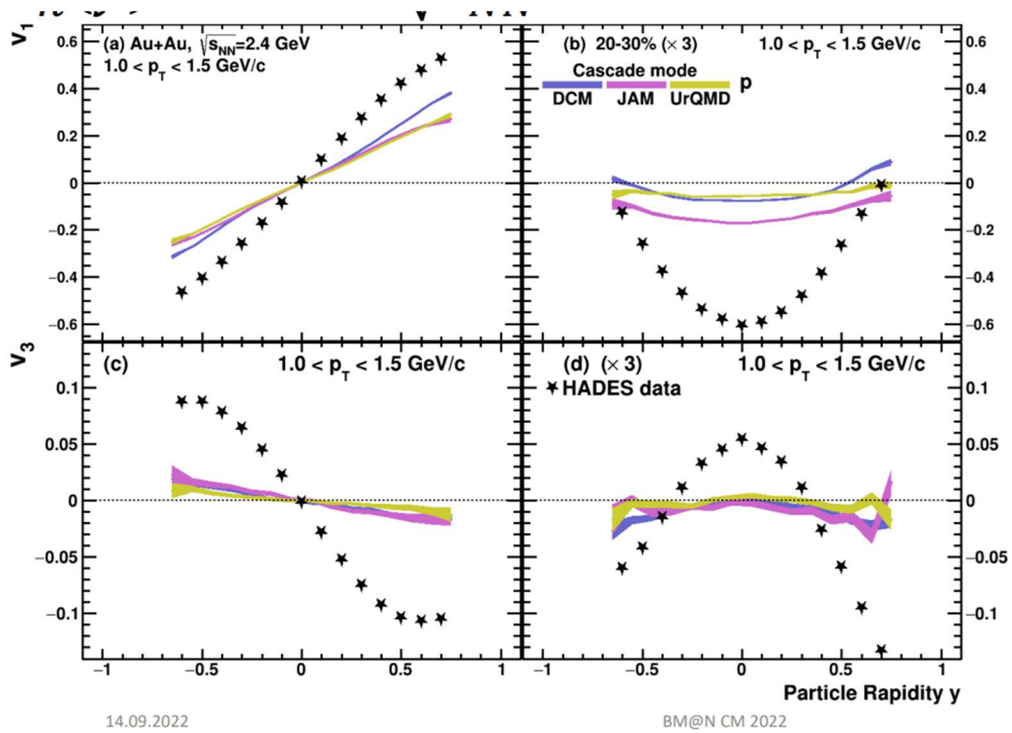


- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments(e.g. STAR-FXT Au+Au

Simulation datasample

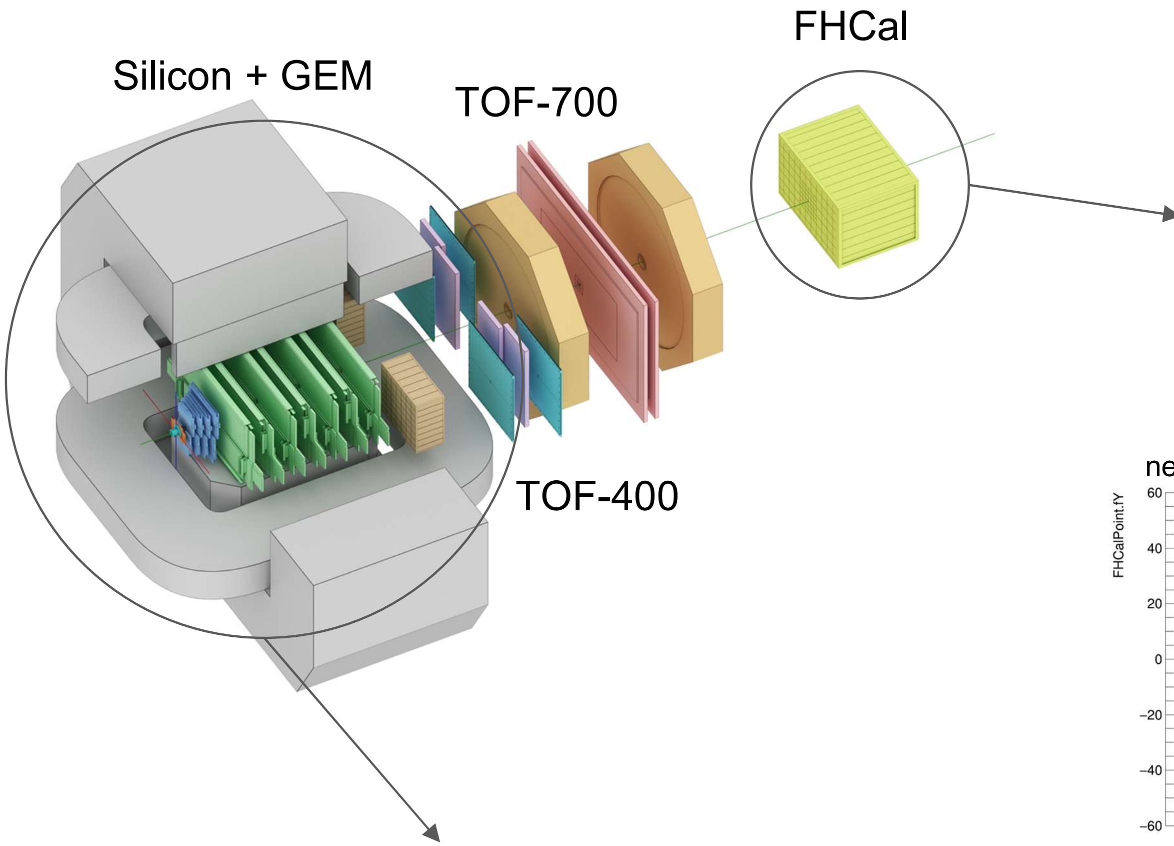
- Xe+Cs nuclei collisions
- DCMQGSM-SMM model (realistic yields of spectator fragments), describes flow poorly
- JAM model (realistic flow signal)
- Geant4 transport code (important for simulation of hadronic showers in the forward calorimeter)

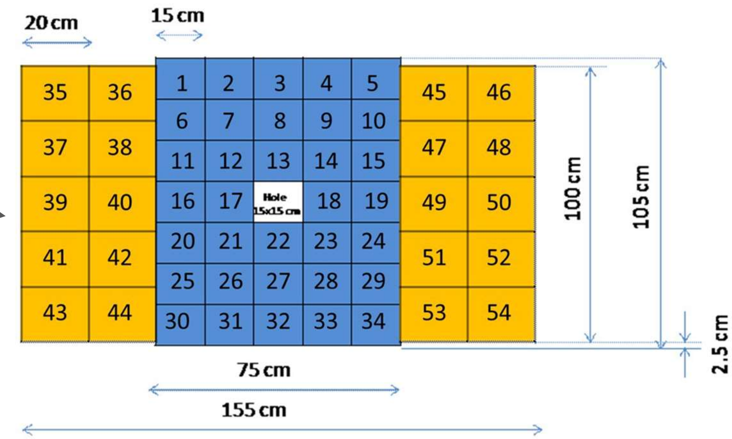
See talk of P.Parfenov

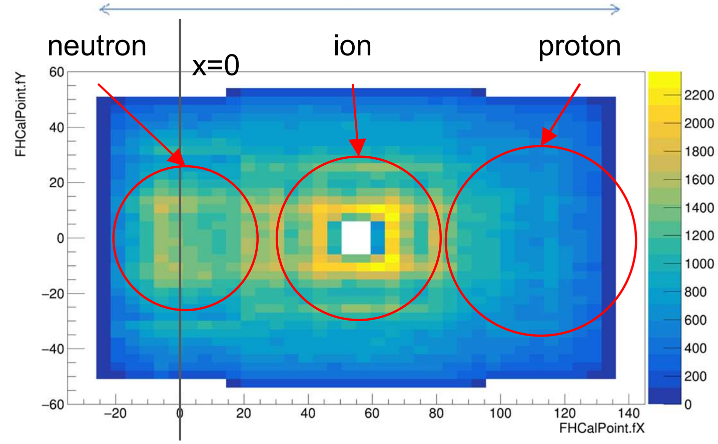


	2A GeV	3A GeV	4A GeV
DCMQGSM-SMM	6M	6M	2M
JAM MD2	3M	3M	5M

The BM@N experiment (GEANT4 simulation for RUN8)







L1 tracking was used together with true-MC PID

Symmetry plane estimation with the azimuthal asymmetry of projectile spector energy

Flow vectors

From momentum of each measured particle define a u_n-vector in transverse plane:

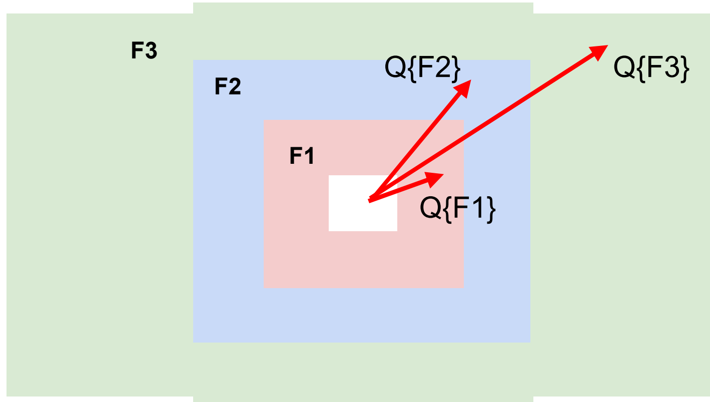
$$u_n = e^{in\phi}$$

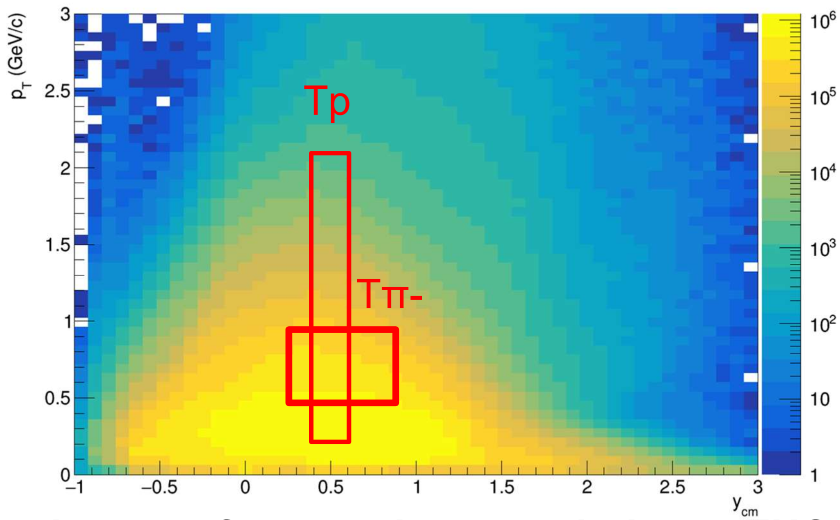
where φ is the azimuthal angle

Sum over a group of u_n-vectors in one event forms Q_n-vector:

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle





Additional subevents from tracks not pointing at FHCal:

Tp: p; 0.4<y<0.6; 0.2 < p_T < 2 GeV/c; w=1/eff

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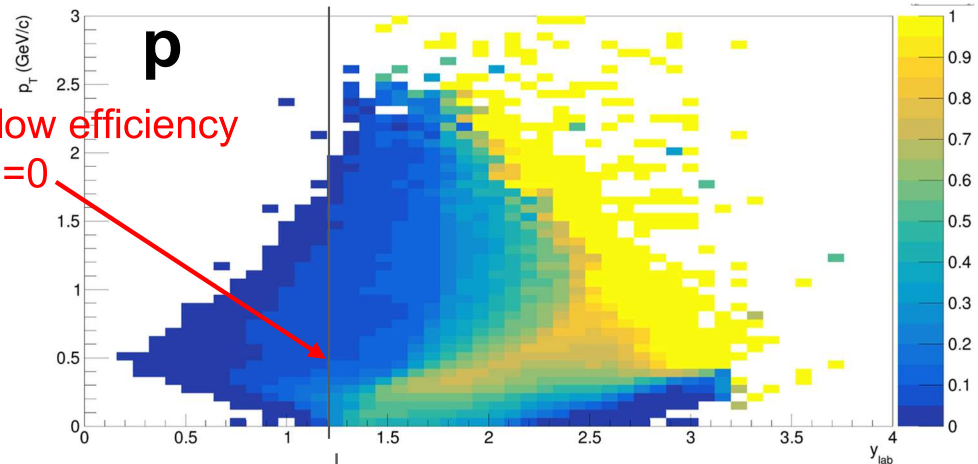
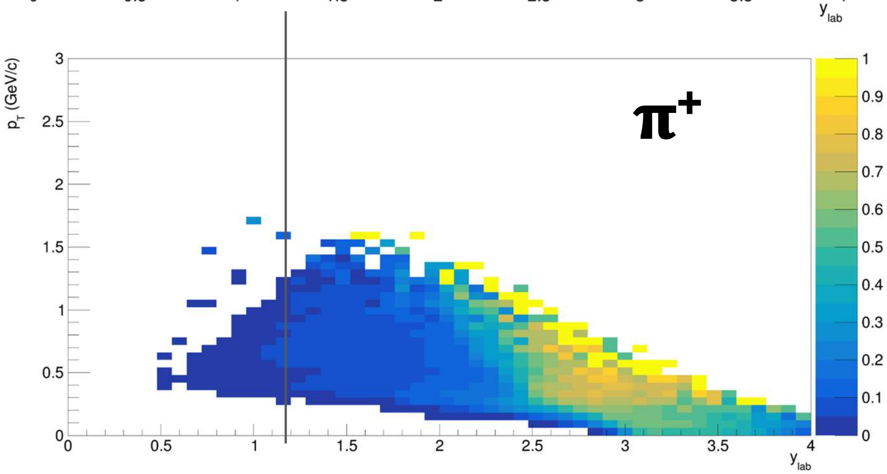
T-: all negative; 1.0<η<2.0; 0.1 < p_T < 0.5 GeV/c; w=1/eff

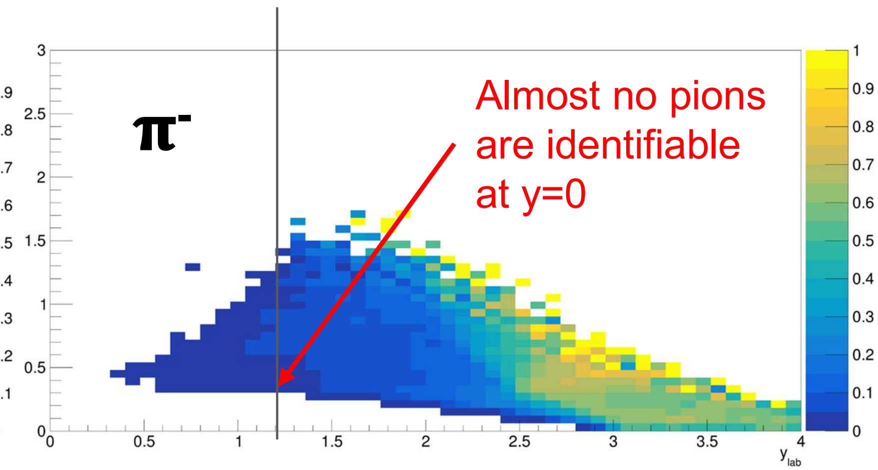
Tracking efficiency (matched to TOF-400 or TOF-700)

Very low efficiency at y_{cm}=0



- Measuring flow at midrapidity is crucial to compare with data from other experiment
- We observe very low efficiency at midrapidity due to very narrow TOF acceptance
- Optimization of TOF detectors position is required (maybe move TOF-700 closer to target?)





Almost no pions are identifiable at y=0

Even worse for TOF-matched tracks

Flow methods for v_n calculation

Tested in HADES:

M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \qquad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

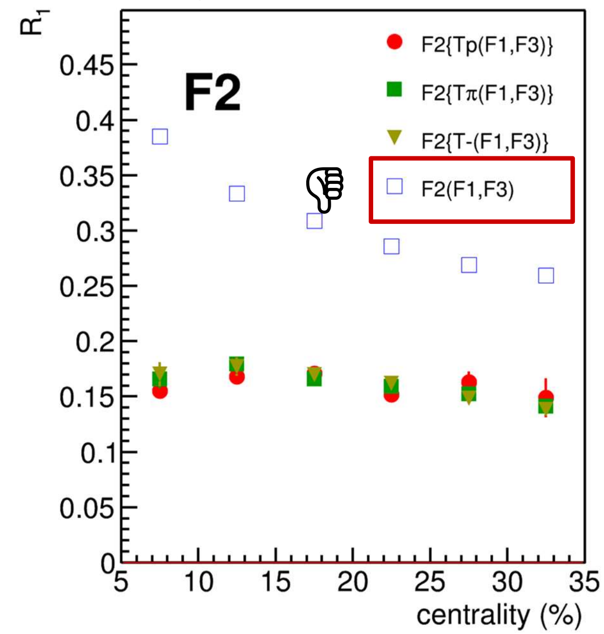
Where R_1 is the resolution correction factor

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

Symbol "F2(F1,F3)" means R_1 calculated via (3S resolution):

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

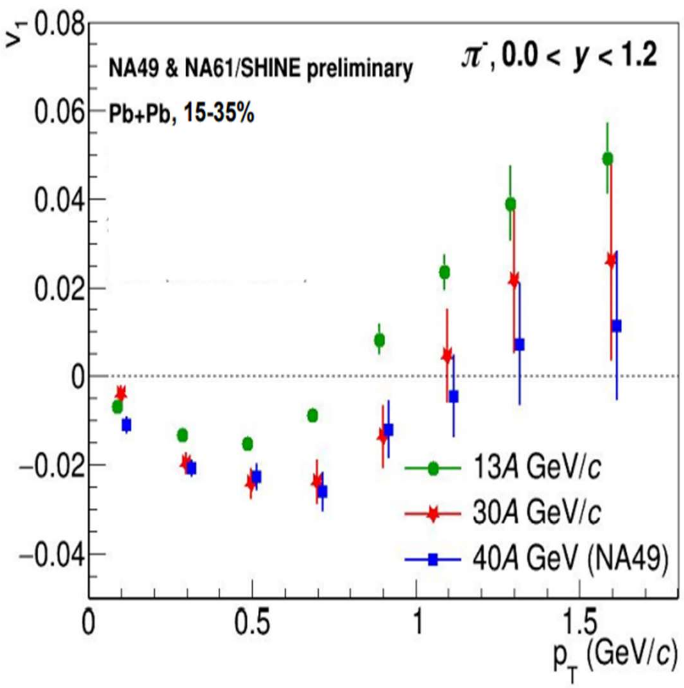
Method helps to eliminate non-flow
Using 2-subevents doesn't

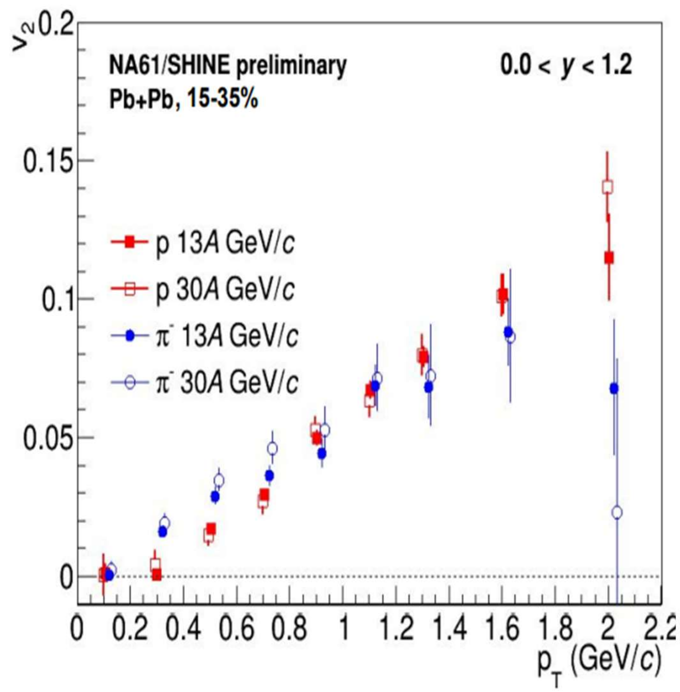


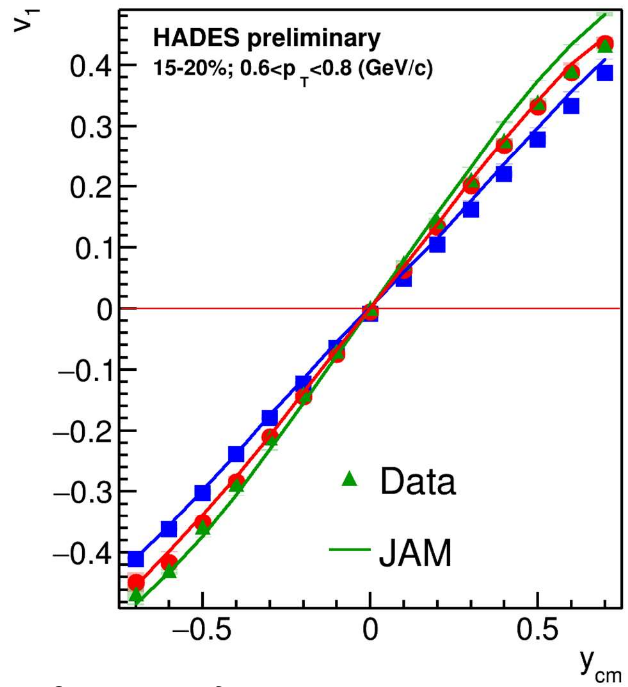
Symbol "F2{Tp}(F1,F3)" means R_1 calculated via (4S resolution):

$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

QnTools framework



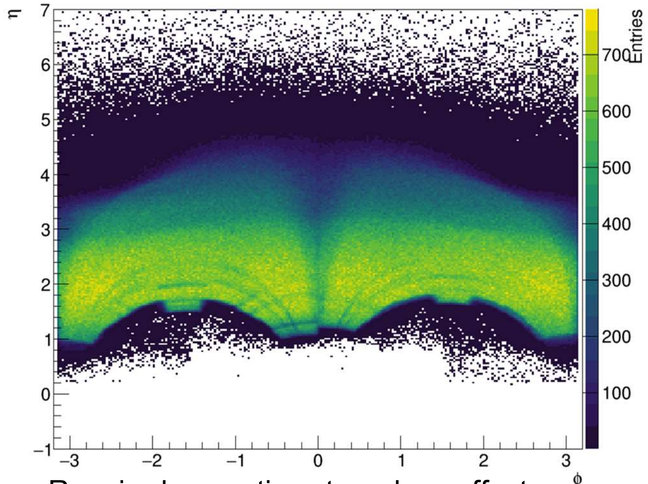




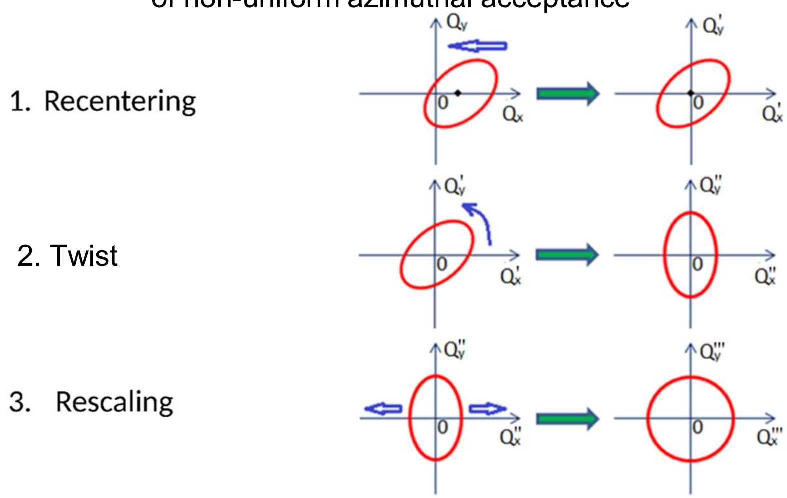
- All the methods used for performance study were carried out using QnTools framework: https://github.com/HeavyIonAnalysis/QnTools (well documented and well-tested)
- Methods for flow measurements in fixed-target experiments were tested on experimental data from NA61/SHINE, HADES and ALICE
- Tested and implemented in MPD root

Azimuthal asymmetry of the BM@N acceptance

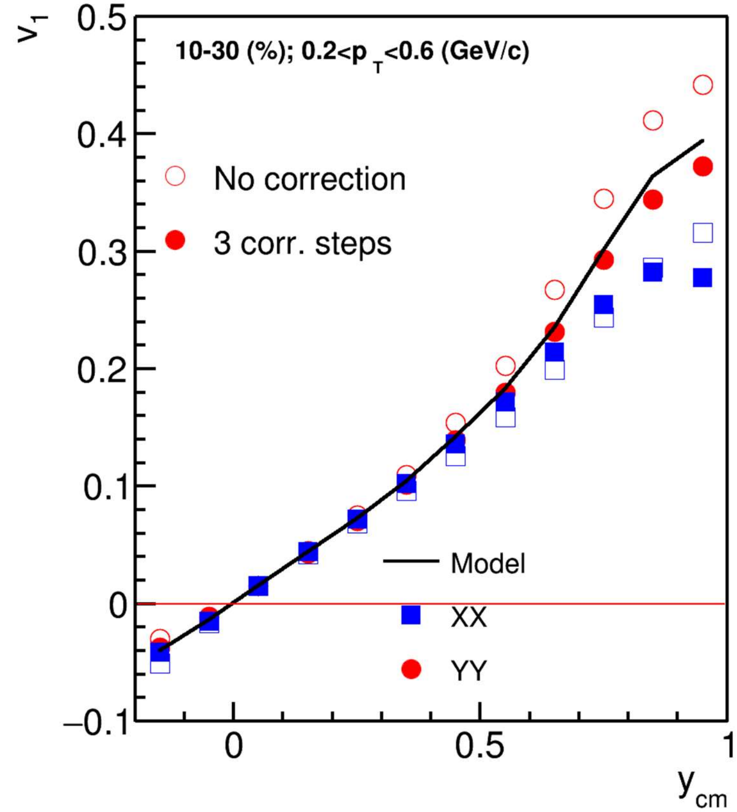
φ-η yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance

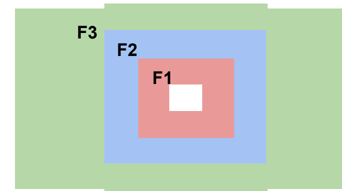


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

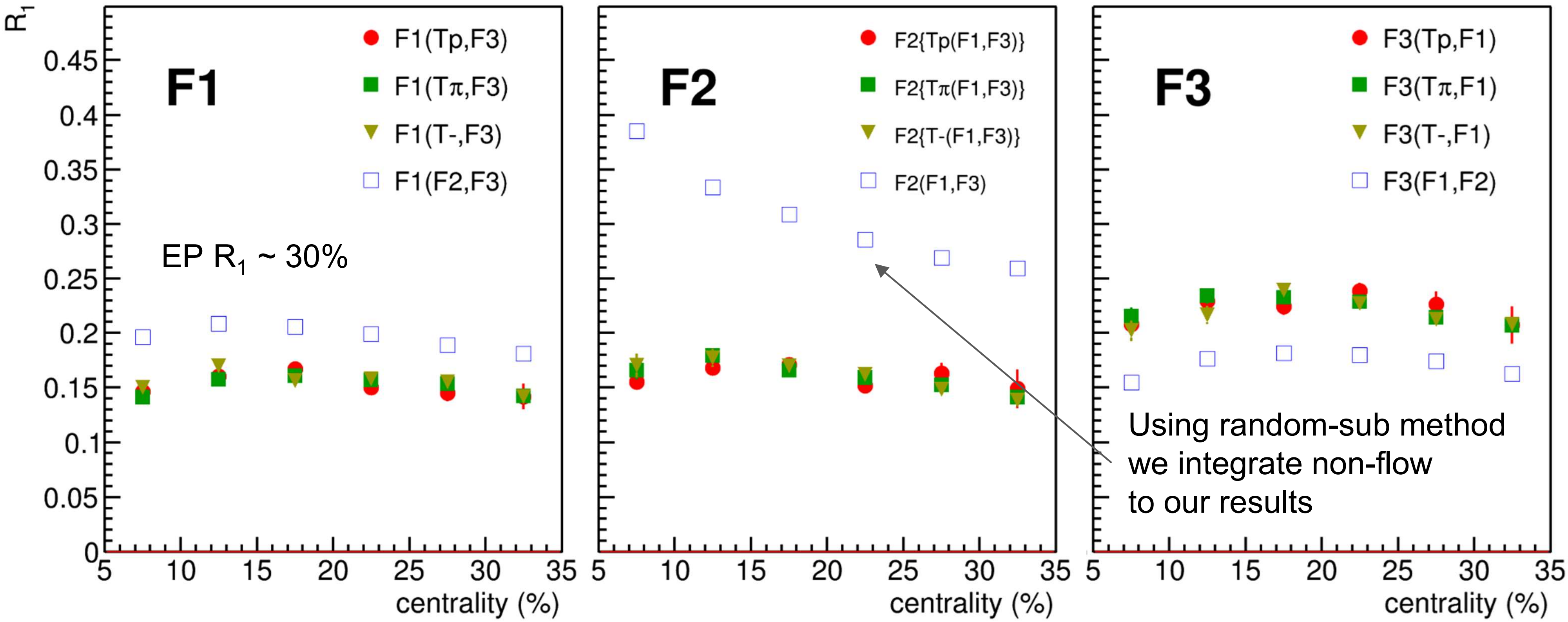


- Better agreement after rescaling for YY
- XX component has too large bias (due to magnetic field)

SP R1: DCMQGCM-SMM Xe+Cs@4A GeV

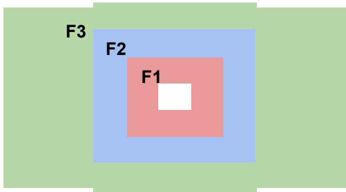


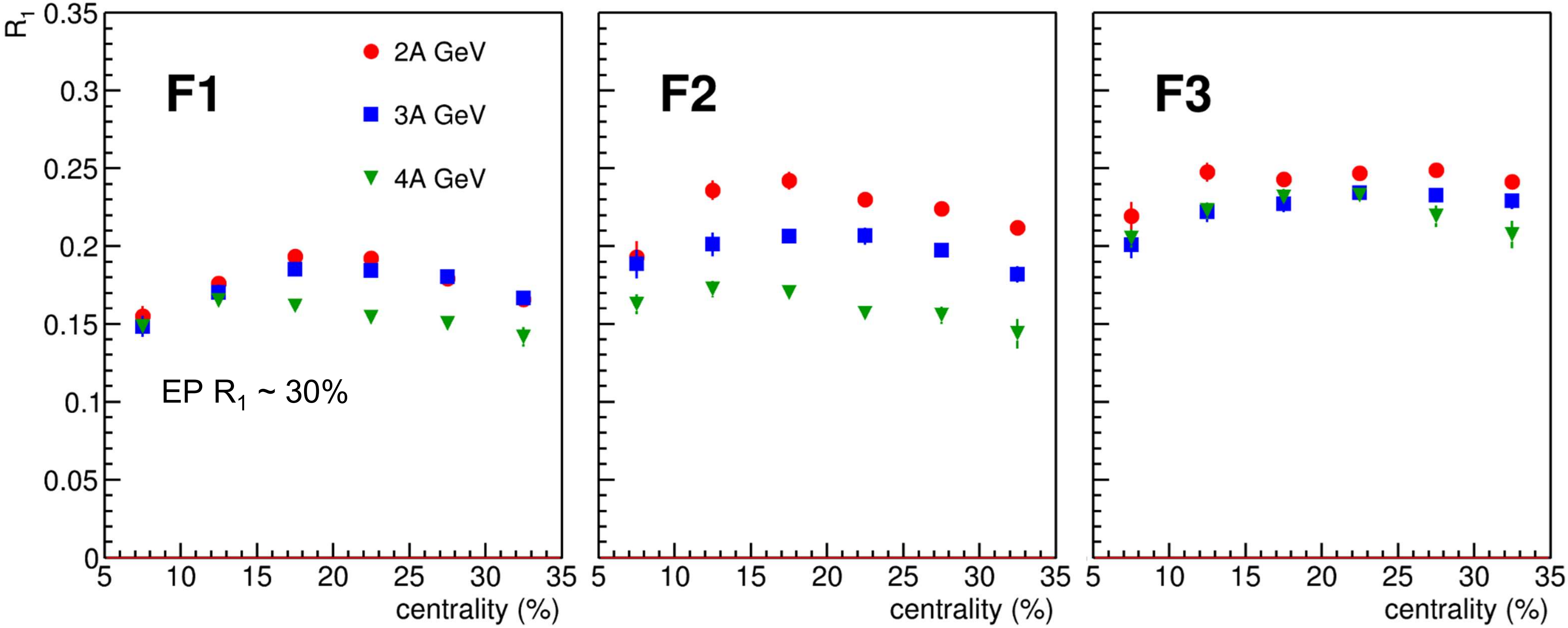
SP gives unbiased estimation of v_n (root-mean-square)
EP gives biased estimation (somewhere between mean and RMS)



Using the additional sub-events from tracking provides a robust combination to calculate resolution

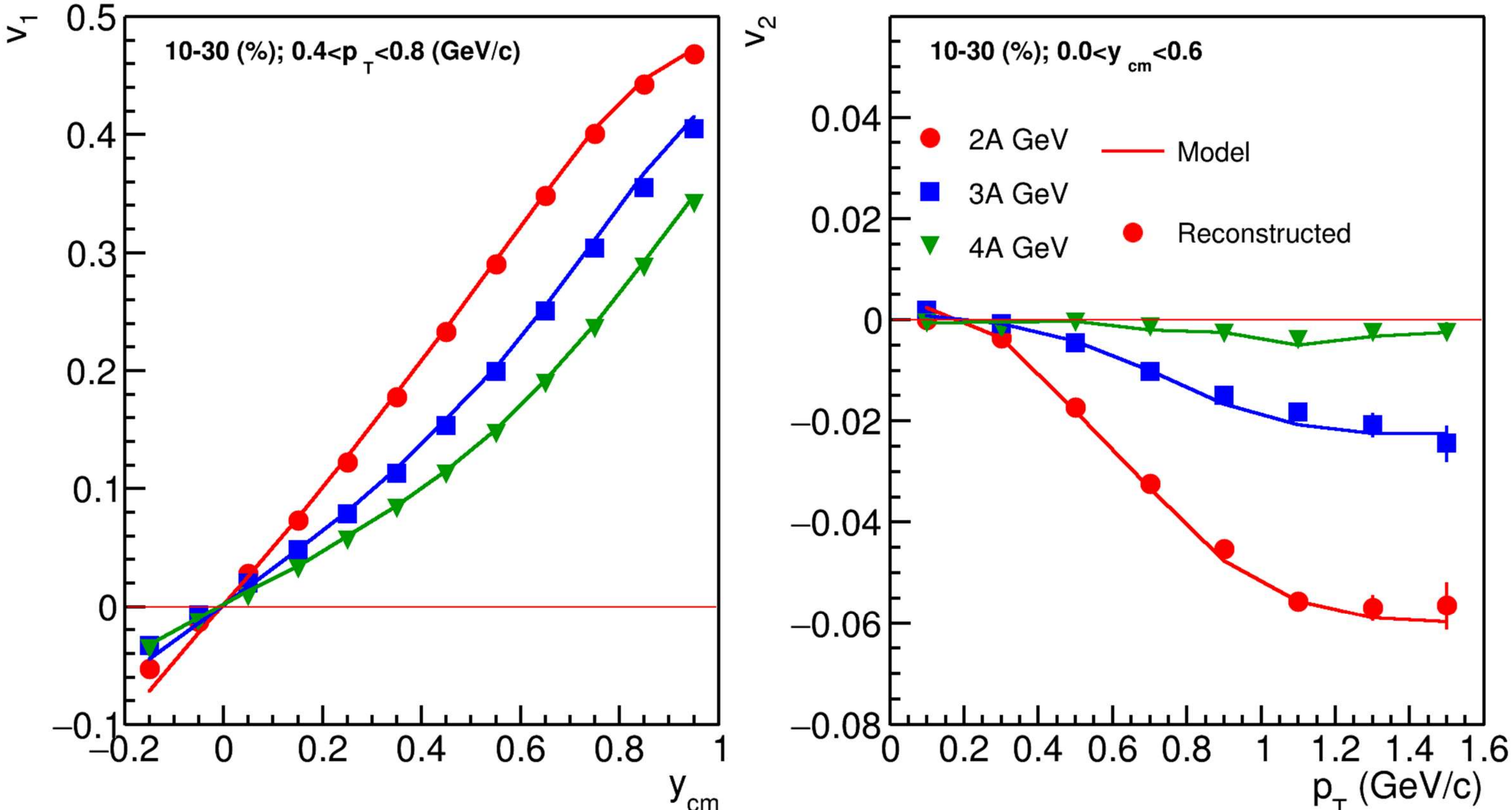
Rec R1: DCMQGCM-SMM Xe+Cs





Resolution is lower for higher energies due to lower v_1

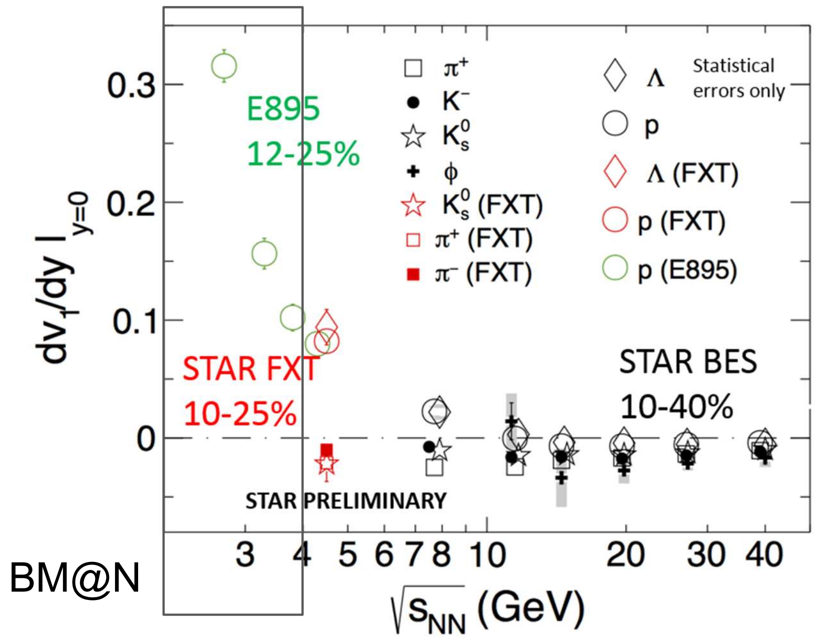
Directed and elliptic flow in Xe+Cs (JAM)



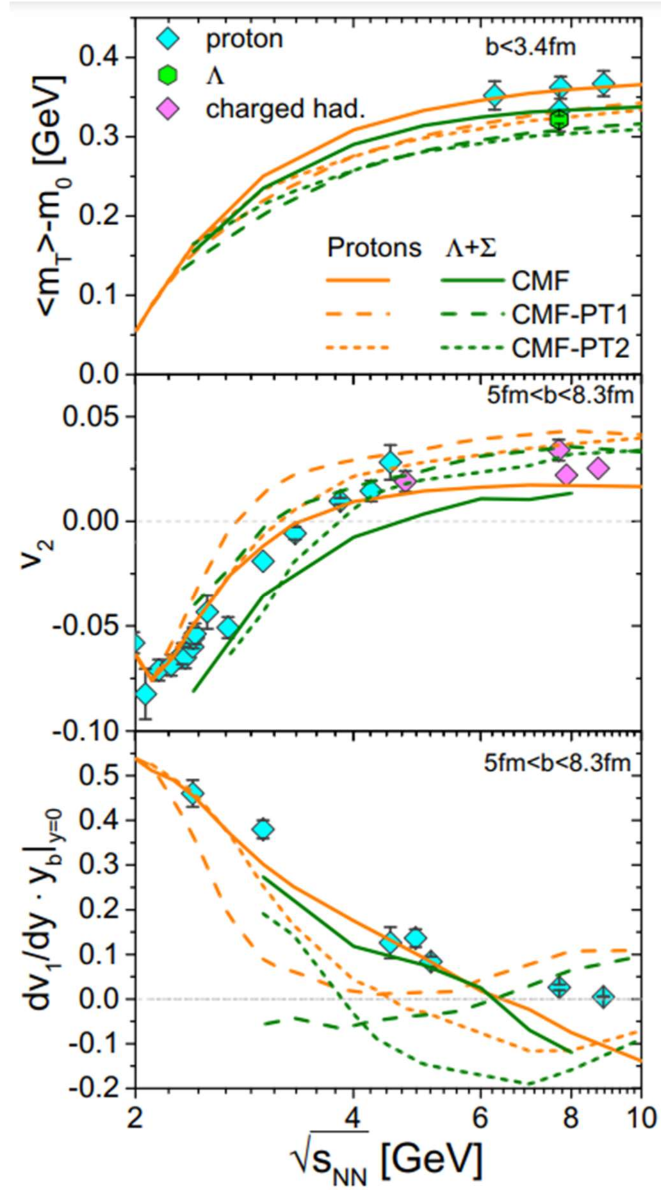
- Optimization of TOF acceptance is required to perform identified hadron flow measurements
- Azimuthal non-uniformity of detector needs to be investigated to use XX component of correlation

- Good agreement between reconstructed and pure model data for all three energies
- The results were shown on AYSS2022, ICPPA2022 and NICA2022 (proceedings are in publication)

Motivation to study the flow of Λ



Nuclear Physics A
Volume 967, November 2017, Pages 808-811



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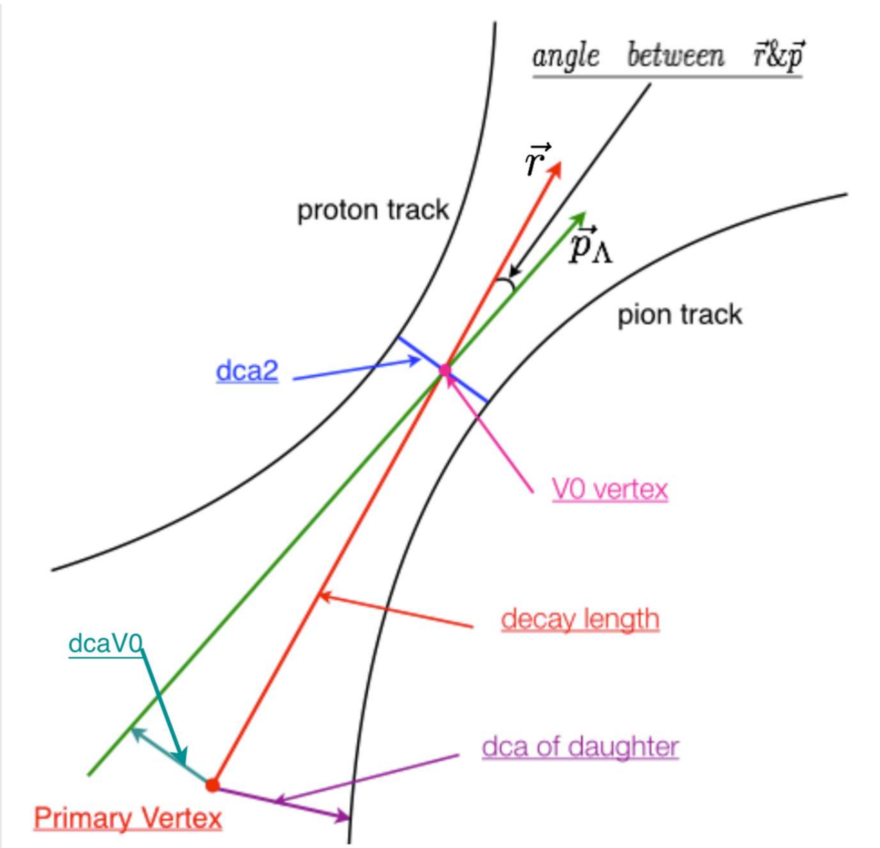
- Flow of Λ-hyperons is a sensitive probe of the hyperon-nuclei interactions
- Flow of Λ-hyperons is sensitive to the EOS of dense matter

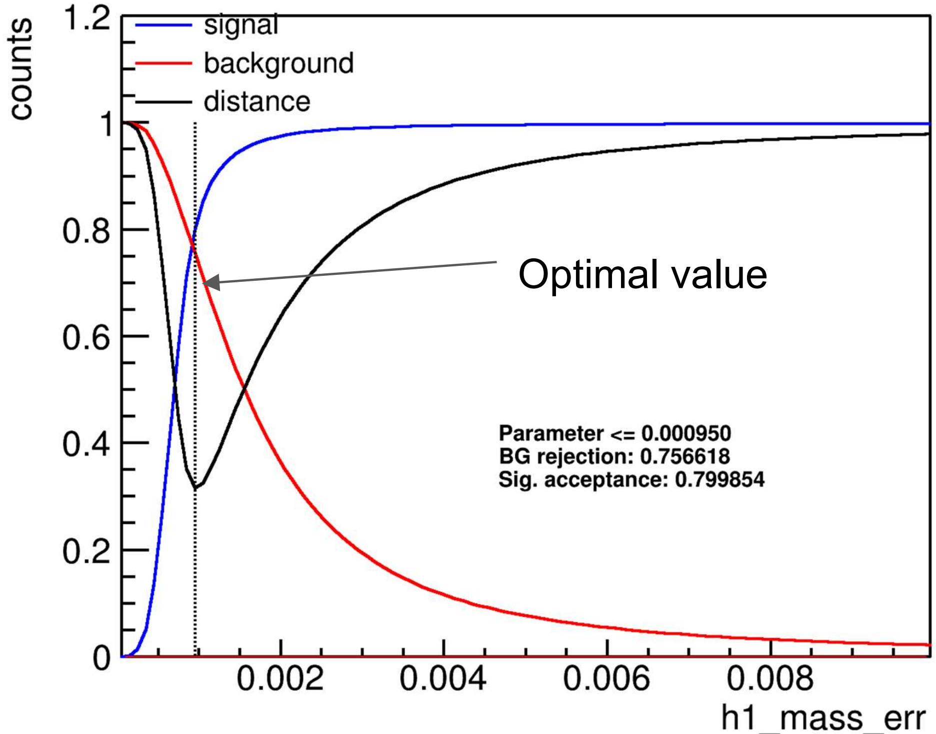
Lambda candidates reconstruction



- DCMQGSM-SMM Xe+Cs@3.0AGeV
- KFParticle framework: well tested and well documented. Used in:

- Link to the framework: https://github.com/HeavyIonAnalysis/PFSimple
- Link to the interface for BM@N data: https://github.com/mam-mih-val/bmn_particle_finder

Lambda candidates selection criteria optimization



Cuts:

- Decay length L>2.25
- Reverse relative error L/dL>6.25
- χ_{GEO} > 40
- DCA > 0.728
- X_{prim}\{p\} >50
- $\cos(p_p p_\Lambda)$ > 0.99
- X_{prim}\{pi\} >535
- X_{TOPO}<51
- Err\{m2\}<0.001

Signal is
signal acceptance ratio (SA):

$$SA(x) = \int_x^{\infty} \frac{dN^{sig}}{dt} dt$$

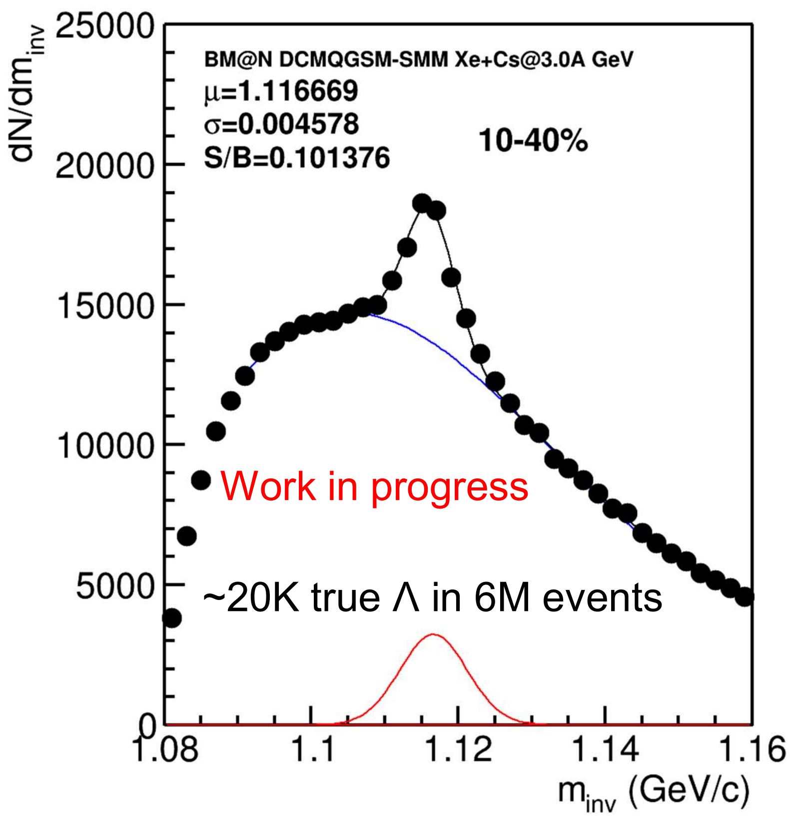
Background
is background rejection ratio (BR):

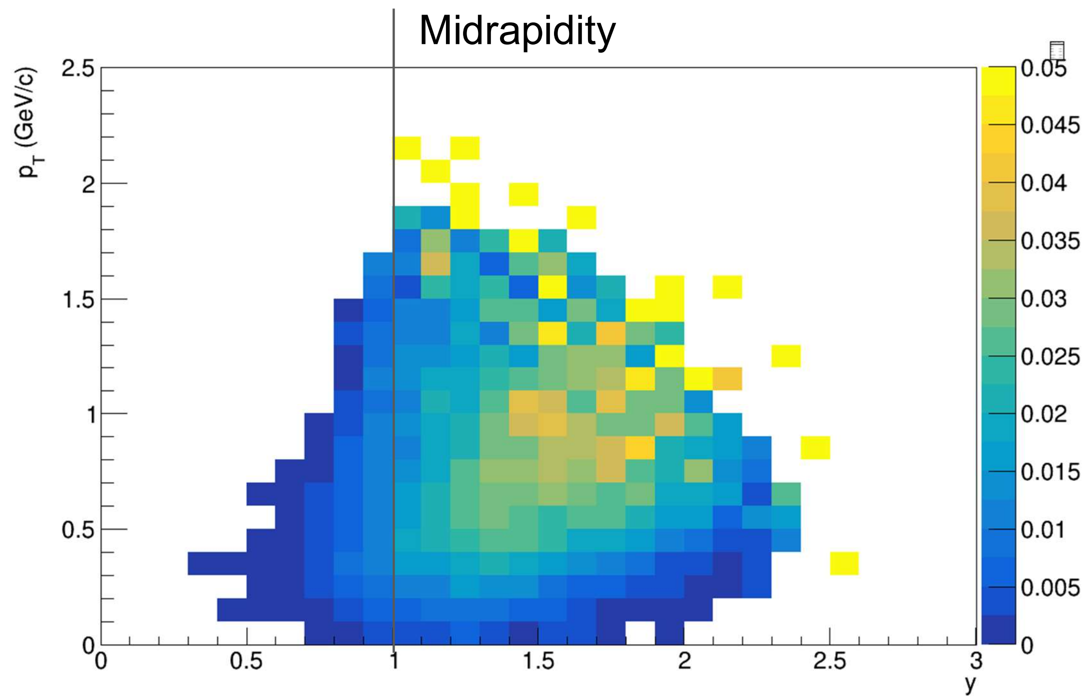
$$BR(x) = \int_{-\infty}^{x} \frac{dN^{bg}}{dt} dt$$

Distanse is (optimization function)
in the phase space from (1, 1):

$$D(x) = \sqrt{(SA(x)-1)^2 + (BR(x)-1)^2}$$

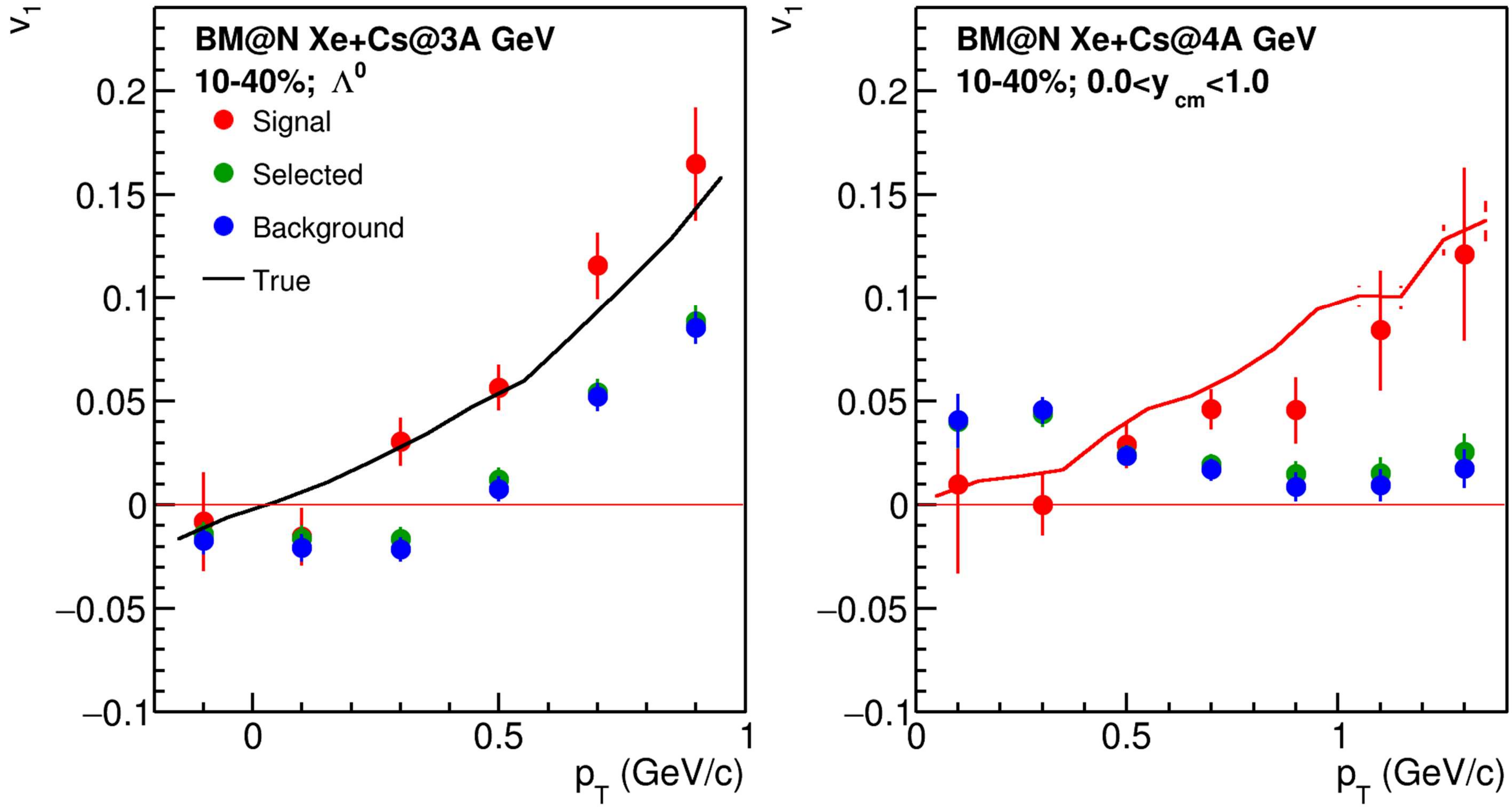
Lambda candidates invariant mass and efficiency





It is possible to achieve S/B~0.7, but it significantly reduces amount of statistics

v_1 of lambda hyperons

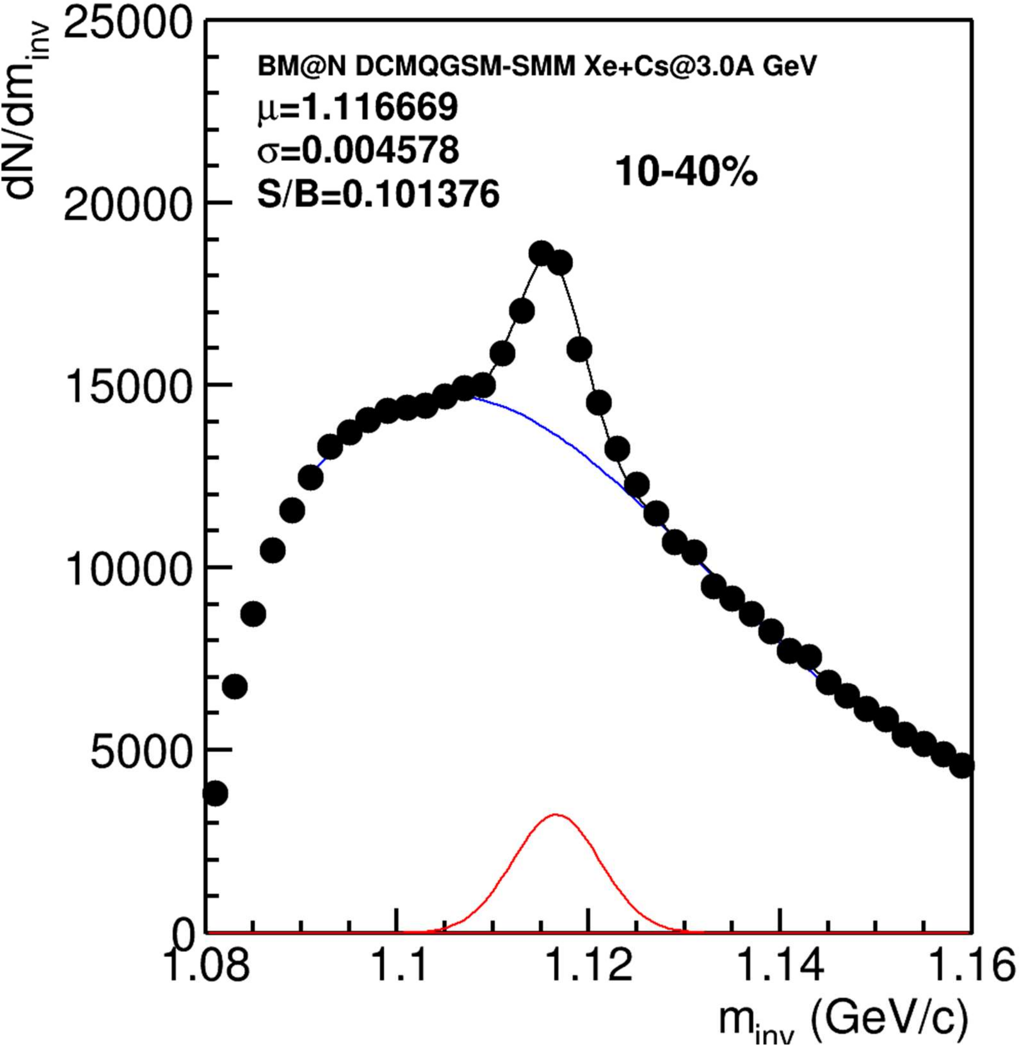


Flow of signal is in a good agreement with model

Summary

- Resolution correction factor is calculated for DCMQGSM-SMM Xe+Cs collisions at beam energies of 4A, 3A and 1.5A GeV:
  - Using only FHCal sub-events for resolution calculation gives biased estimation due to transverse hadronic showers propagation
  - Using additional sub-events from tracking provides with a robust estimation
- Good agreement between model and reconstructed data is observed for v_1 and v_2 at 2A, 3A and 4A GeV
- Results on the feasibility study towards proton v_1 and v_2 were presented on AYSS2022, ICPPA2022 and NICA2022
- Lambda candidates were reconstructed for DCMQGSM-SMM Xe+Cs@3A GeV collisions with KFParticle
- v_1 was measured for lambda candidates
- Further fine-tuning is required for background suppression to separate flow of background and signal

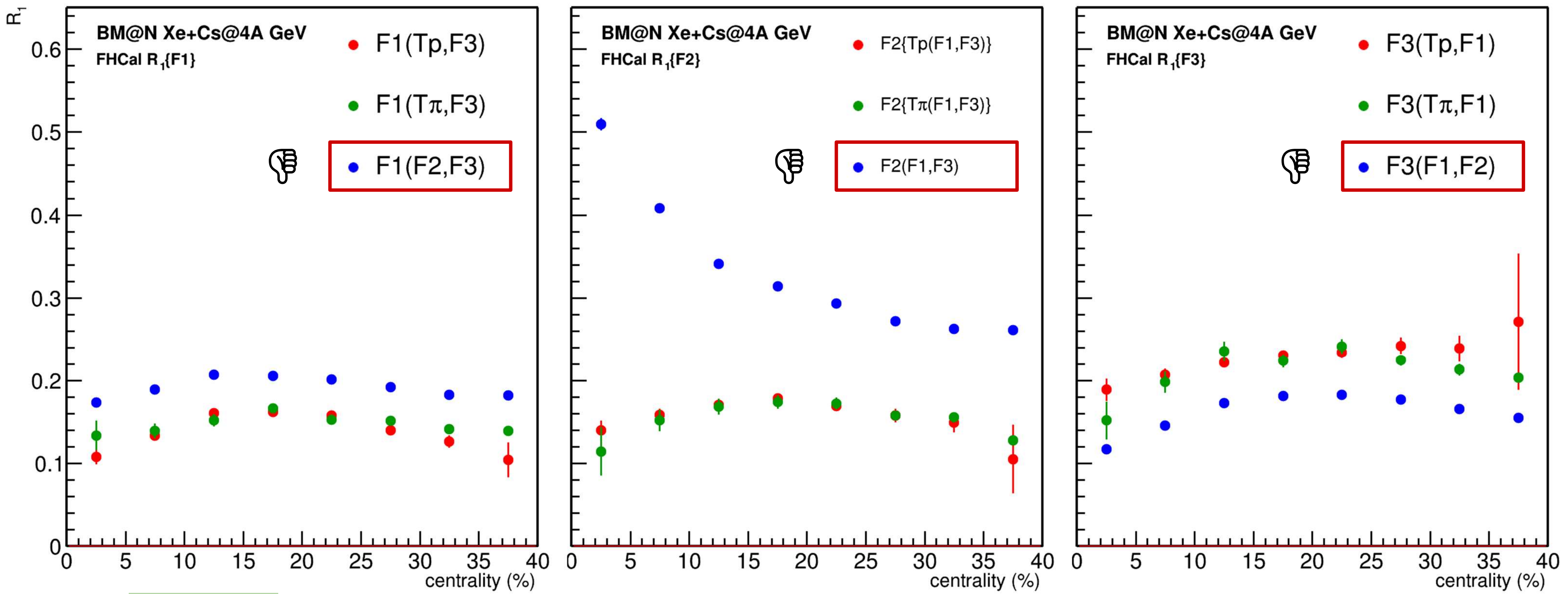
Outlook

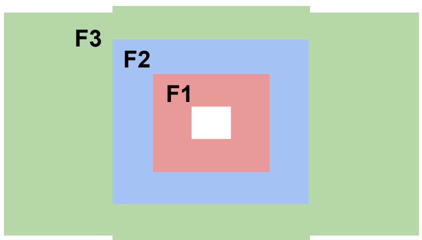


- Improving S/B ratio as well as saving as much signal as possible
- Fitting the $v_1(m_{inv})$ bin-by-bin to separate signal and background flow

BACKUP

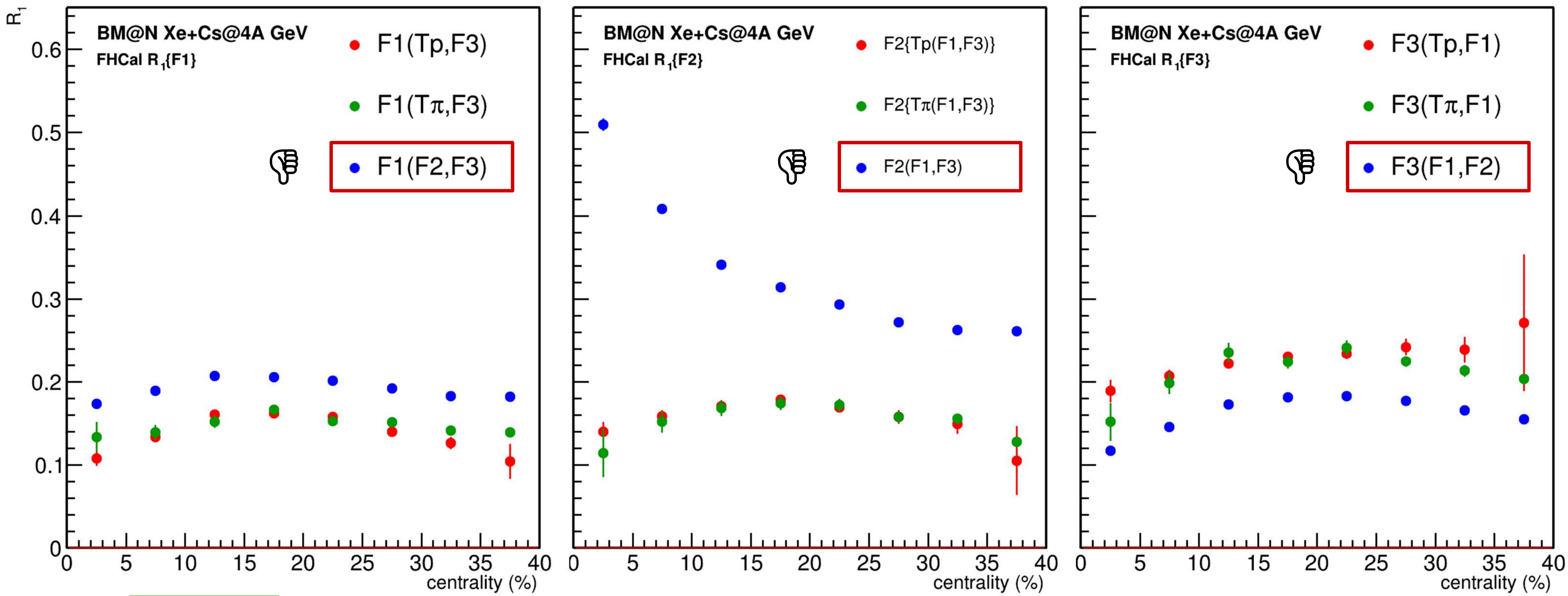
Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV

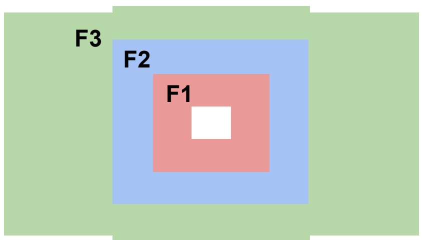




Bias due to leakage of hadronic shower
between neighbouring FHCal subevents:
we shall not use this resolution in the further analysis

Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV





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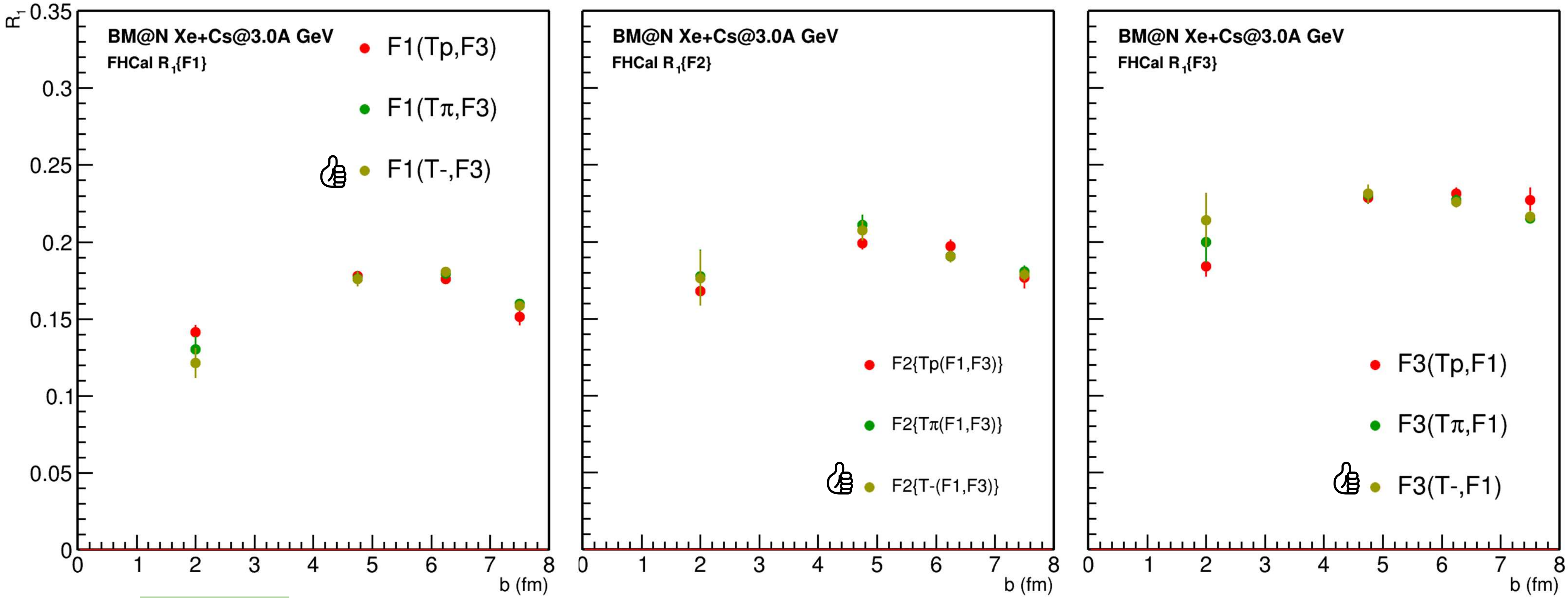

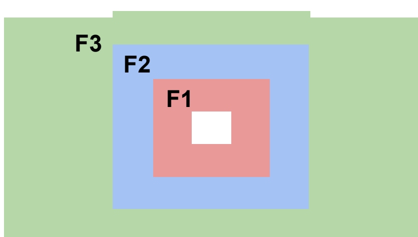

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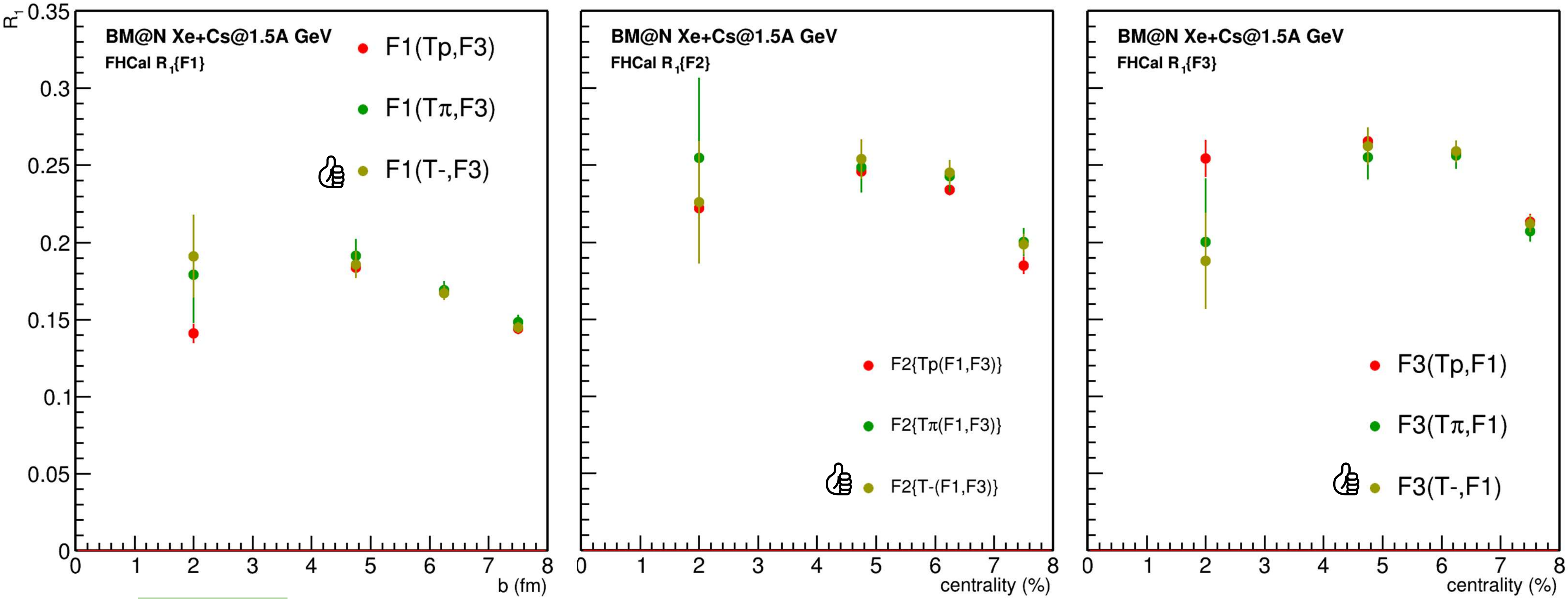
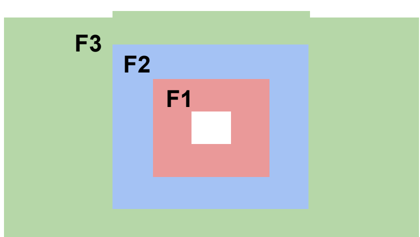
Rec R1: DCMQGCM-SMM Xe+Cs@1.5A GeV





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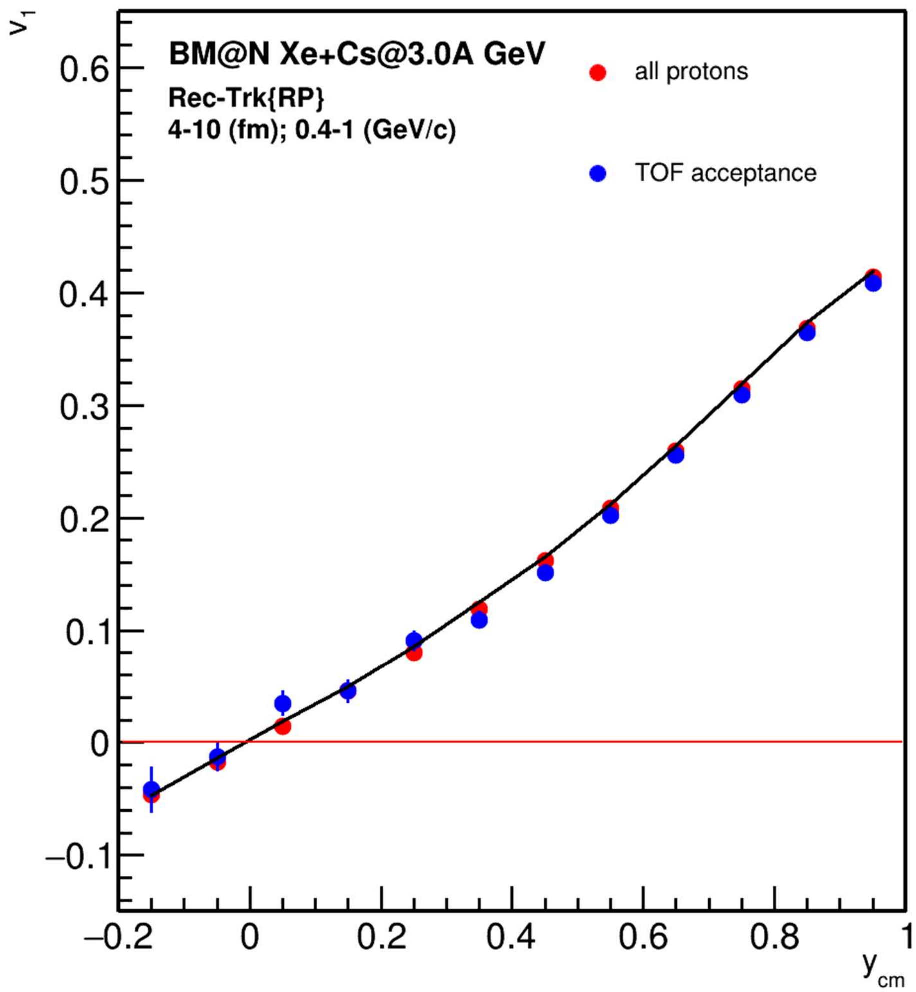
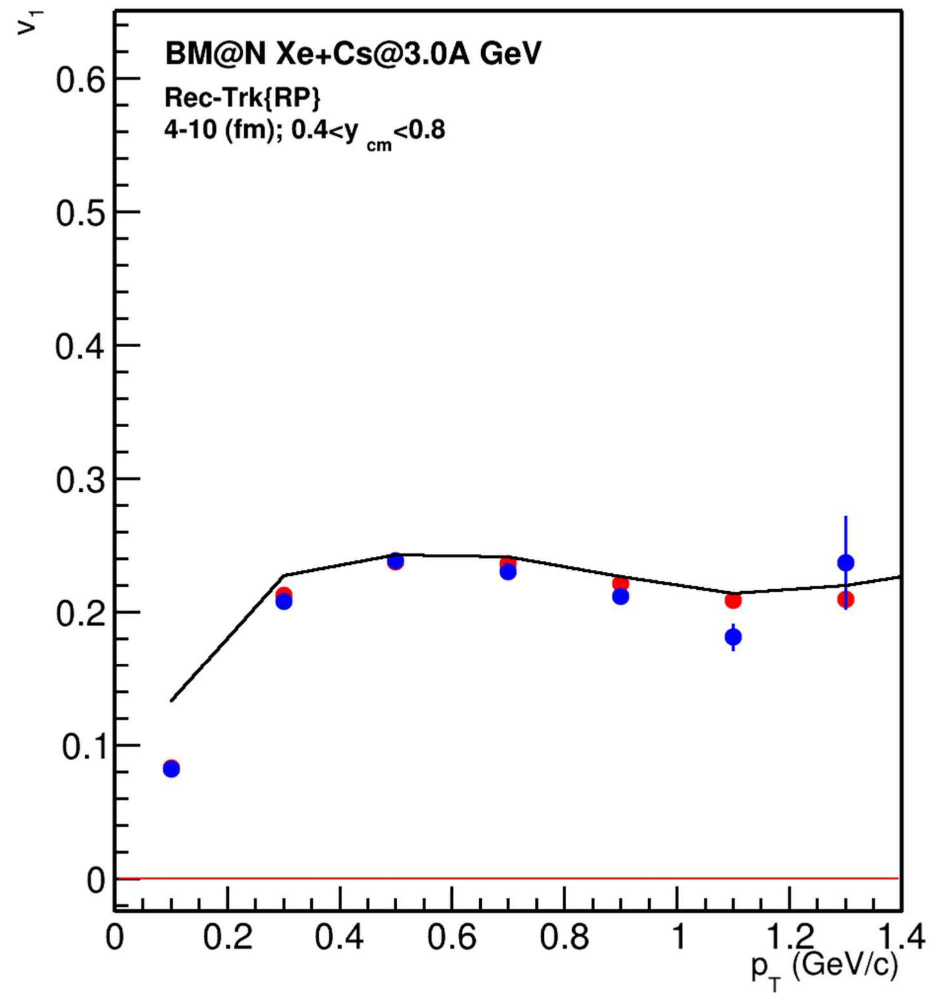
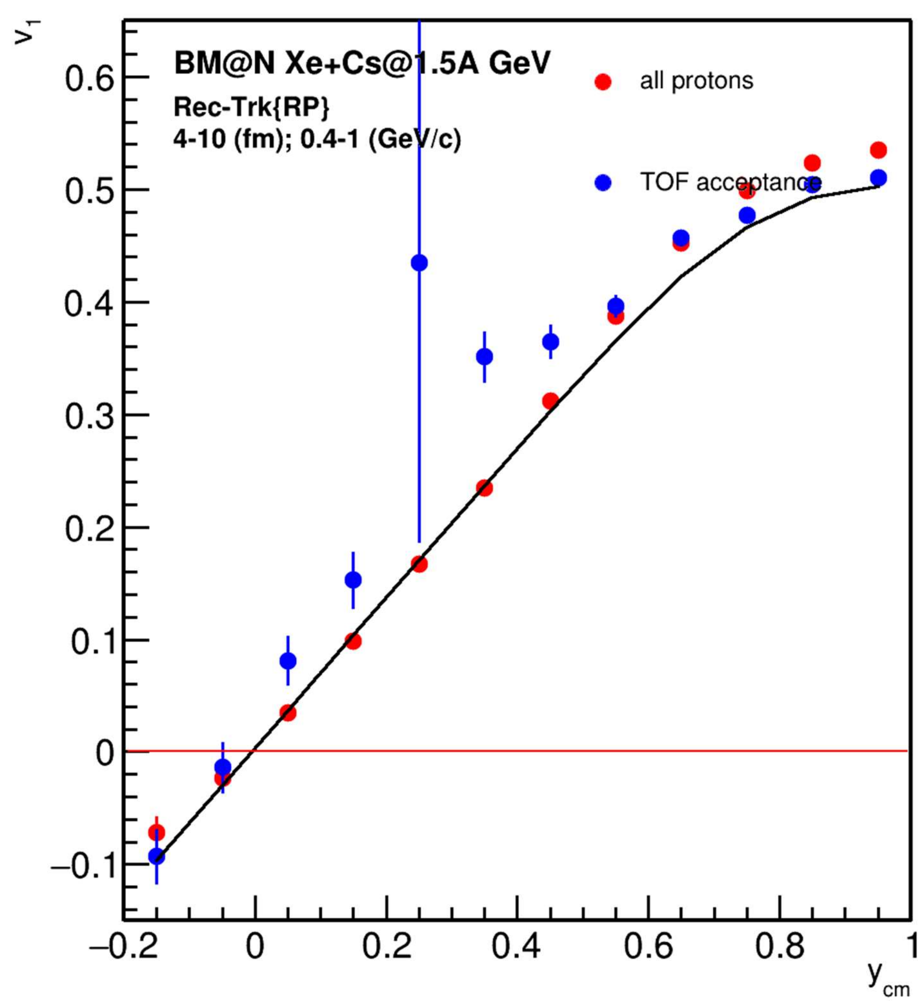
T-: all negative; 1.0<η<2.0; 0.1 < p_T < 0.5 GeV/c; w=1/eff

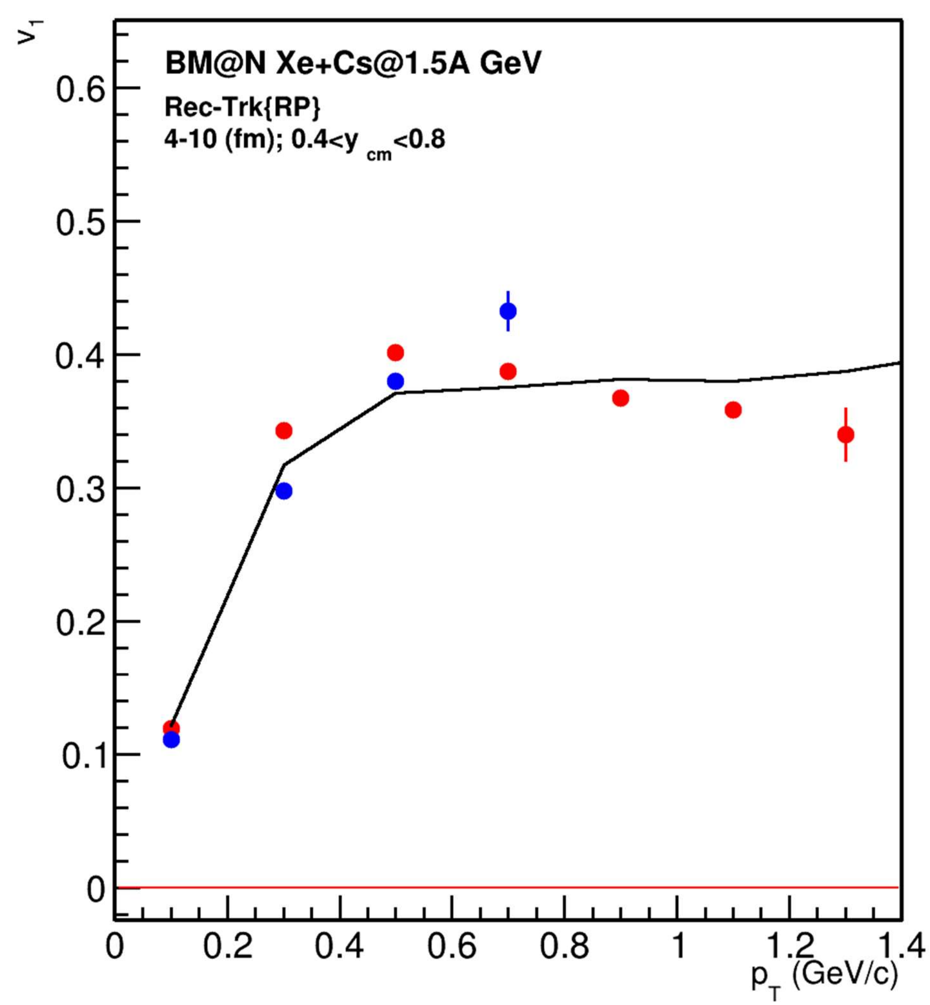
v_1: Xe+Cs@3.0A GeV: JAM (true momenta)



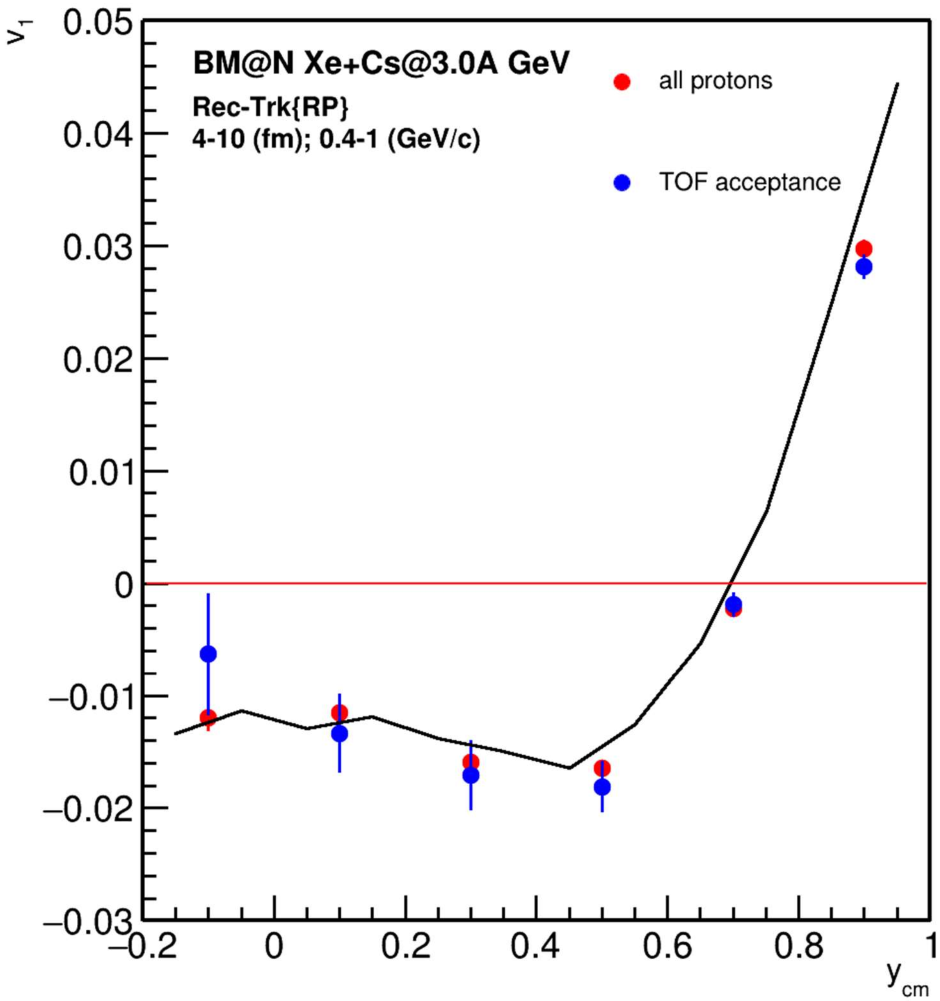


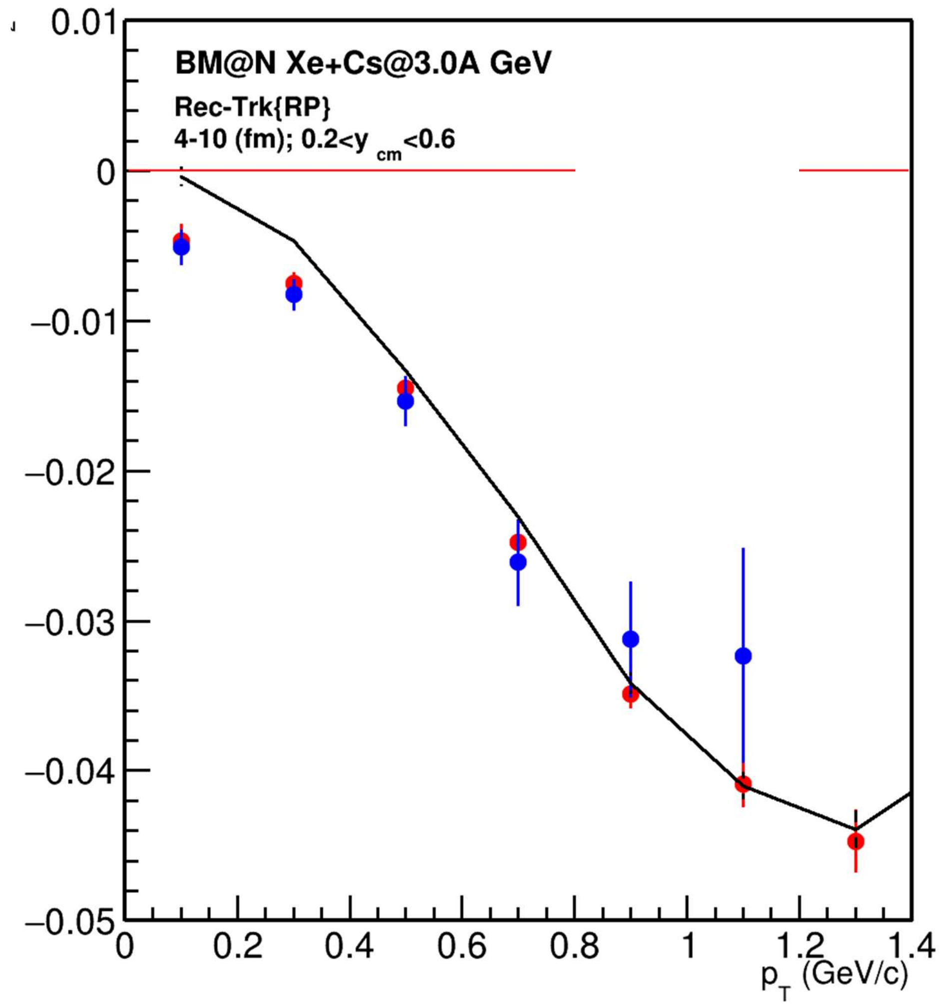
v_1: Xe+Cs@1.5A GeV: JAM (true momenta)



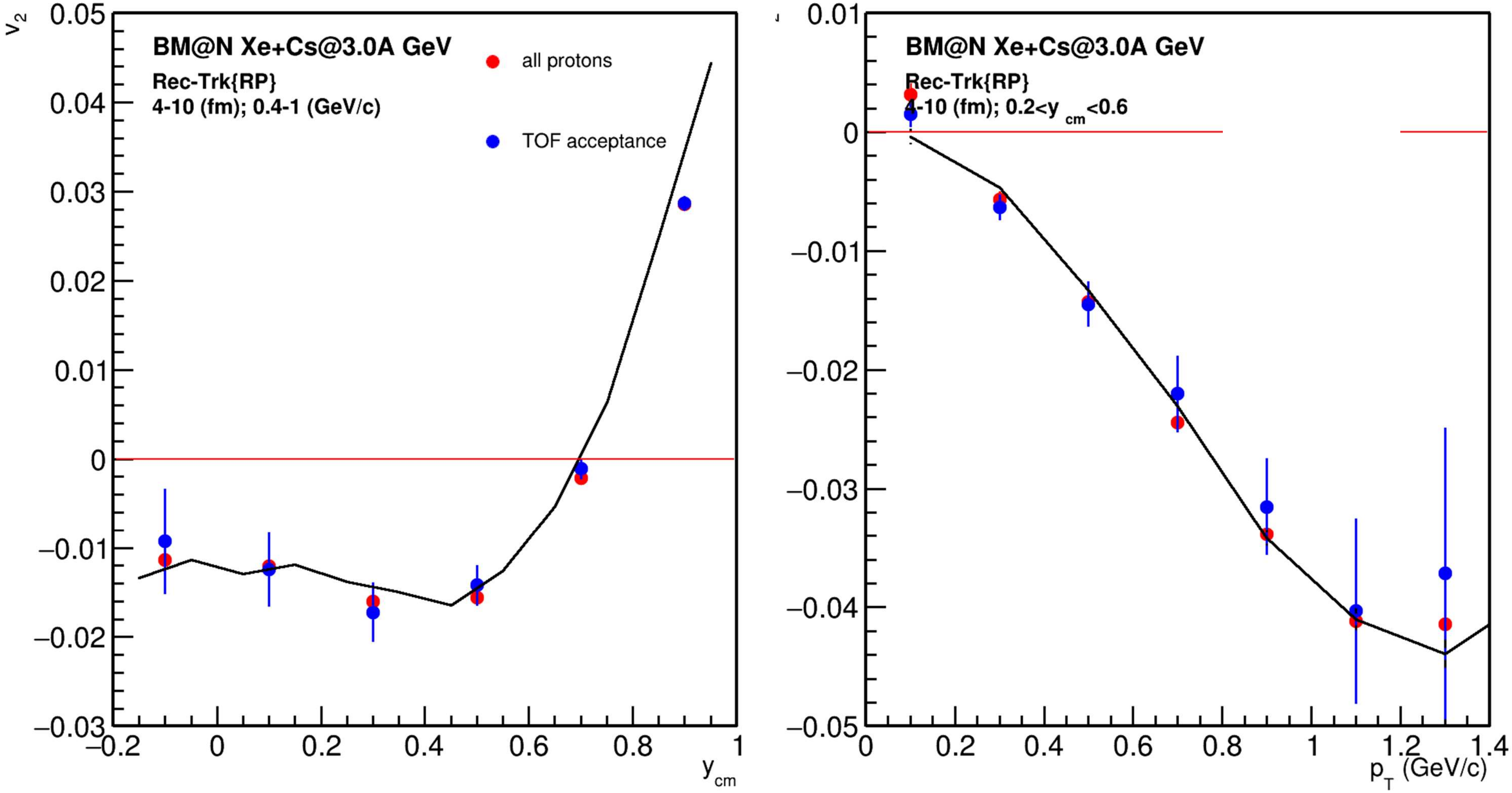


v_2: Xe+Cs@3.0A GeV: JAM (true momenta)



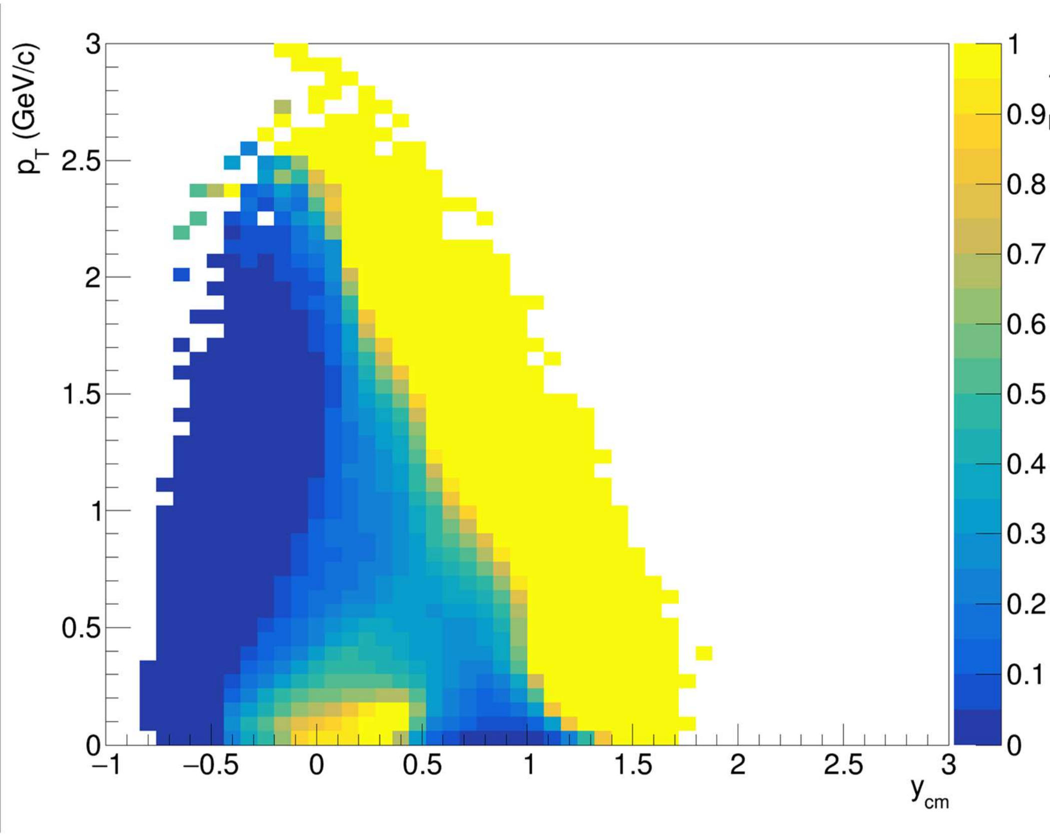


v_2: Xe+Cs@3.0A GeV: JAM (rec momenta)

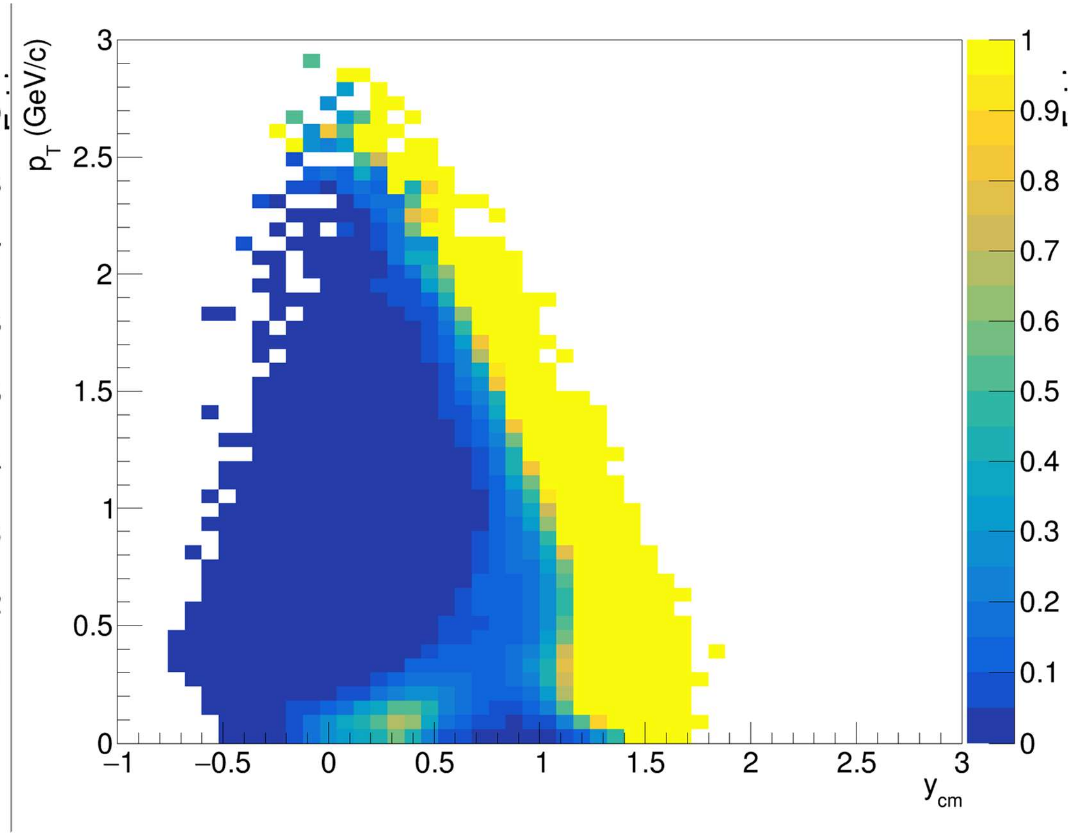


Efficiency for proton reconstruction (JAM, Xe+Cs@1.5A GeV)

Without TOF acceptance

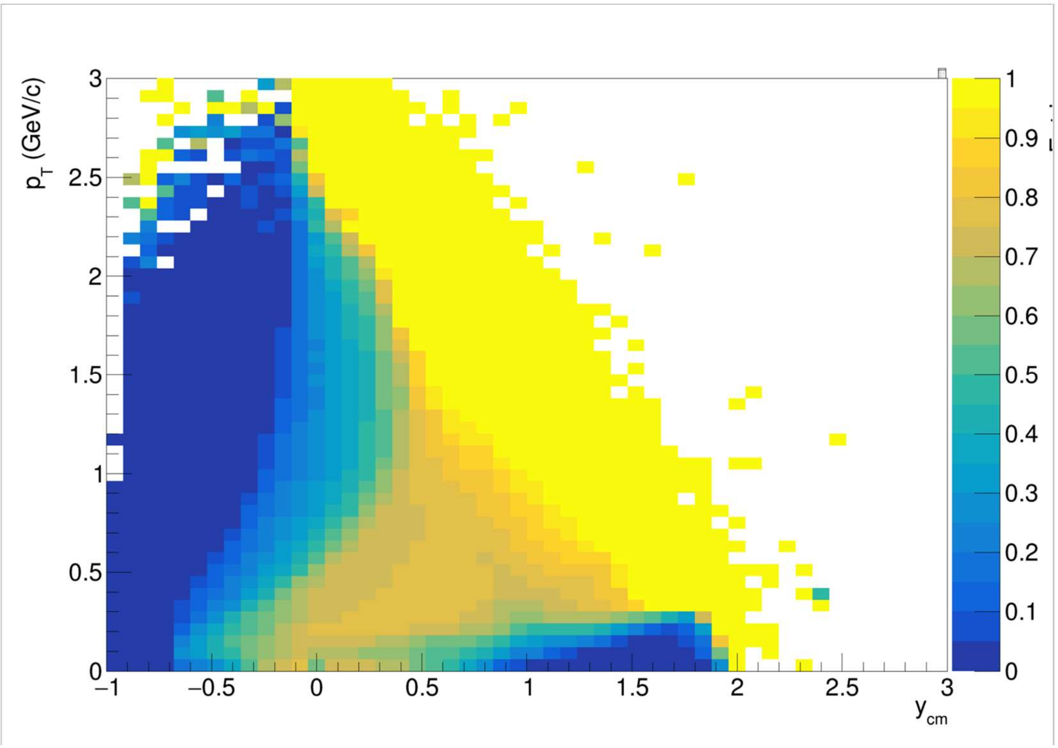


With TOF acceptance

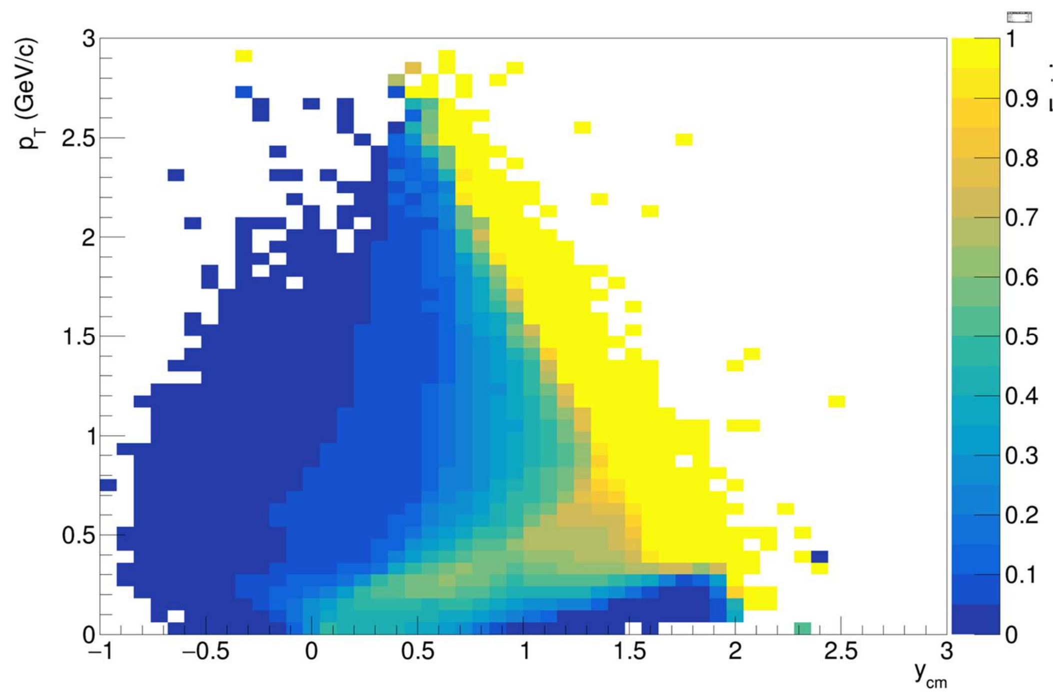


Efficiency for proton reconstruction (JAM, Xe+Cs@3A GeV)

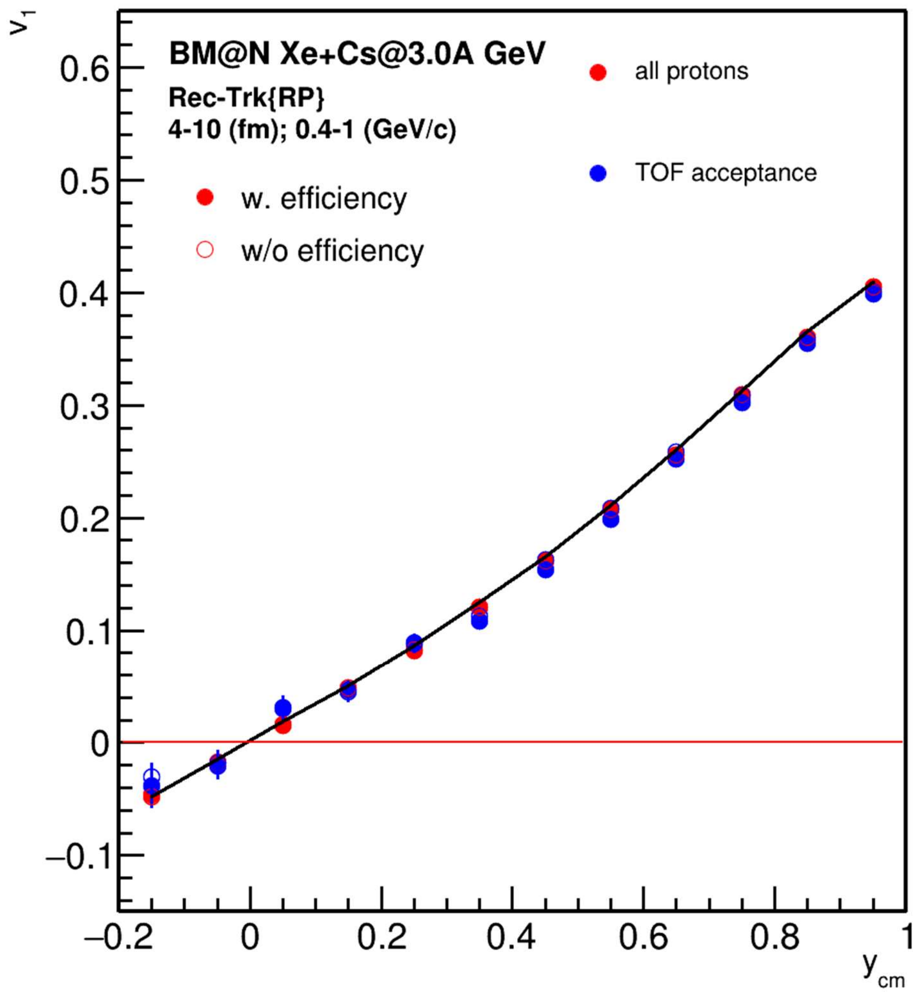
Without TOF acceptance

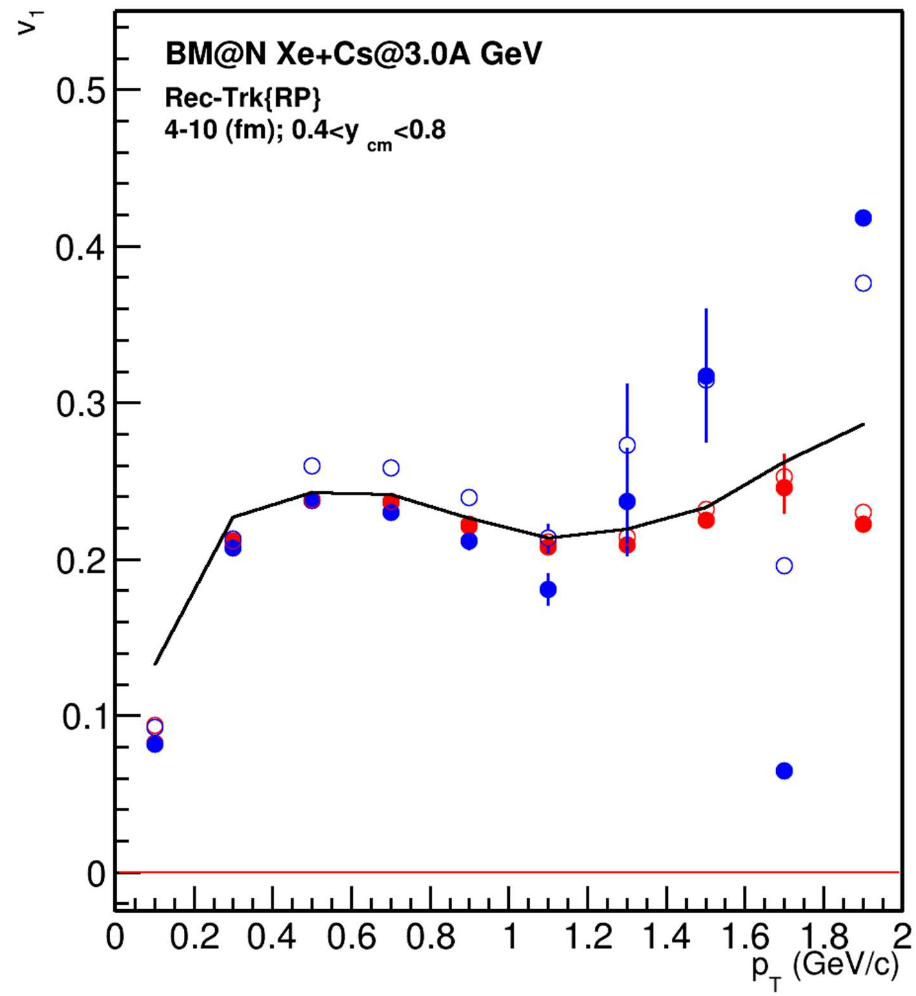


With TOF acceptance

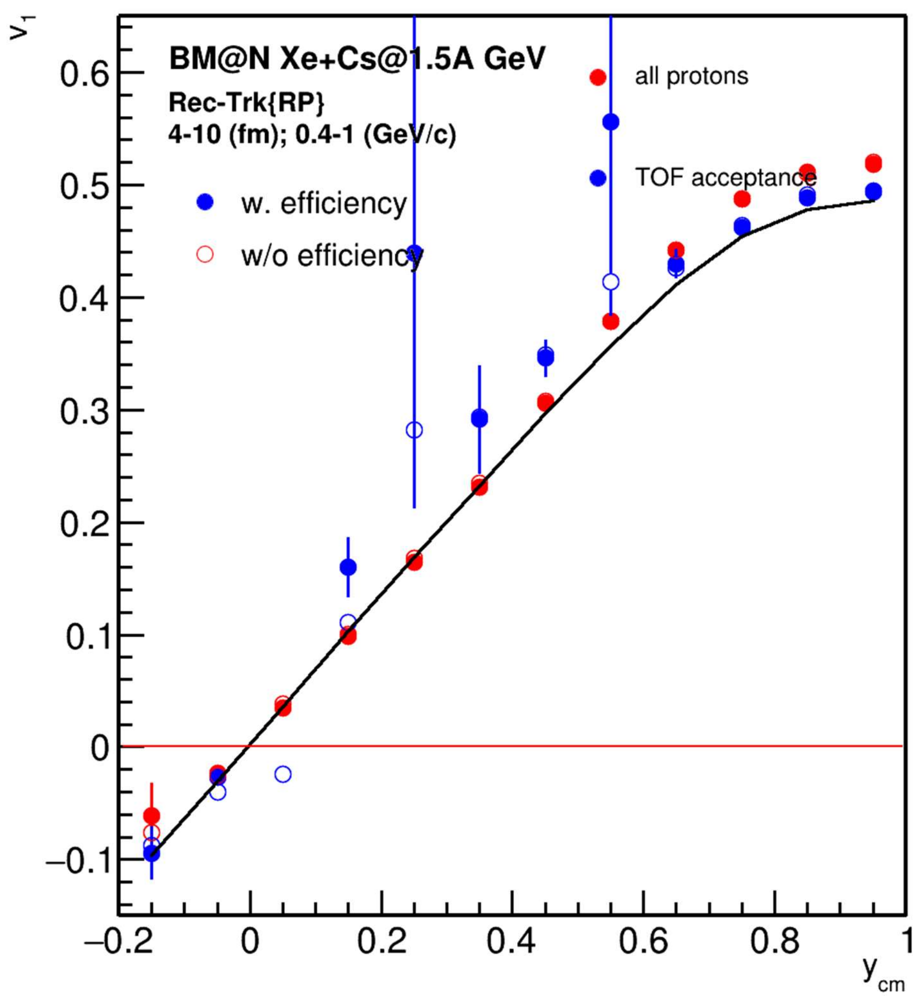


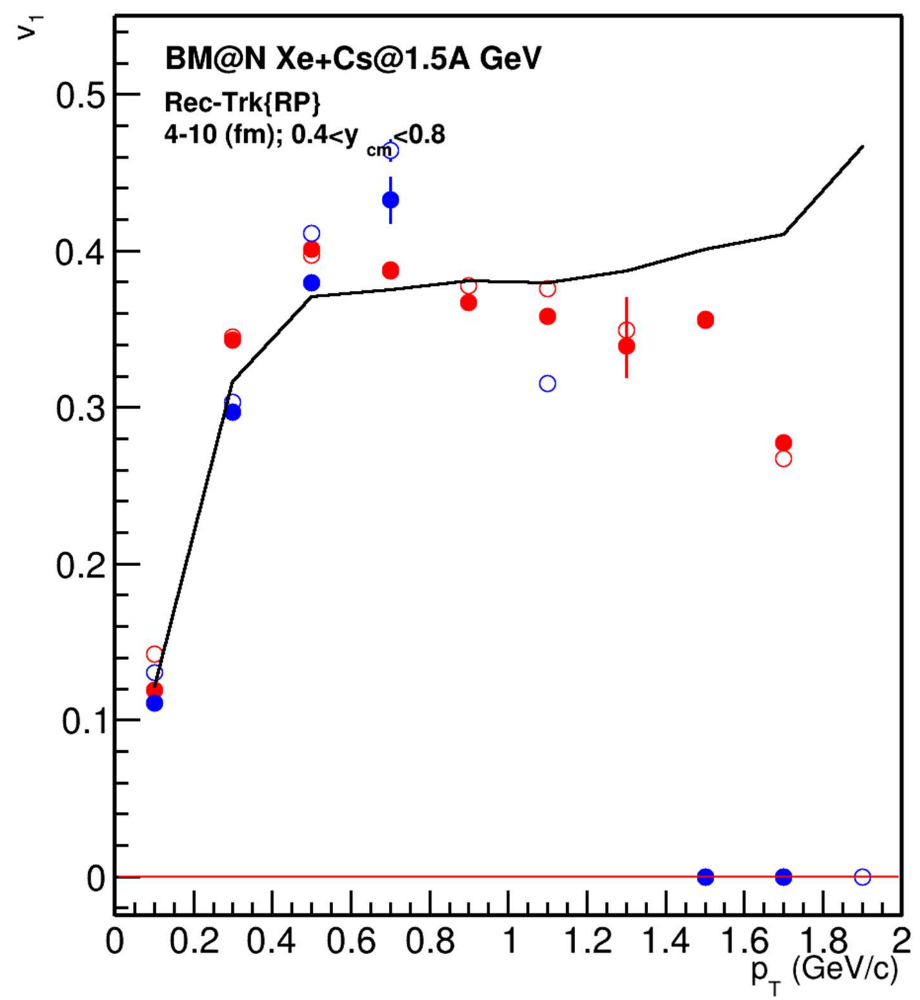
v_1: Xe+Cs@3.0A GeV: JAM (true momenta)





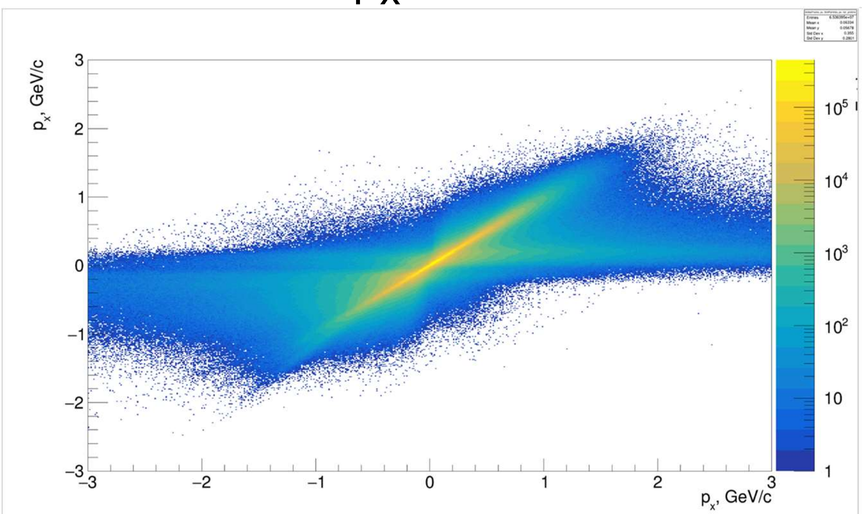
v_1: Xe+Cs@1.5A GeV: JAM (true momenta)

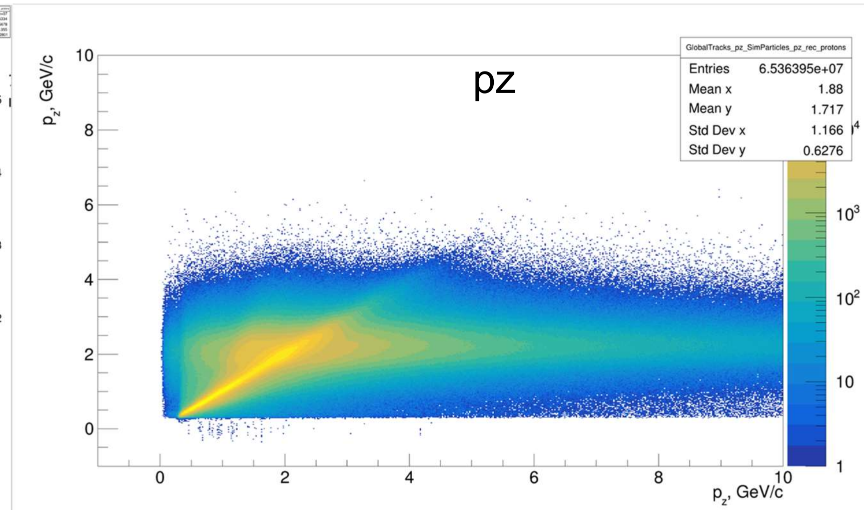




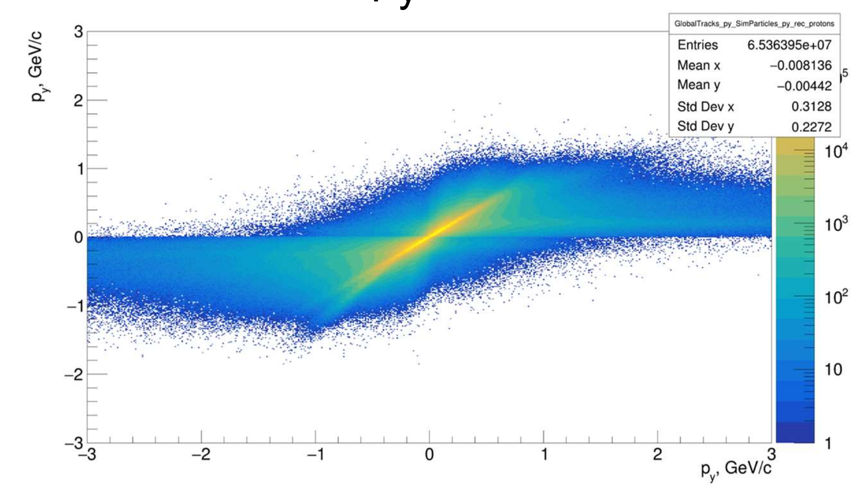
Momentum reconstruction for protons in Xe+Cs@1.5A GeV

Px

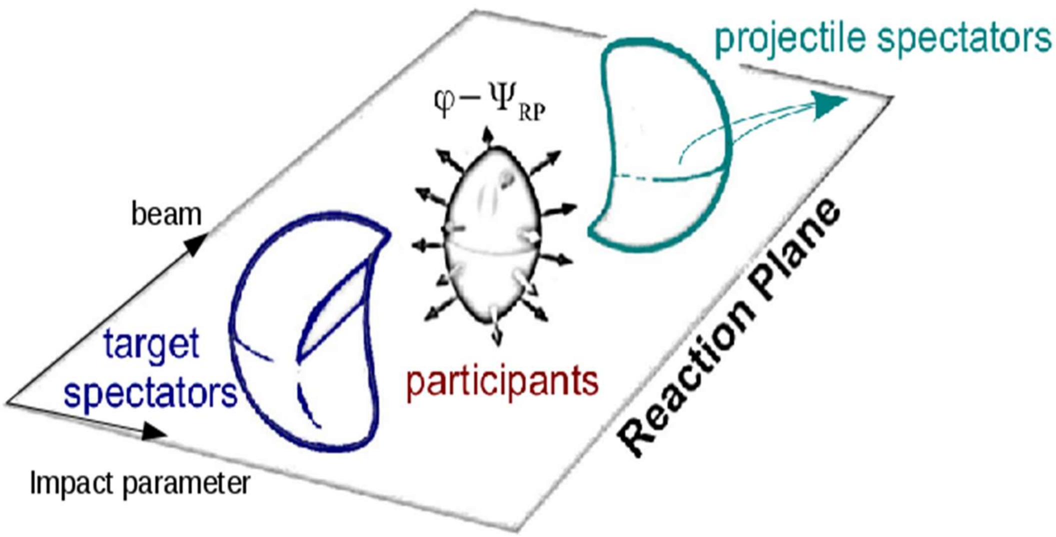




Py



Collision geometry and anisotropic transverse flow



$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_{RP})\right)\right)$$

$$\Downarrow$$

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

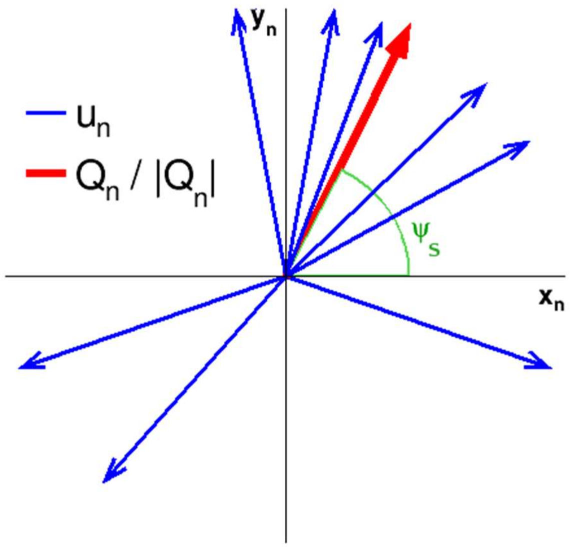
Asymmetry in coordinate space converts

(due to interaction & depending on the properties created matter)

into momentum asymmetry with respect to the collision symmetry plane

Scalar product method for v_n measurement

$\mathbf{u}$ and $\mathbf{Q}$-vectors:



$$\mathbf{u_n} = \{u_{n,x}, u_{n,y}\} = \{\cos n\phi, \sin n\phi\}$$

$$\mathbf{Q_n} = \{Q_{n,x}, Q_{n,y}\} = \frac{1}{\sum\limits_k w^k} \left\{ \sum_k w^k u^k_{n,x}, \sum_k w^k u^k_{n,y} \right\}$$

Scalar product method:

v_n with respect to symmetry plane Ψ_S estimated using group of particles "*a*":

$$v^a_{1,i}(p_T, y) = \frac{2\langle u_{1,i}(p_T, y) Q^a_{1,i}\rangle}{R^a_{1,i}}, \; i = x, y.$$

$R^a_{1,i}$ - 1st order event plane resolution correction

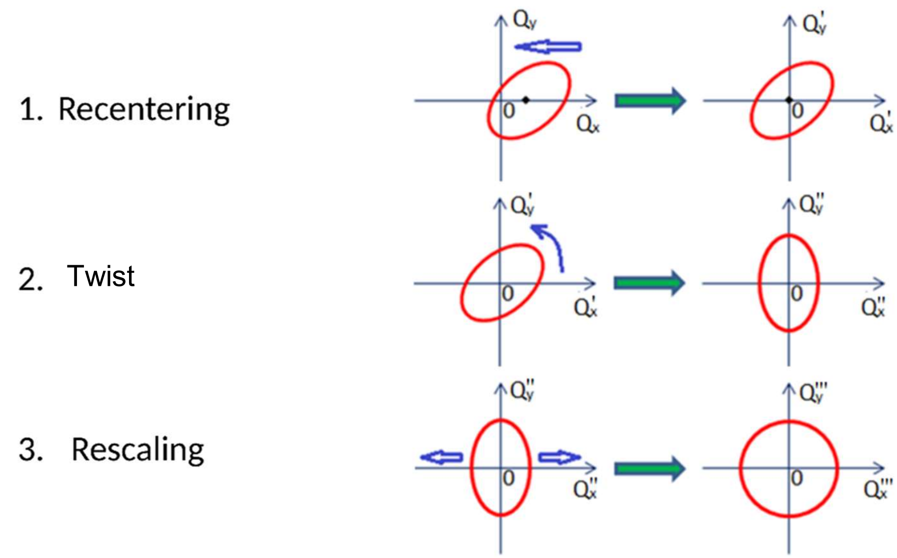
$$R^{a,MC}_{1,x} = \langle Q^a_{1,x} \cos \Psi_{RP}\rangle, \; R^{a,MC}_{1,y} = \langle Q^a_{1,y} \sin \Psi_{RP}\rangle$$

QnTools framework

Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

Originally implemented as QnCorrections framework for ALICE experiment at CERN:
J. Onderwaater, I. Selyuzhenkov, V. Gonzalez

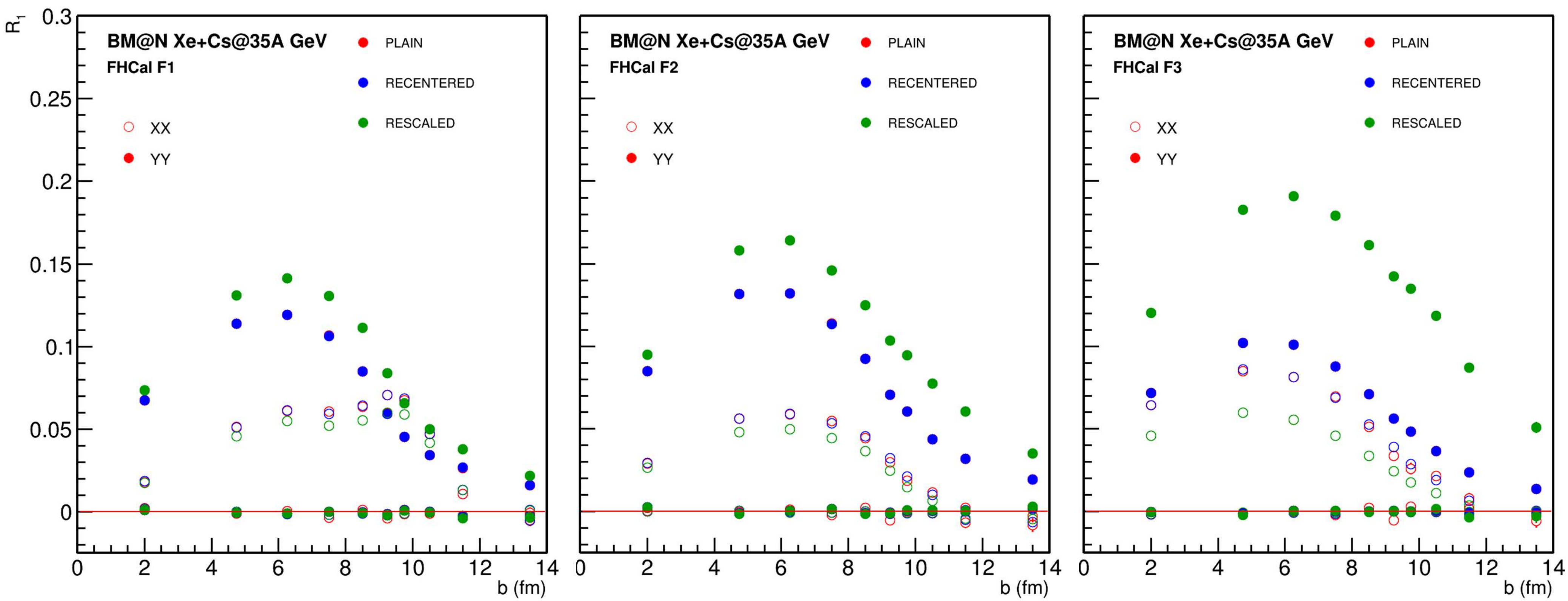
QnTools analysis package:
https://github.com/HeavyIonAnalysis/QnTools



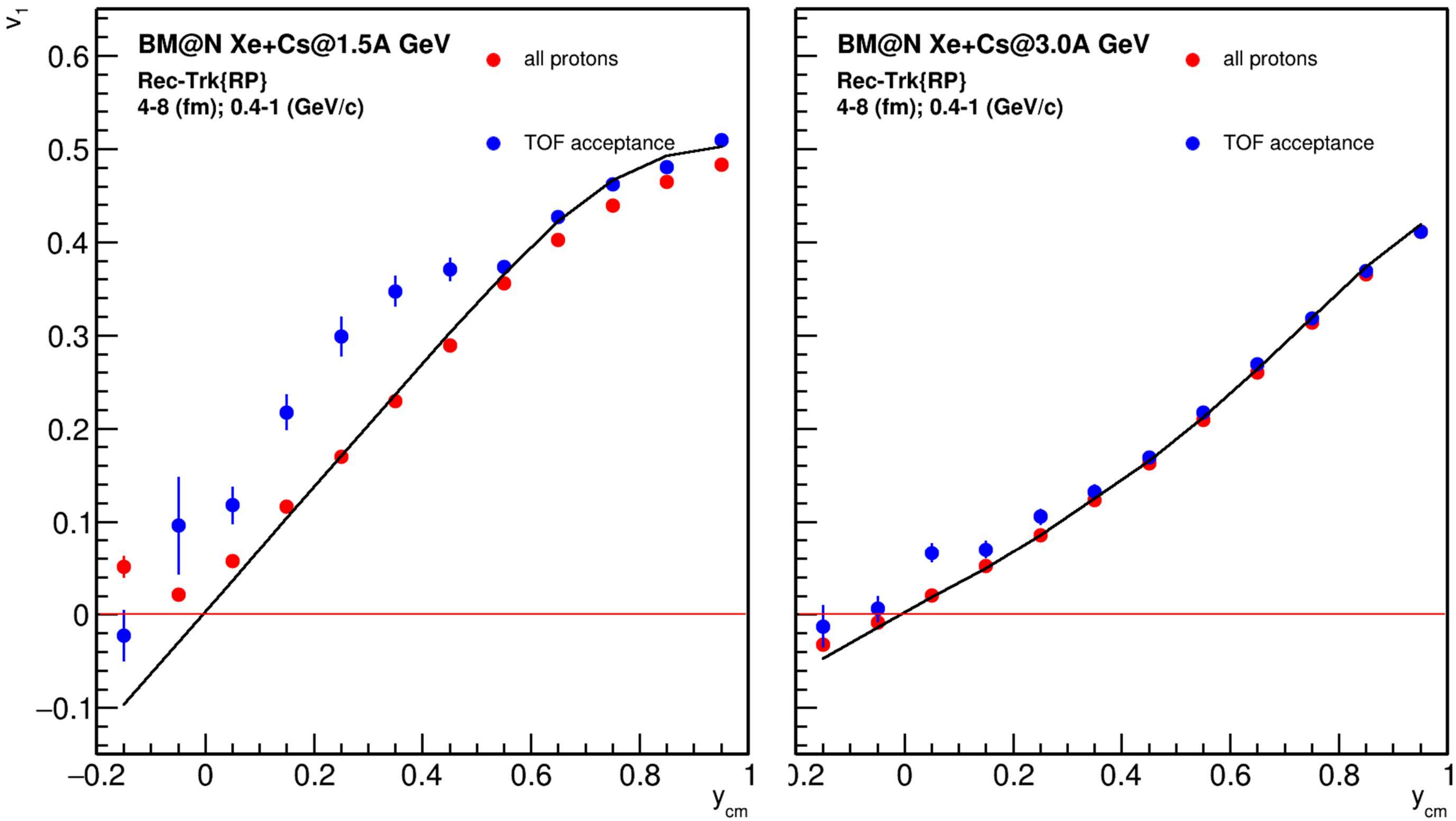
QnTools configuration

Q-vector	Q_n weight	Correction axes	Correction steps	Error calculation	Q_n Normalization
Protons	1	p_T [0.0, 2.00], 5 bins y_{cm}[-0.1, 0.1], 20 bins b, 10 bins	Recentering Twist Rescaling	Bootstrapping, 100 samples	Sum of Weights (SP) Unity (EP)
Fragments	Module charge	b, 10 bins			

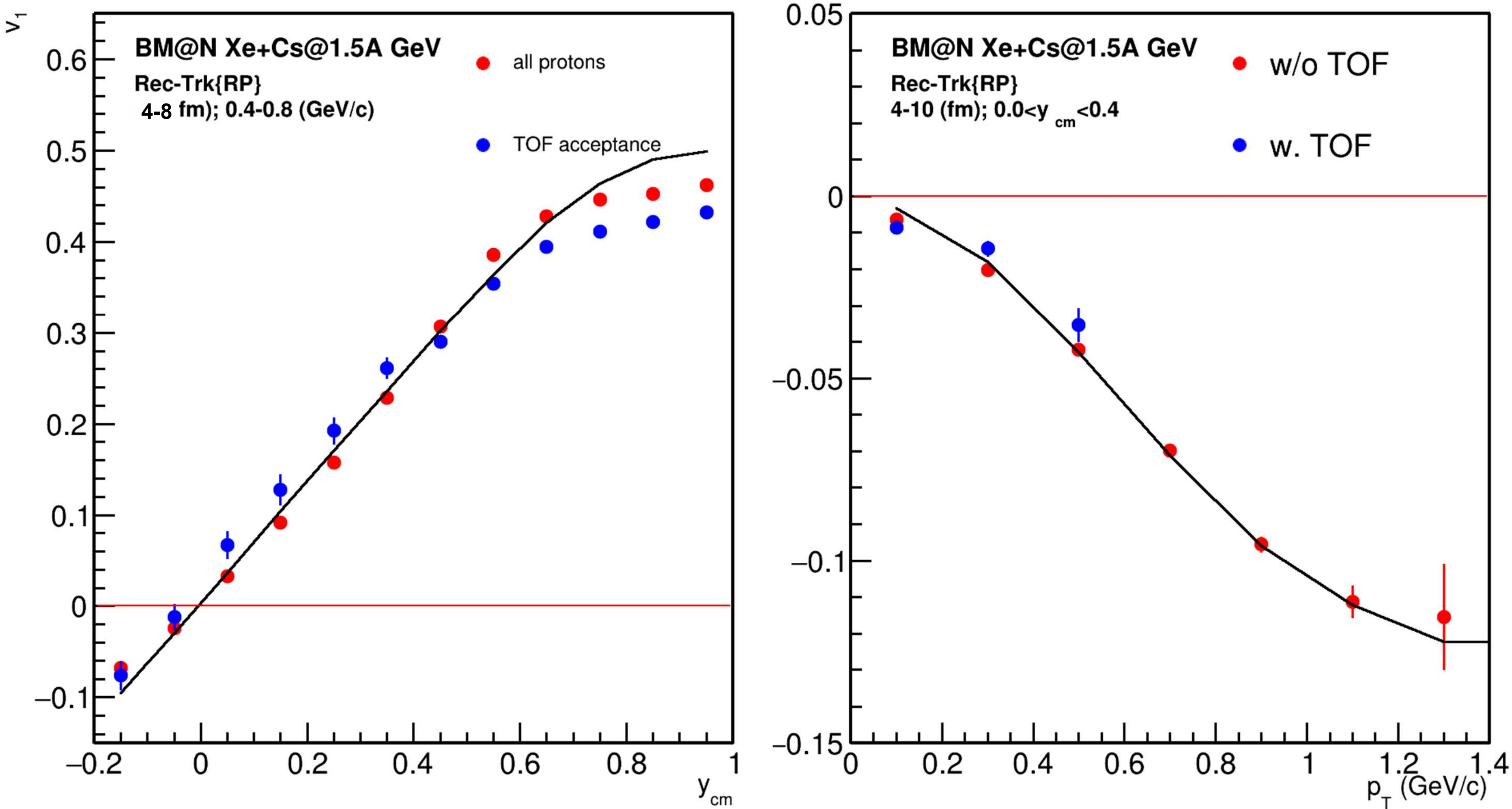
True R1: DCMQGCM-SMM Xe+Cs@3A GeV



v_1: Xe+Cs: True momenta



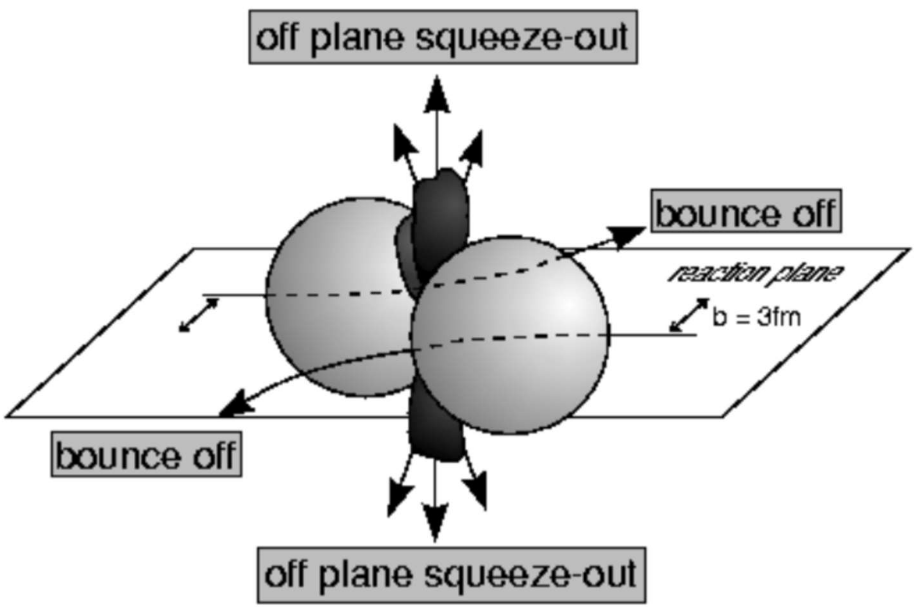
v_2: Xe+Cs@3.0A GeV: JAM (true momenta)



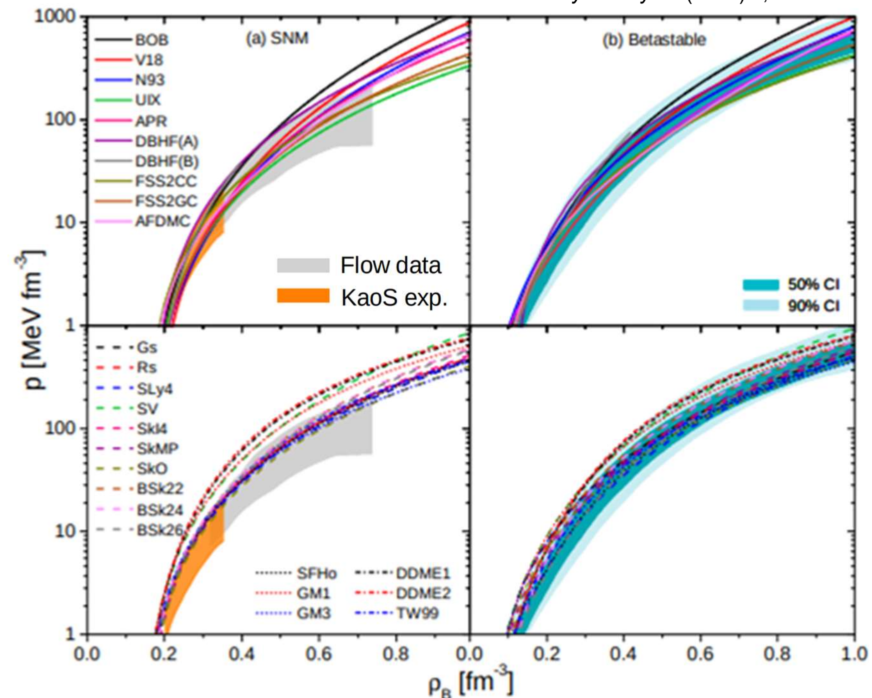
Momentum reconstruction procedure requires refinement at lower energies

Collective flow in heavy-ion collisions

spatial asymmetry of the initial pressure distribution transforms into anisotropic emission of produced particles via interaction inside the overlapping region of colliding nuclei

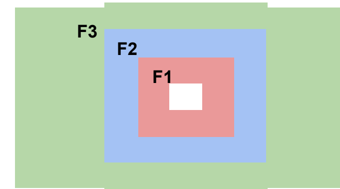


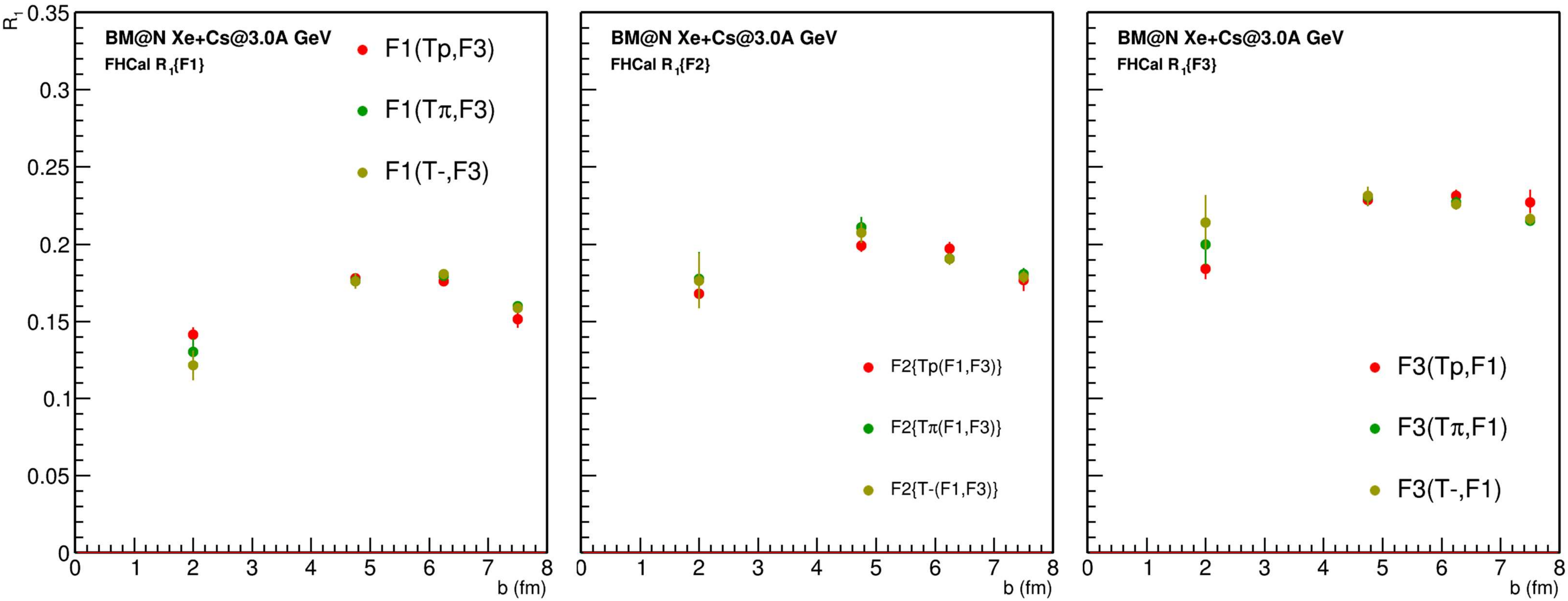
Symmetry 13 (2021) 3, 400



Anisotropic flow measurements can constrain compressibility of the matter created in the collision

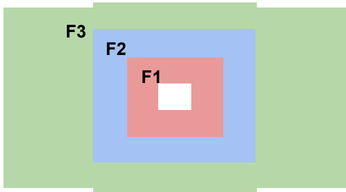
Rec R1: DCMQGCM-SMM Xe+Cs@3A GeV

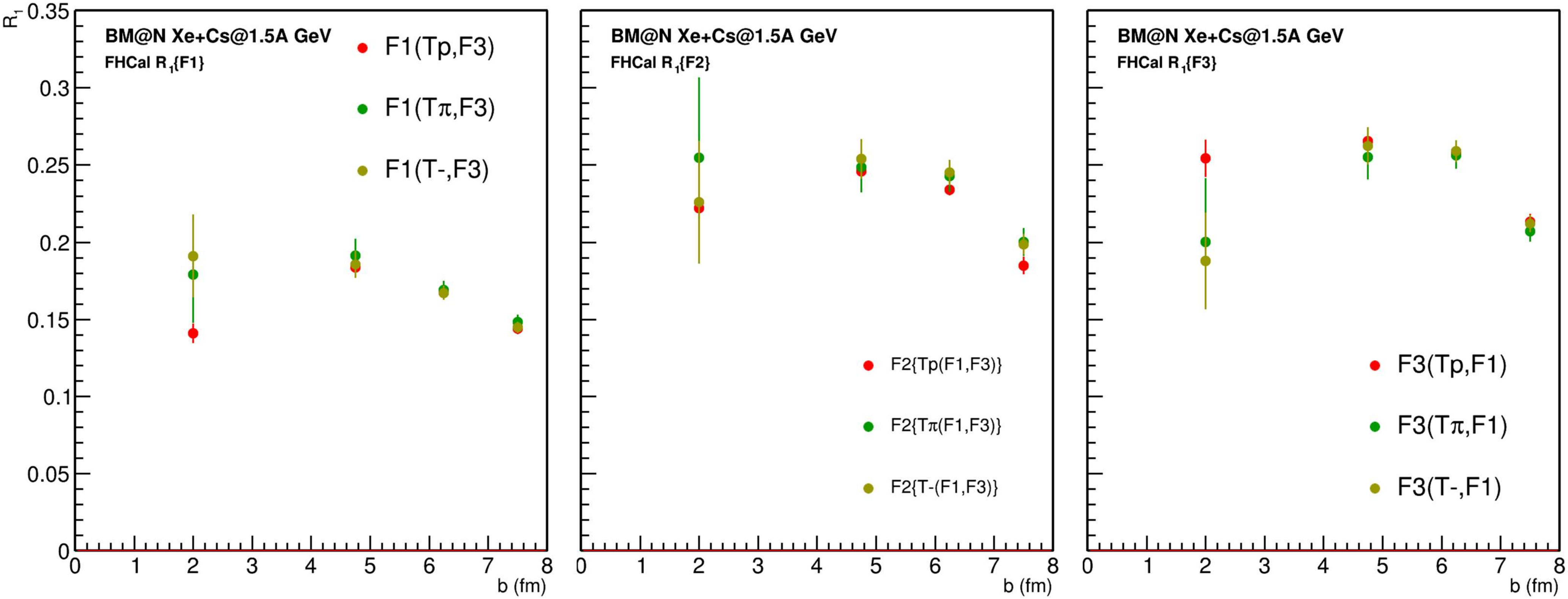




We can use unidentified negatively charged tracks as well for resolution calculation

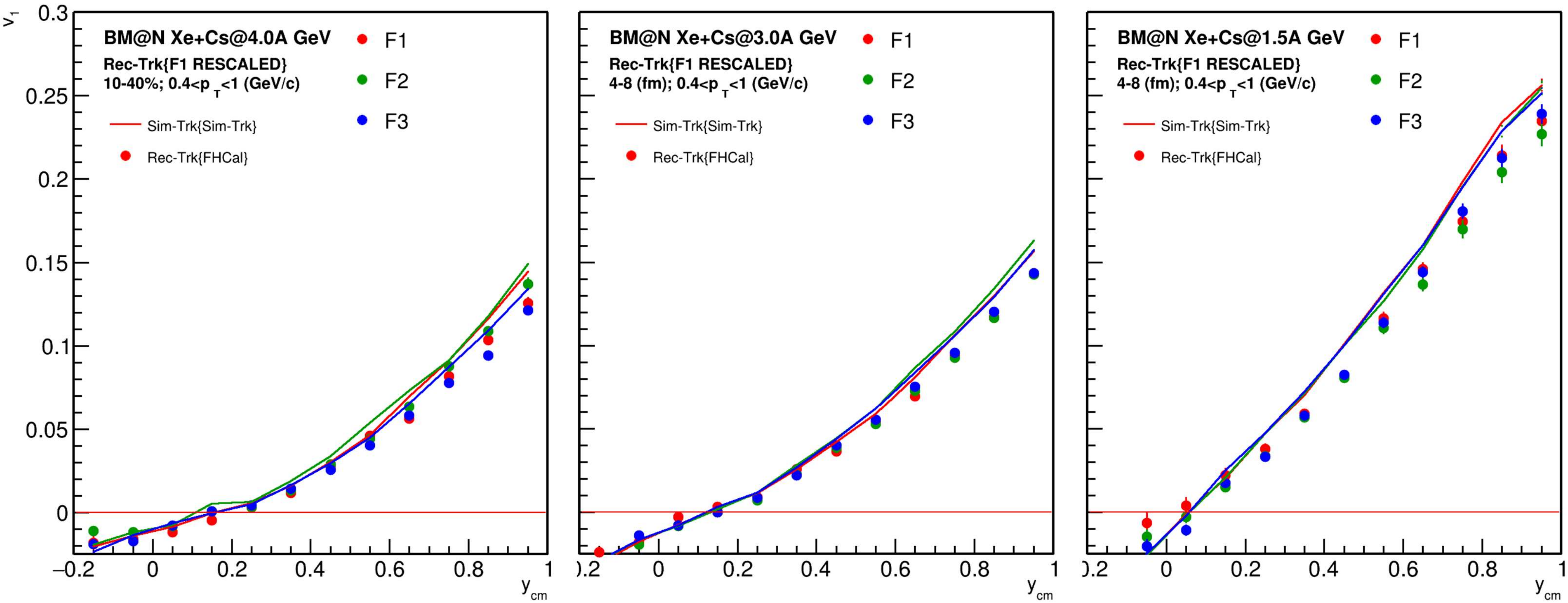
Rec R1: DCMQGCM-SMM Xe+Cs@1.5A GeV





We can use unidentified negatively charged tracks as well for resolution calculation

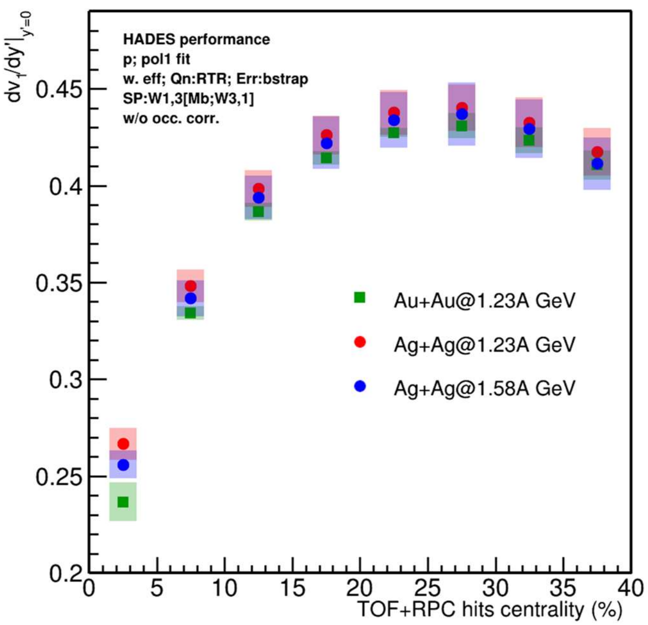
v_1: DCMQGCM-SMM Xe+Cs w.r.t. Spectator plane



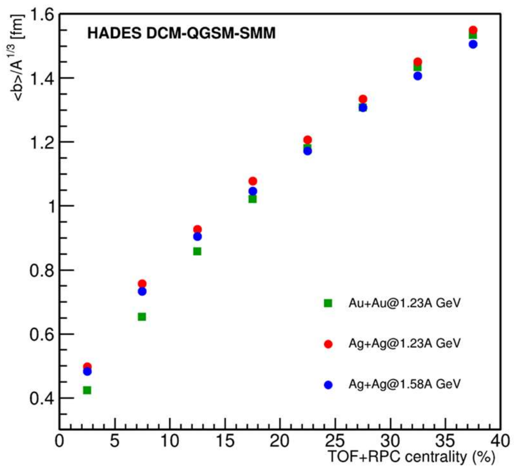
Reasonable agreement between model and reconstructed data

HADES: dv_1/dy scaling with collision energy and system size

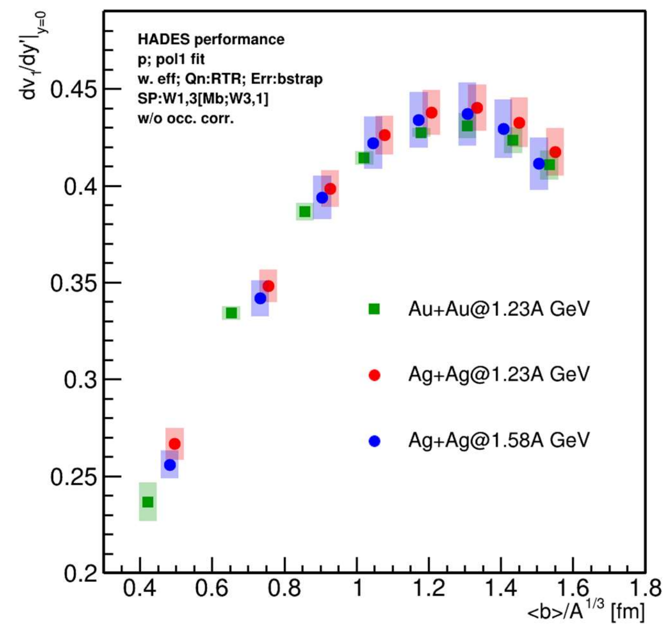
$y_{CM} \rightarrow y' = y_{CM} / y_{beam}$



centrality $\rightarrow$ <b> / $A^{1/3}$



$y' = y_{CM}/y_{beam}$ + <b> / $A^{1/3}$



- After correcting for dependence on the passing time (y_{beam}) dv_1/dy' is independent of the size of colliding nuclei and collision energy and depends only on the relative impact parameter (<b> / $A^{1/3}$)
- Plotting dv_1/dy' vs. <b>/$A^{1/3}$ instead of centrality improves the scaling in central collisions