Performance studies towards flow measurements in BM@N

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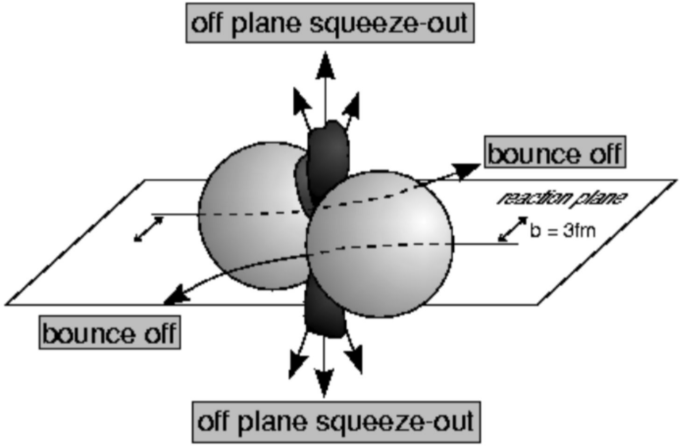
НИЯУ МИФИ

Workshop on physics performance studies at NICA (NICA-2022)
14/12/2022

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:

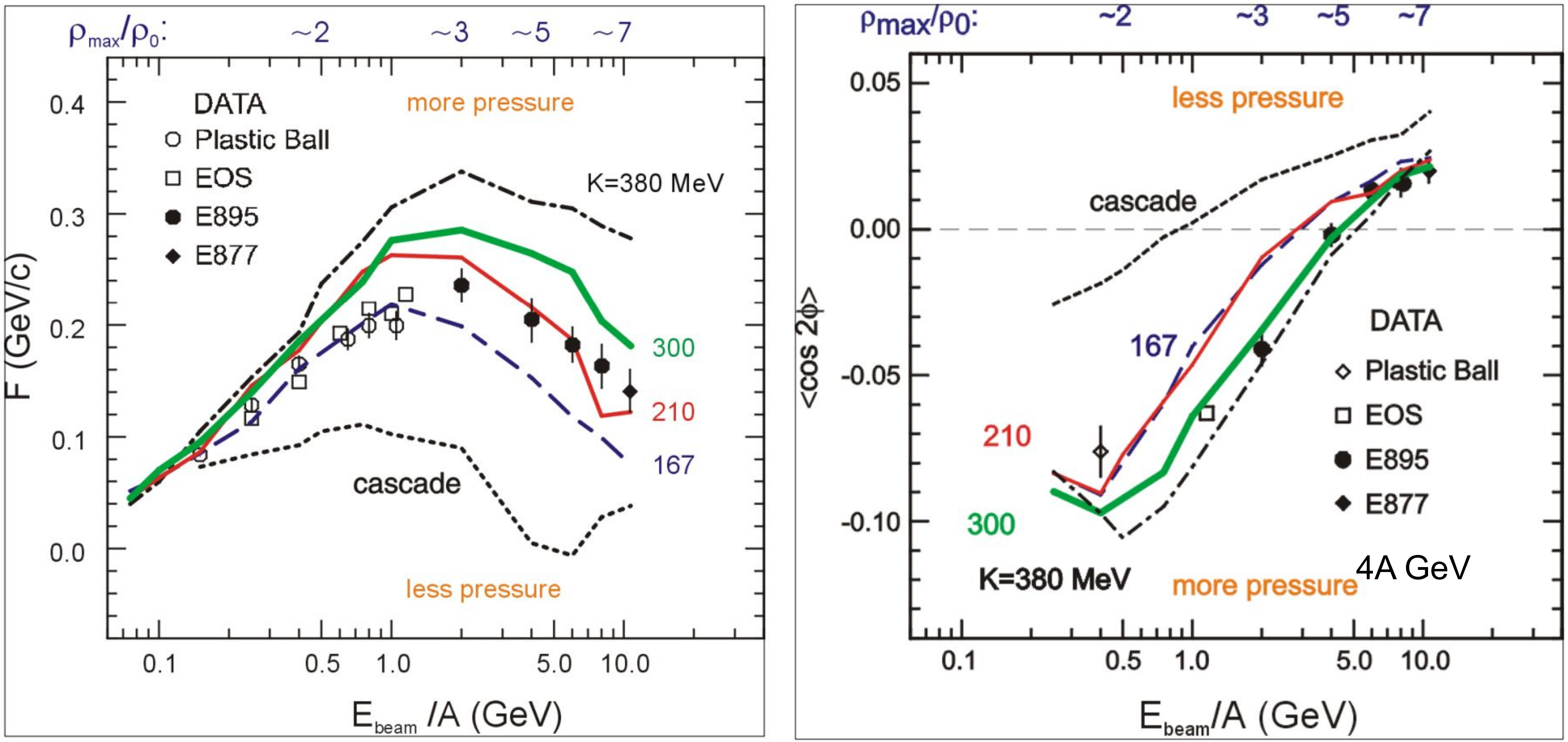
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right] \rangle$$

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

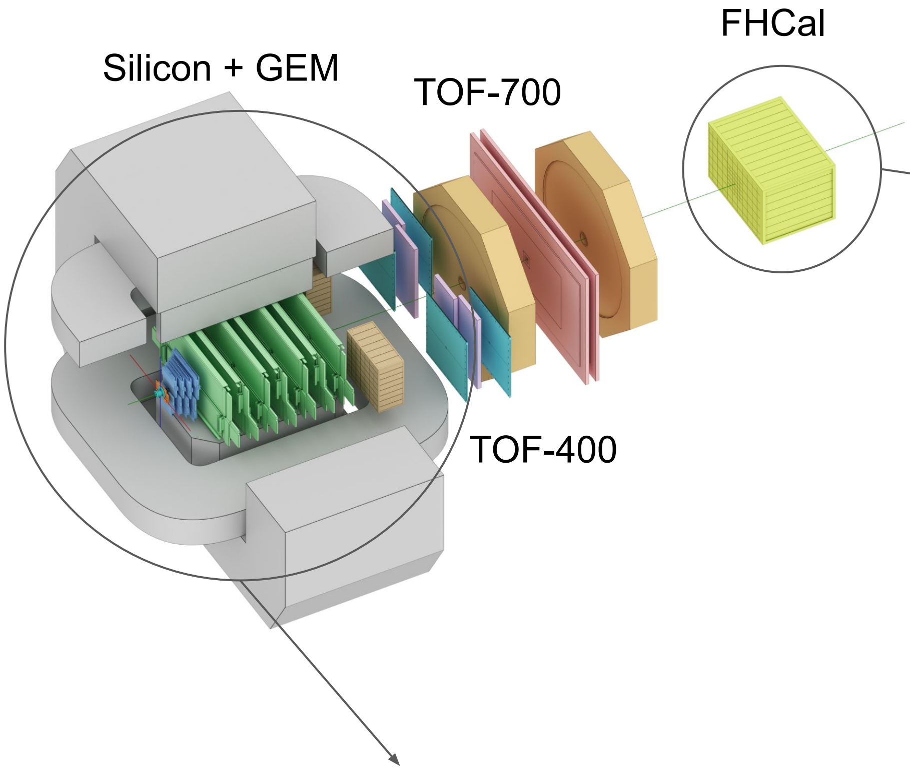


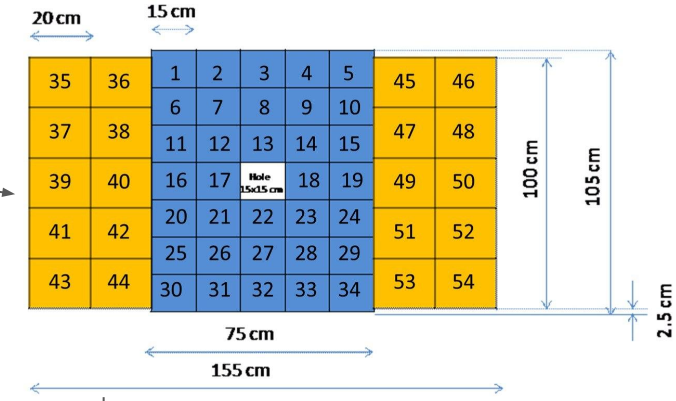
Simulation datasample

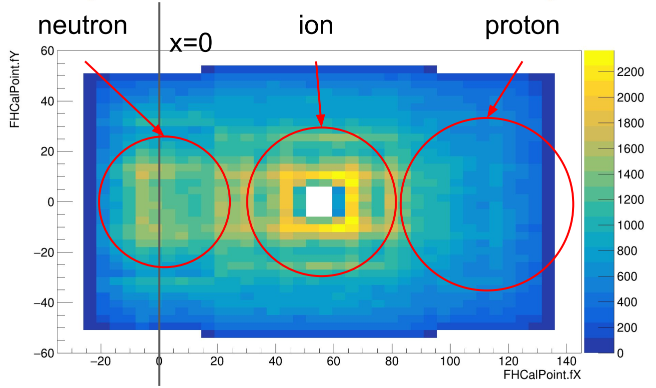
- Xe+Cs nuclei collisions
- DCMQGSM-SMM model (realistic yields of spectator fragments)
- JAM model (realistic flow signal)
- Geant4 transport code (important for simulation of hadronic showers in the forward calorimeter)

	2A GeV	3A GeV	4A GeV
DCMQGSM-SMM	6M	6M	2M
JAM MD3	3M	3M	5M

The BM@N experiment (JINR, Dubna)







Produced particles trajectories are reconstructed using the tracking system inside the dipole magnet

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:

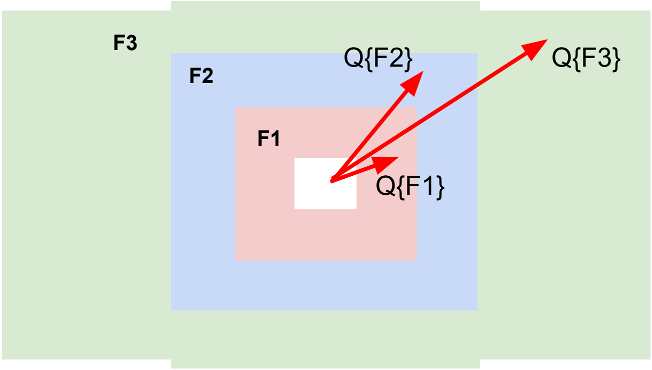
$$u_n = e^{in\phi}$$

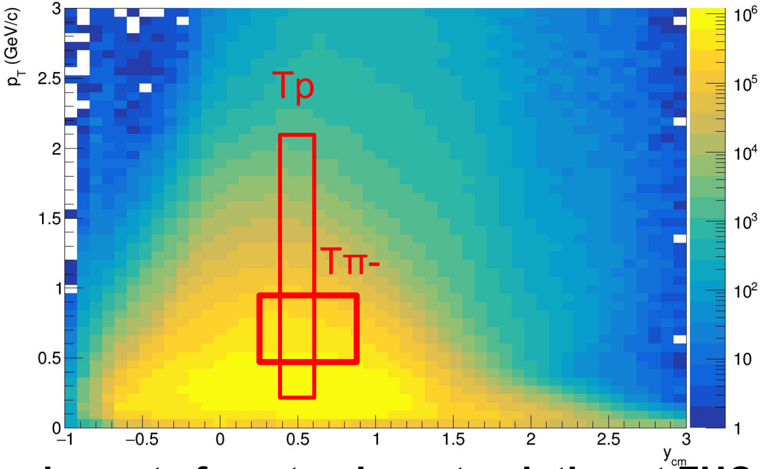
where φ is the azimuthal angle

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
Tπ: π-; 0.2<y<0.8; 0.1 < p_T < 0.5 GeV/c; w=1/eff
T-: all negative; 1.0<η<2.0; 0.1 < p_T < 0.5 GeV/c; w=1/eff

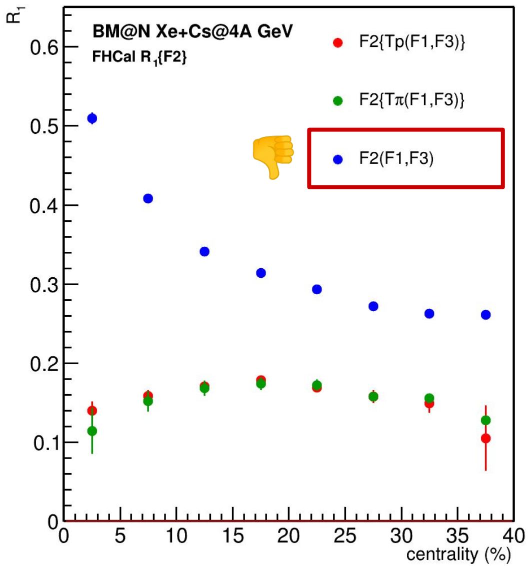
Flow methods for v_n calculation

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):

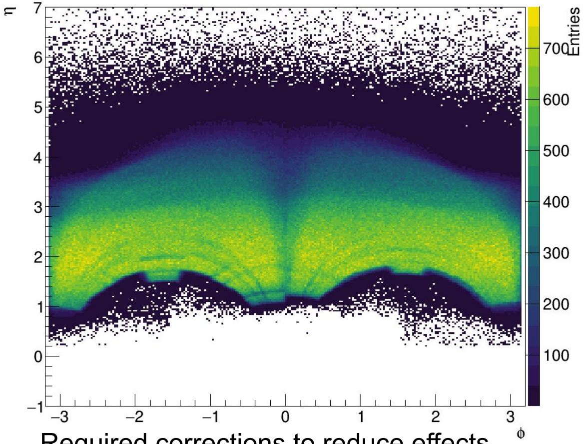
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

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

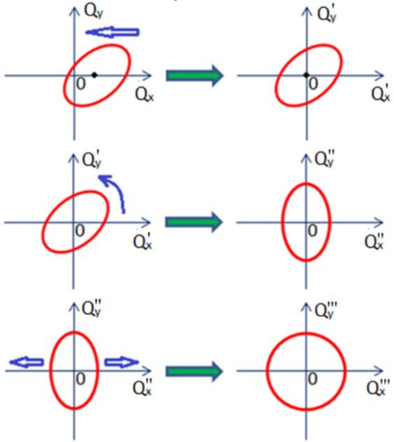
Azimuthal asymmetry of the BM@N acceptance

φ-η yield of protons

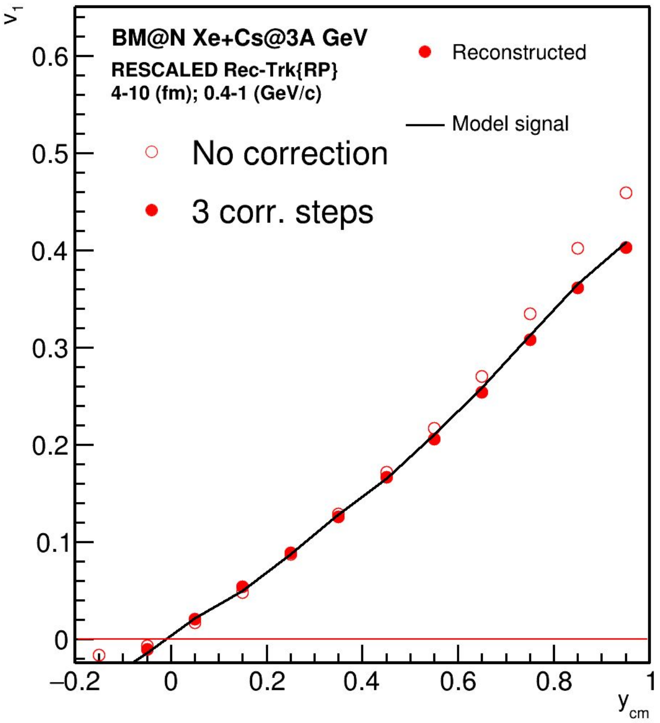


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

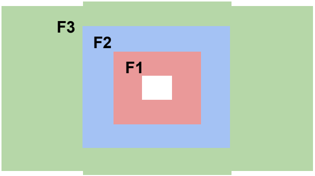


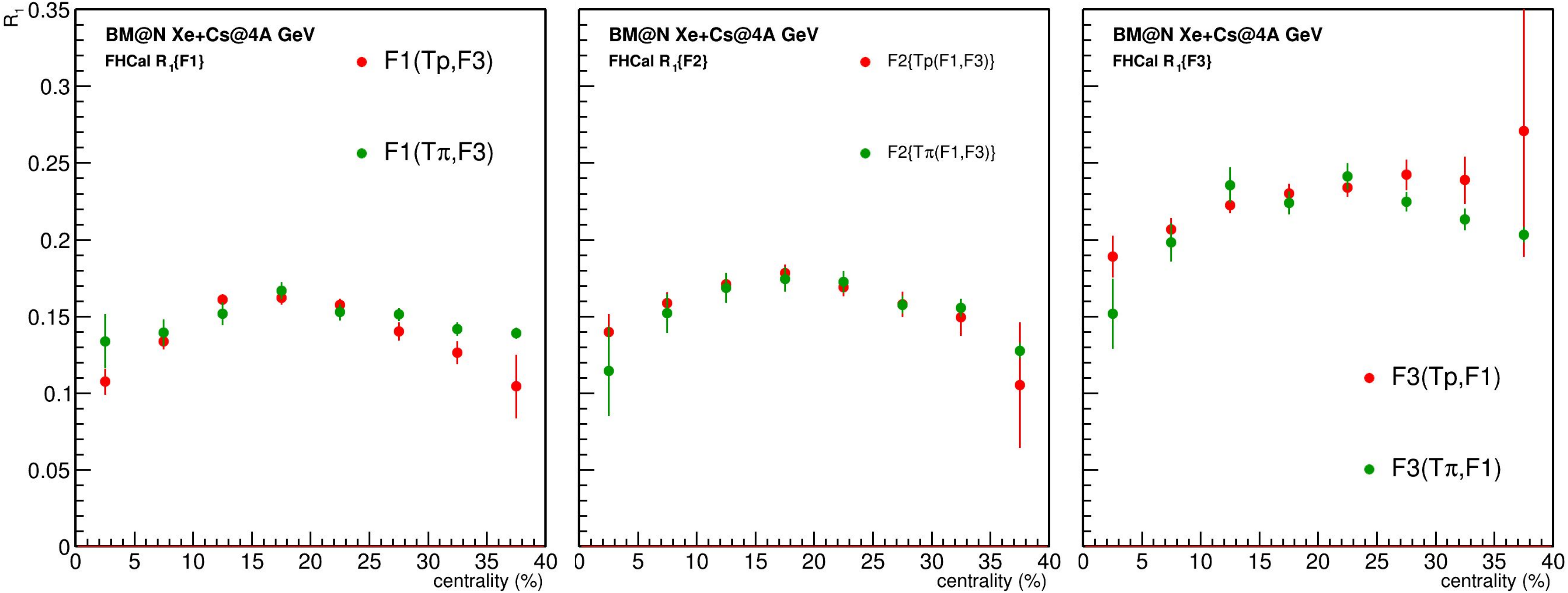
Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



Better agreement after rescaling

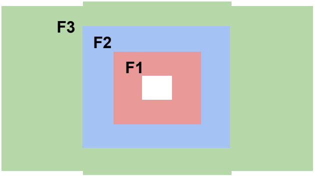
Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV

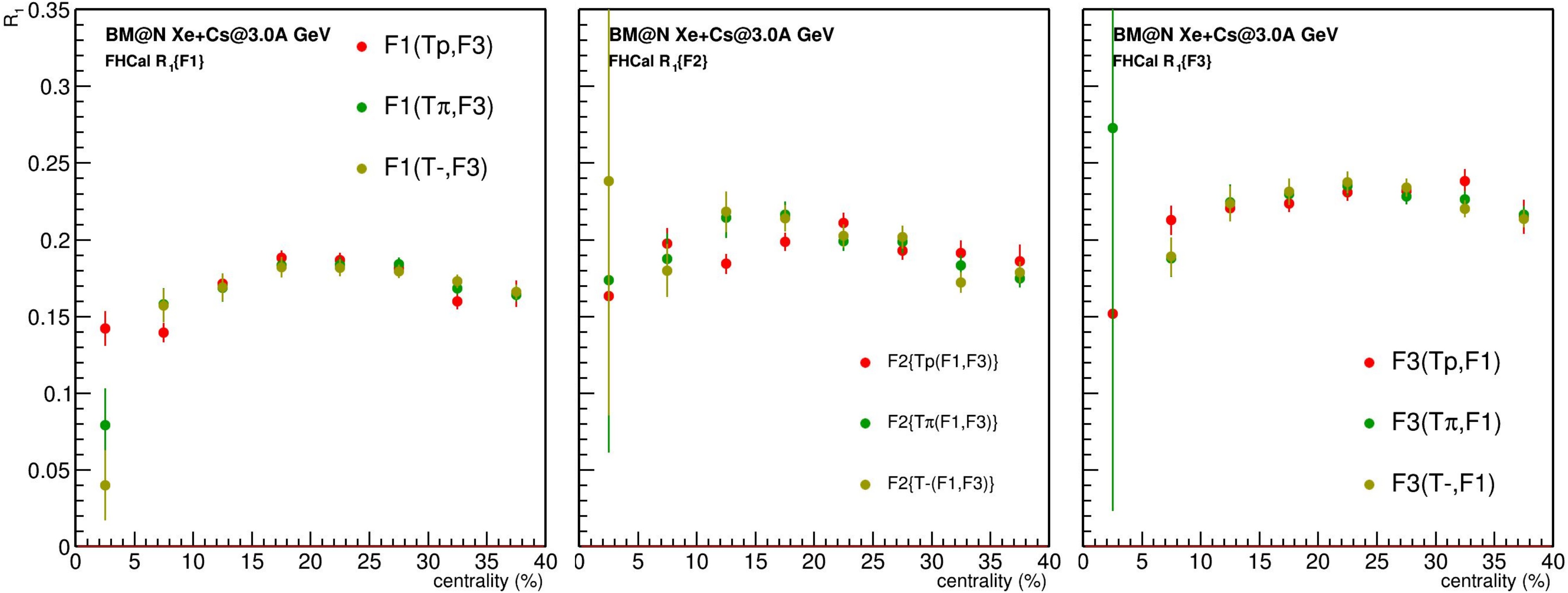




Using the additional sub-events from tracking provides a robust combination to calculate resolution

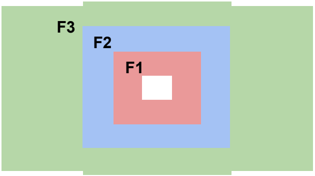
Rec R1: DCMQGCM-SMM Xe+Cs@3A GeV

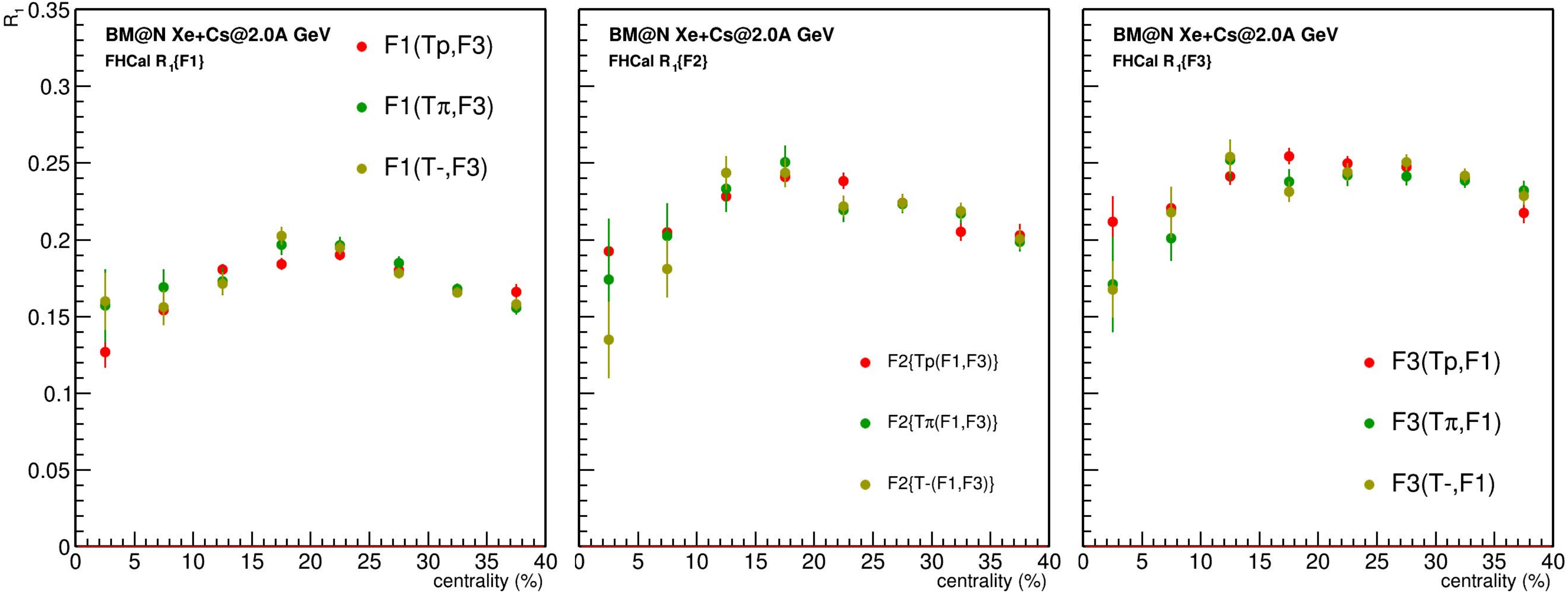




We can use unidentified negatively charged tracks as well for resolution calculation

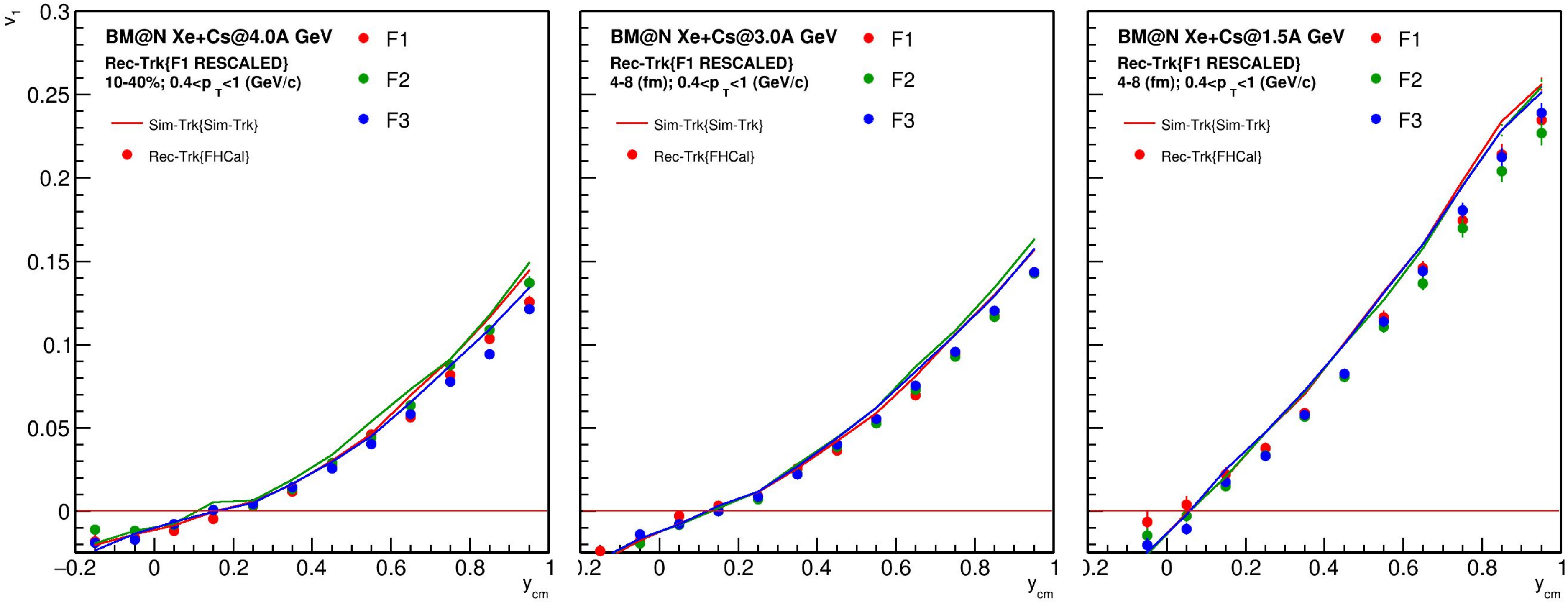
Rec R1: DCMQGCM-SMM Xe+Cs@2.0A GeV





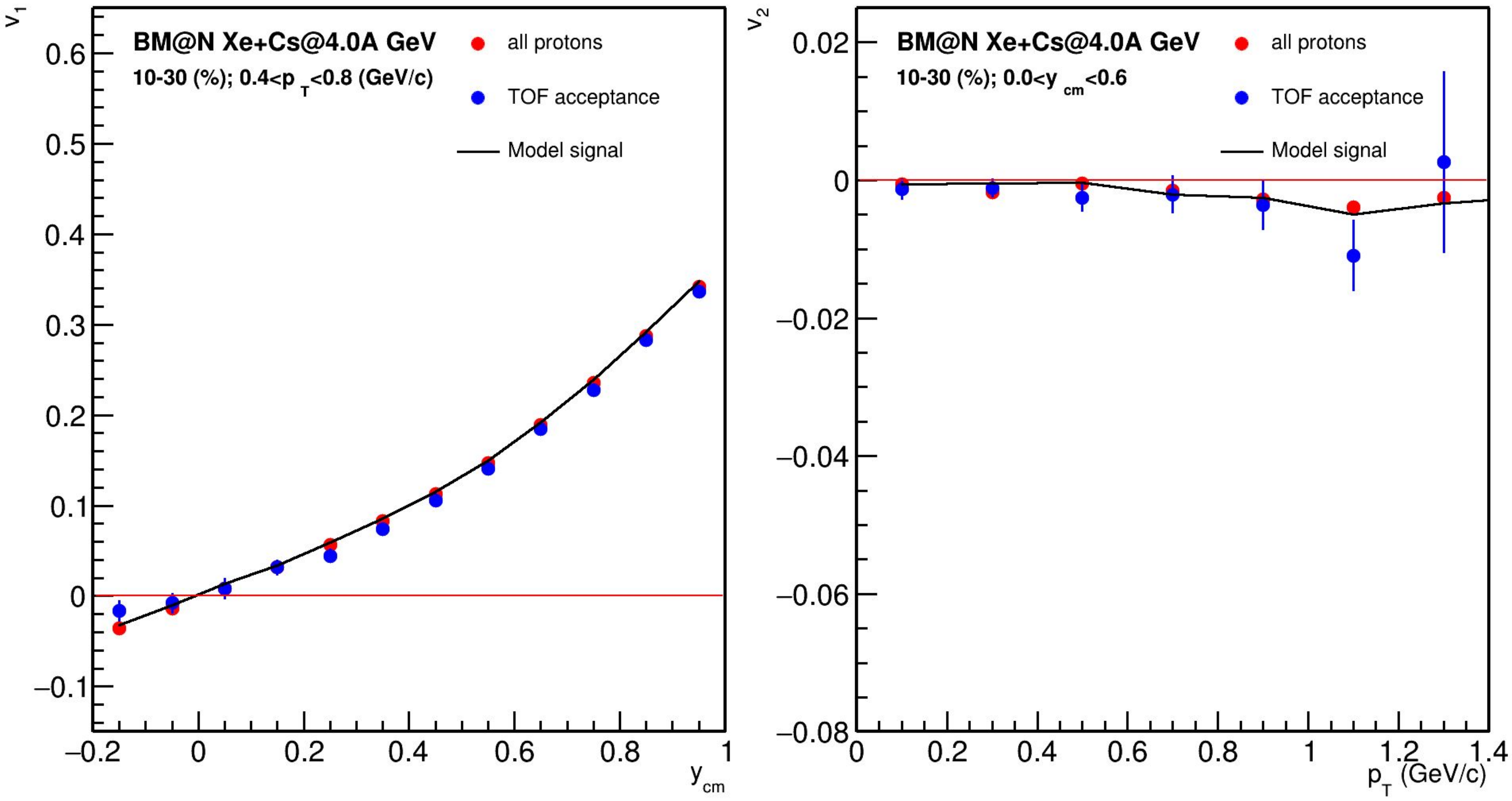
We can use unidentified negatively charged tracks as well for resolution calculation

v_1: DCMQGCM-SMM Xe+Cs



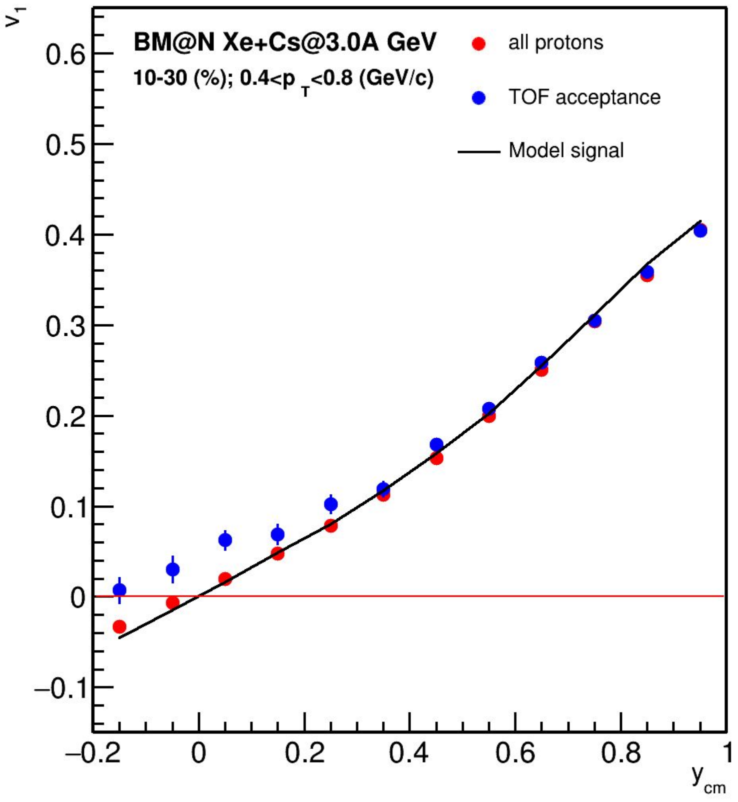
Reasonable agreement between model and reconstructed data

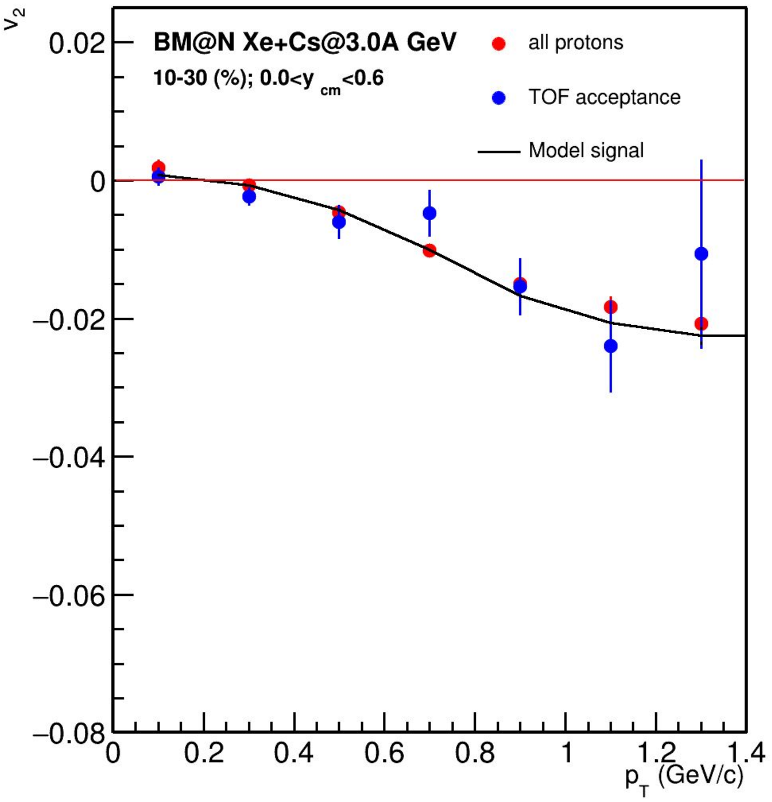
Directed and elliptic flow in Xe+Cs@4A GeV (JAM)



- Good agreement between reconstructed and model data
- Approximately 150-250M events are required to perform multidifferential measurements of v_n

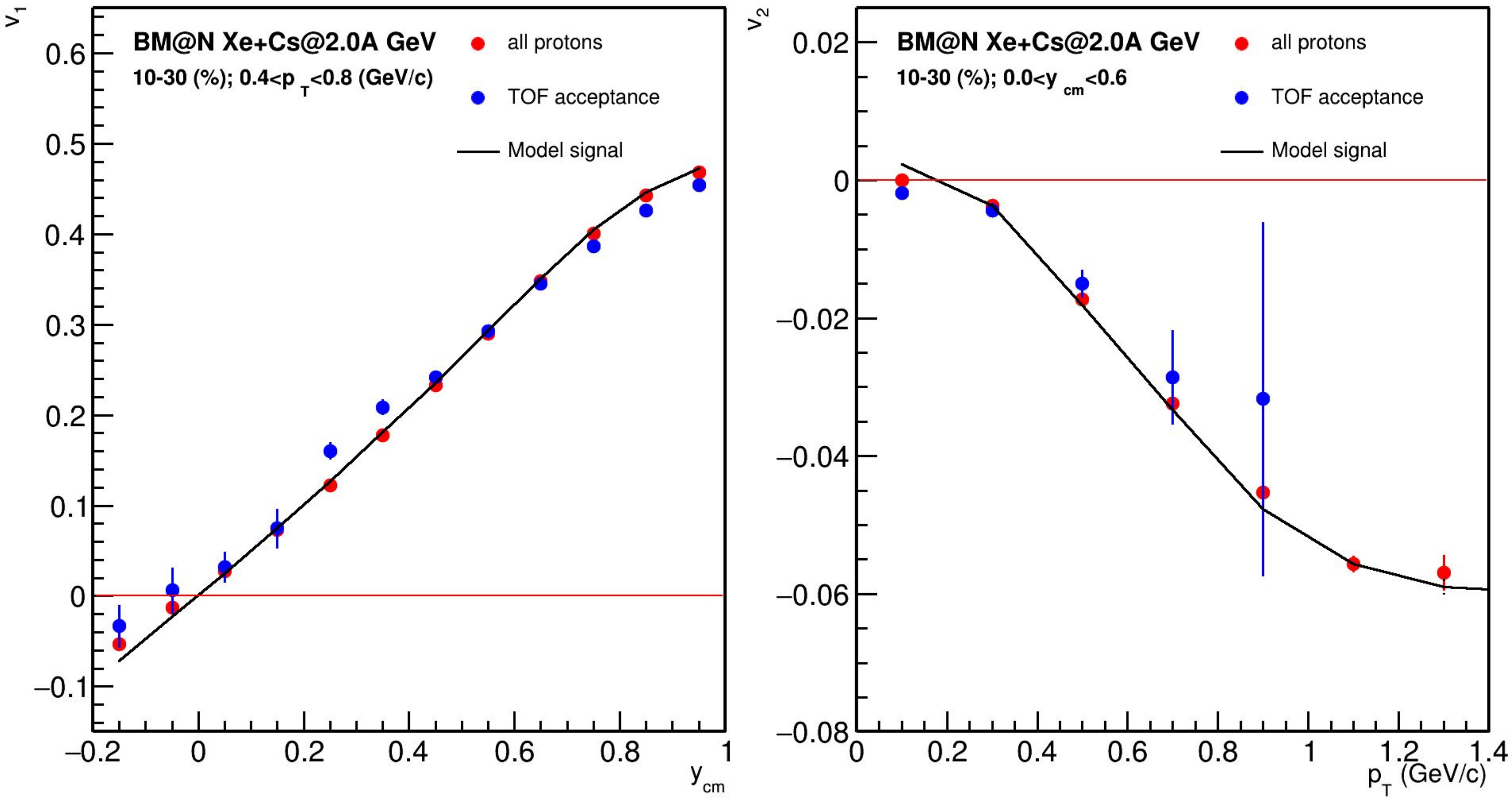
Directed and elliptic flow in Xe+Cs@3A GeV (JAM)





- Good agreement between reconstructed and model data
- Approximately 250-300M events are required to perform multidifferential measurements of v_n

Directed and elliptic flow in Xe+Cs@2.0A GeV (JAM)



- Larger amount of statistics is required to measure v_n at higher p_T
- Approximately 350-500M events are required to perform multidifferential measurements of v_n

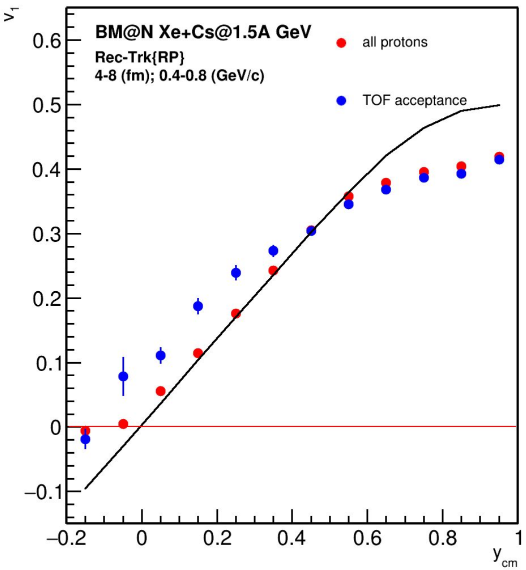
Summary

- 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
- For multidifferential v_n measurements approximately:
  - 150-250M events are required for Xe+Cs@4AGeV
  - 250-300M events are required for Xe+Cs@3AGeV
  - 350-500M events are required for Xe+Cs@1.5AGeV

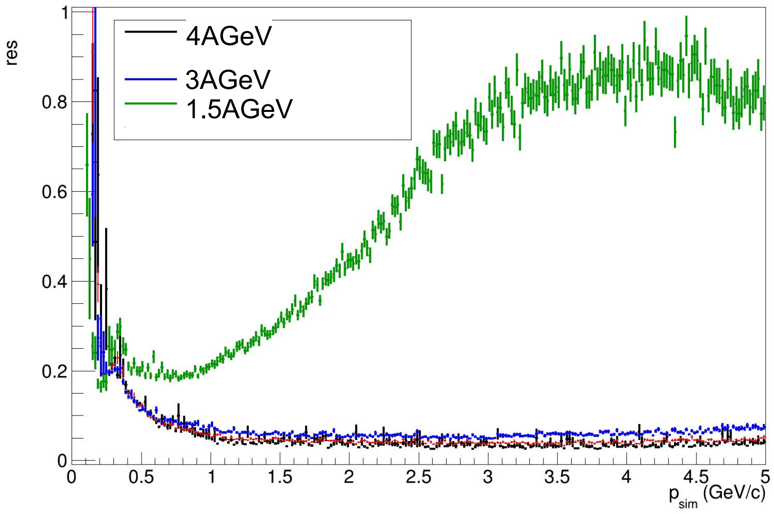
BACKUP

v_1: Xe+Cs@1.5AGeV (JAM)

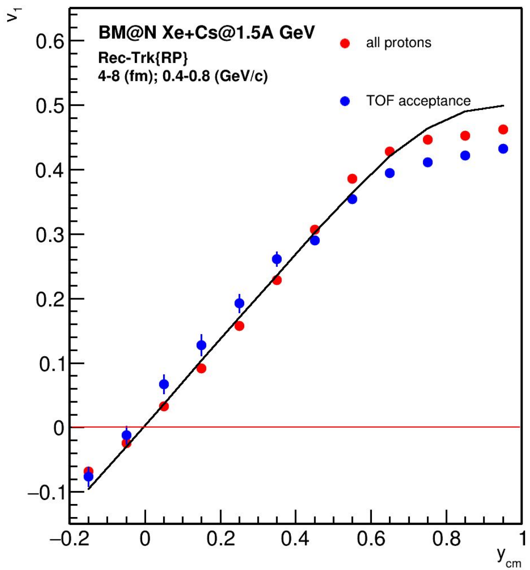
Reconstructed momenta



Momentum resolution

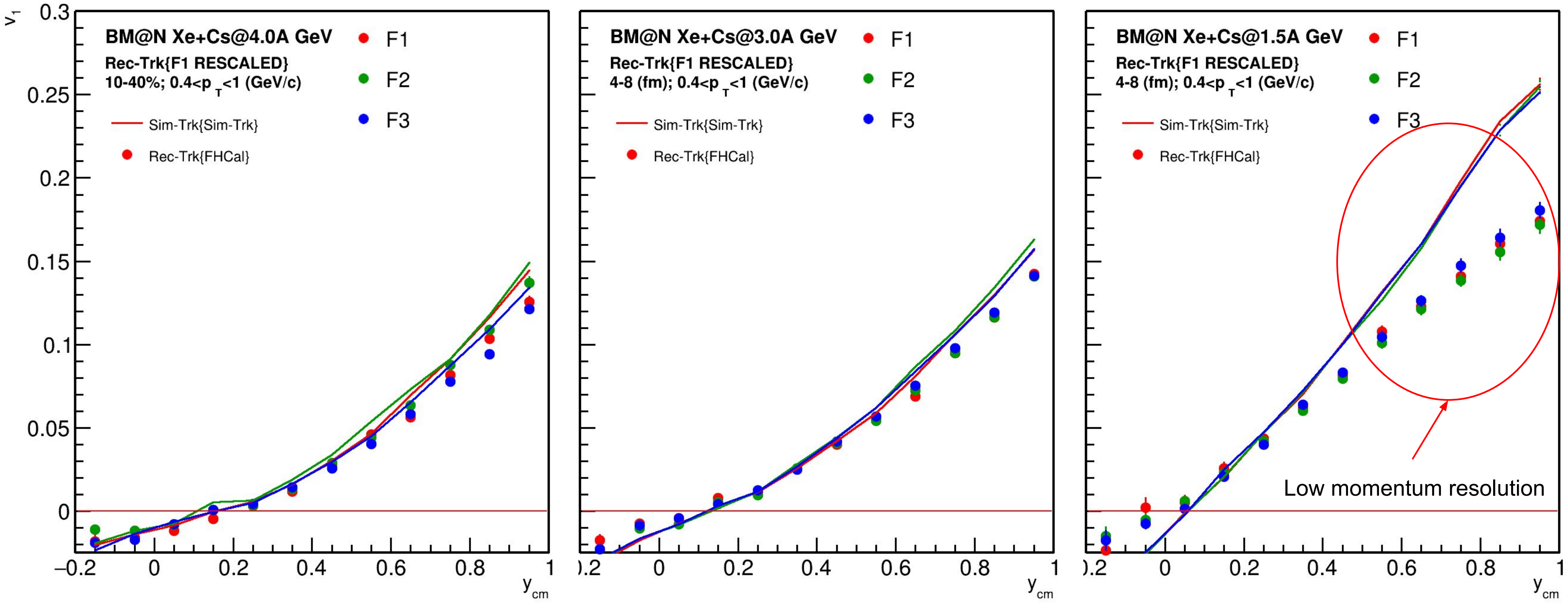


True momenta



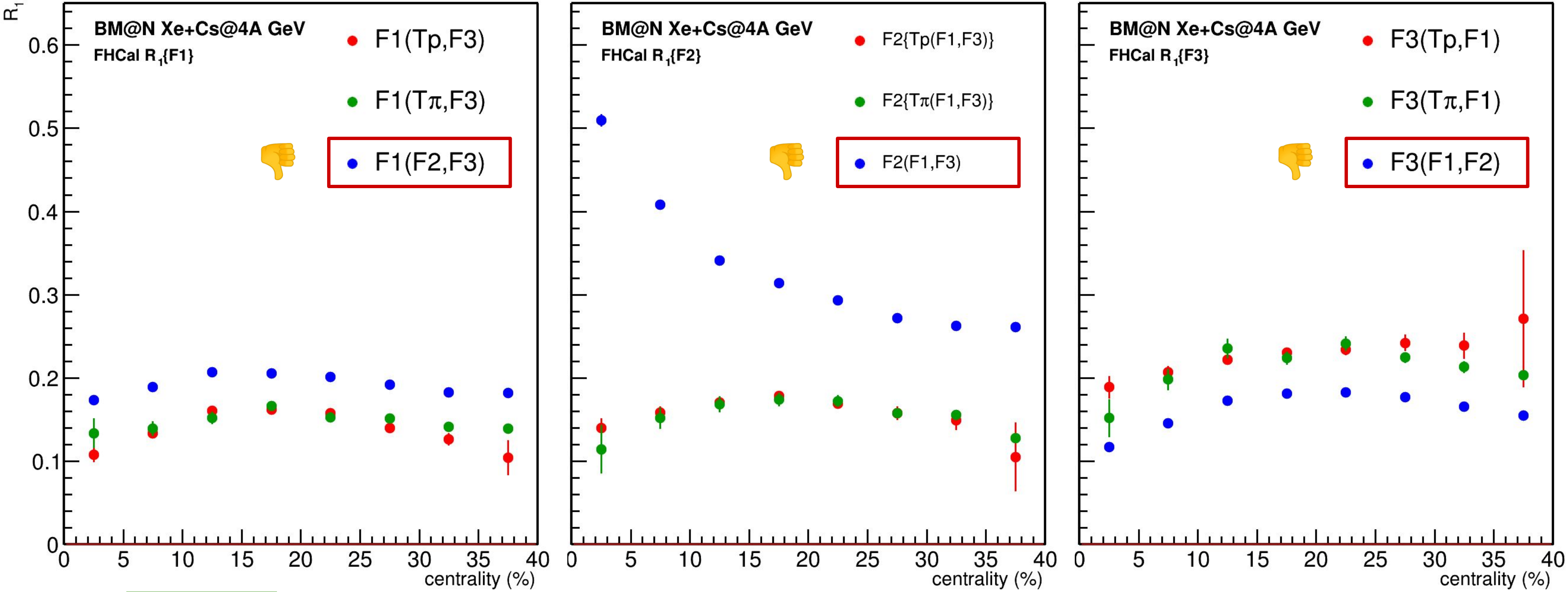
- Poor momentum resolution for lower magnetic field scaling introduces large systematic uncertainty to measured flow data
- Momentum reconstruction procedure for lower field scaling needs to be improved

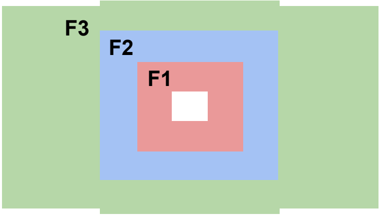
v_1: DCMQGCM-SMM Xe+Cs



Lower magnetic field strength at lower energies (down to 50%) - lower momentum resolution

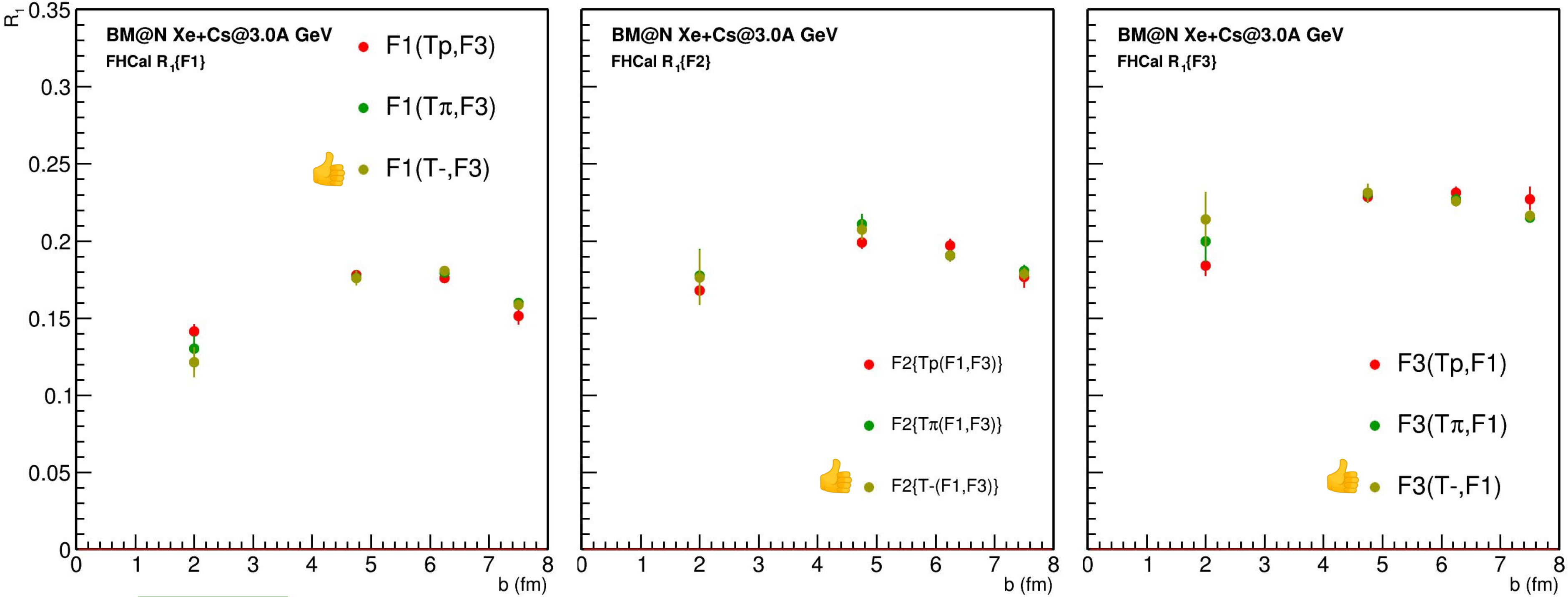
Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV

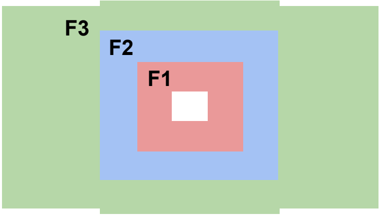




Bias due to leakage of hadronic shower
between neighbouring FHCal subevents:
we shall not use this resolution in the further analysis

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





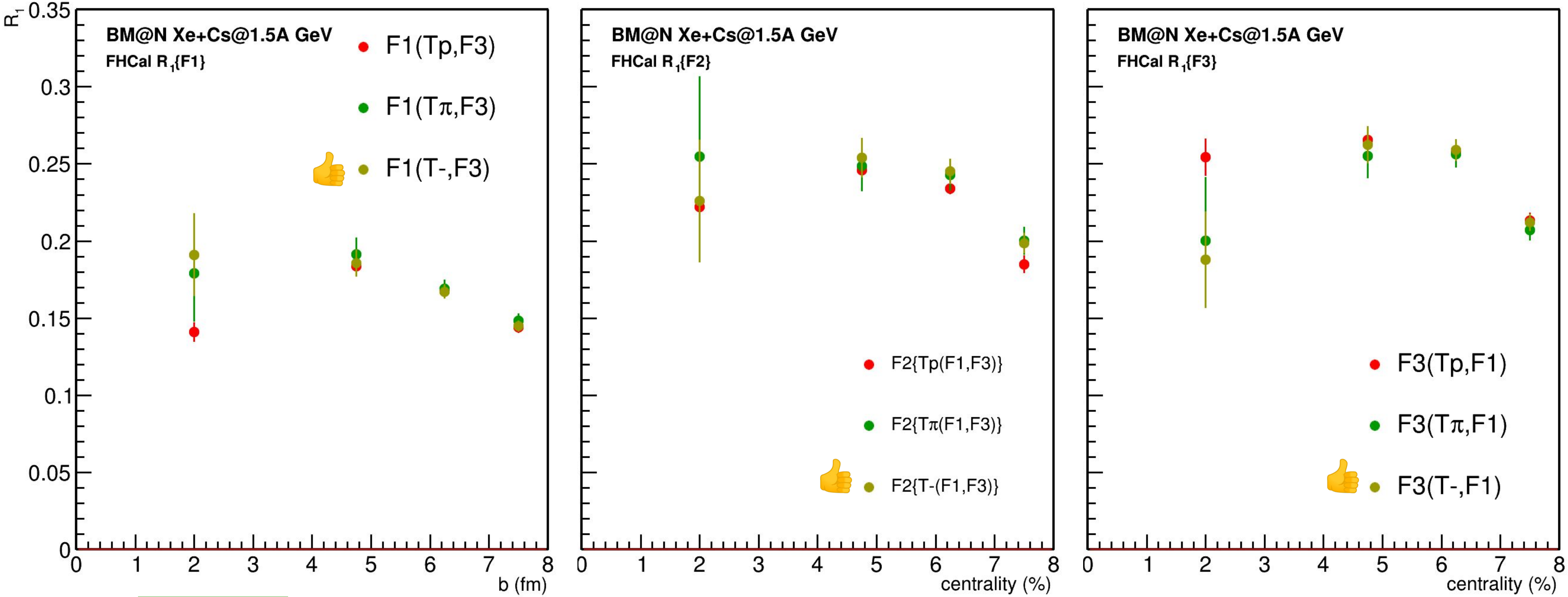
Additional subevents from tracks not pointing at FHCal:

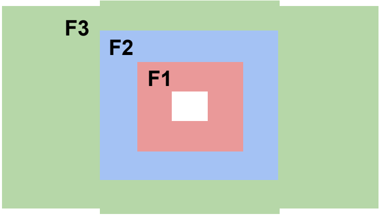
Tp: p; $0.4<y<0.6$; $0.2 < p_T < 2$ GeV/c; w=1/eff

Tπ: π-; $0.2<y<0.8$; $0.1 < p_T < 0.5$ GeV/c; w=1/eff

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

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





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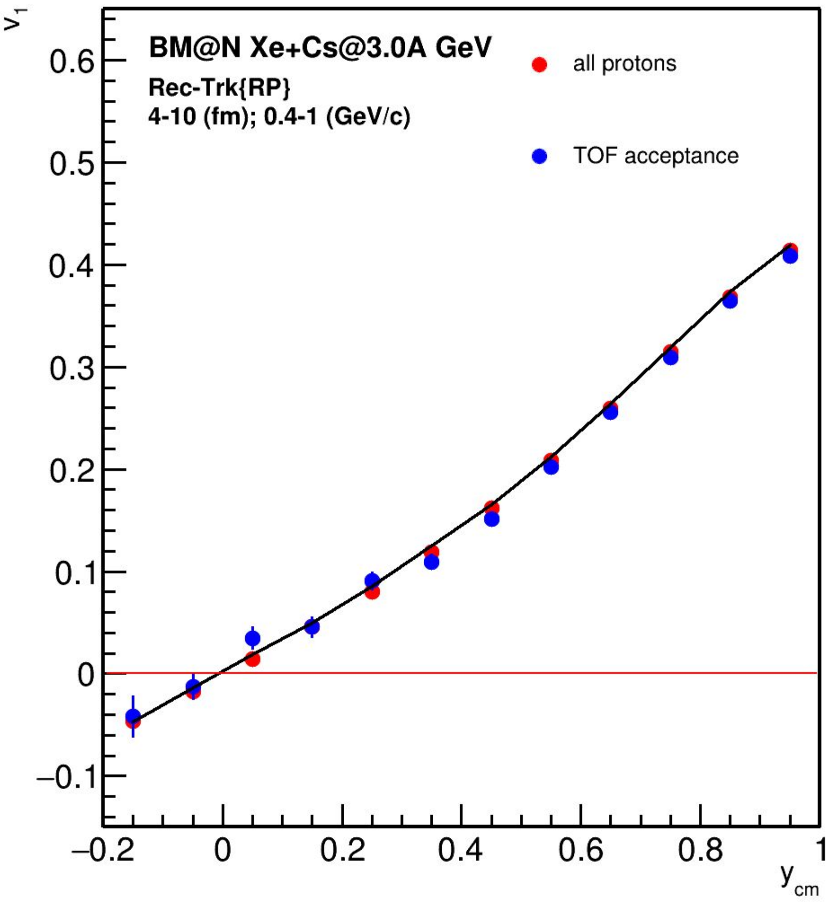
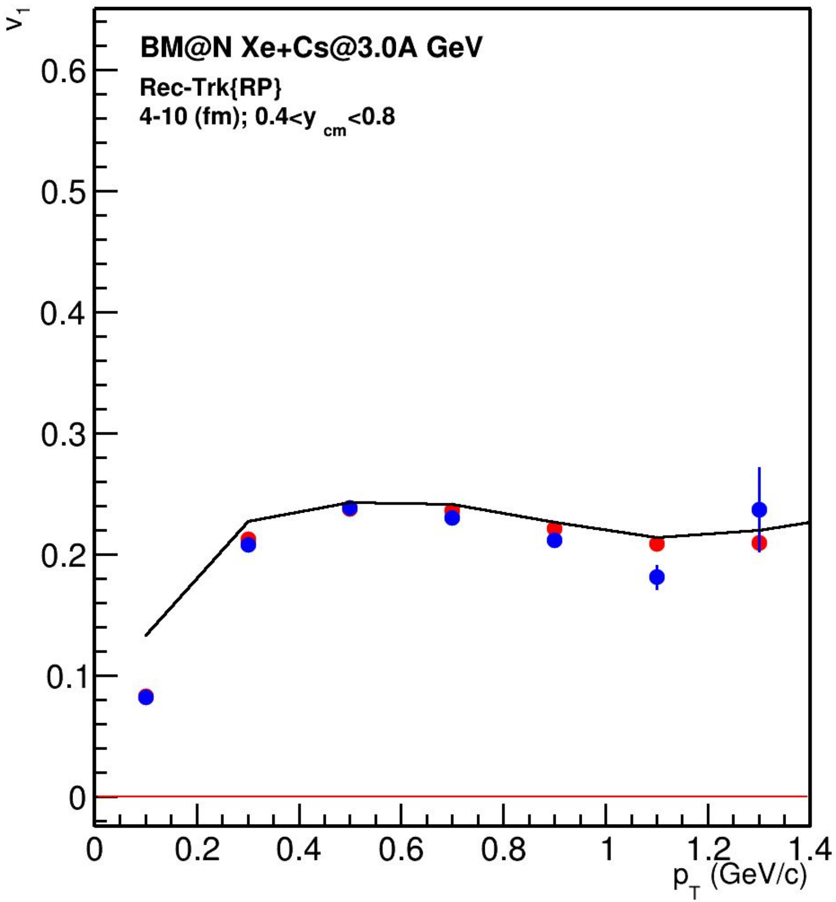
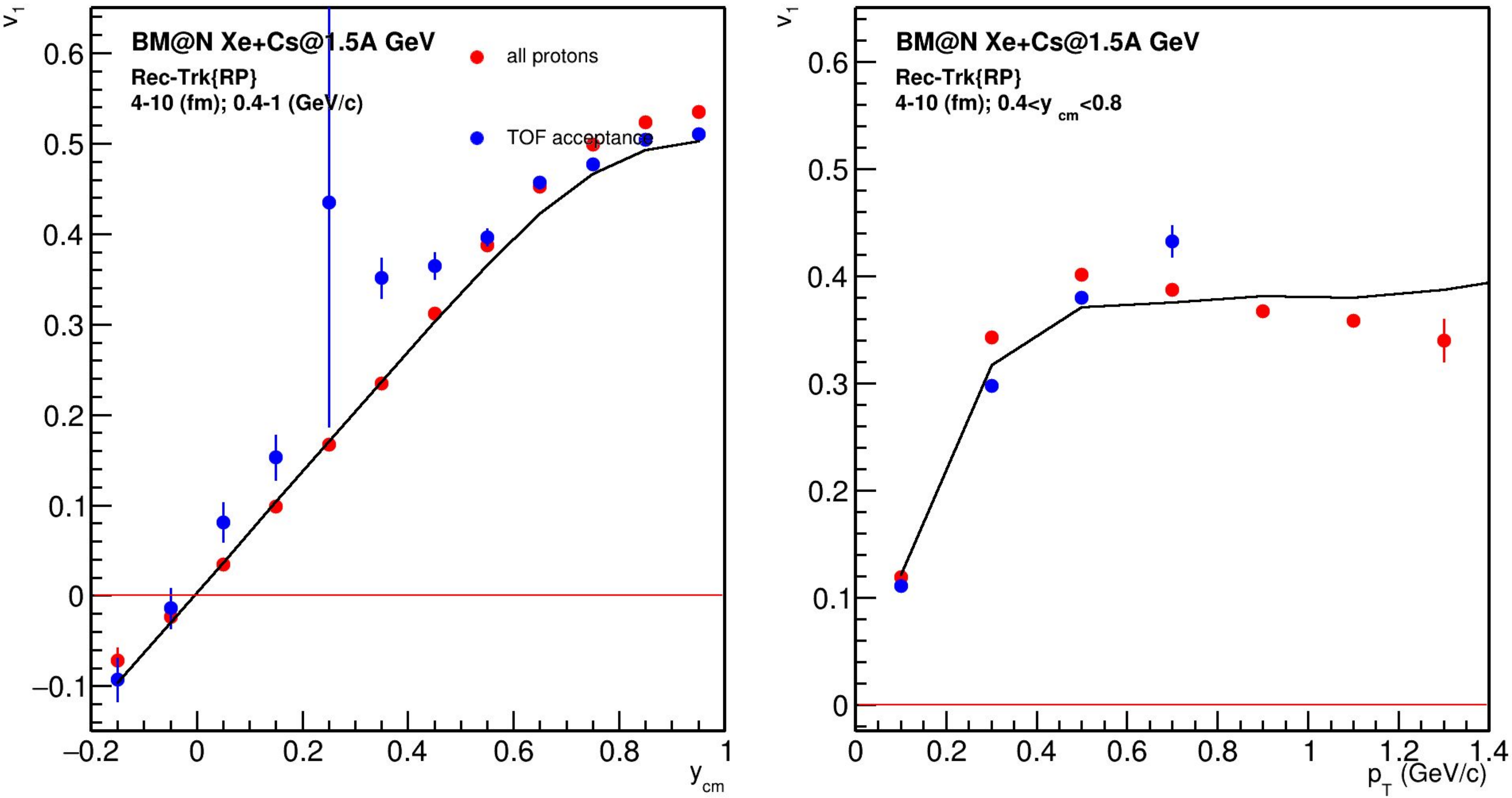
v_1: Xe+Cs@3.0A GeV: JAM (true momenta)

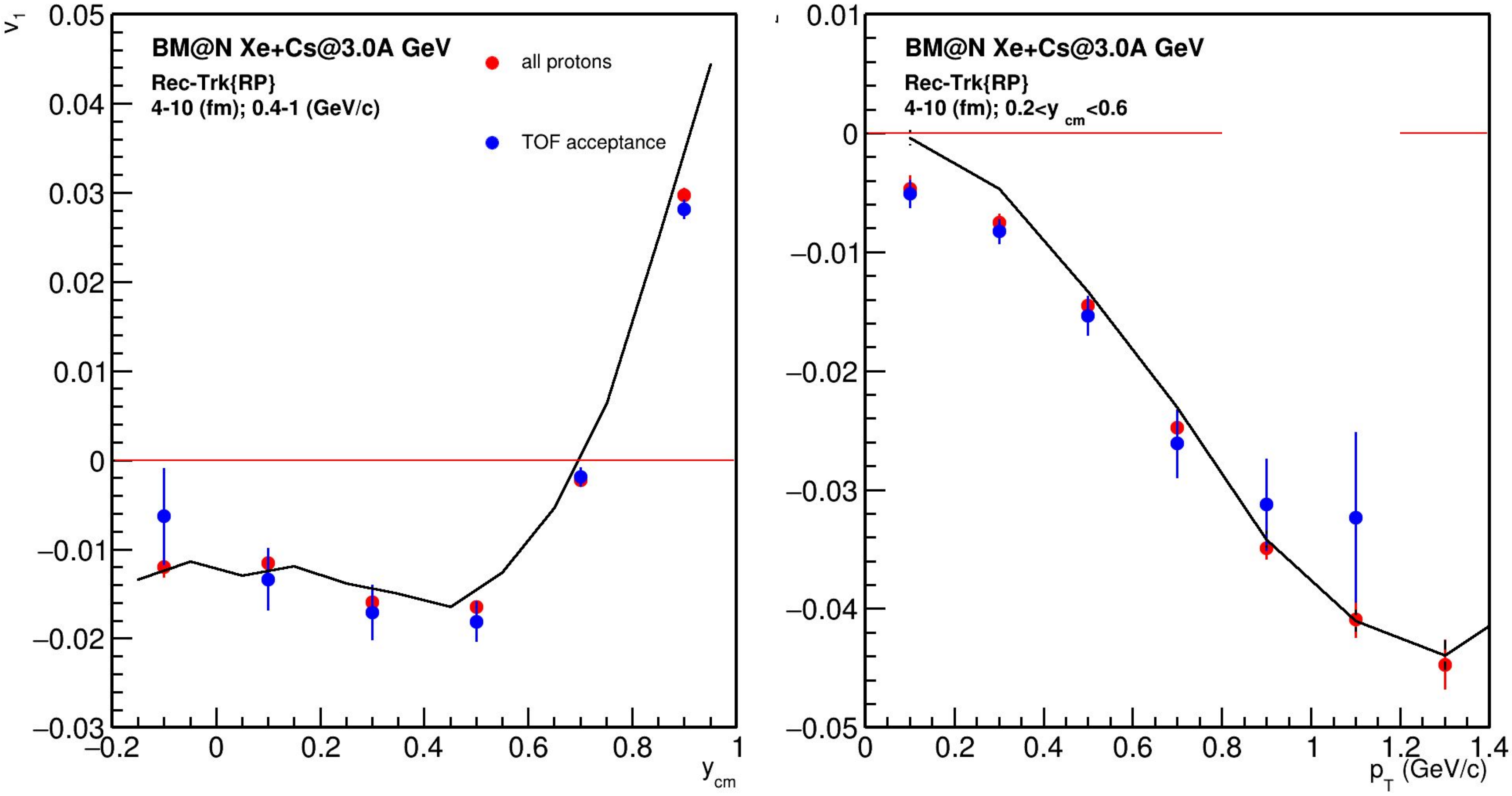




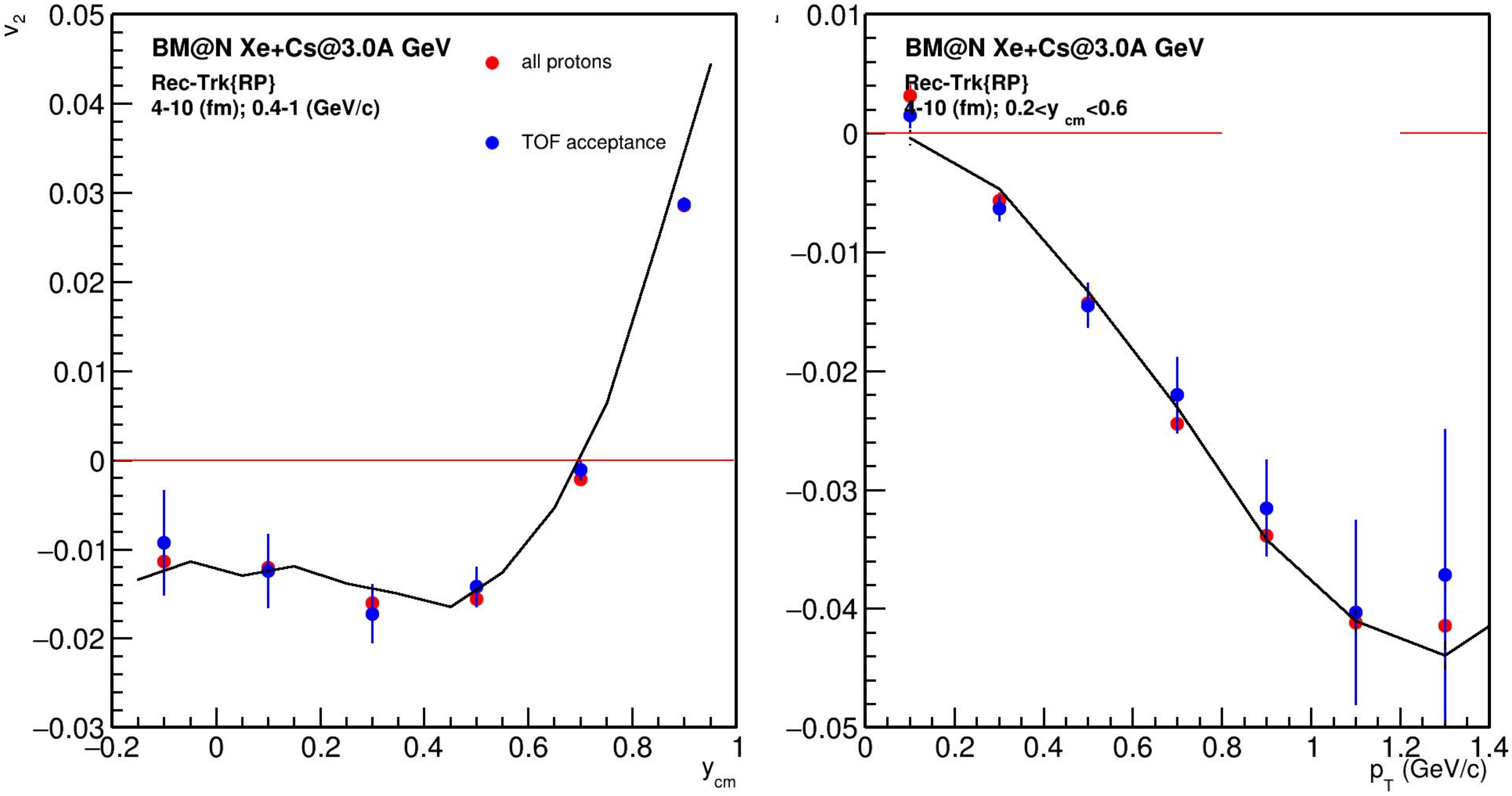
v_1: Xe+Cs@1.5A GeV: JAM (true momenta)



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

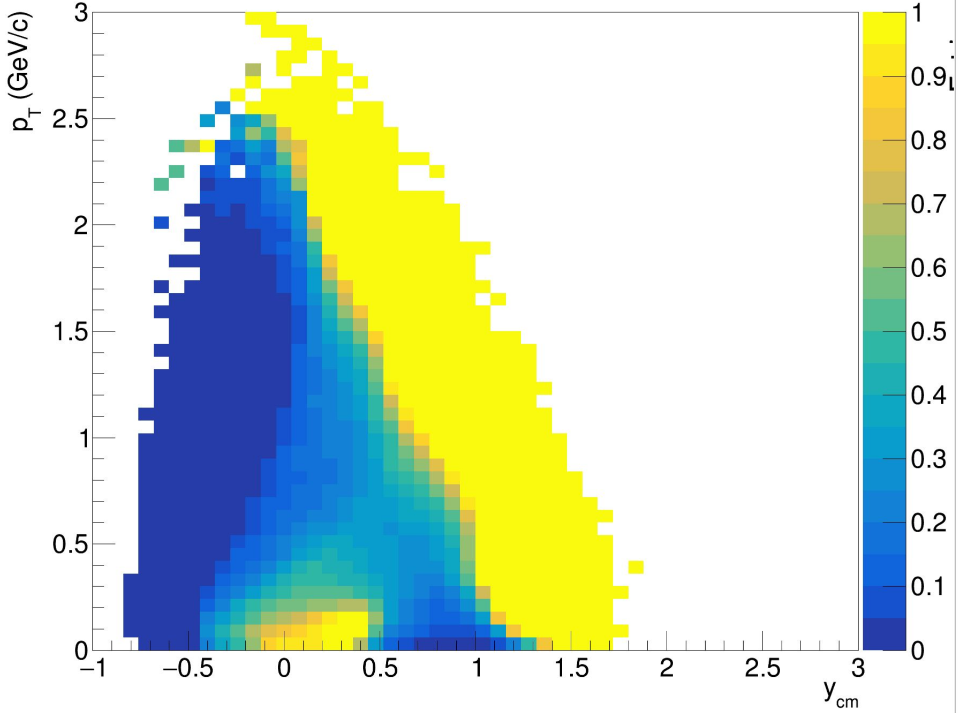


v_2: Xe+Cs@3.0A GeV: JAM (rec momenta)

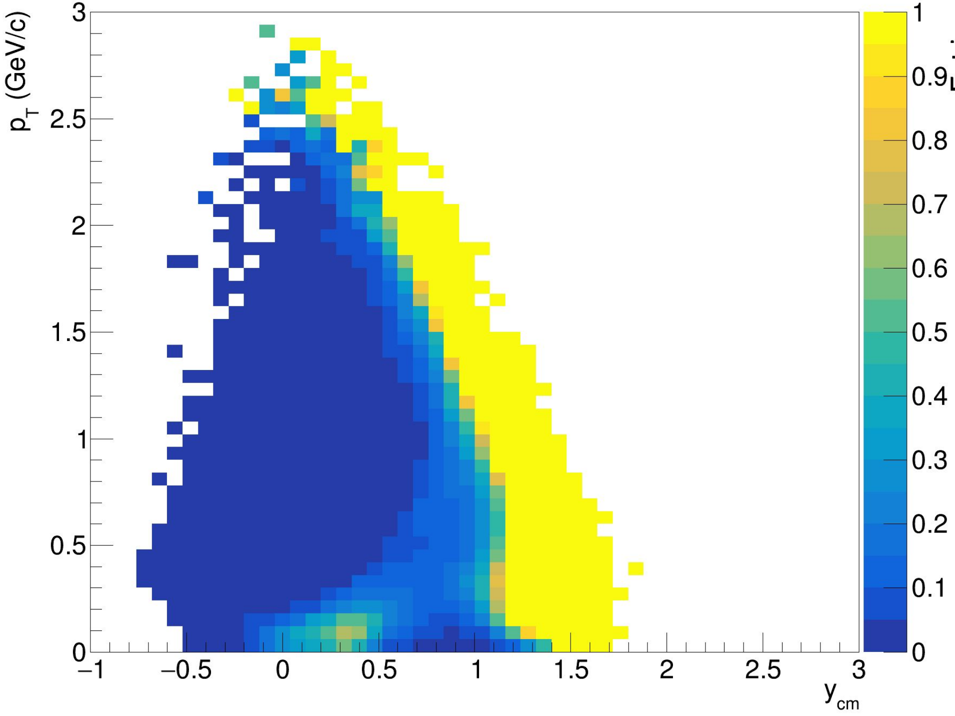


Efficiency for proton reconstruction (JAM, Xe+Cs@1.5A GeV)

Without TOF acceptance

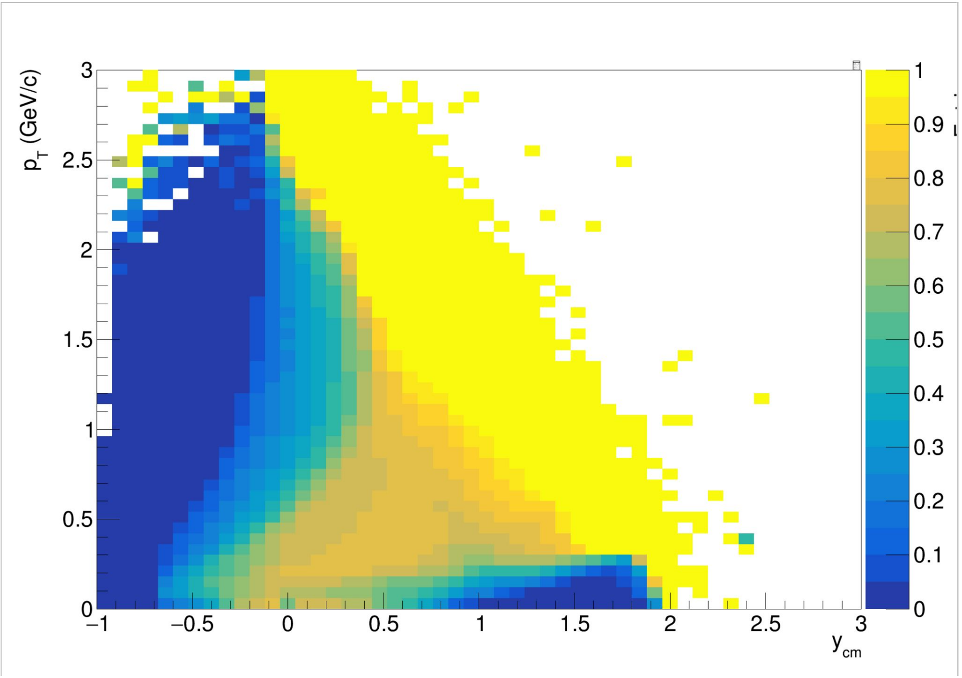


With TOF acceptance

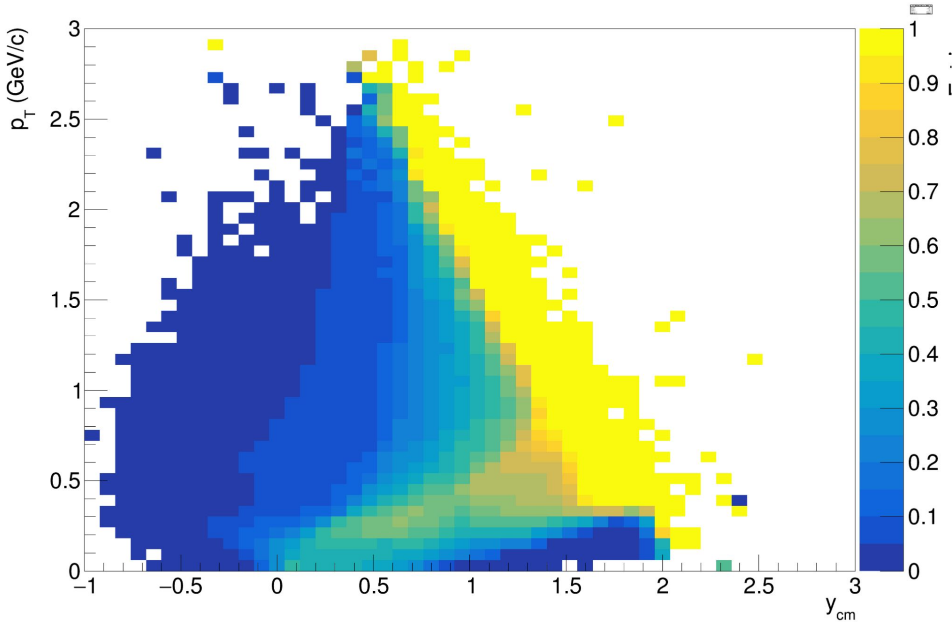


Efficiency for proton reconstruction (JAM, Xe+Cs@3A GeV)

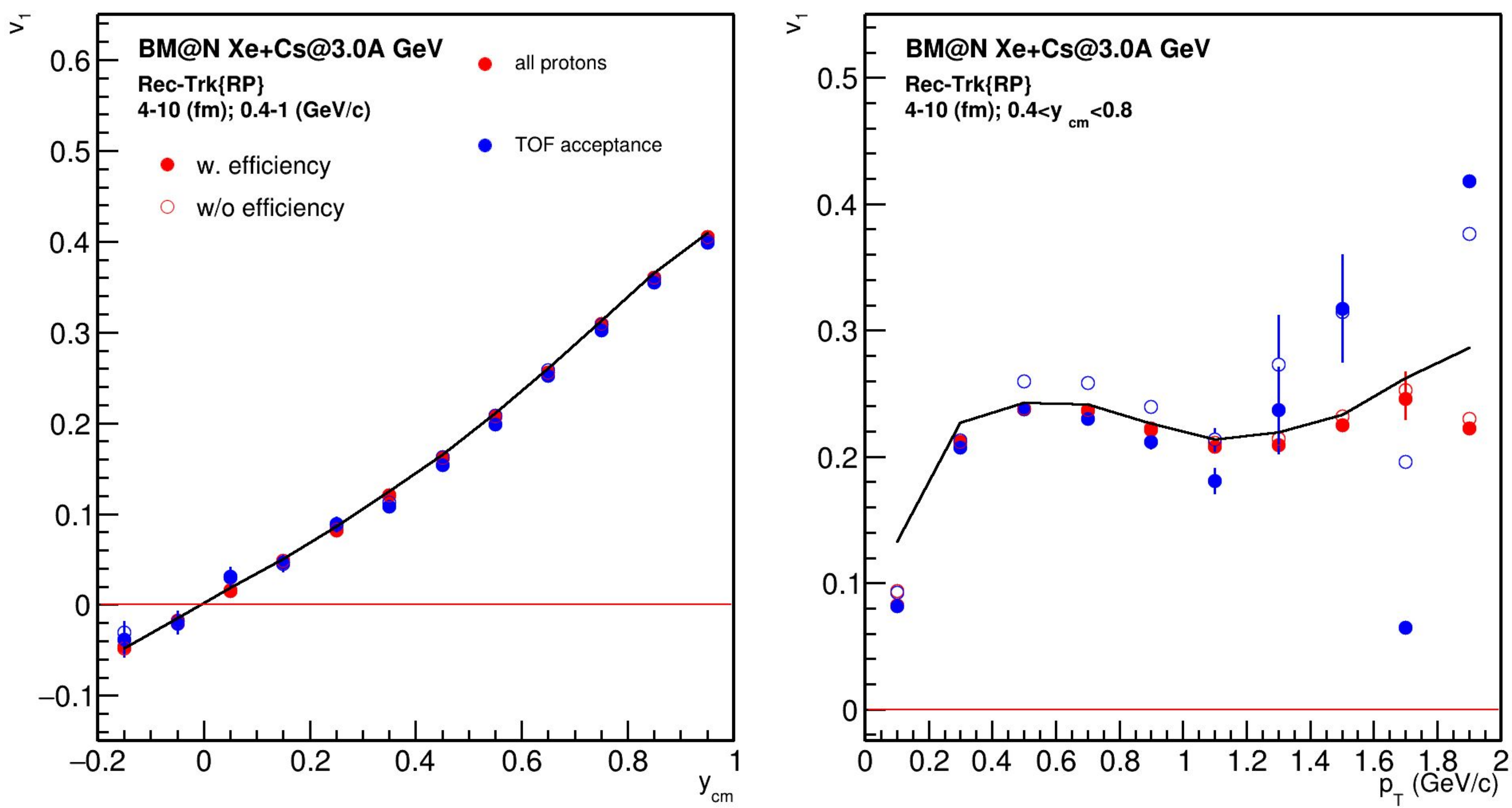
Without TOF acceptance



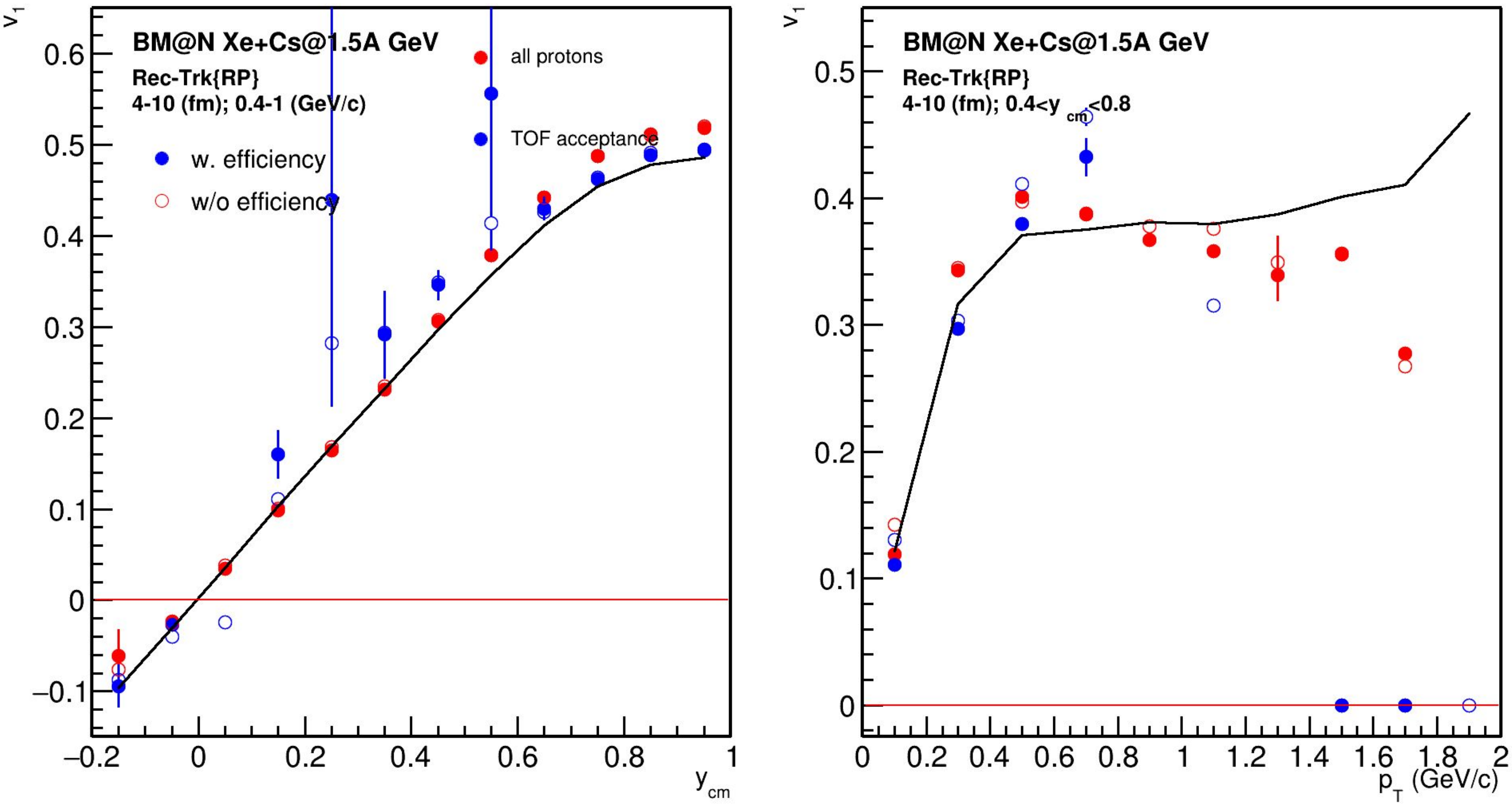
With TOF acceptance



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

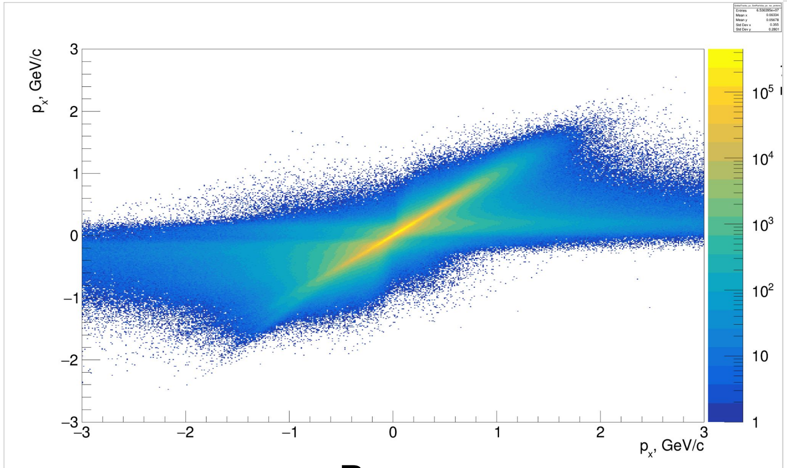


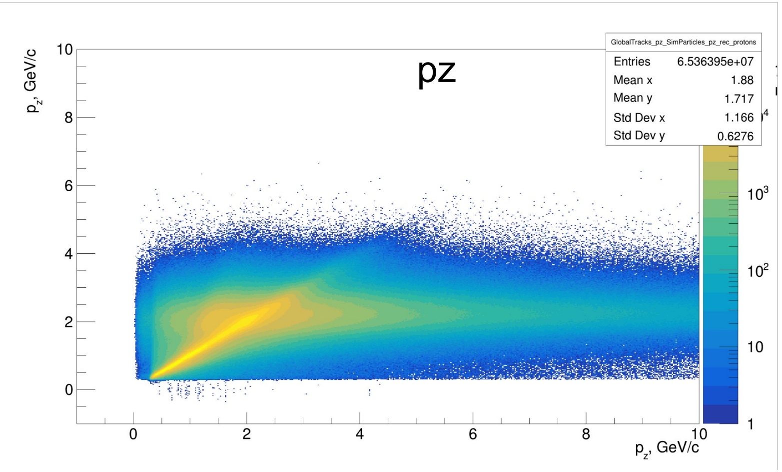
v_1: Xe+Cs@1.5A GeV: JAM (true momenta)



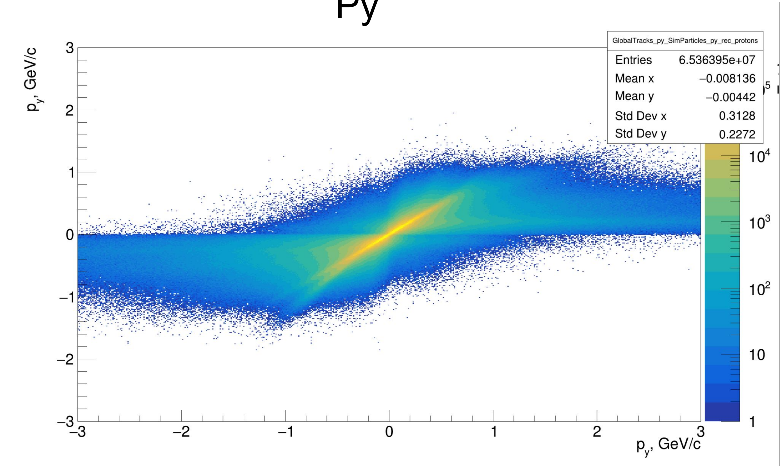
Momentum reconstruction for protons in Xe+Cs@1.5A GeV

Px

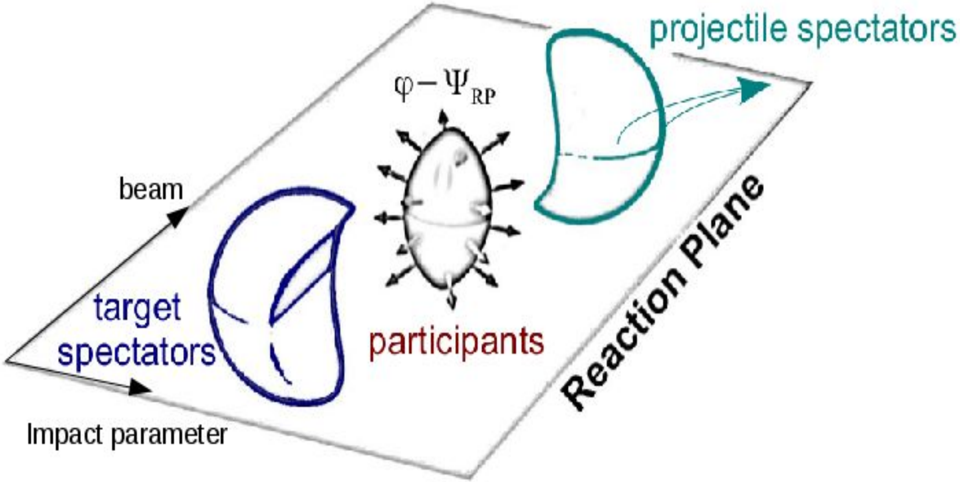




Py



Collision geometry and anisotropic transverse flow



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

⇓

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

Asymmetry in coordinate space converts

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

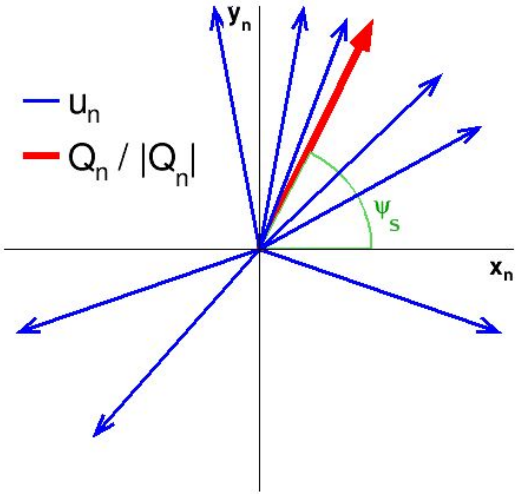
into momentum asymmetry with respect to the collision symmetry plane

Scalar product method for v_n measurement

u and **Q**-vectors:

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

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



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

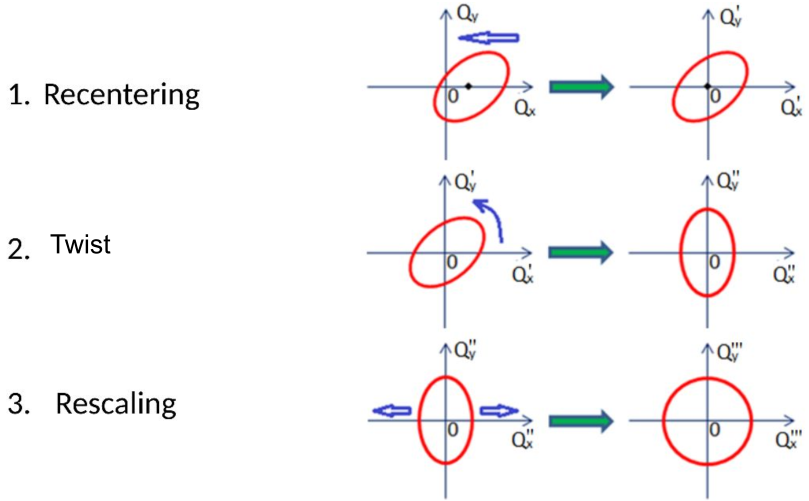
$$R^{a,MC}_{1,x} = \langle Q^a_{1,x} \cos \Psi_{RP}\rangle, \ R^{a,MC}_{1,y} = \langle Q^a_{1,y} \sin \Psi_{RP}\rangle$$

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

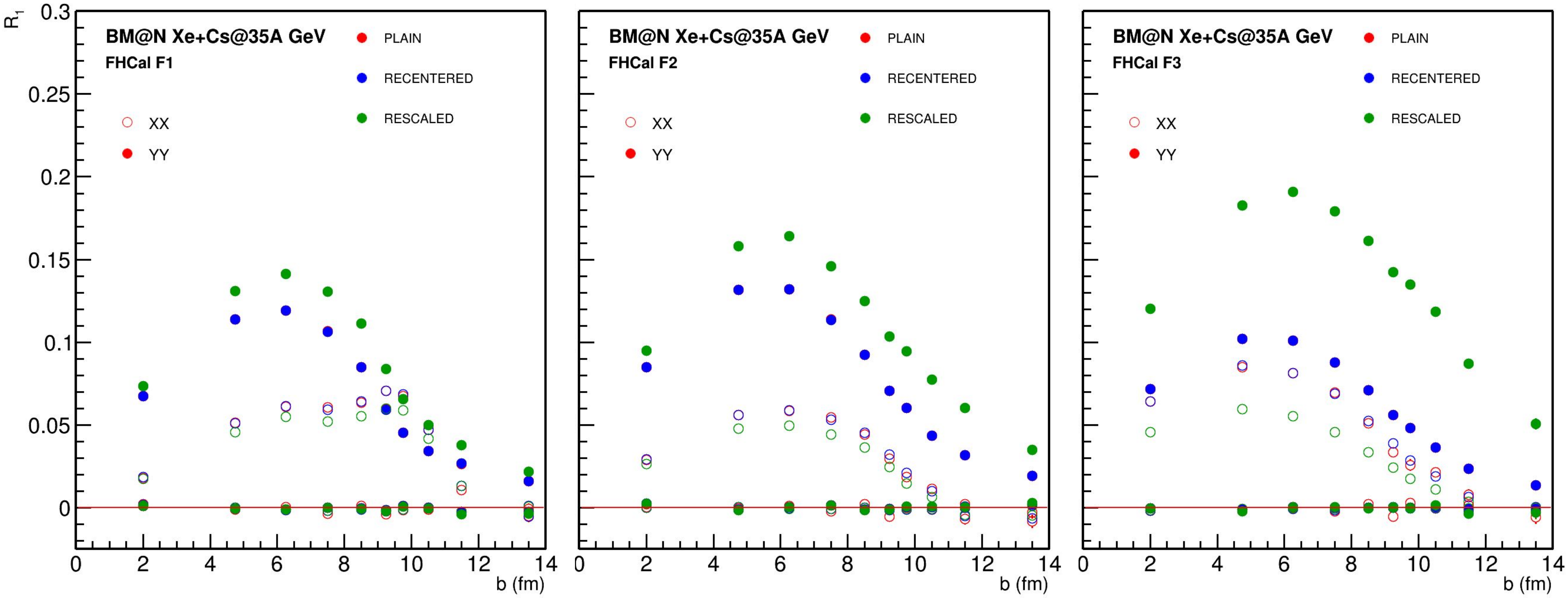
QnTools analysis package:
https://github.com/HeavyIonAnalysis/QnTools



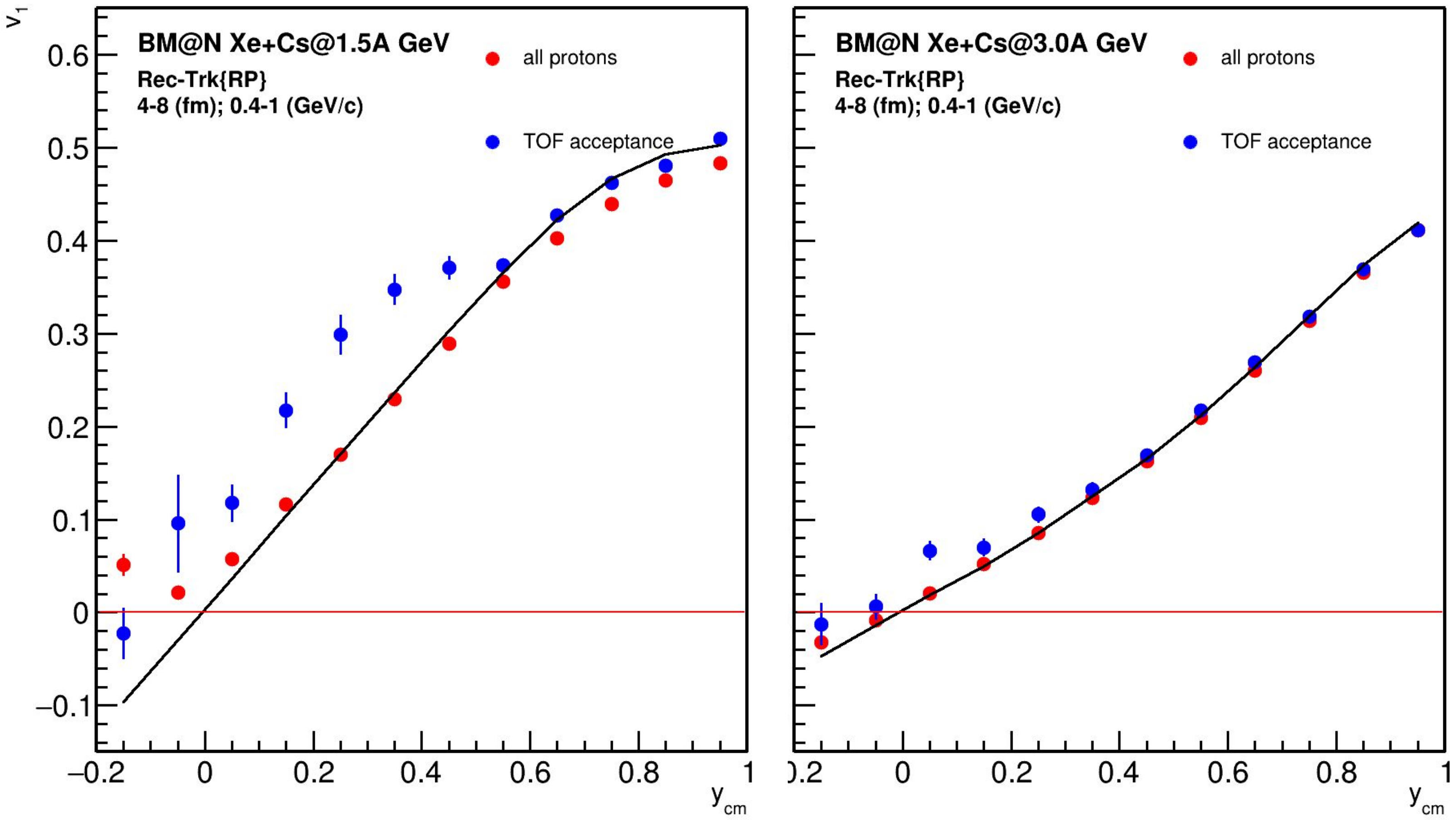
QnTools configuration

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			

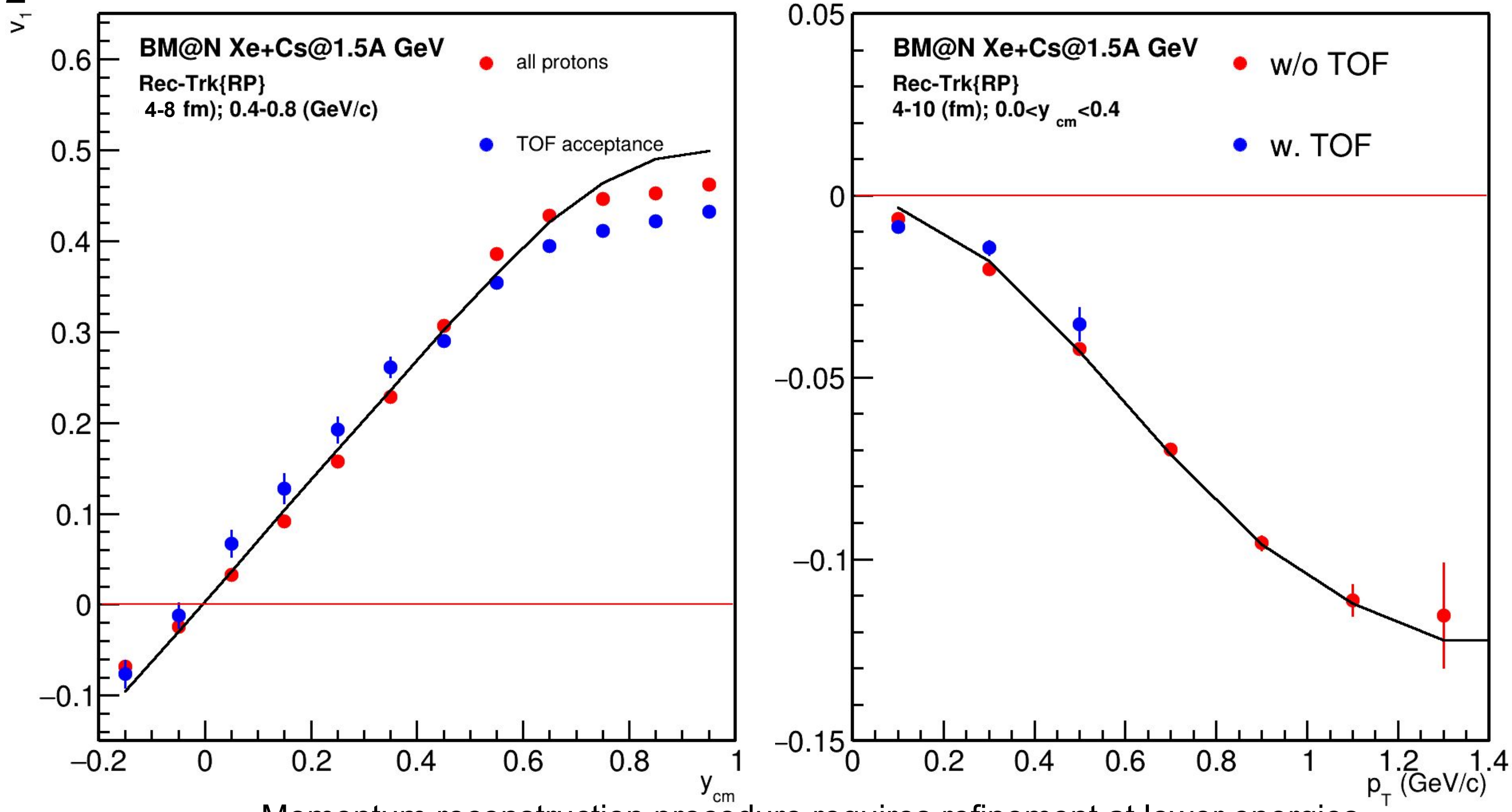
True R1: DCMQGCM-SMM Xe+Cs@3A GeV



v_1: Xe+Cs: True momenta



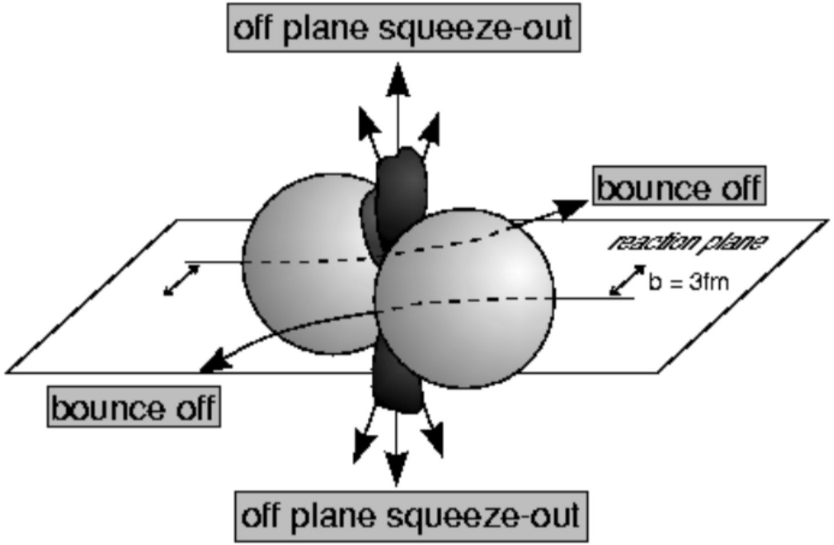
v_2: Xe+Cs@3.0A GeV: JAM (true momenta)



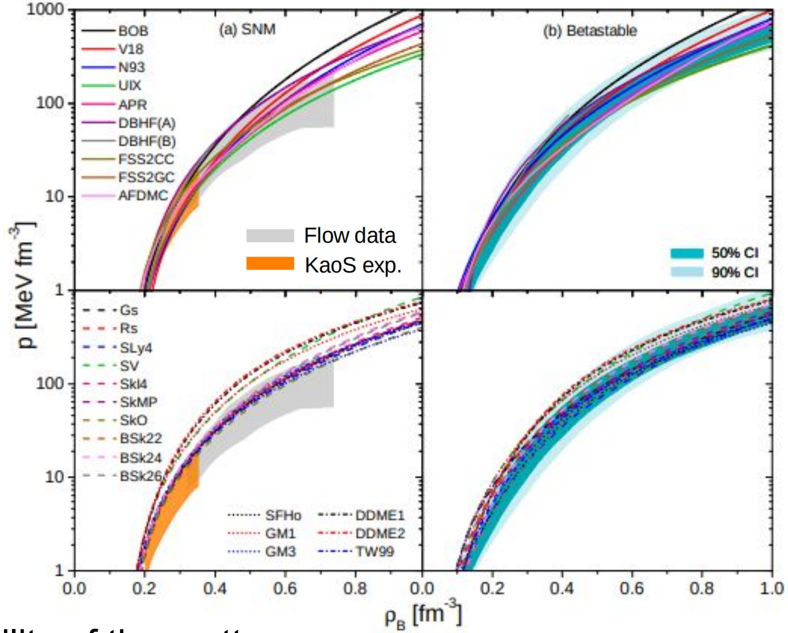
Momentum reconstruction procedure requires refinement at lower energies

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



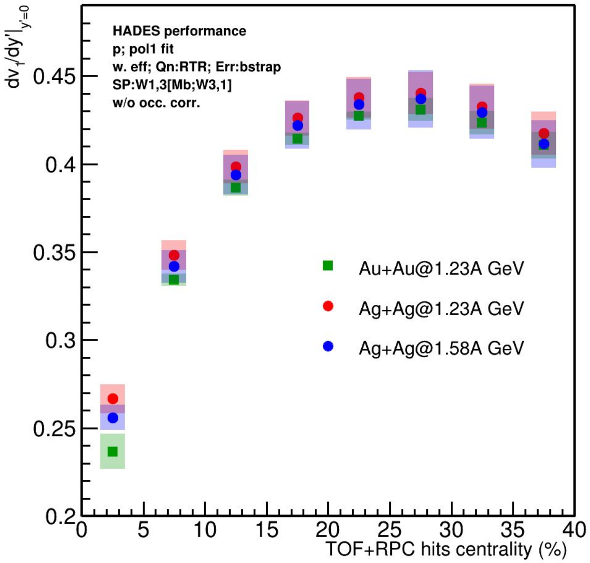
Symmetry 13 (2021) 3, 400



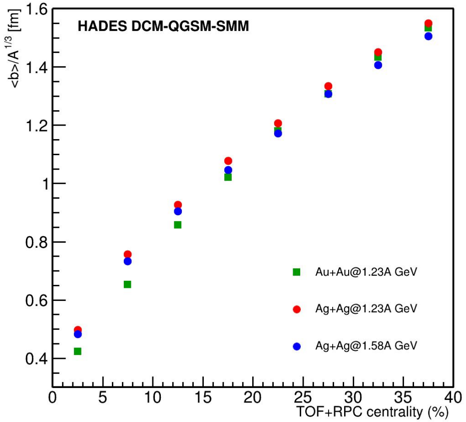
Anisotropic flow measurements can constrain compressibility of the matter created in the collision

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

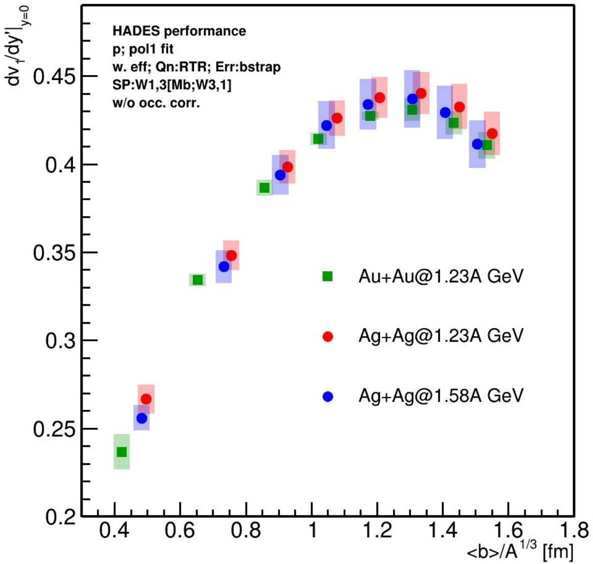
$y_{CM} \rightarrow y' = y_{CM} / y_{beam}$



centrality $\longrightarrow$ <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