Directed flow v_1 in Xe+CsI collisions at 3.8*A* GeV

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(JINR, MEPhI)
With big help of Sergey Sedykh and Aleksandr Zinchenko

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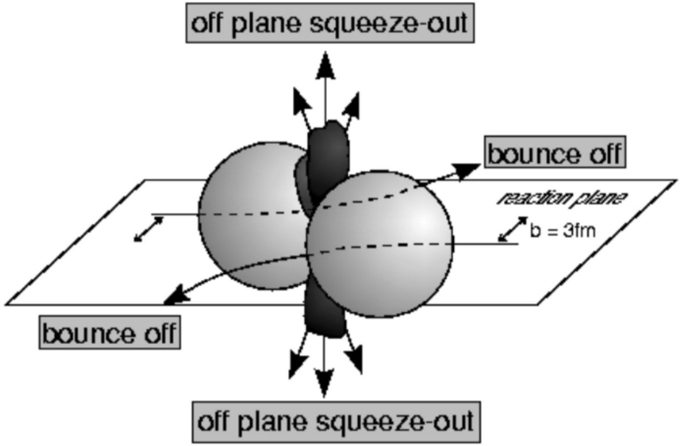
BM@N CM, 14/05/2025

Anisotropic flow & spectators



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

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

Anisotropic flow:

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

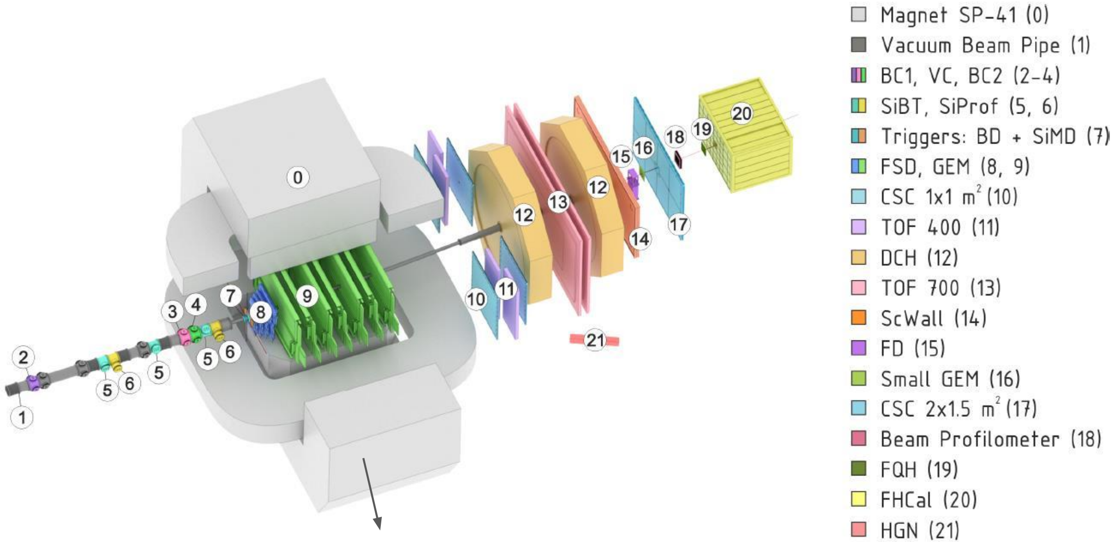
Anisotropic flow is sensitive to:

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

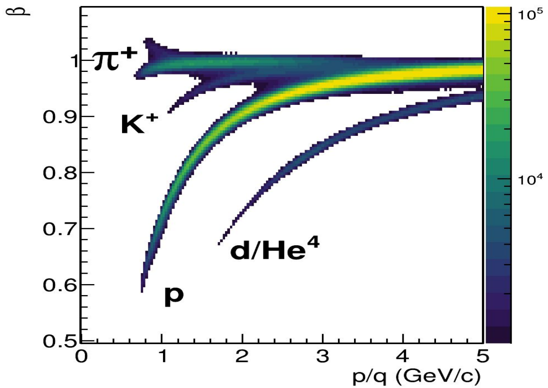
The BM@N experiment (“Baryonic matter at Nuclotron”)

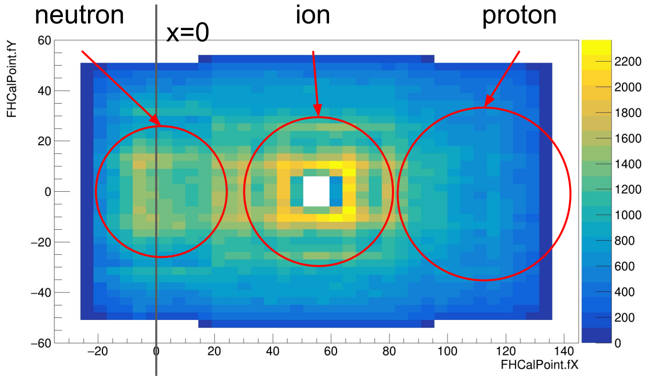
500M of Xe+CsI at E_{kin}=3.8A GeV were collected in the early 2023

Nucl.Instrum.Meth.A 1065 (2024)



Central tracked inside the analysing magnet





The symmetry plane is estimated using the azimuthal asymmetry of the spectator fragment energy deposition in FHCal

Flow vectors

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

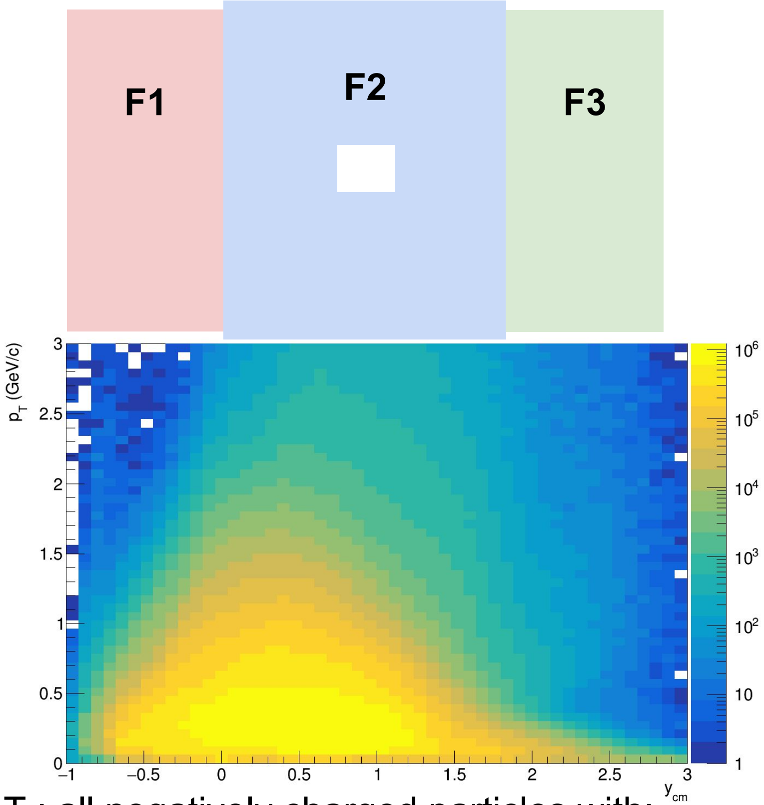
$$u_n = e^{in\phi}$$

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



T-: all negatively charged particles with:

- $1.5 < \eta < 4$
- $p_T > 0.2$ GeV/c

T+: all positively charged particles with:

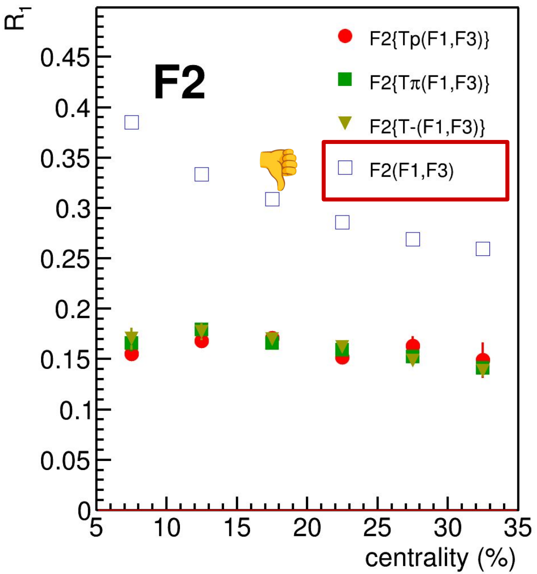
- $2.0 < \eta < 3$
- $p_T > 0.2$ GeV/c

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

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



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):

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

Pile-up rejection analysis note by O.Golosov and S.Sedykh

Analysis Note

Event classification in the Xe+Cs(I) collisions at 3.8 AGeV collected by the BM@N experiment (Run 8)

Oleg Golosov[1,2], Sergey Sedykh[3].

[1]National Research Center "Kurchatov Institute", Moscow, Russia

[2]National Research Nuclear University MEPhI, Moscow, Russia

[3]Joint Institute for Nuclear Research, Dubna, Russia

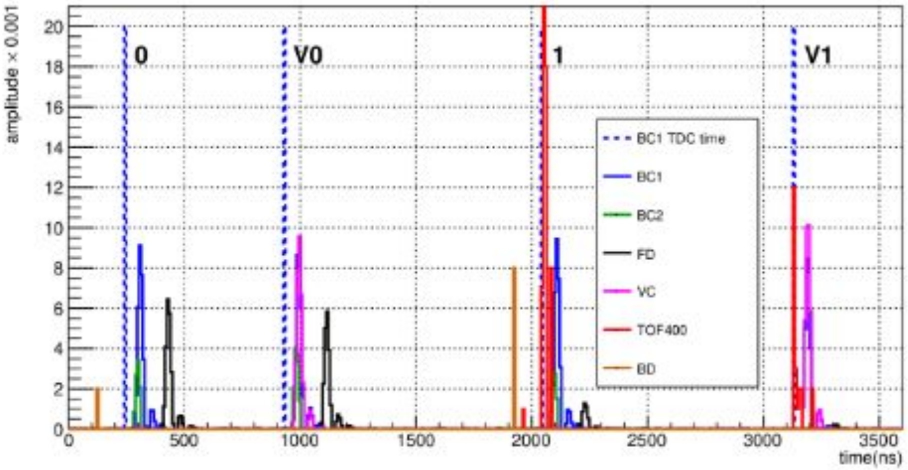
In this note, we present the procedure for event classification in Xe+Cs(I) collisions at 3.8 AGeV collected by the BM@N experiment in December 2022 - January 2023. We discuss the frequency of events of different types depending on the number of incoming beam ions and number of interactions, and show the effect of pile-up on the digitized and reconstructed data from main detector subsystems. Additionally, we describe the implementation and usage of a BmnRoot task aimed at event classification. Pile-up rejection criteria are proposed for the measurement of anisotropic transverse flow.

Link: http://indico.oris.mephi.ru/event/314/contribution/0/material/0/0.pdf

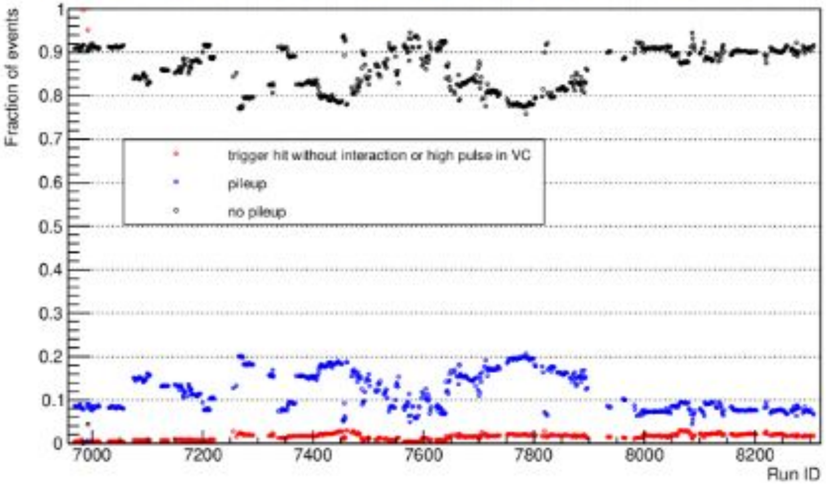
Pileup rejection

- Event classification procedure developed to study effect of pile-up on physics results
- The approach is based on run-by-run calibrated signals from trigger detectors
- ~85% of events pass the preliminary criteria for pileup rejection
- Detailed information and code example can be found in the analysis note

Example event with different types of pileup



Fraction of pileup and non-pileup events



Analysis note on QA by A.Demanov

Analysis Note

Report on the QA and run-by-run systematics in the Xe+Cs(I) run8

Alexander Demanov[1], Mikhail Mamamev, Petr Parfenov, Arkadiy Taranenko,
Valery Troshin, Irina Zhavoronkova
National Research Nuclear University MEPhI, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia

The Xe+Cs(I) event set for an energy of 3.8 GeV lasted several weeks. During such a long period of time, the characteristics of various detector subsystems may change. This may be due to changes in operating conditions and active areas of the detectors, changes in noise levels, failure of individual electronic components, etc. The task of analyzing the quality of experimental data is to select the part of the data that is characterized by the same characteristics of the detector subsystems used in the physical analysis. The entire volume of BM@N experimental data within a single Nuclotron accelerator cycle is divided into separate segments (runs), which can be selected using a special identifier (RunId). Within a single run, the characteristics of the BM@N detector subsystems remain unchanged. A QA (quality assurance) selection procedure was performed to select runs suitable for the analysis. This note describes the software used for the QA procedure and the results of its operation.

Link: http://indico.oris.mephi.ru/event/315/contribution/1/material/slides/0.pdf

Preliminary results for proton and deuteron v_1

Analysis Note

Directed flow v_1 of protons in the Xe+Cs(I) collisions at 3.8 AGeV (BM@N run8)

Mikhail Mamamev[1], Arkadiy Taranenko[2], Alexander Demanov, Petr Parfenov, Valery Troshin.
National Research Nuclear University MEPhI, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

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Analysis Note

Directed flow v_1 of deuterons in the Xe+Cs(I) collisions at 3.8 AGeV (BM@N run8)

Irina Zhavoronkova[1], Mikhail Mamamev[2], Arkadiy Taranenko[3], Alexander Demanov, Petr Parfenov, Valery Troshin.
National Research Nuclear University MEPhI, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

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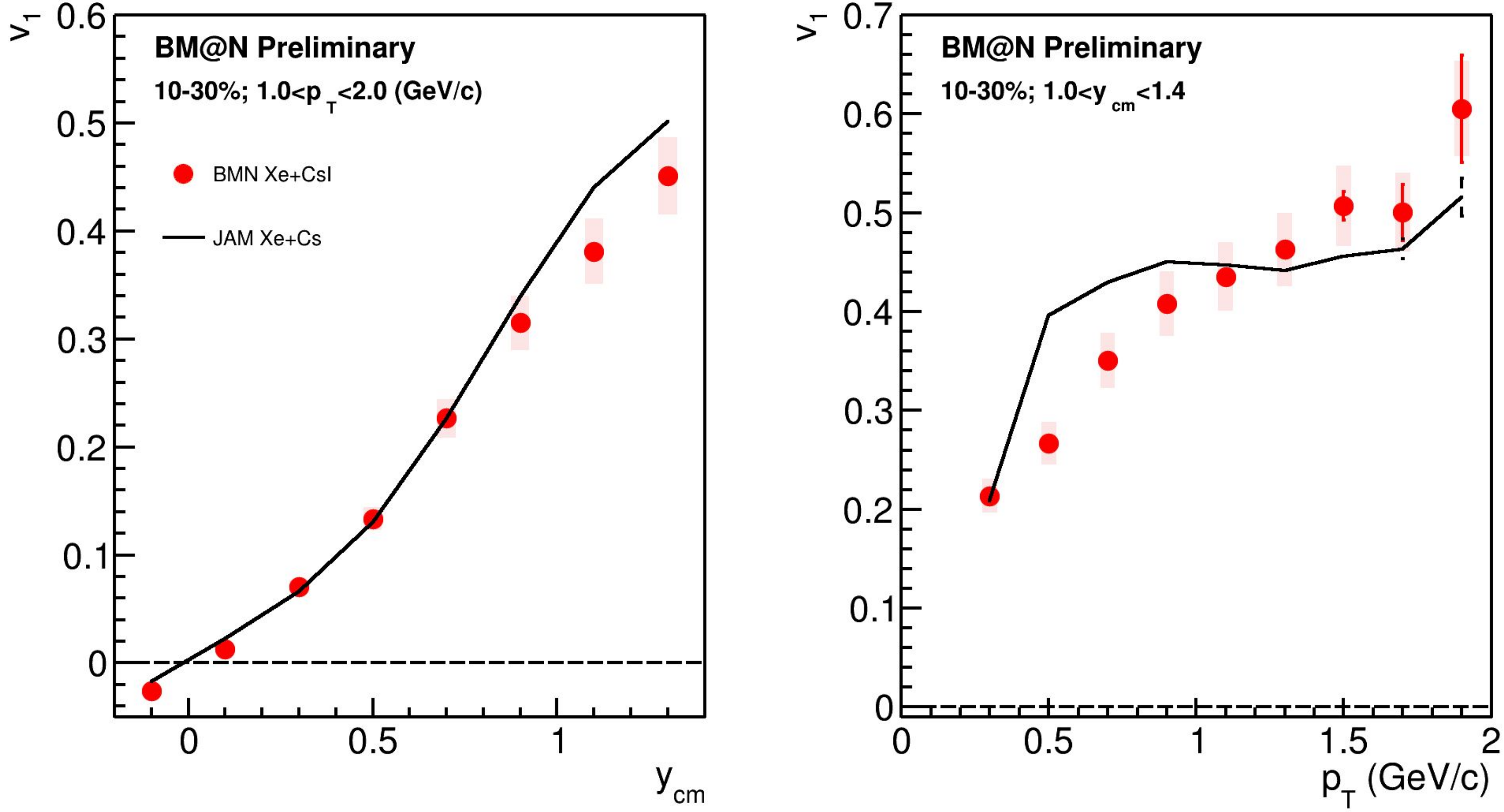
Proton note: https://indico.jinr.ru/event/4750/attachments/19780/34163/ANoteFlowRun8.pdf
Deuteron note: http://indico.oris.mephi.ru/event/310/contribution/1/material/0/0.pdf

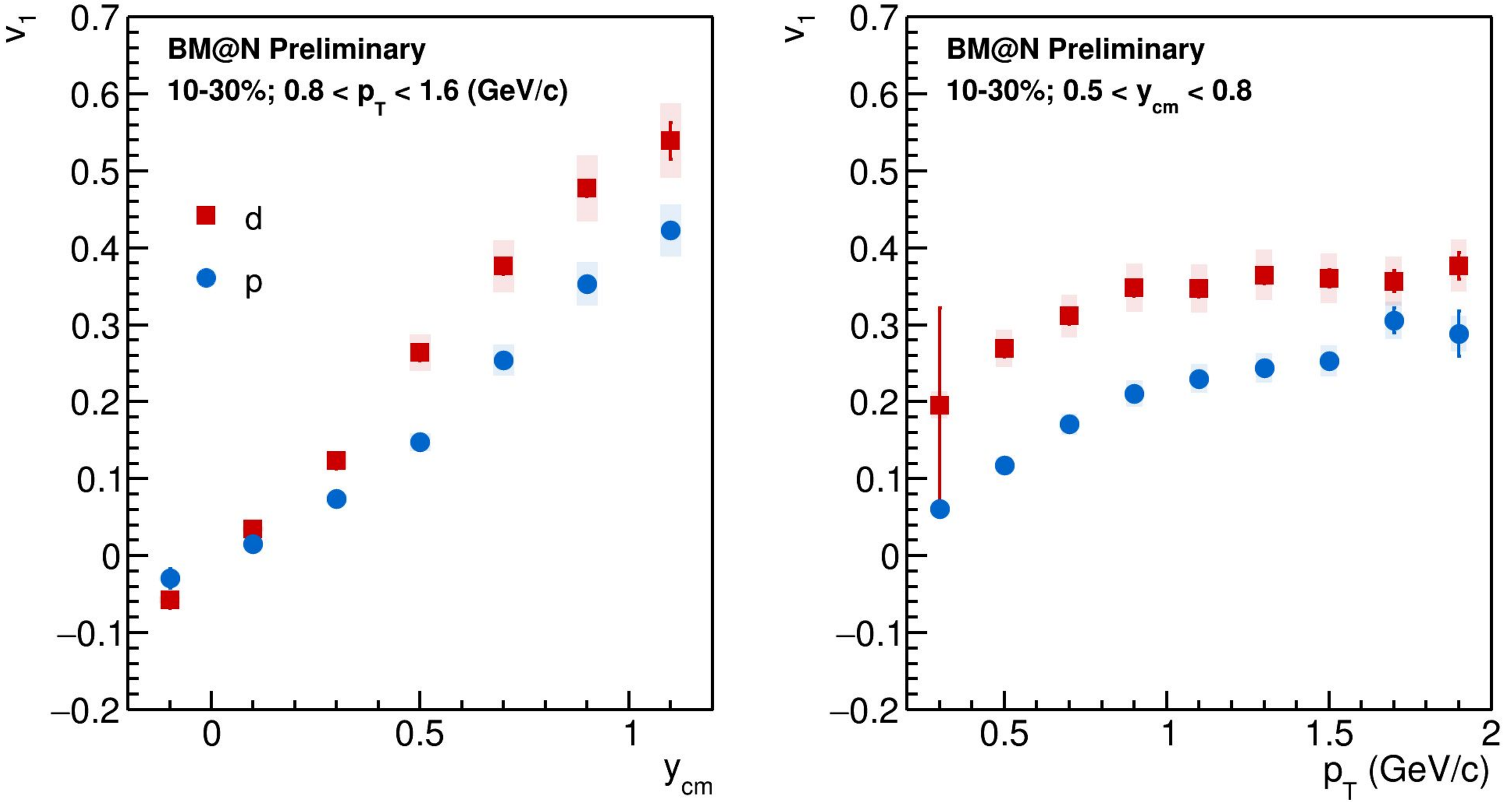
v_1 as a function of pT and y



JAM model describes $v_1(y)$ well

Proton and deuteron v_1 vs rapidity and transverse momentum

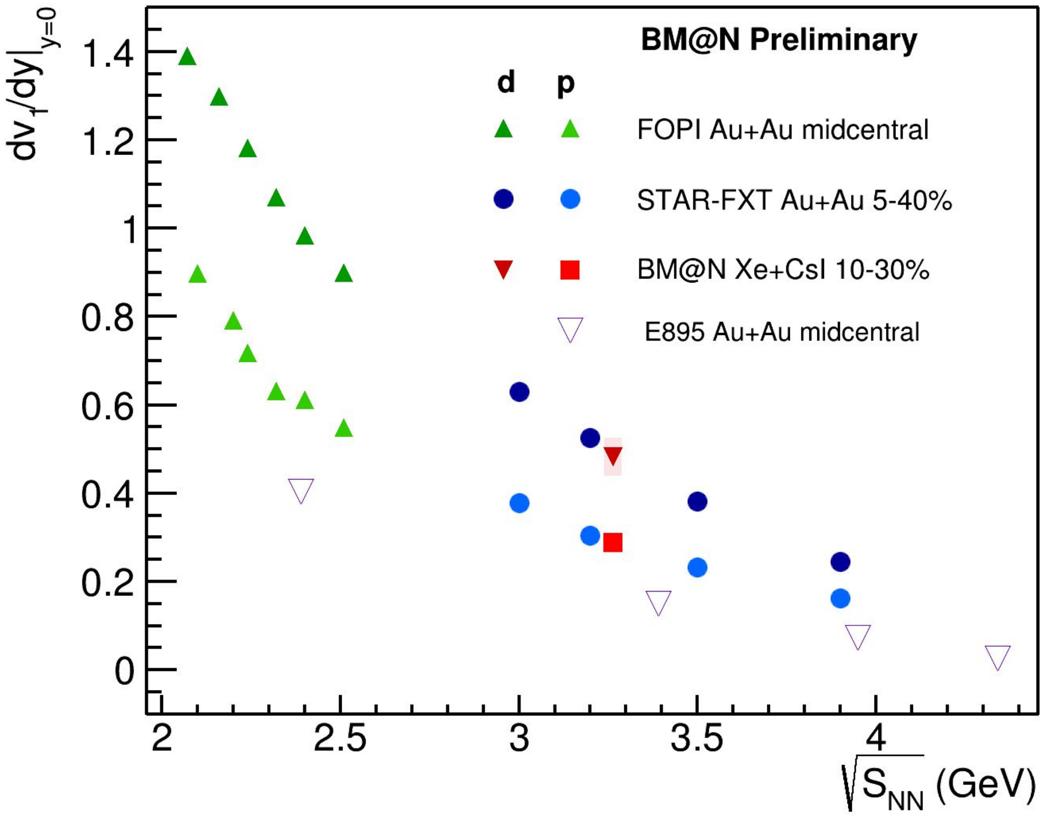
Deuteron data
by I.Zhavoronkova



$dv_1/dy|_{ycm=0}$ vs collision energy

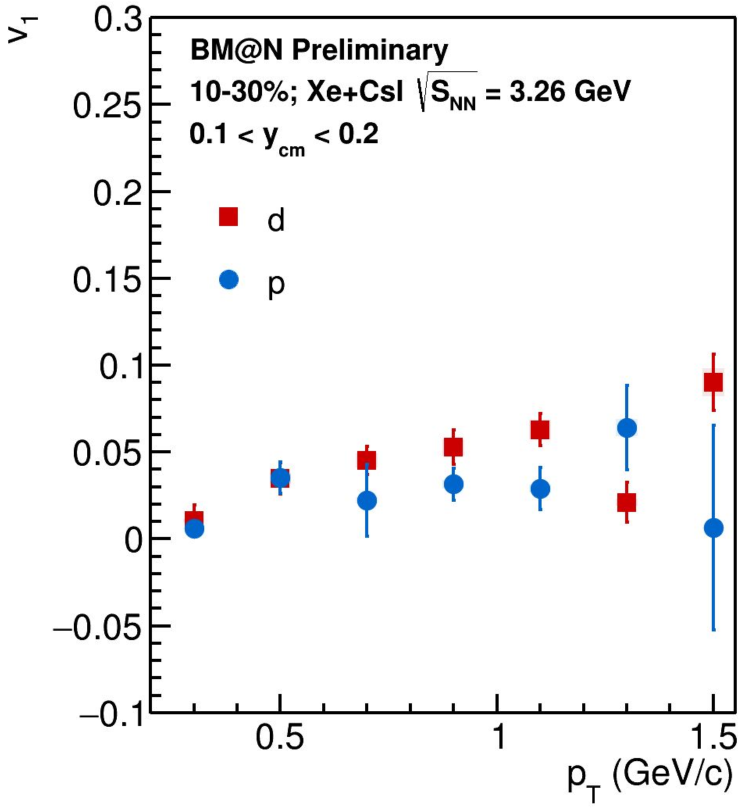
Deuteron data
by I.Zhavoronkova

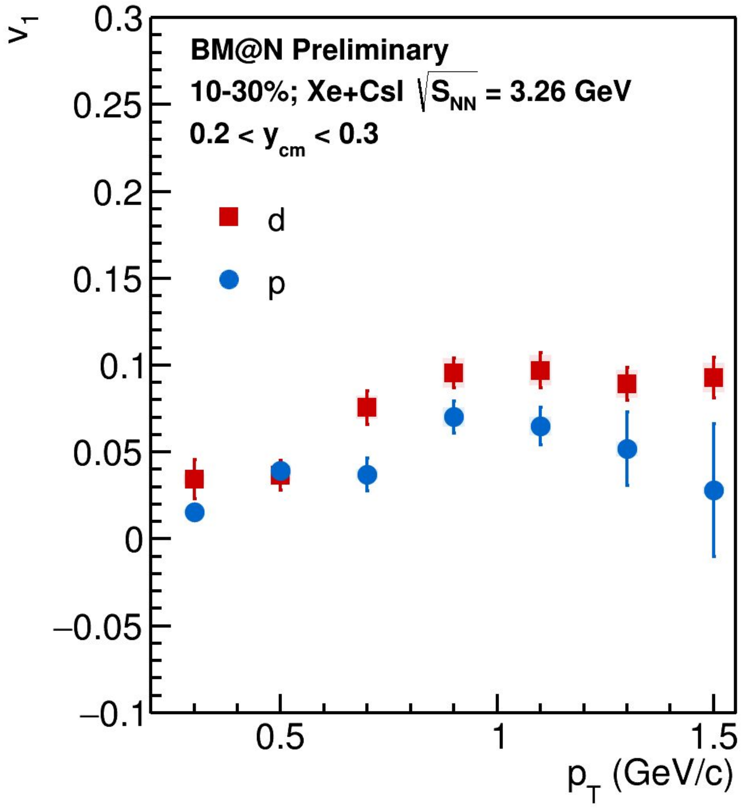
FOPI: Nucl.Phys.A 876 (2012)
STAR: Phys.Lett.B 827 (2022)
E895: Phys.Rev.Lett. 84 (2000)



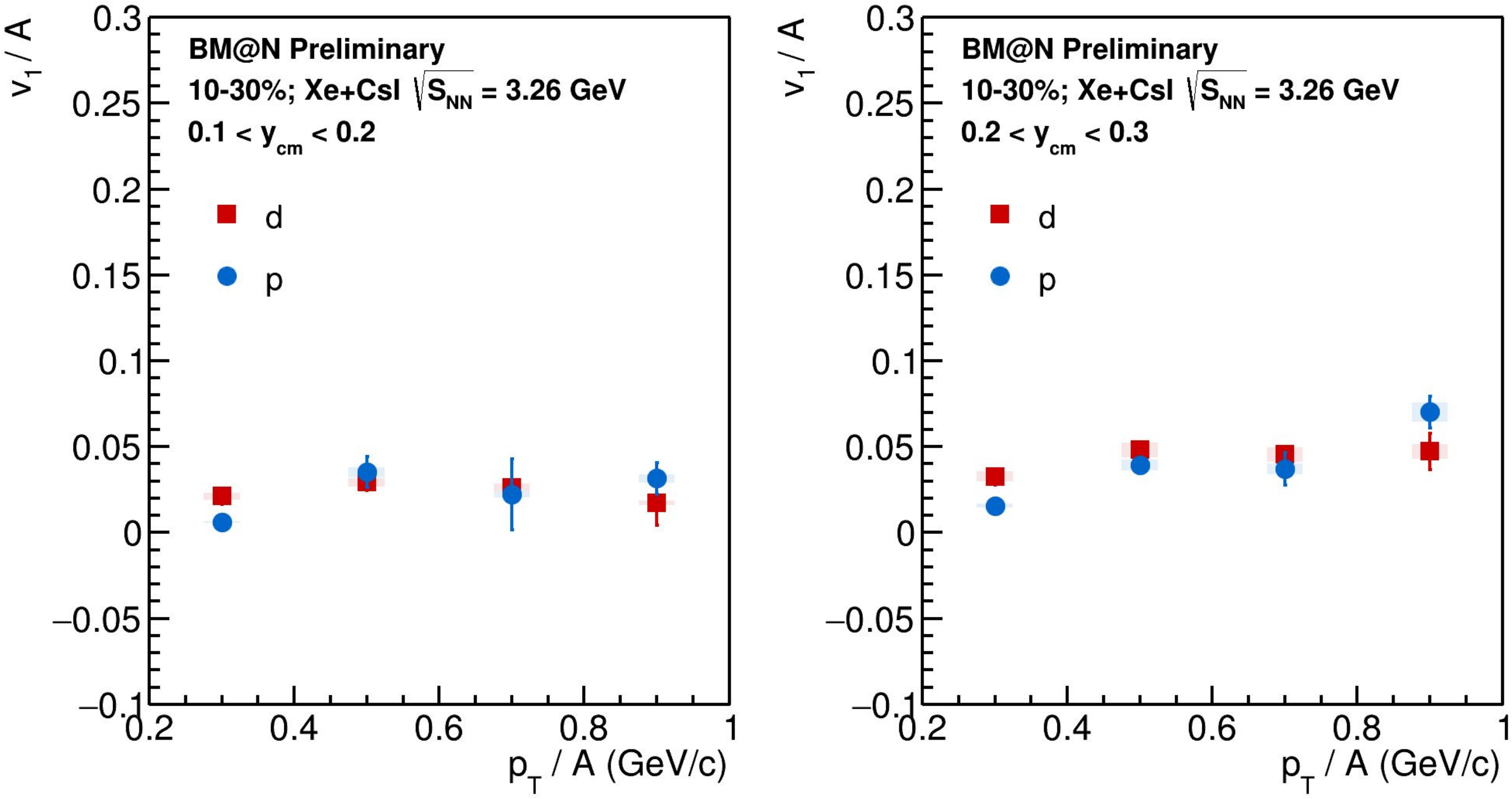
- Both deuteron and proton data from BM@N agree with STAR measurements
- Higher directed flow of proton in BM@N and STAR data suggests more hard equation of state

v_1 of protons and deuterons as a function of p_T



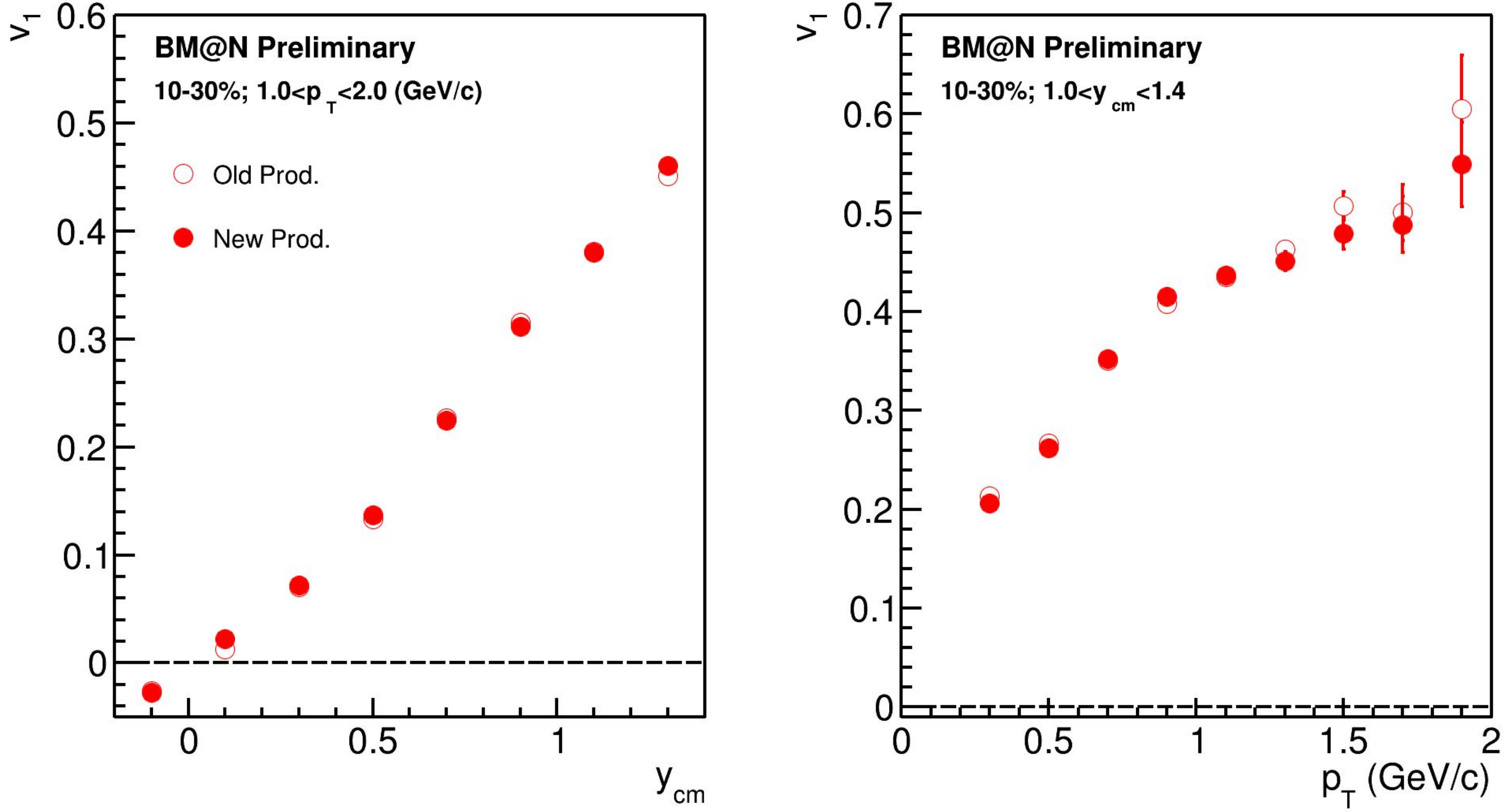


Scaled v_1 of protons and deuterons as a function of scaled p_T/A



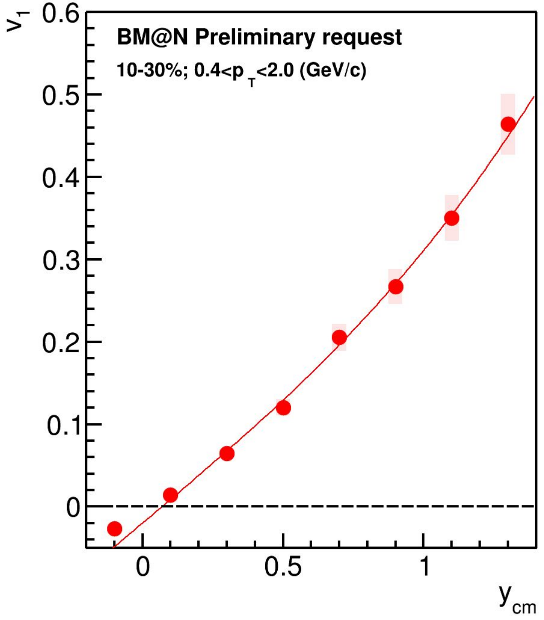
v_1 follows the scaling with mass number A.

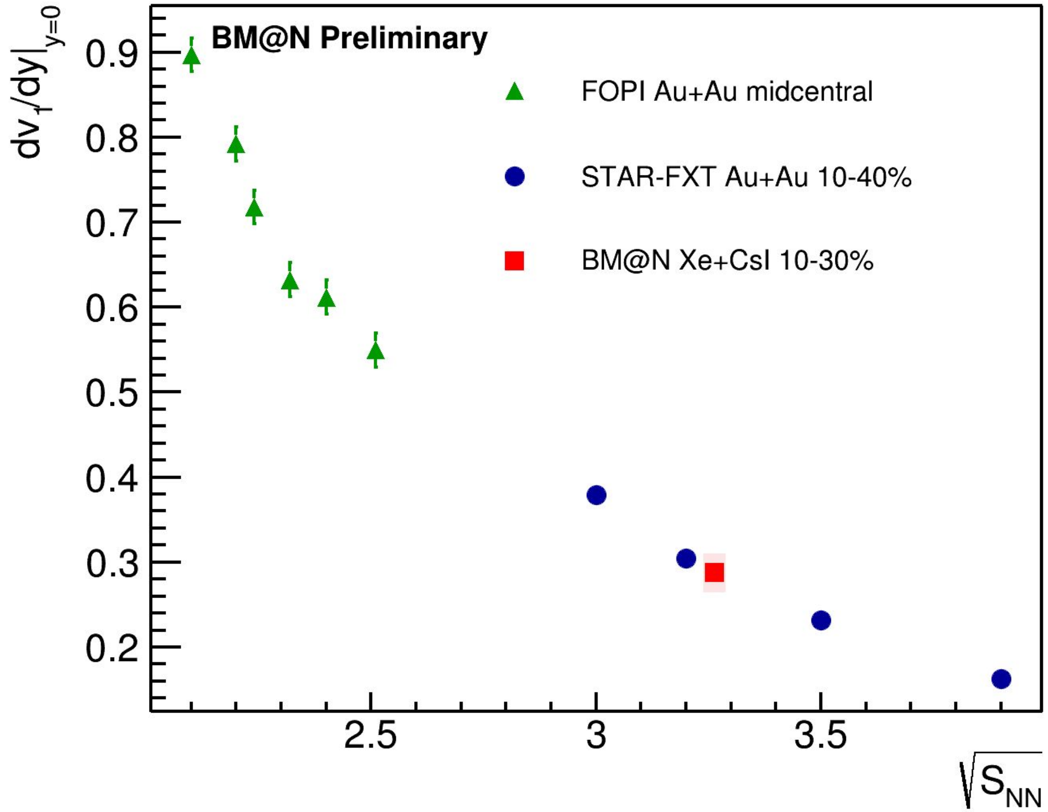
v_1 in new production compared with old one



JAM model describes $v_1(y)$ well

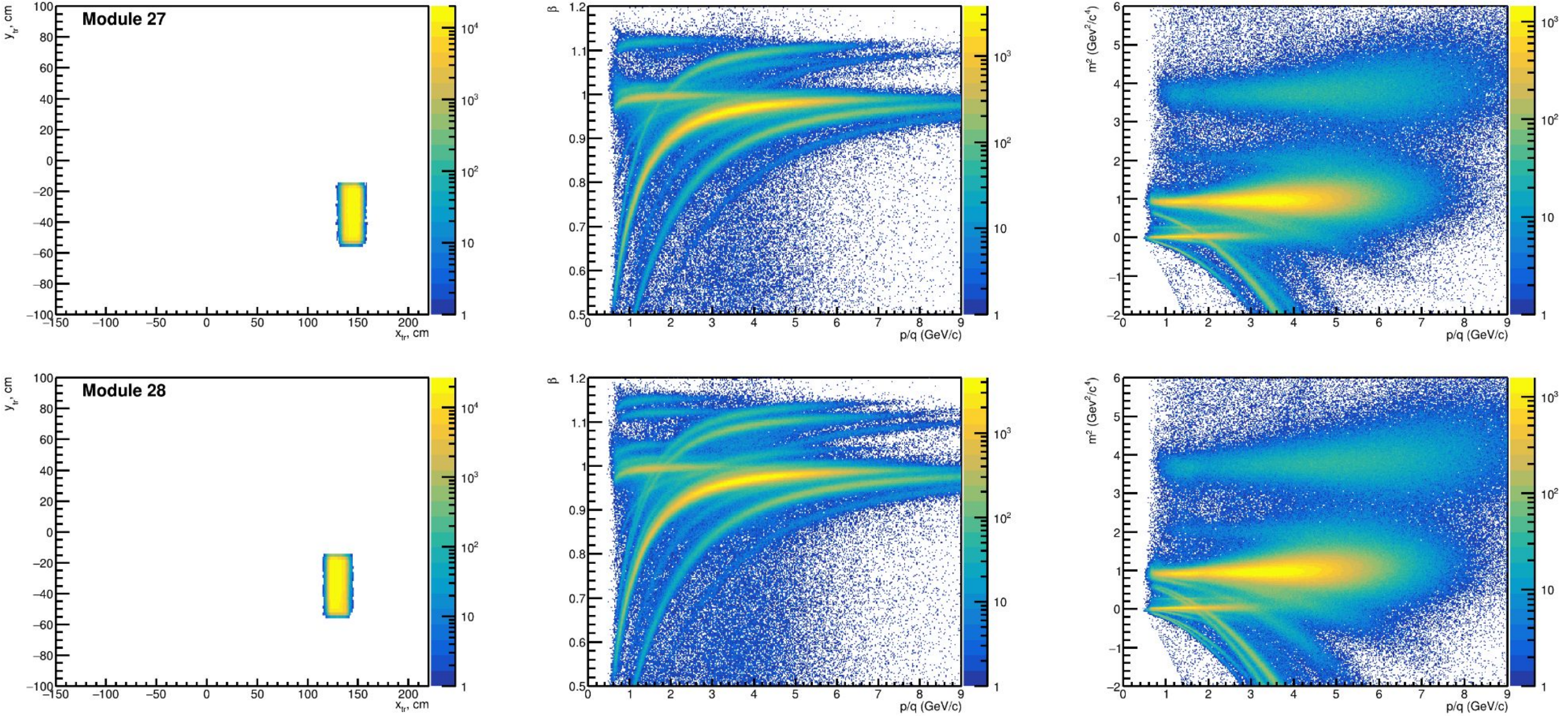
$dv_1/dy|_{y=0}$ vs collision energy





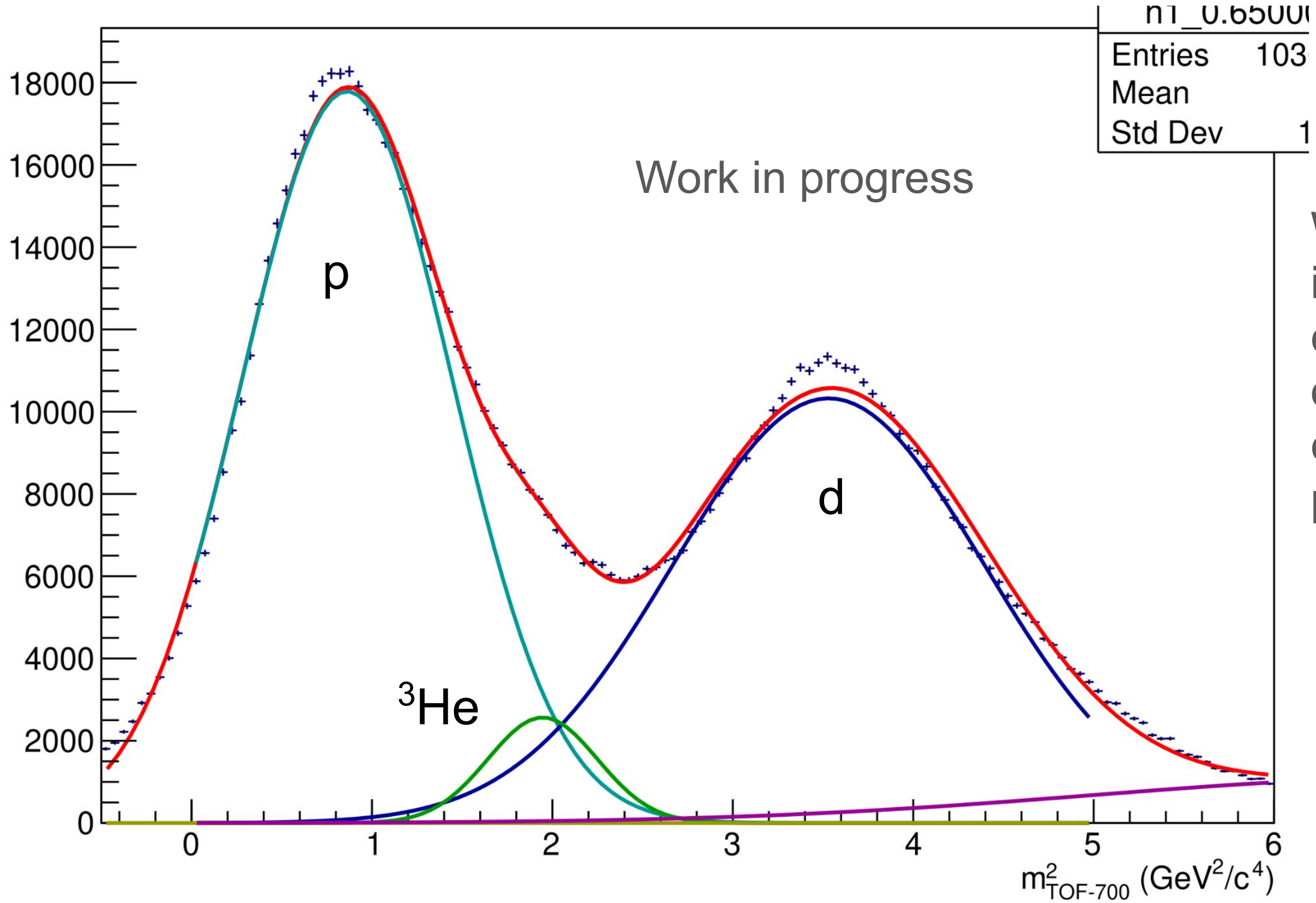
dv_1/dy is in a good agreement with the world data

Observed issue in the production 24.12.0 (now fixed)



We observed an issue with global track matching to new TOF701 hits (now it's fixed)

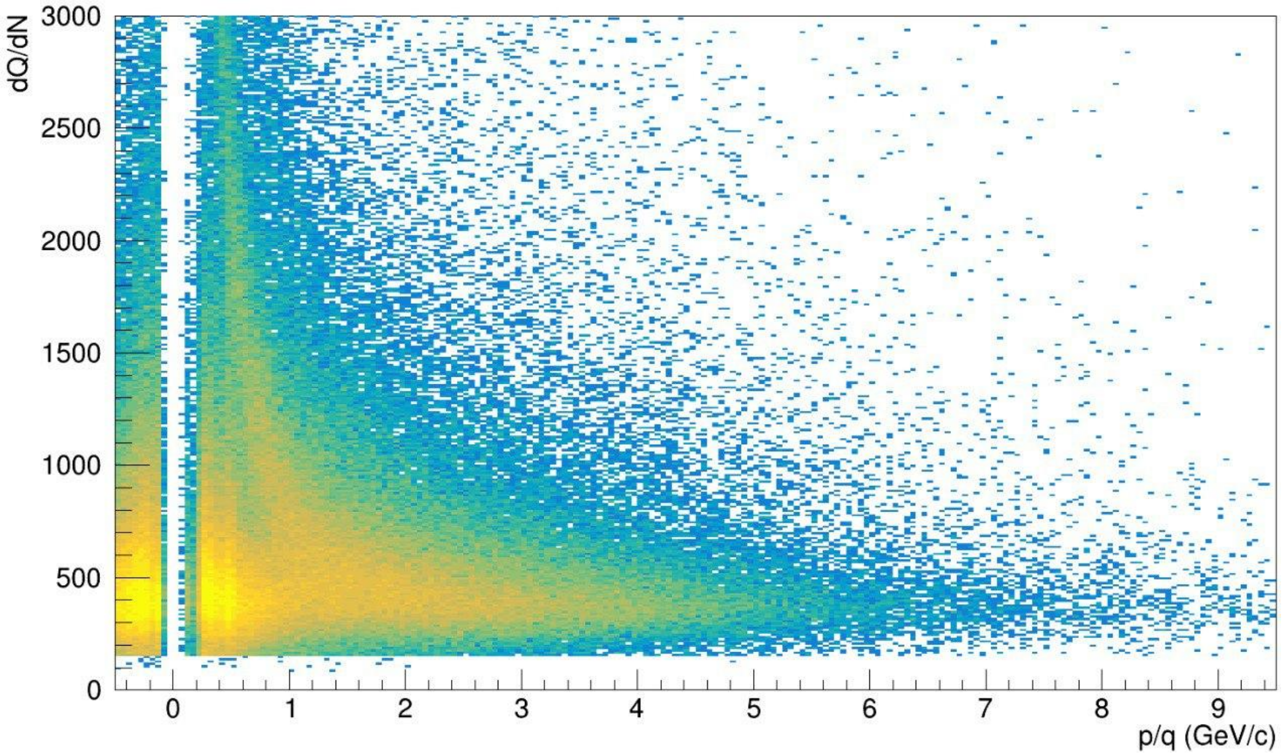
Identification of charged particles



We are working on identifying the charged particles to develop selection criteria maximizing purity

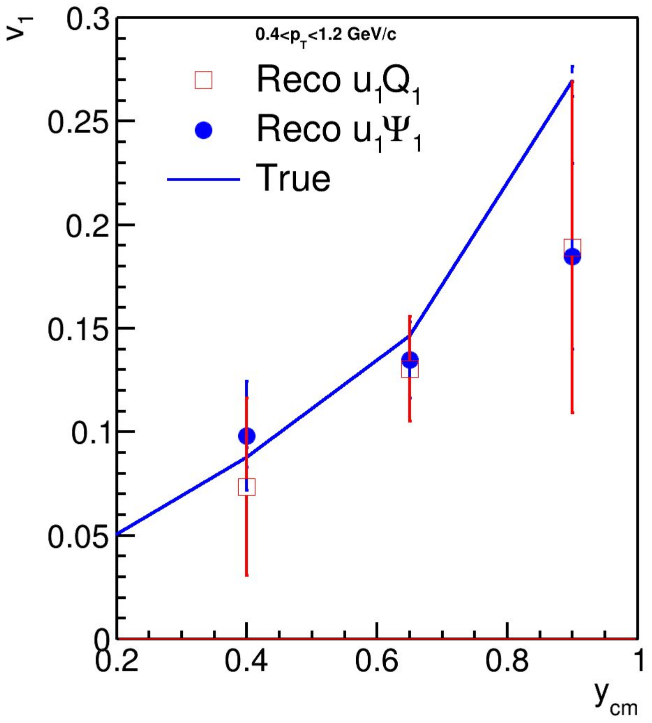
Charge selection using dE/dx in FSD+GEM

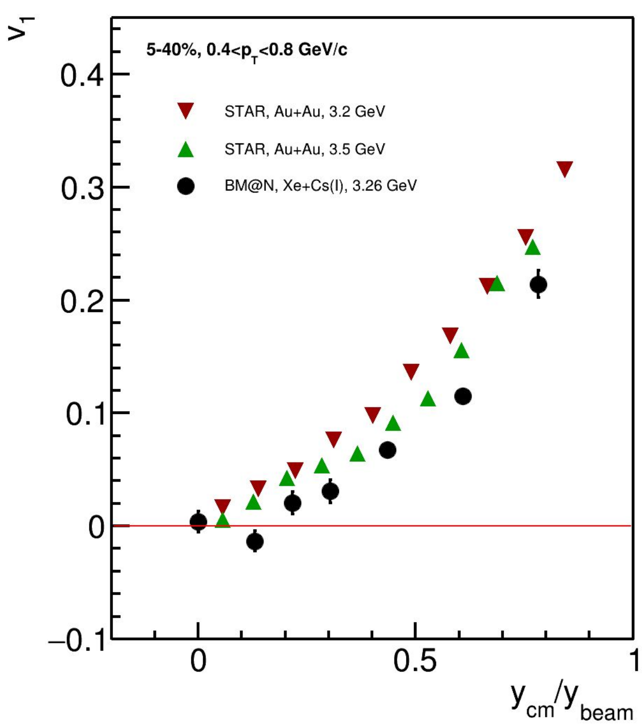
3rd station of FSD



We started calibrating the dE/dx in both FSD and GEM planes to reject the particles with charge > 1 to improve identification

Status of $v_1(y)$ of Λ in BM@N Xe+Cs(I) run at 3.8 AGeV

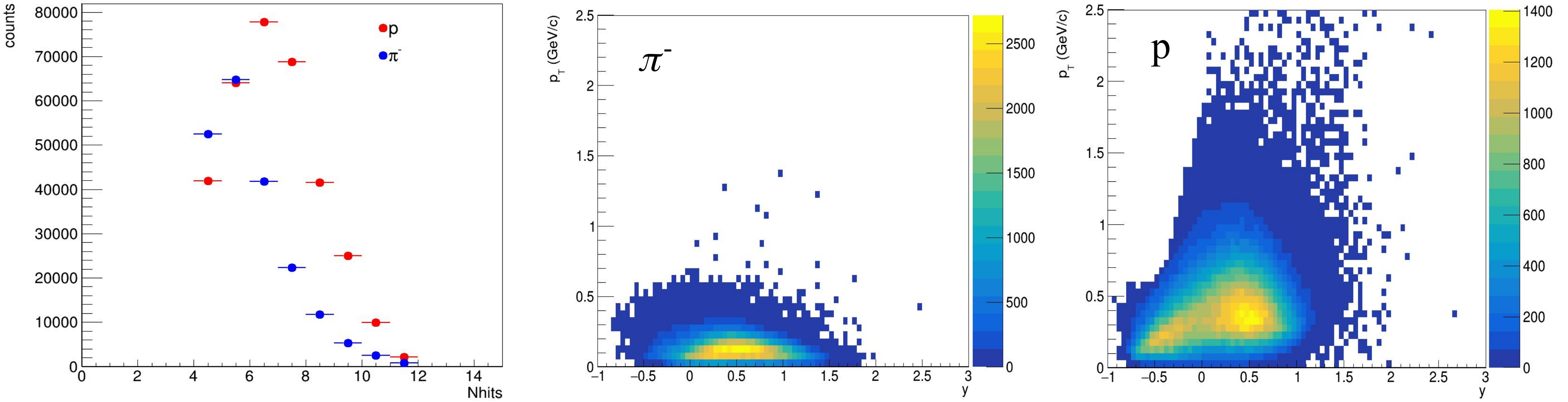




Analysis by V.Troshin

Performance with JAM model (left) and experimental data from Run8 (right). The results are systematically lower, maybe because of the difference in system of the collision

QA of Λ daughters in BM@N with JAM model

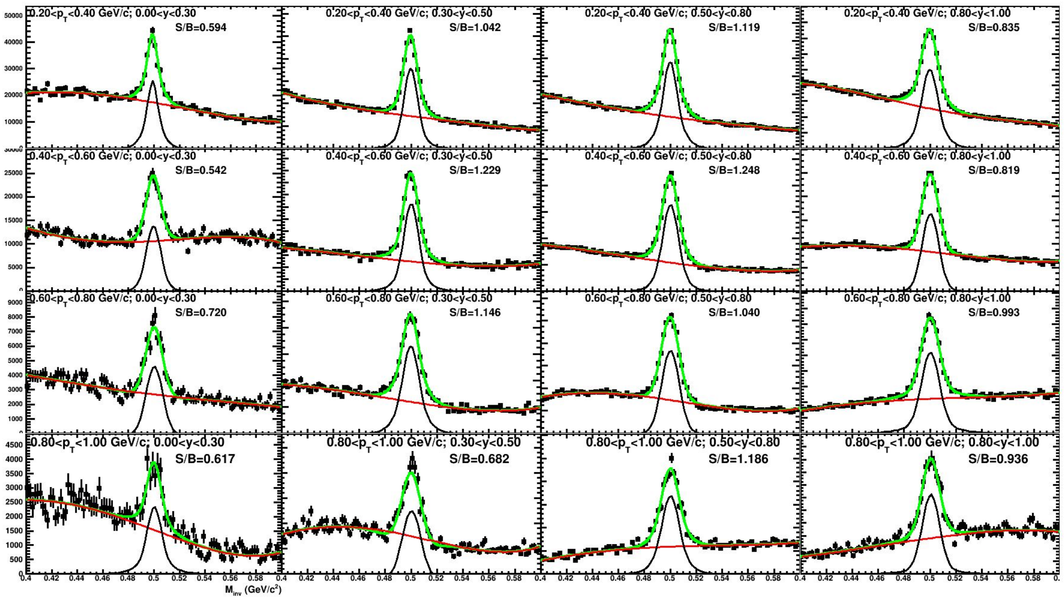


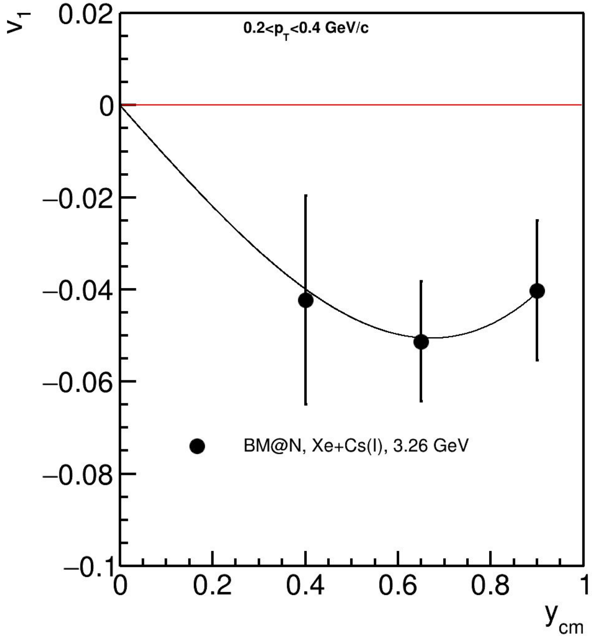
Work in progress:

- Acceptance effects in Λ reconstruction and selection
- System-size effect in v_1 measurements
- Analysis of azimuthal angle φ distributions in p_T-y bins

Analysis by V.Troshin

Status of $v_1(y)$ of K^0_S in BM@N Xe+Cs(I) run at 3.8 AGeV





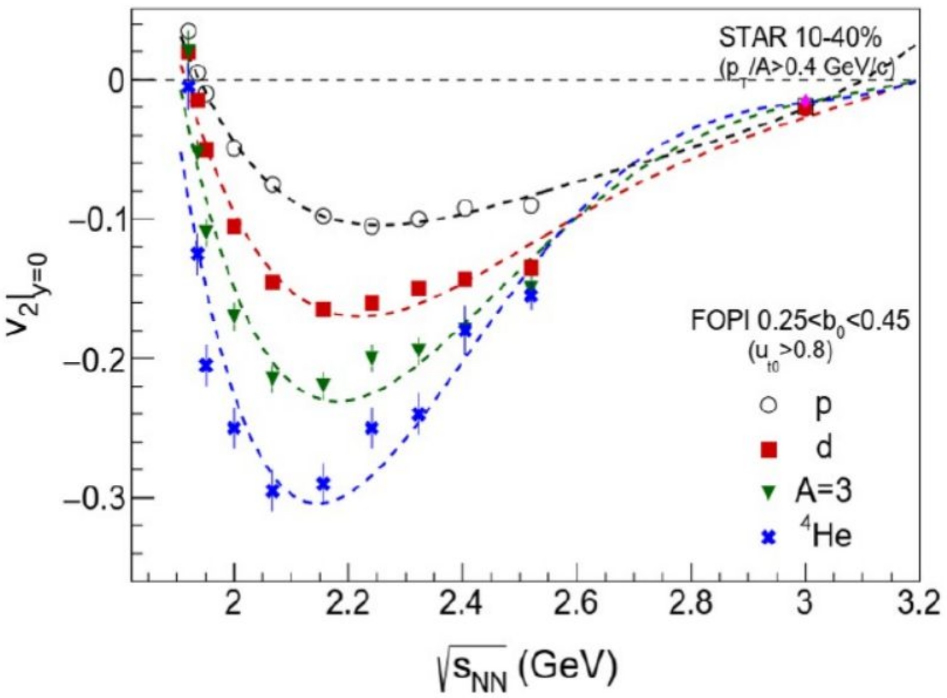
Very limited statistics for the analysis of directed flow

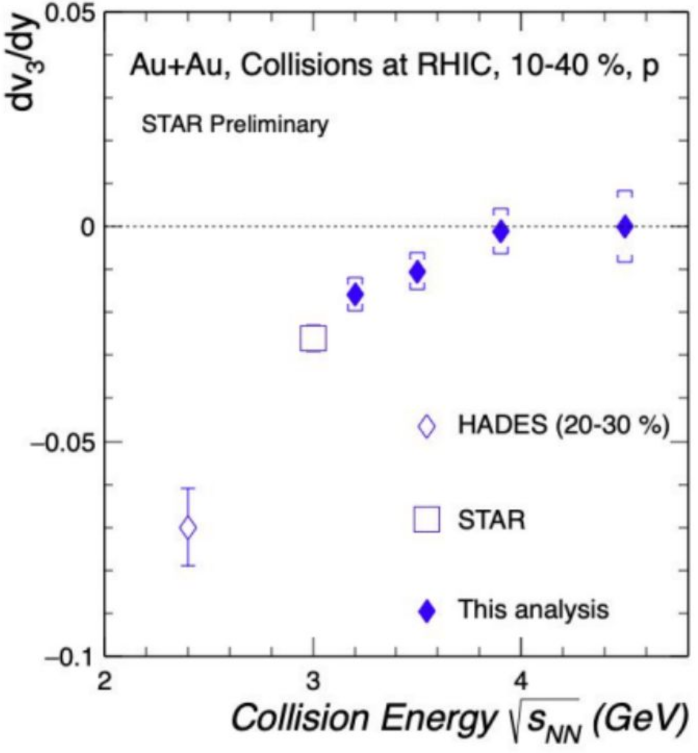
centrality: 10-40%

p_T 0.2-0.4 GeV/c

BES program in the BM@N experiment

EPJ Web Conf. 276 (2023) 01020

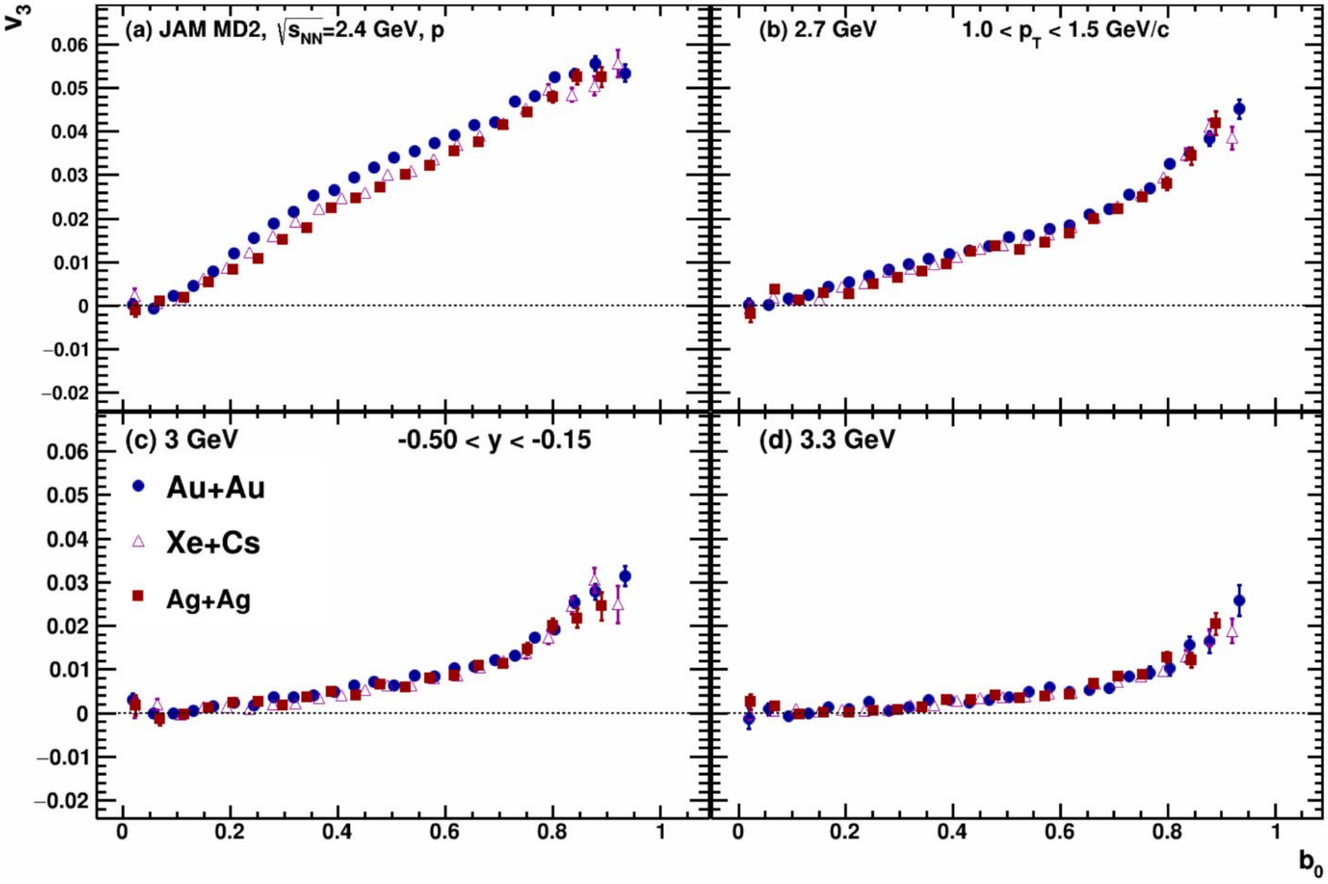




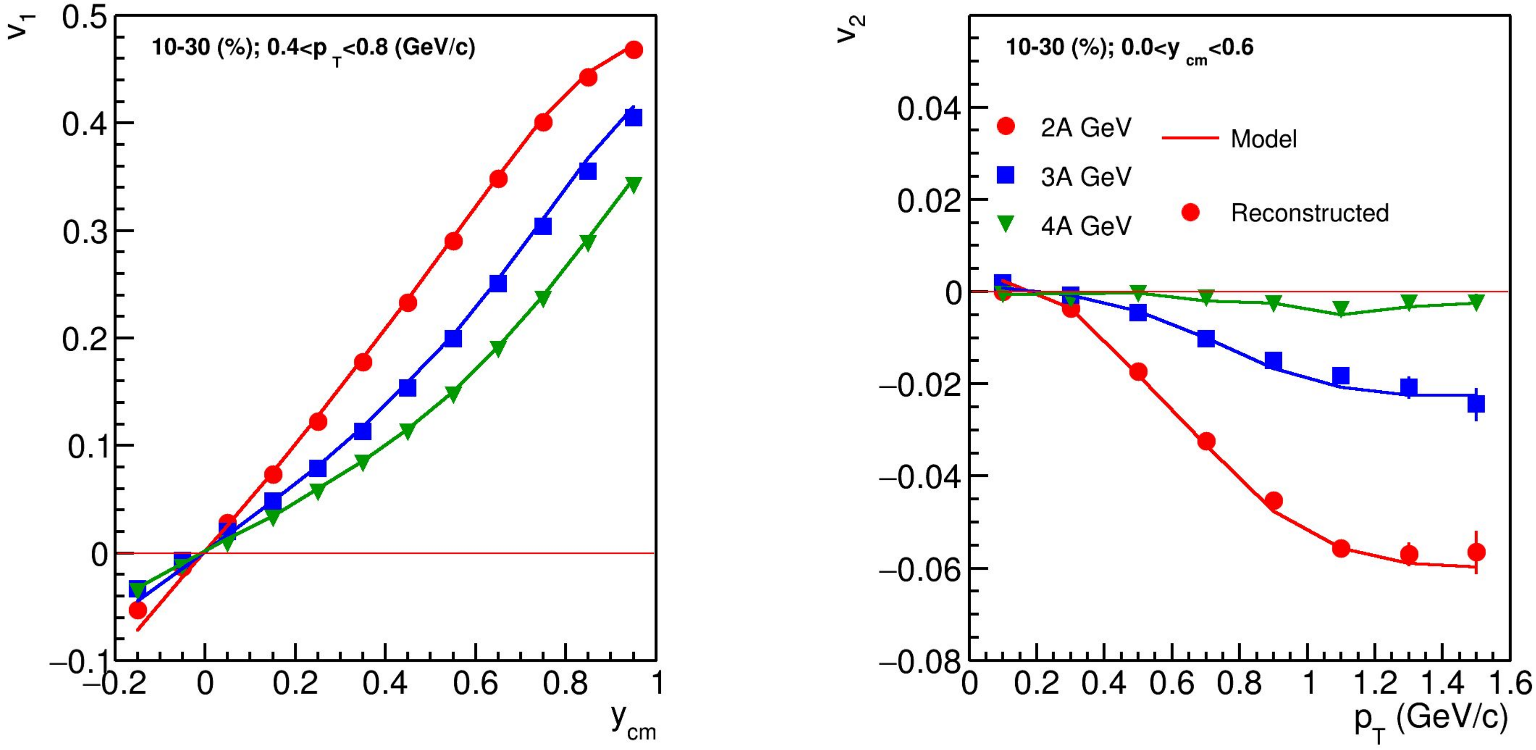
- The're no available measurements of v_n in the region $\sqrt{s_{NN}}$=2.5 – 3.0 GeV
  - The upcoming BM@N BES aims to cover this energy range

Backup

v_3 dependence on system size and collision energy

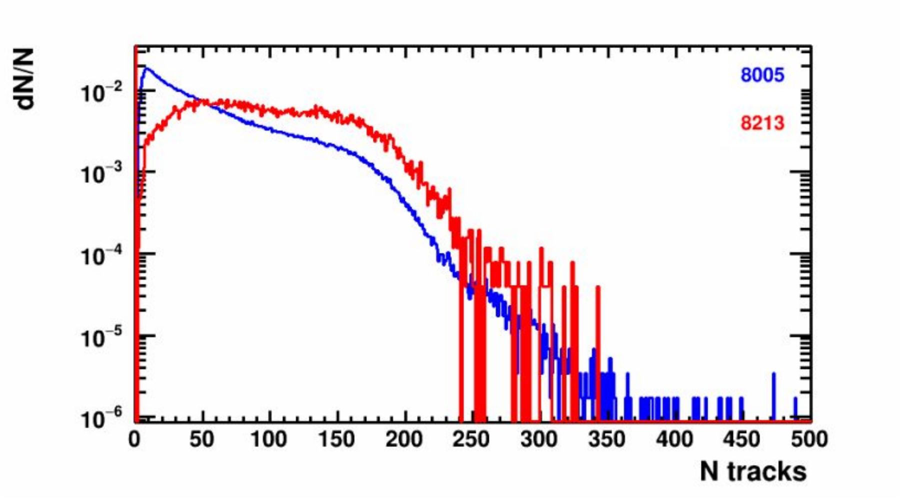


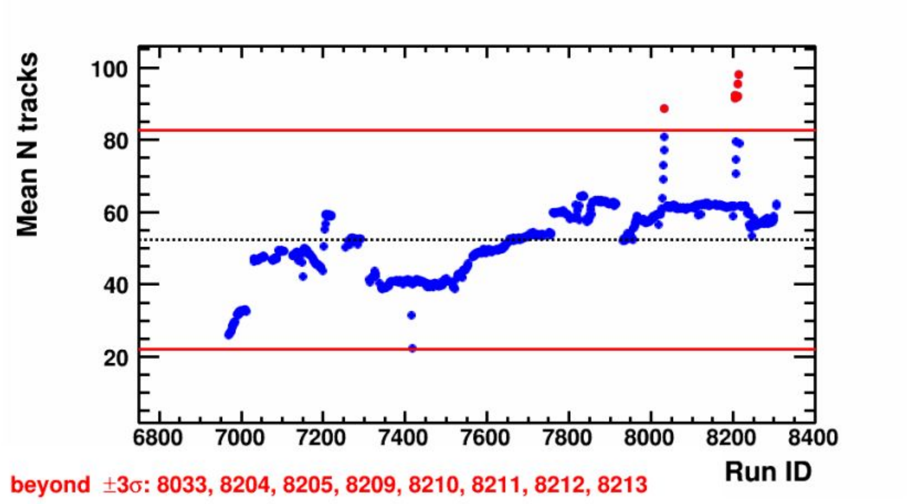
Performance for v_1 and v_2 in Xe+Cs (JAM+GEANT4)



- Good agreement between reconstructed and pure model data for all three energies

Quality assurance for the recent data

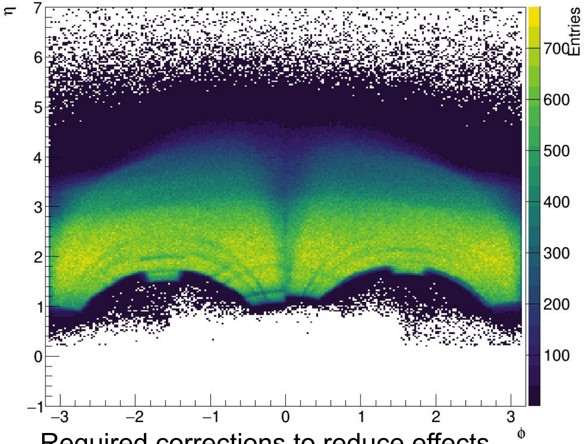




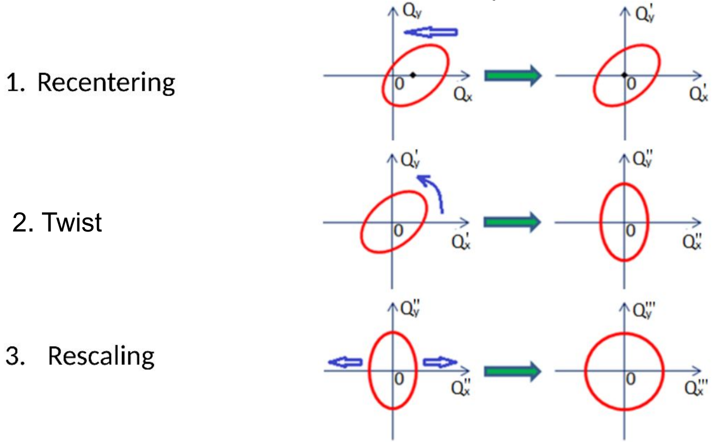
The preliminary list of bad runs based on QA study [18M events] RunId: 6968, 6970, 6972, 6973, 6975, 6976, 6977, 6978, 6979, 6980, 6981, 6982, 6983, 6984, 7313, 7326, 7415, 7417, 7435, 7517, 7520, 7537, 7538, 7542, 7543, 7545, 7546, 7547, 7573, 7575, 7657, 7659, 7679, 7681, 7843, 7847, 7848, 7850, 7851, 7852, 7853, 7855, 7856, 7857, 7858, 7859, 7865, 7868, 7869, 7907, 7932, 7933, 7935, 7937, 7954, 7955, 8018, 8031, 8032, 8033, 8115, 8121, 8167, 8201, 8204, 8205, 8208, 8209, 8210, 8211, 8212, 8213, 8215, 8289.

Azimuthal asymmetry of the BM@N acceptance

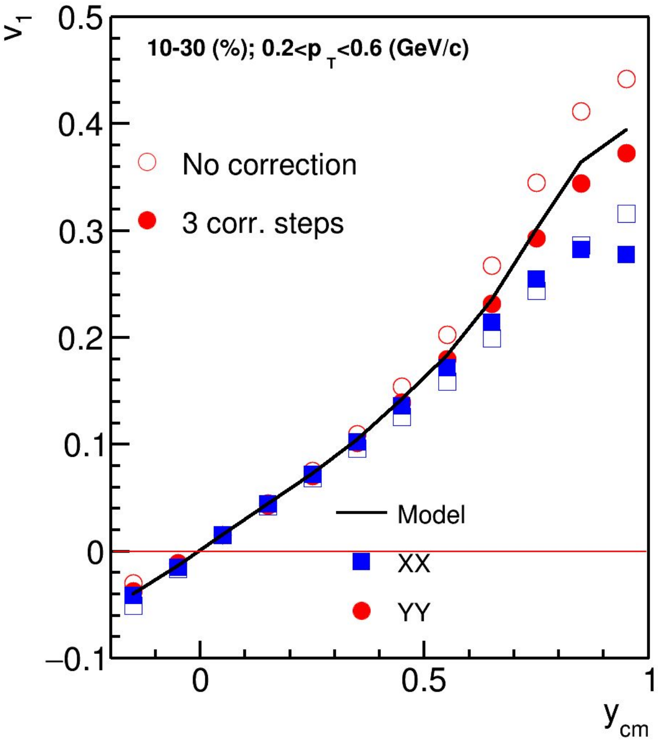
φ-η yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance

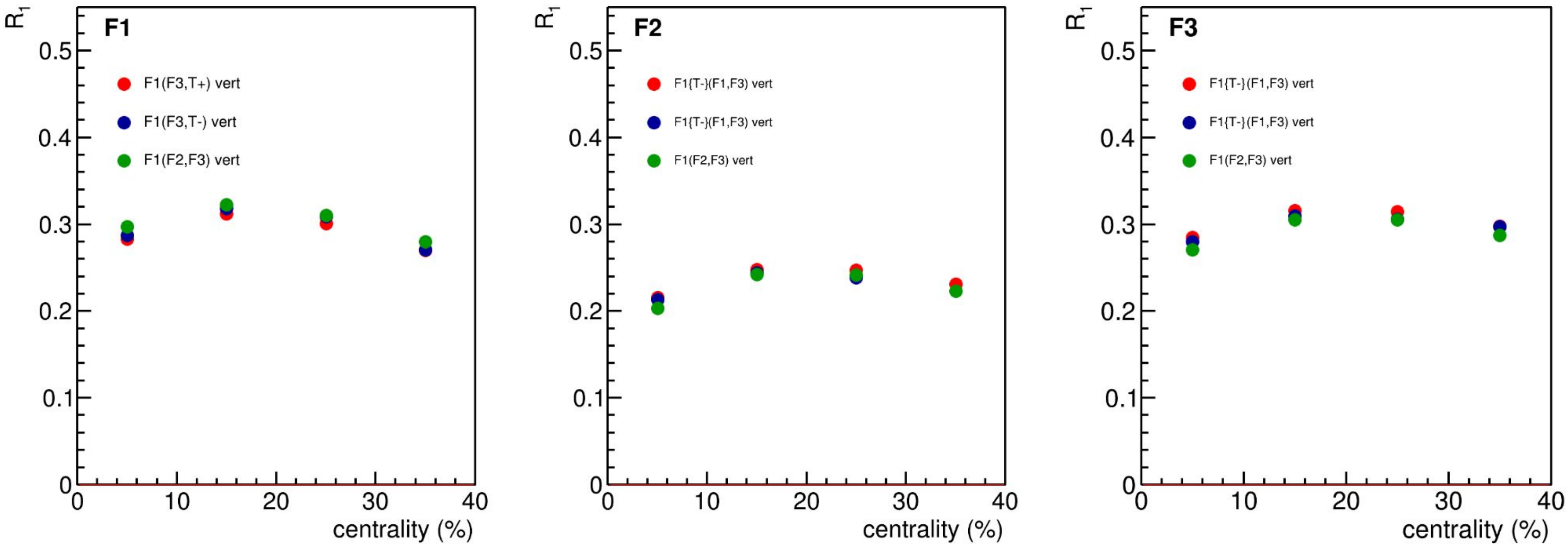


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



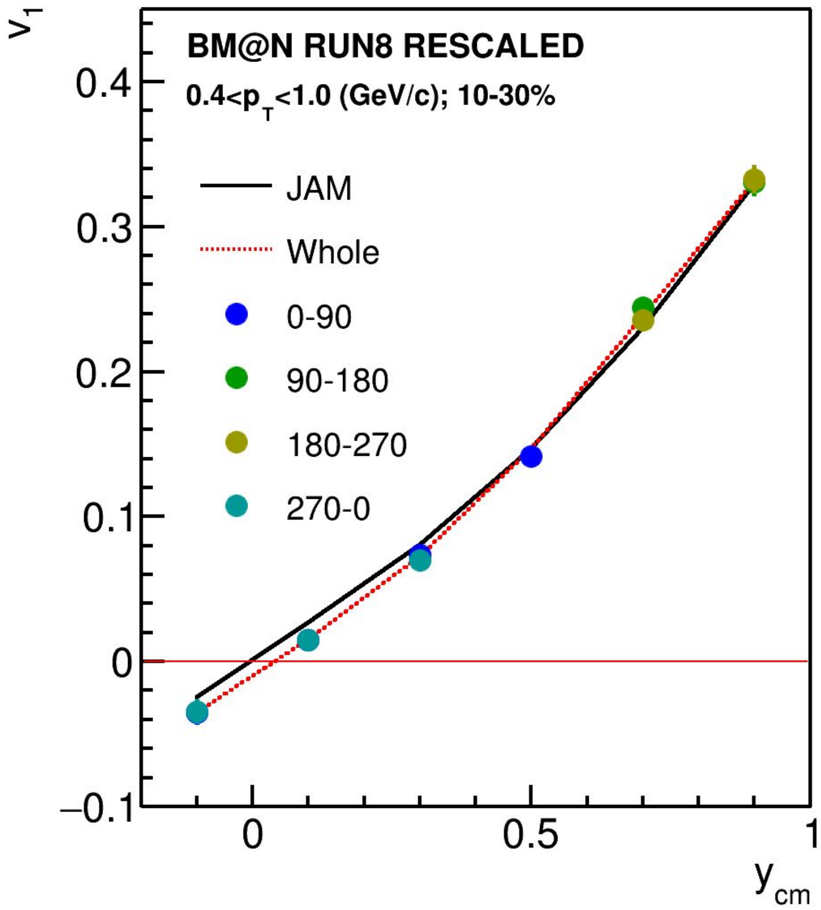
- Better agreement after rescaling for YY
- XX component has too large bias (due to magnetic field)

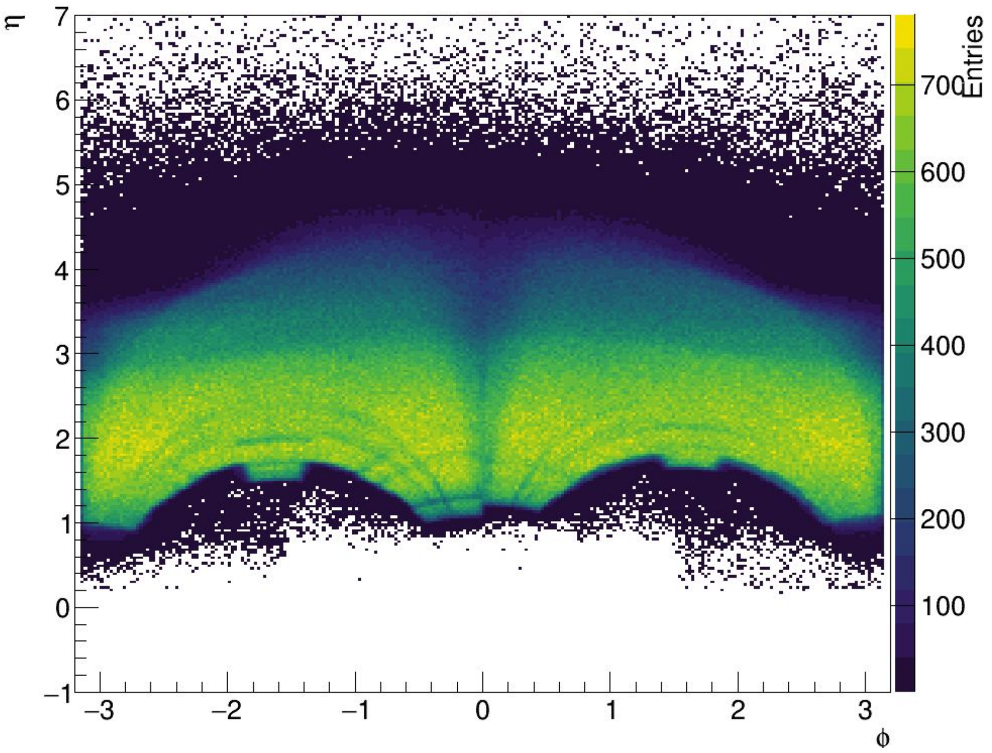
Symmetry plane resolution in Xe+Cs(I) collisions



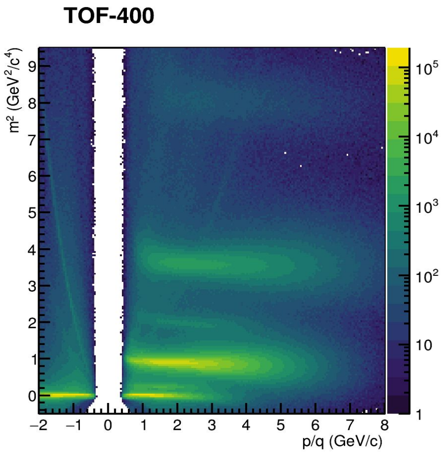
All the estimations for symmetry plane resolutions are in a good agreement

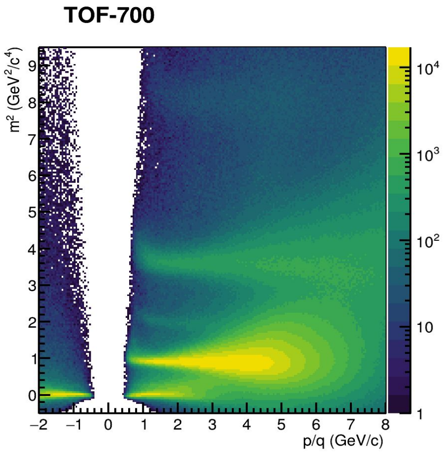
Residual effects of detector non-uniformity

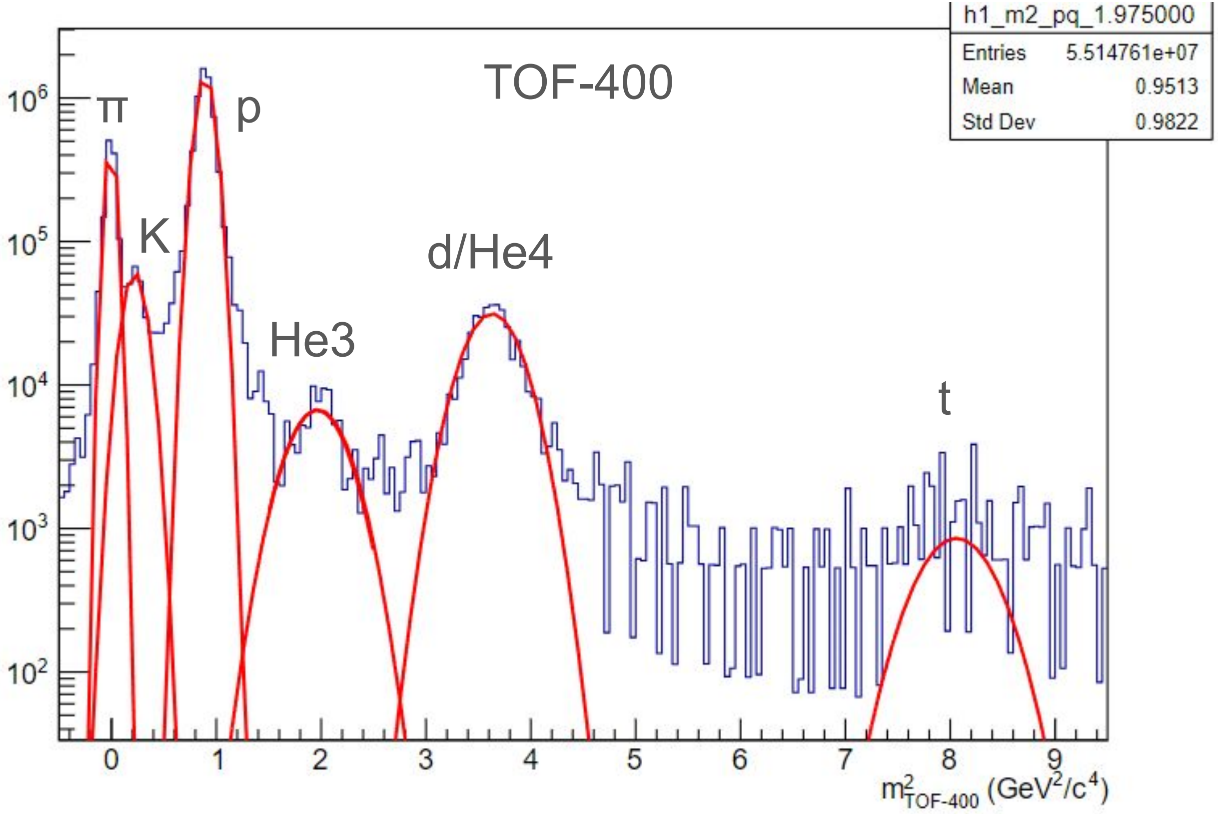




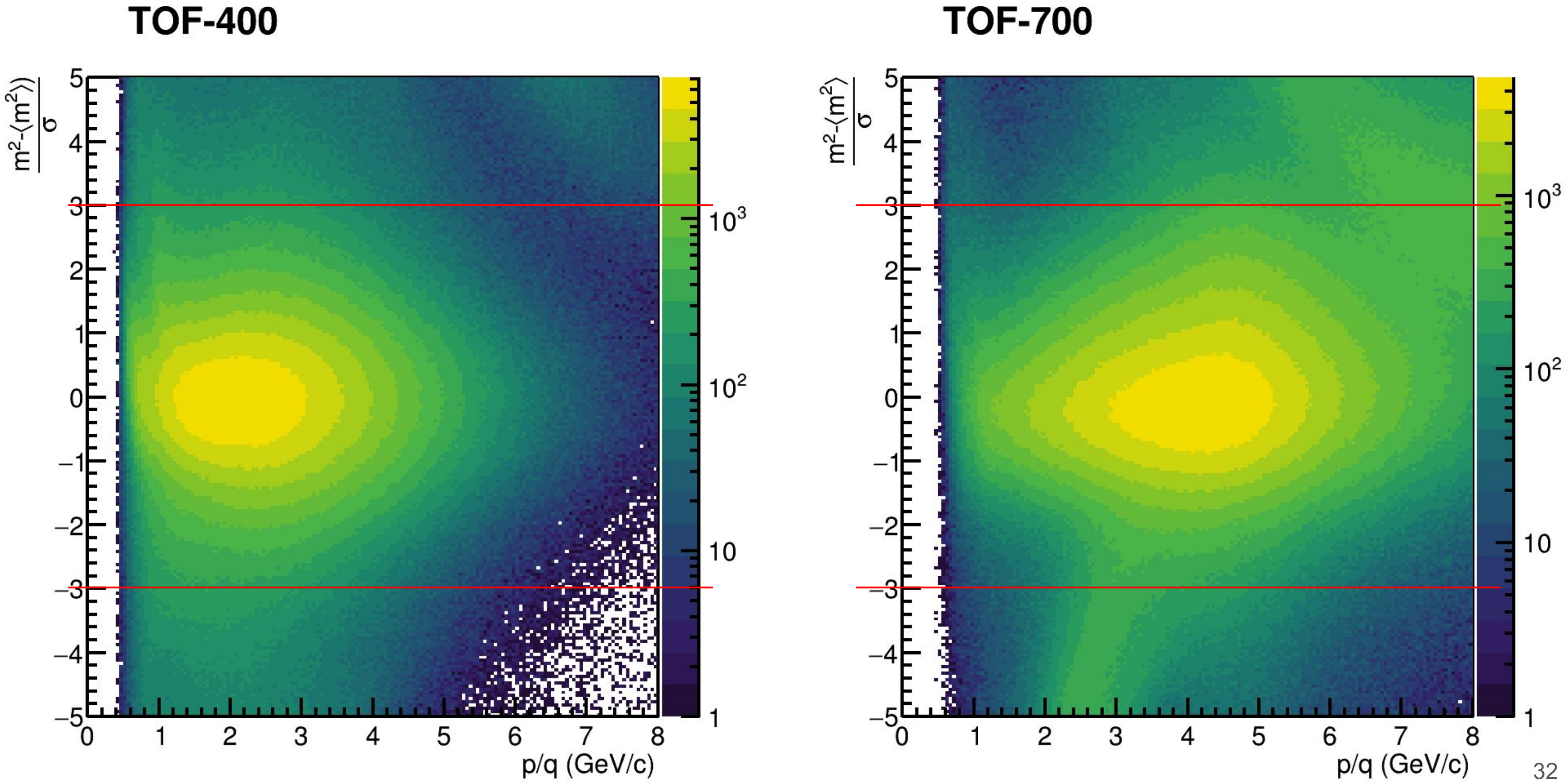
Particle identification



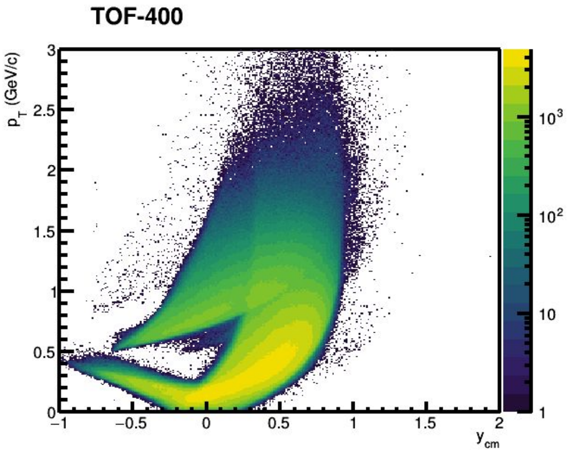


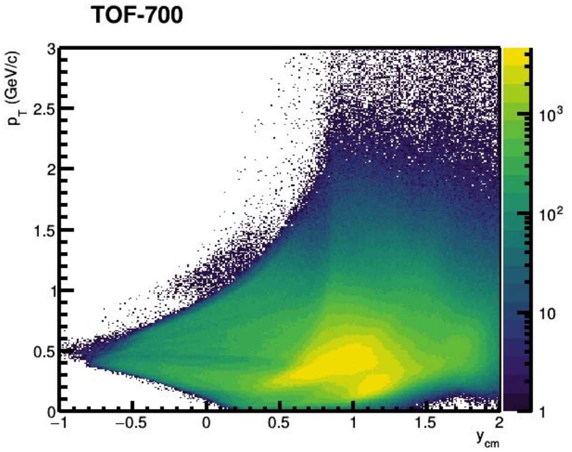


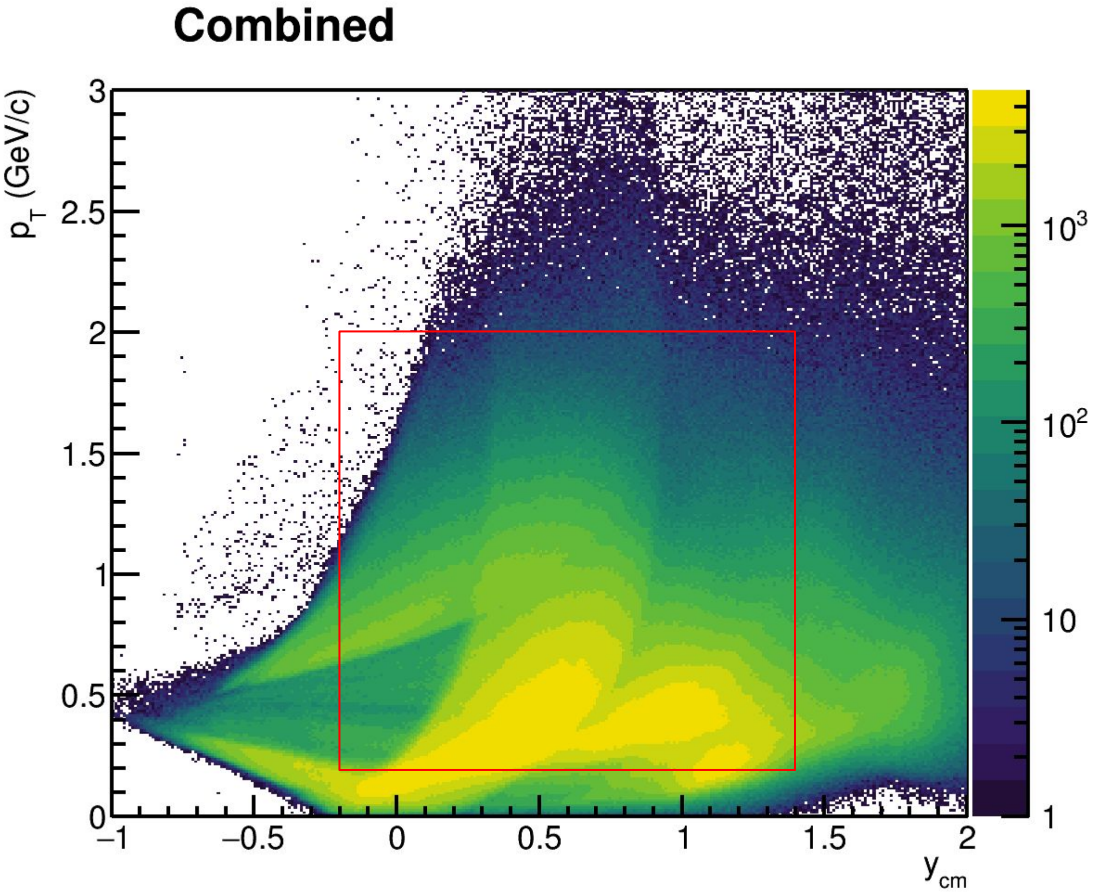
Proton N-sigma distributions



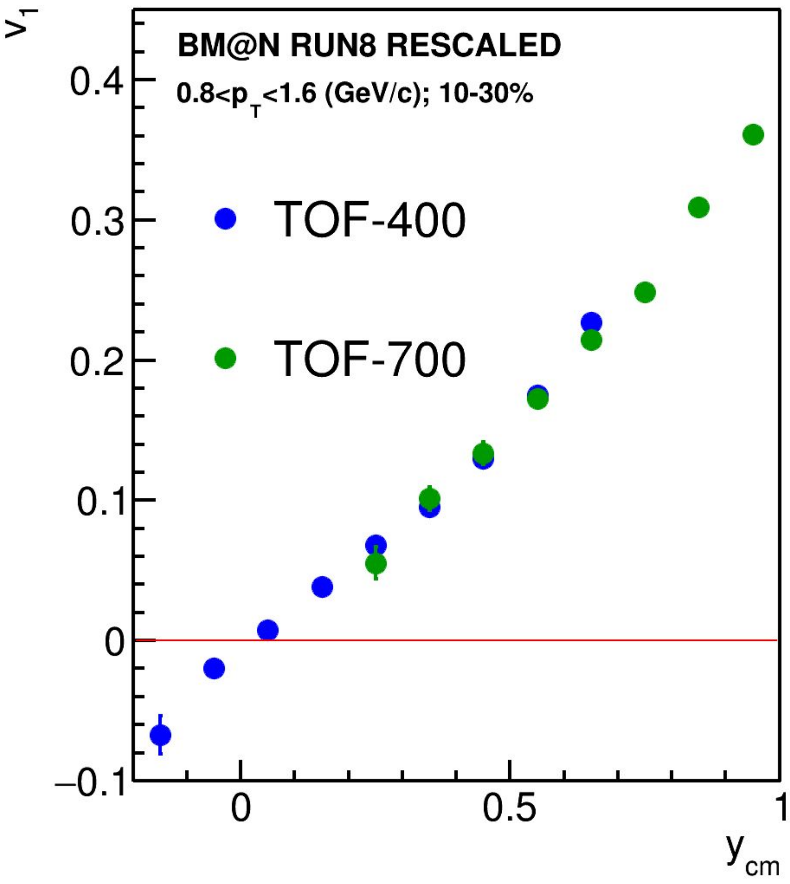
Proton p_T-y acceptance





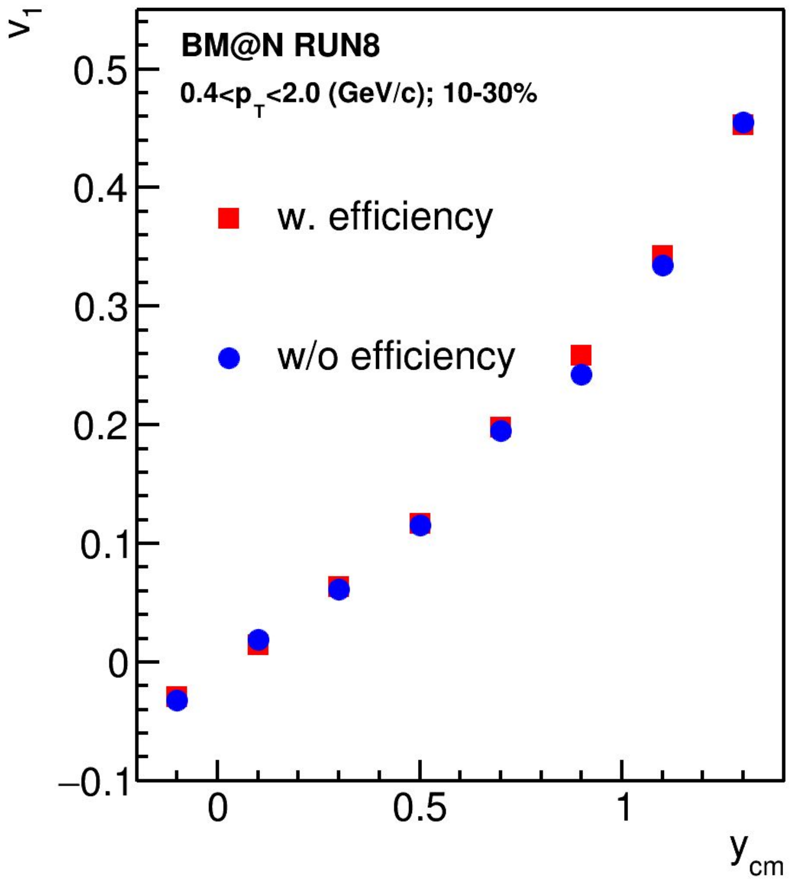


Comparison of the TOF performances

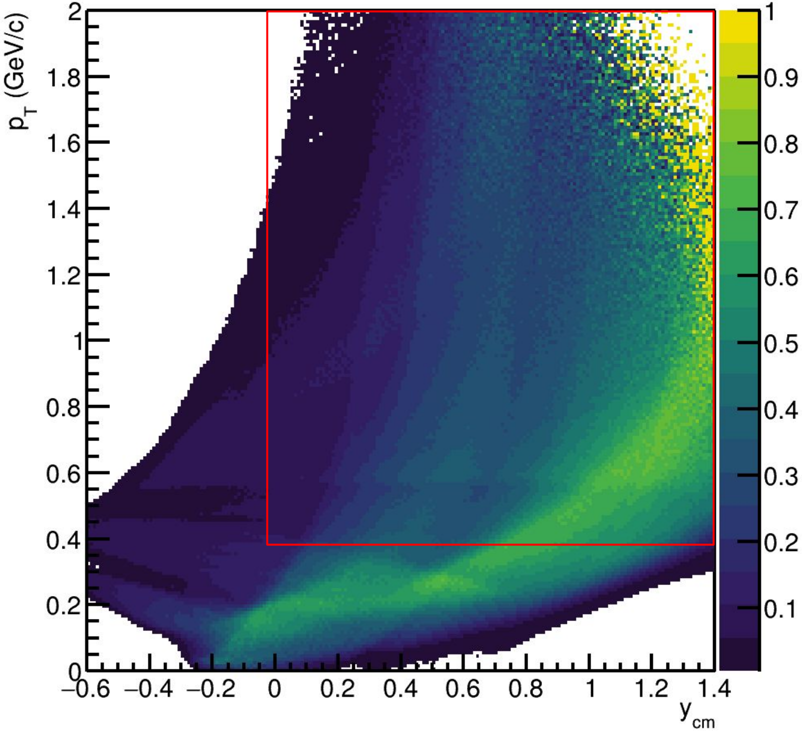


The results from TOF-400 and TOF-700 are in a good agreement

Comparison of the TOF performances

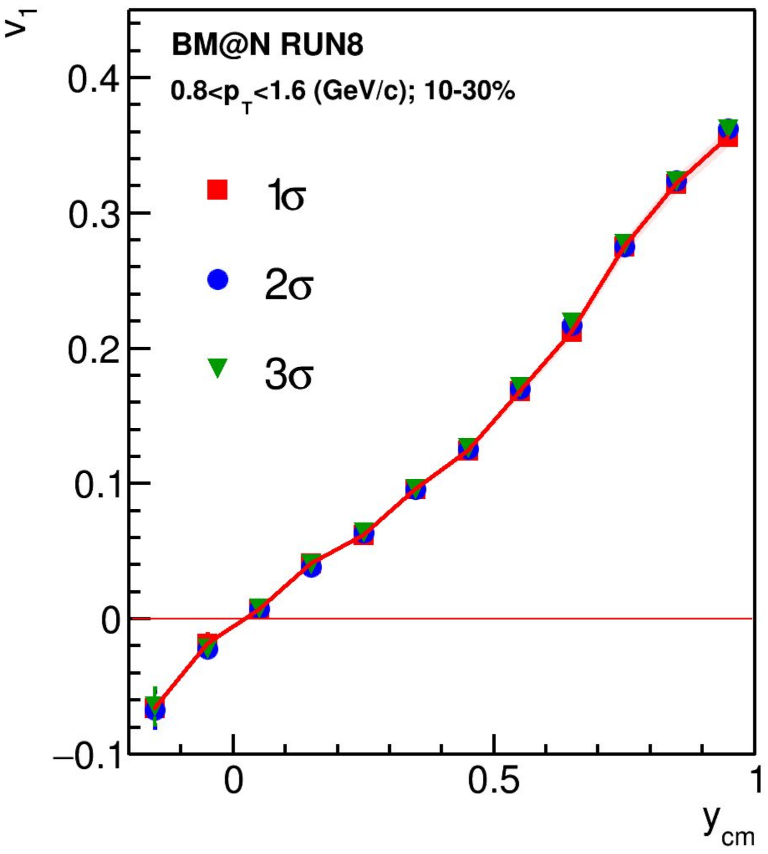


Efficiency using JAM

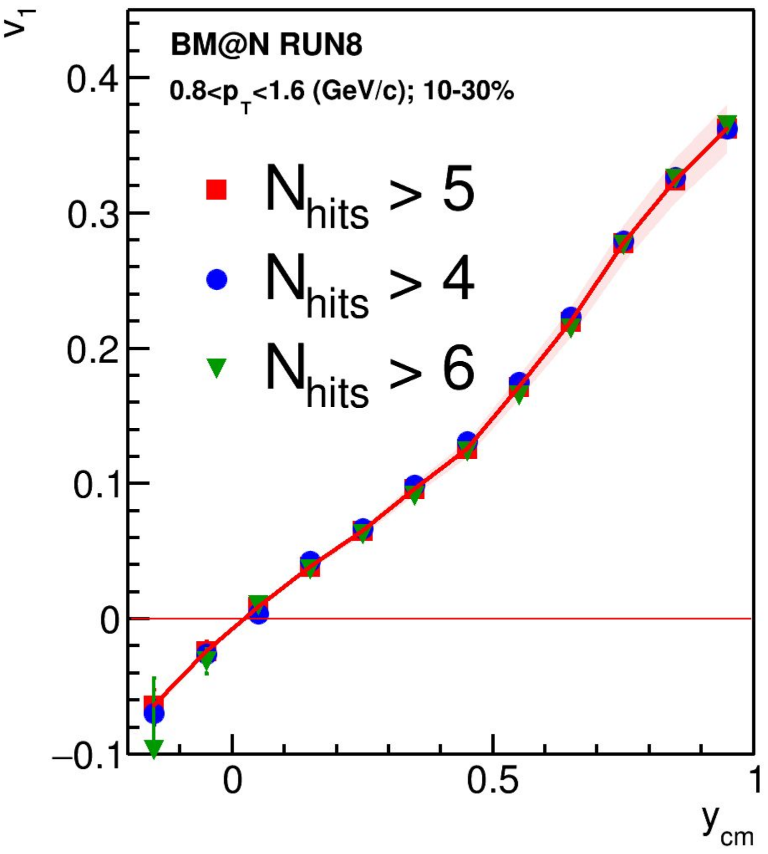


Results with and without efficiency are in a good agreement

Systematics due to identification and tracking

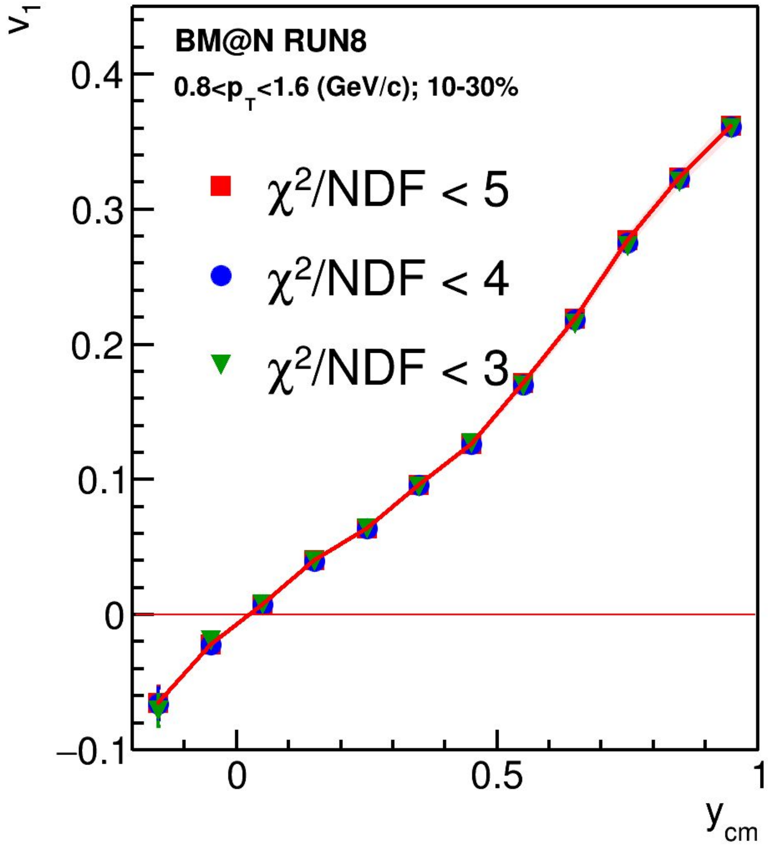


The systematics is below 2%

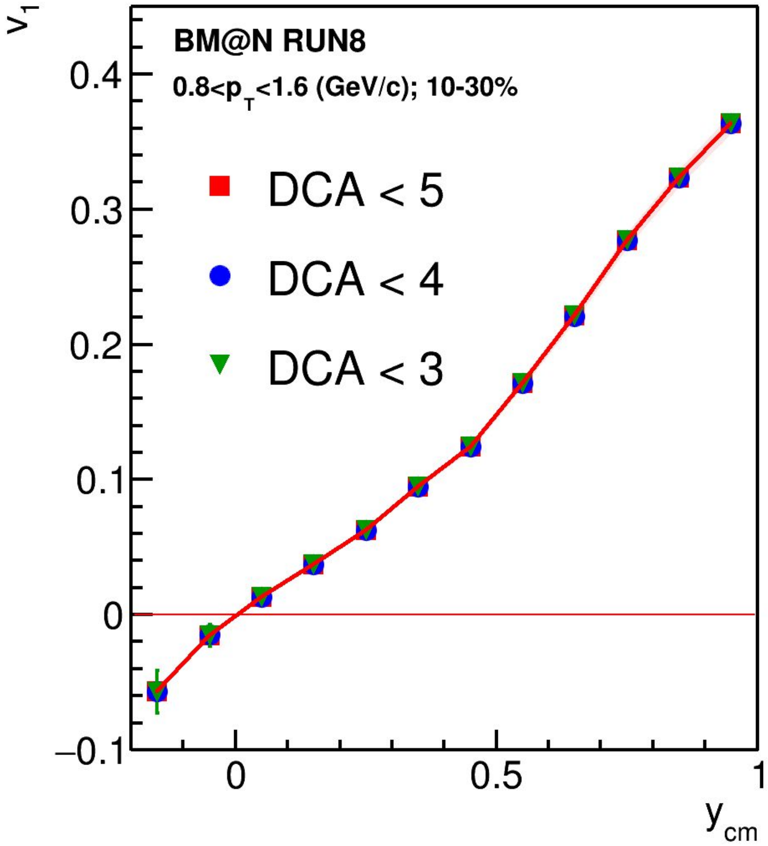


The systematics is below 5%

Systematics due to tracking and secondary

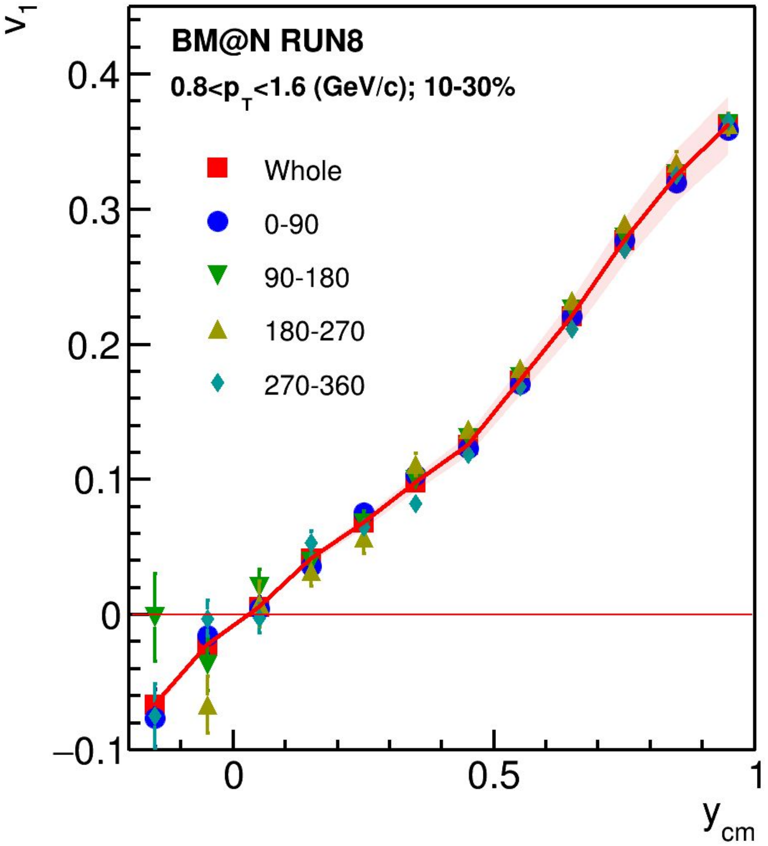


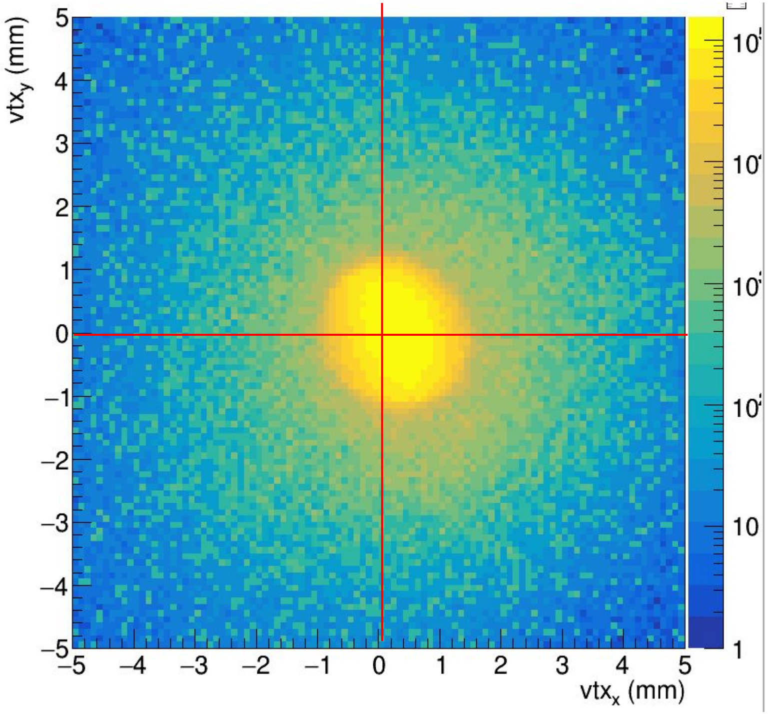
The systematics is below 2%



The systematics is below 1%

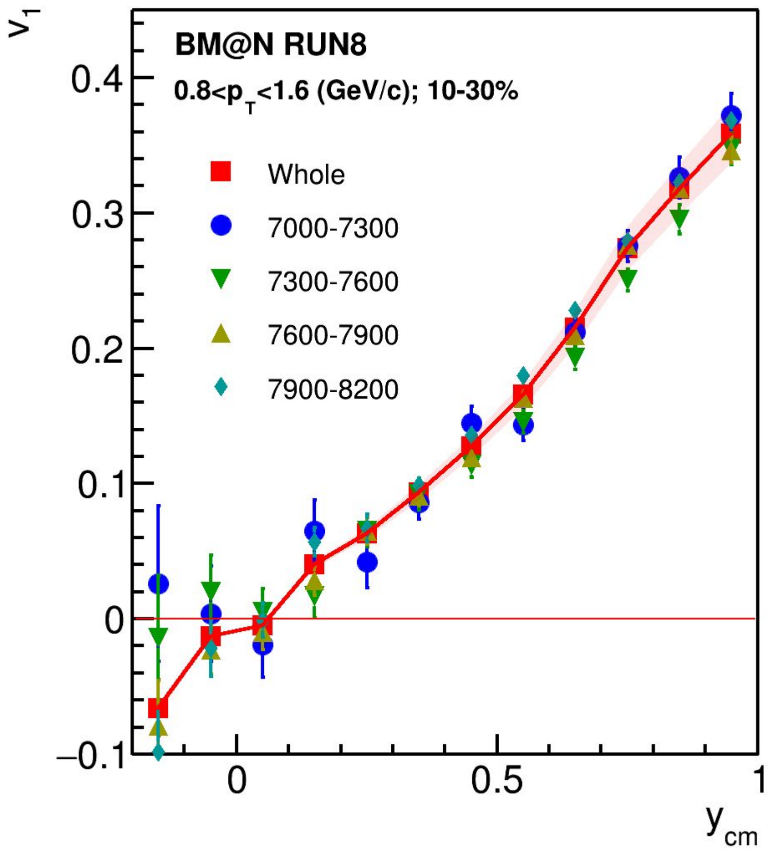
Systematics due vtx position



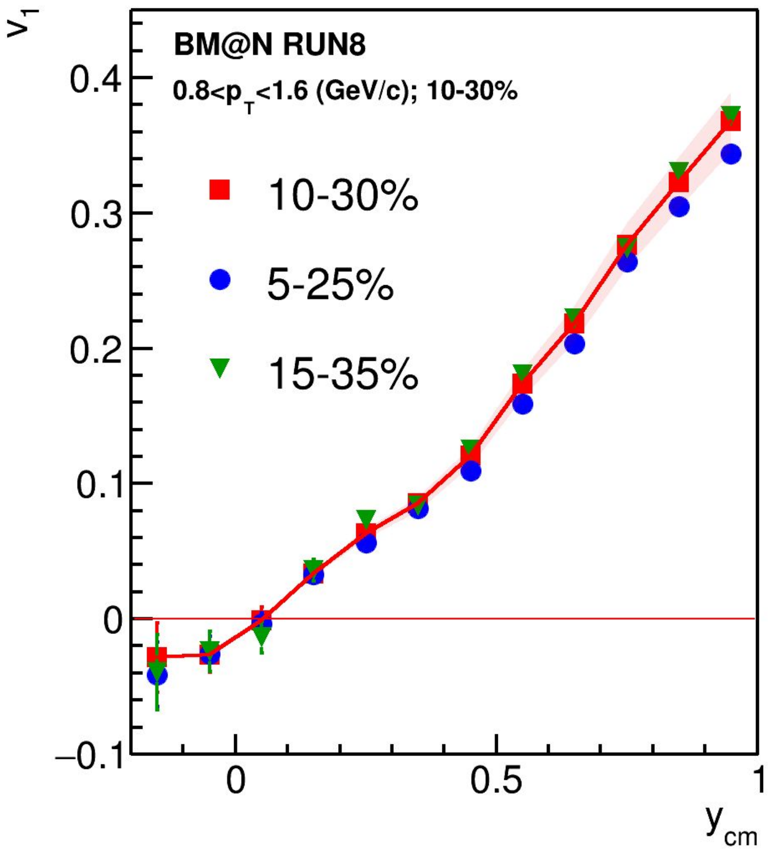


The systematics is below 5%

Cross-check of run-by-run variations and centrality

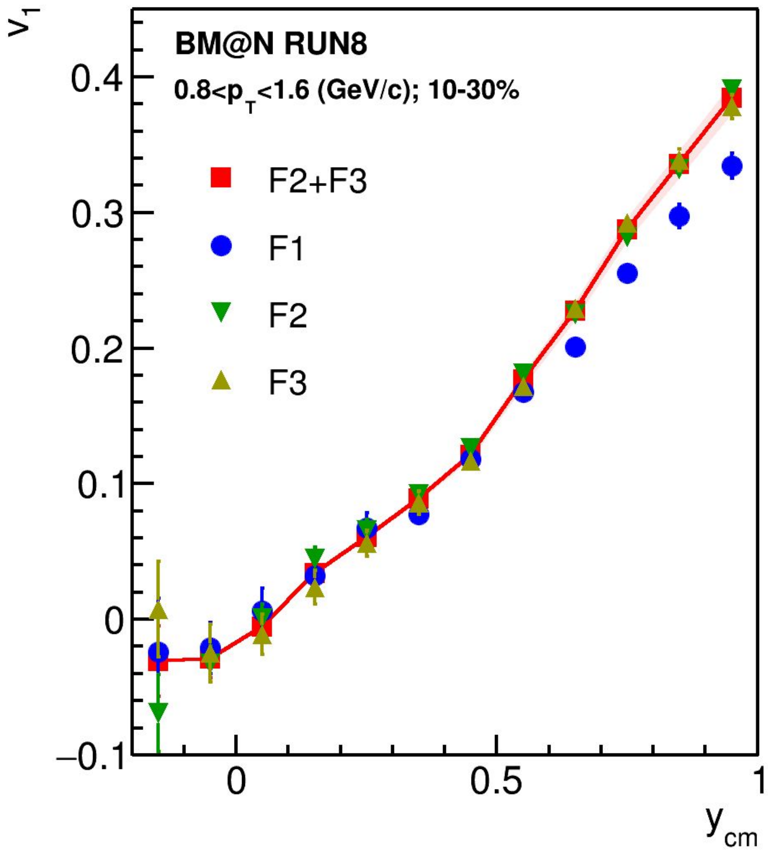


The systematics is below 6%



The systematics is below 6%

Systematics due to symmetry plane estimation (non-flow)



The systematics is below 3%

List of presentations

Weekly meetings (BERDS)

1. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/13.%20BERDS%20Meeting%2004052022/
2. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/14.%20BERDS%20Meeting%2018052022/
3. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/15.%20BERDS%20Meeting%2001062022/
4. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/17.%20BERDS%20Meeting%2015062022/
5. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/20%D1%8E%D0%98%D0%A3%D0%9A%D0%92%D0%AB%20%D0%AC%D1%83%D1%83%D0%B5%D1%88%D1%82%D0%BF%2013.07.2022/
6. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/21.%20BERDS%20Meeting%2020.07.2022/
7. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/22.%20BERDS%20Meeting%2003082022/
8. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/23.%20BERDS%20Meeting%2010082022/
9. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/24.%20BERDS%20Meeting%2012092022/
10. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/26.%20BERDS%20Meeting%2026102022/
11. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2022/28.%20BERDS%20Meeting%2023112022/
12. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2023/07.%20BERDS%20Meeting%2005042023/
13. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2023/16.%20BERDS%20Meeting%2019072023/
14. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2023/20.%20BERDS%20Meeting%2020092023/
15. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2024/04.%20BERDS%20Meeting%2007022024/
16. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2024/06.%20BERDS%20Meeting%2021022024/
17. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2024/07.%20BERDS%20Meeting%2028022024/
18. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2024/09.%20BERDS%20Meeting%2027032024/
19. https://bmn-wiki.jinr.ru/bin/view/Meetings/6.%20Meetings/5.7.2%20Reconstruction/2024/13.%20BERDS%20Meeting%2019062024/

Collaboration and Analysis meetings

9th Collaboration Meeting of the BM@N Experiment at the NICA Facility
https://indico.jinr.ru/event/2912/contributions/17313/
https://indico.jinr.ru/event/2912/contributions/17312/
https://indico.jinr.ru/event/2912/contributions/17407/

10th Collaboration Meeting of the BM@N Experiment at the NICA Facility
https://indico.jinr.ru/event/3531/contributions/20552/
https://indico.jinr.ru/event/3531/contributions/20553/
https://indico.jinr.ru/event/3531/contributions/20554/

Analysis & Software Meeting of the BM@N Experiment
https://indico.jinr.ru/event/3876/contributions/22787/\
https://indico.jinr.ru/event/3876/contributions/22788/
https://indico.jinr.ru/event/3876/contributions/22863/

11th Collaboration Meeting of the BM@N Experiment at the NICA Facility
https://indico.jinr.ru/event/3961/contributions/23786/
https://indico.jinr.ru/event/3961/contributions/23787/
https://indico.jinr.ru/event/3961/contributions/23783/

Analysis and Detector Meeting of the BM@N Experiment
Azimuthal collective anisotropy in the recent Xe+Cs(I) physical run
Report on the QA and run-by-run systematics in the Xe+Cs(I) run

12th Collaboration Meeting of the BM@N Experiment at the NICA Facility
https://indico.jinr.ru/event/4395/contributions/26533/
https://indico.jinr.ru/event/4395/contributions/26539/
https://indico.jinr.ru/event/4395/contributions/26536/

Backup

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

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

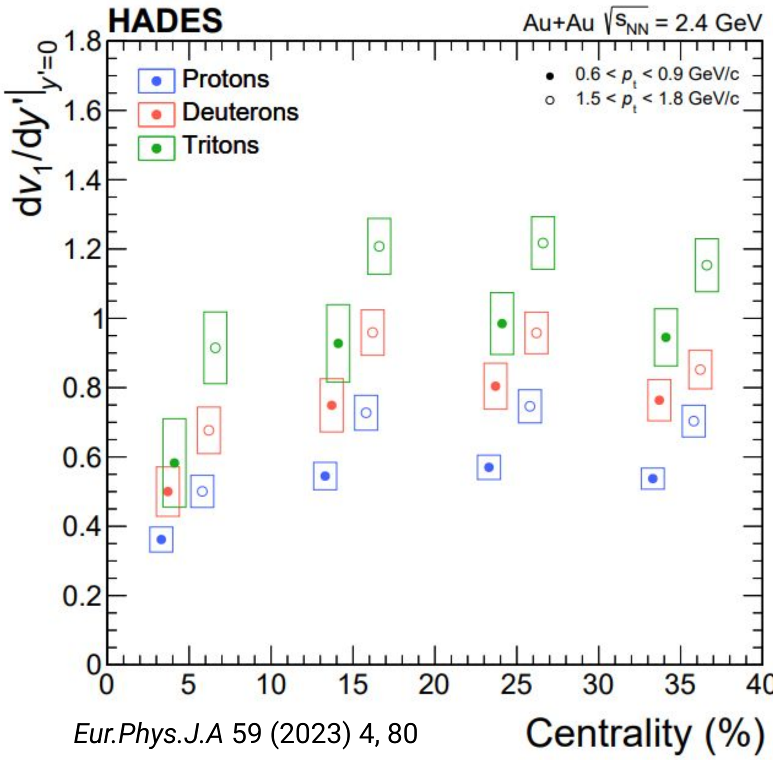
At N→∞ (N≫1)

$$\lim_{n\to\infty} Q_n = \frac{\int d\vec{v} \int d\phi w(\phi, \vec{v}) e^{in\phi} \rho(\phi - \Psi)}{\int d\vec{v} \int d\phi w(\phi, \vec{v}) \rho(\phi - \Psi)} = V_n e^{in\Psi}$$

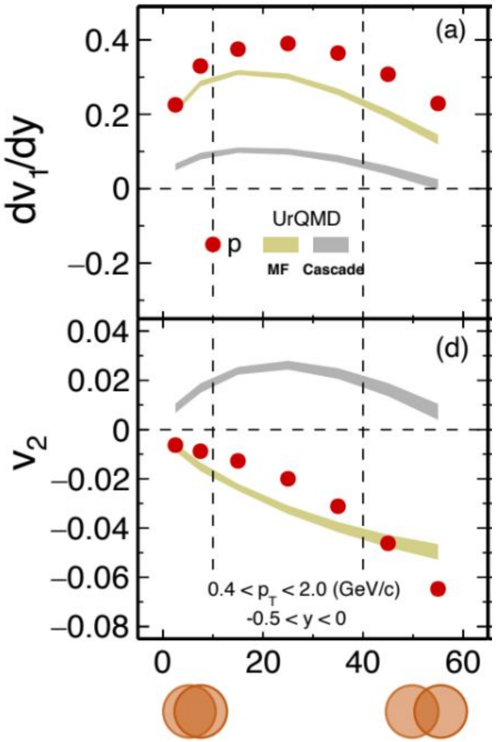
$$\langle u_n Q_n{}^* \rangle = \frac{\int d\vec{v} \int d\phi \int d\Psi_{RP} w(\phi, \Psi_{RP}, \vec{v}) e^{in\phi} V_n(\Psi_{RP}) e^{-in\Psi_n^{EP}} \rho(\phi - \Psi_{RP})}{\int d\vec{v} \int d\phi \int d\Psi_{RP} w(\phi, \Psi_{RP} \vec{v}) \rho(\phi - \Psi_{RP})}$$

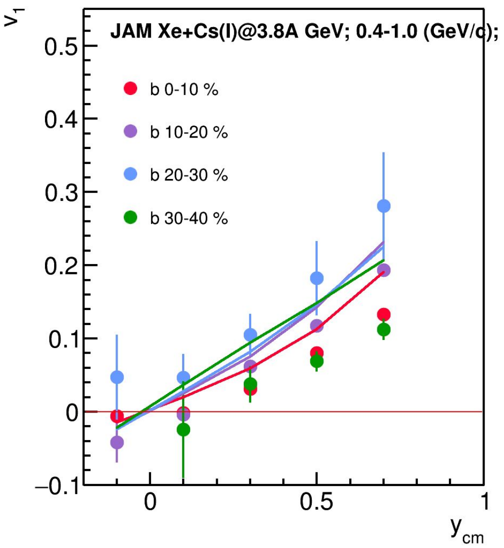
$$= \langle \cos n(\phi - \Psi_{RP}) V_n \cos n(\Psi_{RP} - Psi_n^{EP}) \rangle$$

dv_1/dy as a function of centrality



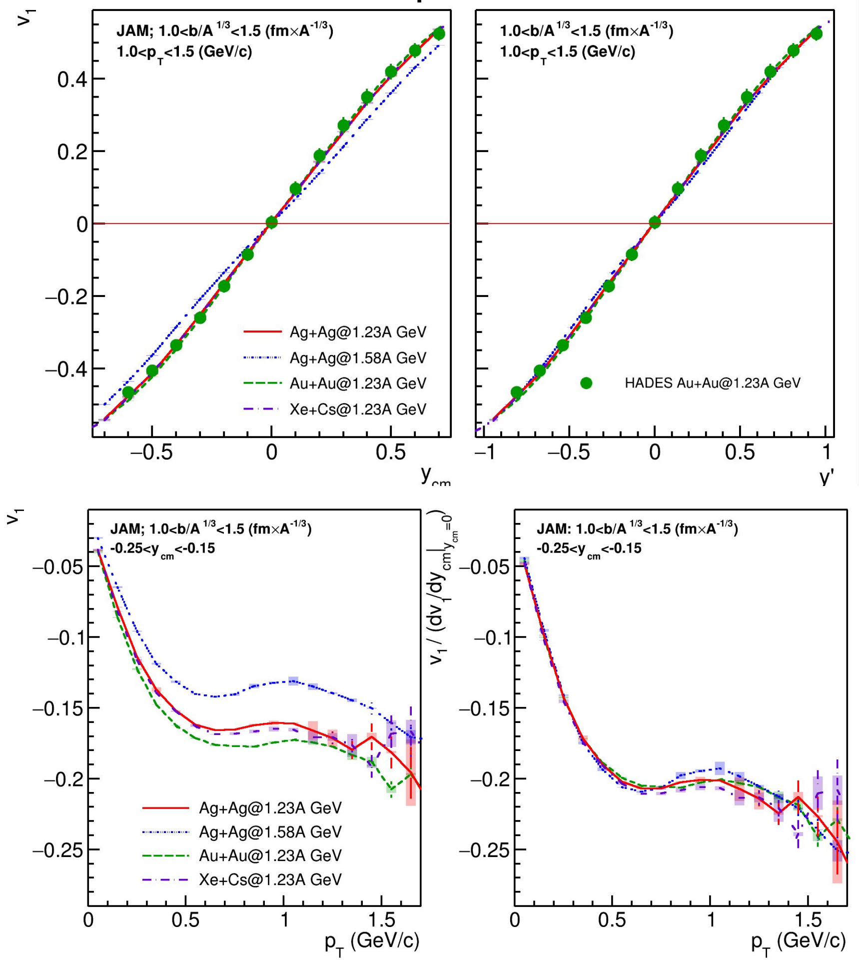
Eur.Phys.J.A 59 (2023) 4, 80





Weak centrality dependence for directed flow

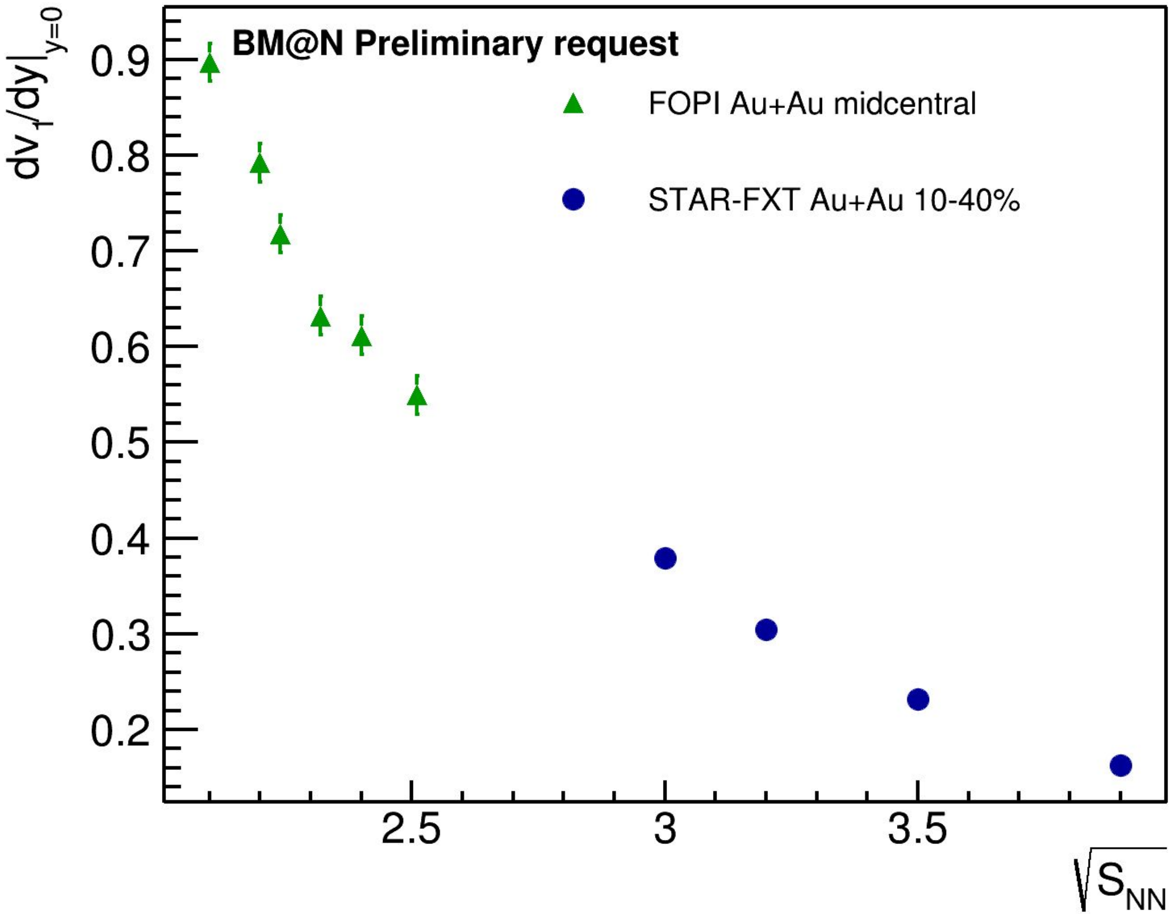
HADES: dv_1/dy scaling with collision energy and system size



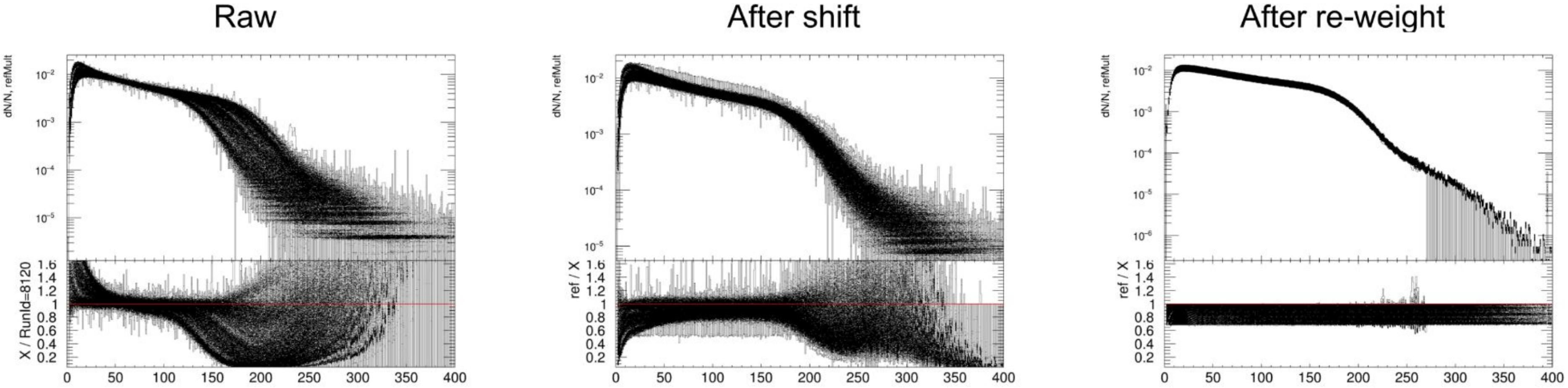
- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments(e.g. STAR-FXT Au+Au

M.Mamaev Particles 2023, 6(2), 622-637

$dv_1/dy|_{y=0}$ vs collision energy

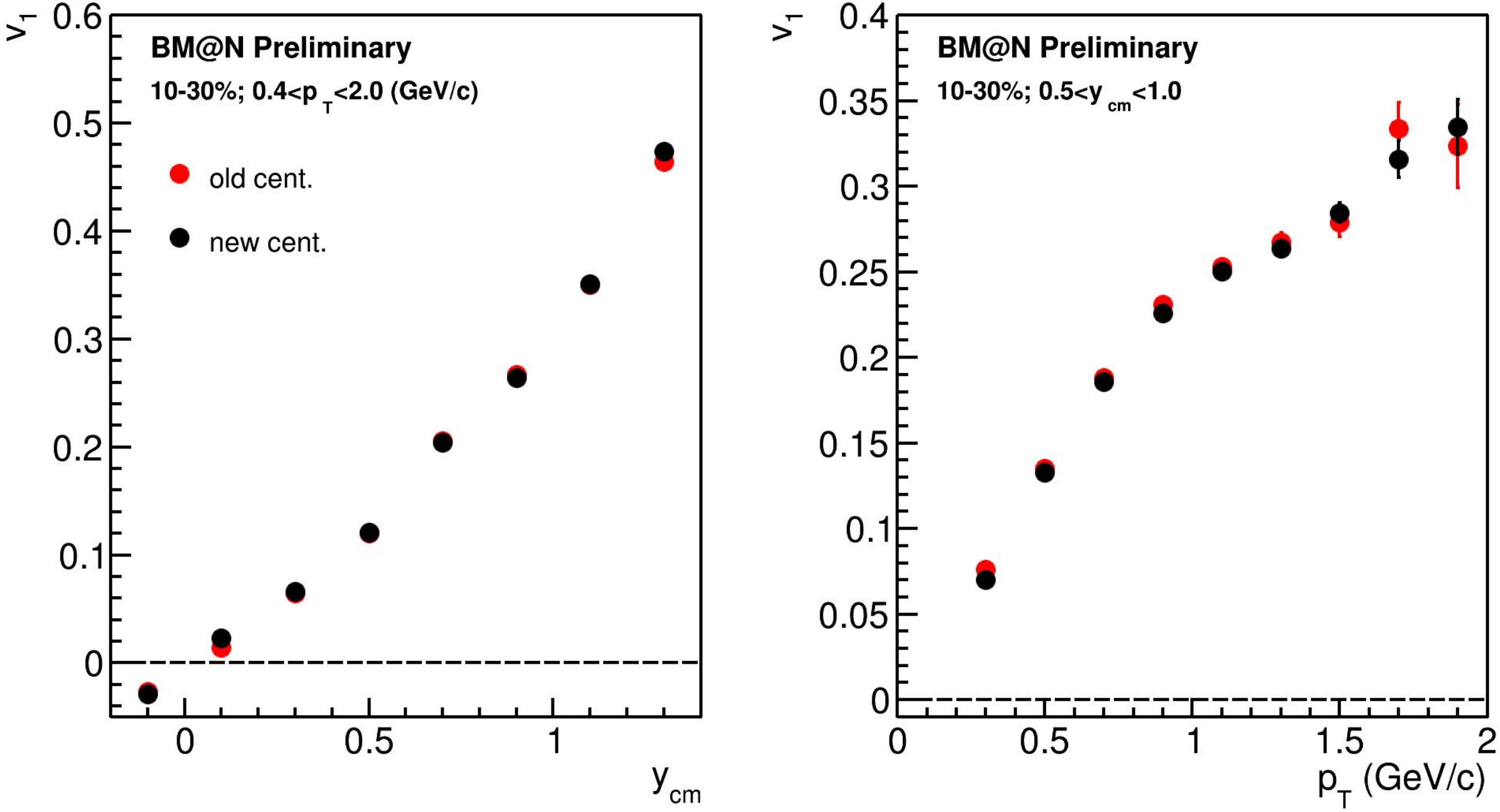


Outlook: Centrality determination



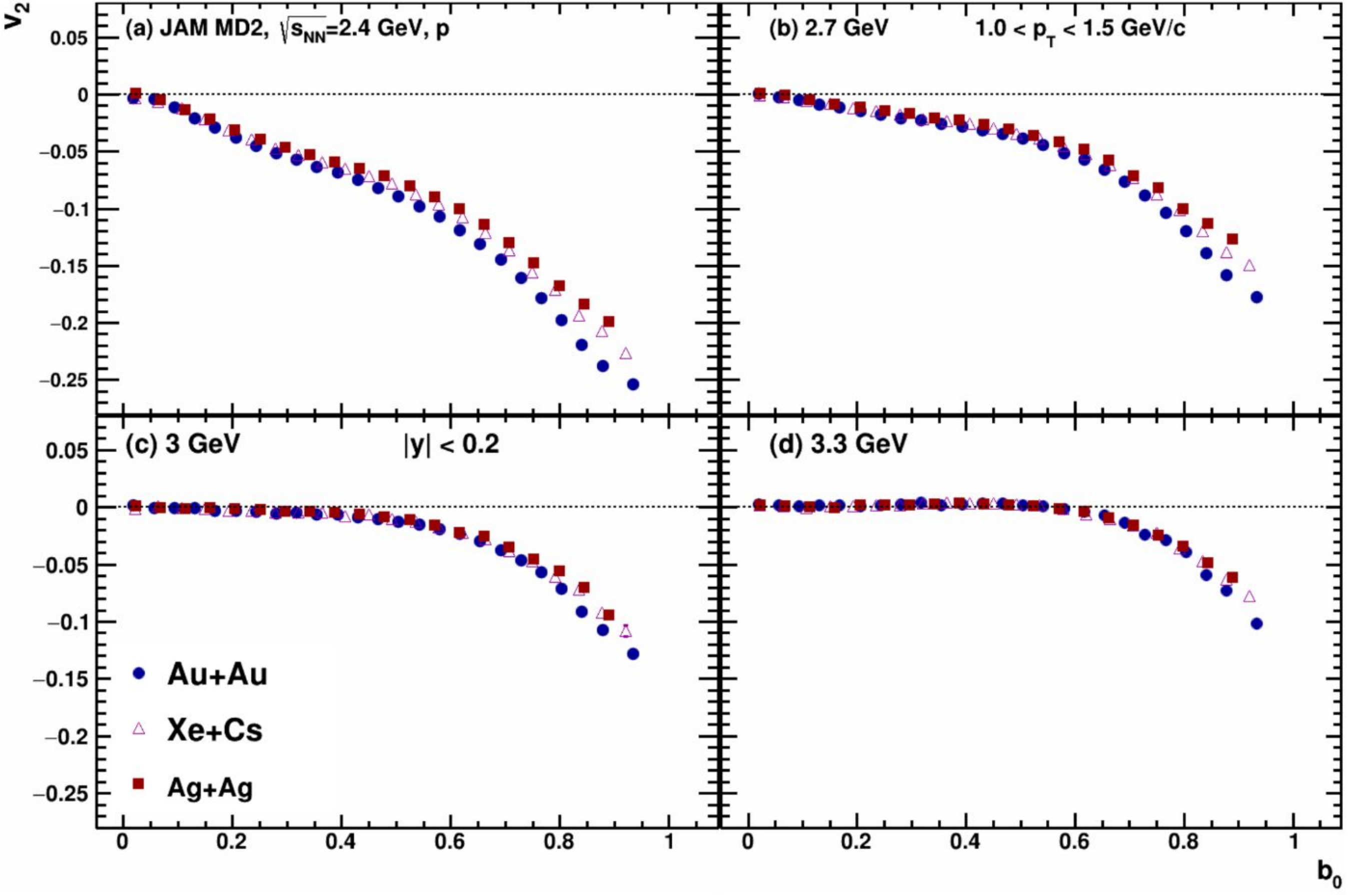
We are planning to use the new centrality based on calibrated multiplicity

v_1 with different centralities



JAM model describes $v_1(y)$ well

v_2 with system size and collision energy

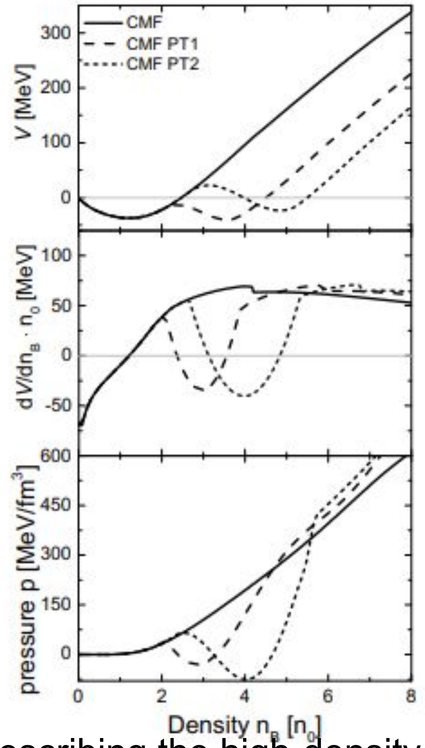


Particles 2022, 5, 561–579.

The results from JAM model in mean-field mode suggest v_2 in lighter systems will be comparable with Au+Au collisions

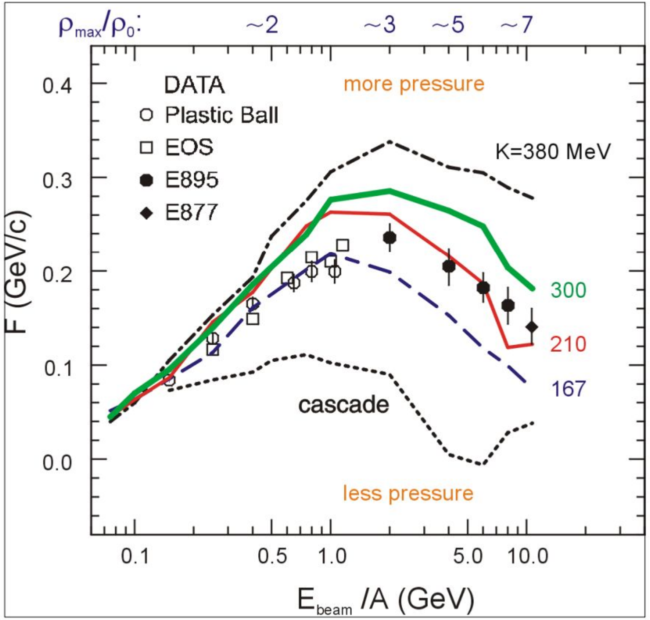
v_n as a function of collision energy

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

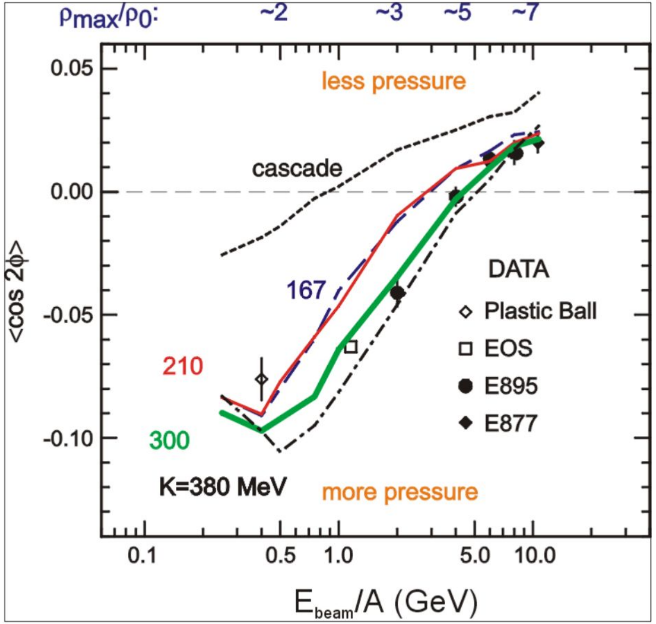


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests softer EOS



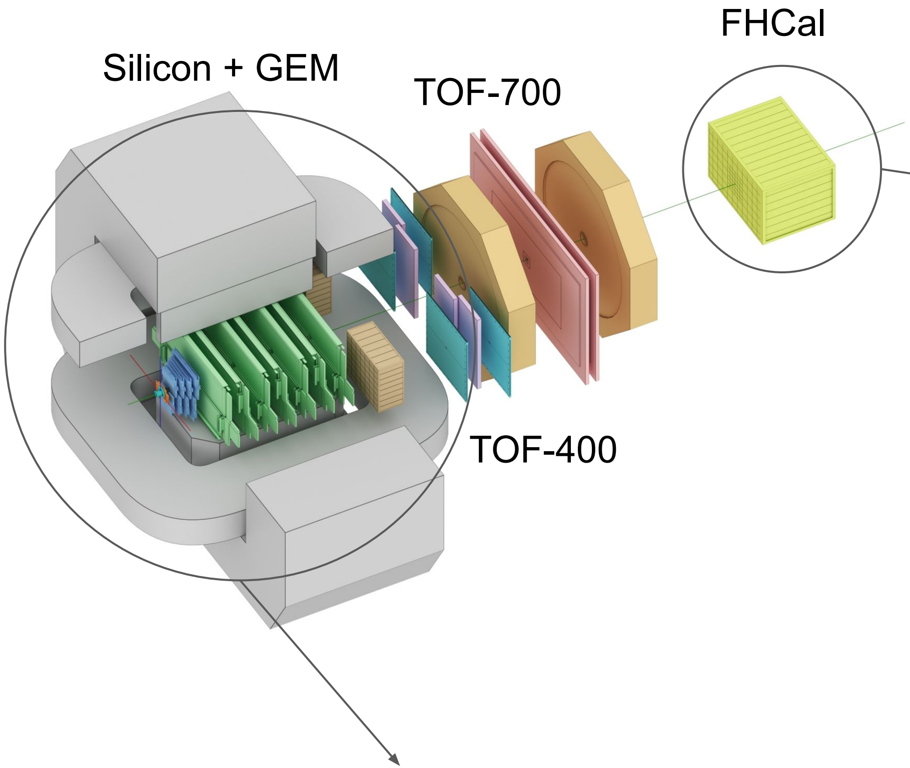
v_2 suggests harder EOS

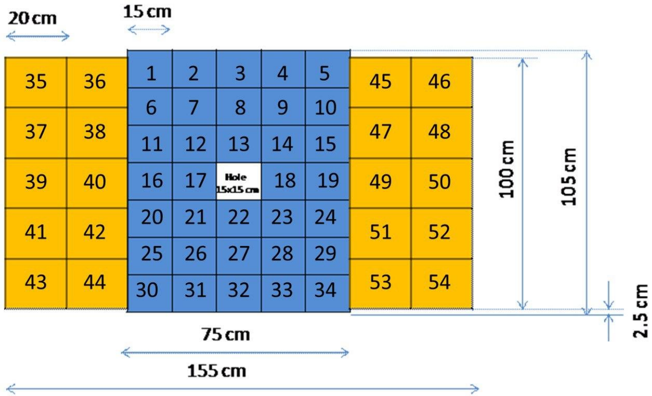


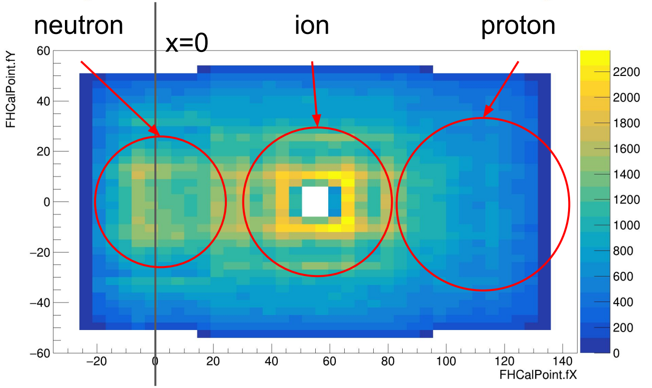
Describing the high-density matter using the mean field
Flow measurements constrain the mean field

Discrepancy is probably due to non-flow correlations

The BM@N experiment (GEANT4 simulation for RUN8)







VF tracking was used

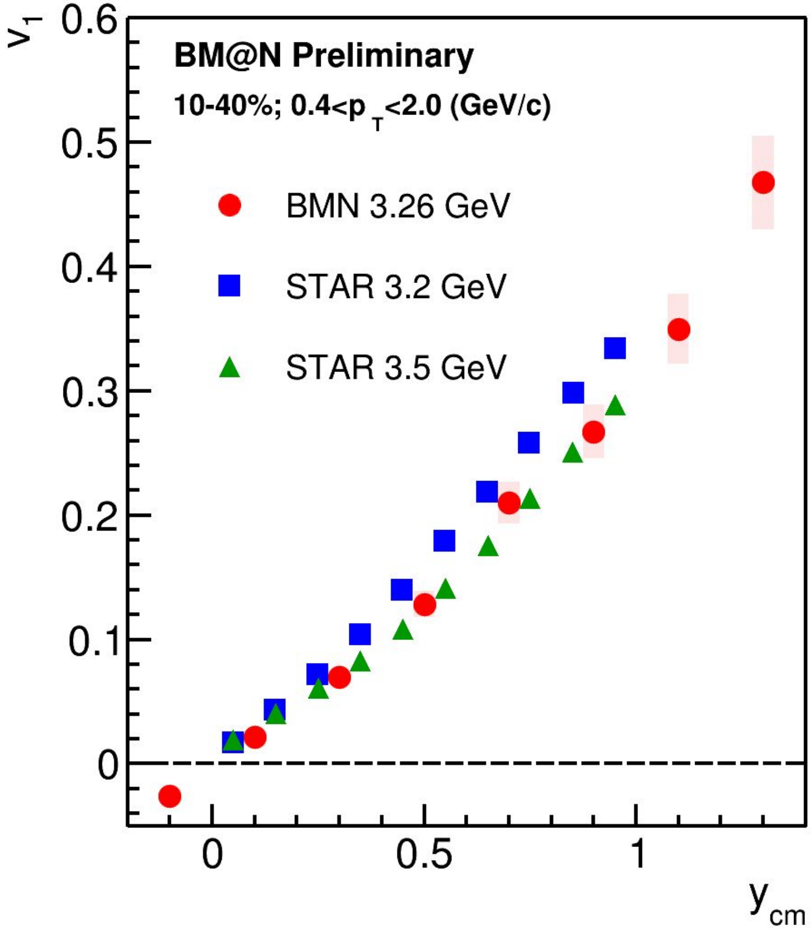
Symmetry plane estimation with the azimuthal asymmetry of projectile spector energy

The last production was used

Total systematic uncertainty

Nhits	chi2	Identification	Secondary	Non-flow	Non-zero v_1 at y_{cm}=0	vtx	Total
5%	2%	2%	1%	4%	2%	5%	8%

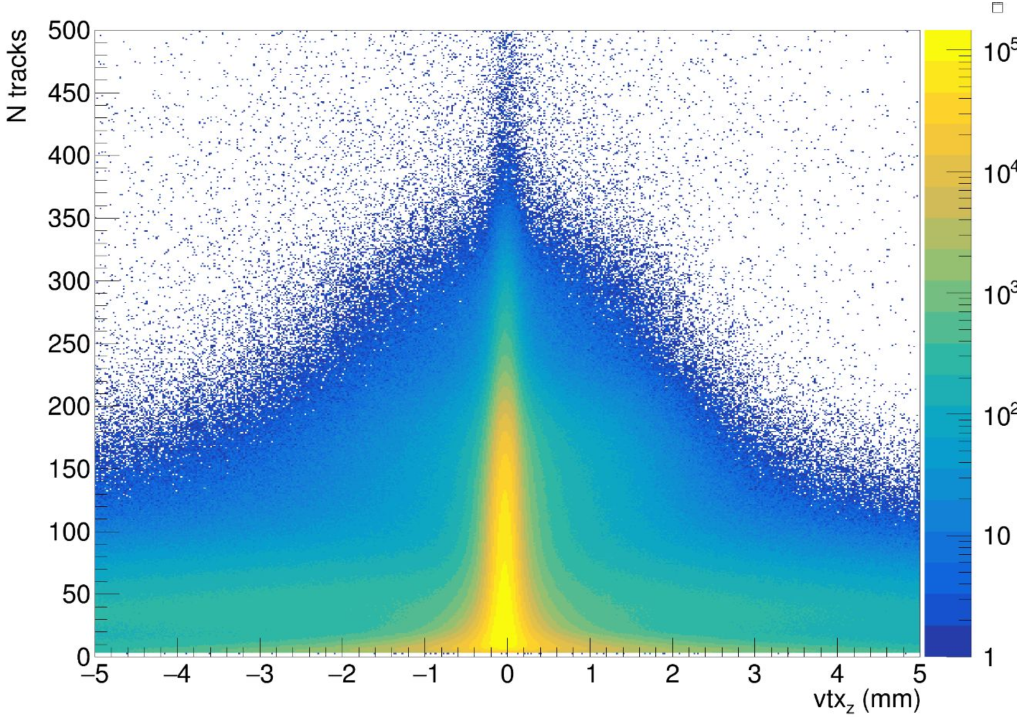
v_1 as a function of y: comparison with STAR

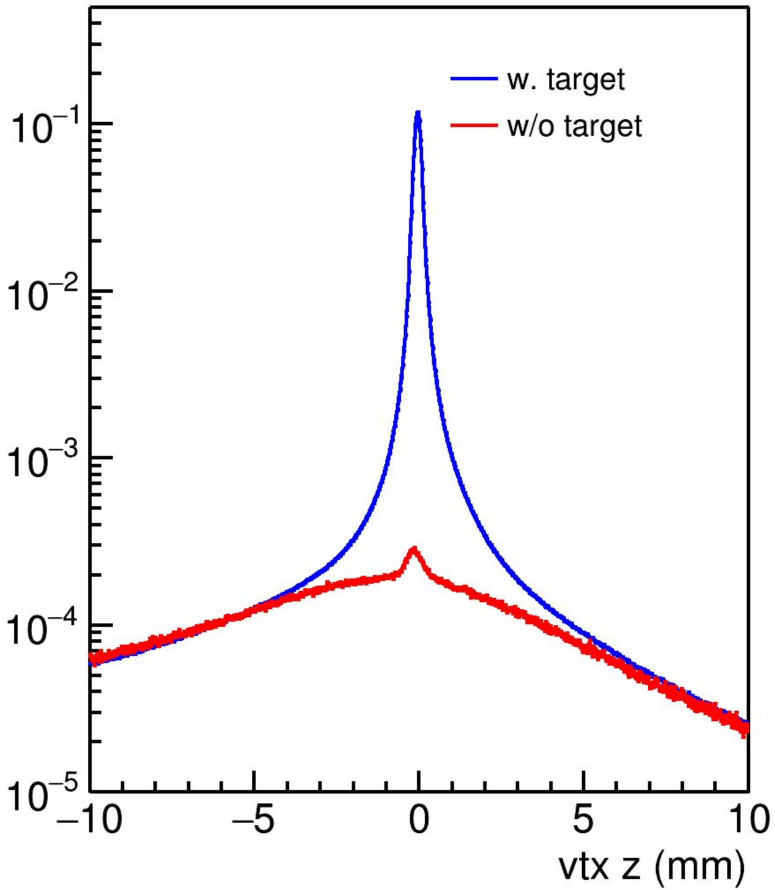


v_1(y) is in a reasonable agreement with STAR DATA

Off-target collisions contribution

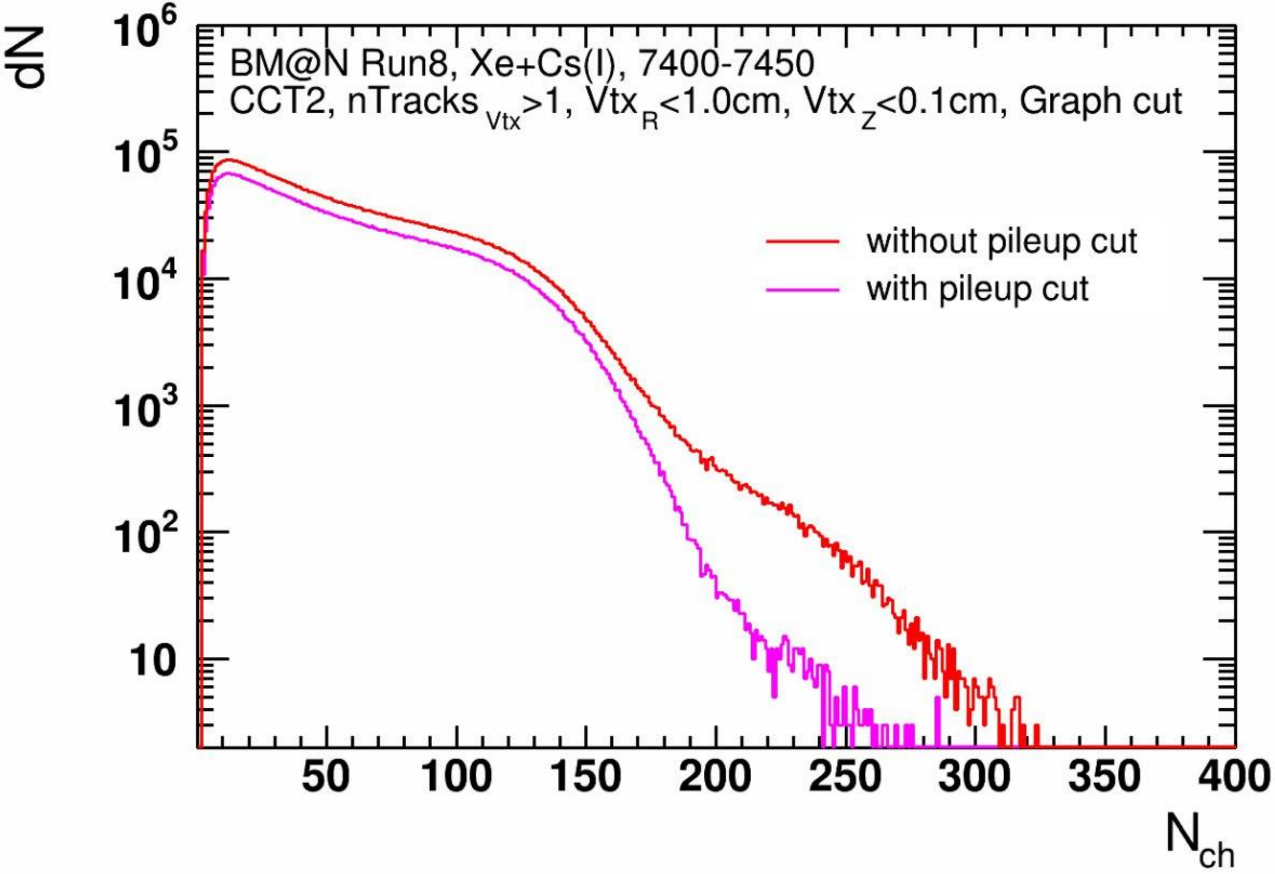
Total empty target contribution: ~5%
In the selected region (-0.1, 0.1): ~0.2%





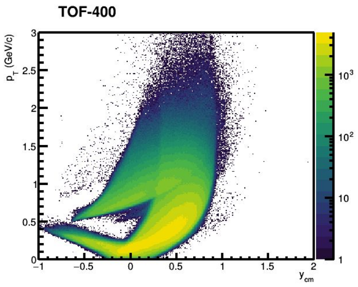
- With target — with all selection criteria used in analysis
- Without target — empty target runs + selection criteria
- Normalized to number of events, then scaled

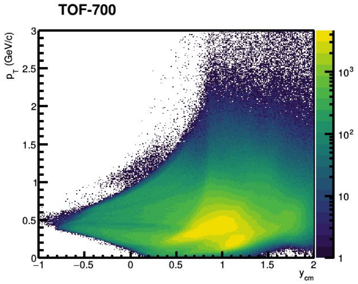
Outlook: Pileup effect

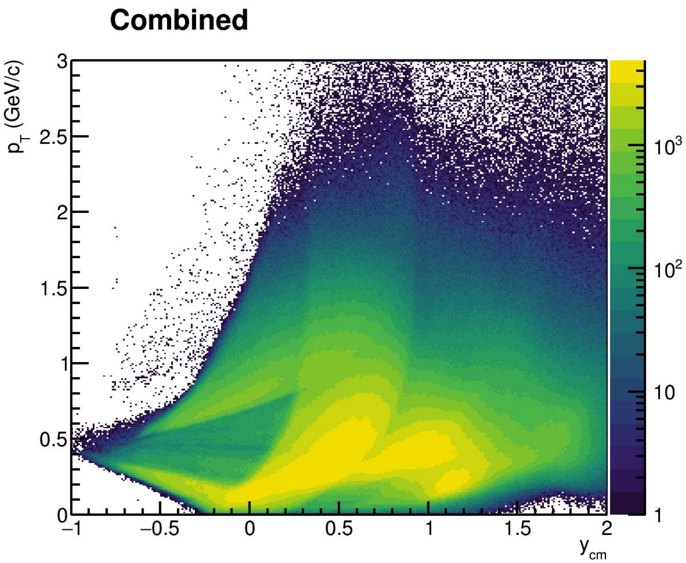


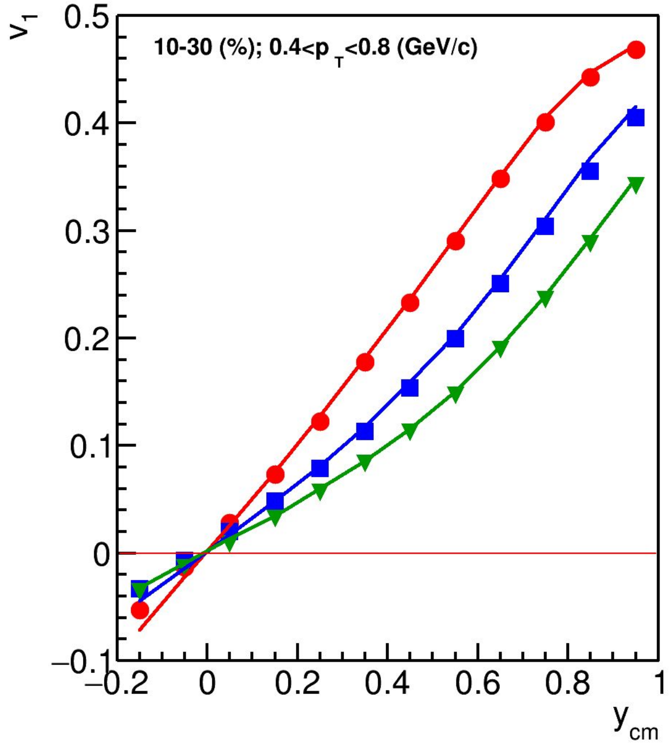
We are going to study the pille-up effect using the selection based on Oleg Golosov's analysis

Increasing the acceptance of TOF-subsystems



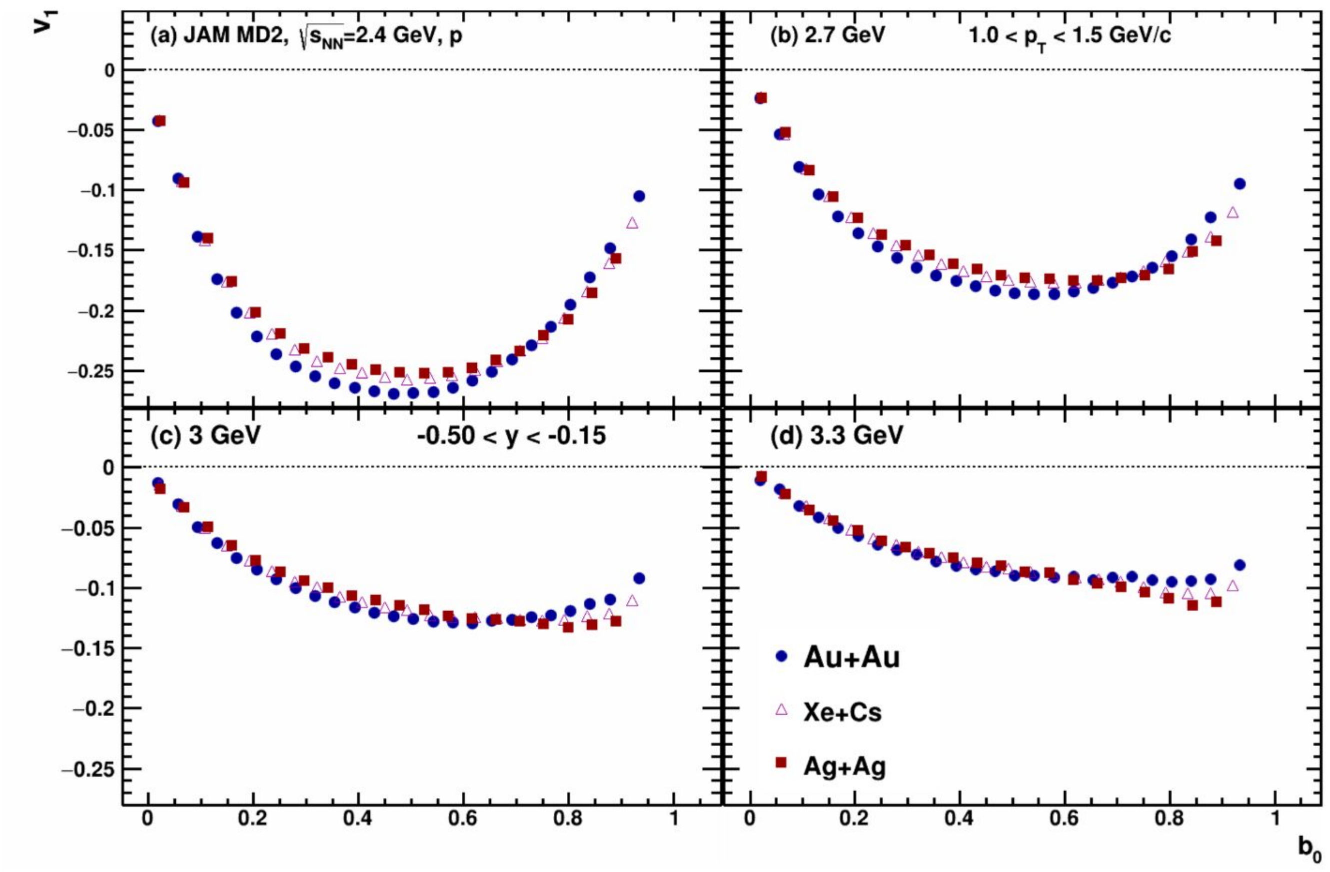






- We need to increase the coverage of the TOF-subsystems in midrapidity
- Measuring the v_n at lower energies are required to study the system size dependence of v_n

v_1 with system size and collision energy



The results from JAM model in mean-field mode suggest v_1 in lighter systems will be comparable with Au+Au collisions

Particles 2022, 5, 561–579.

Summary

- Directed flow of protons is measured as a function of y, p_T and centrality
- v_1 as a function of y is found to be in a reasonable agreement with STAR data

Finalizing the result:

- Pile-up rejection based on Oleg Golosov analysis will be applied
- The off-target events contribution is found to be ~0.2%