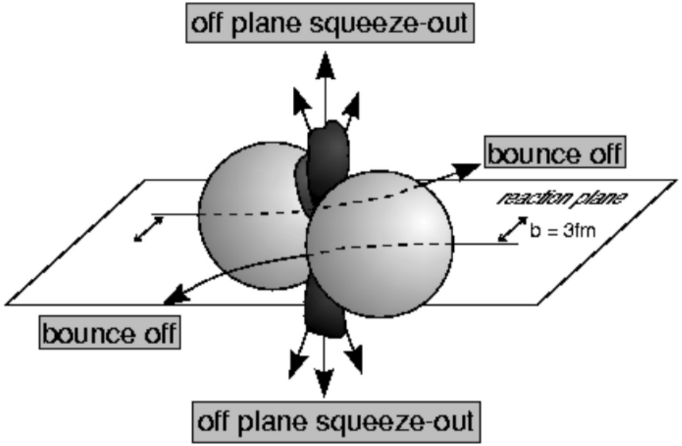
Направленный поток протонов в столкновениях Xe+CsI при энергии 3.8A ГэВ на установке BM@N

Михаил Мамаев (ОИЯИ, НИЯУ МИФИ)
от имени коллаборации BM@N

Работа поддержана Министерством науки и высшего образования РФ, проект "Фундаментальные и прикладные исследования на экспериментальном комплексе класса мегасайенс NICA (ОИЯИ)" № FSWU-2025-0014

Сессия-конференция секции ядерной физики ОФН РАН
17.02.2025

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:

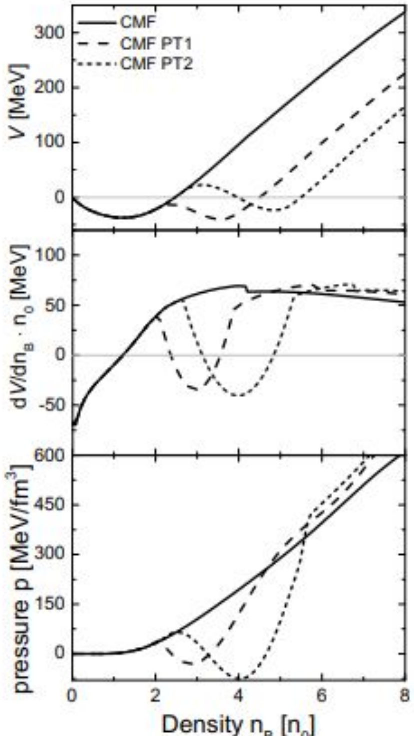
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right]\rangle$$

Anisotropic flow is sensitive to:

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

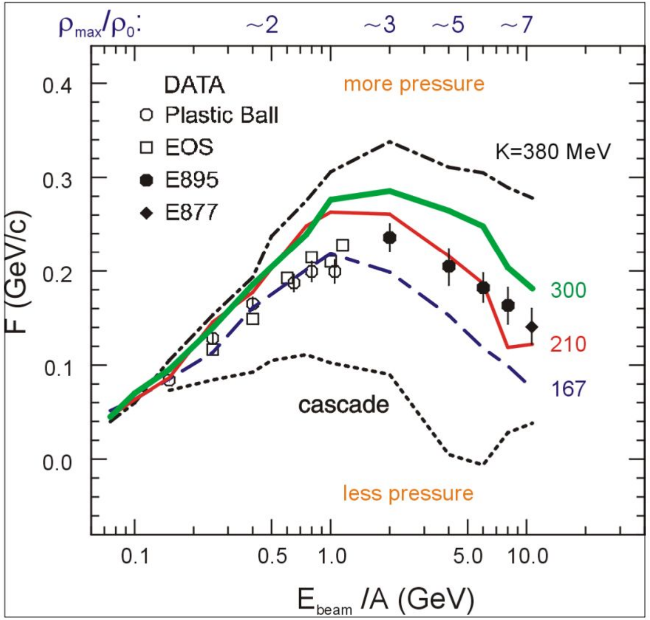
v_n as a function of collision energy

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

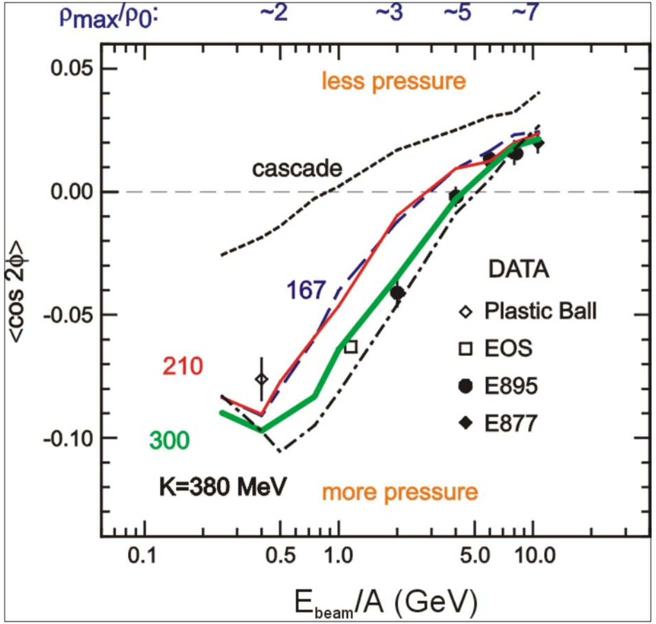


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests softer EOS



v_2 suggests harder EOS

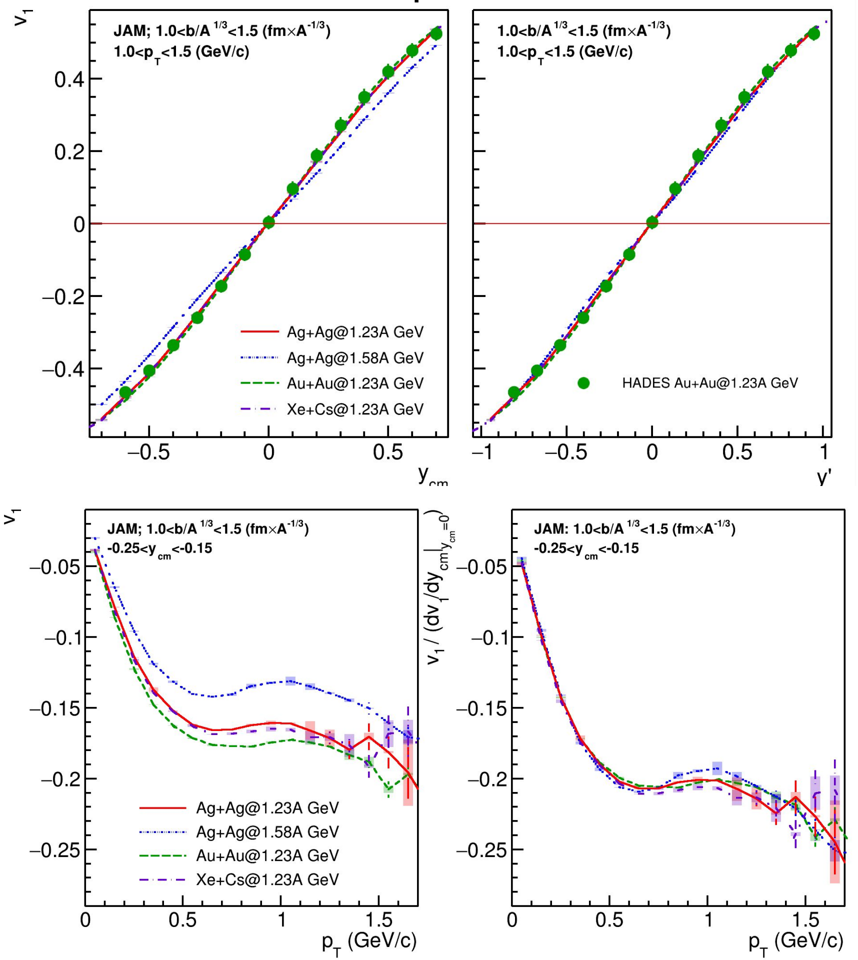


Describing the high-density matter using the mean field

Flow measurements constrain the mean field

Discrepancy is probably due to non-flow correlations

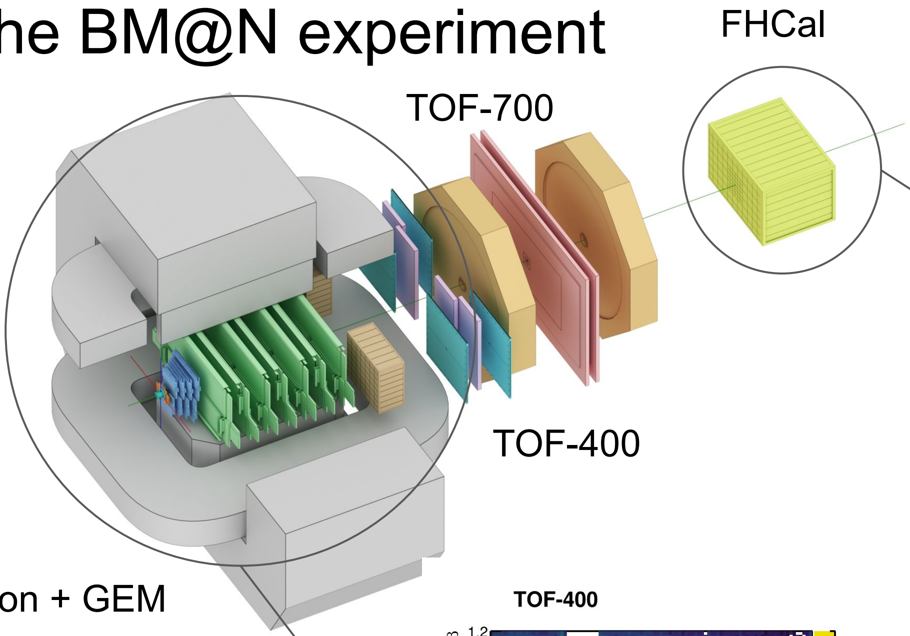
HADES: dv_1/dy scaling with collision energy and system size

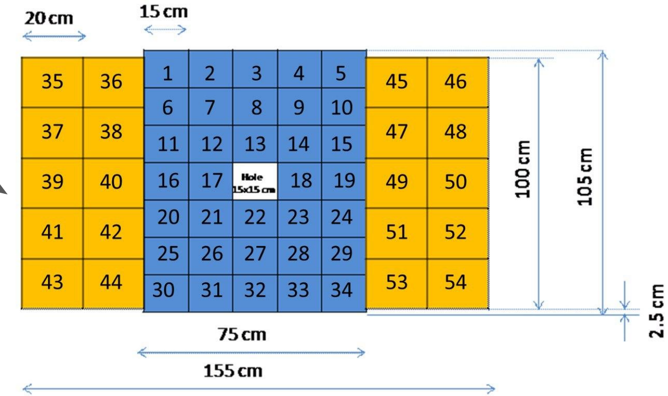


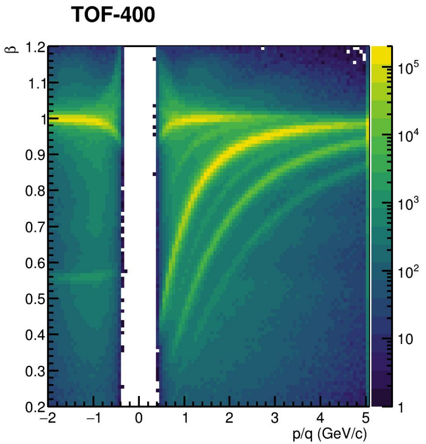
- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments(e.g. STAR-FXT Au+Au

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

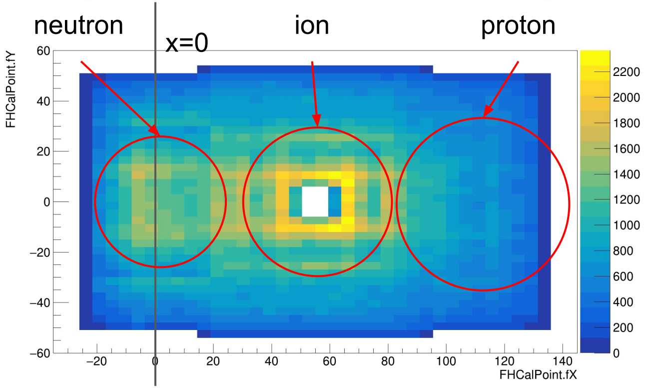
The BM@N experiment







High momentum and time resolution allow to identify particles



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:

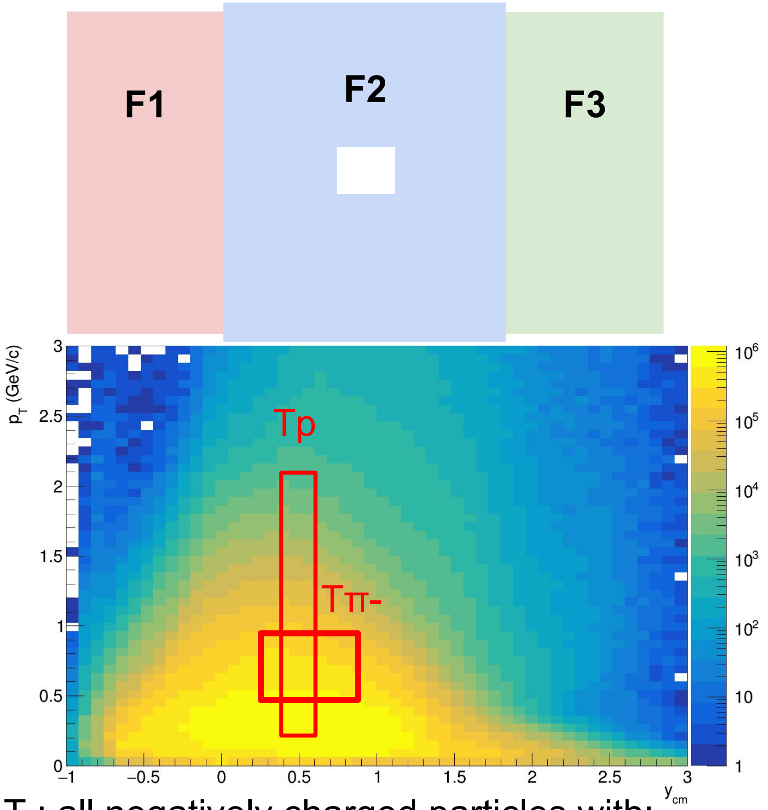
$$u_n = e^{in\phi}$$

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



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

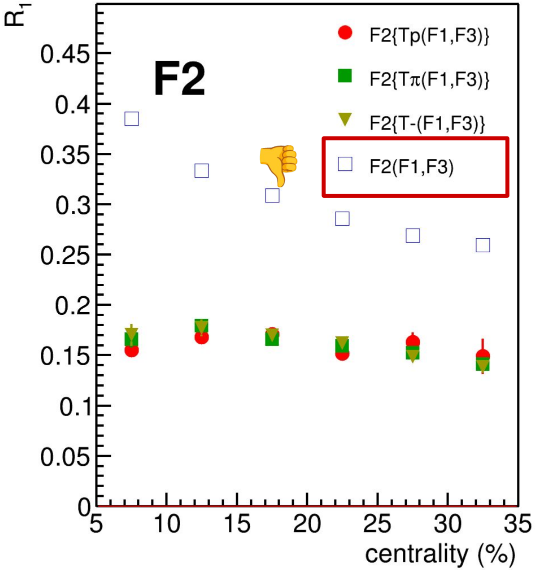
Scalar product (SP) method:

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

Where R_1 is the resolution correction factor

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

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



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

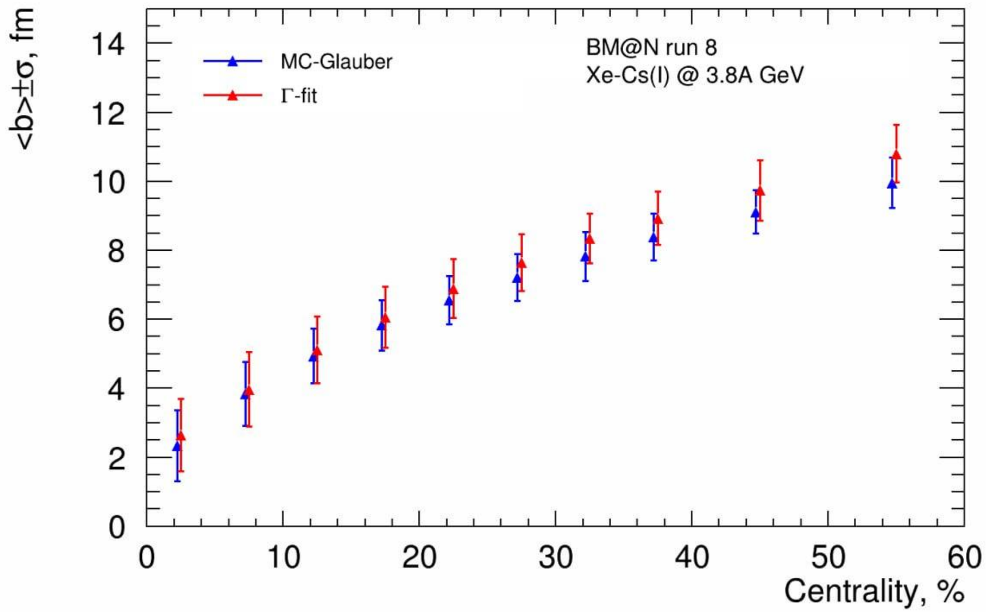
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

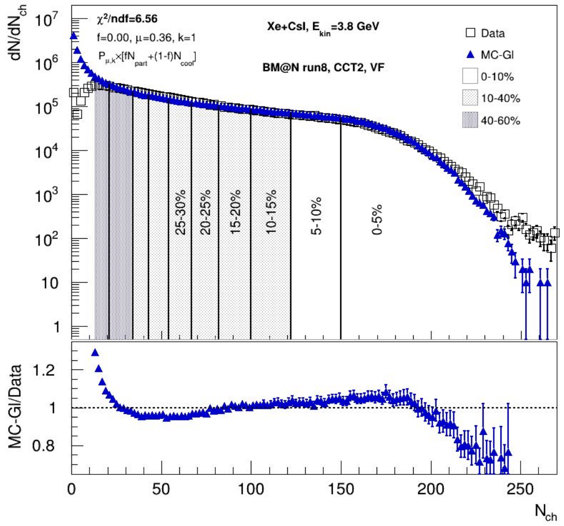
$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

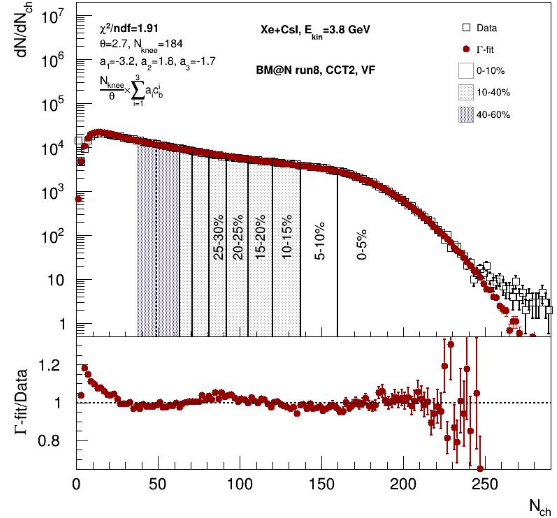
Centrality determination methods

Physics of Atomic Nuclei, 2024, Vol. 87, No. 1, pp. 389–394



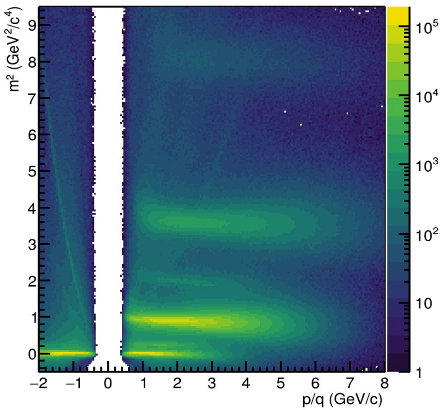
Two methods for centrality determination: MC-Glauber and Γ-fit method are in a good agreement



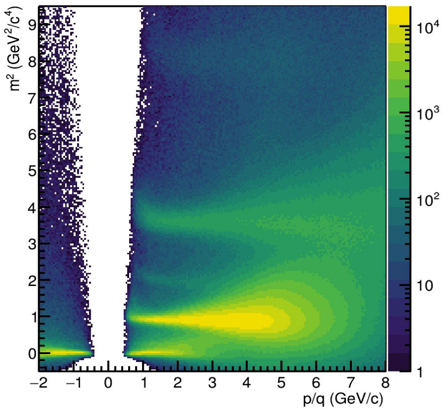


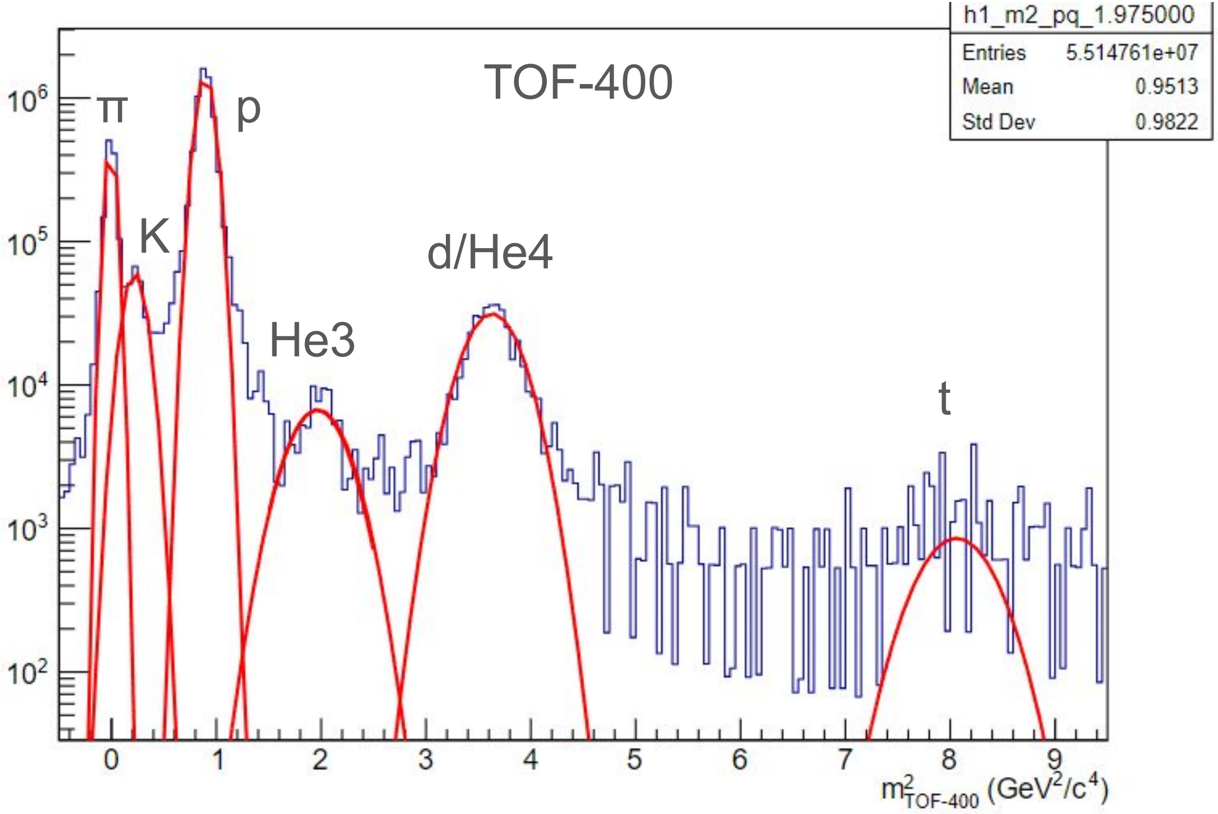
Particle identification

TOF-400

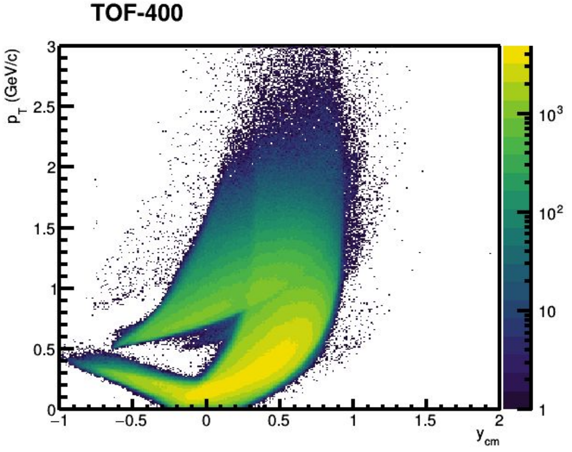


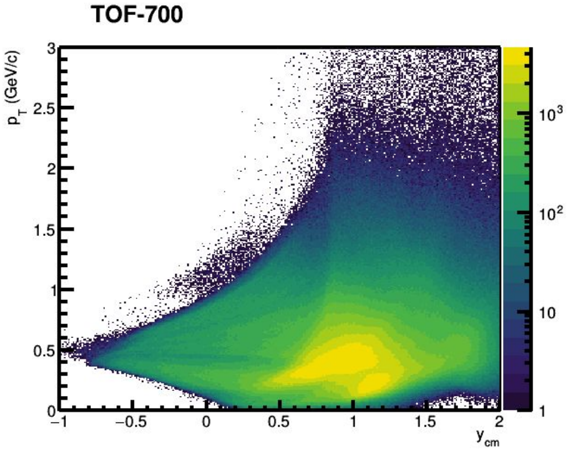
TOF-700

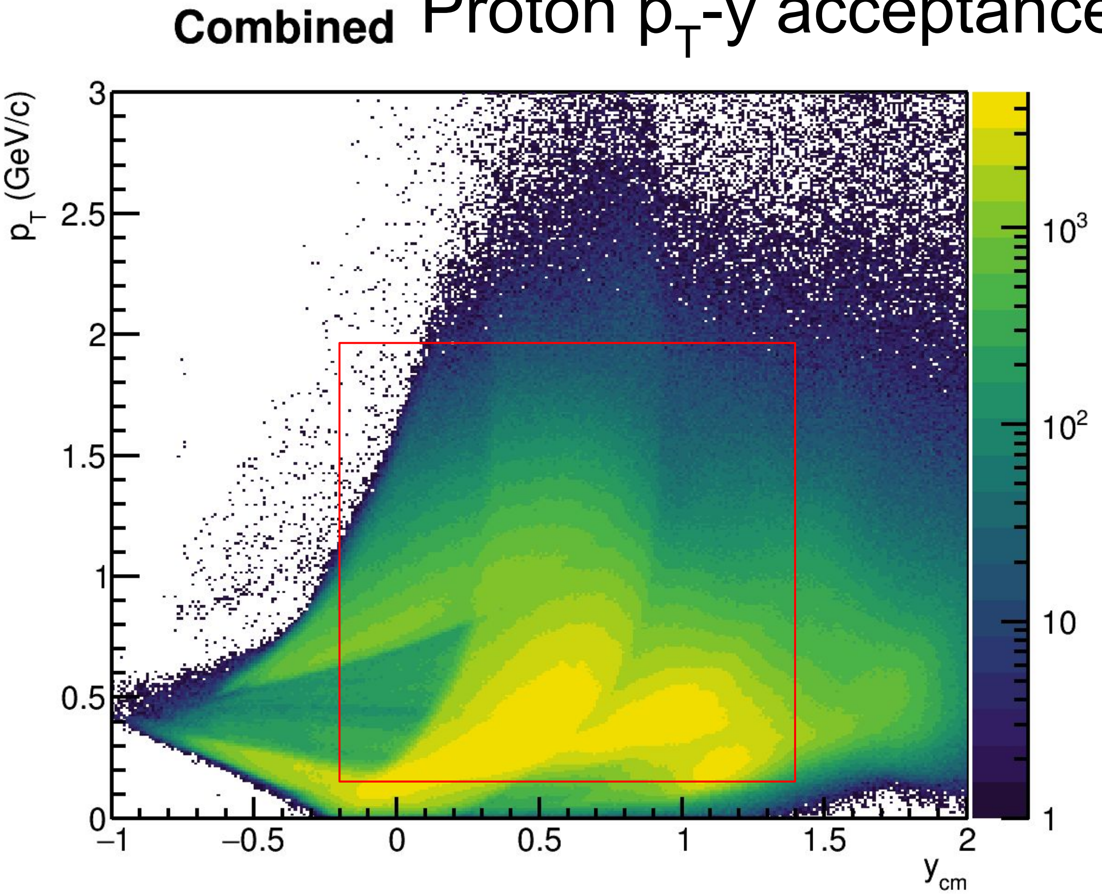




Proton p_T-y acceptance

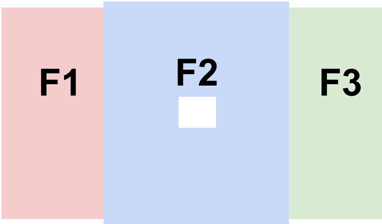


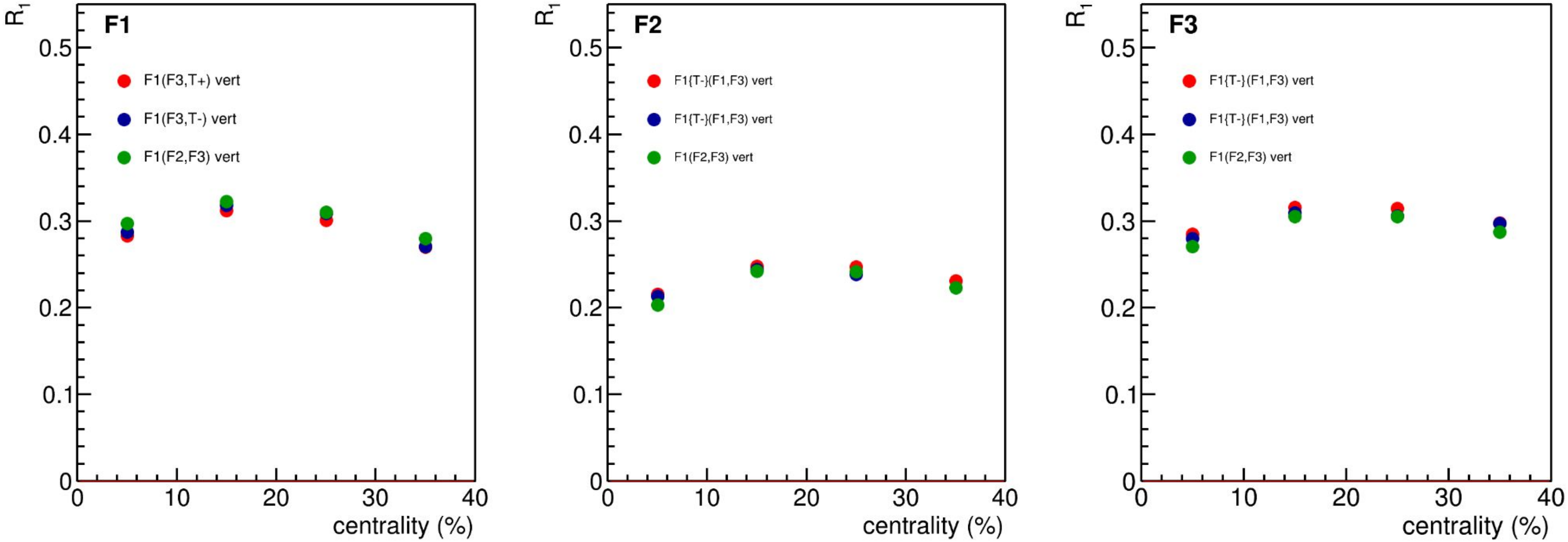




Data is corrected for p_T-y acceptance

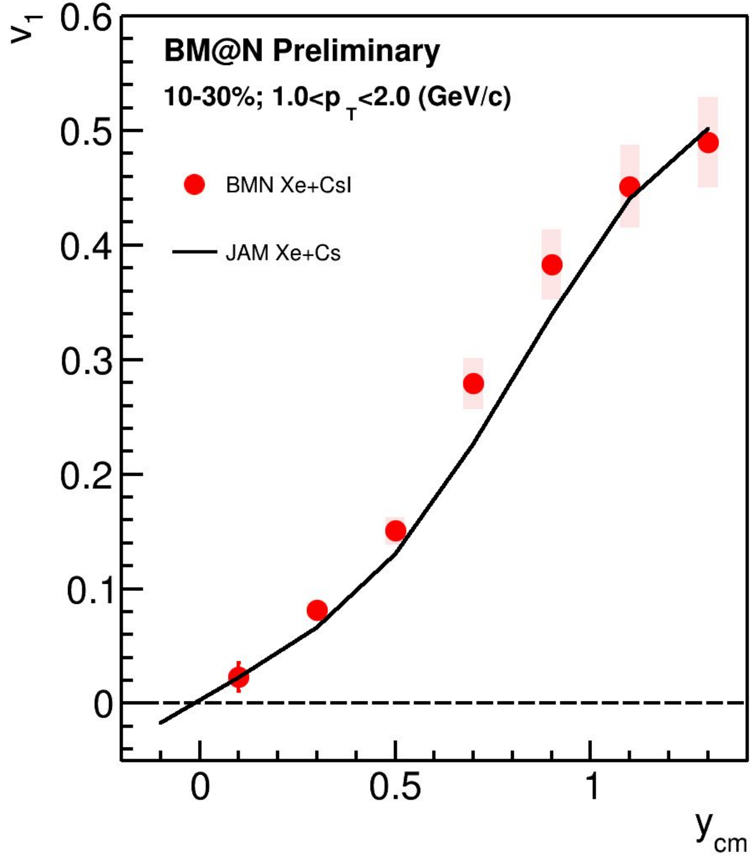
DATA: R_1 in Xe+Cs(I) collisions

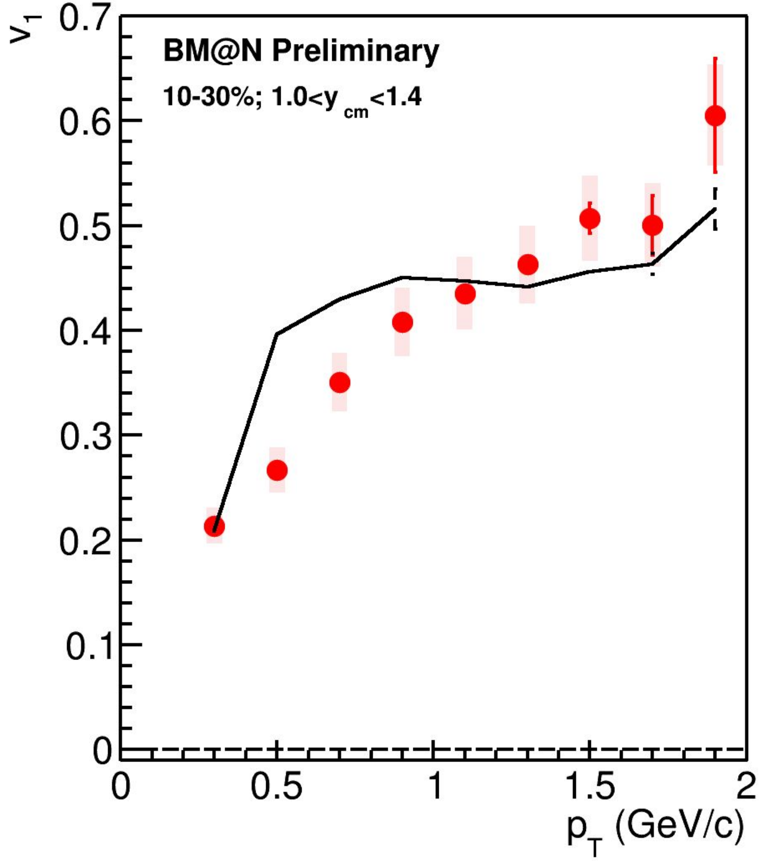




All the estimations for symmetry plane resolutions are in a good agreement

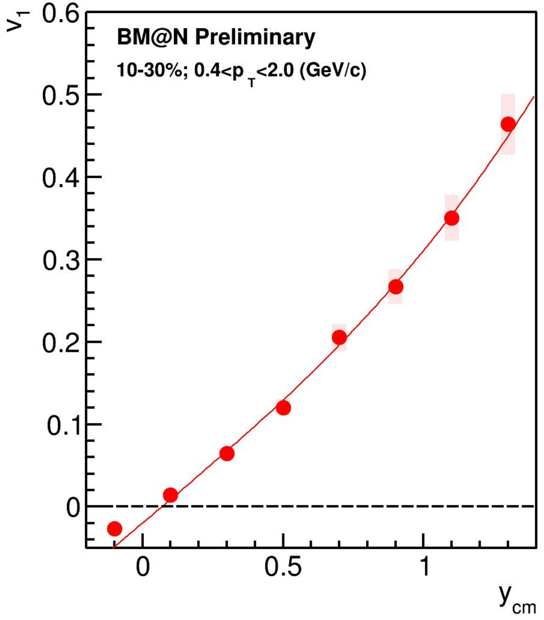
v_1 as a function of pT and y

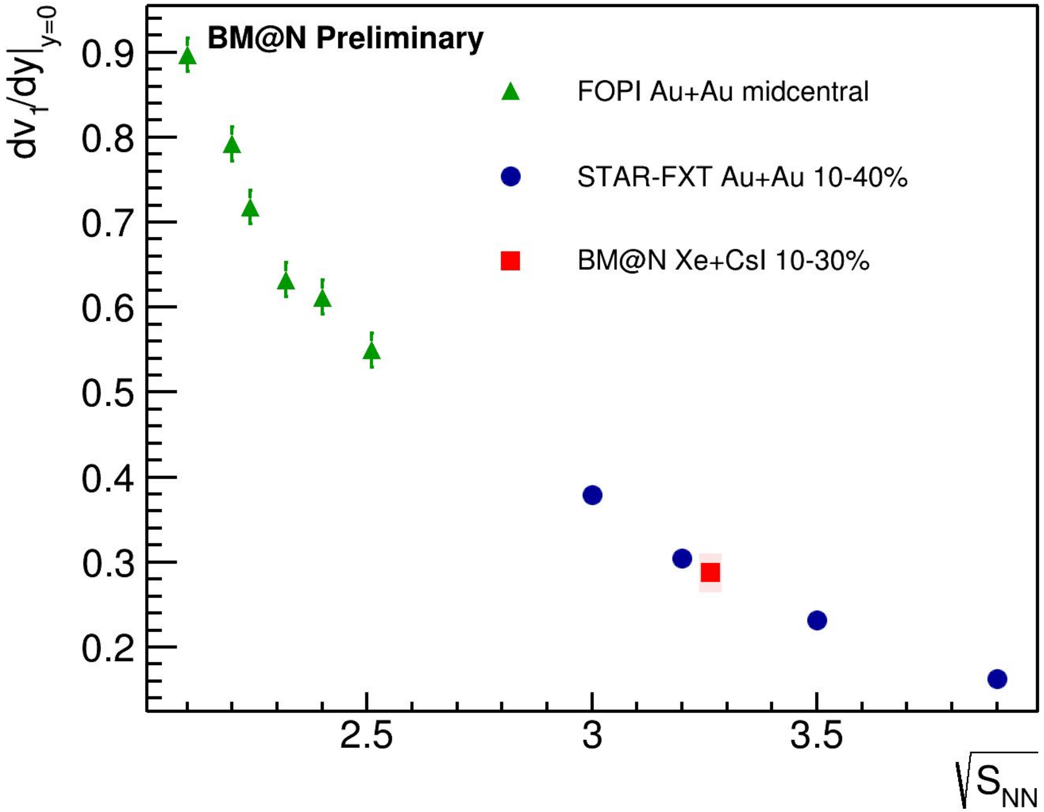




JAM model describes $v_1(y)$ well

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





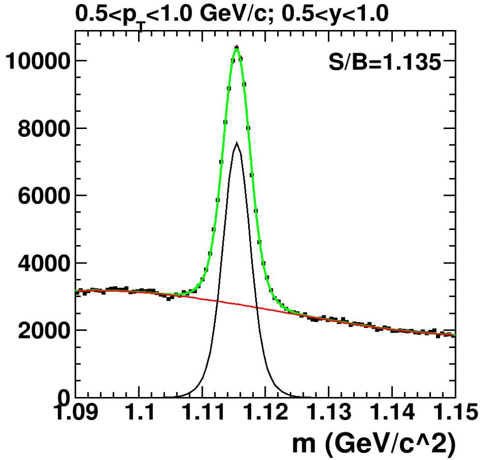
dv_1/dy is in a good agreement with the world data

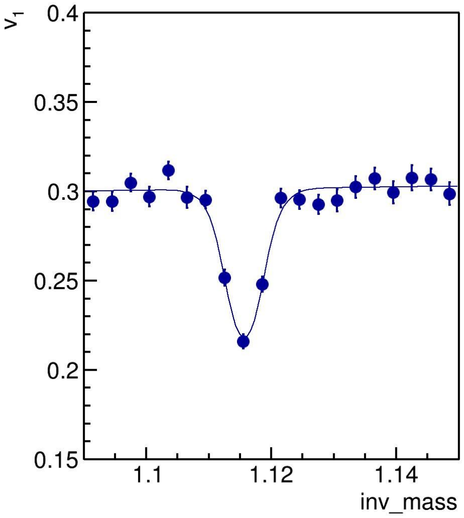
Summary

- Directed flow of protons is measured multidifferentially as a function of p_T, y and centrality
- The JAM model describes the $v_1(y)$ reasonably well in high transverse momentum region
- The directed flow slope at midrapidity $dv_1/dy|_{y=0}$ was extracted
- The results for directed flow slope dv_1/dy of protons are in a good agreement with the world data

Outlook

- 2025-2026 we expect the Beam-Energy scan program (2A, 3A, 4A GeV)
- The results for higher-harmonics flow is in the process of analysis
- The analysis for Λ v_1 is undergoing
  See V.Troshin talk
- Started the analysis for d flow

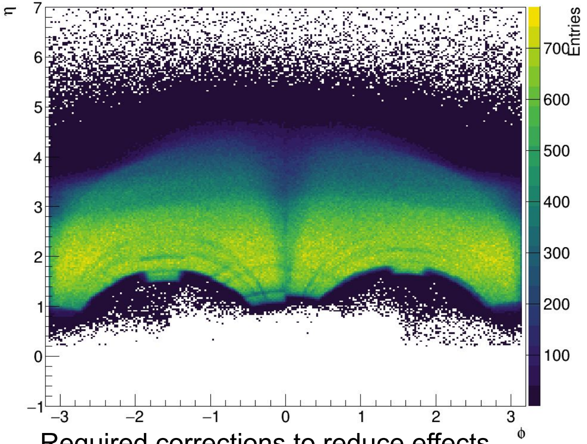




Performance Analysis

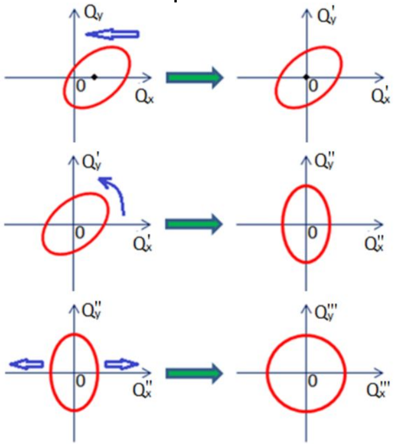
Azimuthal asymmetry of the BM@N acceptance

φ-η yield of protons

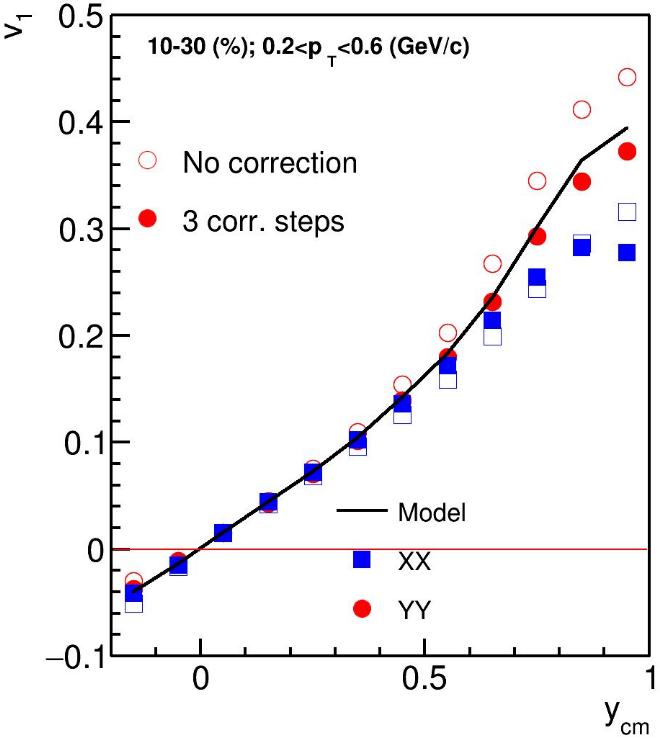


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

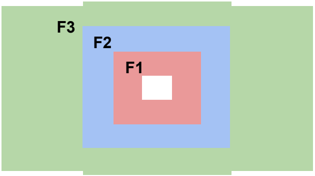


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

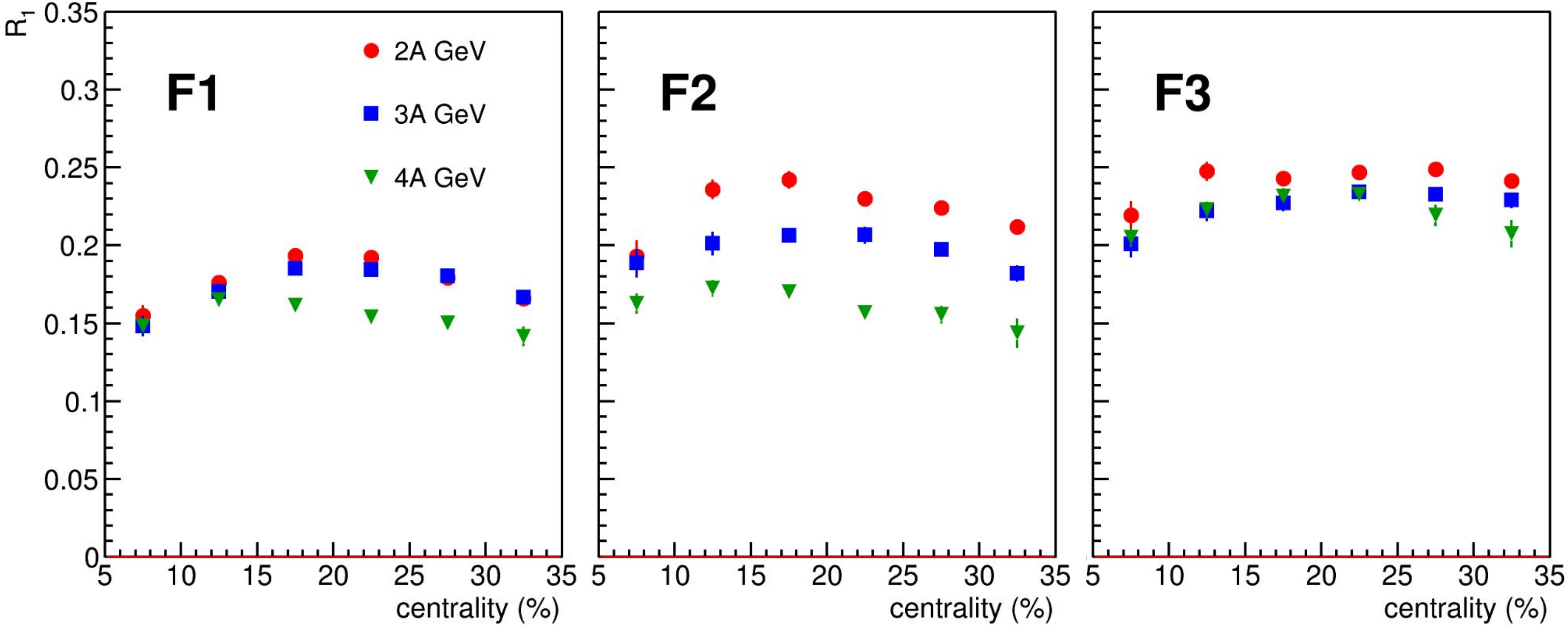


- Better agreement after rescaling for YY
- XX component has too large bias (due to magnetic field)

Performance study: R1

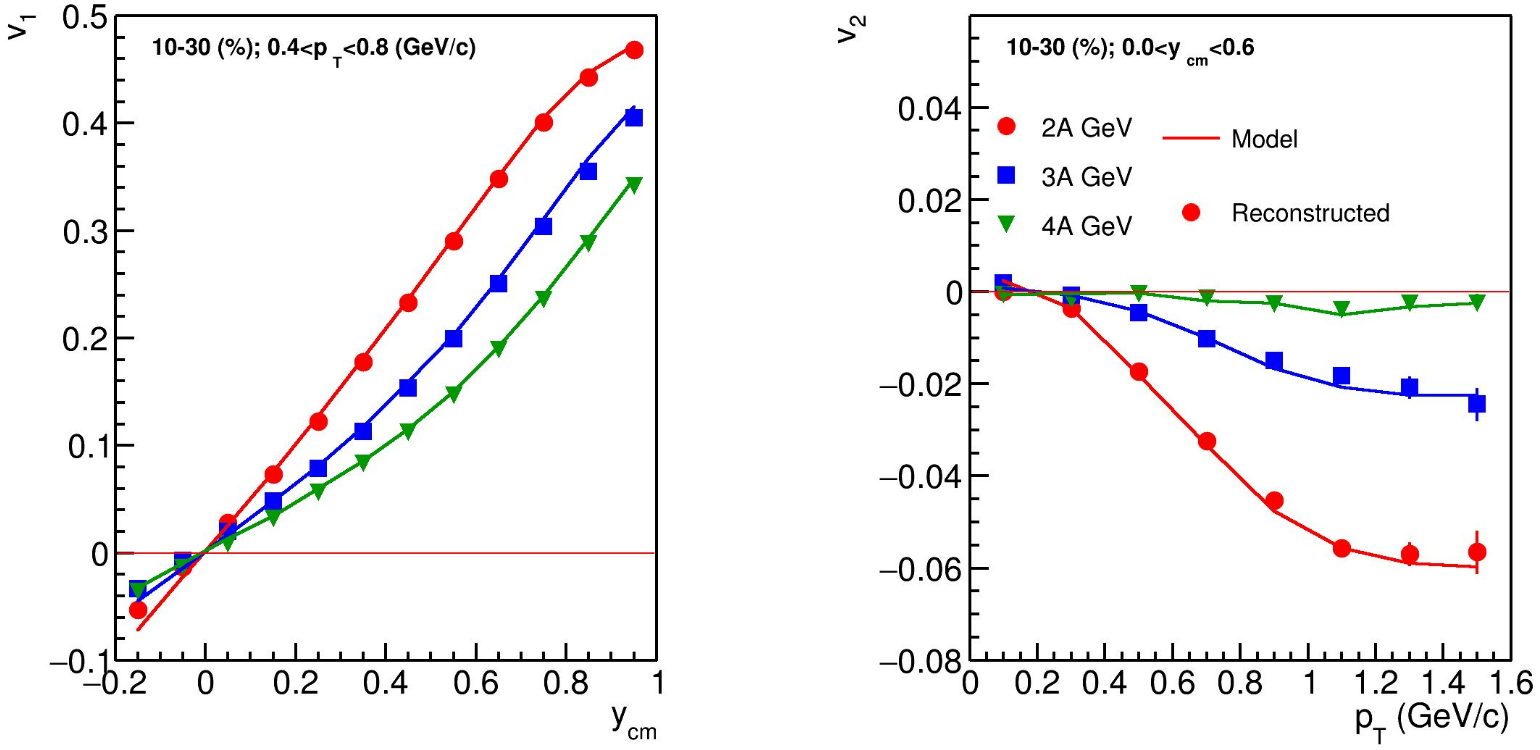


DCMQGSM-SMM



Resolution is lower for higher energies due to lower v_1

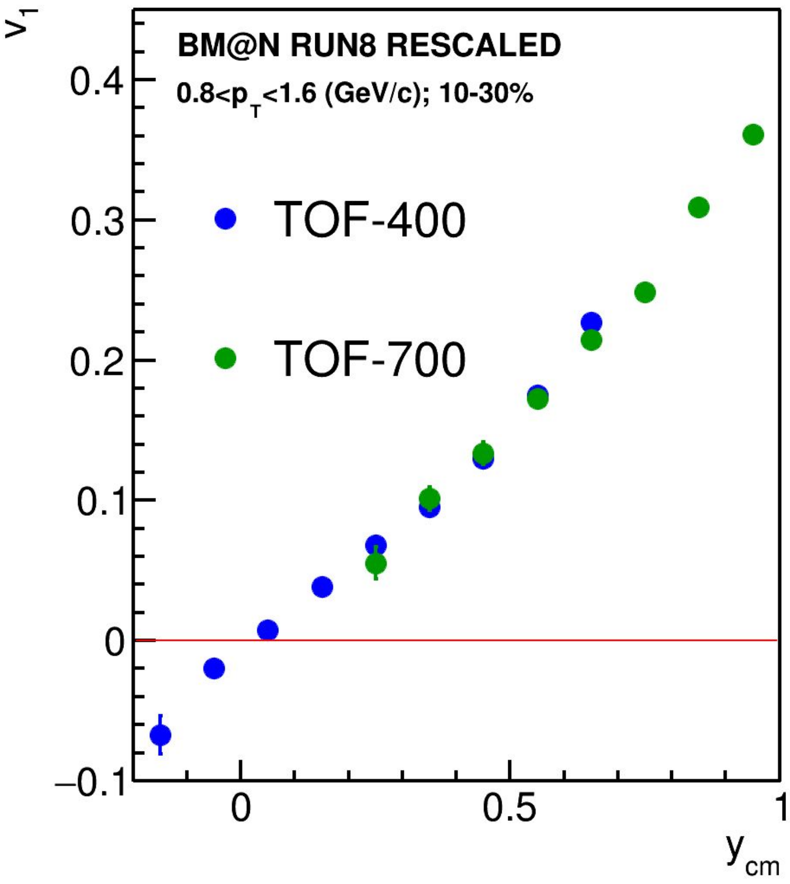
Perfromance study: v_1 and v_2 in Xe+Cs (JAM)

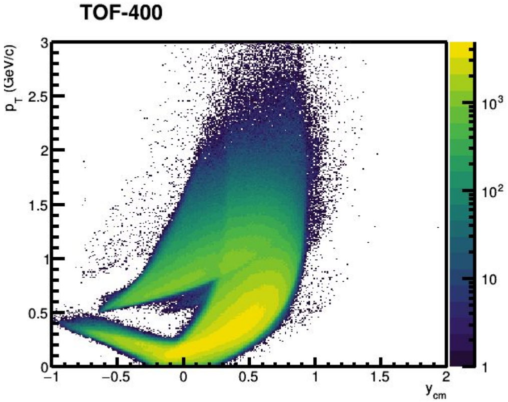


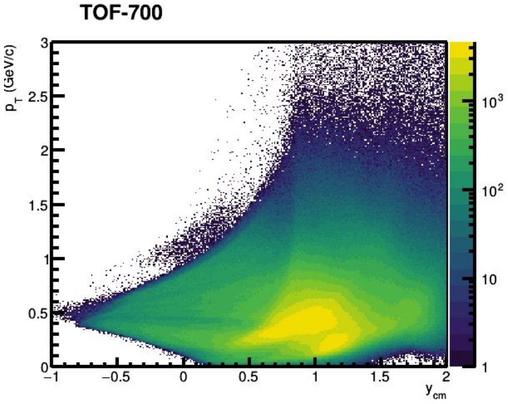
- Good agreement between reconstructed and pure model data for all three energies

Data Analysis

Comparison of the TOF performances

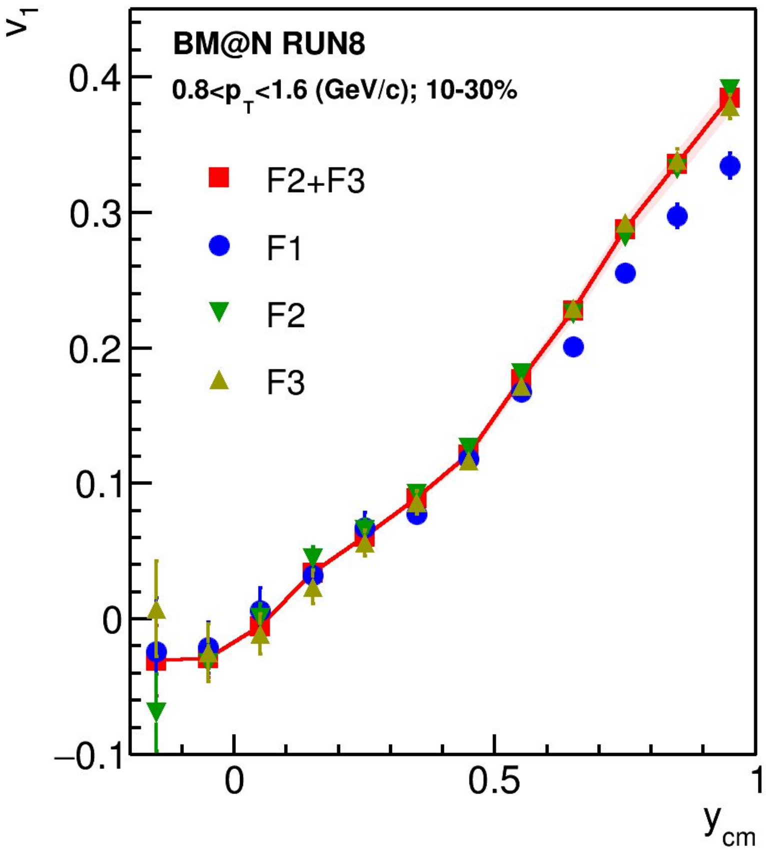


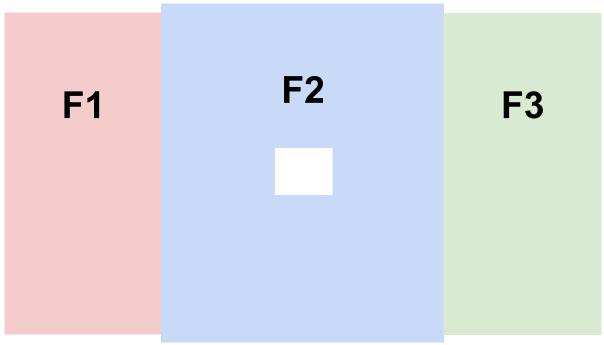




The results from TOF-400 and TOF-700 are in a good agreement

Systematics due to symmetry plane estimation (non-flow)

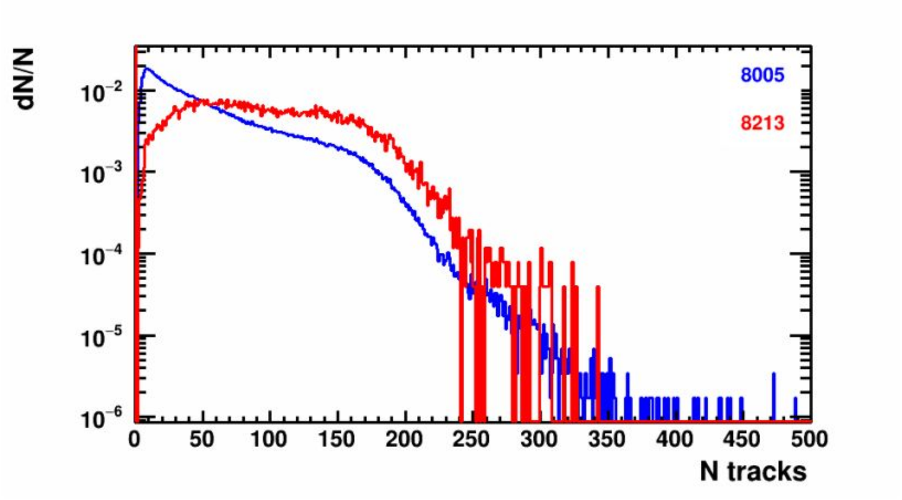


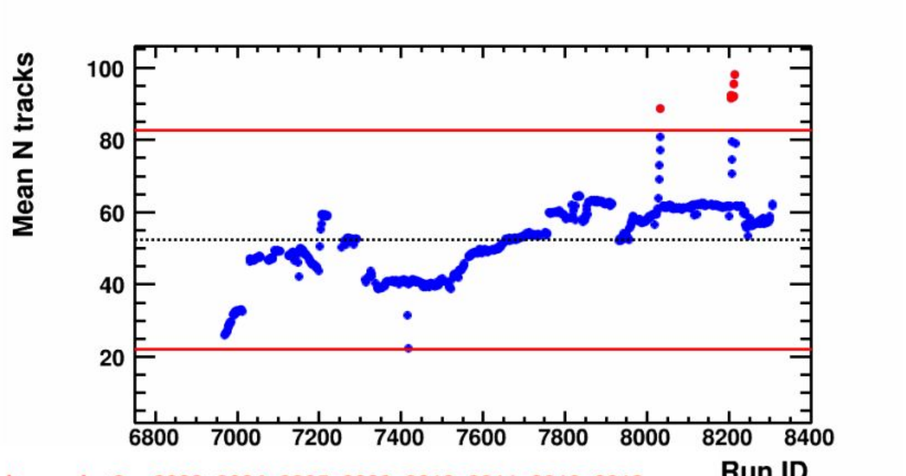


The systematics is below 3%

Backup

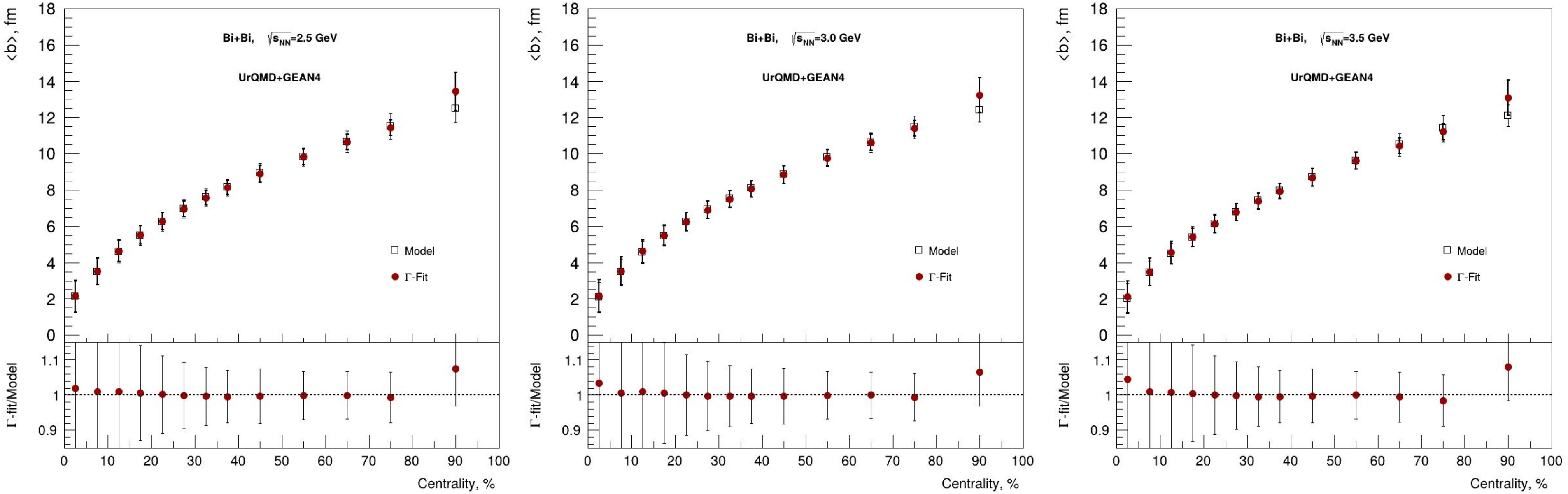
Quality assurance for the recent data





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.

Centrality determination: <b> vs Centrality



Cuts on tracks:

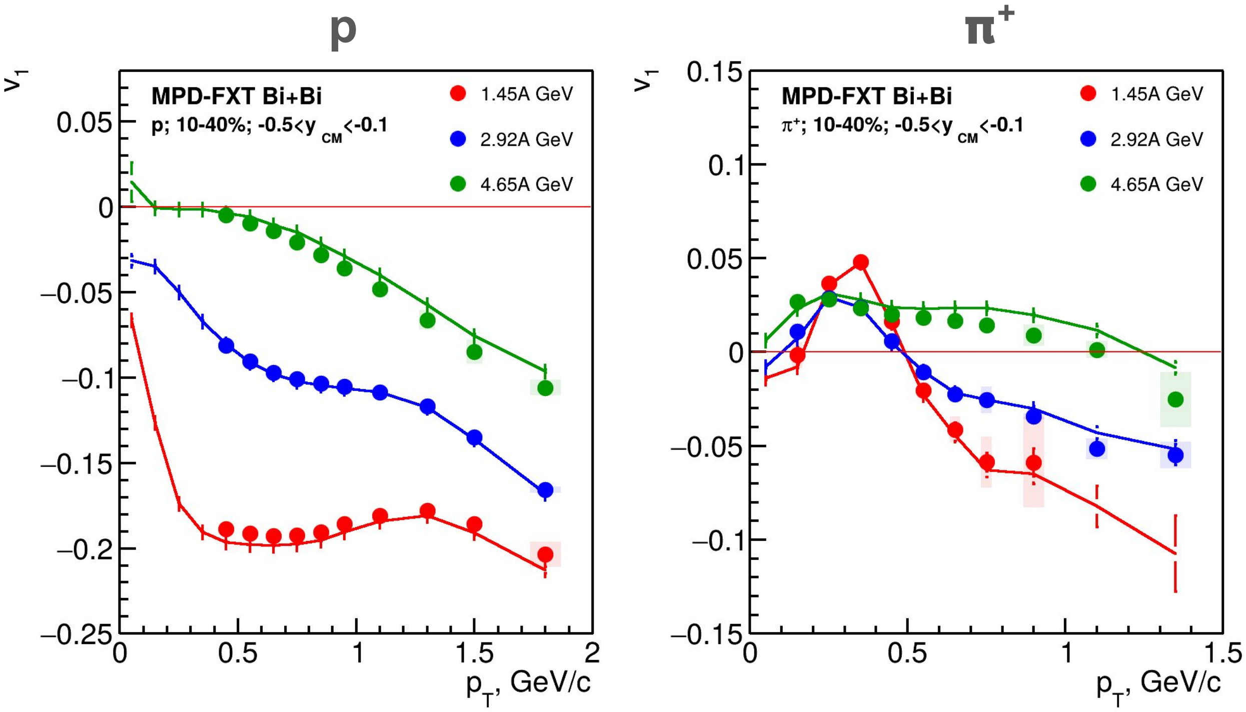
- Nhits>16
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination using inverse Bayes was used

Results: $v_1(p_T)$

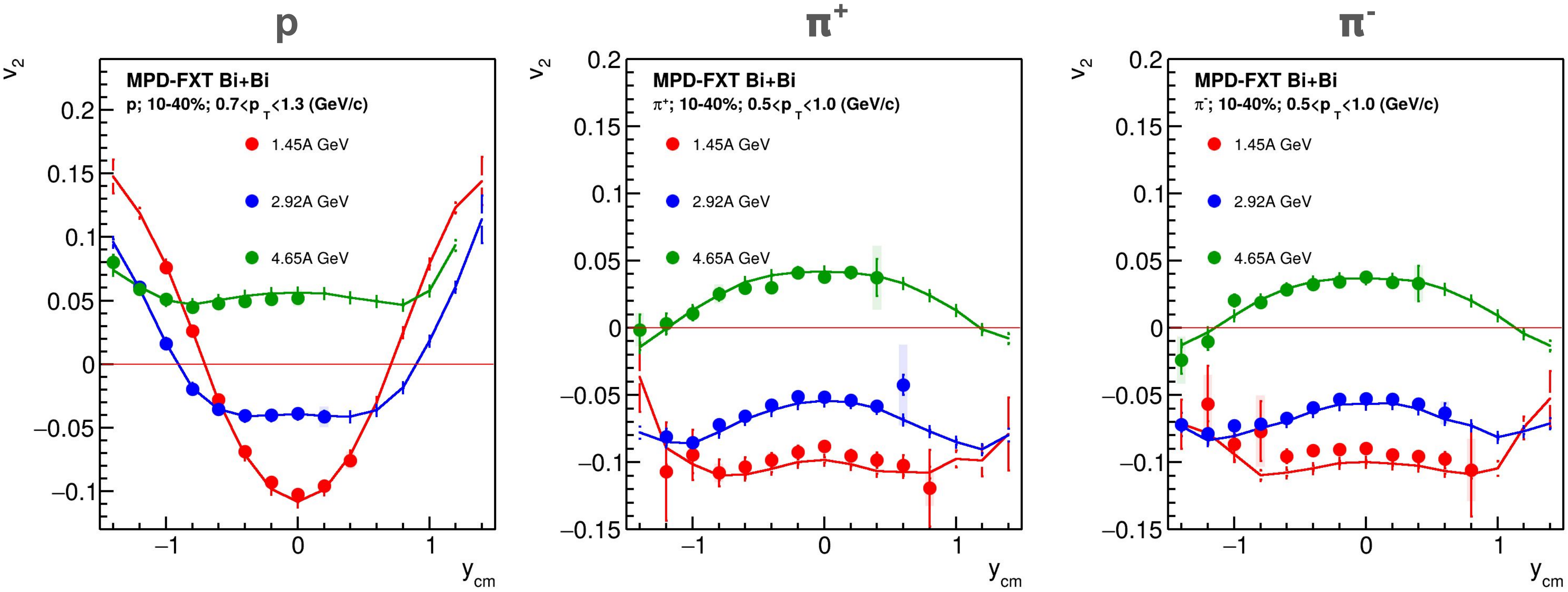
Systematics: xx, yy, F1, F2, F3



Good agreement with MC data

Results: $v_2(y)$

Systematics: xxx, xyy



Good agreement with MC data

The Bayesian inversion method (Γ-fit)

Relation between multiplicity N_{ch} and impact parameter b is defined by

the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-n/\theta} \qquad \frac{\sigma^2}{\langle N_{ch} \rangle} = \theta \simeq const,\ k = \frac{\langle N_{ch} \rangle}{\theta}$$

$c_b = \int_0^b P(b')db'$ – centrality based on impact parameter

Mean multiplicity as a function of c_b can be defined as follows:

$$\langle N_{ch} \rangle = N_{knee} \exp\left(\sum_{j=1}^{3} a_j c_b^j \right)$$

N_{knee}, θ, a_j - 5 parameters

Fit function for N_{ch} distribution:

$$P(N_{ch}) = \int_0^1 P(N_{ch}|c_b)dc_b$$

b-distribution for a given N_{ch} range:

$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(N_{ch}|b)dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

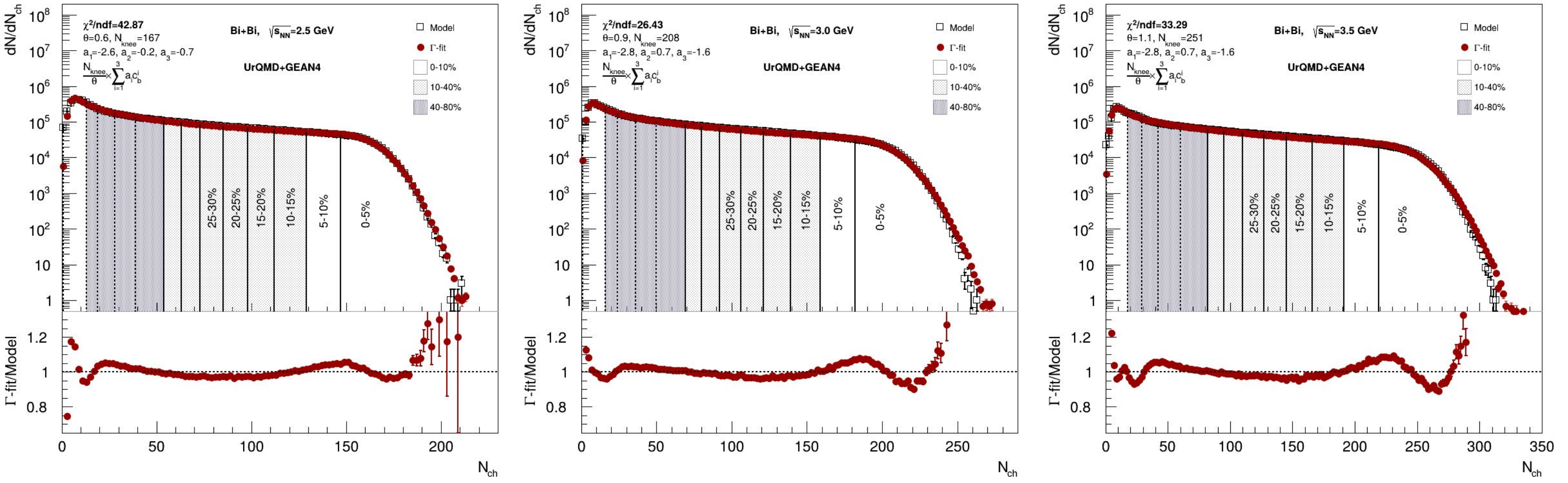
2 main steps of the method:

Fit experimental (model) distribution with P(N)

↓

Construct P(b|E) using Bayes’ theorem:
P(b|N) = P(b)P(N|b)/P(N)

Centrality determination: multiplicity fit



Cuts on tracks:

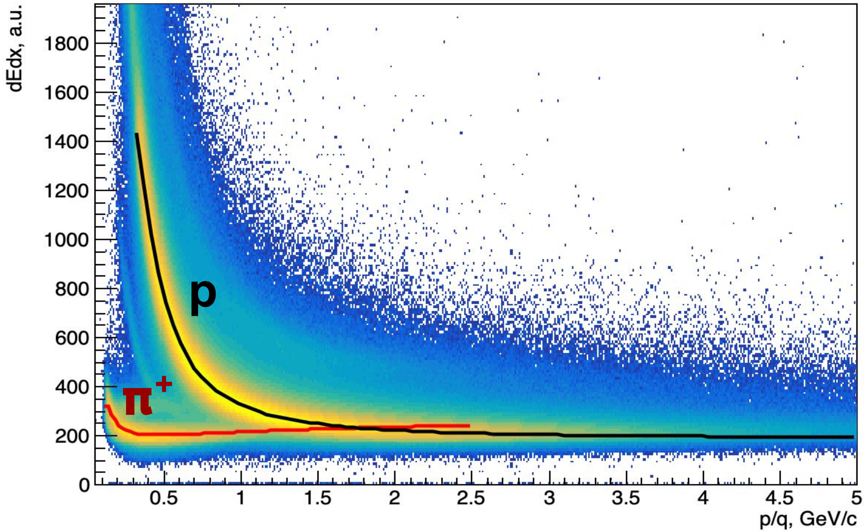
- Nhits>16
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination (Γ-fit) was used

PID procedure

W. Blum, W. Riegler, L. Rolandi, Particle Detection with Drift Chambers (2nd ed.), Springer, Verlag (2008)



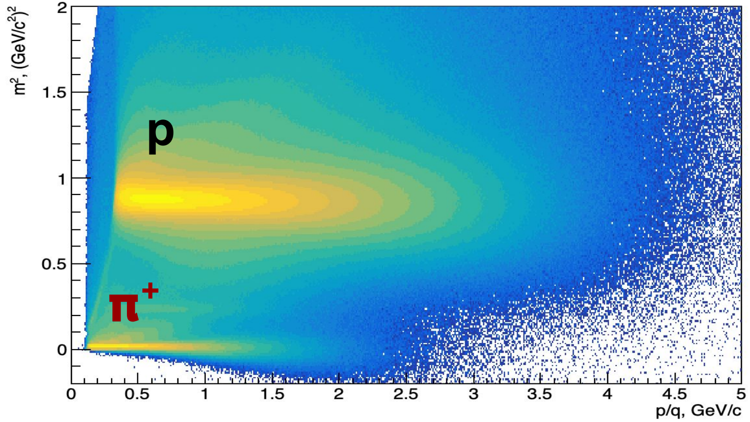
Fit dE/dx distributions with Bethe-Bloch parametrization:

$$f(\beta\gamma) = \frac{p_1}{\beta^{p_4}}\left(p_2 - \beta^{p_4} - \ln\left(p_3 + \frac{1}{(\beta\gamma)^{p_5}}\right)\right)$$

$$\beta^2 = \frac{p^2}{m^2 + p^2}, \beta\gamma = \frac{p}{m}$$

p_i - fit parameters

Fit *(dE/dx - f(βγ))/f(βγ)* with gaus in the slices of p/q and get σ_p(dE/dx)

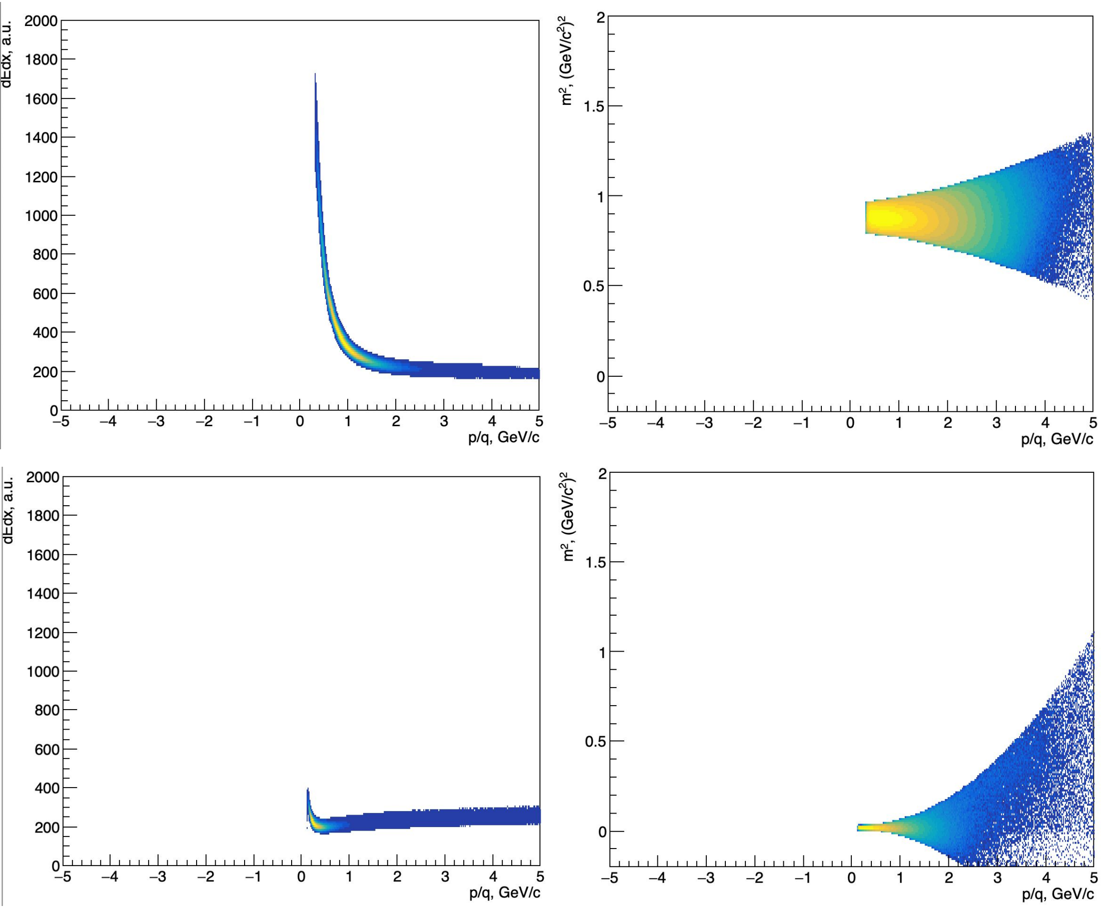


Fit m^2 with gaus in the slices of p/q and get $\sigma_p(m^2)$

(dE/dx,m)→(x,y) coordinates for PID:

$$x_p = \frac{(dE/dx)^{meas} - (dE/dx)_p^{fit}}{(dE/dx)_p^{fit}\sigma_p^{dE/dx}}, \; y_p = \frac{m^2 - m_p^2}{\sigma_p^{m^2}}$$

PID procedure: Results



$$x_p = \frac{(dE/dx)^{meas} - (dE/dx)_p^{fit}}{(dE/dx)_p^{fit}\sigma_p^{dE/dx}}$$

$$y_p = \frac{m^2 - m_p^2}{\sigma_p^{m^2}}$$

Protons:

$$\sqrt{x_p^2 + y_p^2} < 2, \sqrt{x_\pi^2 + y_\pi^2} > 3$$

Pions (π^+):

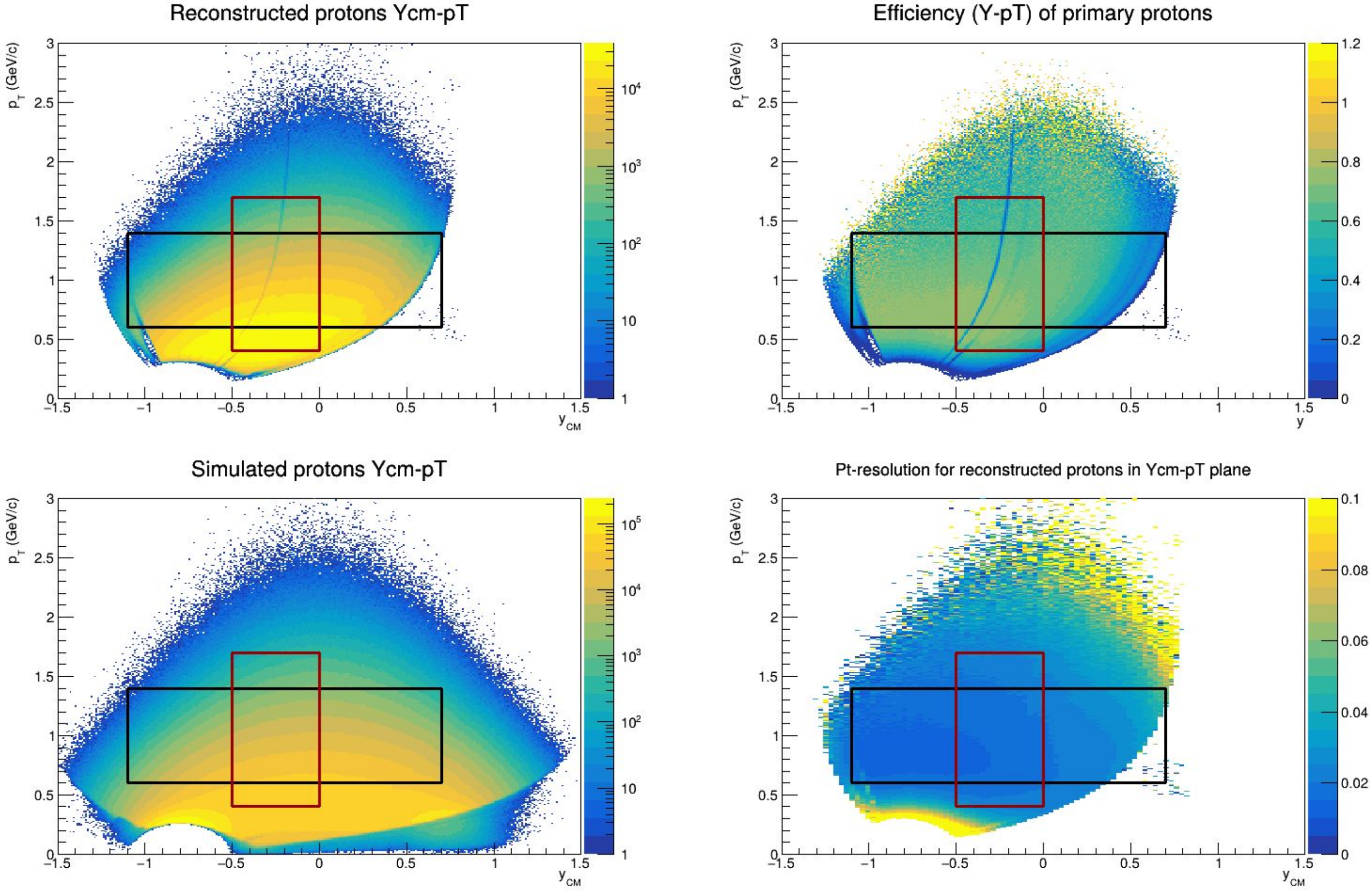
$$\sqrt{x_\pi^2 + y_\pi^2} < 2, \sqrt{x_p^2 + y_p^2} > 3$$

Pions (π^-):

charge<0

(y-pt) distribution, efficiency and δpt (protons)

$$\text{eff} = \frac{\frac{dN}{dydp_T}(\text{reco})}{\frac{dN}{dydp_T}(\text{sim})}$$



$$\Delta p_T = \frac{|p_T^{\text{reco}} - p_T^{\text{mc}}|}{p_T^{\text{mc}}}$$

Bi+Bi $\sqrt{s_{NN}}$=2.5 GeV

Cuts for reco tracks:

- Nhits>27
- DCA< 1 cm
- PID (TPC+TOF)
- Primary (DCA<1 cm)

Cuts for sim particles:

- PID (pdg code)
- Primary (motherId)

Black box: acceptance window for $v_n(y)$

Red box: acceptance window for $v_n(p_T)$

Flow vectors

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

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

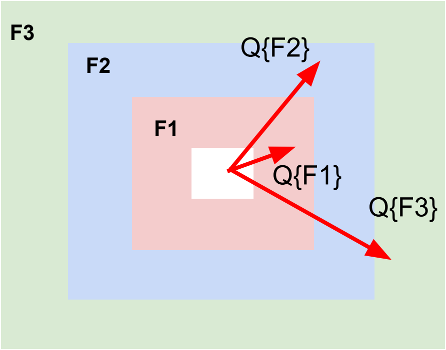
where φ is the azimuthal angle

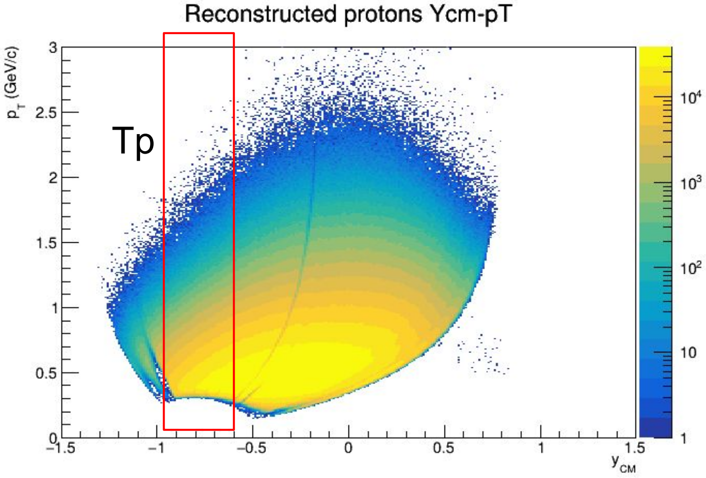
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

Ψ_n^{EP} is the event plane angle

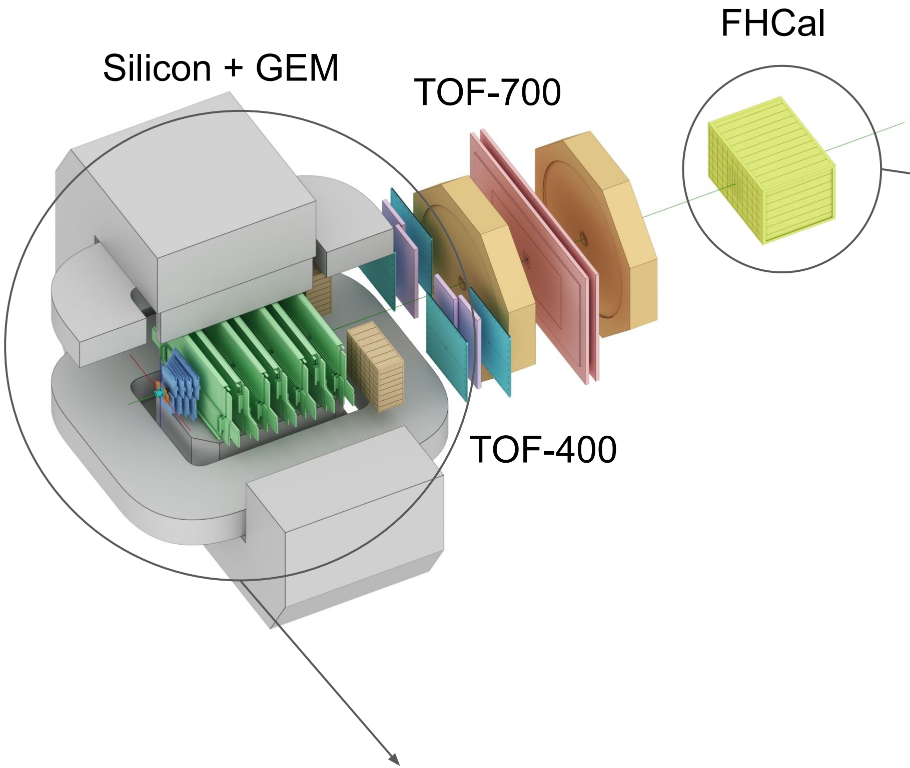
Modules of FHCal divided into 3 groups



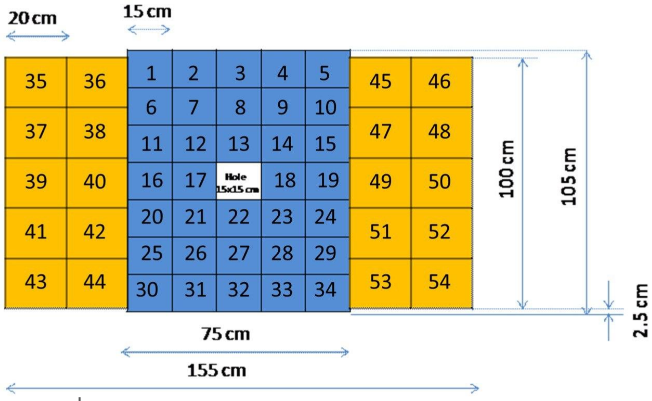


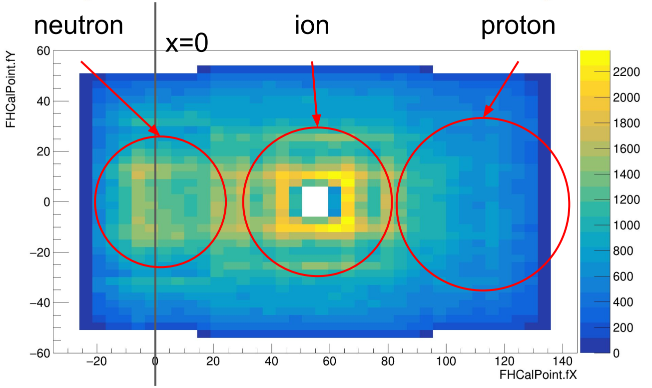
Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

The BM@N experiment (GEANT4 simulation for RUN8)



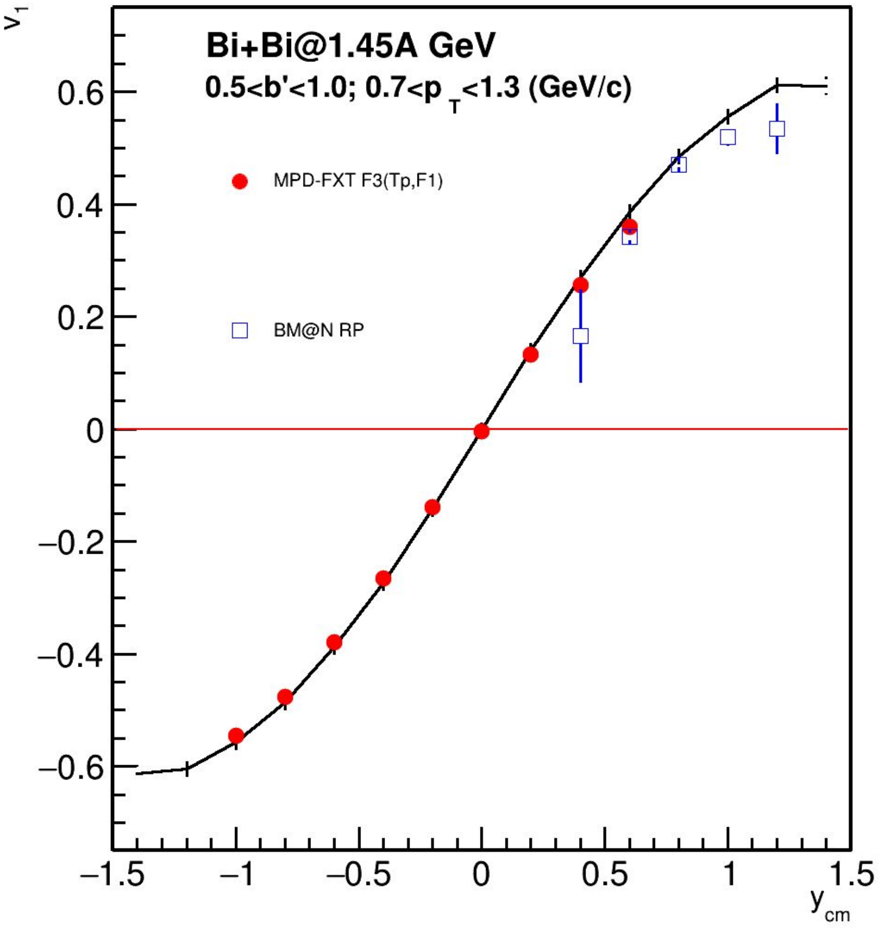
Square-like tracking system within the magnetic field deflecting particles along X-axis





Charge splitting on the surface of the FHCal is observed due to magnetic field

Comparison with BM@N performance



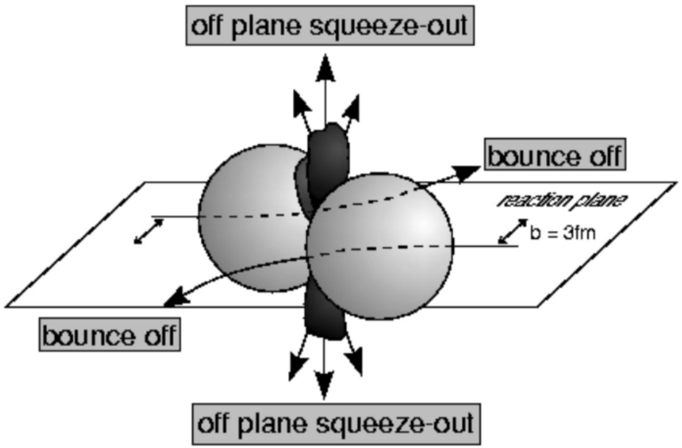
BM@N TOF system (TOF-400 and TOF-700) has poor midrapidity coverage at $\sqrt{s_{NN}}$ = 2.5 GeV

- One needs to check higher energies ($\sqrt{s_{NN}}$ = 3, 3.5 GeV)
- More statistics are required due to the effects of magnetic field in BM@N:
  - Only “yy” component of <uQ> and <QQ> correlation can be used

Despite the challenges, both MPD-FXT and BM@N can be used in v_n measurements:

- To widen rapidity coverage
- To perform a cross-check in the future

Anisotropic flow & spectators



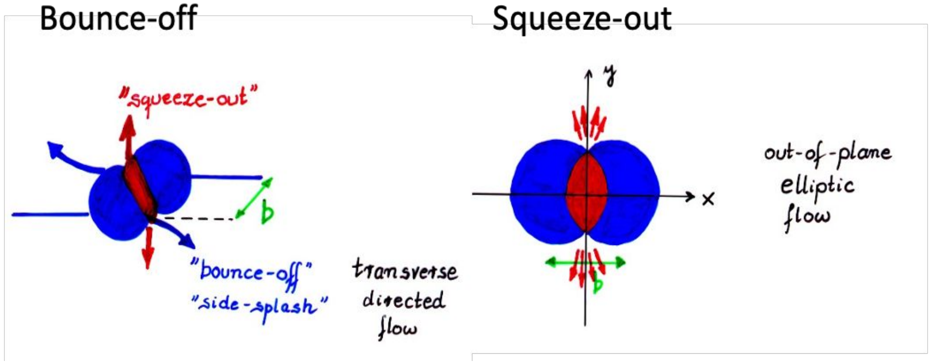
The azimuthal angle distribution is decomposed in a Fourier series relative to reaction plane angle:

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

Anisotropic flow:

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

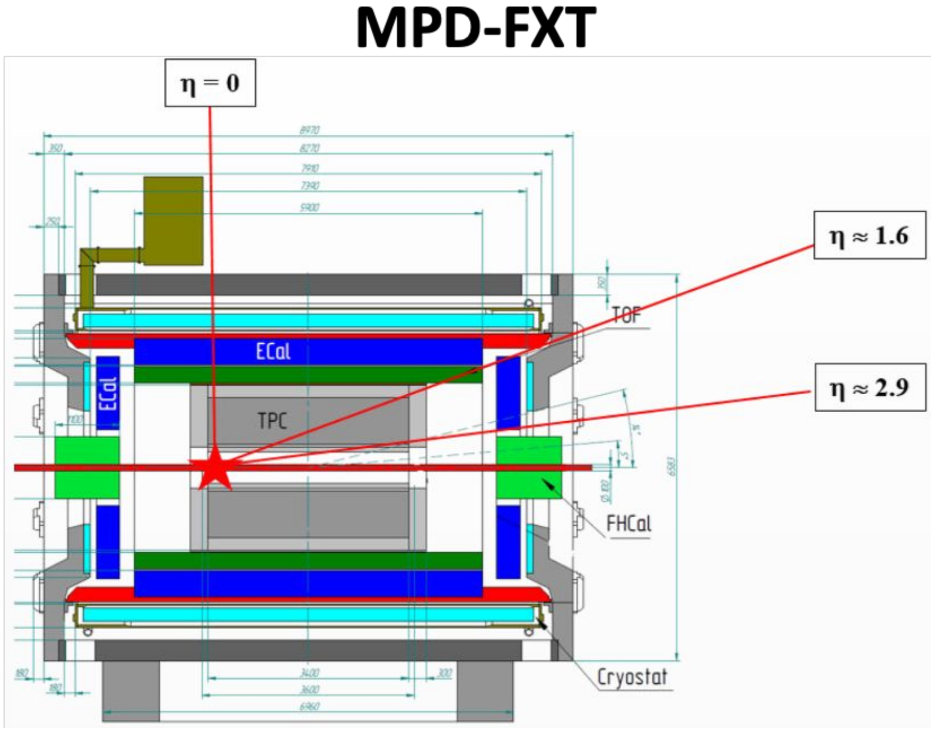
v_1 - directed flow, v_2 - elliptic flow



Anisotropic flow is sensitive to:

- ➢ Compressibility of the created matter $\left(t_{exp} = R/c_s,\ c_s = c\sqrt{dp/d\varepsilon}\right)$
- ➢ Time of the interaction between overlap region and spectators $\left(t_{pass} = 2R/\gamma_{CM}\beta_{CM}\right)$

MPD in Fixed-Target Mode (FXT)



- Model used: UrQMD mean-field
  - Bi+Bi, E_{kin}=1.45 AGeV ($\sqrt{s_{NN}}$ =2.5 GeV)
  - Bi+Bi, E_{kin}=2.92 AGeV ($\sqrt{s_{NN}}$ =3.0 GeV)
  - Bi+Bi, E_{kin}=4.65 AGeV ($\sqrt{s_{NN}}$=3.5 GeV)
- Point-like target at z = -115 cm
- GEANT4 transport
- Multiplicity-based centrality determination
- PID using information from TPC and TOF
- Primary track selection: DCA<1 cm
- Track selection:
  - N_{hits}>27 (protons), N_{hits}>22 (pions)

Flow vectors

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

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

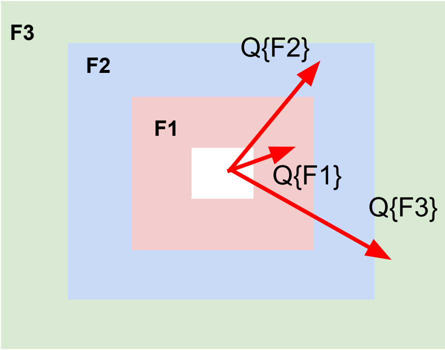
where φ is the azimuthal angle

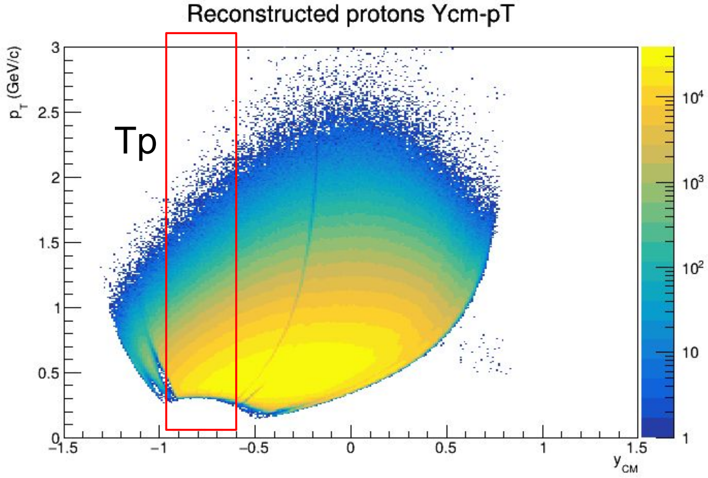
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

Ψ_n^{EP} is the event plane angle

Modules of FHCal divided into 3 groups

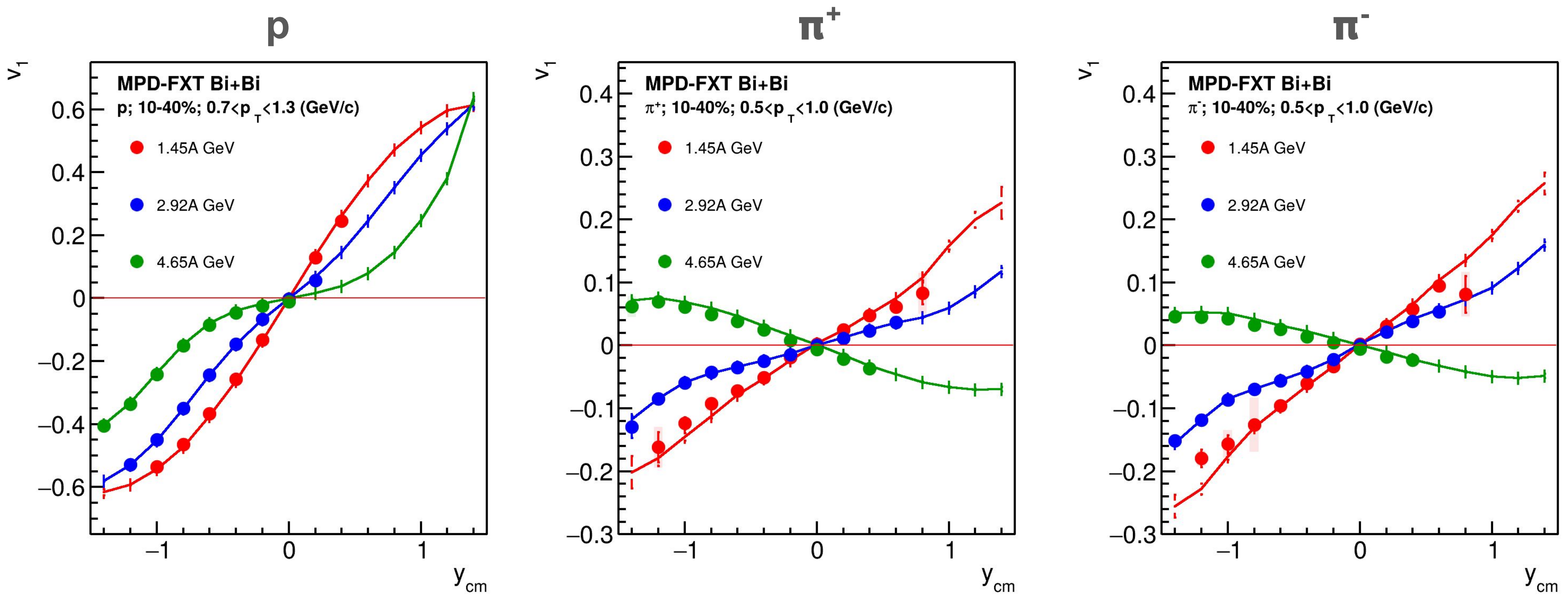




Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

Results: $v_1(y)$

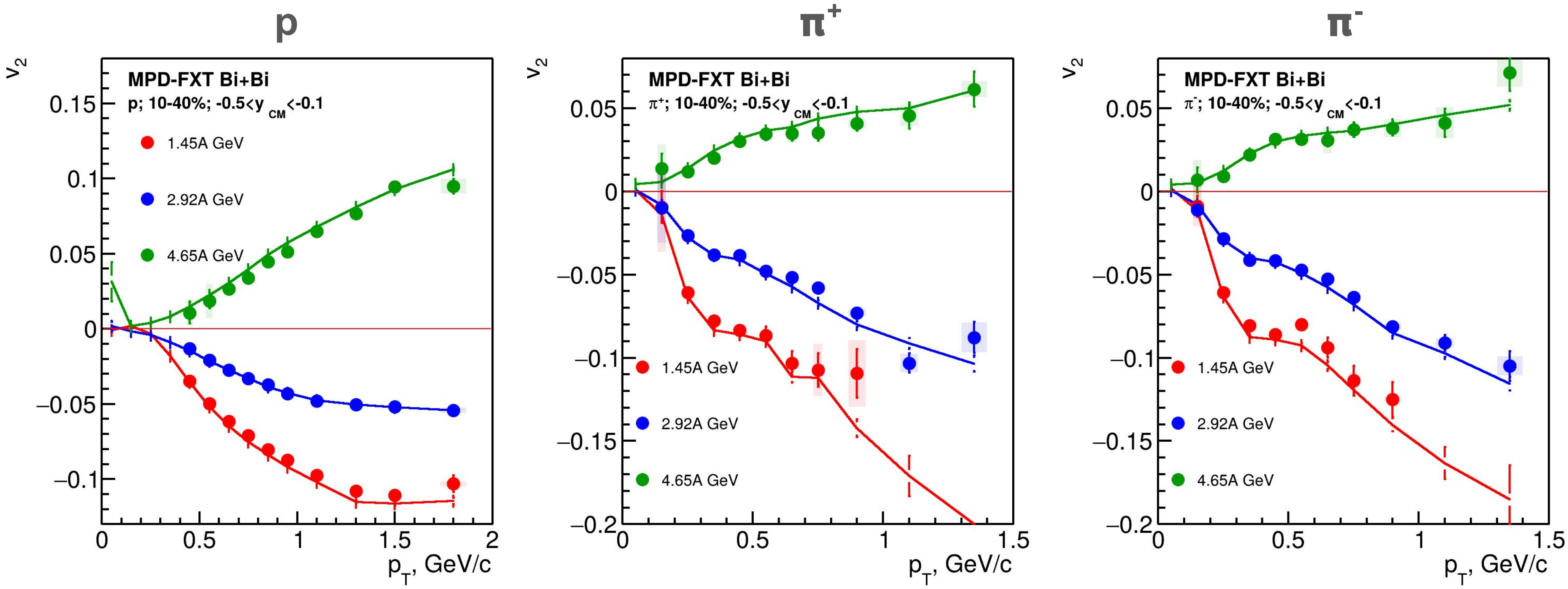
Systematics: xx, yy, F1, F2, F3



Good agreement with MC data

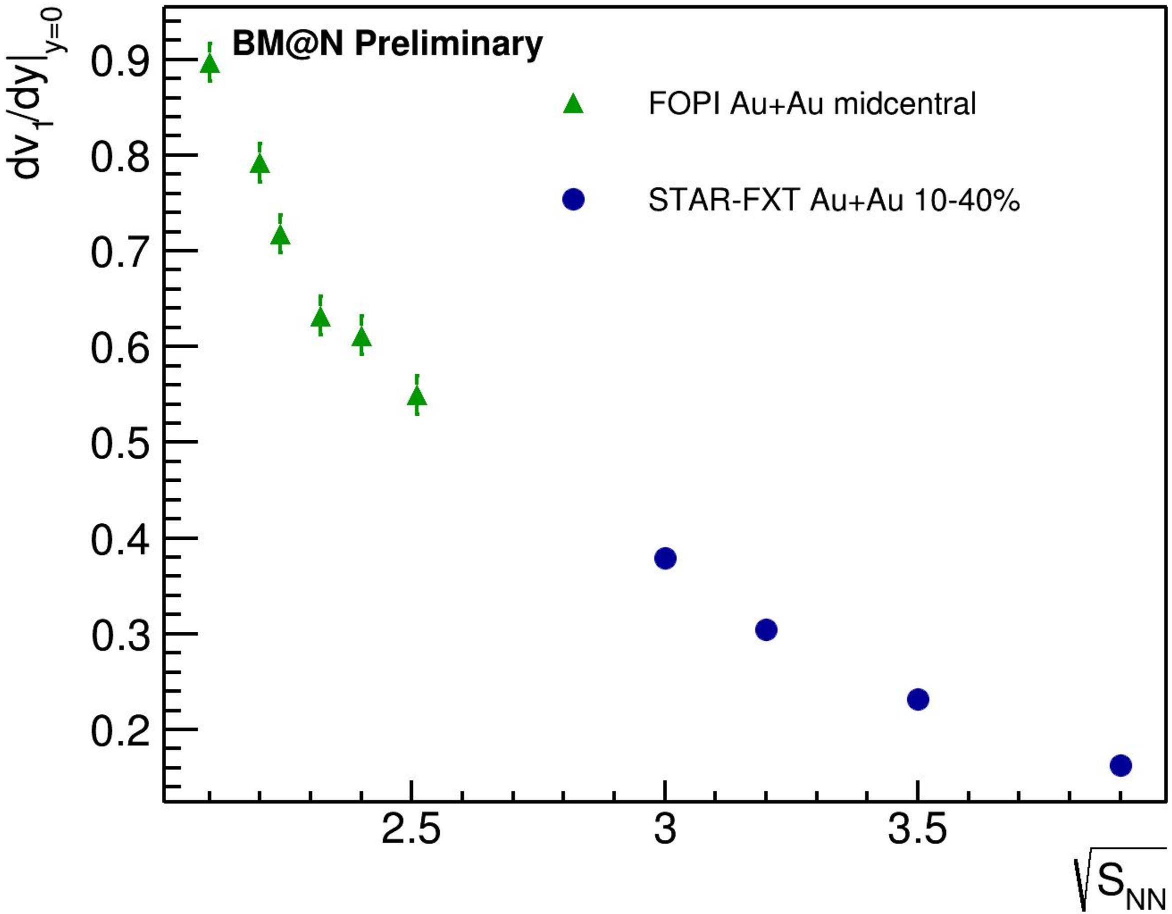
Results: $v_2(p_T)$

Systematics: xxx, xyy

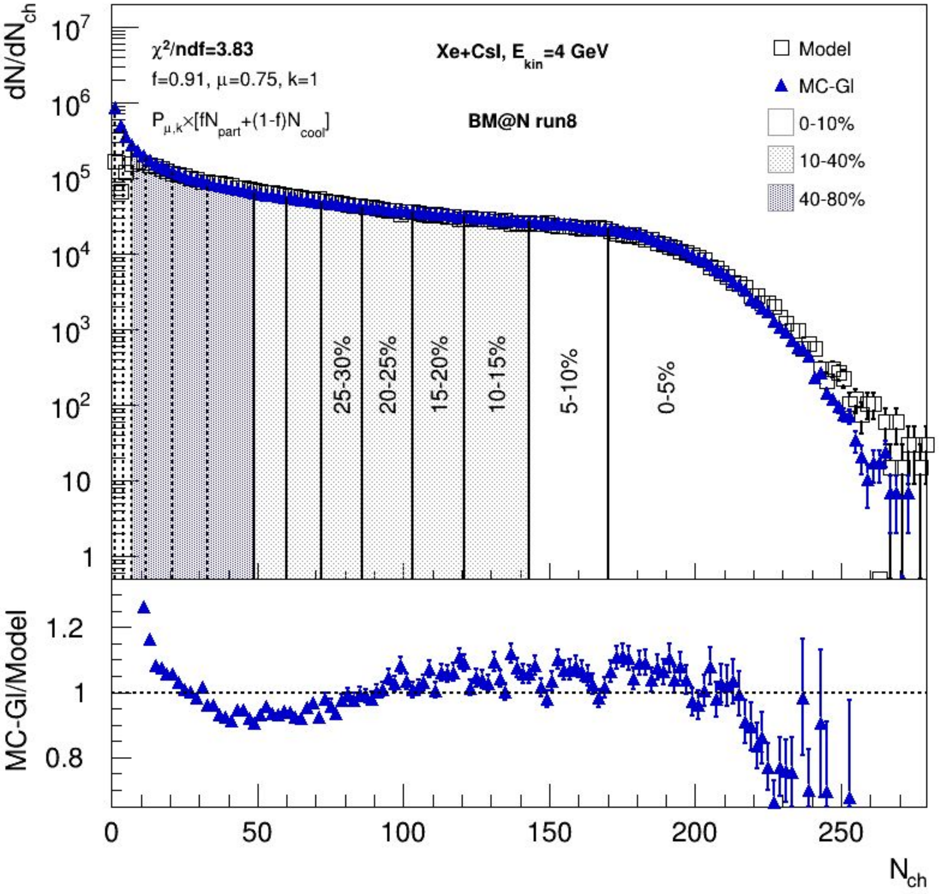


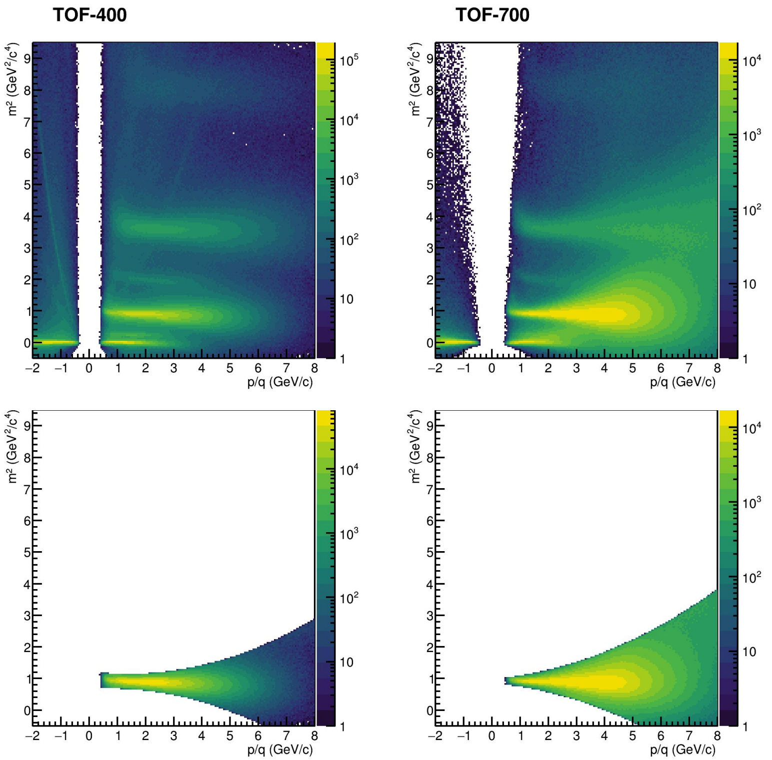
Good agreement with MC data

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



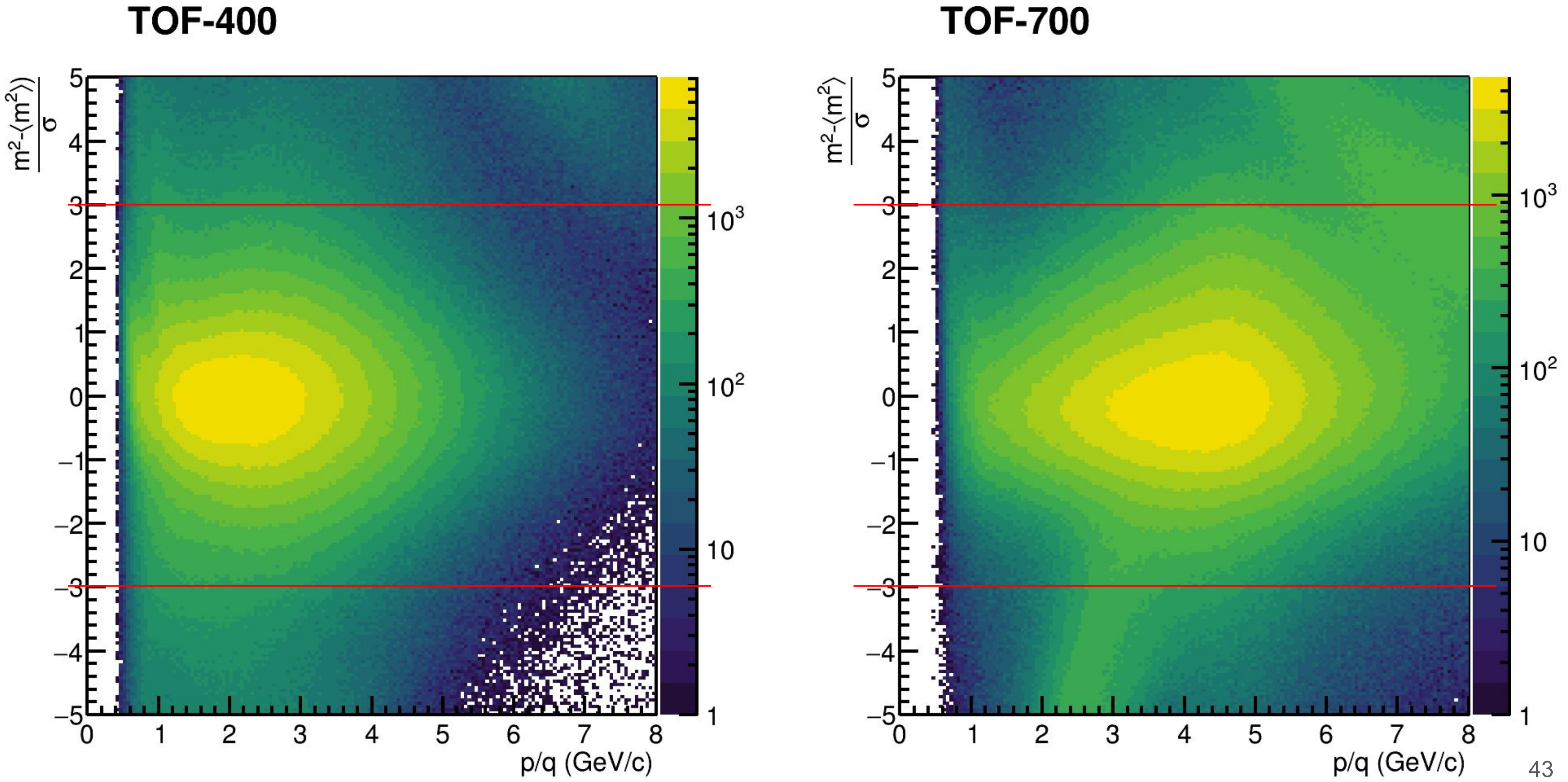
Centrality and particle selection



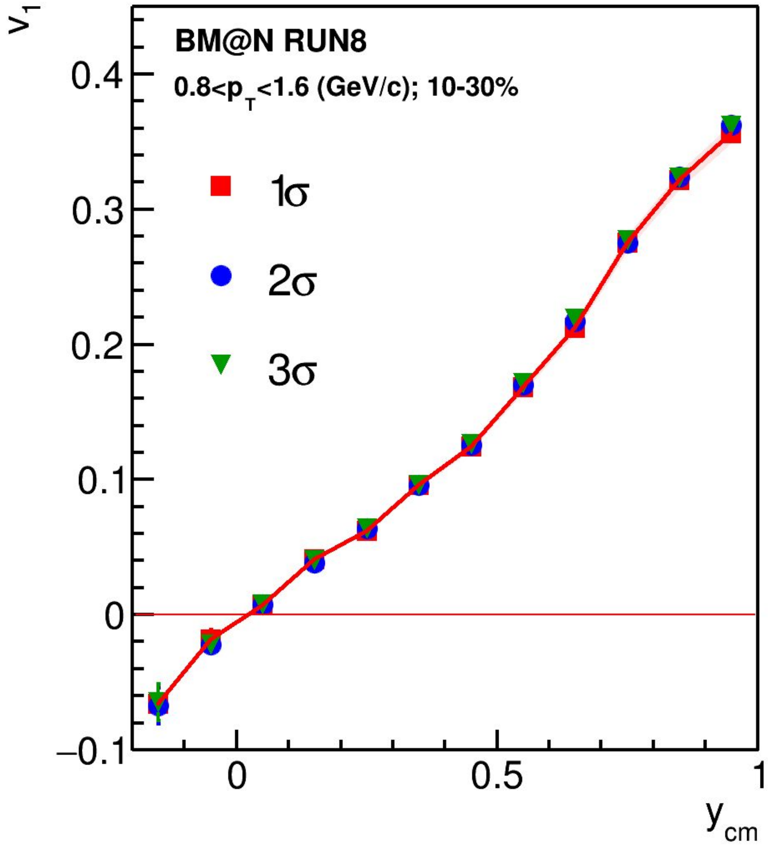


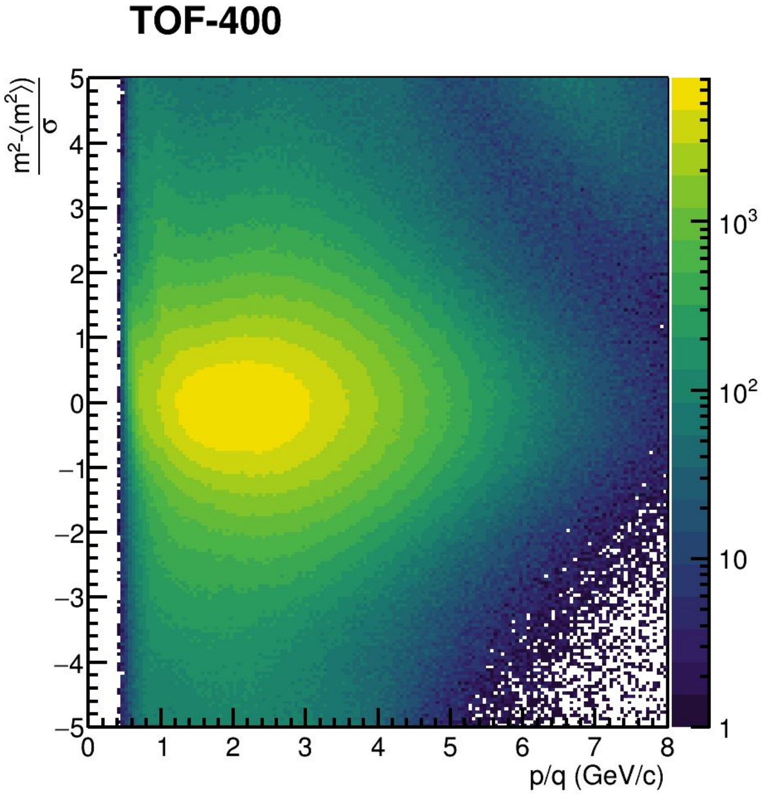
- Half of the recent VF production was analysed
- Event selection criteria (~100M events selected)
    - CCT2 trigger
    - Pile-up cut
    - Number tracks for vertex > 1
- Track selection criteria : $\chi^2 < 5$; $M_p^2 - 3\sigma < m^2 < M_p^2 + 3\sigma$; Nhits > 5

Proton N-sigma distributions



Systematics due to identification and tracking





The systematics is below 2%