First results and perspectives of the anisotropic flow measurements at the BM@N experiment

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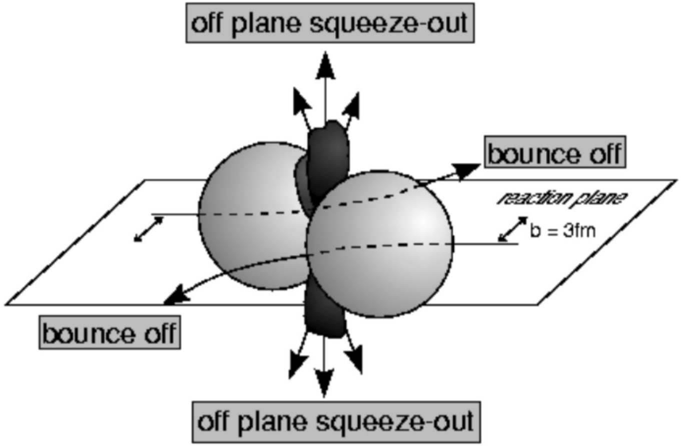
Workshop on physics performance studies at NICA (NICA-2024)
27/11/2024

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:

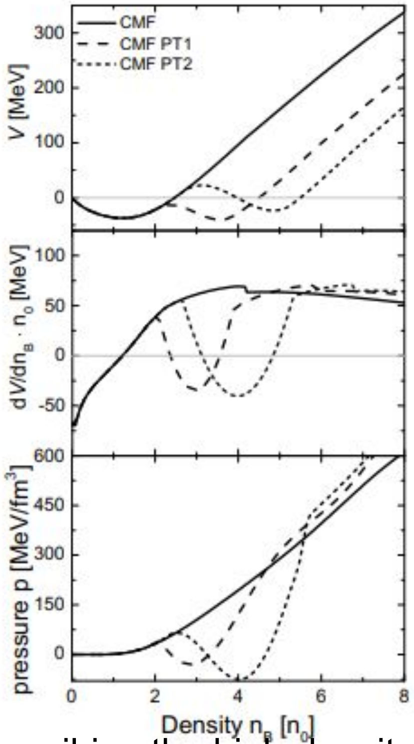
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right] \rangle$$

Anisotropic flow is sensitive to:

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

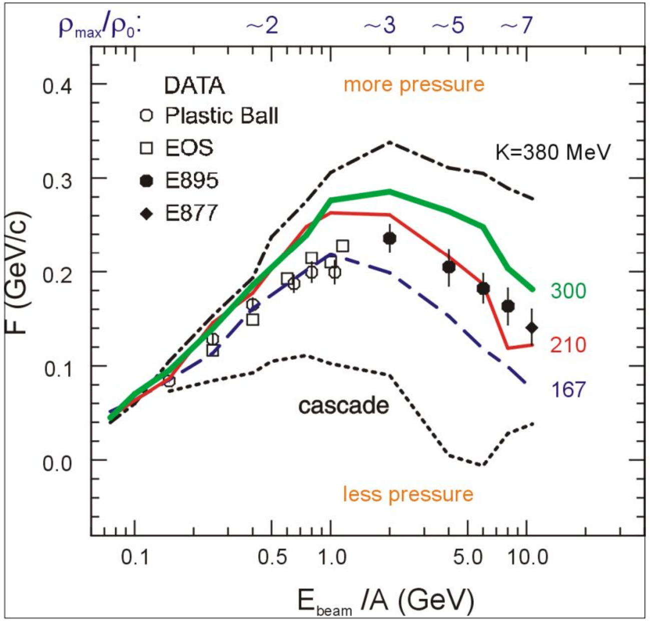
v_n as a function of collision energy

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

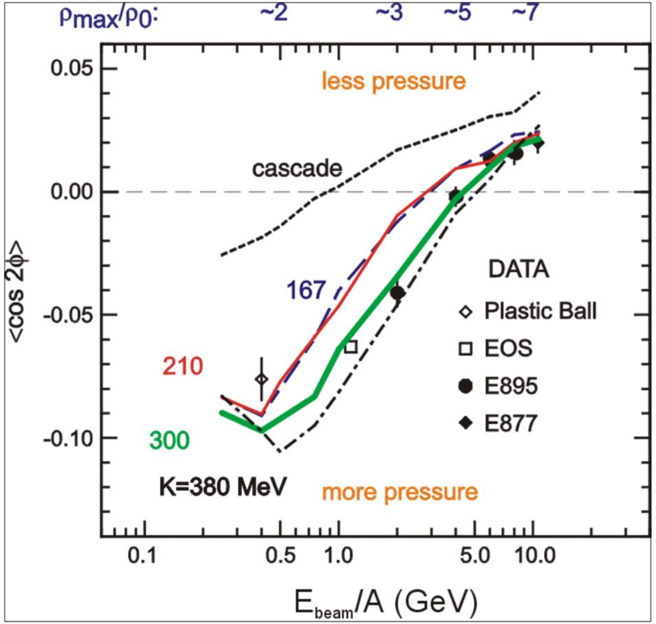


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests softer EOS



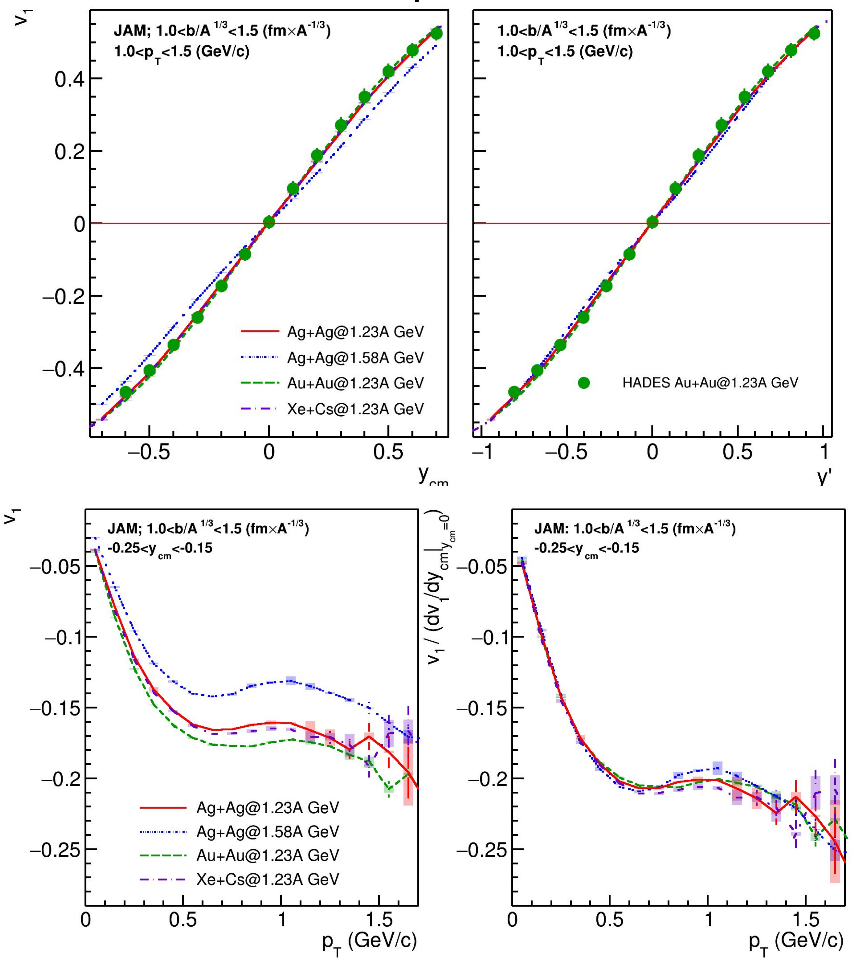
v_2 suggests harder EOS



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

Discrepancy is probably due to non-flow correlations

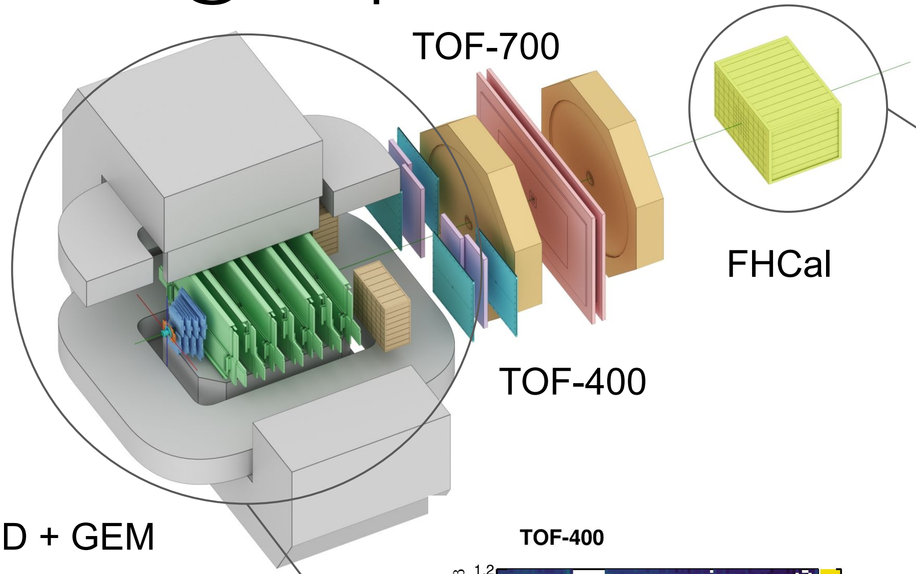
HADES: dv_1/dy scaling with collision energy and system size

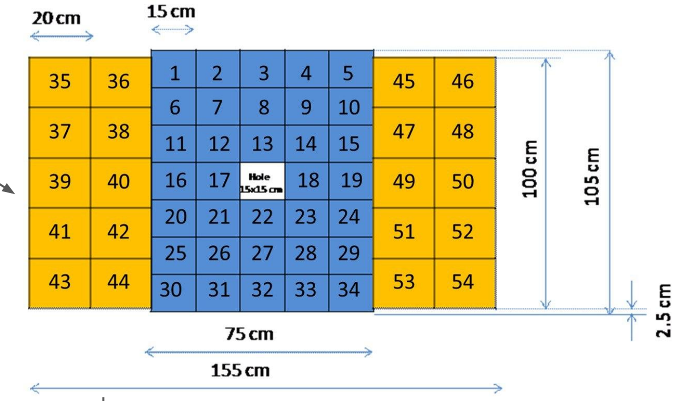


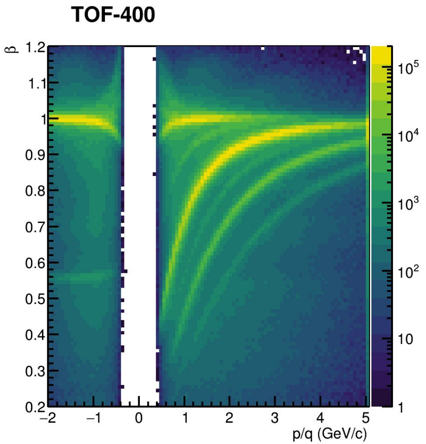
- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments(e.g. STAR-FXT Au+Au

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

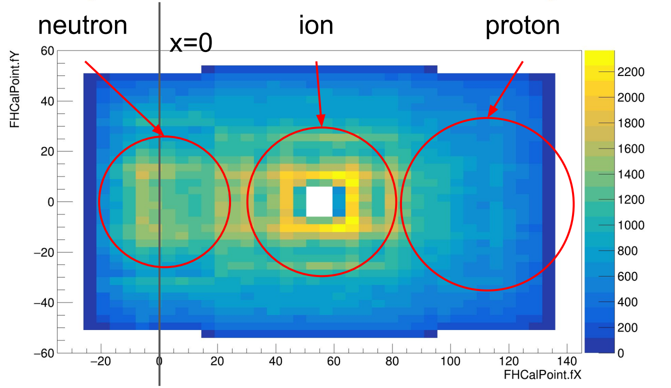
The BM@N experiment in Xe+CsI at 3.8A GeV run







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:

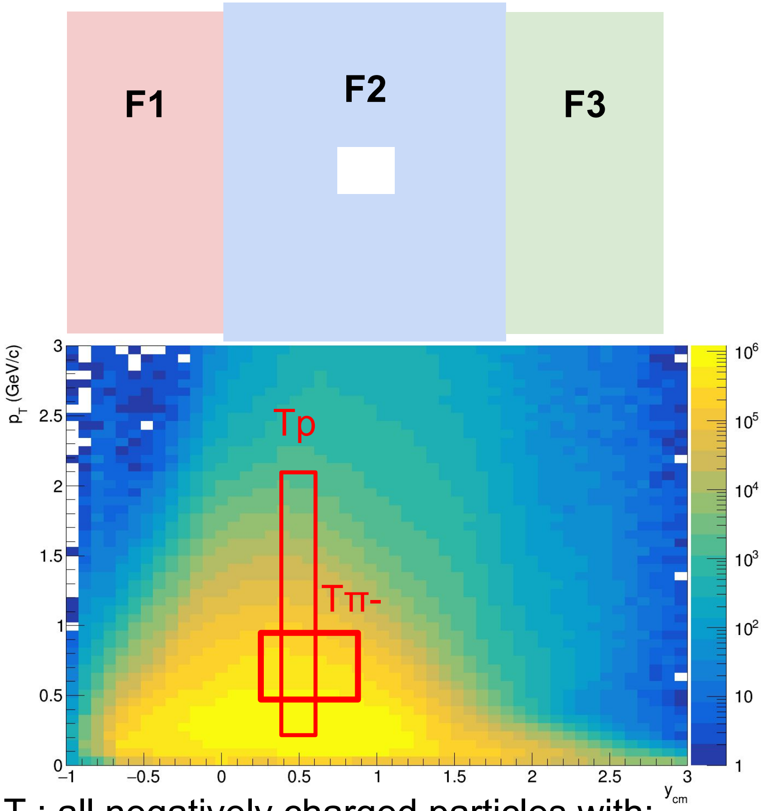
$$u_n = e^{in\phi}$$

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:

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

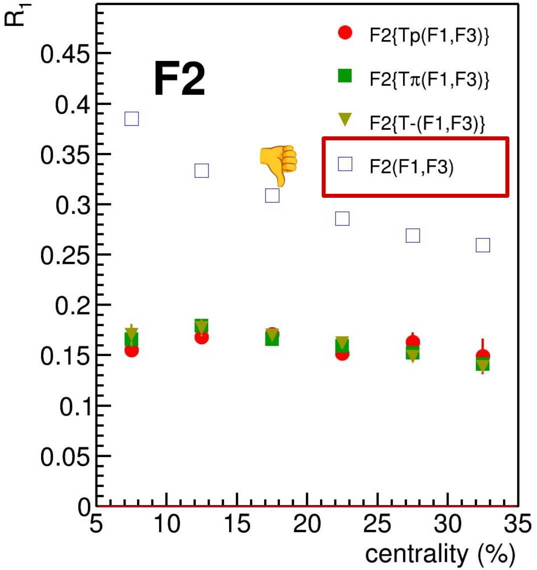
Where R_1 is the resolution correction factor

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

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



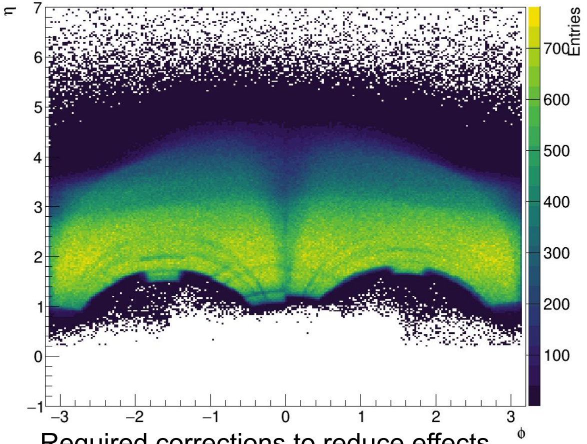
Symbol "F2{Tp}(F1,F3)" means R_1 calculated via (4S resolution):

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

Performance Analysis

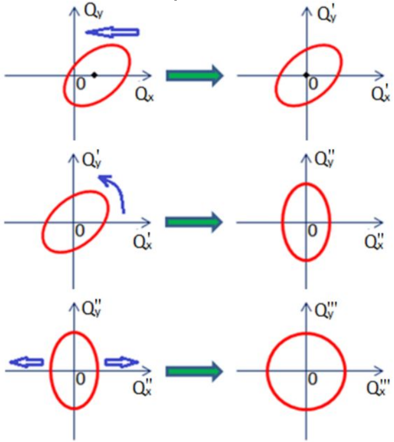
Azimuthal asymmetry of the BM@N acceptance

φ-η yield of protons

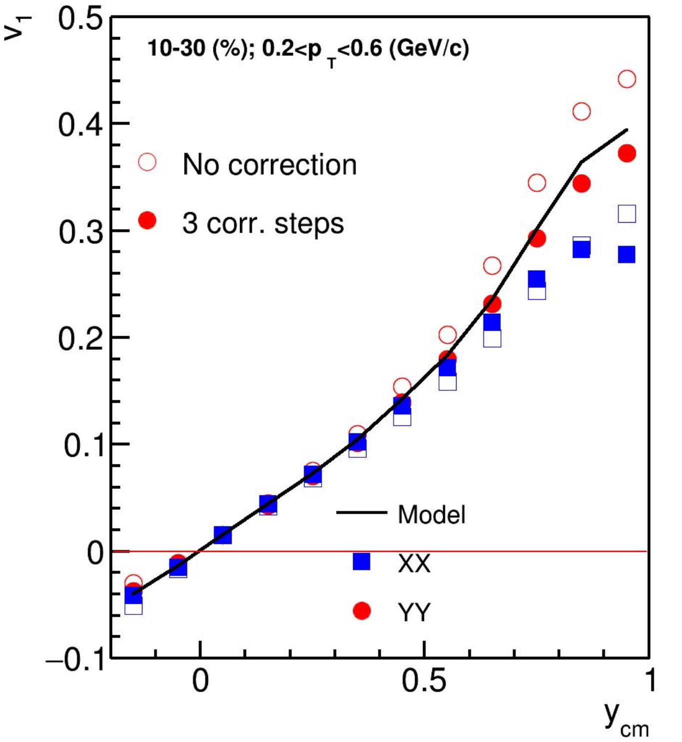


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

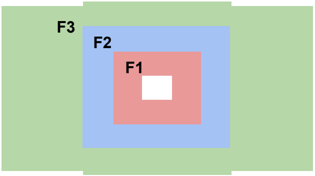


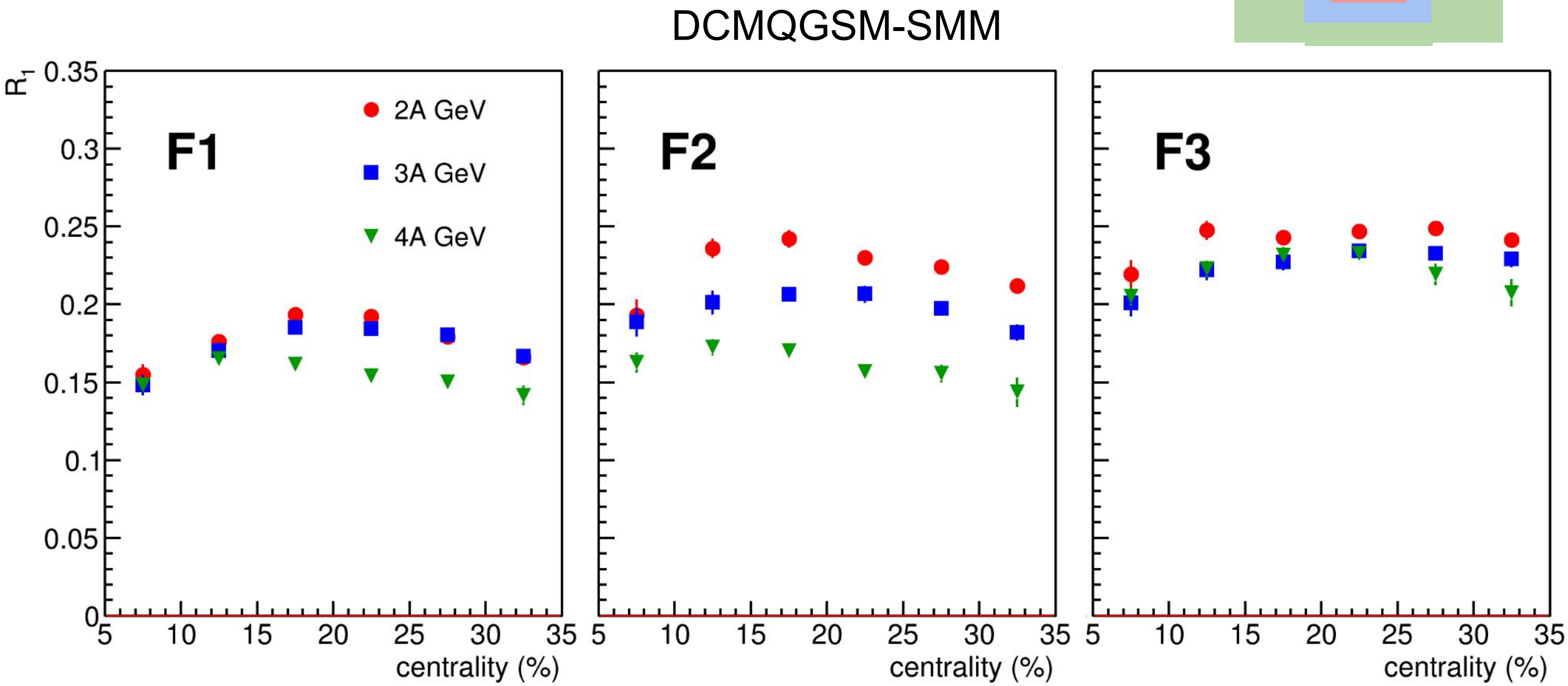
Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



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

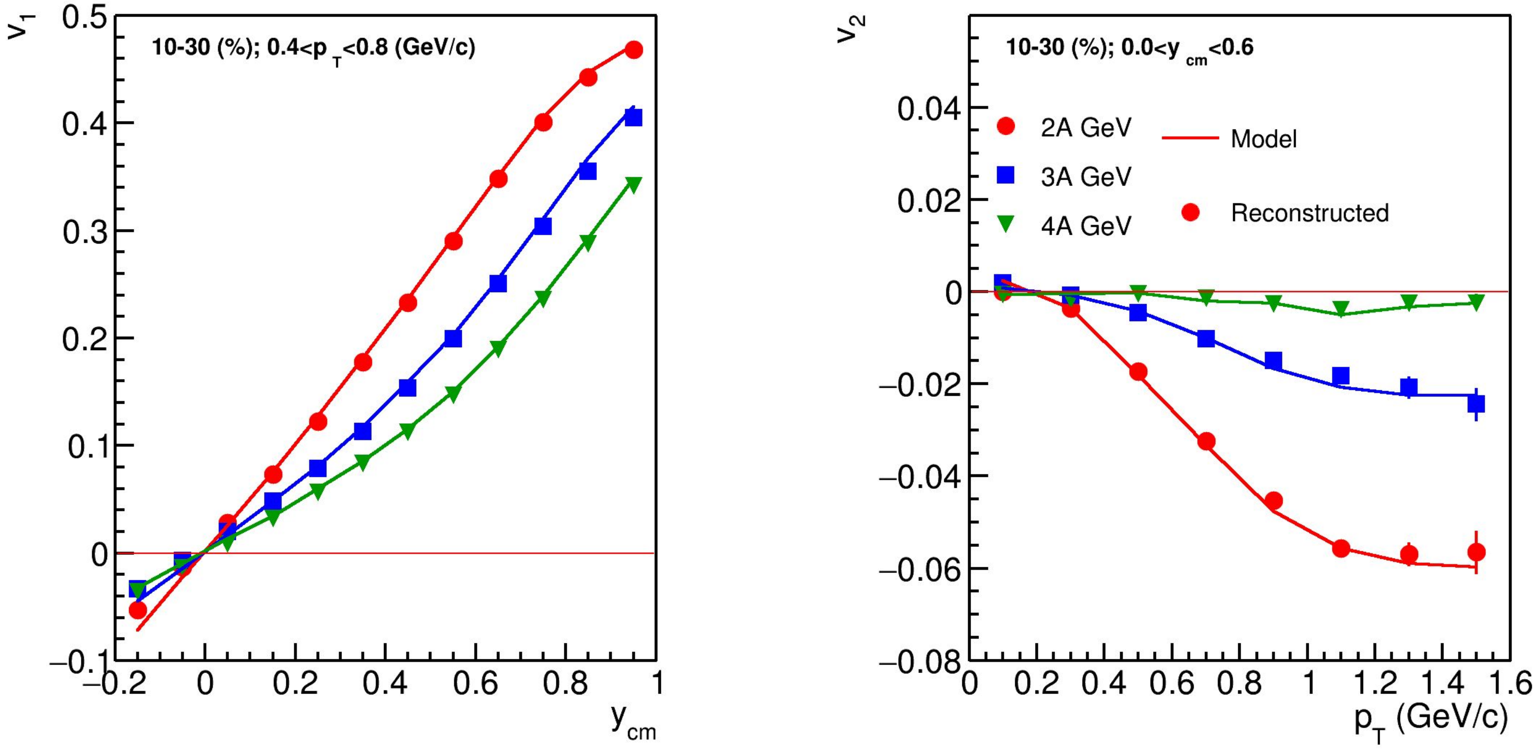
Performance study: R1





Resolution is lower for higher energies due to lower v_1

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

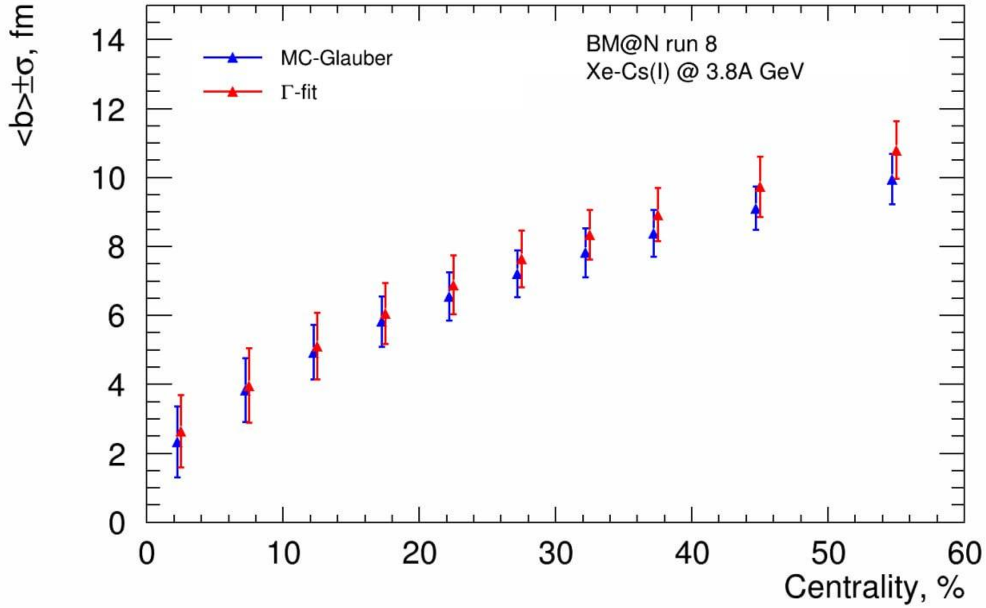


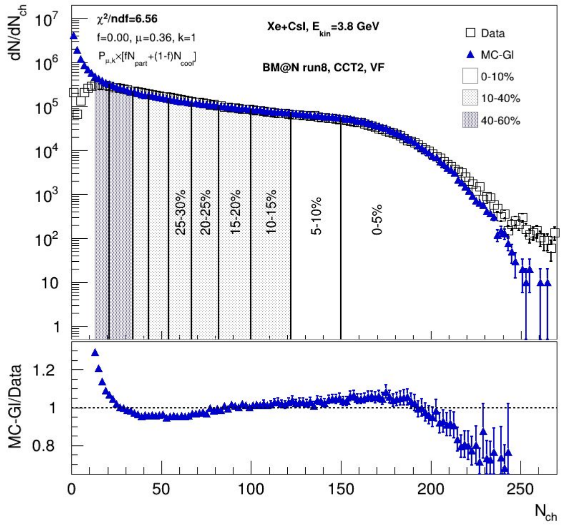
- Good agreement between reconstructed and pure model data for all three energies

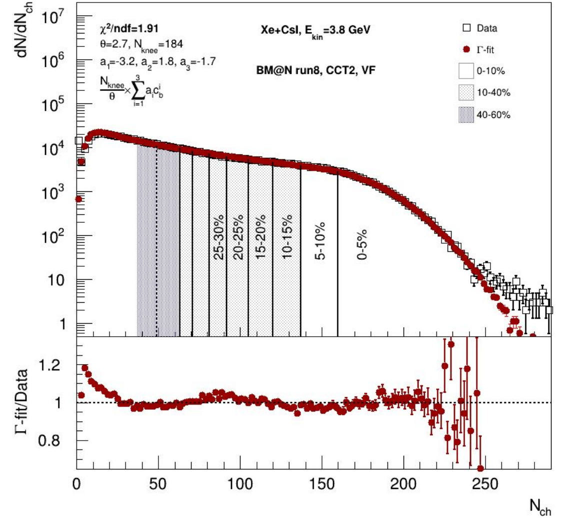
Data Analysis

Centrality determination methods

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

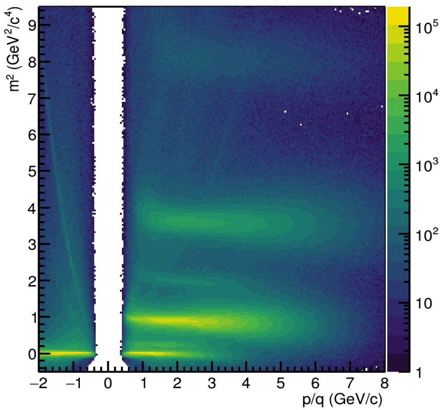


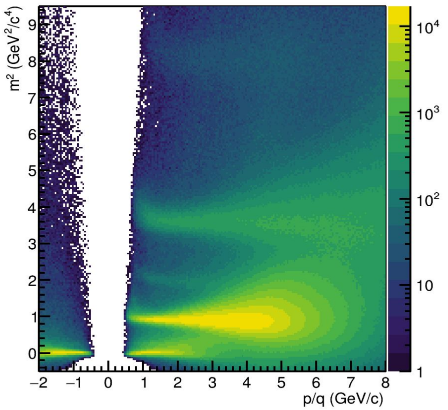


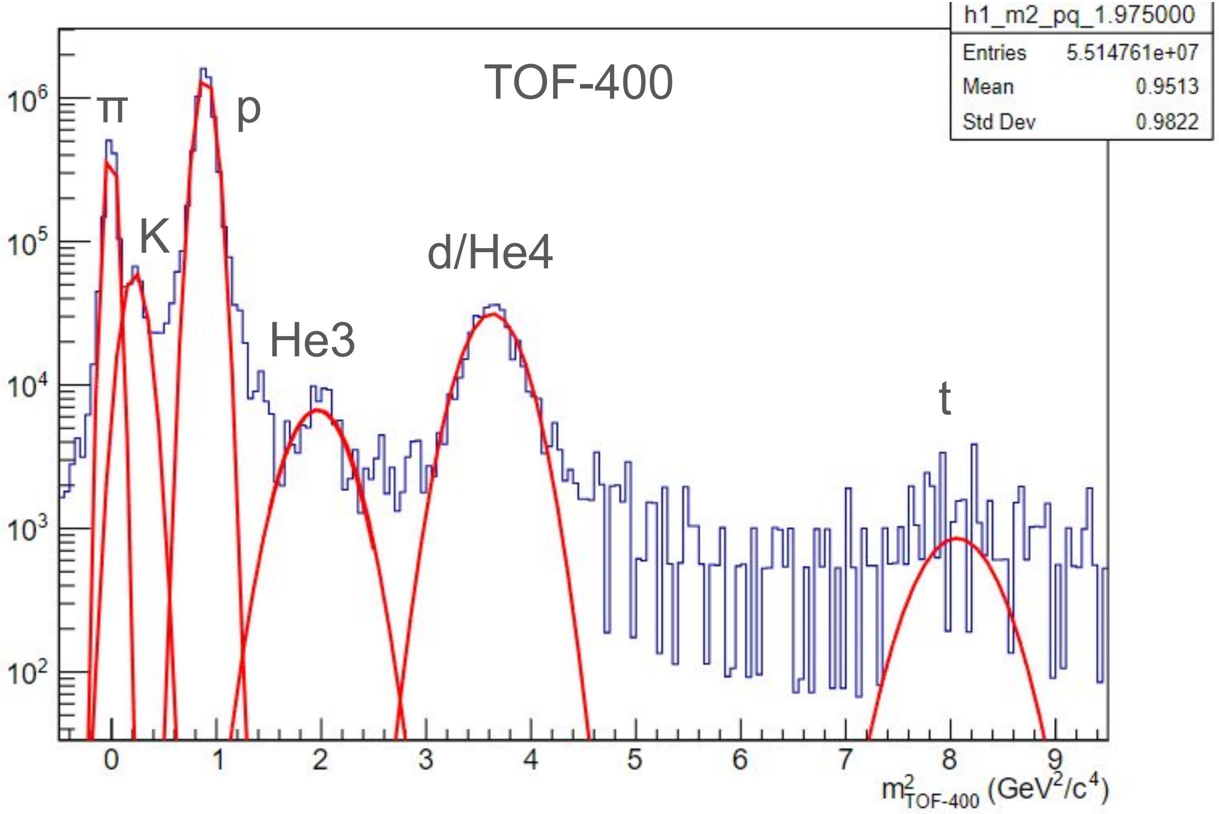


Two methods for centrality determination: MC-Glauber and Γ-fit method are in a good agreement

Particle identification

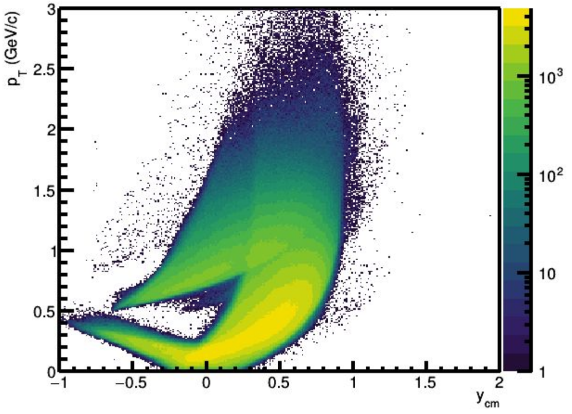




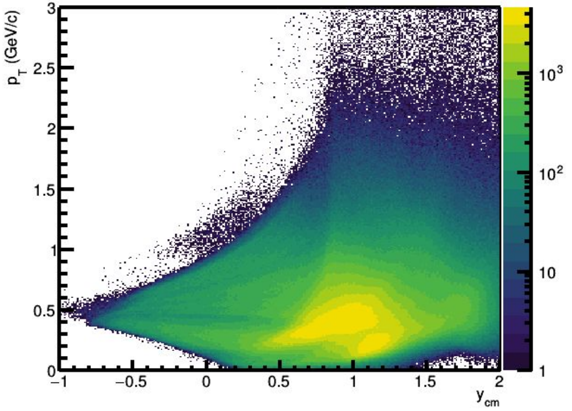


Proton p_T-y acceptance

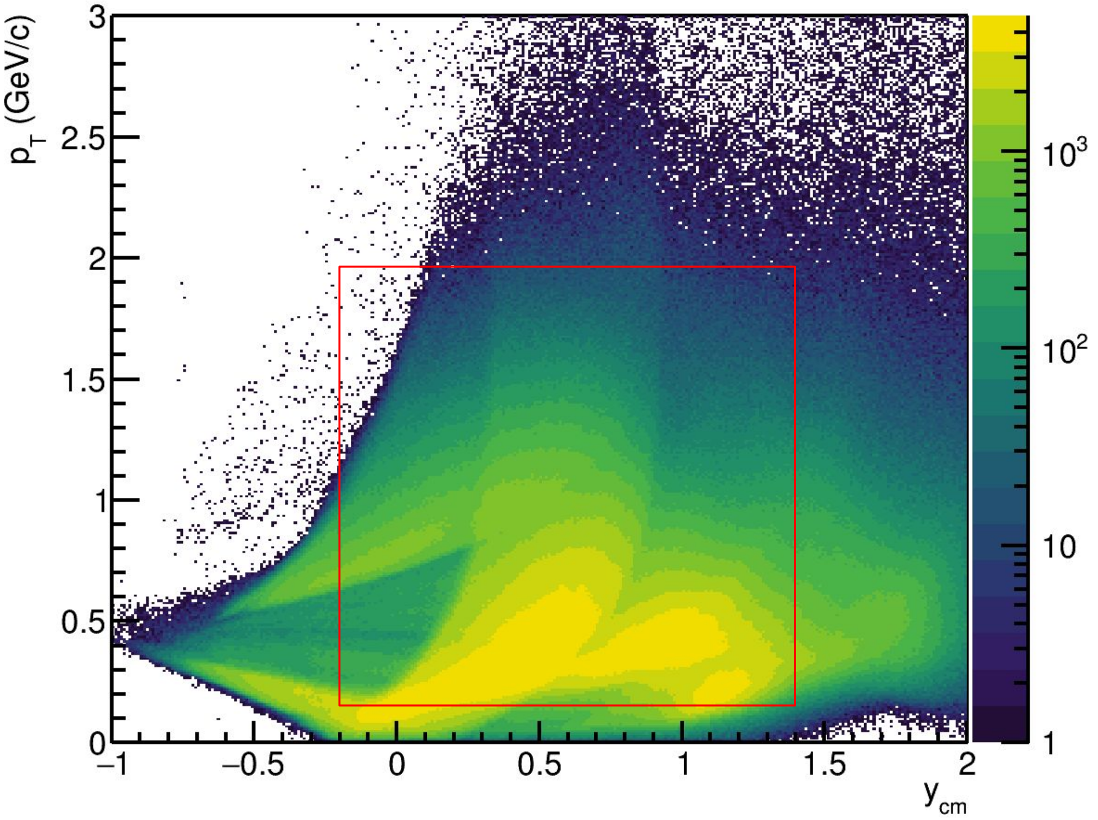
TOF-400



TOF-700

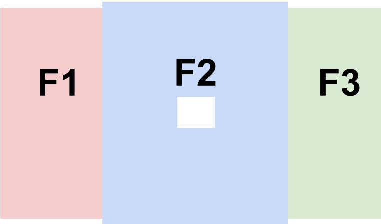


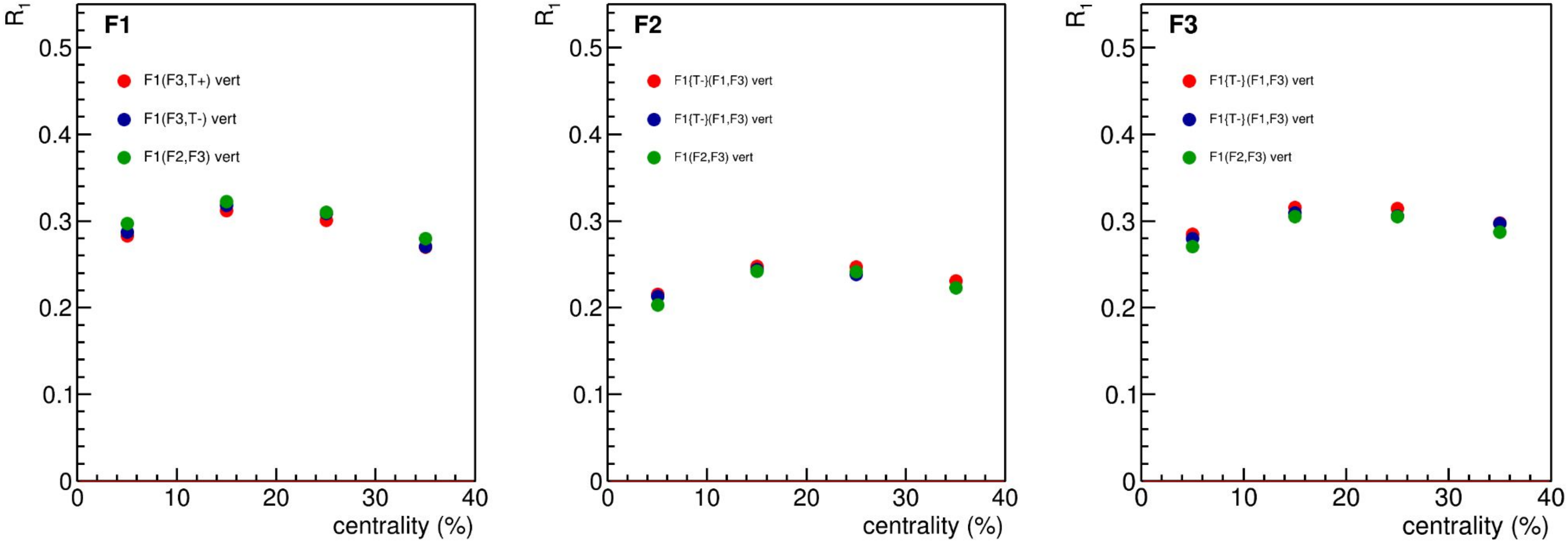
Combined



Data is corrected for p_T-y acceptance

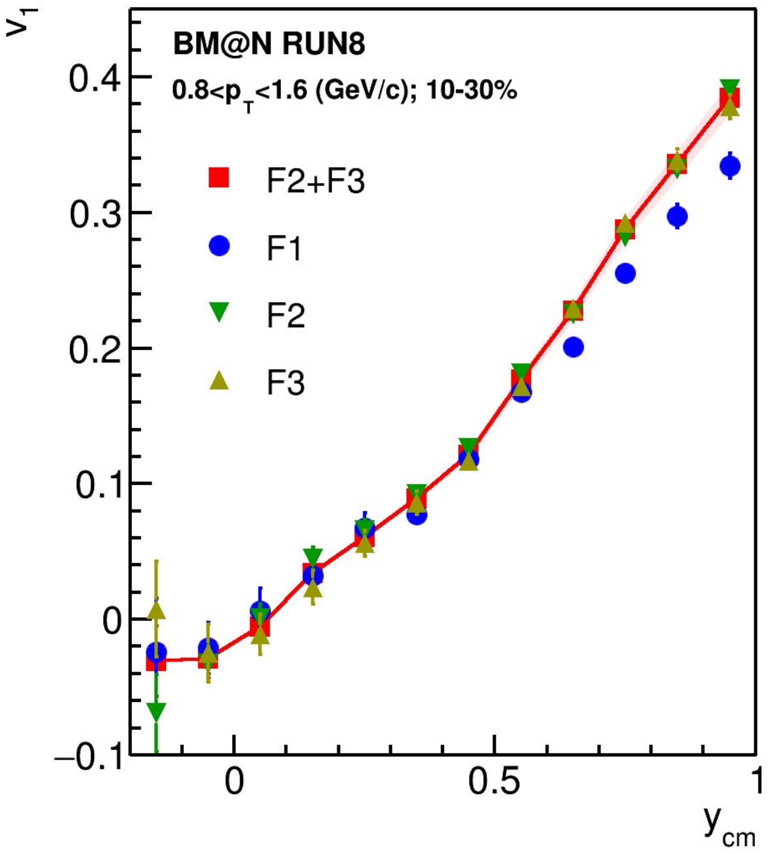
DATA: R_1 in Xe+Cs(I) collisions

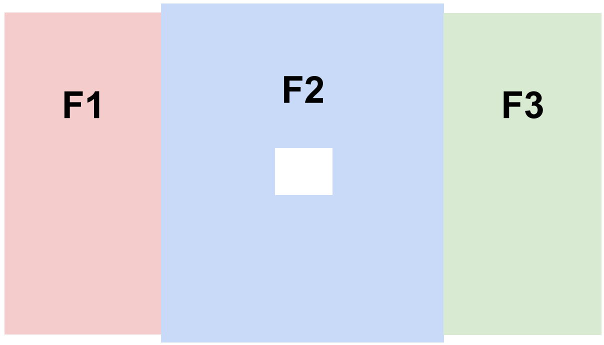




All the estimations for symmetry plane resolutions are in a good agreement

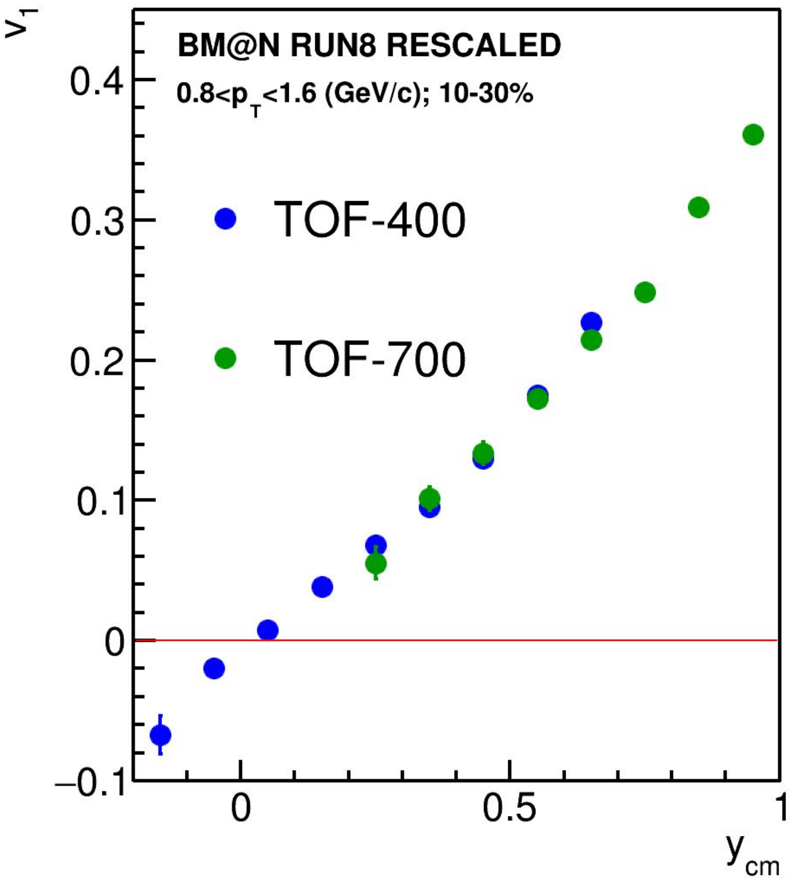
Systematics due to symmetry plane estimation (non-flow)

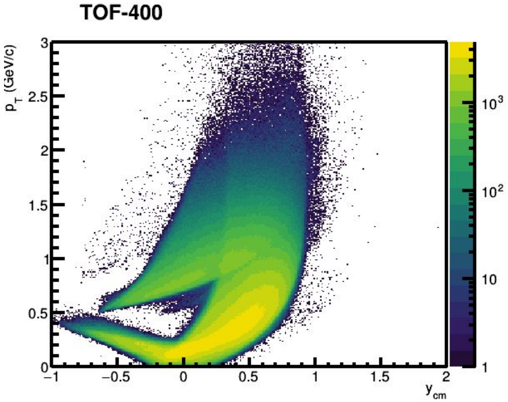


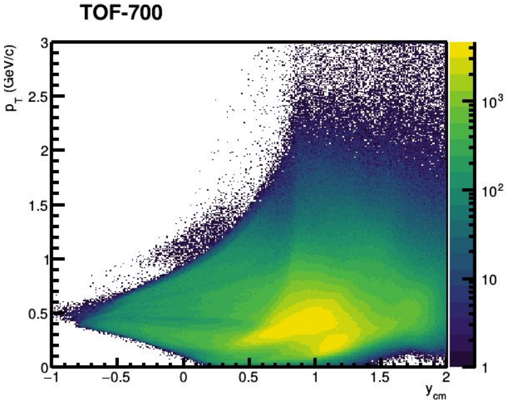


The systematics is below 3%

Comparison of the TOF performances

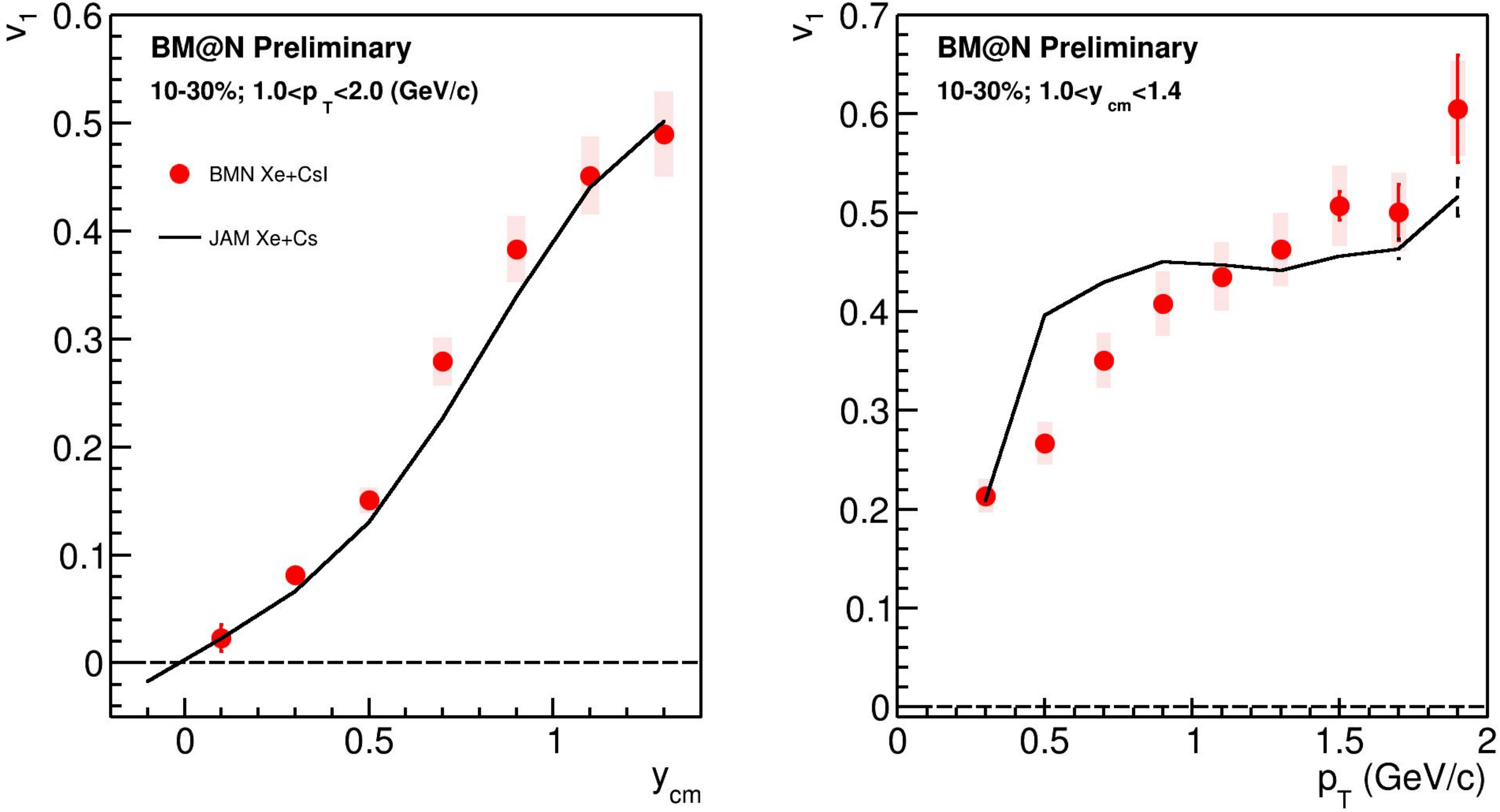






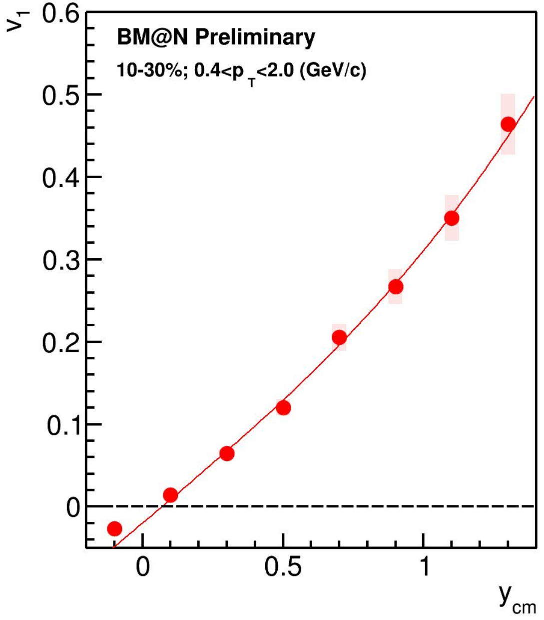
The results from TOF-400 and TOF-700 are in a good agreement

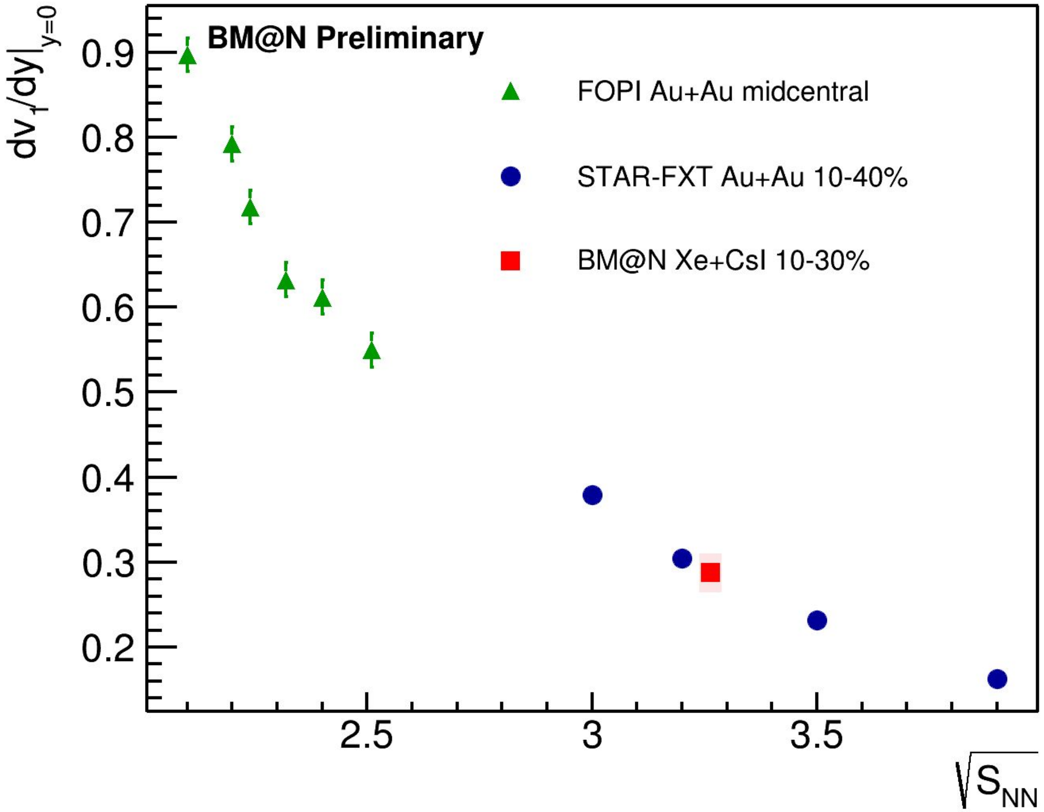
v_1 as a function of pT and y



JAM model describes $v_1(y)$ well

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

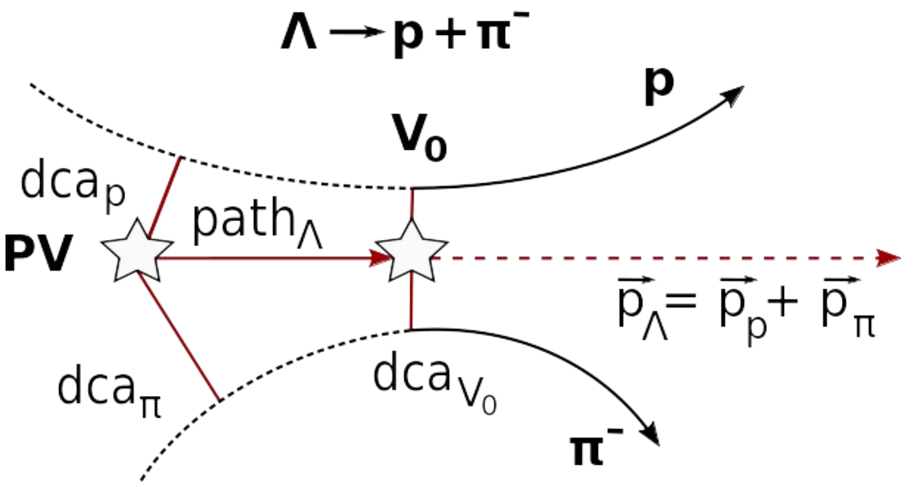


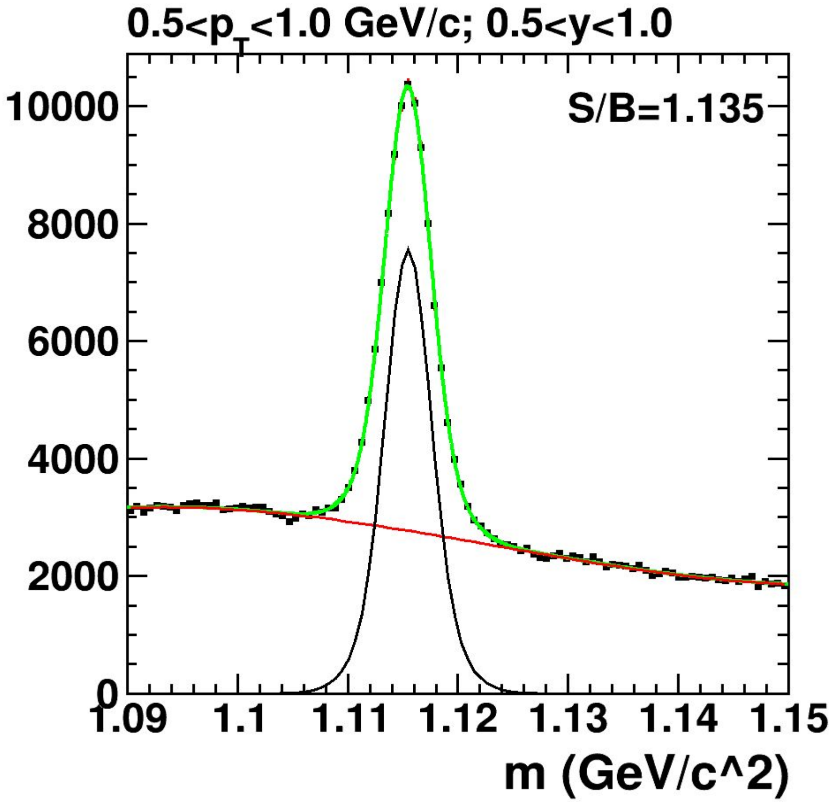


dv_1/dy is in a good agreement with the world data

Λ-hyperon reconstruction

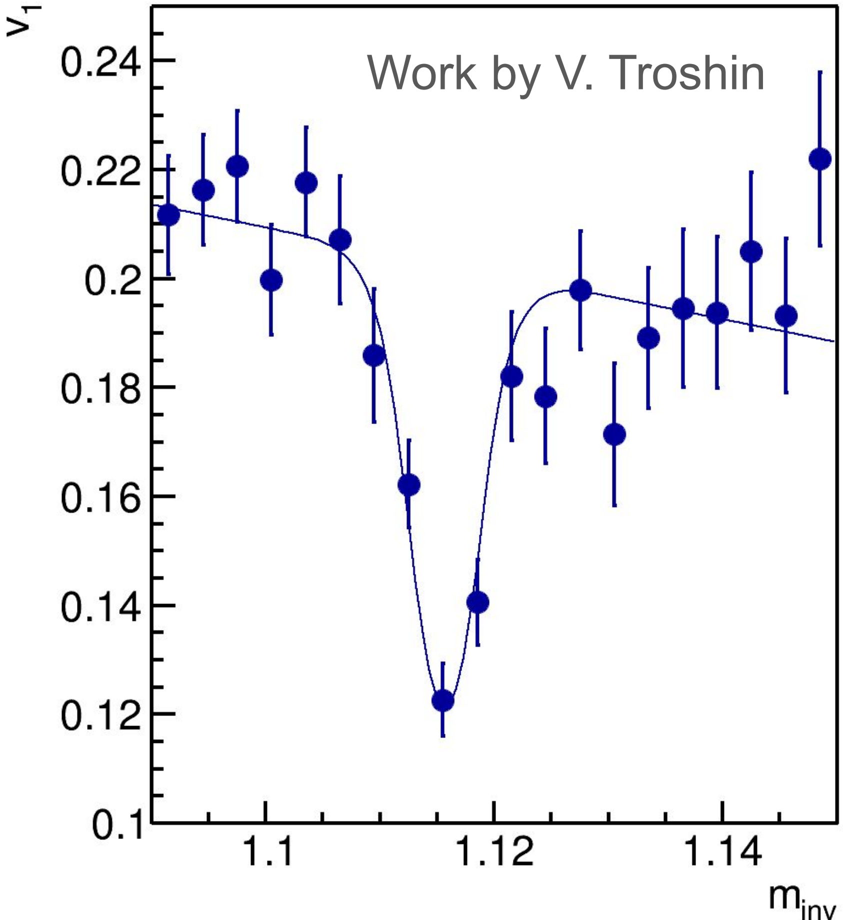
Work by V. Troshin





Λ-hyperon reconstruction is carried out using the KFParticle package tested in STAR, ALICE, NA61/SHINE and CBM

v_1 of Λ-hyperons with invariant mass fit method



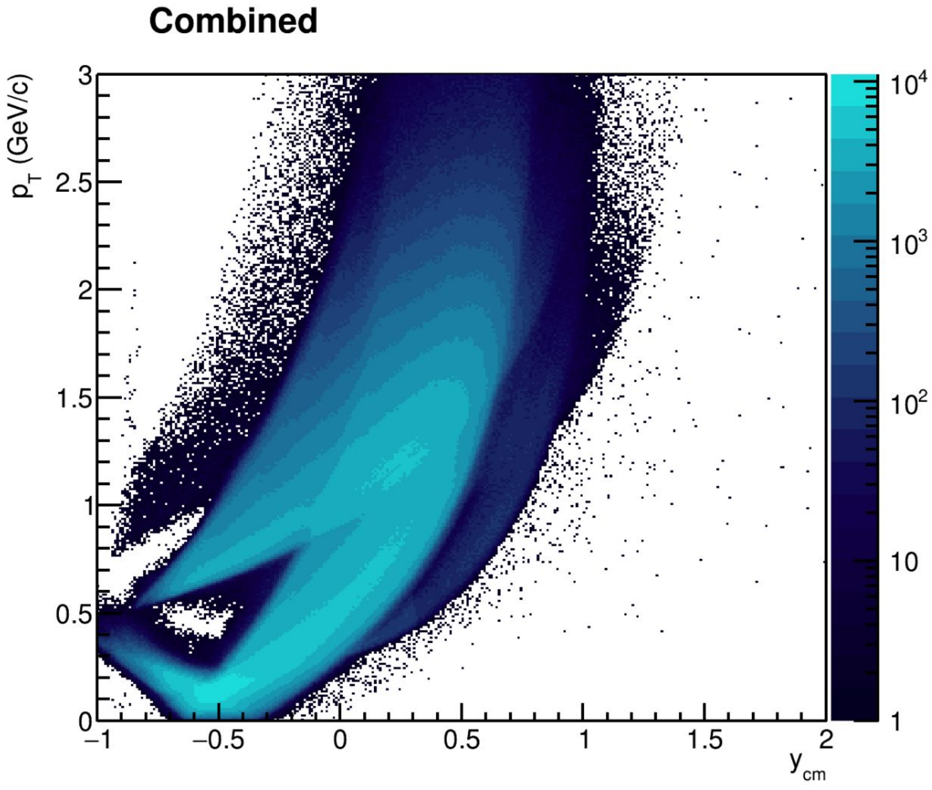
Directed flow for Λ-candidates is measured as a function of m_{inv}

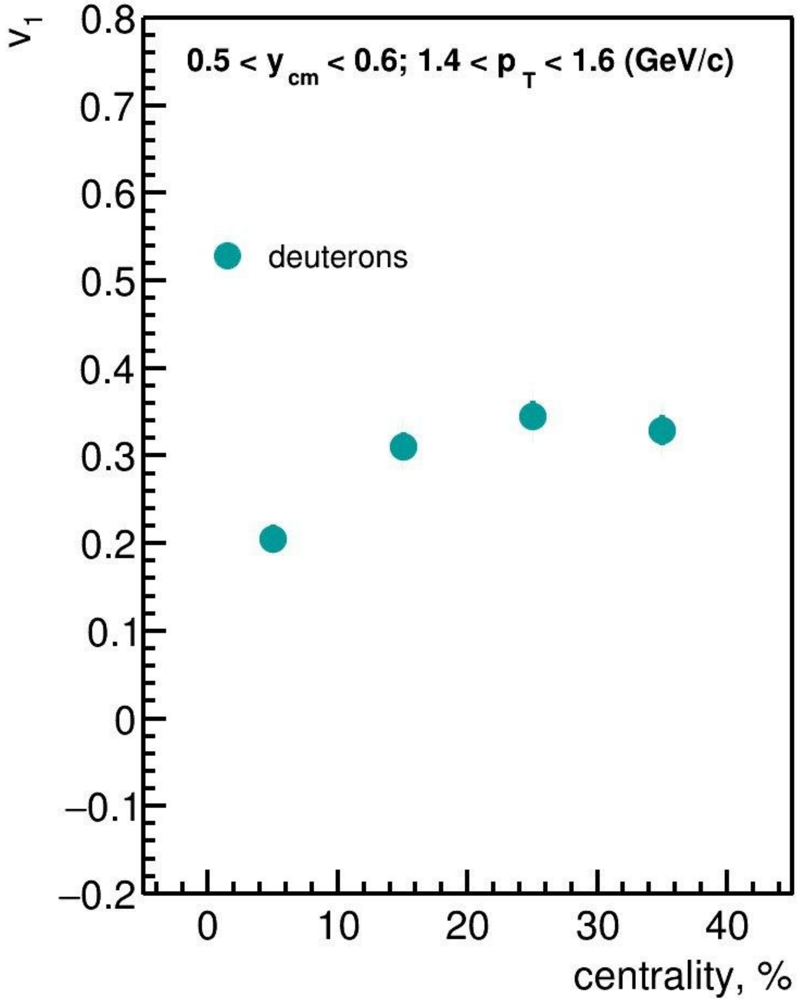
Then $v_1(m_{inv})$ is fitted with a function:

$$v_1^{S+B} = v_1^S \frac{N^S}{N^S + N^B} + v_1^B \frac{N^B}{N^S + N^B}$$

Directed flow of deuterons

Work by I. Zhavoronkova



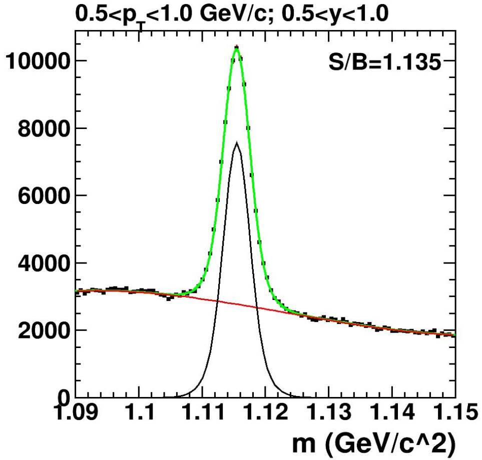


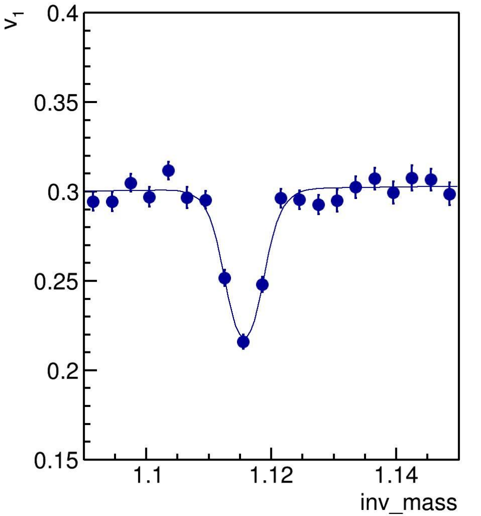
Summary

- 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

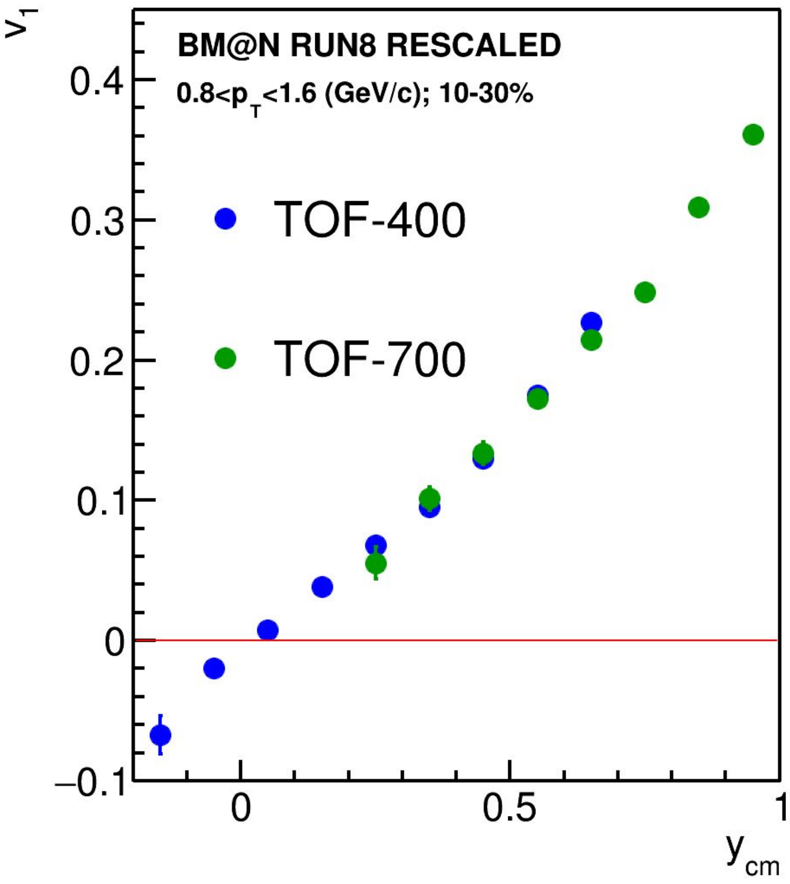
Outlook

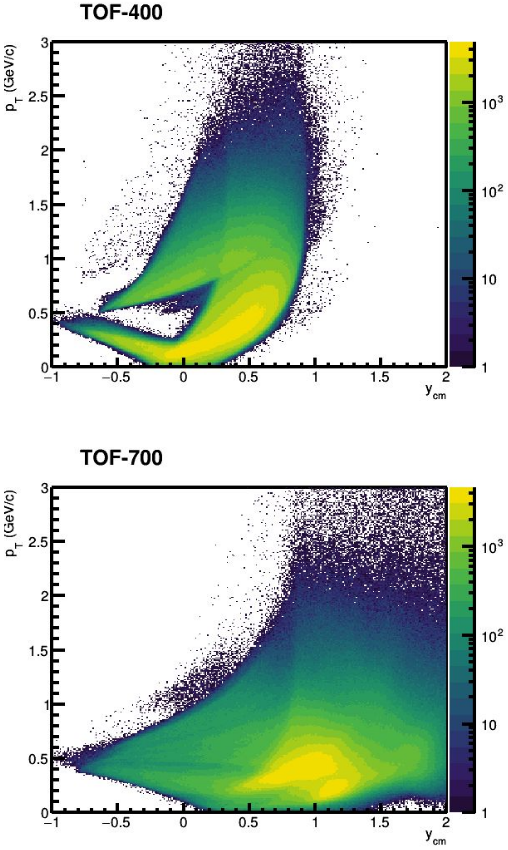
- 2025-2026 we expect the Beam-Energy scan program (2A, 3A, 4A GeV)
- The results for higher-harmonics flow is in the process of analysis
- The analysis for Λ v_1 is undergoing
- Started the analysis for d flow





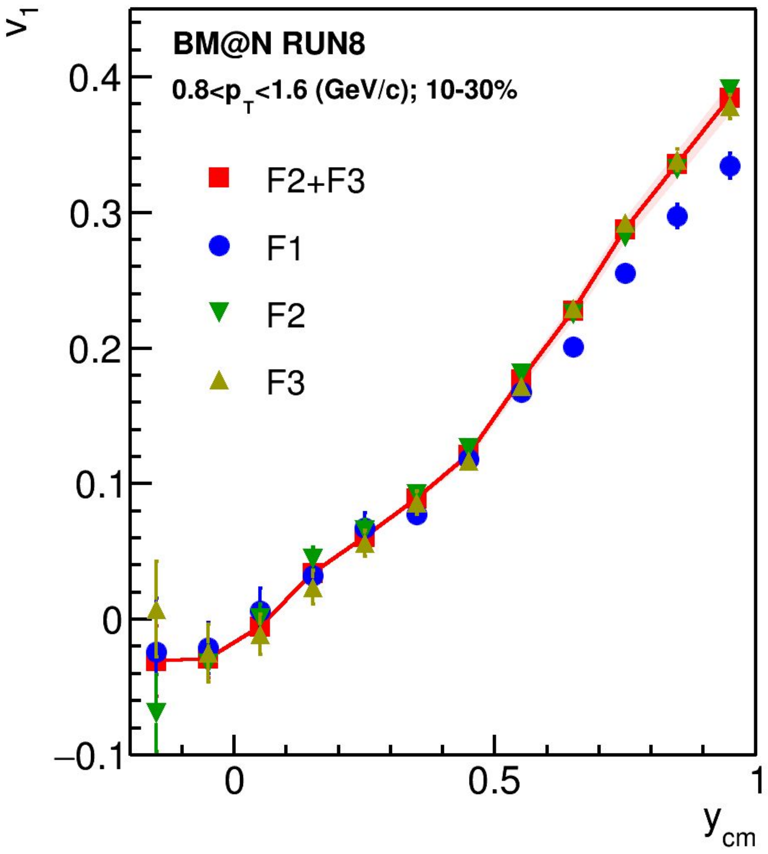
Comparison of the TOF performances

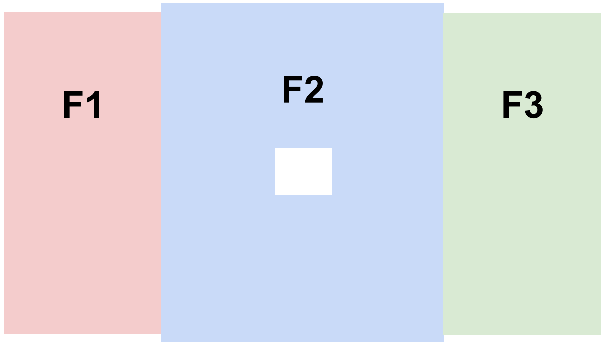




The results from TOF-400 and TOF-700 are in a good agreement

Systematics due to symmetry plane estimation (non-flow)

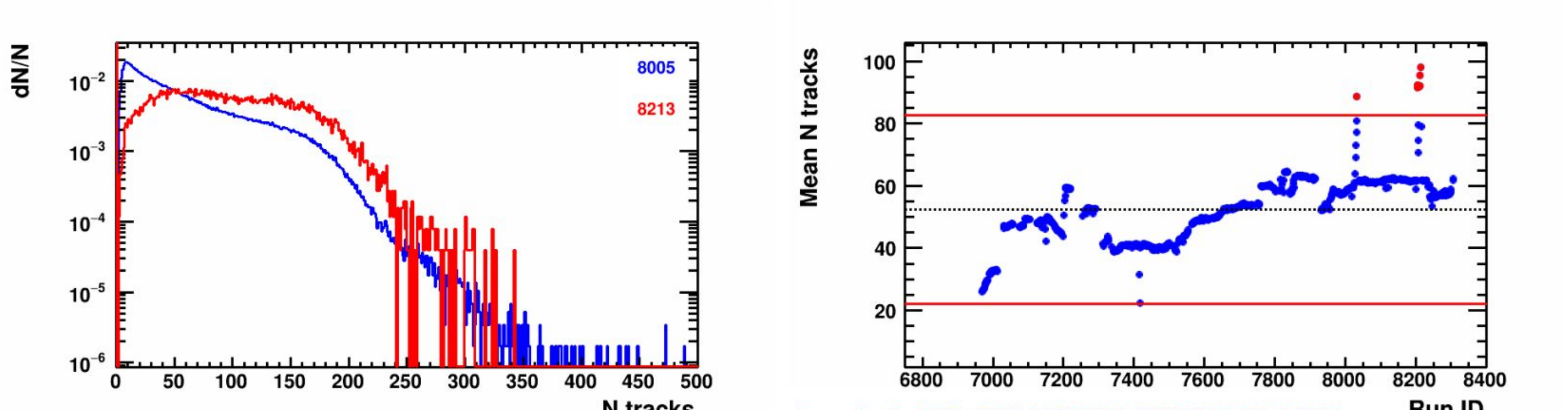




The systematics is below 3%

Backup

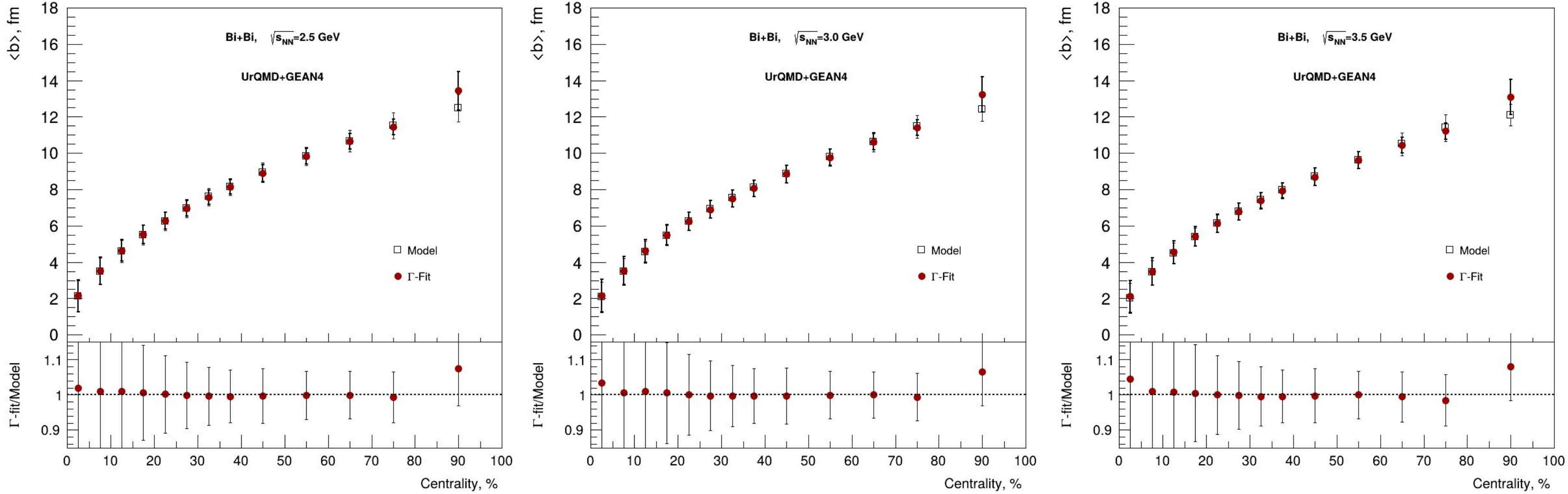
Quality assurance for the recent data



beyond ±3σ: 8033, 8204, 8205, 8209, 8210, 8211, 8212, 8213

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:

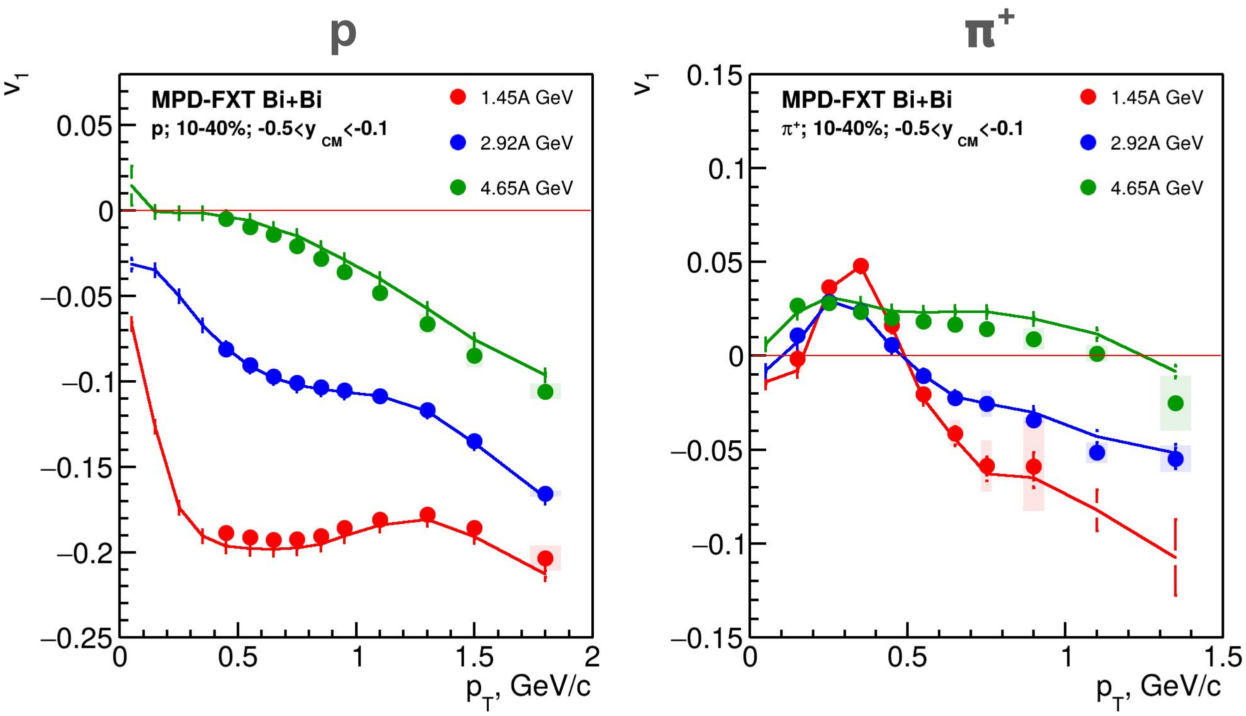
- Nhits>16
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination using inverse Bayes was used

Results: $v_1(p_T)$

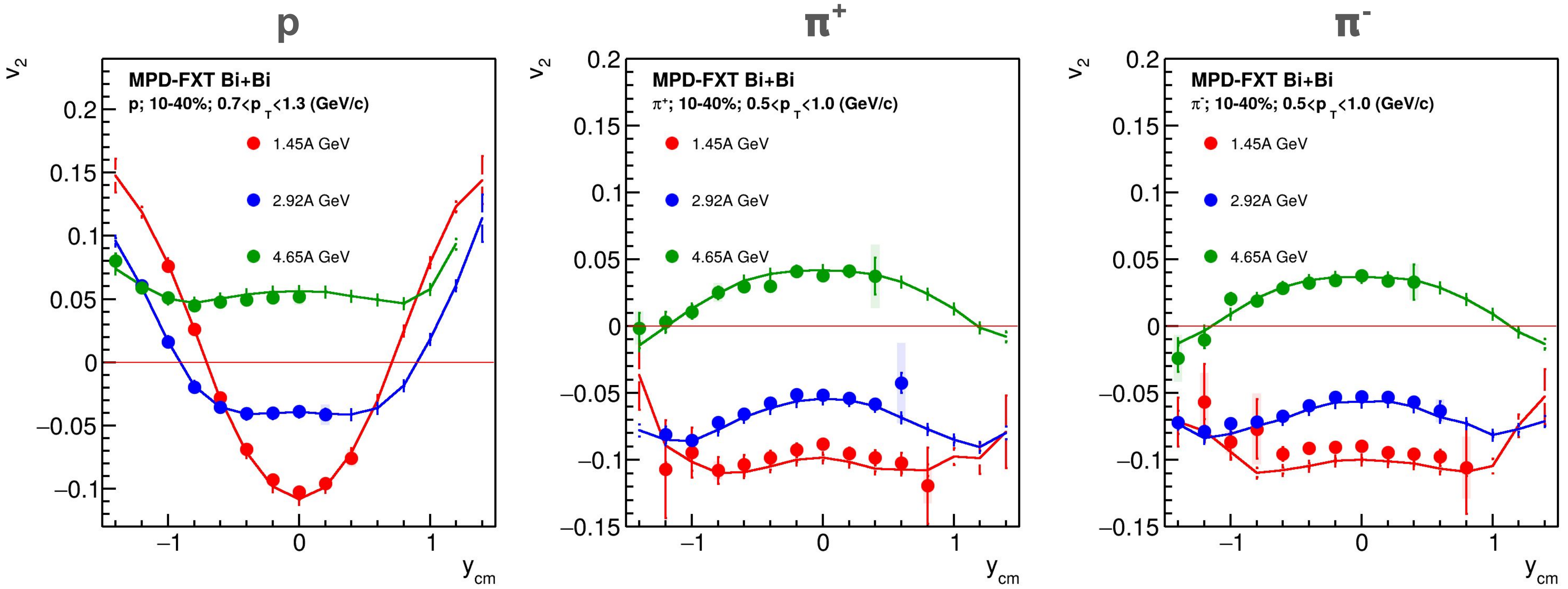
Systematics: xx, yy, F1, F2, F3



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:

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

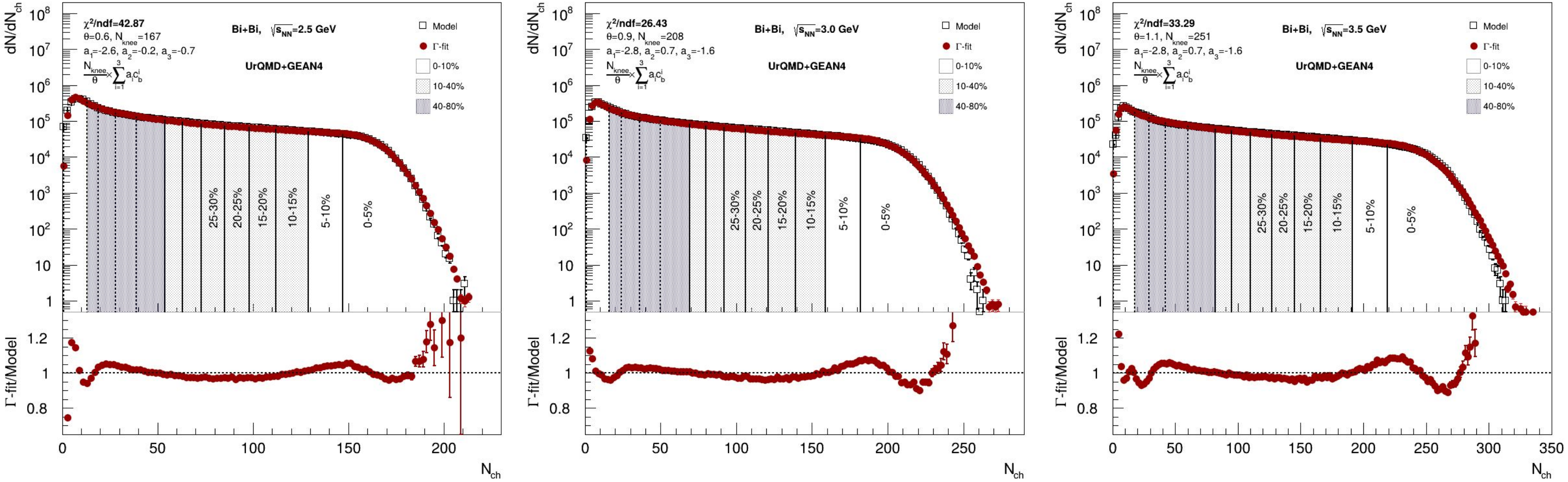
2 main steps of the method:

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:

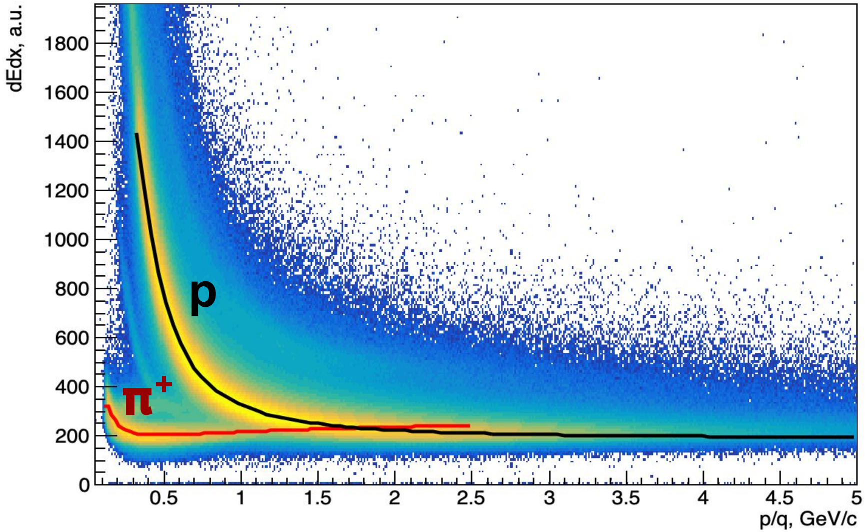
- Nhits>16
- $0 < \eta < 2$

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)



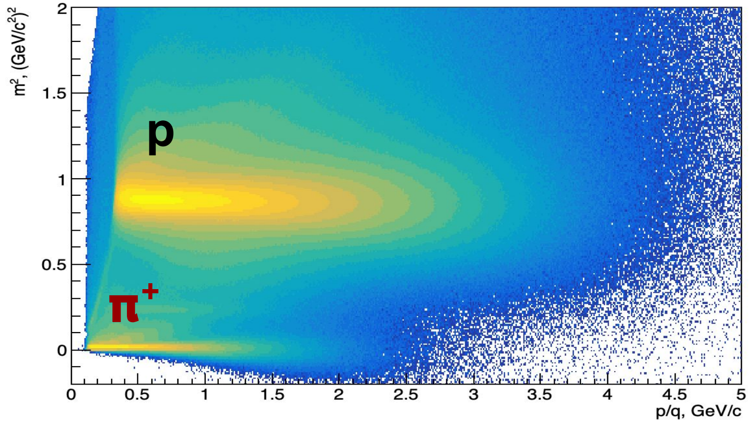
Fit dE/dx distributions with Bethe-Bloch parametrization:

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

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

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)

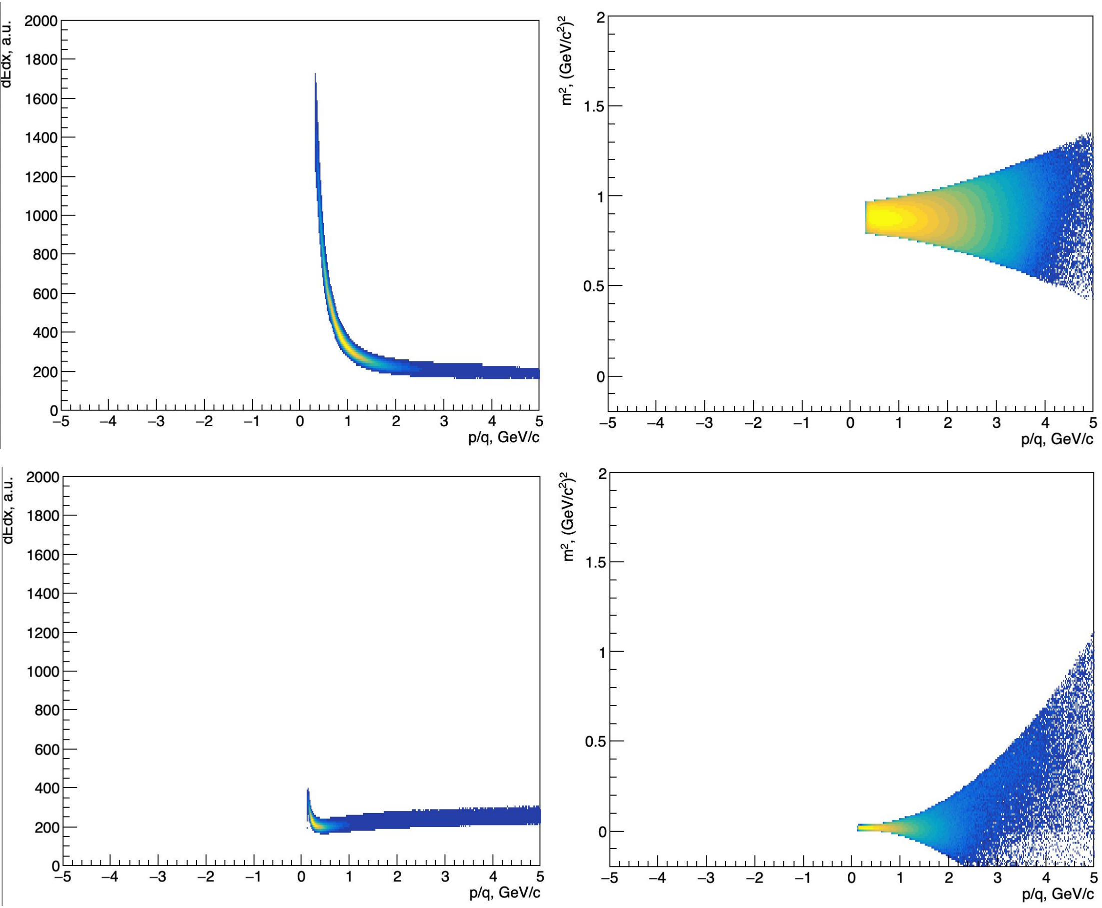


Fit m^2 with gaus in the slices of p/q and get $\sigma_p(m^2)$

(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^+):

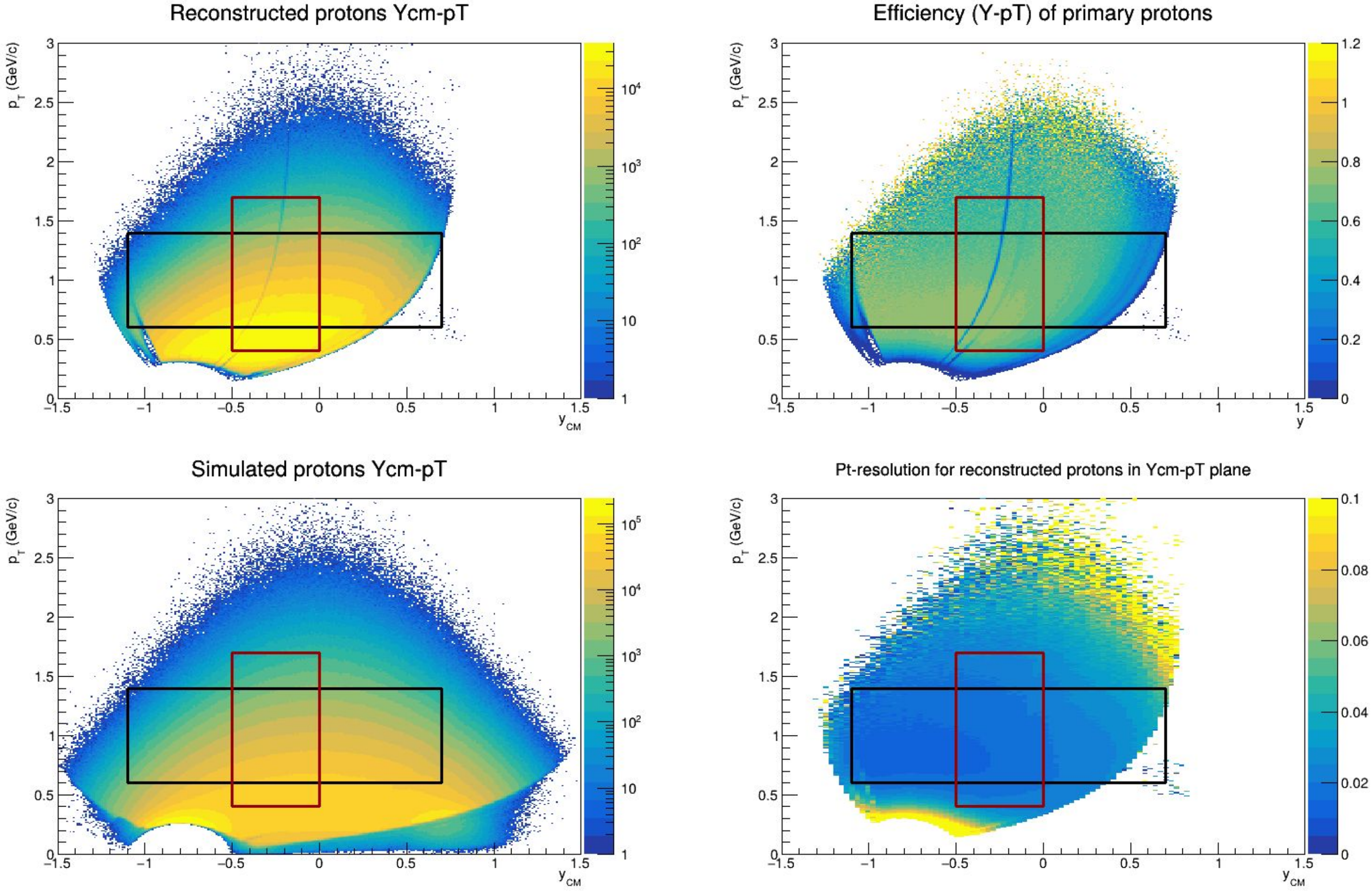
$$\sqrt{x_\pi^2 + y_\pi^2} < 2, \sqrt{x_p^2 + y_p^2} > 3$$

Pions (π^-):

charge<0

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

$$\mathrm{eff} = \frac{\frac{dN}{dy dp_T}(\mathrm{reco})}{\frac{dN}{dy dp_T}(\mathrm{sim})}$$



$$\Delta p_T = \frac{\left|p_T^{\mathrm{reco}} - p_T^{\mathrm{mc}}\right|}{p_T^{\mathrm{mc}}}$$

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:

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

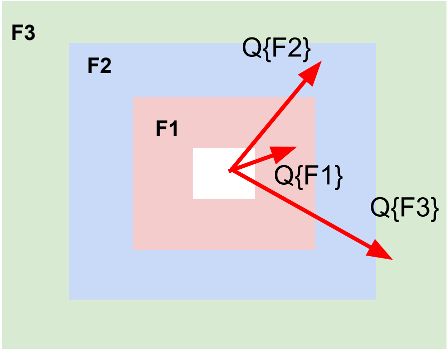
where φ is the azimuthal angle

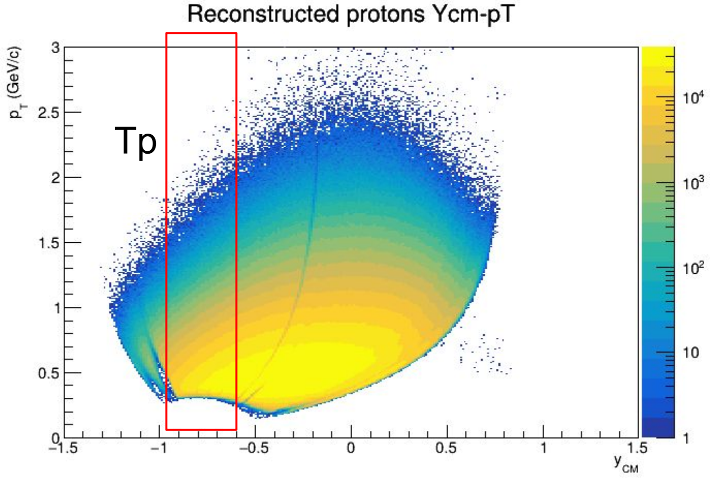
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

Ψ_n^{EP} is the event plane angle

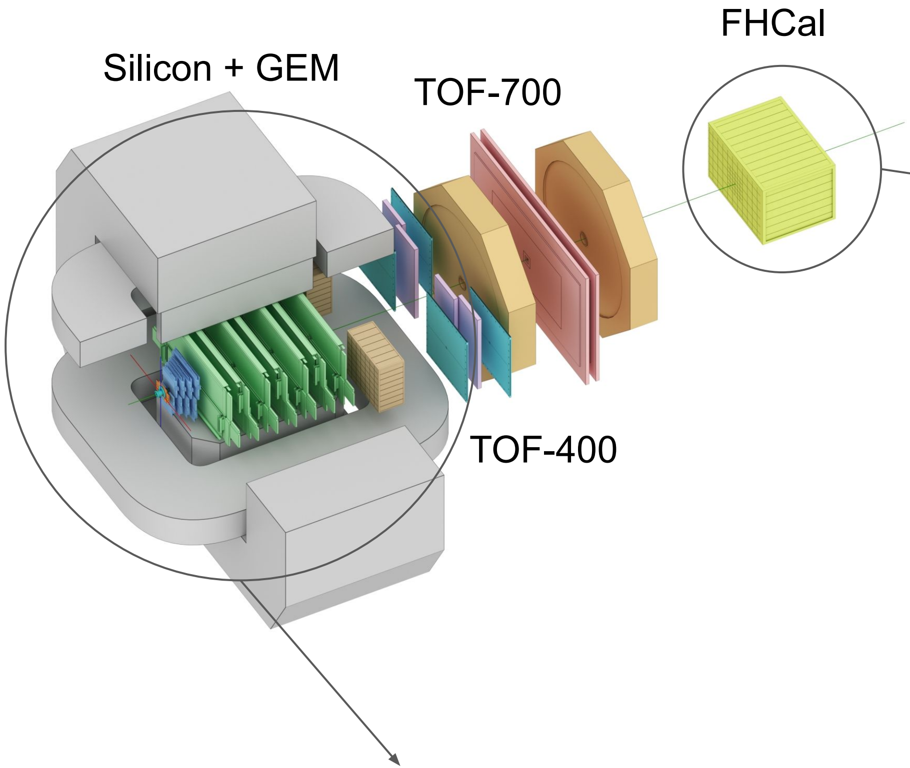
Modules of FHCal divided into 3 groups

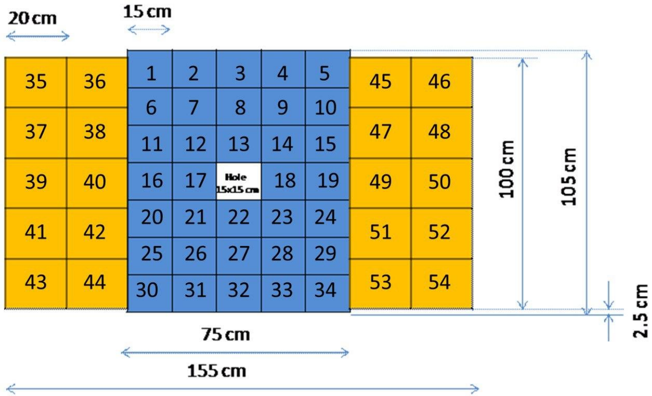


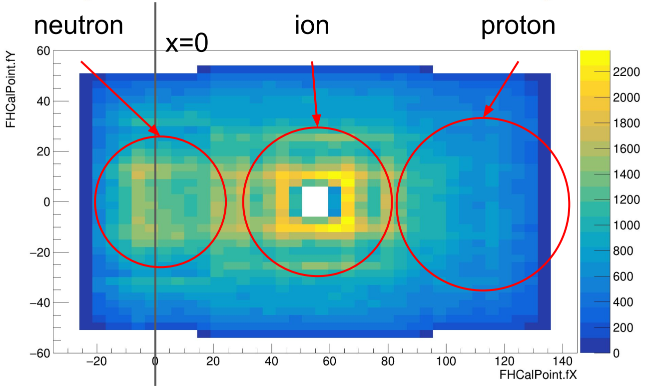


Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

The BM@N experiment (GEANT4 simulation for RUN8)



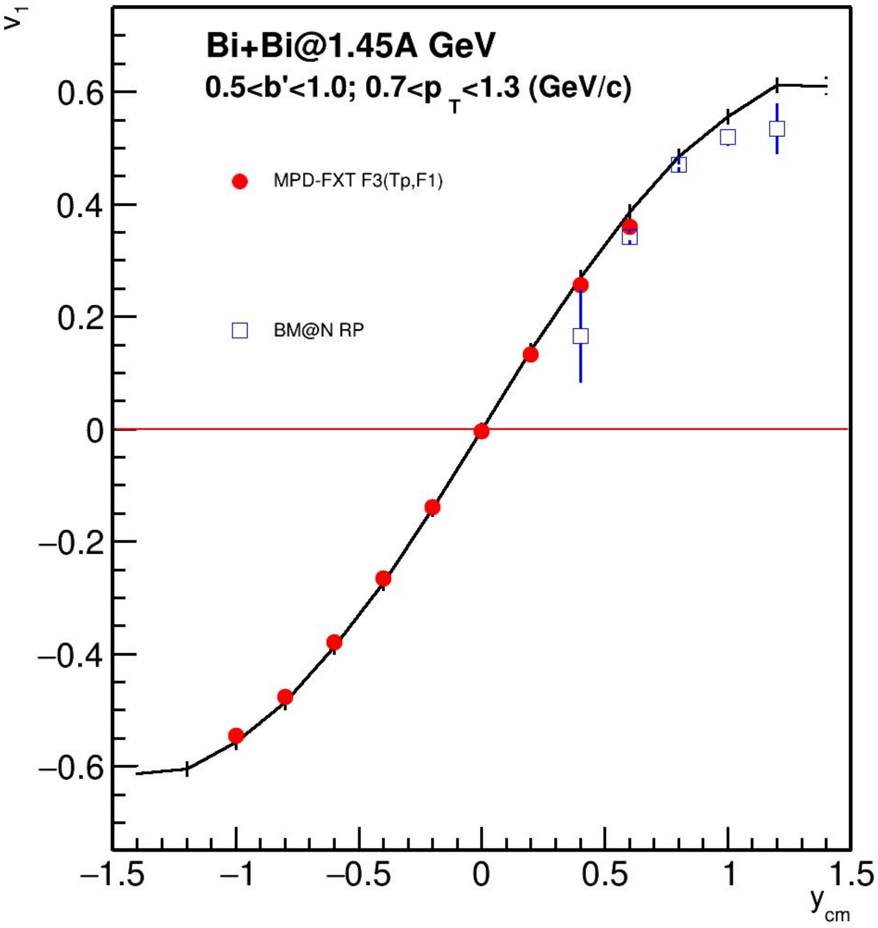




Square-like tracking system within the magnetic field deflecting particles along X-axis

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

Comparison with BM@N performance



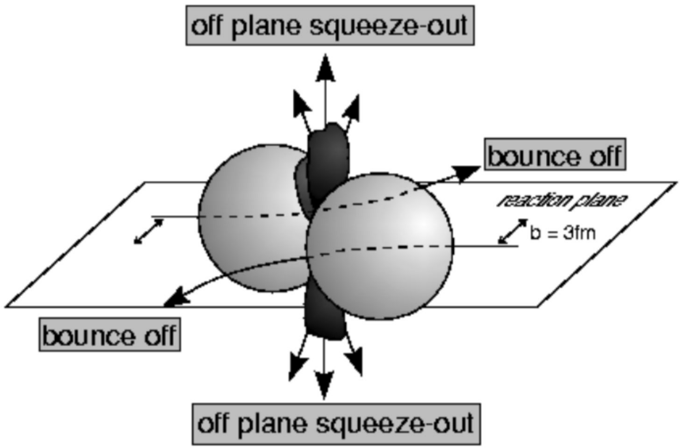
BM@N TOF system (TOF-400 and TOF-700) has poor midrapidity coverage at $\sqrt{s_{NN}}$ = 2.5 GeV

- 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:

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

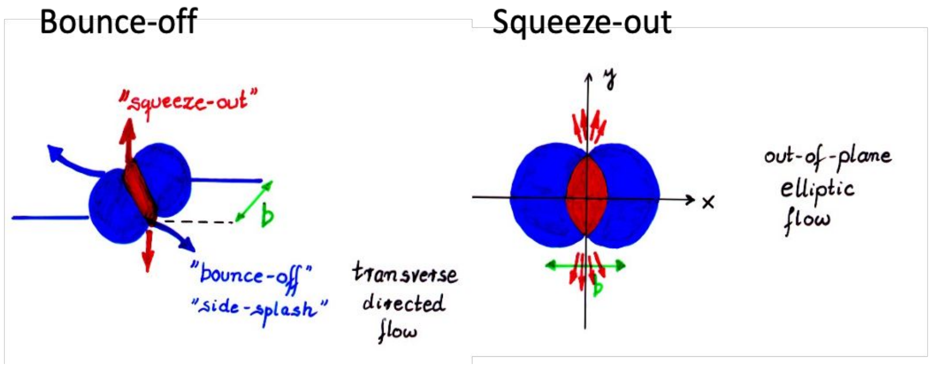
Anisotropic flow:

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

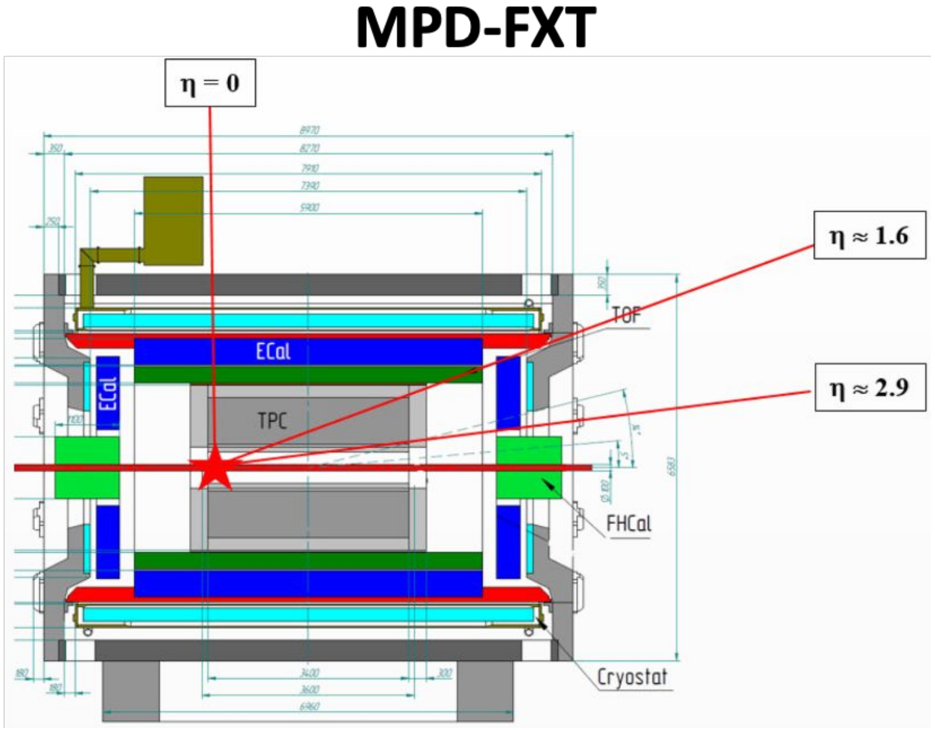
v_1 - directed flow, v_2 - elliptic flow

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:

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

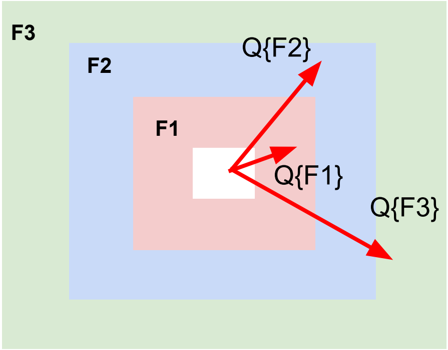
where φ is the azimuthal angle

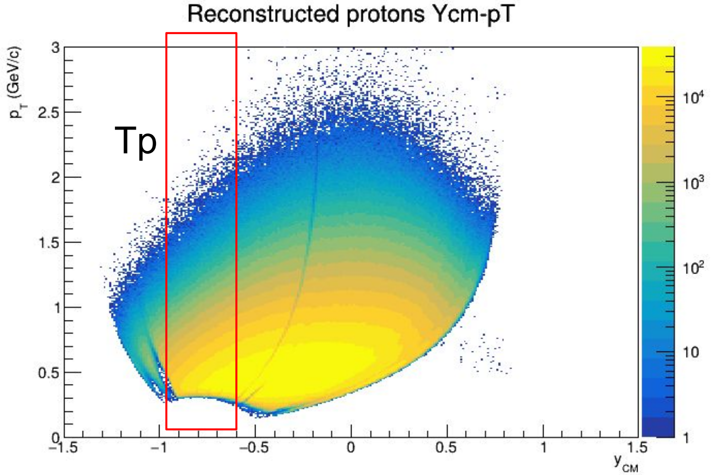
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

Ψ_n^{EP} is the event plane angle

Modules of FHCal divided into 3 groups

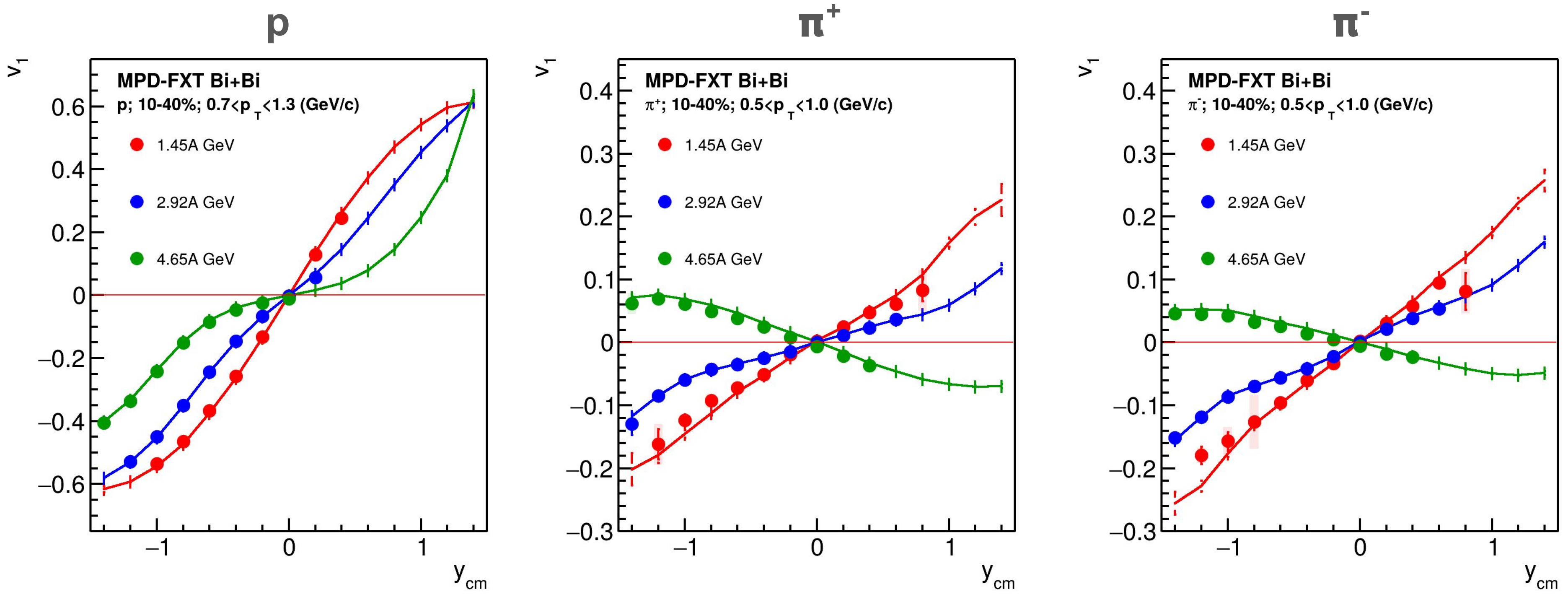




Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

Results: $v_1(y)$

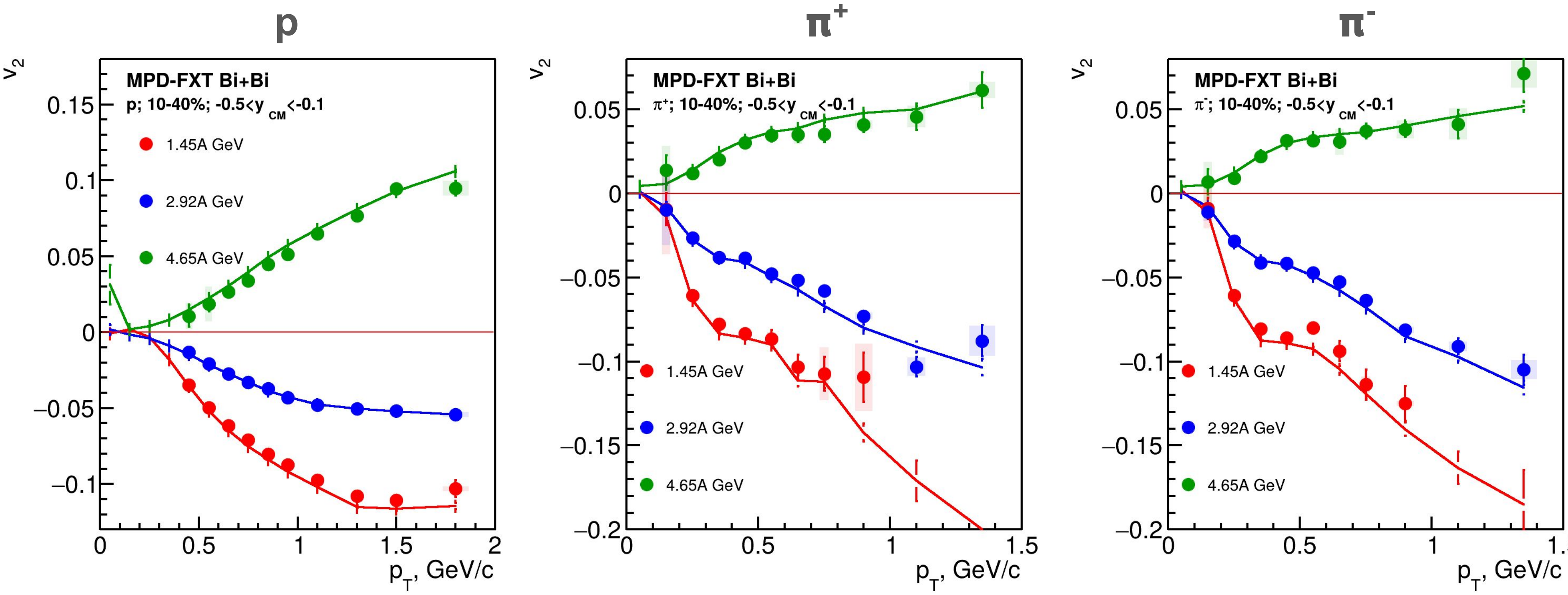
Systematics: xx, yy, F1, F2, F3



Good agreement with MC data

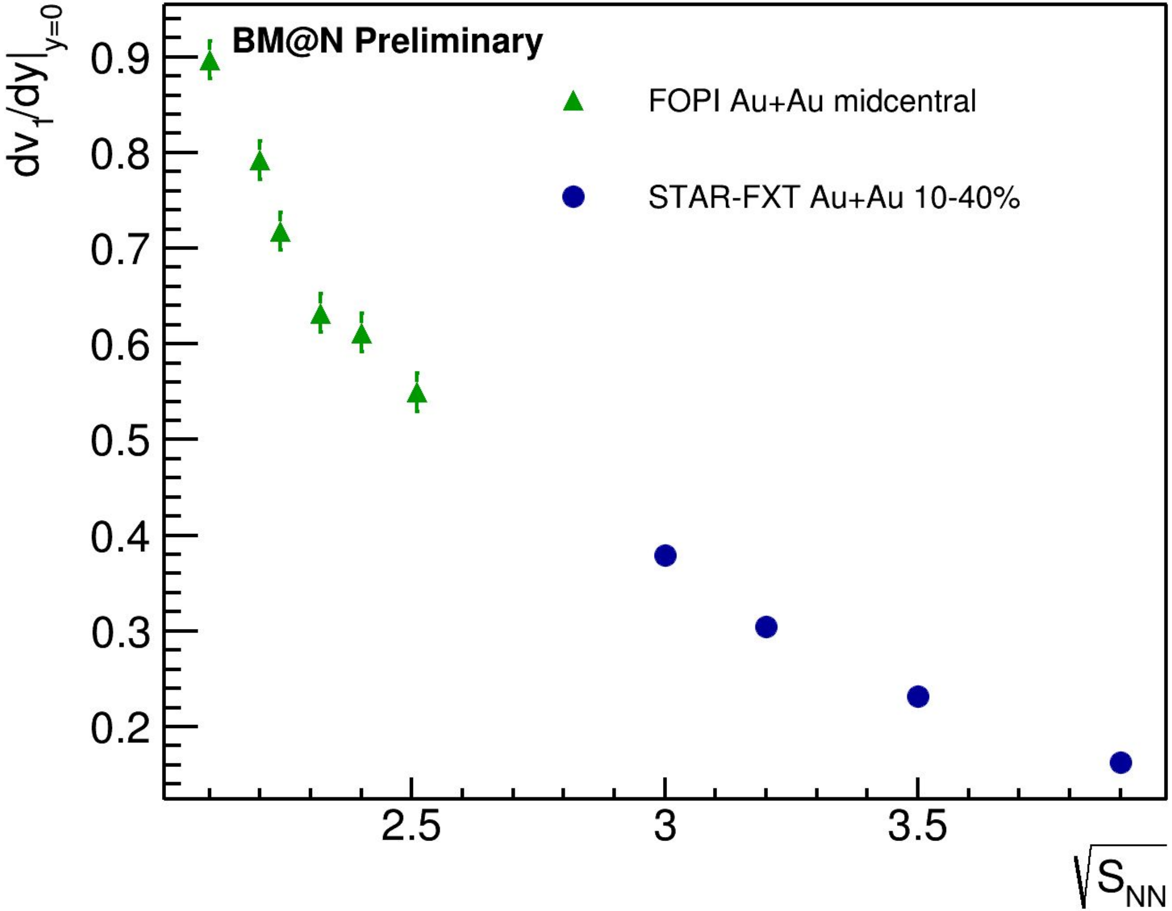
Results: $v_2(p_T)$

Systematics: xxx, xyy

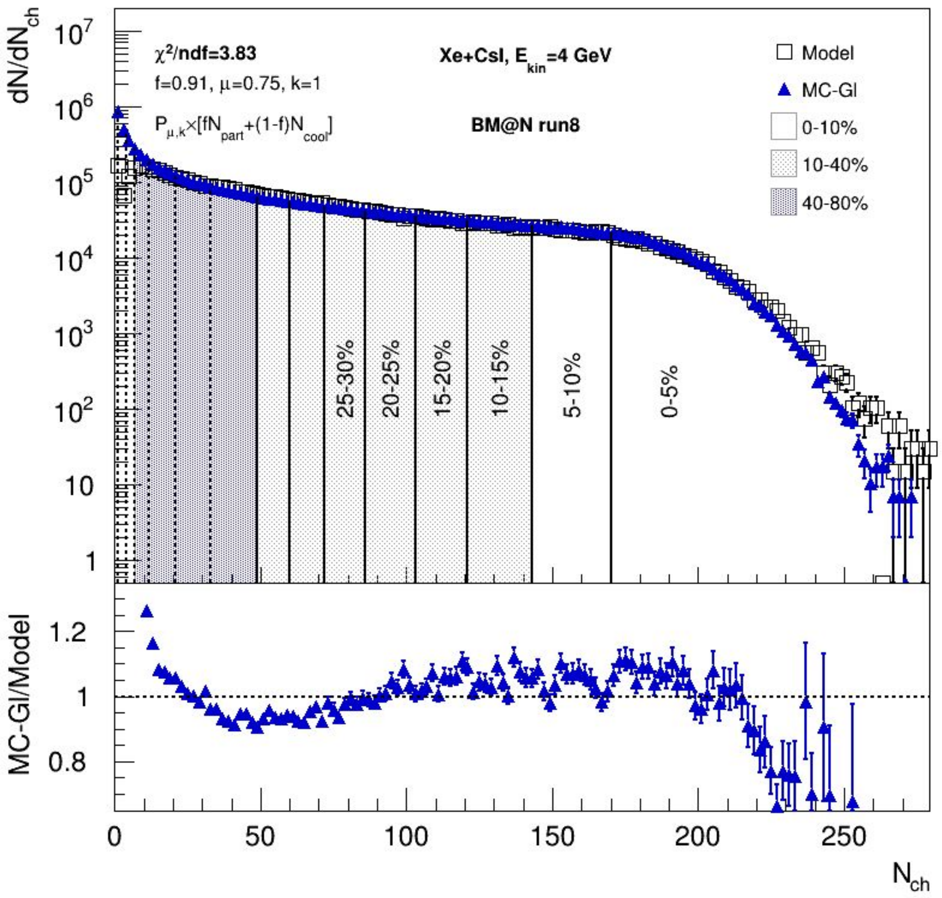


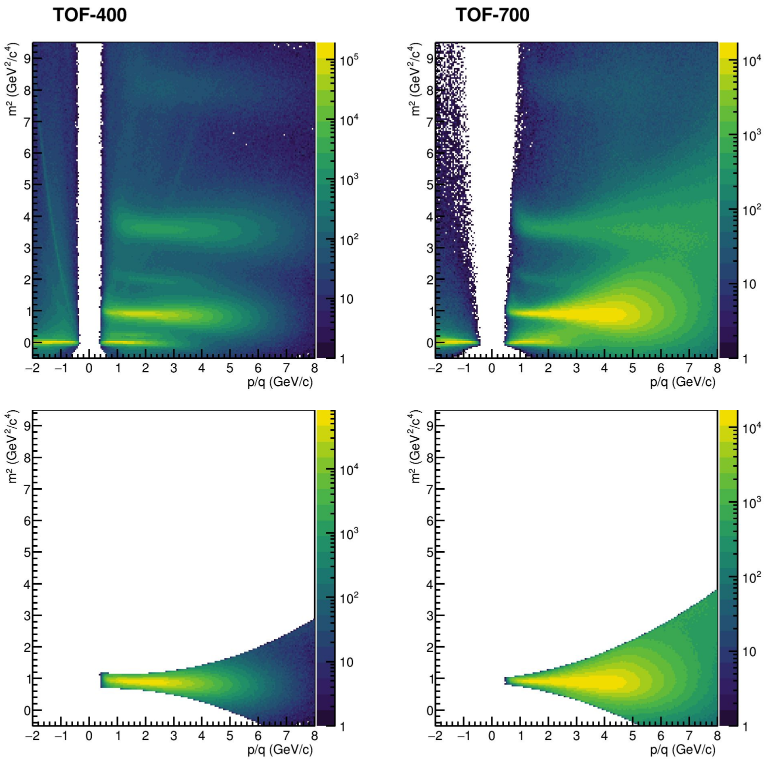
Good agreement with MC data

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



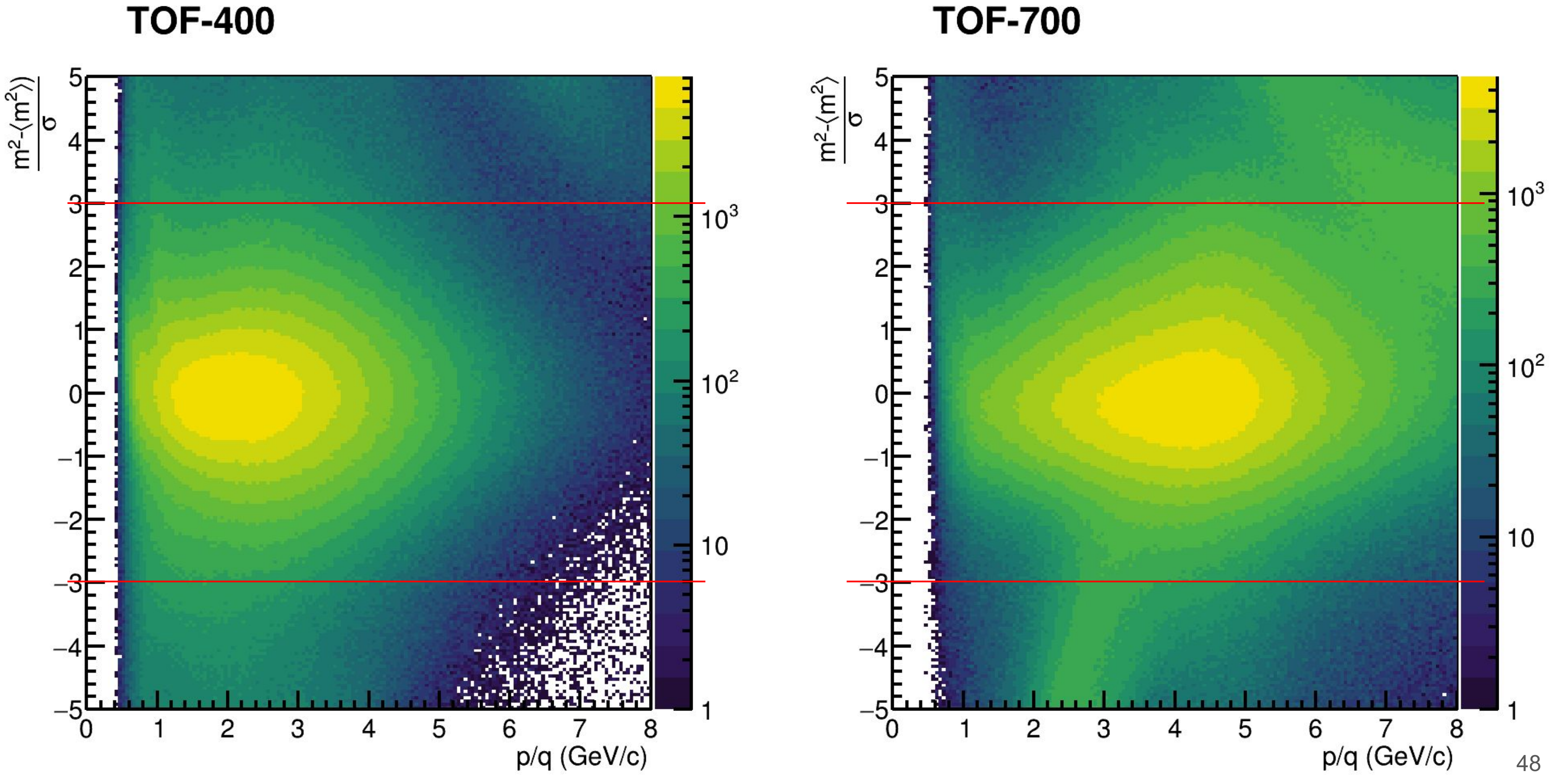
Centrality and particle selection



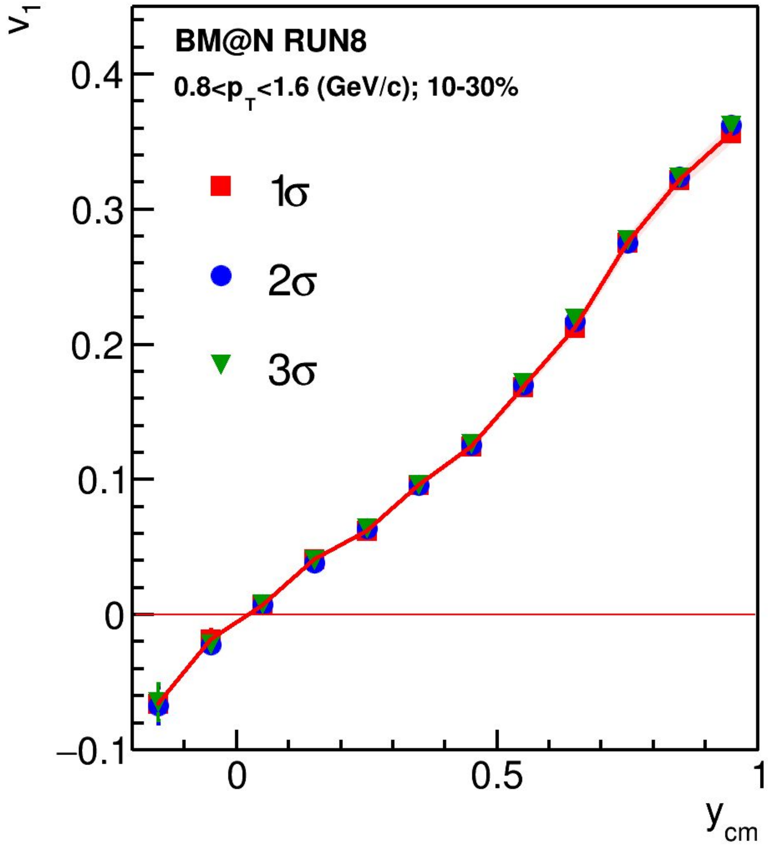


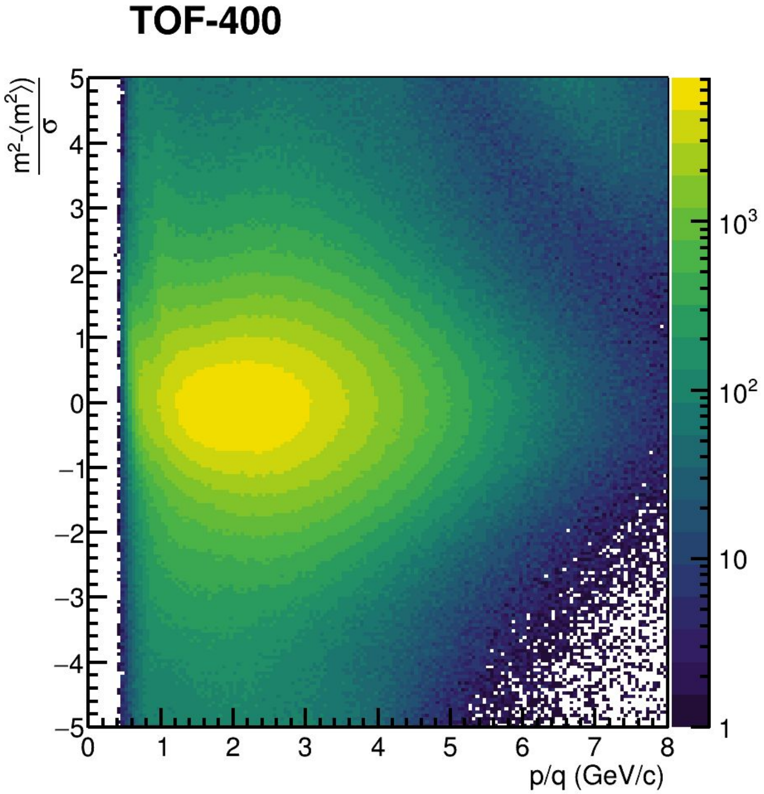
- Half of the recent VF production was analysed
- Event selection criteria (~100M events selected)
  - CCT2 trigger
  - Pile-up cut
  - Number tracks for vertex > 1
- Track selection criteria : $\chi^2 < 5$; $M_p^2 - 3\sigma < m^2 < M_p^2 + 3\sigma$; Nhits > 57

Proton N-sigma distributions



Systematics due to identification and tracking





The systematics is below 2%