Performance study of the anisotropic flow measurements with fixed-target mode of the MPD experiment at NICA

P. Parfenov, M. Mamaev and A. Taranenko
(JINR, NRNU MEPhI)

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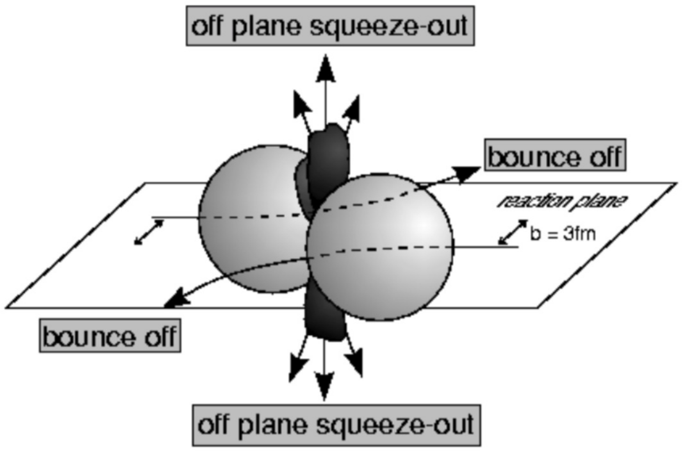
MEPhI
National Research Nuclear University

Anisotropic flow & spectators



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

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

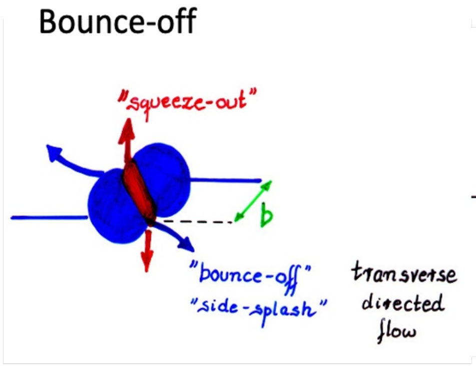
Anisotropic flow:

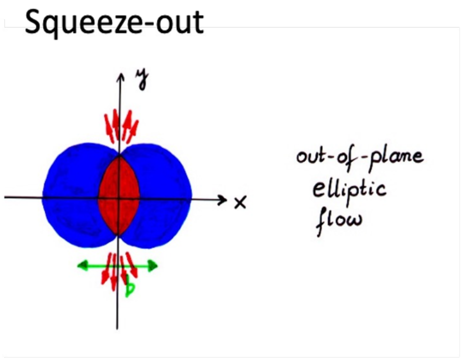
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right] \rangle$$

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
  $(t_{pass} = 2R/\gamma_{CM}\beta_{CM})$

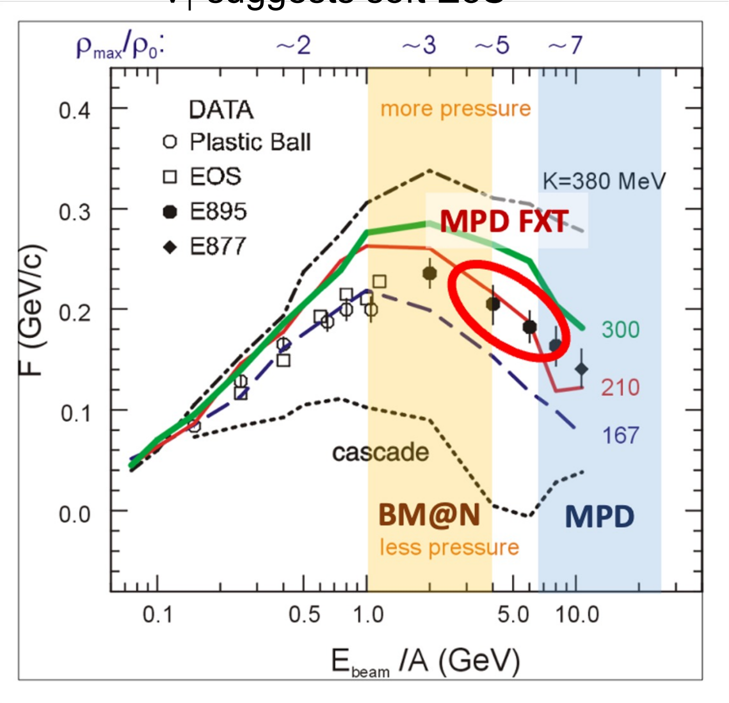




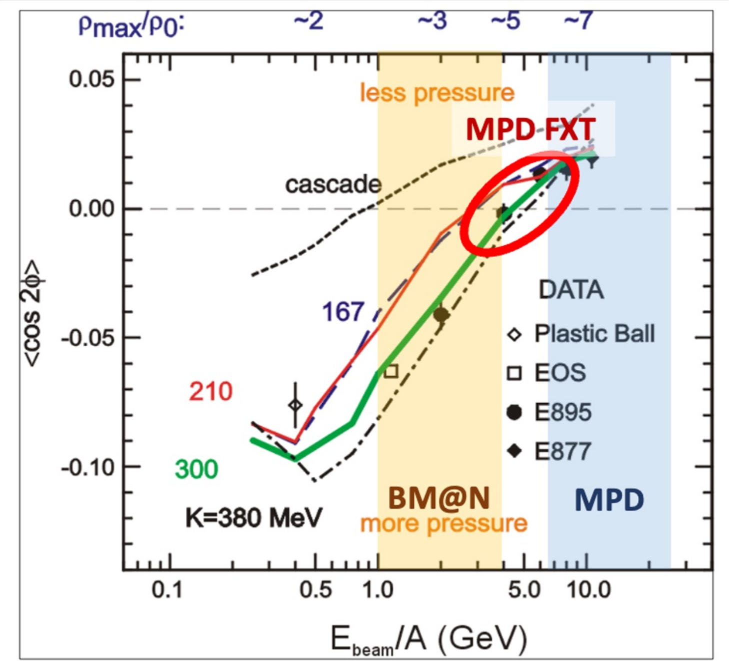
v_n at Nuclotron-NICA energies

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

v_1 suggests soft EoS



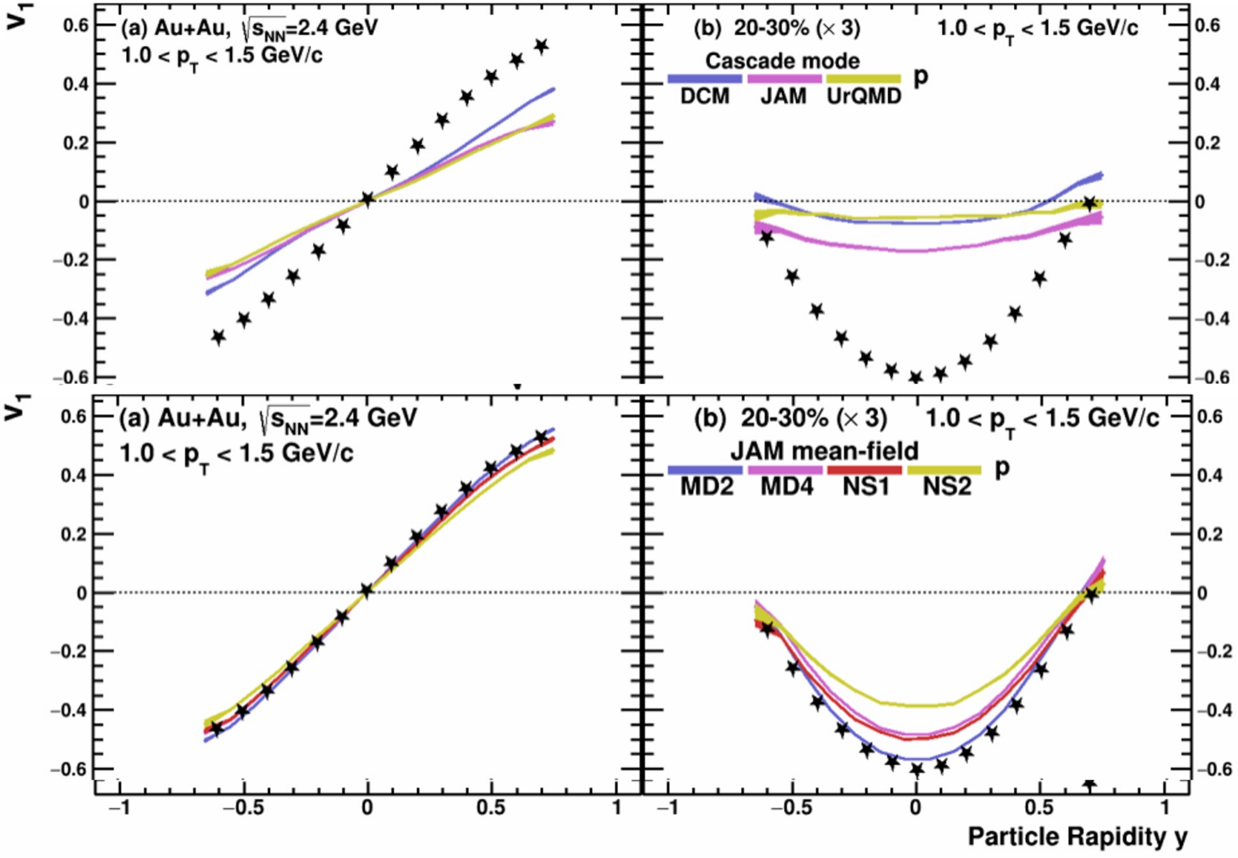
v_2 suggests hard EoS



- **v_n results from the E895 experiment are ambiguous:**
  - v_1 suggests EoS and v_2 suggests hard EoS
- **Additional experimental data are required to address this discrepancy**

Selecting the model

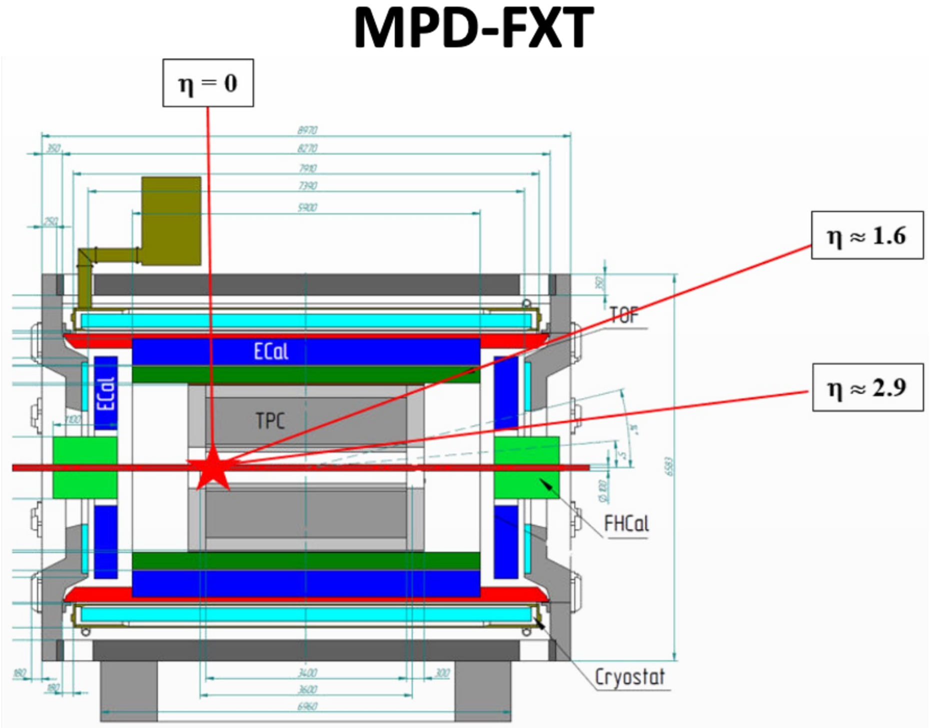
P.Parfenov Particles 5 (2022) 4, 561-579



Cascade models fail to reproduce v_n at low-energy heavy-ion collision

Mean field models reproduce the v_n rather well

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)

The Bayesian inversion method (Γ-fit)

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

the fluctuation kernel:

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

$c_b = \int_0^b P(b')db'$ – 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:

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

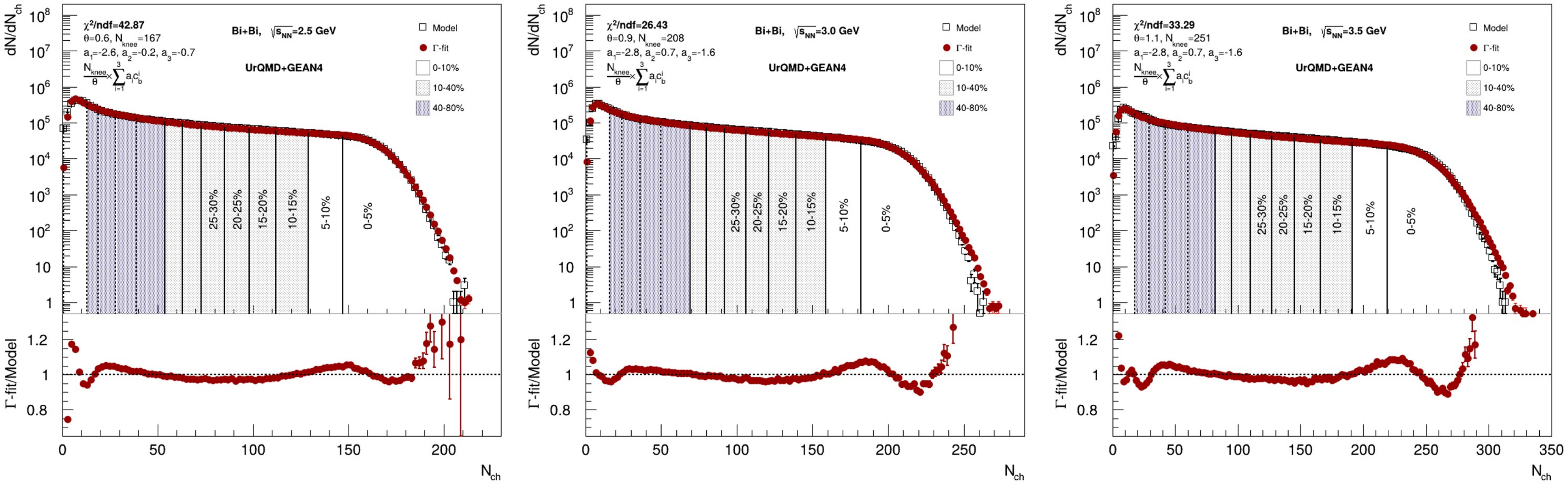
2 main steps of the method:

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:

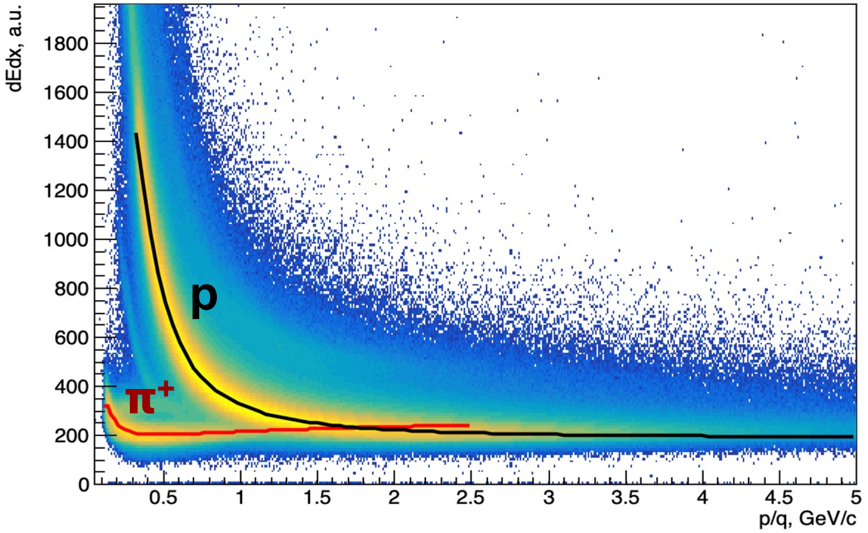
- Nhits>16
- $0 < \eta < 2$

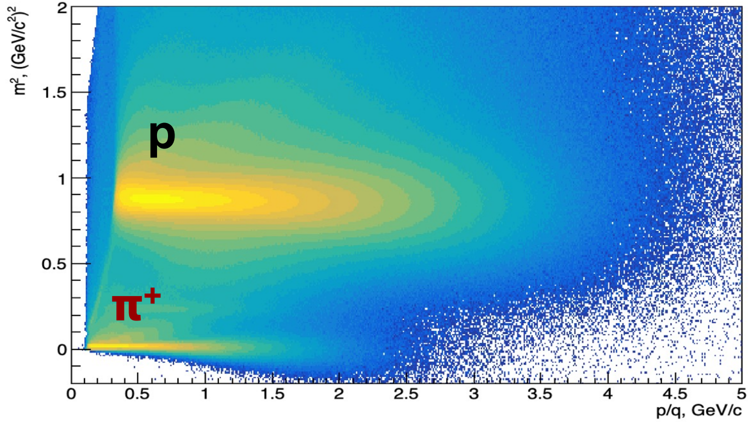
Good agreement between fit and data

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

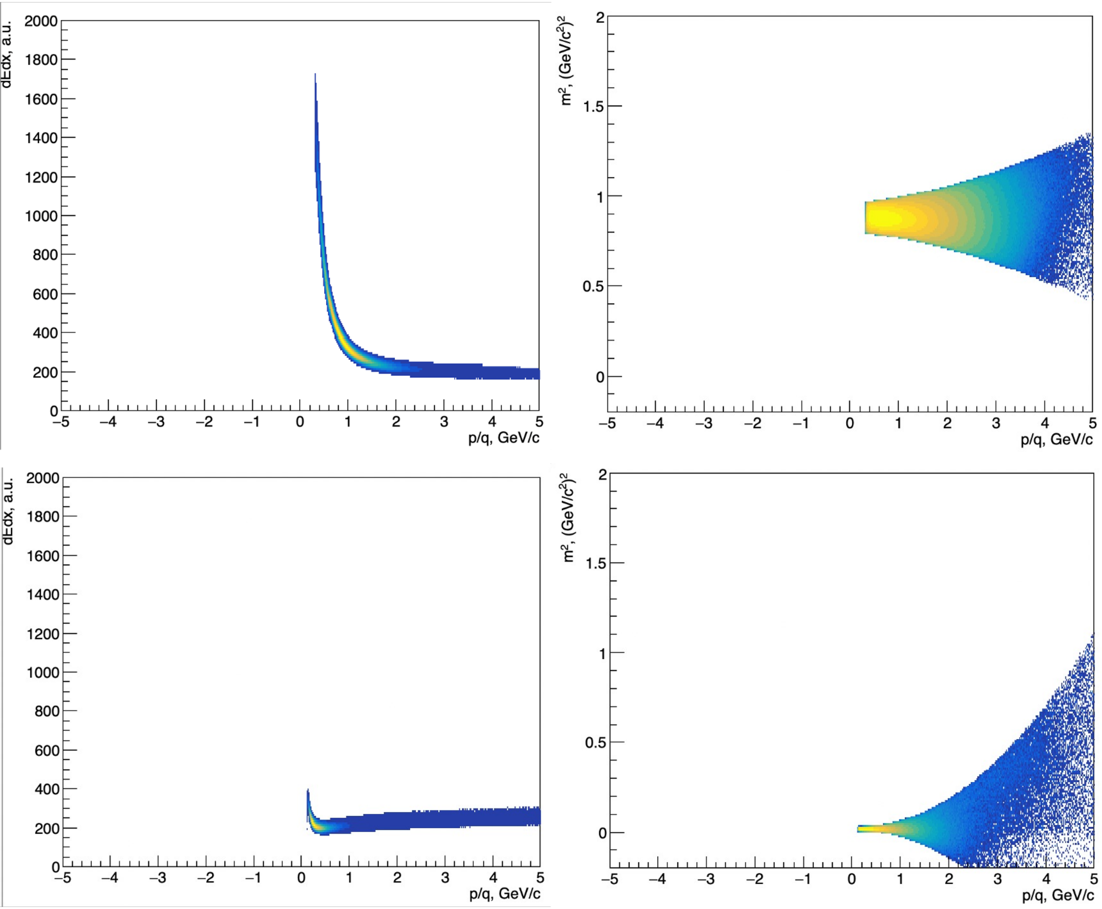
Fit *(dE/dx - f(βγ))/f(βγ)* with gaus in the slices of p/q and get σ_p(dE/dx)

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:

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

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:

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

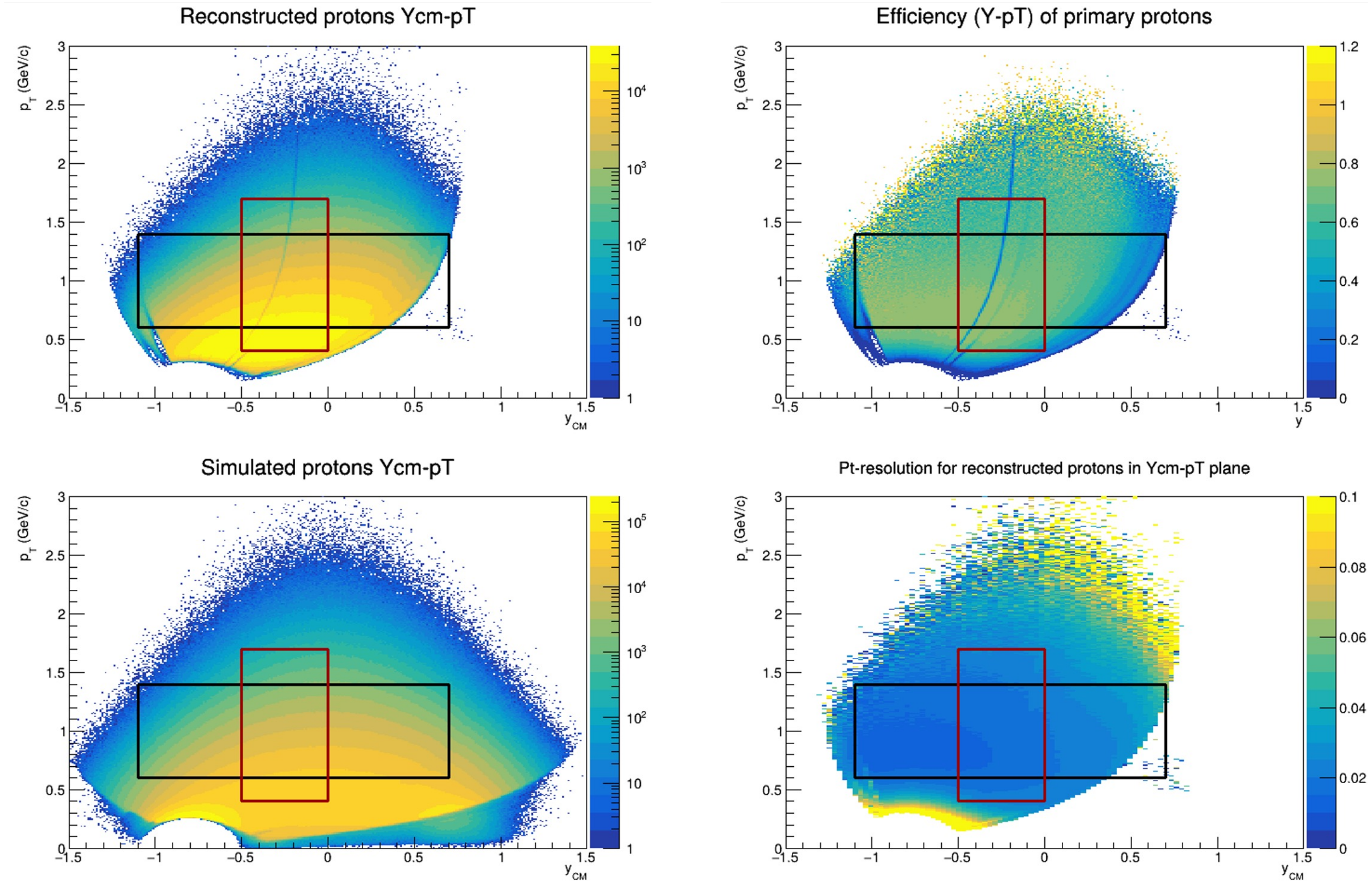
Pions (π^+):

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

Pions (π^-):

charge<0

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



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

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

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:

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

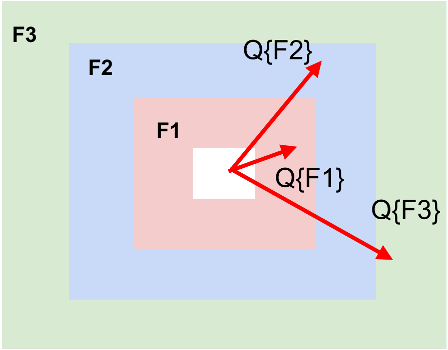
where φ is the azimuthal angle

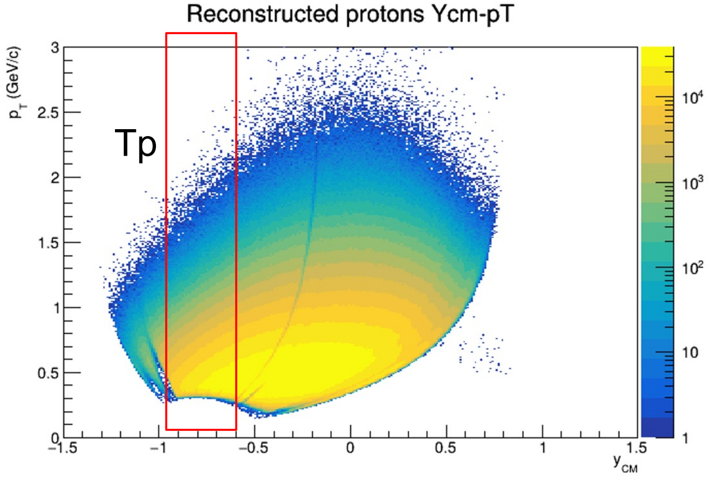
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

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;

Flow methods for v_n calculation

Tested in HADES:

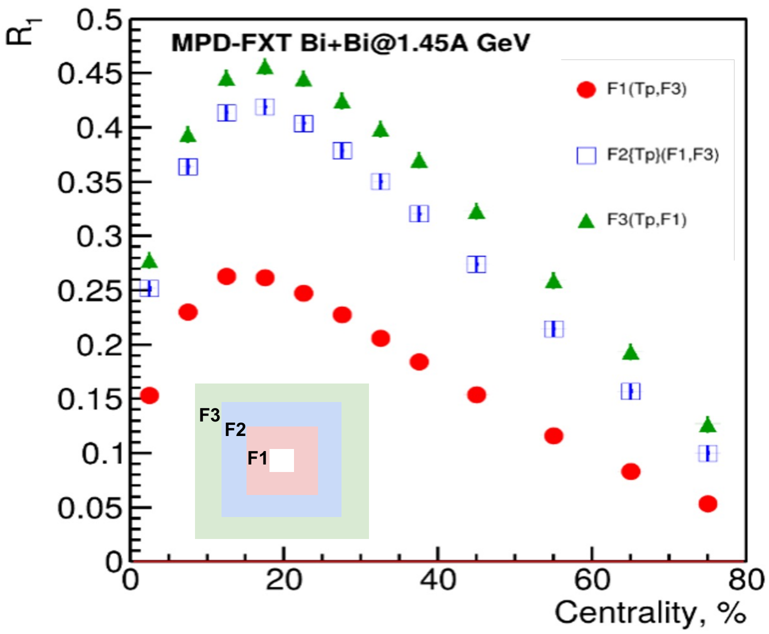
M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

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):

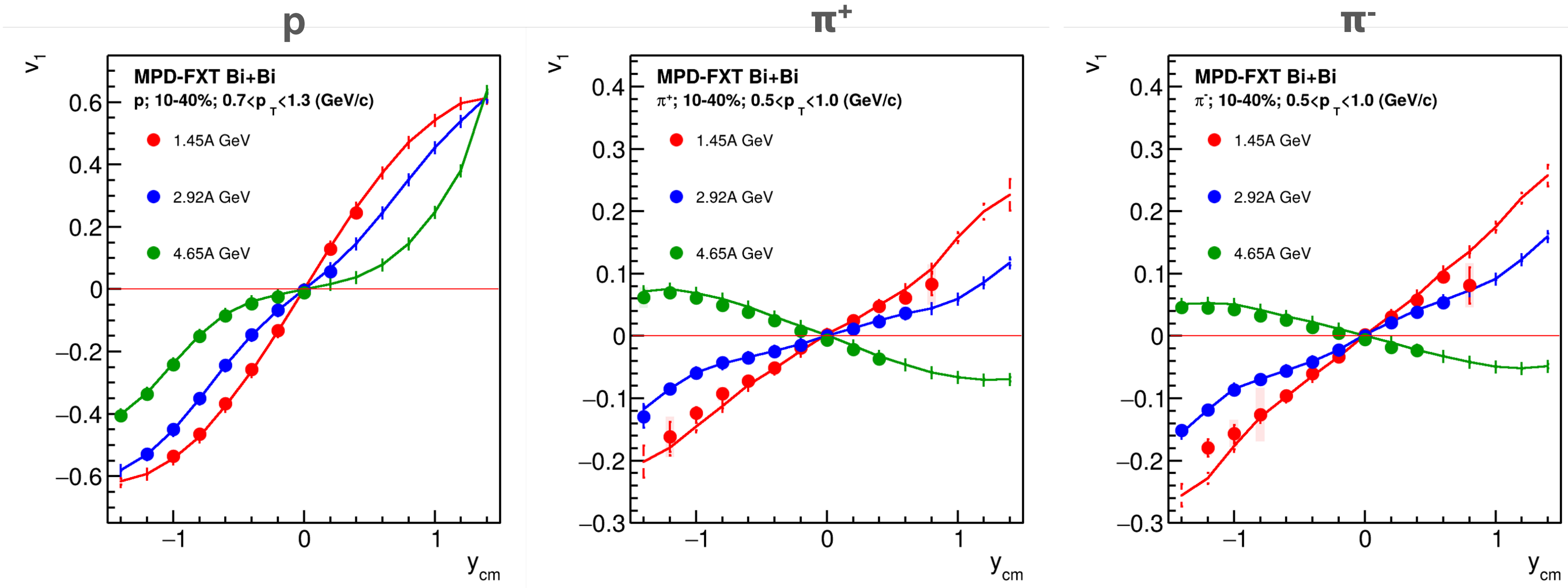
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

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

Results: $v_1(y)$

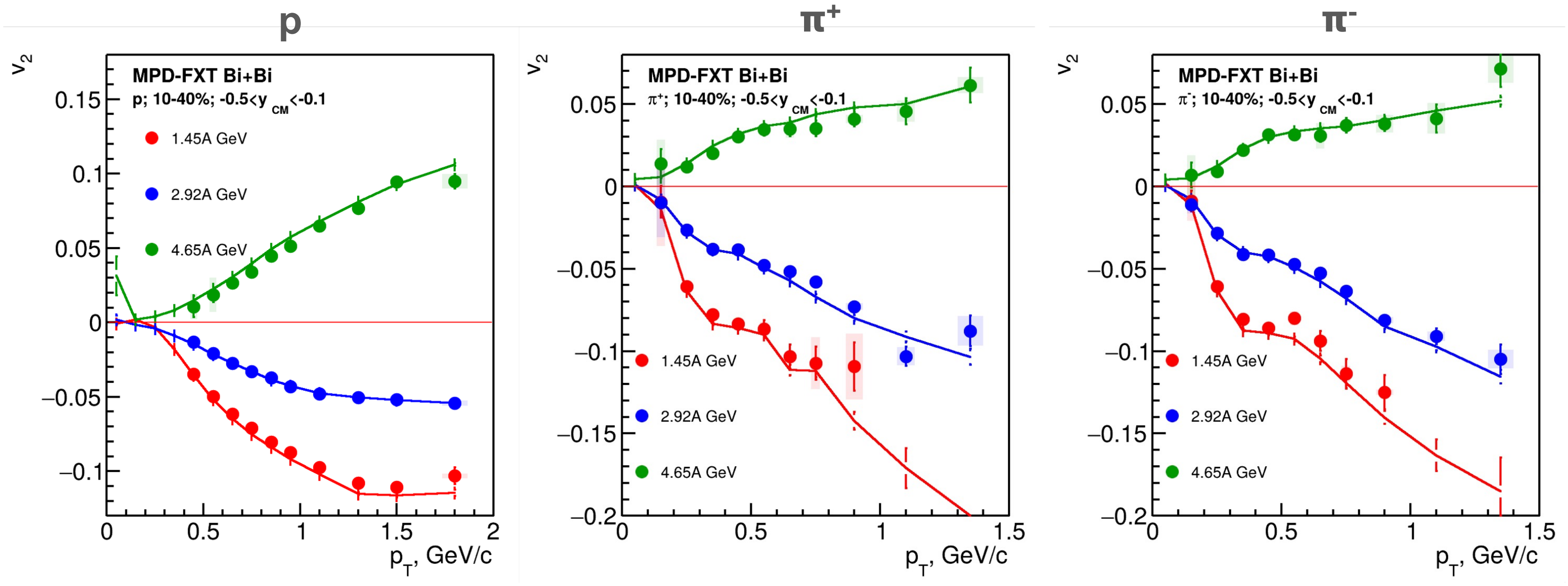
Systematics: xx, yy, F1, F2, F3



Good agreement with MC data

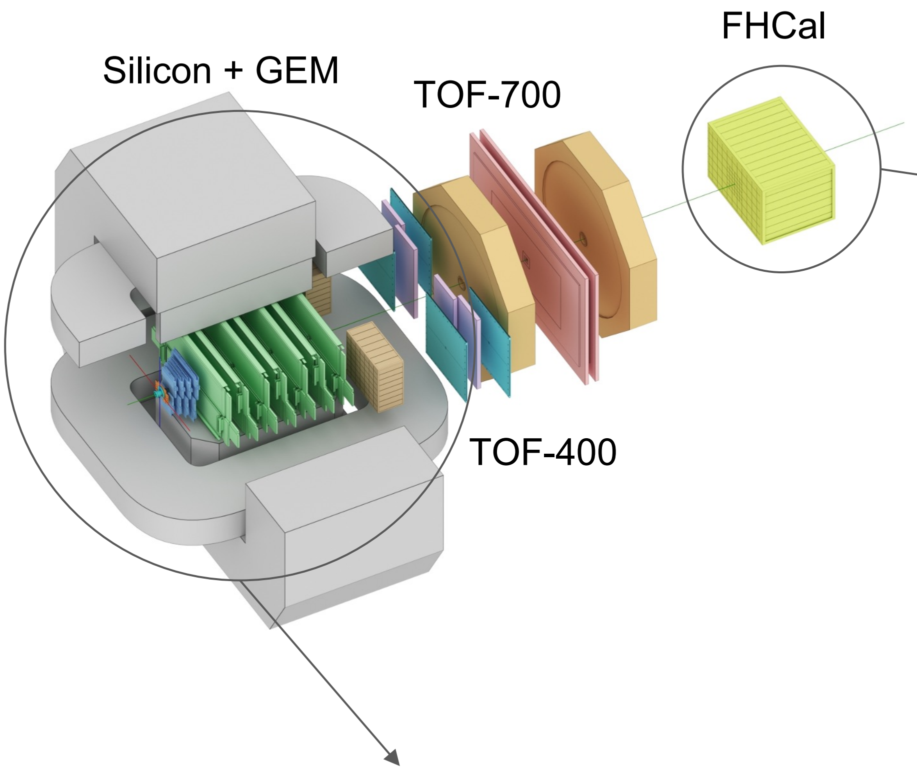
Results: $v_2(p_T)$

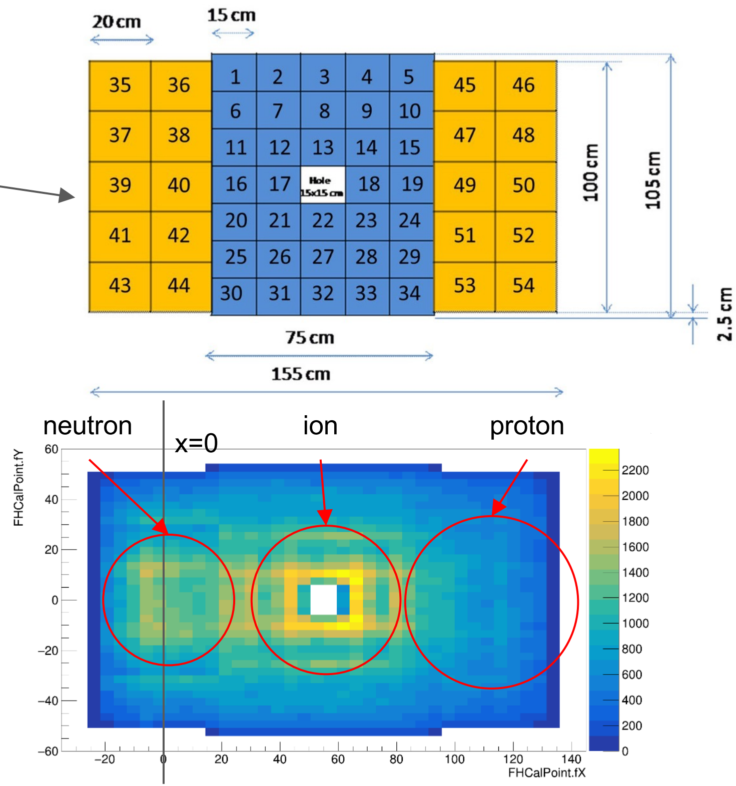
Systematics: xxx, xyy



Good agreement with MC data

The BM@N experiment (GEANT4 simulation for RUN8)

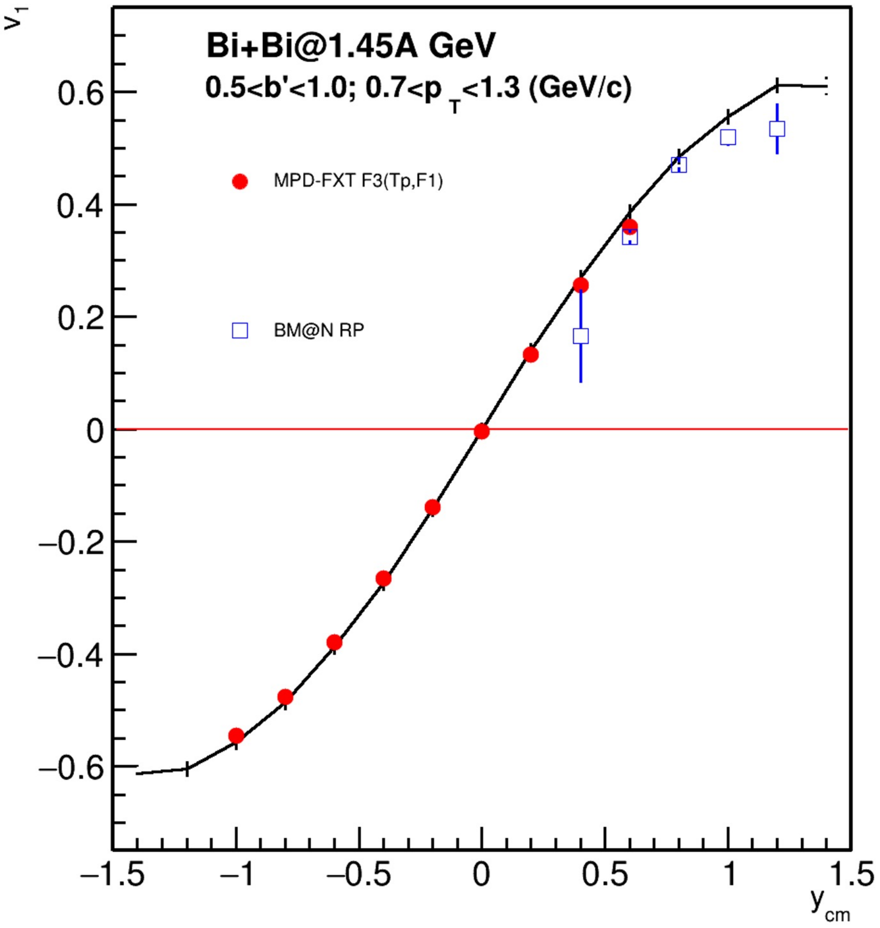




Square-like tracking system within the magnetic field deflecting particles along X-axis

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

Summary

- **Performance study for the anisotropic flow measurements was shown for the MPD-FXT using realistic procedures for centrality determination, primary track selection and PID:**
    - Multiplicity-based centrality determination using Γ-fit shows good agreement between fit and data
    - Overall good agreement between the estimated fit and impact parameter with the corresponding values taken directly from the model

- **Basic PID was performed using dE/dx from TPC and m^2 from TOF**

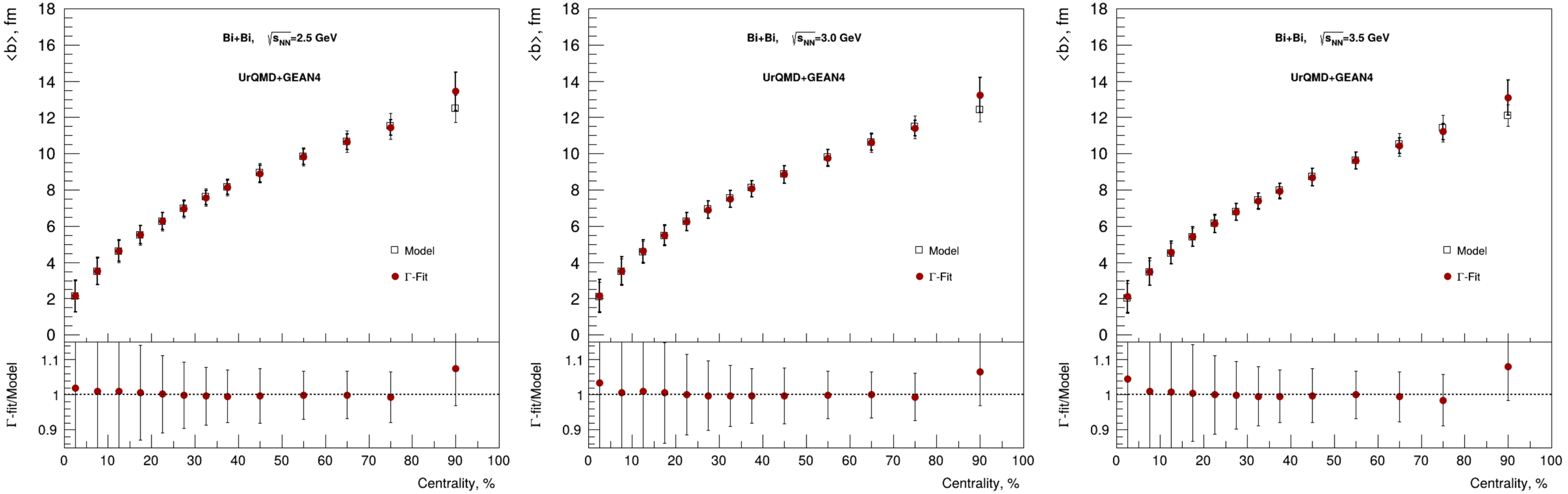
- **Directed and elliptic flow of protons and pions were measured for $\sqrt{s_{NN}}$ = 2.5, 3, 3.5 GeV:**
    - Good agreement between reconstructed and model data within corresponding acceptance windows for all particle species

- **Both MPD-FXT and BM@N can complement each other in terms of v_n:**
    - Cross-checks can be performed to test the implemented flow measurement techniques
    - Using results from both experiments can widen the rapidity coverage - **no single fixed target experiment can achieve that!**

New data from the BM@N and MPD (MPD-FXT) is required to address existing discrepancies in the experimental data and provide further constraints for the EoS in the models

Backup

Centrality determination: <b> vs Centrality



Cuts on tracks:

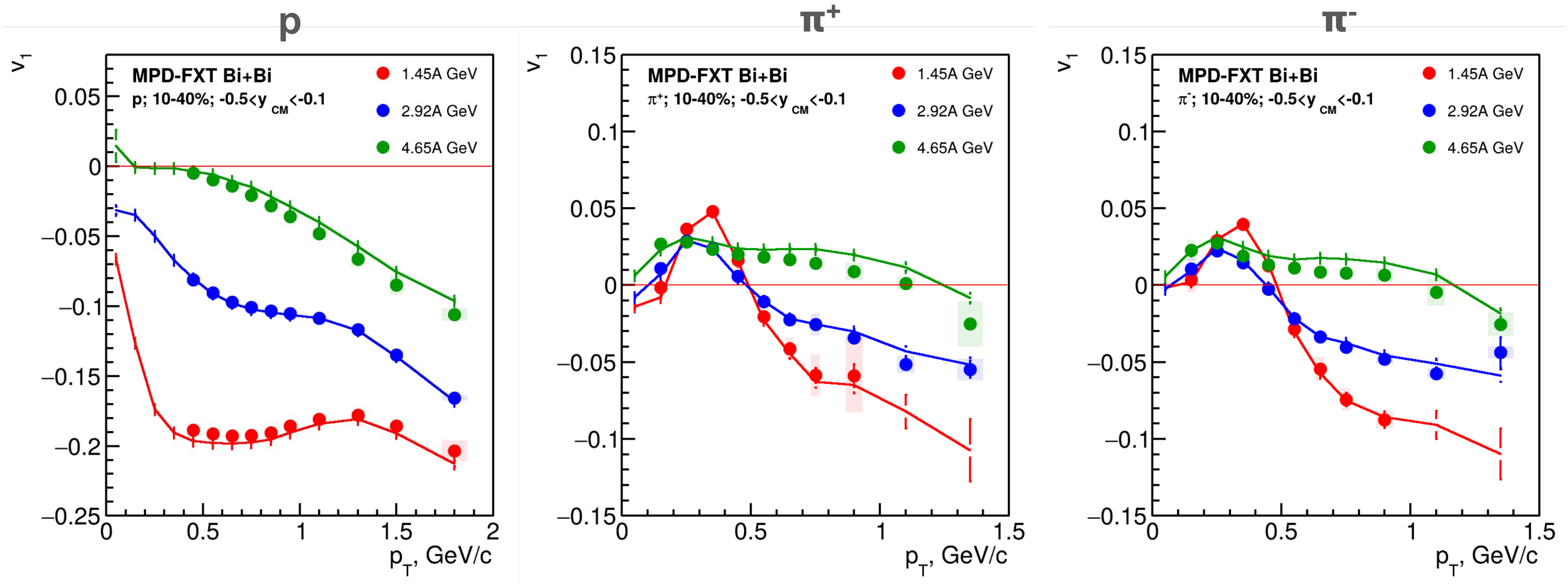
- Nhits>16
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination using inverse Bayes was used

Results: $v_1(p_T)$

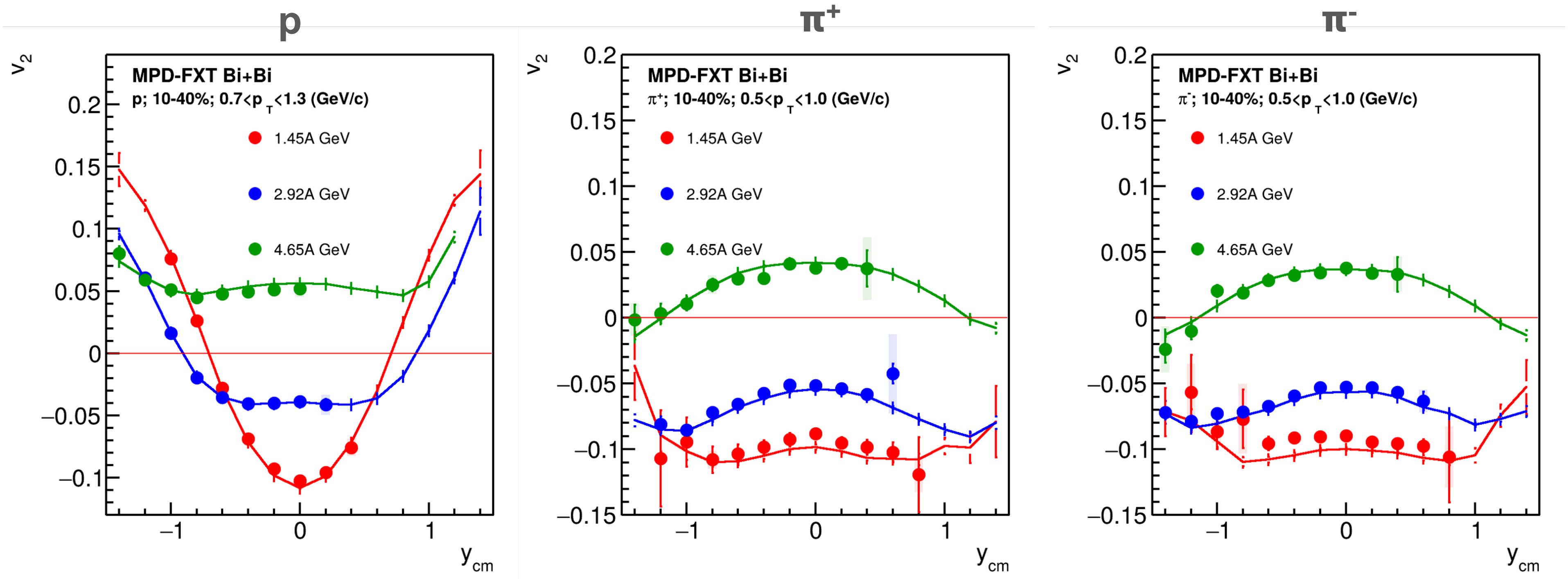
Systematics: xx, yy, F1, F2, F3



Good agreement with MC data

Results: $v_2(y)$

Systematics: xxx, xyy



Good agreement with MC data