Higher-harmonic proton flow and differential v_1, v_2 measurements in the fixed-target mode of the MPD Experiment at NICA

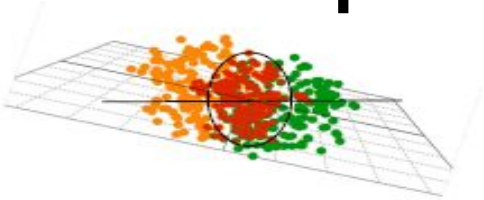
P. Parfenov and A. Taranenko
(JINR, NRNU MEPhI)

8th International Conference on Particle Physics and Astrophysics
27-30 October 2026

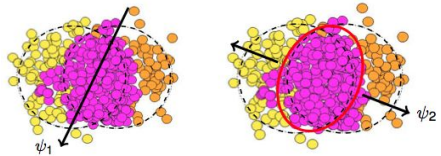
The work has been supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental and applied research at the NICA (JINR) megascience experimental complex" № FSWU-2025-0014

Anisotropic flow

v_1 - directed flow; v_2 - elliptic flow; v_3 - triangular flow; v_4 - quadrangular flow;

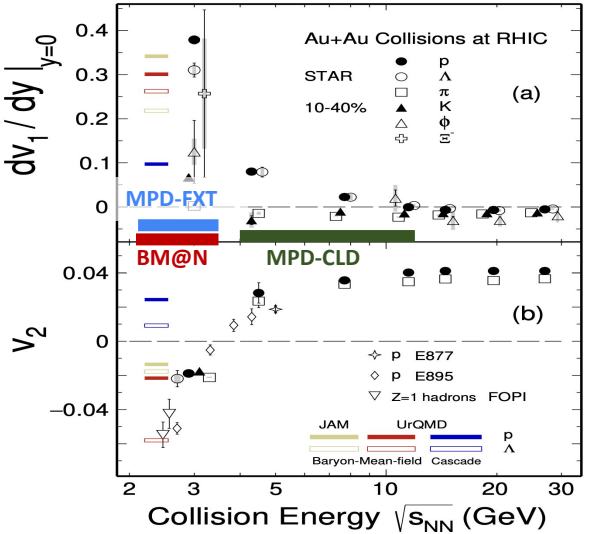


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$



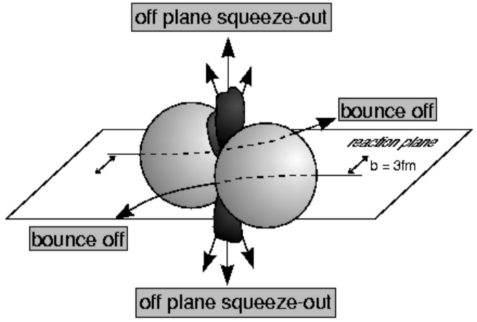
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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



STAR, Phys.Lett.B 827 (2022) 137003

Initial eccentricity (and its attendant fluctuations) ϵ_n drive momentum anisotropy v_r with specific viscous modulation



At Nuclotron-NICA:

Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$=2-11 GeV

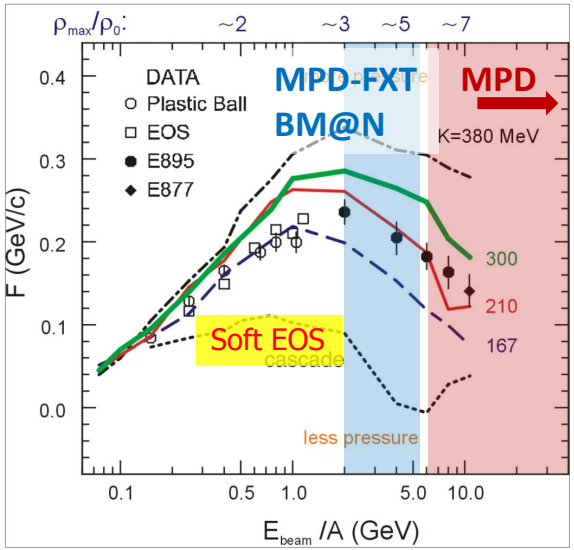
Anisotropic flow at Nuclotron-NICA energies is a delicate balance between:

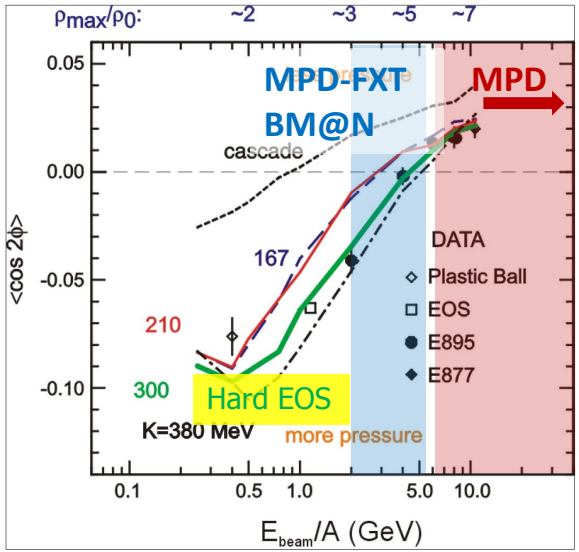
I. **The ability of pressure developed early in the reaction zone** $(t_{exp} = R/c_s)$

II. **The passage time for removal of the shadowing by spectators** $(t_{pass} = 2R/\gamma_{CM}\beta_{CM})$

Sensitivity of the collective flow to the EOS

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002)





$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{\mathrm{cm}})}\right|_{y/y_{\mathrm{cm}}=1}$$

$$v_2 \equiv \langle \cos(2(\varphi - \Psi_{RP})) \rangle$$

Anisotropic flow sensitive to the EoS

EoS extraction: define incompressibility

$$K_0 = 9\rho^2 \frac{\partial^2(E_A)}{\partial \rho^2}$$

Discrepancy in the interpretation:

- v_1 suggests soft EoS (K_0≈210 MeV)
- v_2 suggests hard EoS (K_0≈380 MeV)

New measurements using new data and modern analysis techniques might address this discrepancy

Additional measurements are essential to clarify the previous results
What about flow of higher harmonics?

Higher-order flow measurements

$v_n(\Psi_1)$ and $v_n(\Psi_n)$ are two distinct observables:

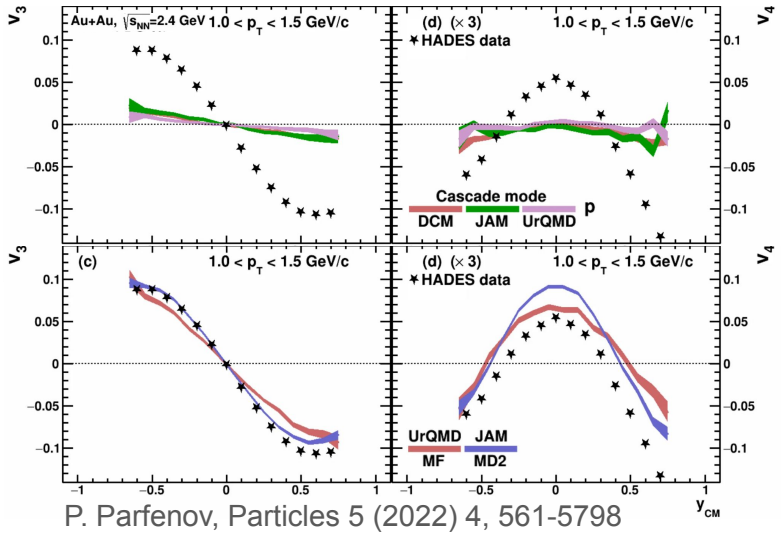
- $v_n(\Psi_n)$ originates from the event-by-event geometric fluctuations (uncorrelated with RP or Ψ_1)
- $v_n(\Psi_1)$ most probably originates from:
  - Initial geometry of the collision;
  - Mean-field potential in the medium.

Generally, they have been measured in different beam energy ranges:

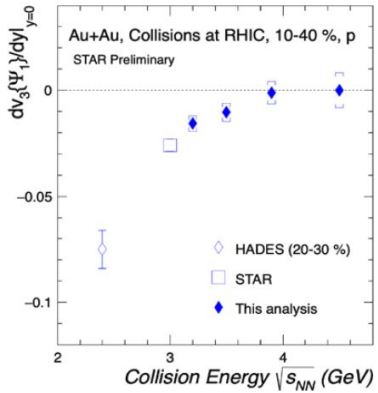
- At low $\sqrt{s_{NN}}$: $v_n(\Psi_1)\neq 0$, $v_n(\Psi_n)\neq 0$;
- At high $\sqrt{s_{NN}}$: $v_n(\Psi_1)=0$, $v_n(\Psi_n)\neq 0$.

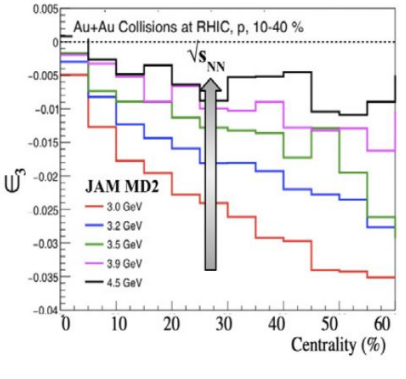
At the moment, there are few experimental results for such measurements yet they can provide valuable insight into properties of the EOS at $\sqrt{s_{NN}} \lesssim 5$ GeV.

Is MPD-FXT capable of such measurements?



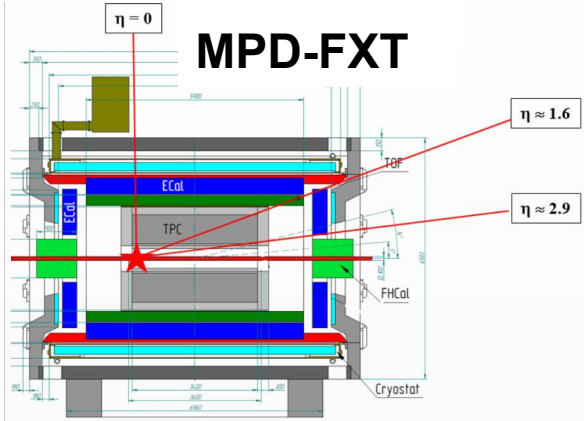
P. Parfenov, Particles 5 (2022) 4, 561-5798





S.R. Sharma, EPJ Web Conf. 364 (2026) 04008

Flow vectors



From momentum of each measured particle define a u_n-vector in transverse plane: $u_n = e^{in\phi}$

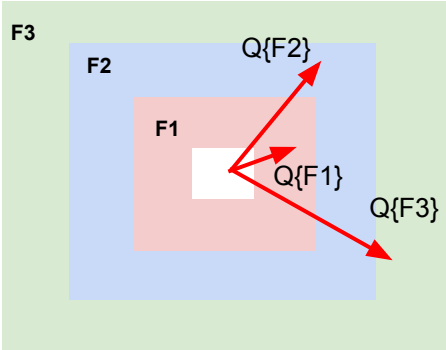
where φ is the azimuthal angle

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

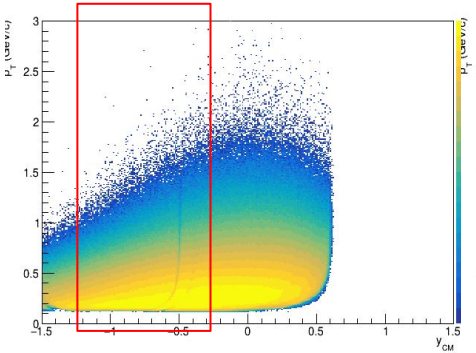
$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle

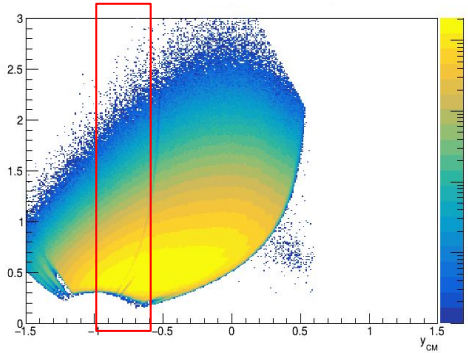
Modules of FHCal divided into 3 groups



Tπ-



Tp



Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;
Tπ: π-; -1.5<y<-0.2;

Flow methods for v_n calculation

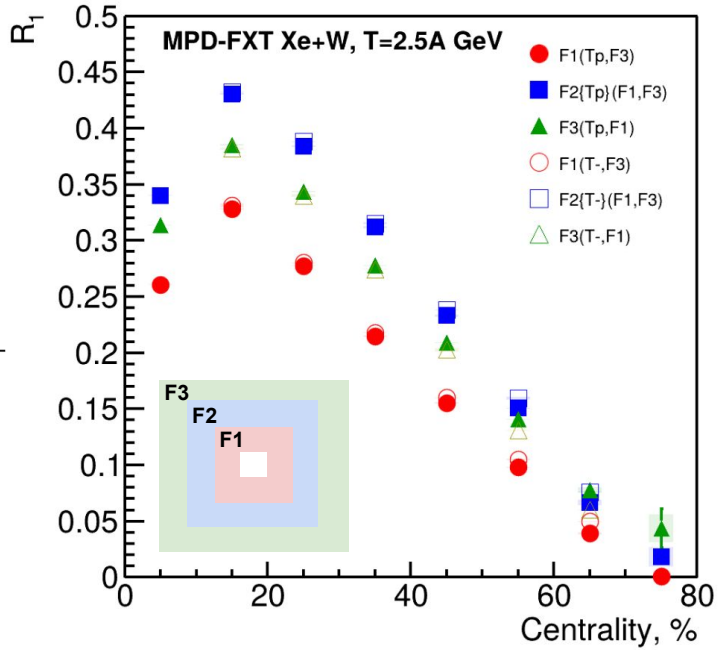
Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}} \quad v_3 = \frac{\langle u_3 Q_1^{F1} Q_1^{F2} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F2} R_1^{F3}} \quad v_4 = \frac{\langle u_4 Q_1^{F1} Q_1^{F1} Q_1^{F1} Q_1^{F1} \rangle}{\left(R_1^{F1}\right)^4}$$

Where R_1 is the resolution correction factor

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



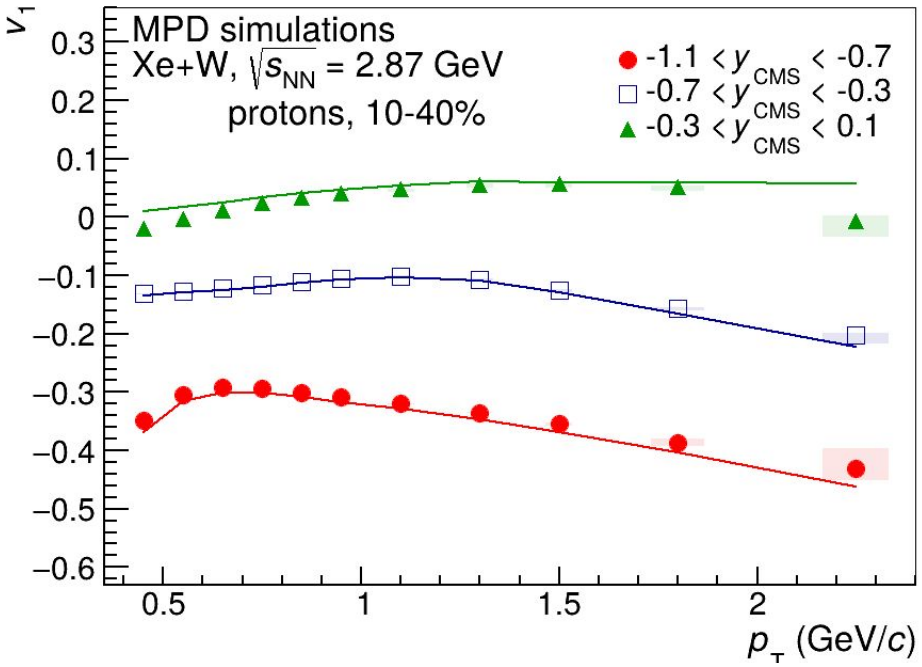
Symbol “F2(F1,F3)” means R_1 calculated via (3S resolution):

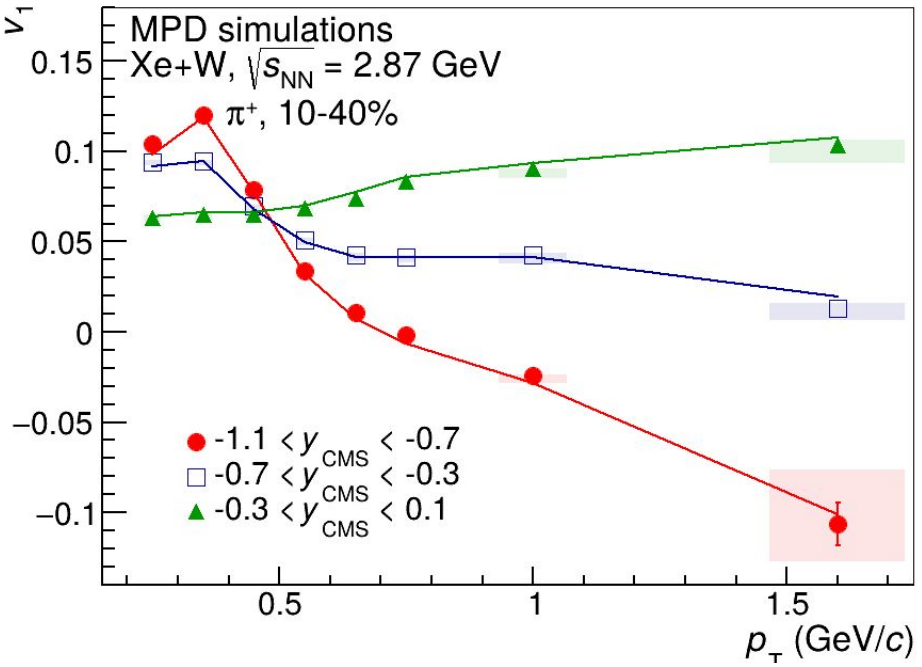
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

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

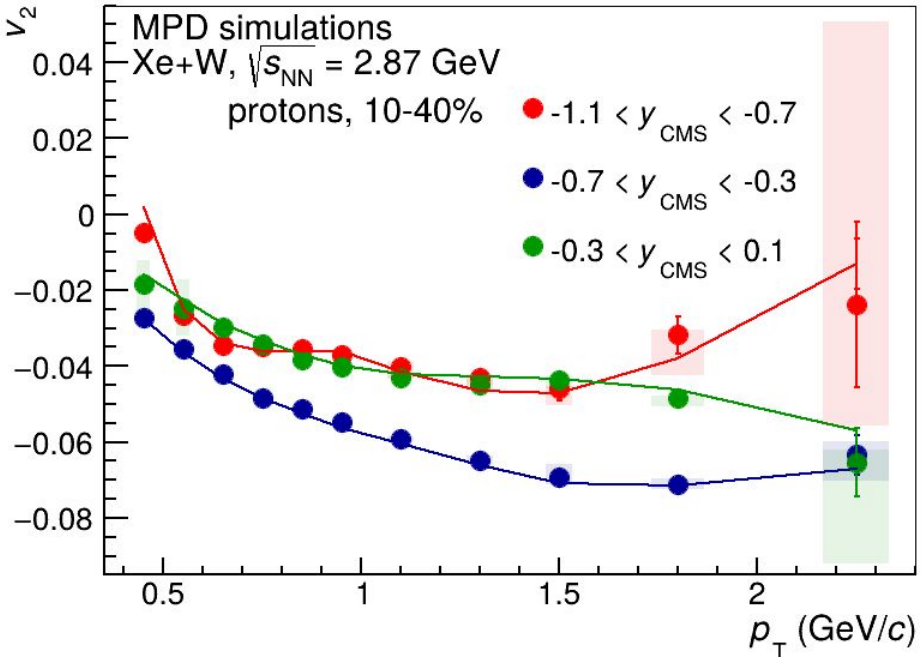
Directed flow in MPD-FXT

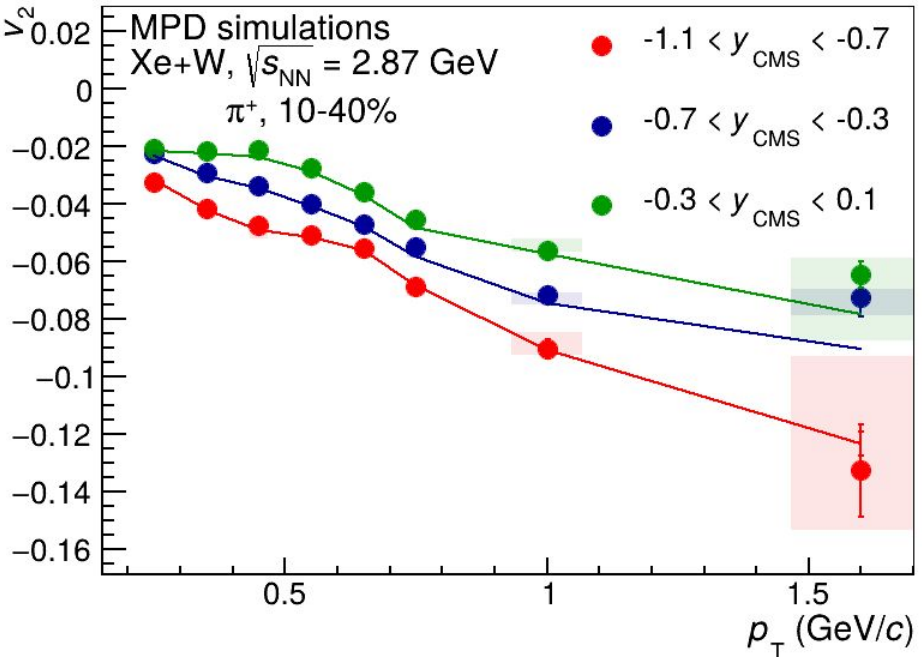




The large statistics (~100M) allows to perform differential flow measurements for v_1 and v_2.
MPD-FXT shows a good performance for a wide (centrality,p_T,y_{CMS})-range

Elliptic flow in MPD-FXT

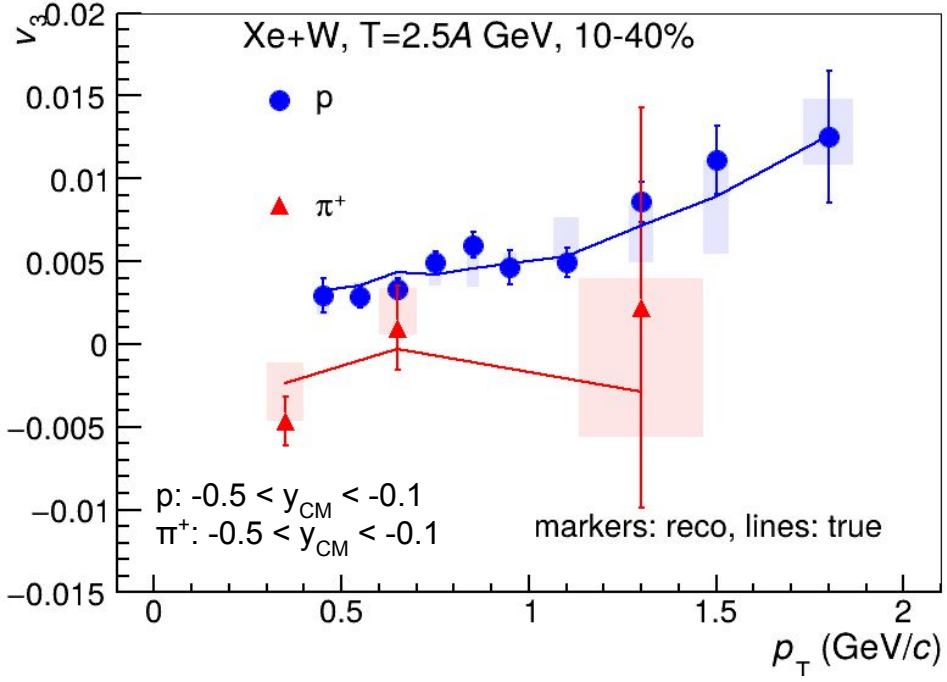


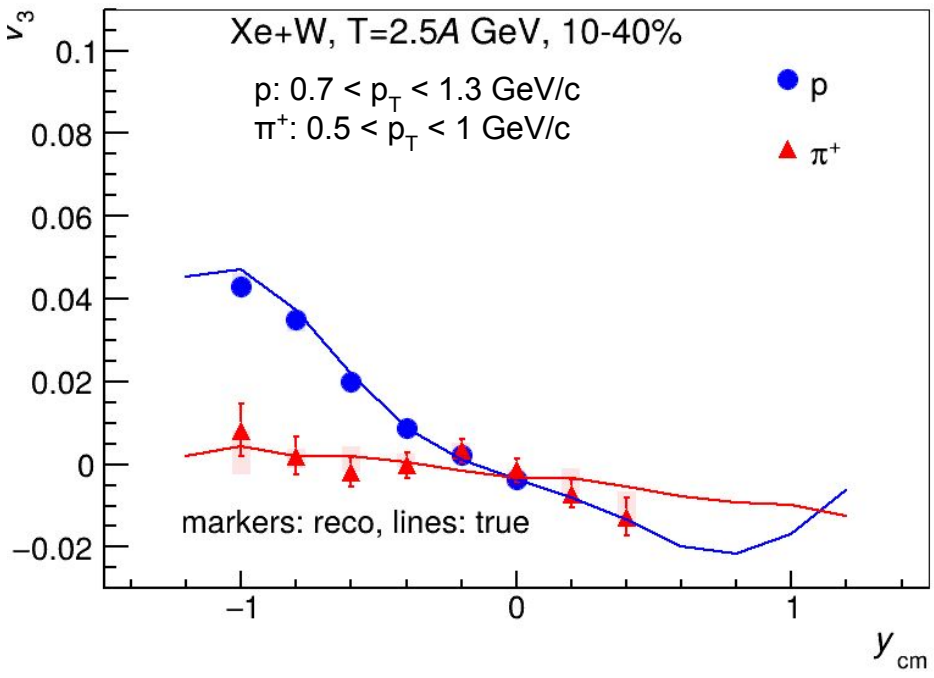


The large statistics (~100M) allows to perform differential flow measurements for v_1 and v_2.
MPD-FXT shows a good performance for a wide (centrality,p_T,y_{CMS})-range

Flow of higher harmonics: v_3 in MPD-FXT

Systematics sources: different projections, different symmetry planes

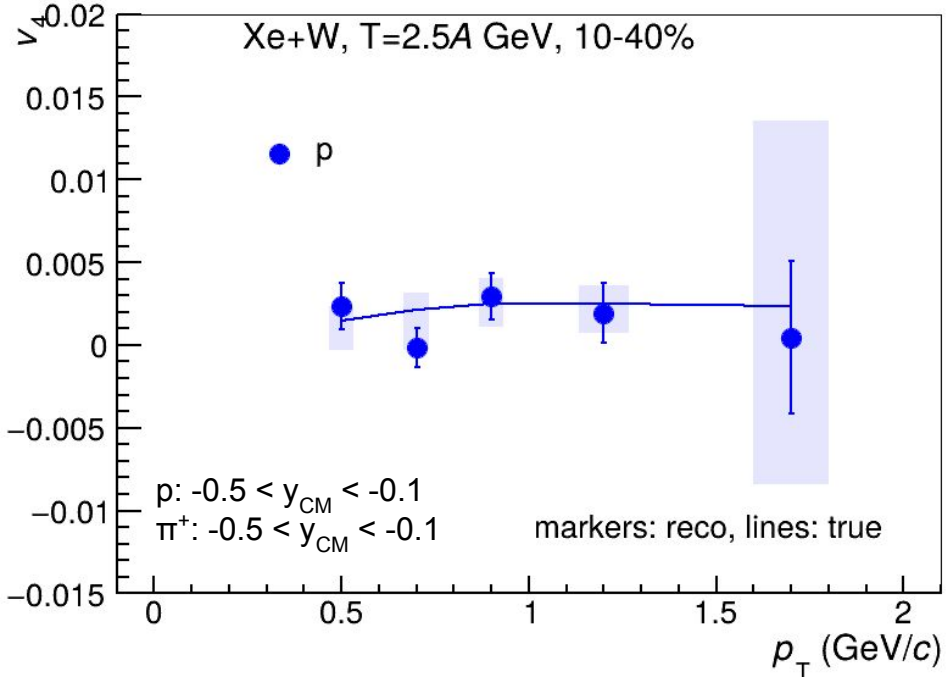


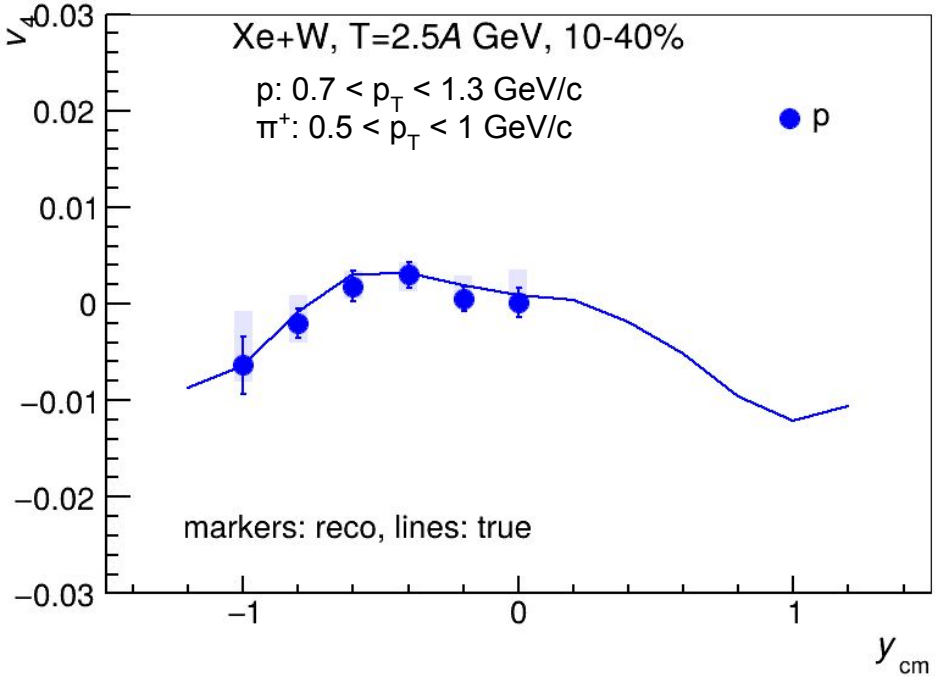


Higher flow harmonics w.r.t. first-order symmetry plane require higher order correlations ⇒ more susceptible to systematics, requires more statistics

Flow of higher harmonics: v_4 in MPD-FXT

Systematics sources: different projections, different symmetry planes
Not enough statistics for pions - only protons are shown





Higher flow harmonics w.r.t. first-order symmetry plane require higher order correlations ⇒ more susceptible to systematics, requires more statistics

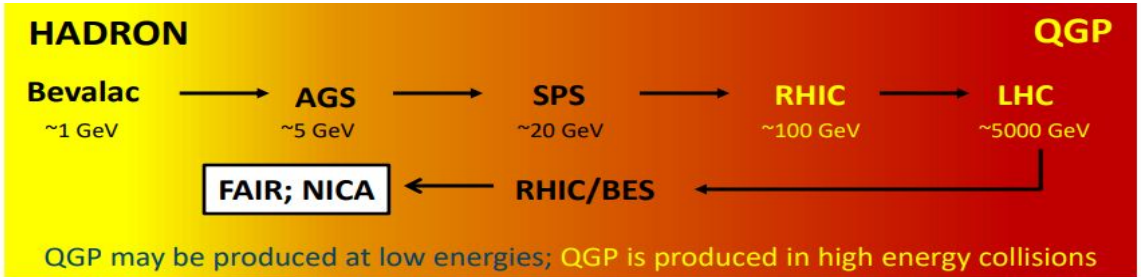
Summary

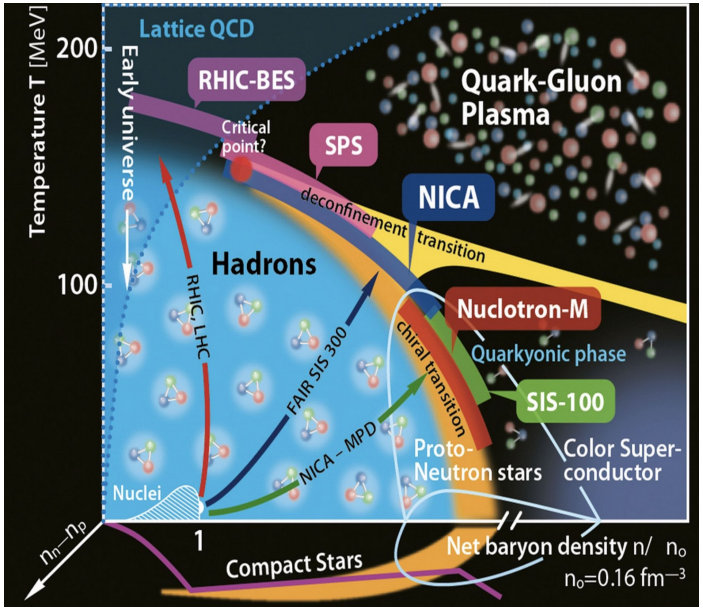
- **Feasibility study shows that MPD-FXT configuration is capable of the precise differential measurements of the anisotropic flow coefficients using realistic centrality determination and particle identification techniques**
- **Directed and elliptic flow of protons and pions were measured for at T=2.5A GeV (√sNN = 2.87 GeV):**
  - Good agreement between reconstructed and model data within corresponding acceptance windows for protons and pions
  - Large data set was prepared with realistic reconstruction - that allows for the differential study of v1 and v2 of identified charged hadrons;
- **Feasibility studies of higher harmonics flow at MPD-FXT:**
  - First results are promising - both v3 and v4 show good agreement between reconstructed and generated data;
  - However, the nature of such measurements requires higher order correlations that are both more demanding of statistics and more susceptible to the systematics bias

Thank you for your attention!

Backup

Relativistic heavy-ion collisions



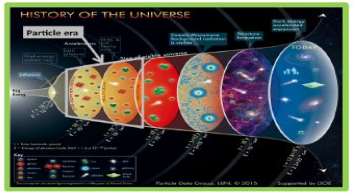


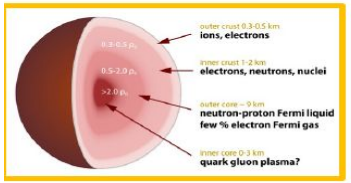
1970s-2000s – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)
2005s – QGP formation was observed at RHIC and it behaves as almost perfect liquid
2005-2010s – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

Since 2010s – Beam energy scans to study QCD phase diagram: search for the 1st order phase transition and CEP at Intermediate T, high μ_B

Relativistic heavy-ion collisions allows us to study QCD phase diagram

- **High beam energies ($\sqrt{s_{NN}}$>100 GeV):**
  - High T, $\mu_B \approx 0$
  - Evolution of the early Universe
- **Low beam energies (2.4<$\sqrt{s_{NN}}$<11 GeV):**
  - Intermediate T, high μ_B
  - Inner structure of the compact stars, neutron star mergers





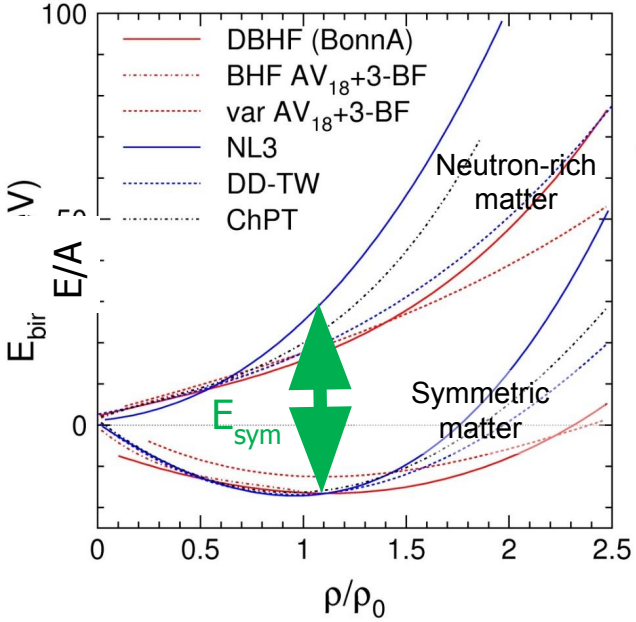
EOS for high baryon density matter

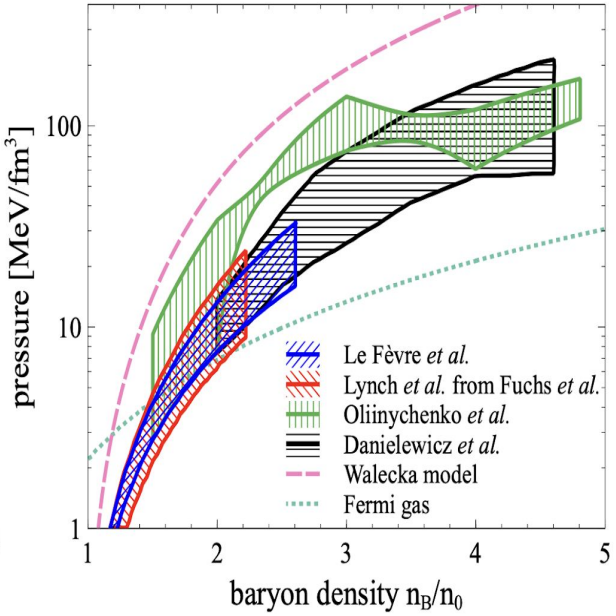
The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

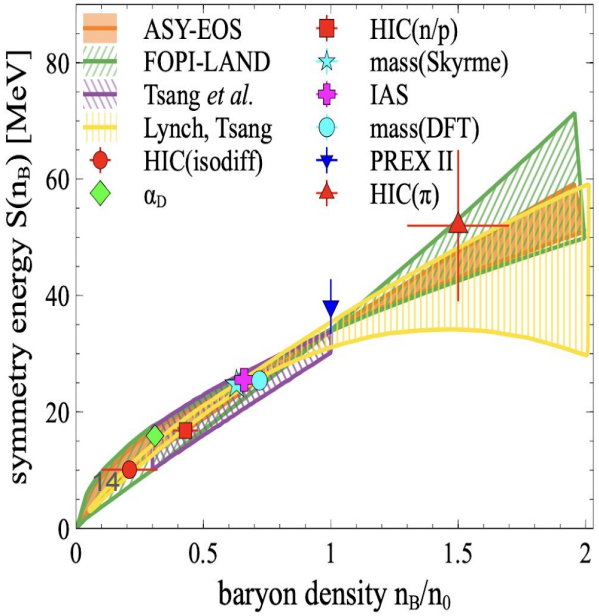
Isospin asymmetry: $\delta = (\rho_n - \rho_p)/\rho$

Symmetric matter

Symmetry energy







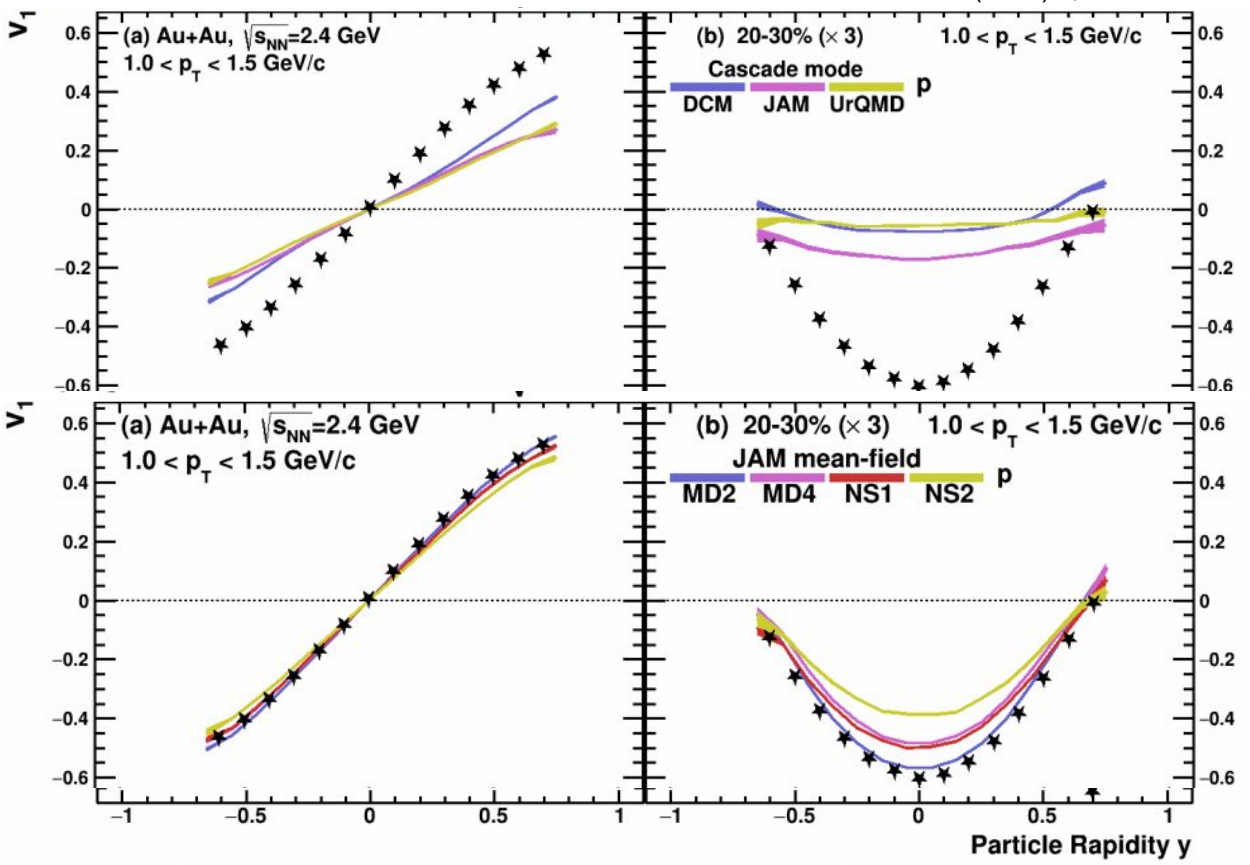
Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

New data is needed to further constrain transport models with hadronic d.o.f.

Selecting the model for the feasibility studies

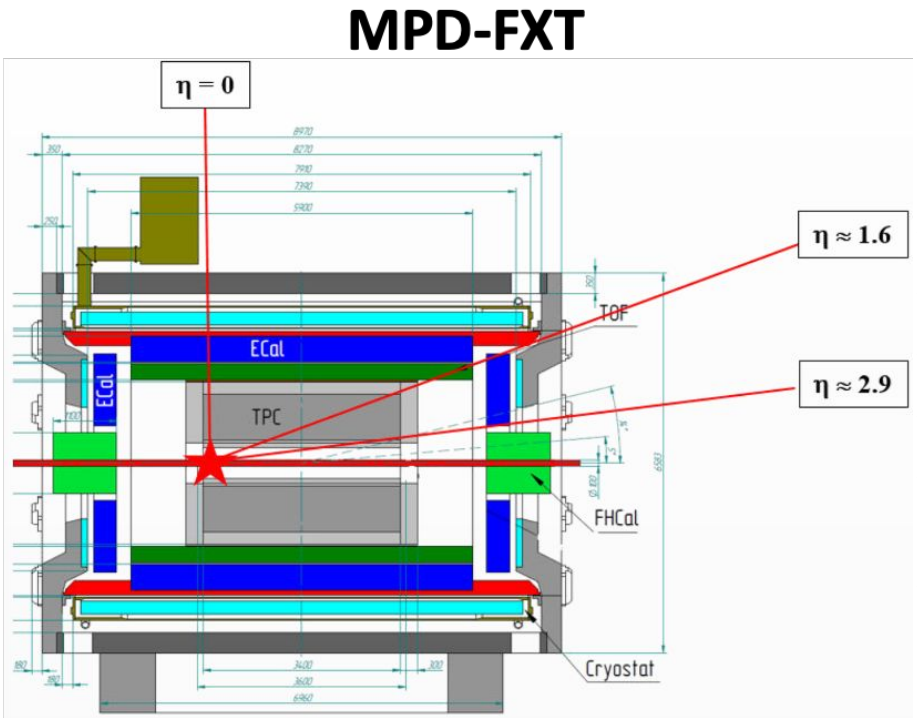
P.Parfenov Particles 5 (2022) 4, 561-579



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

Mean field models reproduce the v_n rather well

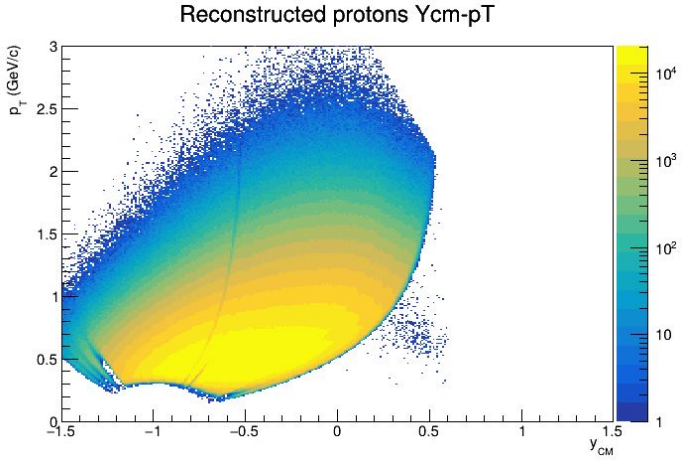
MPD in Fixed-Target Mode (FXT)

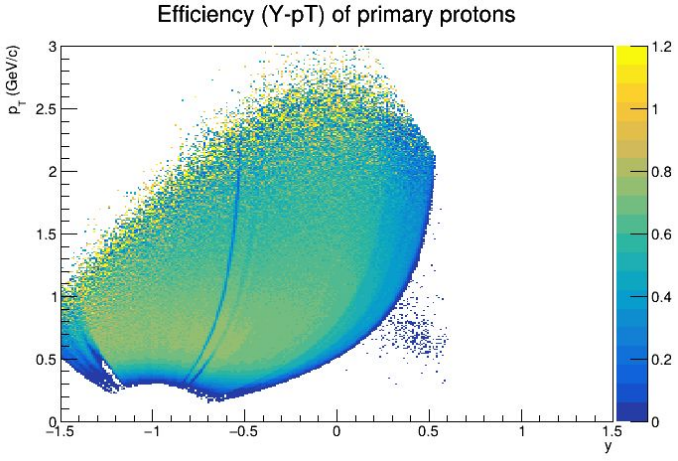


- Model used: UrQMD mean-field
  - Xe+W, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
  - Xe+Xe, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
- Point-like target at z = -85 cm, y = 1 cm
- GEANT4 transport
- Multiplicity-based centrality determination
- PID using information from TPC and TOF
- Primary track selection:
  - DCA<1 cm (protons) DCA<0.2 cm (pions)
- Track selection:
  - N_{hits}>27 (protons), N_{hits}>22 (pions)

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

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





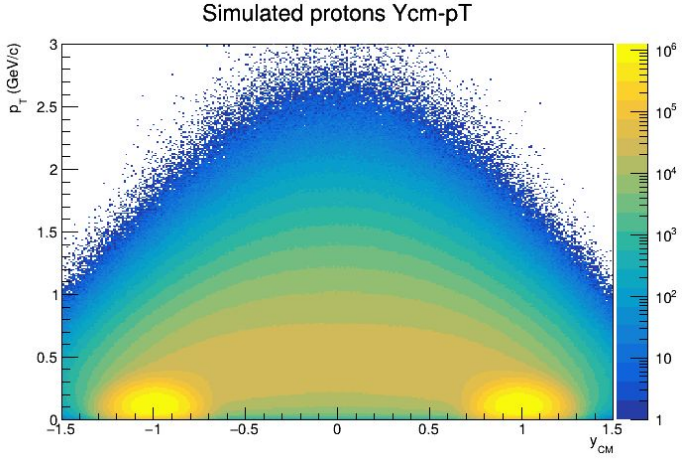
$$\Delta p_T = \frac{|p_T^{\mathrm{reco}} - p_T^{\mathrm{mc}}|}{p_T^{\mathrm{mc}}}$$

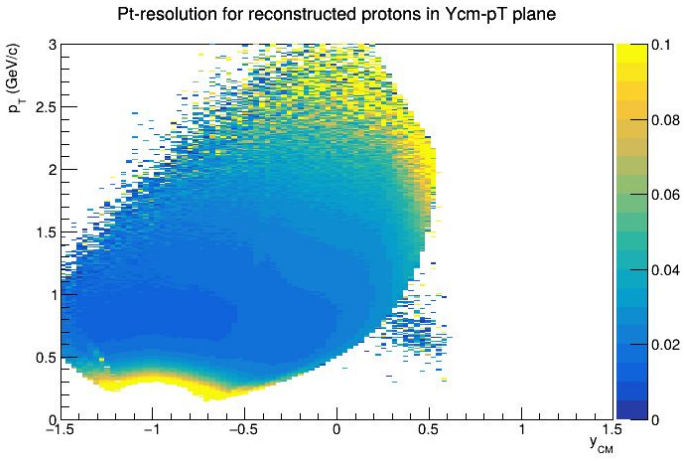
Xe+W/Xe T=2.5A GeV

Cuts for reco tracks:

Protons:

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





Pions:

- Nhits>22
- DCA< 0.2 cm
- PID (TPC+TOF)

Cuts for sim particles:

- PID (pdg code)
- Primary (motherId)

$v_{3,4}$ measurements

For v_3 we would need 4-particle correlations:

$$v_3 = \frac{\langle u_3 Q_1^{F1} Q_1^{F2} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F2} R_1^{F3}} \quad \text{or} \quad v_3 = \frac{\langle u_3 Q_1^{F1} Q_1^{F1} Q_1^{F1} \rangle}{\left(R_1^{F1}\right)^3}$$

The same for F2, F3

And 5-particle for v_4:

$$v_4 = \frac{\langle u_4 Q_1^{F1} Q_1^{F1} Q_1^{F1} Q_1^{F1} \rangle}{\left(R_1^{F1}\right)^4}$$

The same for F2, F3

That includes 8 non-zero components for v_3 and 16 for v_4, which may increase the systematic uncertainty and ultimately require more statistics for robust measurements.

Such multi-particle correlations were implemented in QnTools framework