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

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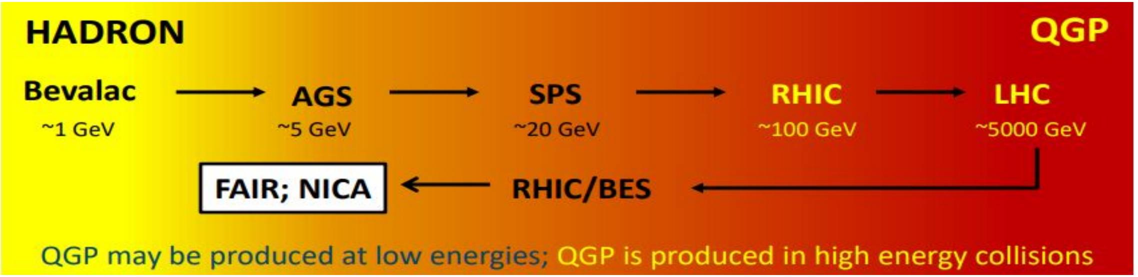
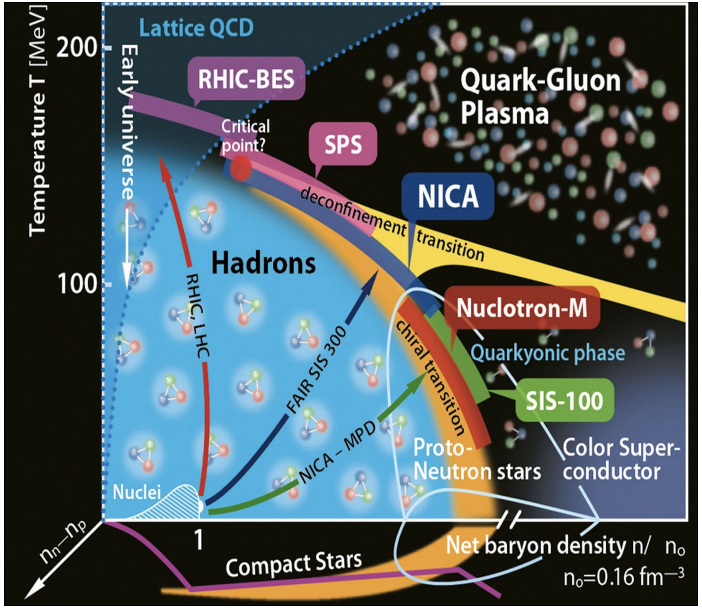
Relativistic heavy-ion collisions



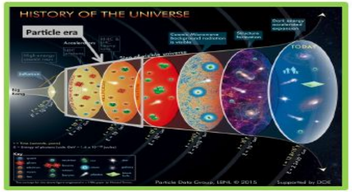
<u>1970s-2000s</u> – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)
<u>2005s</u> – QGP formation was observed at RHIC and it behaves as almost perfect liquid
<u>2005-2010s</u> – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

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

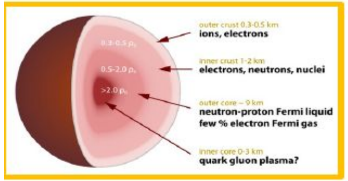


Relativistic heavy-ion collisions allows us to study QCD phase diagram

➢ **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

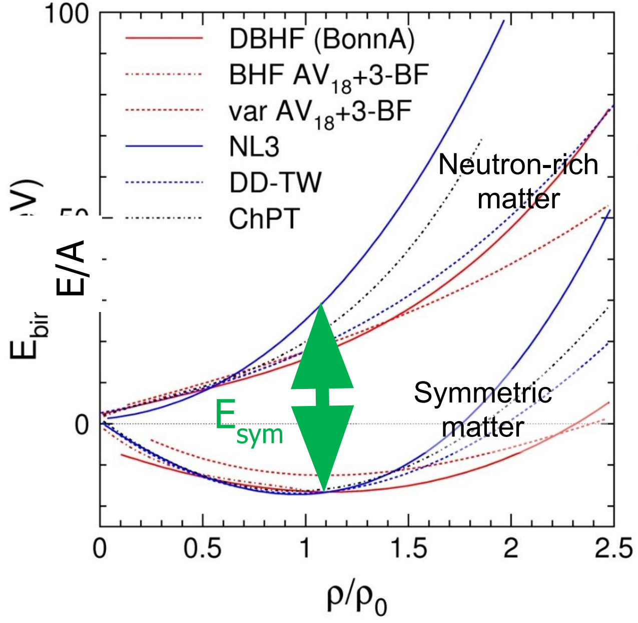
The binding energy per nucleon: $E_A(\rho, \delta) = \boxed{E_A(\rho, 0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

Isospin asymmetry:

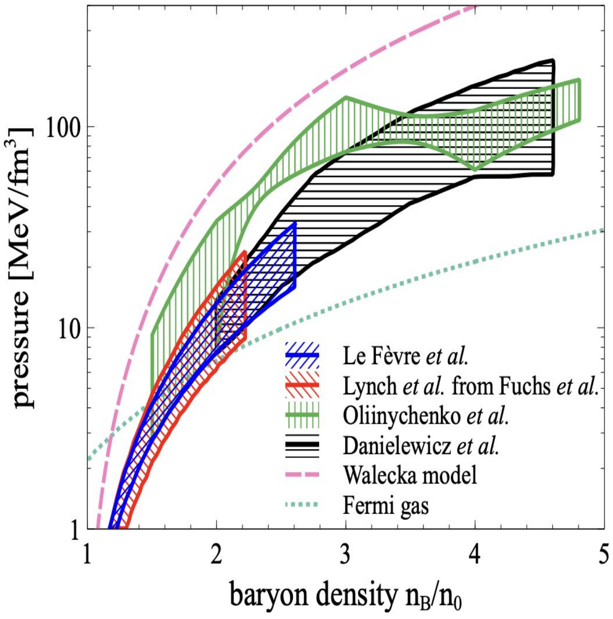
$$\delta = (\rho_n - \rho_p)/\rho$$

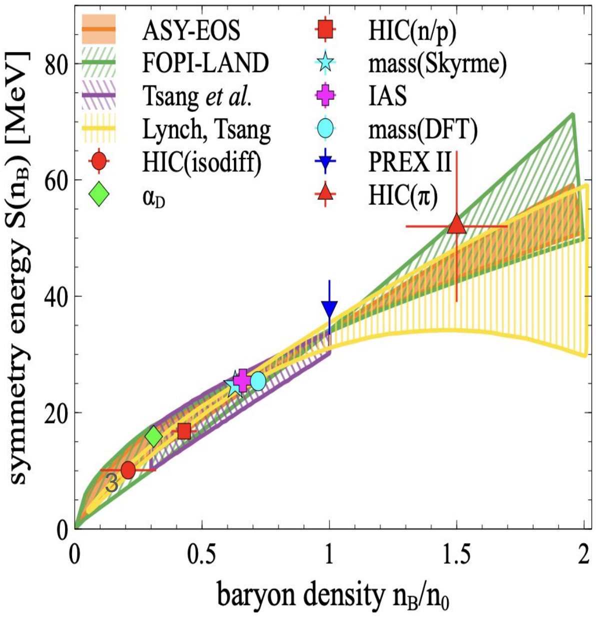
Symmetric matter

Symmetry energy



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

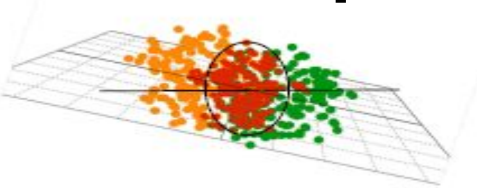




A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

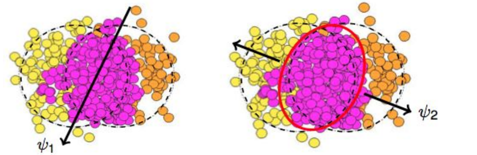
New data is needed to further constrain transport models with hadronic d.o.f.

Anisotropic flow



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

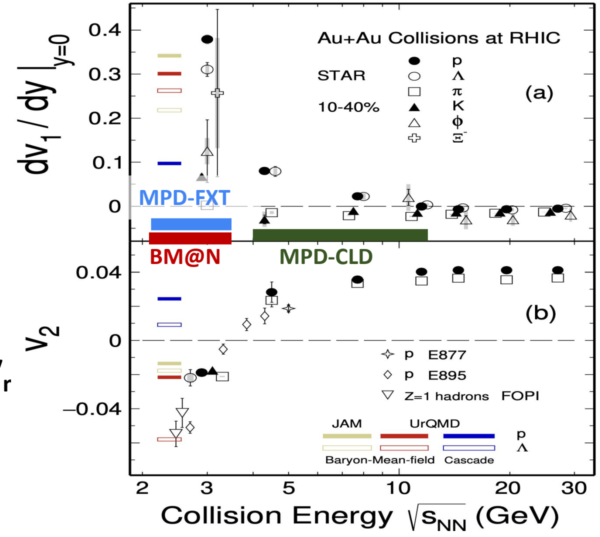
v_1 - directed flow; v_2 - elliptic flow;



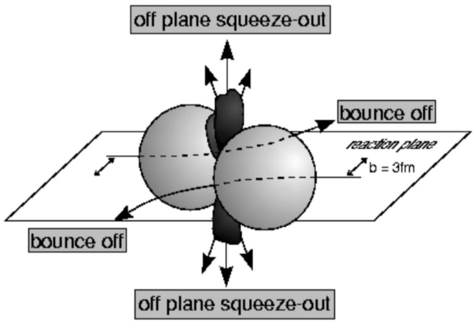
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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

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

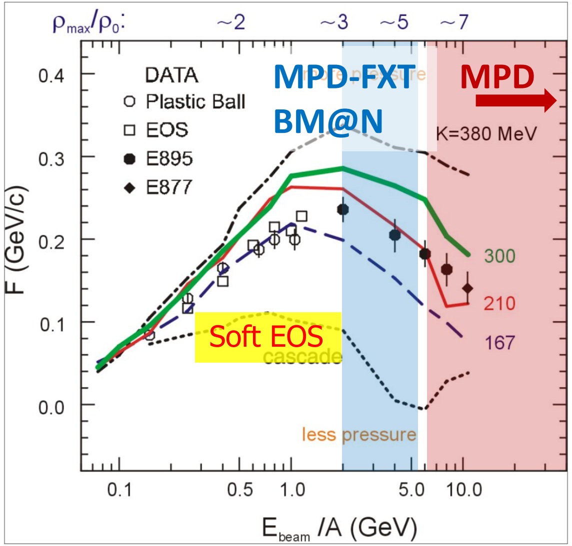
Anisotropic flow at Nuclotron-NICA energies is a delicate balance between:

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

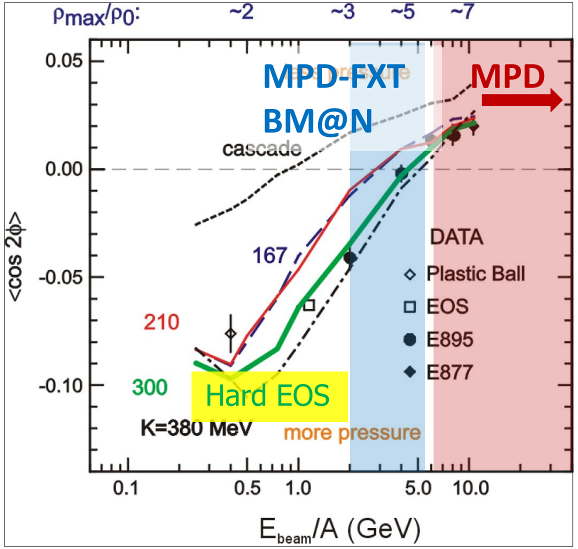
II. **The passage time for removal of the shadowing by spectators** $(t_{pass} = 2R/\gamma_{CM}\beta_{CM})$

Sensitivity of the collective flow to the EOS

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



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



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

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:

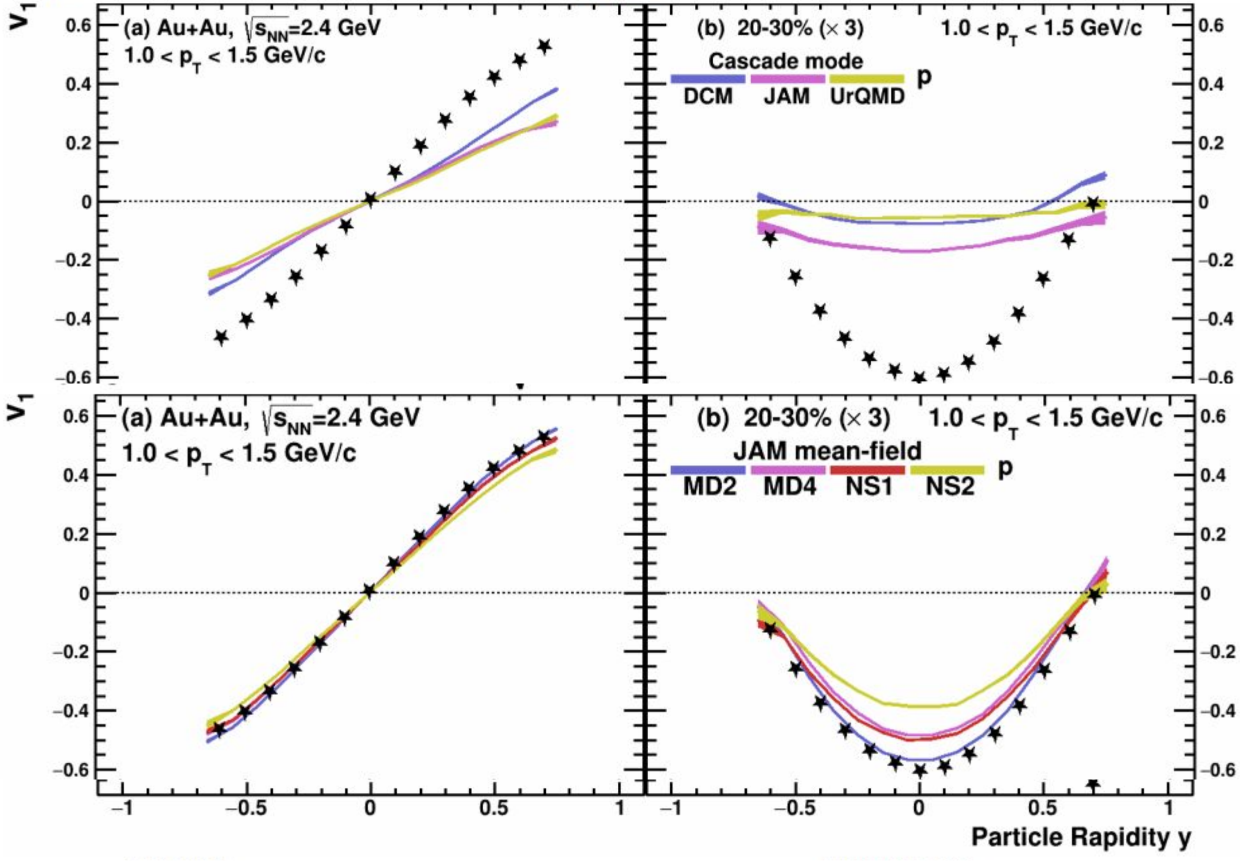
- v_1 suggests soft EoS ($K_0 \approx 210$ MeV)
- v_2 suggests hard EoS ($K_0 \approx 380$ MeV)

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

Additional measurements are essential to clarify the previous results

Selecting the model for the feasibility studies

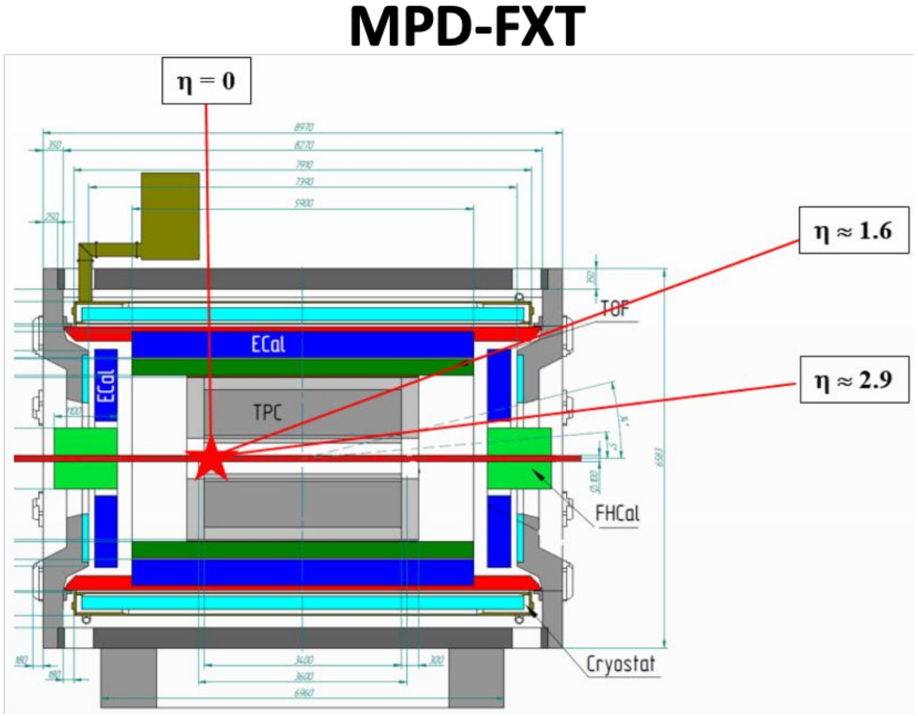
P.Parfenov Particles 5 (2022) 4, 561-579



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

Mean field models reproduce the v_n rather well

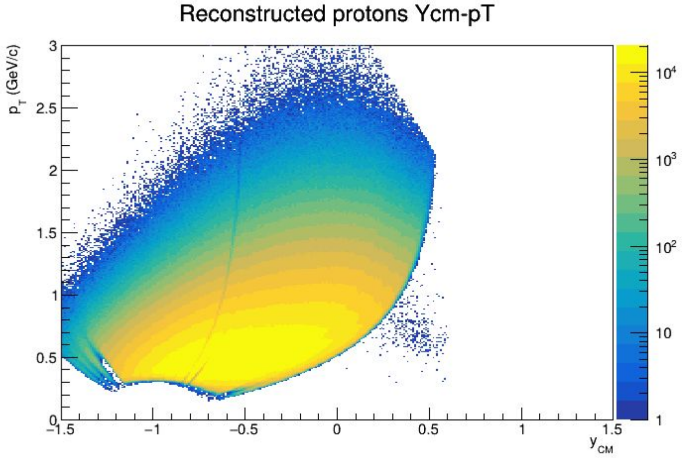
MPD in Fixed-Target Mode (FXT)

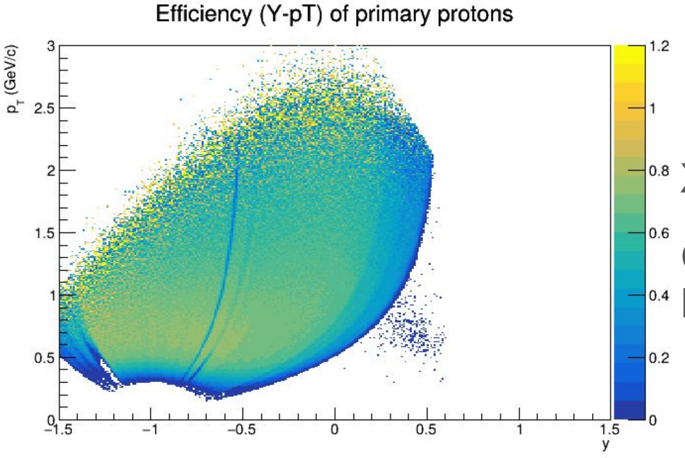


- Model used: UrQMD mean-field
    - Xe+W, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
    - Xe+Xe, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
- Point-like target at z = -85 cm, y = 1 cm
- GEANT4 transport
- Multiplicity-based centrality determination
- PID using information from TPC and TOF
- Primary 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)

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





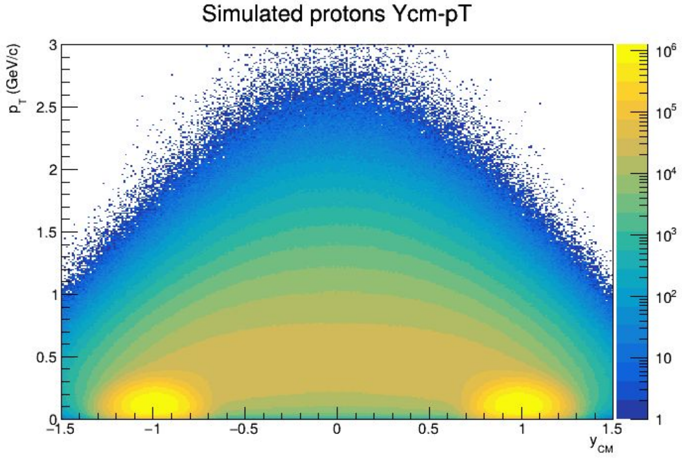
$$\Delta p_T = \frac{|p_T^{\mathrm{reco}} - p_T^{\mathrm{mc}}|}{p_T^{\mathrm{mc}}}$$

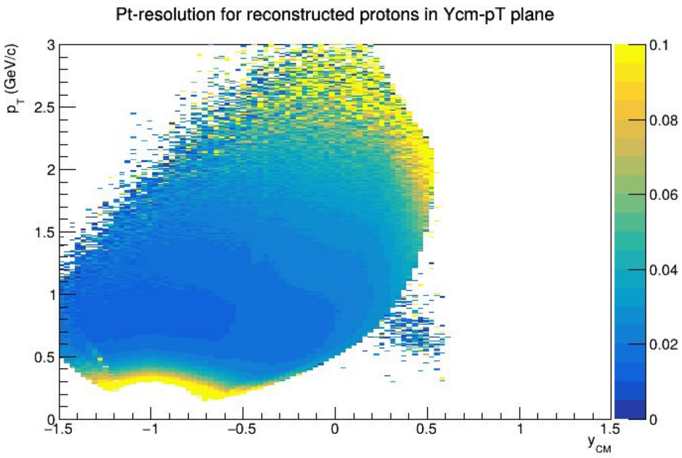
Xe+W/Xe T=2.5A GeV

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)

Flow vectors

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

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

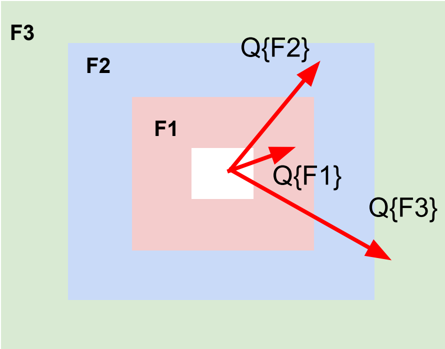
where φ is the azimuthal angle

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

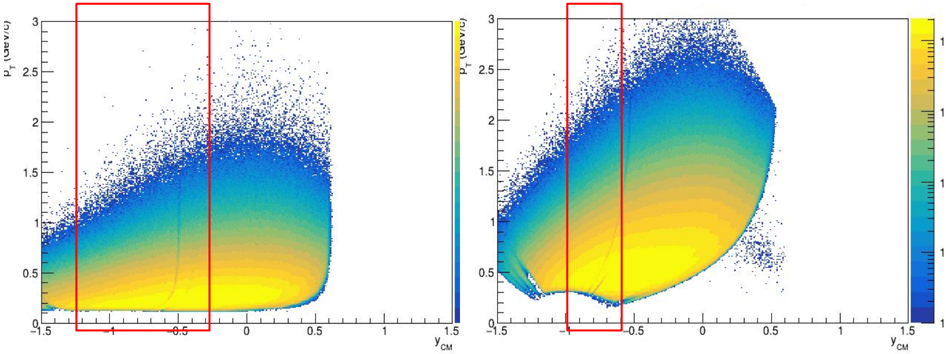
$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

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

Tested in HADES:

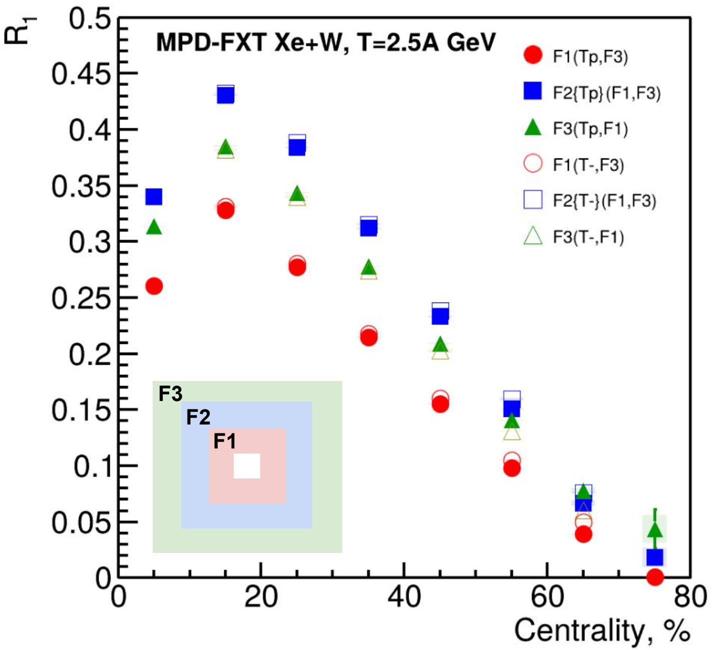
M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

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):

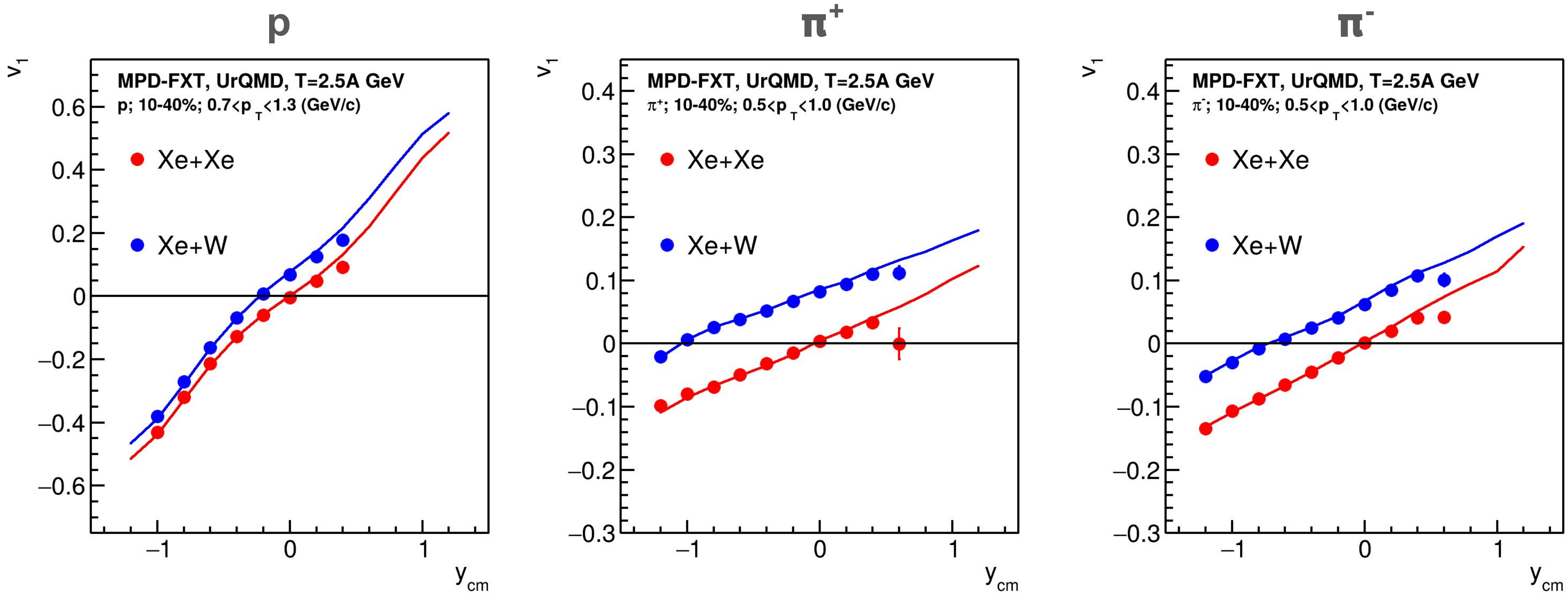
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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: $v_1(y)$

markers - reco; lines - model

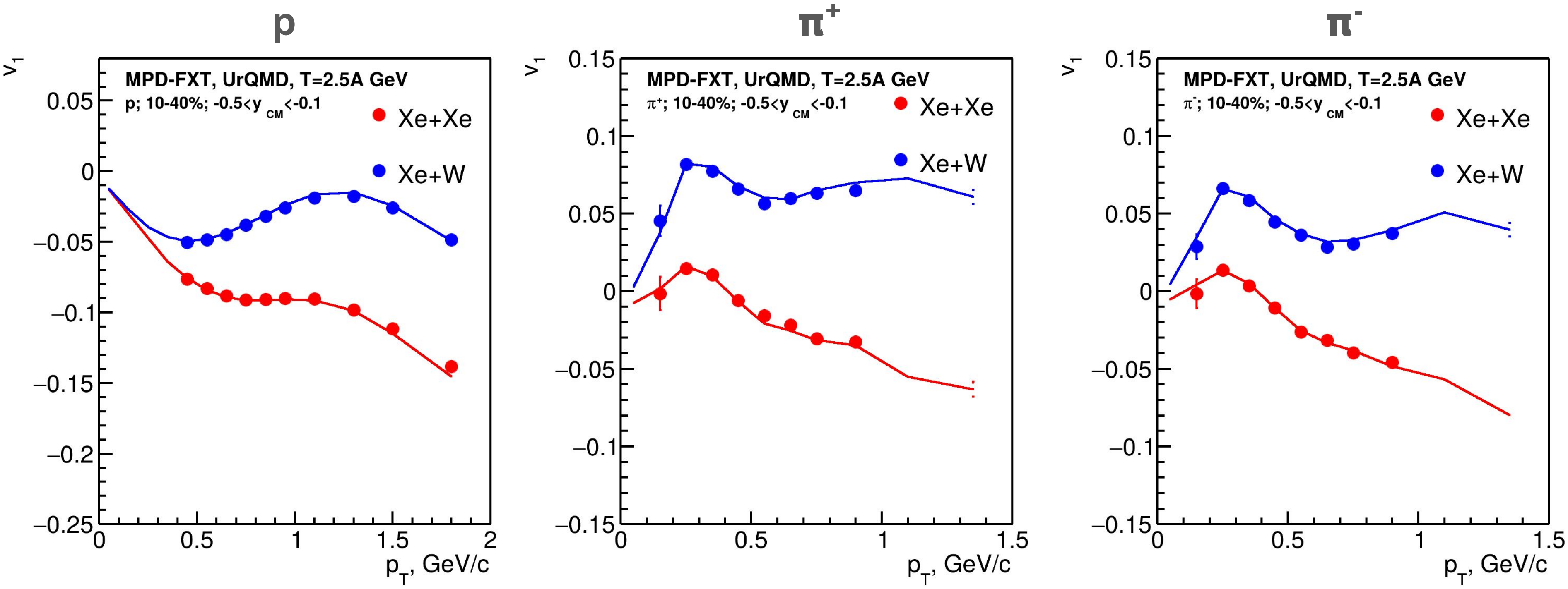


Good agreement for protons and pions for y<0.5

Clear shift in $v_1(y_{cm})$ for Xe+W - preferential deflection of the participants

Results: $v_1(p_T)$

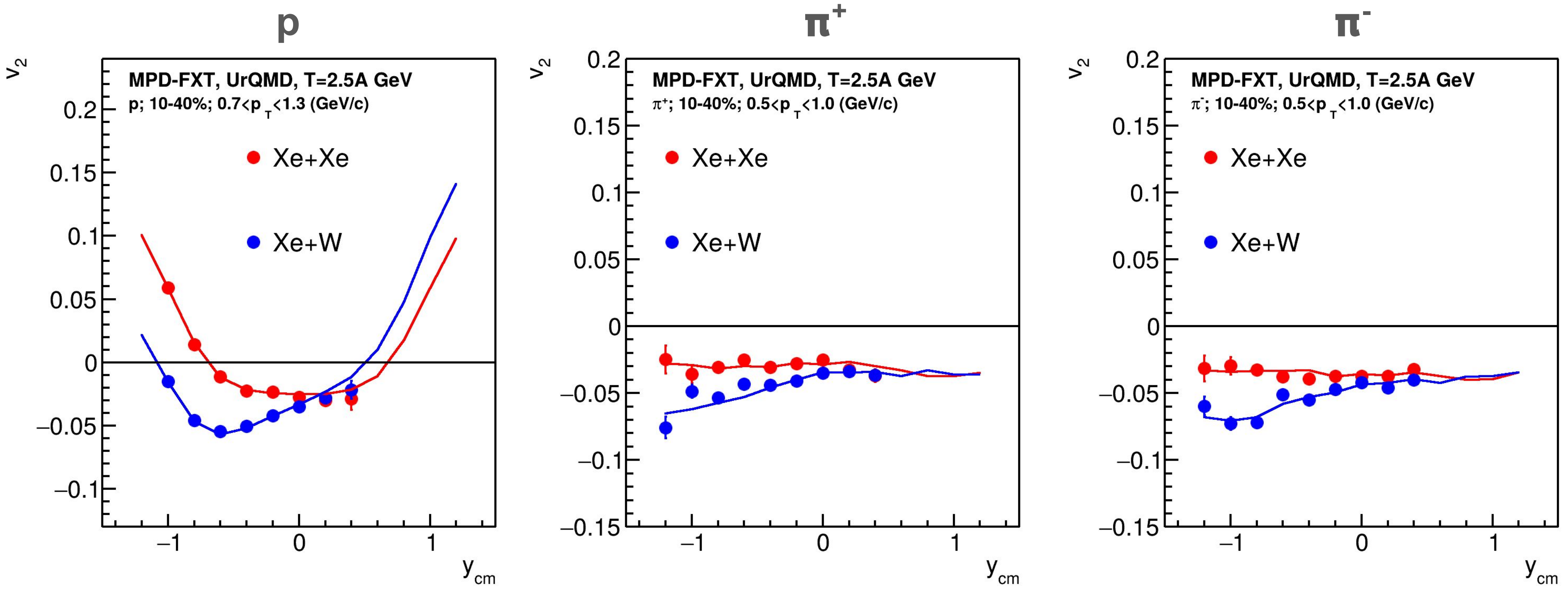
markers - reco; lines - model



Good agreement for protons and pions

Results: $v_2(y)$

markers - reco; lines - model

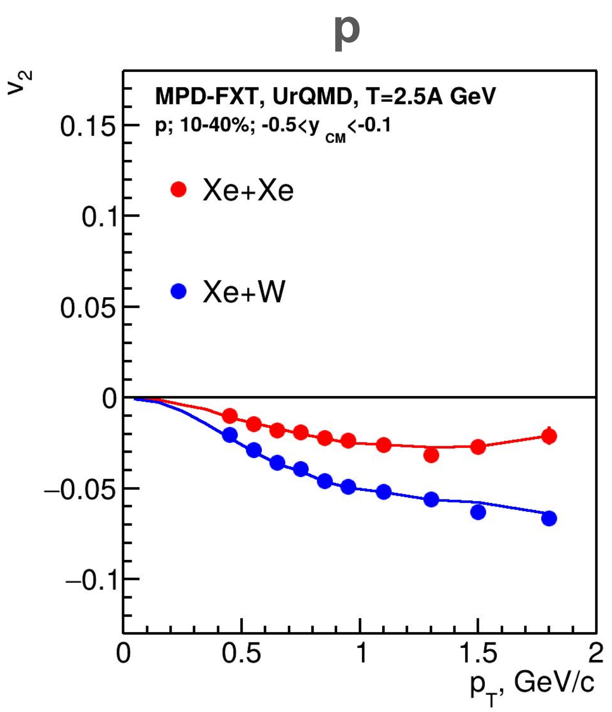


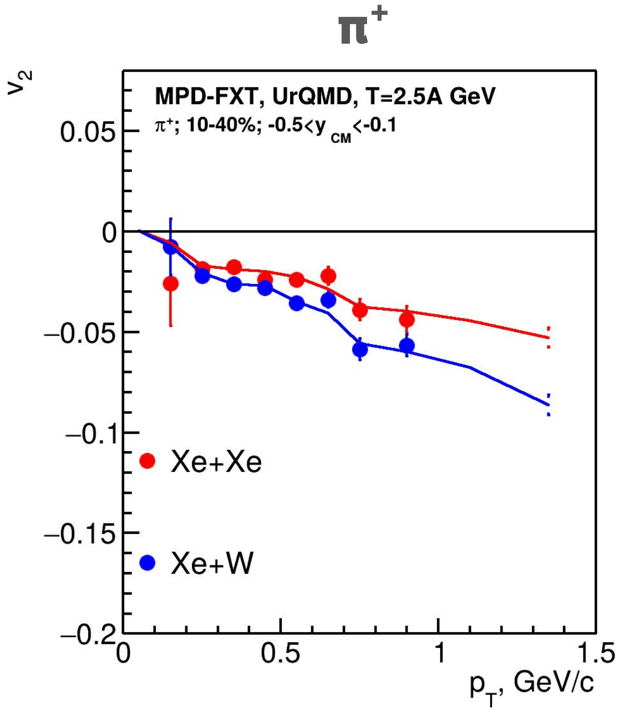
Good agreement for protons and pions for y<0.5

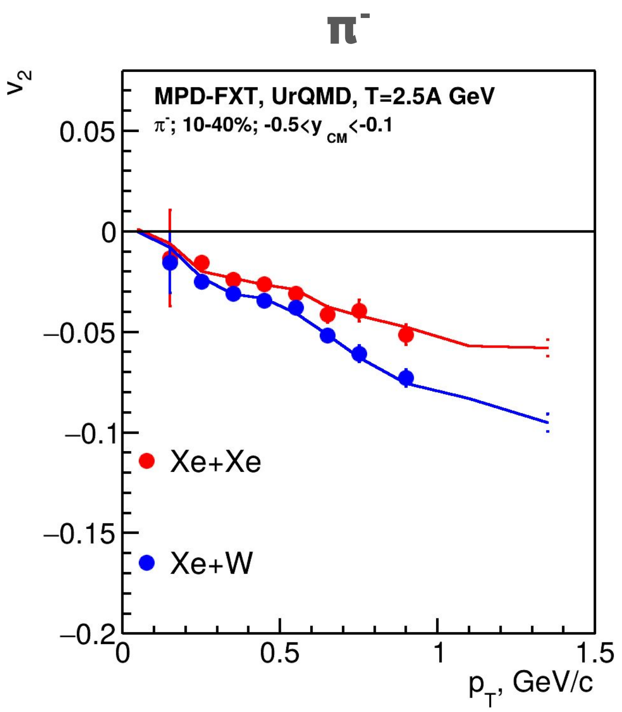
Asymmetric $v_2(y_{cm})$ dependence for Xe+W

Results: $v_2(p_T)$

markers - reco; lines - model







Good agreement for protons and pions

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**

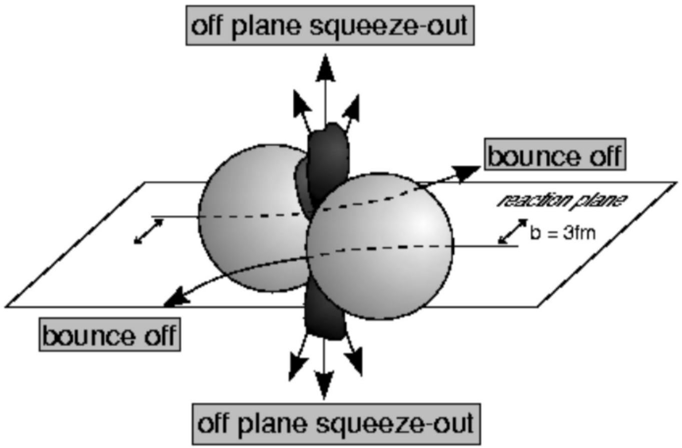
- **Directed and elliptic flow of protons and pions were measured for at T=2.5A GeV ($\sqrt{s_{NN}}$ = 2.87 GeV):**
  - Good agreement between reconstructed and model data within corresponding acceptance windows for protons and pions

- **Two colliding systems (Xe+W, Xe+Xe) were compared:**
  - There is a clear shift in $v_1(y_{cm})$ for Xe+W, consistent with the participant deflection dynamics in asymmetric systems;
  - Noticeable $v_2(y_{cm})$ dependence in both systems, with characteristically asymmetric behavior for Xe+W collisions

Thank you for your attention!

Backup

Anisotropic flow & spectators



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

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

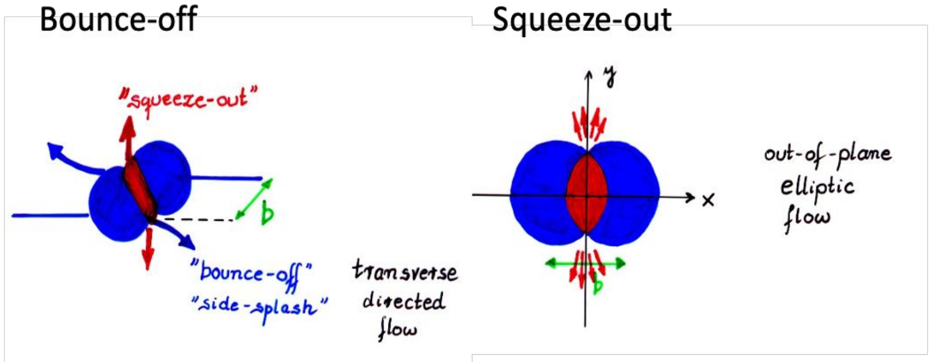
Anisotropic flow:

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

v_1 - directed flow, v_2 - elliptic flow

Anisotropic flow is sensitive to:

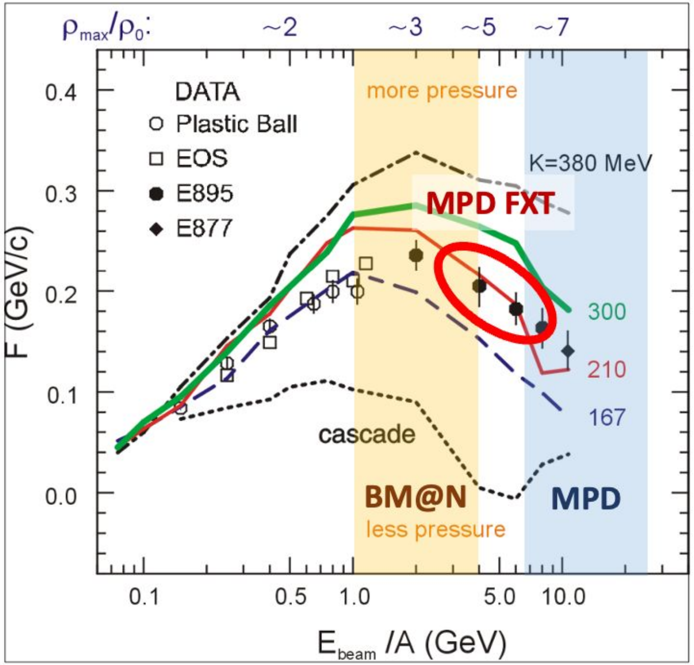
- ➢ Compressibility of the created matter $\left(t_{exp} = R/c_s,\ c_s = c\sqrt{dp/d\varepsilon}\right)$
- ➢ Time of the interaction between overlap region and spectators $\left(t_{pass} = 2R/\gamma_{CM}\beta_{CM}\right)$



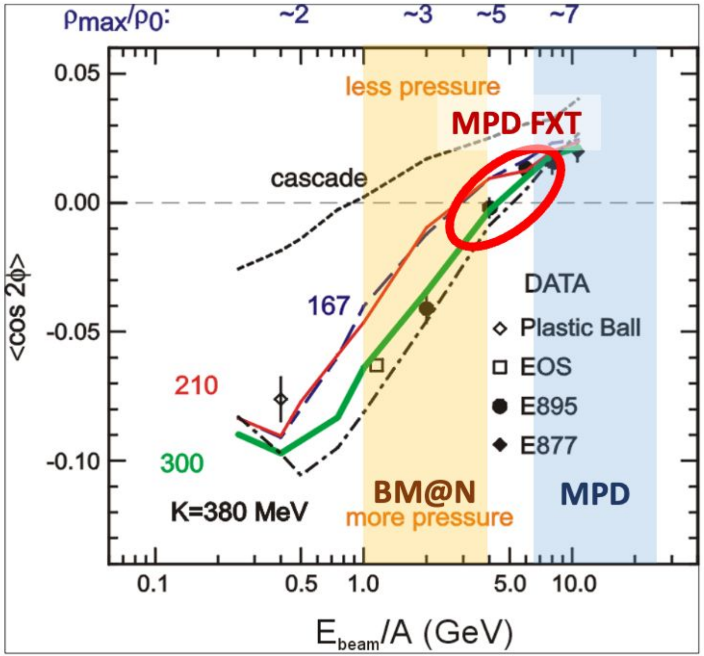
v_n at Nuclotron-NICA energies

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

v_1 suggests soft EoS



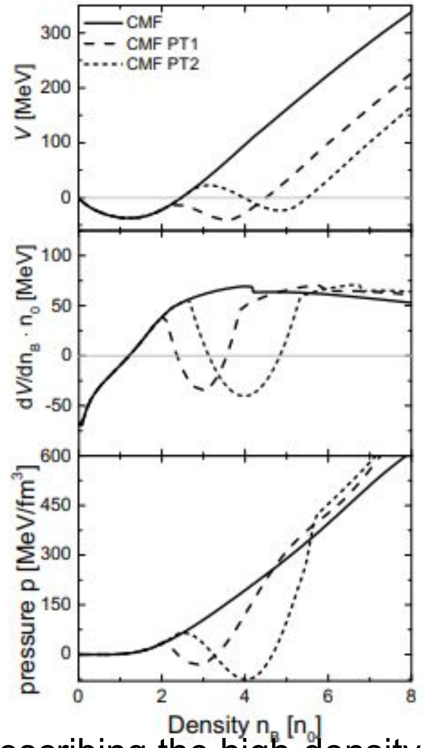
v_2 suggests hard EoS



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

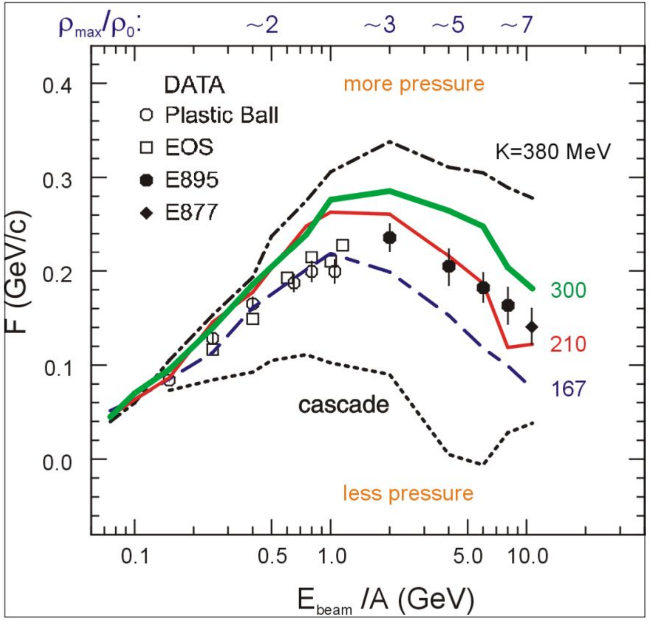
v_n as a function of collision energy

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

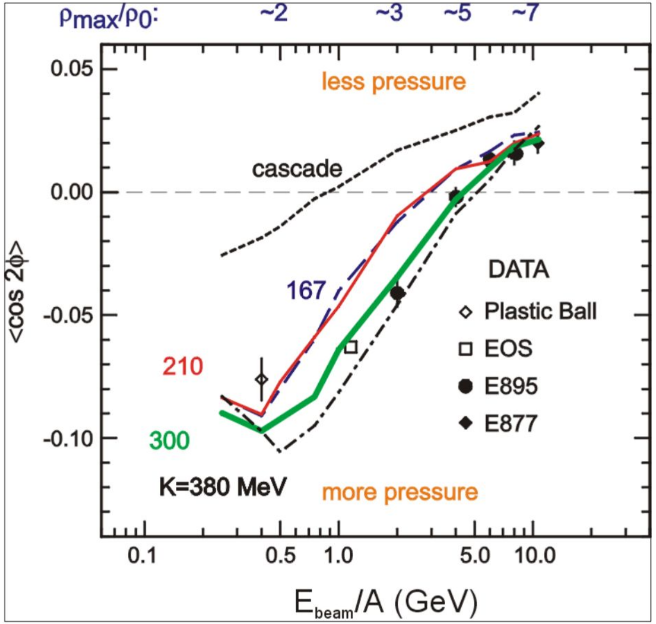


EPJ Web of Conferences 276, 01021 (2023)

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 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:

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

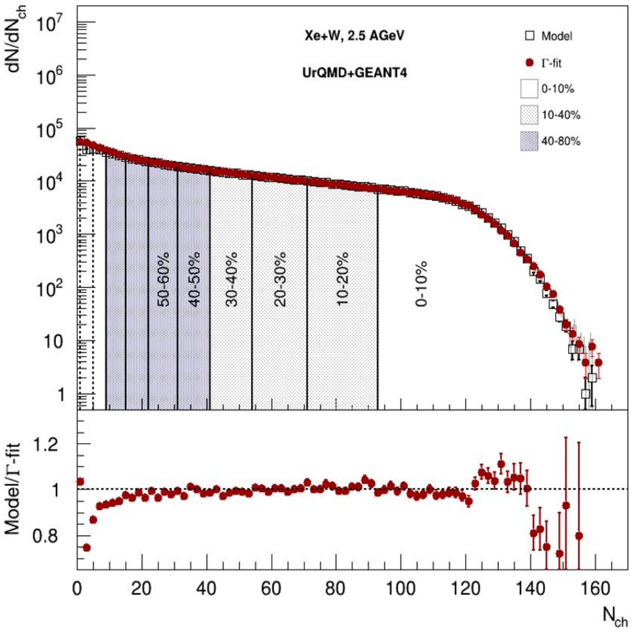
Fit experimental (model) distribution with P(N)

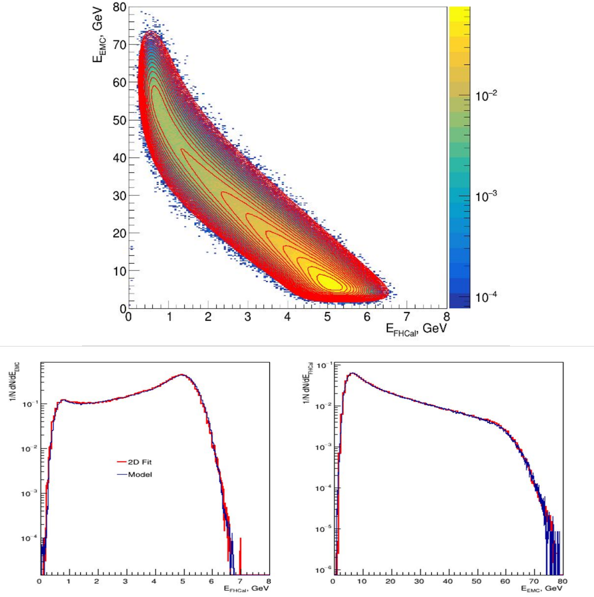
↓

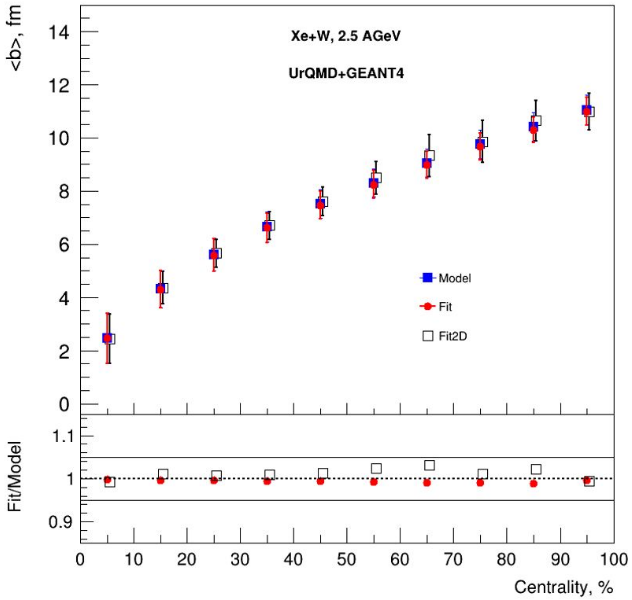
Construct P(b|E) using Bayes' theorem:
P(b|N) = P(b)P(N|b)/P(N)

Bayesian approach for centrality in MPD-FXT

See D. Idrisov's talk





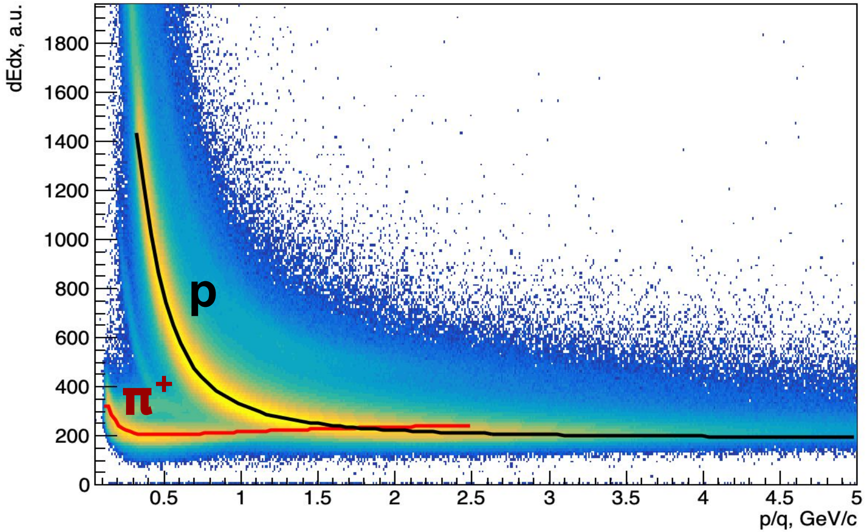


Both 1D and 2D bayesian inversion techniques can be employed for centrality determination

We can suppress auto-correlation effects by using energy from EMC (with specific selection) it is important for fluctuation studies (cumulants of net-proton, kaons, etc.)

PID procedure

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

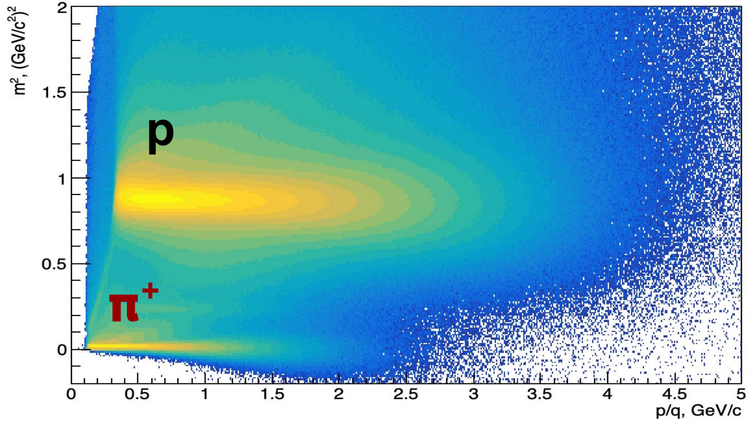


Fit dE/dx distributions with Bethe-Bloch parametrization:

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

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

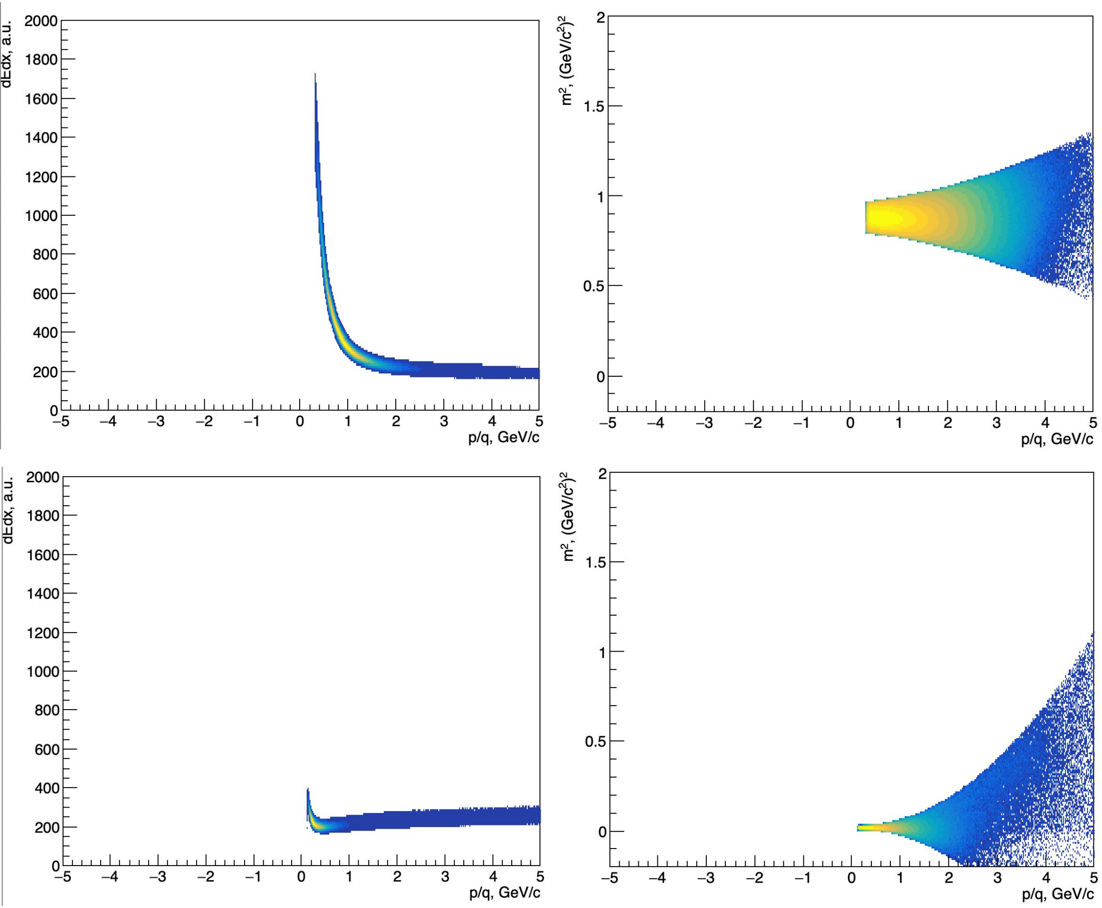


Fit m^2 with gaus in the slices of p/q and get $\sigma_p(m^2)$

(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:

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

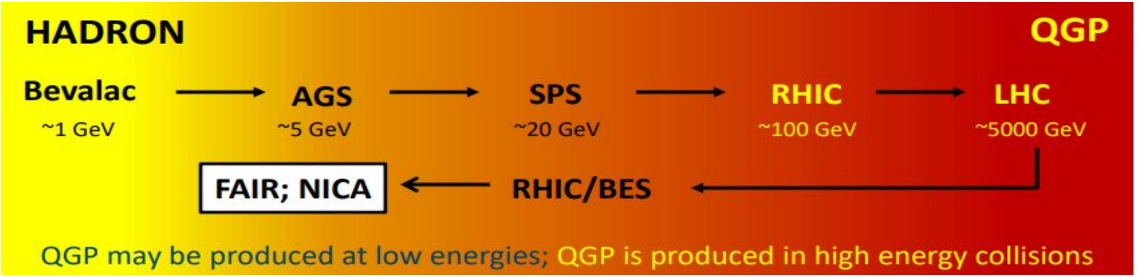
Pions (π^+):

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

Pions (π^-):

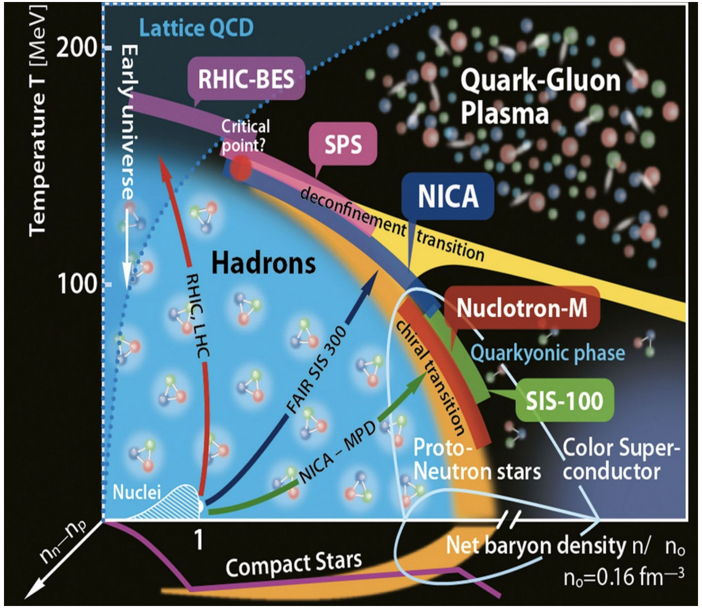
charge<0

Relativistic heavy-ion collisions



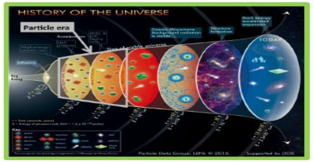
<u>1970s-2000s</u> – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)
<u>2005s</u> – QGP formation was observed at RHIC and it behaves as almost perfect liquid
<u>2005-2010s</u> – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

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

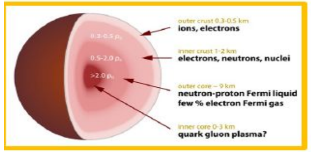


Relativistic heavy-ion collisions allows us to study QCD phase diagram

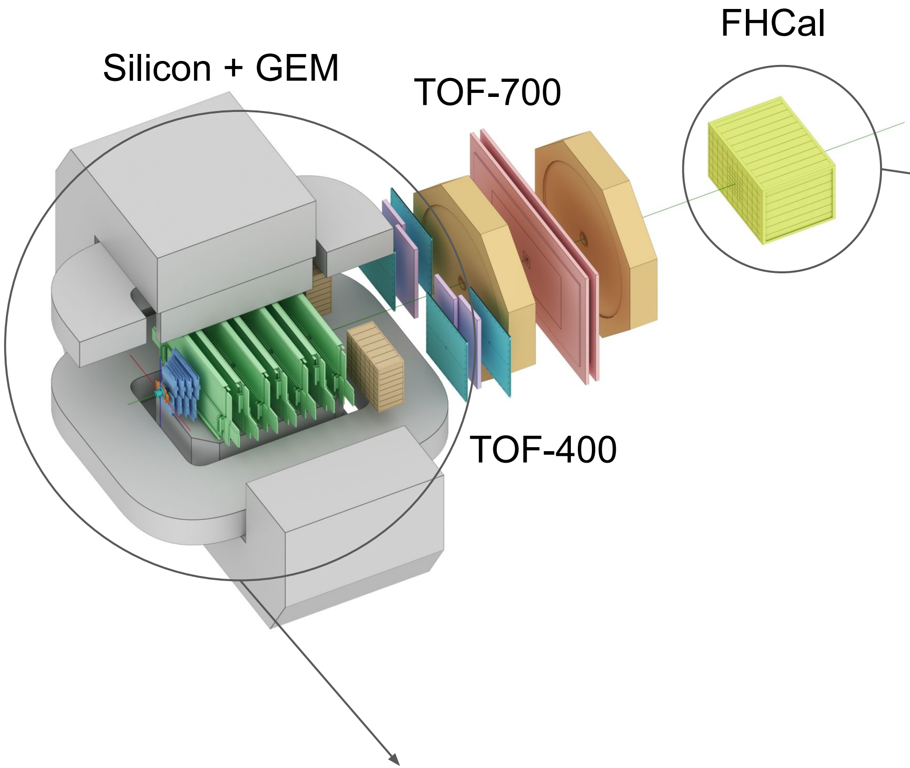
- **High beam energies ($\sqrt{s_{NN}}$>100 GeV):**
  - High T, $\mu_B \approx 0$
  - Evolution of the early Universe

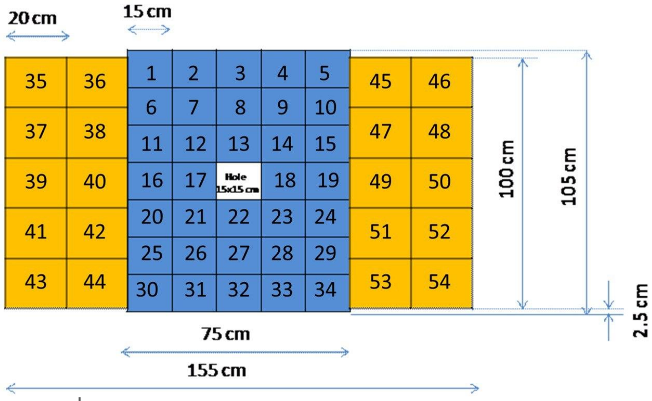


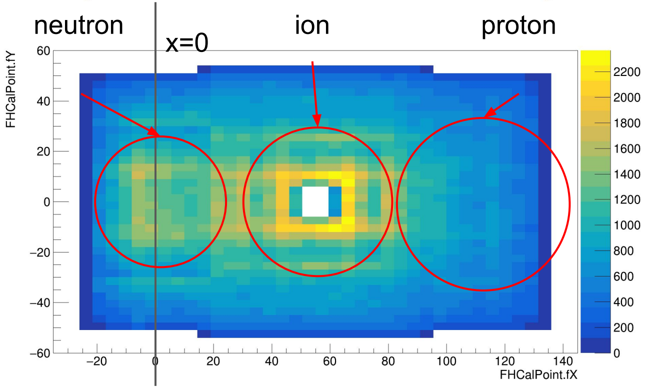
- **Low beam energies (2.4<$\sqrt{s_{NN}}$<11 GeV):**
  - Intermediate T, high μ_B
  - Inner structure of the compact stars, neutron star mergers



The BM@N experiment (GEANT4 simulation for RUN8)



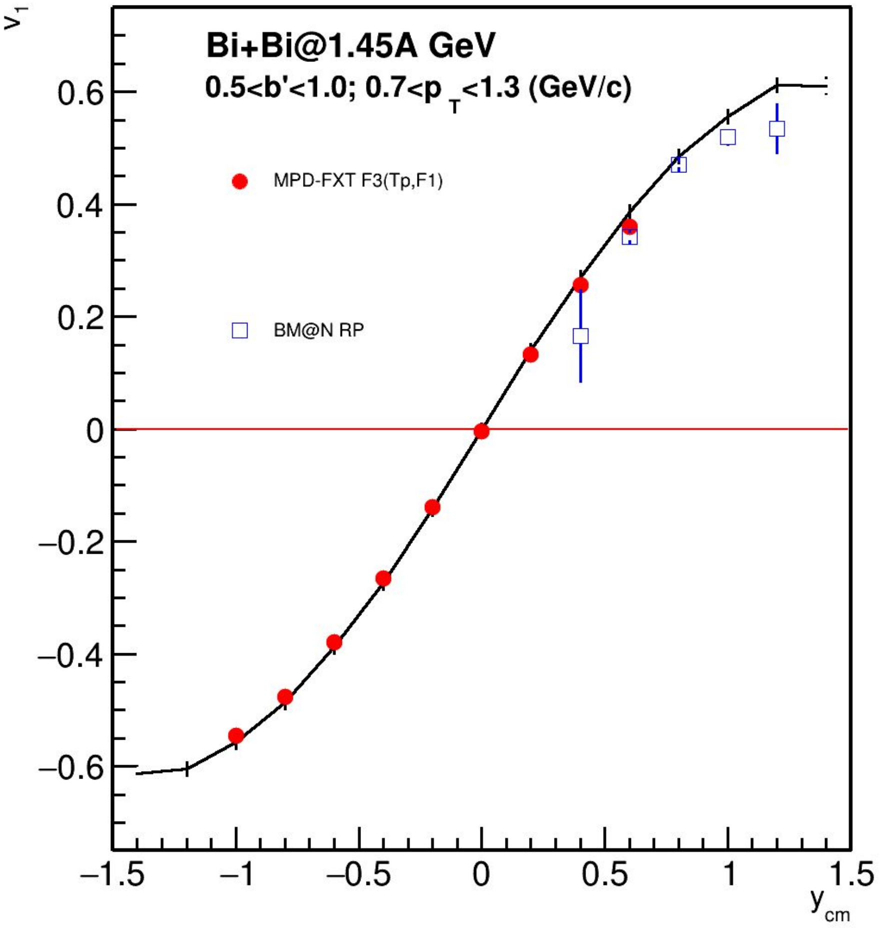




Square-like tracking system within the magnetic field deflecting particles along X-axis

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