Directed flow of protons in Xe+CsI collisions at the beam energy of 3.8A GeV with the BM@N experiment

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Abstract

In heavy-ion collisions at beam energies of several GeV per nucleon, hot and dense strongly interacting matter is formed—a state of matter akin to that found in astrophysical environments such as neutron star interiors and neutron star mergers. Collective flow, particularly the directed flow of particles produced in these collisions, serves as a sensitive probe of the properties of this extreme matter. We present the first measurements of proton directed flow in Xe+CsI collisions at 3.8A GeV, obtained by the BM@N experiment during its 2023 data-taking campaign. The results show good agreement with existing world data, confirming the consistency of our measurements with previous experimental findings. Additionally, we compare our data with theoretical predictions from the Jet-AA-Model, providing new insights into the dynamics of nuclear matter under extreme conditions.

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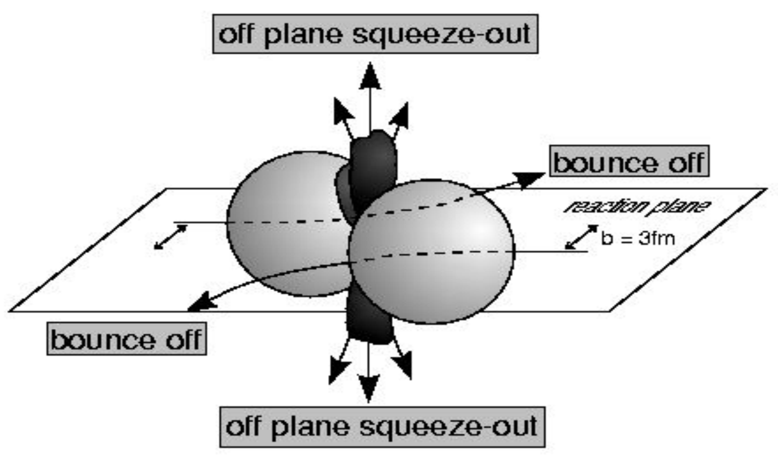
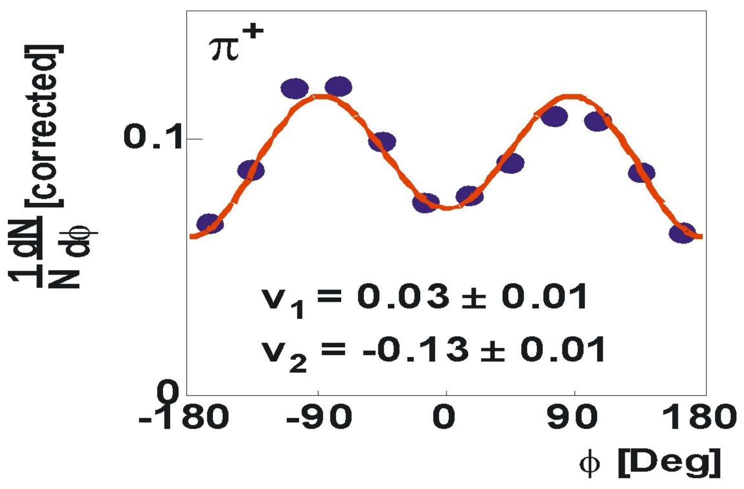
Anisotropic flow





Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)
Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)

Spatial asymmetry of the energy distribution within the overlap region transforms into momentum anisotropy of the produced particles. The anisotropy is observed with respect to **Reaction Plane** spanned on the vectors of impact parameter and beam direction and quantified by decomposing the azimuthal angle distribution with respect to reaction plane:

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

coefficients of the decomposition:

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

v_1 is directed flow, v_2 — elliptics and v_3 — triangular

Equation of state of compressed baryonic matter

Energy per nucleon in dense baryonic matter can be described by the formula:

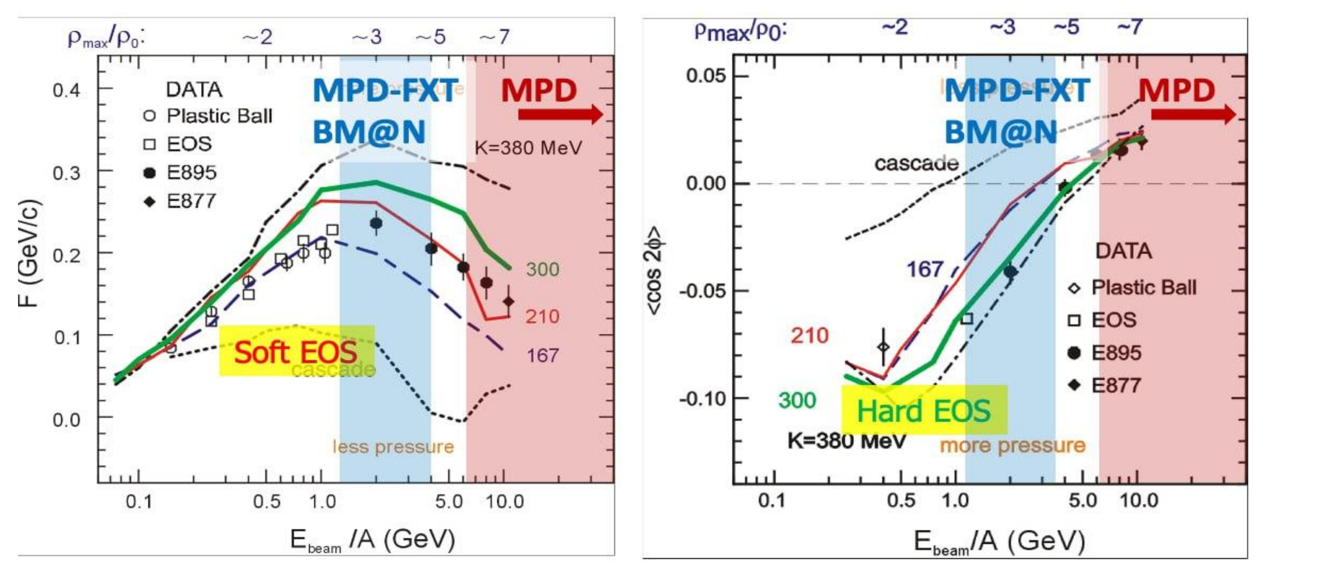
$$\frac{E}{A} = E_A(n_B) + E_{sym}(n_B)\frac{(n_p - n_n)^2}{n_B^2}$$

where E_A is a term for isospin-symmetric matter, E_{sym} is the term for isospin-asymmetry and n_p and n_n is the number of protons and neutrons respectively, while $n_B = n_p + n_n$.

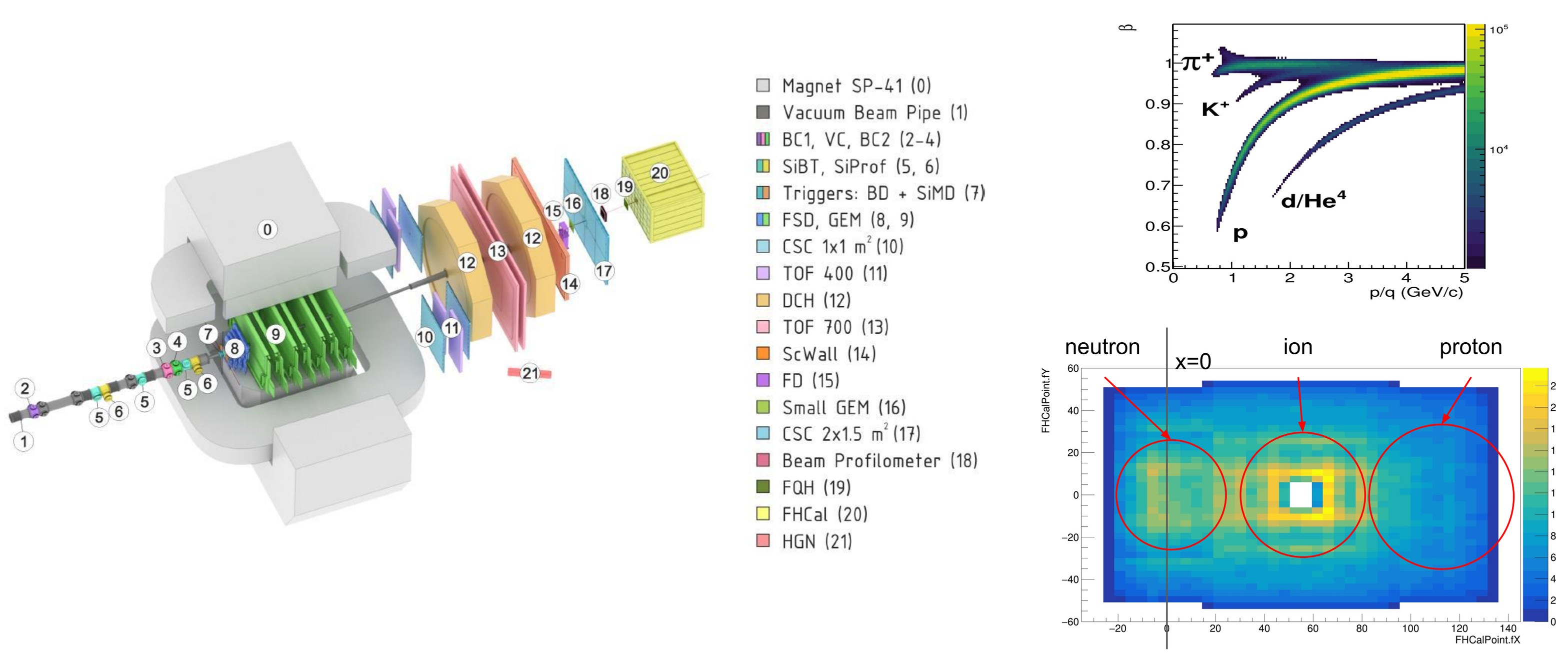
Comparing the theoretical predictions for anisotropic flow with experimental measurements from AGS it was observed that data for v_1 are better described with softer Equation of State (K_{nm}~210 MeV) whereas for v_2 harder Equation of State (K_{nm}~300-380 MeV) is more suitable

Additional measurements are required to address the discrepancy

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



The Baryonic Matter at Nuclotron (BM@N) spectrometer



In early 2023 Baryonic matter at Nuclotron (BM@N) finished its first physical run collecting more than 500M Xe+CsI collisions at the beam energy of 3.8*A* GeV

For reconstructing the trajectories of charged particles the Central Tracking system was used consisting of 4 planes of Forward Silicon Detector (8) and 7 planes of Gaseous Electron Multipliers (9). Tracking system is placed in a magnetic field of SP-41 analysing magnet (0). Particle identification was carried out using 2 Time-Of-Flight detectors TOF400 (11) and TOF700 (13) constructed of multigap Resistive Plate Chambers.

Remnants of colliding nuclei (spectators) are deflected by the expanding matter within the overlap region of colling ions in reaction plane. Using the asymmetry of the energy deposition in Forward Hadron Calorimeter (FHCal, 20) one can estimate the reaction plane orientation in each event

Flow vectors in the BM@N experiments

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

$$u_n = (\cos n\varphi, \sin n\varphi)$$

where φ is the azimuthal angle of particle.

Sum over a group of u_n-vectors in a single event gives an estimation of reaction plane orientation in the event:

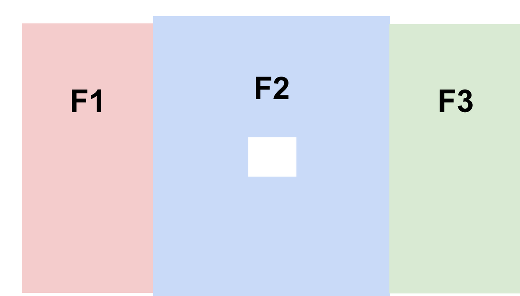
$$Q_n = \frac{\sum_{k=1}^{M} w_k u_n^k}{\sum_{k=1}^{M} w_k} = |Q_n|(\cos n\Psi_n^{SP}, \sin n\Psi_n^{SP})$$

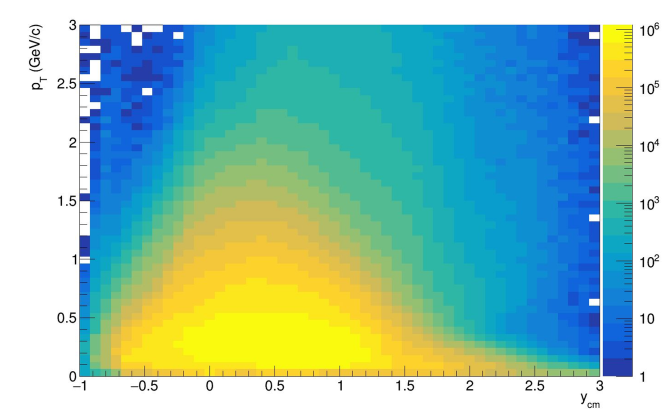
Ψ_n^{SP} is the symmetry plane angle, an estimation of the reaction plane angle in this event

In the BM@N 3 Q-vectors are defined from the modules of the FHCal:

$$Q_1^x = \frac{\sum_{k=1}^{M} E_k \cos\varphi_k}{\sum_{k=1}^{M} E_k} \qquad Q_1^y = \frac{\sum_{k=1}^{M} E_k \sin\varphi_k}{\sum_{k=1}^{M} E_k}$$

where φ_k is the azimuthal angle and E_k is the energy deposition in the k-th module. Additionally, 2 Q-vectors were introduced from charged particle trajectories

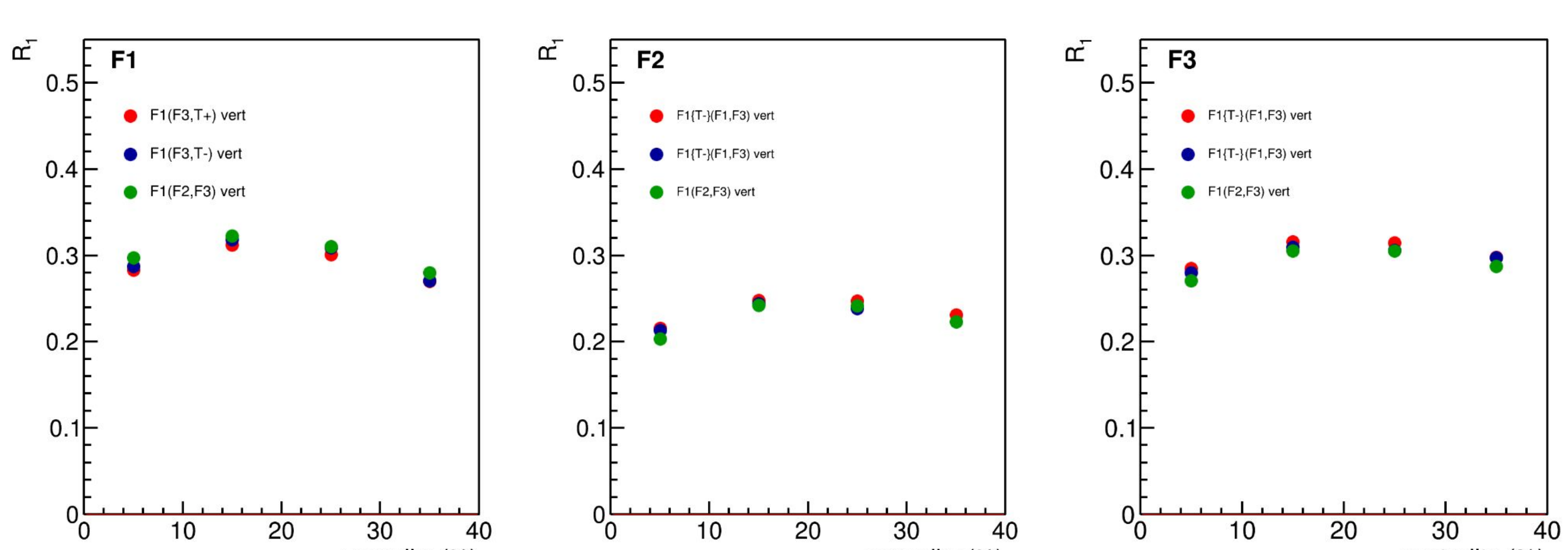




T-: all negatively charged particles with:
- $1.5 < \eta < 4$
- $p_T > 0.2$ GeV/c

T+: all positively charged particles with:
- $2.0 < \eta < 3$
- $p_T > 0.2$ GeV/c

Symmetry-plane resolution with FHCal



For the flow measurements Scalar Product method was chosen. The observable for the directed flow can be expressed as an average of the projection of particle u-vector on symmetry-plane Q-vector:

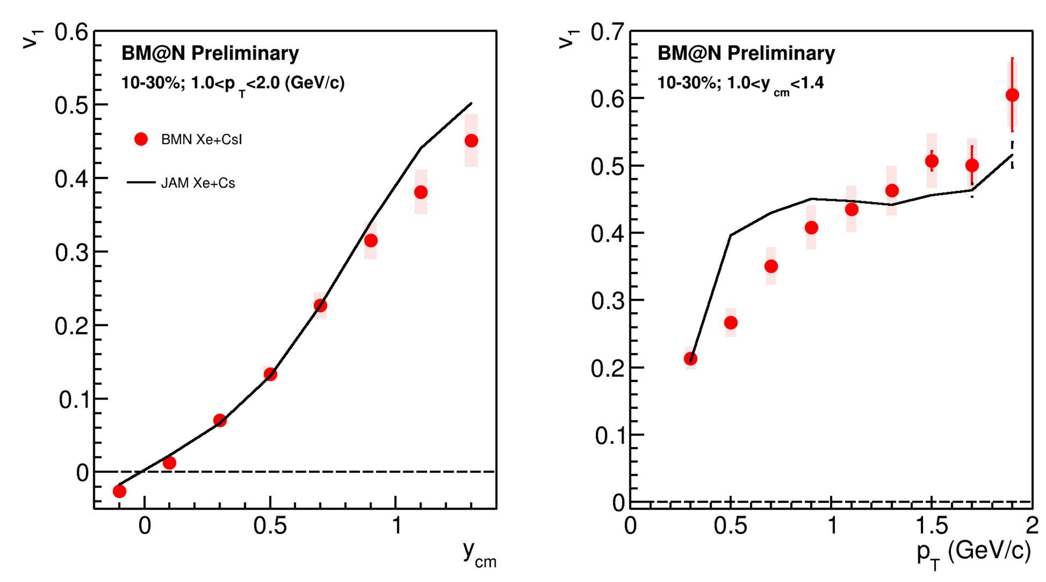
$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}}$$

where symmetry plane resolution R_1 is calculated using 3-subevent method

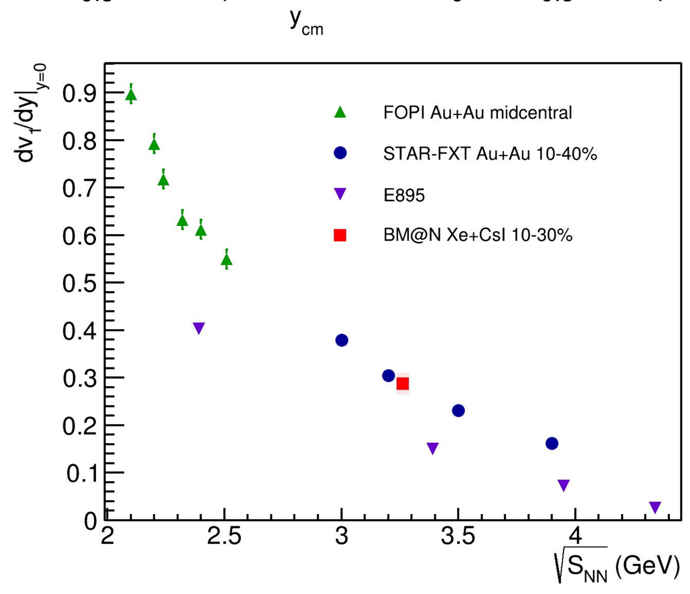
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}} \qquad R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle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

Resolution can be calculated with several combinations of Q_1-vectors with different rapidity separation. Agreement of different estimations for R_1 suggests low non-flow contribution.

Directed flow of protons in the BM@N experiment



JAM Model in mean-field mode with momentum dependent potential describes well rapidity-dependence of v_1, although fails to describe shape of transverse momentum dependence



Directed flow slope at midrapidity $dv_1/dy|_{y=0}$ is in agreement with the STAR data