Directed flow in Heavy-Ion Collisions

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Motivation

- Heavy-Ion collision physics may be classified according to the **beam energy** and **impact parameter**

- Deal with the physics learned from **semi-central collisions** at intermediate beam energy (a few hundred MeV/u)

- Collisions produce a **flow of energetic particles** and the matter flow depends on the detailed properties of nuclear matter

Impact parameter

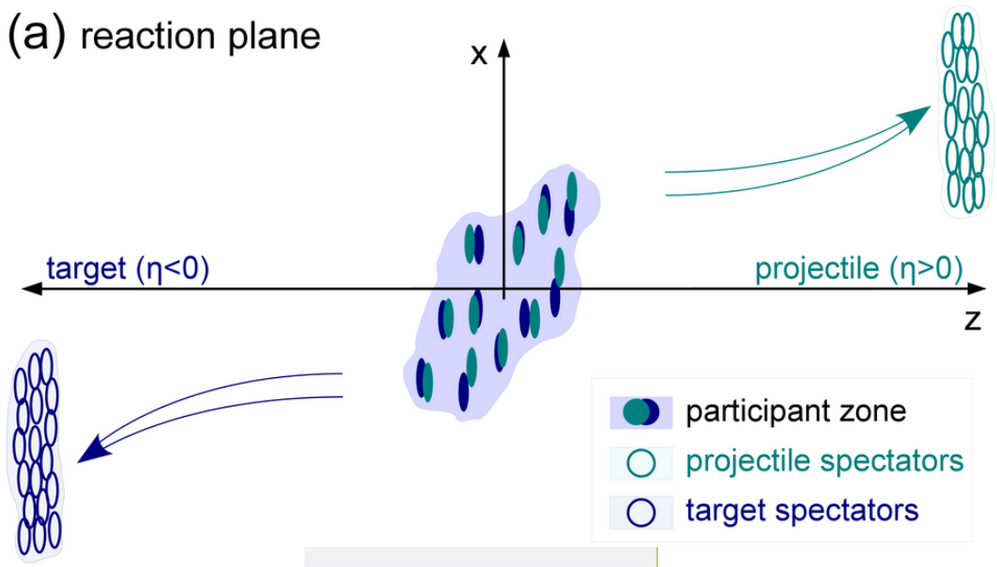
- **Perpendicular distance** from the target nucleus to the initial line of motion of the incident nucleus

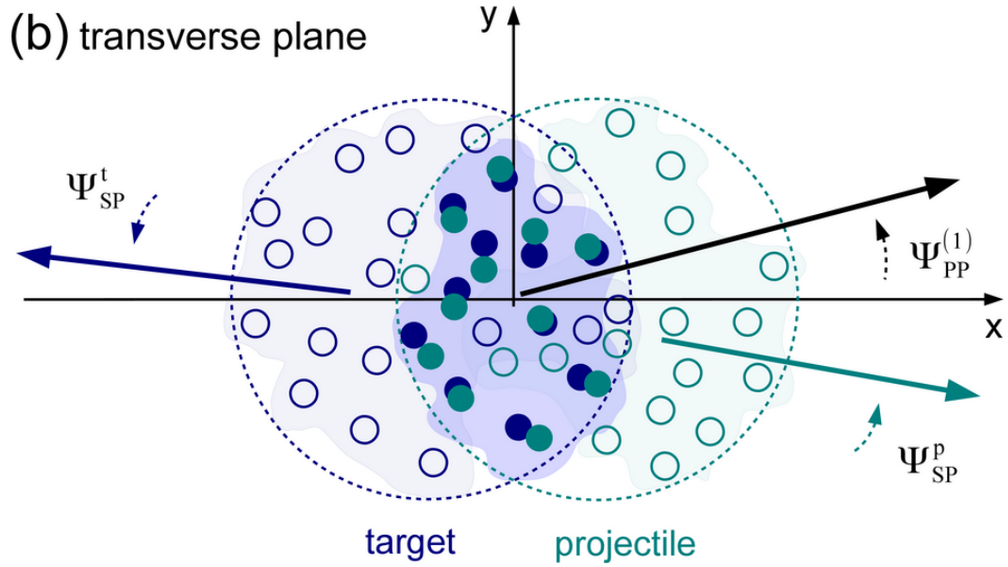
- Characterizing the collisions such as central (head-on), near central, near peripheral or peripheral

- Experimental : charged-particle multiplicity, total transverse momentum and total transverse energy

- Smaller impact parameter, larger average $\mathbf{p}_T$

Collective flow





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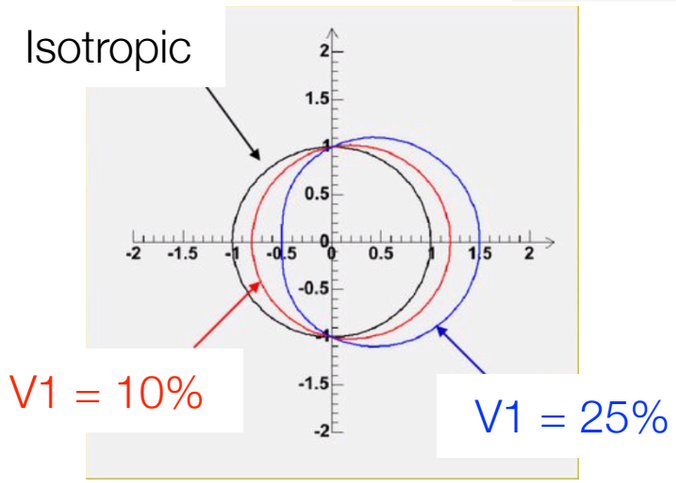

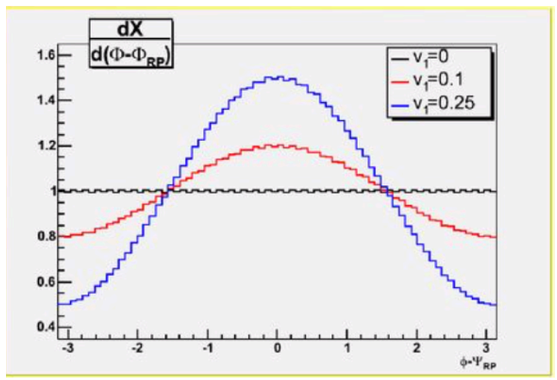

$$f(\phi; y, p_t) \propto 1 + 2 \sum_{n=1,2} v_n(y, p_t) \cos(n\phi) \,,$$

- Directed flow - first harmonic coefficient v_1 in a Fourier decomposition of the particle azimuthal distribution w.r.t one of the collision symmetry planes

Collective flow in reaction plane

- reaction plane - vectors of impact parameter and beam velocity

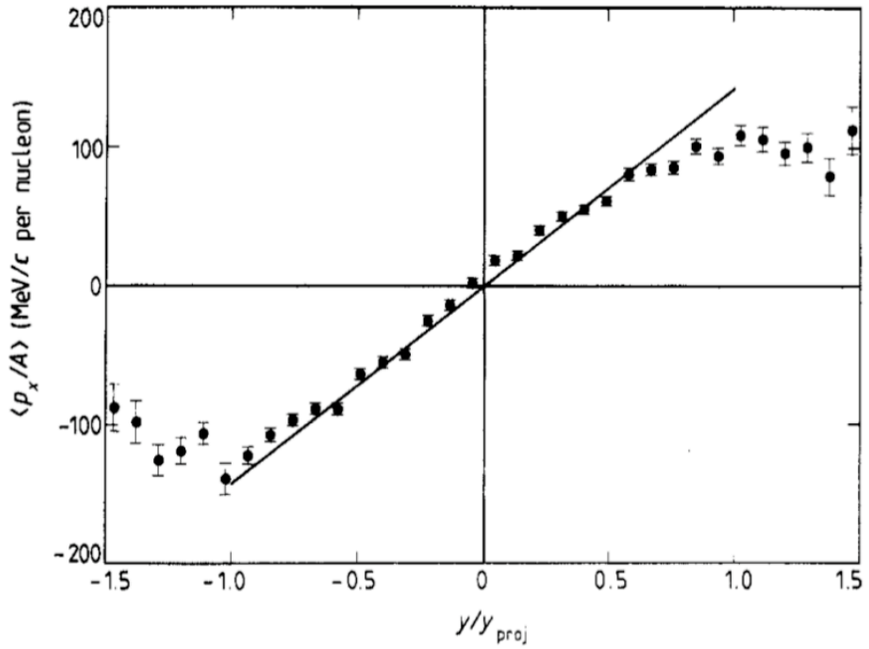

Figure 23. Mean transverse momentum per nucleon projected into the reaction plane as a function of the normalised centre-of-mass rapidity for 400 MeV per nucleon Nb + Nb in the third multiplicity bin. The slope of the full line represents the flow obtained from fitting the data.

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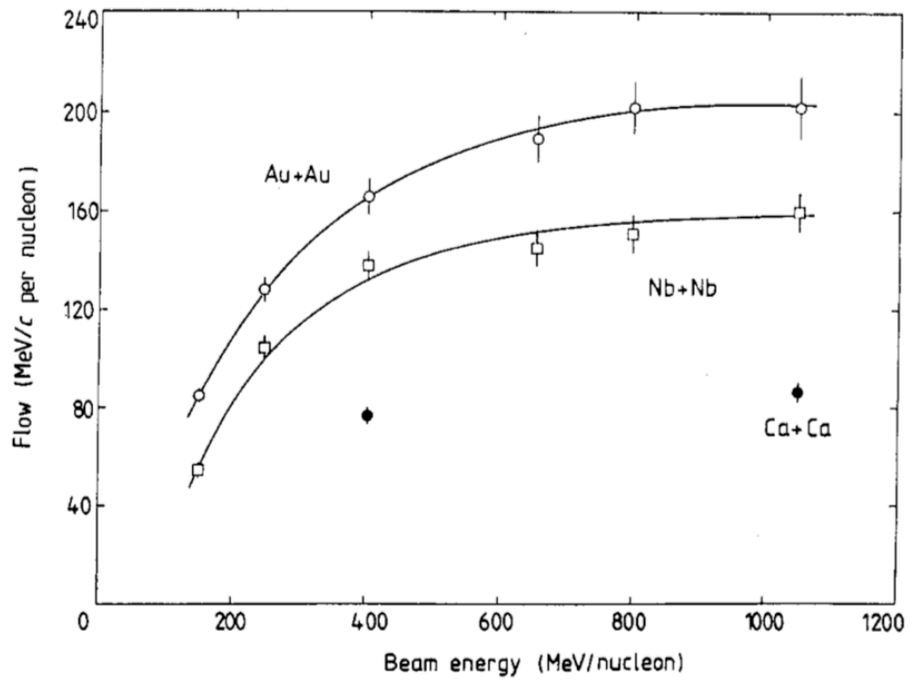
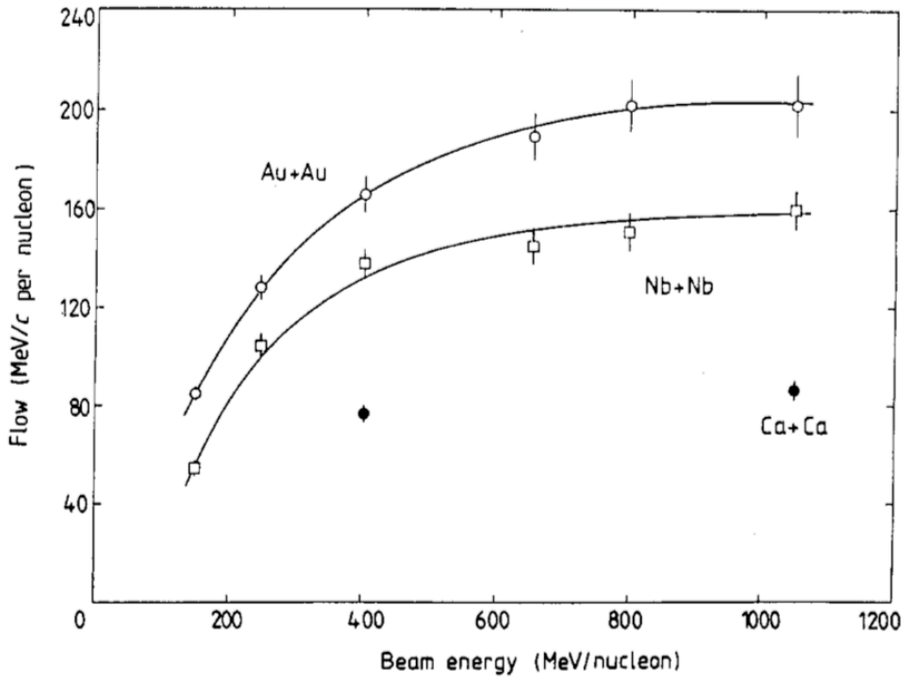


Figure 25. Flow of semicentral collisions ($50\% \leq N_p/N_p^{max} < 100\%$) as a function of beam energy.

- S-shaped curve centered at mid-rapidity
- slope of the distribution of $\langle p_X \rangle$ at mid-rapidity is flow angle (or flow value)

Collective flow in reaction plane



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PRC 93, 044609 (2016)

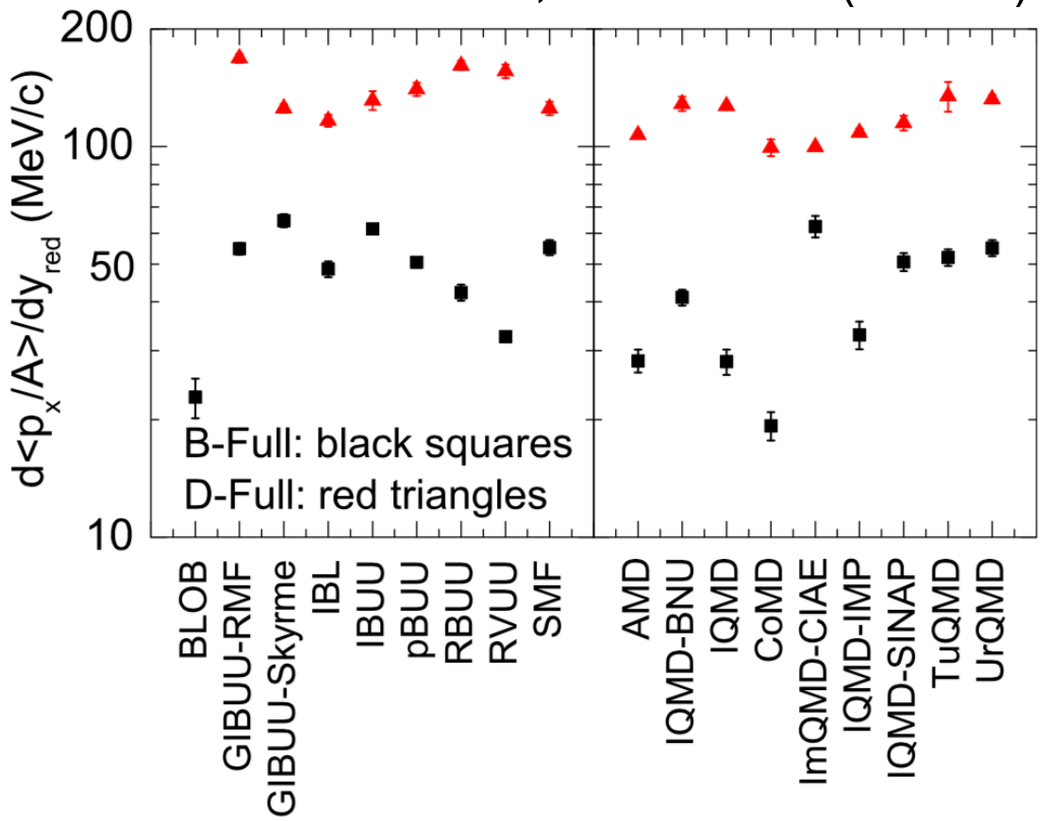


FIG. 13. Slope parameters of the transverse flow of nine BUU-type (left) and nine QMD-type (right) models from the B-full mode (black squares) and D-full mode (red triangles). The error bars are the fitting uncertainties. Where they are not seen they are smaller than the symbols.

Parity doublet model in Heavy-Ion Collisions

- **GOAL : origin of nucleon mass**
- Contribution to baryon masses by chiral invariant mass, m_0
- Nucleons and the chiral partner, N*(1535), belong to same multiplet
- Chiral symmetry is restored, nucleon and the chiral partner have save chiral invariant mass, m_0
- Previous studies of PDM on nuclear matter (PRC 97, 065202) and structure (arXiv: 1805.03402)

Lagrangian & EoM of Parity doublet model

$$
\begin{aligned}
\mathcal{L} = & \bar{\psi}_1 i\partial\!\!\!/ \psi_1 + \bar{\psi}_2 i\partial\!\!\!/ \psi_2 + m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2) \\
& + g_1\bar{\psi}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_1 + g_2\bar{\psi}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_2 \\
& - g_{\omega NN}\bar{\psi}_1\gamma_\mu\omega^\mu\psi_1 - g_{\omega NN}\bar{\psi}_2\gamma_\mu\omega^\mu\psi_2 \\
& - g_{\rho NN}\bar{\psi}_1\gamma_\mu\vec{\rho}^\mu\cdot\vec{\tau}\psi_1 - g_{\rho NN}\bar{\psi}_2\gamma_\mu\vec{\rho}^\mu\cdot\vec{\tau}\psi_2 \\
& - e\bar{\psi}_1\gamma^\mu A_\mu\frac{1-\tau_3}{2}\psi_1 - e\bar{\psi}_2\gamma^\mu A_\mu\frac{1-\tau_3}{2}\psi_2 + \mathcal{L}_M
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_M = & \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} \\
& - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + \frac{\bar{\mu}^2}{2}(\sigma^2+\vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2+\vec{\pi}^2)^2 + \frac{\lambda_6}{6}(\sigma^2+\vec{\pi}^2)^3 + \epsilon\sigma \\
& + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\left(-\vec{\nabla}^2 + m_\sigma^2\right)\langle\tilde{\sigma}(\vec{x})\rangle = & -\bar{N}(\vec{x})N(\vec{x})\left.\frac{\partial\, m_N(\tilde{\sigma})}{\partial\tilde{\sigma}}\right|_{\tilde{\sigma}=\langle\tilde{\sigma}(\vec{x})\rangle} \\
& + (-3f_\pi\lambda + 10f_\pi^3\lambda_6)\langle\tilde{\sigma}(\vec{x})\rangle^2 \\
& + (-\lambda + 10f_\pi^2\lambda_6)\langle\tilde{\sigma}(\vec{x})\rangle^3 \\
& + 5f_\pi\lambda_6\langle\tilde{\sigma}(\vec{x})\rangle^4 + \lambda_6\langle\tilde{\sigma}(\vec{x})\rangle^5
\end{aligned} \tag{12}
$$

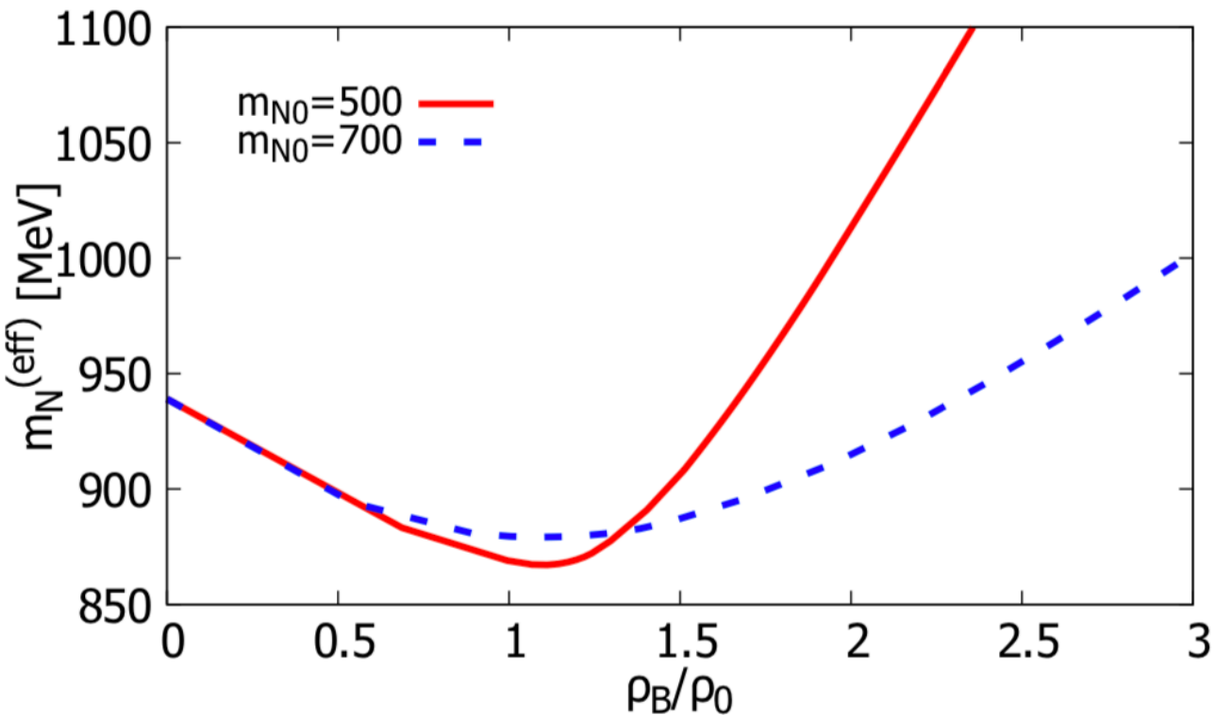
$$
\left(-\vec{\nabla}^2 + m_\omega^2\right)\langle\bar{\omega}(\vec{x})\rangle = g_{\omega NN}N^\dagger(\vec{x})N(\vec{x})\,, \tag{13}
$$

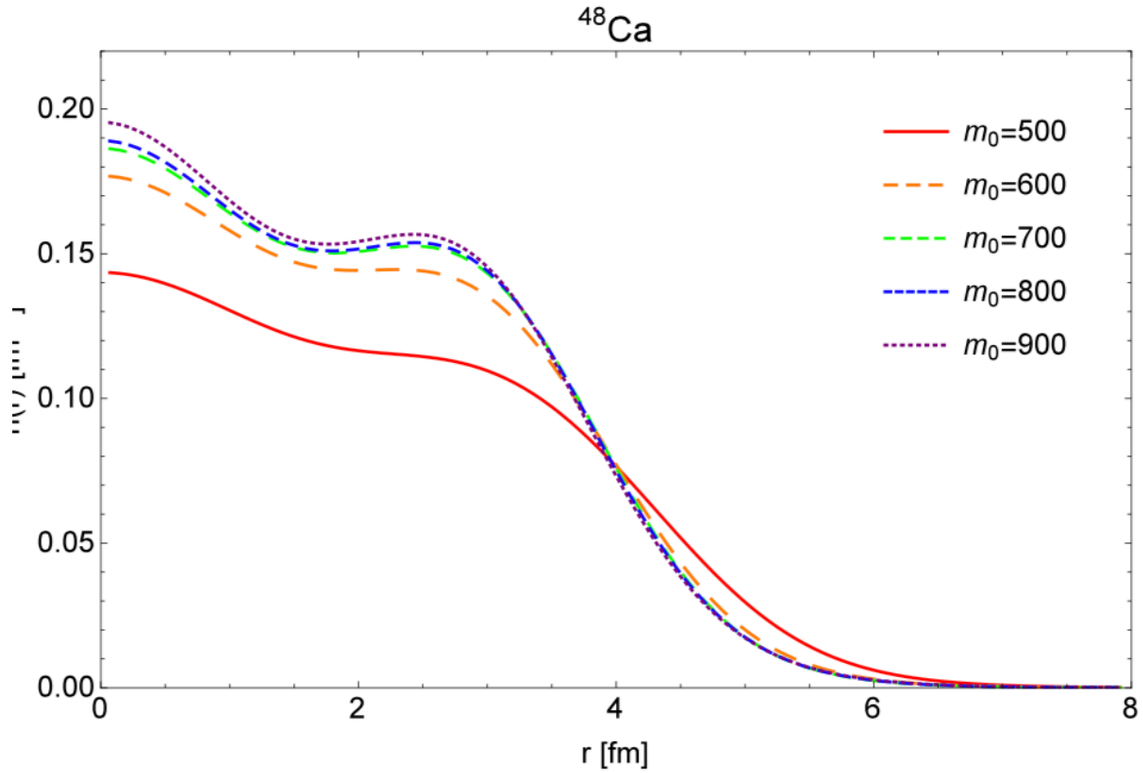
$$
\left(-\vec{\nabla}^2 + m_\rho^2\right)\langle\bar{\rho}(\vec{x})\rangle = g_{\rho NN}N^\dagger(\vec{x})\tau^3N(\vec{x})\,, \tag{14}
$$

$$
-\vec{\nabla}^2\langle A_0(\vec{x})\rangle = eN^\dagger(\vec{x})\frac{1-\tau_3}{2}N(\vec{x})\,. \tag{15}
$$

Parity doublet model
with dense matter & nuclear structure

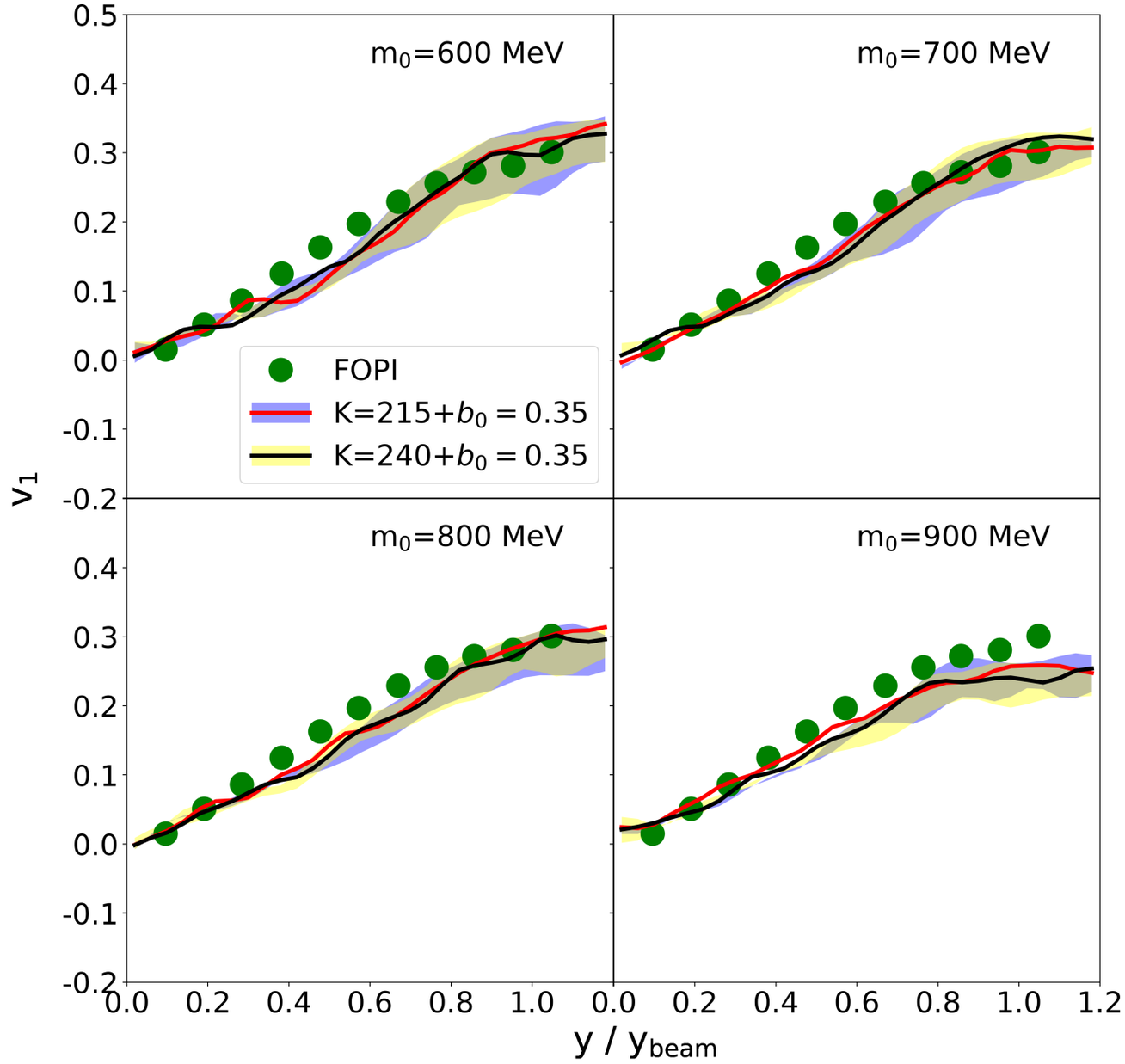
$$\frac{E}{A} - m_N = -16 \text{ MeV}\,, \quad n_0 = 0.16 \text{ fm}^{-3},$$
$$K = 240 \pm 40 \text{ MeV}\,, \quad E_{\rm sym} = 31 \text{ MeV}\,.$$





Transverse flow with FOPI experiment

- Au + Au @ 400 MeV/u
- Proton directed flow
- $0.25 < b_0 < 0.45$
  $b_0 = b/b_{max}$
  $b_{max} = 1.15(A_P^{1/3}+A_T^{1/3})$
- $v1 = \langle p_x / (p_x^2 + p_y^2)^{1/2} \rangle$
- Excluding pion production
  (only elastic scattering)



Balance Energy

- Attractive vs repulsive interaction - disappearance of flow
- E_{beam} ~ 10 MeV/u : primarily attractive in nucleus-nucleus potential
- From attractive-dominant to repulsive-dominant as incident energy is raised
- Another good tester for nuclei matter model : stiffness of EoS

Balance Energy

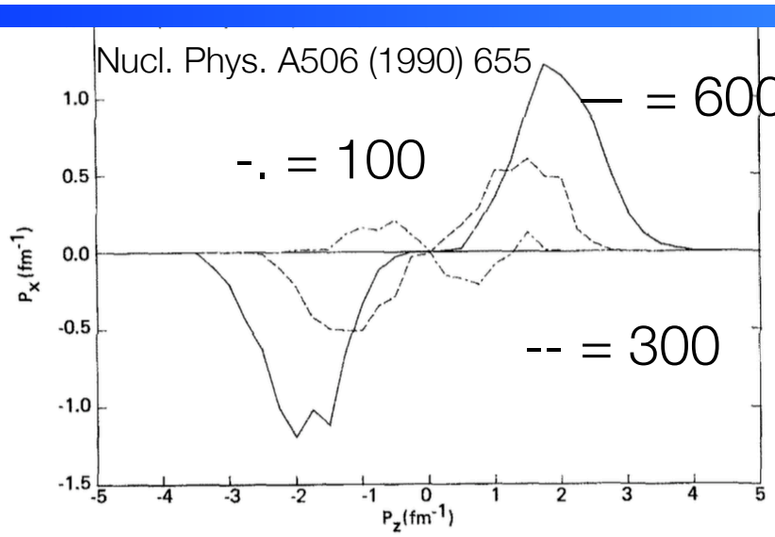


Fig. 3. The transverse momentum projected onto the reaction plane and averaged over all perpendicular momentum P_x as a function of the longitude momentum P_z for the reaction $^{16}O+^{16}O$ at an impact parameter $b=2$ fm. The solid curve is for an incident energy of 600 MeV/nucleon, dashed curve for 300 MeV/nucleon and dash-dotted curve for 100 MeV/nucleon.

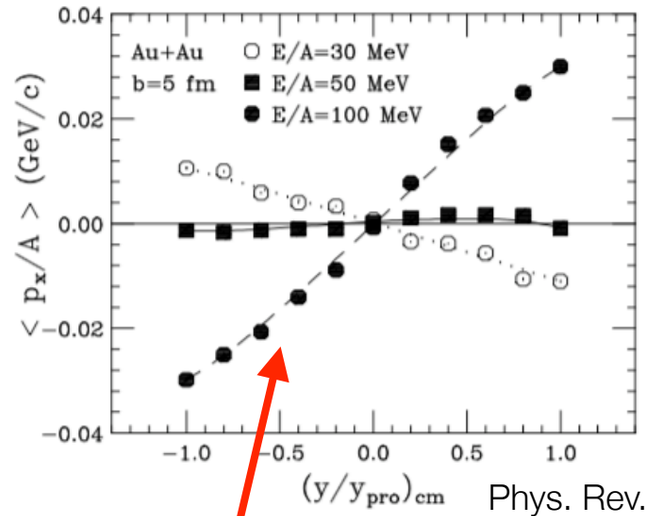


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FIG. 1. Total (upper) and differential (lower) transverse flow analysis for the reaction of Au+Au at an impact parameter of 5 fm and beam energies of 30, 50 and 100 MeV/nucleon.

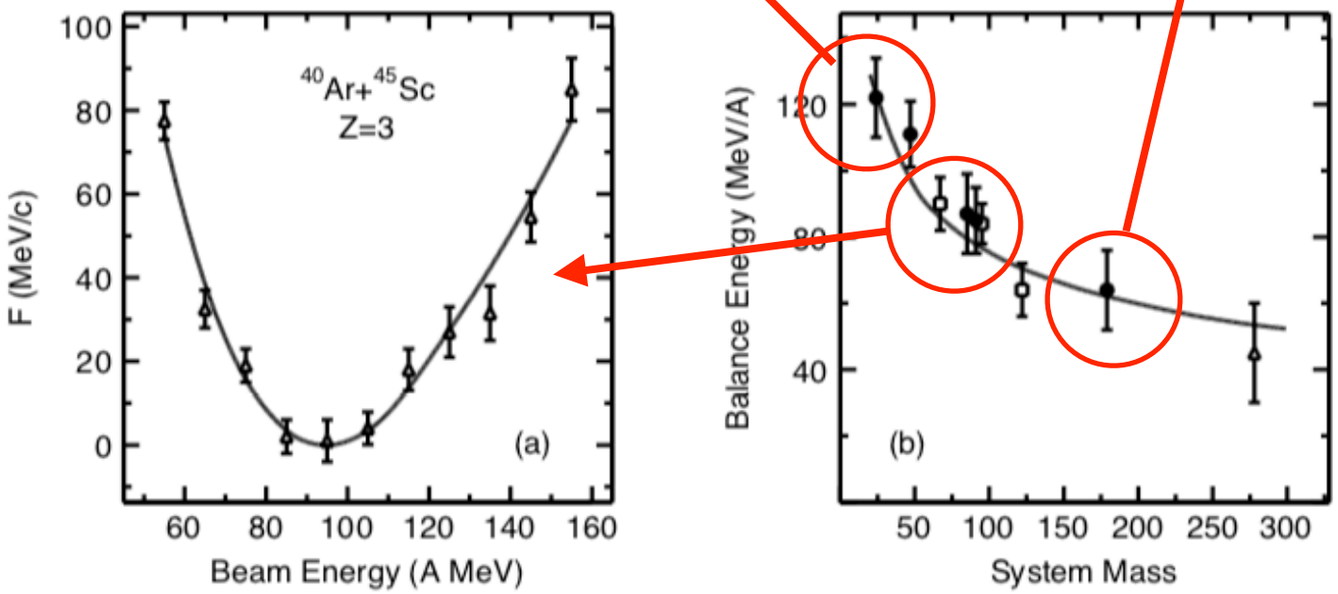

Figure 6 (*a*) Sideward flow, F, as a function of incident energy for ^{40}Ar+^{45}Sc, after Pak et al (93); (*b*) system-mass dependence of the balance energy. The lines suggest an $A^{-1/3}$ dependence.

Ann. Rev .Nucl. Part. Sci. 47 (1997) 663

Conclusions and future plan

- Directed flow is physical observable of HIC and affected by the properties of nuclear matter
- Application of a new nuclear matter model to transport simulation
- Comparing directed flow of Parity doublet model with FOPI experiment, smaller chiral invariant mass, lower than 900 MeV prefer to experiment
- Balance energy is another hint for testing nuclear matter model
- Balance energy of parity doublet model will suggest another constraint for chiral invariant mass

Thank you for your attention