Anisotropic flow and properties of strongly interacting matter in nuclear collisions at RHIC energies

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

Particle Physics at Intermediate and High Energies
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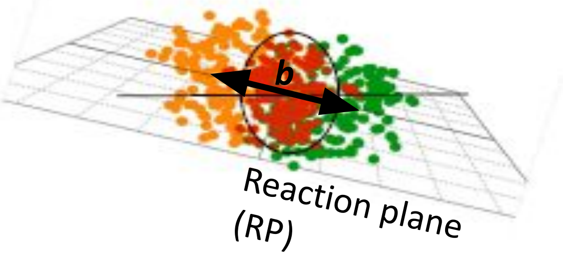
Outline

- Introduction: anisotropic flow
- Flow at different beam energies
- Scaling properties of anisotropic flow
- Outlook for flow measurements at NICA

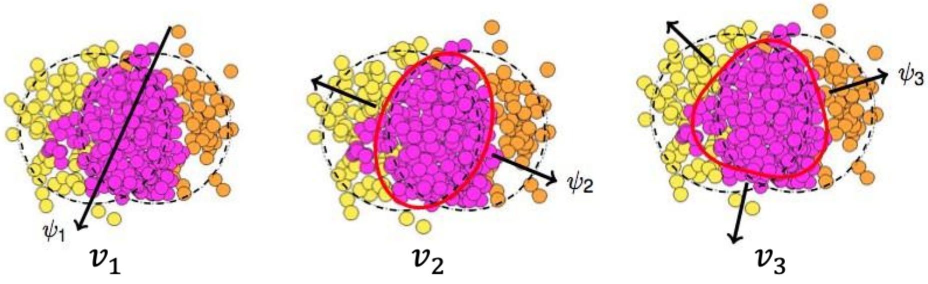
Anisotropic collective flow

Anisotropy of the initial spatial geometry



Multiple scattering in the overlap region

Momentum anisotropy of the final-state particles



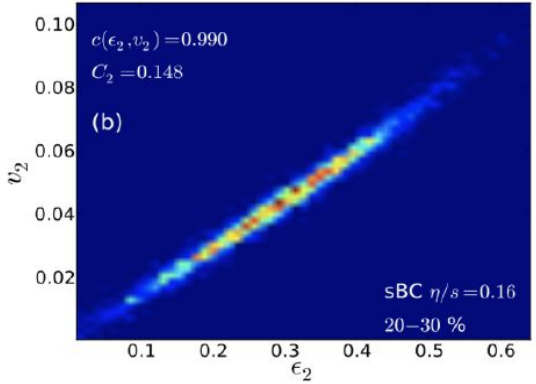
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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

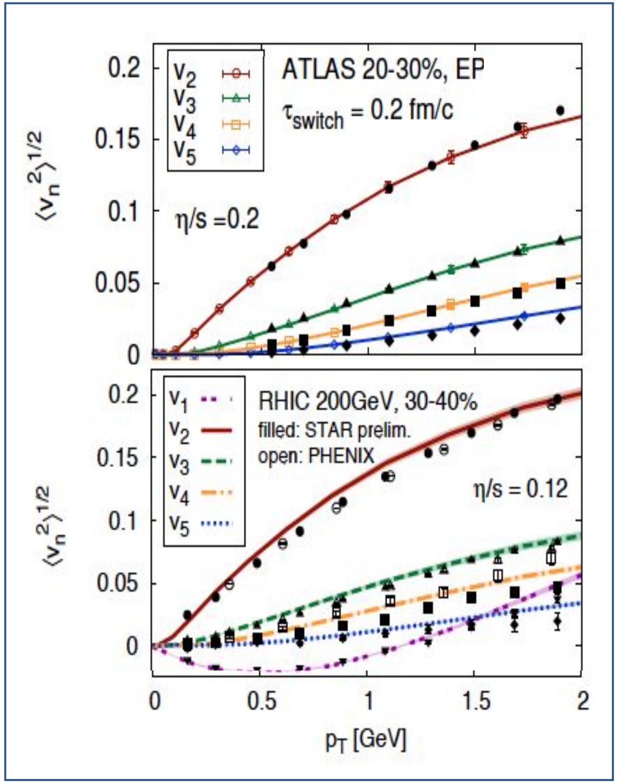
v_1 - directed flow, v_2 - elliptic flow, v_3 -triangular flow

Initial eccentricity (and its attendant fluctuations) ε_n drives momentum anisotropy v_n with specific viscous modulation

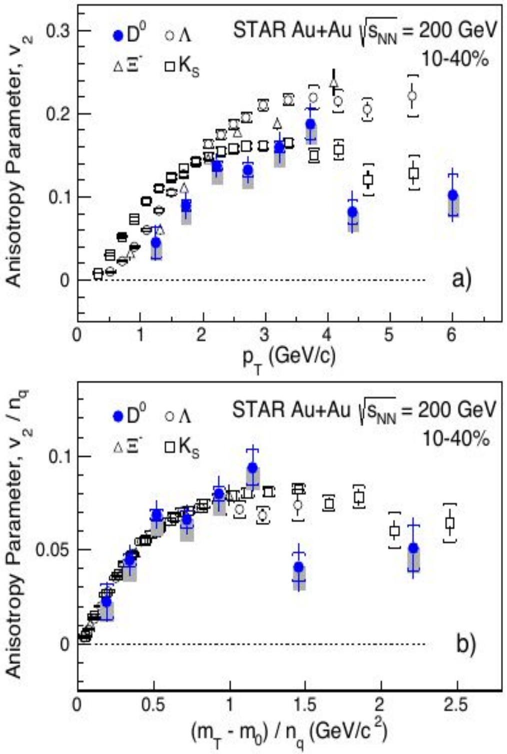


Anisotropic flow at LHC/top RHIC

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



STAR PRL118 (2017) 212301



$\boldsymbol{v_n(p_T,\mathbf{Centrality})}$ - sensitive to the early stages of the collision

Important constrain for transport properties and EOS (η/s, ζ/s, etc.)

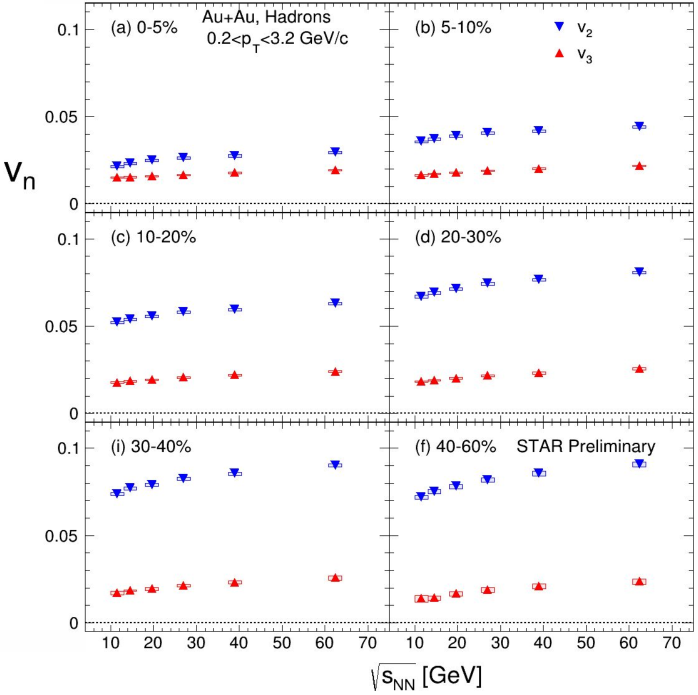
$\boldsymbol{v_n}$ of identified hadrons:

- **Mass ordering at p_T<2 GeV/c** (hydrodynamic flow, hadron rescattering)
- **Baryon/meson grouping at p_T>2 GeV/c** (recombination/coalescence) Number of constituent quark (NCQ) scaling

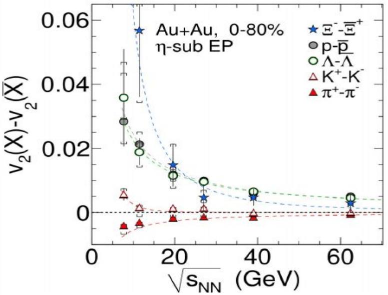
v_n at BES and v^{int} scaling

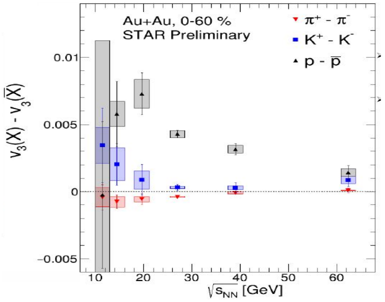
$$v_n(int.) \equiv |v_n^{int}| = |\langle v_n(p_T, y, \text{centrality}, \text{PID}) \rangle_{p_T, y}|$$

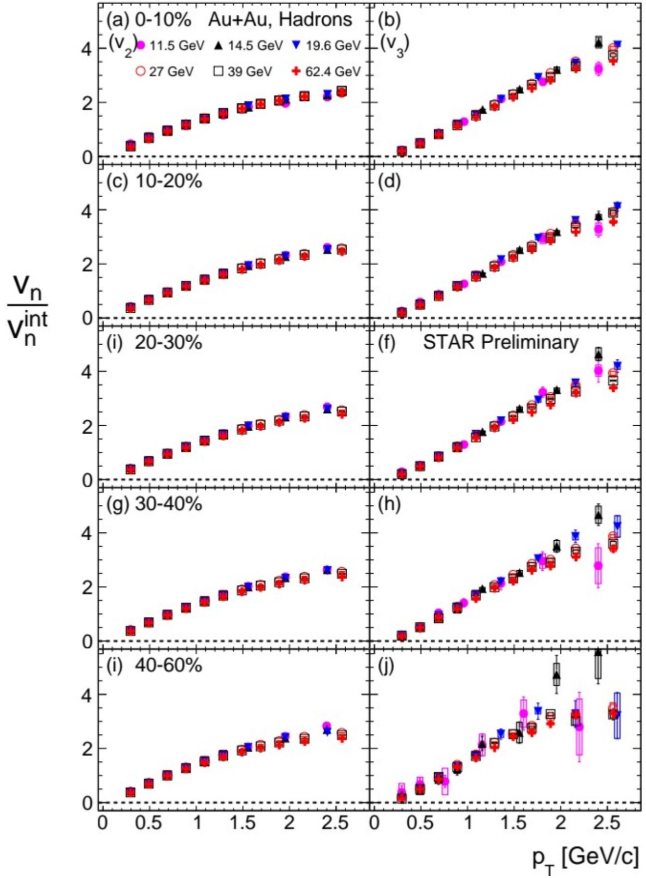
Petr Parfenov, J.Phys.Conf.Ser. 1690 (2020) 1, 012128



PRC 88 (2013) 14902



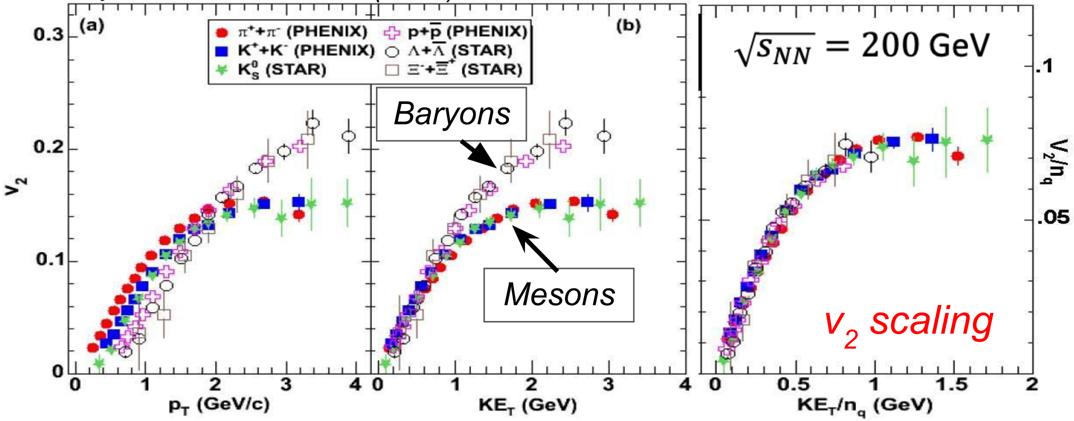




- Integrated v_2 and v_3 decrease with decreasing collision energy
- Increasing v_n particle-antiparticle difference with decreasing energy
- Scaling works at top RHIC and BES energy range

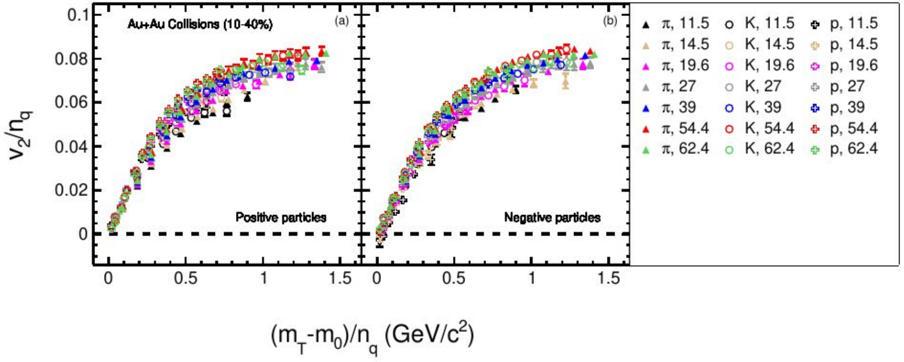
Scaling relations at RHIC/LHC – NCQ (KE_T/n_q) scaling

Phys. Rev. Lett. 98, 162301 (2007)



NCQ scaling: $v_n(p_T) \rightarrow v_n/n_q^{n/2}(KE_T/n_q)$

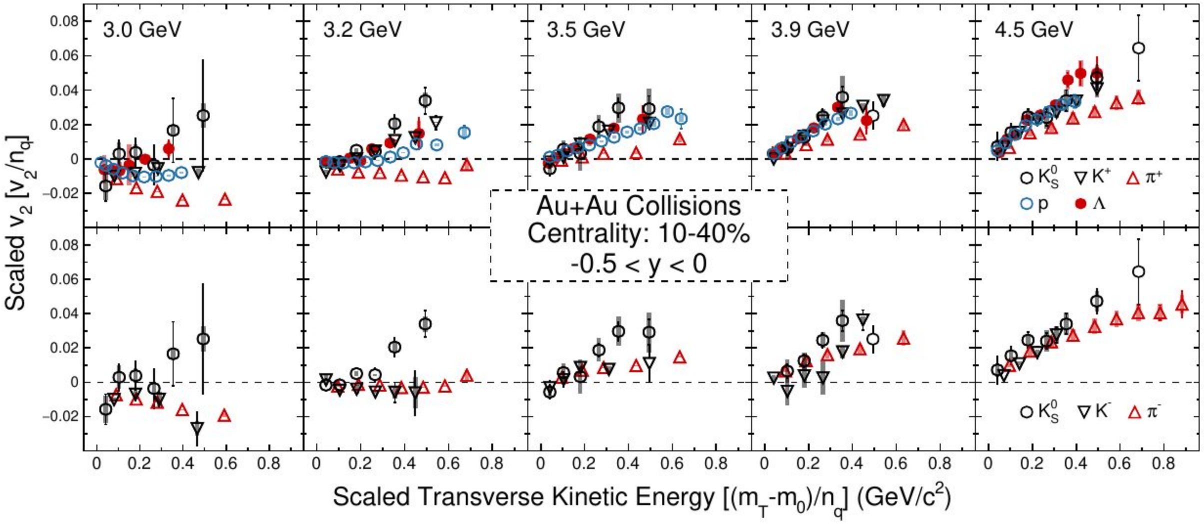
$$n_q = \begin{cases} 2 \text{ for mesons} \\ 3 \text{ for baryons'} \end{cases} \qquad KE_T = \sqrt{m^2 + p_T^2} - m$$



Significant part of flow at RHIC developed at partonic level

Scaling provides an additional constraint for the mechanism for hadronization at RHIC

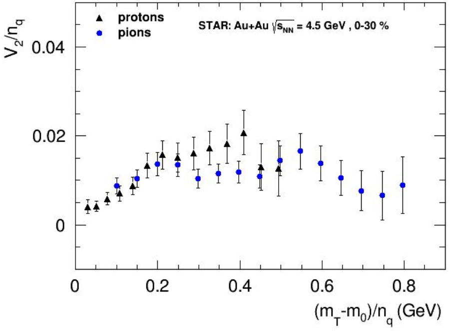
Disappearance of partonic collectivity?

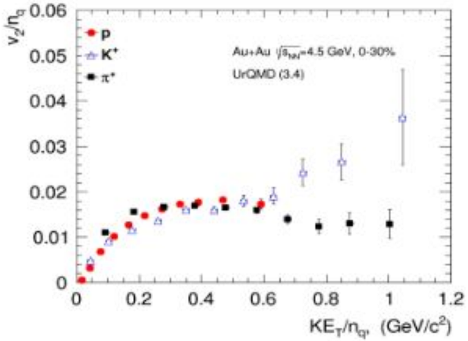


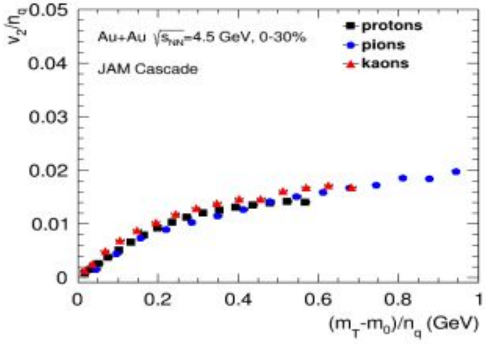
Breaking of NCQ scaling around 3.2 GeV might

"imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region"

However…





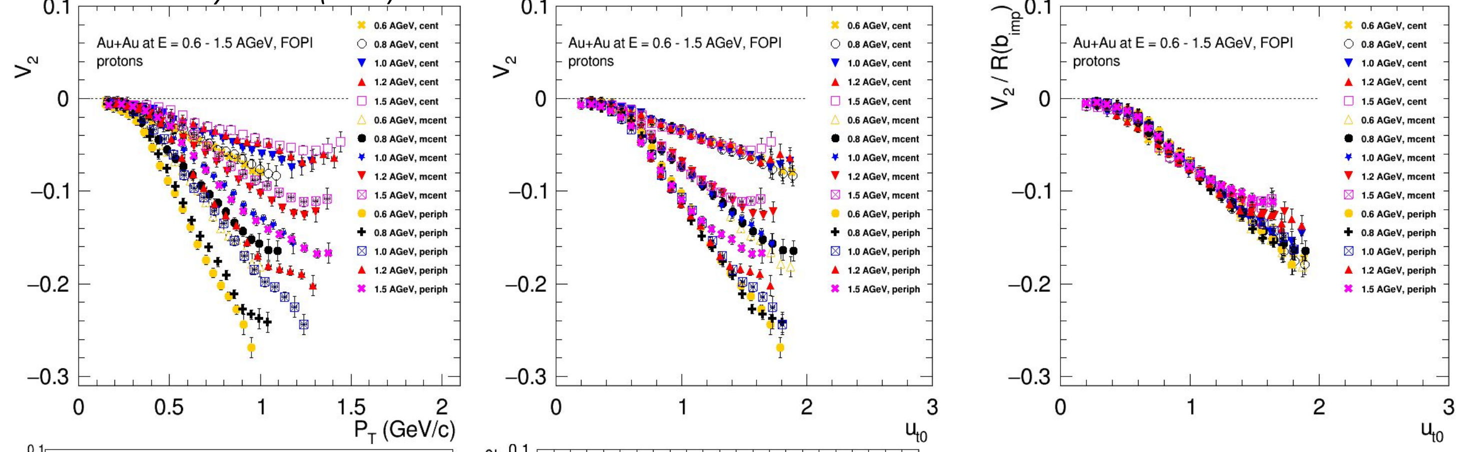


NCQ scaling at 4.5 GeV holds even in hadronic cascade models

we need to be careful

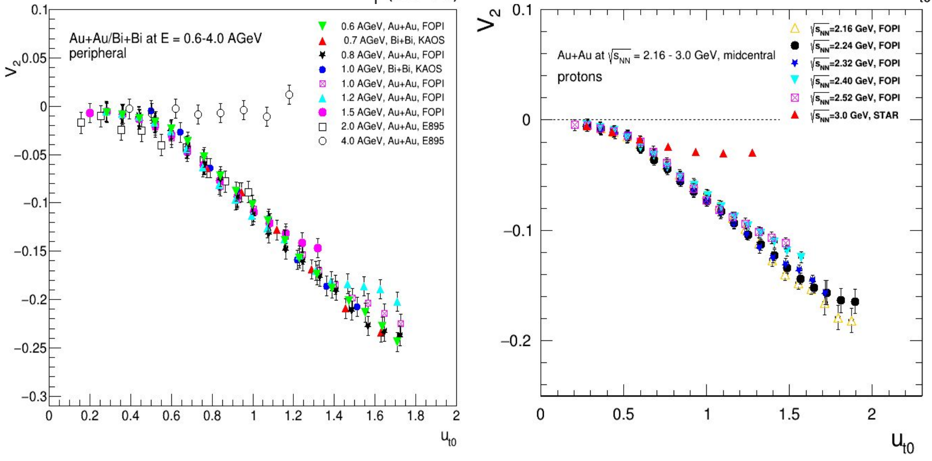
Scaling relations at SIS – scaling with passage time

Nucl. Phys A 876 (2012) 1-60



$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2 R m_0}$$

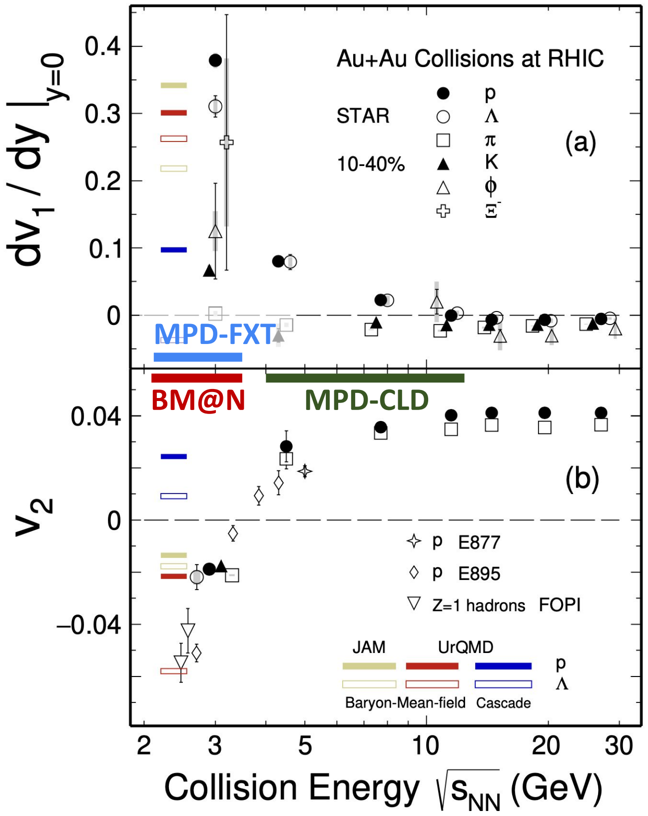
$$t_{pass} = \frac{2R}{\beta_{CM} \gamma_{CM}}$$



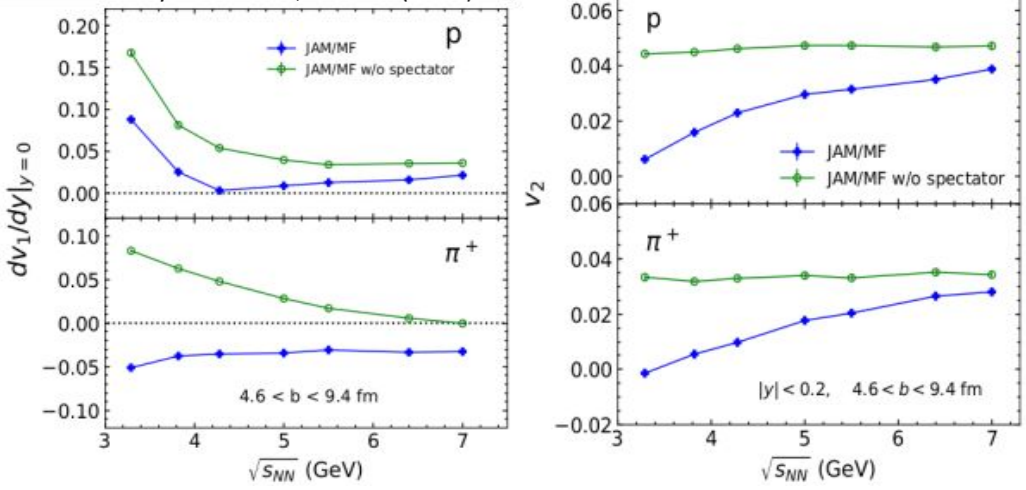
- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

Anisotropic flow at Nuclotron-NICA energies

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



Phys. Rev. C 97, 064913 (2018)



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 ($t_{exp} = R/c_s$)

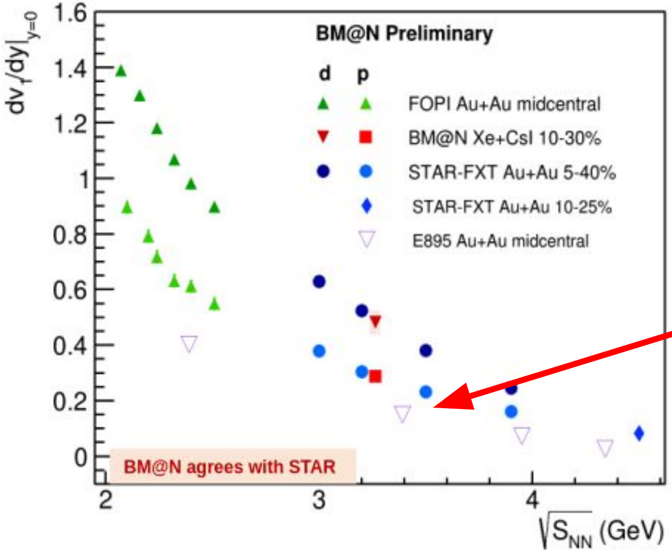
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Anisotropic flow at Nuclotron-NICA: 2.5-3.5 GeV

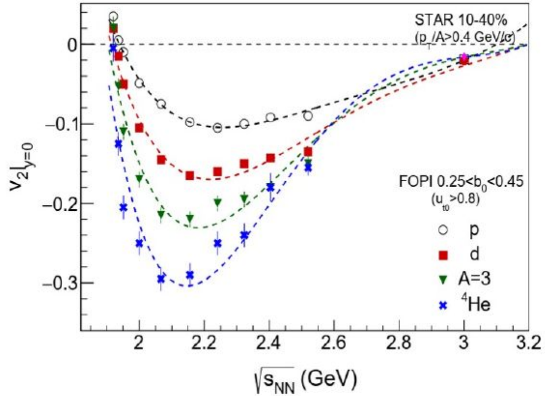
v_1 analysis at the BM@N experiment was done by:

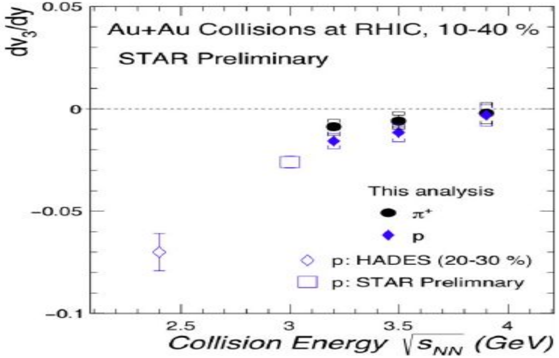
Protons: M. Mamaev

Deutrons: I. Zhavoronkova



Discrepancy!





<u>Experiments at Nuclotron-NICA will help to:</u>

- ➢ Solve the issue with discrepancies between v_n from different experiments (E895 vs STAR; FOPI vs HADES, …)
- ➢ Map beam energy region 2.5-3 GeV which lacks experimental data
- ➢ Add system size scan to the physical program on top of BES

Summary

- **Anisotropic flow can be used to extract information about properties of the strongly interacting matter:**
  - Equation of state (EoS), speed of sound (c_s), specific shear viscosity (η/s), specific bulk viscosity (ζ/s), …
- **Scaling with the integral anisotropic flow:**
  - Holds up for a wide energy range for different particle species, colliding systems and centrality classes
  - Breaks near v_n=0 (for v_2, its near $\sqrt{s_{NN}}$ = 3.3 GeV)
- **NCQ scaling:**
  - Holds up for energies $\sqrt{s_{NN}}$ > 4 GeV and can signify a partonic degree of freedom during flow formation
  - Scaling at around $\sqrt{s_{NN}}$ = 4.5 GeV in the experimental data and pure string/hadronic cascade models can be accidental- more thorough study should be performed (different energies, colliding systems, etc.)
- **Scaling with the passage time:**
  - Holds up for energies $\sqrt{s_{NN}}$ = 2-2.7 GeV and breaks around $\sqrt{s_{NN}}$ ≥ 3 GeV
  - Shows that at this energy range, $v_2(\sqrt{s_{NN}})$ changes predominantly due to t_{pass}

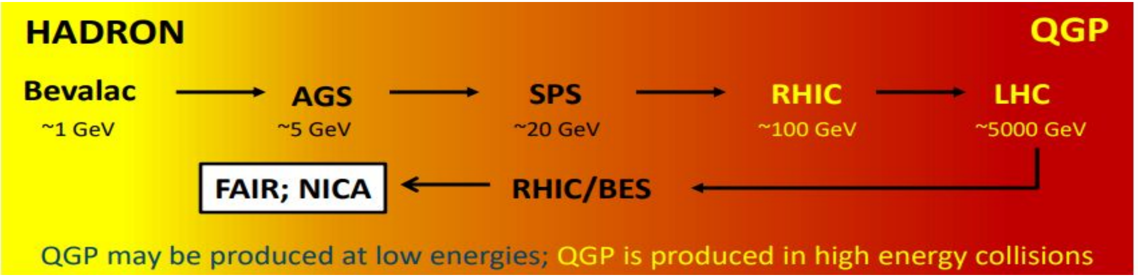
Scaling relations provide a useful tool to:

➢ perform comparison between results from different experiments with different system size, beam energy, centrality definition, etc.

➢ constrain existing models and distinguish between different mechanisms contributing to the flow formation

Backup slides

Relativistic heavy-ion collisions

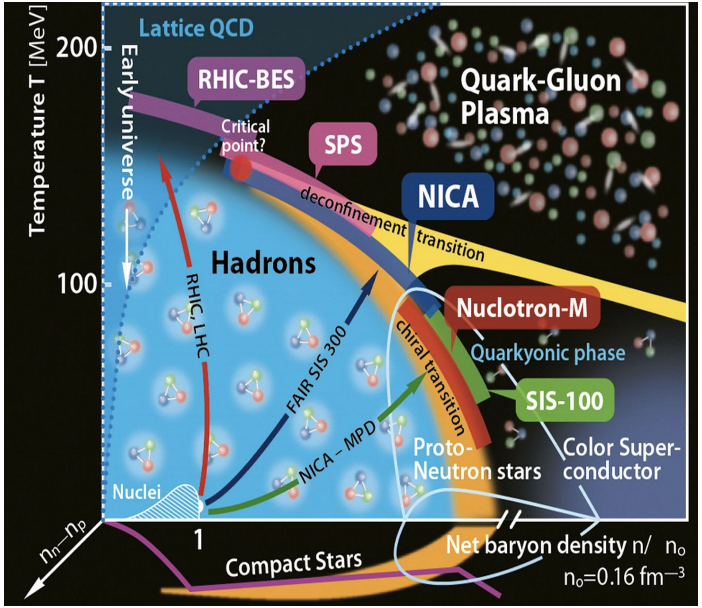


1970s-2000s – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)

2005s – QGP formation was observed at RHIC and it behaves as almost perfect liquid

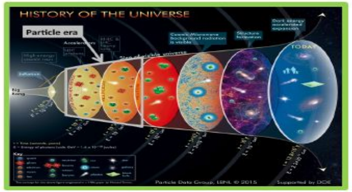
2005-2010s – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

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

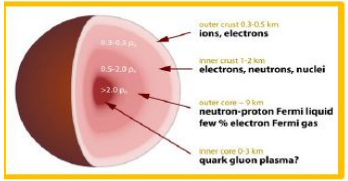


Relativistic heavy-ion collisions allows us to study QCD phase diagram

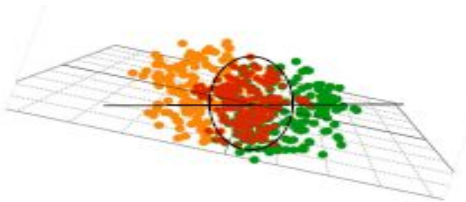
- **High beam energies ($\sqrt{s_{NN}}$>100 GeV):**
  - High T, $\mu_B \approx 0$
  - Evolution of the early Universe



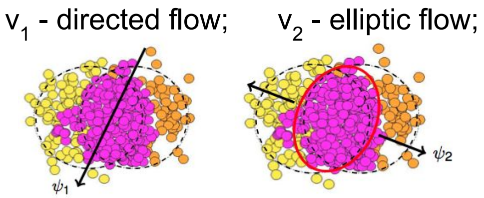
- **Low beam energies (2.4<$\sqrt{s_{NN}}$<11 GeV):**
  - Intermediate T, high μ_B
  - Inner structure of the compact stars, neutron star mergers



Anisotropic flow



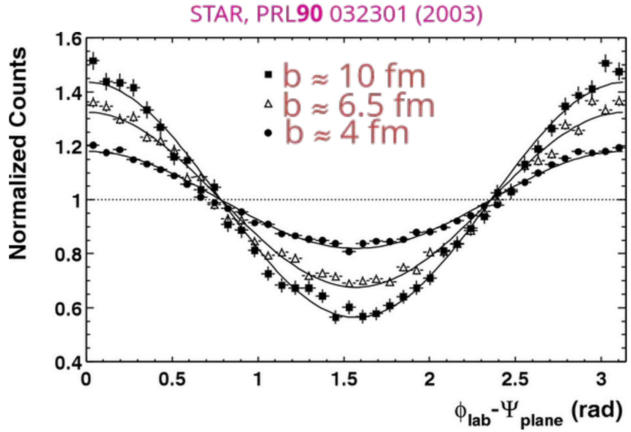
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$



Phys.Rev.C 58 (1998) 1671-1678

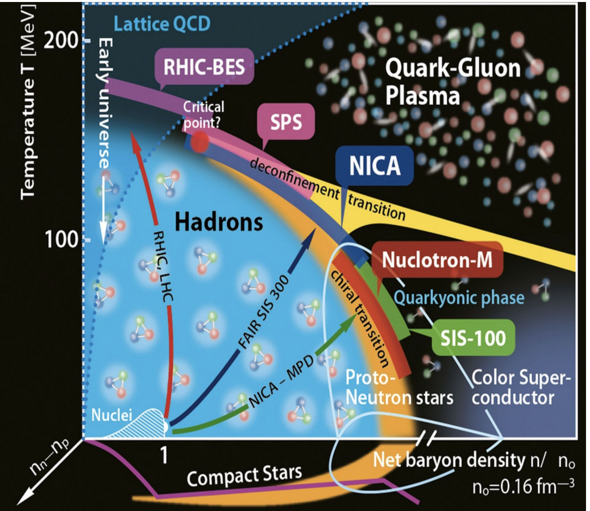
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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



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

QCD Phase Diagram



Relativistic heavy ion collisions allow us to study different regions of the QCD phase diagram

- **Top RHIC/LHC energies:** access to high T and small μB
- **RHIC-BES/SPS/NICA/Nuclotron:** access to different systems and a broad domain of the (T, μ_B)-plane
  - Equation of state (EoS), speed of sound (c_s), specific shear viscosity (η/s), specific bulk viscosity (ζ/s), …

EoS for high baryon density matter

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

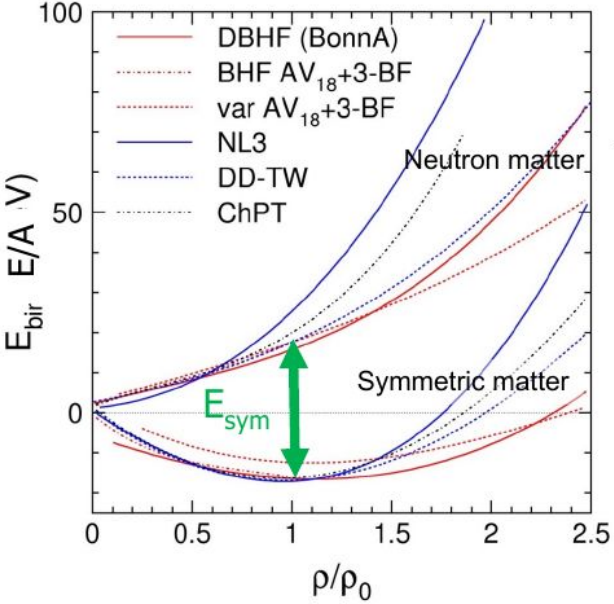
Isospin asymmetry:

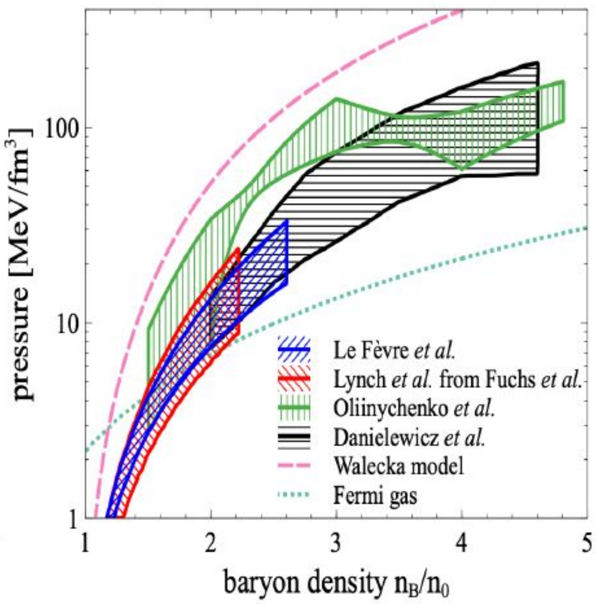
$$\delta = (\rho_n - \rho_p)/\rho$$

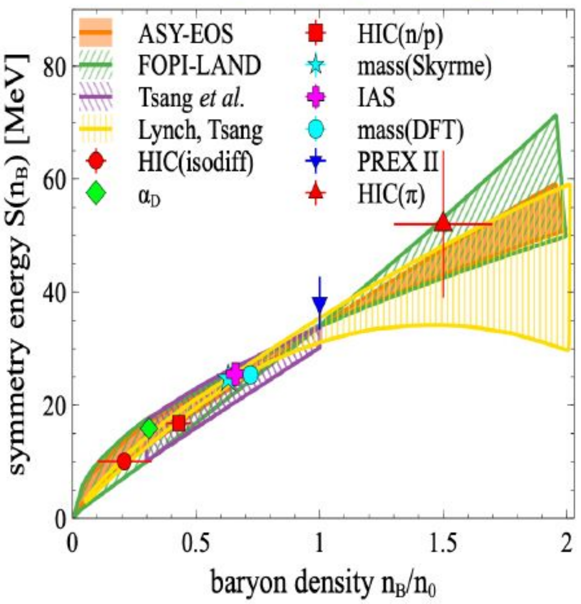
$$P \propto \rho^2 \frac{\mathrm{d}E_A}{\mathrm{d}\rho}$$

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

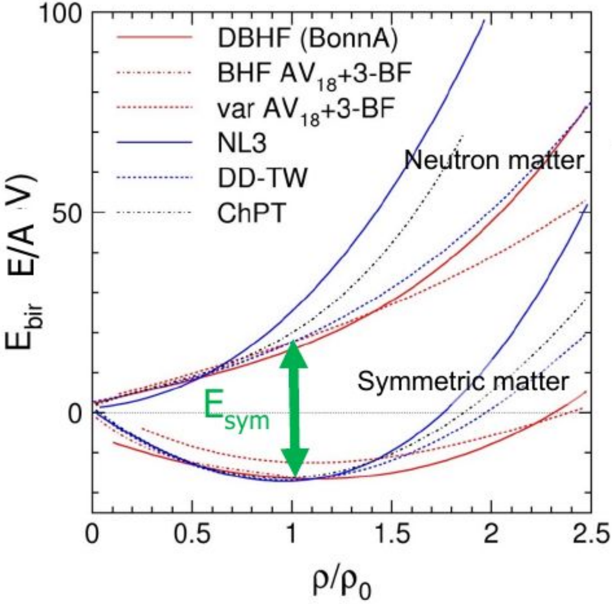
New data is needed to further constrain transport models with hadronic d.o.f.

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:

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



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

Symmetric matter

- Being extensively studied nowadays
- Using observables (flow, meson yields, etc.) to find incompressibility K_0
- One of the main sources of uncertainty: discrepancy between experimental data

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

Symmetry energy

- No experimental data for beam energies $\sqrt{s_{NN}}$ >0.8 GeV
- One of the main parameter to study is the E_{sym} slope ***L***
- One needs to establish observables sensitive to ***L*** and obtain new experimental data

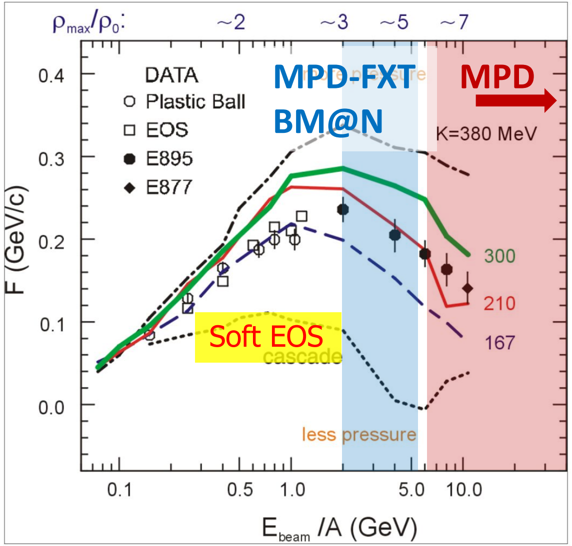
$$L = 3\rho \frac{\mathrm{d}E_{sym}}{\mathrm{d}\rho}$$

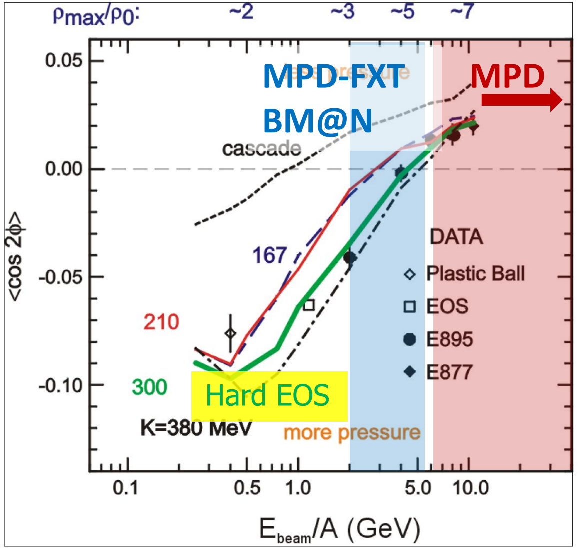
A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

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

Sensitivity of the collective flow to the EOS

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





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

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

Anisotropic flow sensitive to the EoS

EoS extraction: define incompressibility

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

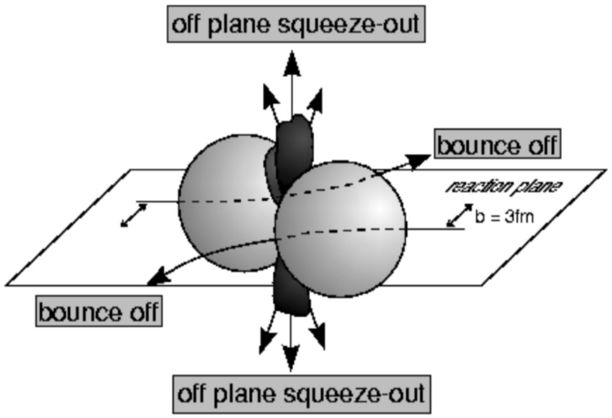
Discrepancy in the interpretation:

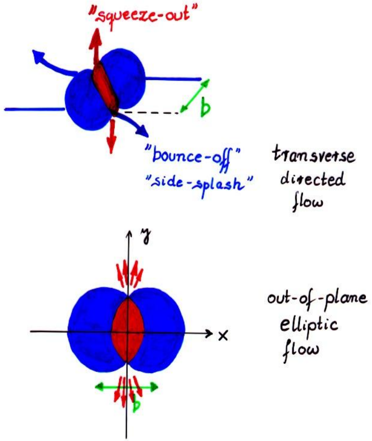
- v_1 suggests soft EoS (K_0≈210 MeV)
- v_2 suggests hard EoS (K_0≈380 MeV)

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

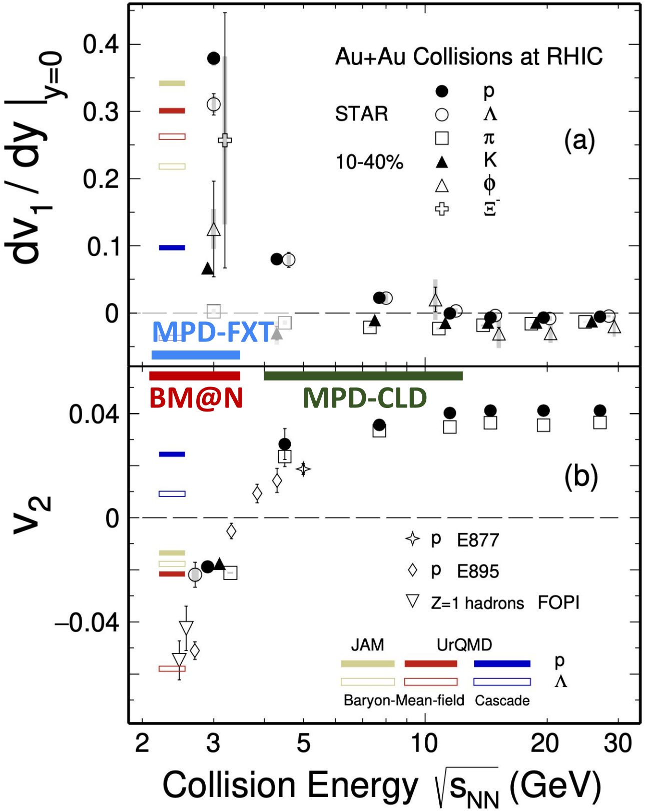
Additional measurements are essential to clarify the previous results

Anisotropic flow at Nuclotron-NICA energies





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



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