Anisotropic flow at high-baryon density

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MEPhI
National Research
Nuclear University

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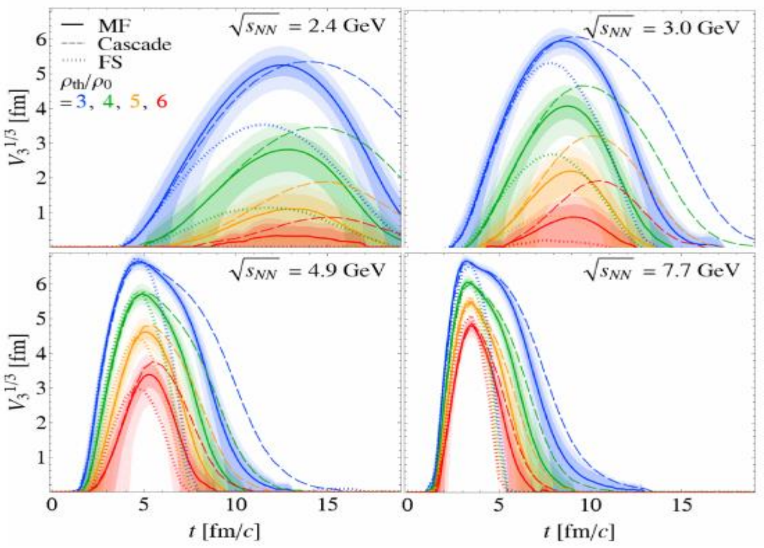
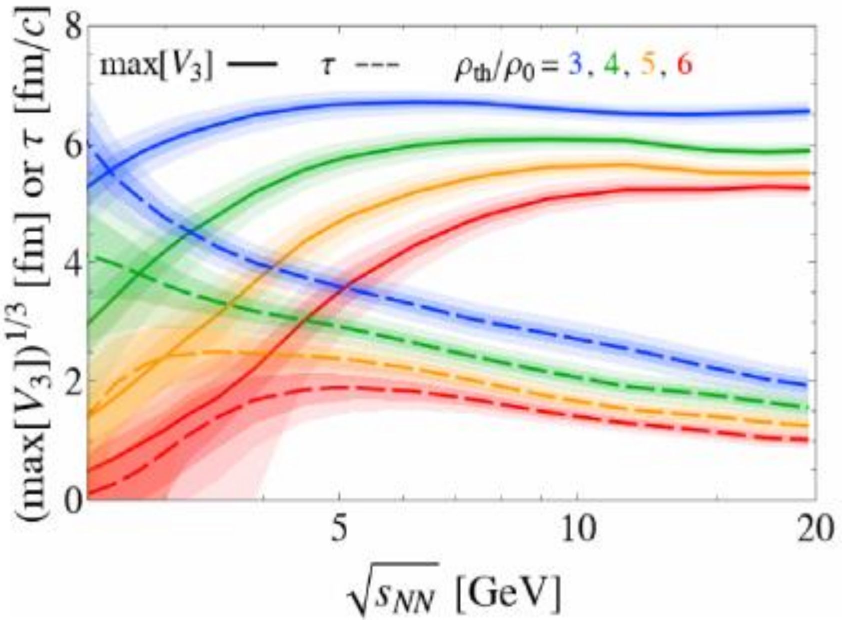
Optimal collision energy for realizing high baryon-density matter

H. Taya, A. Jinno, M. Kitazawa, Y. Nara https://arxiv.org/abs/2409.07685



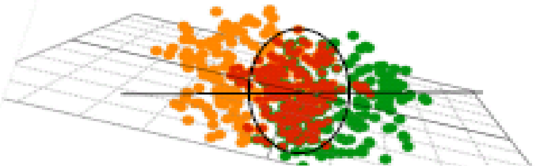
Dense region disappears more quickly for larger $\sqrt{s_{NN}}$

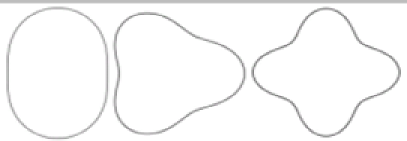


$\sqrt{s_{NN}}$ dependence of the maximum volume max[V3] (solid) and the lifetime τ (dashed)

The optimal energy is around $\sqrt{s_{NN}}$=3−4GeV, where a baryon density ρ/ρ_0 = 3 nuclear density is realized with a substantially large space-time volume. Higher and lower energies are disfavored due to short lifetime and low density

Anisotropic Flow at RHIC-LHC



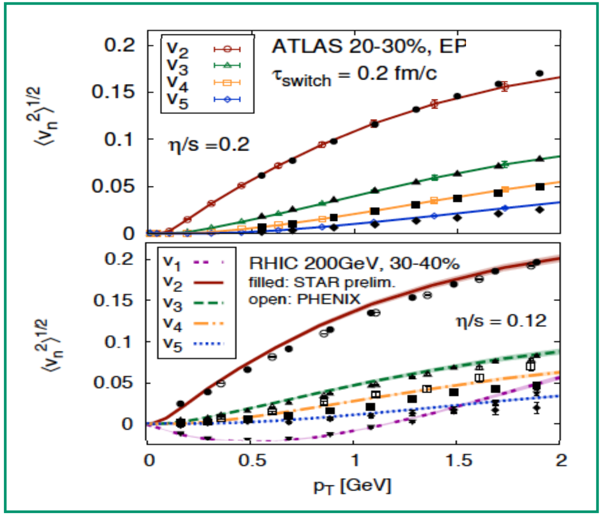


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

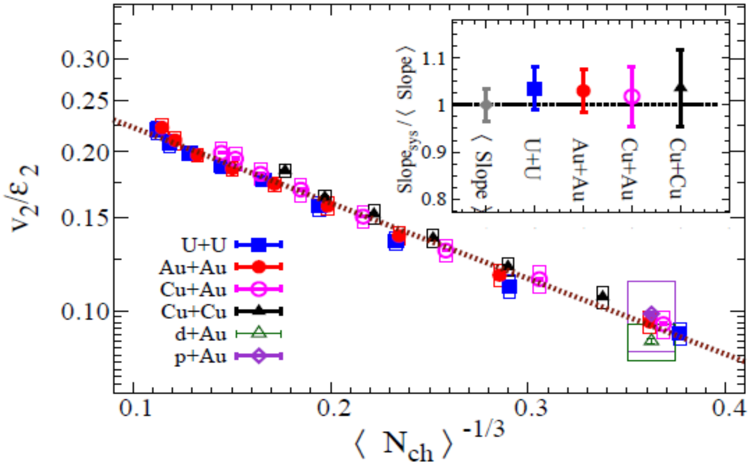
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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

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

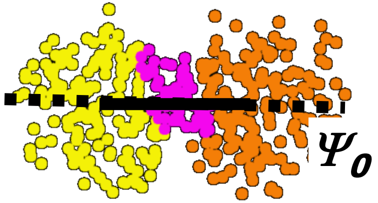


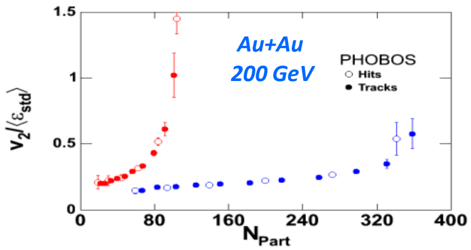
STAR, Phys. Rev. Lett. 122 (2019) 172301



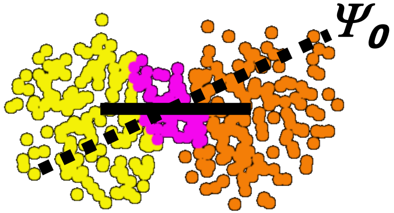
System size scan at top RHIC energy

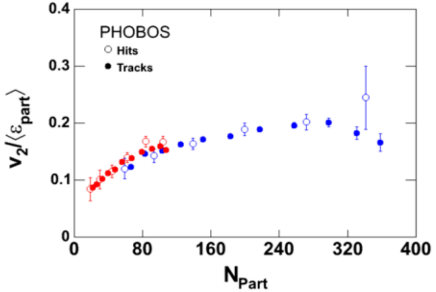
2001-2005 $\varepsilon_{\text{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2}$



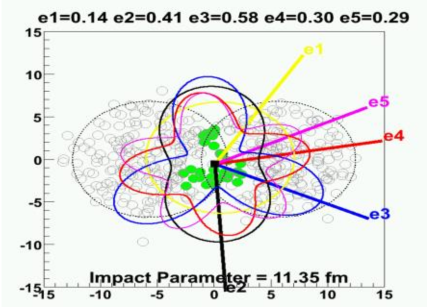


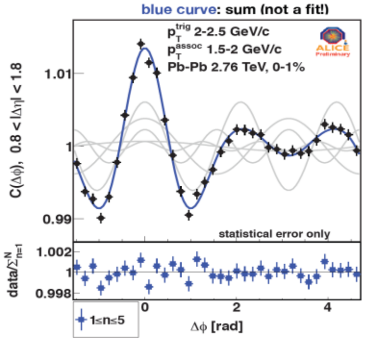
2005-2011 $\langle \epsilon_{\text{part}} \rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$





2011-2012 $\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$



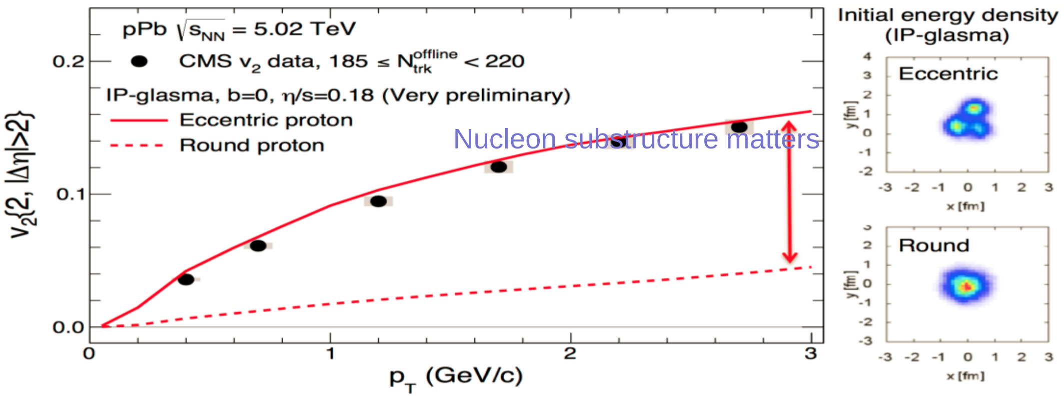


For "lumpy" *profile* $\varphi \neq \varphi + \pi$

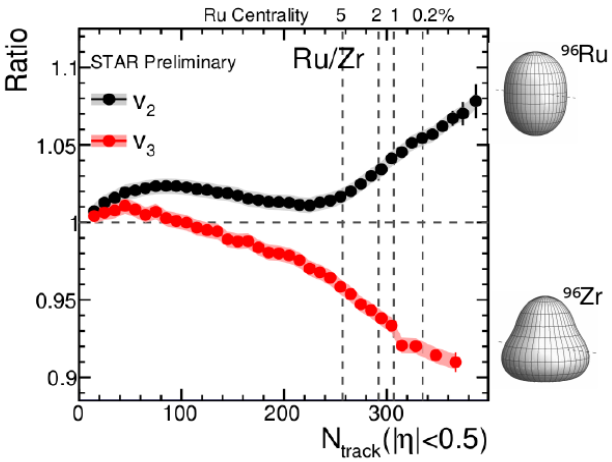
Odd harmonics $\neq 0$

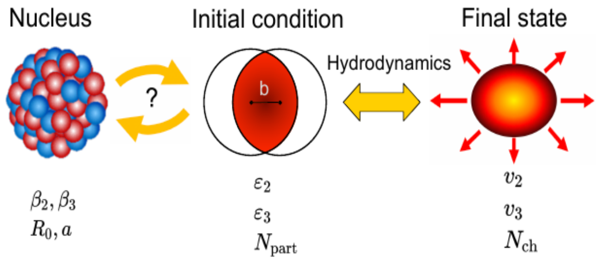
System size scan at top RHIC energy

2011-2020



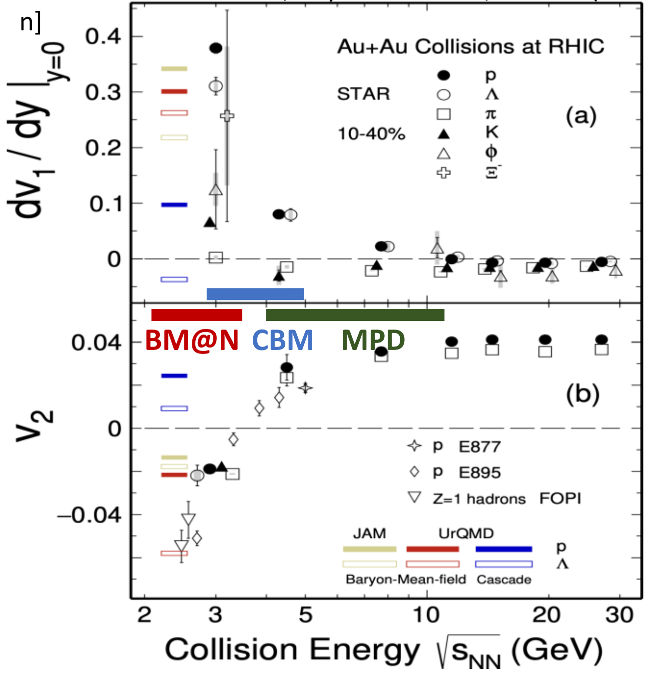
2020-2024

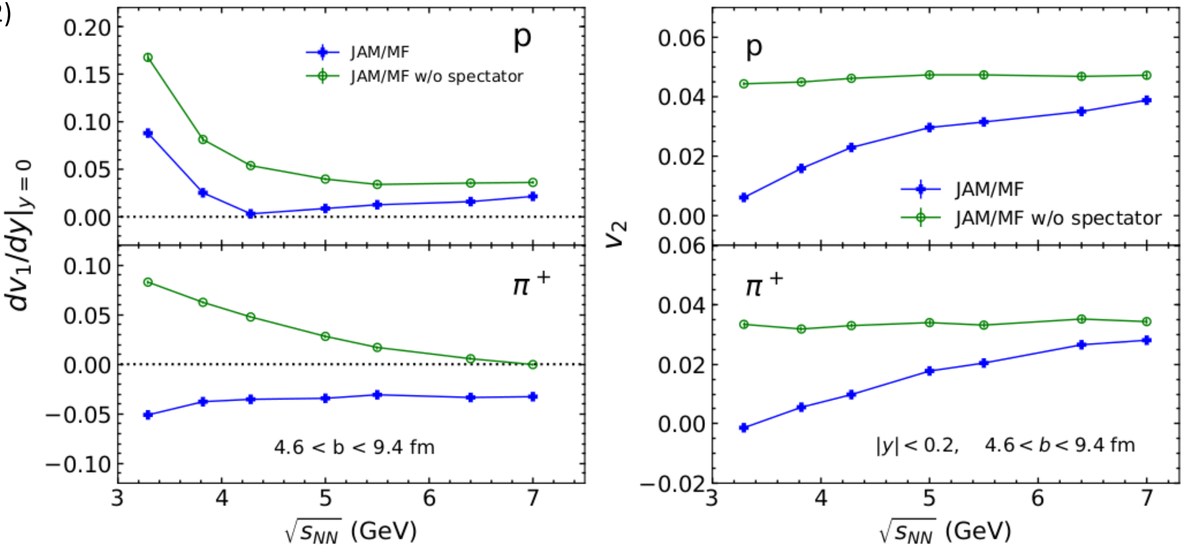




Anisotropic flow in heavy-ion collisions at high baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)





Phys. Rev. C 97, 064913 (2018)

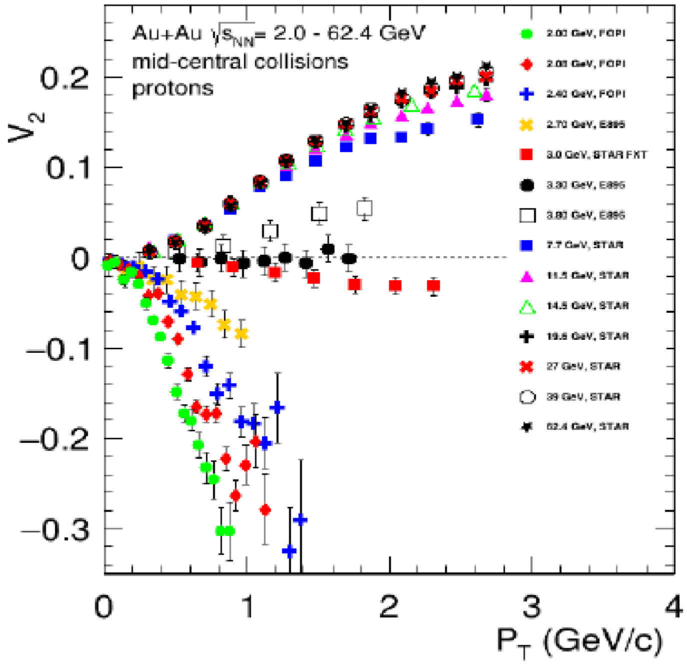
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

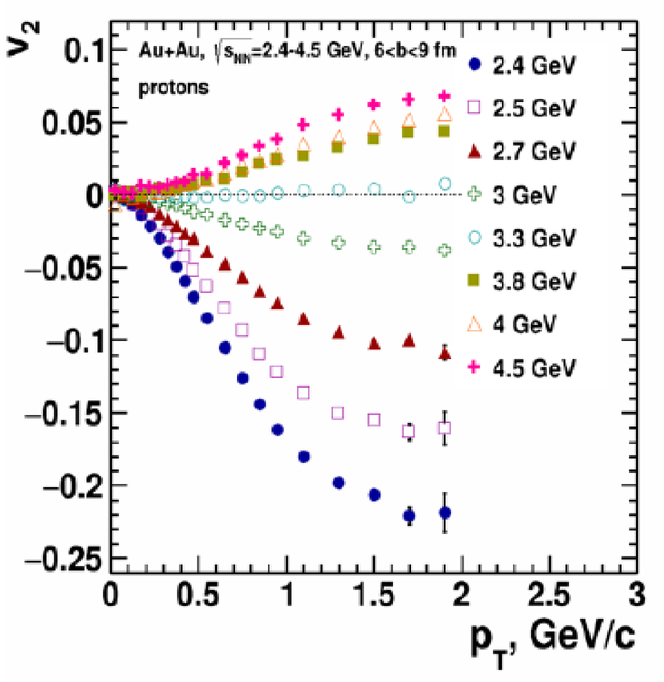
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$, $c_s = c\sqrt{dp/d\varepsilon}$) and

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

Anisotropic flow in Au+Au collisions at Nuclotron-NICA energies

M. Mamaev, Particles 6 (2023) 2, 622-637





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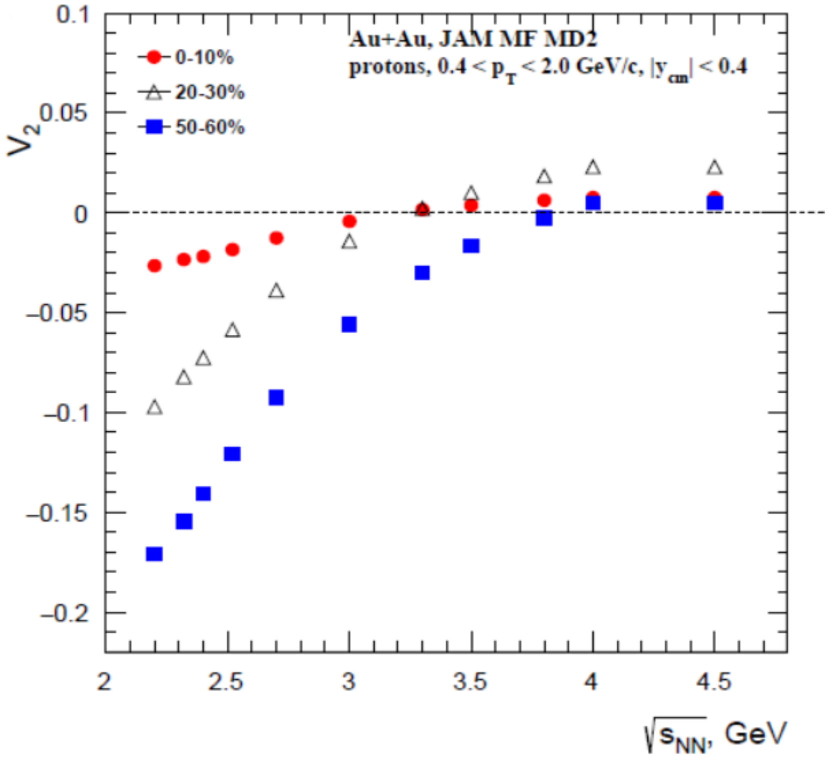
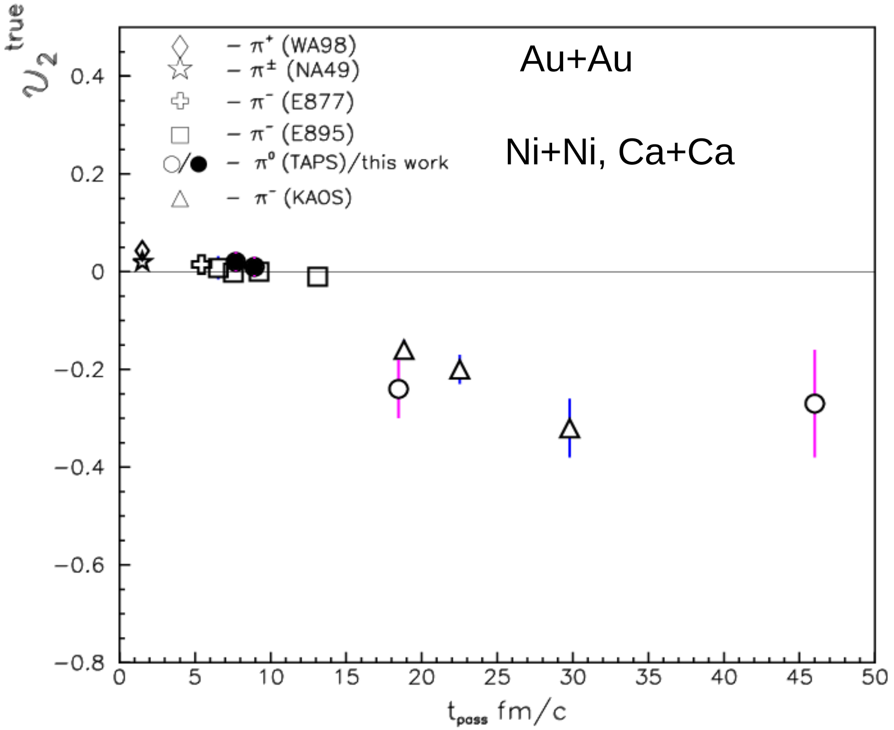
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Elliptic flow: transition from out-of-plane to in-plane: geometry

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

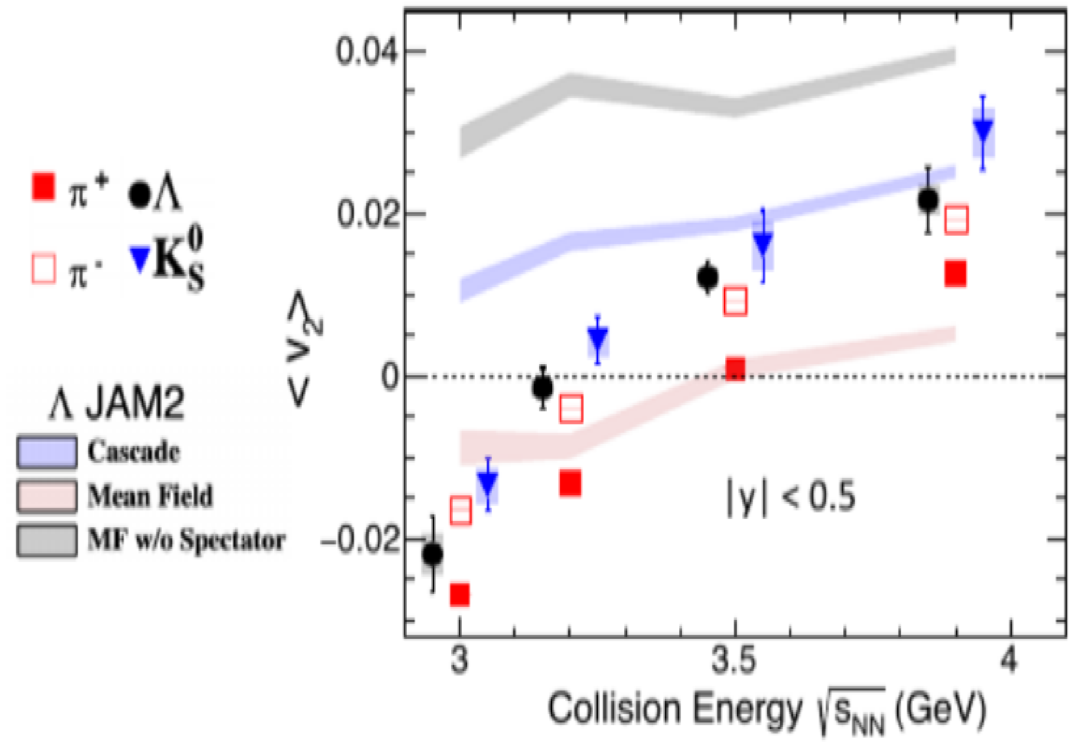


A.T Czech.J.Phys. 50S4 (2000) 139-166

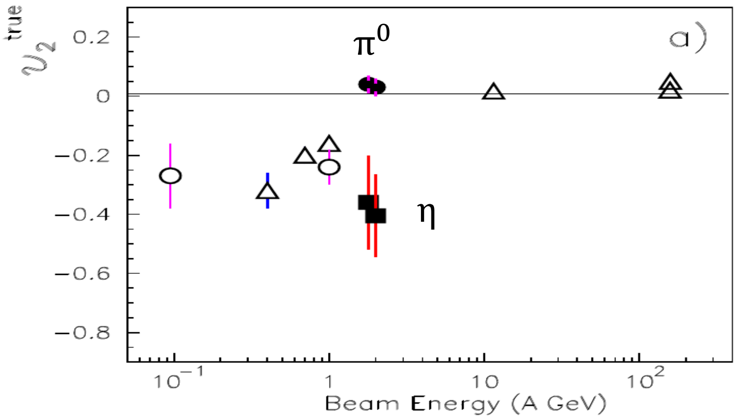


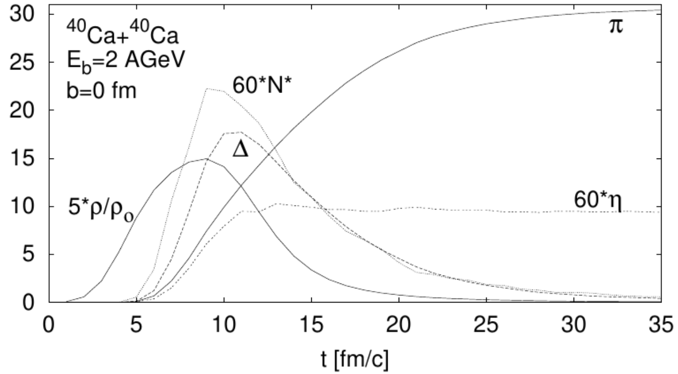
Elliptic flow: transition from out-of-plane to in-plane: PID

Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024

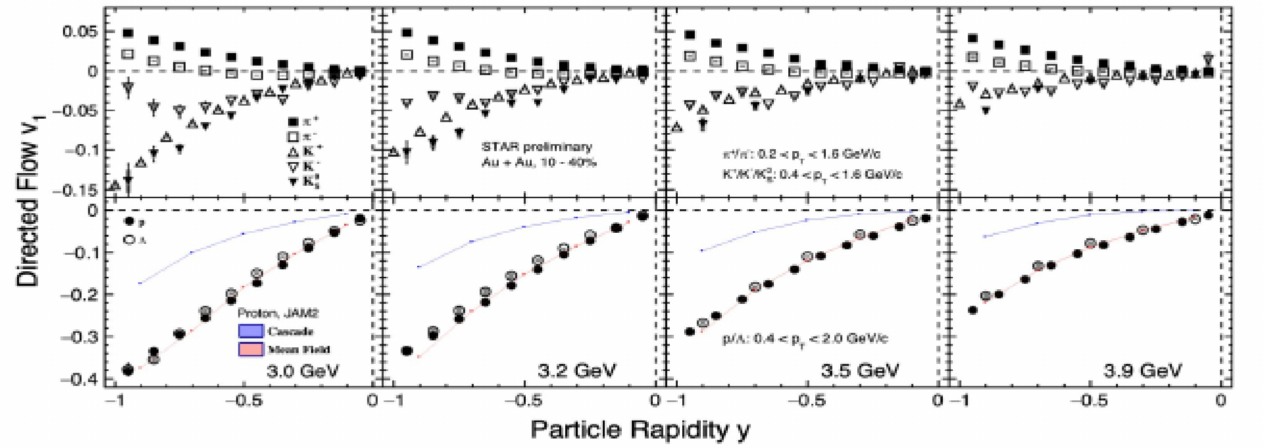


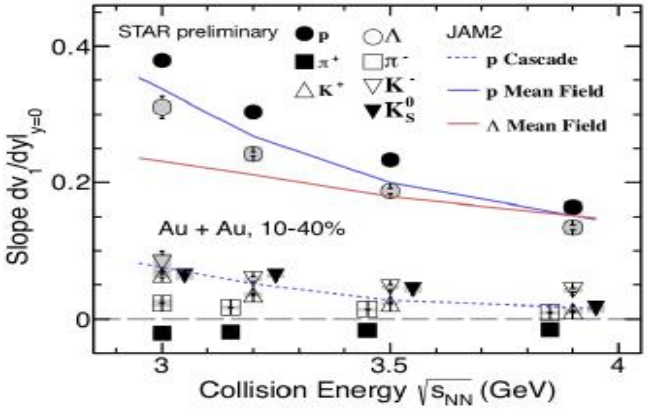
A.T Czech.J.Phys. 50S4 (2000) 139-166

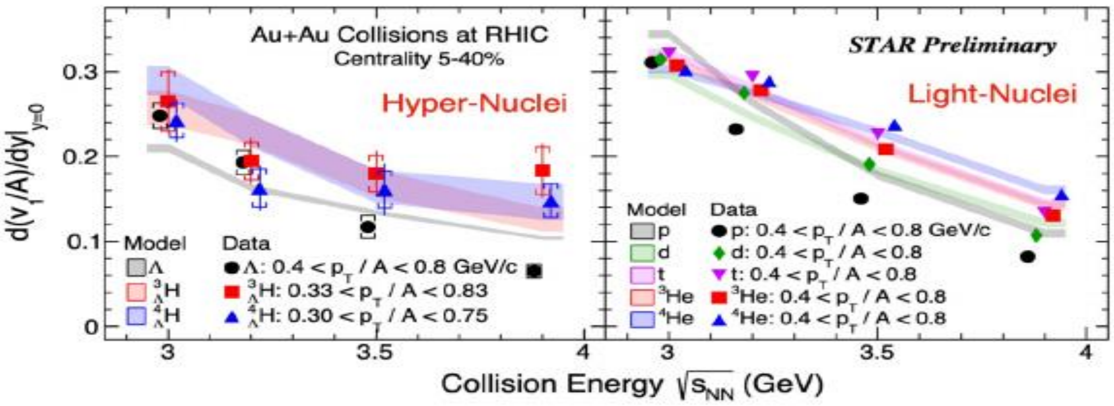




STAR preliminary results from BES – II program – directed flow







Vn of protons in Au+Au collisions at 2.4 GeV - HADES

Determination of EOS

New level of precision - multi differential

Additional information from higher orders

Models:

JAM 1.9 NS3 (hard EOS, mom.-indep.)

JAM 1.9 MD1 (hard EOS, mom.-dep.)

JAM 1.9 MD4 (soft EOS, mom.dep.)

UrQMD 3.4 (hard EOS, mom.-indep.)

GiBUU Skyrme 12 (soft EOS)

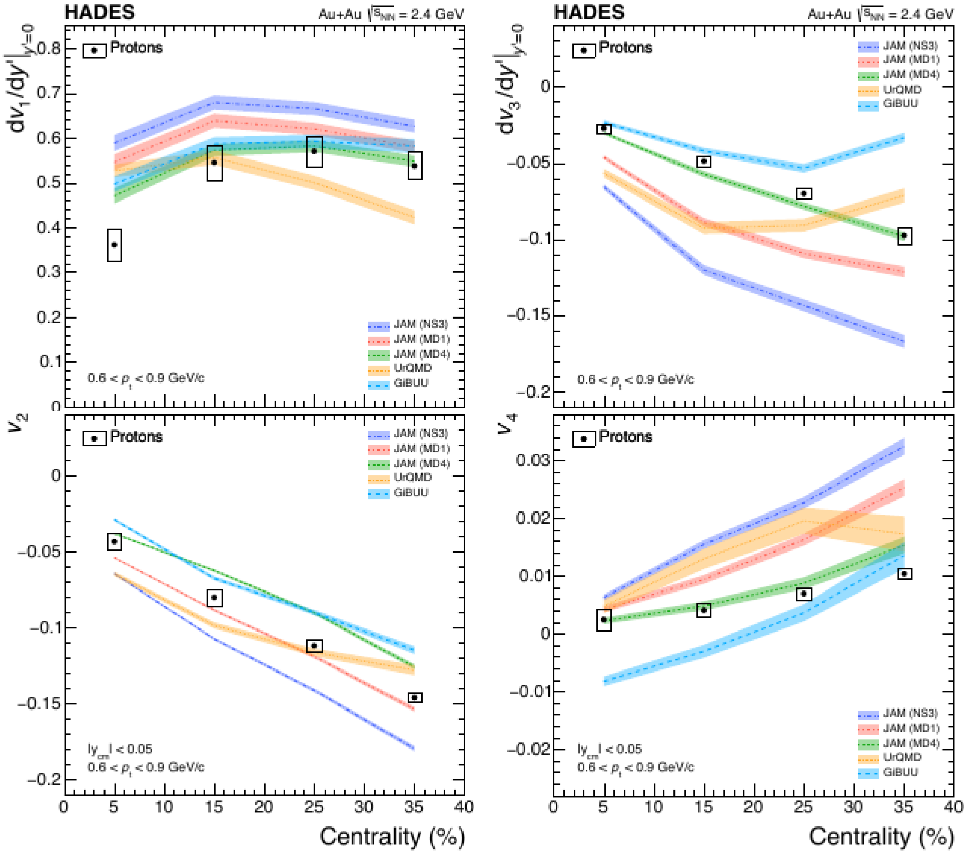
Model	EOS	K (MeV)	m^*/m	mom-dep.
JAM 1.90591	NS1	380	0.83	no
	MD1	380	0.65	yes
	MD4	210	0.83	yes
UrQMD 3.4	Hard	380		no
GiBUU 2019 (patch7)	Skyrme 12	240	0.75	no

Conclusions

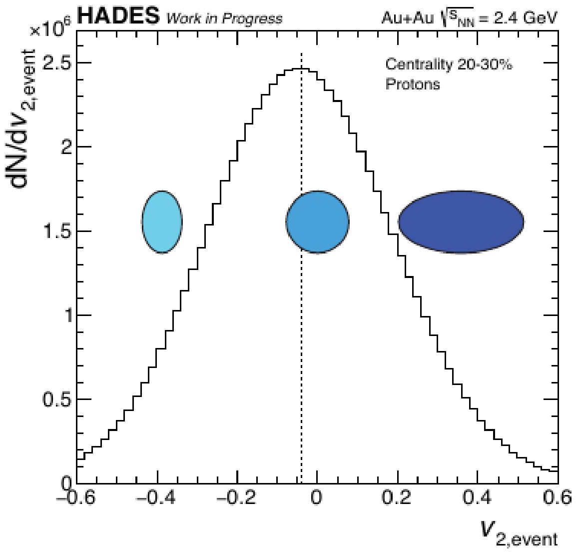
Overall trend reasonably described, but no model works everywhere

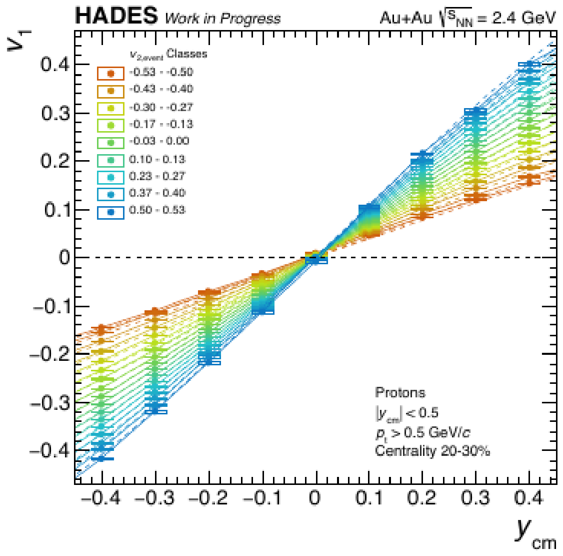
Several systematic deviations can be linked to different implementation in transport codes

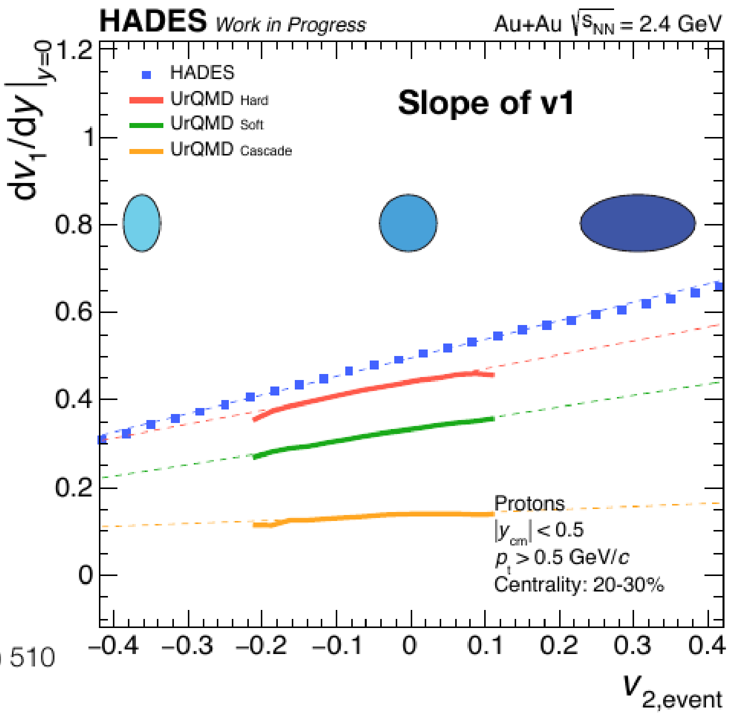
Mechanism of light nuclei production is essential for the description of the data



New HADES results   on flow correlations

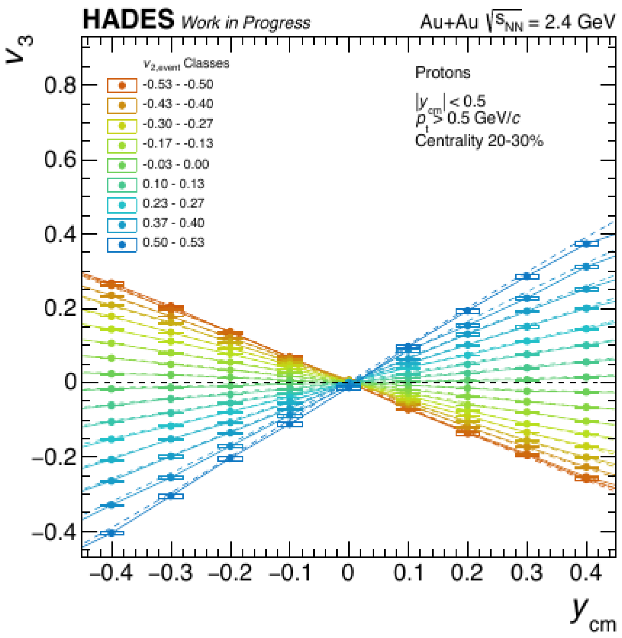


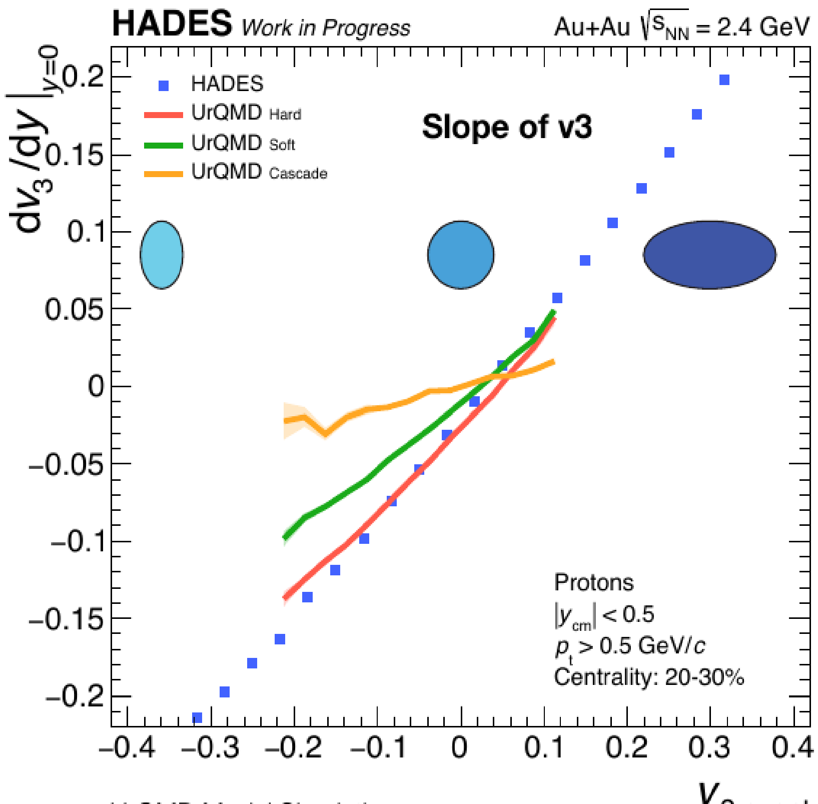




UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

New HADES results on flow correlations



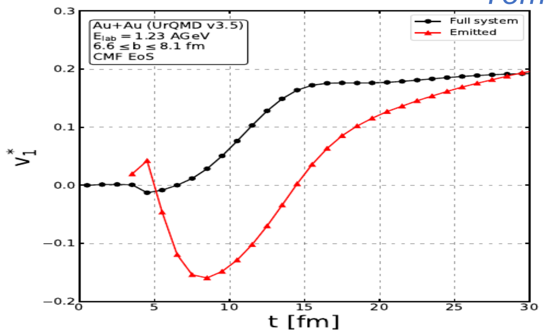


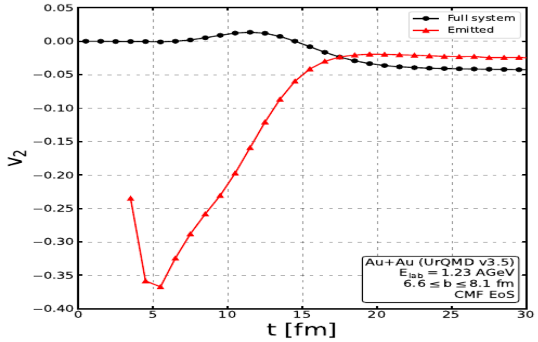
Slope of the Triangular Flow v_3

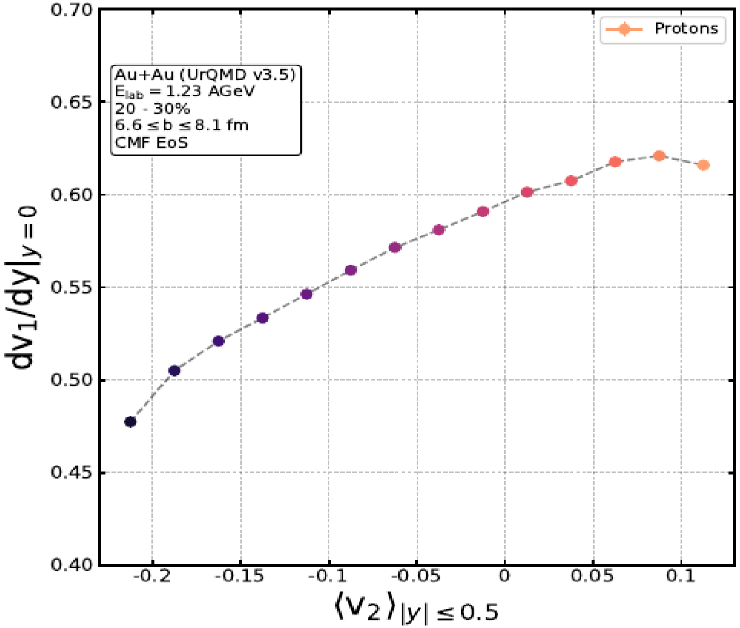
A strong sensitivity to the EoS is seen

Decoding the flow evolution using hadron V_1- V_2 correlations and dileptons

Tom Reichert et al., Phys.Lett.B 841 (2023) 137947

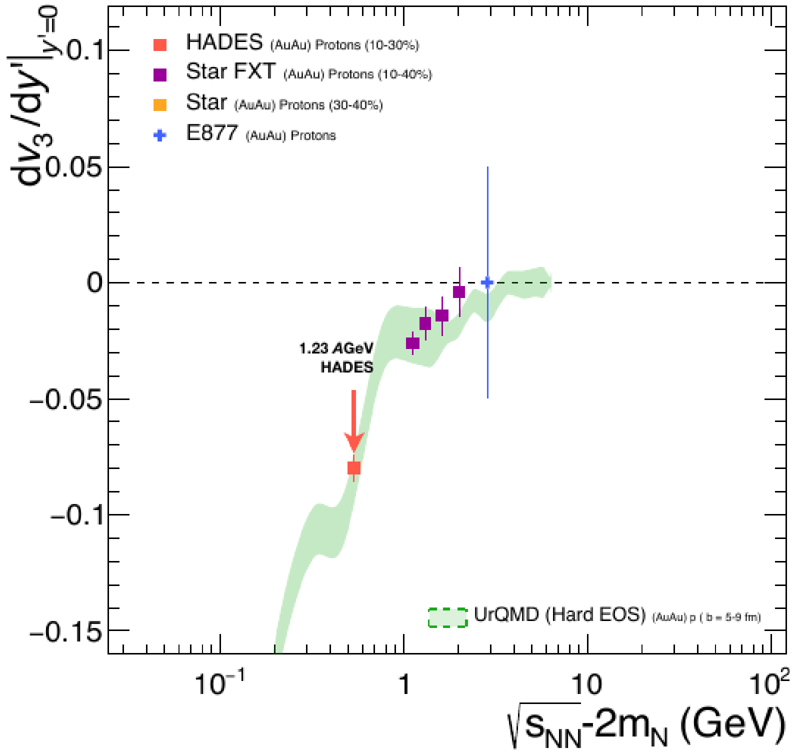


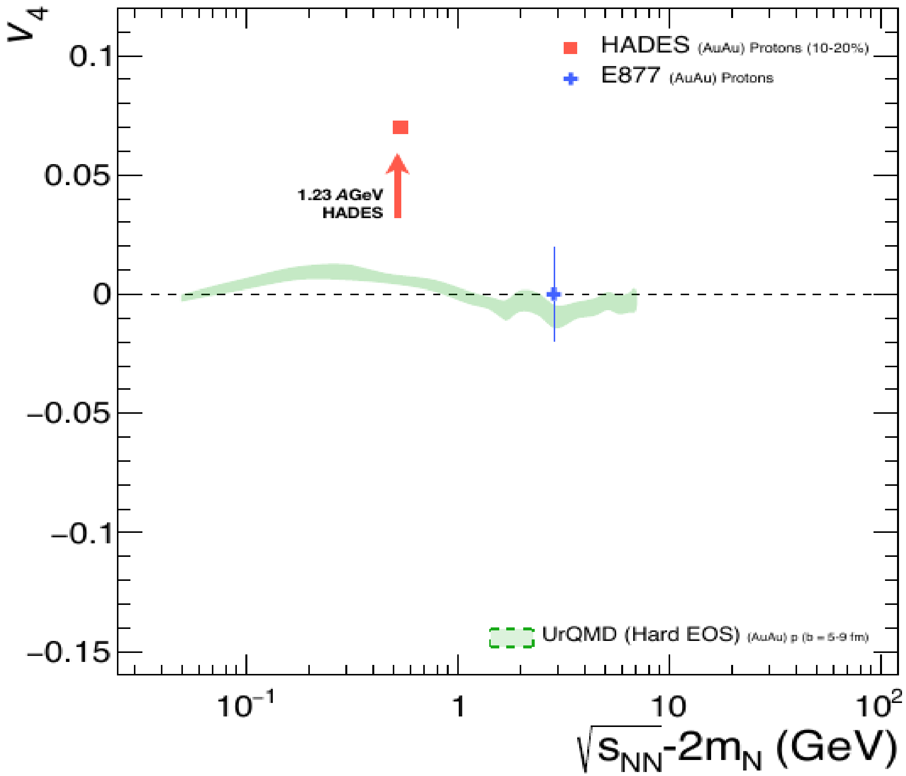




The elliptic flow is initially positive (v2 > 0) due to the early pressure gradient. This positive v2 transfers its momentum to the spectators, which creates the directed flow v1.
In turn, the spectator shadowing of the in-plane expansion results in a negative v2 for the observable final state hadrons. propose a measurement of v1−v2 flow to pin down this evolution pattern.

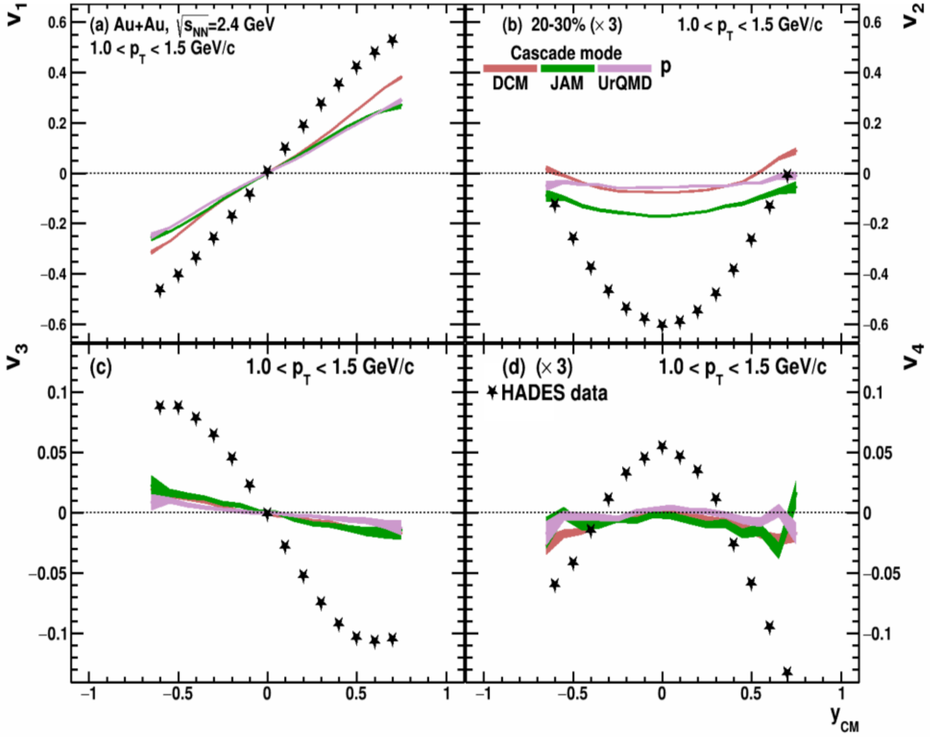
Collision energy dependence of v3 and v4

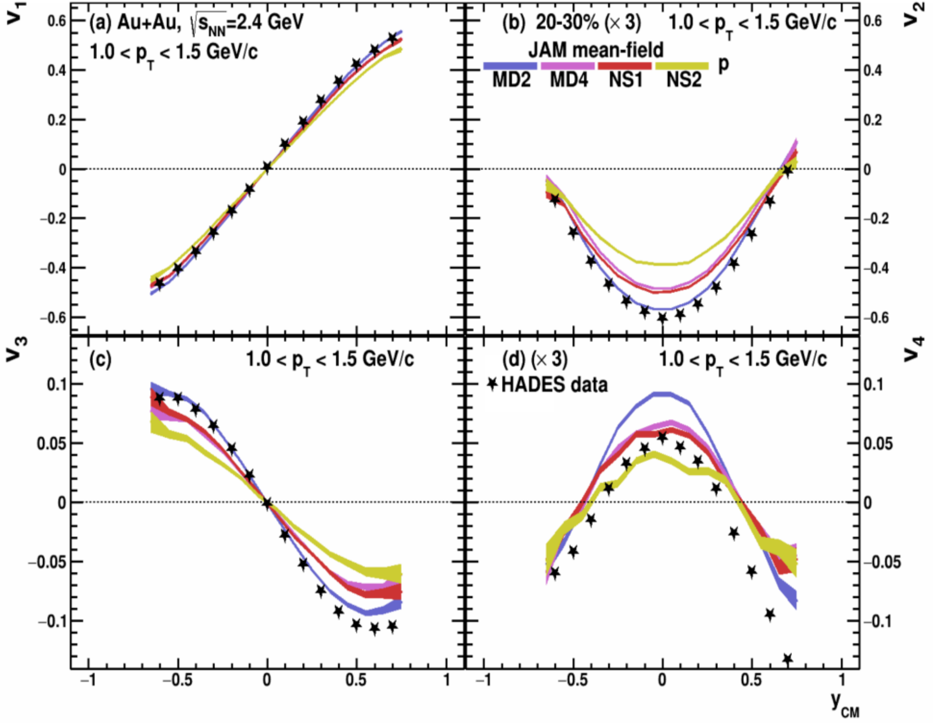




Flow of protons - models vs data

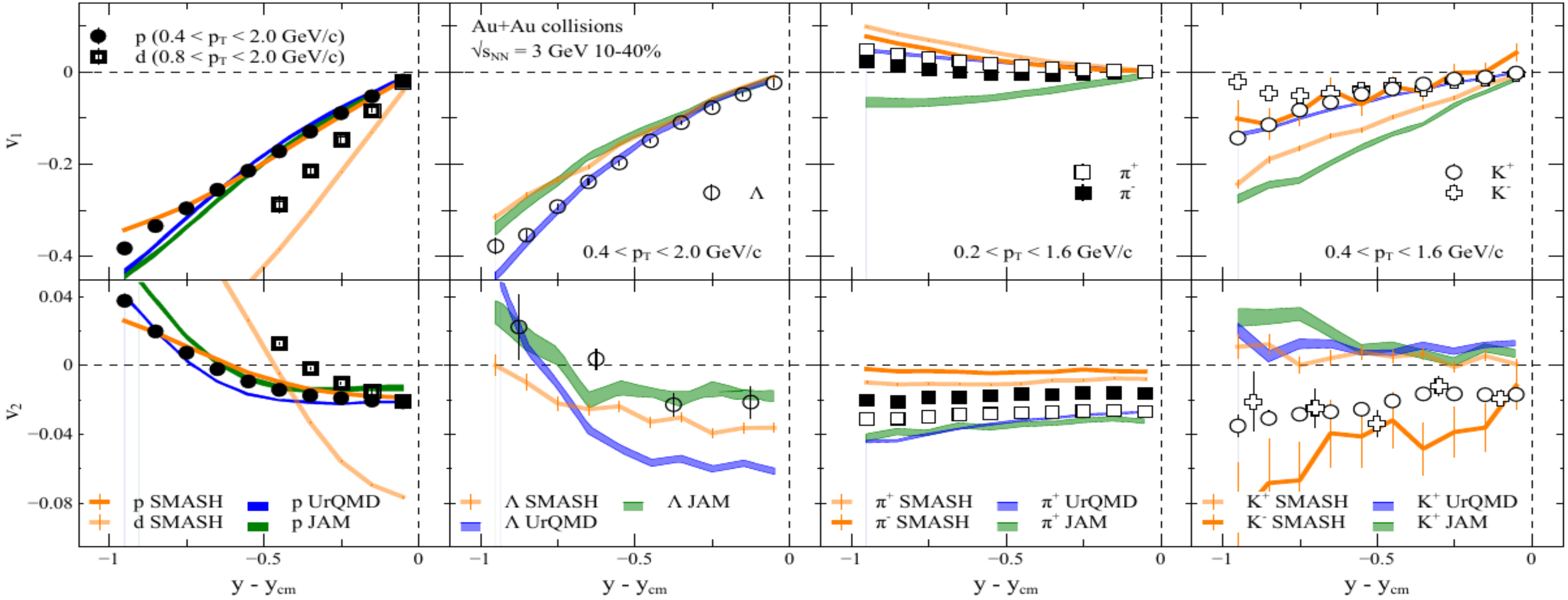
P. Parfenov, Particles 5 (2022) 4, 561-579





Describing proton flow is not enough

Prog.Part.Nucl.Phys. 134 (2024) 104080

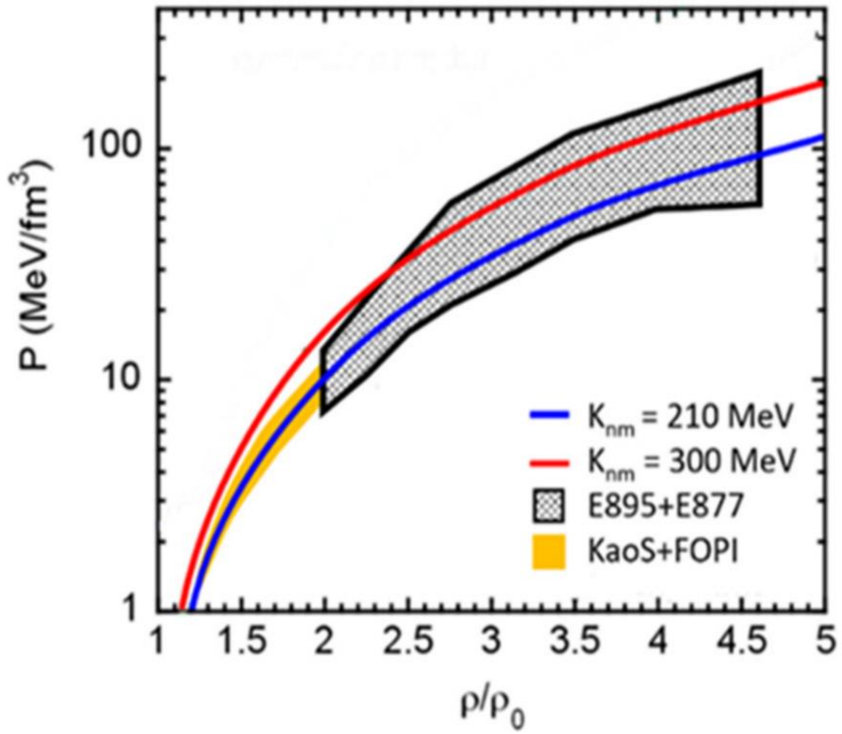


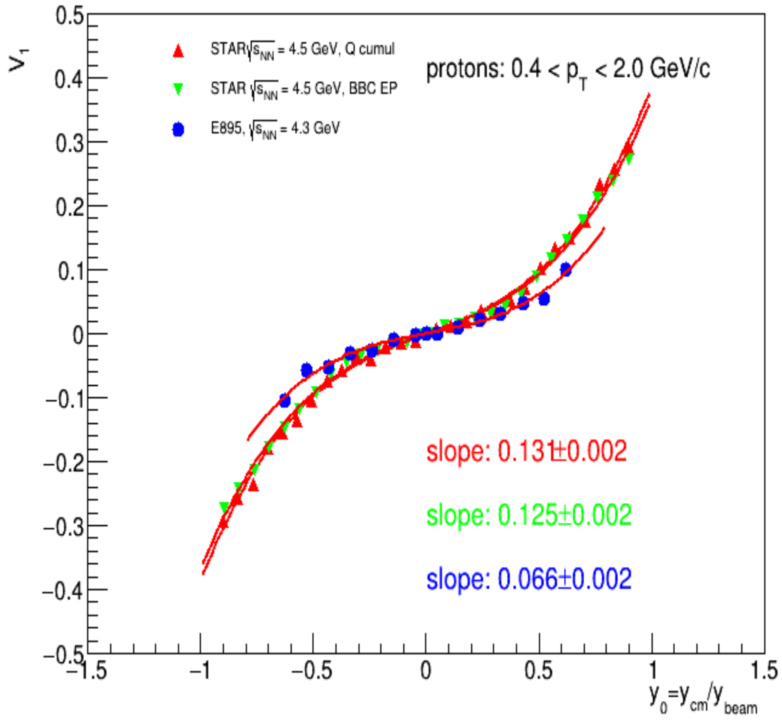
Strange baryons are not well described — the results may depend on:

- nucleon-hyperon and hyperon-hyperon interactions
- in-medium modifications of interactions

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

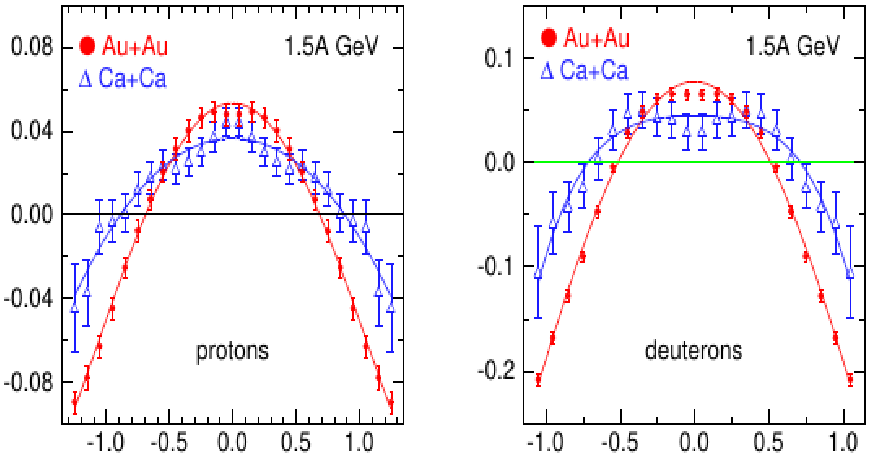
The main source of existing systematic errors in v_n measurements

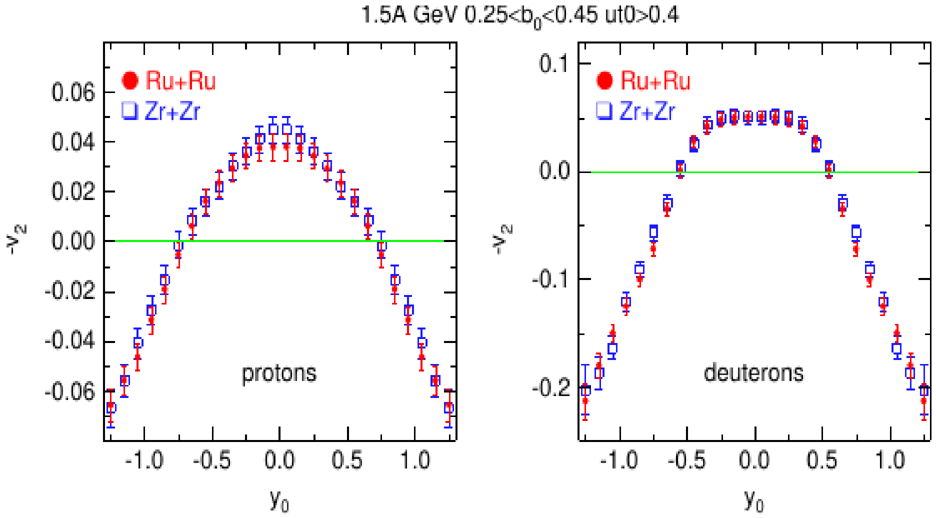


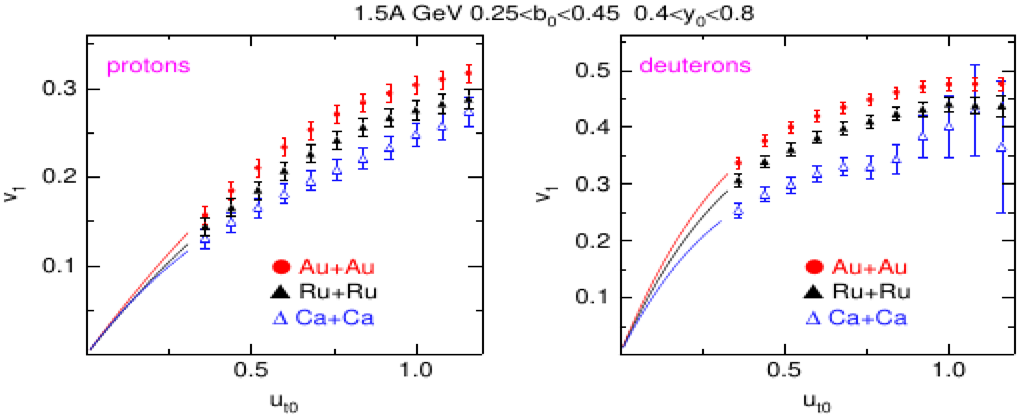


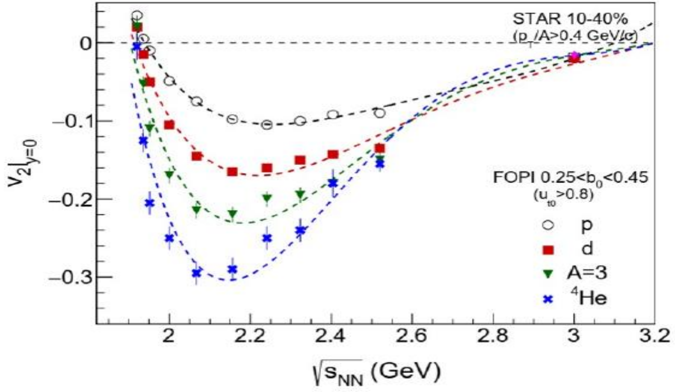
The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)

FOPI Ion-Ion collisions at 1.5 AGeV

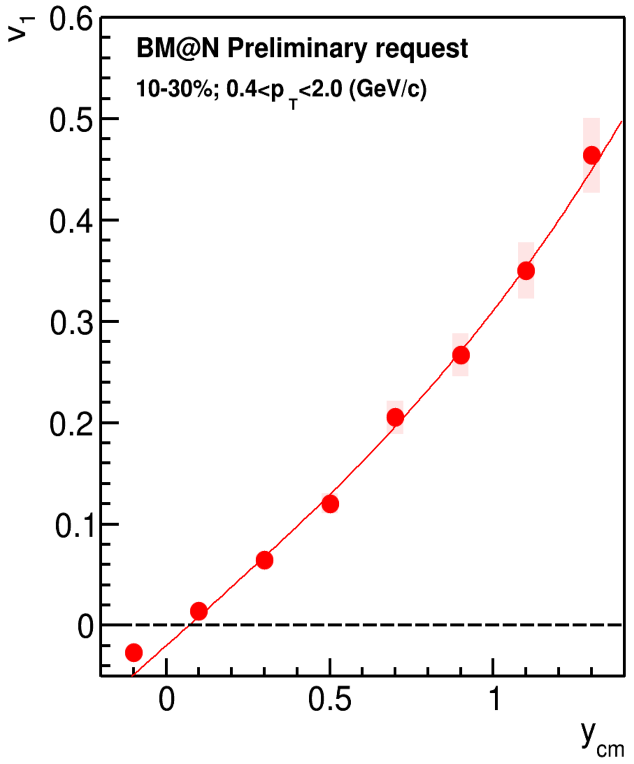


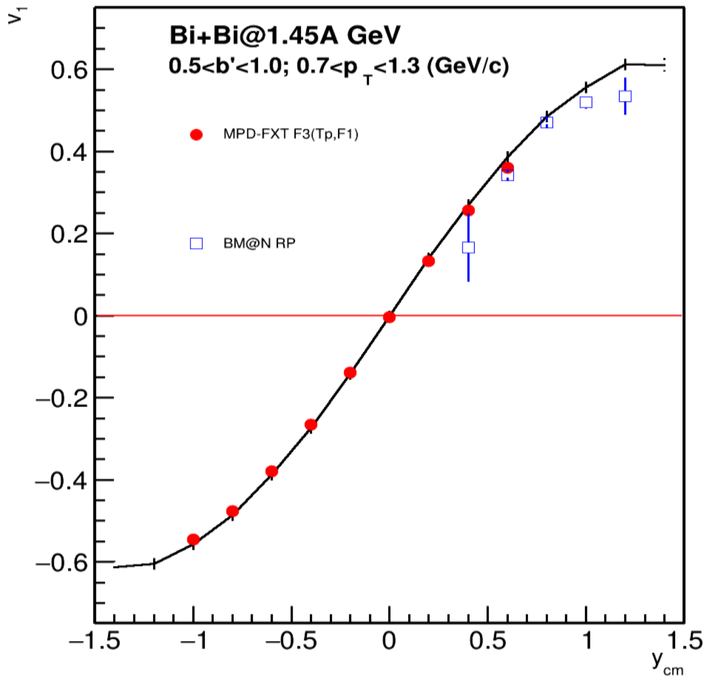






Directed flow of protons: BM@N – MD FXT

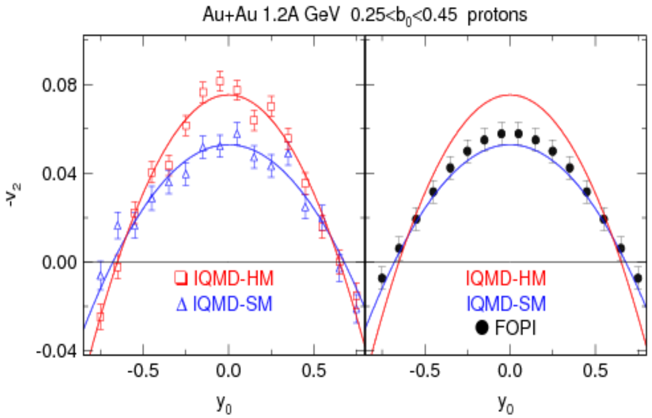


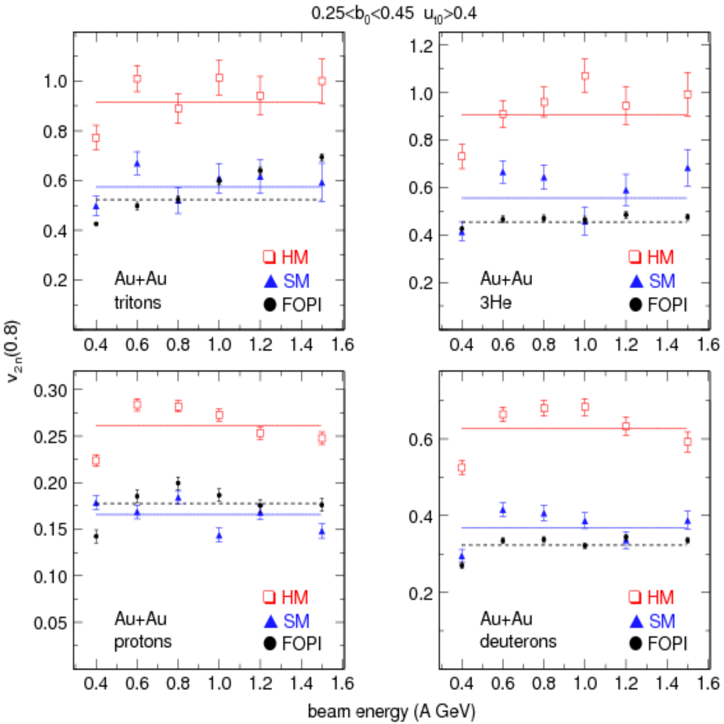


Rapidity dependence of v2 and EOS

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)





V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

Large rapidity coverage is important for flow measurements

Summary and outlook

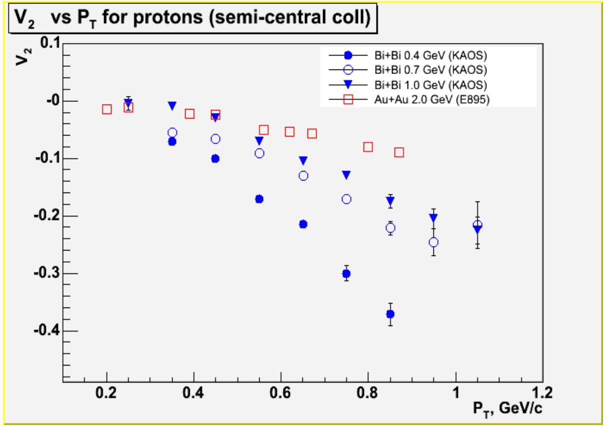
- Measurements of anisotropic flow, flow fluctuations, correlations between flow of different harmonics are sensitive to many details of the initial conditions and the system evolution. It may provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc.
- **v_n at energies 2.5-11 GeV (SIS, STAR BESII, NICA, FAIR) shows strong energy dependence: possible** transition between hadronic and partonic matter.
- **System size scan is very important in order to understand the effect of spectators on the experimental observables**

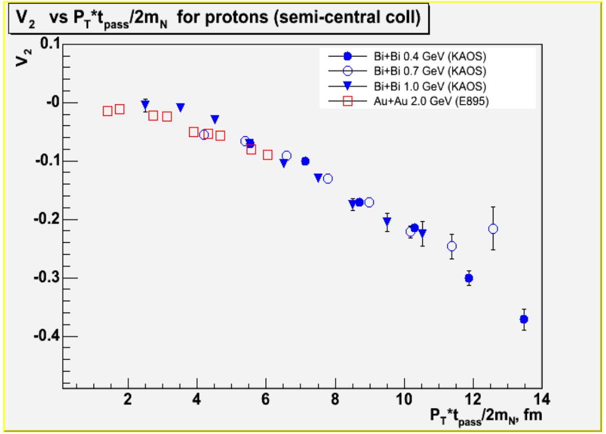
Large rapidity coverage is important for flow measurements

Backup

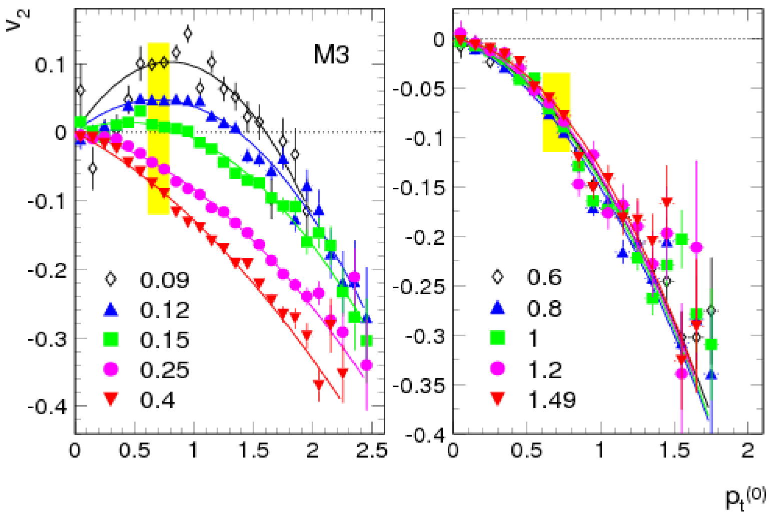
v_2 Flow at SIS-AGS: scaling relations

(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295





FOPI: v_2 of protons from
Elab=0.09 to 1.49 GeV
Phys.Lett. B612 (2005) 173-180



The rather good scaling observed suggest that c_s does not change significantly over beam energy range 0.4 – 2.0 AGeV.

Vn of protons in Au+Au collisions at 2.4 GeV - HADES

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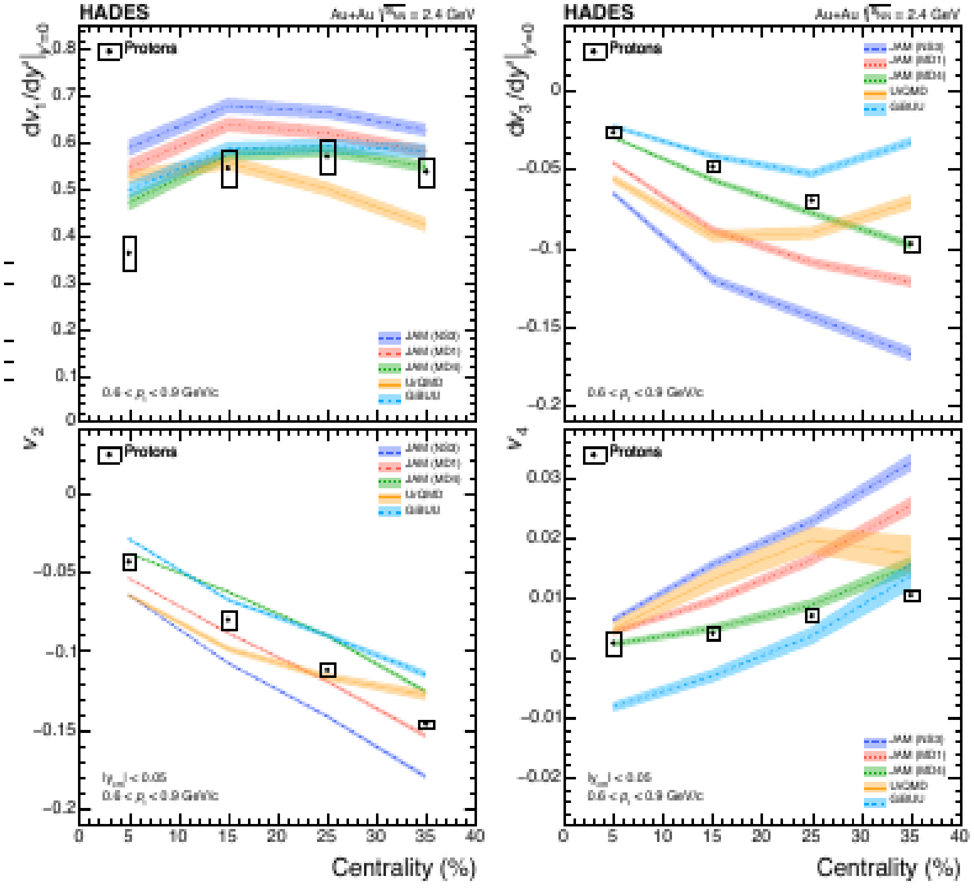

Describing proton flow is not enough

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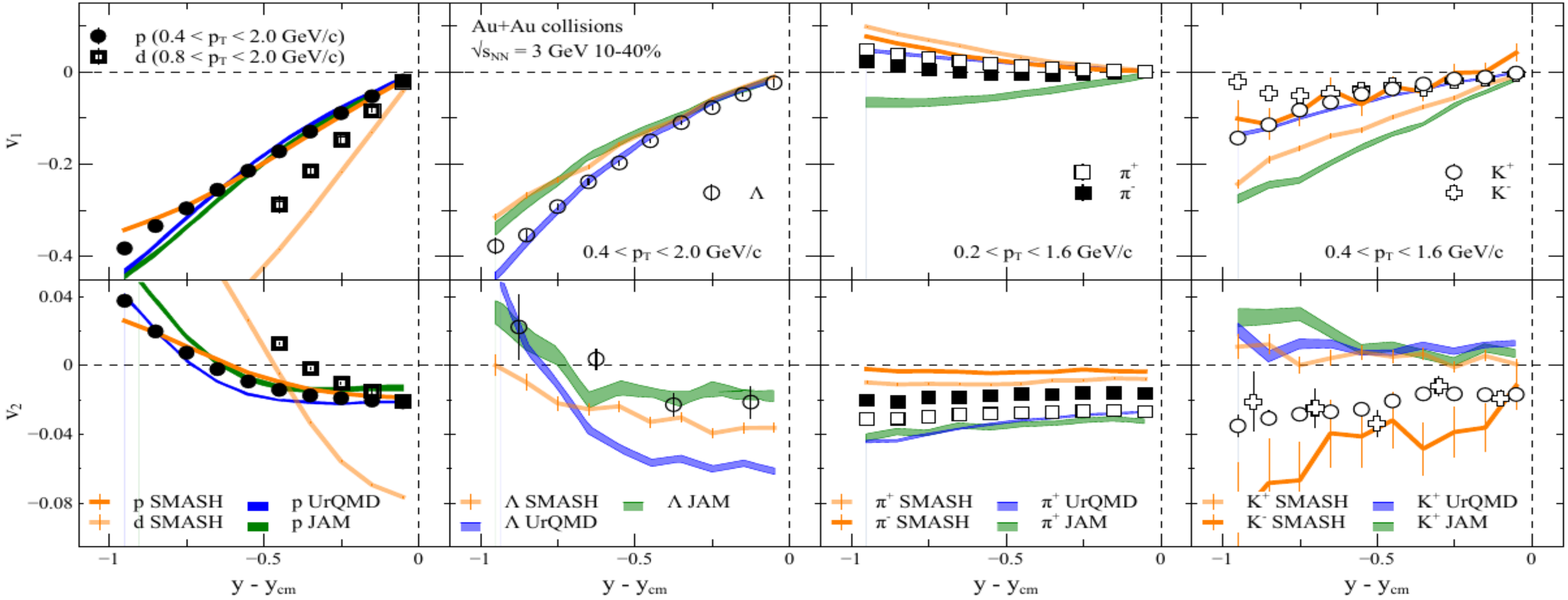

Strange baryons are not well described — the results may depend on:

- nucleon-hyperon and hyperon-hyperon interactions
- in-medium modifications of interactions

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don’t have mean-fields for mesons