What can we learn from particle flow in BES experiments

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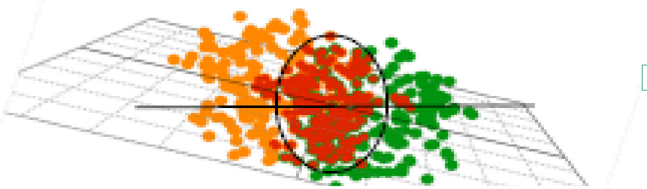
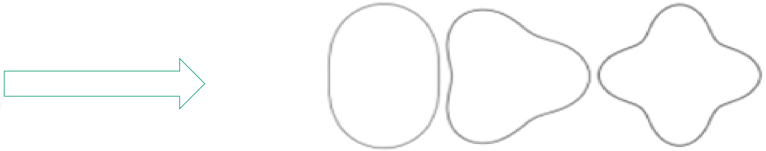
11th MPD Collaboration Meeting, JINR , Dubna, 18-20 April 2023

OUTLINE

1. Flow and sQGP at RHIC/LHC
2. Scaling properties of anisotropic flow
3. Flow results from Beam Energy Scans
4. Outlook for flow measurements at NICA

Anisotropic Flow at RHIC-LHC



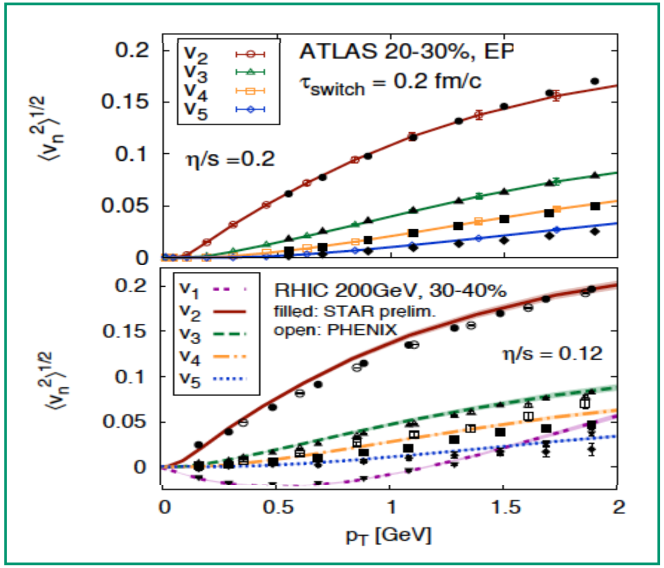


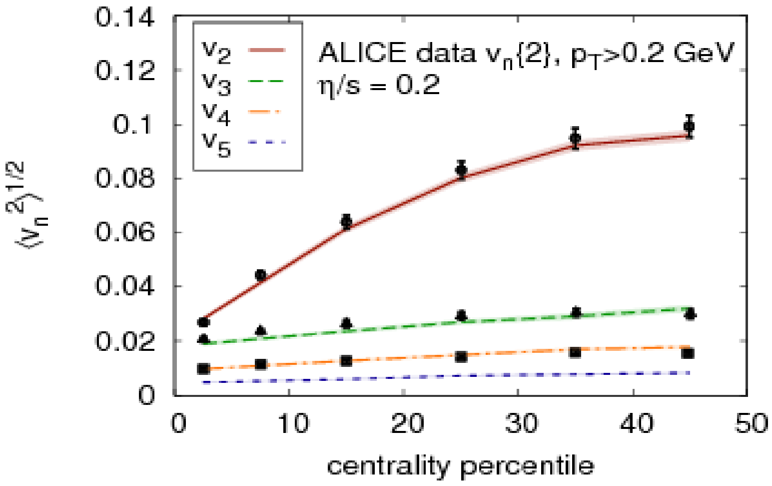
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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

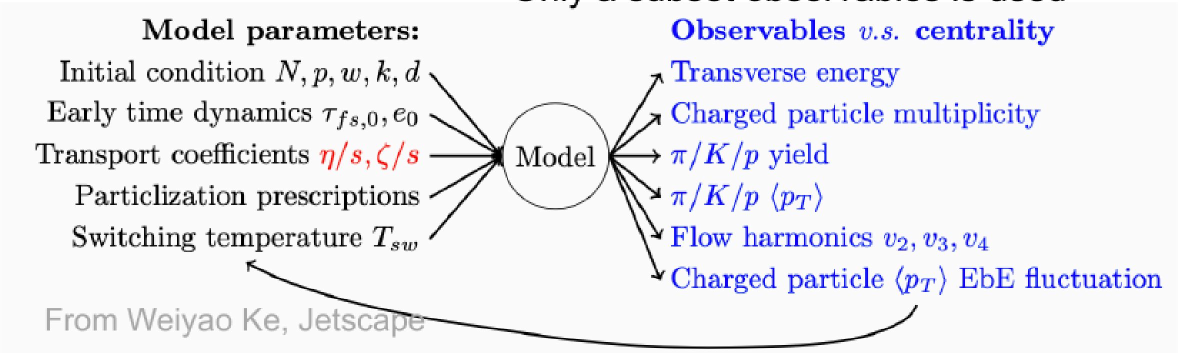




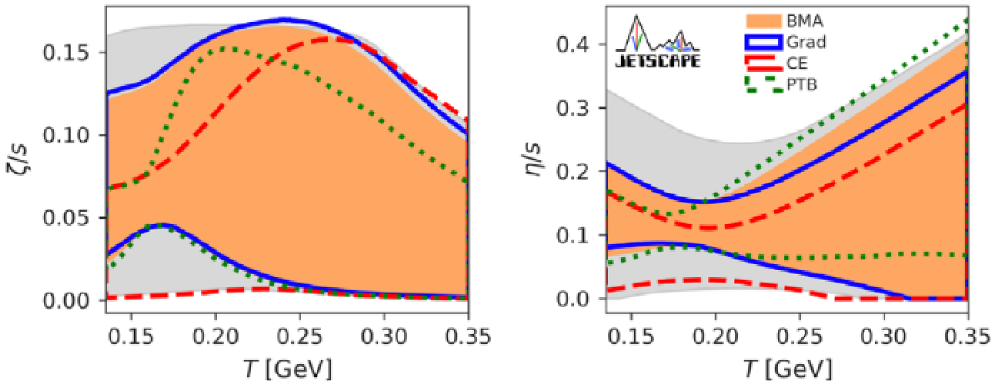
State-of-the-art modeling of HI collisions

- Data-model comparison via Bayesian inference to optimize constraining power.

Only a subset observables is used



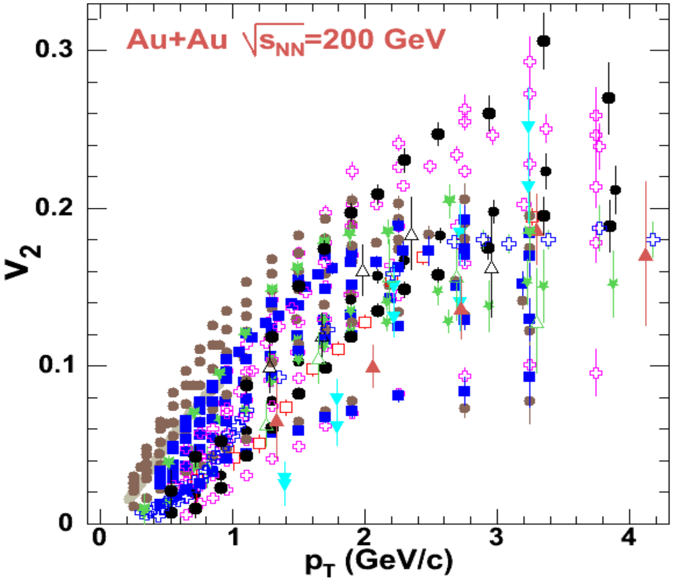
- Detailed temperature dependence of viscosity!



Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

Anisotropic Flow at RHIC – scaling relations



PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

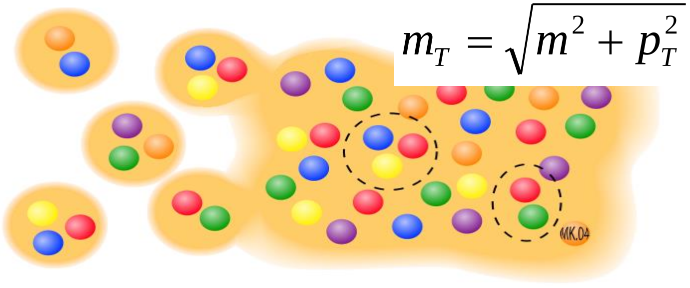
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

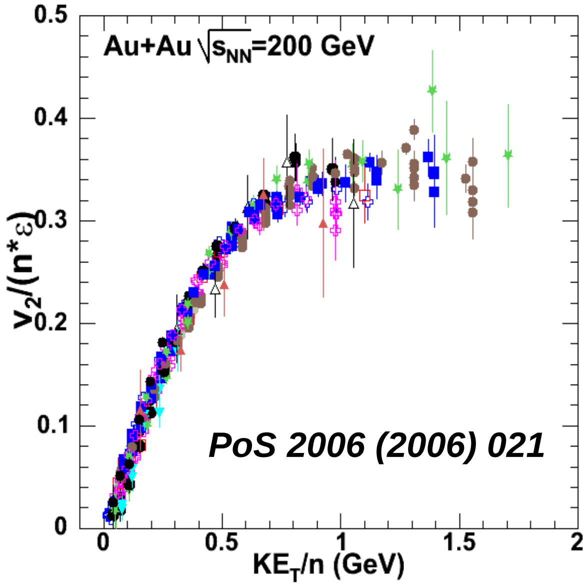
STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S : min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias

$$KE_T = m(\gamma_T - 1)$$
$$= m_T - m$$

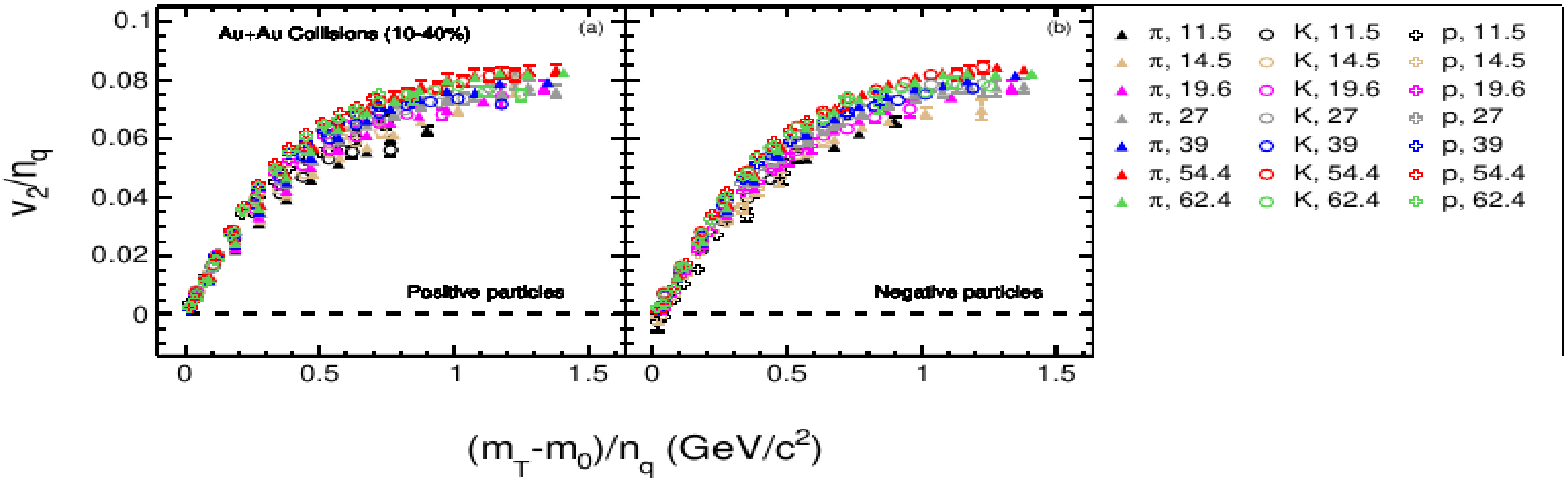
$$m_T = \sqrt{m^2 + p_T^2}$$

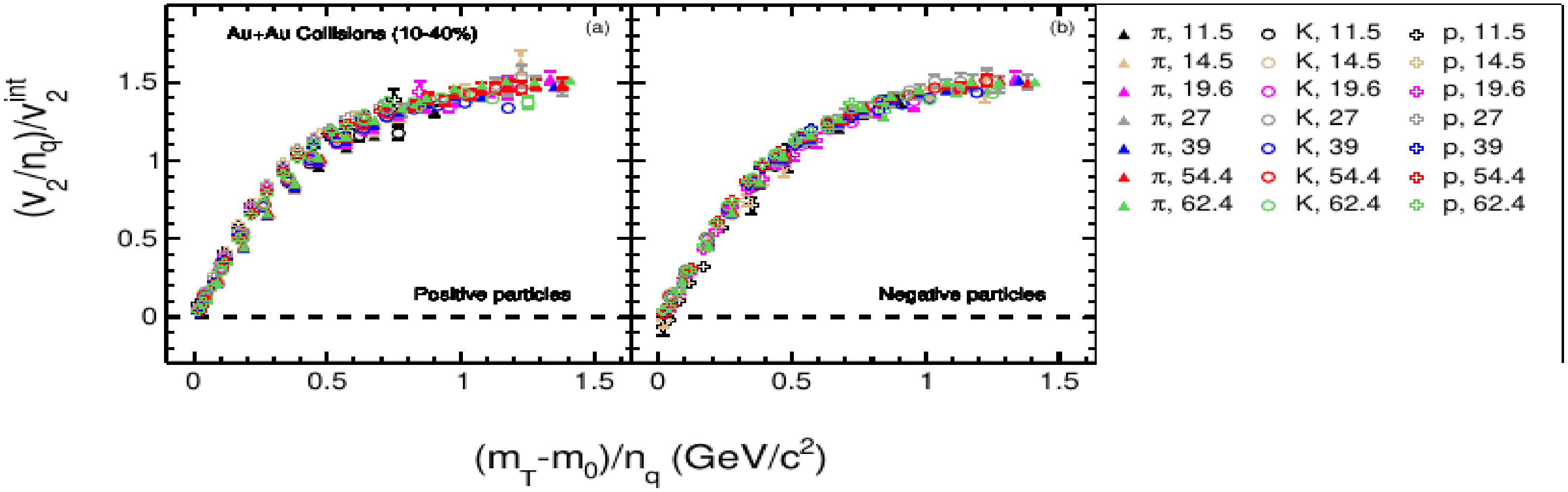




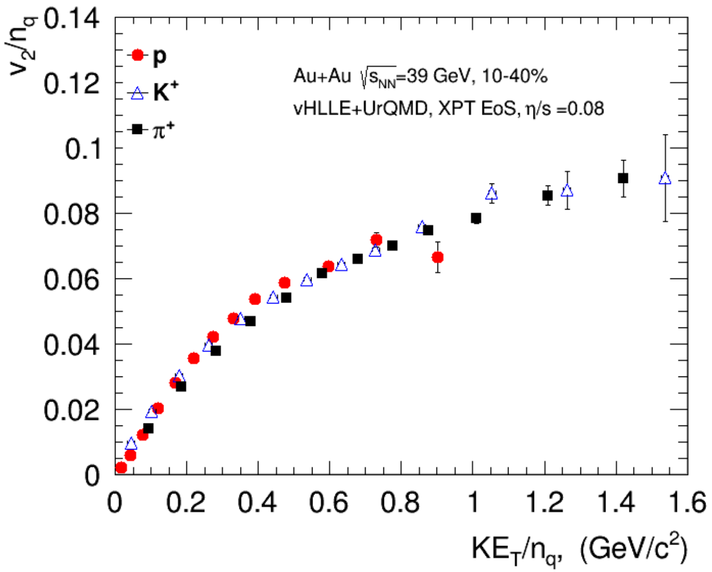
n=2 for mesons and n=3 for baryons

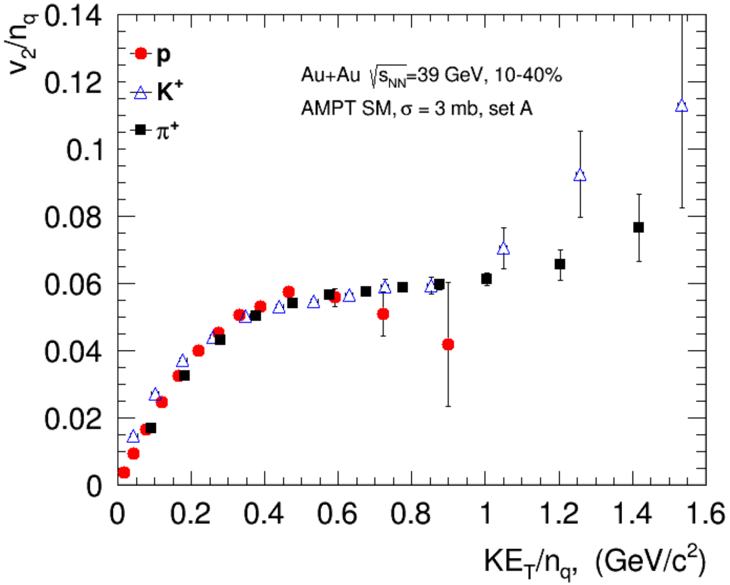
Anisotropic Flow at RHIC – scaling relations





KE_T / n_q scaling : hybrid models





UrQMD + 3D viscous hydro model vHLLE + UrQMD

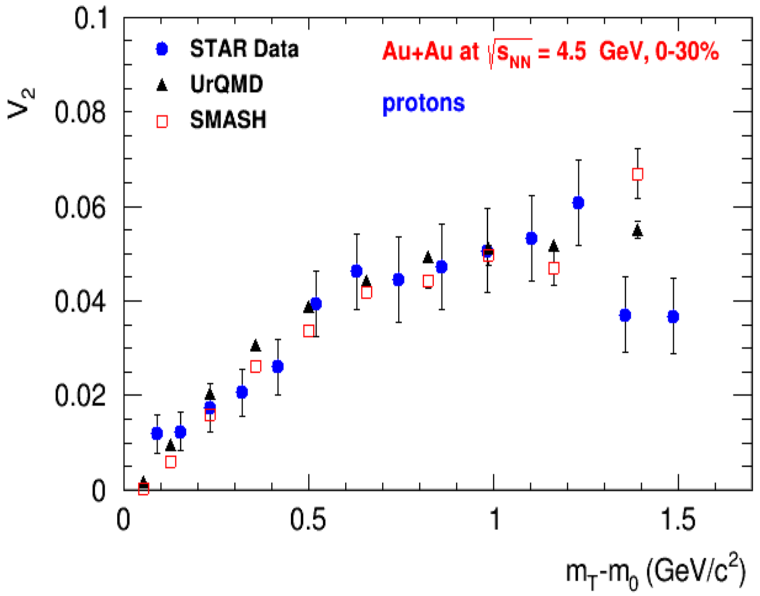
Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle

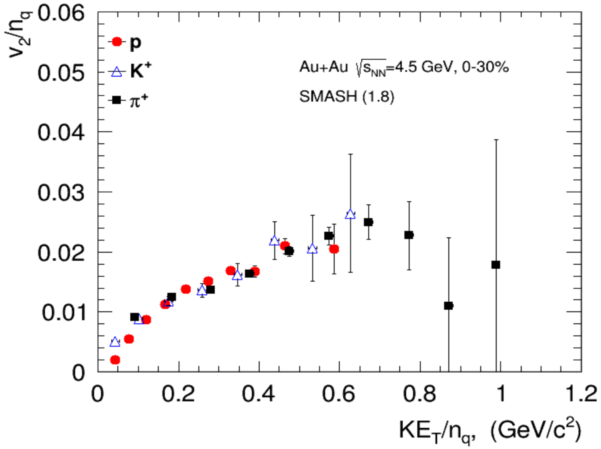
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) EOS (XPT)
Hadronic phase: model UrQMD

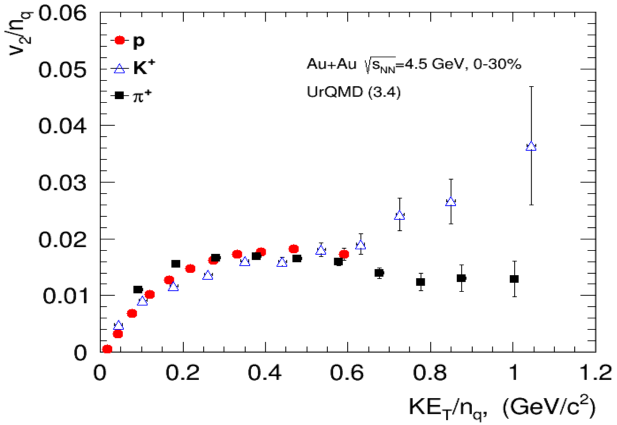
A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions. (v1.26t9b/v2.26t9b)
Initial conditions: model HIJING
QGP phase: Zhang's parton cascade for modeling partonic scatterings
Hadronic phase: model ART

Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal: Physical Review C 72, 064901 (2005).

KE_T / n_q scaling : String/Hadronic Cascade models



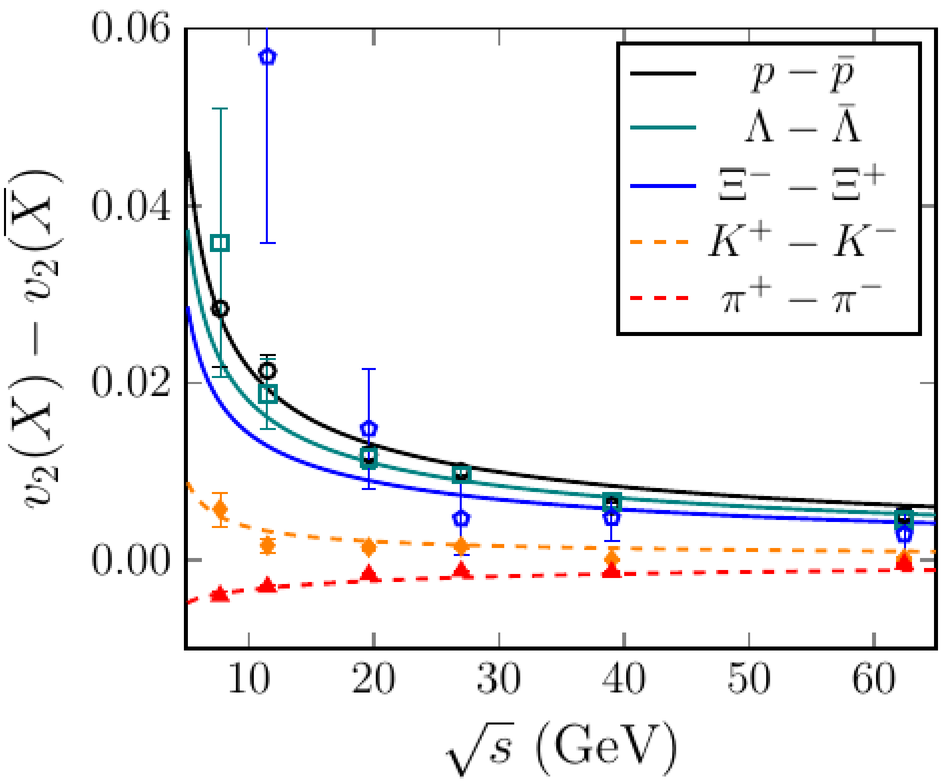


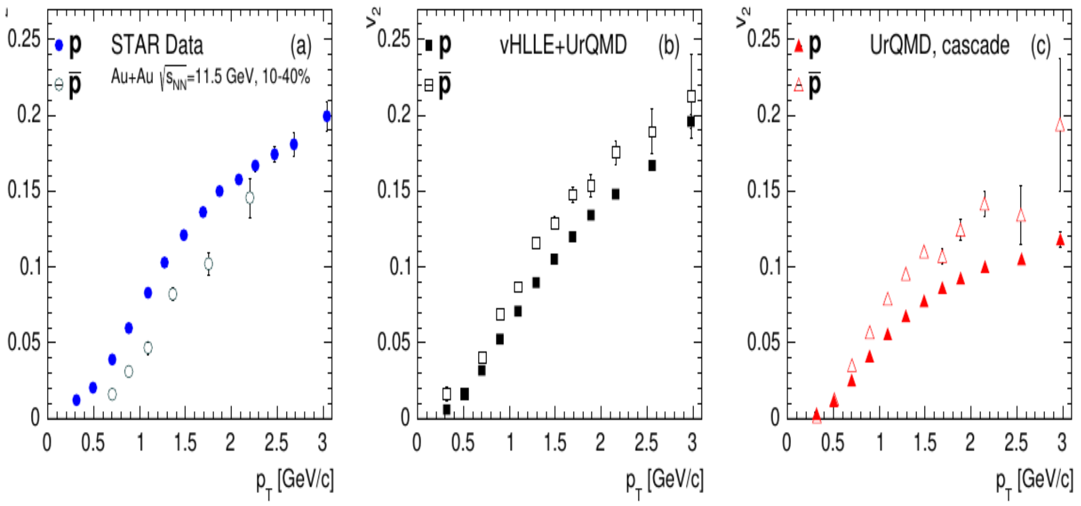


STAR Collaboration, arxiv.org/abs/2007.14005

Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV

Anisotropic flow of particles and anti-particles





Yoshitaka Hatta
Analytic approaches to relativistic hydrodynamics
Nuclear Physics A 00 (2018) 1–8

for a hadron species X with the quantum numbers B, S, I (baryon number, strangeness, isospin). Then the following 'master formula' can be obtained from (19) [7]

$$\frac{\Delta v_2^X}{v_2^{X,ideal}} \approx \frac{27K}{80} \left(\mu_B B + \mu_S S + \mu_I I \right) . \qquad (24)$$

Anisotropic Flow at RHIC/LHC is acoustic

PRC 84, 034908 (2011)
P. Staig and E. Shuryak.

- v_n **measurements are sensitive to system shape** (ε_n), **system** size (RT) **and transport coefficients** $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

arXiv:1305.3341
Roy A. Lacey, et al.

- **Acoustic ansatz**
  - ✓ **Sound attenuation in the viscous matter reduces the magnitude of** v_n.
- **Anisotropic flow attenuation,**

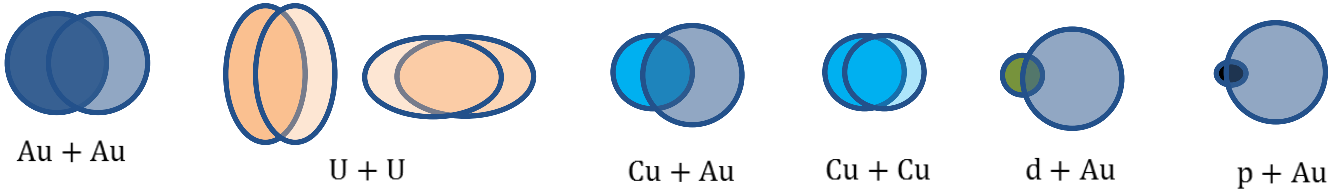
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

- **From macroscopic entropy considerations** $S \sim (RT)^3 \propto \frac{dN}{d\eta}$

PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

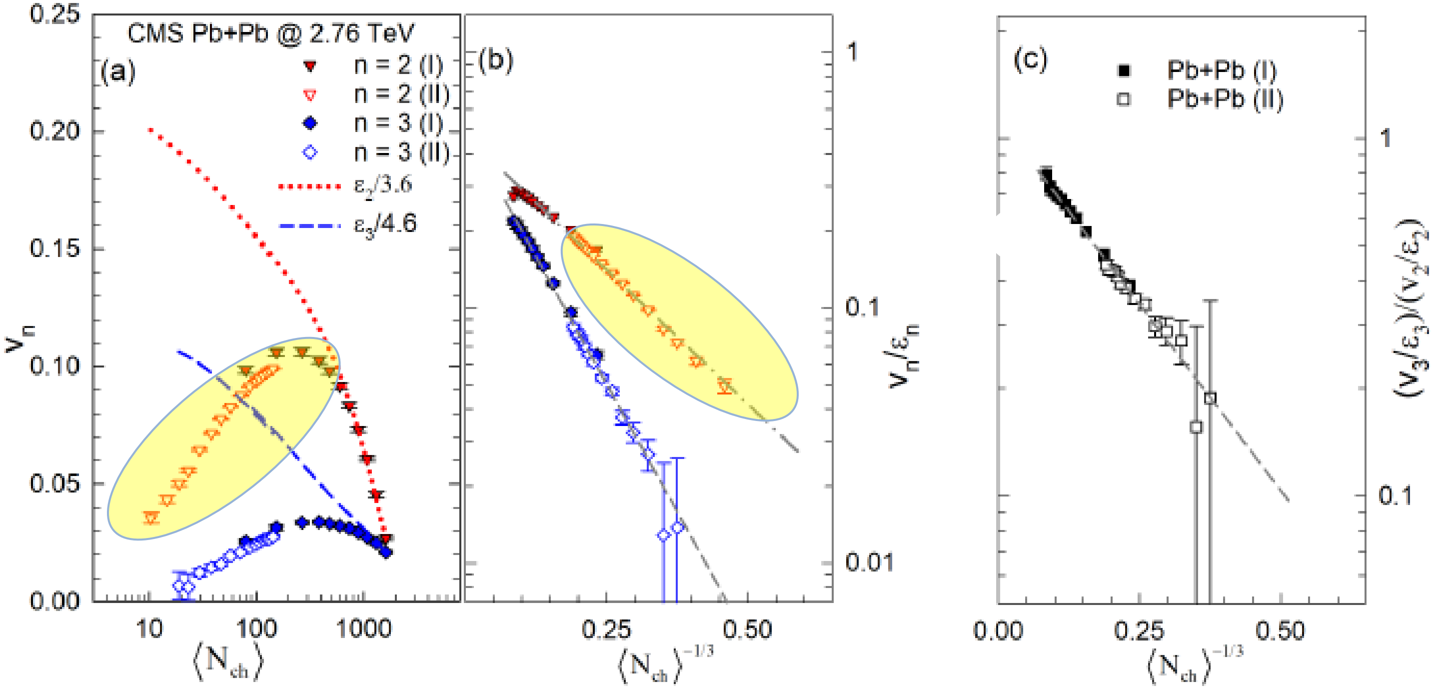
$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{-\frac{1}{3}}$$



Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

Acoustic Scaling – System size

Phys. Rev. C **98**, 031901(R), 2018



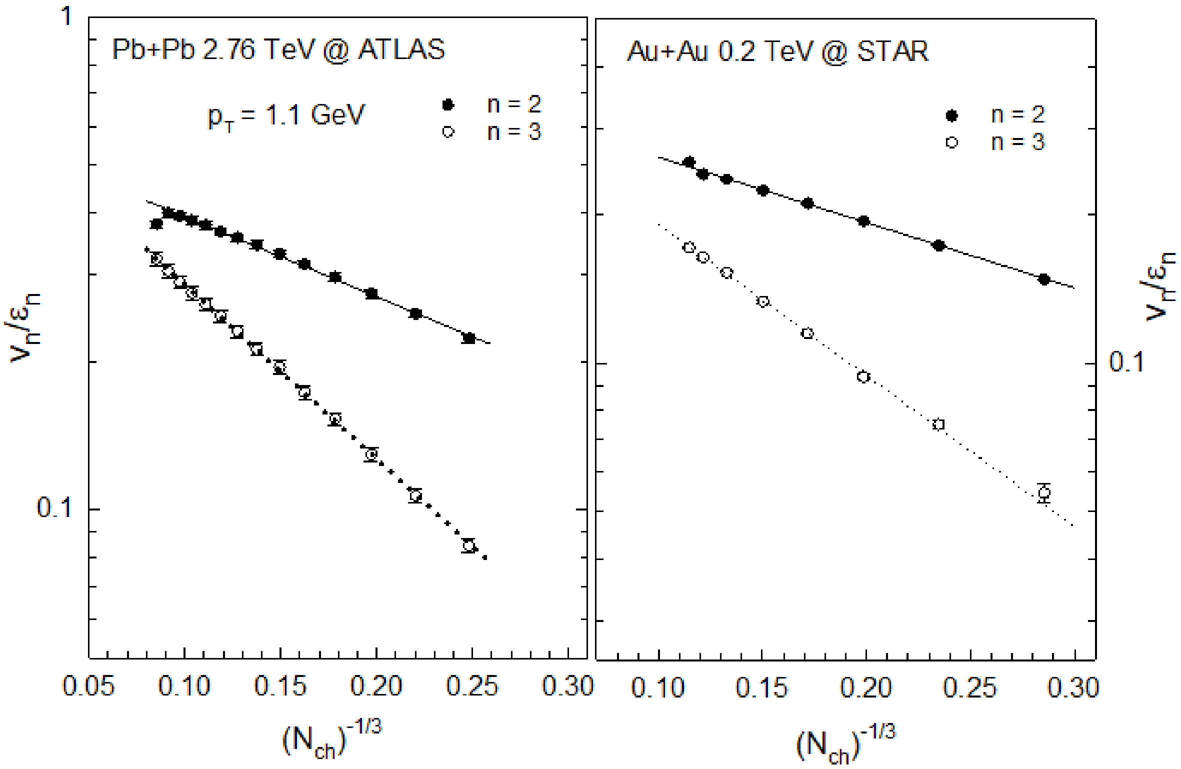
- Eccentricity change <u>alone</u> is not sufficient

- ✓ Characteristic 1/(RT) viscous damping validated
- ✓ Viscous damping supersedes the influence of eccentricity for "small" systems
  - ✓ Important constraint for η/s & ζ/s

Acoustic Scaling –

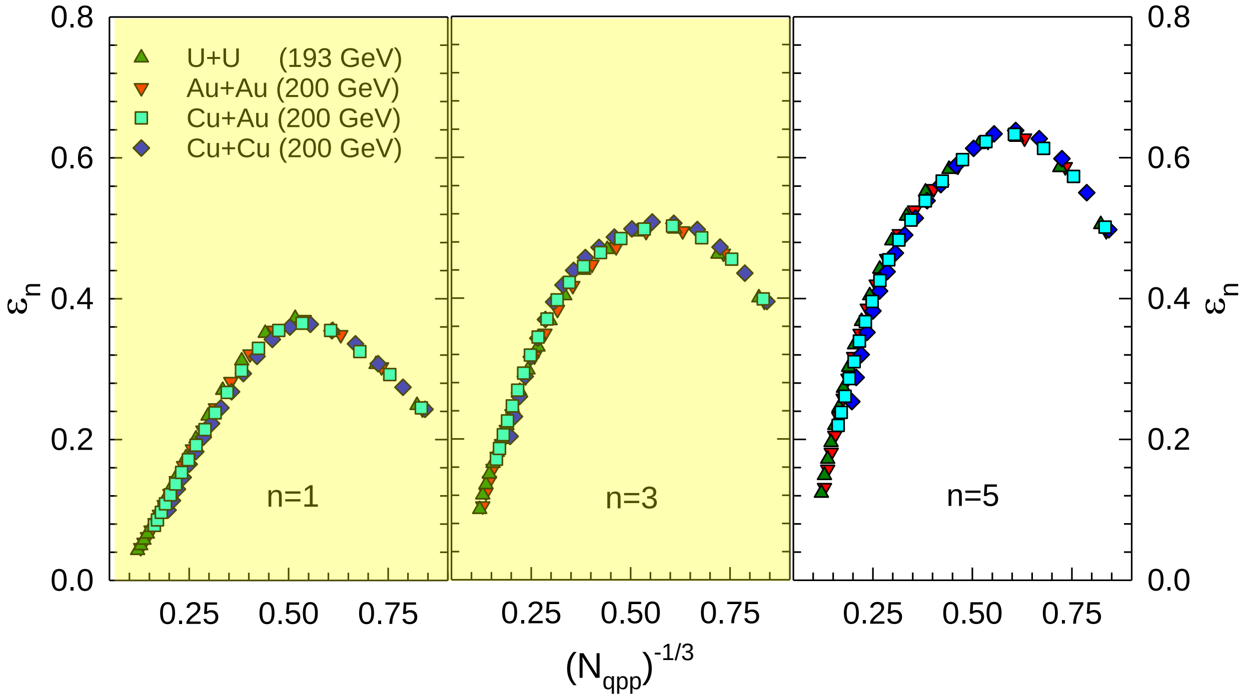
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



- ✓ Characteristic 1/(RT) viscous damping validated
  - ✓ Clear pattern for n^2 dependence of viscous attenuation
  - ✓ Important constraint for η/s & ζ/s

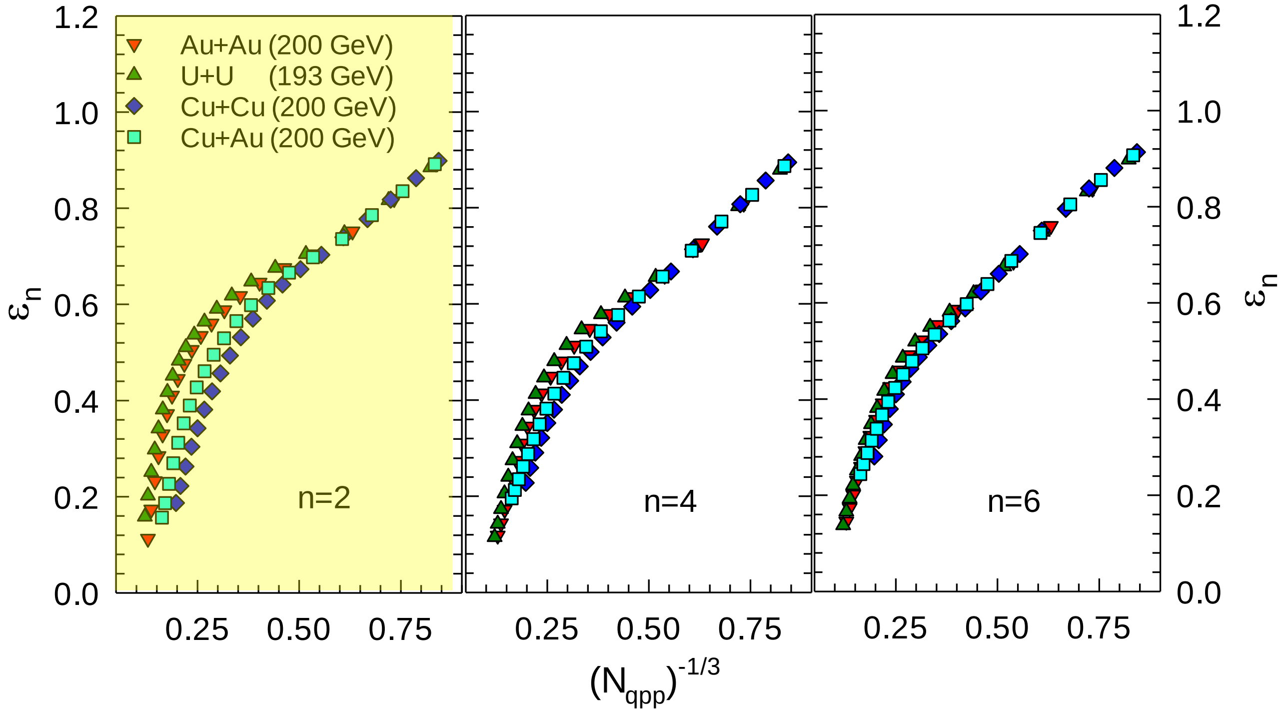
Acoustic Flow – Expected Shape Response



- Odd eccentricity moments are fluctuations driven
  - ✓ Little, if any, system dependence for A+A(B) collisions for similar geometric size

courtesy of R.A. Lacey

Acoustic Flow – Expected Shape Response



- **Even eccentricity moments are shape driven**
  - ✓ **Sizeable system dependence for A+A(B) collisions in central & mid-central collisions**
  - ✓ **System independence in peripheral collisions**

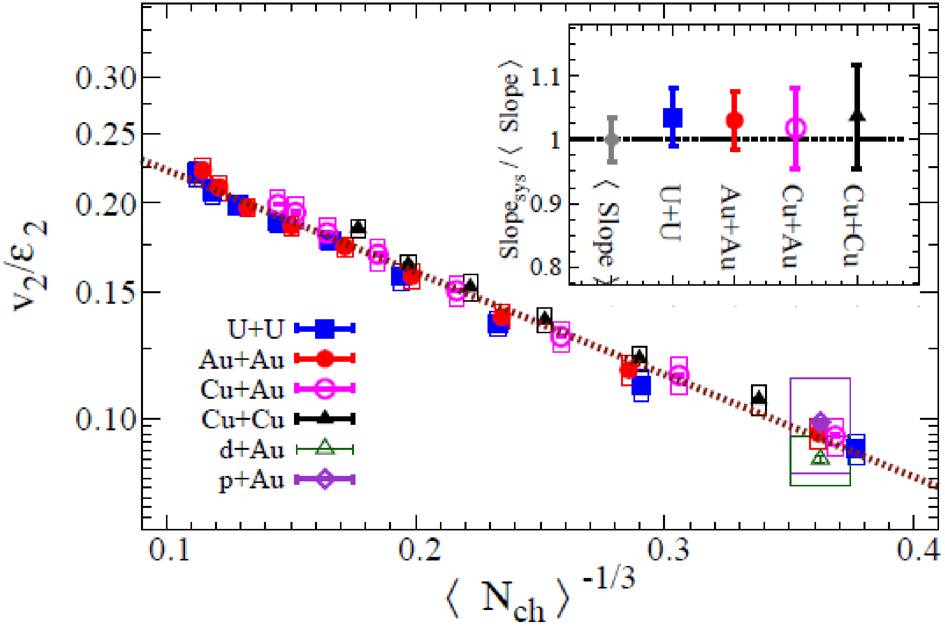
courtesy of R.A. Lacey

Flow is acoustic

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

$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2},$$
$$\beta \propto \left(\frac{4}{3}\frac{\eta}{s} + \frac{\xi}{s}\right)\frac{1}{RT}$$

$\langle N_{ch}\rangle$ dependence of $\frac{v_2}{\varepsilon_2}$ for several systems



- ✓ **Characteristic 1/(RT) viscous damping validated**
- ✓ **Viscous damping supersedes the influence of eccentricity for "small" systems**
  - ✓ **Similar slopes imply similar $\frac{\eta}{s}$.**

Beam energy dependence of V_n

- Anisotropic flow attenuation:

$$v_n \propto k\,\varepsilon_n, \qquad k = e^{-\beta n^2}$$

$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \qquad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

- From macroscopic entropy considerations:

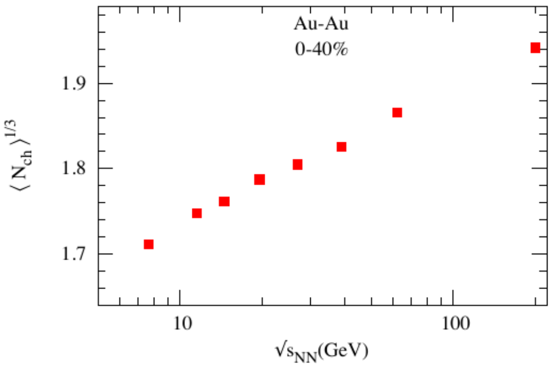
$$S \sim (RT)^3 \sim \langle N_{Ch}\rangle \text{ then } RT \sim \langle N_{Ch}\rangle^{1/3}$$

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -\left(\frac{\eta}{s}\right)\langle N_{Ch}\rangle^{-1/3}$$

Using two different harmonics :

$$\left[\ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right) + \ln\left(\frac{\varepsilon_2^{1/2}}{\varepsilon_n^{1/n}}\right)\right]\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$

$$\beta'' = \ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right)\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$

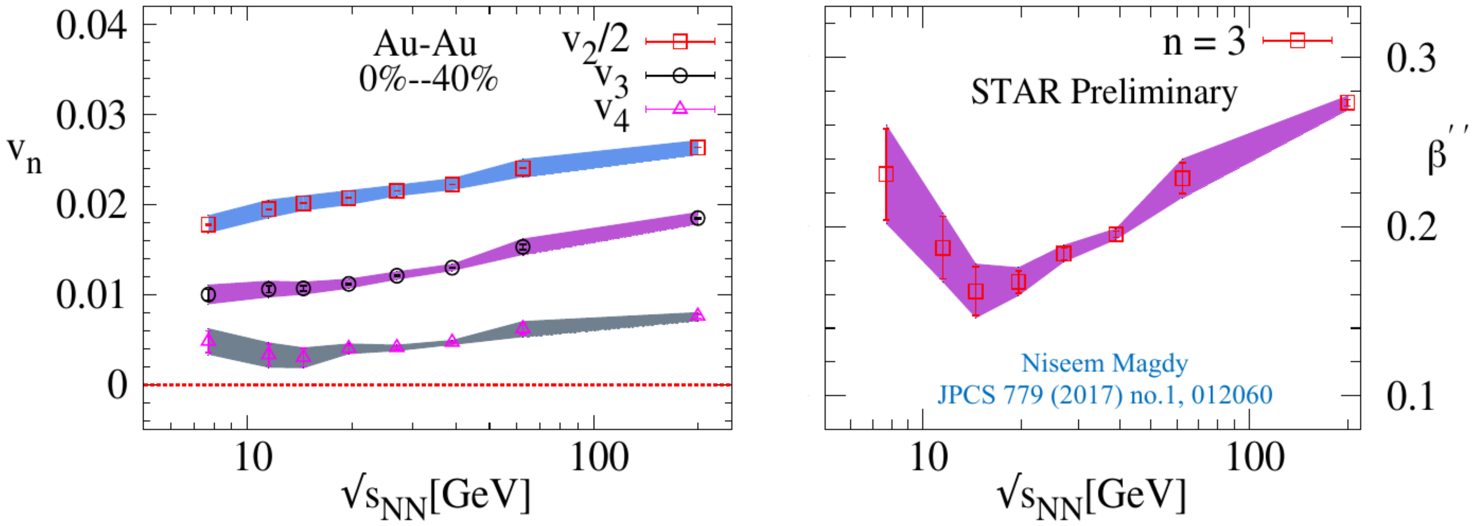


19

Beam energy dependence of V_n

$$\beta'' = \ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right)\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$

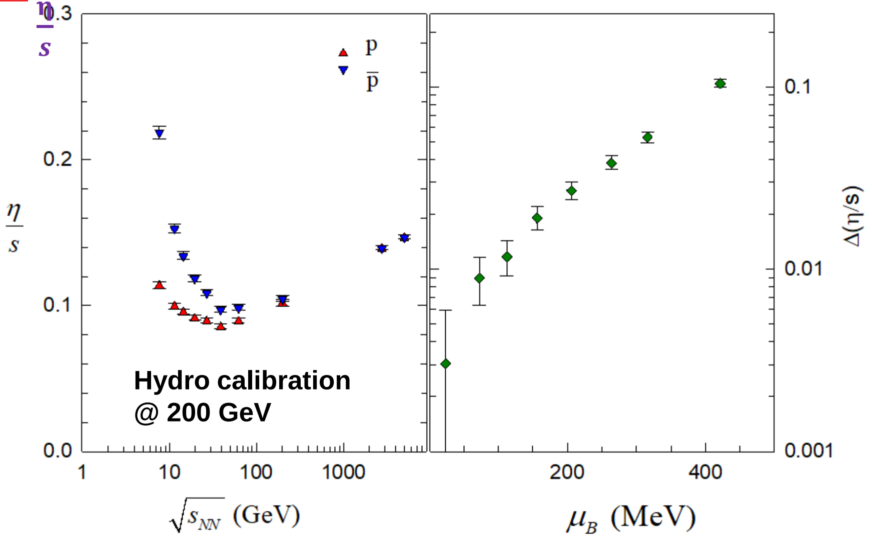
A: is constant

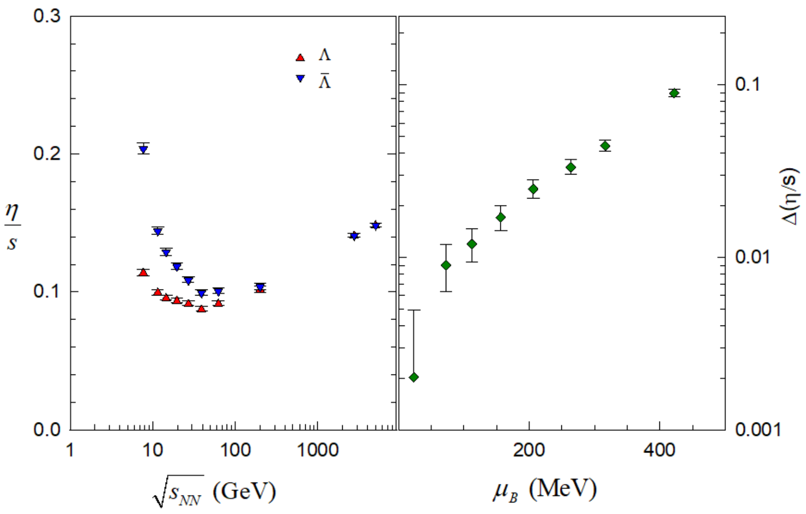


V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (***η***/***s***), indicates a non-monotonic behavior as a function of beam energy.

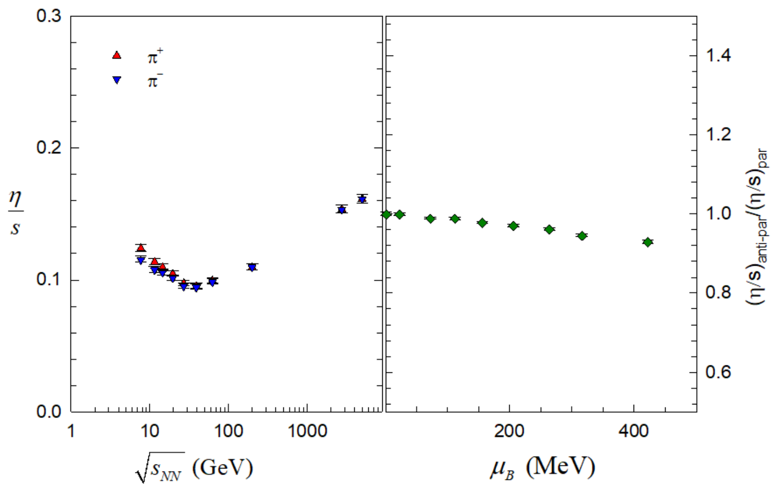
Beam-energy-dependent specific viscosity

$\sqrt{s_{NN}}$ dependence of the extracted values of $\frac{\eta}{s}$





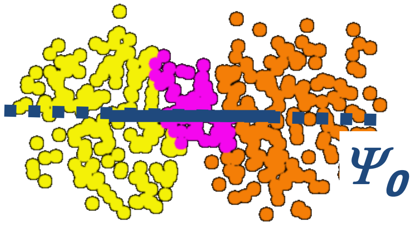
$\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$

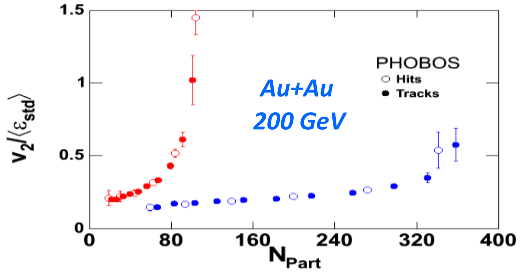


- Specific viscosity extracted across beam energies
  - ✓ Nonmonotonic patterns suggestive of critical behavior?
  - ✓ μ_B –dependent particle/anti-particle dependence

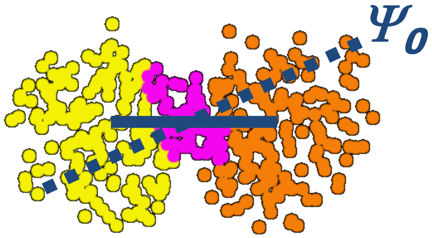
Charged currents drive particle/anti-particle viscosity difference

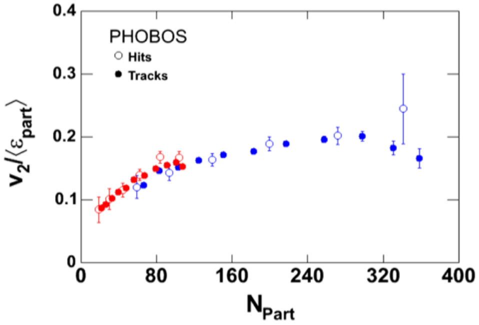
2001-2005 $\varepsilon_{\rm std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2}$



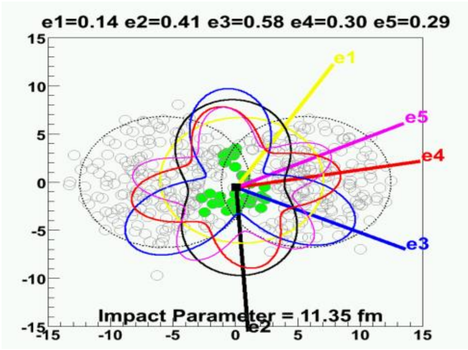


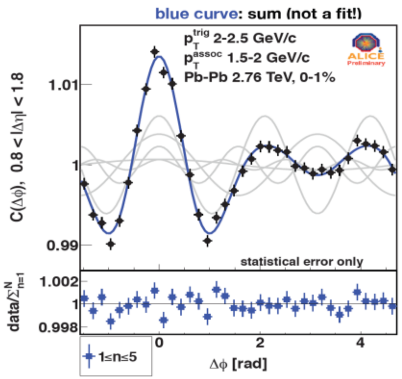
2005-2011 $\langle\epsilon_{\rm part}\rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$





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

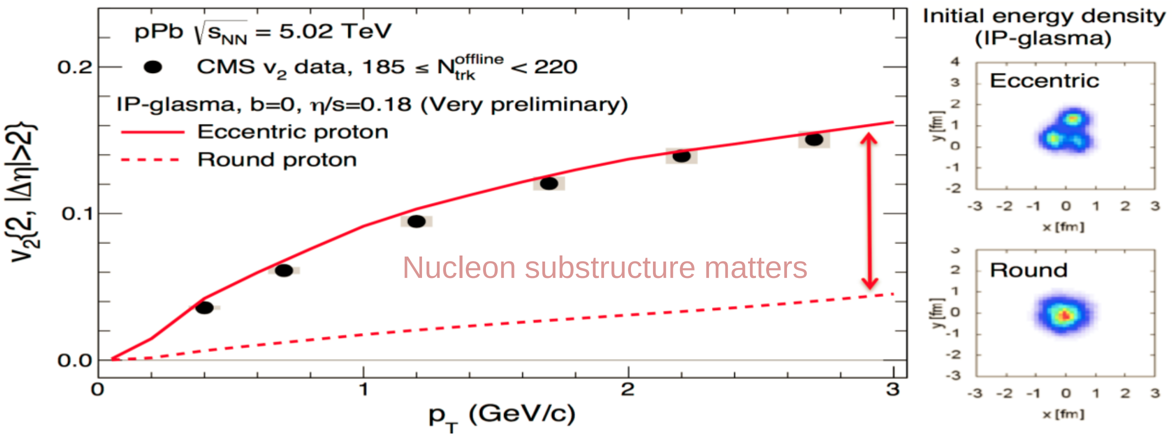




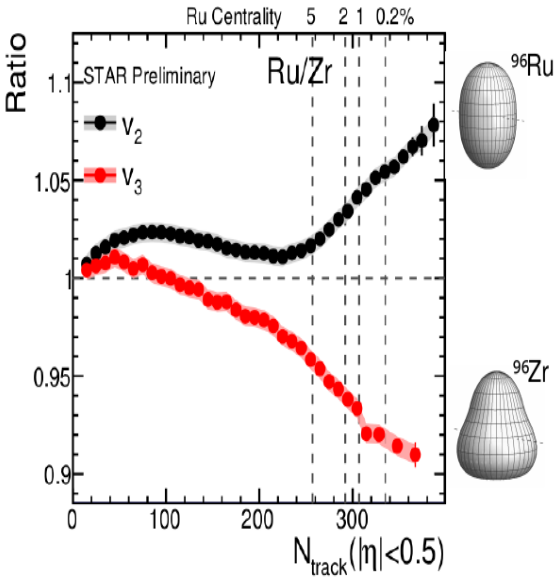
For "lumpy" *profile* $\varphi \neq \varphi + \pi$

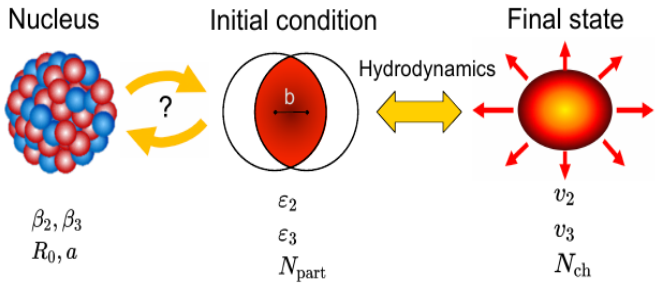
Odd harmonics $\neq 0$

2011-2016

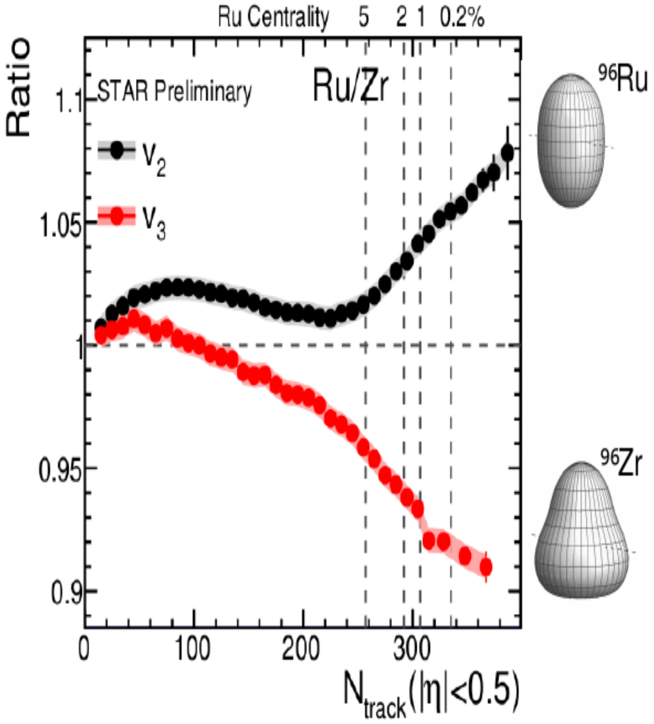


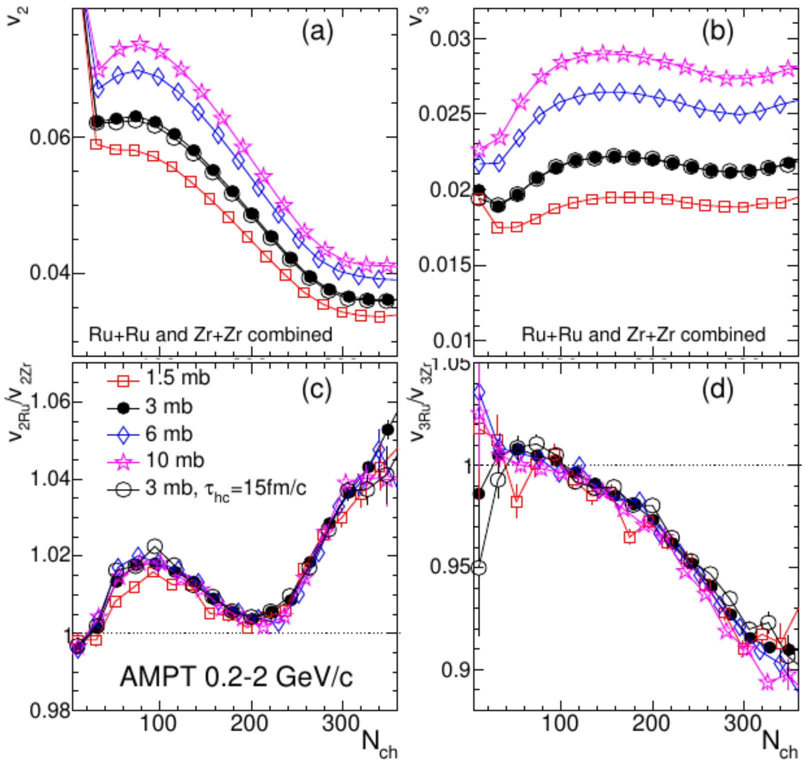
2020-2022





2022: Nuclear structure via V_n ratio

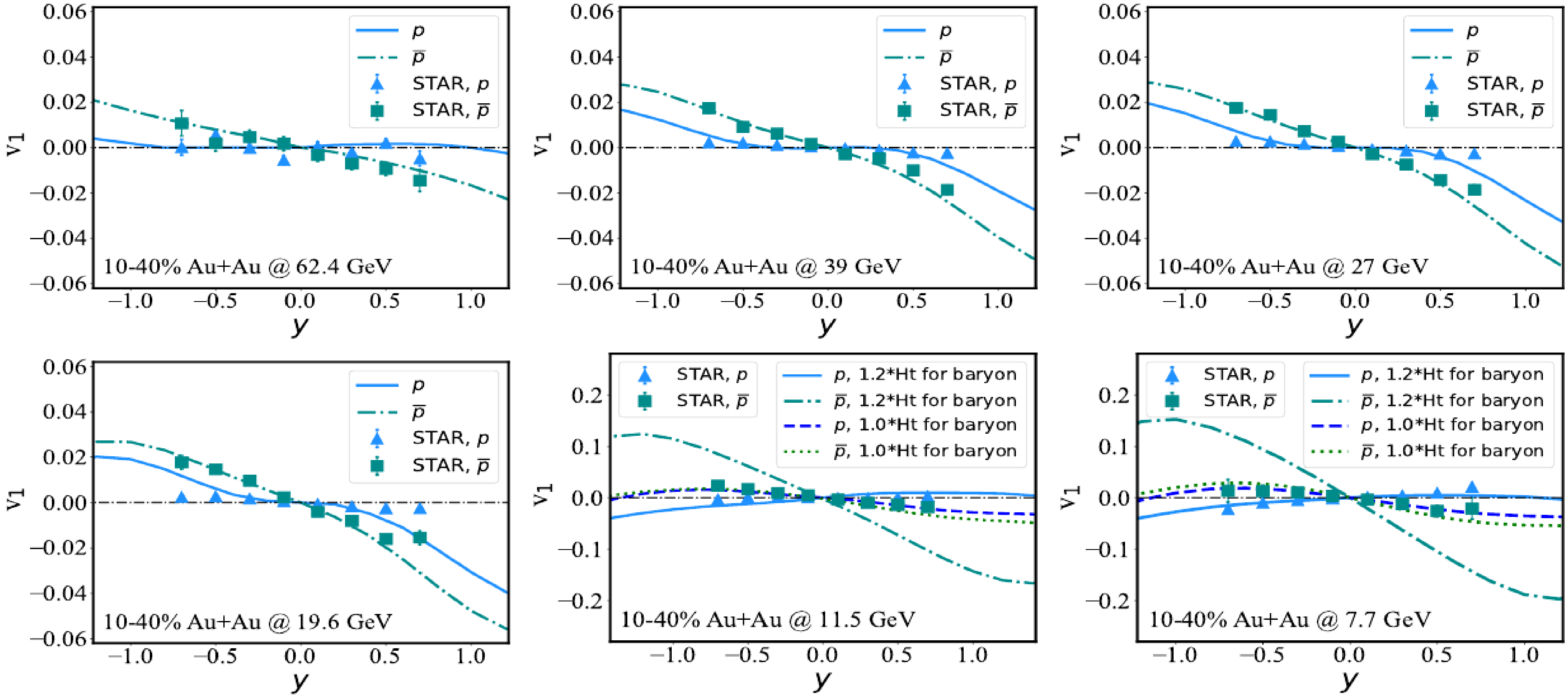




Phys.Rev.C 105 (2022) 1, 014901 • e-Print: 2109.00131

The V_n ratio for isobars – not affected by final state – is a good tool for precision studies of nuclear shapes.

Directed flow BES

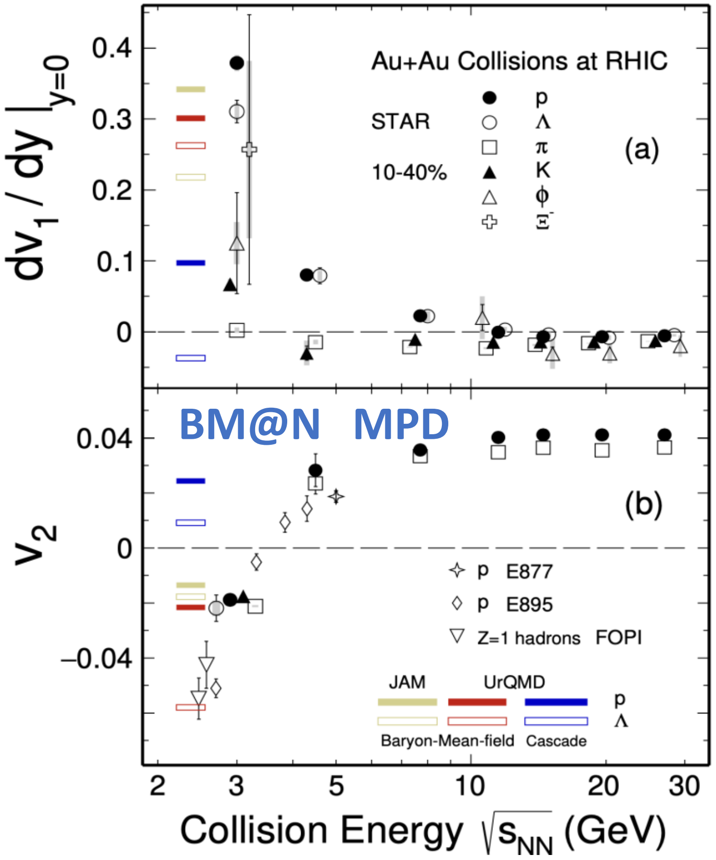


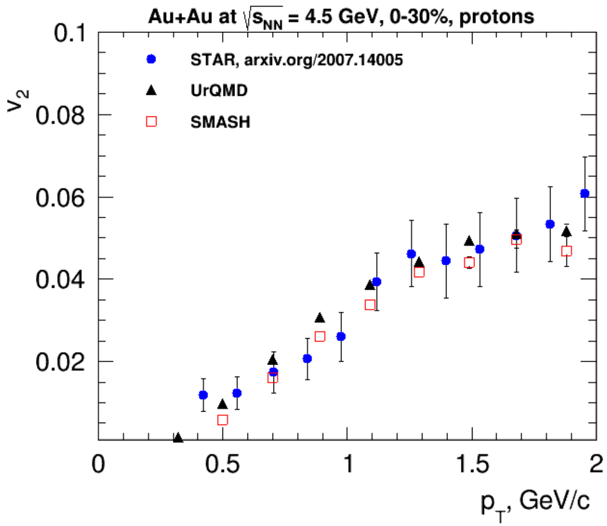
o *include both a tilted deformation of the QGP fireball with respect to the longitudinal direction and a non-zero longitudinal flow velocity gradient in the initial state*

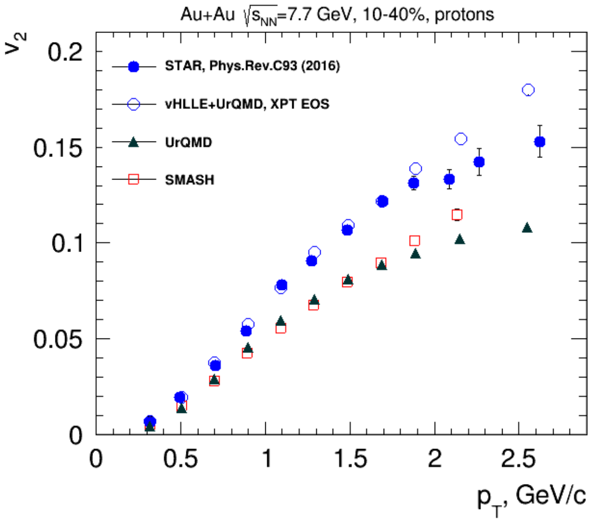
Phys.Rev.C 107 (2023) 3, 3 • e-Print: 2301.02960 [nucl-th]

Anisotropic flow at NICA energies

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





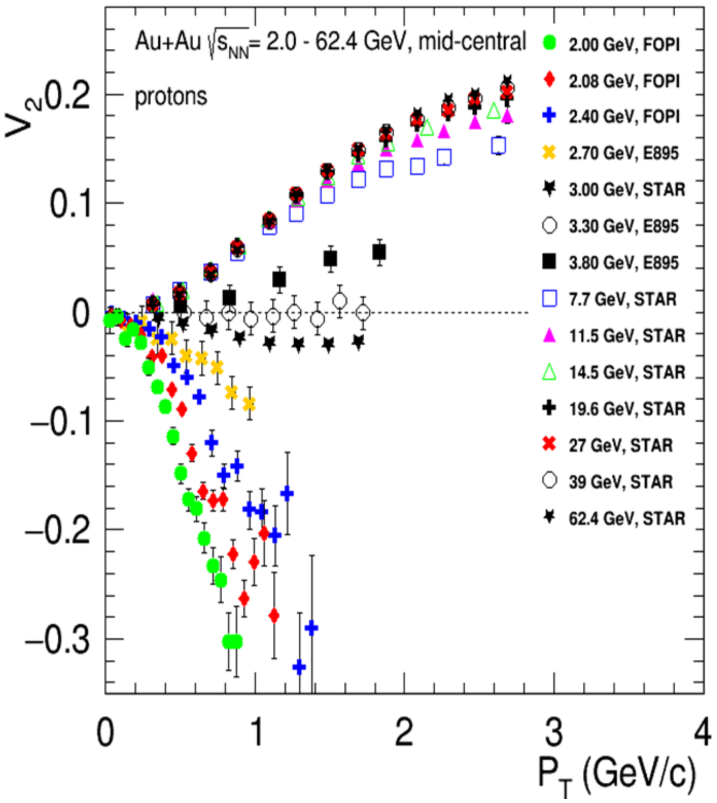


- **Strong energy dependence of v_1 and v_2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below
- **Lack of differential measurements of v_2 at NICA energies (p_T, centrality, PID,…)**
- **v_2 is sensitive to the properties of strongly interacting matter:**
  - at $\sqrt{s_{NN}}$ = 4.5 GeV pure string/hadronic cascade models (UrQMD, SMASH,…) give similar v_2 signal compared to STAR data
  - at $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…)

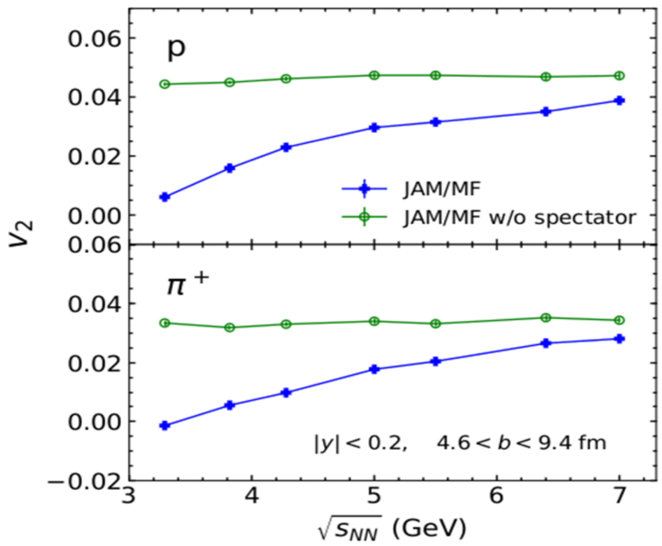
- Make predictions for the anisotropic flow measurements $v_n(p_T, y)$ at BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) energies

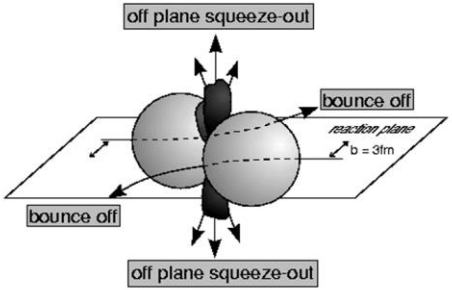
Beam Energy Dependence of Elliptic Flow (v_2)

EPJ Web Conf. 204 (2019) 03009



Phys. Rev. C 97, 064913 (2018)

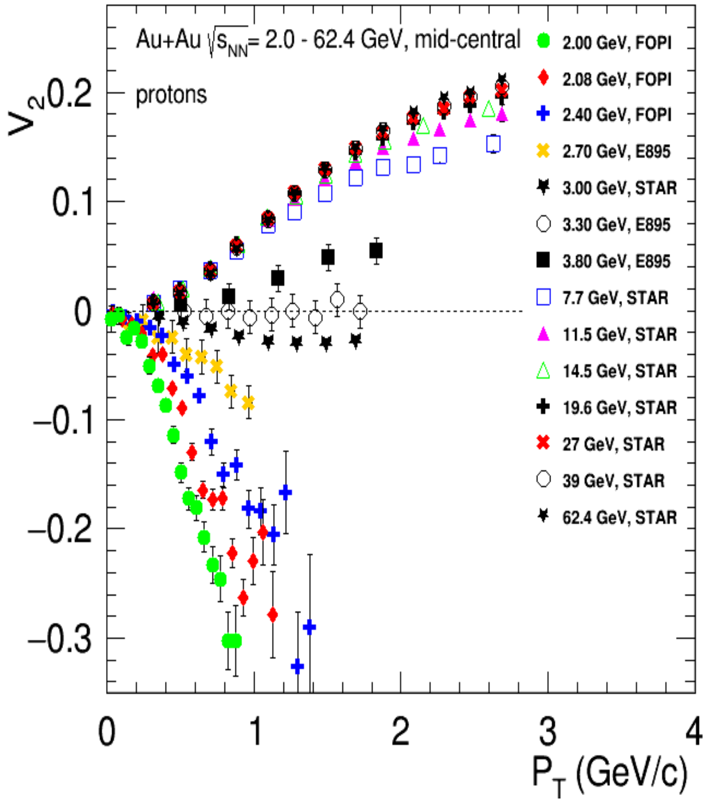


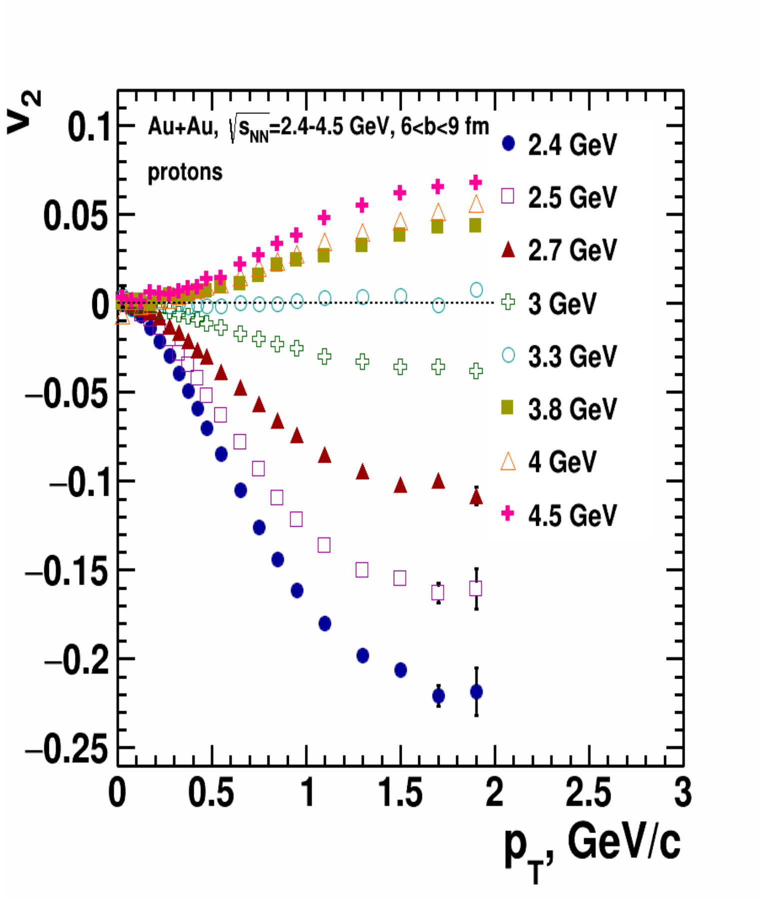


- **Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below

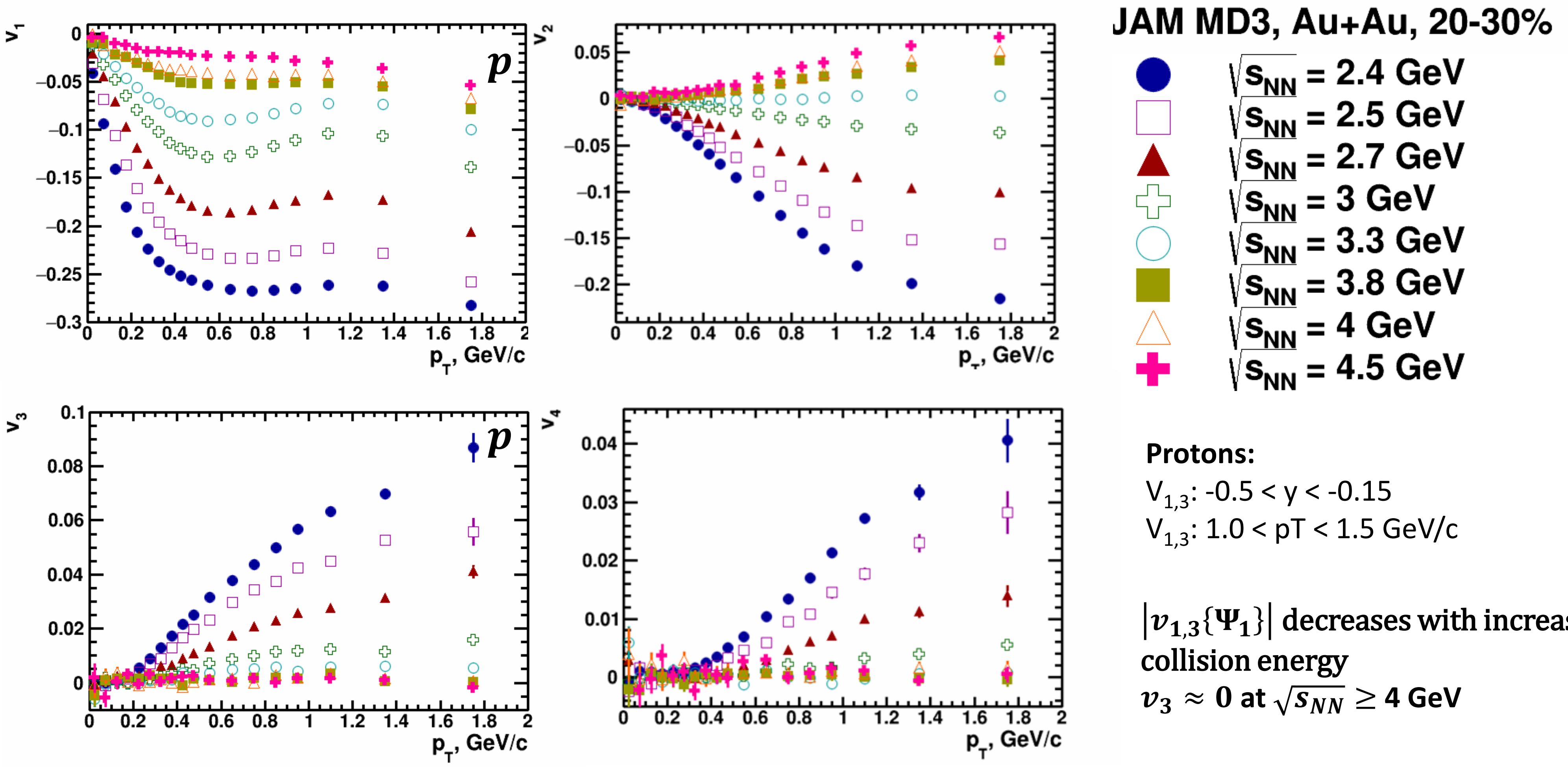
Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009





$v_{1,2,3,4}(p_T)$ Au+Au $\sqrt{s_{NN}}$=2.4-4.5 GeV: BM@N+MPD



Protons:

$V_{1,3}$: -0.5 < y < -0.15

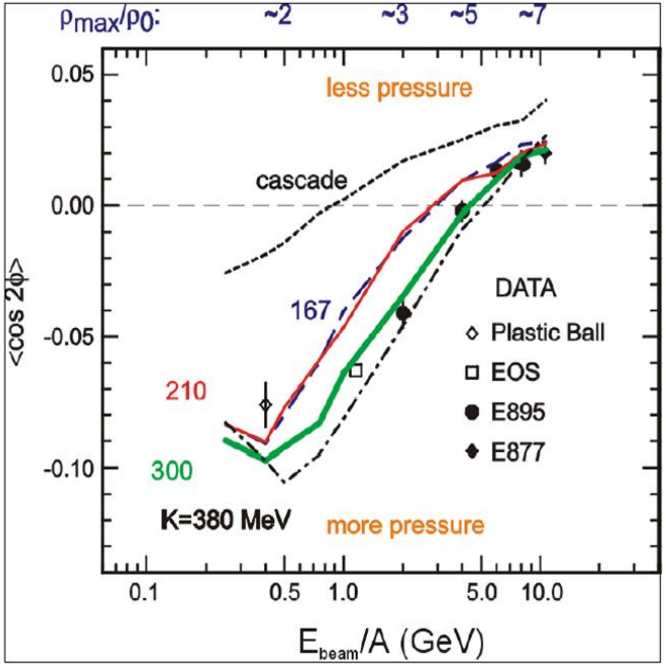
$V_{1,3}$: 1.0 < pT < 1.5 GeV/c

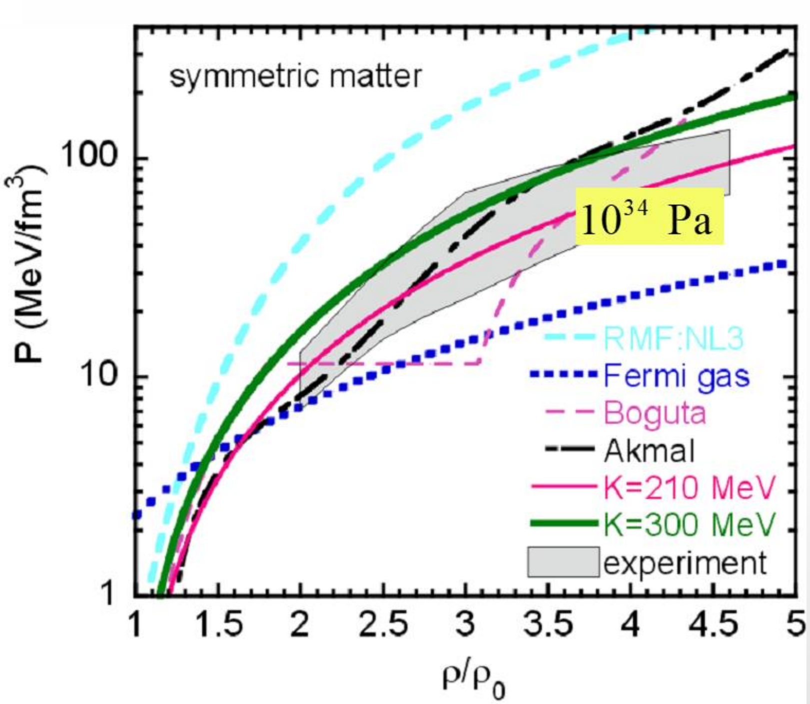
$|v_{1,3}\{\Psi_1\}|$ decreases with increasing collision energy

$v_3 \approx 0$ at $\sqrt{s_{NN}} \geq 4$ GeV

Flow at AGS: Constraints for the Hadronic EOS

Danielewicz, Lacey, Lynch, Science 298 (2002) 1592-1596





Passage time: **$2R/(\beta_{cm}\gamma_{cm})$**

Expansion time: **R/c_s**

$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

$$c_s = \sqrt{K/9m_N} \approx 0.15c, 0.21c$$

Flow at AGS/Nuclotron = Interplay of passage/expansion times

Sensitivity of Au+Au collisions to the symmetric nuclear matter equation of state at 2–5 nuclear saturation densities

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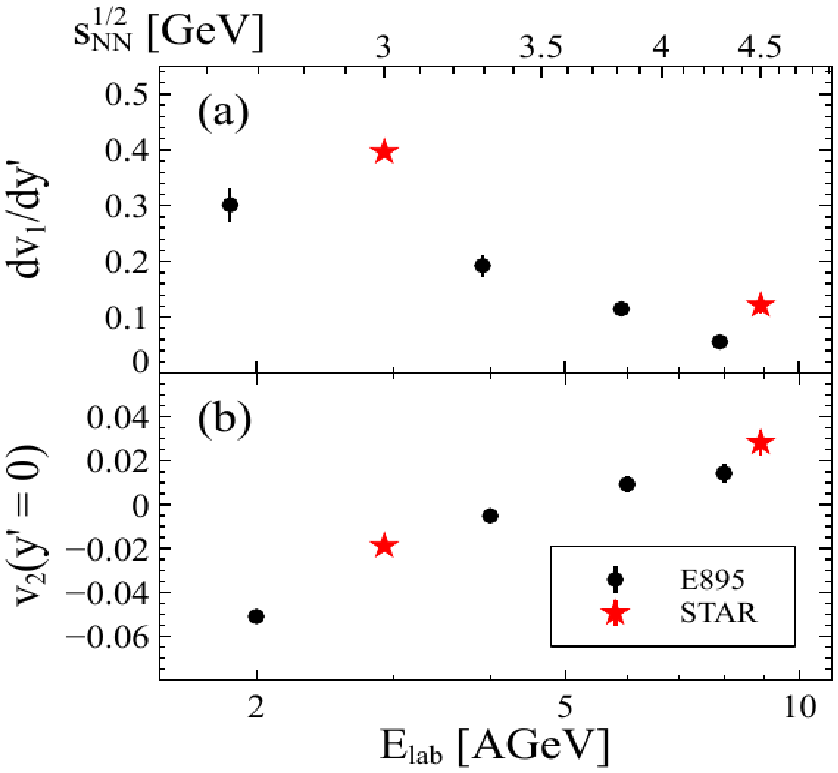
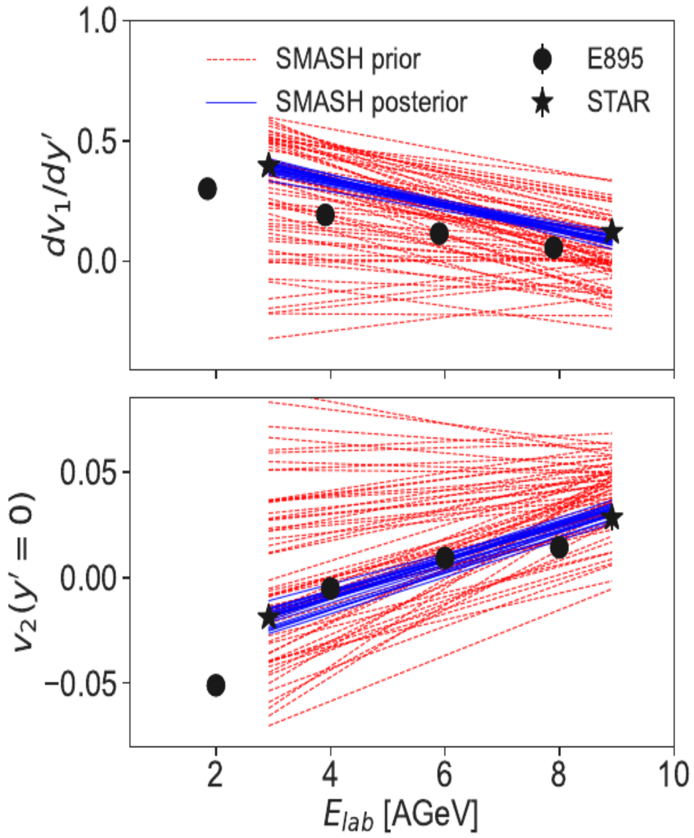


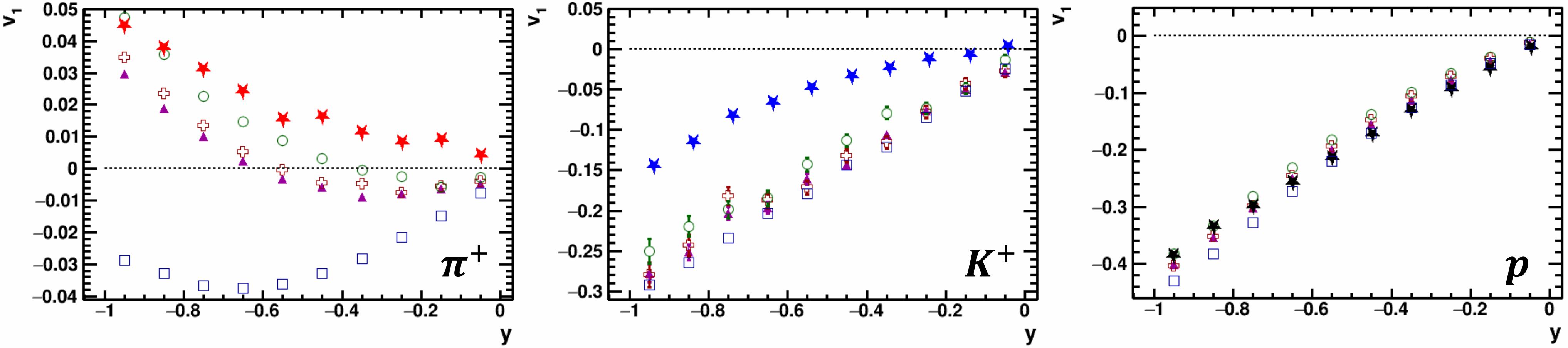


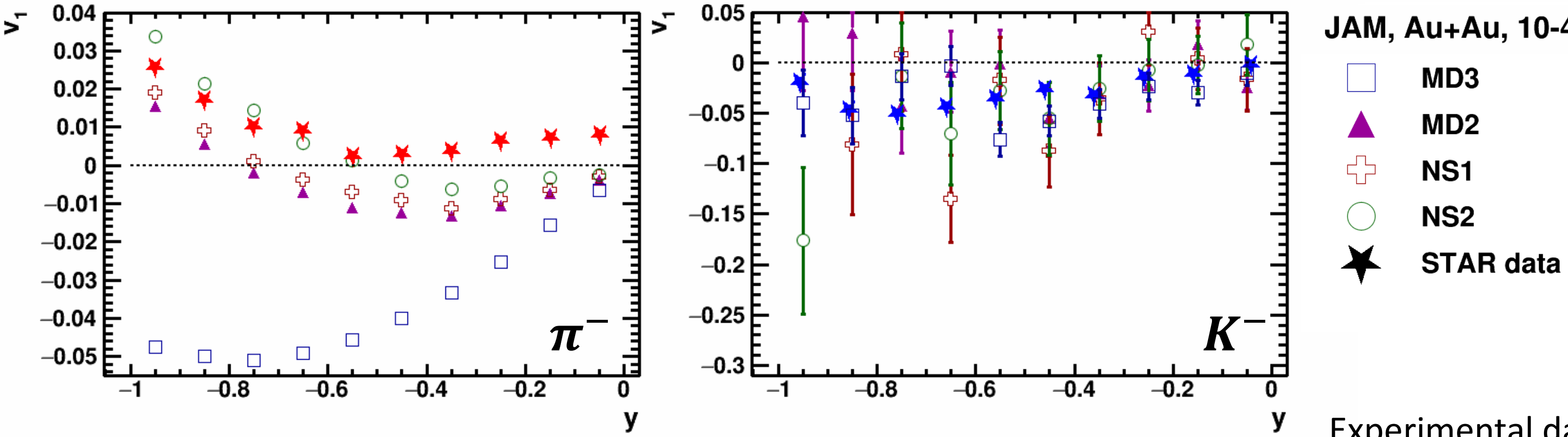
Summary and outlook

- **v_n at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
  - Detailed JAM model calculations for differential measurements of v_n at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV
  - v_2 from cumulants of different orders

Back-up slides

$v_1(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data





Kinematic cuts:
$v_1(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
$v_1(y)$ of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
$v_1(y)$ of p: 0.4 < pT < 2.0 GeV/c

JAM does not describe all particle species equally well
v_1 of pions is most sensitive to different EOS

Experimental data points were taken from:
Mohamed Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]