Systematic study of anisotropic flow in relativistic heavy-ion collisions

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OUTLINE

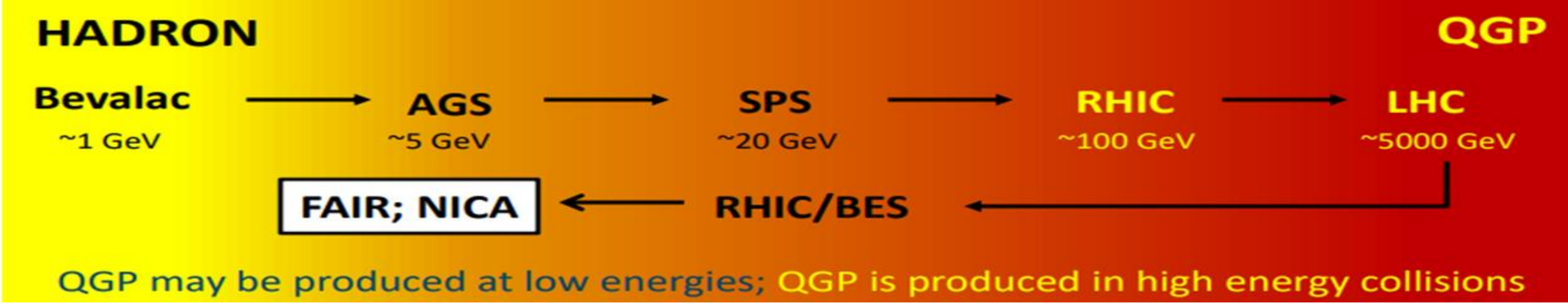
1) Anisotropic flow: introduction

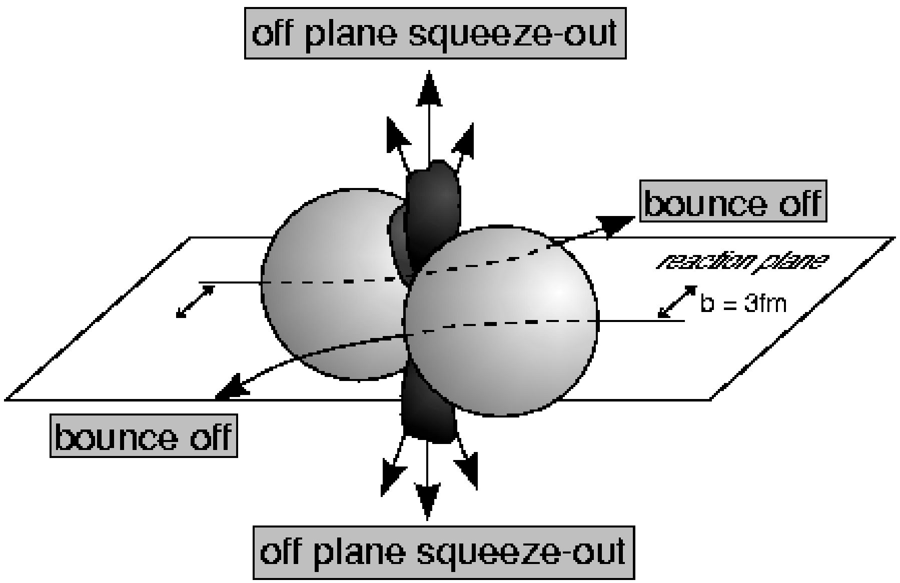
1) Flow and sQGP at RHIC/LHC?

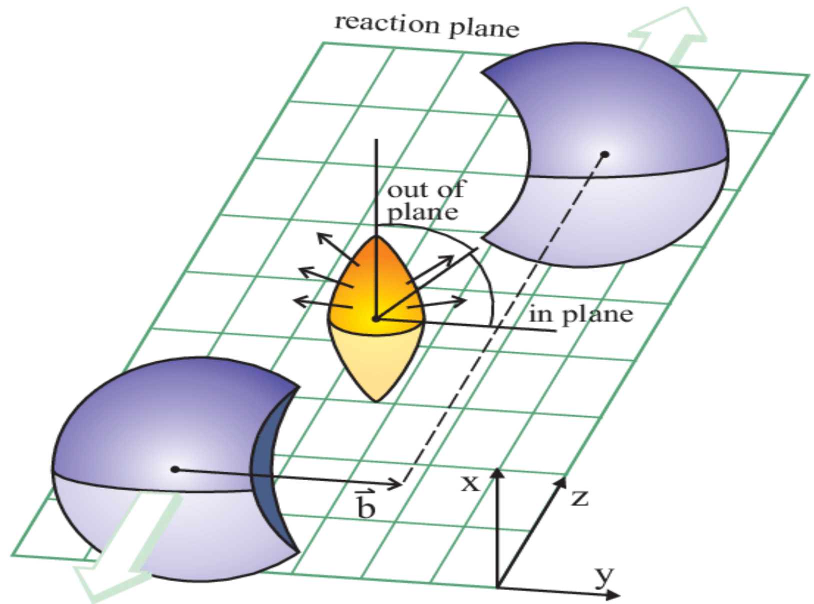
2) Scaling properties of anisotropic flow

3) Flow results from Beam Energy Scans

4) Outlook for flow measurements at NICA





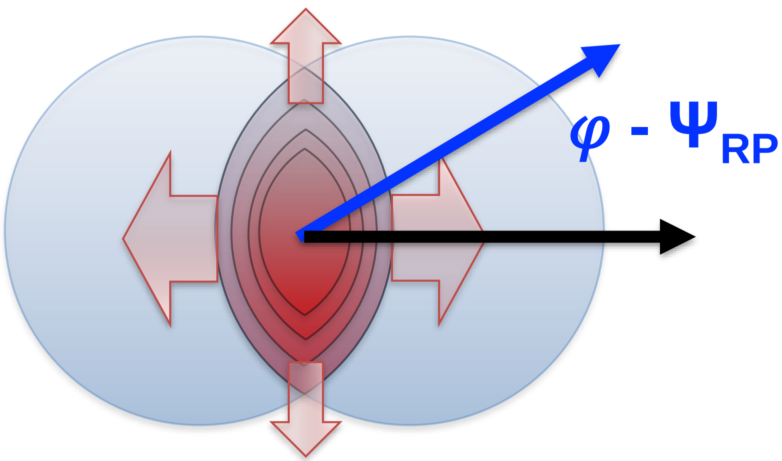


Anisotropic Flow in Heavy-Ion Collisions – 35 years

Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)

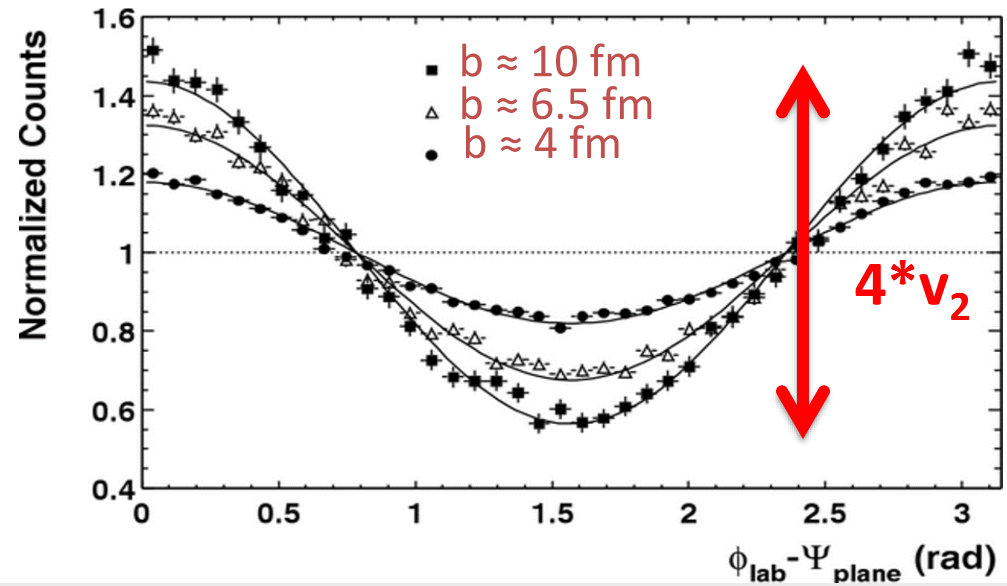
Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)

Azimuthal anisotropy of particles at HIC



Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

STAR, PRL**90** 032301 (2003)



$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos(2(\varphi-\Psi_{RP}))+\dots\right)$$

- The sinus terms are skipped by symmetry arguments
- From the properties of Fourier's series one has

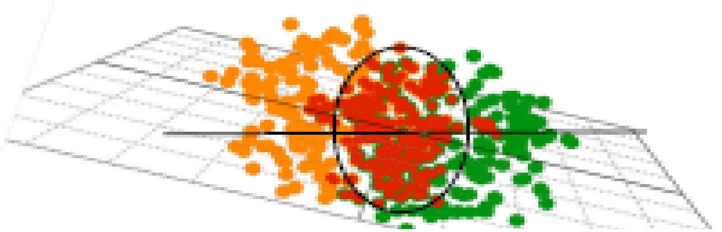
$$v_n=\langle\cos[n(\varphi-\Psi_{RP})]\rangle$$

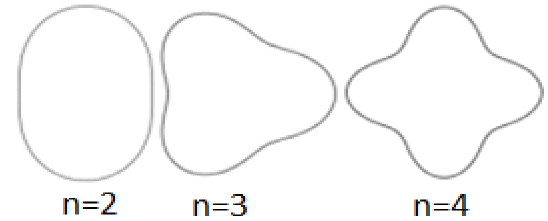
- Fourier coefficients $\mathbf{v_n}$ quantify anisotropic flow:

v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior of particles in event or multiparticle azimuthal correlation

Anisotropic Flow at RHIC-LHC

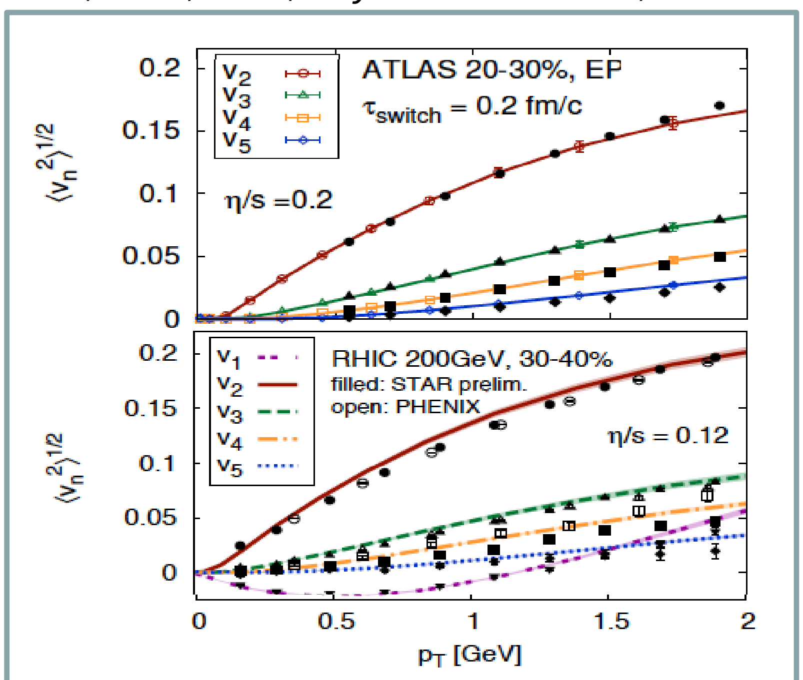


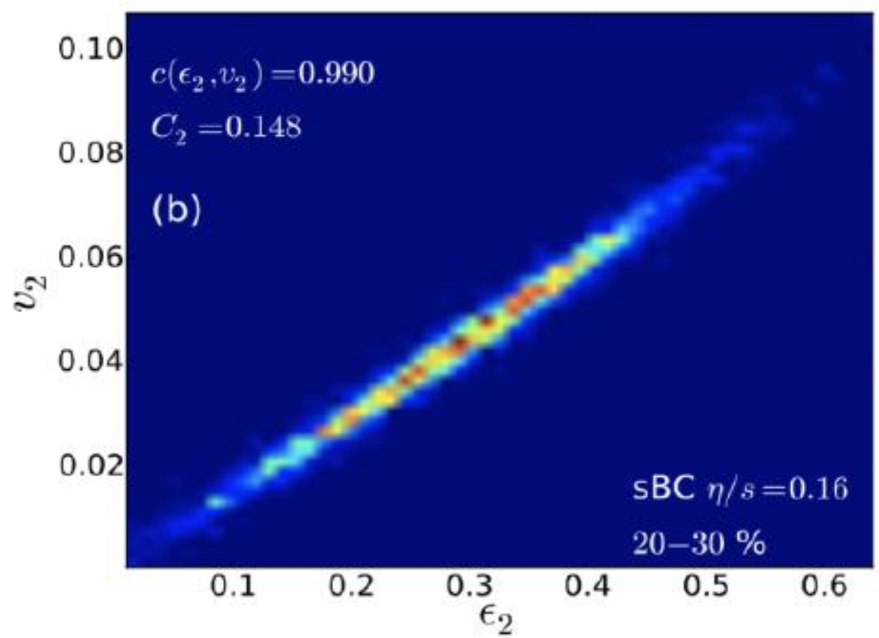


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}} \quad \Longrightarrow \quad \frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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

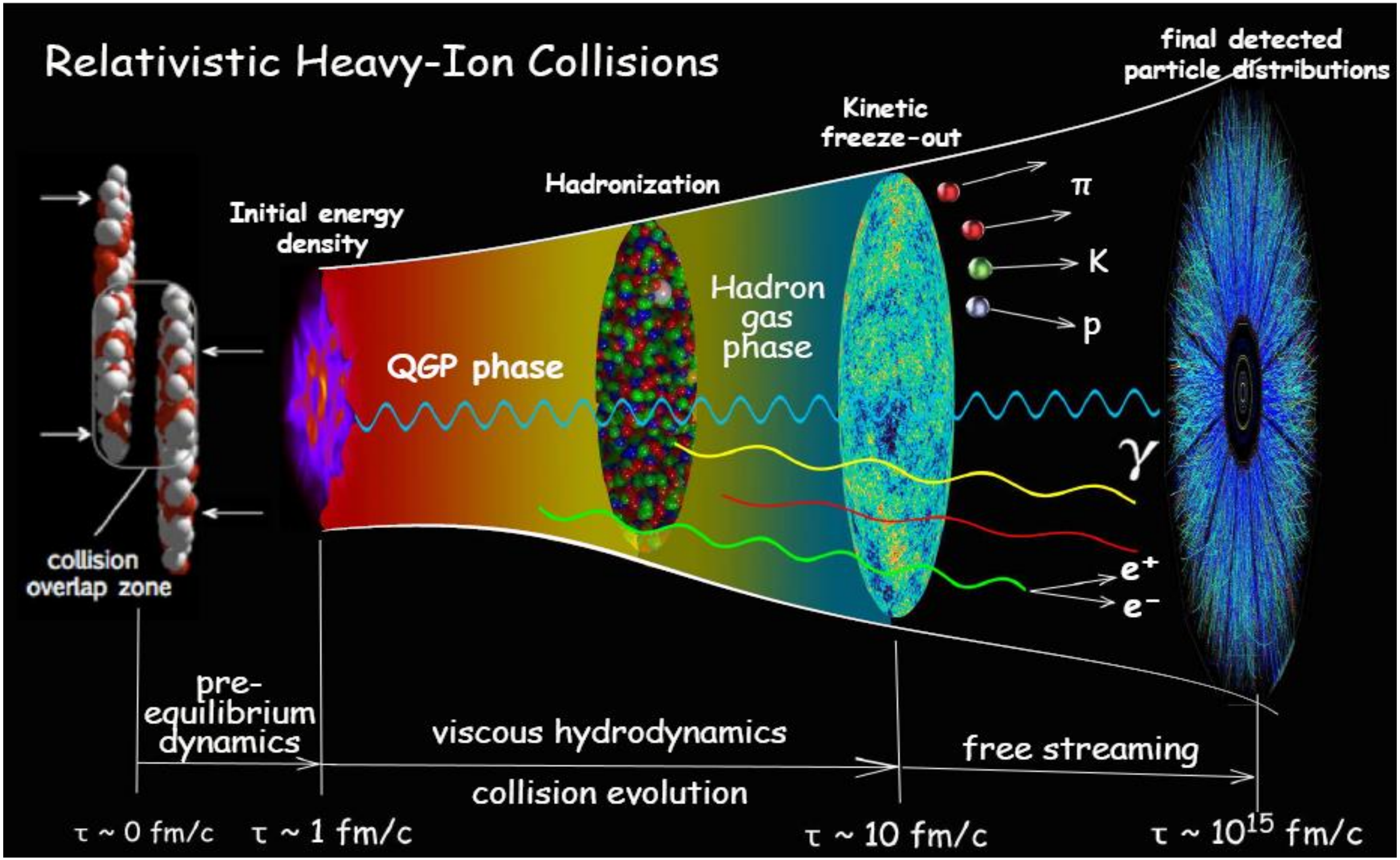
Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302





Evolution of the system created in RHIC

Fireball is ~10^{-15} meters across and lives for $5*10^{-23}$ seconds



200+200 nucleons in 10^{-22} seconds = 1000-30000 hadrons

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

Flow is acoustic

R. Lacey Phys. Rev. C 110 (2024) 3, L031901

$$v_n(p_T, cent) = \varepsilon_n e^{-\frac{\beta}{RT}\left[n(n+\kappa p_T^2)\right]}, \quad RT \equiv \mathbf{R} \propto \left\langle \mathrm{N}_{\mathrm{chg}} \right\rangle^{1/3}$$

Same harmonic with variable centrality

$$\frac{v_n(p_T, cent)}{\varepsilon_n} = \left(\frac{v_n'(p_T, cent)}{\varepsilon_n'}\right) e^{-\frac{\beta}{\mathbf{R}}\left[n(n+\kappa p_T^2)\right]\left(1-\frac{\mathbf{R}}{\mathbf{R}'}\right)},$$

For two harmonics at a fixed centrality

$$\frac{v_n(p_T)}{\varepsilon_n} = \left(\frac{v_m(p_T)}{\varepsilon_m}\right)^{\frac{n}{m}} e^{\frac{\beta}{\mathbf{R}}(m-n)},$$

$$v_n(p_T, \mathrm{cent}) = \varepsilon_n(\mathrm{cent}) e^{-\frac{\beta}{\mathbb{R}}[n(n+\kappa p_T^2)]}, \qquad n = 2, 3,$$

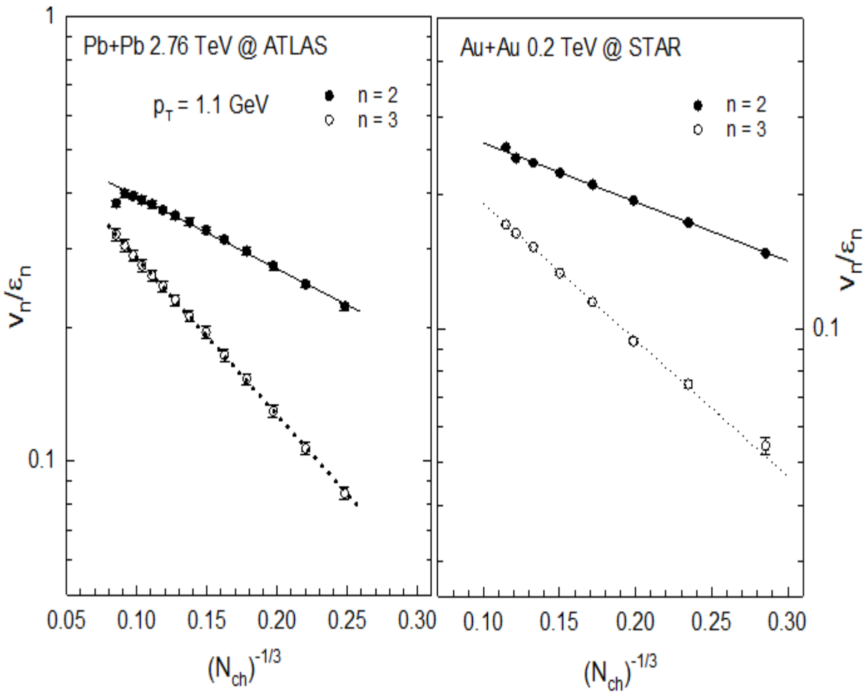
where $\beta \propto \eta/s$, $\delta_f = \kappa p_T^2$ [13, 35], and $\mathbb{R} \propto \langle N_{\mathrm{chg}} \rangle^{1/3}_{|\eta| \leq 0.5}$

$$\frac{v_n(p_T, 0)}{\varepsilon_n(0)} e^{\frac{n\beta}{\mathbb{R}_0}[n+\kappa p_T^2]} = \frac{v_n'(p_T, \mathrm{cent})}{\varepsilon_n'(\mathrm{cent})} e^{\frac{n\beta}{\mathbb{R}_0}[n+\kappa p_T^2]\left(\frac{\mathbb{R}_0}{\mathbb{R}'}-1\right)}. \qquad \frac{v_2(p_T, \mathrm{cent})}{\varepsilon_2(\mathrm{cent})} e^{\frac{2\alpha\beta}{\mathbb{R}_0}} = \left(\frac{v_3(p_T, \mathrm{cent})}{\varepsilon_3(\mathrm{cent})}\right)^{\frac{2}{3}},$$

Flow is acoustic

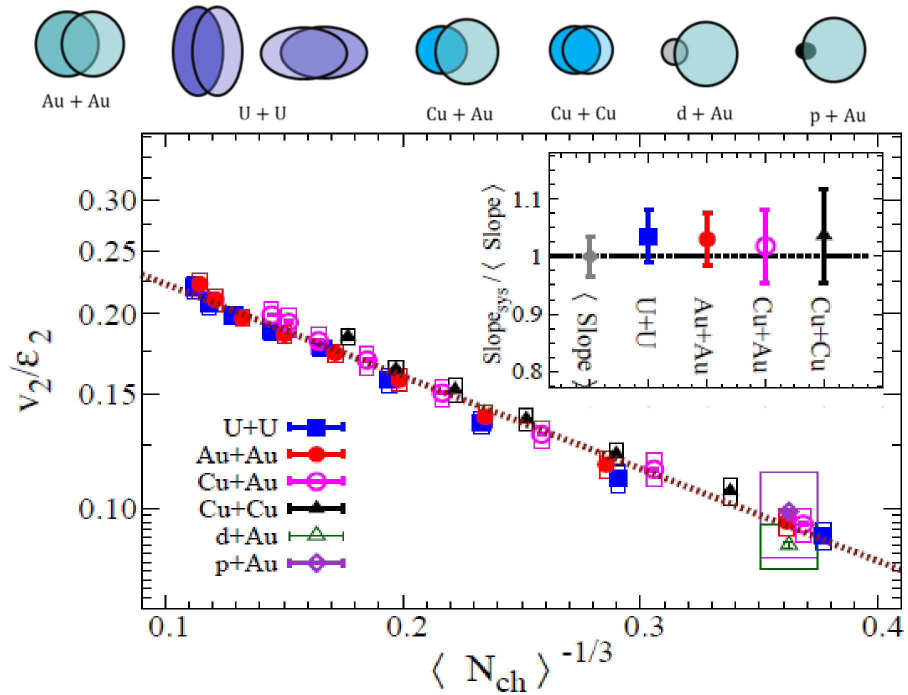
R. Lacey Phys. Rev. C **98**, 031901(R), 2018

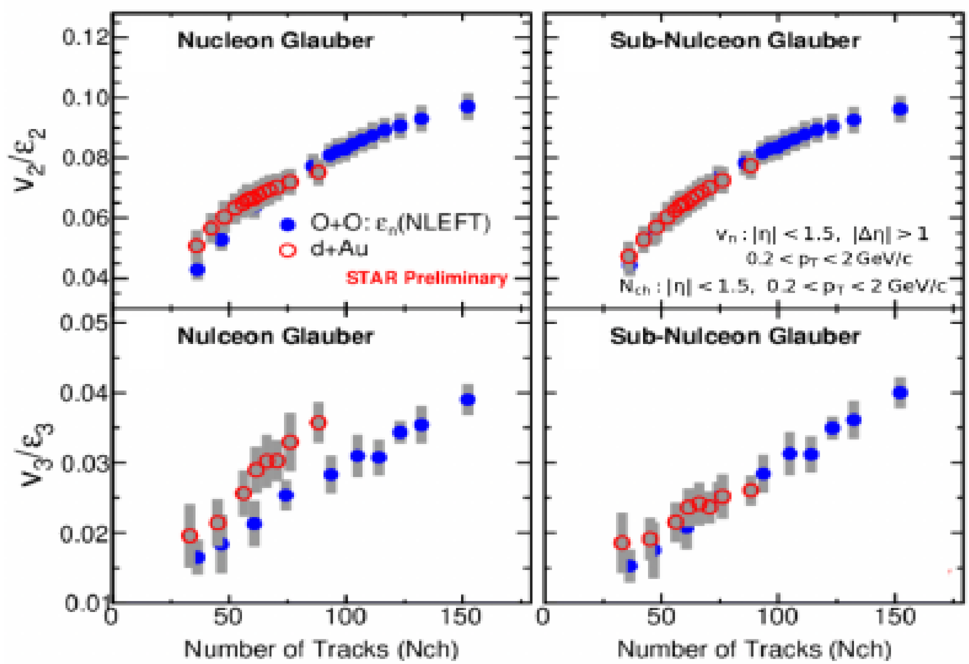
STAR, Phys. Rev. Lett. 122 (2019) 172301



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

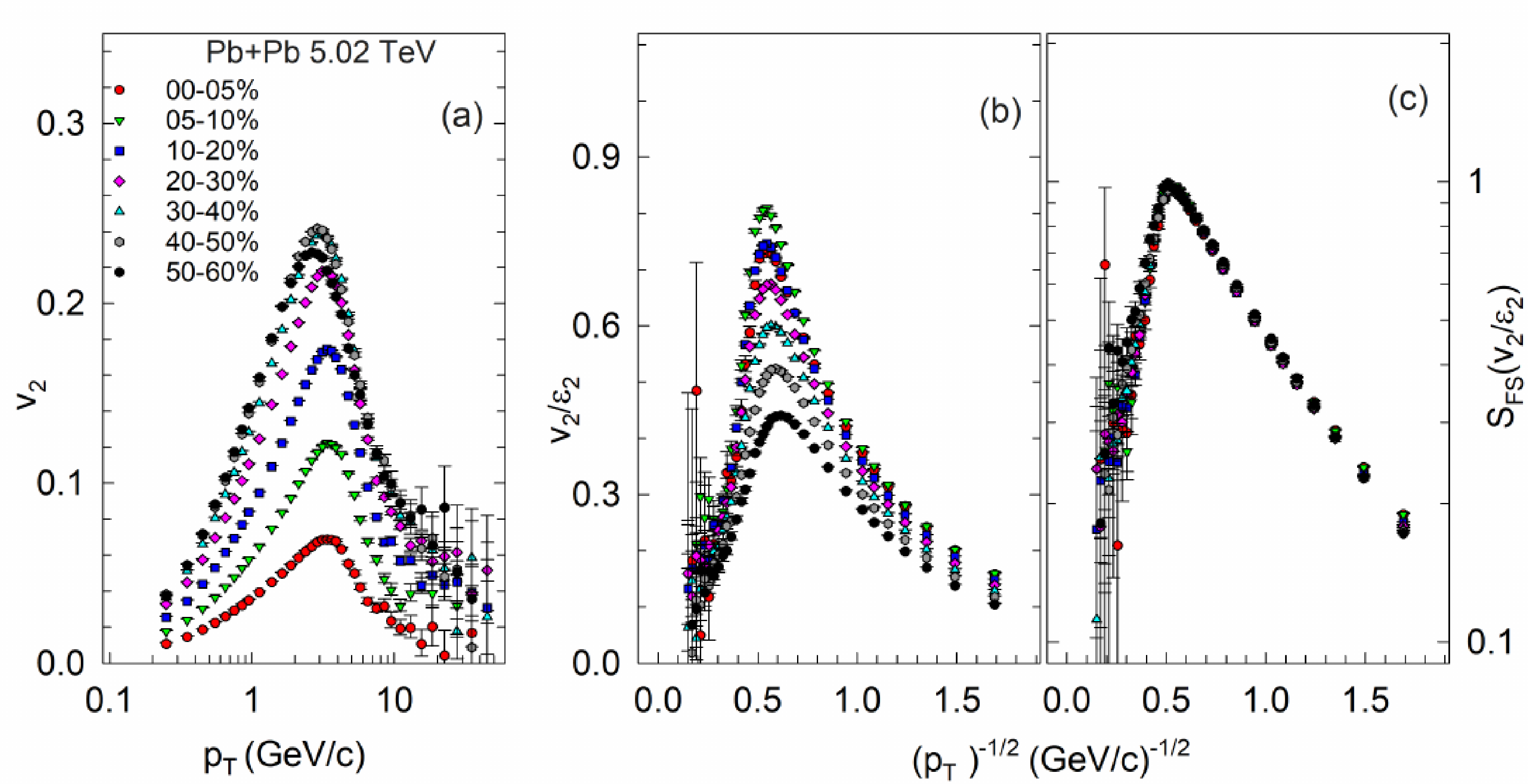
$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



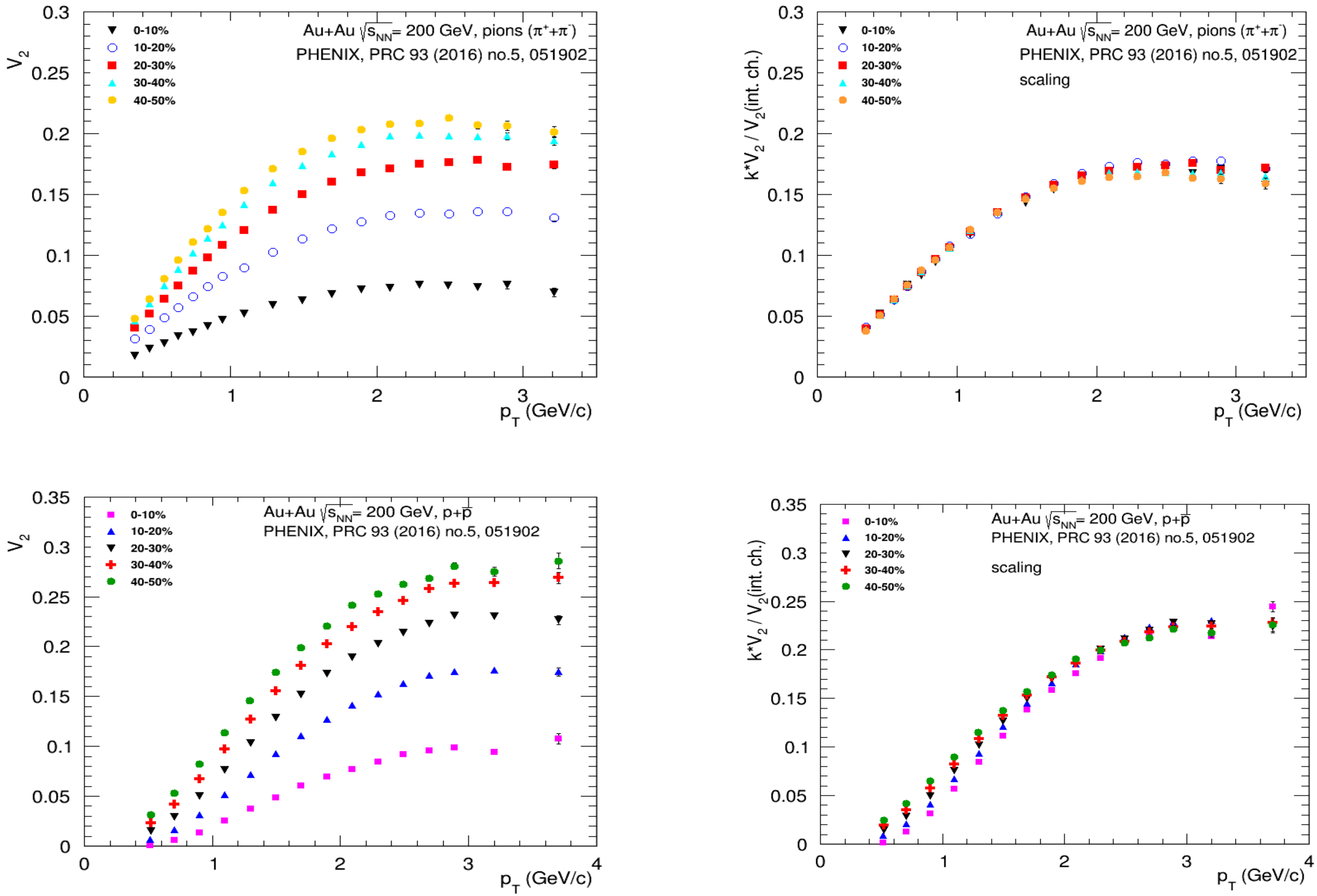


Flow is acoustic

R. Lacey Phys. Rev. C 110 (2024) 3, L031901



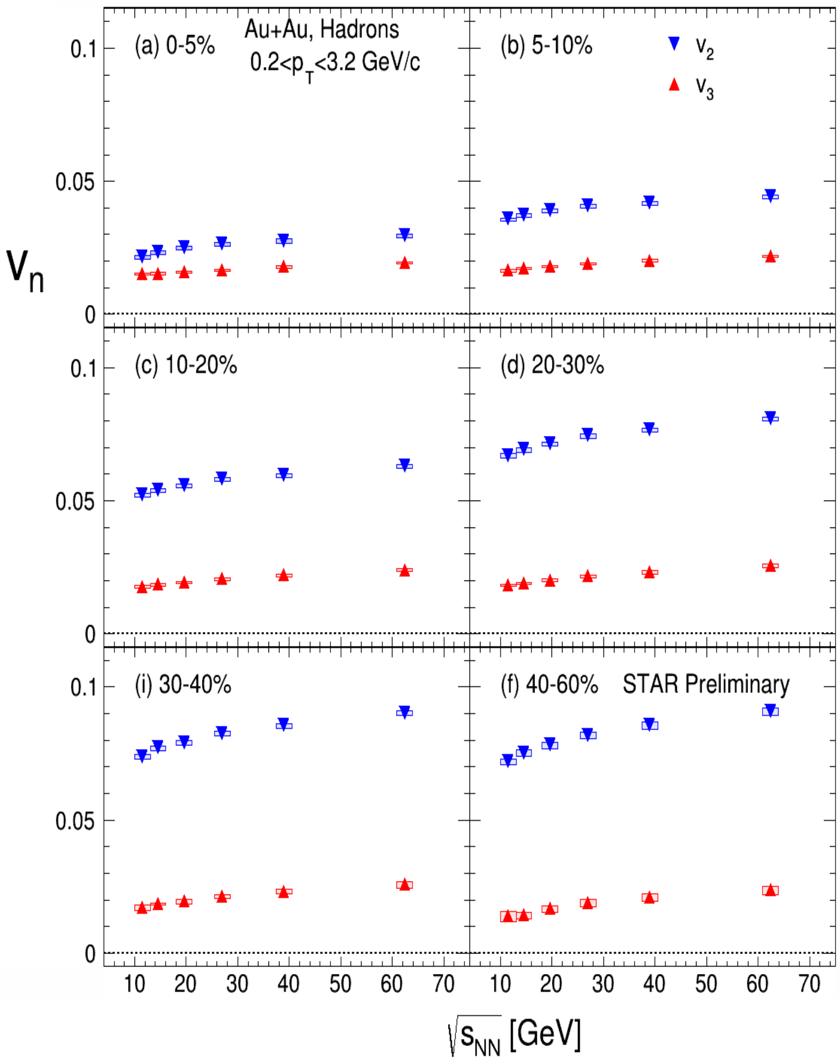
Scaling with integral flow of charged hadrons

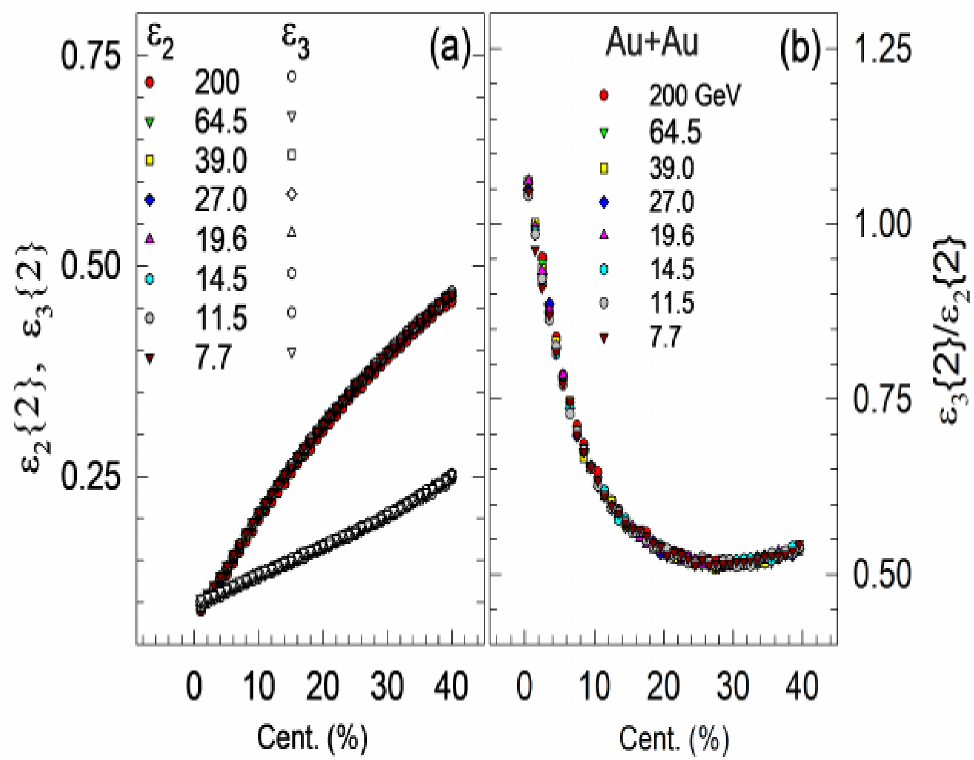


for protons the strong radial flow "blueshifts" the entire flow signal to higher p_T : $p_T \sim p_T^{th} + mc\beta$

Beam-energy dependence of v_2 and v_3

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



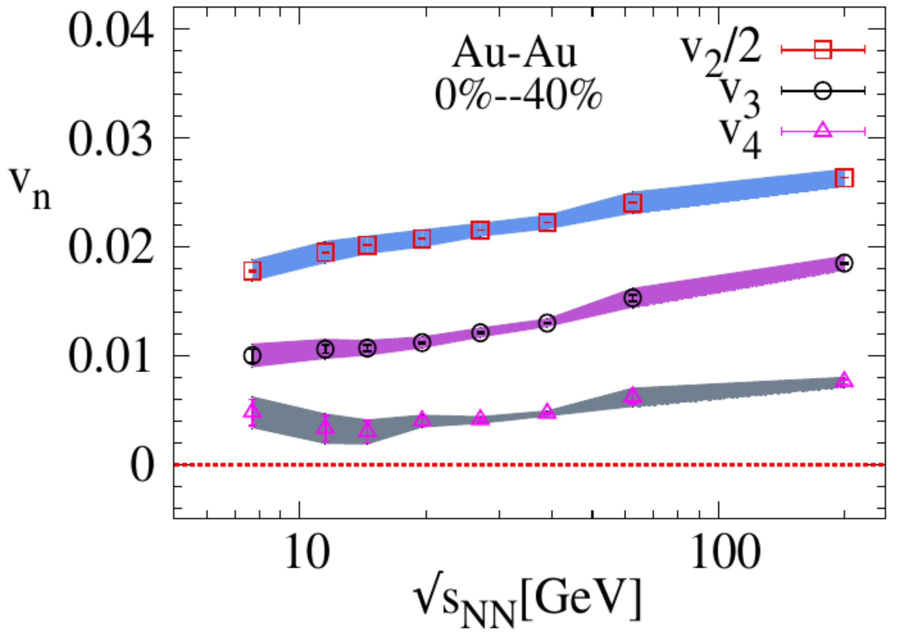


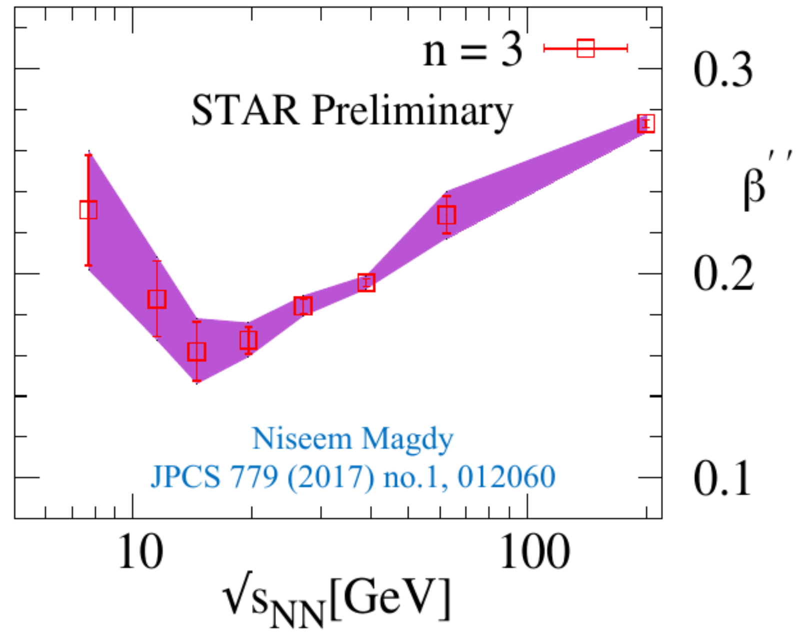
Integrated v_2 and v_3 decrease with decreasing collision energy

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

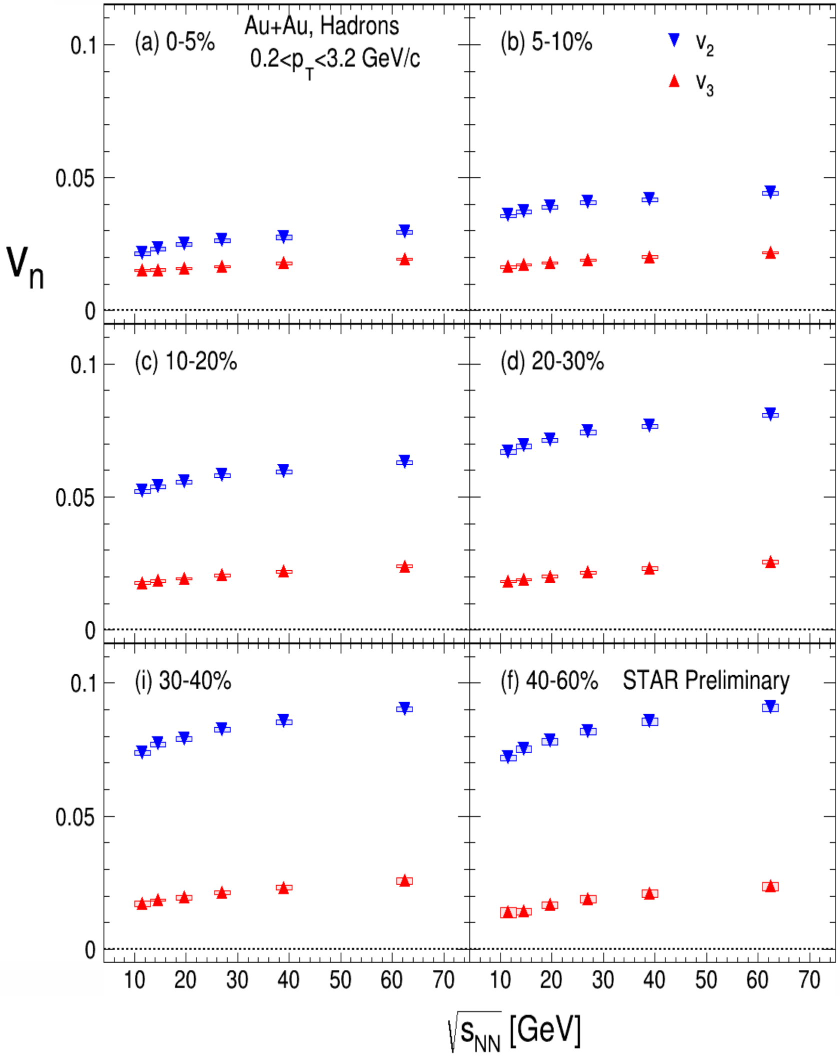


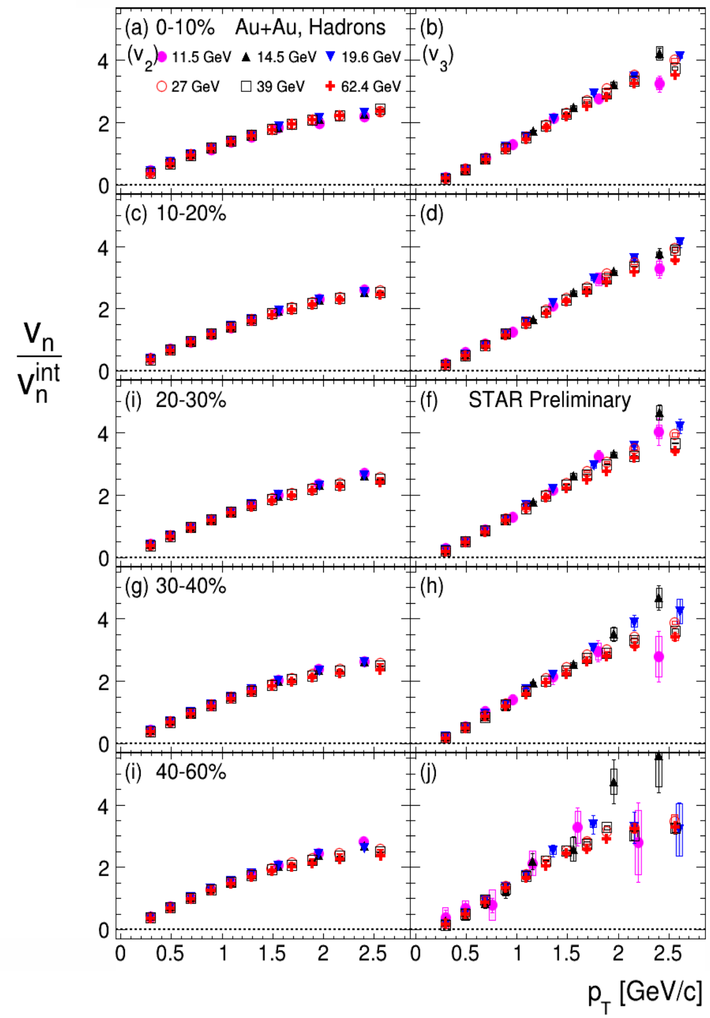


V_n shows a monotonic increase with collision energy. The viscous coefficient, which encodes the transport coefficient (***η/s***), indicates a non-monotonic behavior as a function of collision energy.

Beam-energy dependence of v_2 and v_3

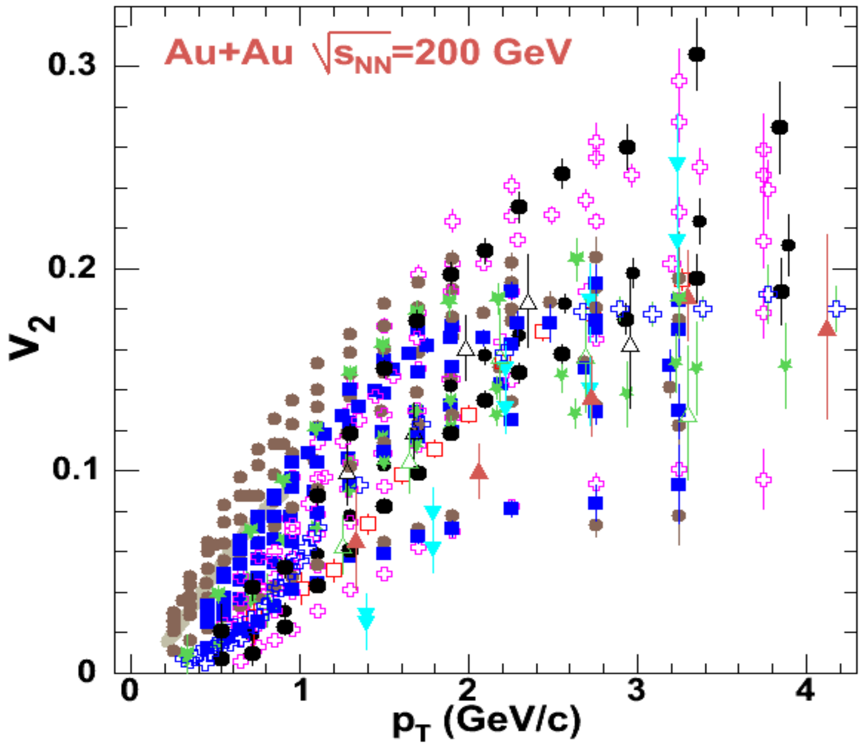
J.Phys.Conf.Ser. 1690 (2020) 1, 012128





Integrated v_2 and v_3 decrease with decreasing collision energy
Similar shape of p_T dependence of normalized v_2 and v_3 for all centralities and collision energies

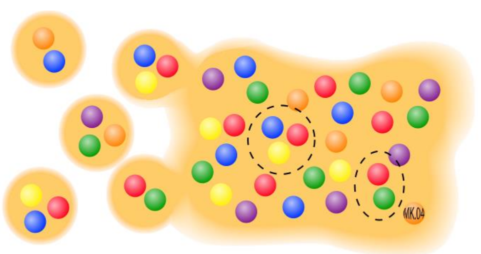
Anisotropic Flow at RHIC – partonic?

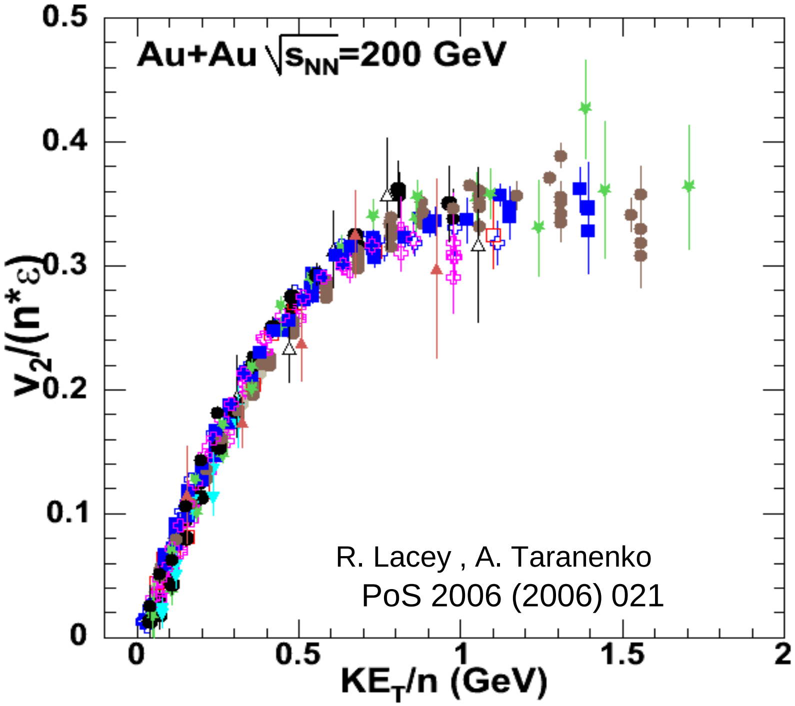


PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p+\bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

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
- ϕ : min.bias

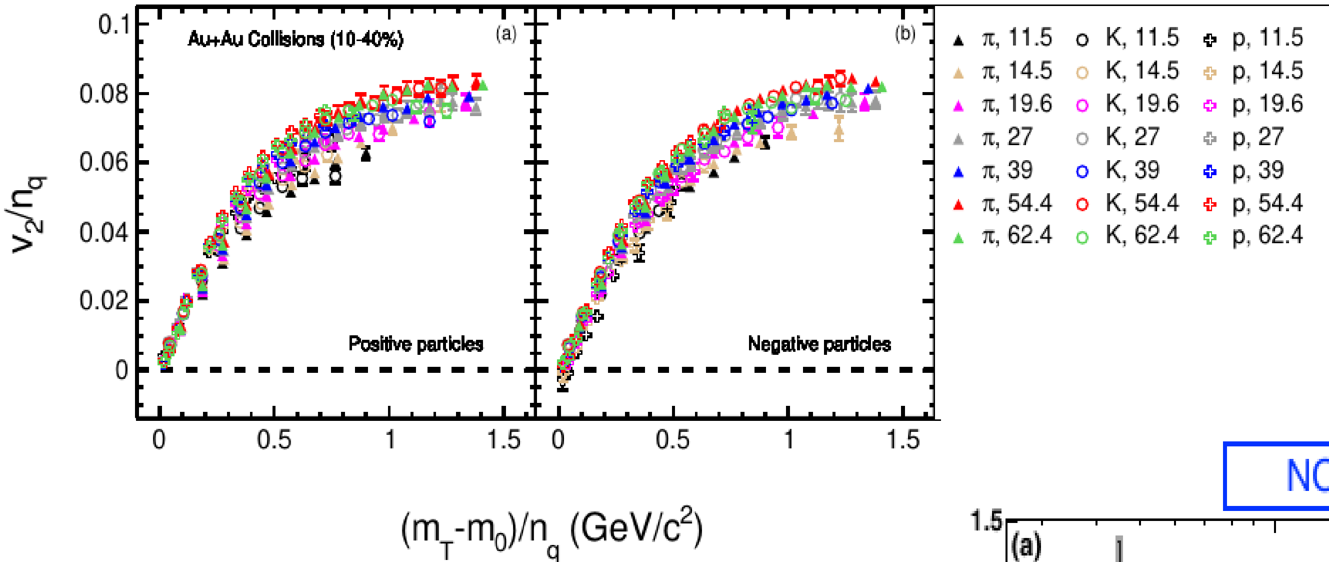
$$KE_T = m(\gamma_T - 1) = m_T - m$$

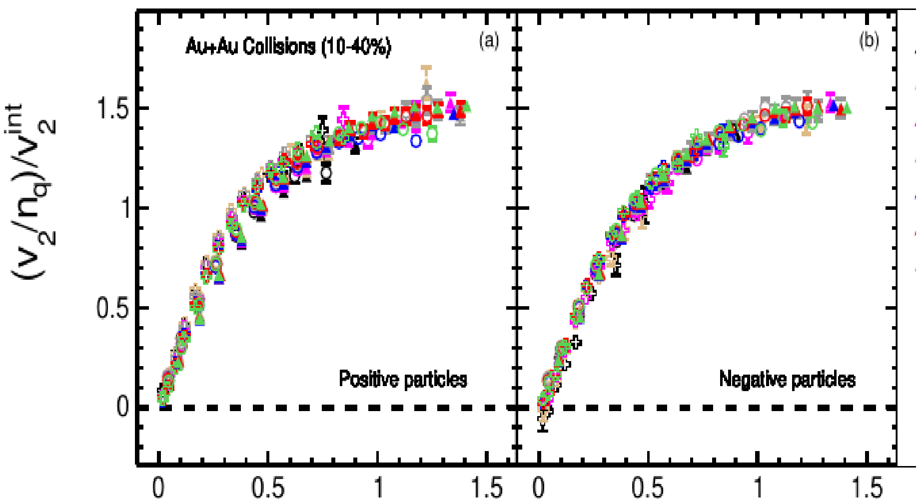




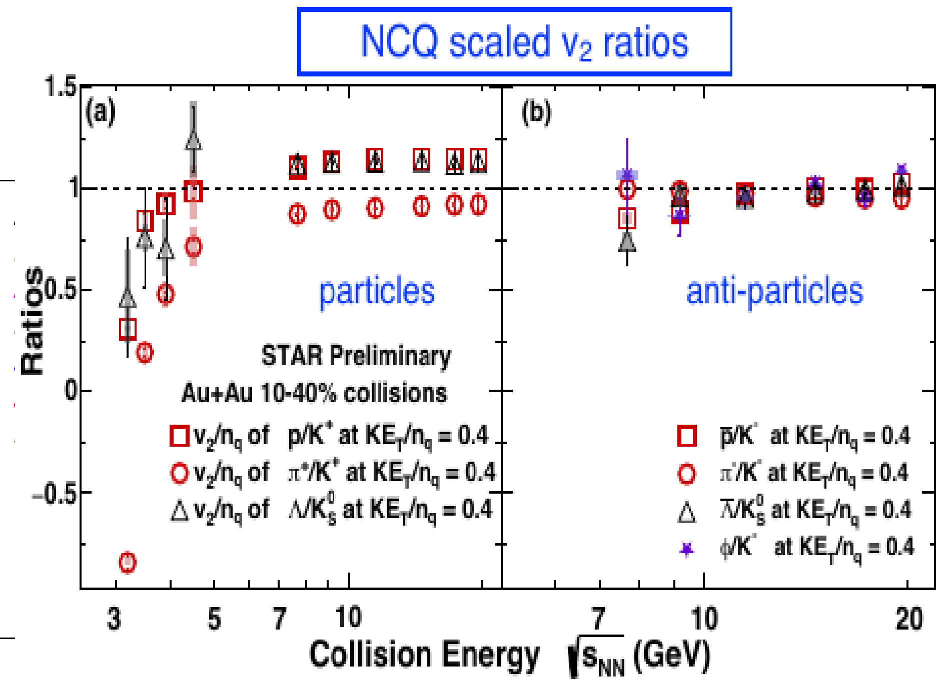
n=2 for mesons and
n=3 for baryons

Elliptic flow from STAR BES program





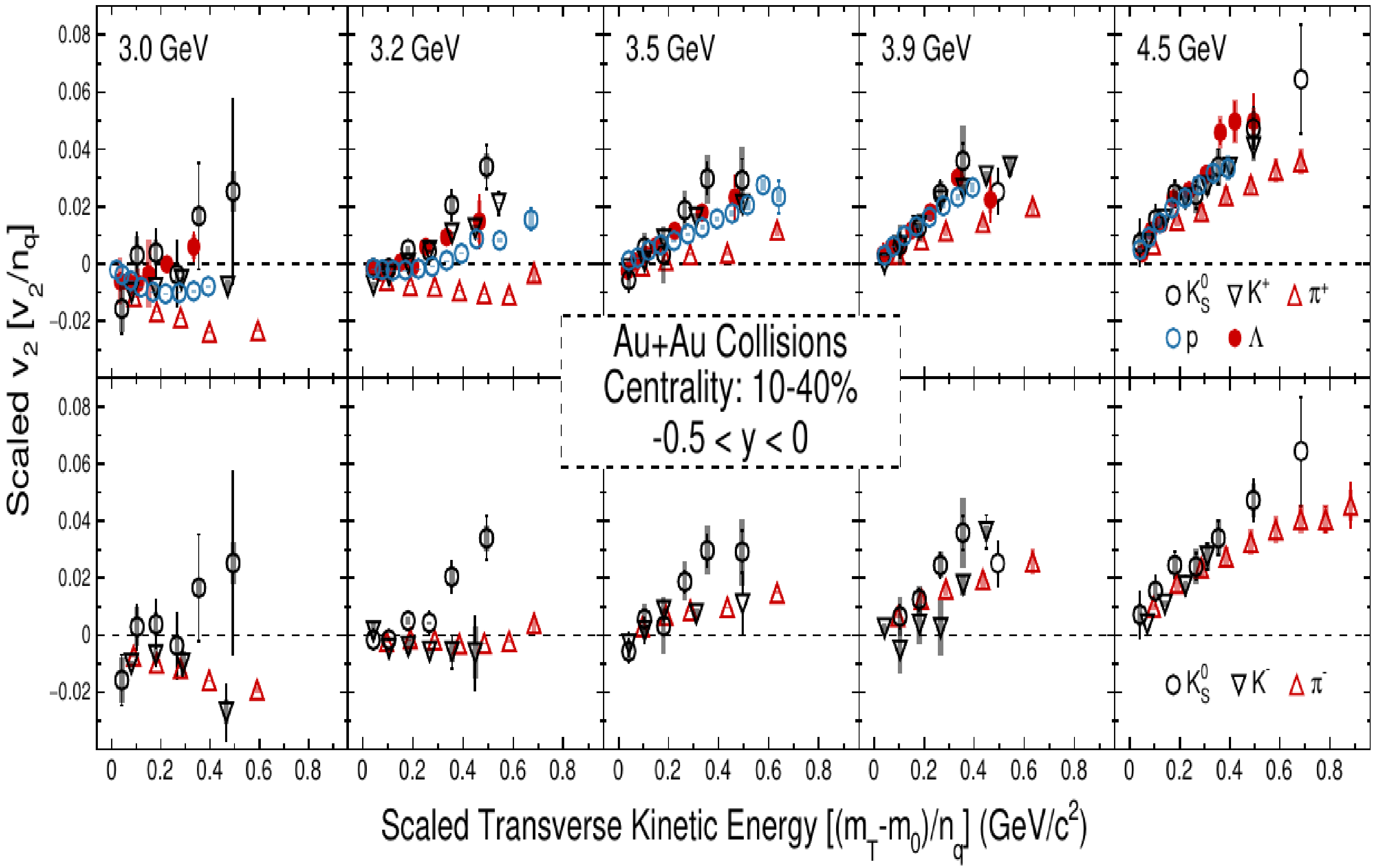
$(m_T-m_0)/n_q$ (GeV/c^2)



STAR , Phys Rev C93, 14907 (2016)

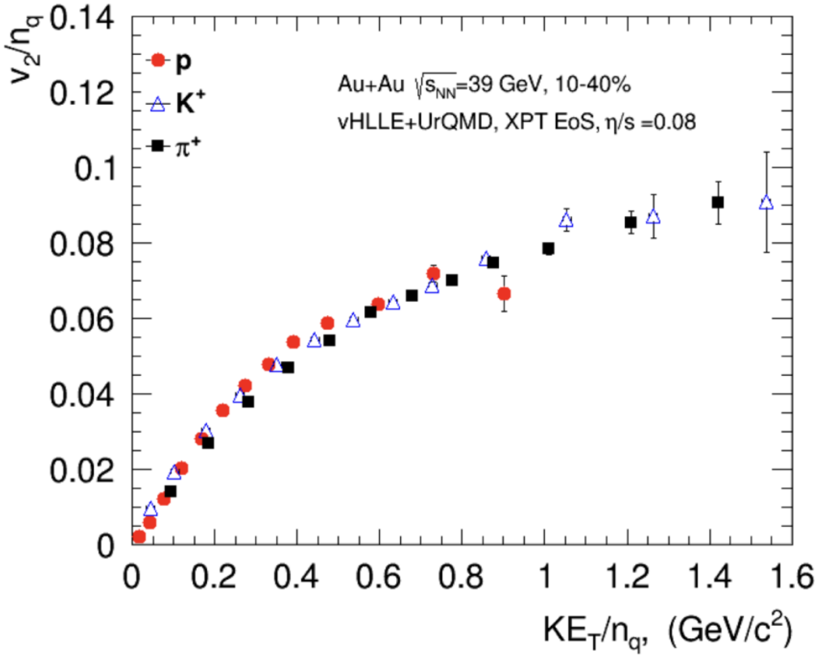
Anisotropic Flow at RHIC BES

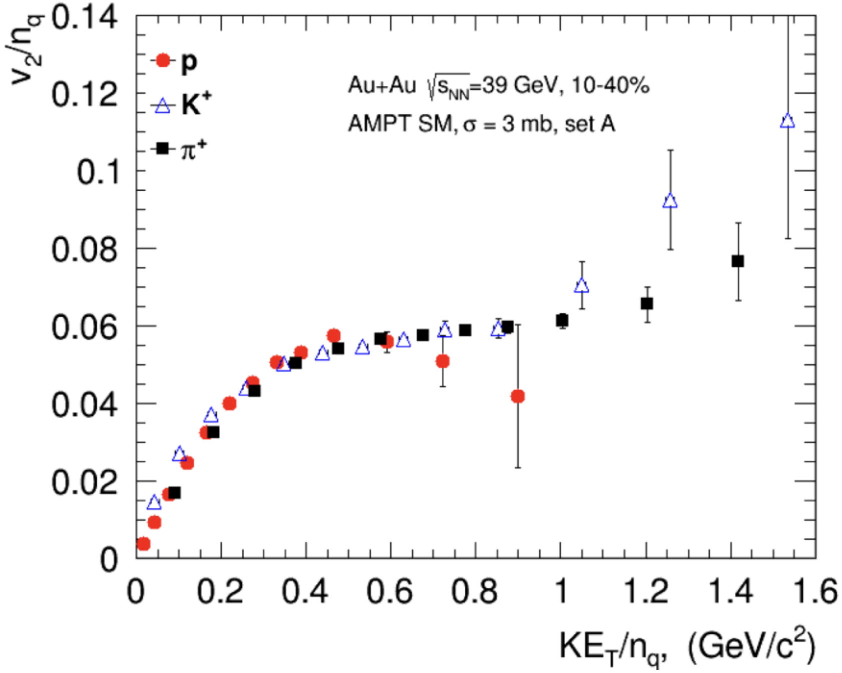
Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024



At high energies, data follows NCQ scaling, indicating partonic collectivity???
NCQ scaling for v2 breaks completely at 3.5 GeV and below,

NCQ scaling: hybrid models

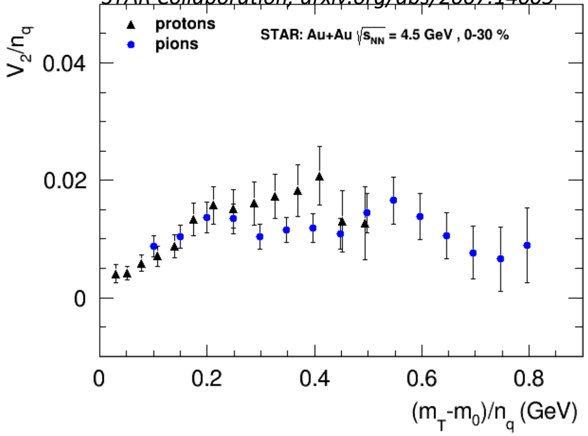




- Hybrid models with QGP phase are used for BES energy range ($\sqrt{s_{NN}} = 7.7 - 200$ GeV), such as vHLLE+UrQMD and AMPT SM
- NCQ scaling holds for hybrid models well

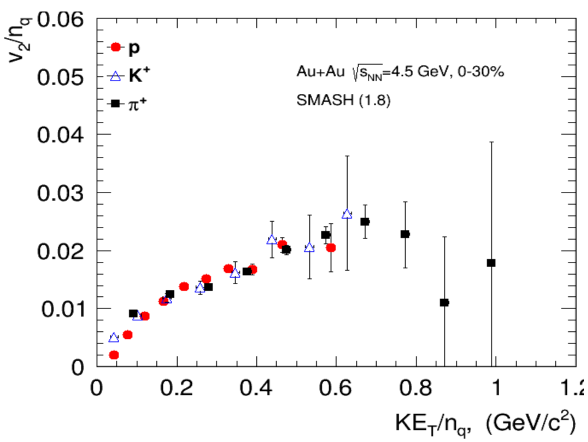
NCQ scaling: cascade models

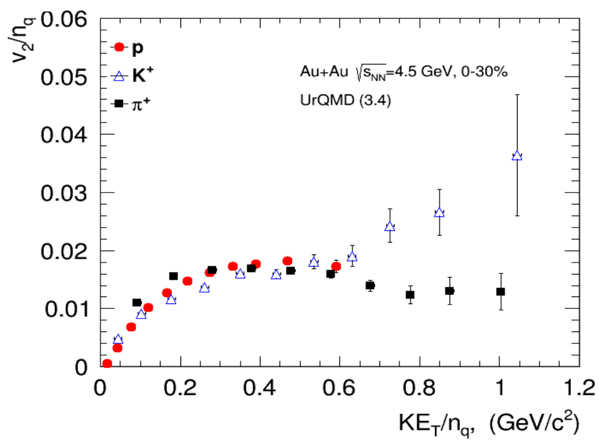
STAR Collaboration, arxiv.org/abs/2007.14005

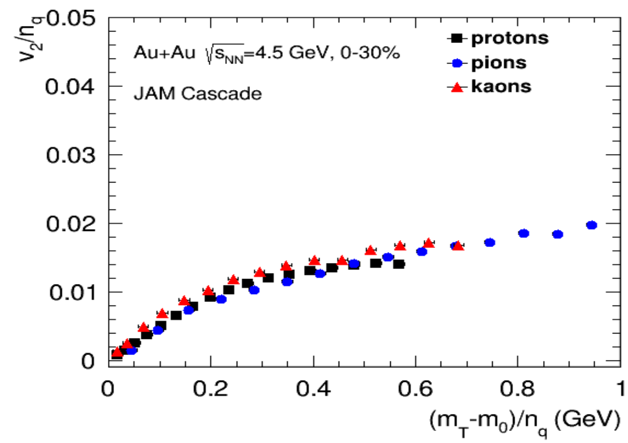


- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

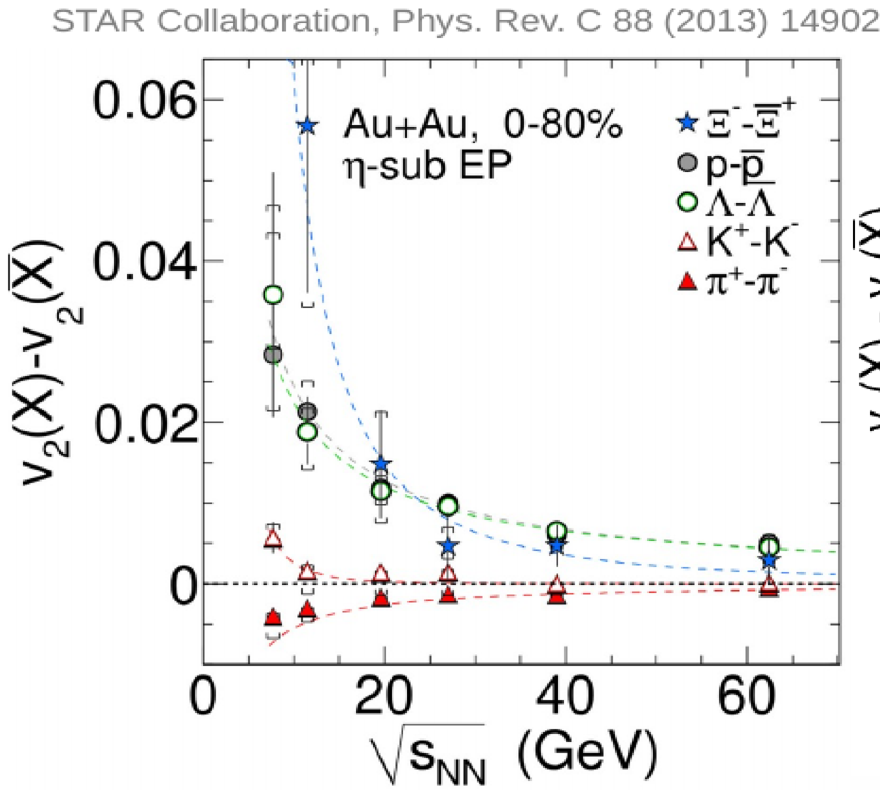
KE_T/n_q scaling at 4.5 GeV might be accidental – more careful studies should be performed



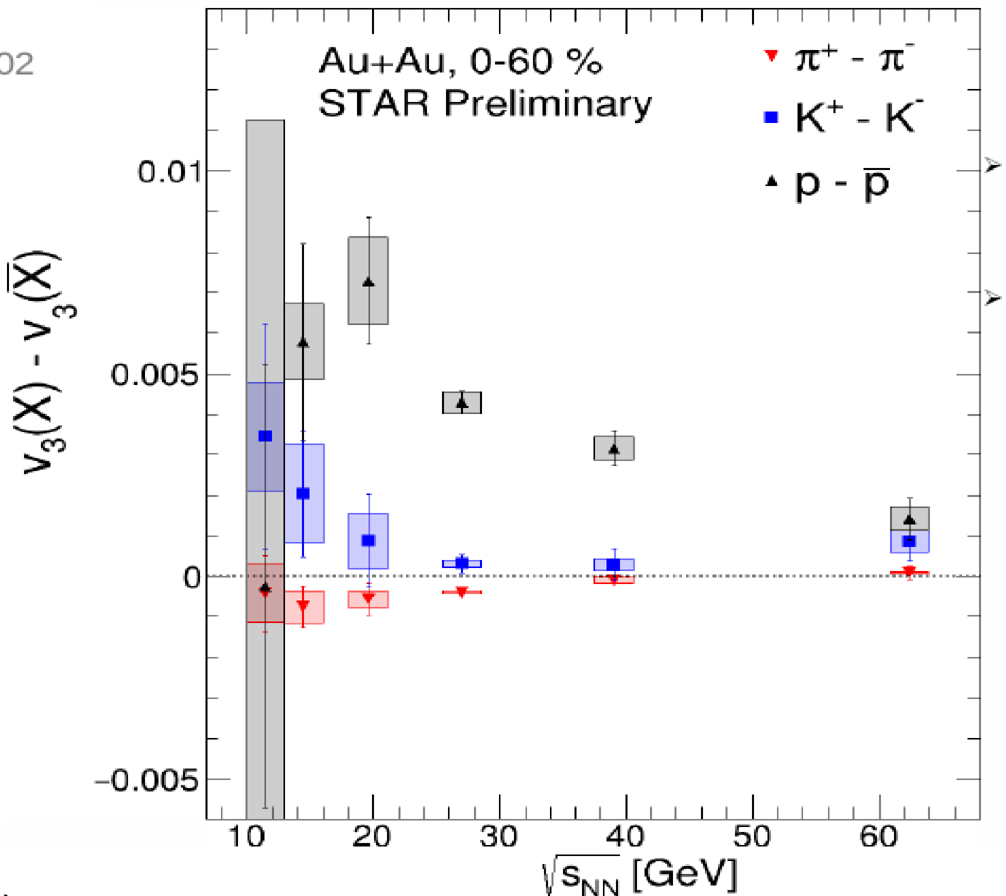




Anisotropic Flow of particles and antiparticles



STAR Collaboration, Phys Rev C93, 14907 (2016)

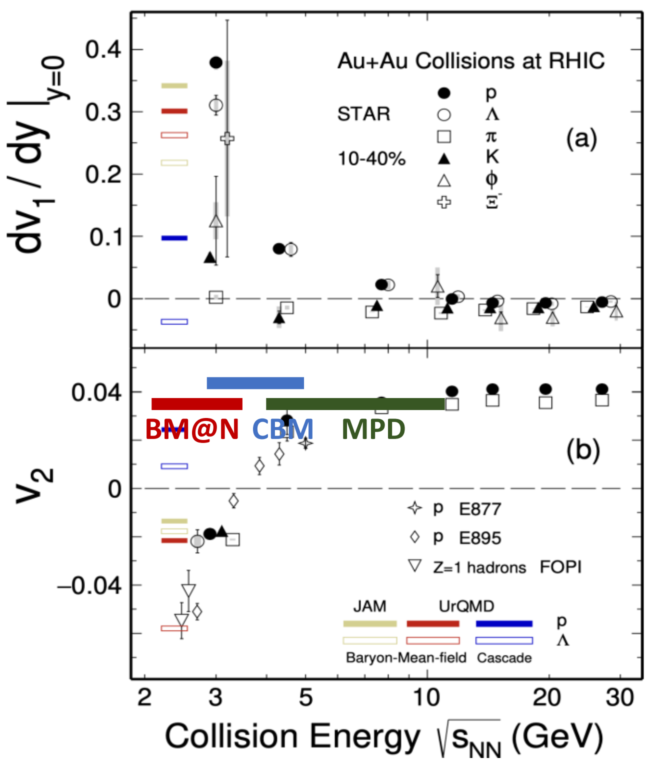


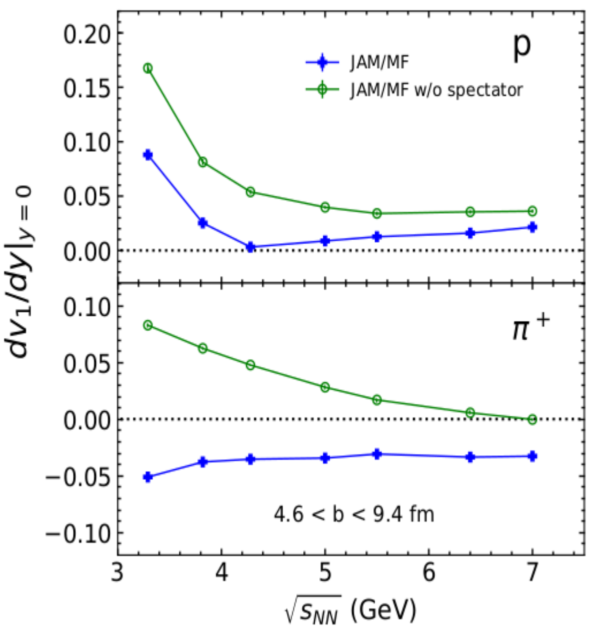
J.Phys.Conf.Ser. 1690 (2020) 1, 012128

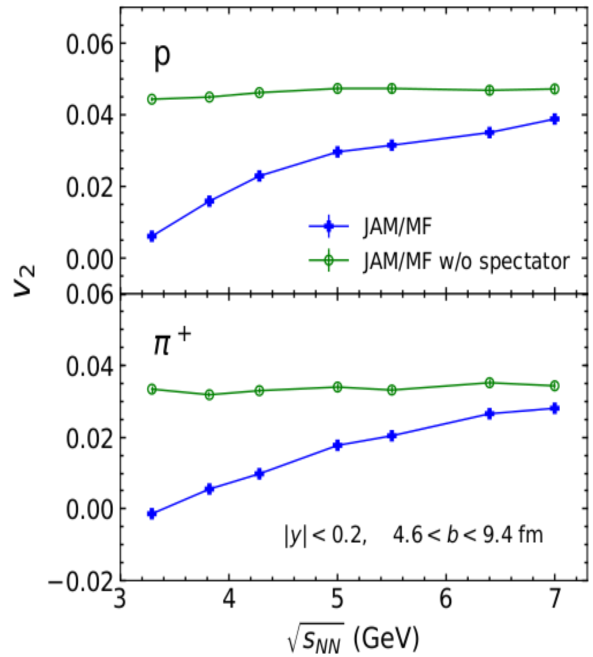
Energy-dependent difference in elliptic and riangular flow between particles and antiparticles. This difference is increasing with decreasing collision energy and is almost identical for all baryons. It is larger for baryons than mesons.

Anisotropic flow in heavy-ion collisions at high baryon density

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







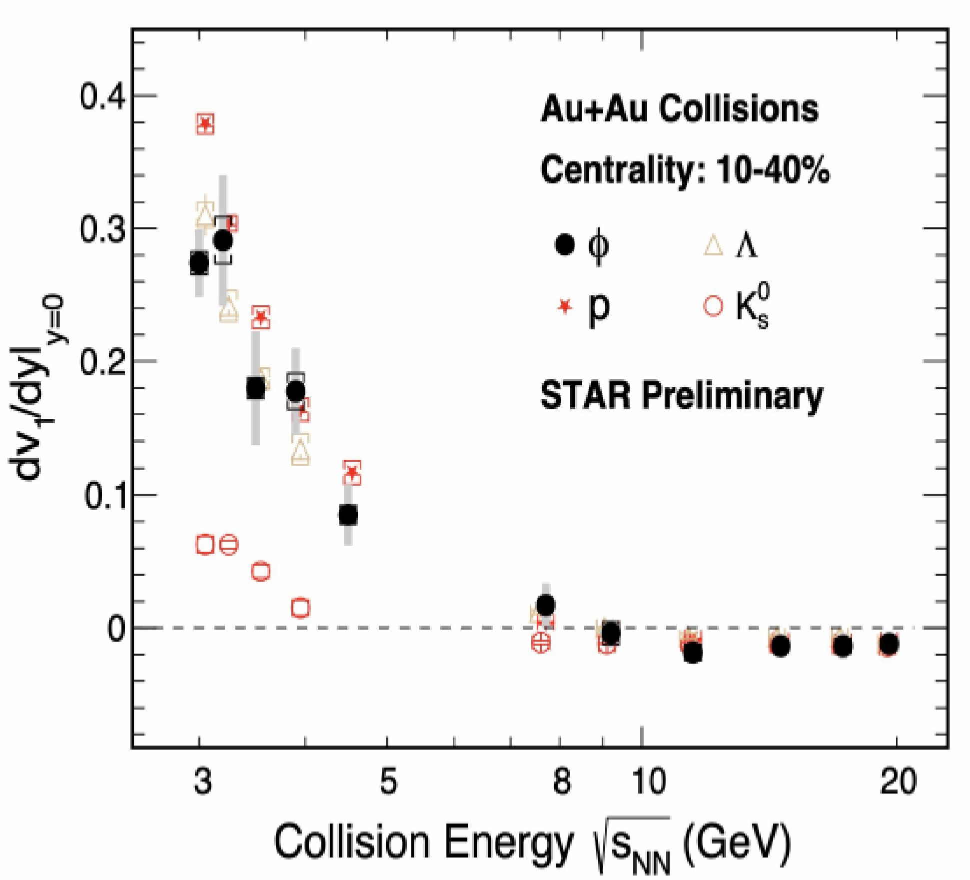
Phys. Rev. C 97, 064913 (2018)

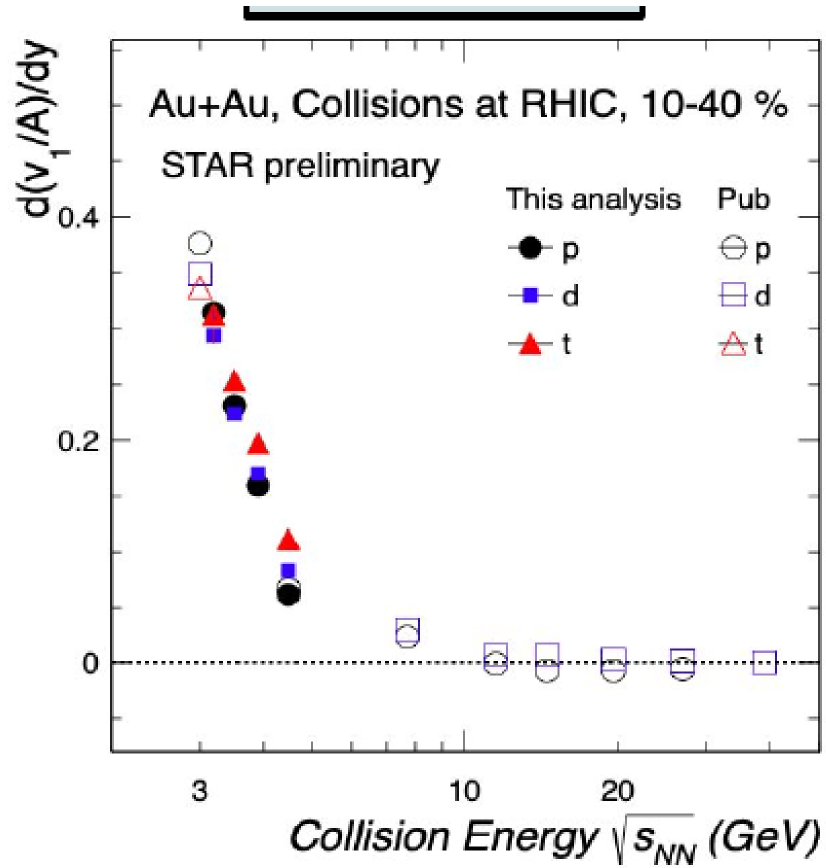
Anisotropic flow at NICA energies is a delicate balance between:

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

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

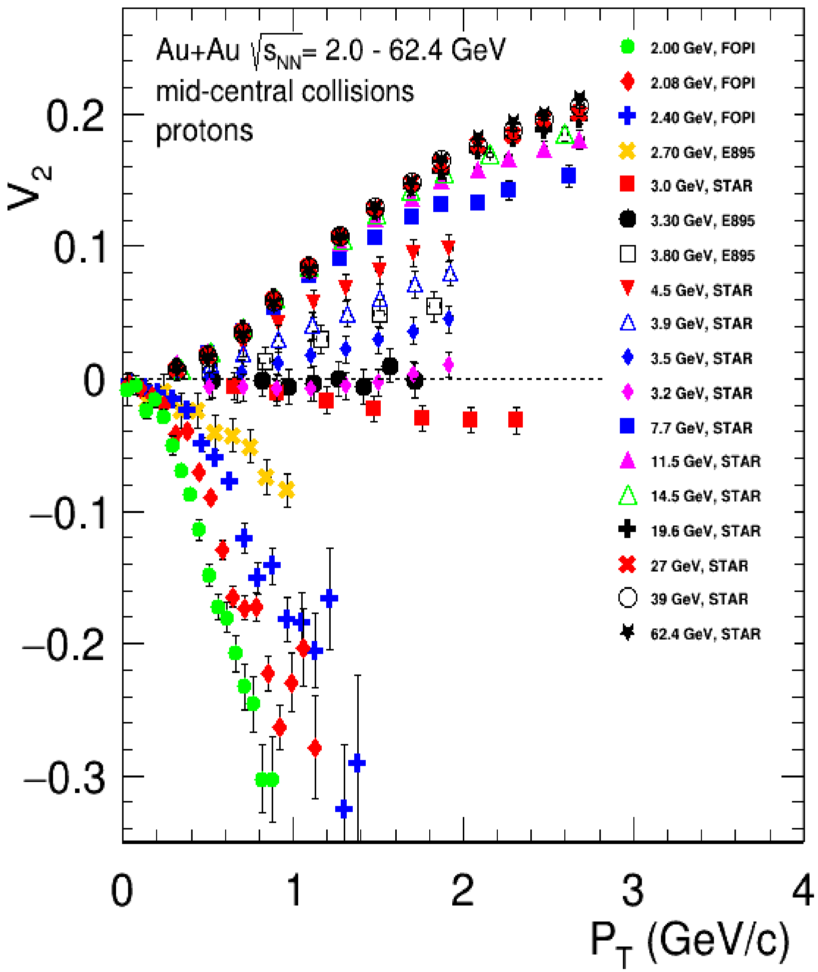
Beam Energy Dependence of Directed Flow (v_1)

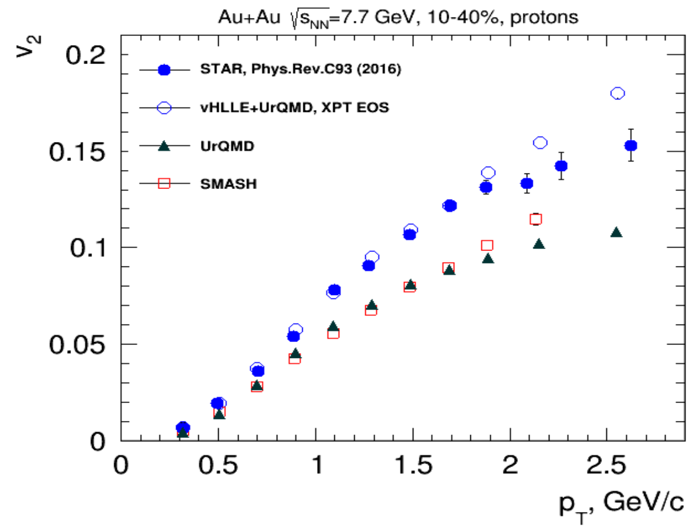


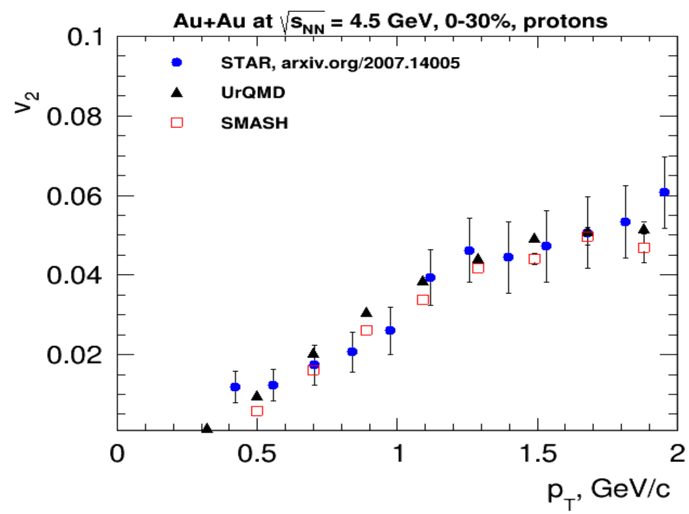


- **Strong energy dependence of v_1 at $\sqrt{s_{NN}}$ = 2.4-7 GeV**

Beam Energy Dependence of Elliptic Flow (v_2)



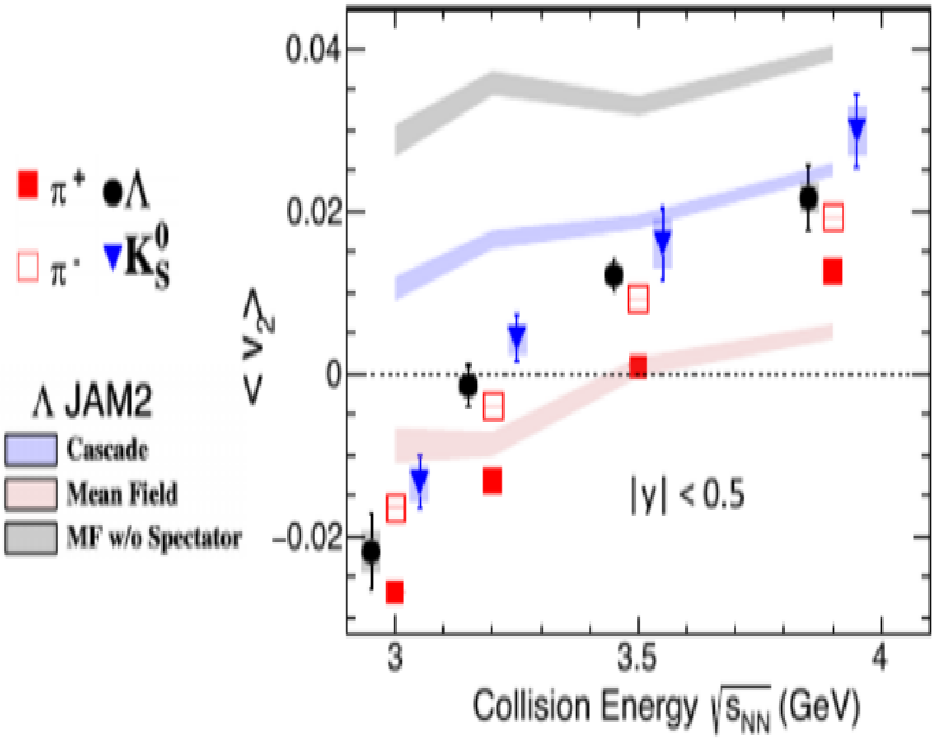


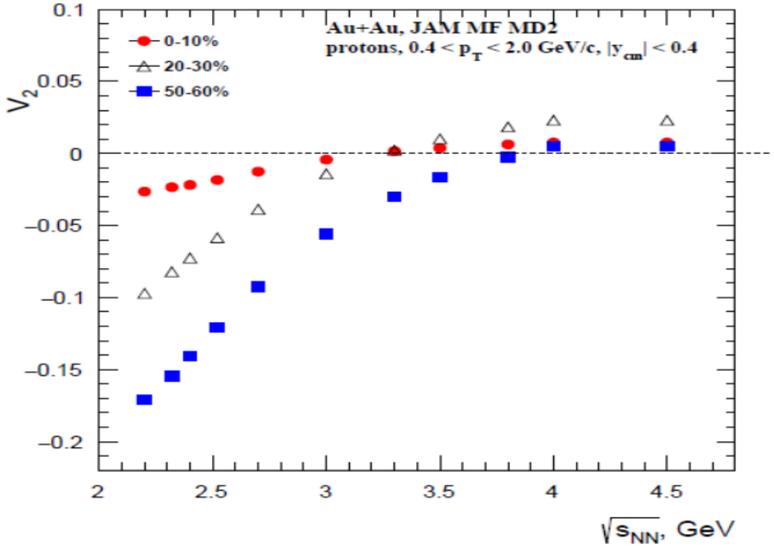


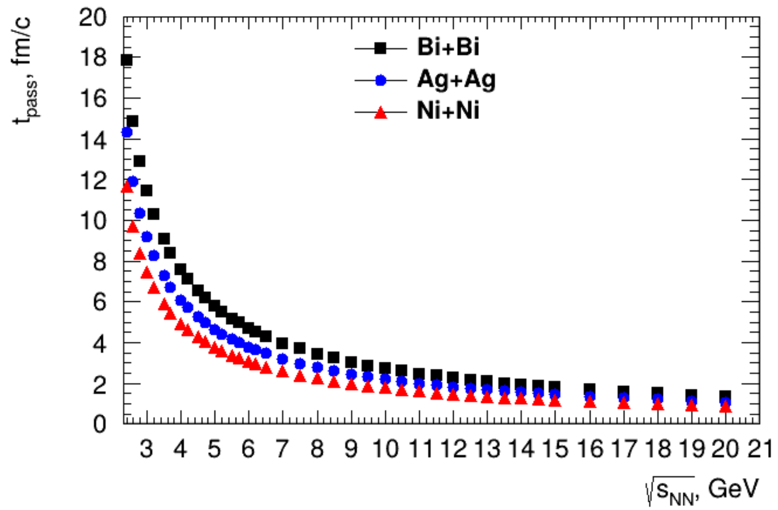
- **Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 2.4-7 GeV**

Beam Energy Dependence of Elliptic Flow (v_2)

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

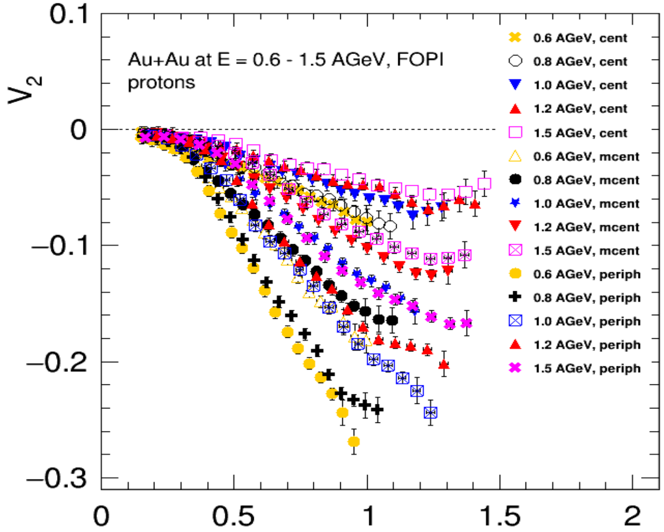


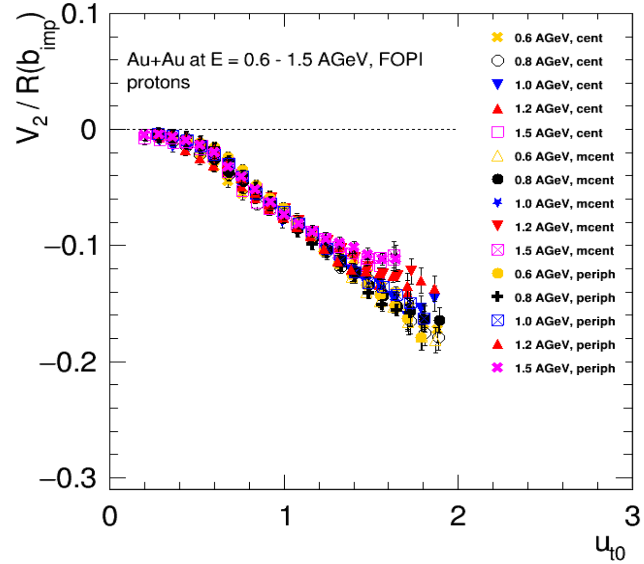




- **Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 2.4-7 GeV**

Scaling relations at SIS – scaling with passage time

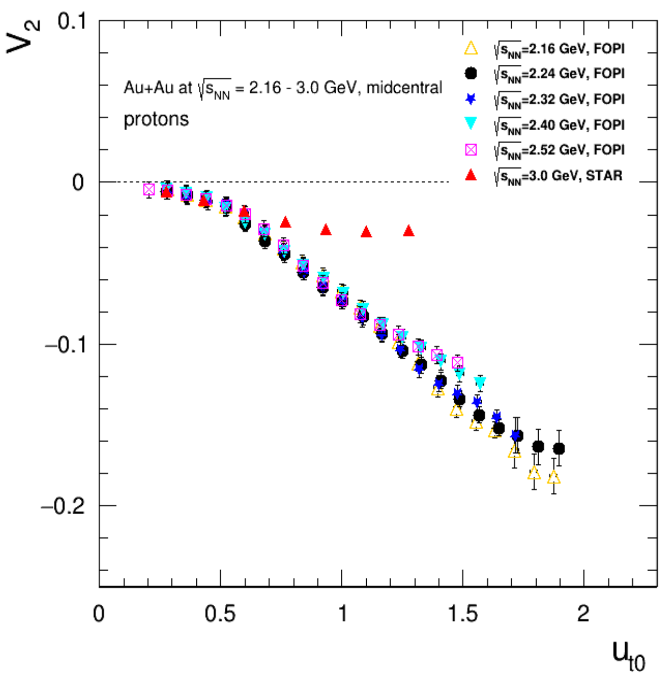




$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2 R m_0}$$

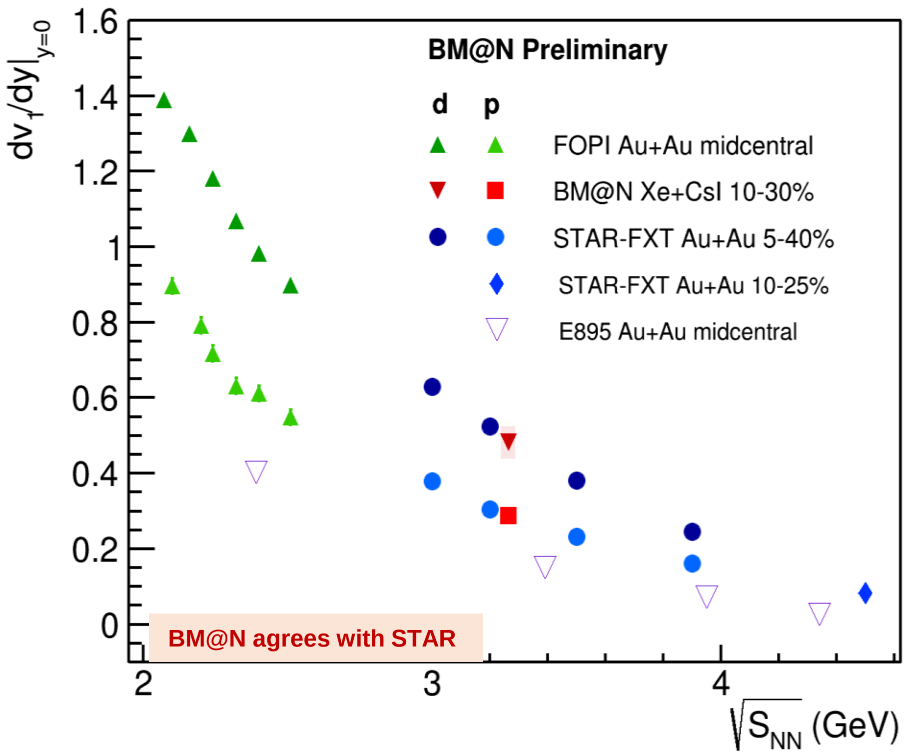
$$t_{pass} = \frac{2R}{\beta_{CM} \gamma_{CM}}$$

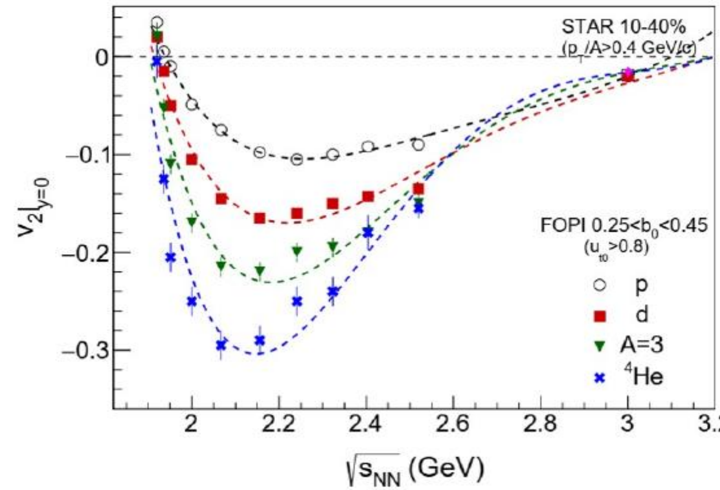
Nucl. Phys A 876 (2012) 1-60

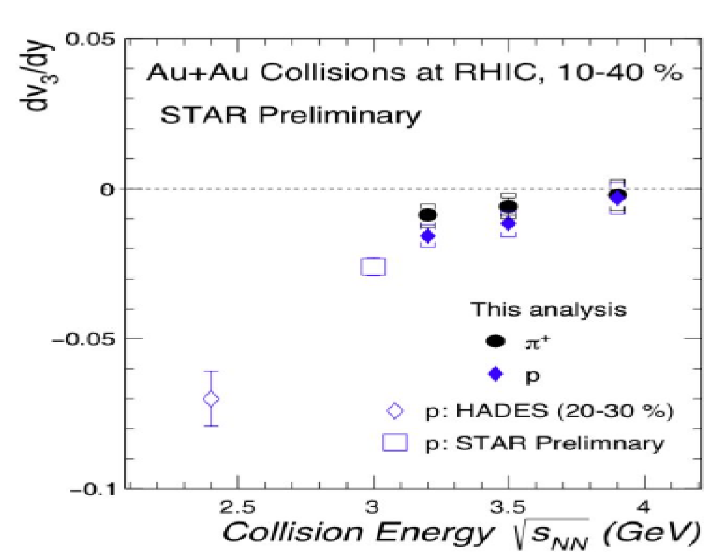


- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

Anisotropic flow at Nuclotron / NICA: 2.5-3.5 GeV







Please see talk of Mikhail Mamaev

Summary and outlook

- **NCQ scaling:**
  - Holds up for energies $\sqrt{s_{NN}} > 4$ GeV in both experimental data and models (hybrid and pure string/hadronic cascade models)
  - Scaling at $\sqrt{s_{NN}} = 4.5$ GeV in the experimental data and pure string/hadronic cascade models can be accidental – more thorough study should be performed
- **Scaling with passage time:**
  - Holds up for energies $\sqrt{s_{NN}} = 2 - 2.7$ GeV and breaks at $\sqrt{s_{NN}} \geq 3$ GeV
  - Shows that at this energy range $v_2\left(\sqrt{s_{NN}}\right)$ changes due to the change of the passage time t_{pass} of the spectators

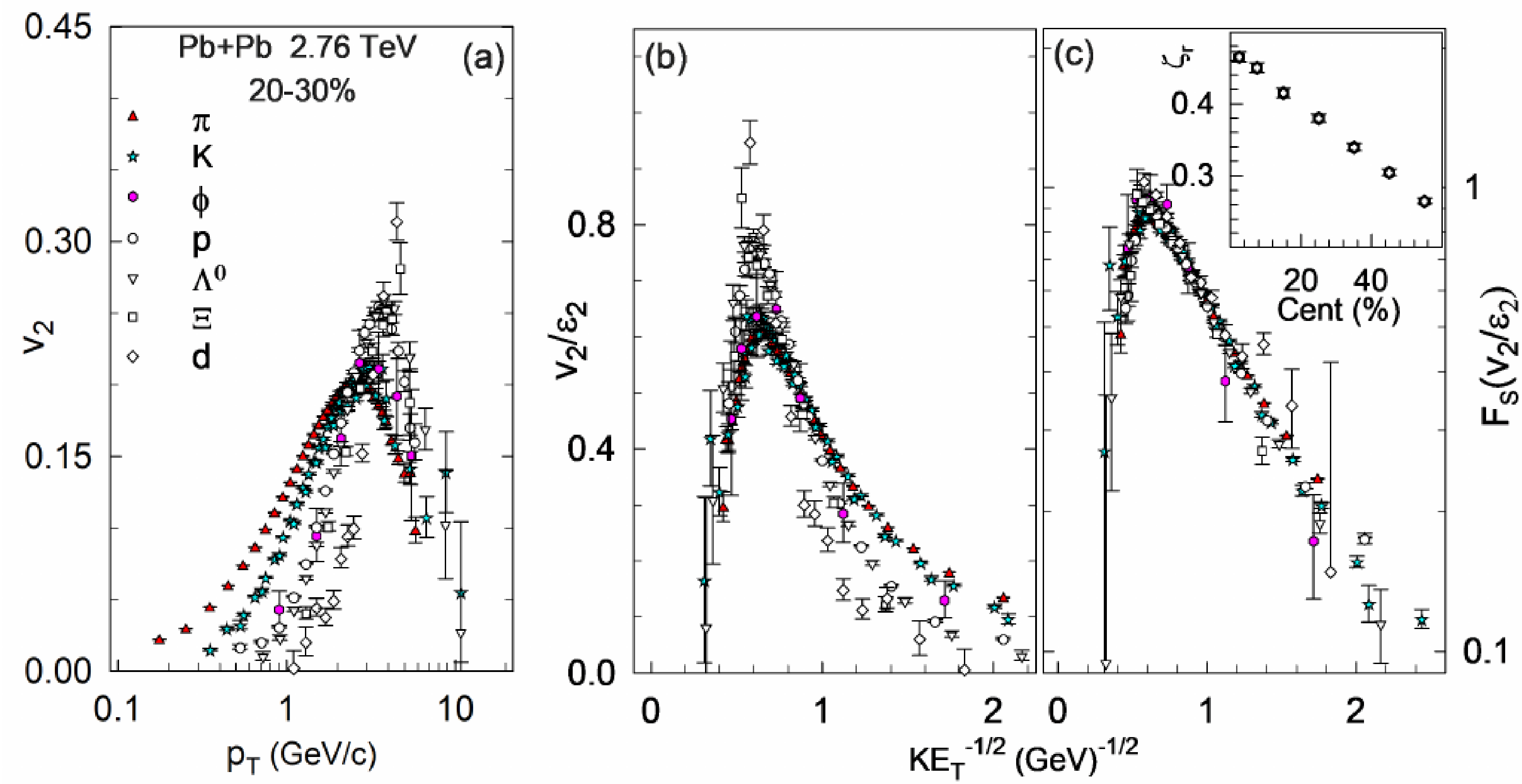
Scaling relations provide a useful tool

➢ to perform comparison between results from different experiments with different system size and beam energies

➢ to constrain existing models

Flow is acoustic

R. Lacey Phys. Rev. C 110 (2024) 3, L031901



$$\frac{v'_n(p_T)}{\varepsilon'_n} e^{\frac{n\beta'}{\mathbb{R}_0}[n+\kappa p_T^2]\left(\frac{\mathbb{R}_0}{\mathbb{R}'}-1\right)} = e^{-n_B\zeta_B \frac{2\beta}{\alpha\mathbb{R}_0}} \left(\frac{v'''_n(p_T)}{\varepsilon'''_n}\right)^{\zeta_B} e^{\frac{n\beta\zeta_r}{\mathbb{R}_0}[n+\kappa p_T^2]\left(\frac{\mathbb{R}_0}{\mathbb{R}'}-1\right)},$$

$$\frac{v'_2(p_T,\mathrm{cent})}{\varepsilon'_2(\mathrm{cent})} e^{\frac{2\alpha\beta'}{\mathbb{R}_0}} = e^{-2n_B\zeta_B\frac{2\alpha\beta}{\mathbb{R}_0}} \left(\frac{v_3(p_T,\mathrm{cent})}{\varepsilon_3(\mathrm{cent})}\right)^{\frac{2}{3}\zeta_B},$$