Study of the beam energy dependence of anisotropic flow in relativistic heavy ion collisions using scaling relations.

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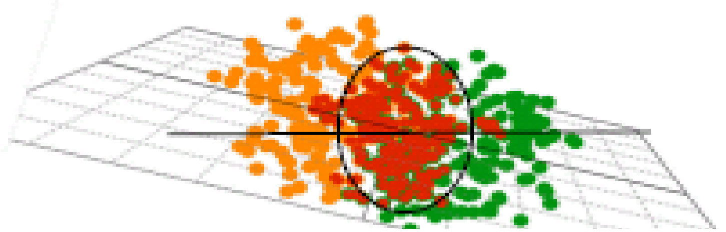
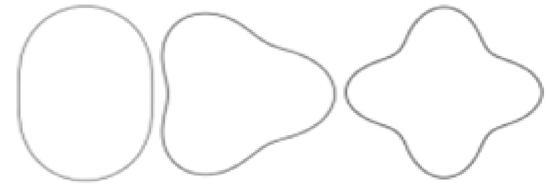
OUTLINE

1. **Scaling relation for flow (V_n) and sQGP at RHIC/LHC**
2. **Scaling tests for (V_n) from Beam Energy Scan (RHIC)**

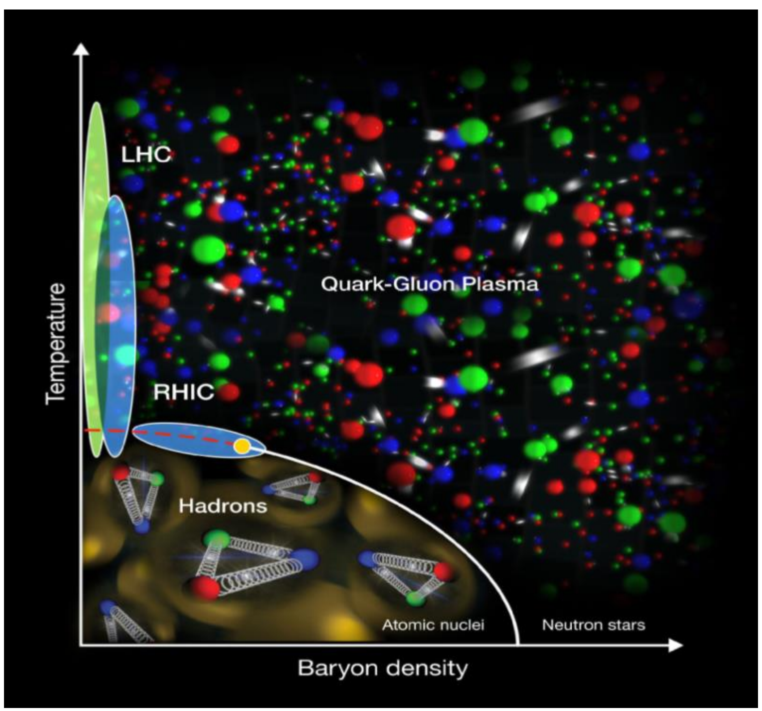
Anisotropic Flow at RHIC-LHC



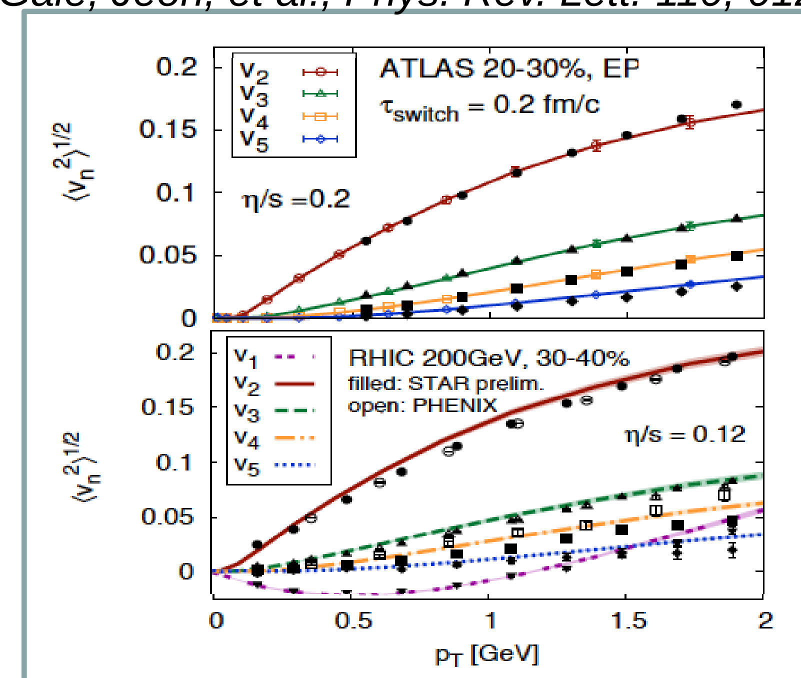


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}} \quad \Rightarrow \quad \frac{dN}{d\phi} \propto \left(1+2\sum_{n=1} v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right)$$

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



Scaling properties of collective flow

"Change of collective-flow mechanism indicated by scaling analysis of transverse flow " A. Bonasera, L.P. Csernai , Phys. Rev. Lett. 59 (1987) 630

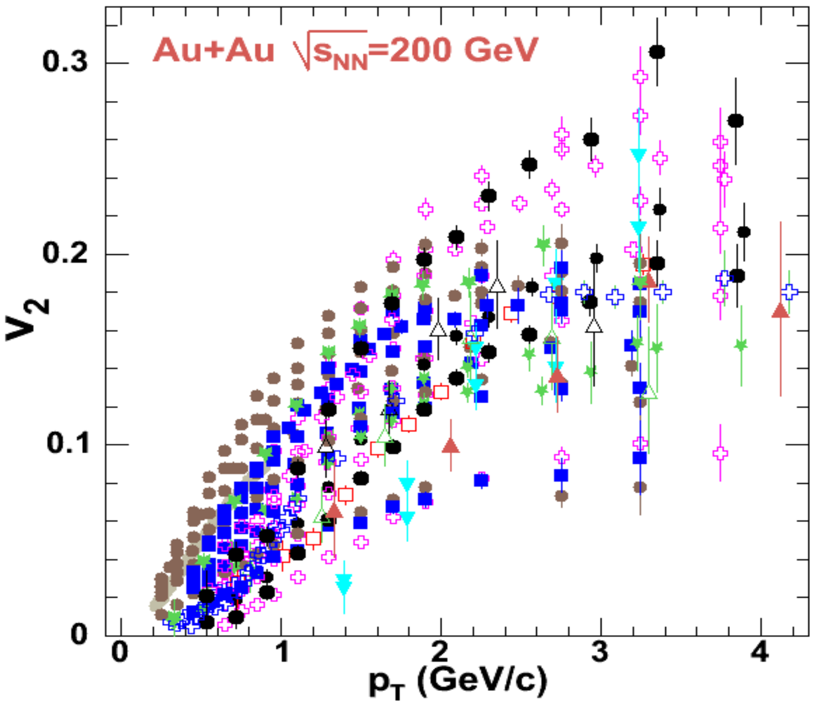
The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features

"Collective flow in heavy-ion collisions", W. Reisdorf, H.G. Ritter Ann.Rev. Nucl.Part.Sci. 47 (1997) 663-709 :

There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.

4

Anisotropic Flow at RHIC – scaling relations



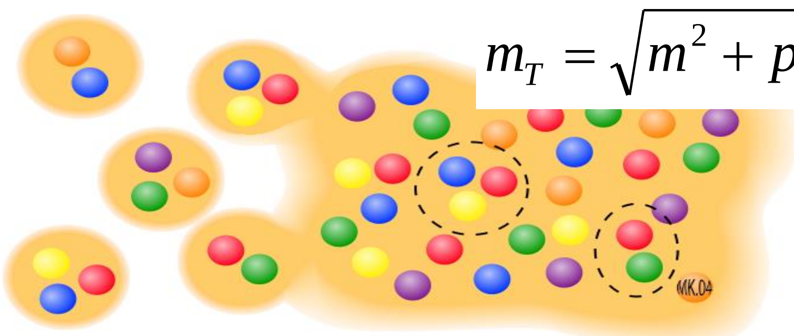
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

- $\pi^+ + \pi^-$: 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%

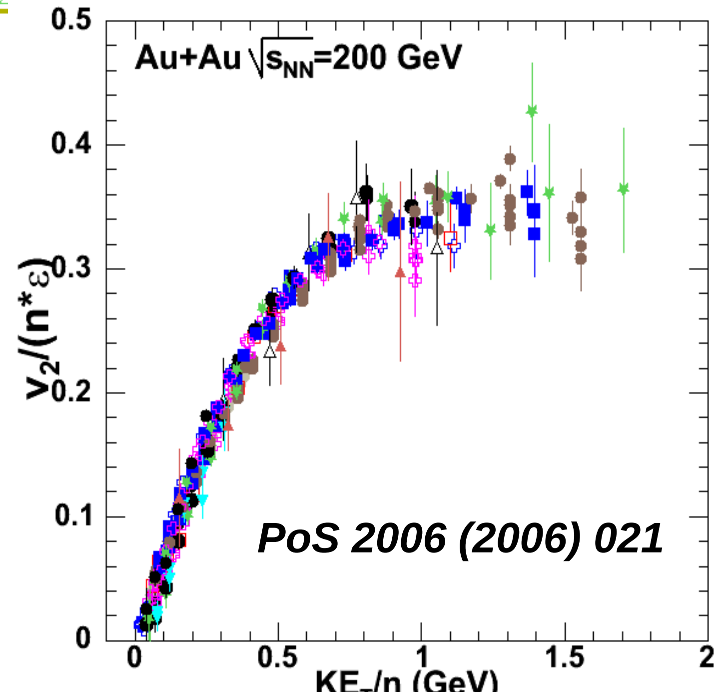
STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: 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

Flow 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,

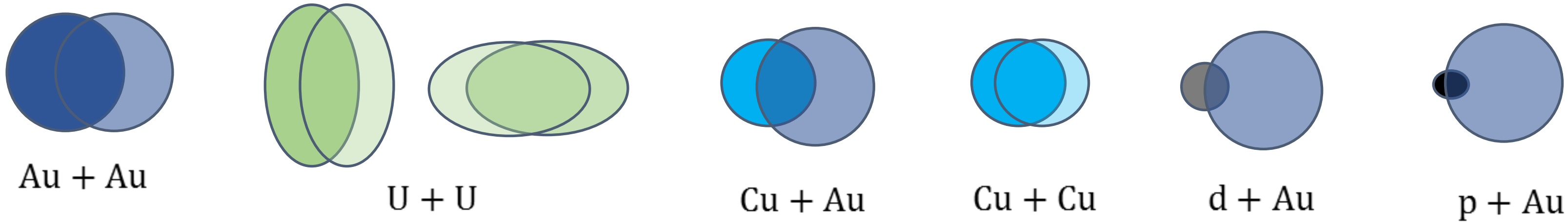
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

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

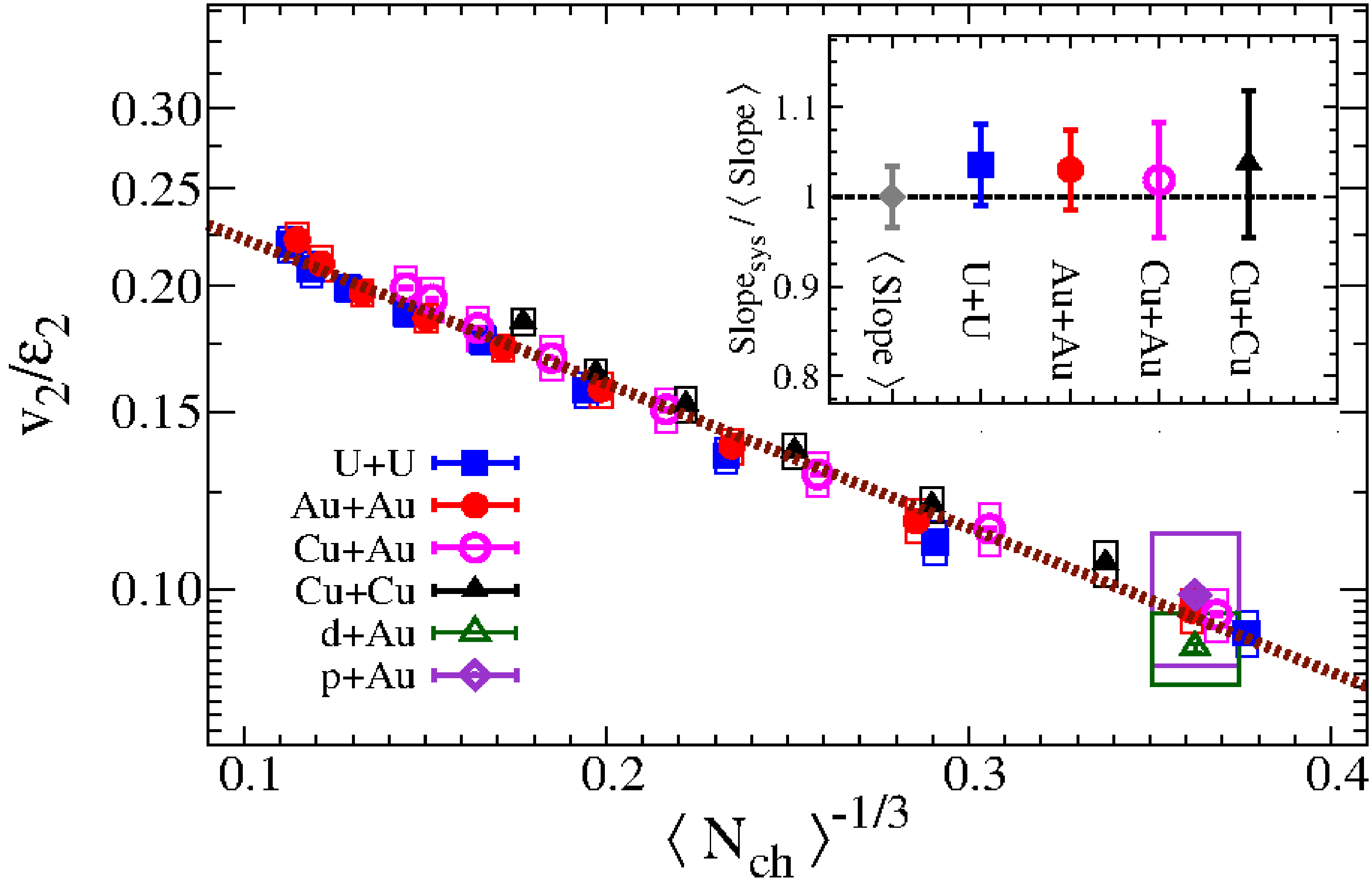
$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}}$$

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



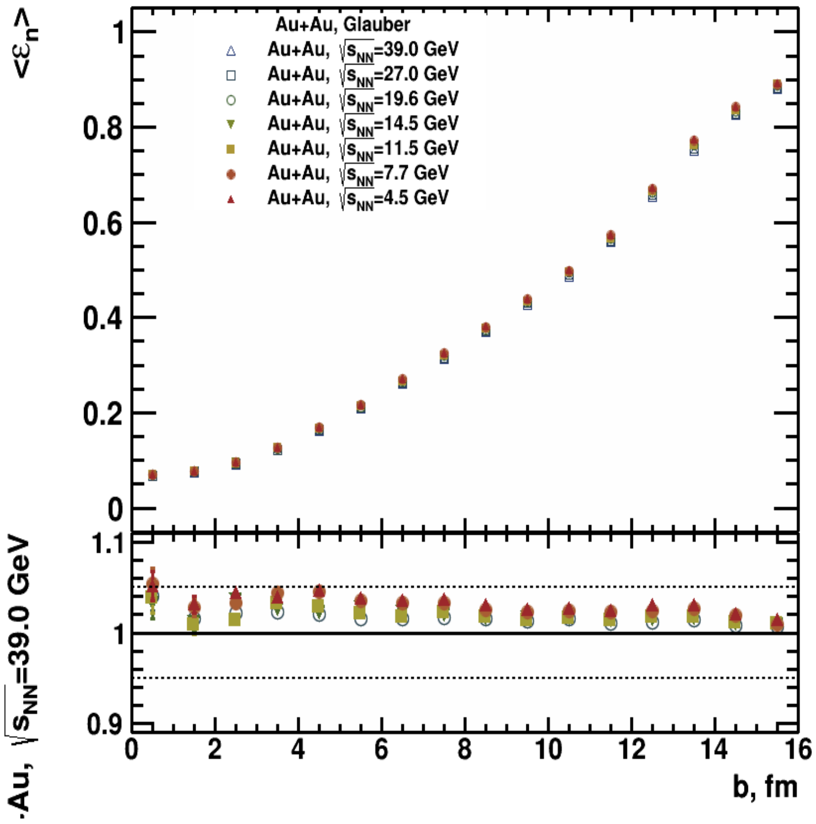
Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

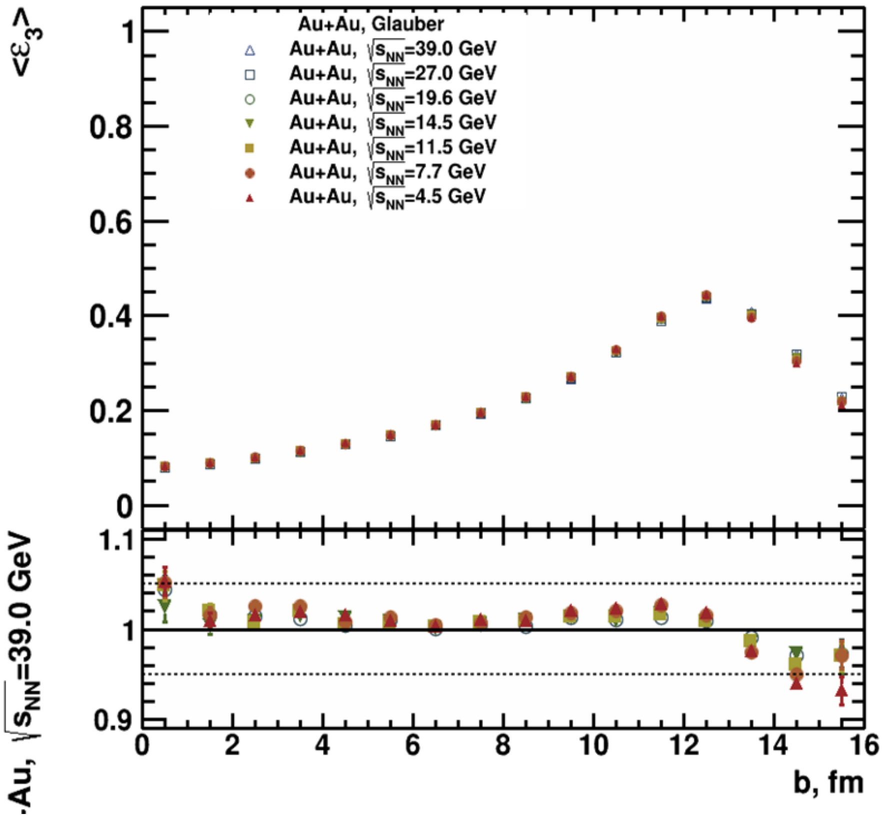
STAR: V_2 for different colliding systems



Phys.Rev.Lett. 122 (2019) 17, 172301

Collision energy dependence: ε_n

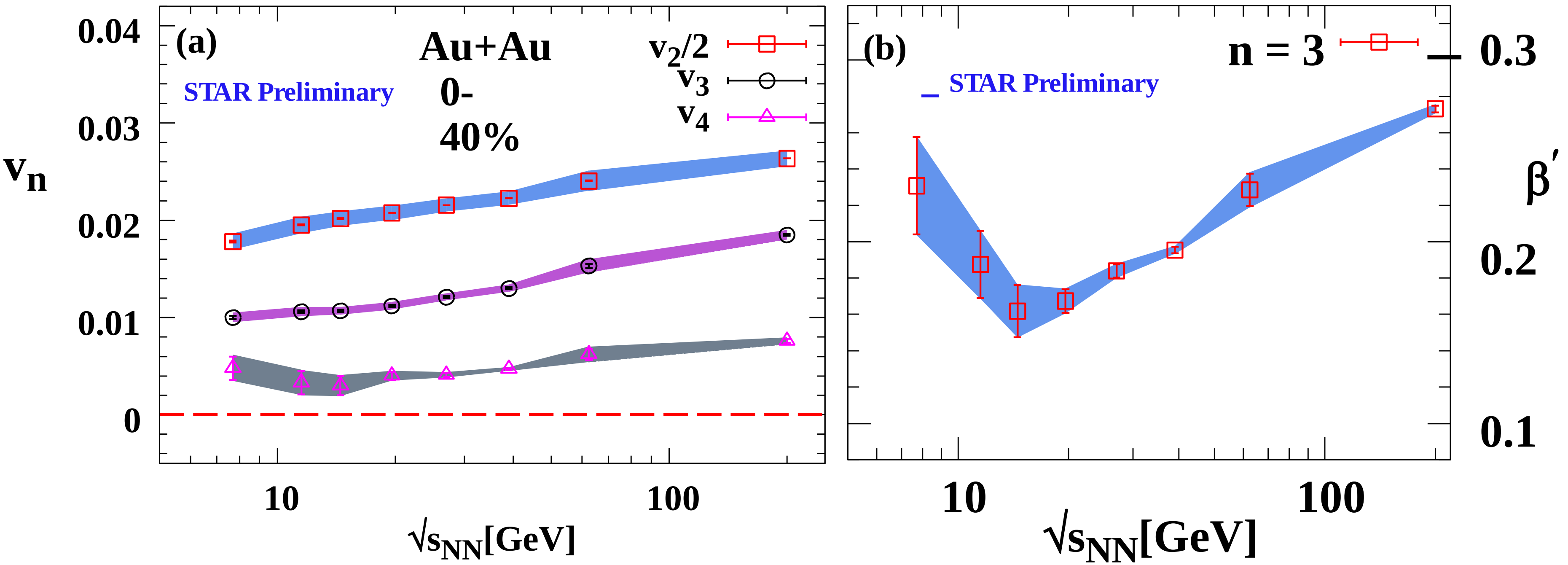




$$\mathrm{VC} = \ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$\mathrm{VC} \propto \frac{\eta}{s}$$

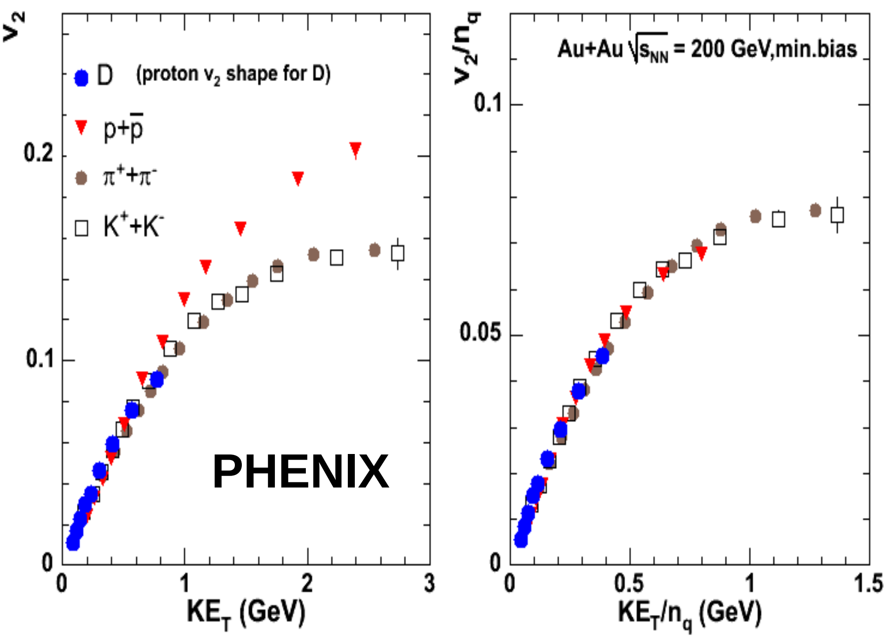
Niseem Magdy, SQM 2016



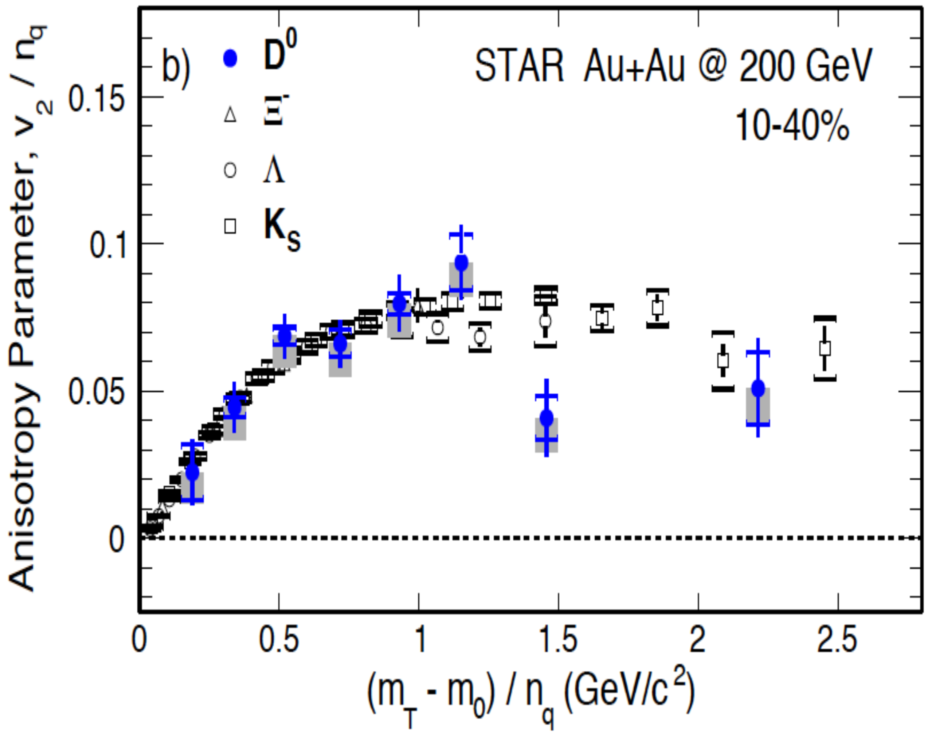
V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (η/s), indicates a non-monotonic behavior as a function of beam energy.

Elliptic flow of D meson in 2006-2017

PoS 2006 (2006) 021

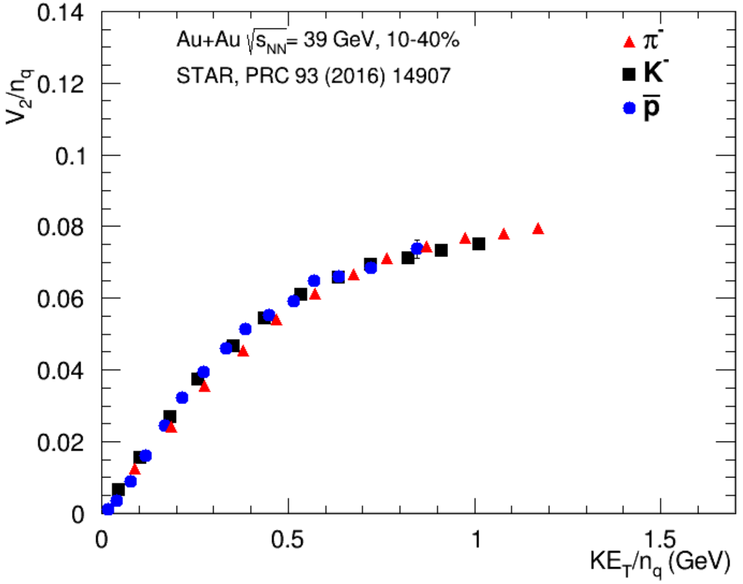


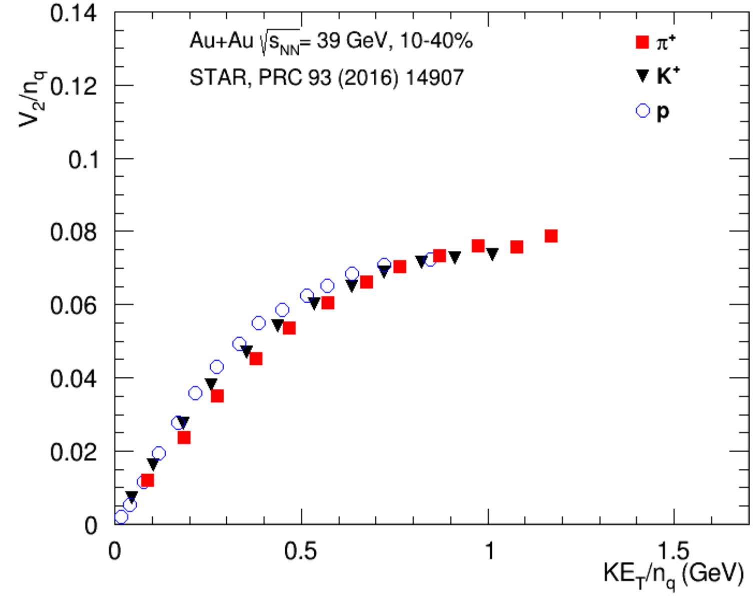
PRL118 (2017) 212301

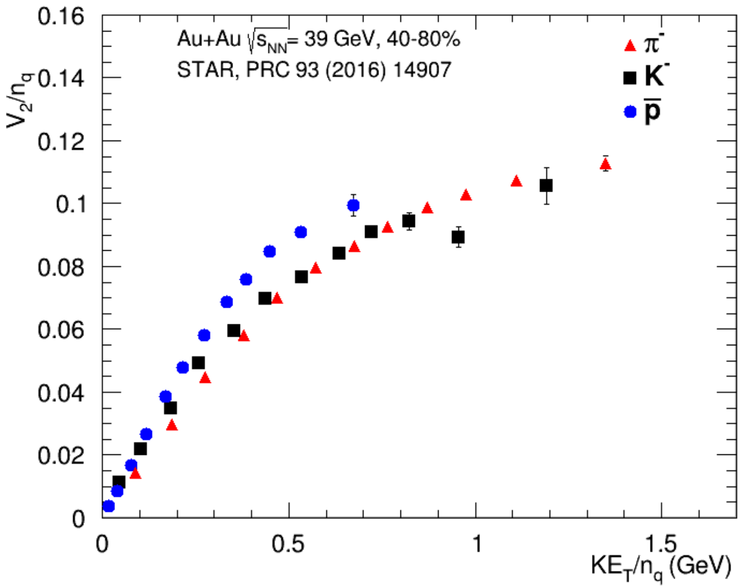


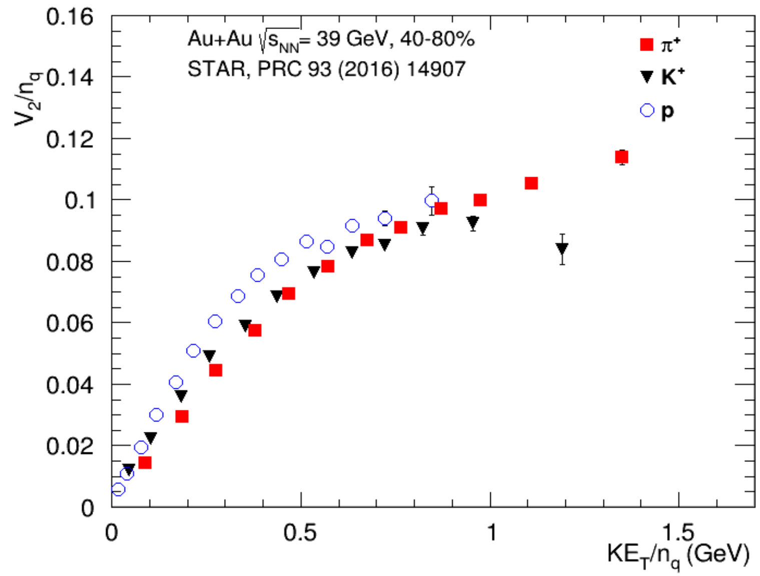
The D meson not only flows, it scales over the measured range

Quality of KE_T / n_q scaling : BES data

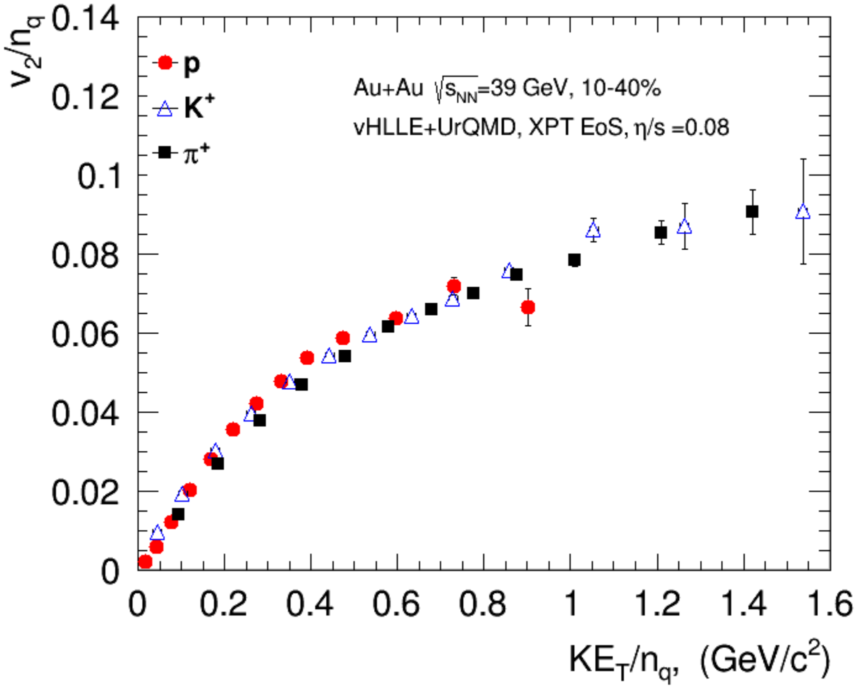


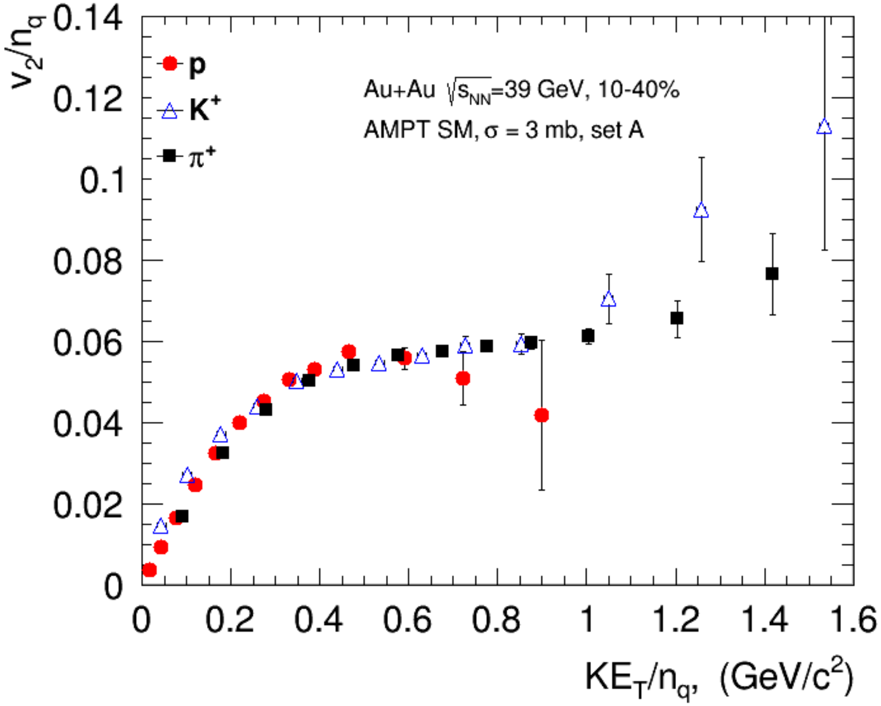






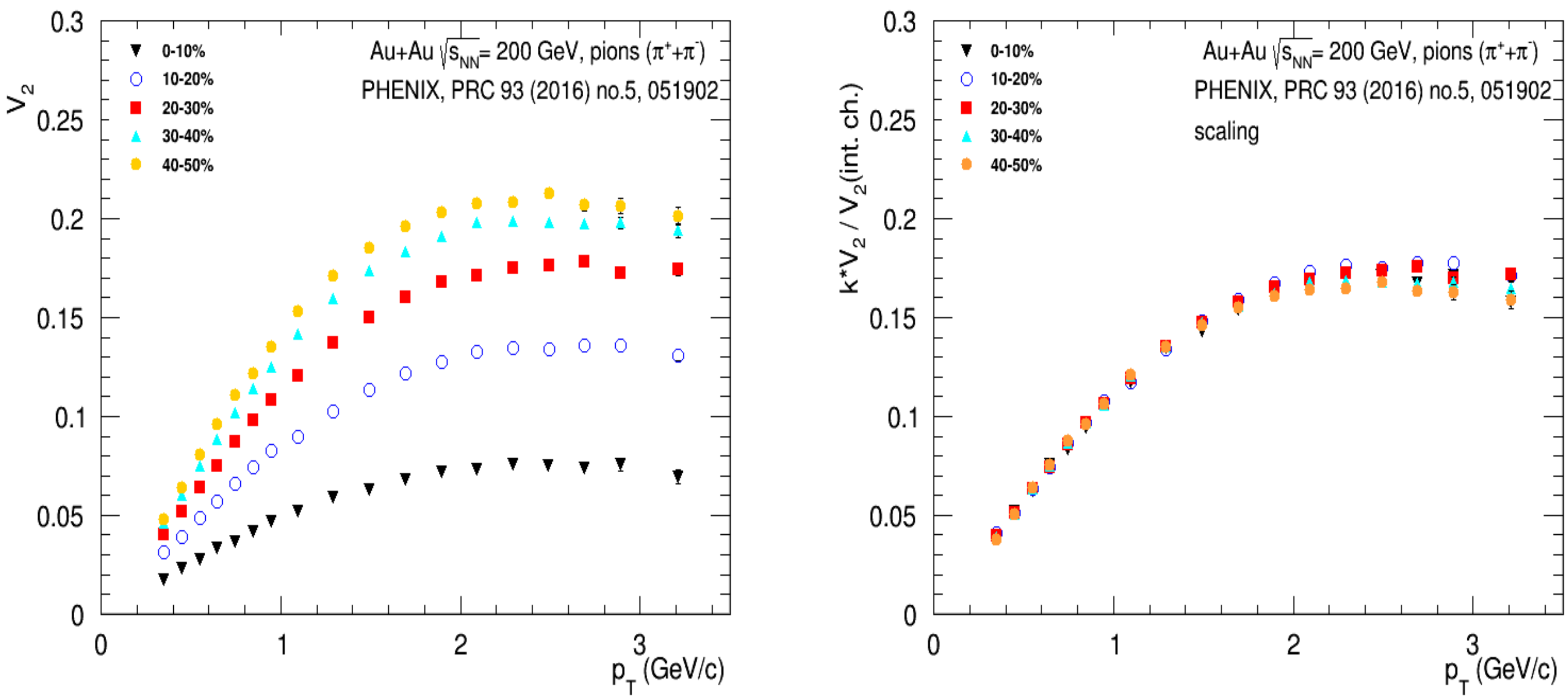
KE_T / n_q scaling : models





V_2 of identified hadrons at top RHIC energy: pions

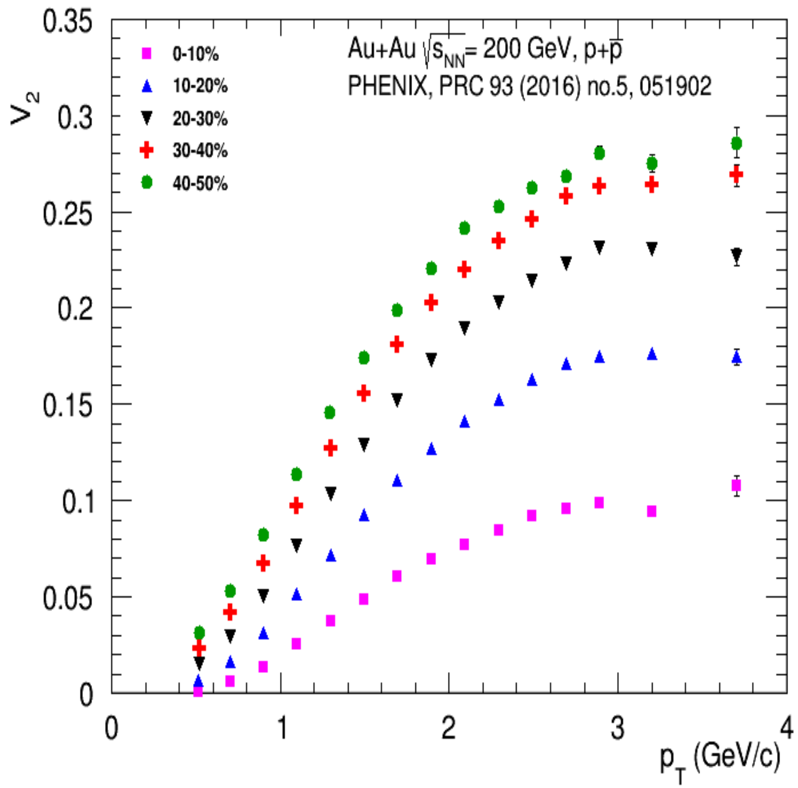
Scaling with integral flow of charged hadrons

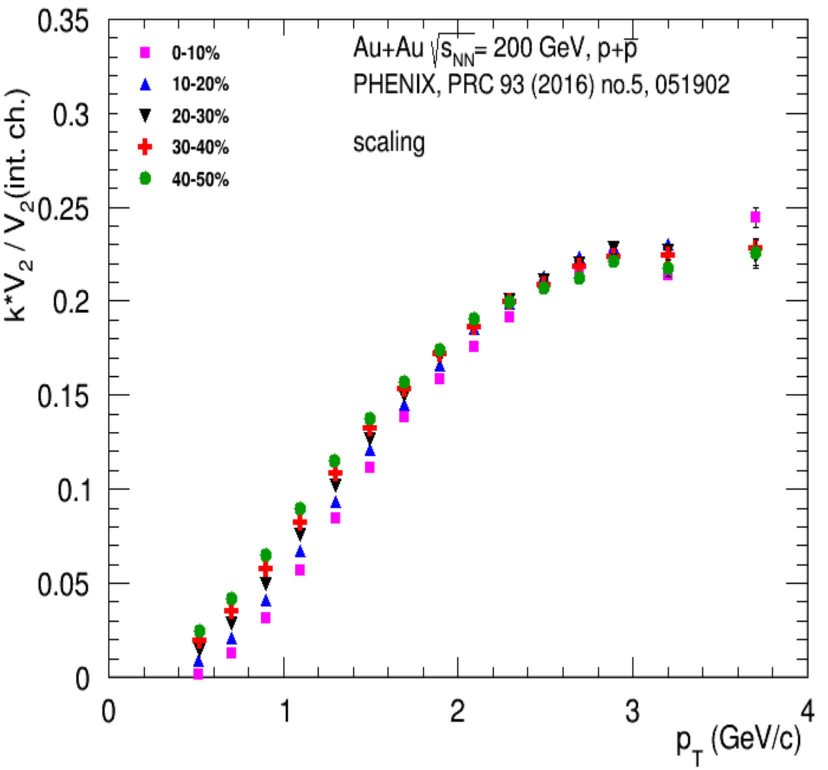


$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)$???

V_2 of identified hadrons at top RHIC energy: protons

Scaling with integral flow of charged hadrons



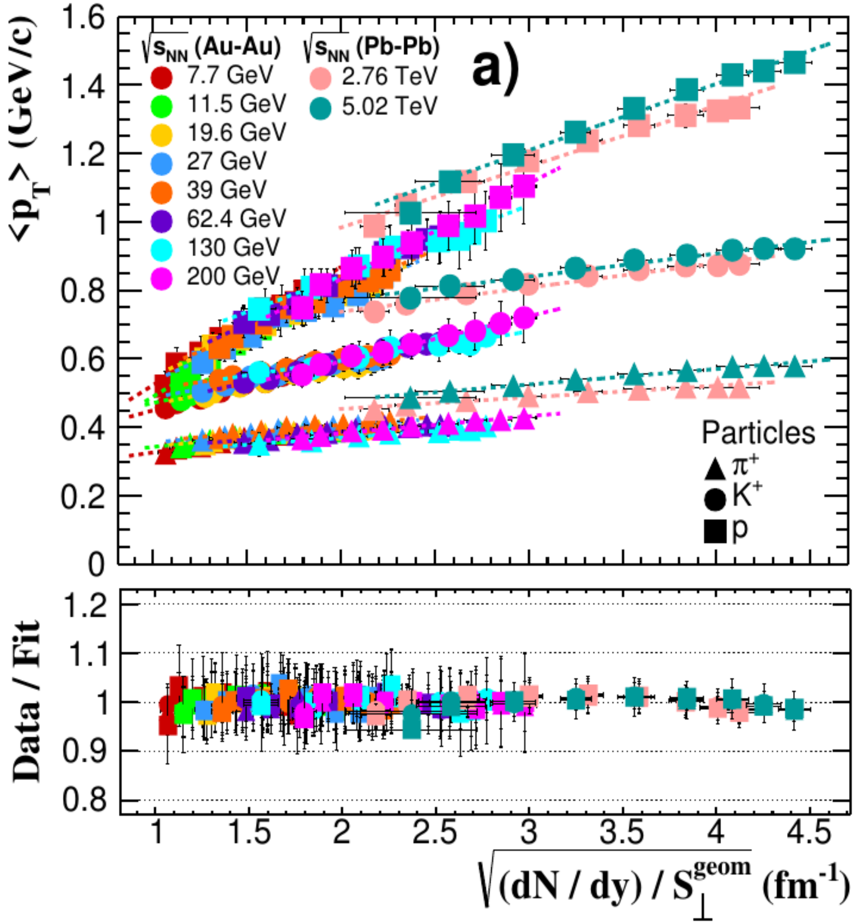


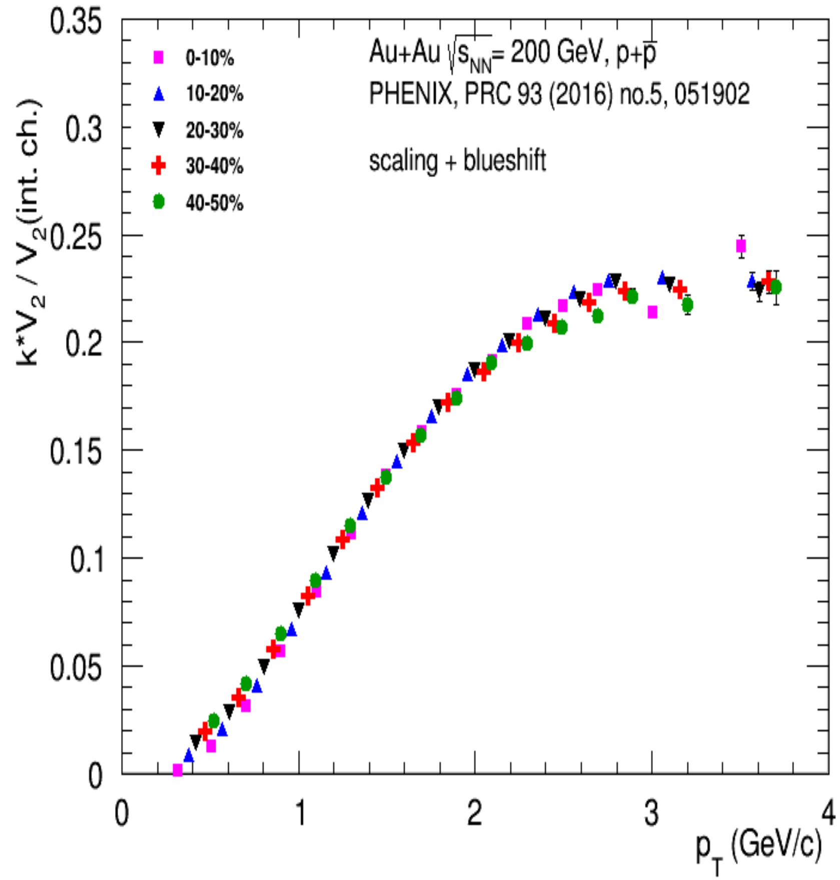
for protons the strong radial flow “blueshifts” the entire flow signal to higher p_T : $p_T \sim p_T^{th} + mc\beta$

V_2 of identified hadrons at top RHIC energy: protons

Use the geometrical scaling to estimate "blue shift" for protons

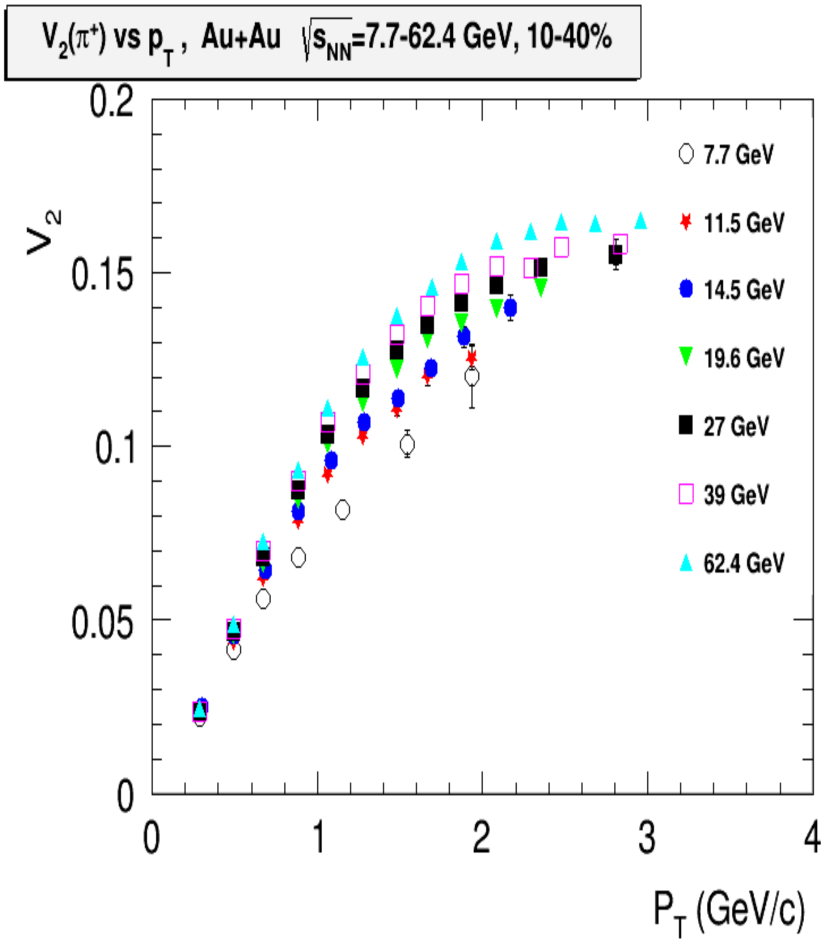
M. Petrovici at el, Phys Rev C 98 (2018)

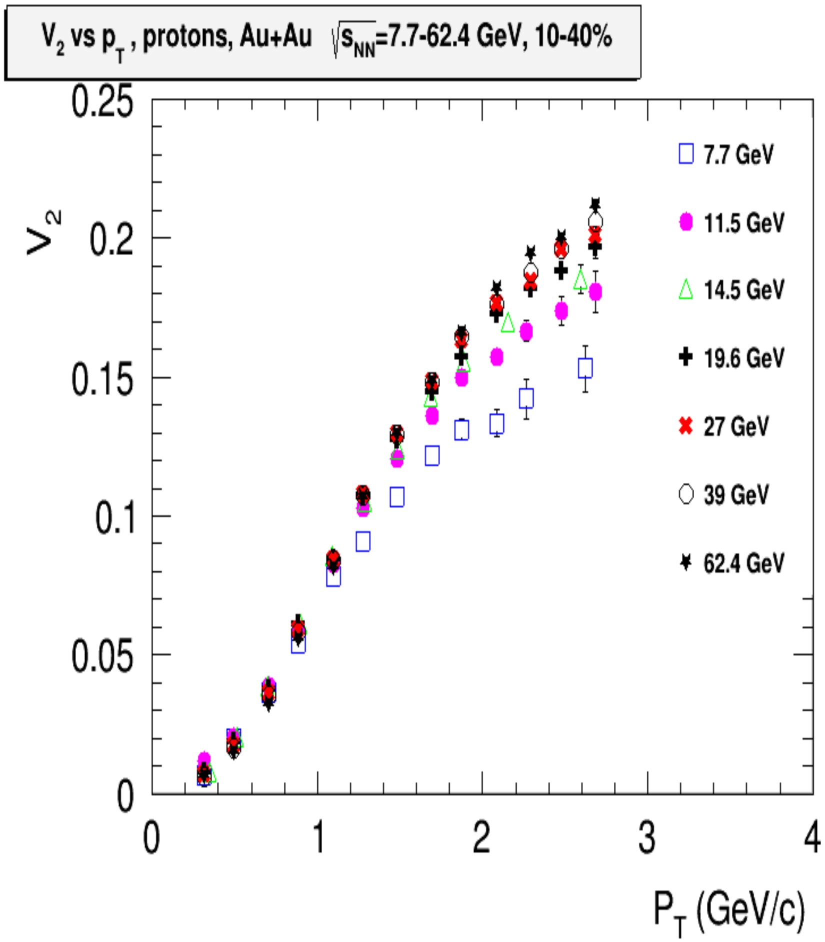




Elliptic Flow at RHIC–BES: $\sqrt{s_{NN}}$ = 7.7-62.4 GeV

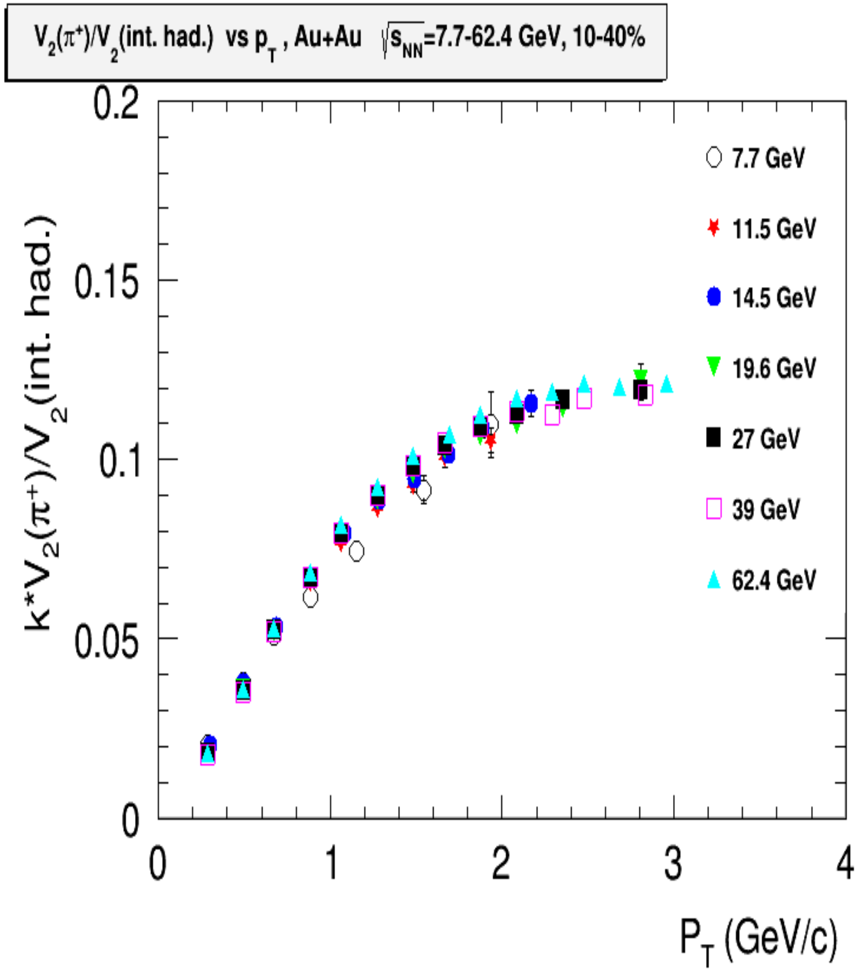
Phys. Rev. C **93** (2016) 14907

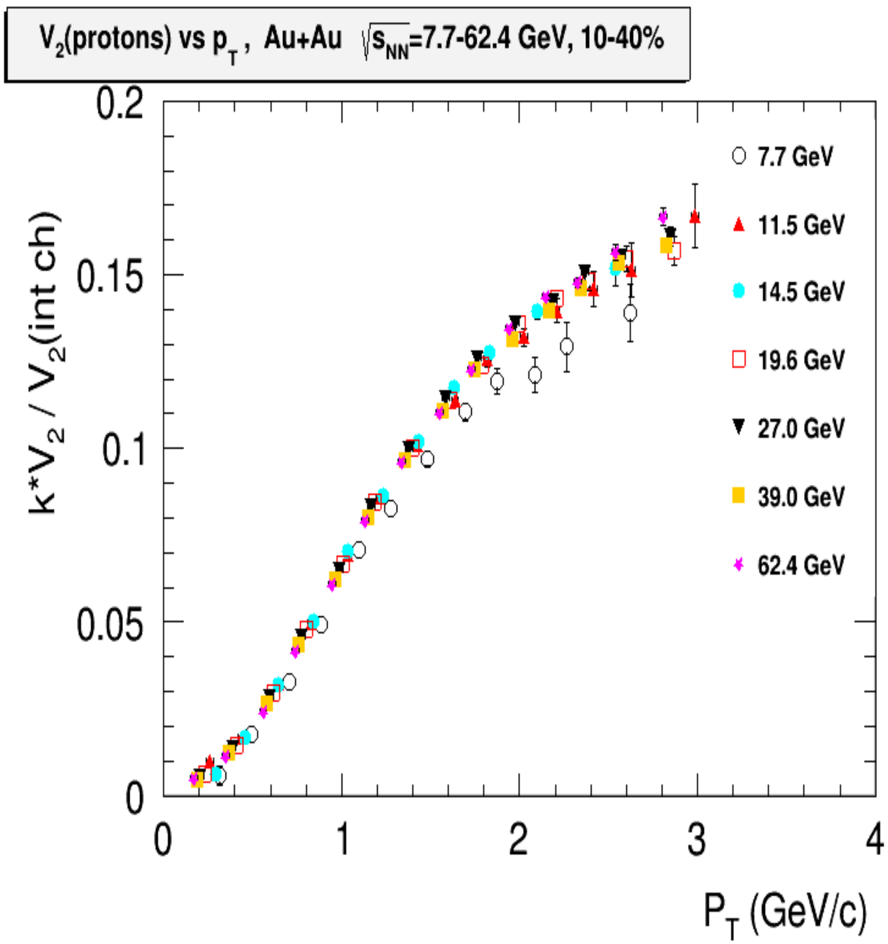




$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

Elliptic Flow at RHIC–BES: $\sqrt{s_{NN}}$ = 7.7-62.4 GeV



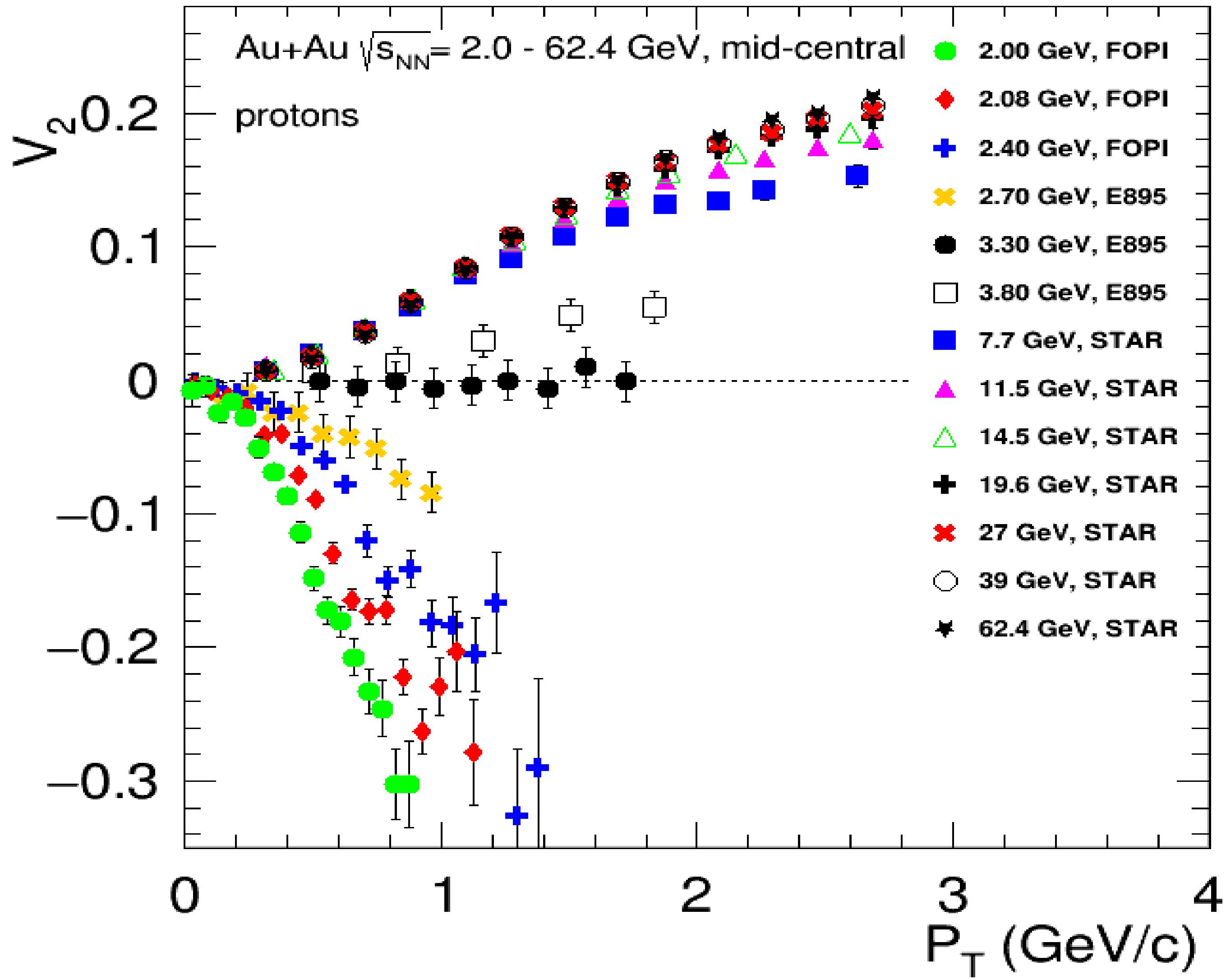


$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T)???$$

Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

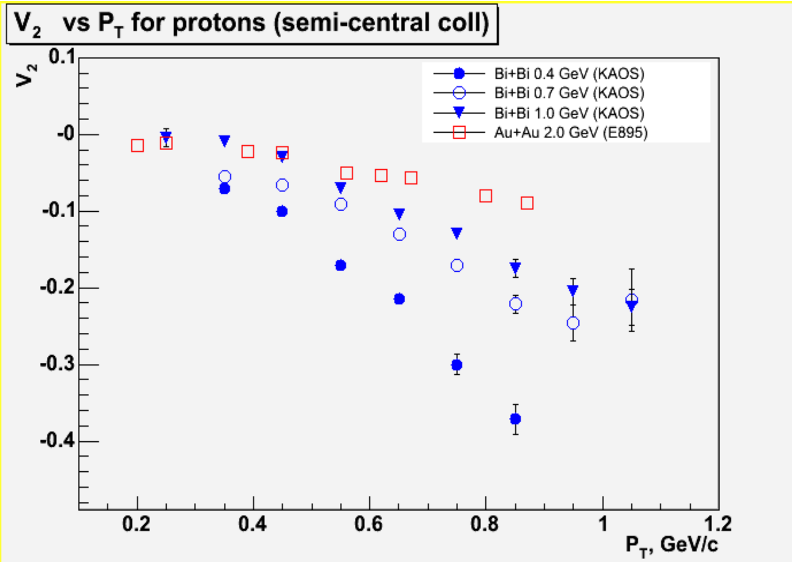
FOPI (15-29%)
E895 (12-25%)
STAR (10-40%)

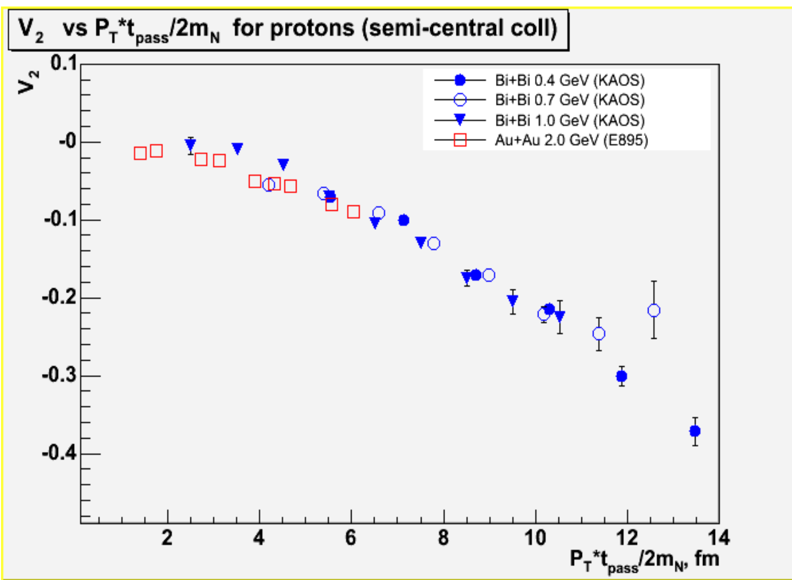


High precision differential measurements of anisotropic flow?

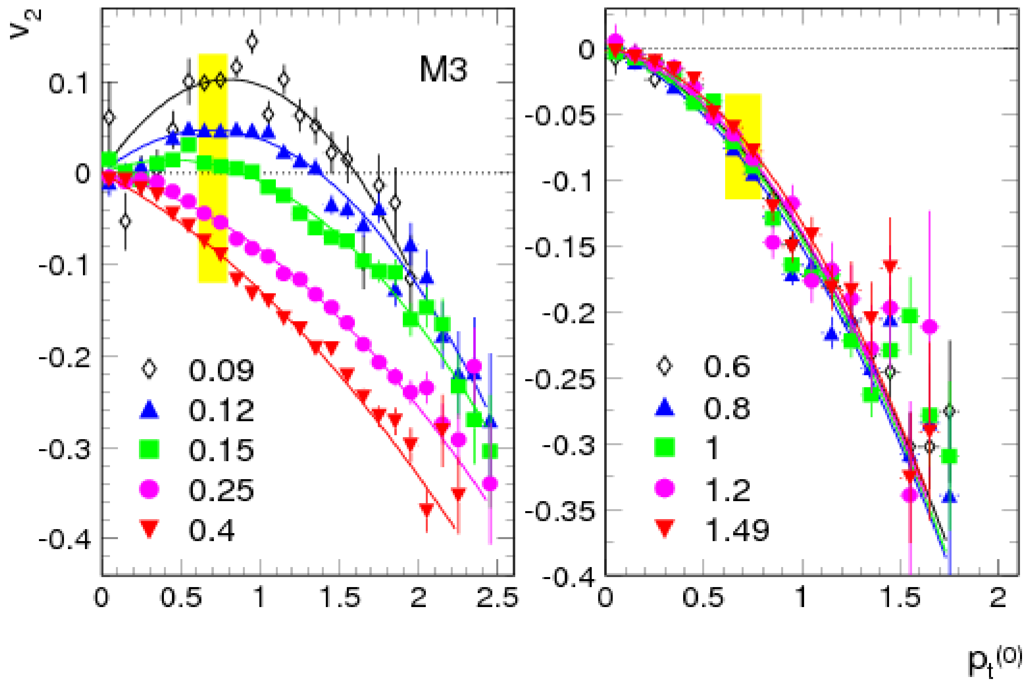
v_2 Flow at SIS-AGS: scaling relations

(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. .

Conclusions and Perspectives

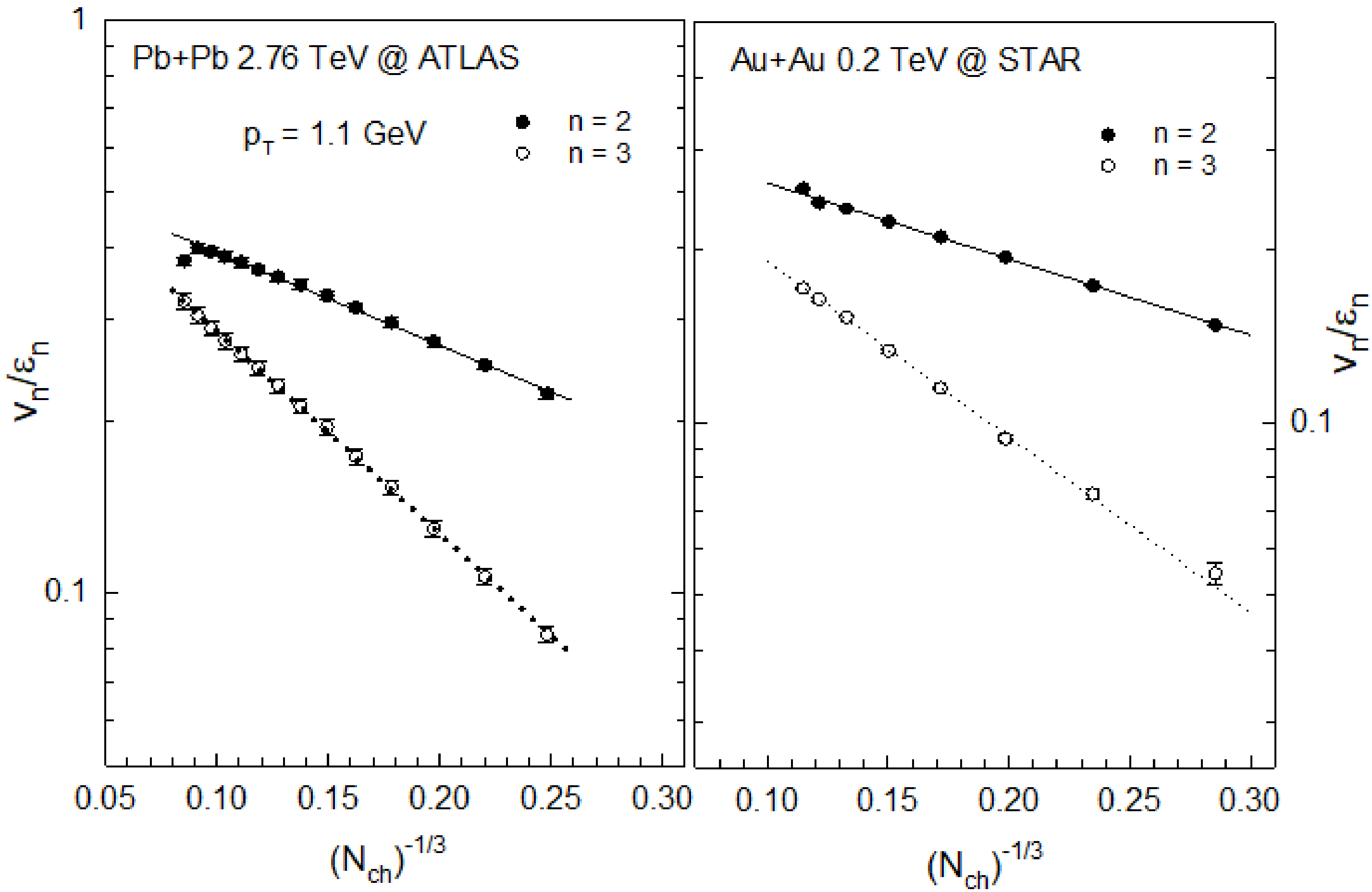
- **Anisotropic flow measurements provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc. Scaling relations help to understand the physics of the process.**

- **BM@N/NICA/FAIR energies are very interesting: transition between hadronic and partonic matter.**

Acoustic Scaling –

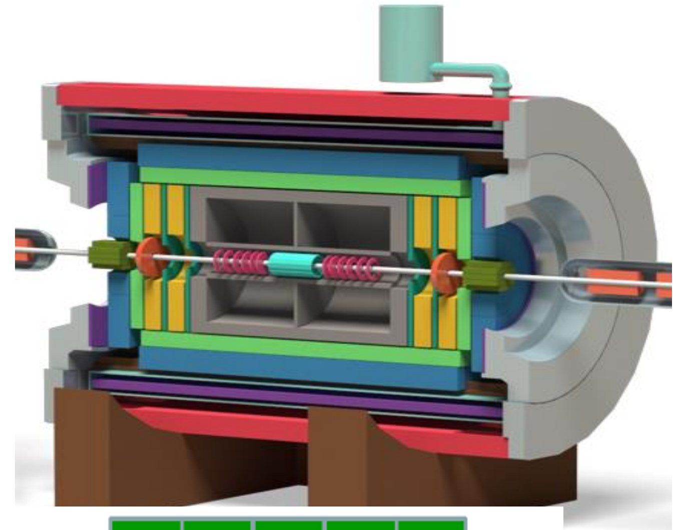
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

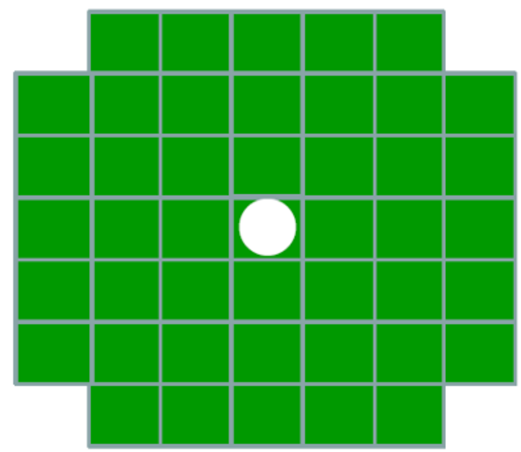
$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



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

Flow performance study for FHCAL TDR (2018)





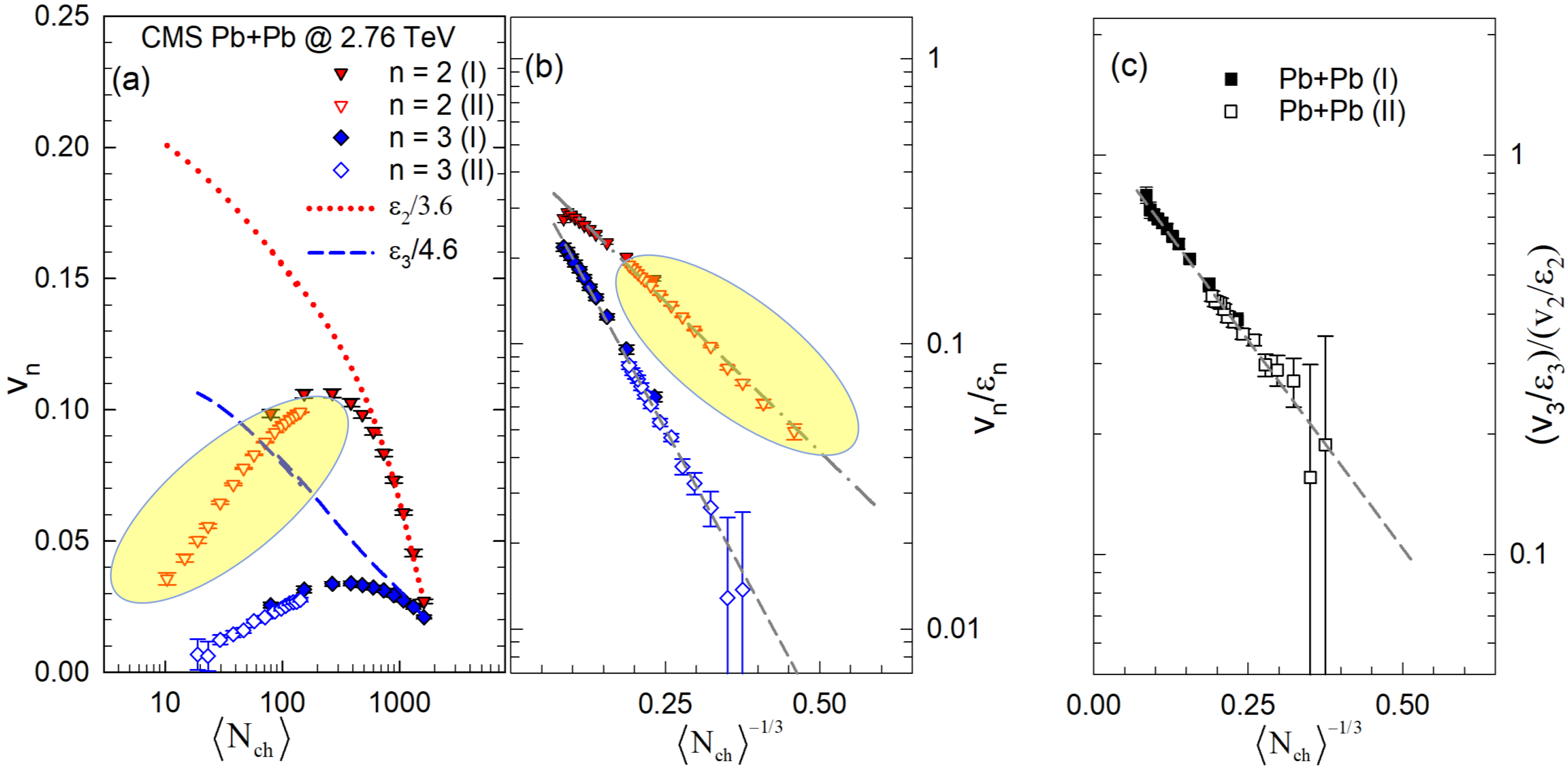
FHCal coverage:
$2.2<|\eta|< 4.8$

http://mpd.jinr.ru/doc/mpd-tdr/

Acoustic Scaling - RT

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

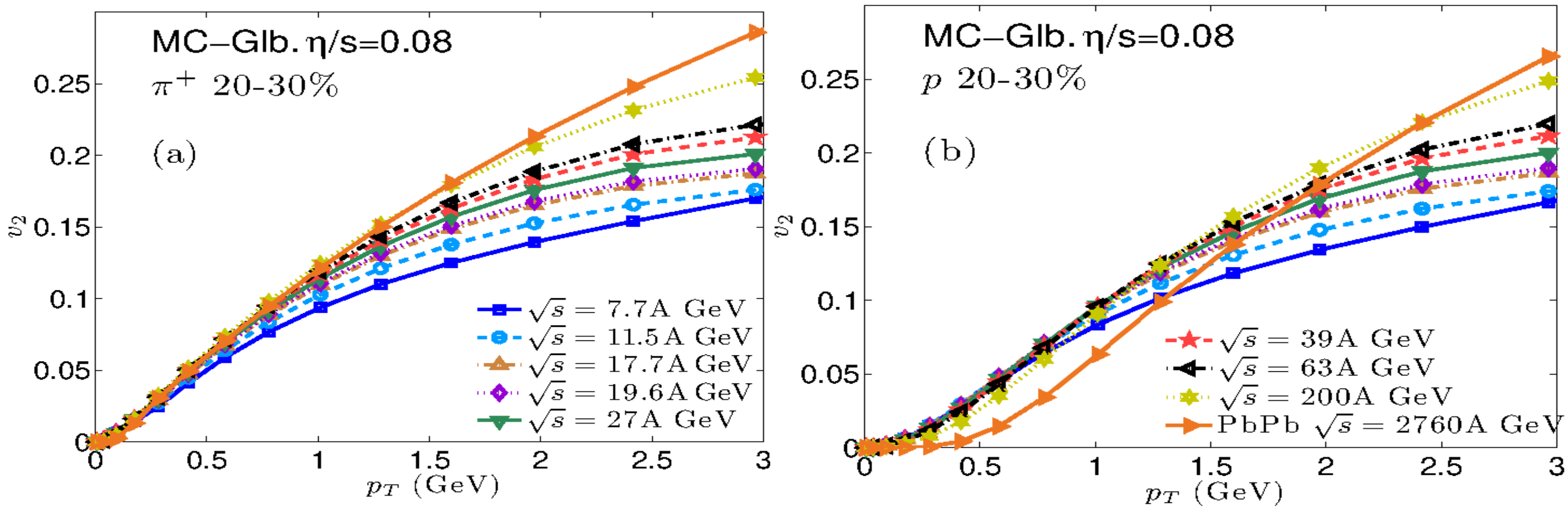
R.A. Lacey et al Phys. Rev. C **98**, 031901(R), 2018



- ✓ Characteristic 1/(RT) viscous damping validated
- ✓ Clear pattern for n^2 dependence of viscous attenuation
- ✓ Viscous damping supersedes the influence of eccentricity for "small" systems

v_2 of identified hadrons from RHIC to LHC (viscous hydrodynamics)

Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations

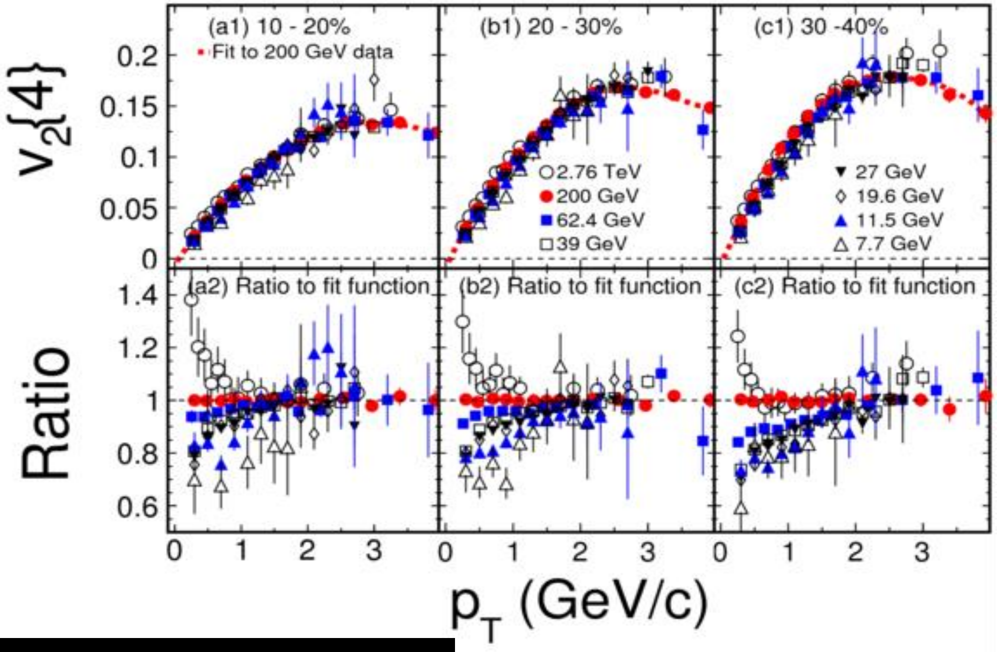


✓ **For pions $v_2(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_2(p_T)$.**

✓ For protons the strong radial flow "blueshifts" the entire flow signal to higher p_T .

Beam Energy Dependence of Elliptic Flow (v_2)

STAR: Phys. Rev. C 86 (2012) 54908



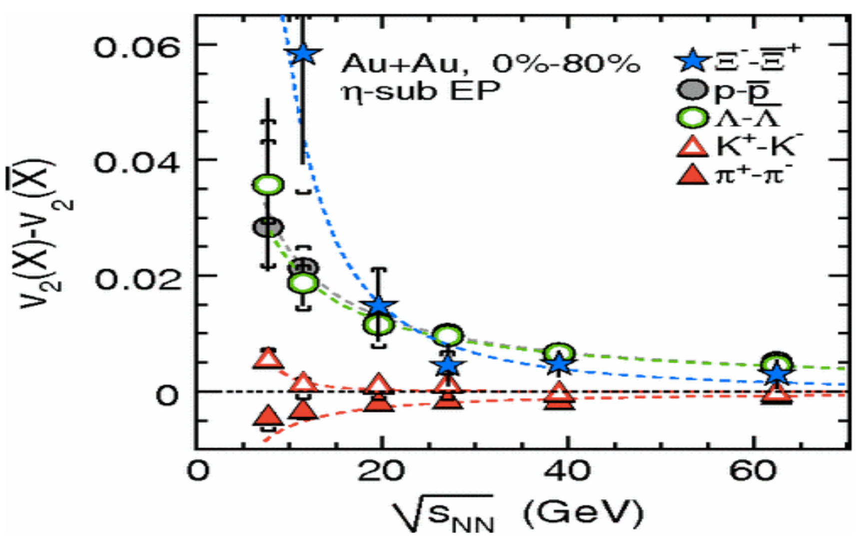
Surprisingly consistent as the energy changes by a factor ~400

Initial energy density changes by nearly a factor of 10

No evidence from v2 of charged hadrons for a turn off of the QGP

How sensitive is v_2 to QGP?

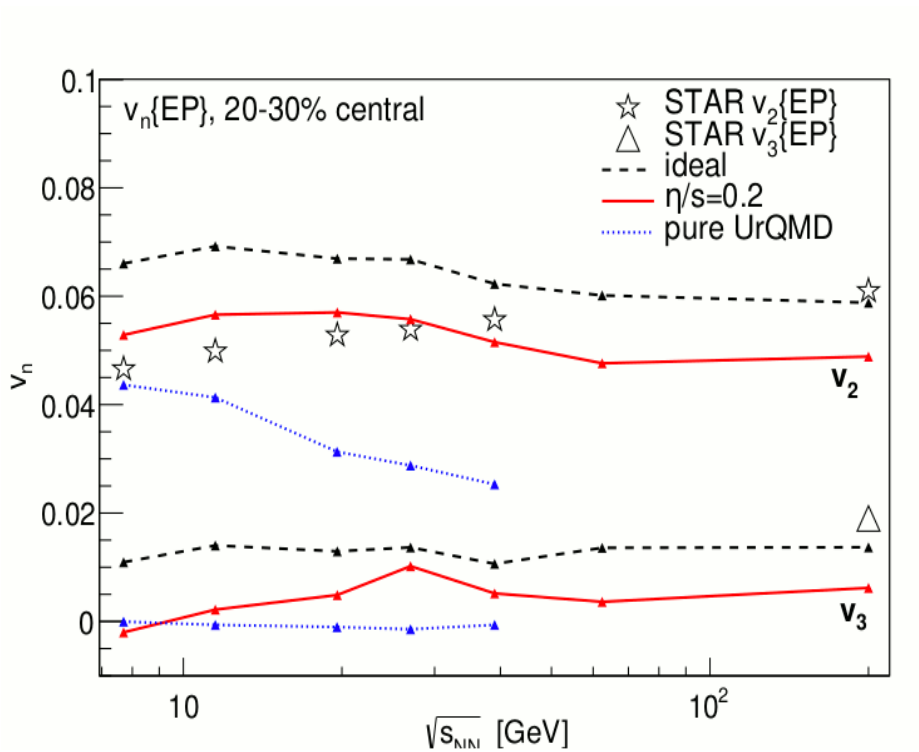
Phys. Rev. Lett. 110, 142301 (2013)

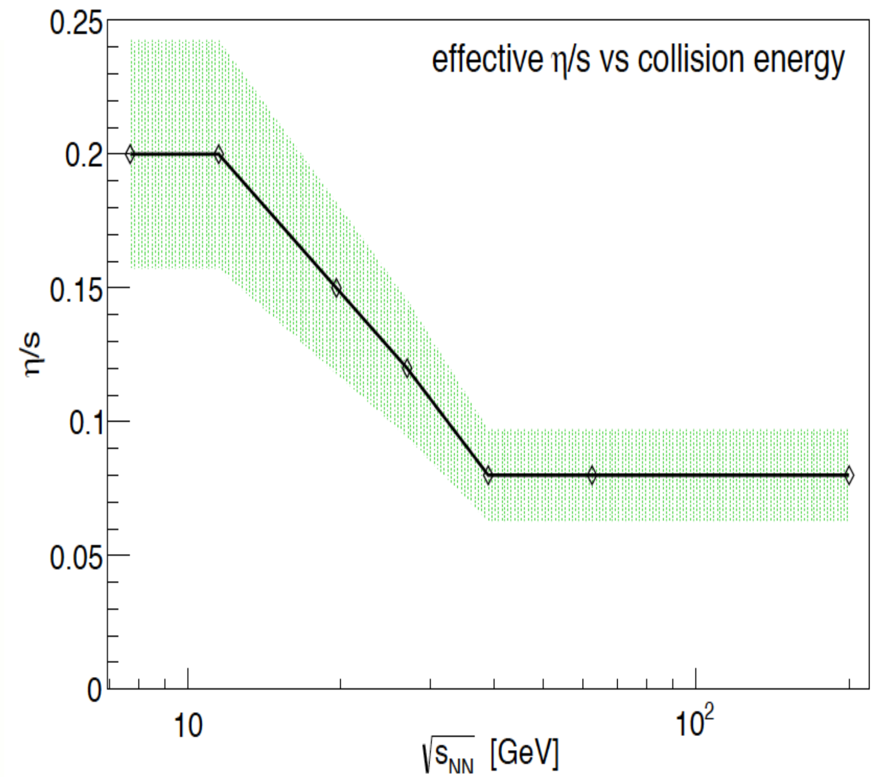


Substantial particle-antiparticle split at lower energies

Elliptic and triangular flow at RHIC BES

Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901





Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears