Исследование зависимости коллективных потоков в ядро-ядерных столкновений от энергии с помощью скейлинговых соотношений

Аркадий Тараненко[1,2]

1. *НИЯУ МИФИ*
2. *ЛФВЭ ОИЯИ*

Сессия-конференция секции ядерной физик ОФН РАН, посвященная 70-летию В.А. Рубакова
Москва, Президиум РАН, 17-21 февраля 2025

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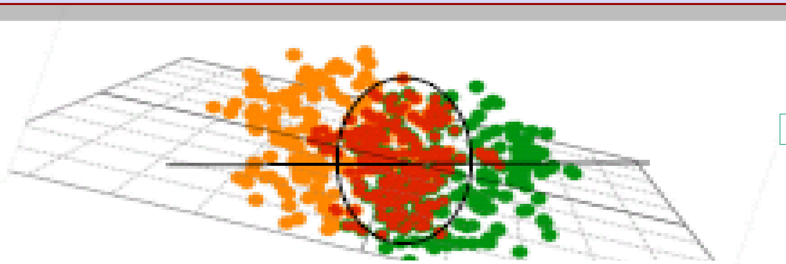
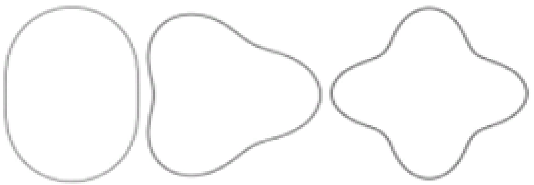
Outline

- Introduction
- Scaling relations for anisotropic flow at RHIC
- Scaling relations for anisotropic flow at NICA
- Summary and outlook

Anisotropic Flow at RHIC-LHC



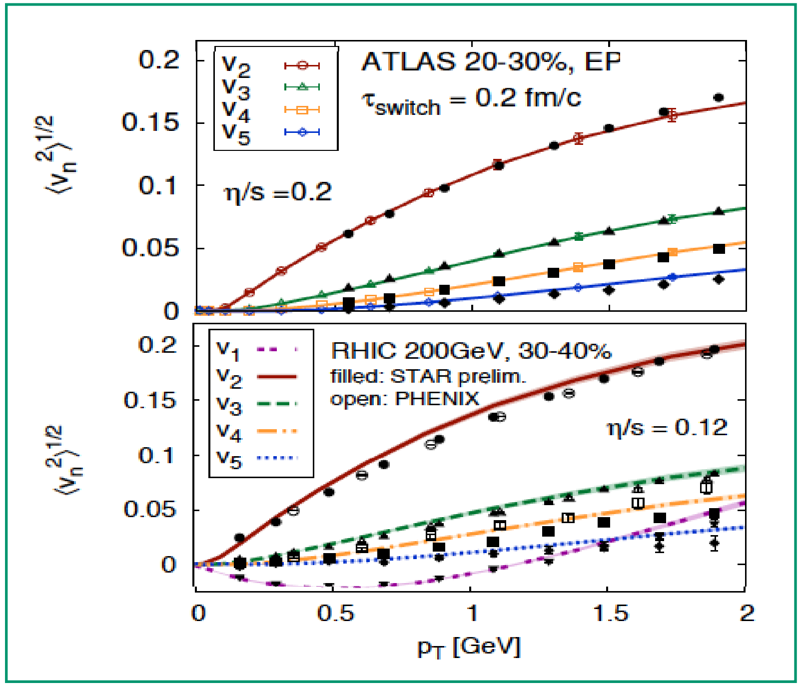


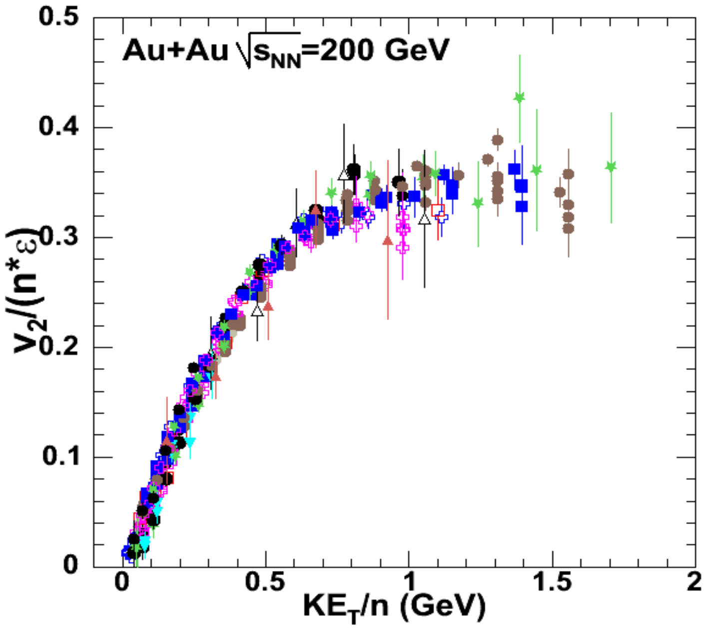
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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

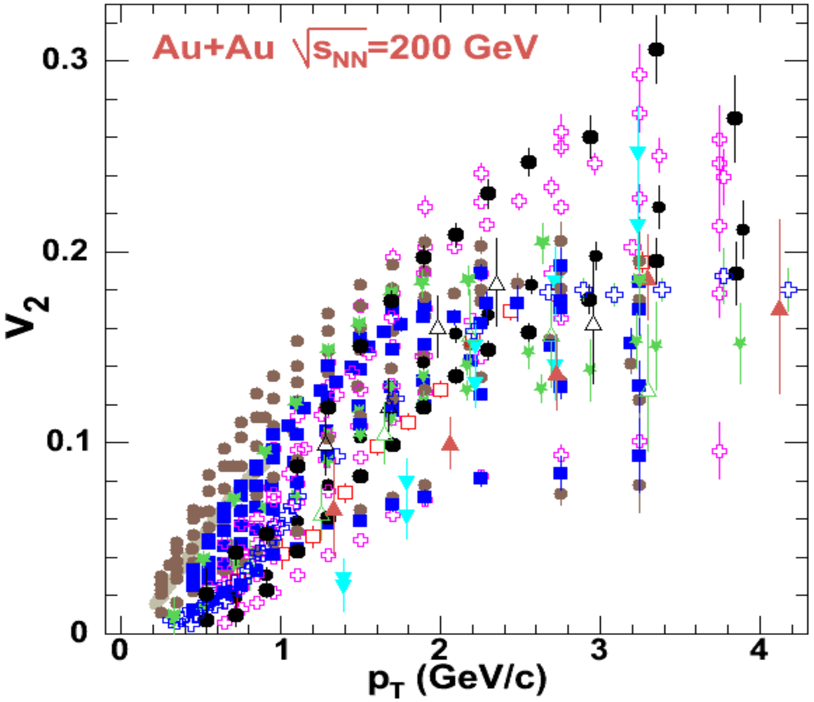
Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

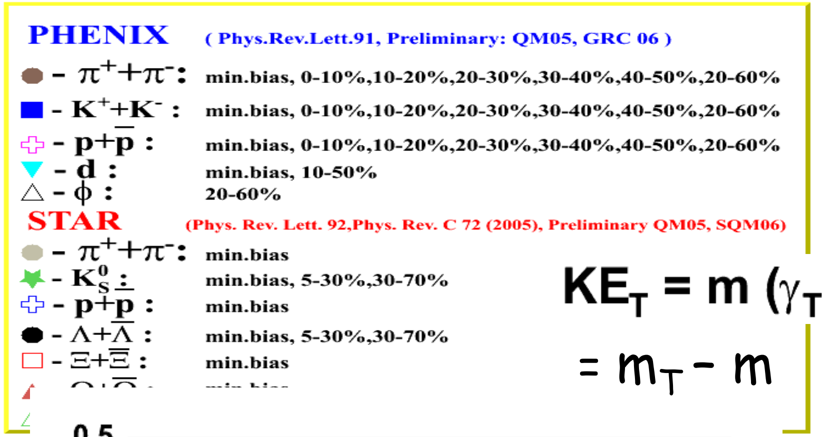




Anisotropic Flow at RHIC – scaling relations

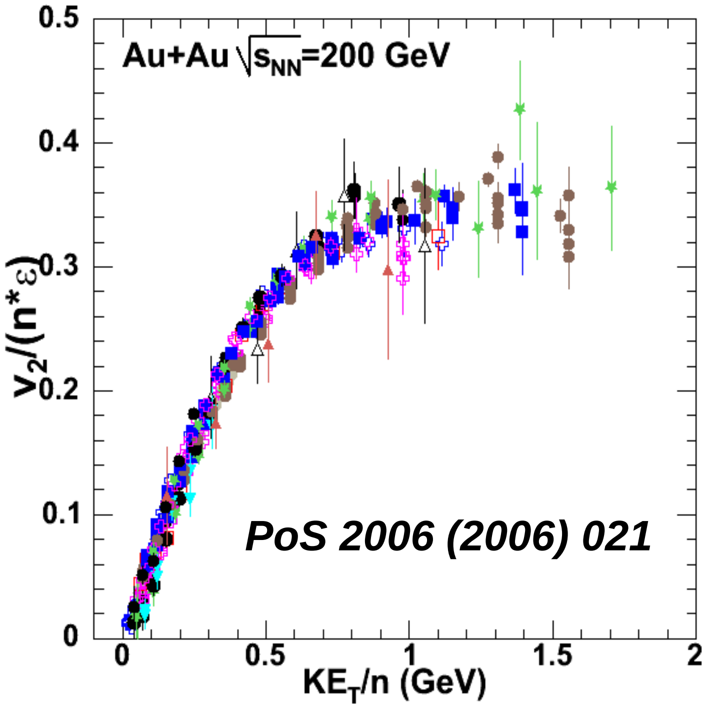
Significant part of flow at RHIC developed at partonic level

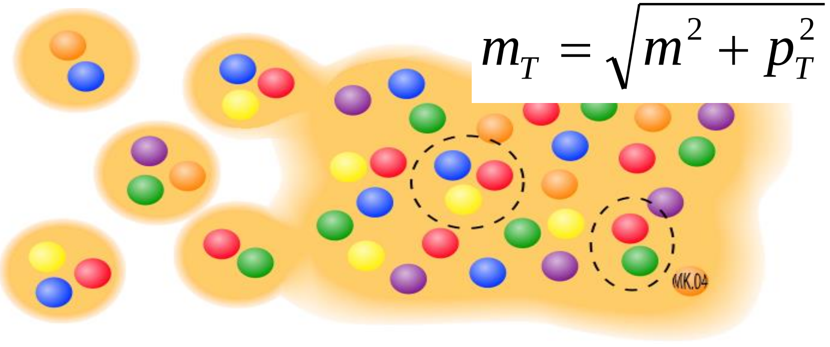




$KE_T = m(\gamma_T - 1)$

$= m_T - m$



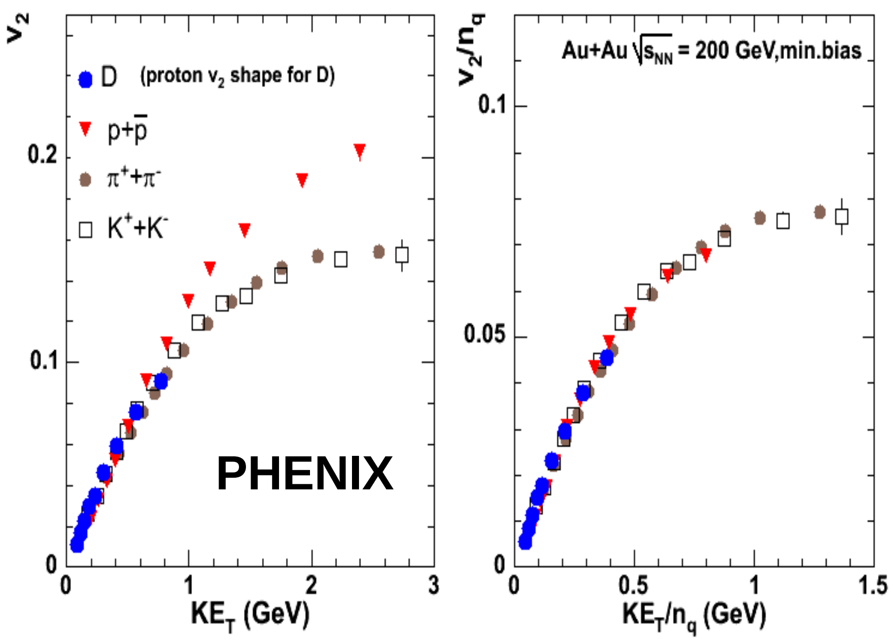


$$m_T = \sqrt{m^2 + p_T^2}$$

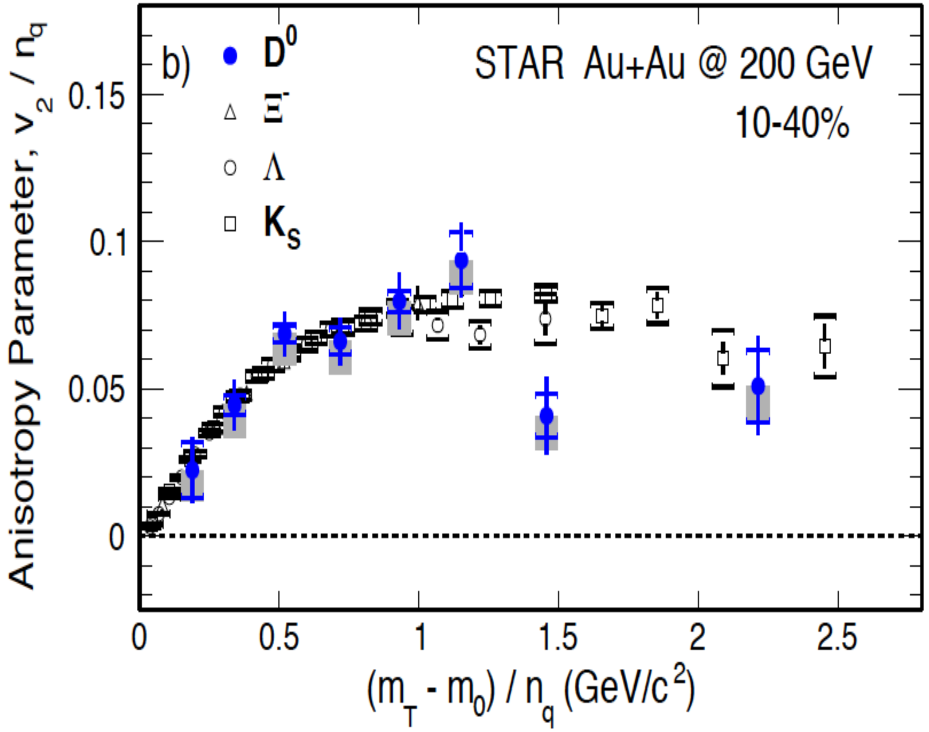
n=2 for mesons and n=3 for baryons

Elliptic flow of D meson in 2006-2017

PoS 2006 (2006) 021



STAR, PRL118 (2017) 212301

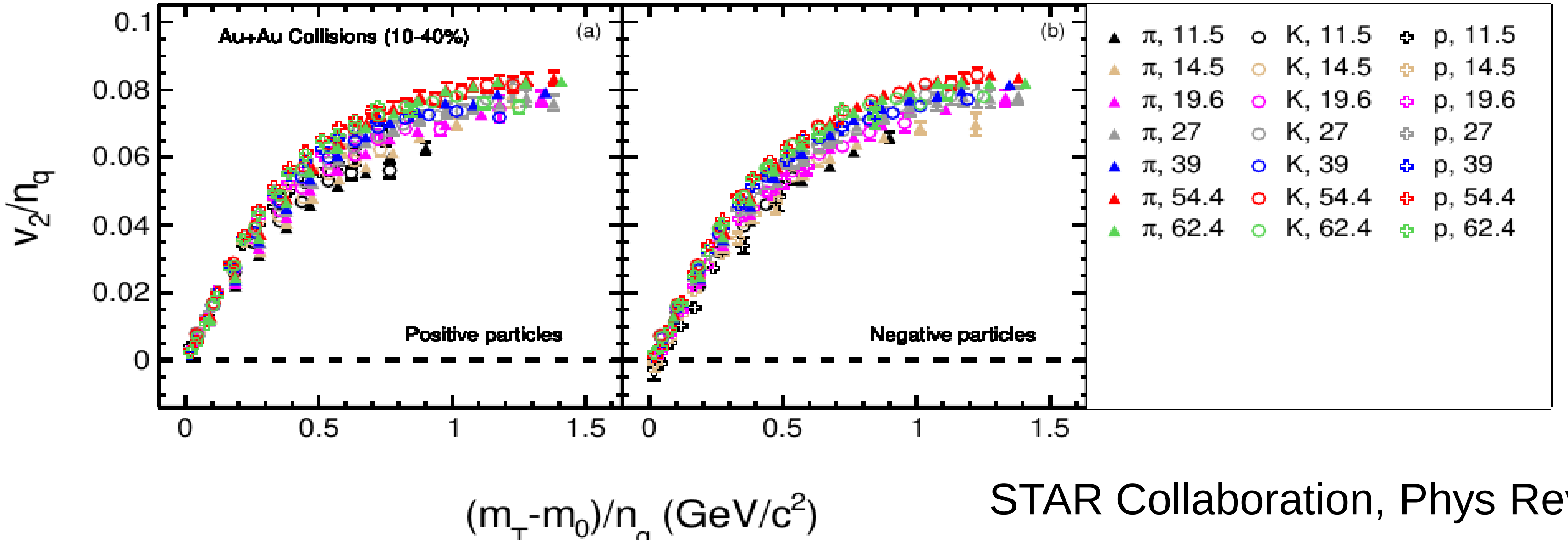


The D meson not only flows, it scales over the measured range

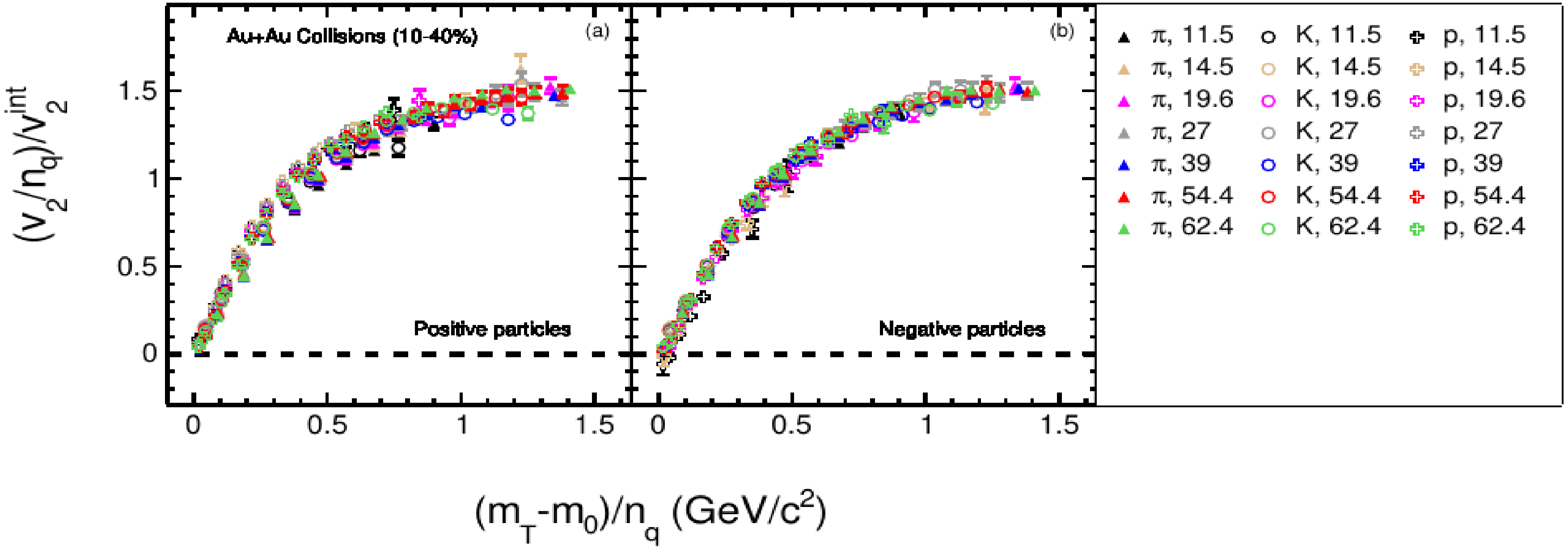
Significant part of flow at RHIC developed at partonic level

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

Elliptic flow from STAR BES program

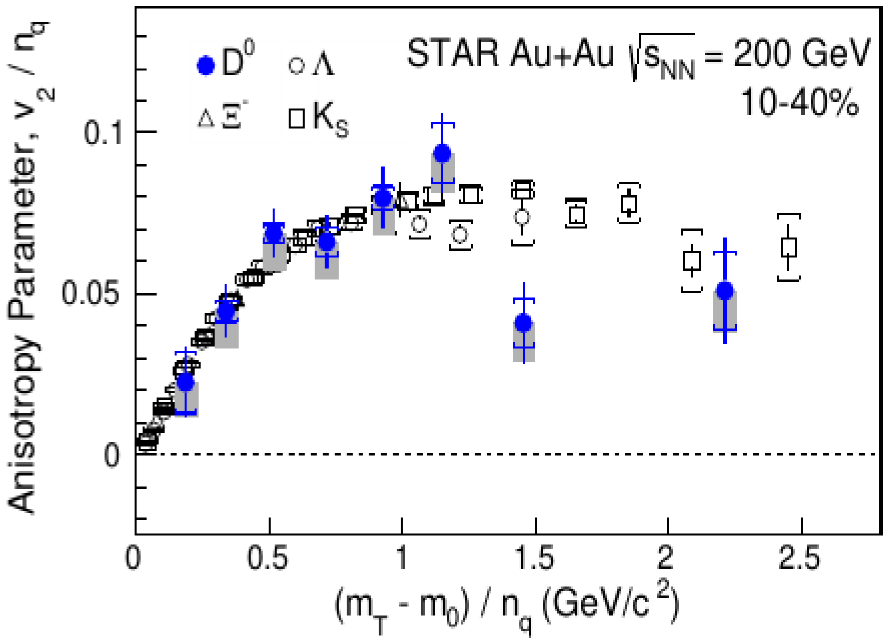


STAR Collaboration, Phys Rev C93, 14907 (2016)

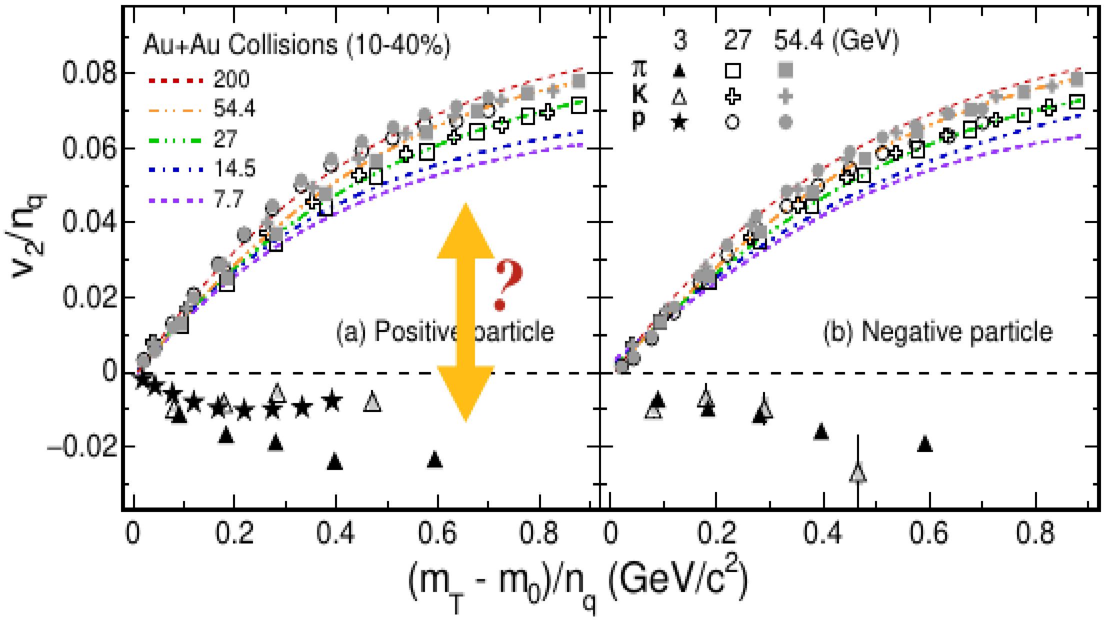


Elliptic flow from STAR BES program

STAR Collaboration, Phys. Rev. Lett. 118, 212301 (2017)



STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)



1) 200 GeV: Partonic collectivity

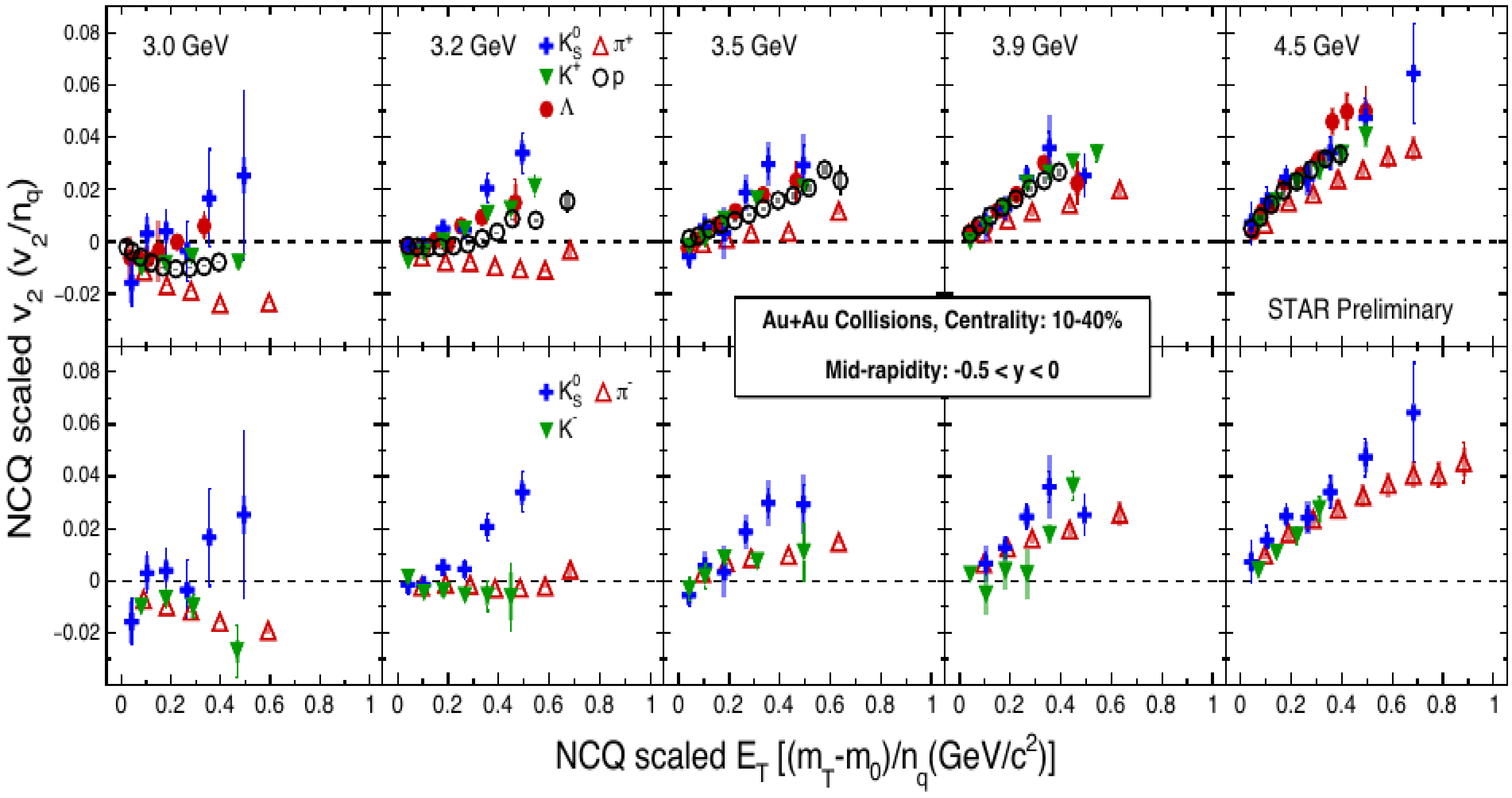
2) 3.0 GeV: Hadronic interaction dominates

3) Change of degree of freedom: 3.0 → 7.7 GeV ?

Elliptic flow from STAR BES program

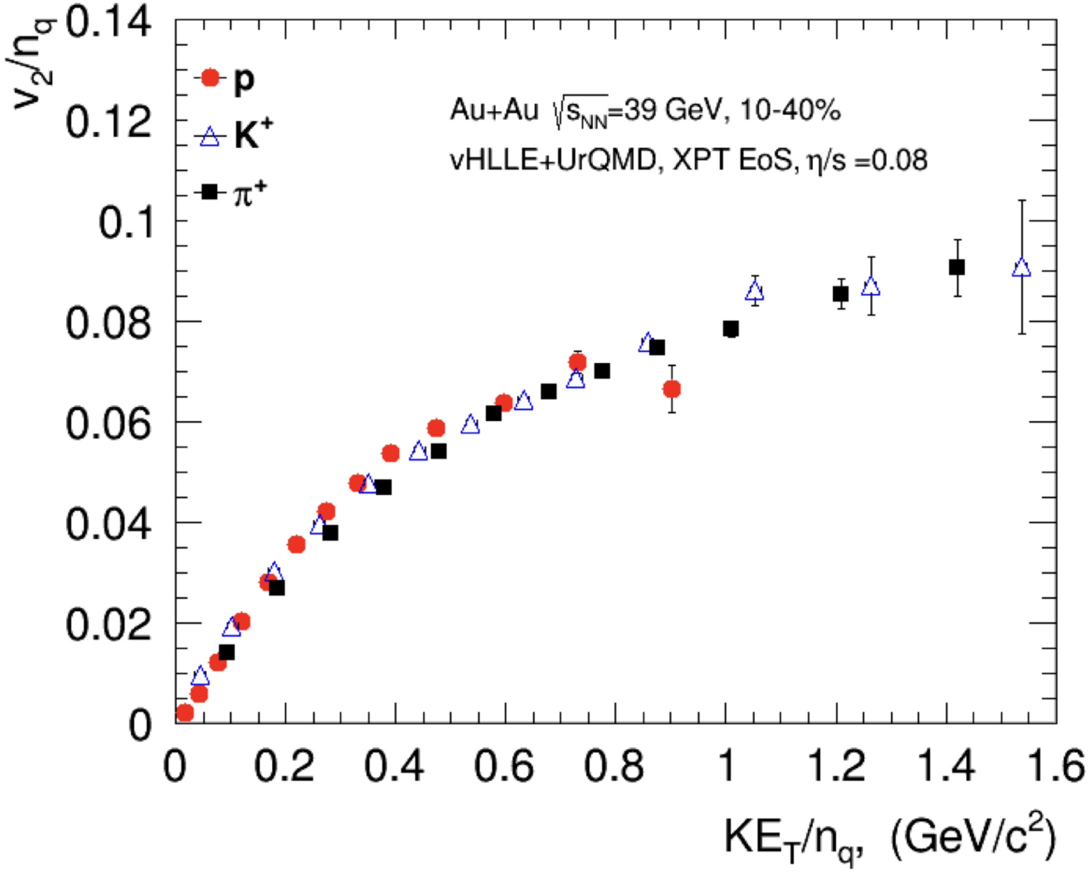
STAR Flow talk at CPOD2024

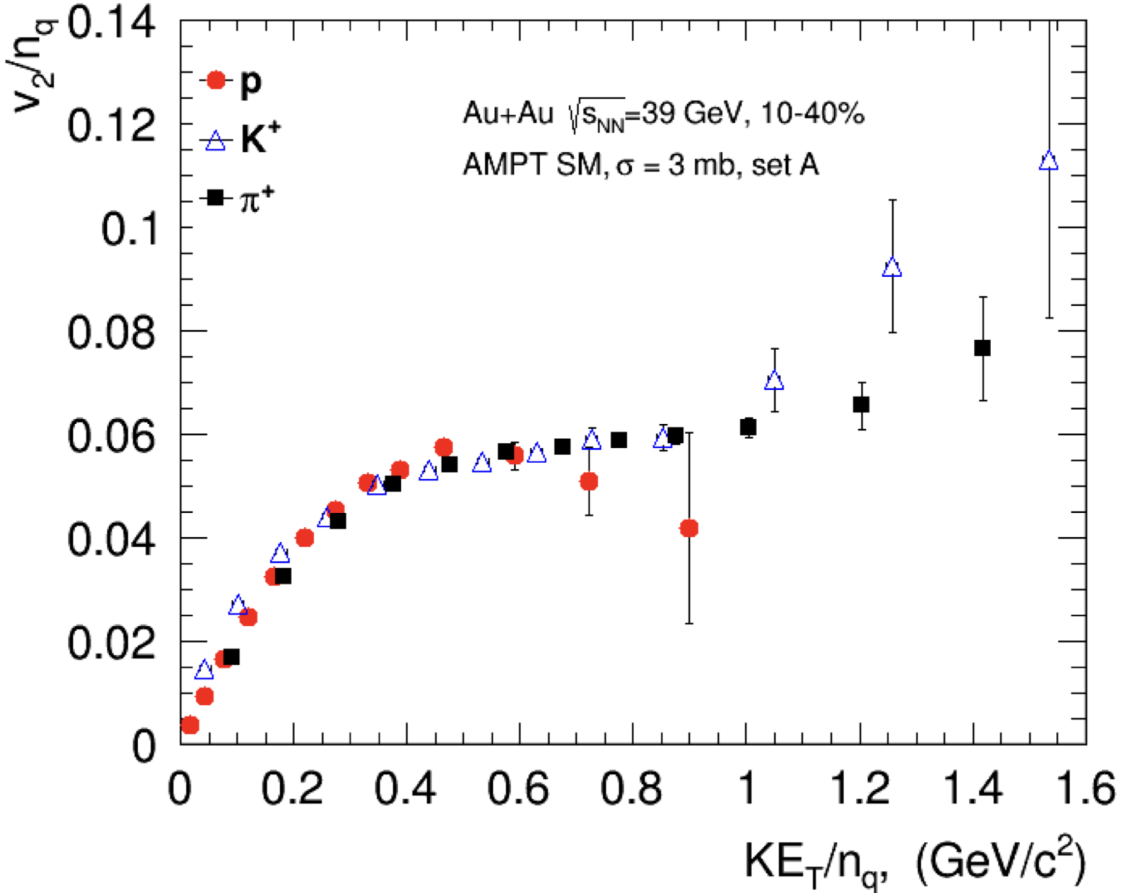
Hadronic interaction



Partonic collectivity

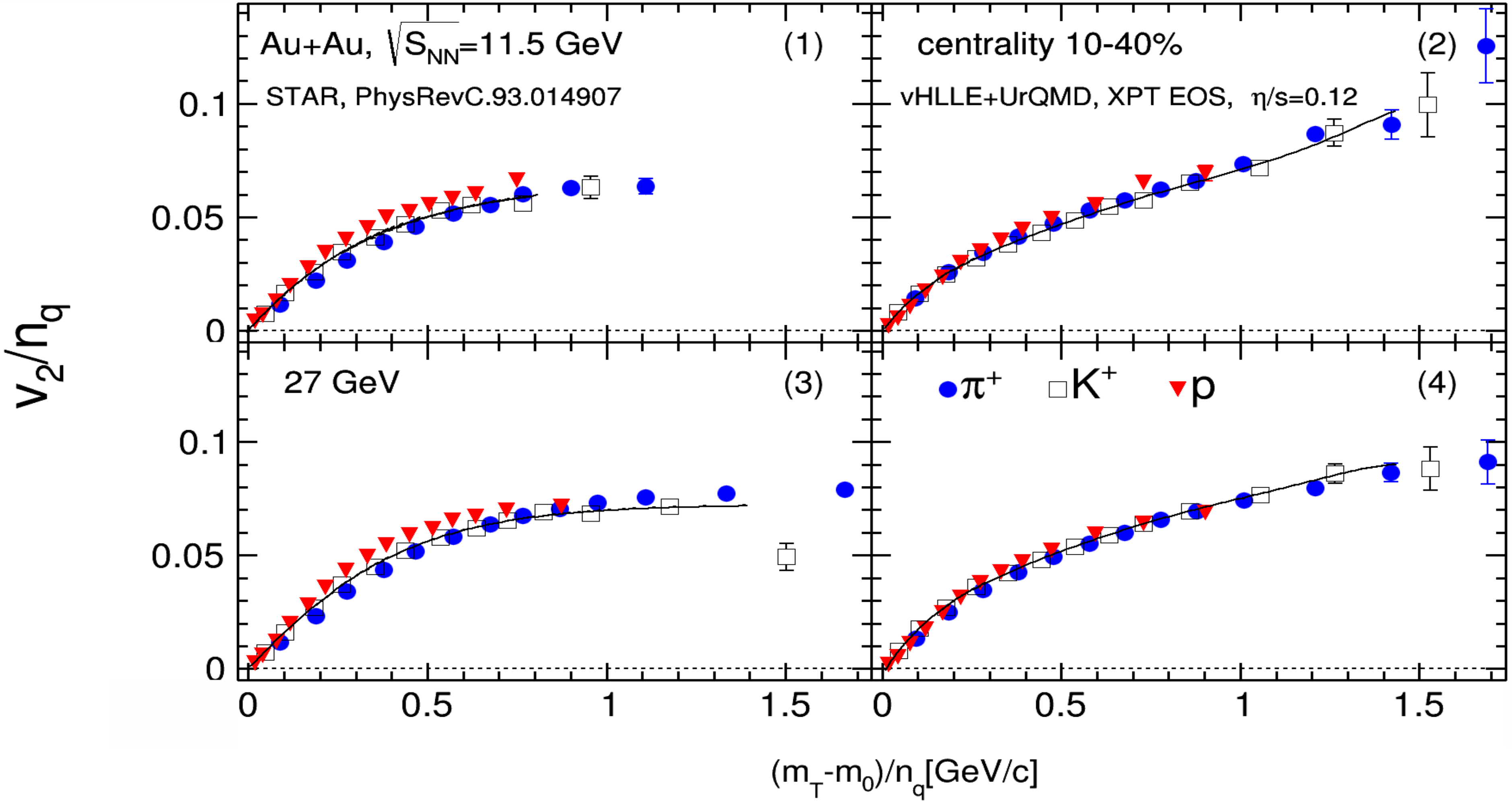
NCQ scaling: hybrid models





- 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

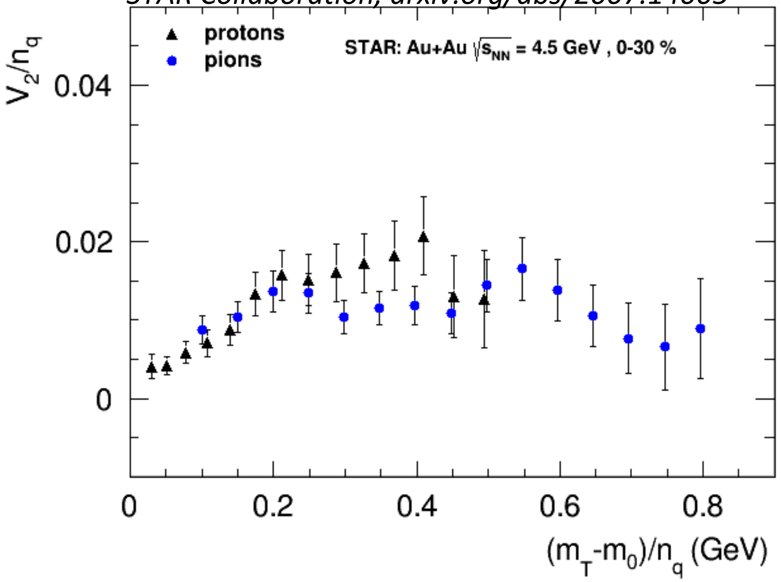
NCQ scaling: hybrid models



- 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

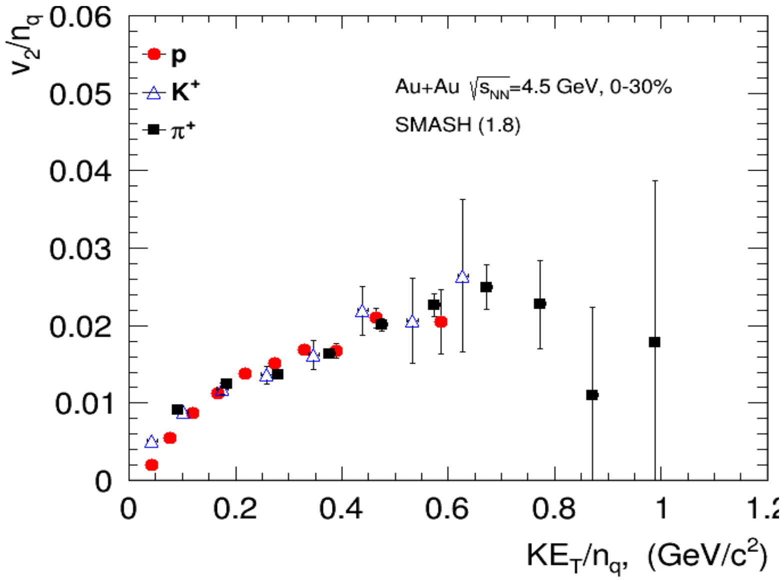
NCQ scaling: hybrid and cascade models

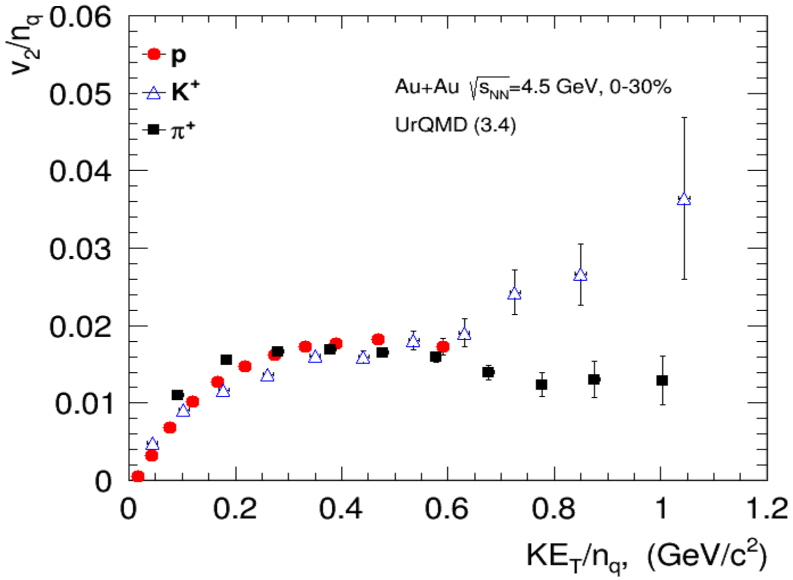
STAR Collaboration, arxiv.org/abs/2007.14005

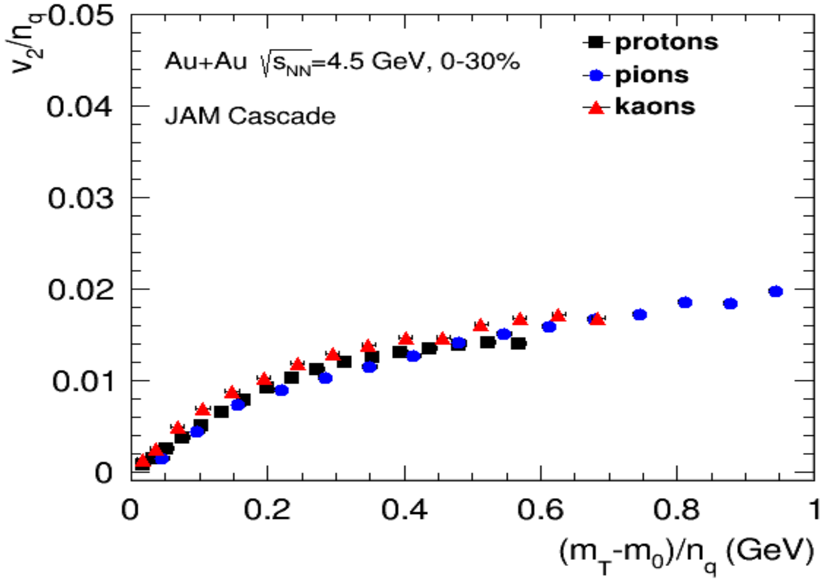


- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

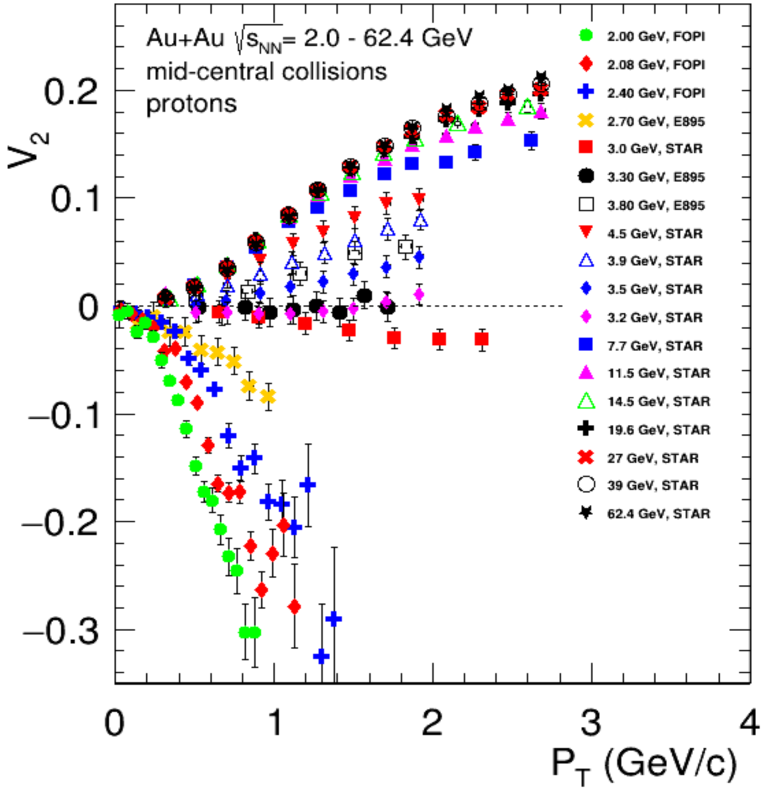
KE_T/n_q scaling at 4.5 GeV might be accidental – more careful studies should be performed

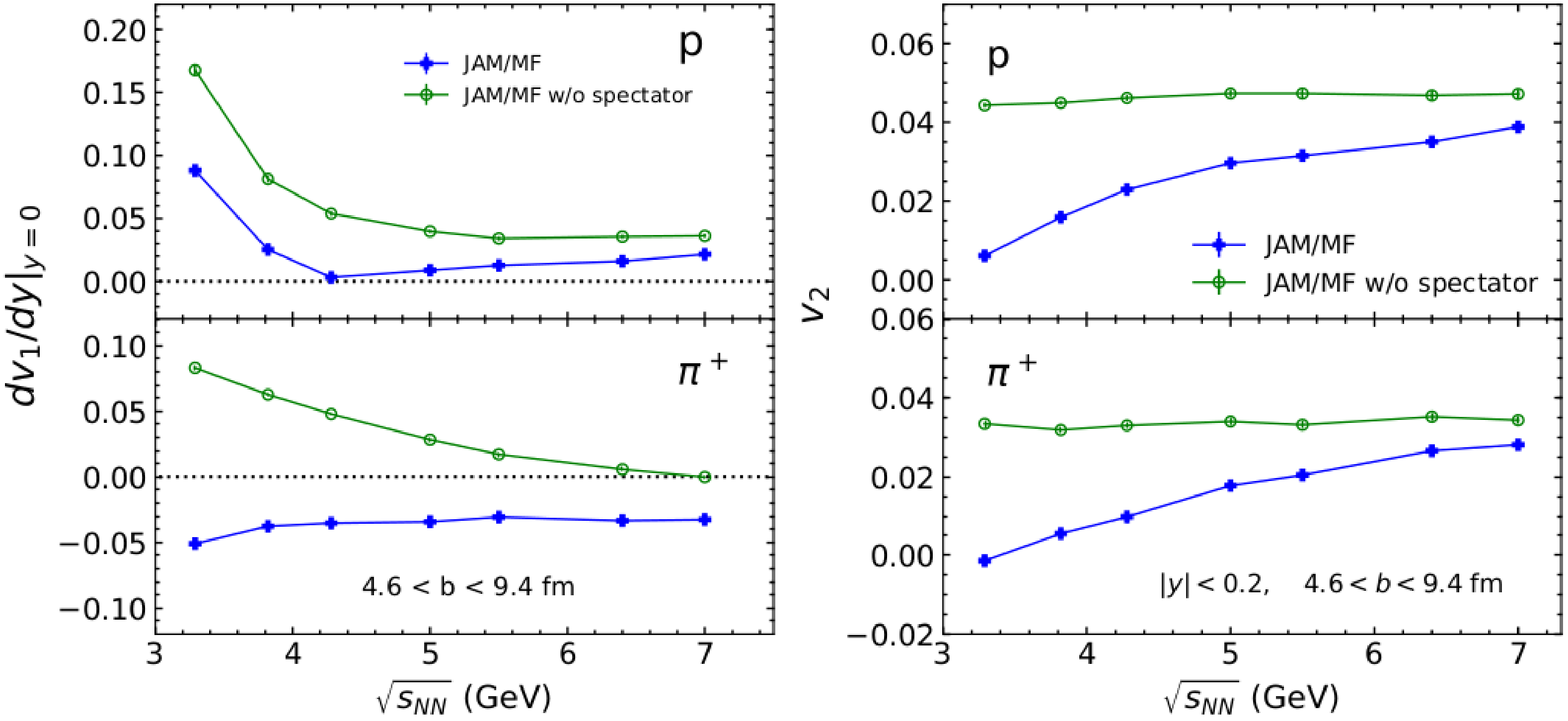






Anisotropic flow in Au+Au collisions at Nuclotron-NICA energies





$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} \boldsymbol{v_n} \cos[n(\phi - \Psi_{RP})], \qquad v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

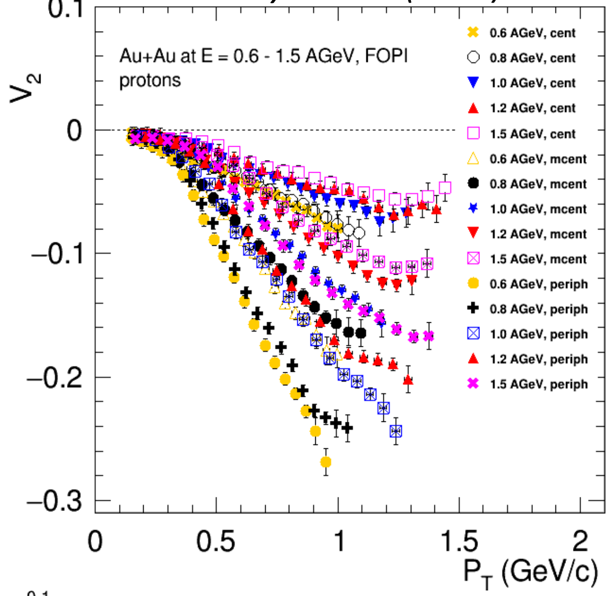
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

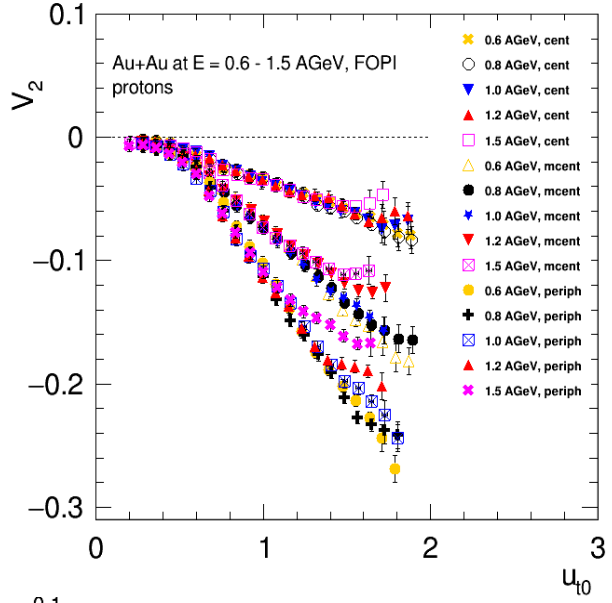
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$, $c_s = c\sqrt{dp/d\varepsilon}$) and

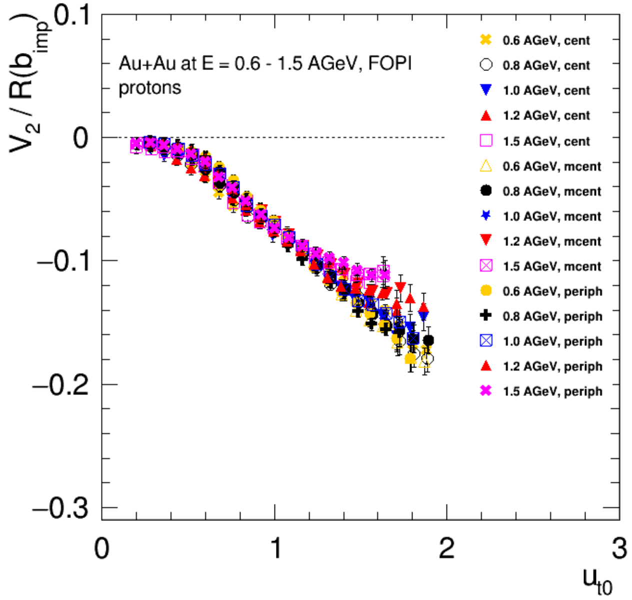
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Scaling relations at SIS – scaling with passage time

Nucl. Phys A 876 (2012) 1-60

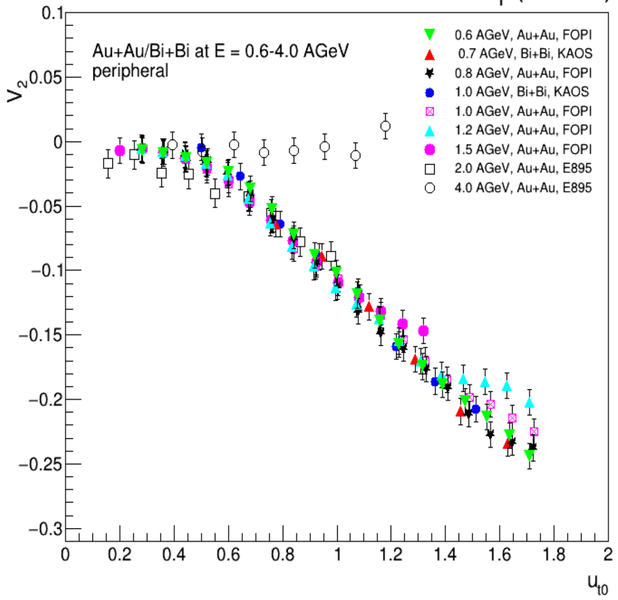


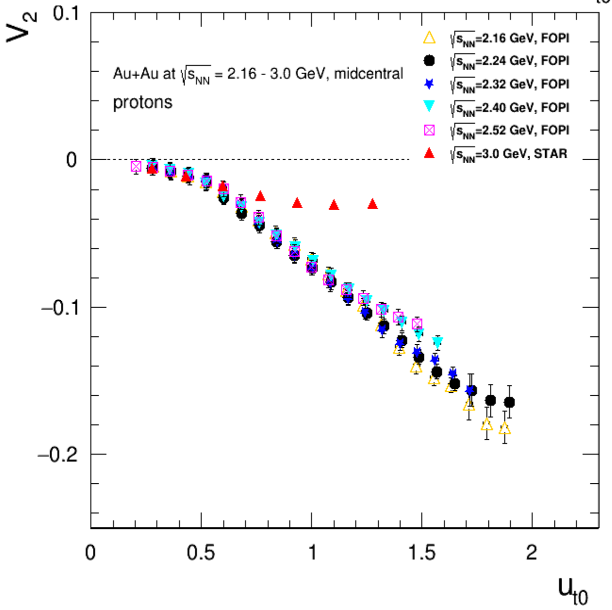




$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2 R m_0}$$

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





- 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)

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

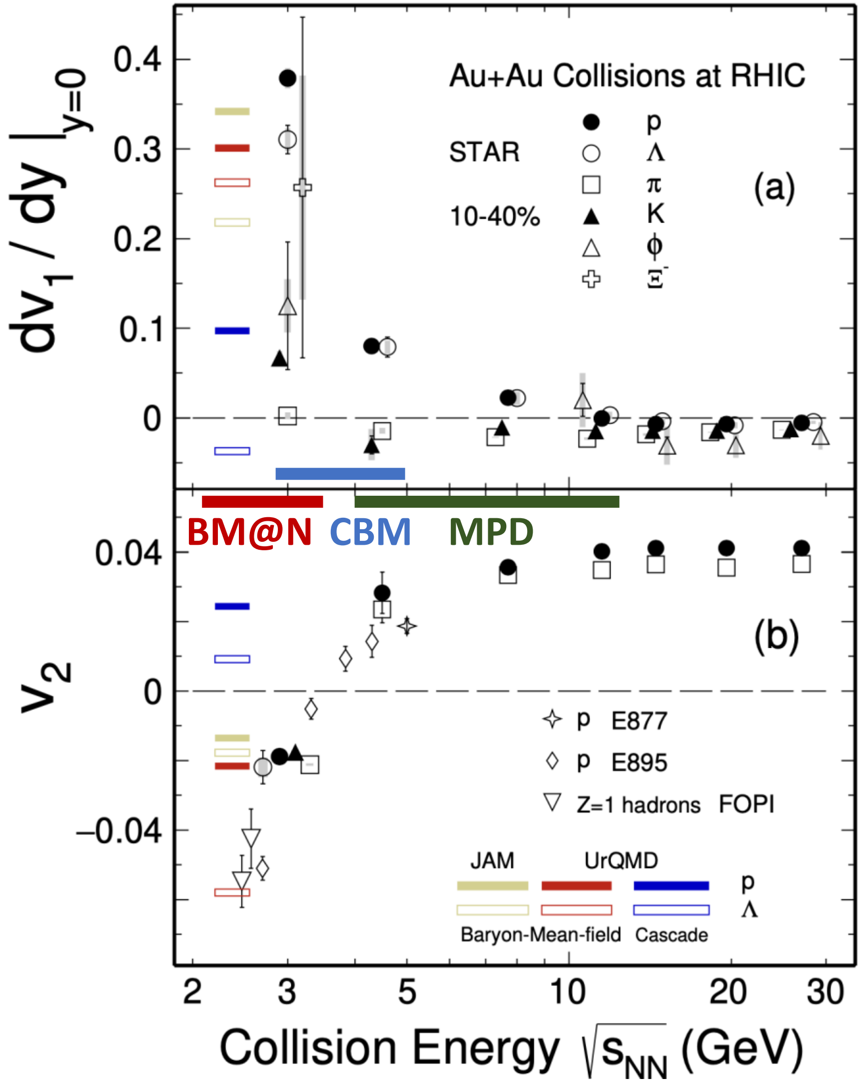
Scaling relations provide a useful tool

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

➢ to constrain existing models

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

M. Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} \boldsymbol{v_n} \cos[n(\phi - \Psi_{RP})], \qquad v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$=2-11 GeV

Makes it difficult to perform comparisons between different experiments for v_2 (change of sign with energy)

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 ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Goal of this work:

- Perform scaling tests for anisotropic flow at Nuclotron-NICA energy range and make predictions what one can expect at BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV)

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 :

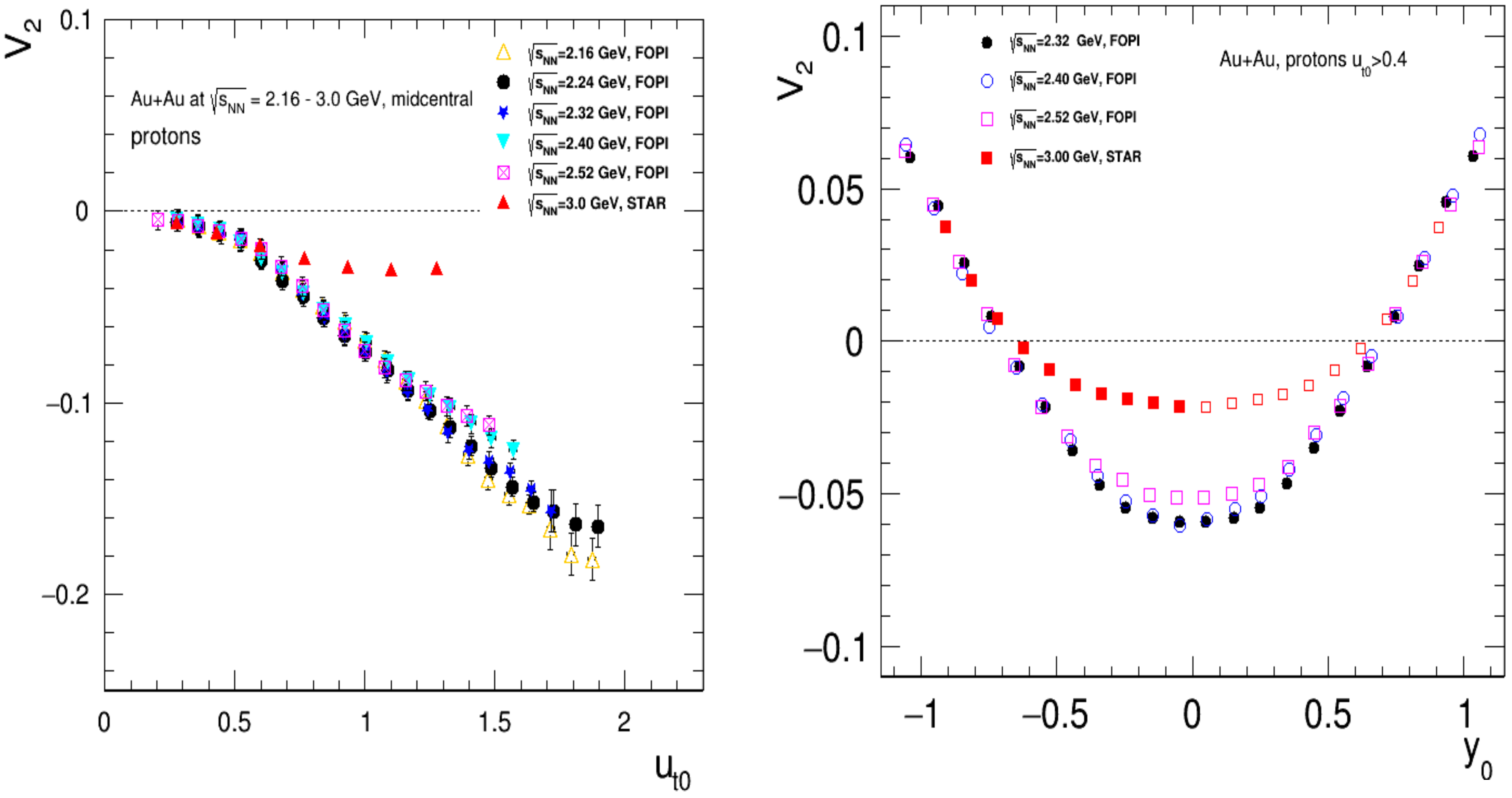
There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and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

The idea to look for scaling relations and use them was proposed a long time ago

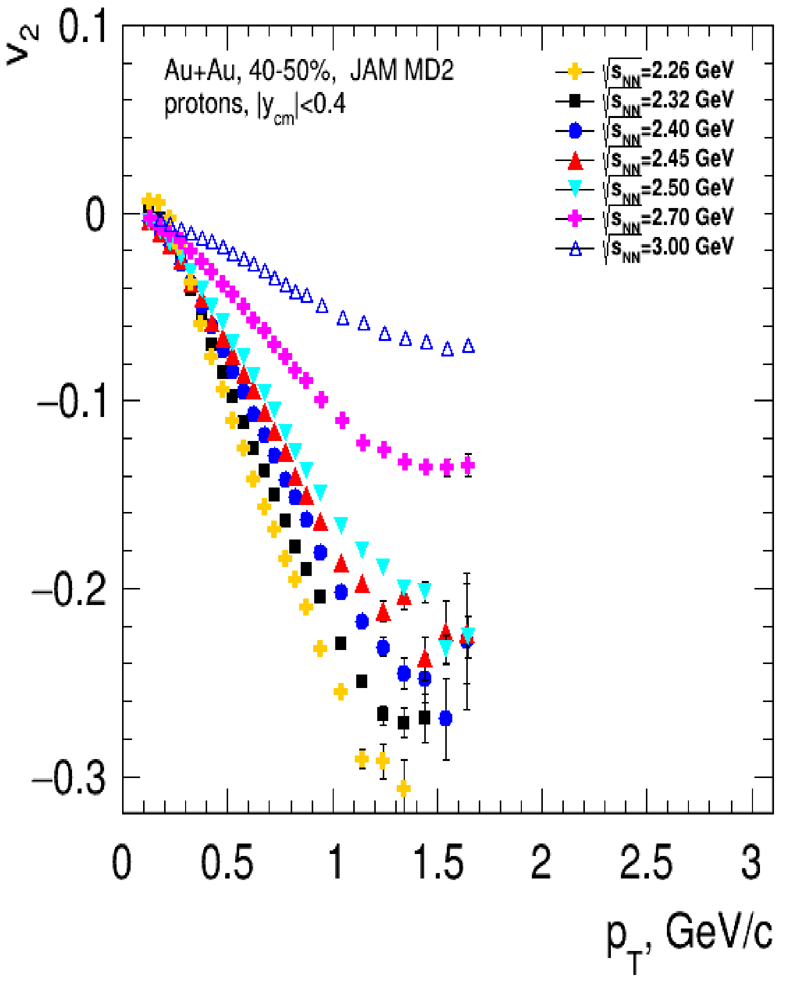
$v_n(\sqrt{s_{NN}}, R, \mathrm{centrality}, \mathrm{PID}, p_T, y) = v_n(\sqrt{s_{NN}}, R, \mathrm{centrality}) \times v_n(\mathrm{PID}, p_T, y)$ **?**

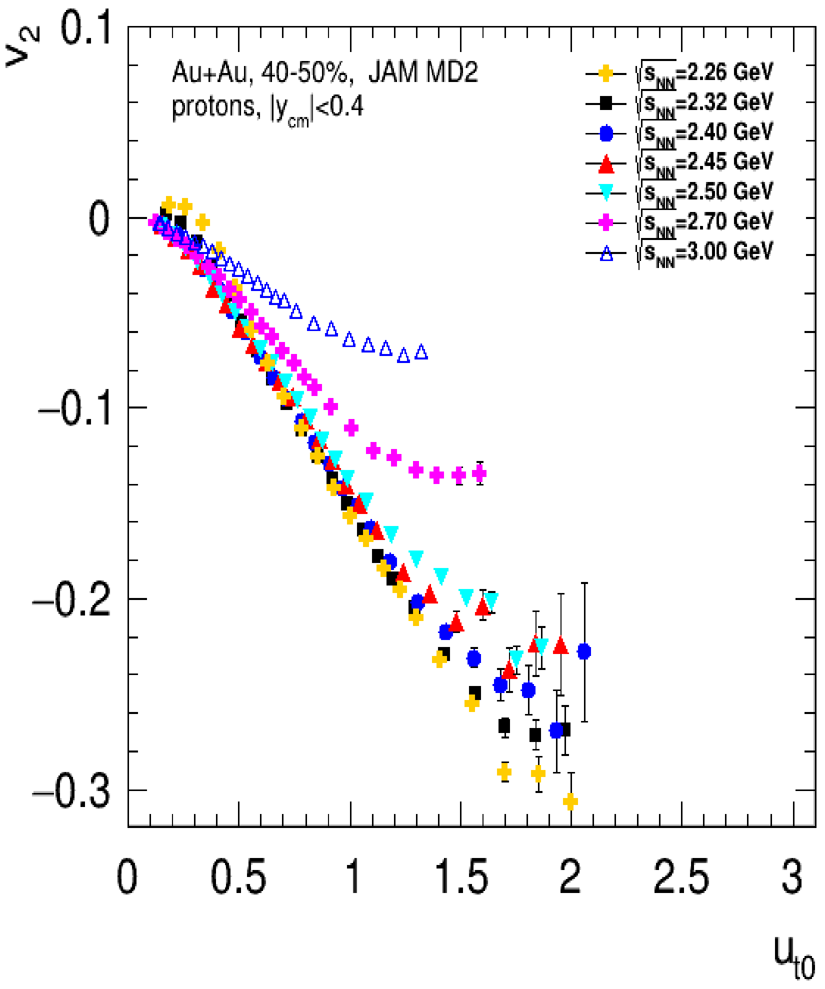
u_{t0} scaling: FOPI/STAR data

STAR published results for protons : Scaling breaks at $\sqrt{s_{NN}}$=3GeV – but holds at forward rapidity?

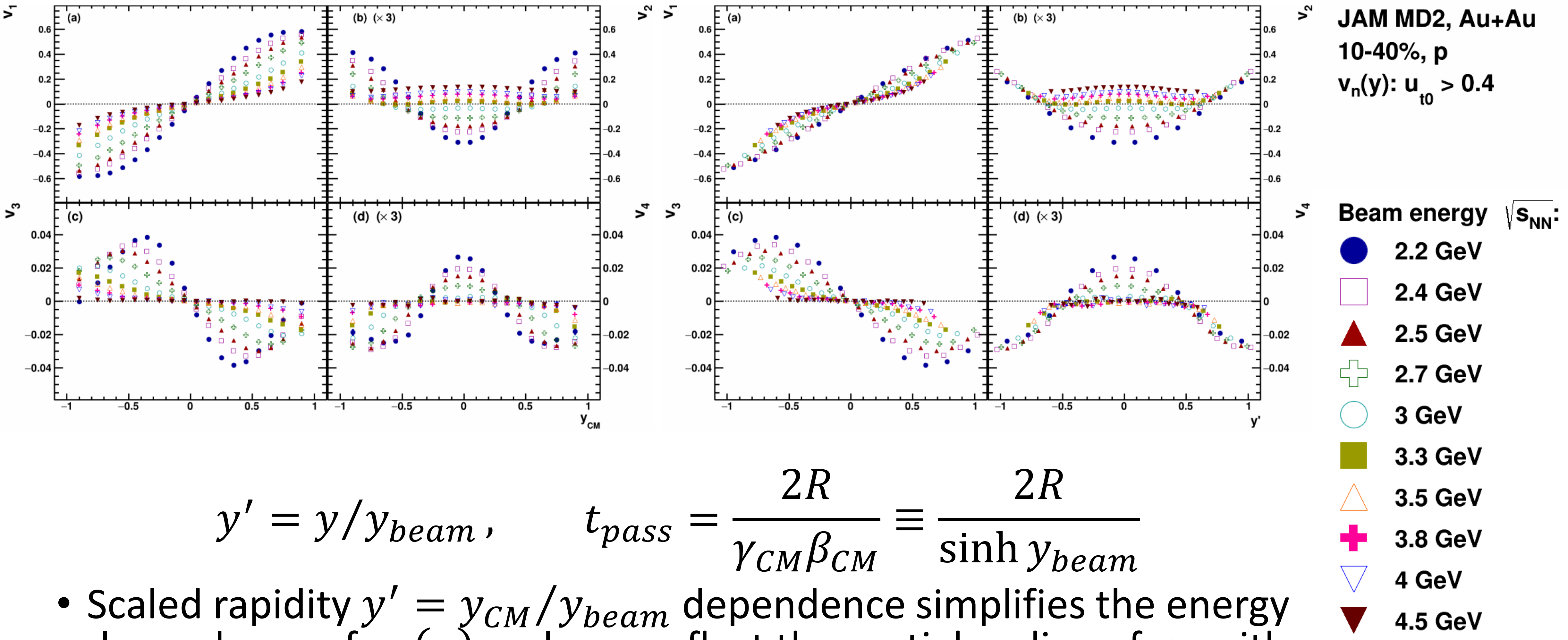


Do we see ut0 scaling in the models?





y' scaling: mean-field models

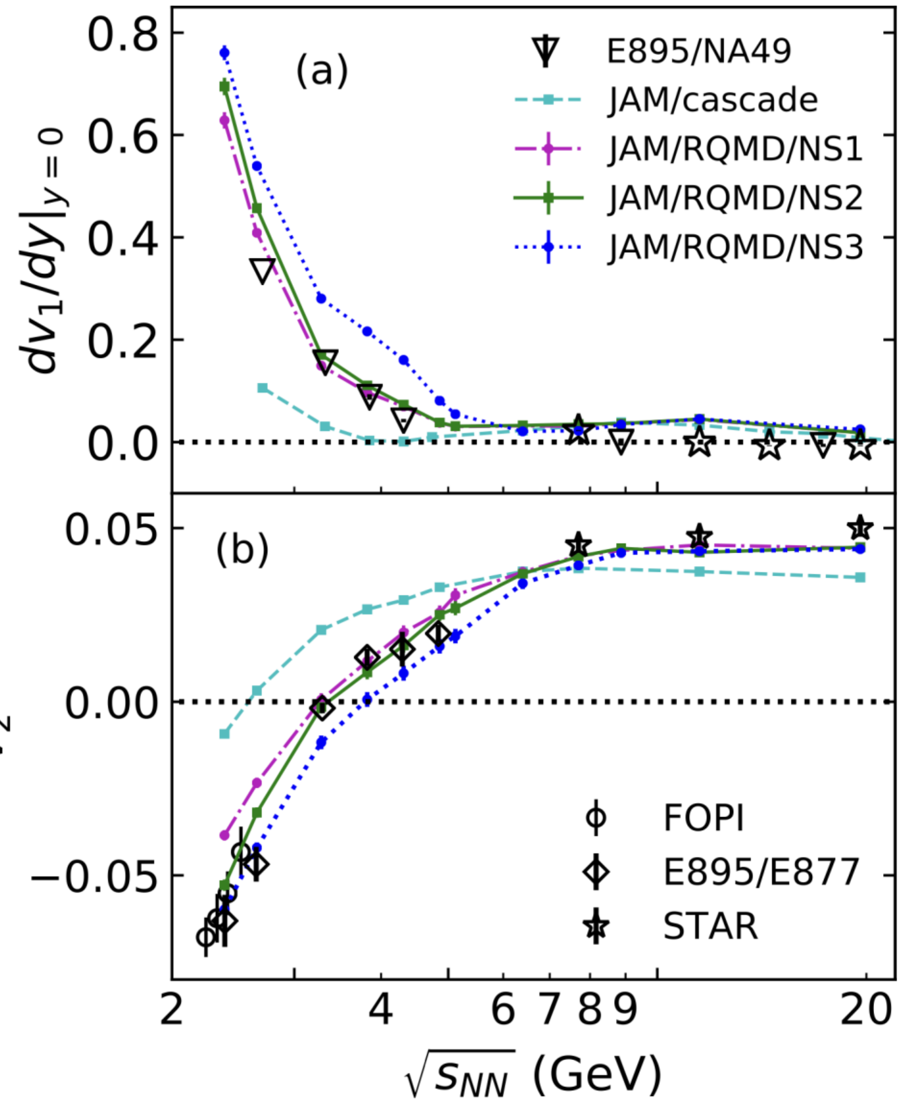


$$y' = y/y_{beam}\,, \qquad t_{pass} = \frac{2R}{\gamma_{CM}\beta_{CM}} \equiv \frac{2R}{\sinh y_{beam}}$$

- Scaled rapidity $y' = y_{CM}/y_{beam}$ dependence simplifies the energy dependence of $v_n(y)$ and may reflect the partial scaling of v_n with t_{pass}

Anisotropic flow study at $\sqrt{s_{NN}}$=2-4 GeV with JAM model

Y.Nara, et al., Phys. Rev. C 100, 054902 (2019)



To study energy dependence of v_n, JAM microscopic model was selected (ver. 1.90597)

NN collisions are simulated by:

- $\sqrt{s_{NN}}$<4 GeV: resonance production
- 4<$\sqrt{s_{NN}}$<50 GeV: soft string excitations
- $\sqrt{s_{NN}}$>10 GeV: minijet production

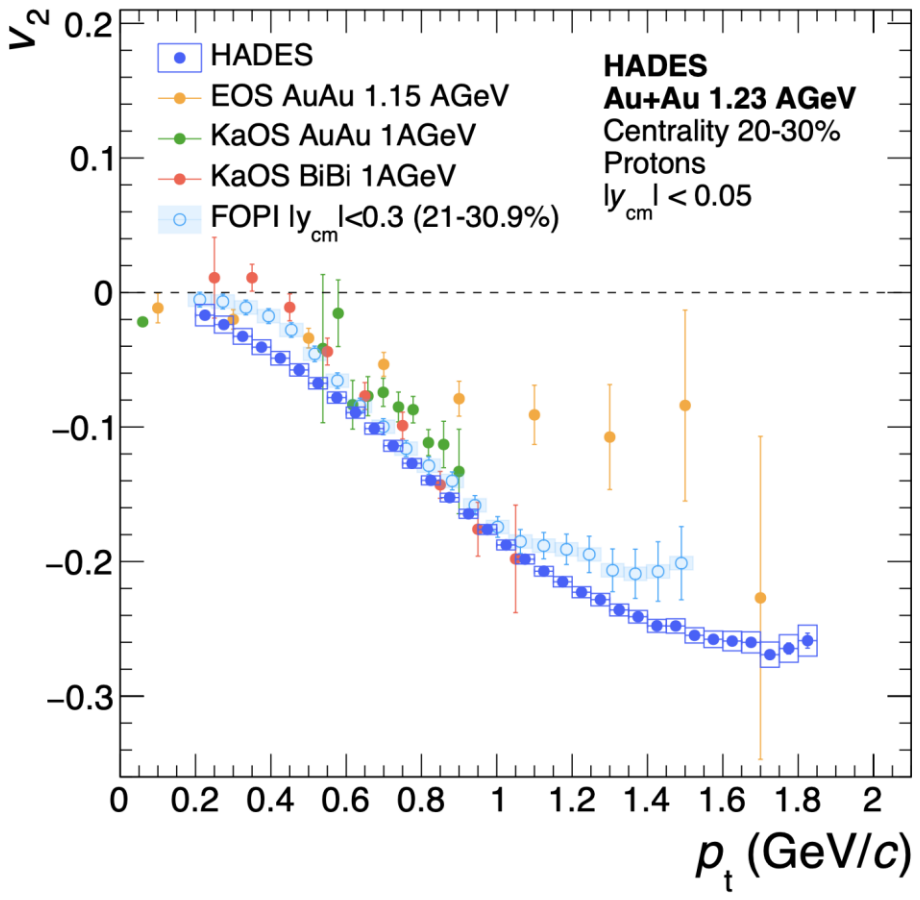
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

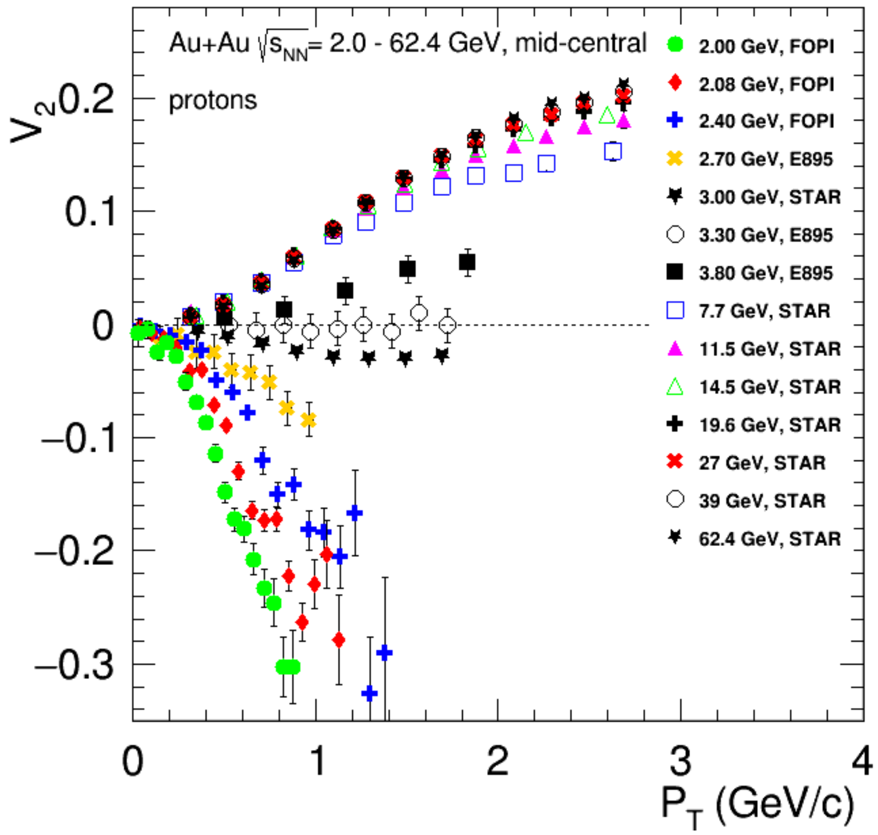
Different EOS were used:

- **MD2** (momentum-dependent potential): K=380 MeV, m^*/m=0.65, $U_{opt}(\infty)$=30
- **MD4** (momentum-dependent potential): K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=67
- **NS1**: K=380 MeV, m^*/m=0.83, $U_{opt}(\infty)$=95
- **NS2**: K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=98

Y.Nara, T.Maruyama, H.Stoecker Phys. Rev. C 102, 024913 (2020)
Y.Nara, H.Stoecker Phys. Rev. C 100, 054902 (2019)

Why do we need new measurements at BM@N, CBM and MPD?





- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV), CBM ($\sqrt{s_{NN}}$=2.7-4.9 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust v_n measurements