Anisotropic flow and its scaling properties at Nuclotron-NICA energies

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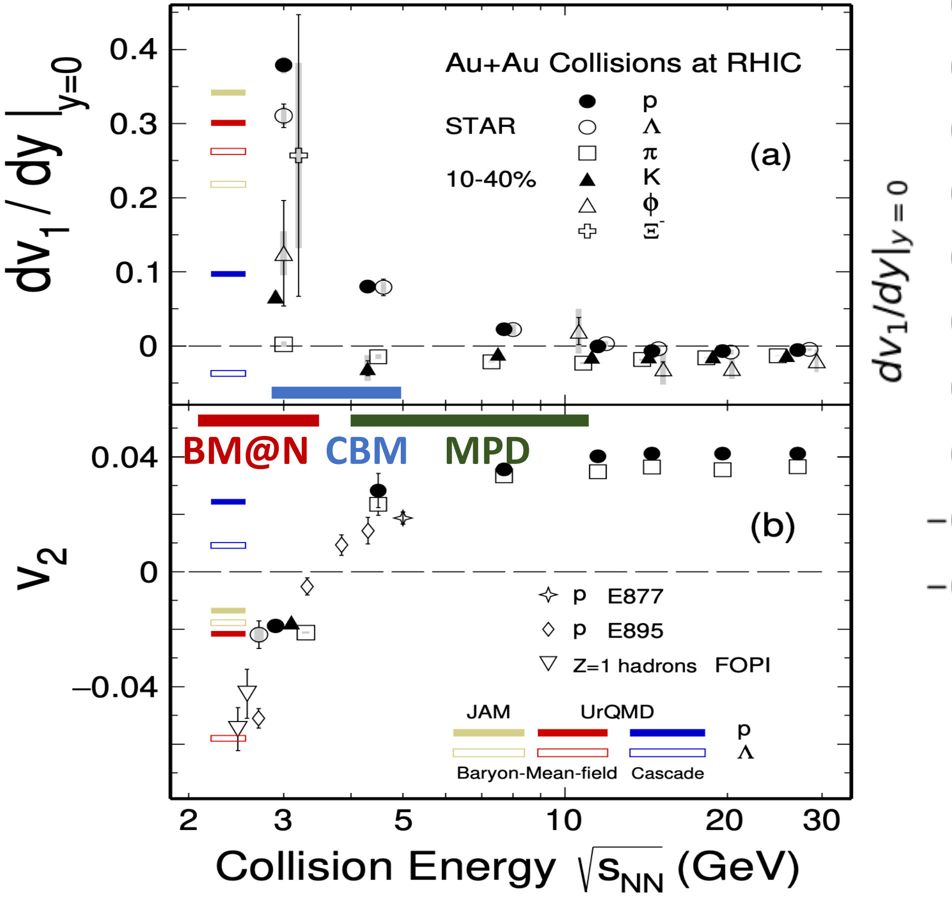
Mikhail Lomonosov
1711-1765

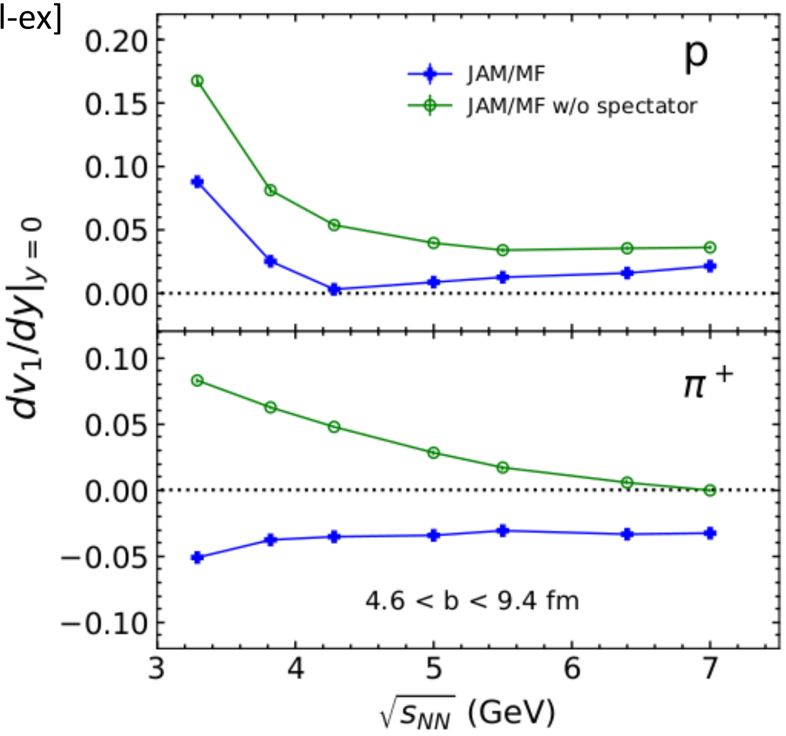
Outline

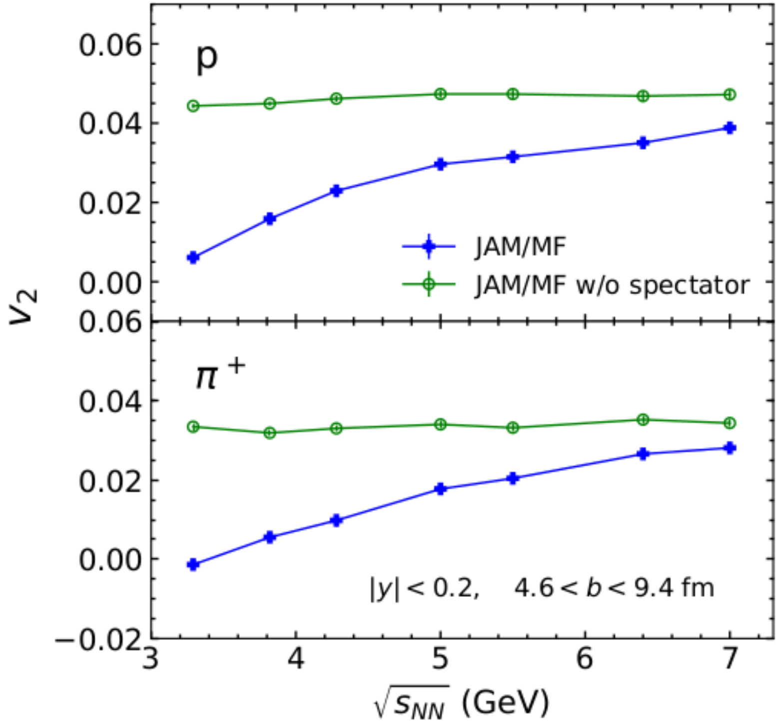
- Introduction
- Scaling relations for anisotropic flow at RHIC
- Scaling relations for anisotropic flow at SIS-AGS
- Summary and outlook

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

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







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

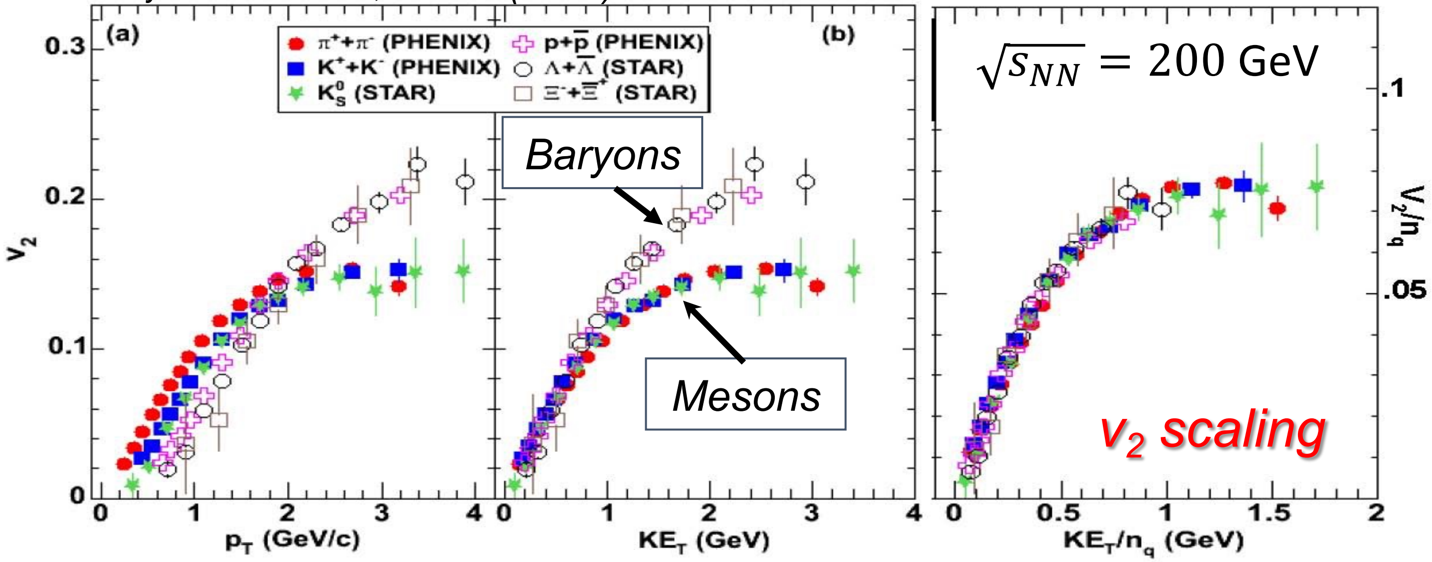
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

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

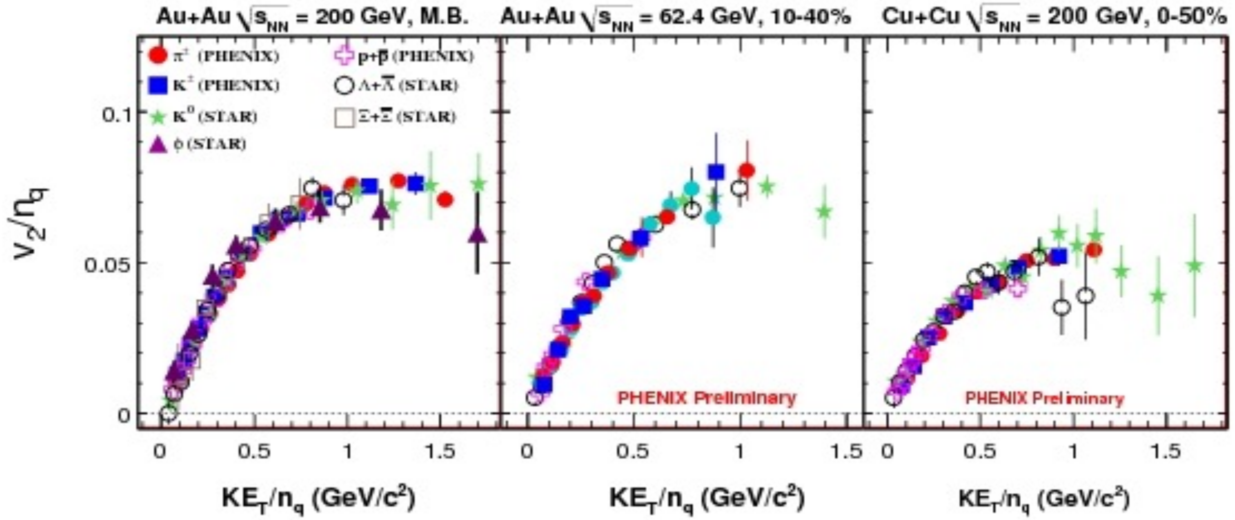
Scaling relations at RHIC/LHC – NCQ (KE_T/n_q) scaling

Phys. Rev. Lett. 98, 162301 (2007)



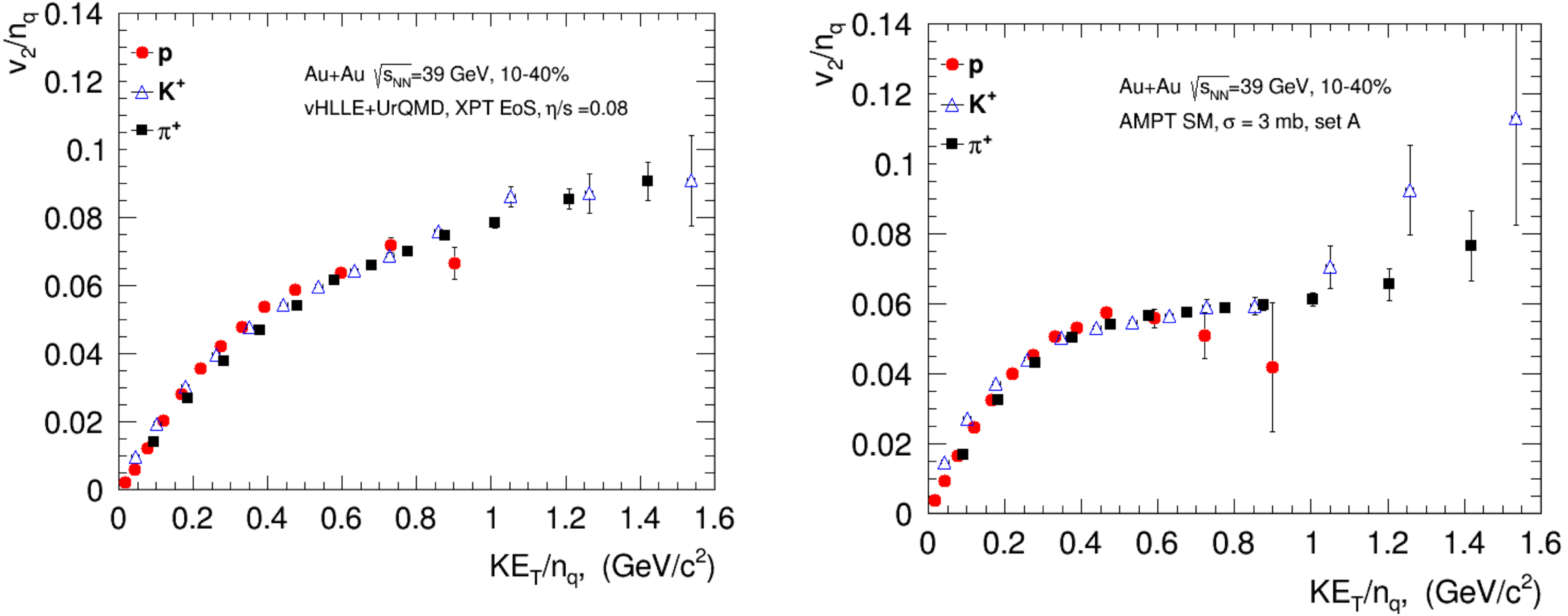
NCQ scaling: $v_n(p_T) \to v_n/n_q^{n/2}(KE_T/n_q)$

$$n_q = \begin{cases} 2 \text{ for mesons} \\ 3 \text{ for baryons'} \end{cases} \qquad KE_T = \sqrt{m^2 + p_T^2} - m$$



- Significant part of flow at RHIC developed at partonic level
- Scaling provides an additional constraint for the mechanism for hadronization at RHIC

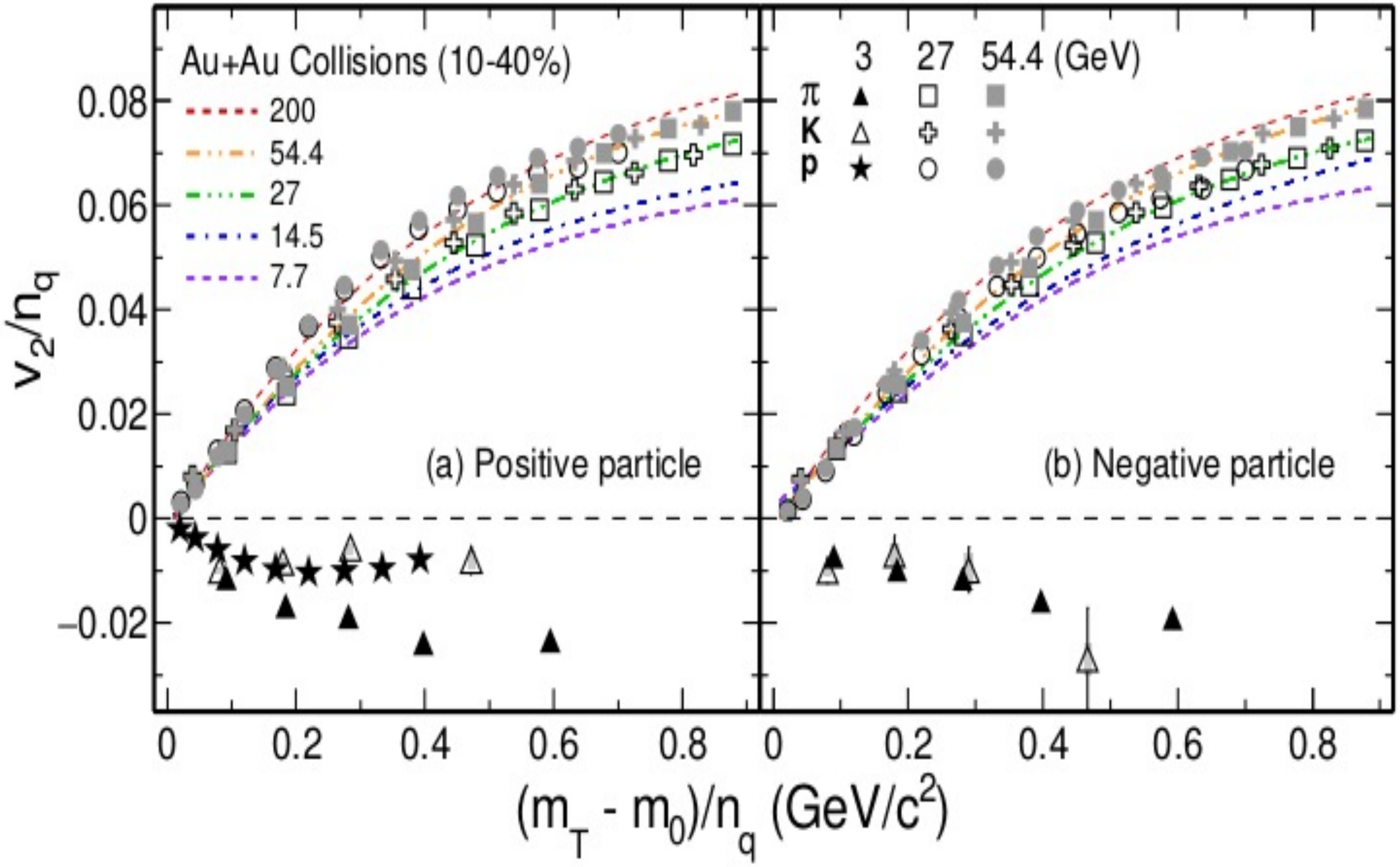
NCQ scaling: hybrid models



- 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

Dissapearence of partonic collectivity in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC

Phys. Lett. B 827, 137003 (2022)

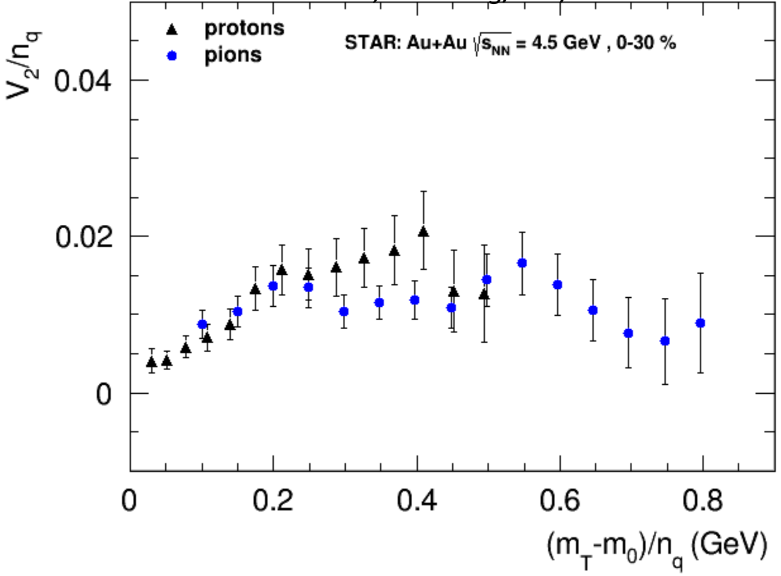


Breaking of NCQ scaling at 3 GeV

"imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region"

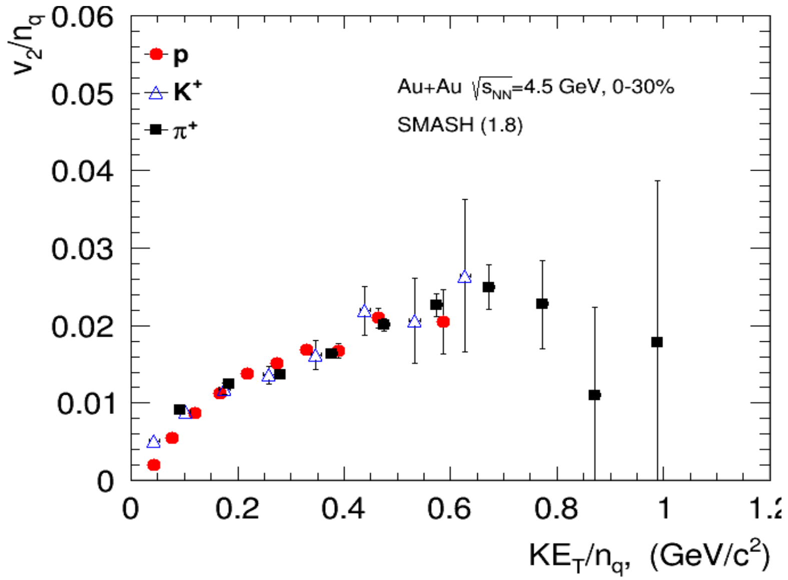
NCQ scaling: hybrid and cascade models

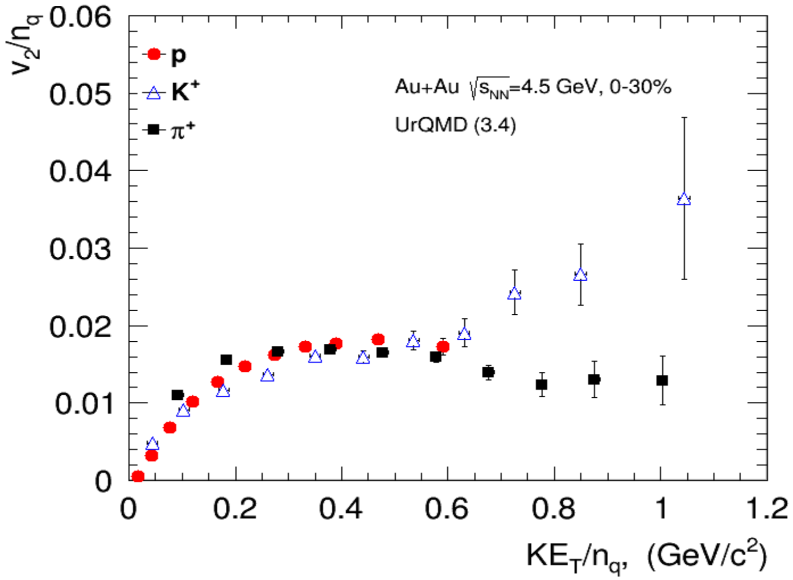
STAR Collaboration, arxiv.org/abs/2007.14005

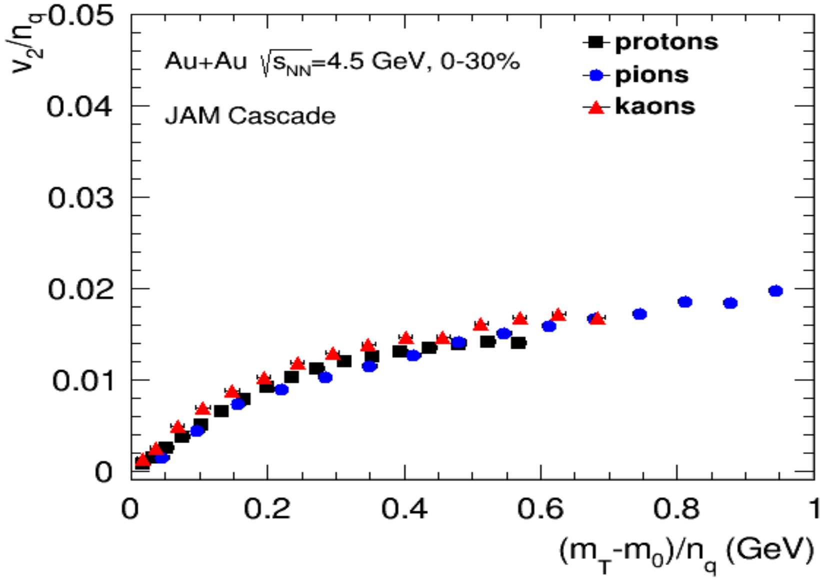


- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

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

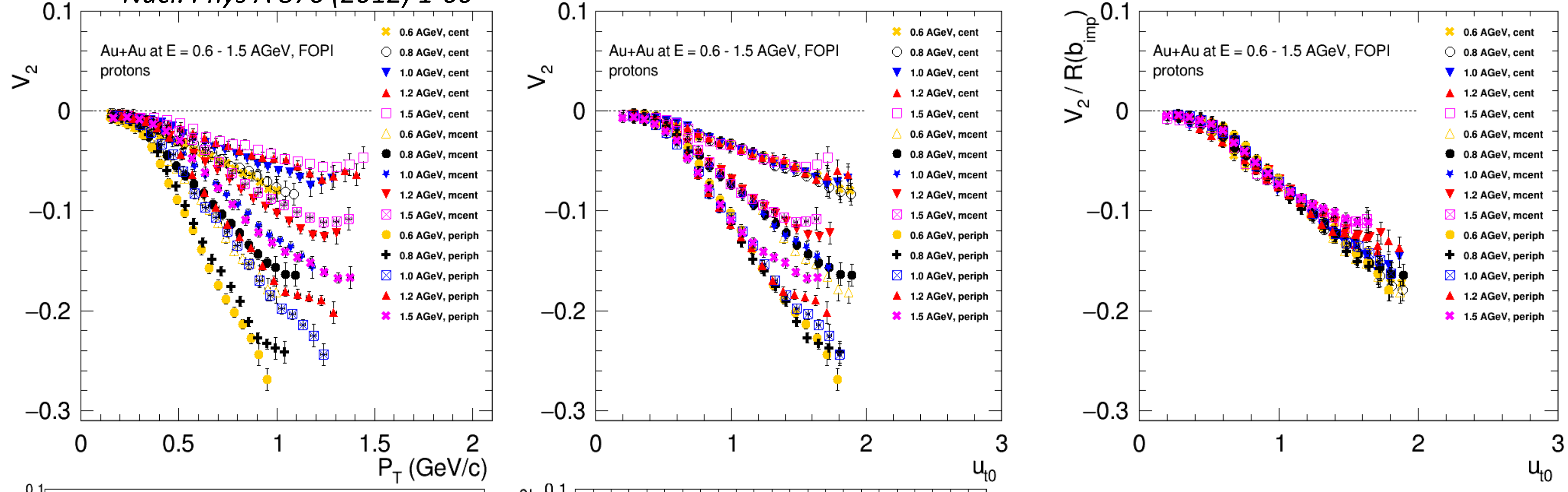






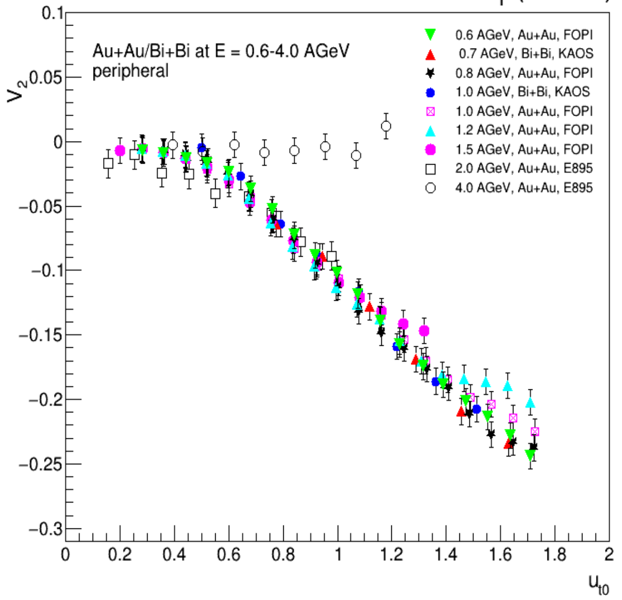
Scaling relations at SIS – scaling with passage time

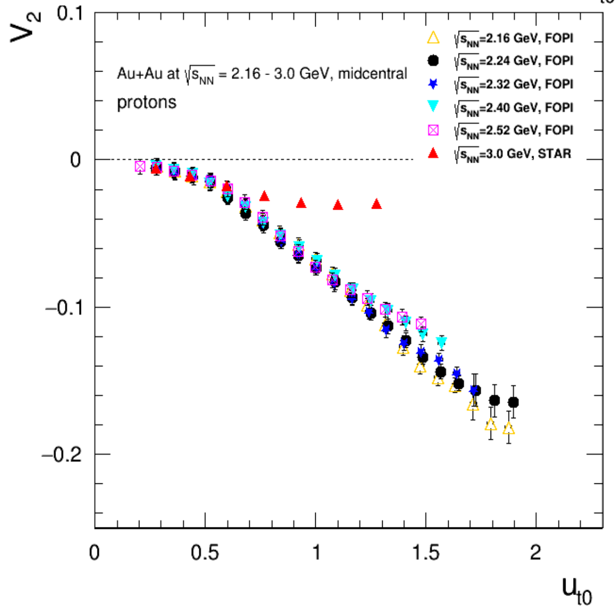
Nucl. Phys A 876 (2012) 1-60



$$u_{t0} = \frac{p_T}{m_0\beta_{CM}\gamma_{CM}} \equiv \frac{p_T t_{pass}}{2Rm_0}$$

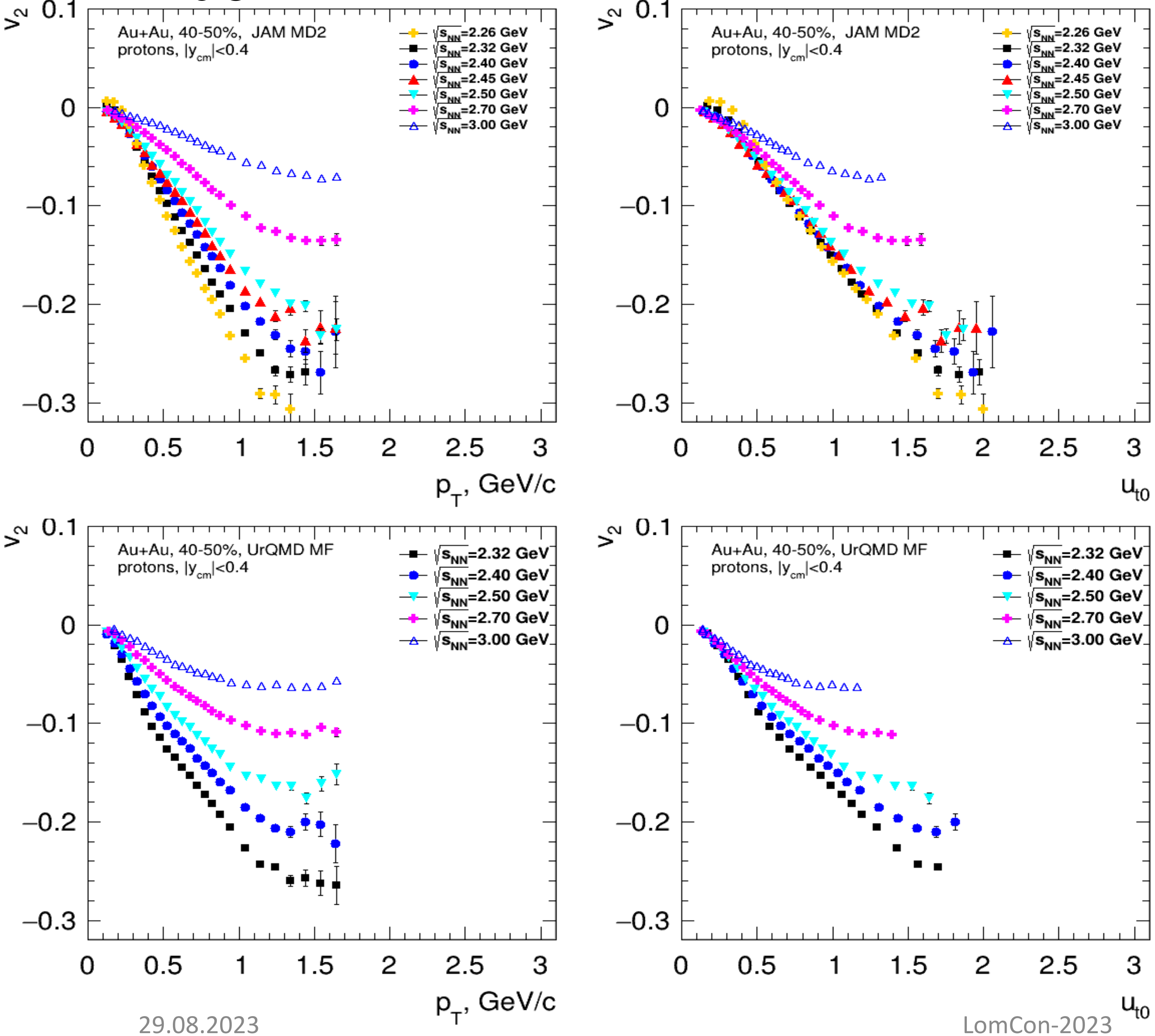
$$t_{pass} = \frac{2R}{\beta_{CM}\gamma_{CM}}$$





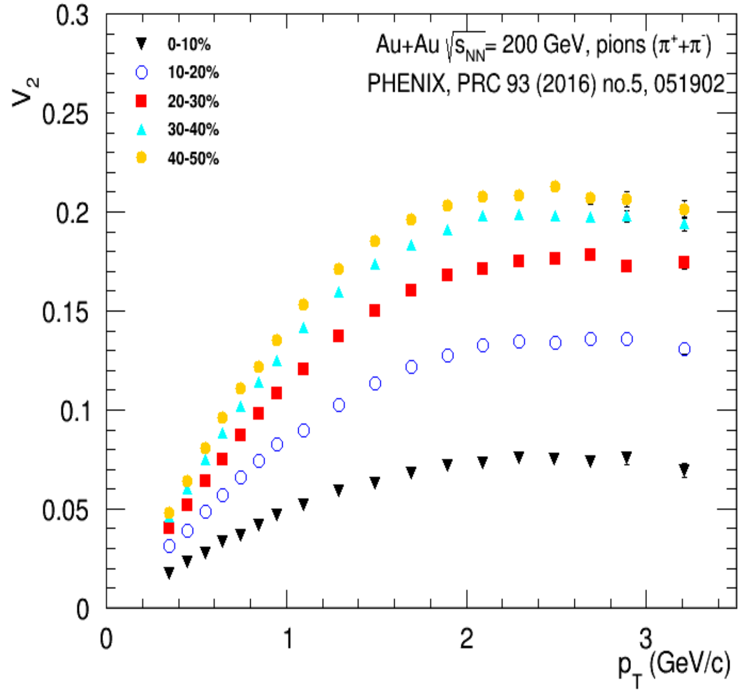
- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

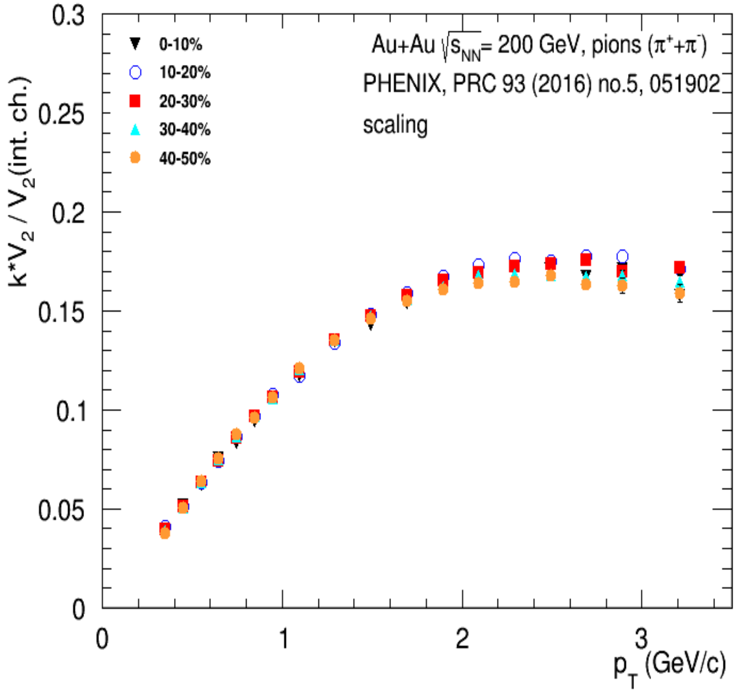
u_{t0} scaling: mean-field models



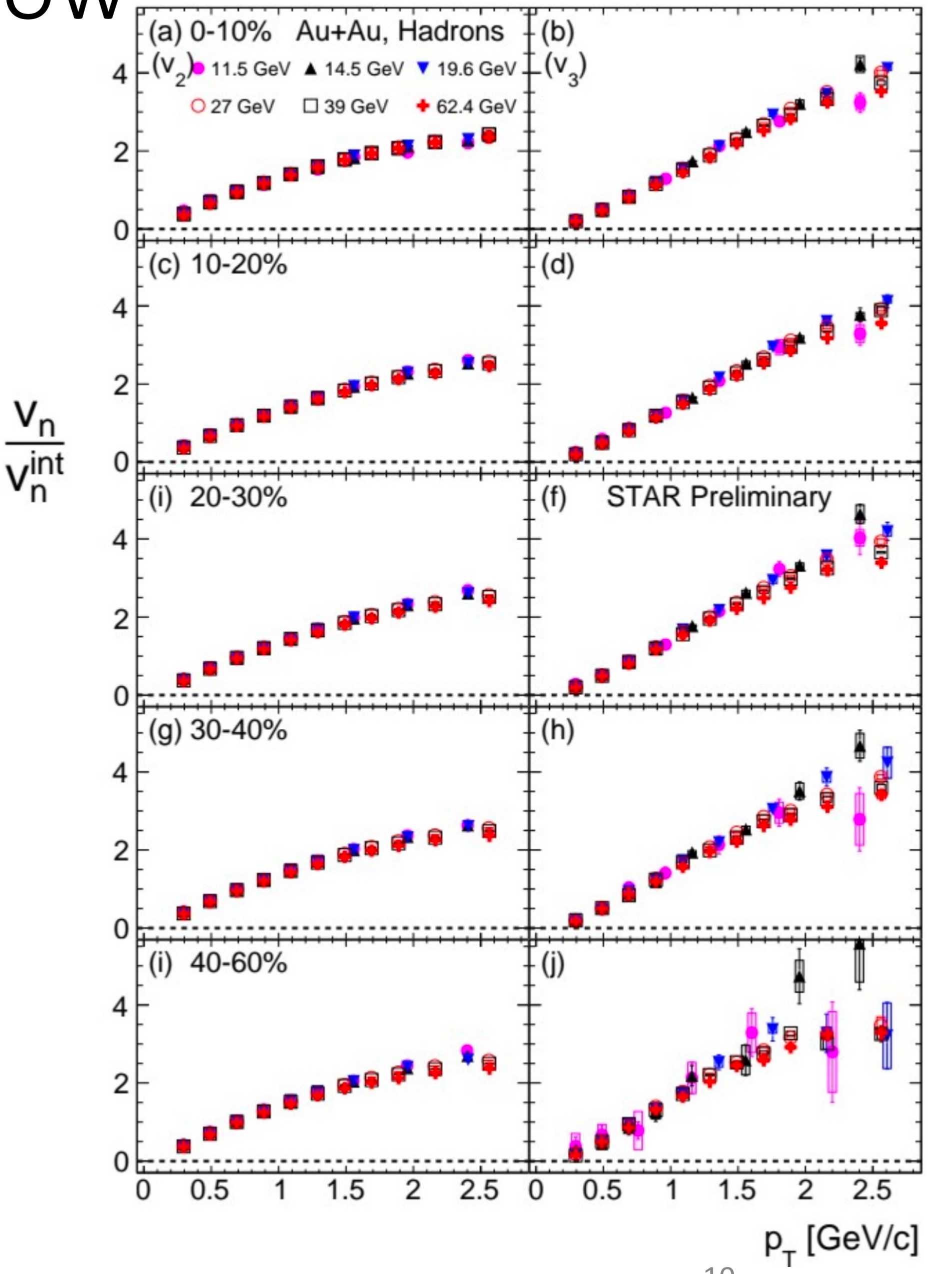
- Scaling holds for both JAM and UrQMD models with mean-field potentials for all EOS
- Similar trend with experimental data: scaling breaks at around $\sqrt{s_{NN}} \geq 2.7$ GeV
- Scaling can provide additional constraints for models

Scaling with integral anisotropic flow





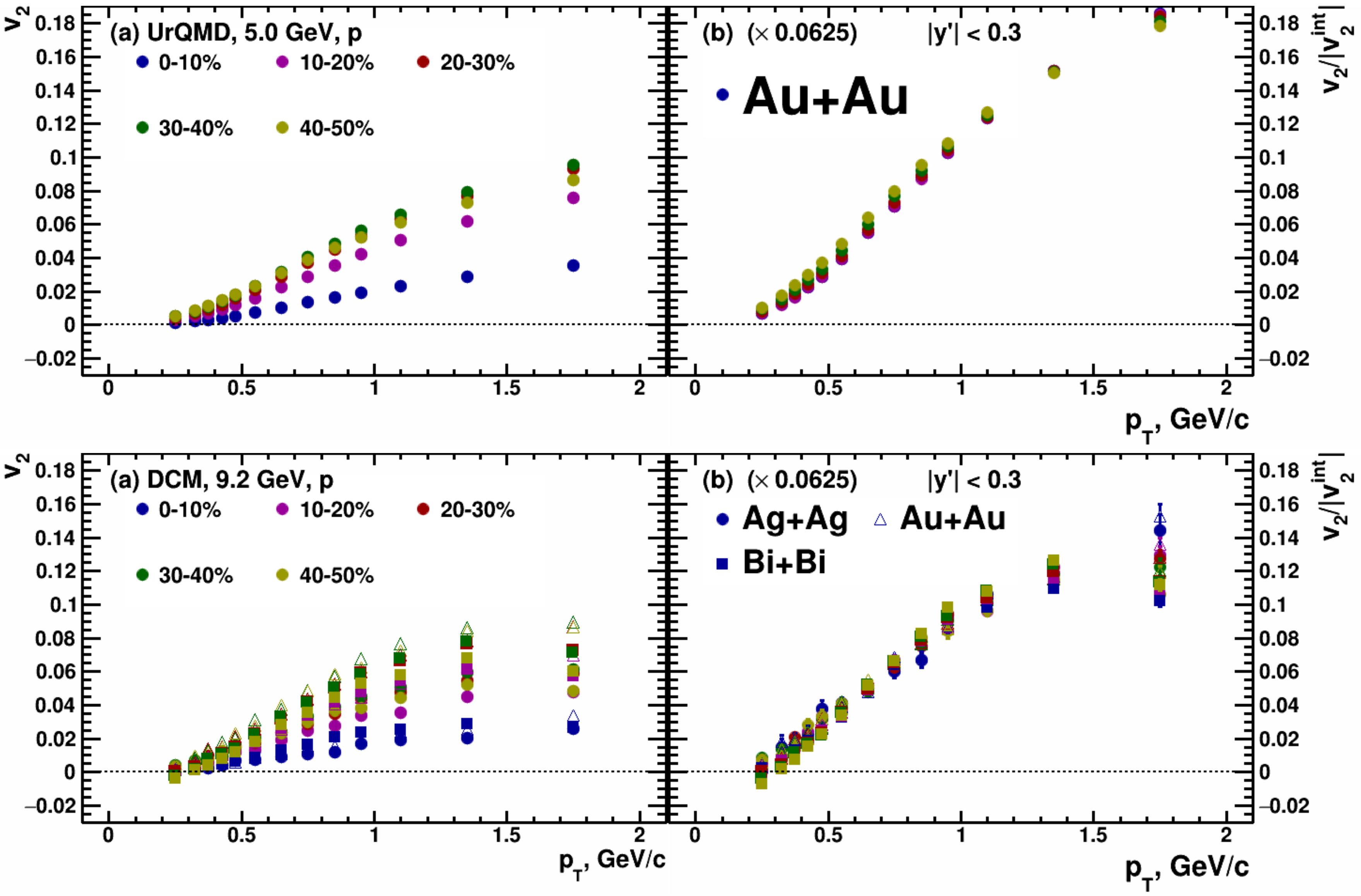
J.Phys.Conf.Ser. 1690 (2020) 1, 012128



$$v_n(int.) \equiv |v_n^{int}| = |\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}|$$

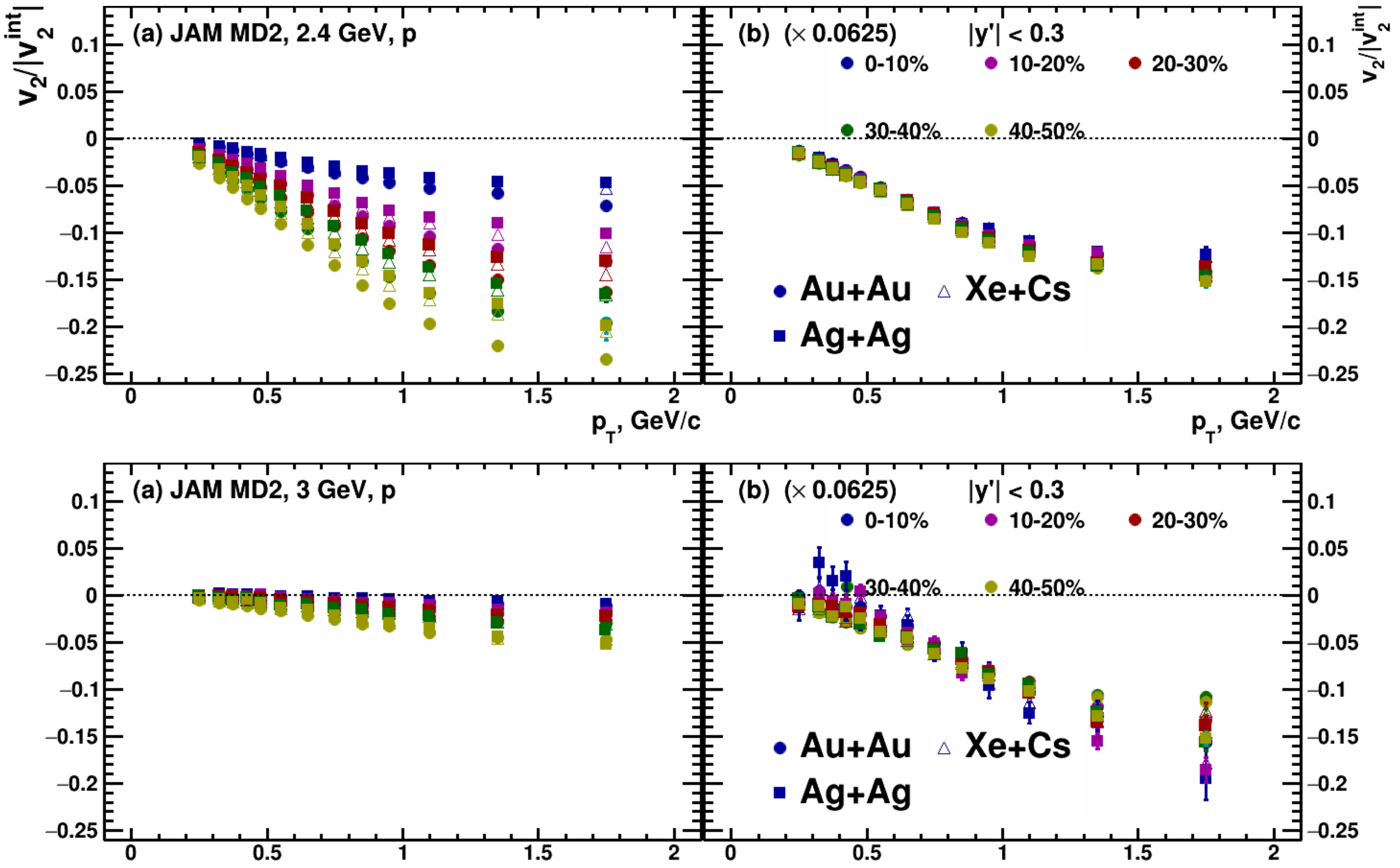
- Scaling works at top RHIC and BES energy range
- Similar trend for pions, kaons and protons

$\left|v_n^{int}\right|$ scaling: cascade models – NICA energies



Scaling works for both UrQMD and DCM-QGSM-SMM models at $\sqrt{s_{NN}} = 5, 9.2$ GeV for different collision systems

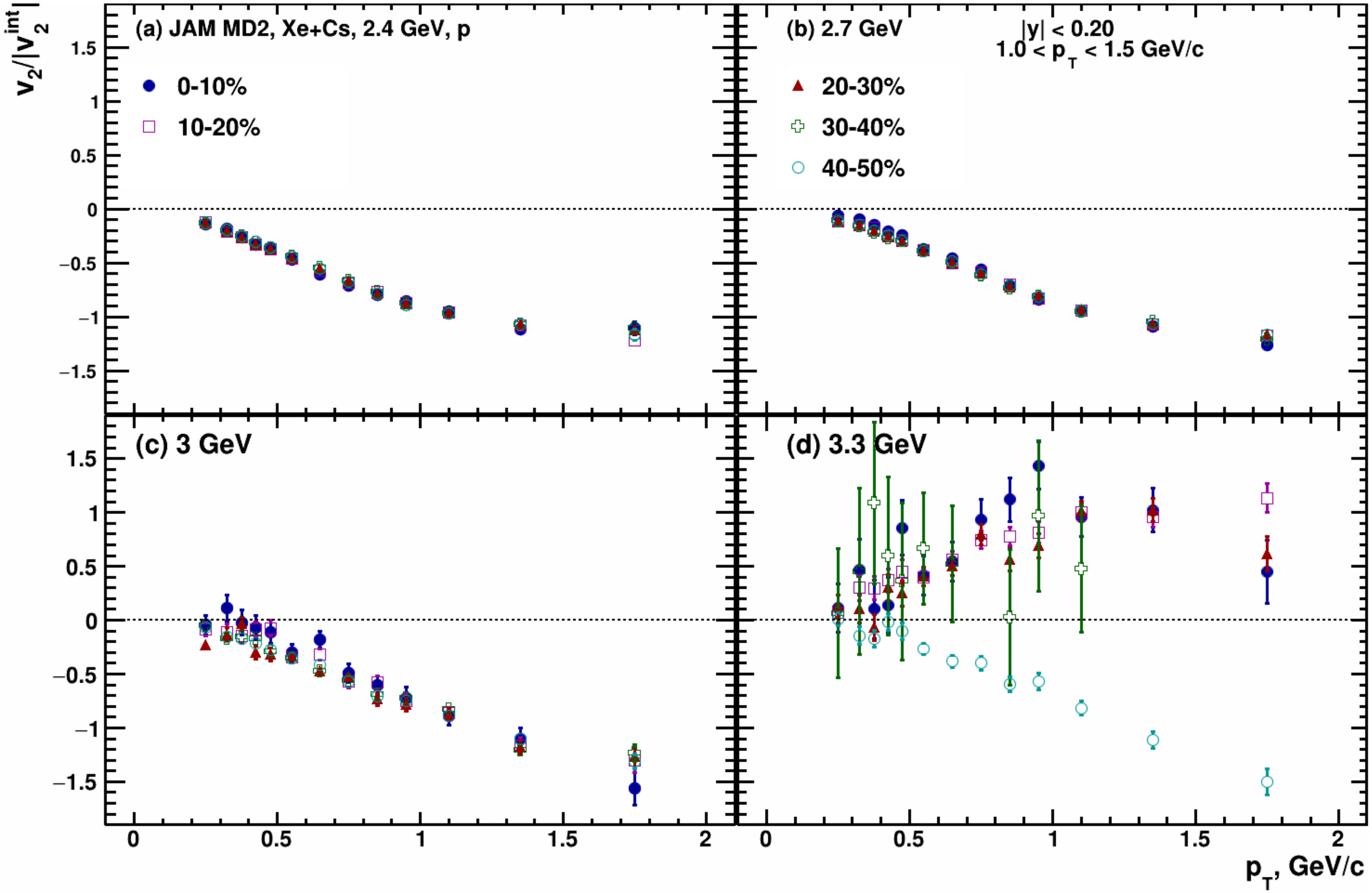
$\left|v_n^{int}\right|$ scaling: JAM MD2 model – Nuclotron energies



Scaling works for JAM model at $\sqrt{s_{NN}} = 2.4$ GeV for Au+Au, Xe+Cs and Ag+Ag collisions

Starts breaking at $\sqrt{s_{NN}} = 3$ GeV

$|v_2^{int}|$ scaling: JAM MD2 model – Nuclotron energies



Scaling works for energy range $\sqrt{s_{NN}} = 2.4 - 3$ GeV and breaks at $\sqrt{s_{NN}} = 3.3$ GeV where v_2 changes sign

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 with integral anisotropic flow:**
  - Holds up for a wide energy range for different particle species, colliding systems and centrality classes
  - Breaks in the energy range where v_2 changes sign, transitioning from out-of-plane ($v_2 < 0$) to in-plane ($v_2 > 0$)

Scaling relations allow to separate different contributions to anisotropic flow originating from different energies, particle masses, initial conditions, etc. from general fluid-dynamical features

Scaling relations also provide a useful tool

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

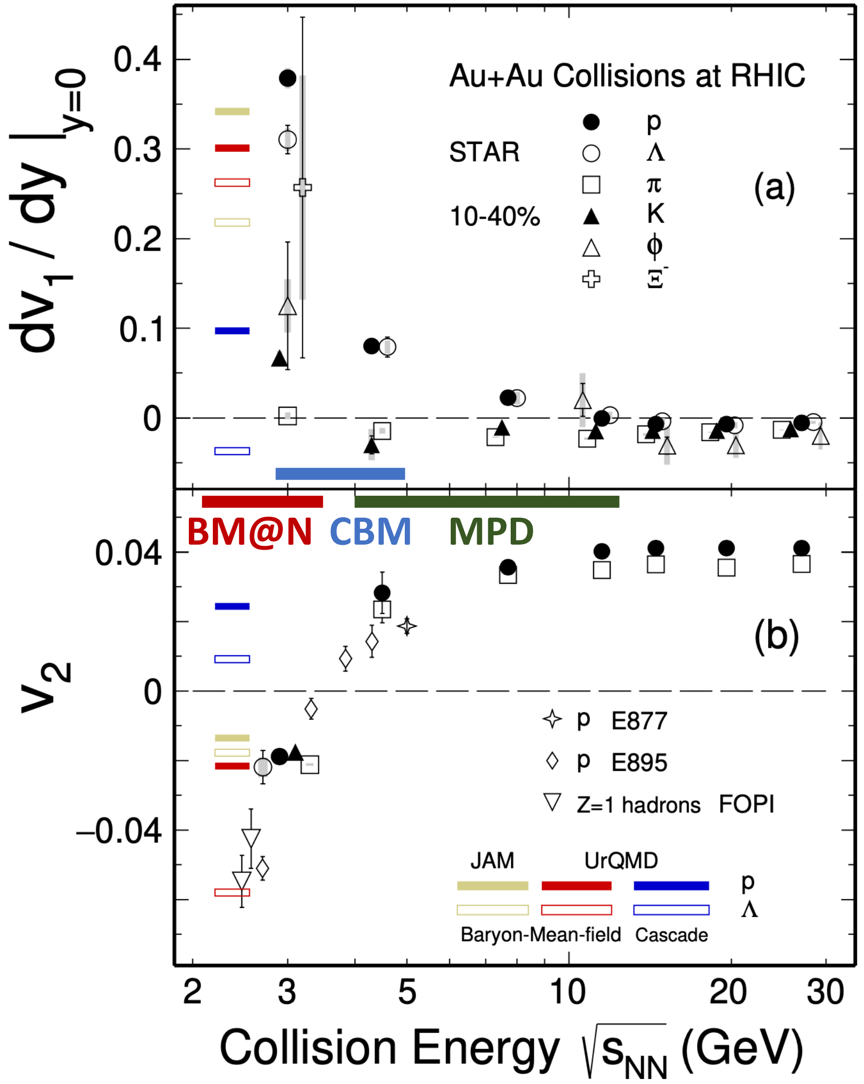
➢ to constrain existing models

Thank you for your attention!

Backup slides

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

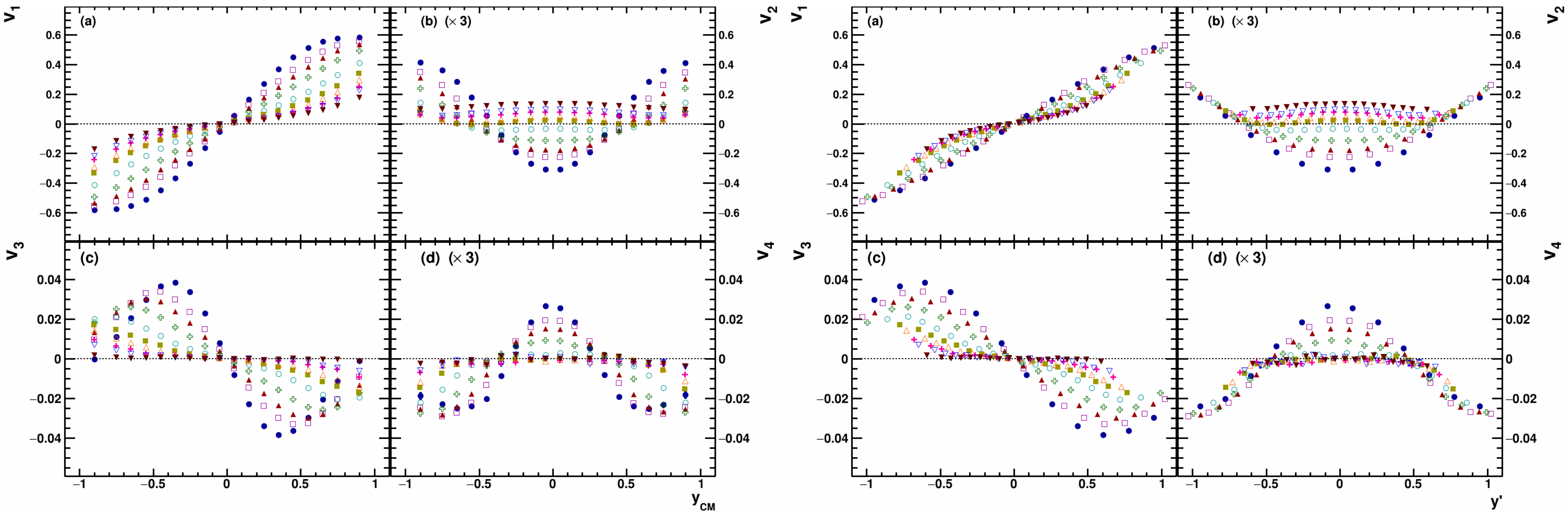
"Collective flow in heavy-ion collisions", W. Reisdorf, H.G. Ritter Ann.Rev. Nucl.Part.Sci. 47 (1997) 663-709 :

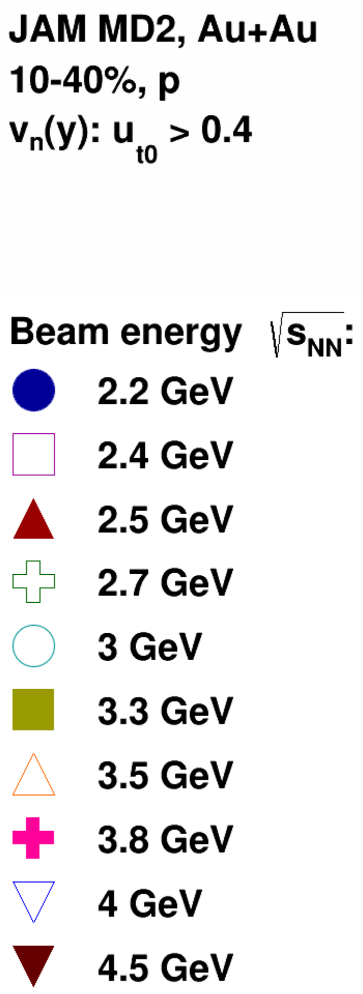
There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and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

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

y' scaling: mean-field models





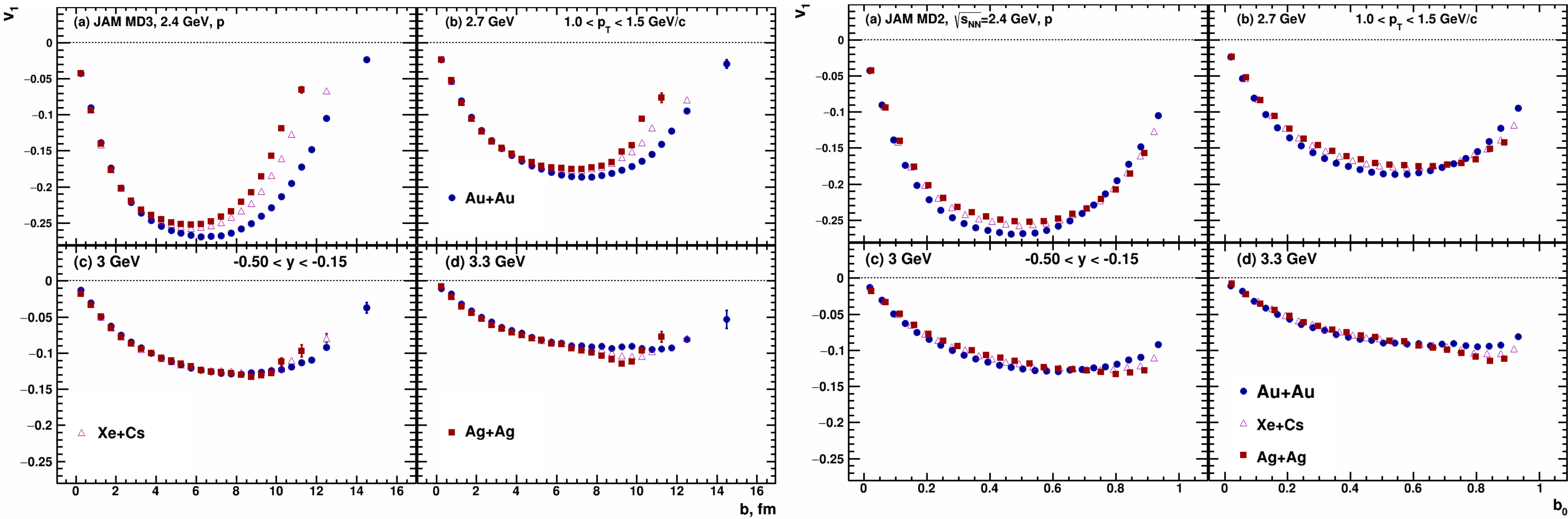
$$y' = y/y_{beam}\,, \qquad t_{pass} = \frac{2R}{\gamma_{CM}\beta_{CM}} \equiv \frac{2R}{\sinh y_{beam}}$$

- 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}

Scaling with system size

$$b_0 = {}^{b}/_{b_{max}}$$

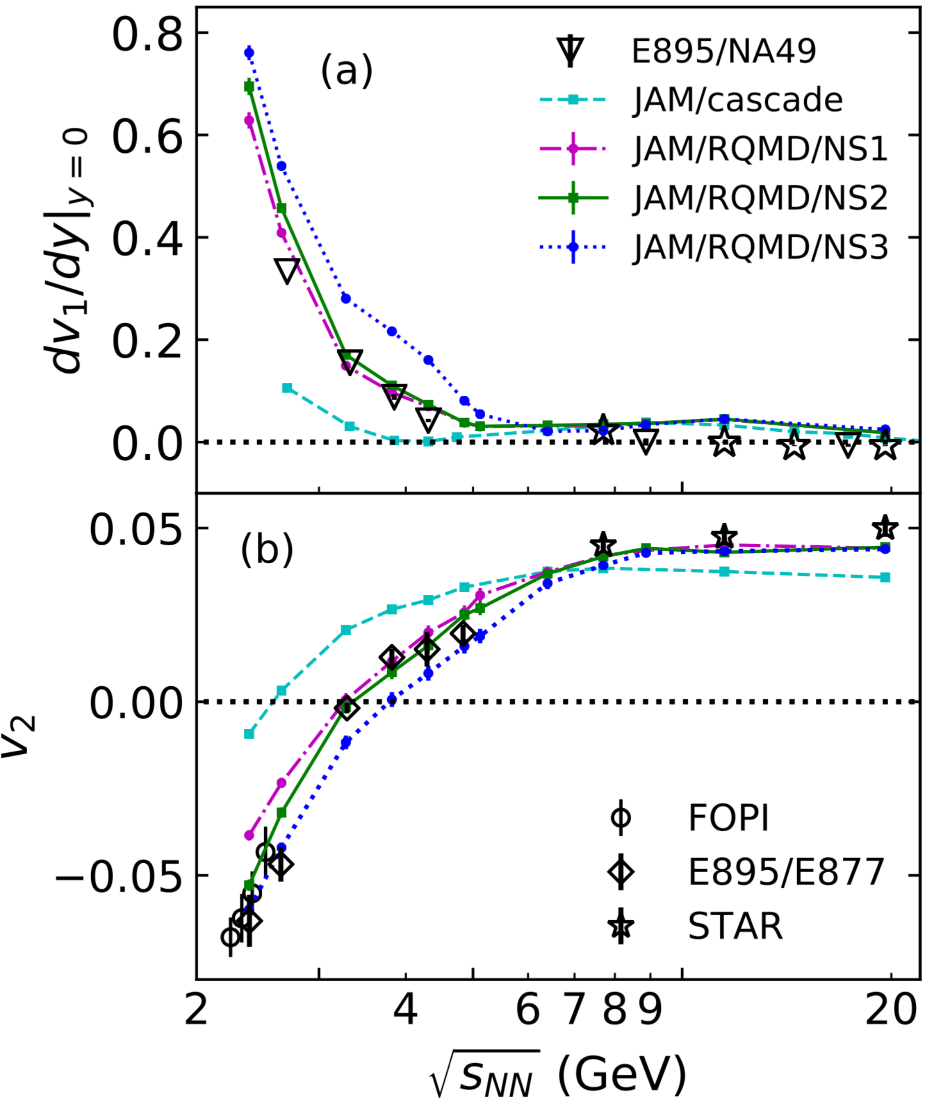
$$b_{max} = 1.15\left(A_{targ}^{1/3} + A_{proj}^{1/3}\right)$$



- Scaling with b_0 can be useful for comparison of the v_n results for different colliding systems
- Difference between v_n for Au+Au, Xe+Cs and Ag+Ag decreases with increasing $\sqrt{s_{NN}}$

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

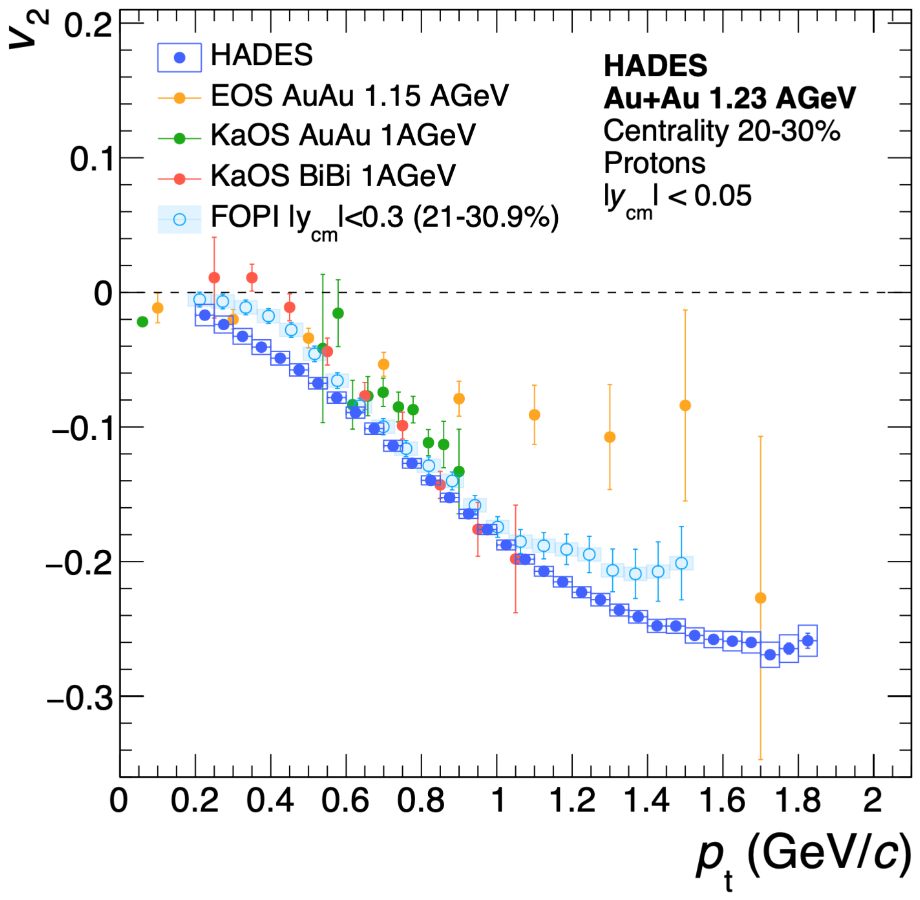
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

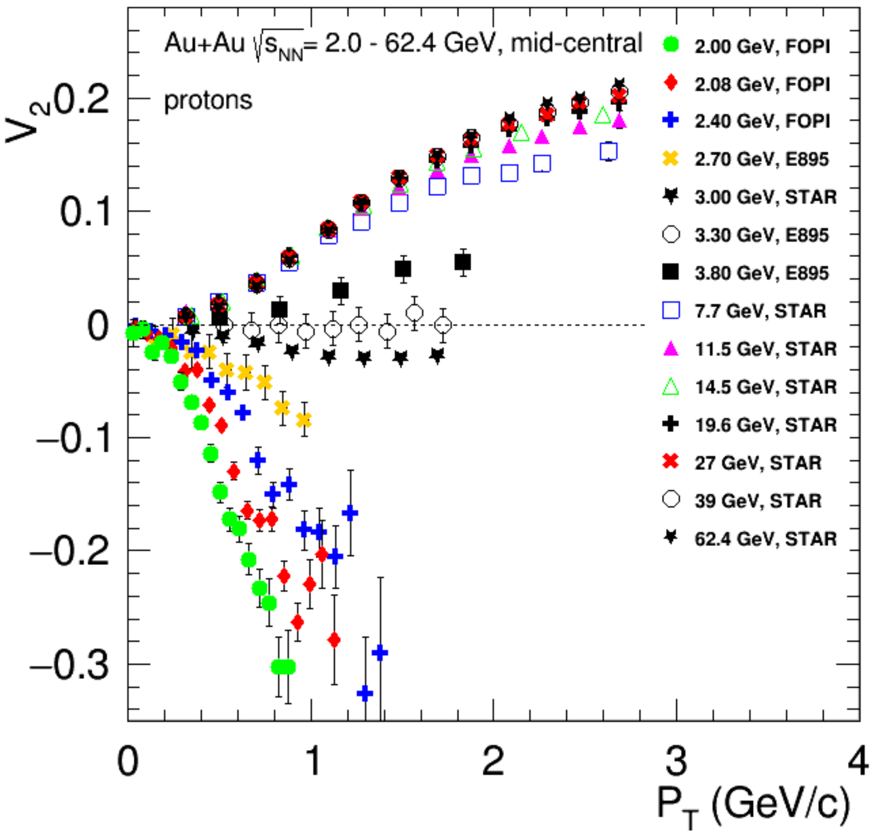
Different EOS were used:

- **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?

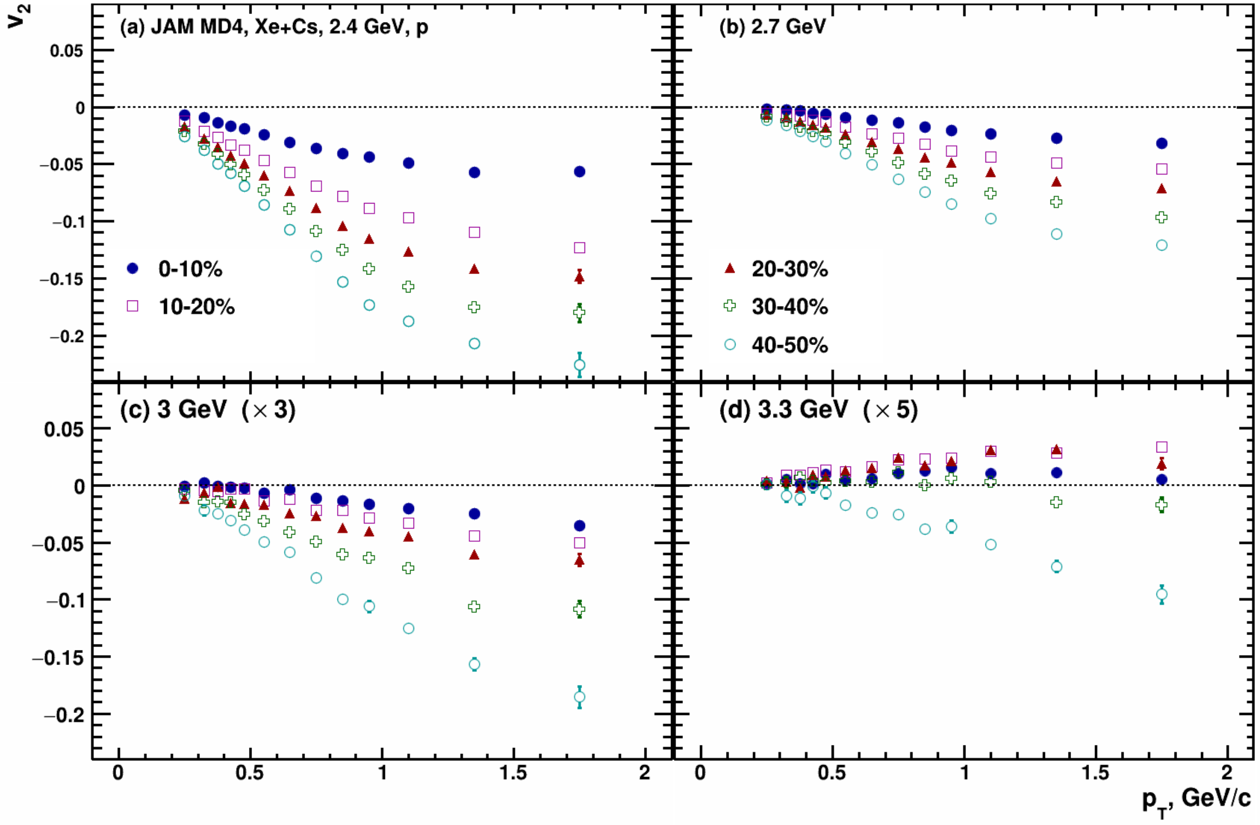


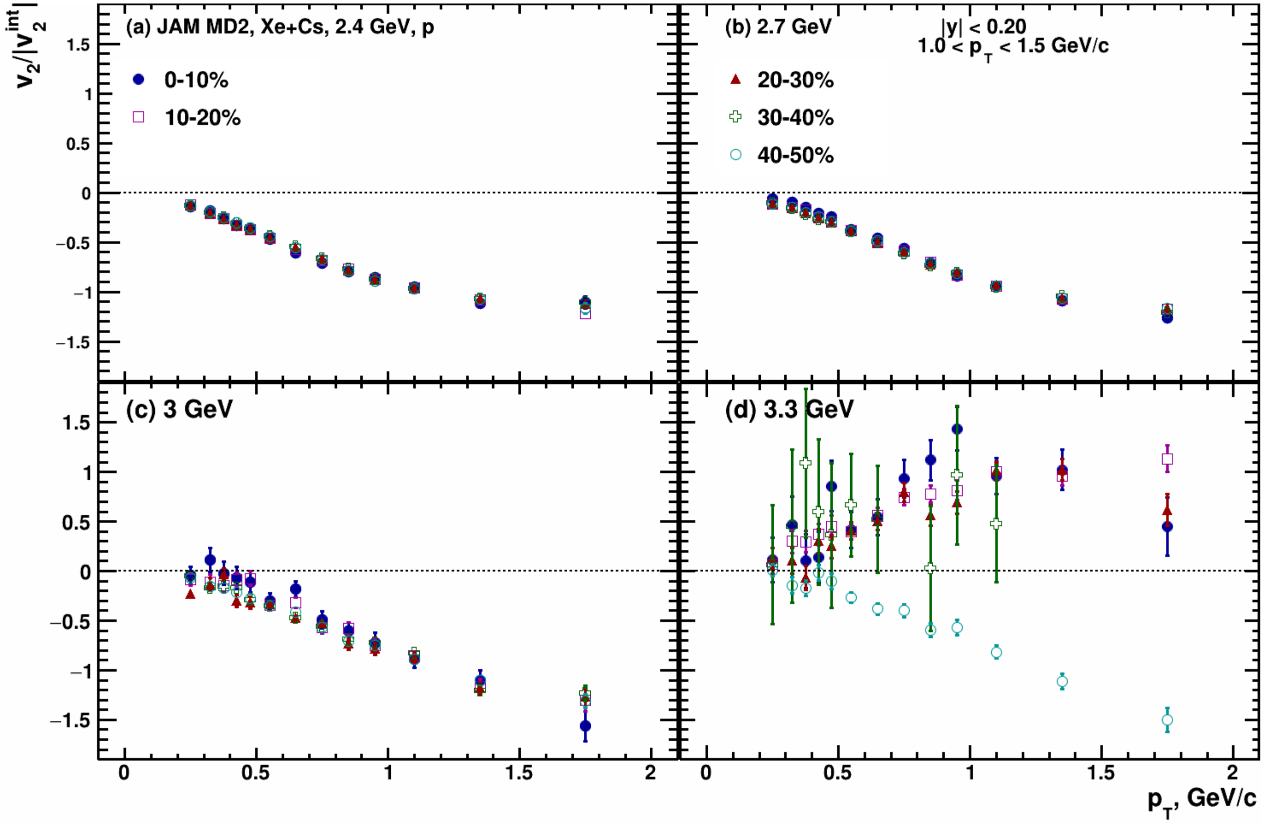


- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV), CBM ($\sqrt{s_{NN}}$=2.7-4.9 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments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

Scaling with integrated v_2

$$\left|v_2^{int}\right| = \left|\langle v_2(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}\right|$$





Scaling with integrated flow coefficient allows to perform comparison results from different centralities, beam energies and colliding systems

Scaling breaks at $\sqrt{s_{NN}} = 3.3$ GeV for v_2