Anisotropic flow measurements at Nuclotron-NICA and Equation of State

Petr Parfenov[1,2,3], Mikhail Mamaev[1,2,3], Valery Troshin[1,2], Arkadiy Taranenko[1,2]

With big help from Andrey Moshkin (VBLHEP JINR) and Dmitry Podgainy (LIT JINR)

[1]VBLHEP JINR, Dubna
[2]National Research Nuclear University MEPhI, Moscow
[3]INR RAS, Moscow

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Outline

- **Introduction:**
  - EoS for high badyon density matter
- **Anisotropic flow at Nuclotron-NICA**
  - Extracting EoS information using v_n
- **Comparison of v_n results from models and experiments**
  - Comparison with HADES, STAR results
- **Study of the E_{sym} at Nuclotron-NICA**
- **Summary and Outlook**

EOS for high baryon density matter

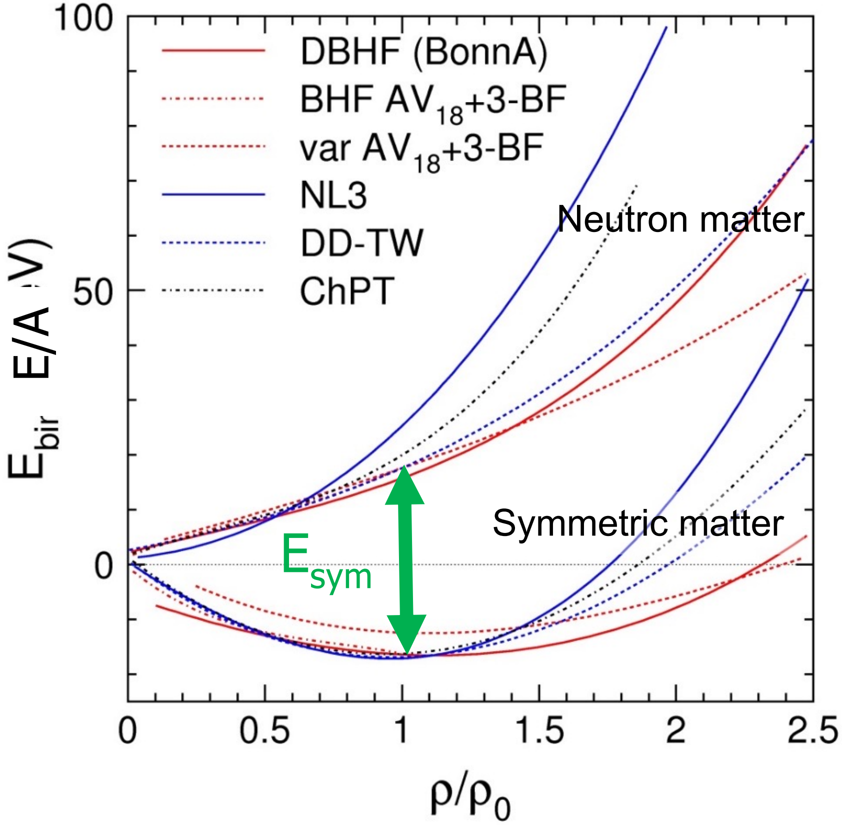
The binding energy per nucleon: $E_A(\rho, \delta) = \boxed{E_A(\rho, 0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

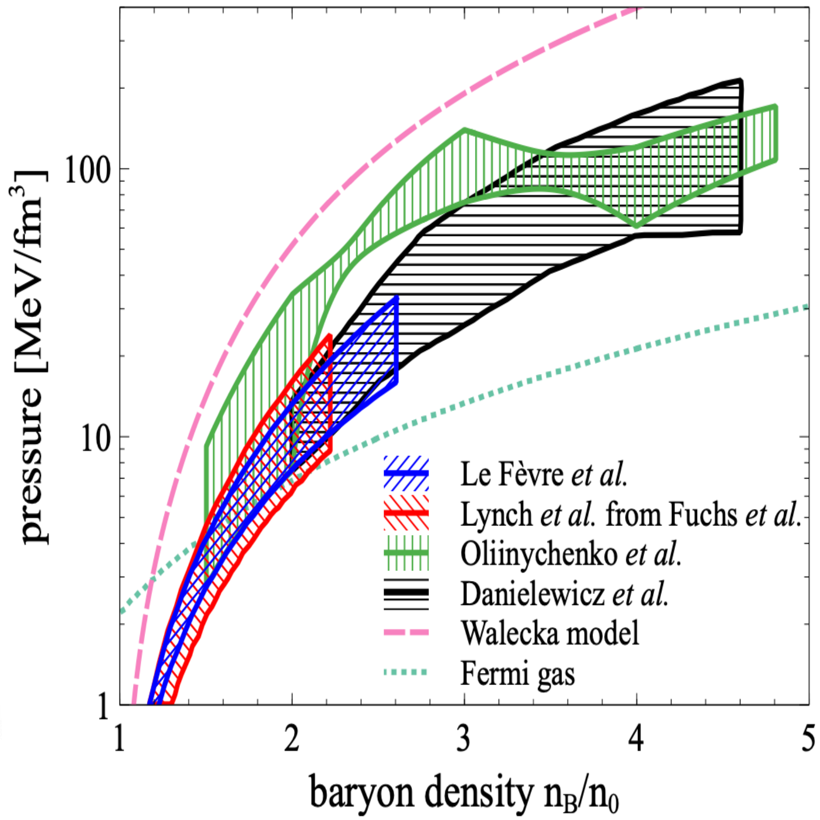
Isospin asymmetry:

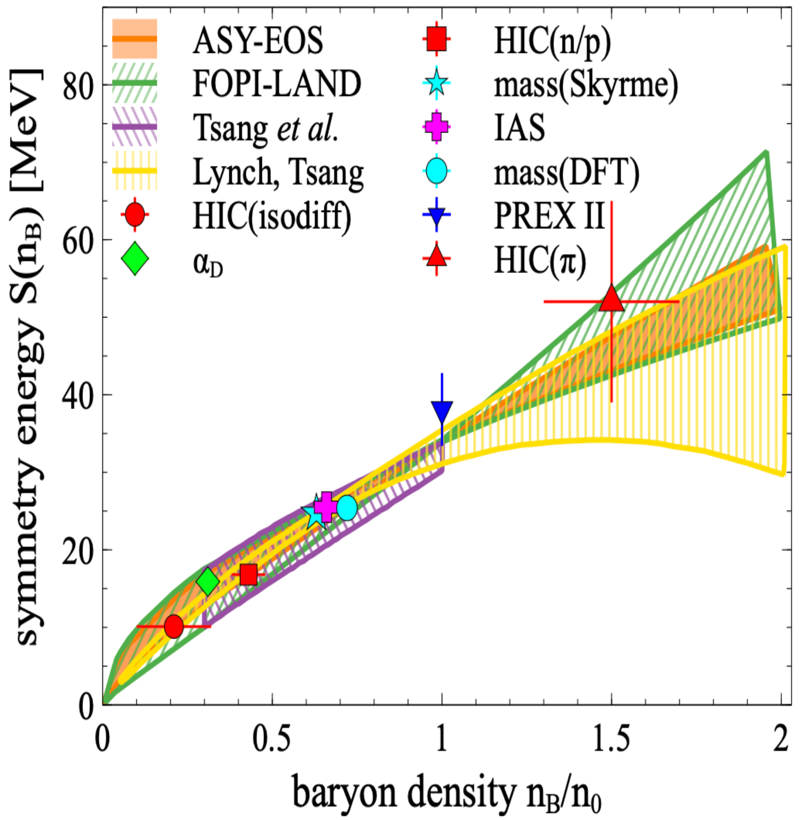
$$\delta = (\rho_n - \rho_p)/\rho$$

Symmetric matter

Symmetry energy





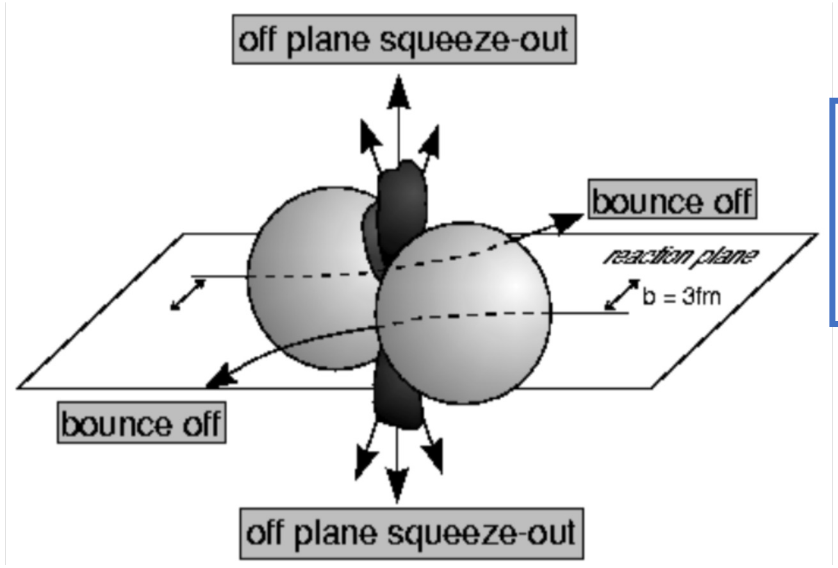


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

New data is needed to further constrain transport models with hadronic d.o.f.

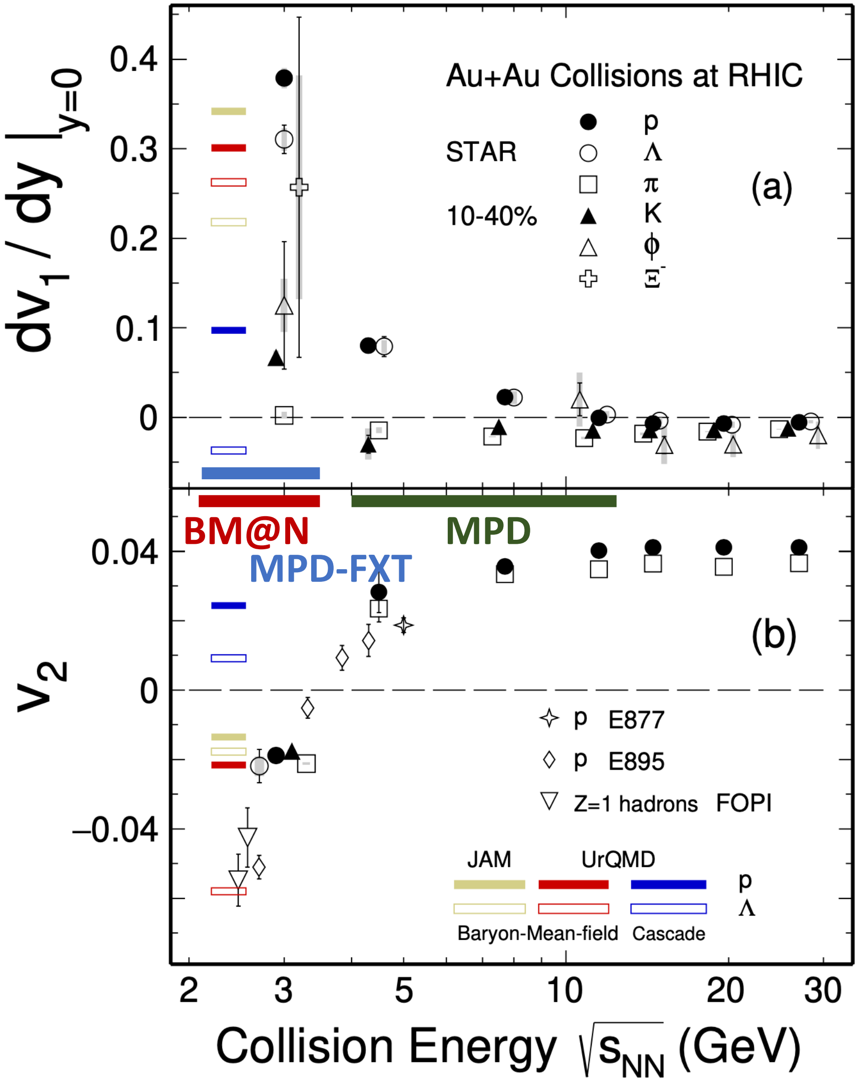
Anisotropic flow at Nuclotron-NICA energies



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

v_1 – directed flow, v_2 – elliptic flow

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



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

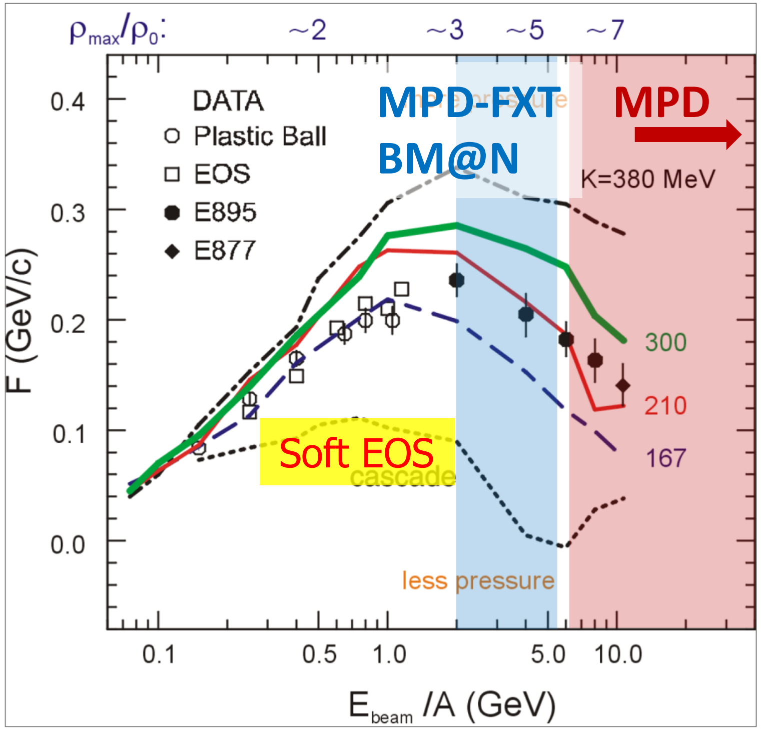
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$)

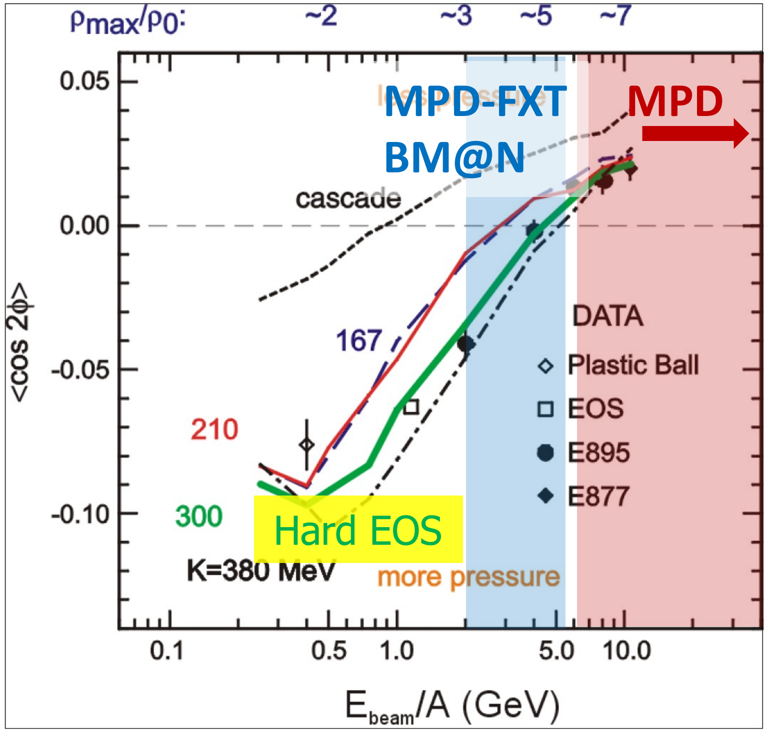
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Sensitivity of the collective flow to the EOS

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



$$F = \left. \frac{d\langle p_x/A \rangle}{d(y/y_{cm})} \right|_{y/y_{cm}=1}$$



$$v_2 \equiv \langle \cos(2(\varphi - \Psi_{RP})) \rangle$$

EoS extraction: define incompressibility

$$K_0 = 9\rho^2 \frac{\partial^2(E_A)}{\partial \rho^2}$$

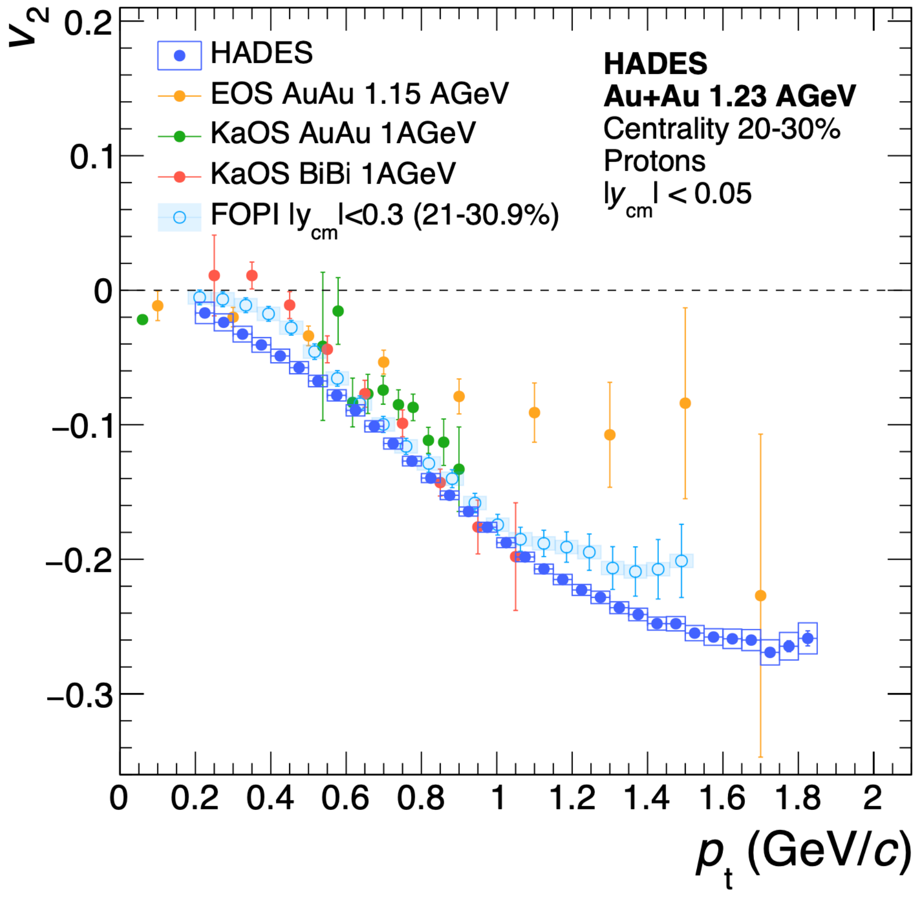
Discrepancy in the interpretation:

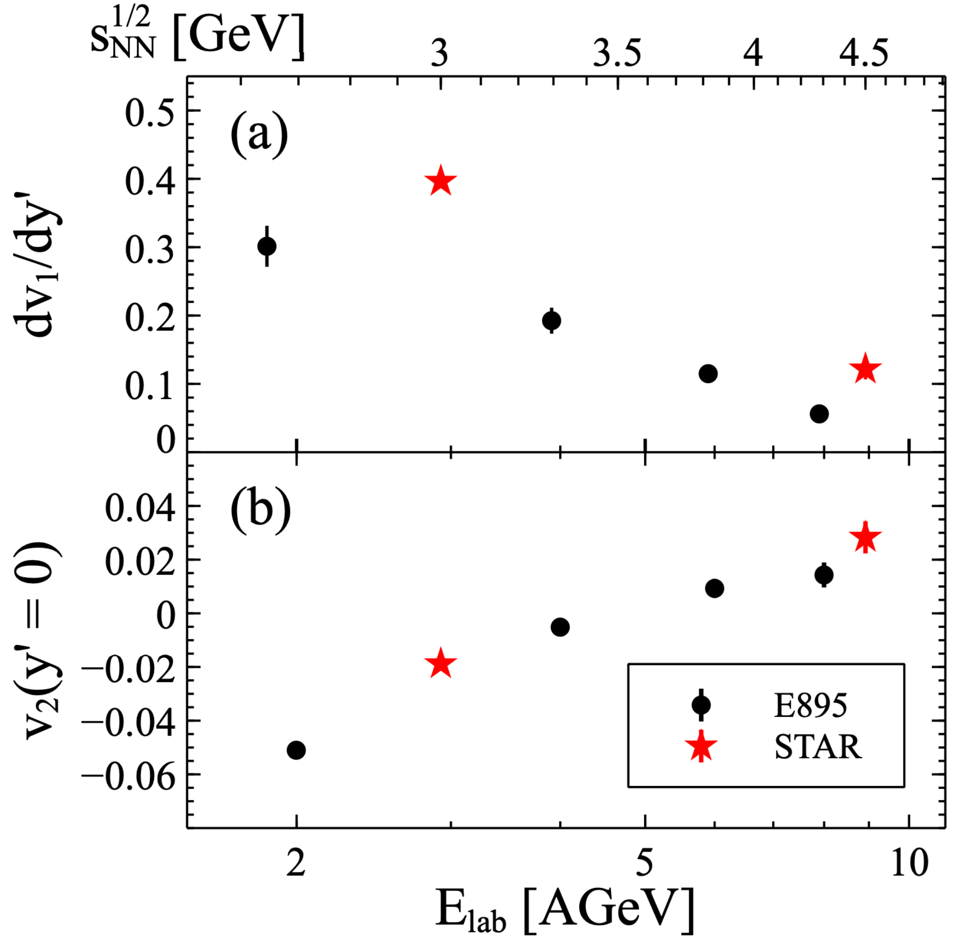
- v_1 suggests soft EoS (K_0≈210 MeV)
- v_2 suggests hard EoS (K_0≈380 MeV)

New measurements using new data and modern analysis techniques might address this discrepancy

Additional measurements are essential to clarify the previous results

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

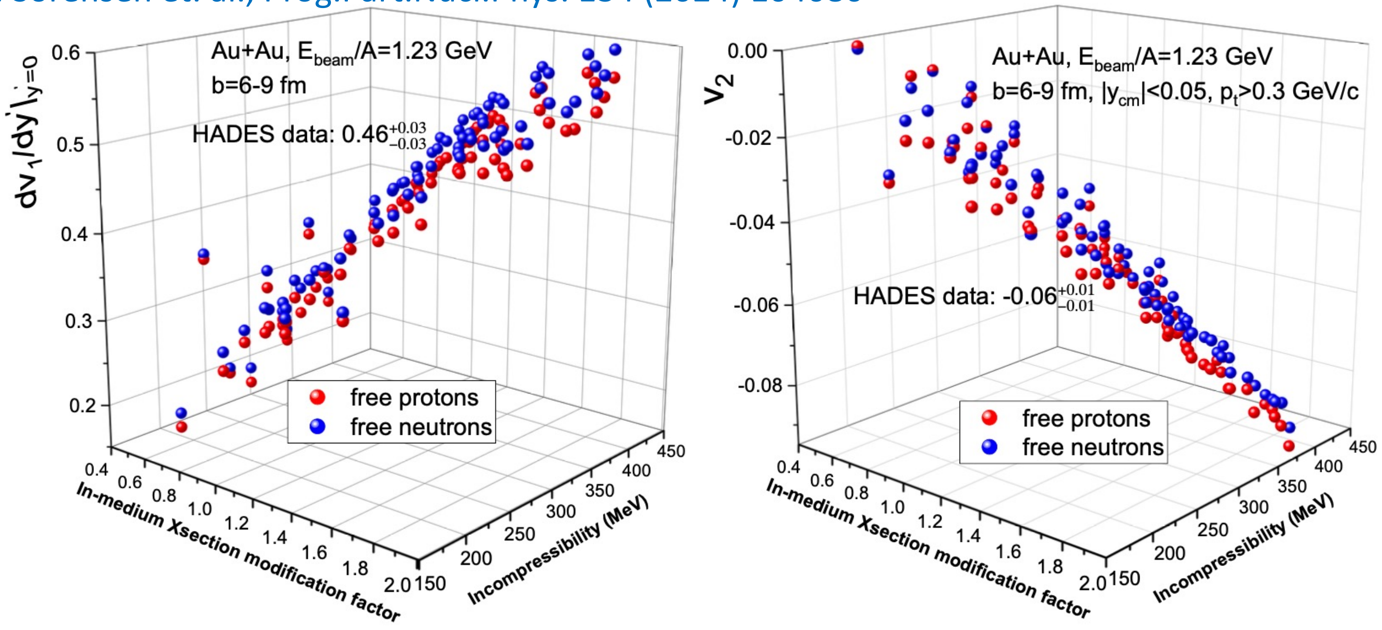




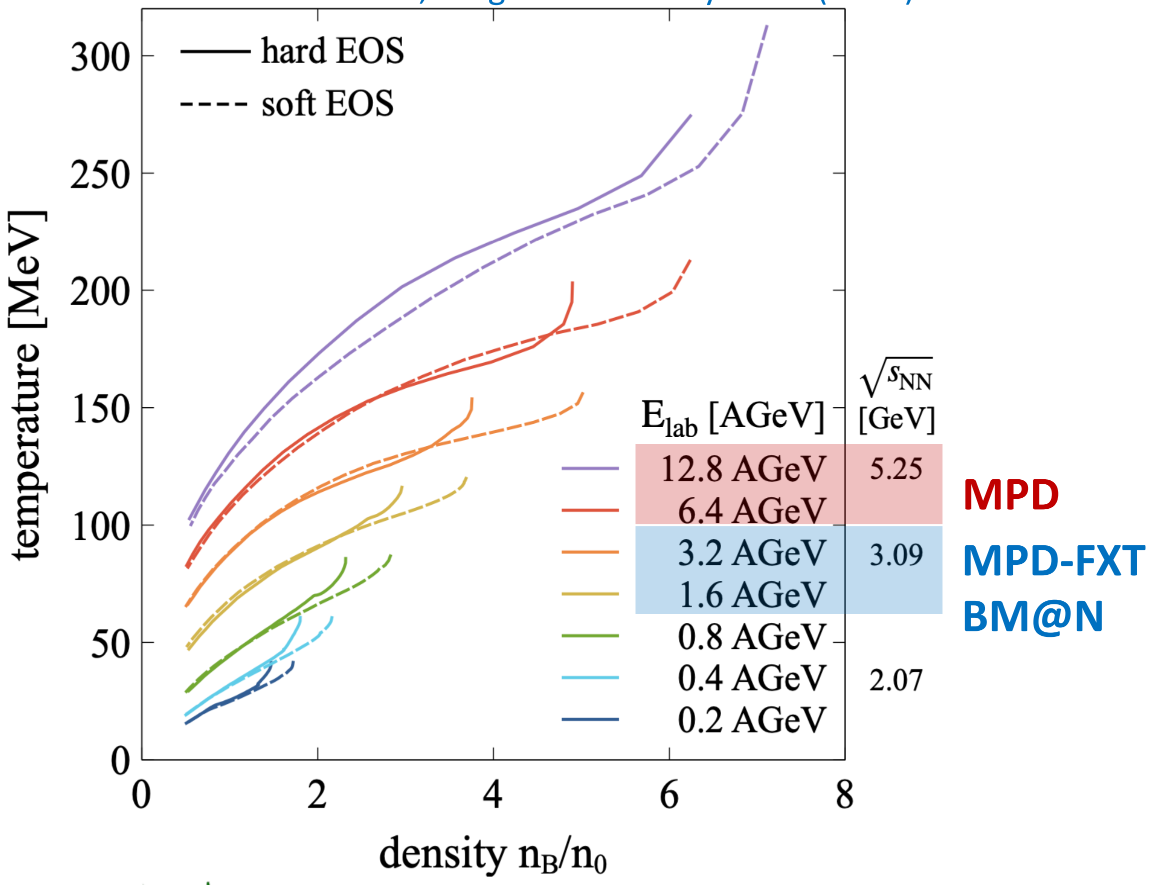
- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust v_n measurements

Sensitivity of the collective flow to the EOS

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

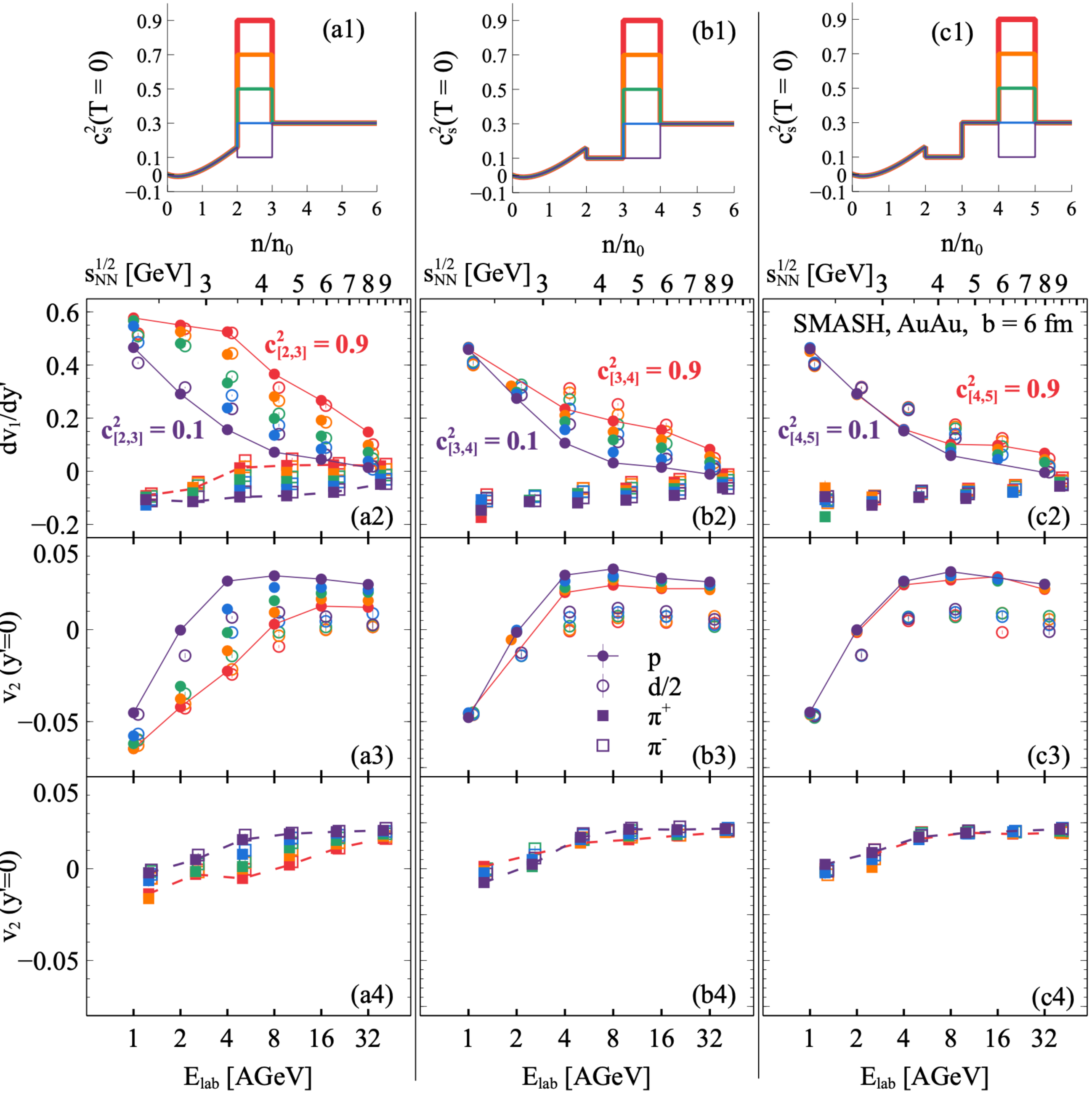


Incompressibility K_0:
parameter which specifies the behavior of EOS in the given baryon densities $K_0 = K_0(n_B)$

Models with flexible EOS for different (K_0, n_B) are required

Nuclotron-NICA coverage in terms of density: $2 \lesssim n_B/n_0 \lesssim 8$

Sensitivity of the collective flow to the EOS

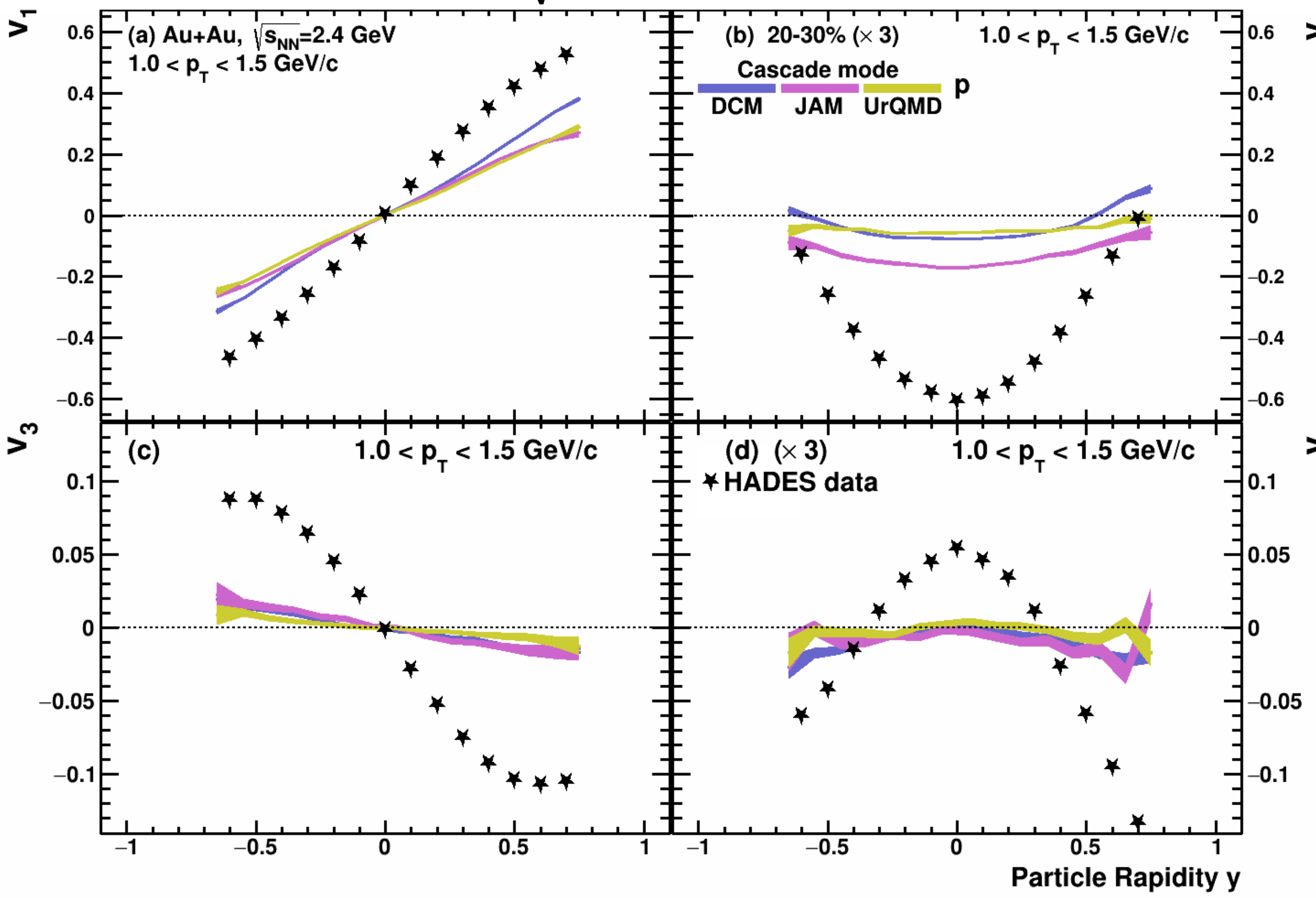


A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

- SMASH model with flexible EOS was used to test the sensitivity of the v_n to changes of EOS in a specific density range n/n_0:
  - $\mathbf{2 < n_B/n_0 < 3}$: dv_1/dy' and v_2 of pions, protons and deuterons are very sensitive to the EOS
  - $\mathbf{3 < n_B/n_0 < 4}$: dv_1/dy' and v_2 of protons and deuterons are sensitive to the EOS
  - $\mathbf{4 < n_B/n_0 < 5}$: weak sensitivity to the EOS

The most precise constraints can be achieved from the flow of identified hadrons (*π*±,*K*±,*p*,…) and light nuclei (*d*,*t*,…)

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models



P. Parfenov, Particles 5, no.4, 561-579 (2022)

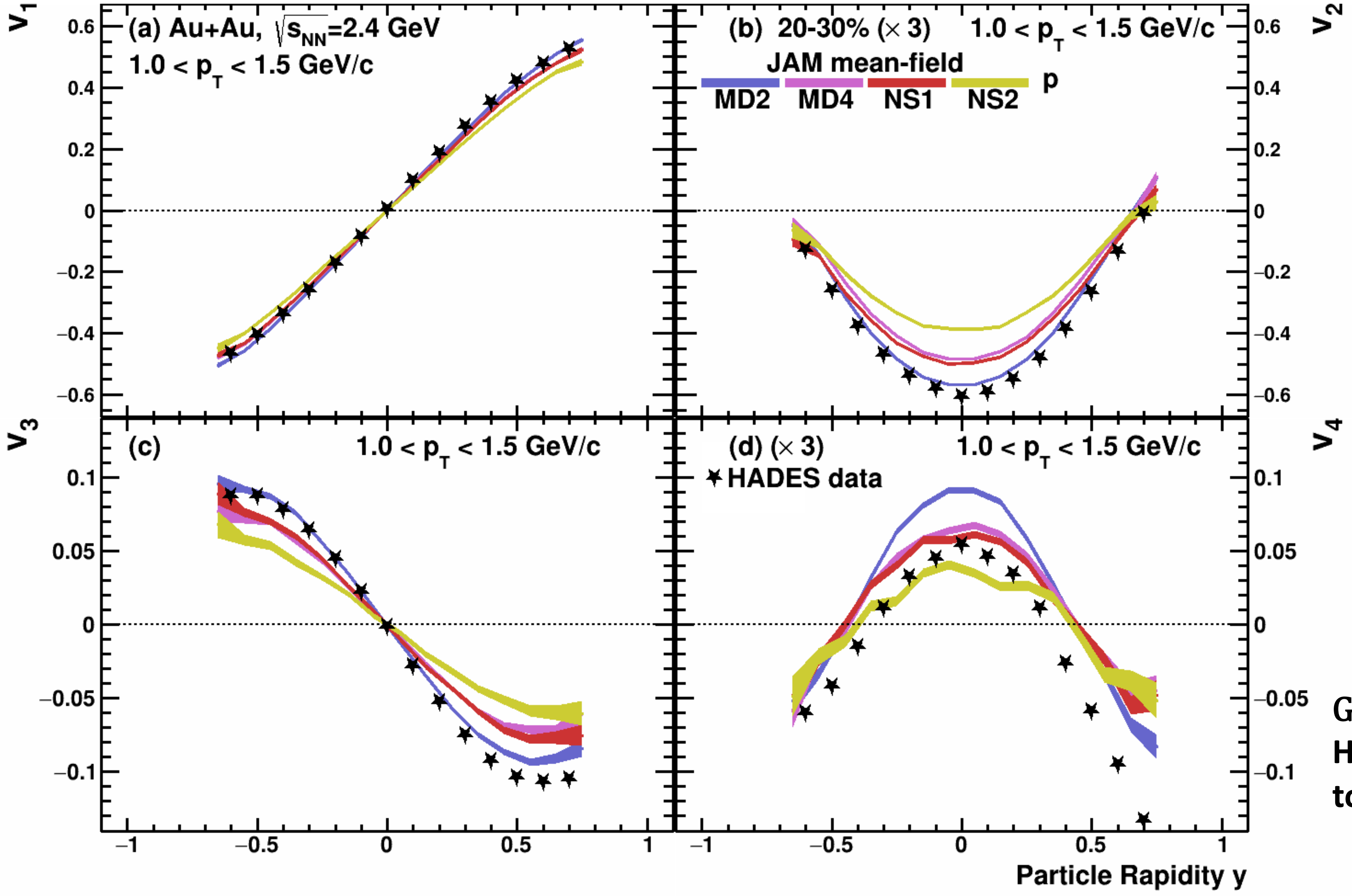
Kinematic cuts:

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

$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Cascade models fail to reproduce HADES experimental data

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data



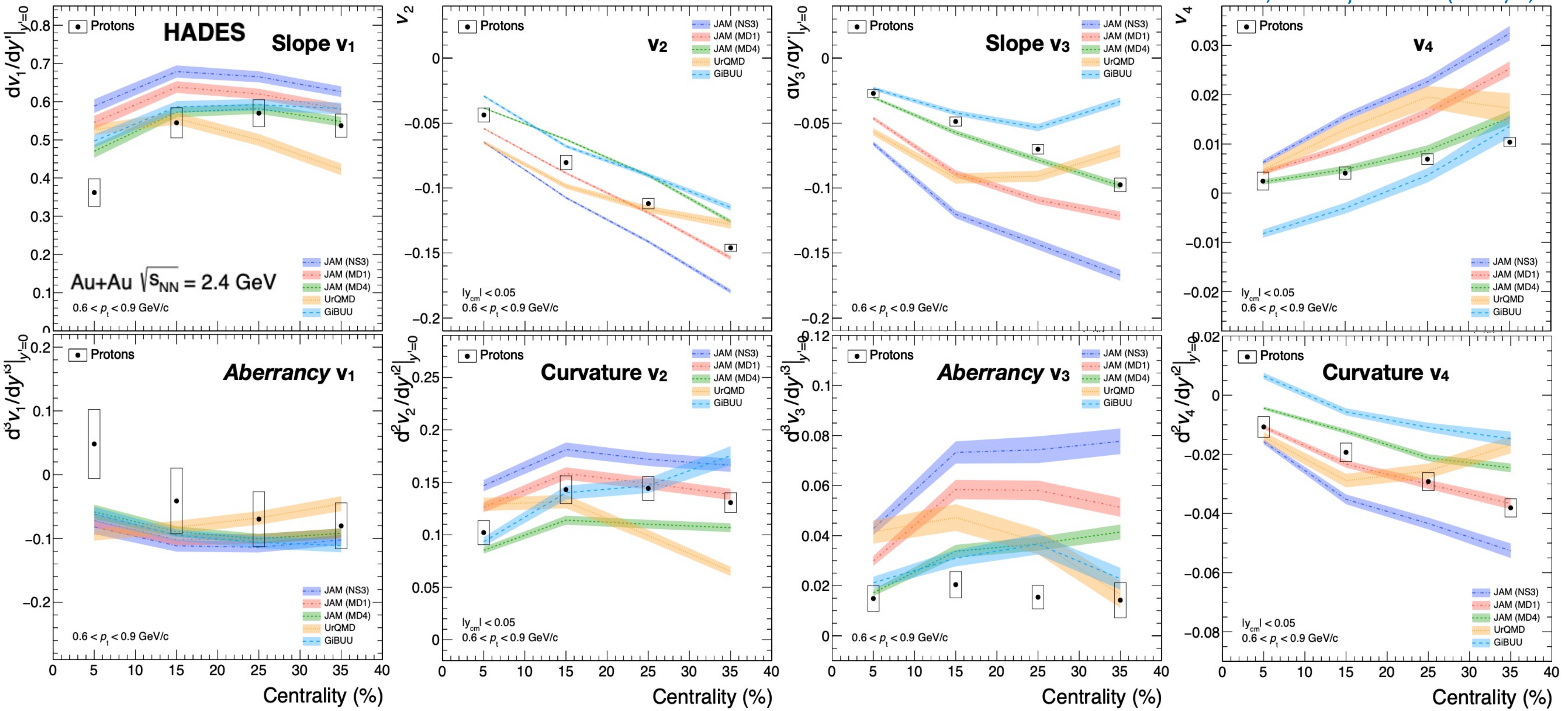
P. Parfenov, Particles 5, no.4, 561-579 (2022)

Kinematic cuts:
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Good agreement for $v_n(y)$
Higher harmonics are more sensitive to different EOS than v_1

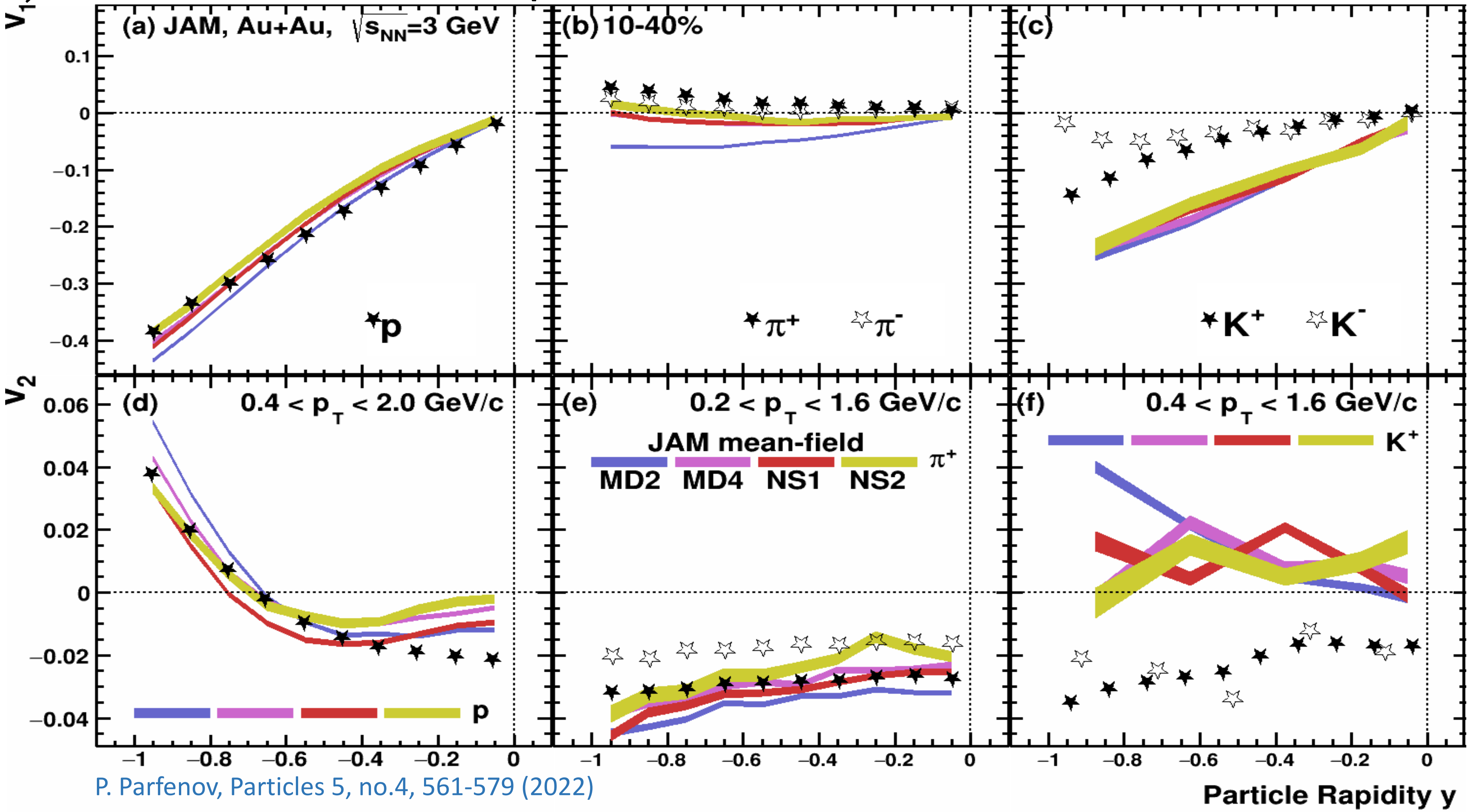
$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data

HADES, Eur. Phys. J. A 59 (2023) 4, 80



Overall trend reasonably well described, but no model works everywhere

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



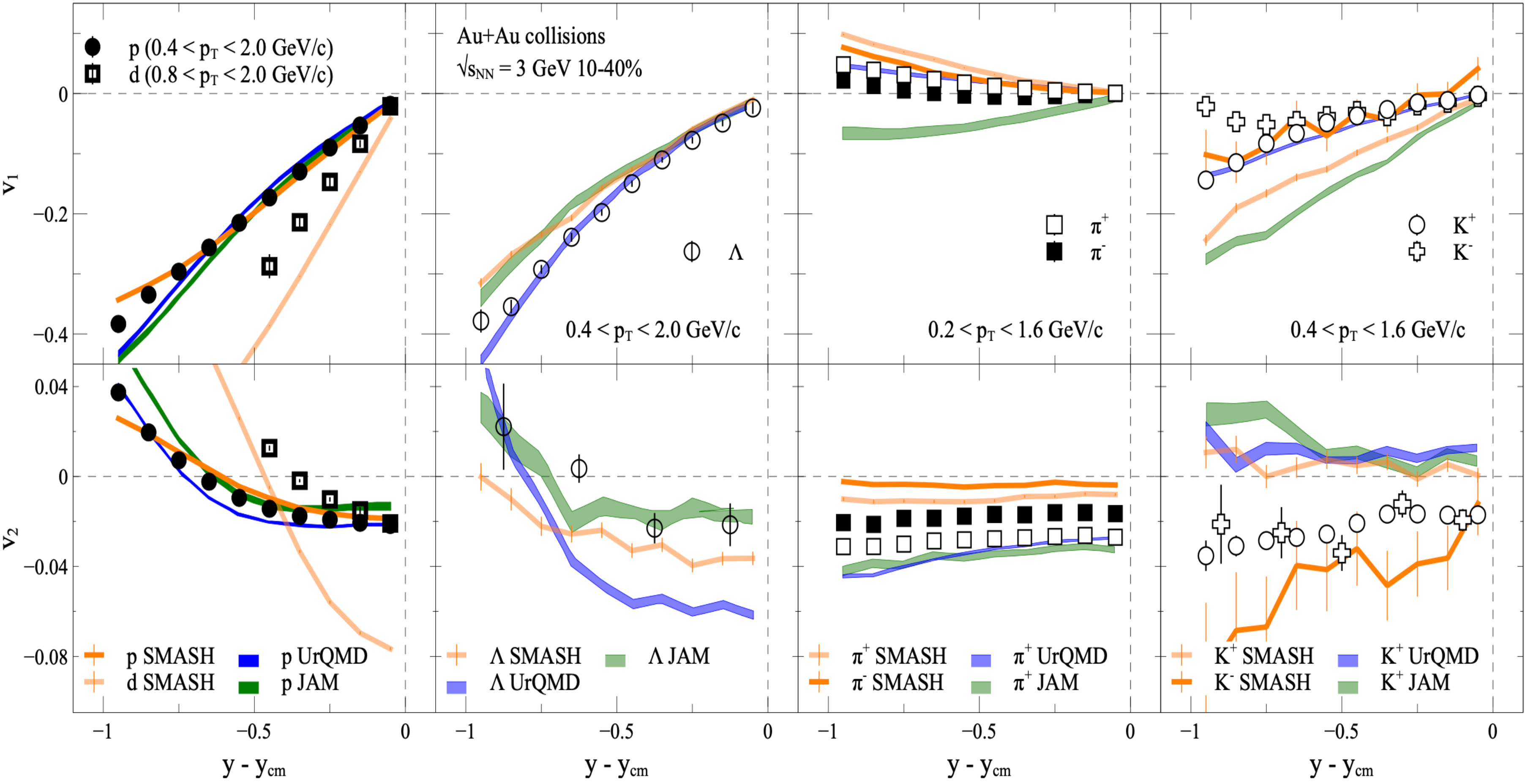
P. Parfenov, Particles 5, no.4, 561-579 (2022)

Models do not describe all particle species equally well

v_1, v_2 of protons are described by JAM, UrQMD (hard EOS) and SMASH (hard EOS with softening at higher densities)

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



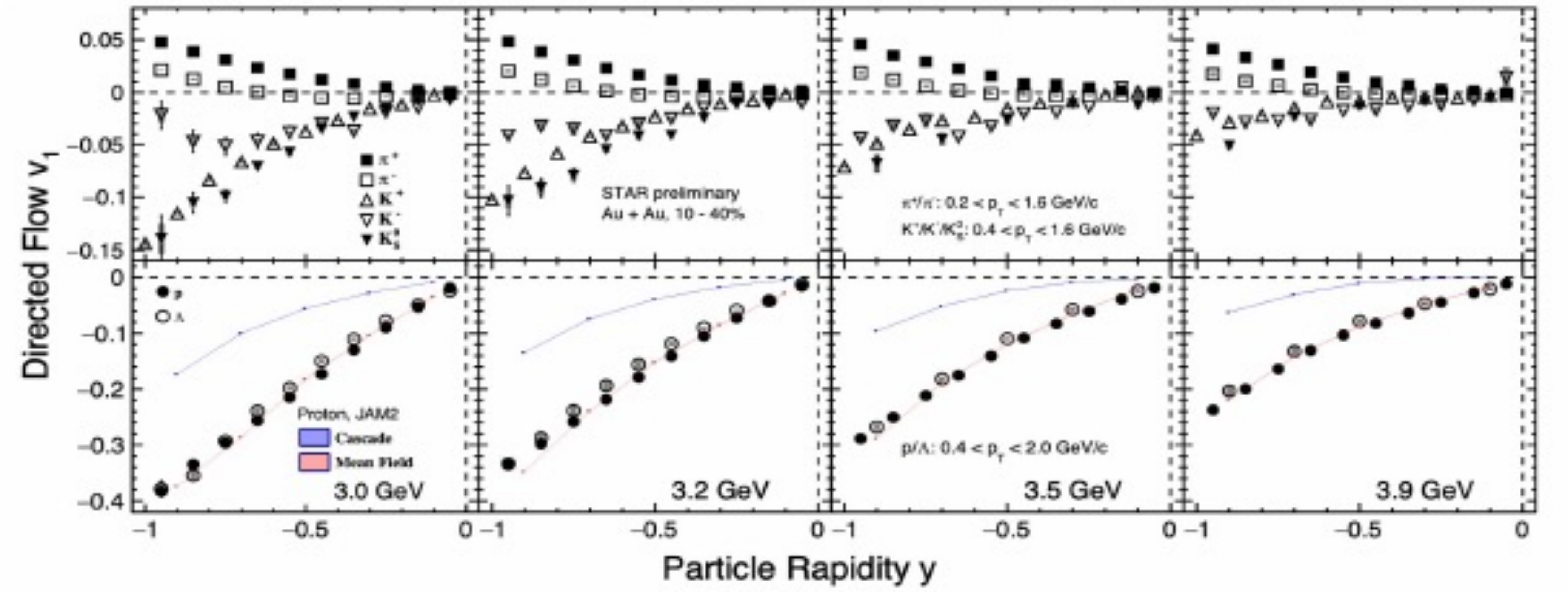
Model description of v_n:

- Good overall agreement for v_n of protons
- v_n of light nuclei is not described
- v_n of Λ is not well described
  - nucleon-hyperon and hyperon-hyperon interactions
- Light mesons (π,K) are not described
  - No mean-field for mesons

Models have a huge room for improvement in terms of describing v_n

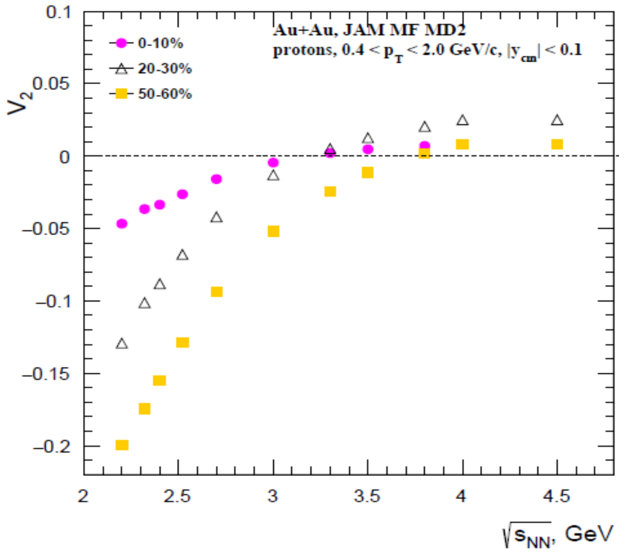
New STAR results from BES-II

Results from QM 2023

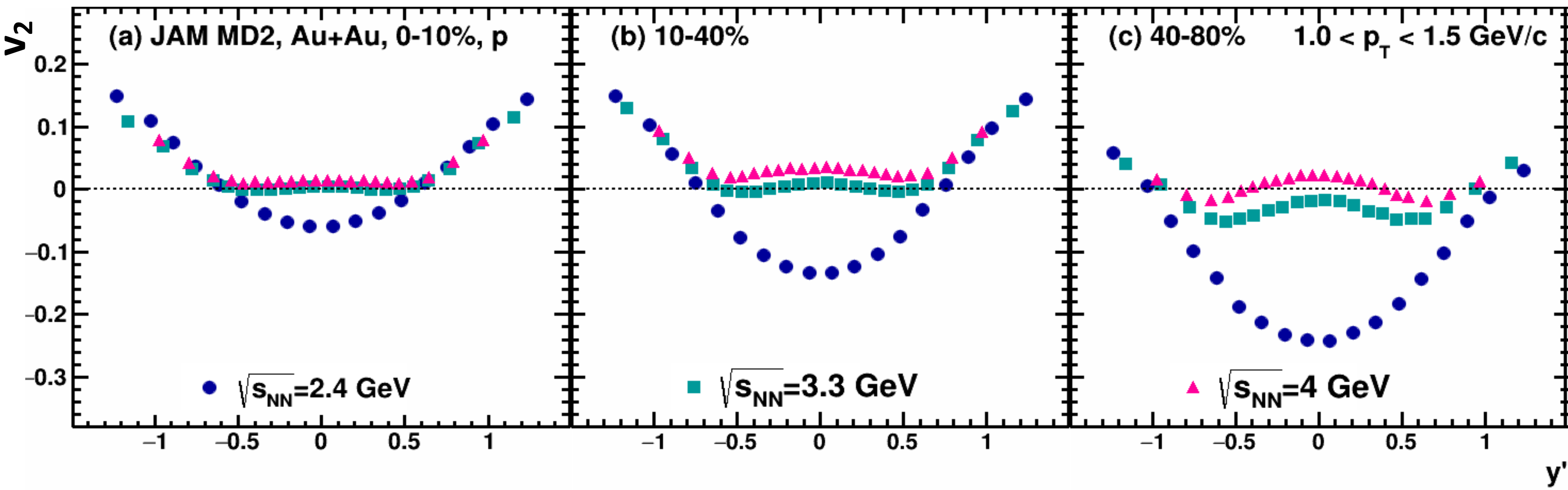


New preliminary results from STAR BES-II were presented at QM-2023 for Au+Au at $\sqrt{s_{NN}}$=3, 3.2, 3.5, 3.9 GeV

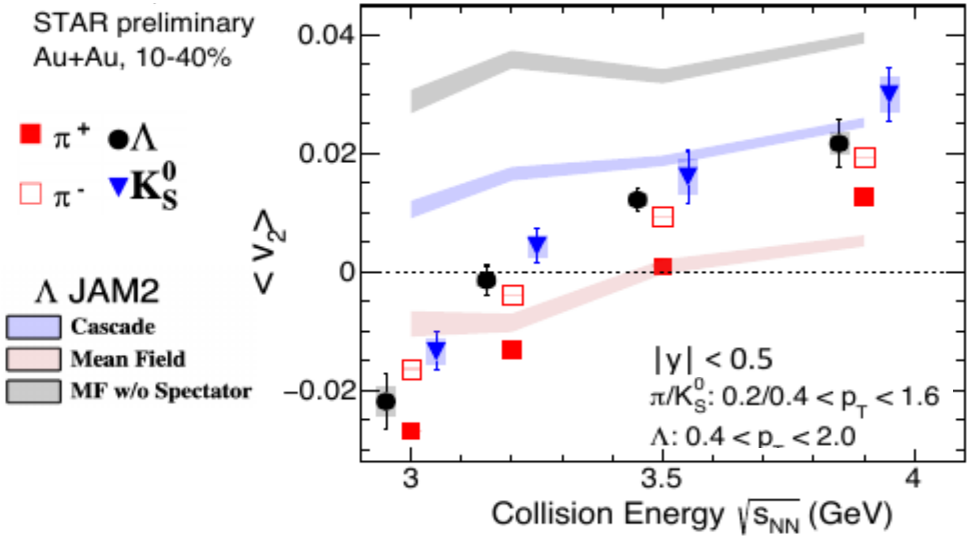
v_2 transition from out-of-plane to in-plane



P. Parfenov, Particles 5, no.4, 561-579 (2022)



Results from QM 2023



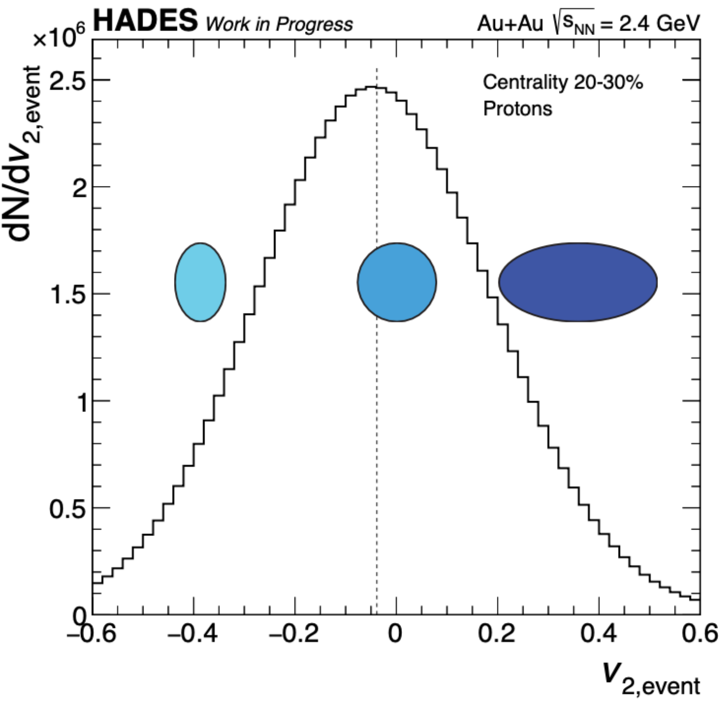
Transition of v_2 from out-of-plane to in-plane can be a good tool to constrain models and extract information about EOS

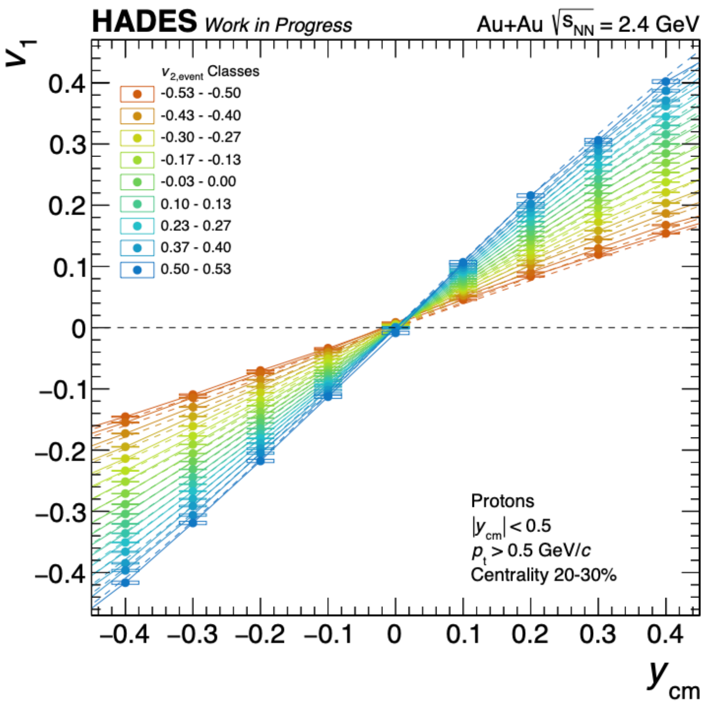
- $v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV for central and mid-central collisions for protons
- $v_2 < 0$ for peripheral collisions
- Models can not reproduce v_2 of $\pi^{\pm}$, $K^{\pm}$, $K^0{}_S$, Λ

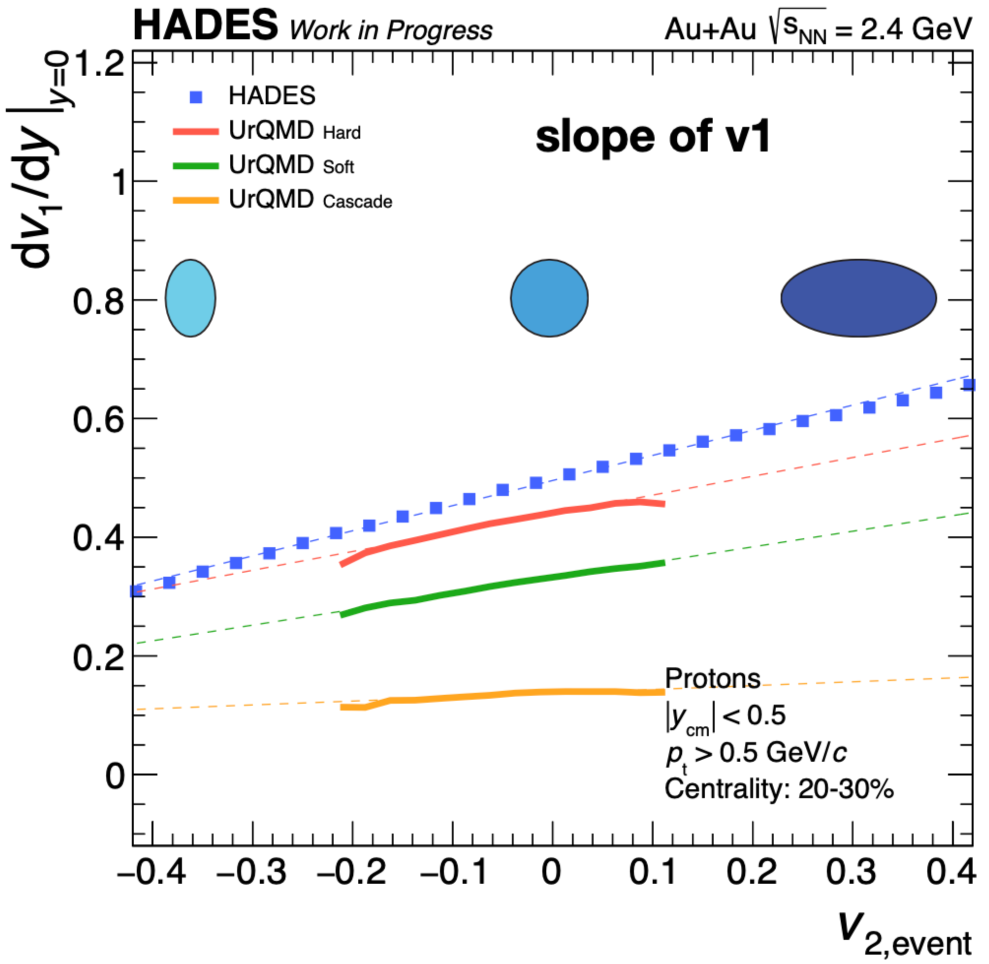
Transition from out-of-plane to in-plane depends on centrality, rapidity and particle species

Event-wise flow correlations

B. Kardan, EMMI Workshop 2024



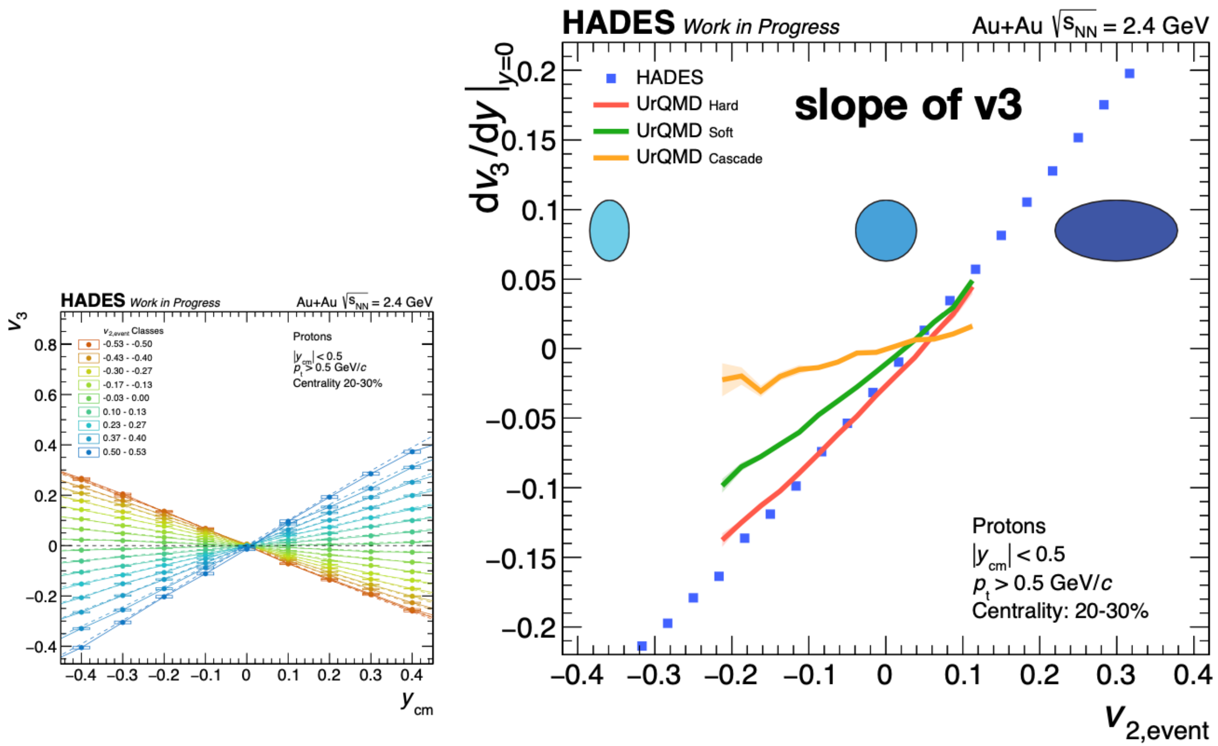




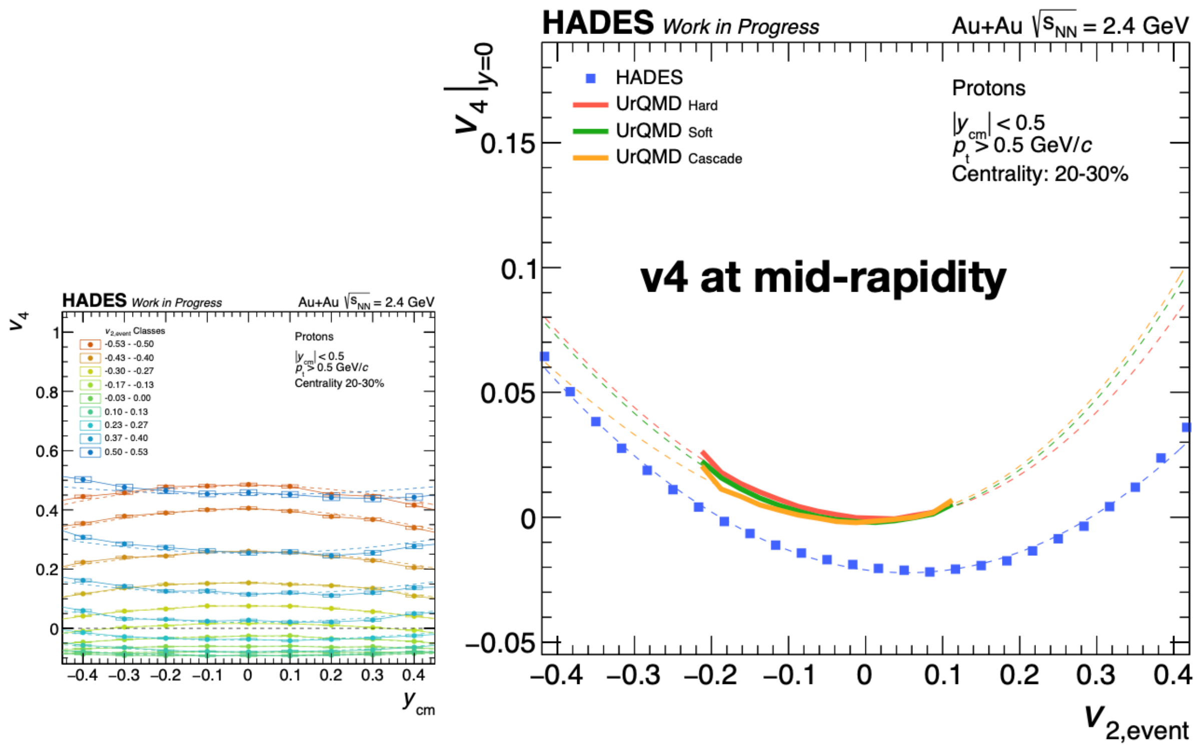
- Events can be characterized based on the event-wise magnitude of the elliptic flow $v_{2,event}$
- UrQMD can not discribe $dv_1/dy|_{y=0}$ of protons as a function of $v_{2,event}$
- Strong sensitivity to the EOS

Event-wise flow correlations

B. Kardan, EMMI Workshop 2024



$dv_3/dy|_{y=0}$ of protons as a function of $v_{2,event}$ shows strong sensitivity to EoS

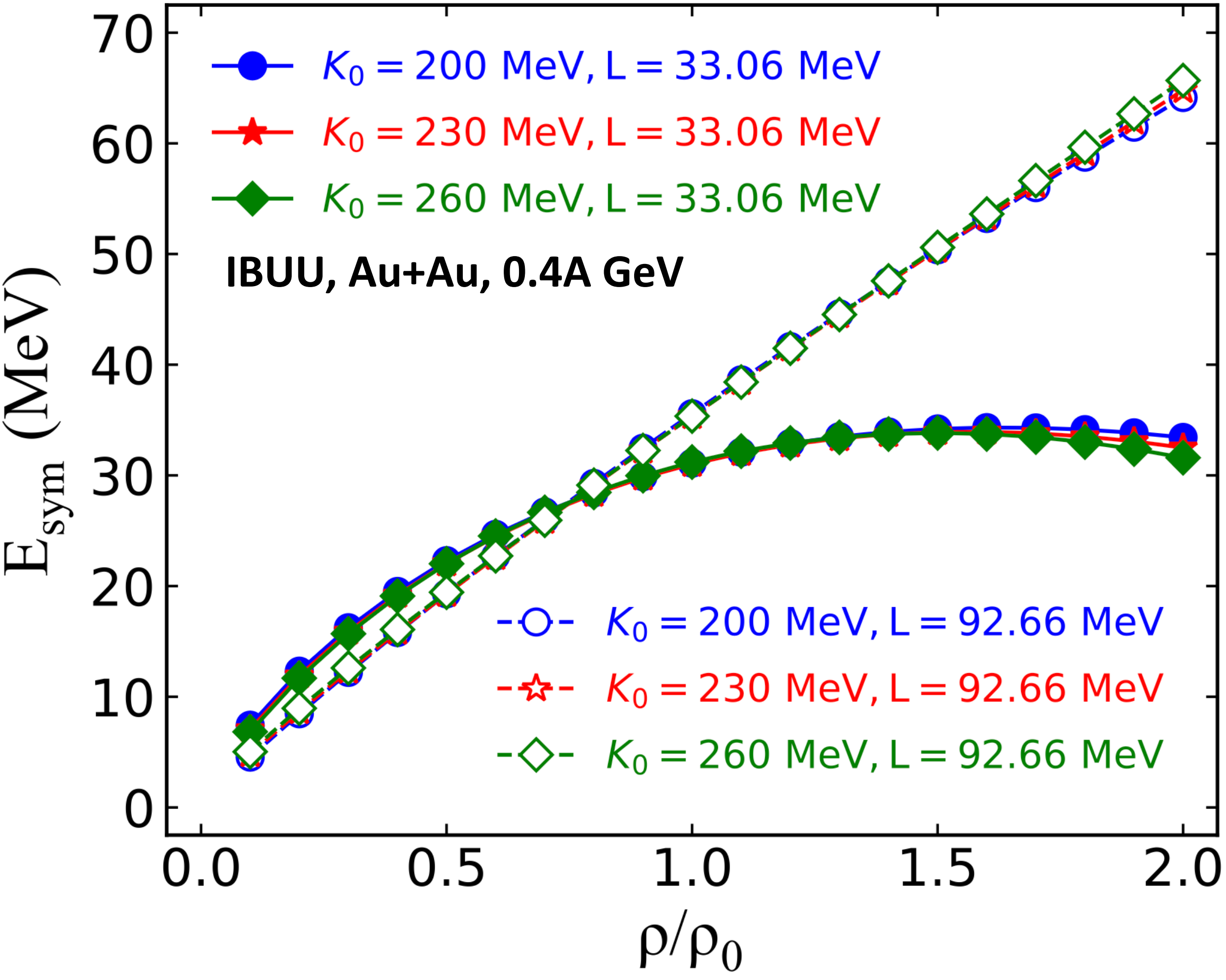


Models overestimate v_4 of protons as a function of $v_{2,event}$ compared to the HADES data

Mean-field models do not reproduce experimental data on the event-wise flow correlations of protons

Symmetry energy in high-density region

X.X. Long, G.F. Wei, arXiv:2402.12912 (2024)



- Nuclotron-NICA density region:

$$\mathbf{2 \lesssim n_B/n_0 \lesssim 8}$$

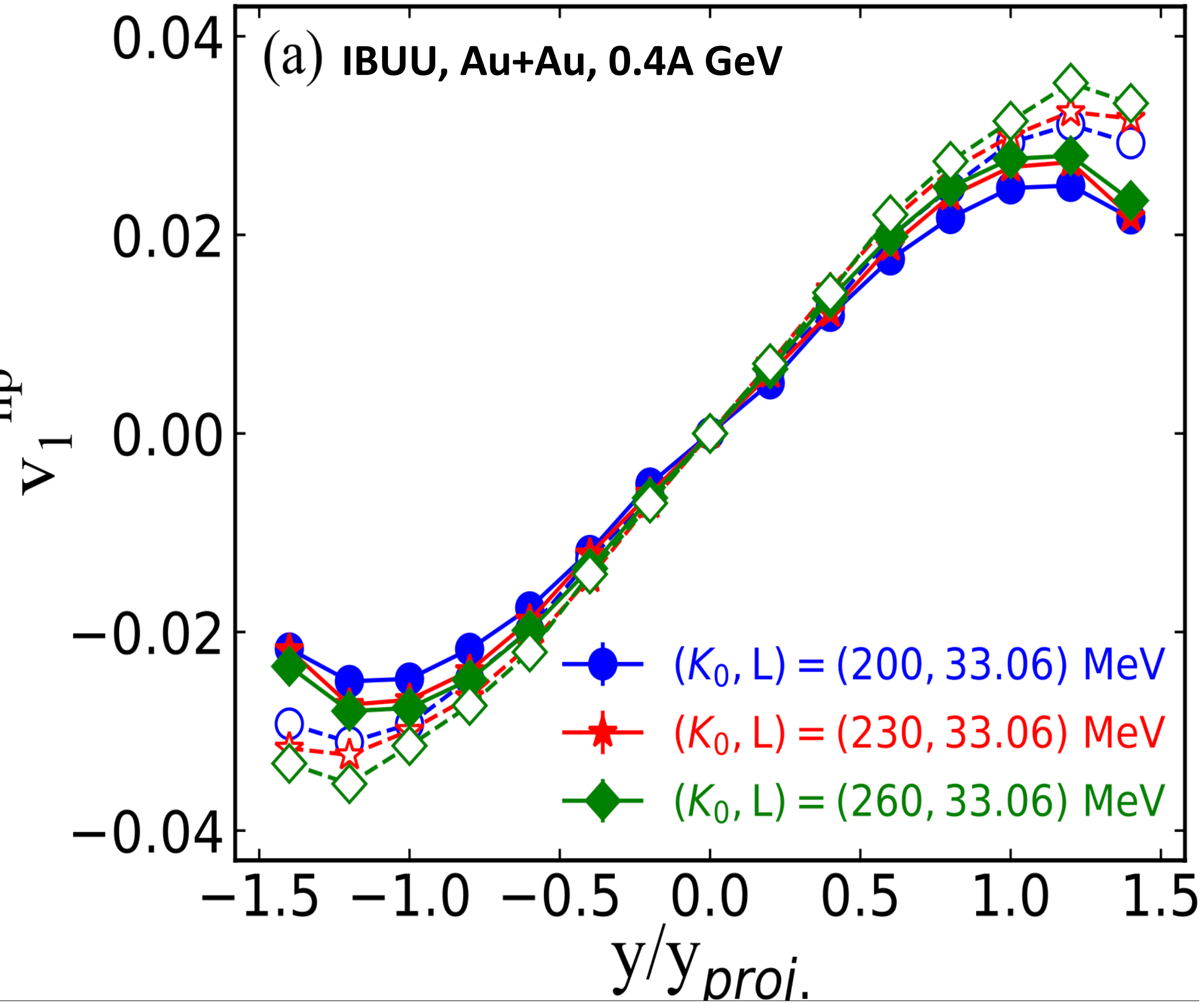
- Symmetry energy E_{sym} has strong density dependence and can be described with its slope *L*:

$$L = 3\rho \frac{dE_{sym}(\rho)}{d\rho}$$

What observables can we use to extract information about *L*?

Using v_1^{np} to study L

X.X. Long, G.F. Wei, arXiv:2402.12912 (2024)



One can define free neutron-proton differential directed flow:

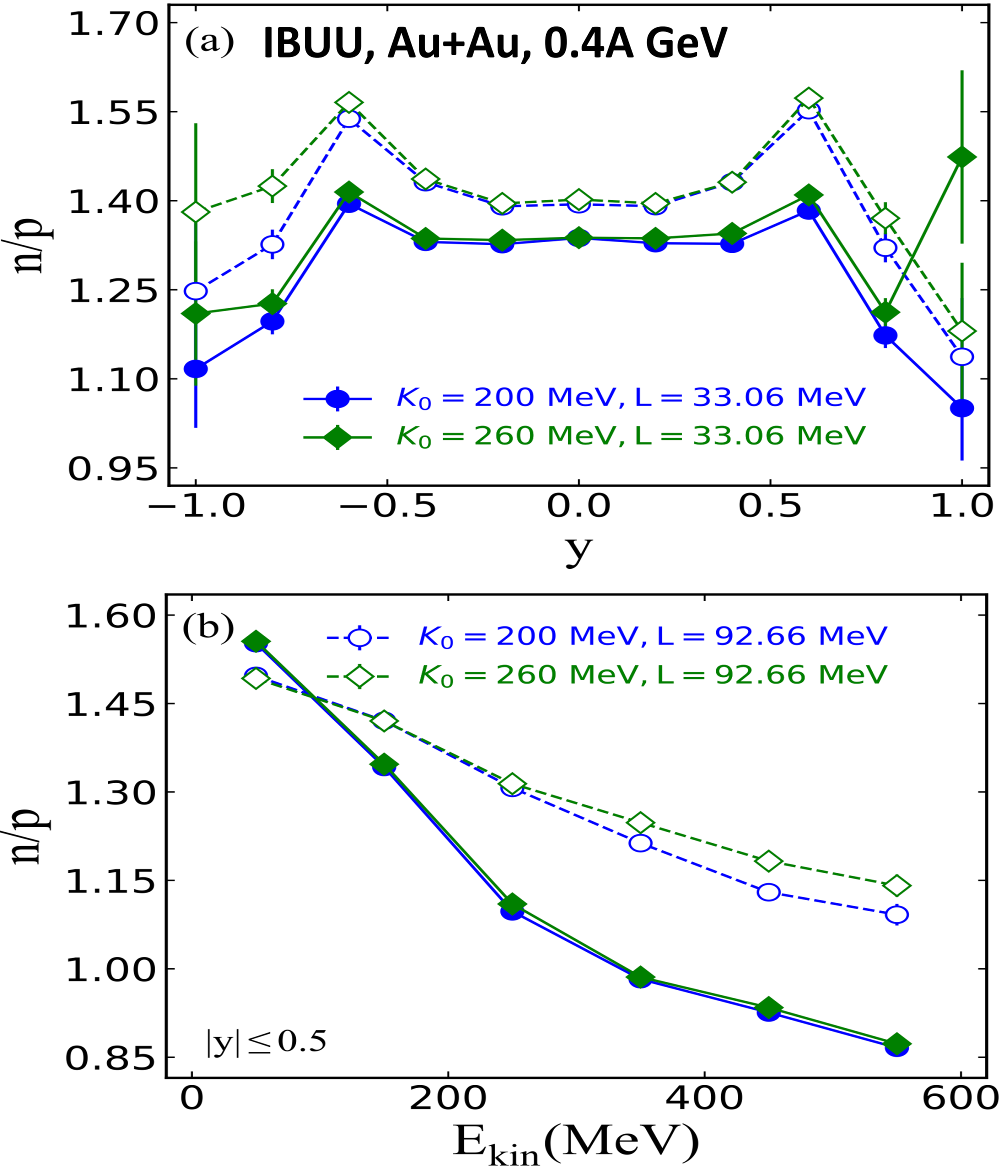
$$v_1^{np} = \frac{N_n(y)}{N(y)} \langle v_1^n(y) \rangle - \frac{N_p(y)}{N(y)} \langle v_1^p(y) \rangle$$

$N_n(y), N_p(y), N(y)$ - total number of neutrons, protons and nucleons respectively

- v_1^{np} sensitive to both K_0 and L which may lead to ambigous interpretation
  - More observables might be necessary for robust study of L

Using $dN/dy\,(n,p)$, $dN/dE_{kin}(n,p)$ to study L

X.X. Long, G.F. Wei, arXiv:2402.12912 (2024)

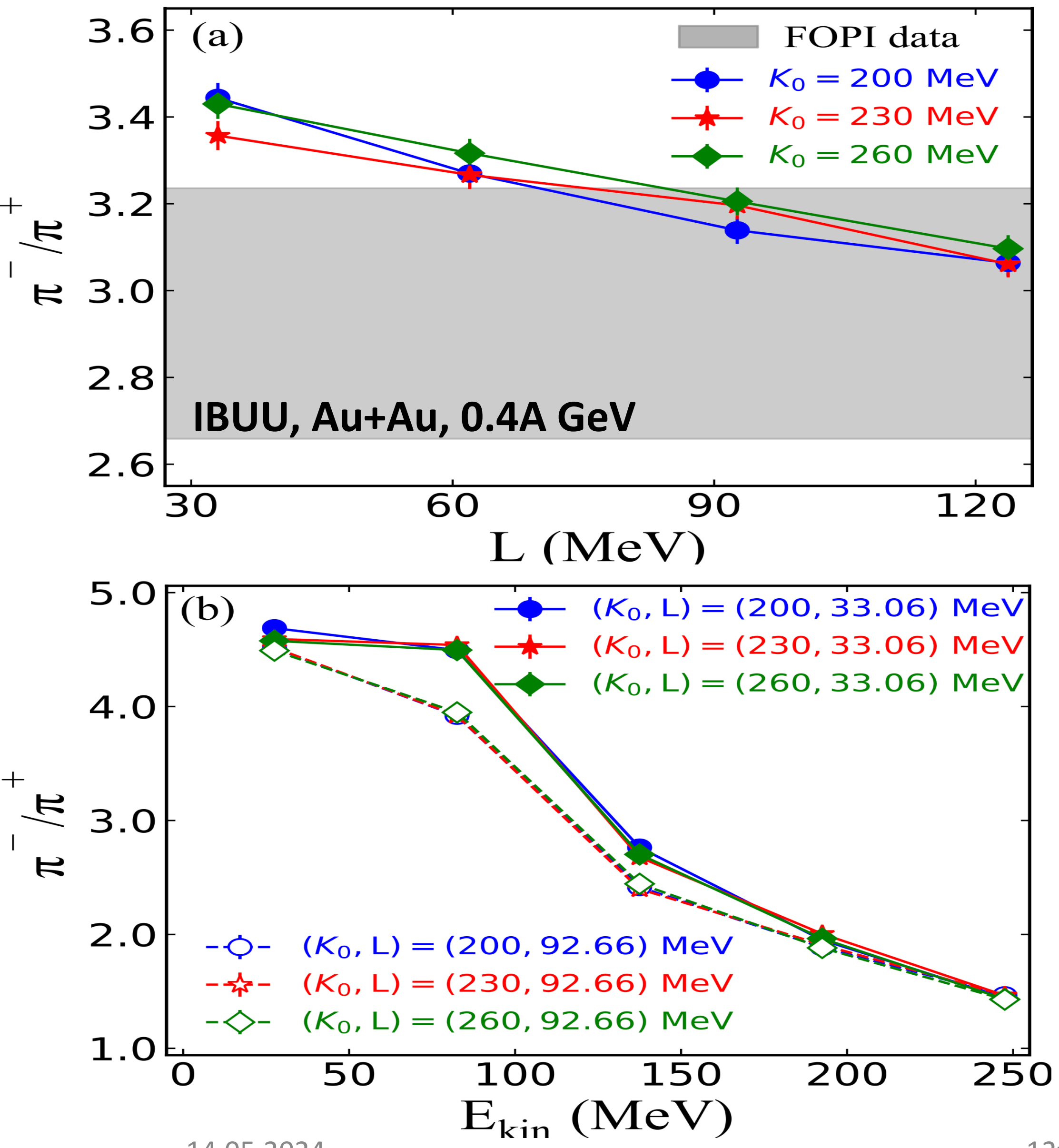


Rapidity and kinetic energy distributions of n/p ratios can be used to study L

- n/p ratios show strong dependence on L and significantly weaker dependence on K_0
- n/p ratios require less statistics than anisotropic flow measurements

Using $dN/dE_{kin}(\pi^+, \pi^-)$ to study L

X.X. Long, G.F. Wei, arXiv:2402.12912 (2024)

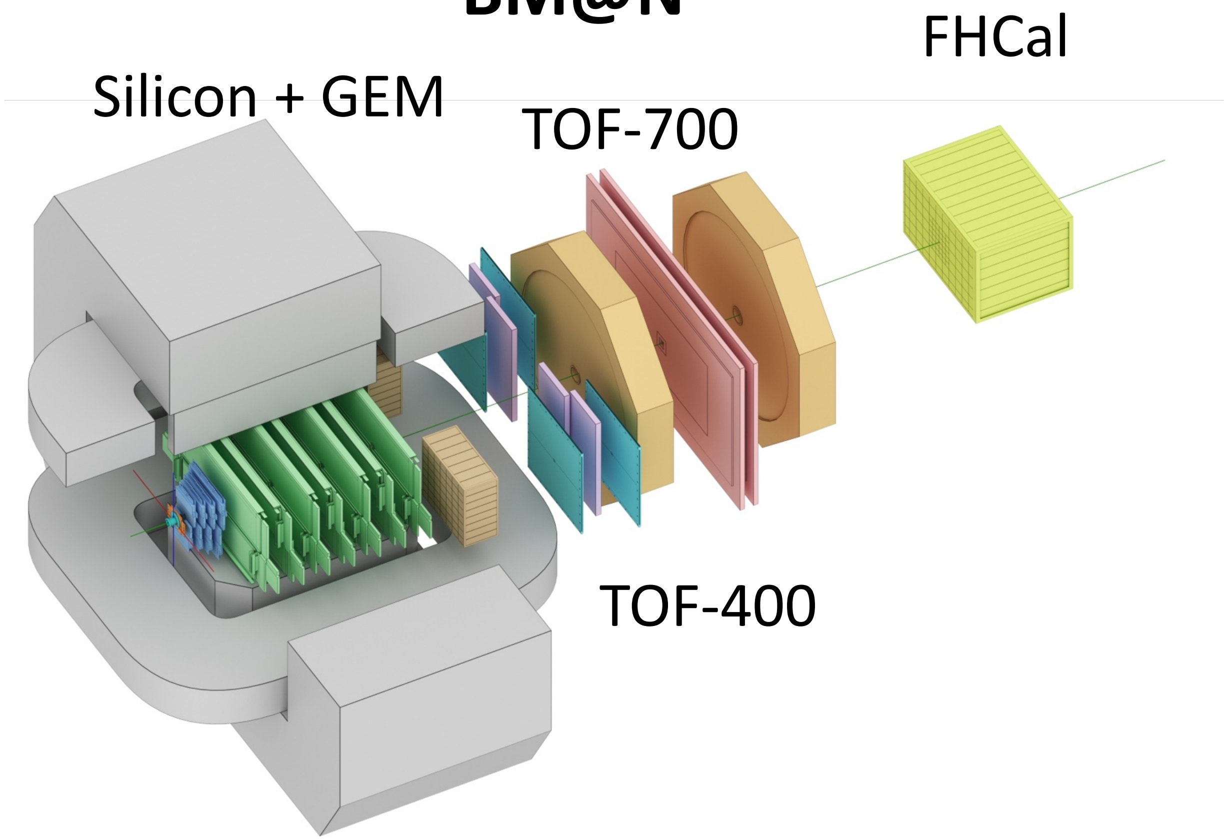


Rapidity and kinetic energy distributions of π^-/π^+ ratios can be used to study L

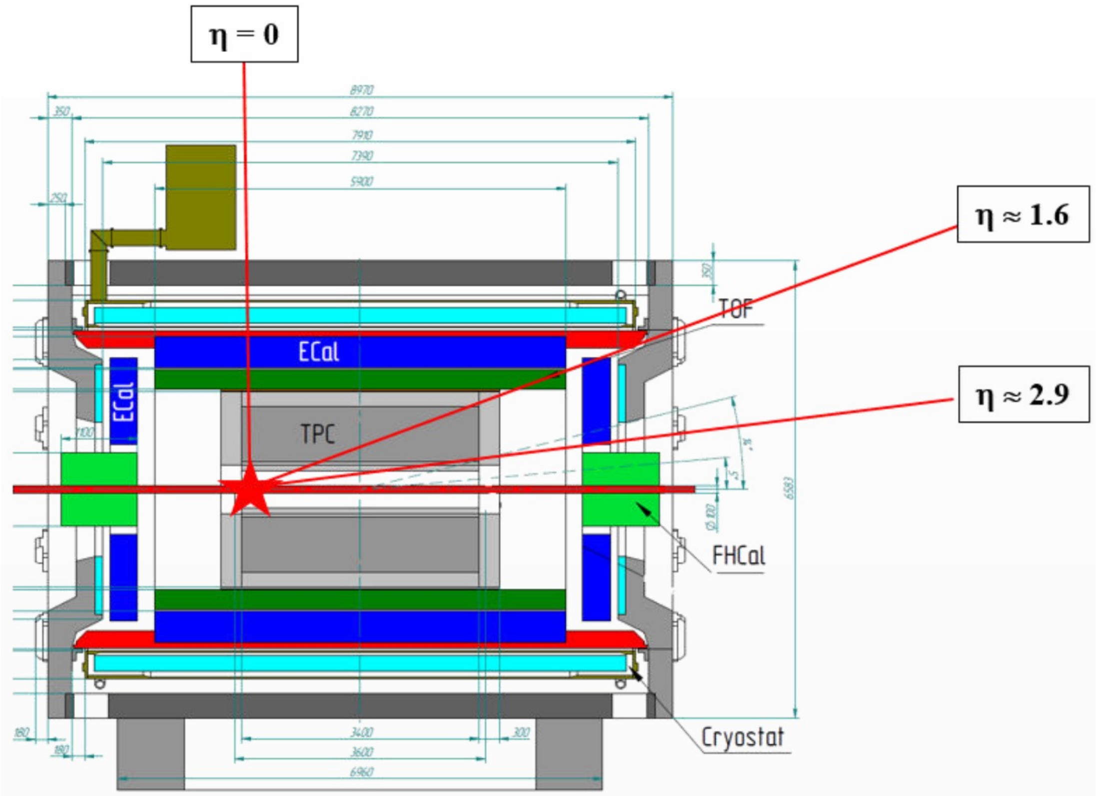
- Noticeable dependence on L and almost no sensitivity to K_0
- Requires less statistics than anisotropic flow measurements
- However, it might be a bit challenging to identify π^+ using TOF-400, TOF-700 near midrapidity at Nuclitron energies

The BM@N and MPD-FXT experiments

BM@N



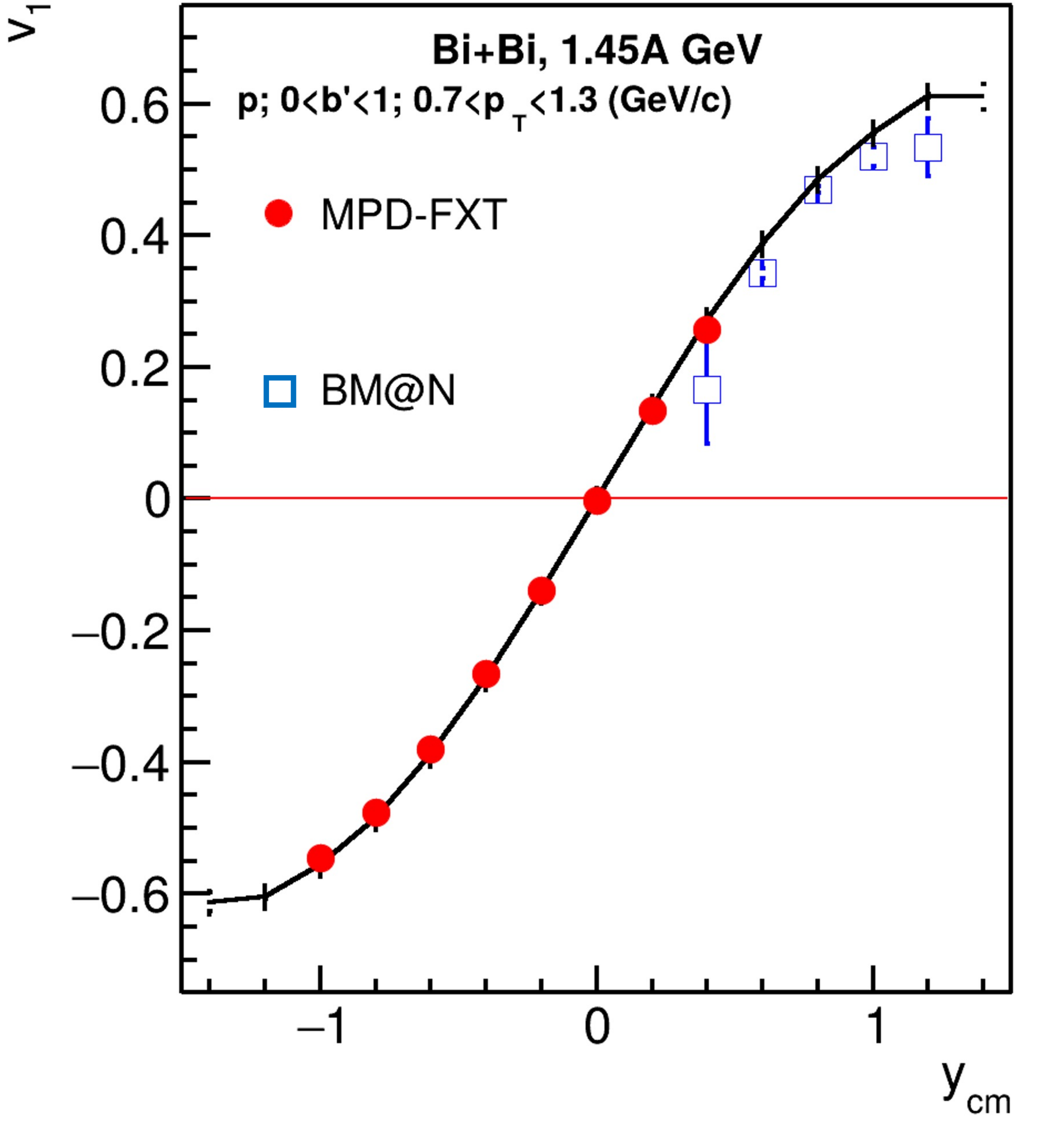
MPD-FXT



Detectors used for anisotropic flow measurements:

- **Tracking system:** FwdSi+GEM (BM@N); TPC (MPD-FXT)
- **PID:** TOF-400, TOF-700 (BM@N); TPC, TOF (MPD-FXT)
- **EP measurements:** FHCal (BM@N), FHCal (MPD-FXT)

Comparison of MPD-FXT and BM@N performances



BM@N TOF system (TOF-400 and TOF-700) has poor midrapidity coverage at $\sqrt{s_{NN}}$ = 2.5 GeV

- One needs to check higher energies ($\sqrt{s_{NN}}$ = 3, 3.5 GeV)
- More statistics are required due to the effects of magnetic field in BM@N:
  - Only “yy” component of <uQ> and <QQ> correlation can be used

Despite the challenges, both MPD-FXT and BM@N can be used in v_n measurements:

- To widen rapidity coverage
- To perform a cross-check in the future

Summary

- **Extracting EOS information from the measurements:**
  - One should consider baryon dependency for the incompressibility $K = K(n_B)$
  - Observables can be sensitive to the EOS in different n_B/n_0 regions
- **Comparison with STAR BES at $\sqrt{s_{NN}}$=3 GeV and HADES at $\sqrt{s_{NN}}$=2.4 GeV:**
  - Good overall agreement with experimental data for v_n of protons using mean-field models with hard EOS
  - Models do not describe all particle species equally well (mesons, Λ, light nuclei)
  - Event-wise flow correlations of protons can not be described by current models
- **Out-of-plane to in-plane transition of v_2:**
  - This transition depends on beam energy, centrality, rapidity range, and particle species
- **Symmetry energy study in Nuclotron-NICA:**
  - v_1^{np} can be used to measure symmetry energy slope L but it requires a lot of statistics
  - n/p ratios of (y, E_{kin})-dependencies are sensitive to L and less statistics hungry
  - π^-/π^+ ratios of (y, E_{kin})-dependencies are also sensitive to L however it might be challenging to measure π^+ near midrapidity using BM@N TOF systems at Nuclotron energies
- **Both MPD-FXT and BM@N can complement each other in terms of v_n:**
  - Cross-checks can be performed to test the implemented flow measurement techniques
  - Using results from both experiments can widen the rapidity coverage - **no single fixed target experiment can achieve that!**

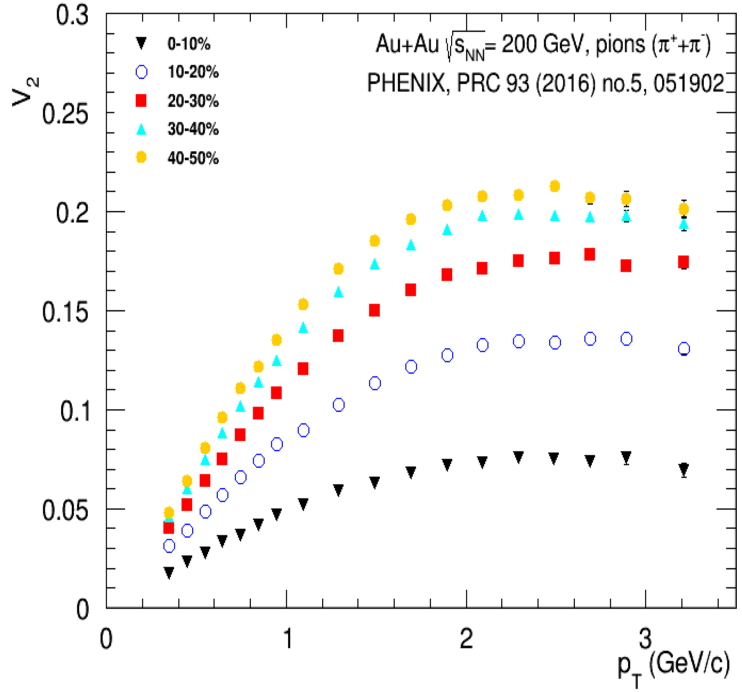
New data from the BM@N and MPD (MPD-FXT) is required to address the discrepancies in the existing data and provide further constraints for the EoS in the models

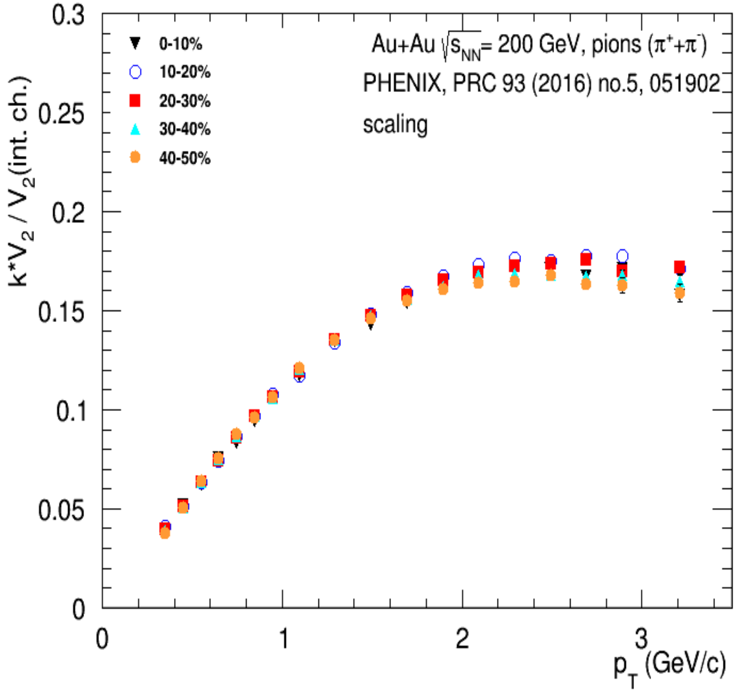
Thank you for your attention!

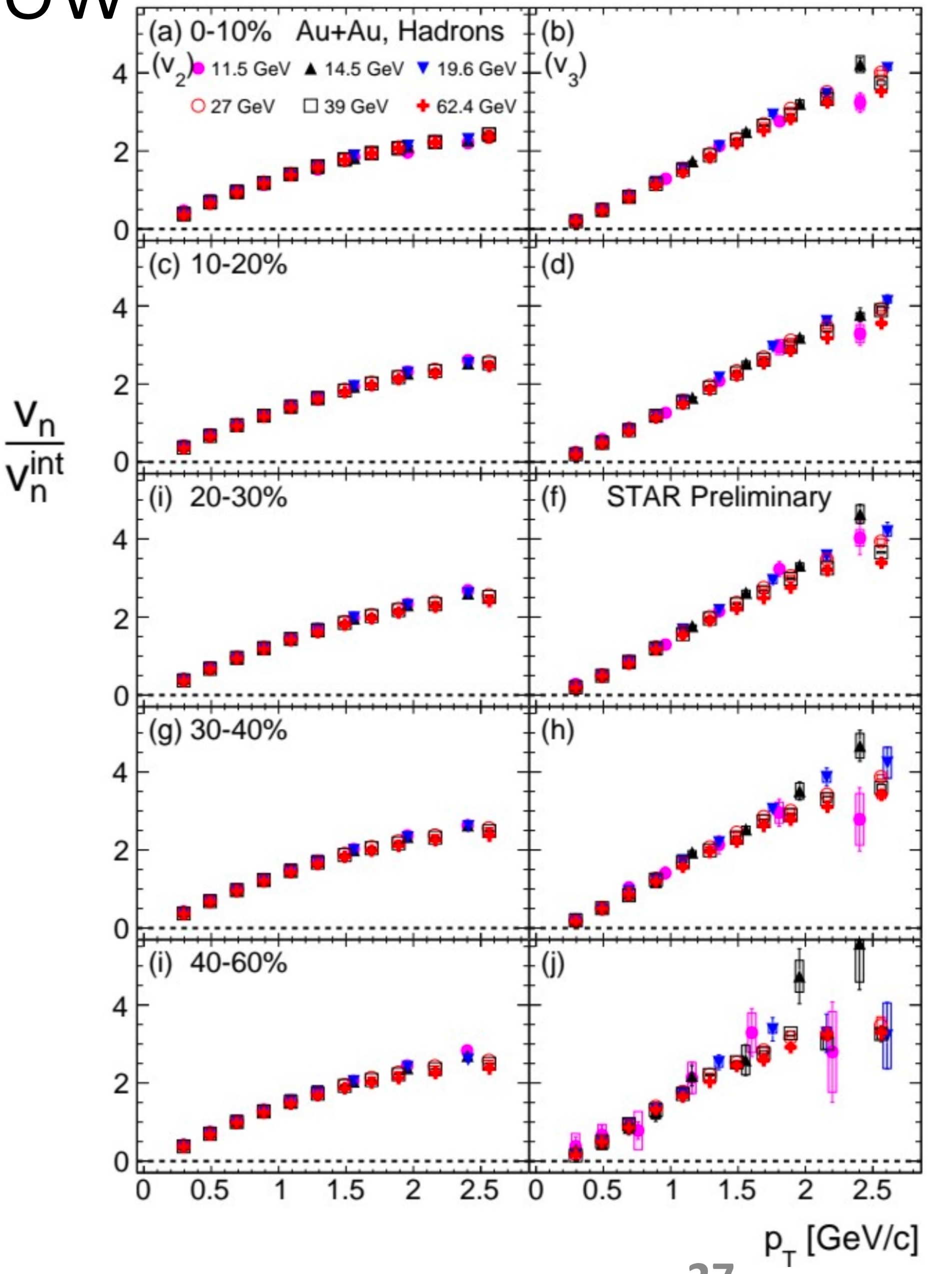
Backup

Scaling with integral anisotropic flow

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





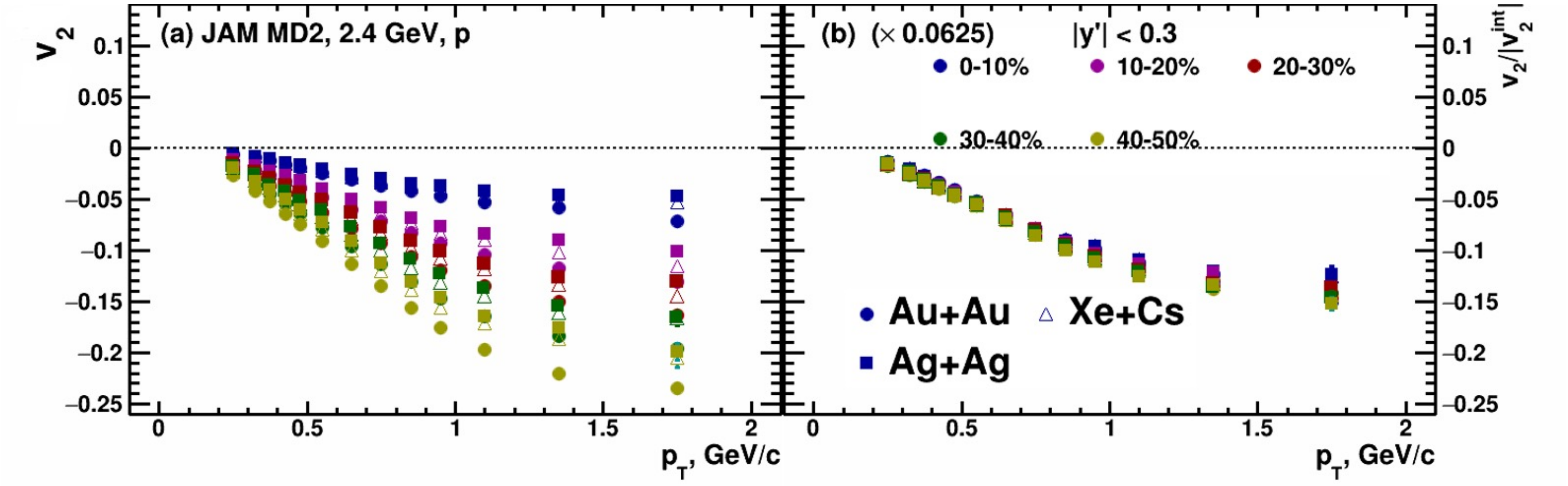


$$v_n(int.) \equiv \left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}\right|$$

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

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

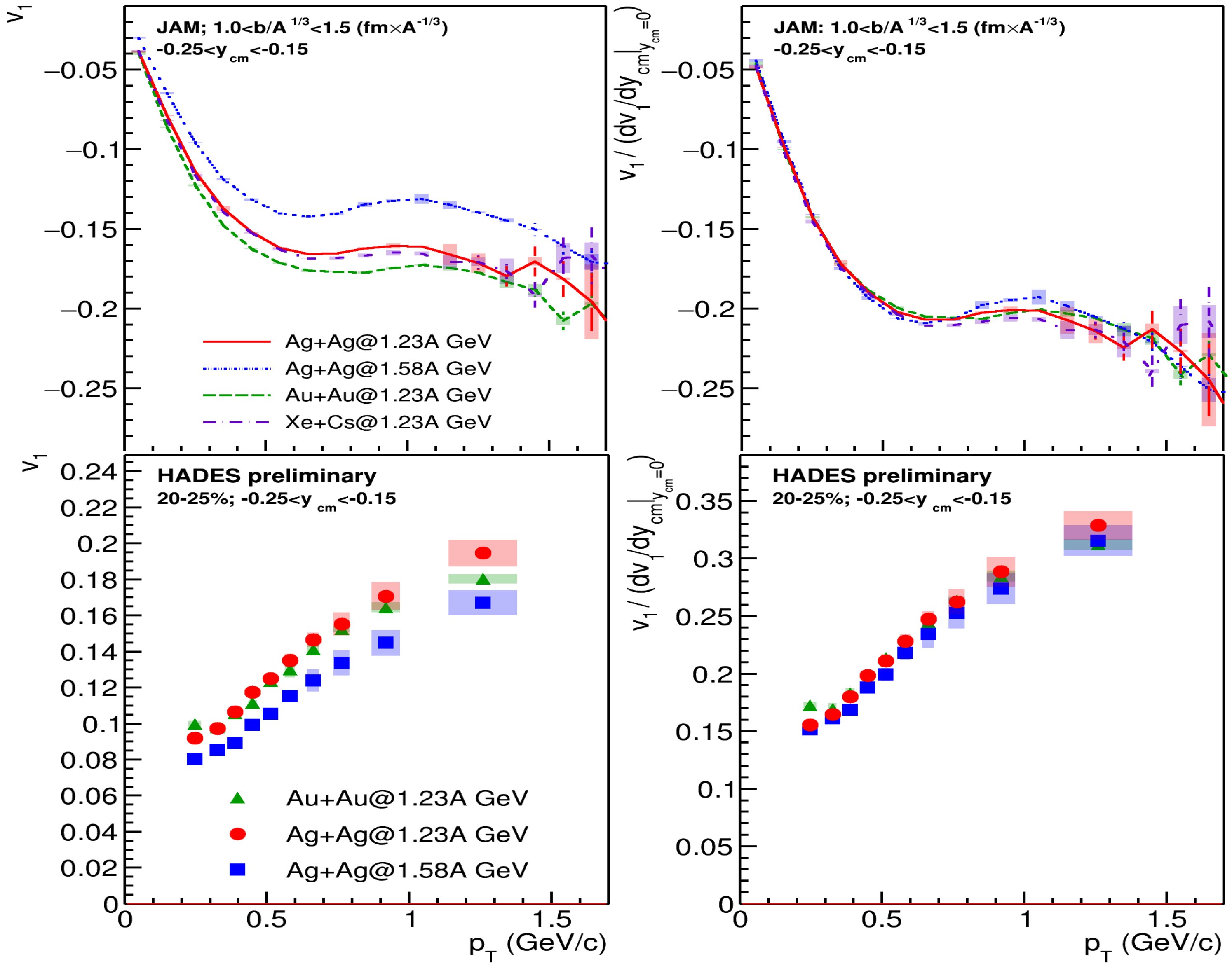
$$\left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}\right|$$



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

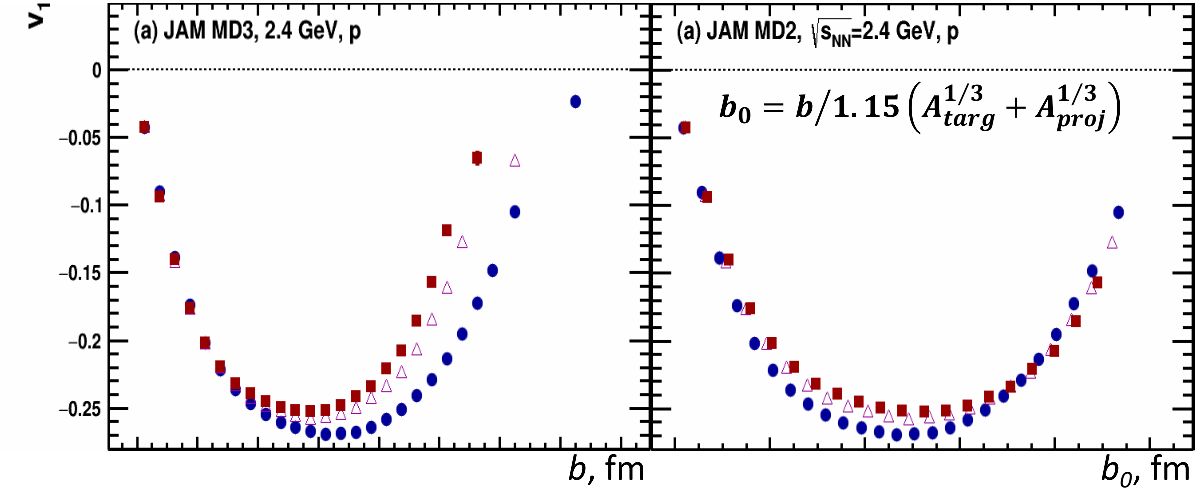
Provides a useful tool to make comparison of v_n results from different colliding systems

Scaling with v_1 slope



Scalings with $dv_1/dy\,|_{y=0}$ slope can be useful for comparison of the $v_n(y, p_T)$ results for different colliding systems

Scaling with system size



- **Scalings with b_0 works for model data**
- **Scaling with $y'(t_{pass}) = y/y_{beam}$ and $\langle b\rangle/A^{1/3}$ can be applied on the experimental data**