Anisotropic flow measurements at Nuclotron-NICA and Equation of State

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For the MPD Collaboration

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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
  - Scaling with system size
- Summary and Outlook

EOS for high baryon density matter

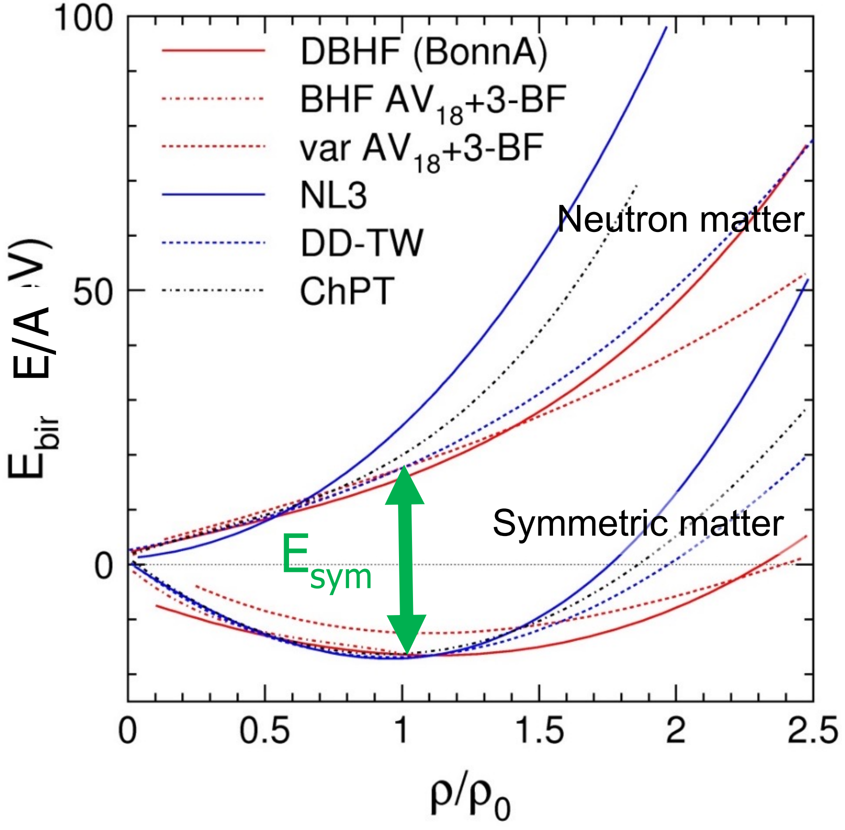
The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

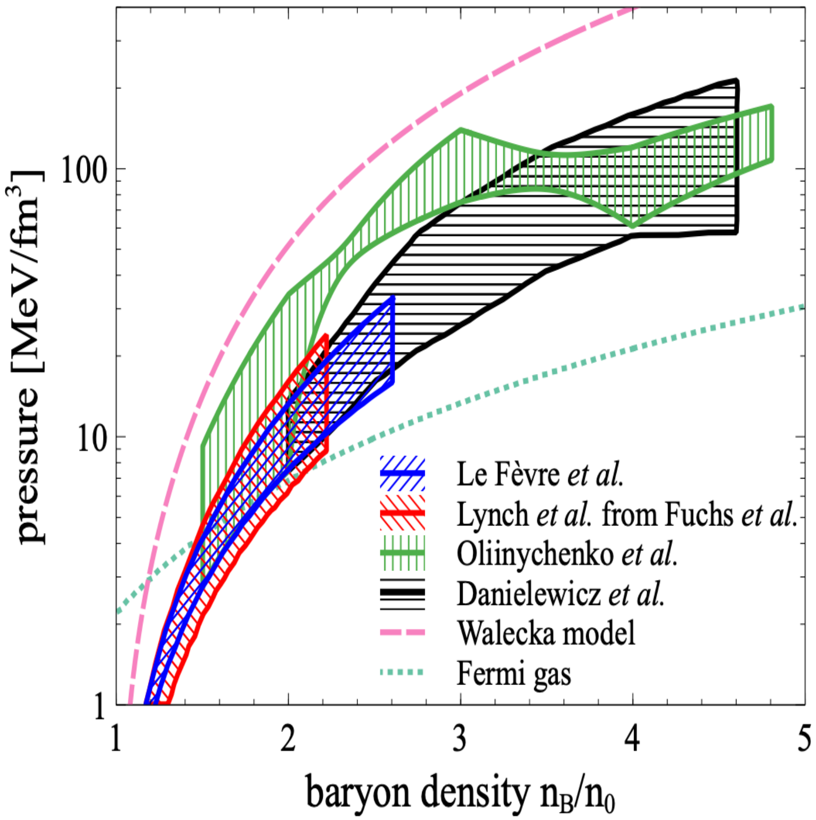
Isospin asymmetry:

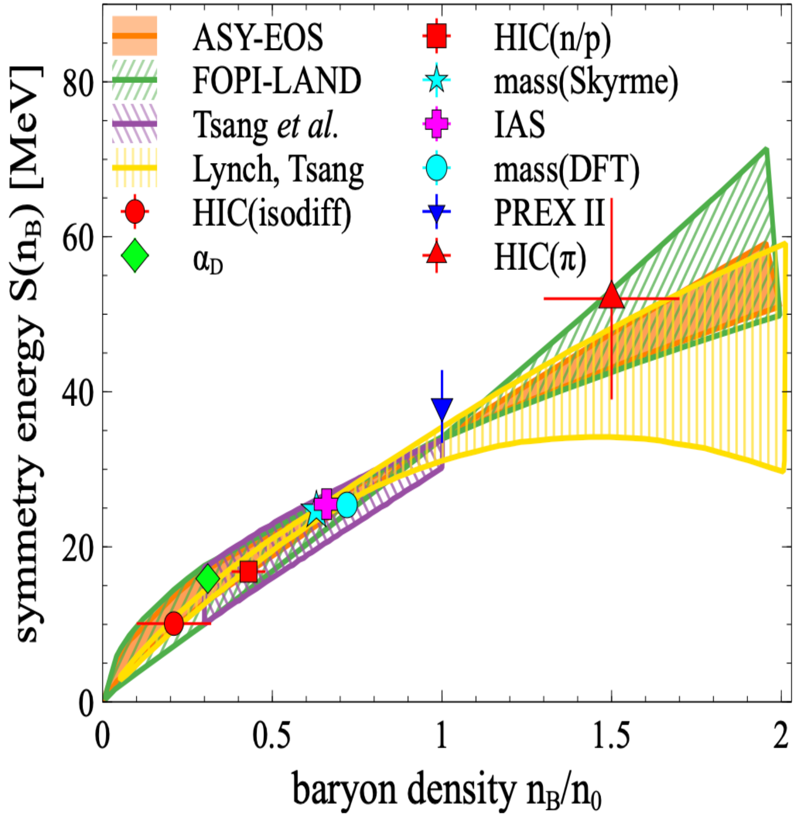
$$\delta = (\rho_n - \rho_p)/\rho$$

Symmetric matter

Symmetry energy





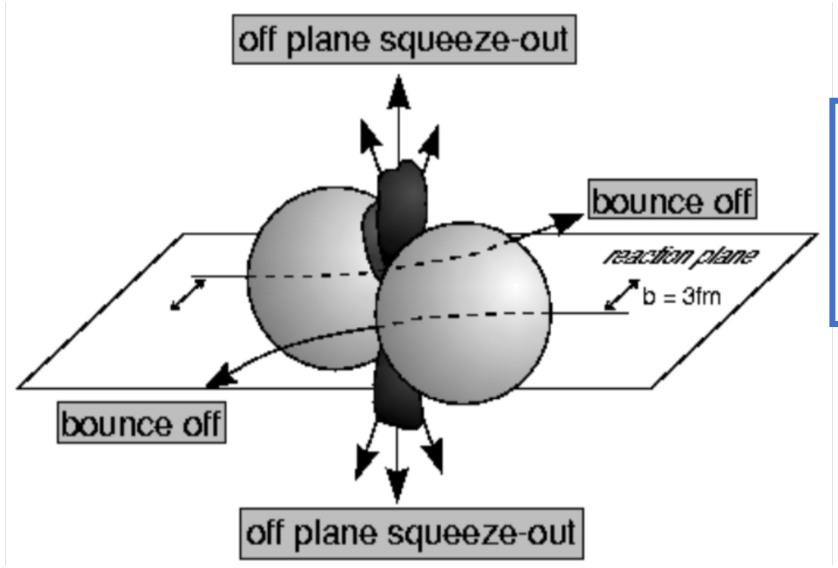


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

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.

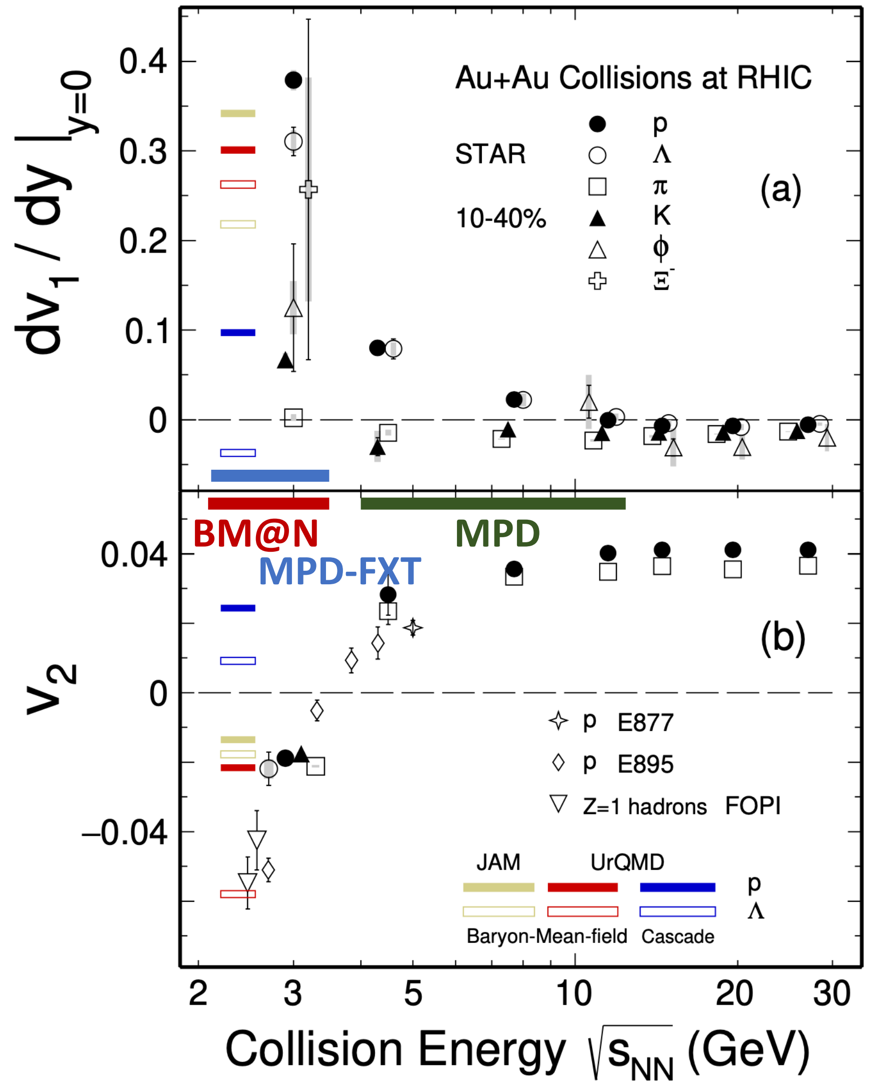
Anisotropic flow at Nuclotron-NICA energies



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

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

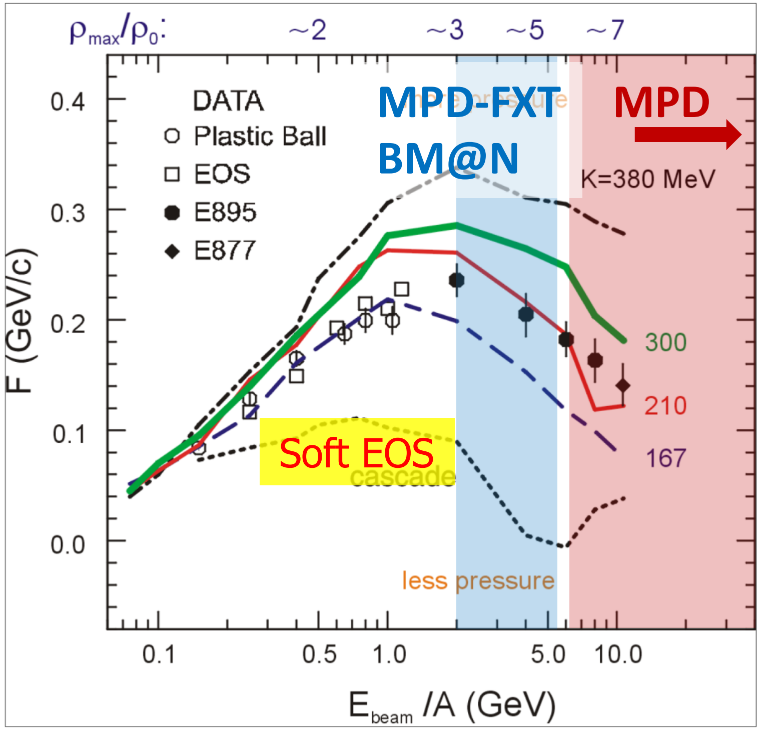
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

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

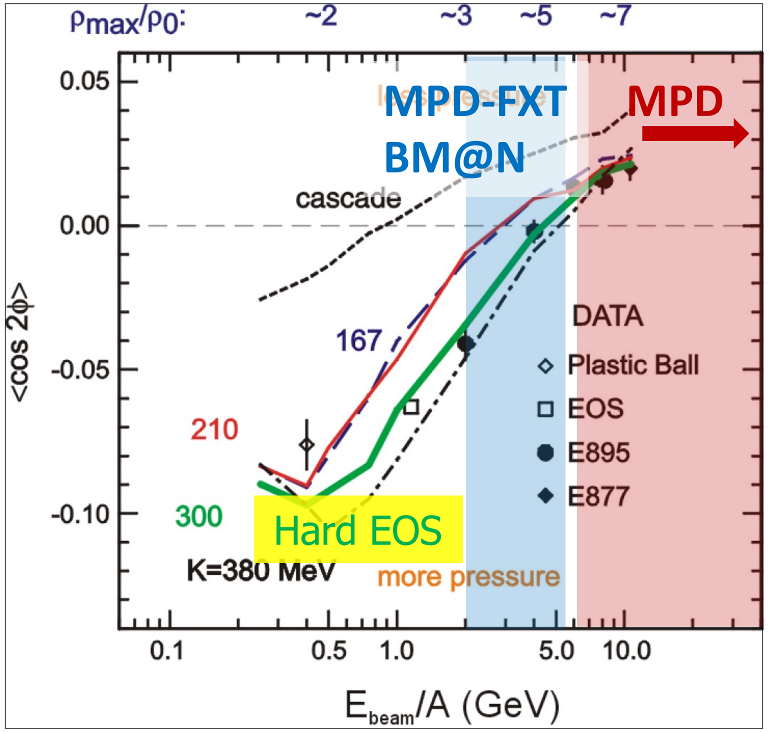
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

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

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

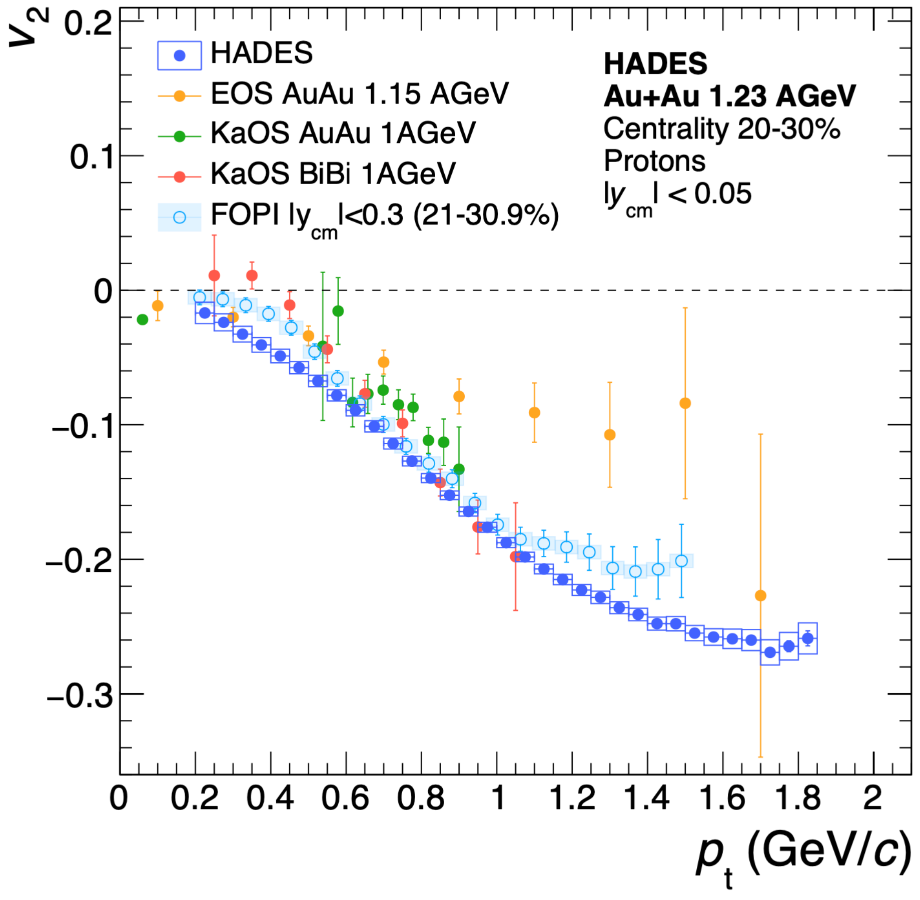
Discrepancy in the interpretation:

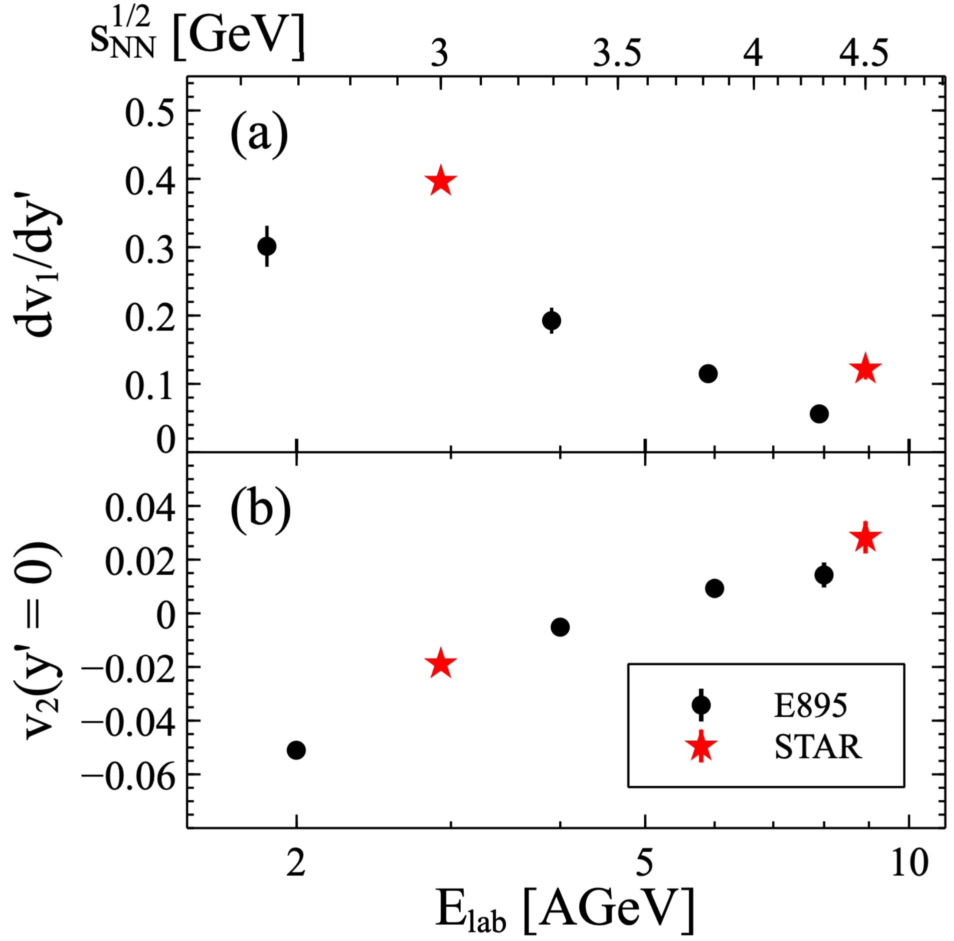
- v_1 suggests soft EoS ($K_0 \approx 210$ MeV)
- v_2 suggests hard EoS ($K_0 \approx 380$ MeV)

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?

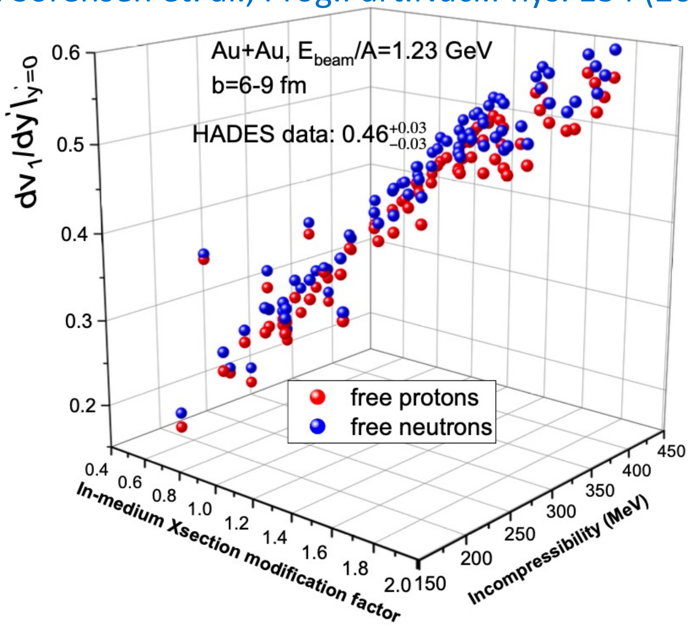


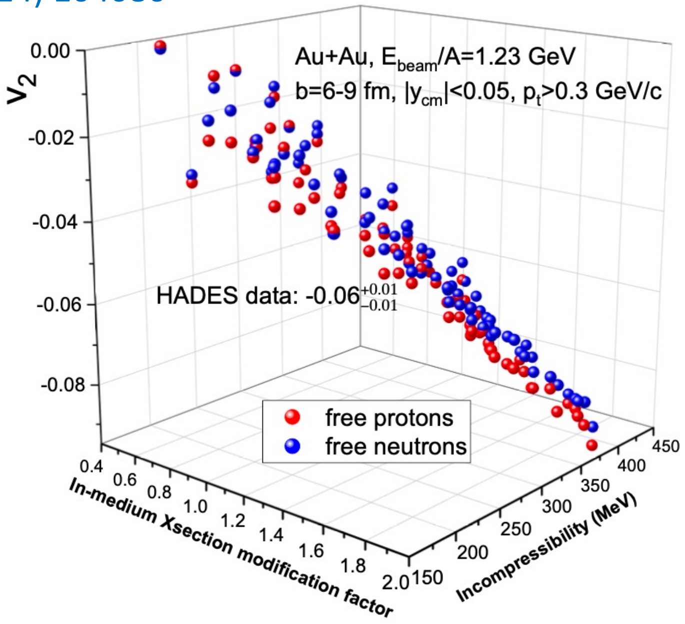


- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more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

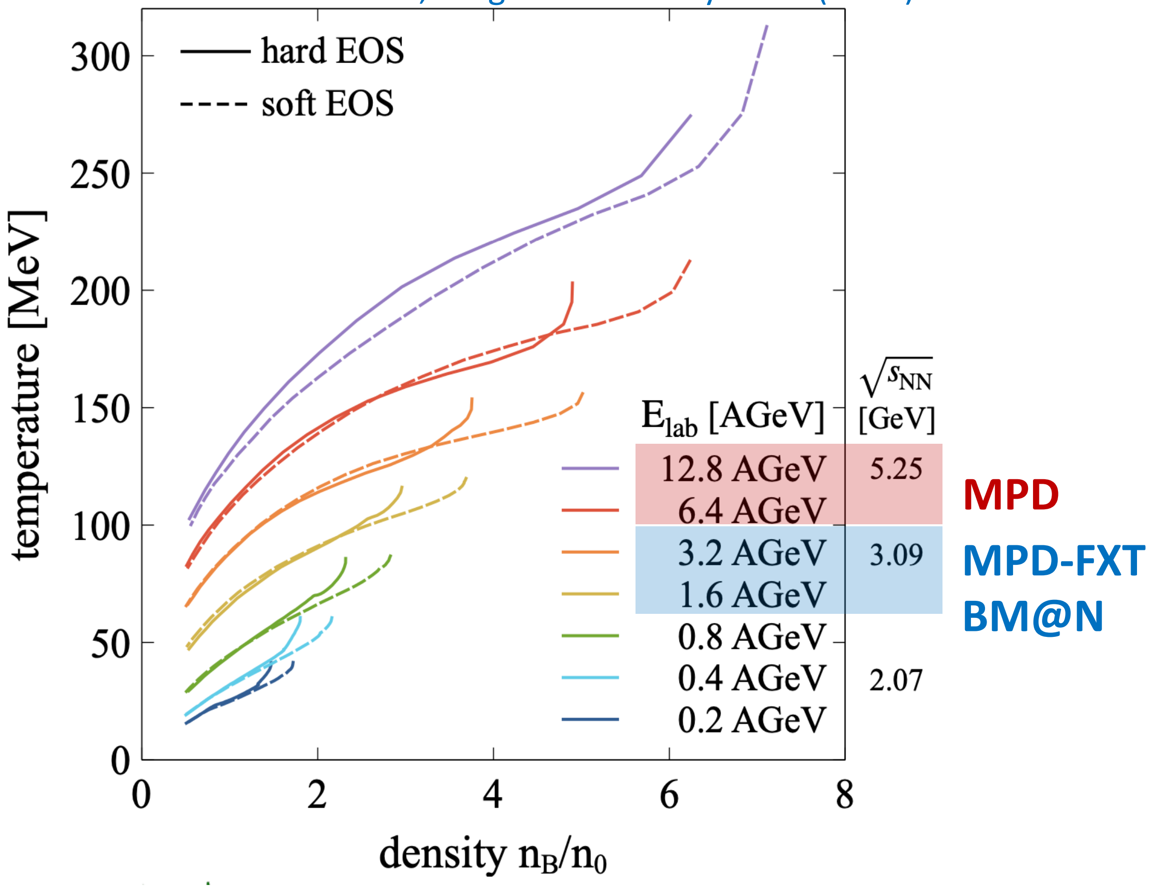
Sensitivity of the collective flow to the EOS

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





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

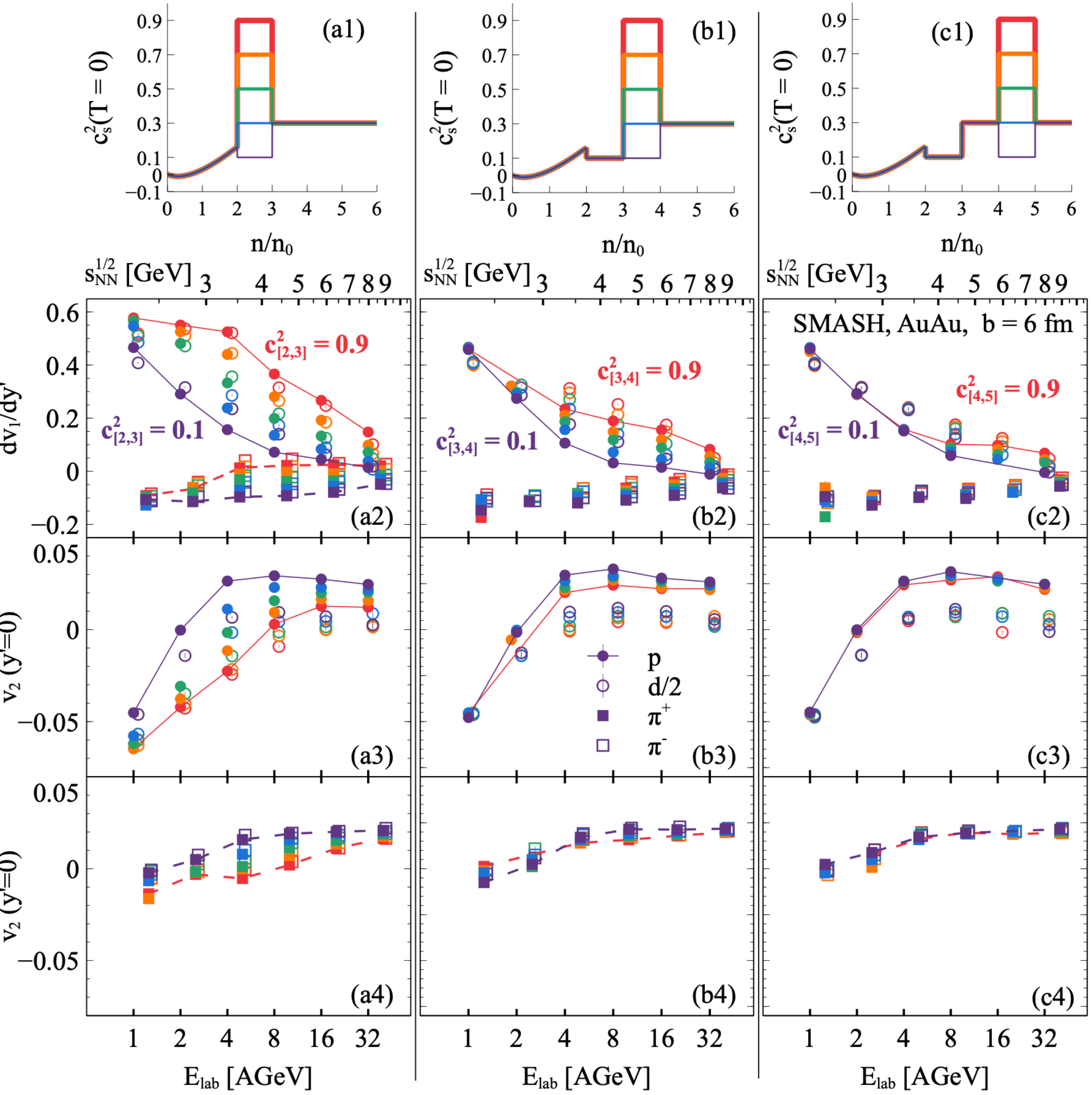


Incompressibility K_0:
parameter which specifies the behavior of EOS in the given baryon densities $K_0 = K_0(n_B)$

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

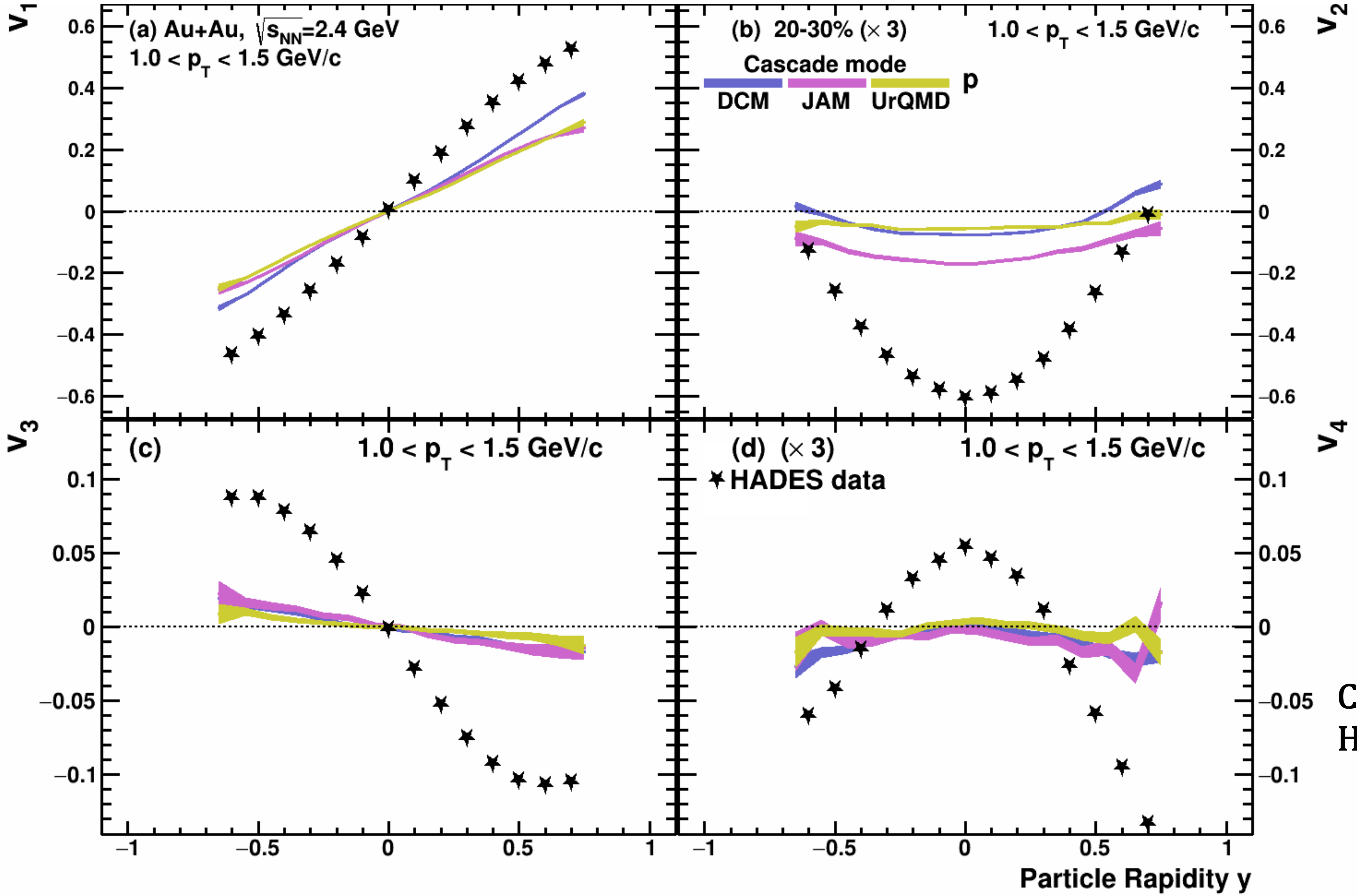


A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

- 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
  - $\mathbf{3 < n_B/n_0 < 4}$: weak sensitivity to the EOS

The most precise constraints can be achieved from the flow of identified hadrons (*π*$^{\pm}$,*K*$^{\pm}$,*p*,…) and light nuclei (*d*,*t*,…)

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

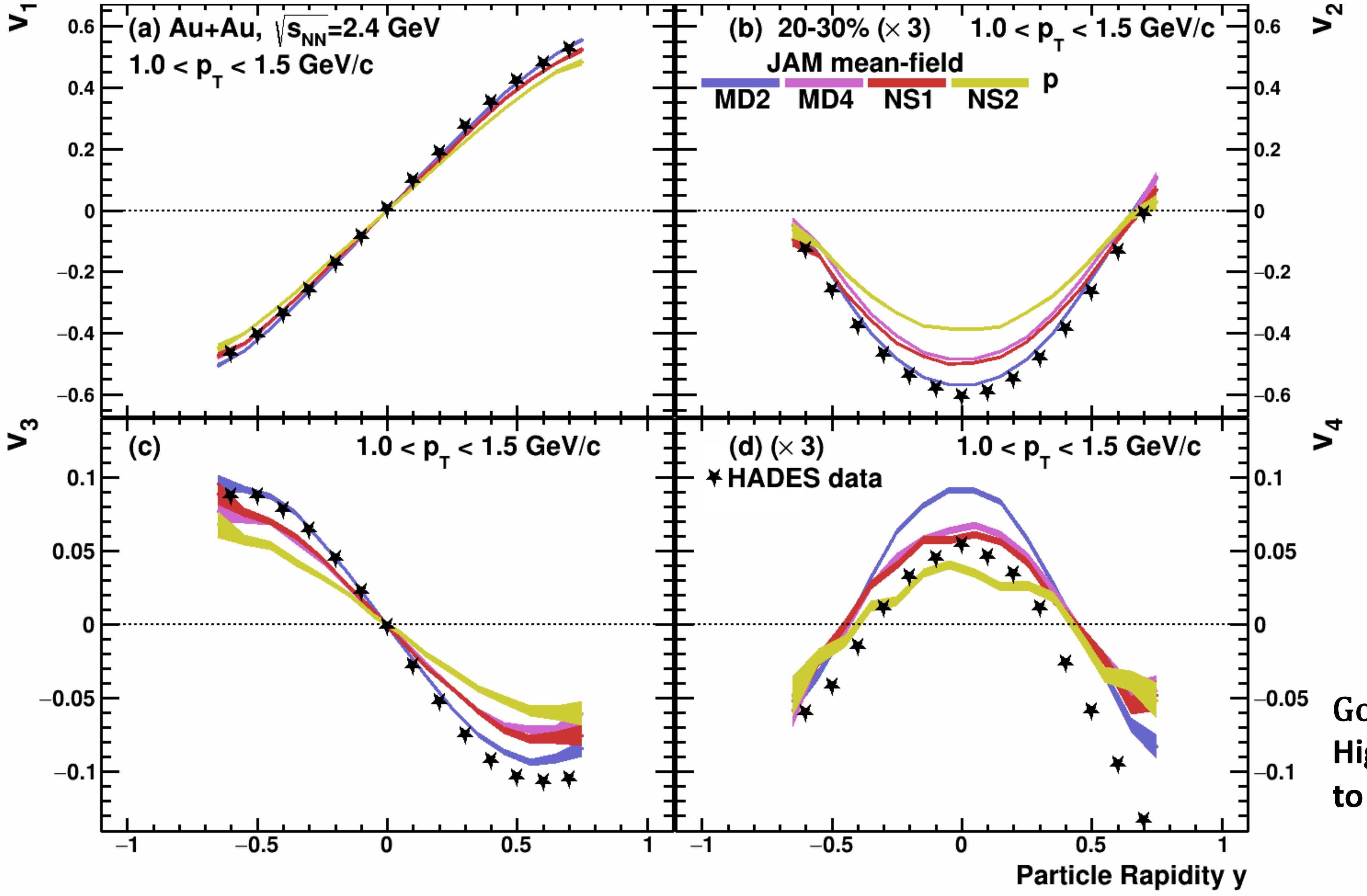


P. Parfenov, Particles 5, no.4, 561-579 (2022)

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



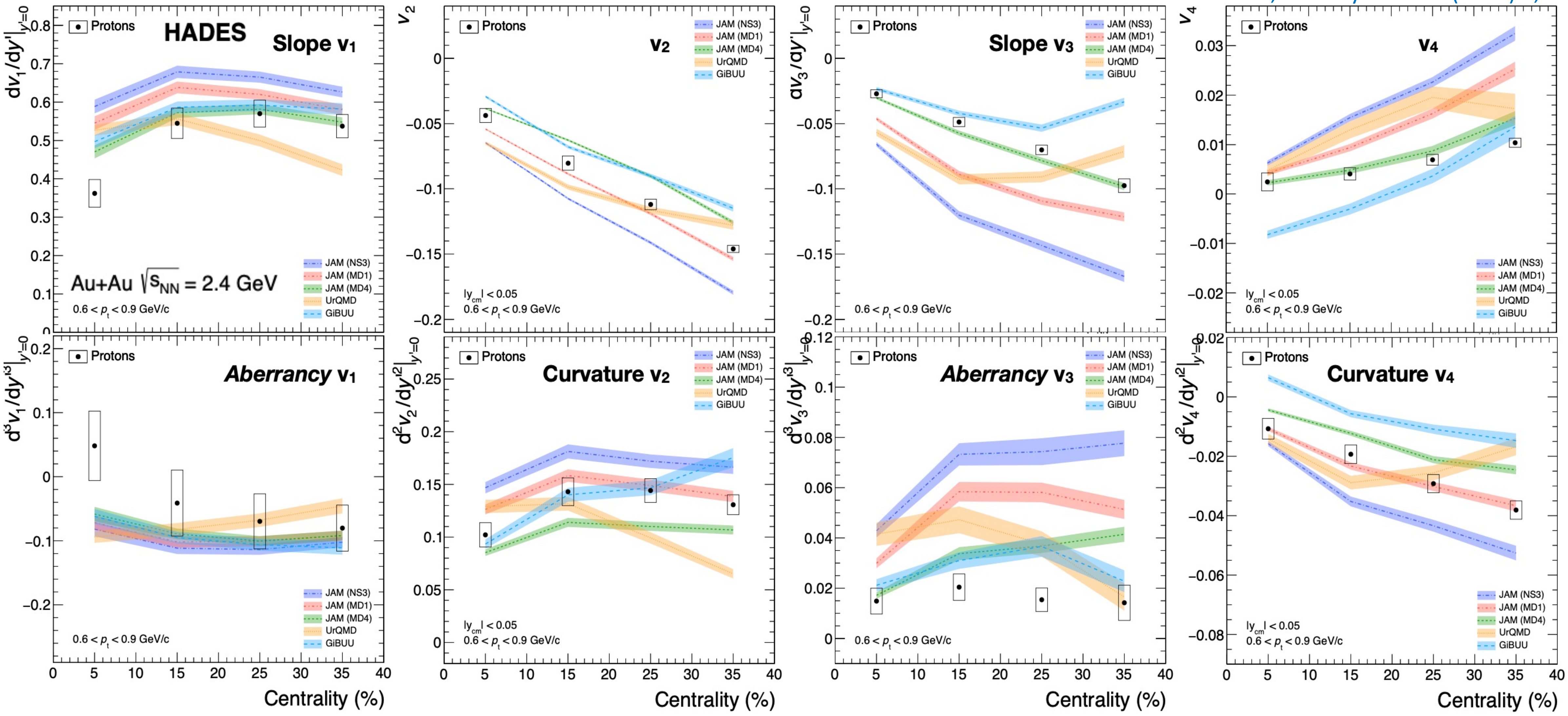
P. Parfenov, Particles 5, no.4, 561-579 (2022)

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

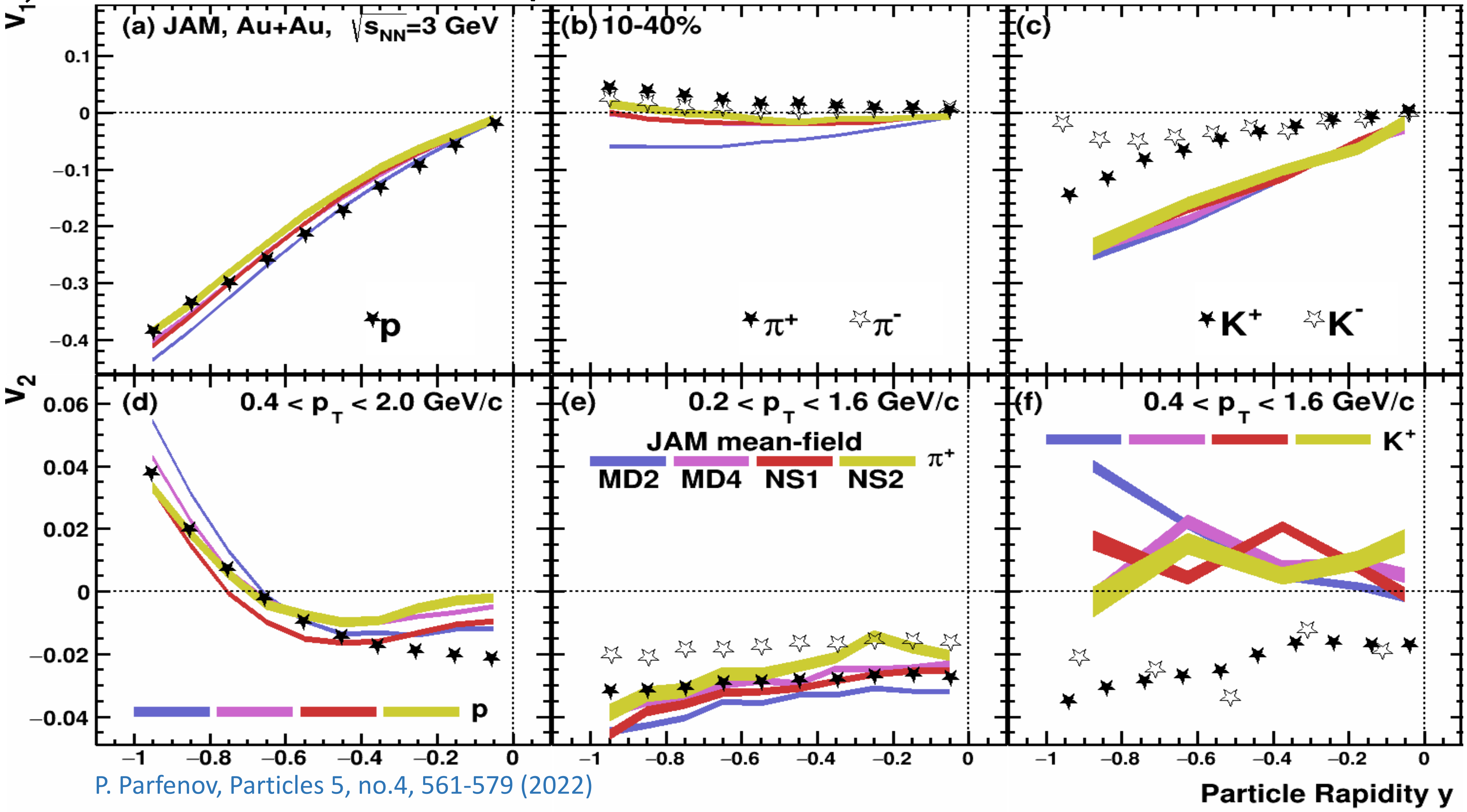
$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data

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



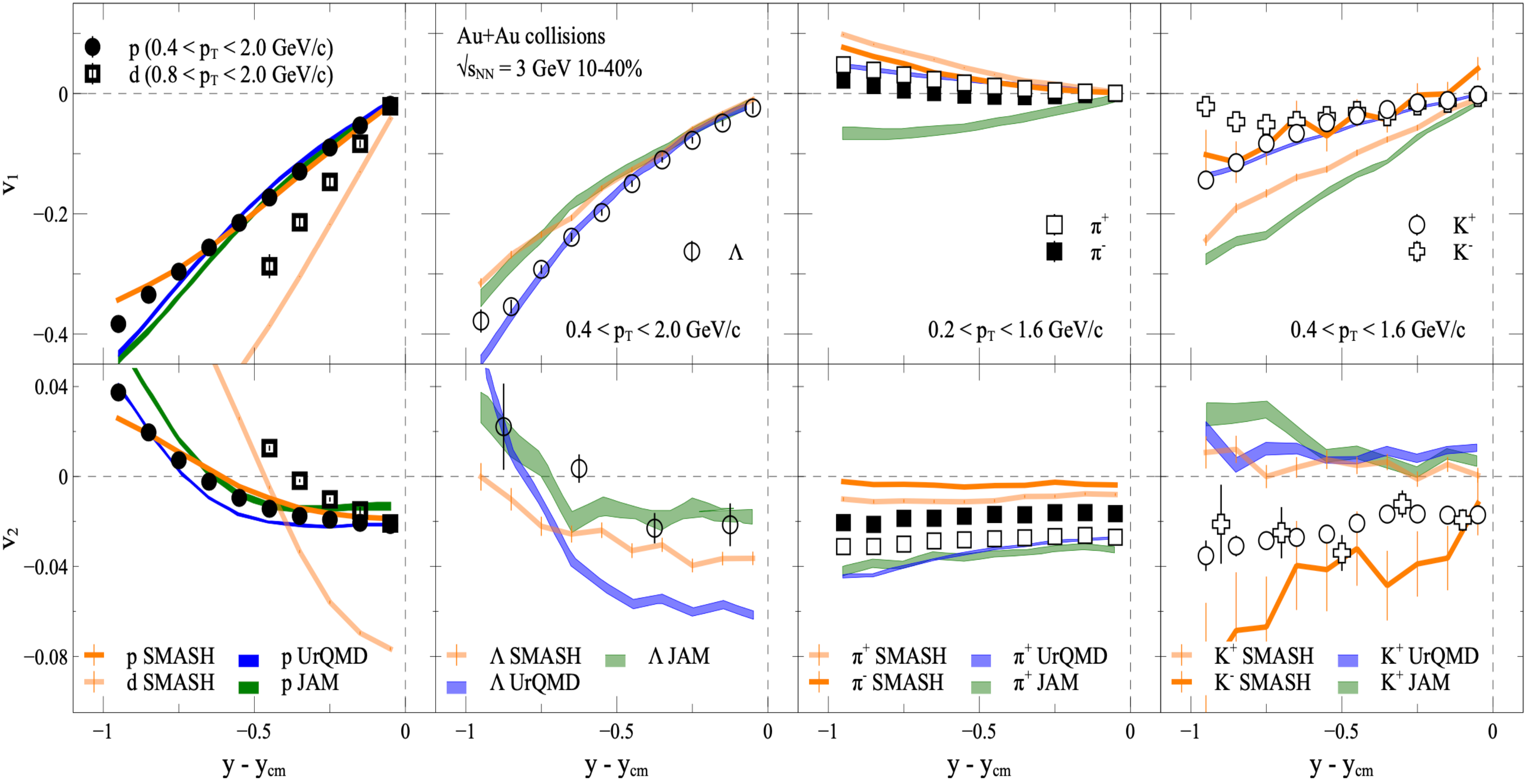
P. Parfenov, Particles 5, no.4, 561-579 (2022)

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



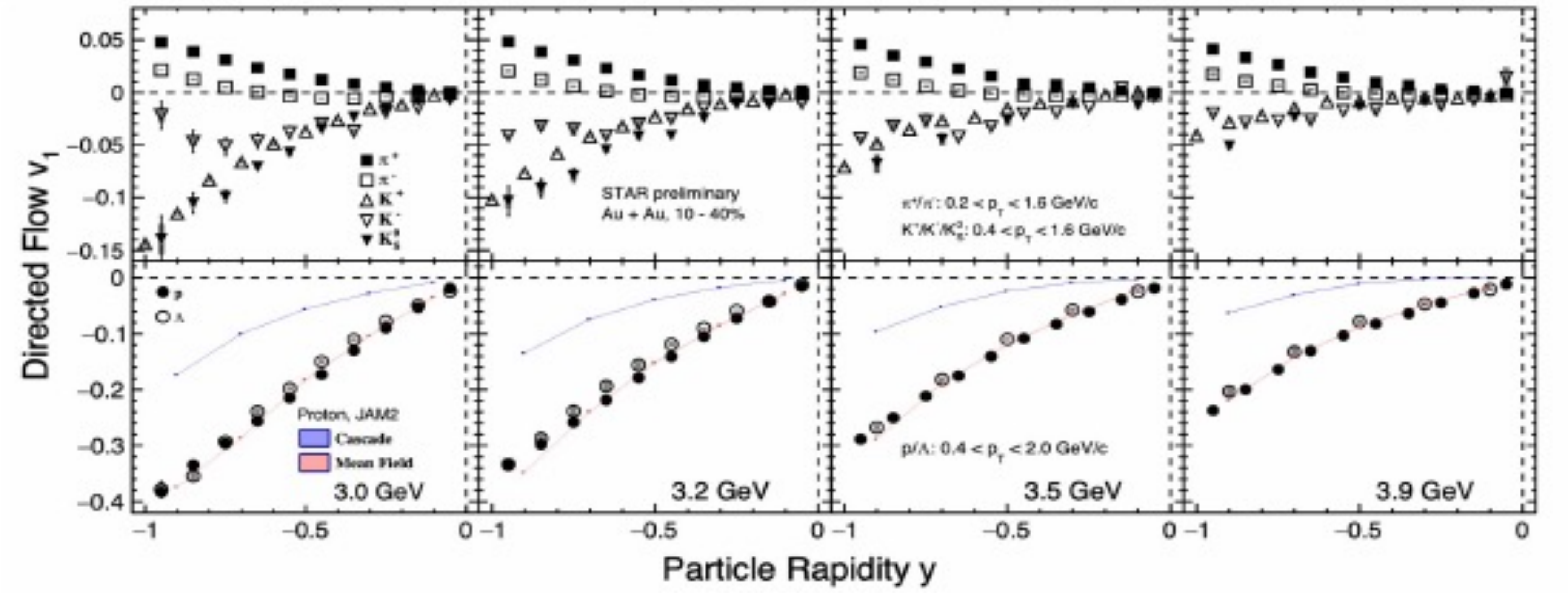
Model description of v_n:

- 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

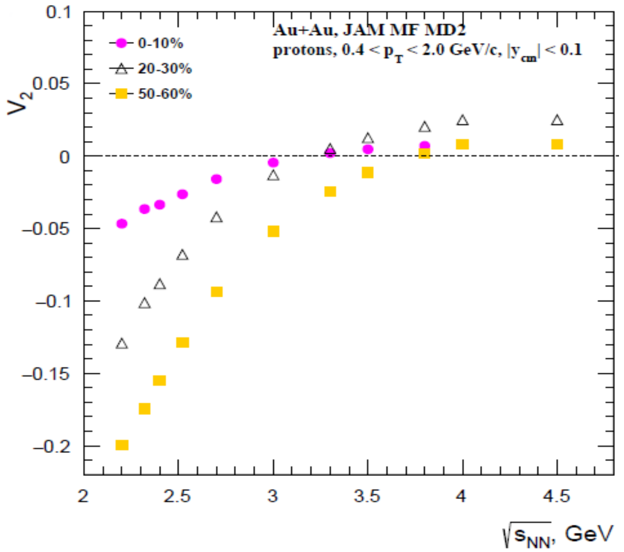
New STAR results from BES-II

Results from QM 2023

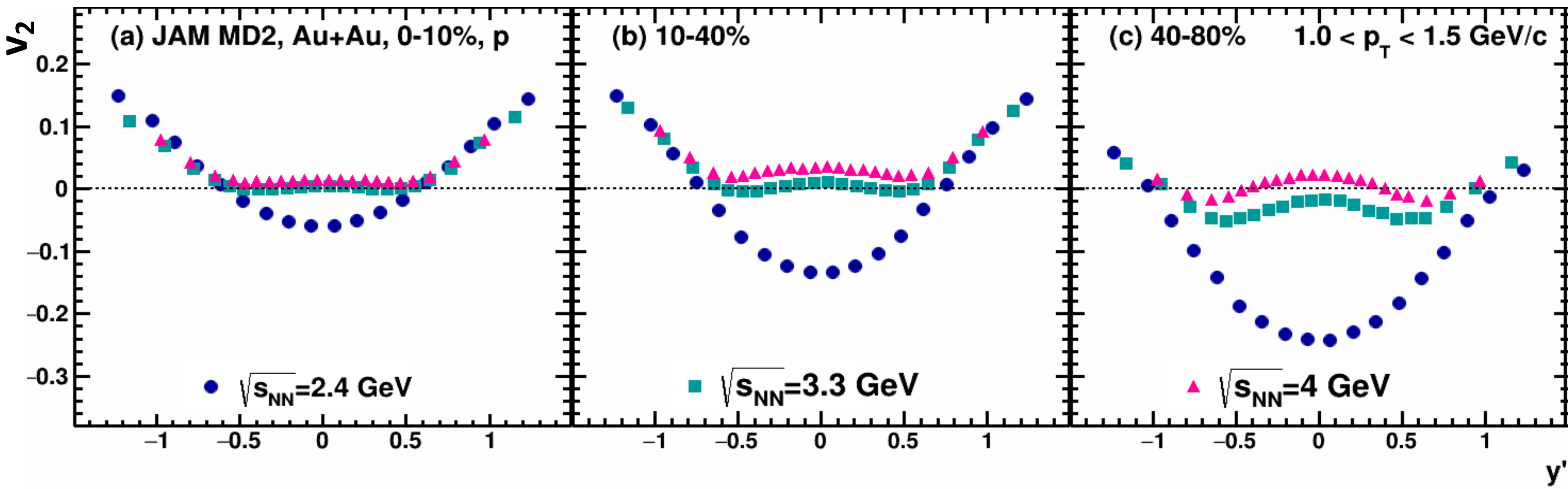


New preliminary results from STAR BES-II were presented at QM-2023 for Au+Au at $\sqrt{s_{NN}}$=3, 3.2, 3.5, 3.9 GeV

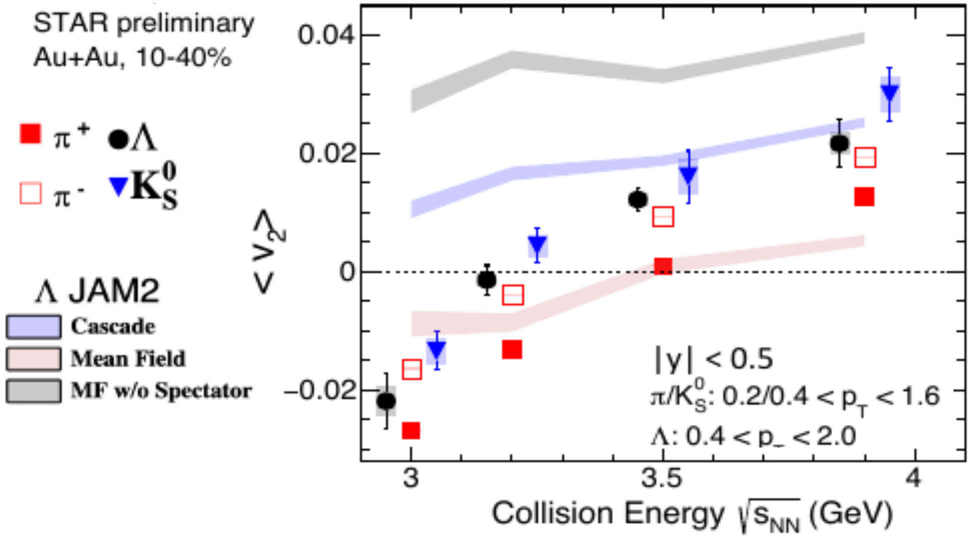
v_2 transition from out-of-plane to in-plane



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



Results from QM 2023



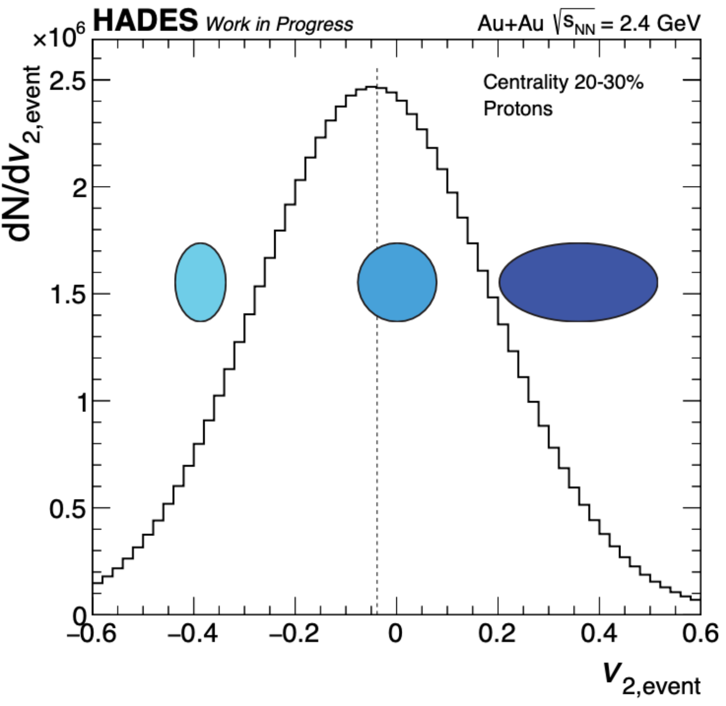
Transition of v_2 from out-of-plane to in-plane can be a good tool to constrain models and extract information about EOS

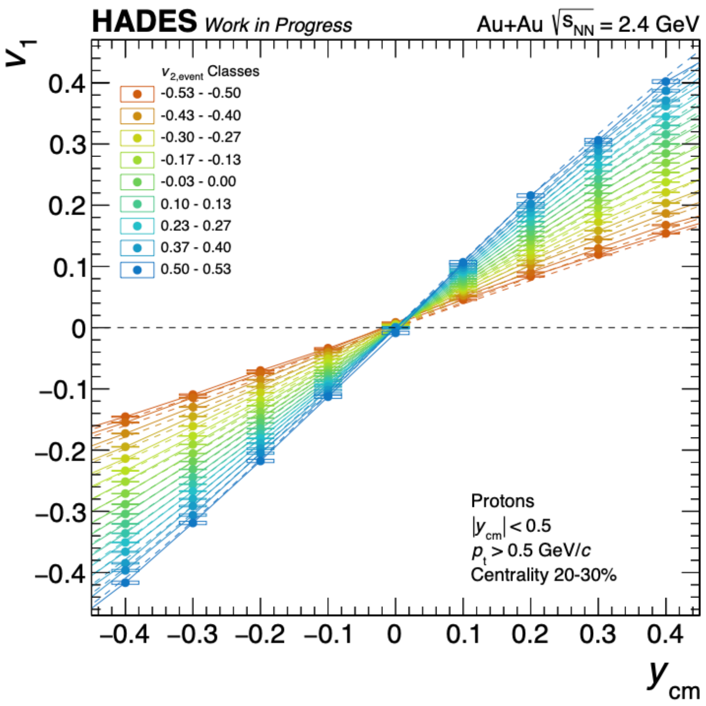
- $v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV for central and mid-central collisions for protons
- $v_2 < 0$ for peripheral collisions
- Models can not reproduce v_2 of $\pi^{\pm}$, $K^{\pm}$, $K^0{}_S$, Λ

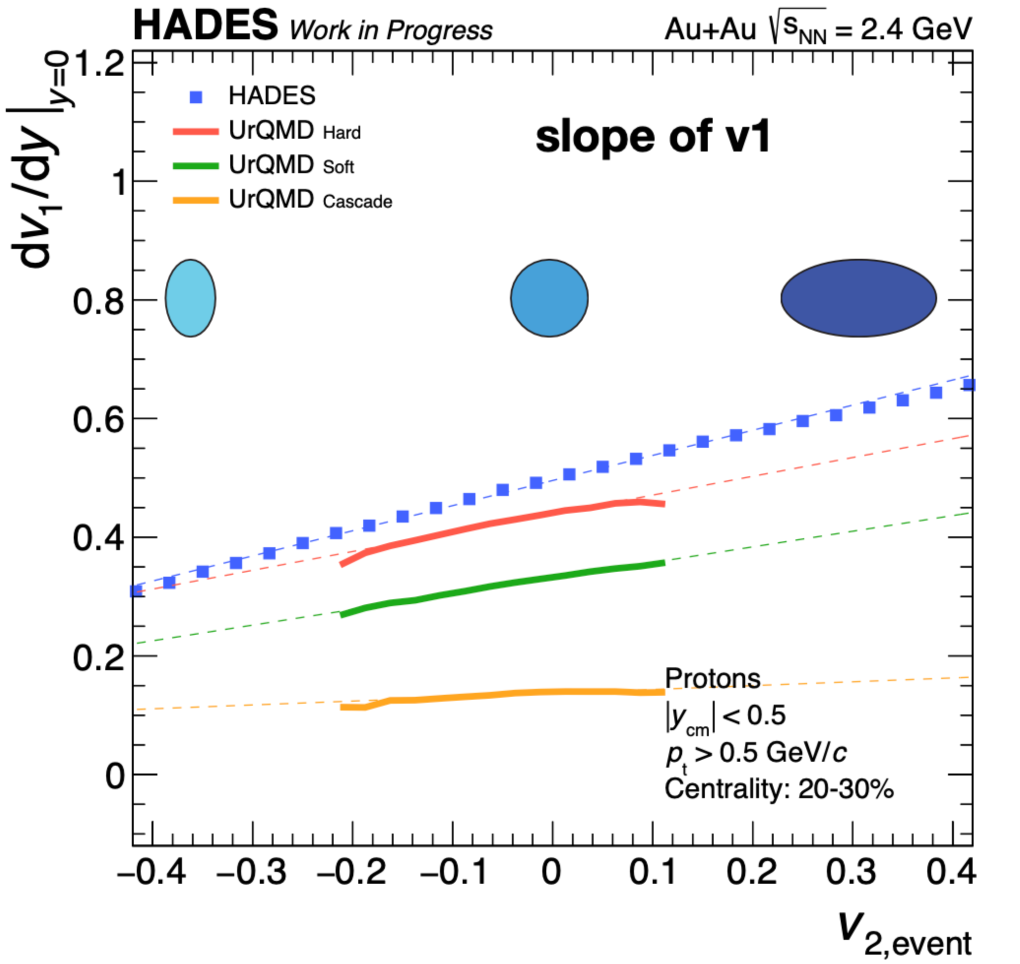
Transition from out-of-plane to in-plane depends on centrality, rapidity and particle species

Event-wise flow correlations

B. Kardan, EMMI Workshop 2024



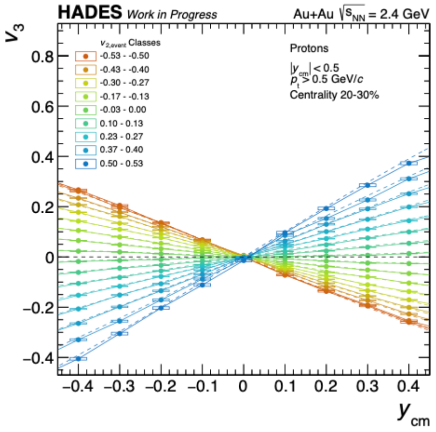


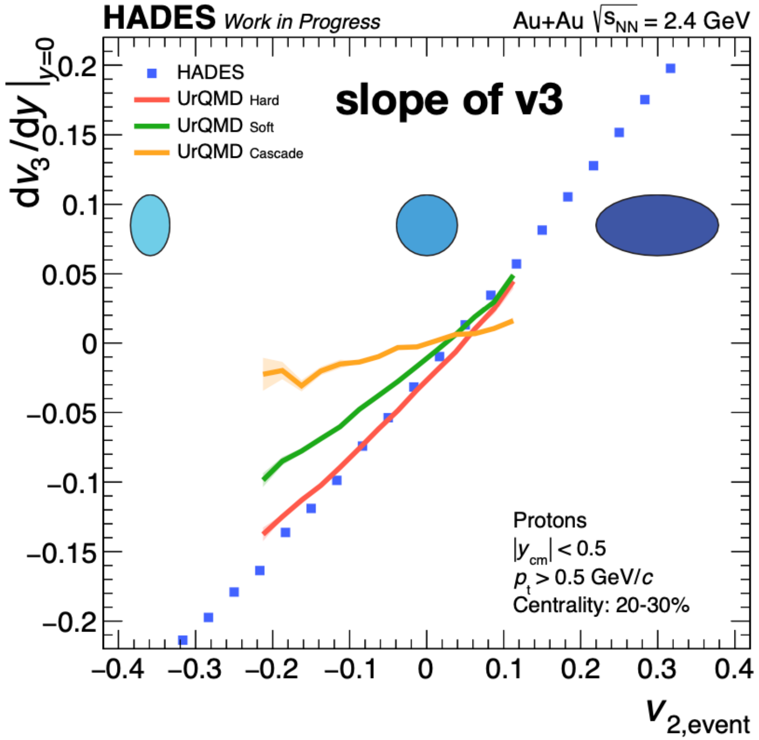


- Events can be characterized based on the event-wise magnitude of the elliptic flow $v_{2,event}$
- UrQMD can not discribe $dv_1/dy|_{y=0}$ of protons as a function of $v_{2,event}$
- Strong sensitivity to the EOS

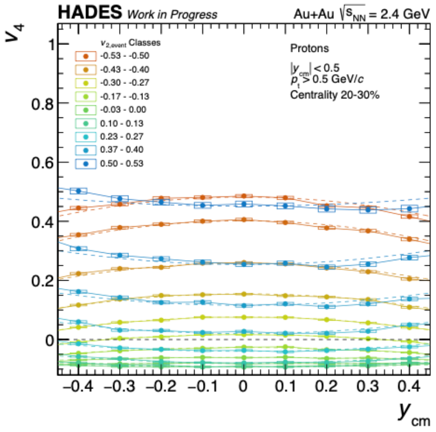
Event-wise flow correlations

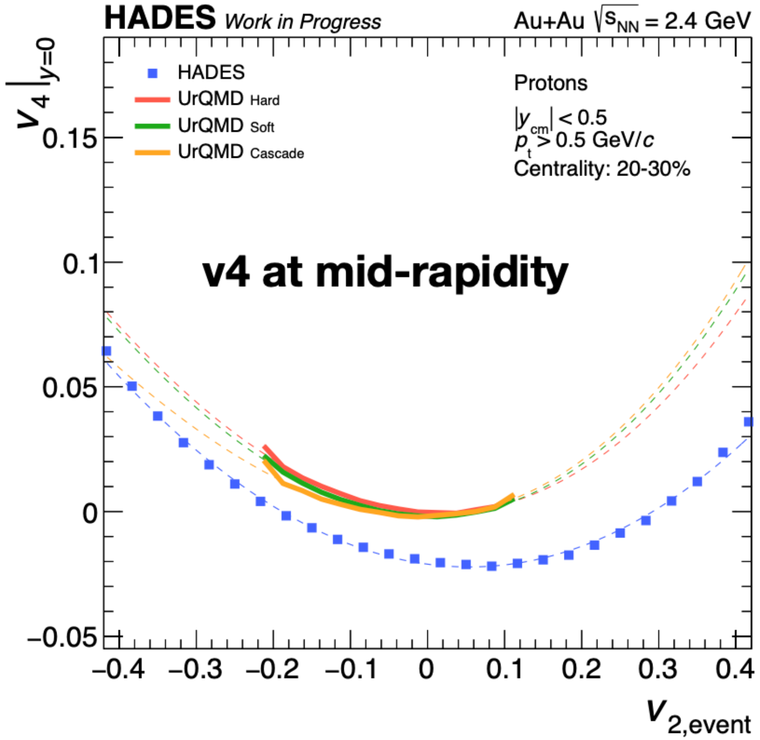
B. Kardan, EMMI Workshop 2024





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



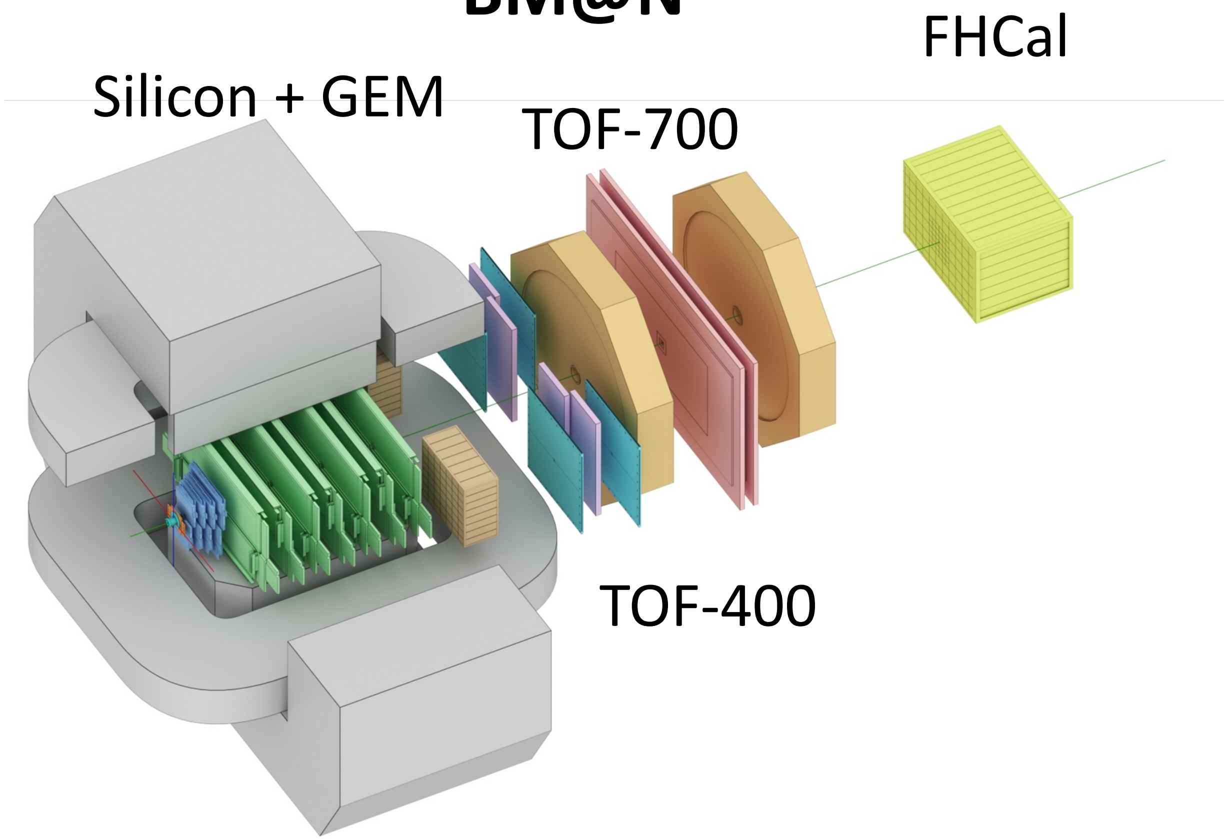


Models overestimate v_4 **of protons as a function of** $v_{2,event}$ **compared to the HADES data**

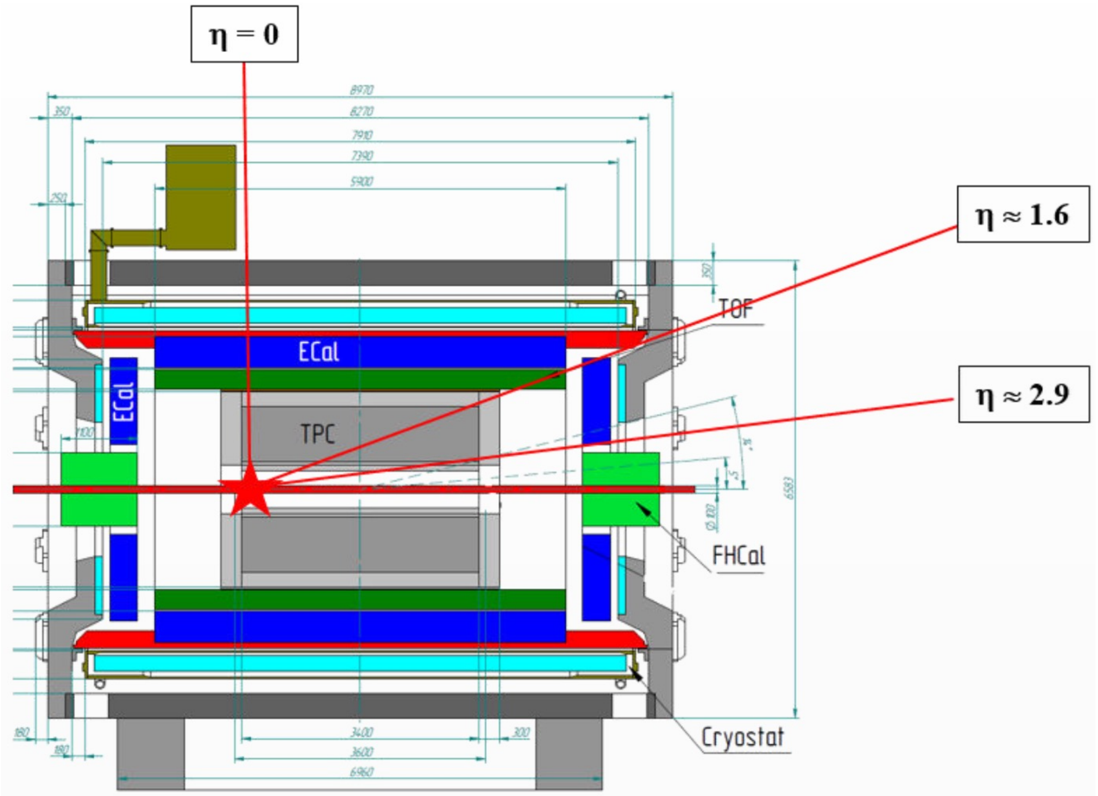
Mean-field models do not reproduce experimental data on the event-wise flow correlations of protons

The MPD-FXT and BM@N experiments

BM@N



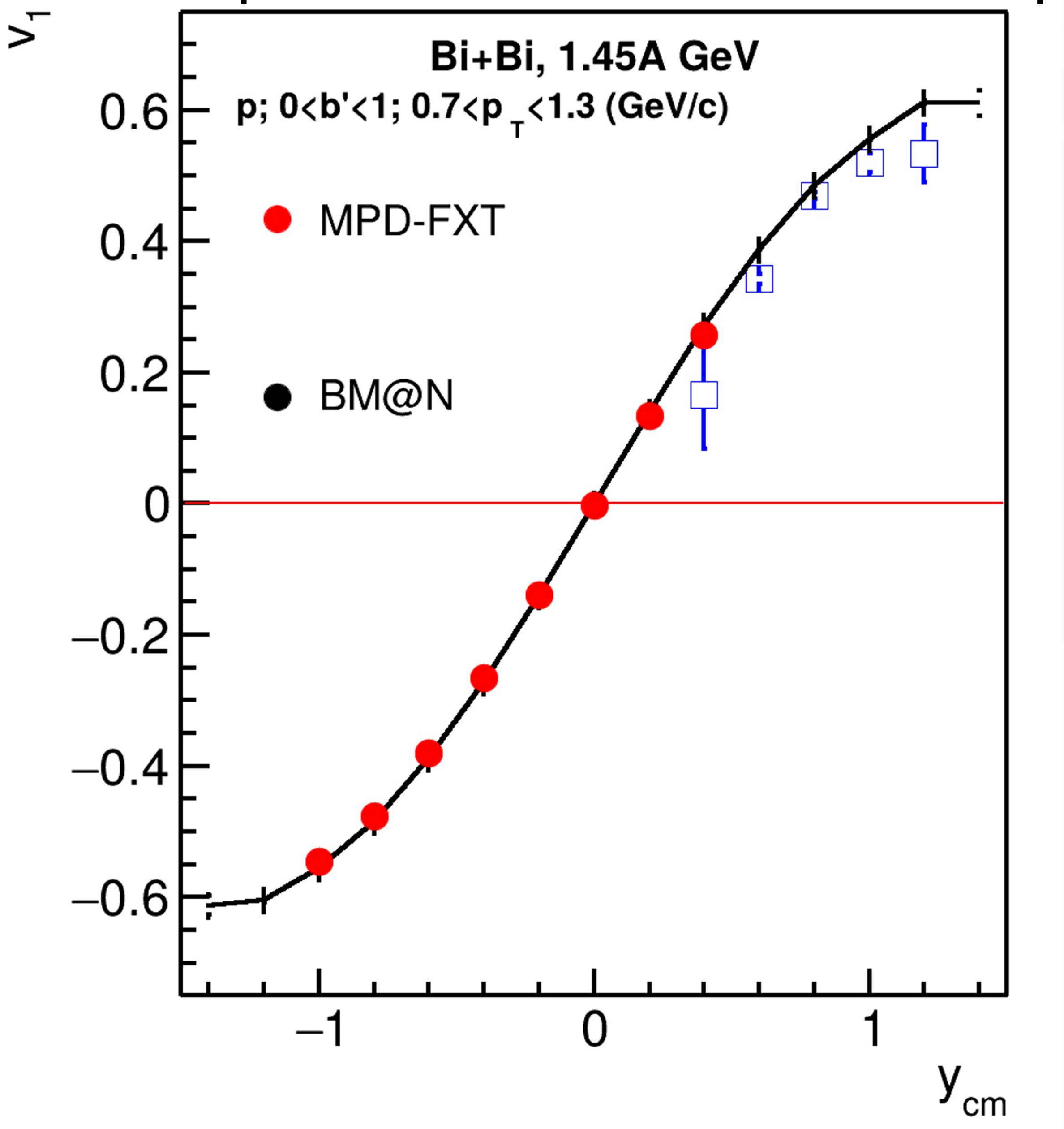
MPD-FXT



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 with BM@N performance



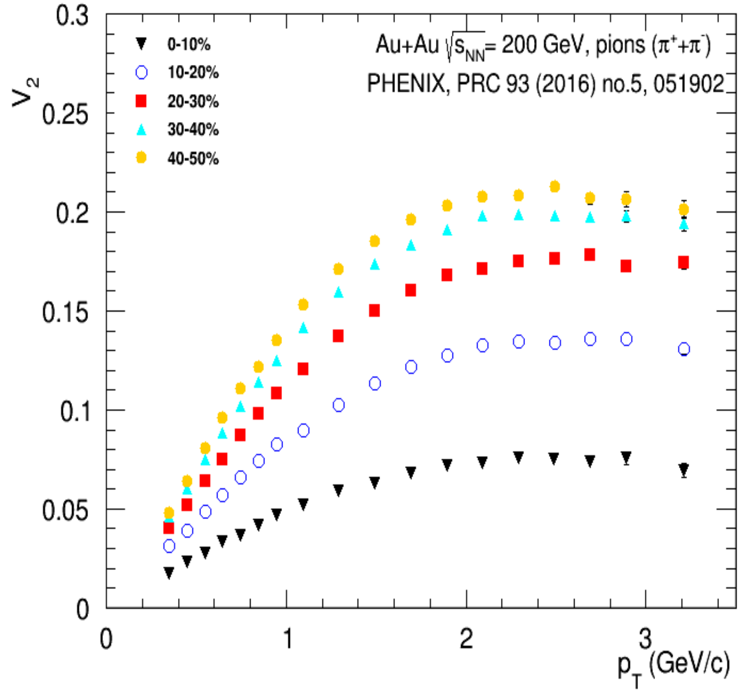
BM@N TOF system (TOF-400 and TOF-700) has poor midrapidity coverage at $\sqrt{s_{NN}}$ = 2.5 GeV

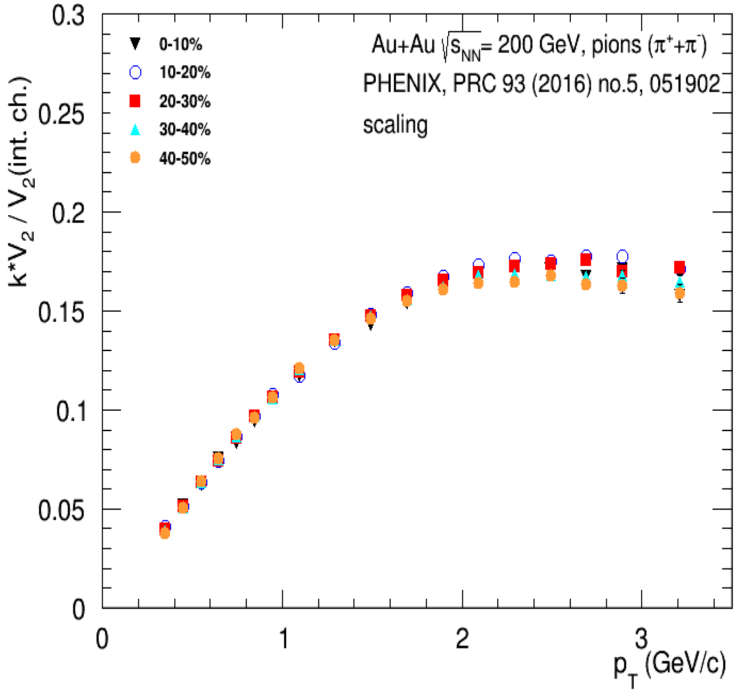
- One needs to check higher energies ($\sqrt{s_{NN}}$ = 3, 3.5 GeV)
- More statistics are required due to the effects of magnetic field in BM@N:
    - Only "yy" component of <uQ> and <QQ> correlation can be used

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

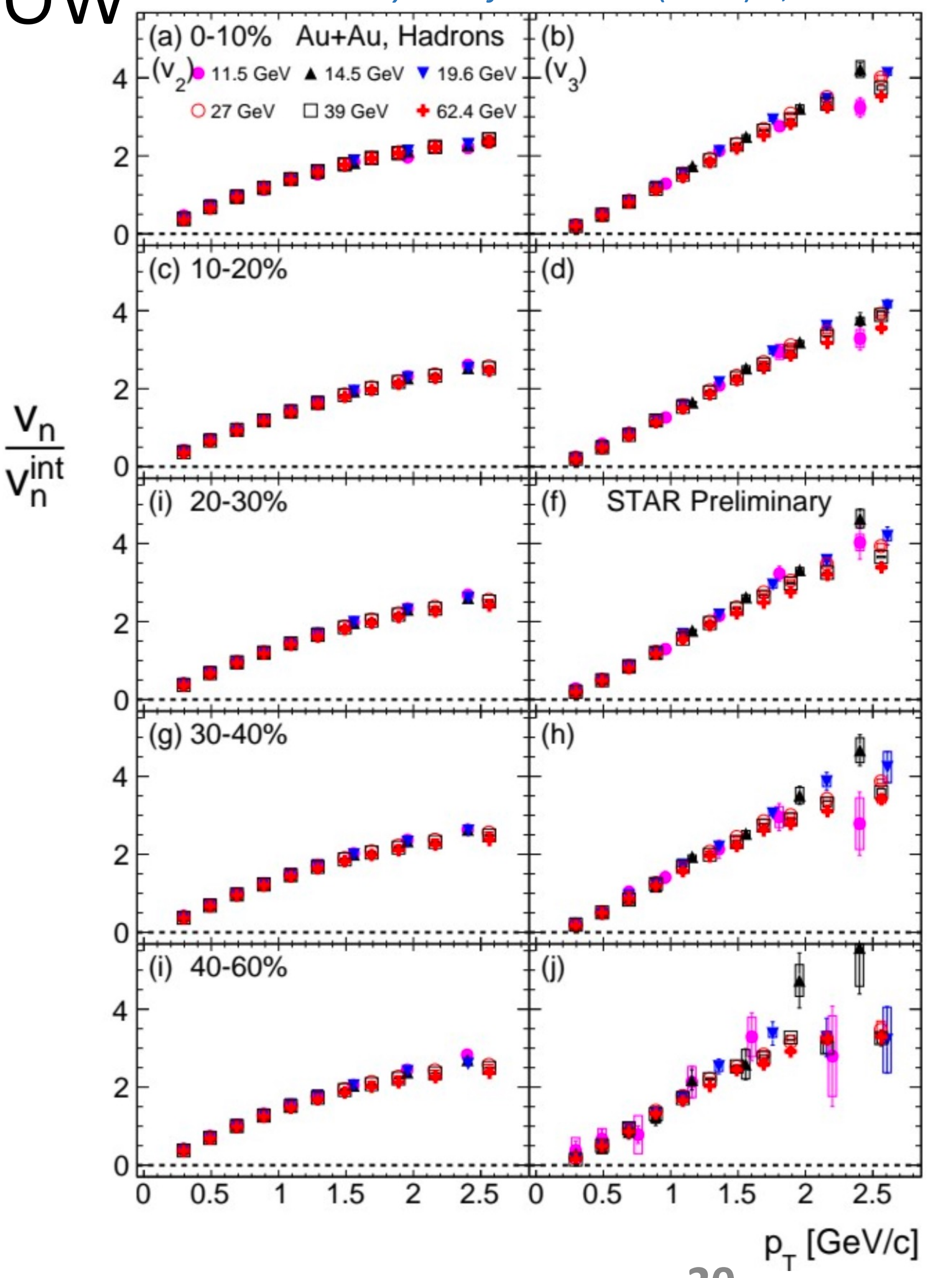
- To widen rapidity coverage
- To perform a cross-check in the future

Scaling with integral anisotropic flow





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

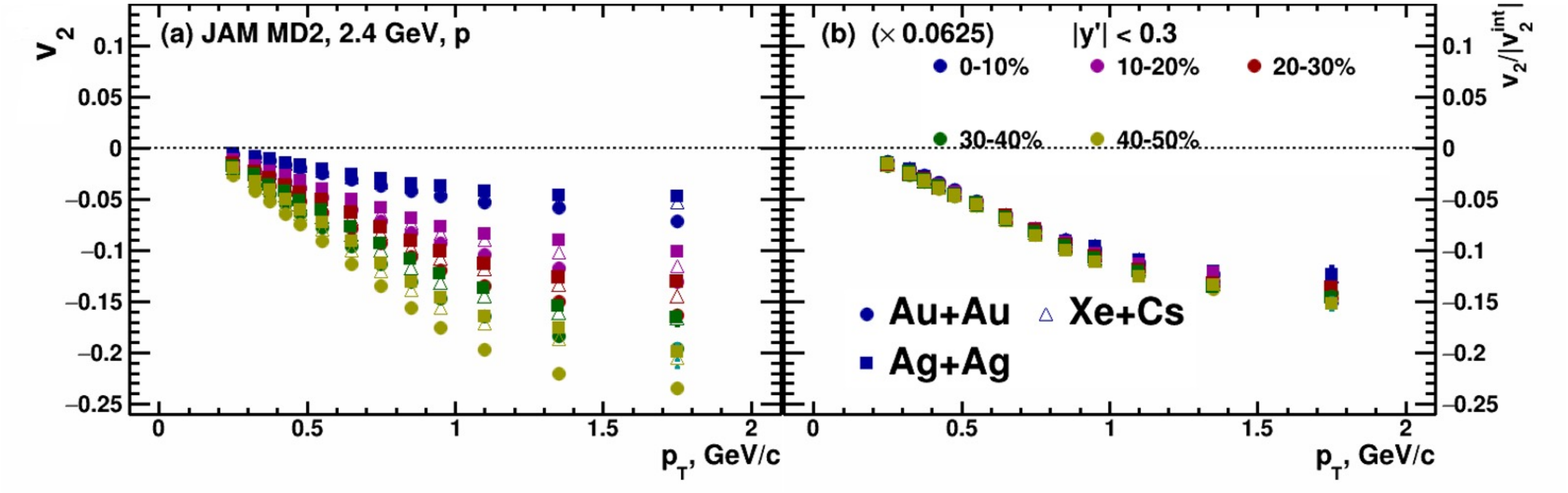


$$v_n(int.) \equiv |v_n^{int}| = |\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}|$$

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

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

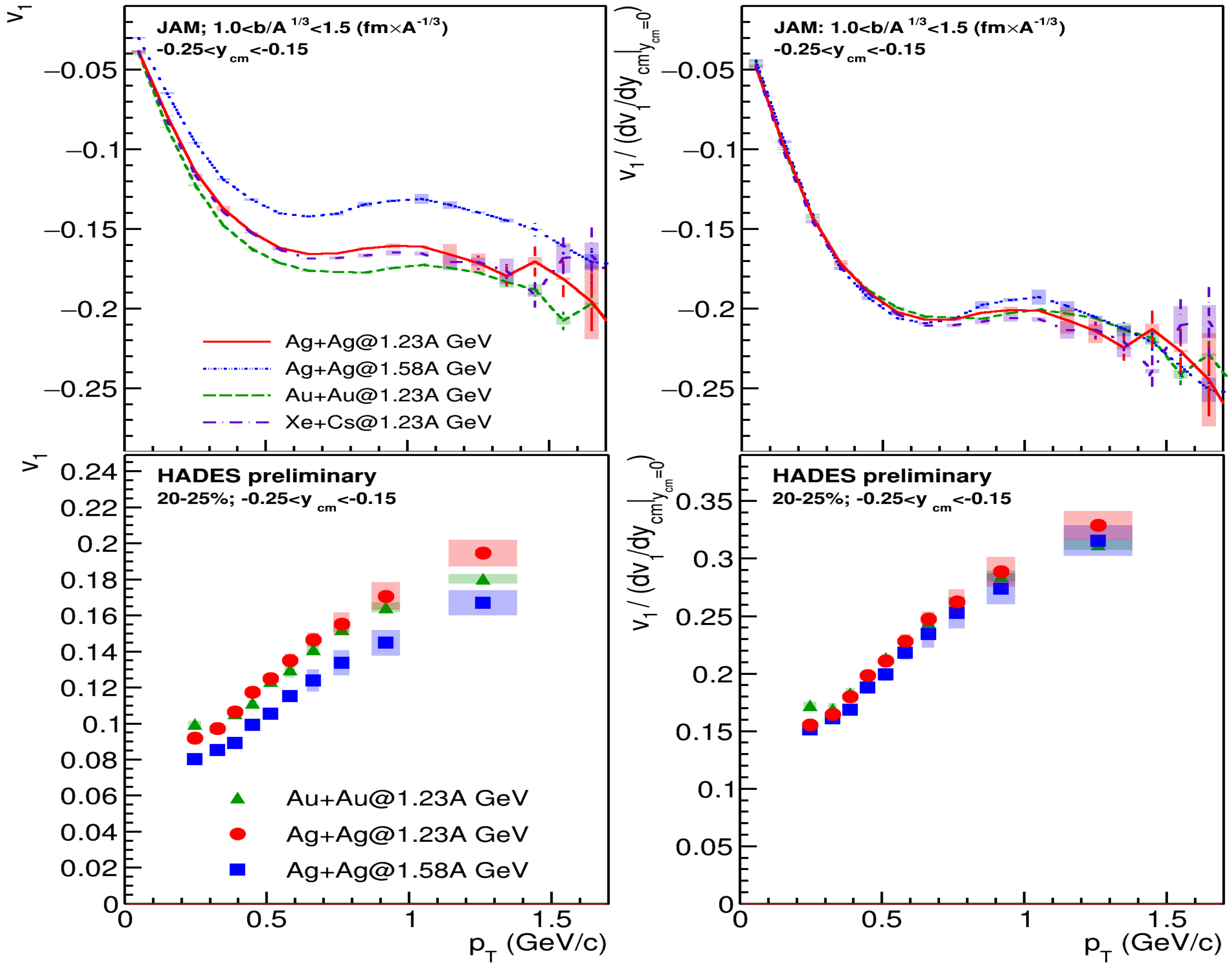
$$|v_n^{int}| = |\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}|$$



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

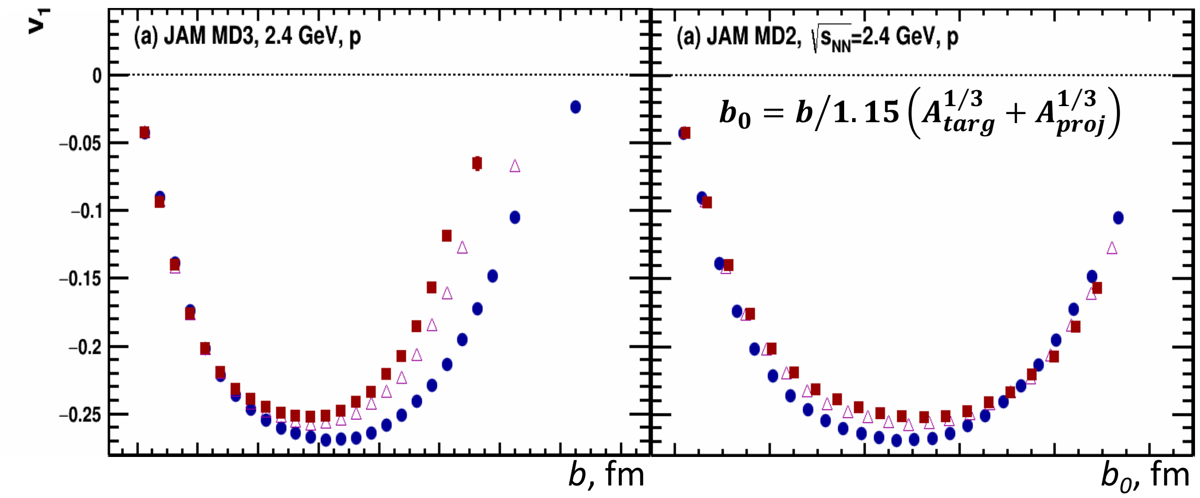
Provides a useful tool to make comparison of v_n results from different colliding systems

Scaling with v_1 slope

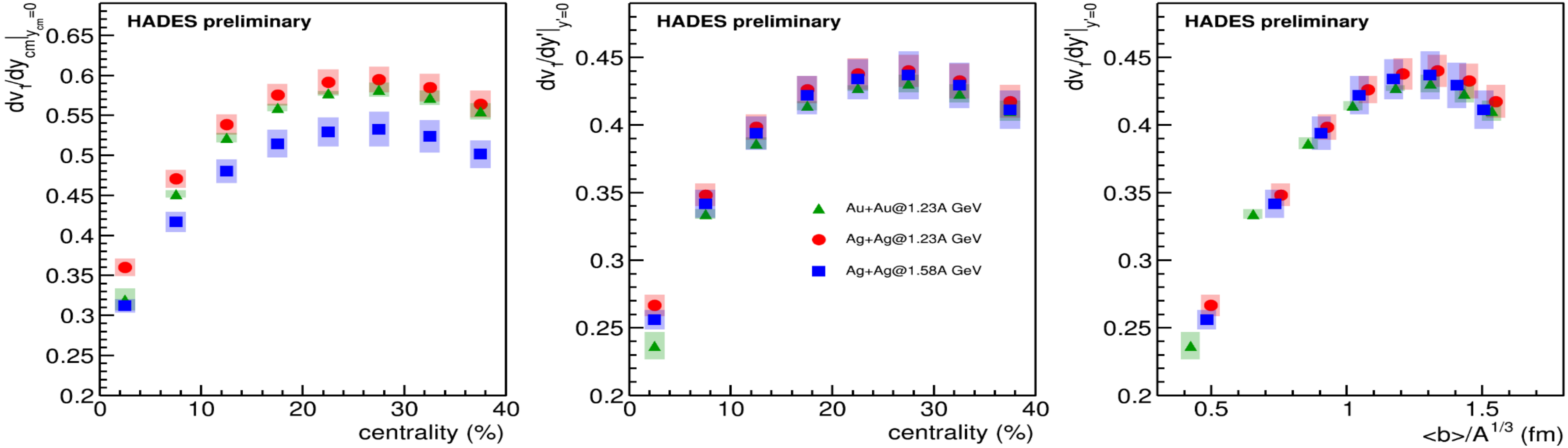


Scalings with $dv_1/dy\,|_{y=0}$ slope can be useful for comparison of the $v_n(y, p_T)$ results for different colliding systems

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**



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
- **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!**
- **Scaling relations can be used to compare results from MPD, MPD-FXT and BM@N with the existing experimental data for $\sqrt{s_{NN}} \leq$ 3 GeV and further constrain models:**
  - Scaling with system size provides a useful tool to make comparison of v_n results from different colliding systems

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!