Model comparison with experimental data on collective flow at Nuclotron and NICA energies

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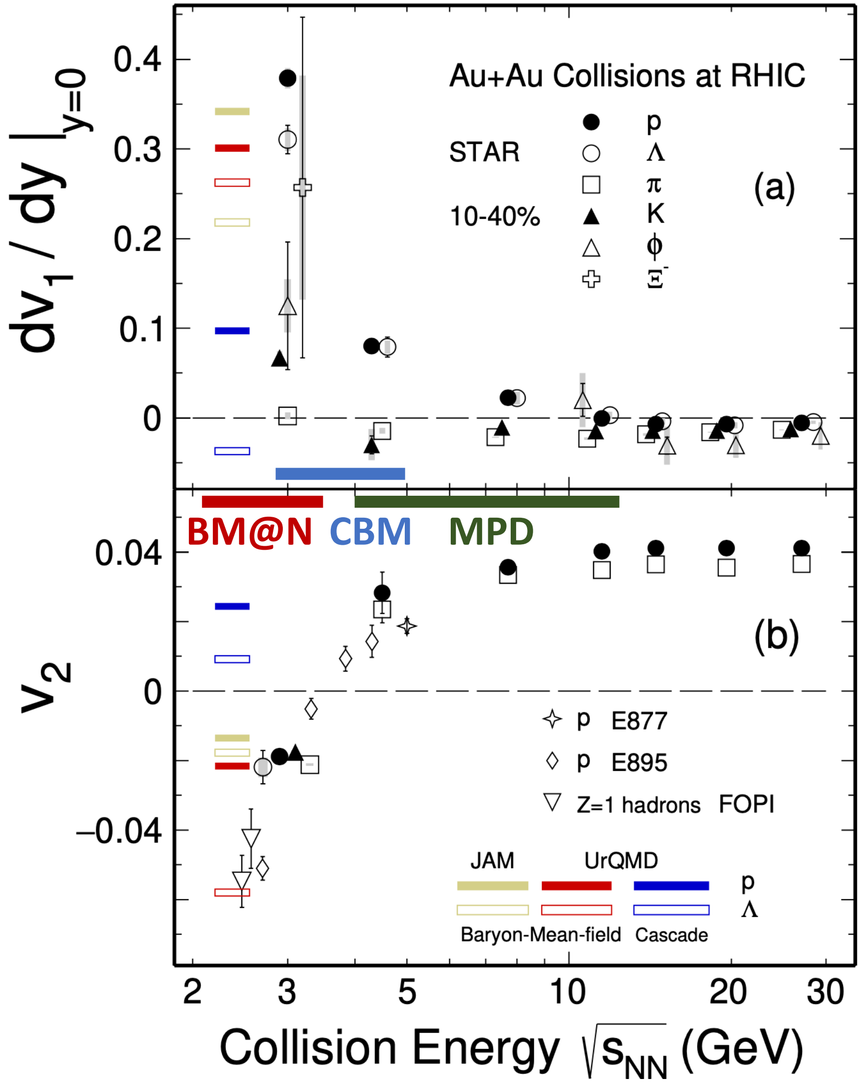
Outline

- Introduction
- Anisotropic flow at $\sqrt{s_{NN}}$ = 4.5 – 11.5 GeV: hybrid and pure hadronic models vs. existing data
- Anisotropic flow at $\sqrt{s_{NN}}$ = 2.4 – 4.5 GeV: hadronic models with different EOS vs. data from HADES and STAR BES FXT
- What to expect from detailed $v_n(p_T, y)$ measurements at Nuclotron and NICA energies?
- Summary and outlook

Anisotropic flow in Au+Au collisions at FAIR/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

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

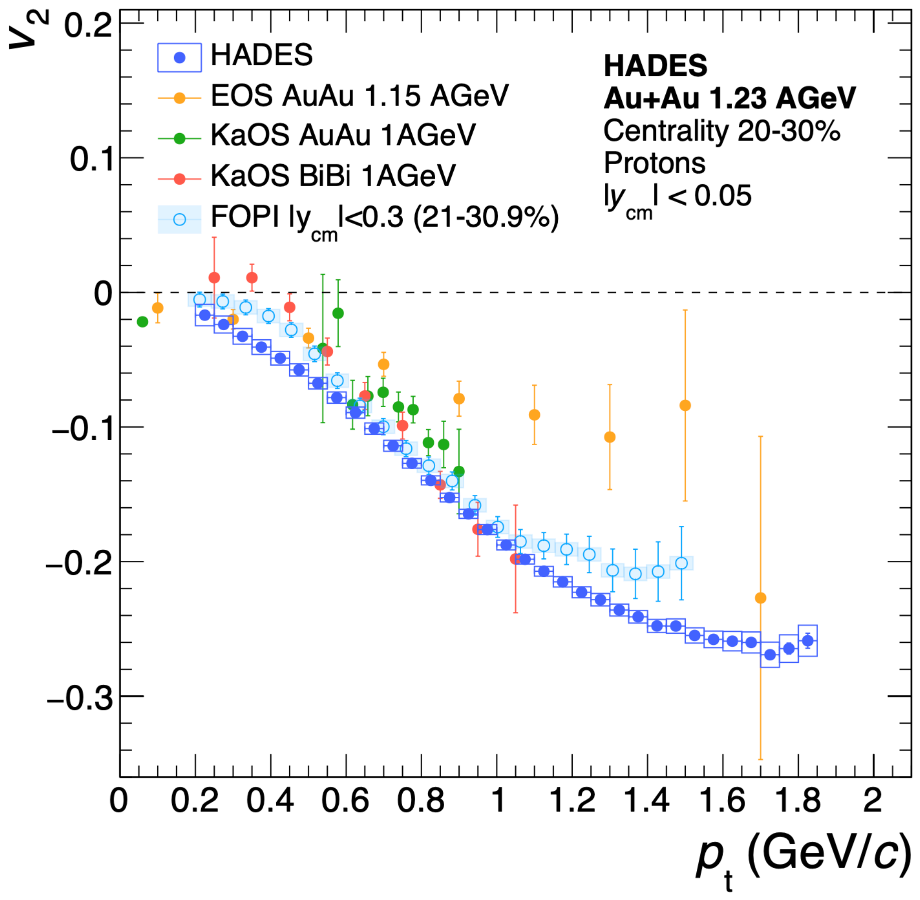
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$) and

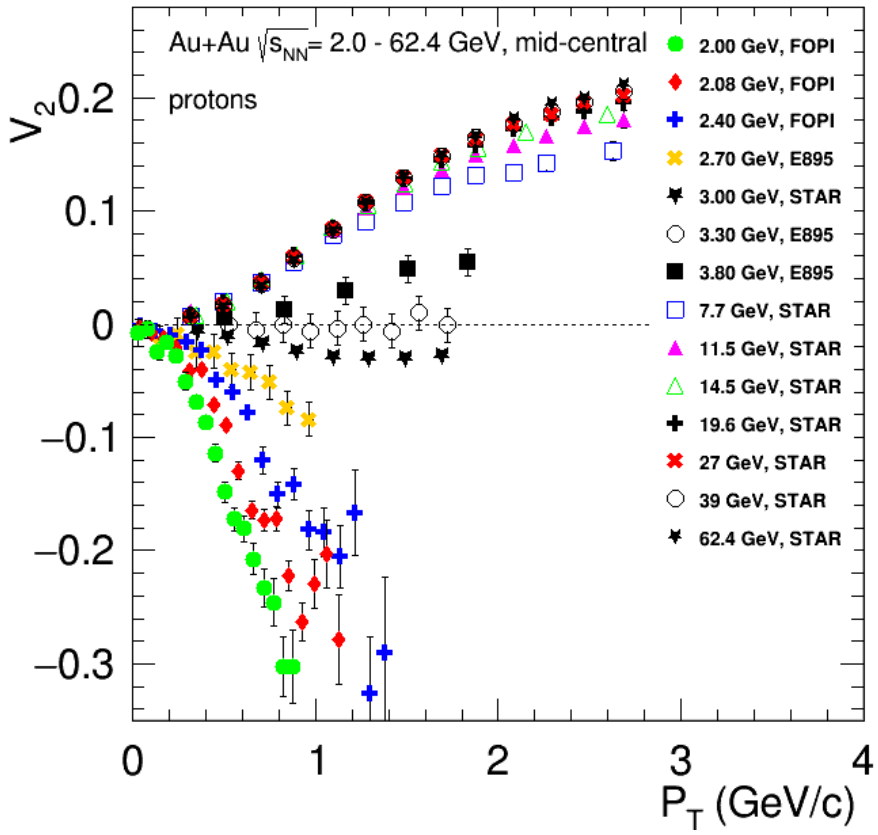
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Goal of this work:

- Perform simulation with different models and make comparison with STAR BES (3, 4.5, 7.7, 11.5 GeV) and HADES (2.4 GeV) published experimental data
- Make predictions for the anisotropic flow measurements $v_n(p_T, y)$ at BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) energies

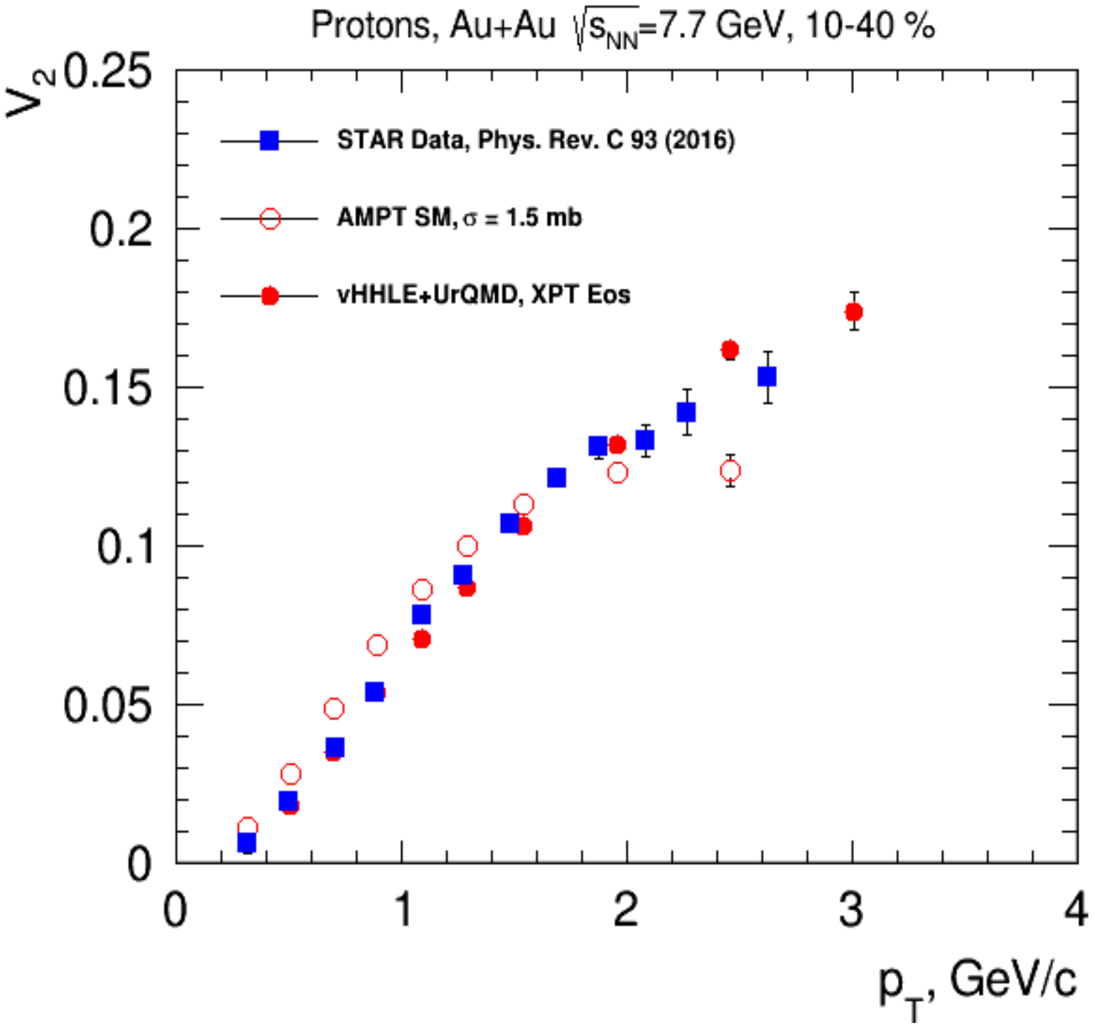
Why do we need new measurements at BM@N and MPD?

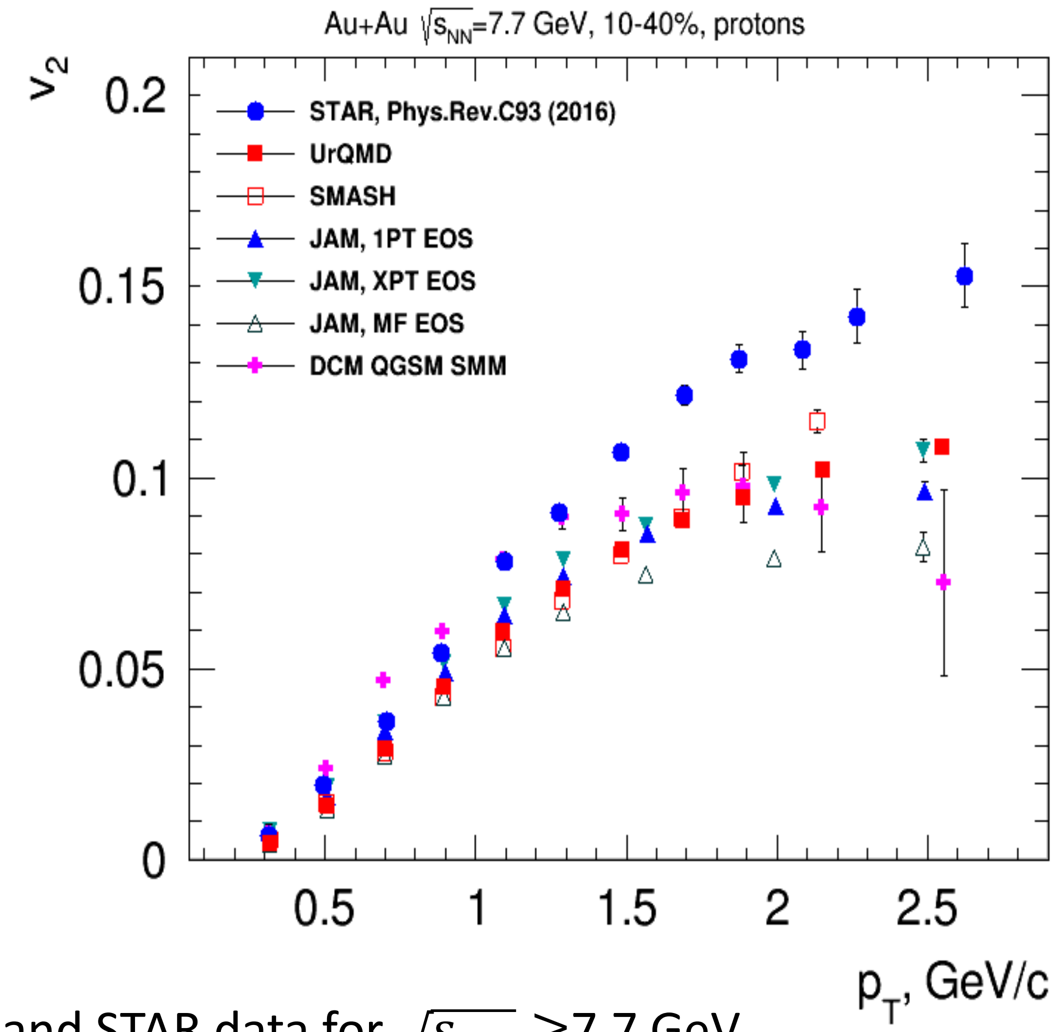




- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust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

Elliptic flow at NICA energies: Models vs. Data comparison



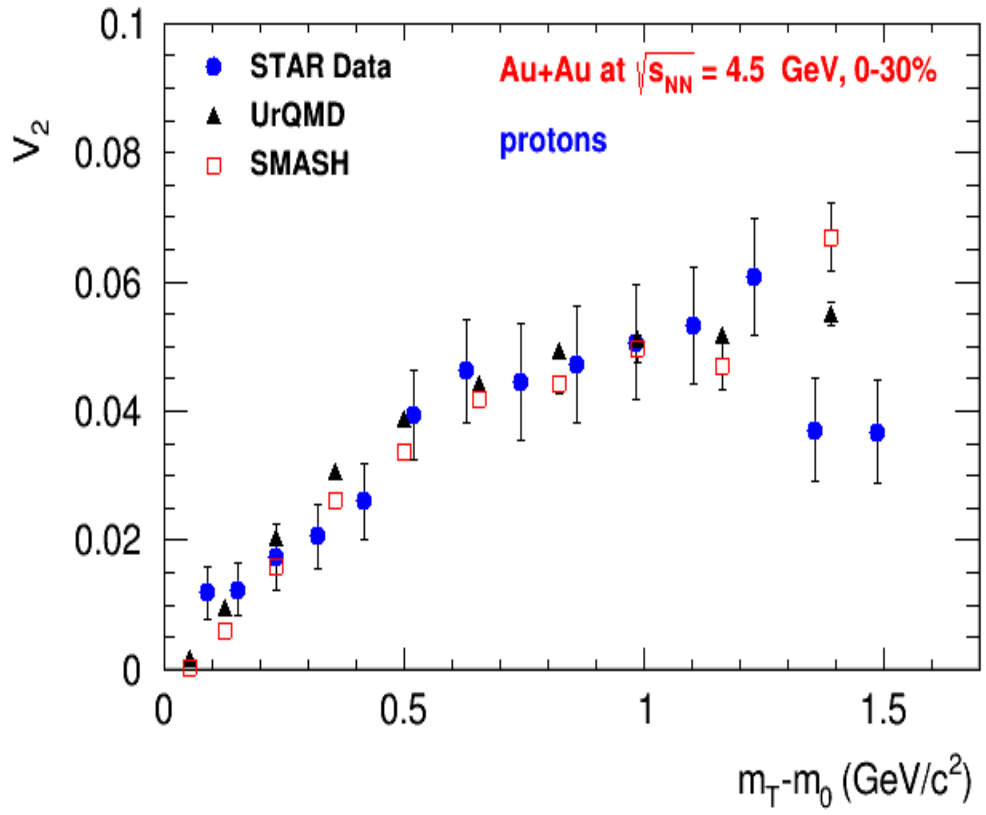


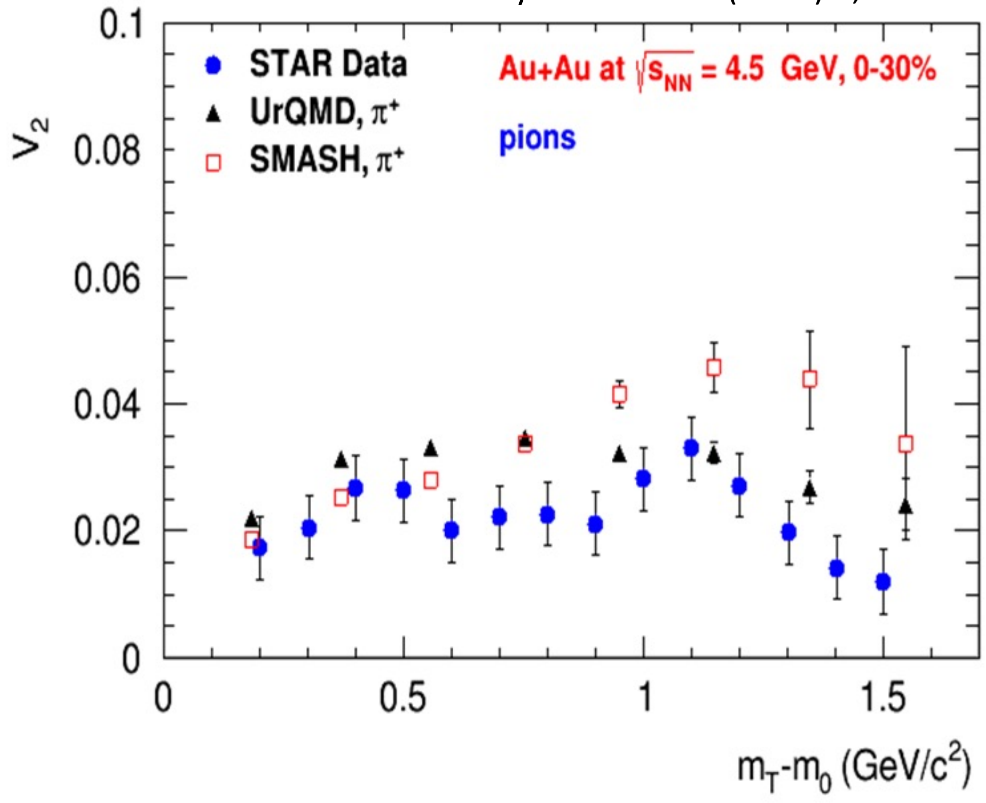
Good agreement between vHLLE+UrQMD, AMPT models and STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

Elliptic flow at NICA energies: Models vs. Data comparison

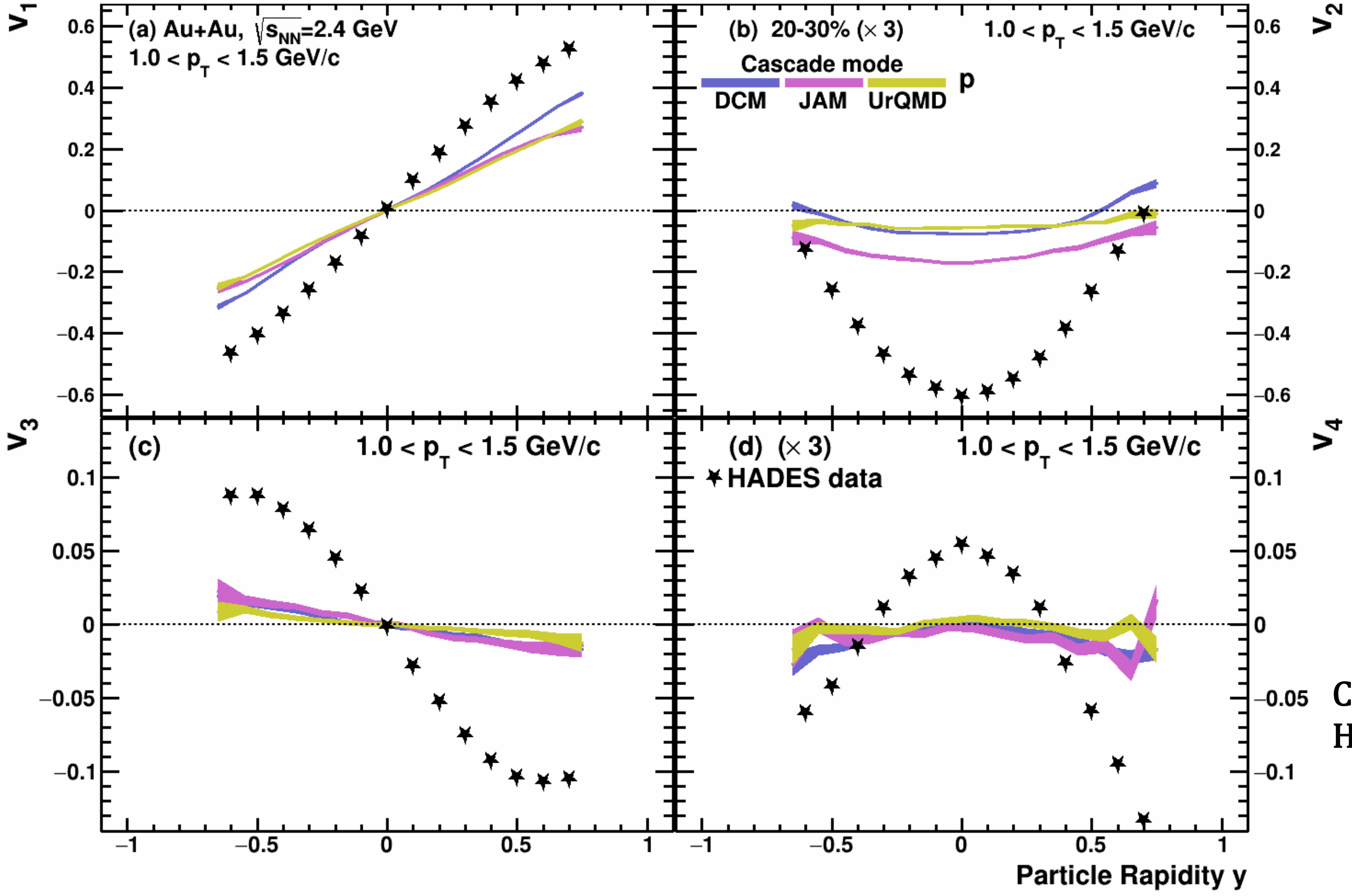
Phys. Rev. C 103 (2021) 3, 034908





Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$ =4.5 GeV

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



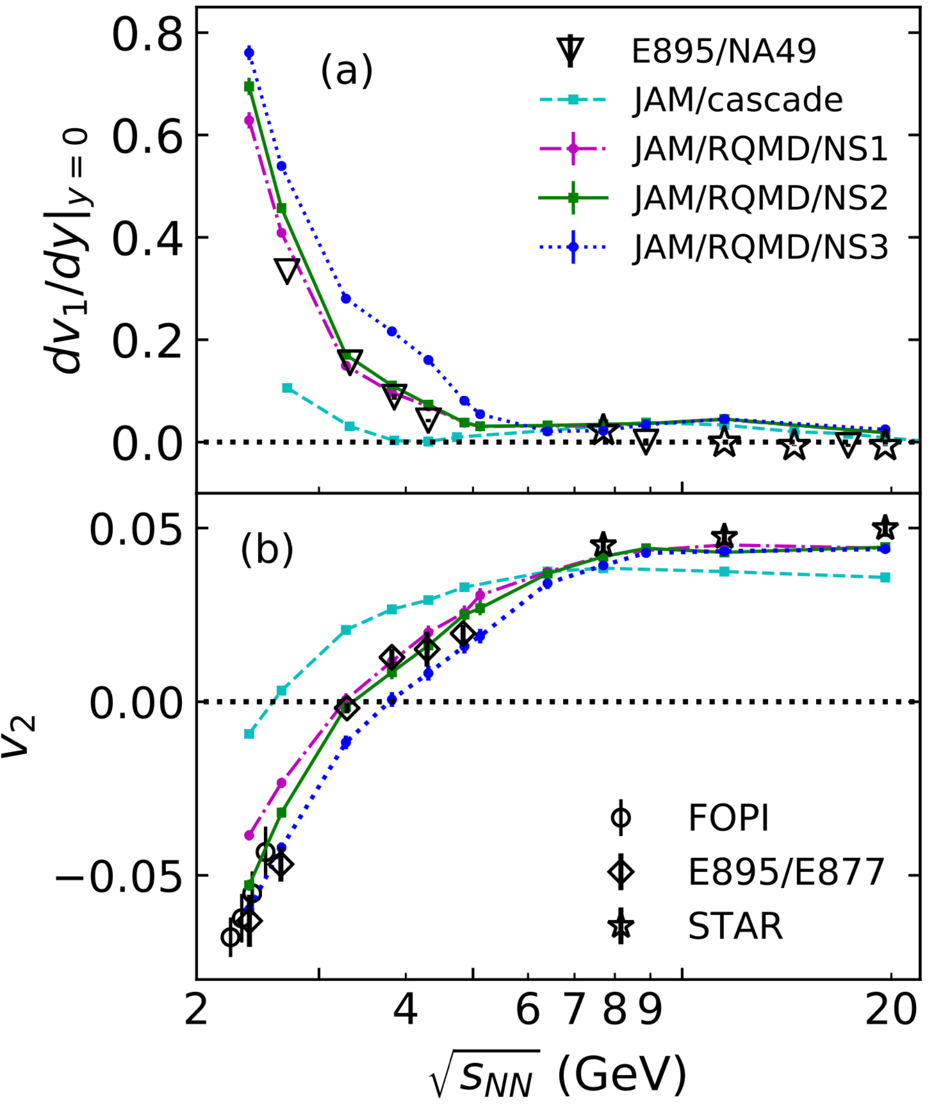
Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

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

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

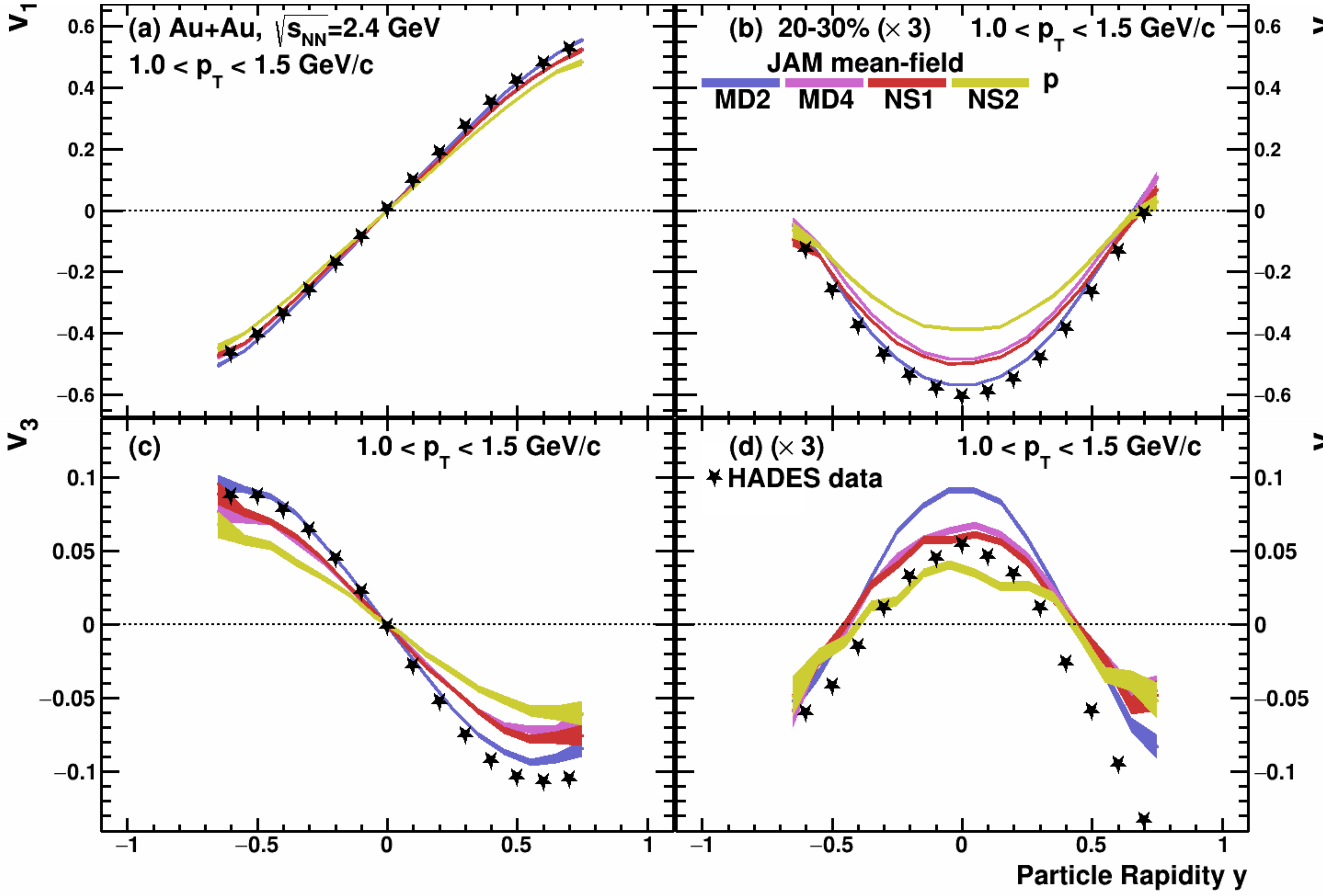
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

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)

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

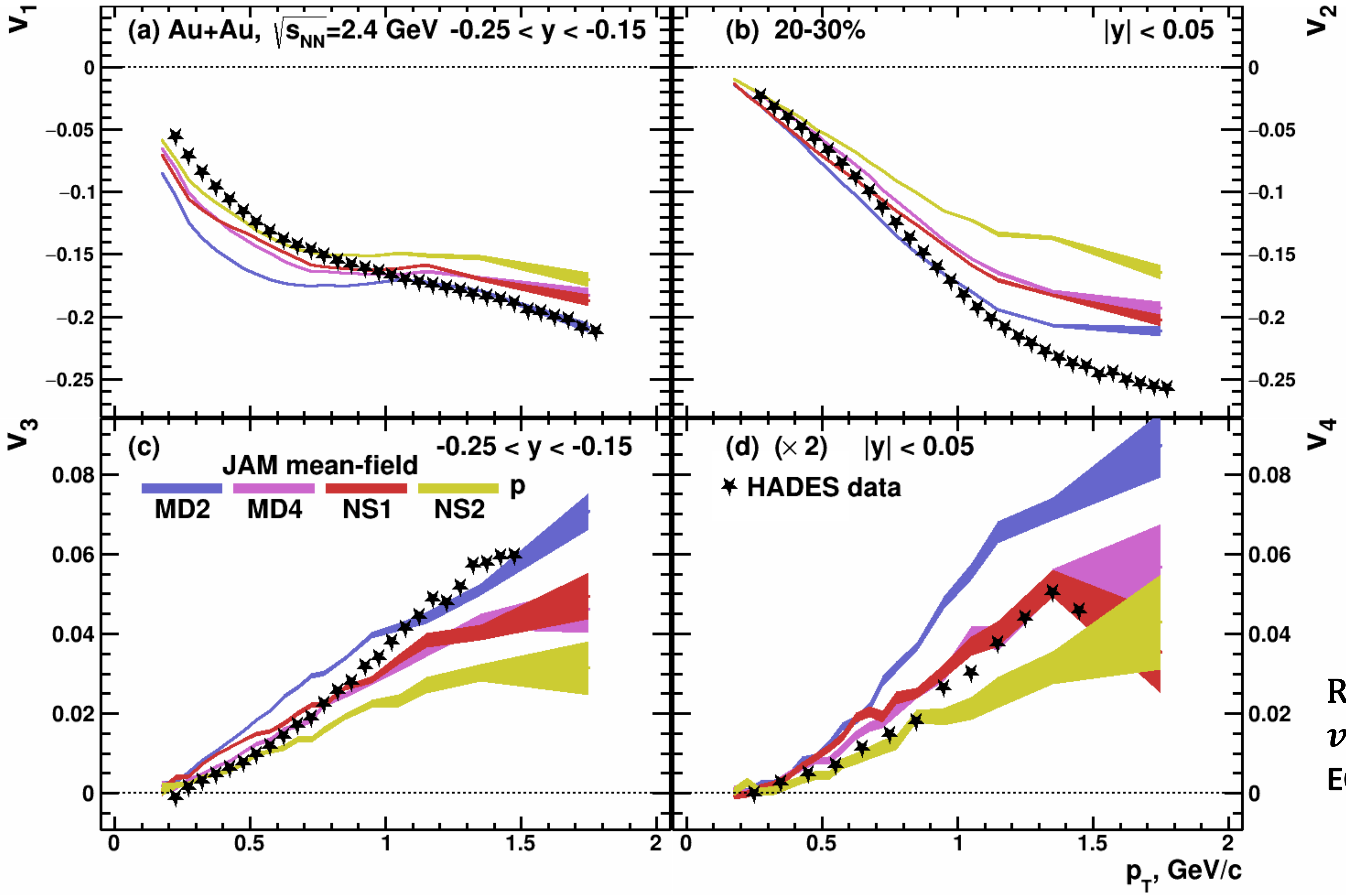


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

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
More JAM results with different EOS are needed

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

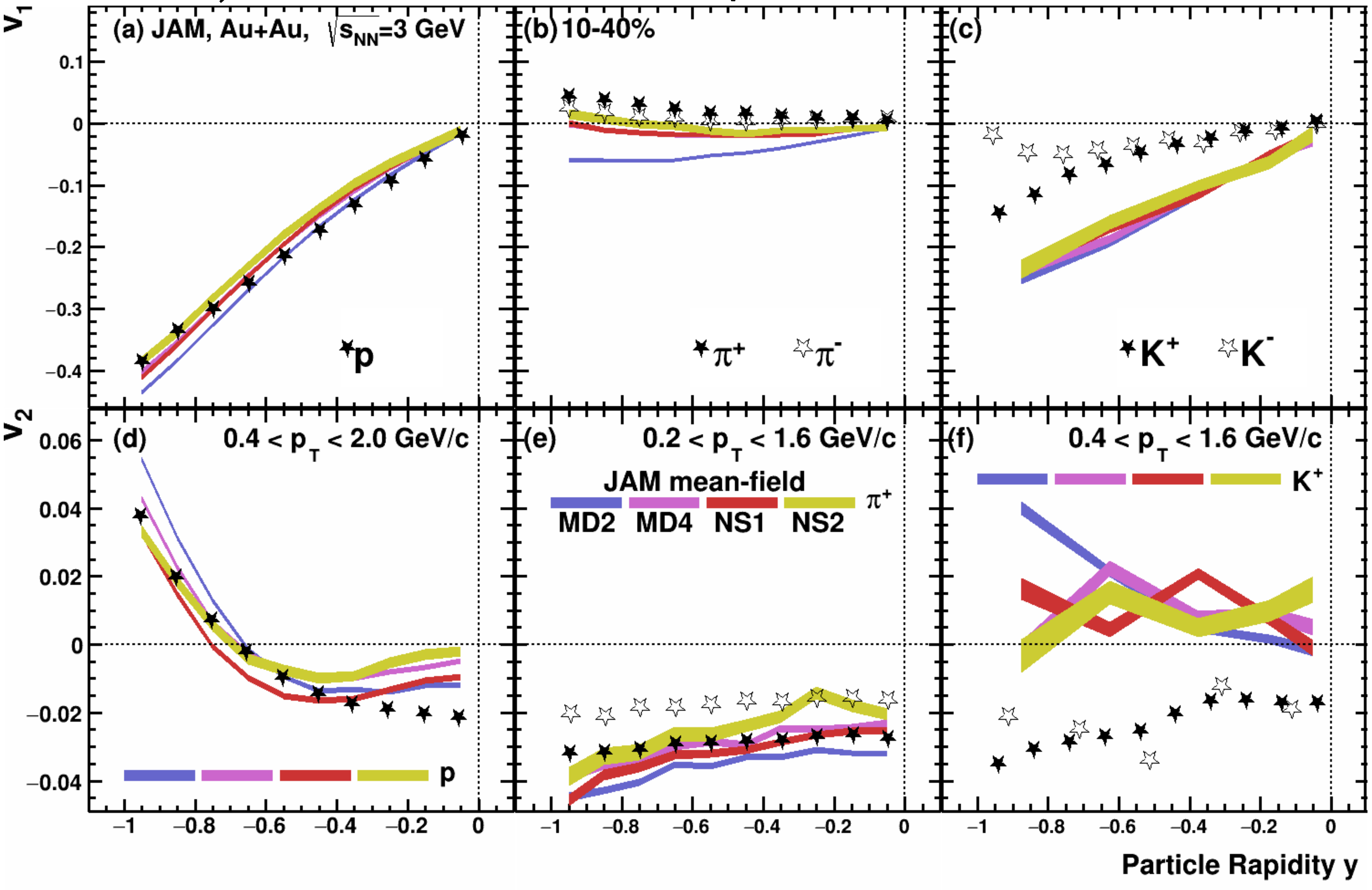


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{2,4}(p_T)$: -0.05 < y < 0.05

Reasonable agreement for $v_n(p_T)$
$v_{3,4}$ are more sensitive to different EOS than v_1

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

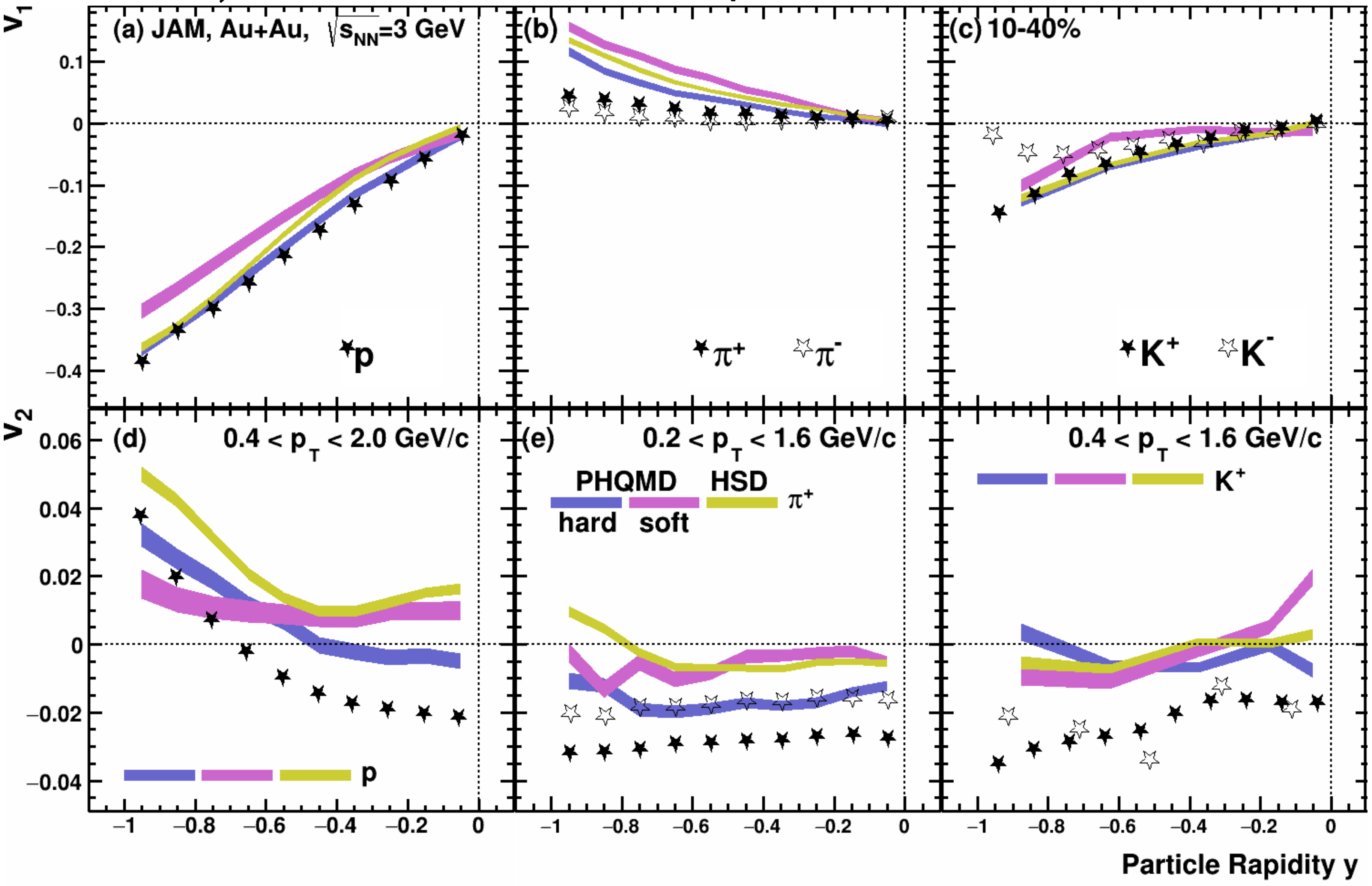


Experimental points are taken from:

M. Abdallah et al. [STAR Collaboration] *Phys.Lett.B* 827 (2022) 137003

JAM does not describe all particle species equally well
v_1 of pions is most sensitive to different EOS

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

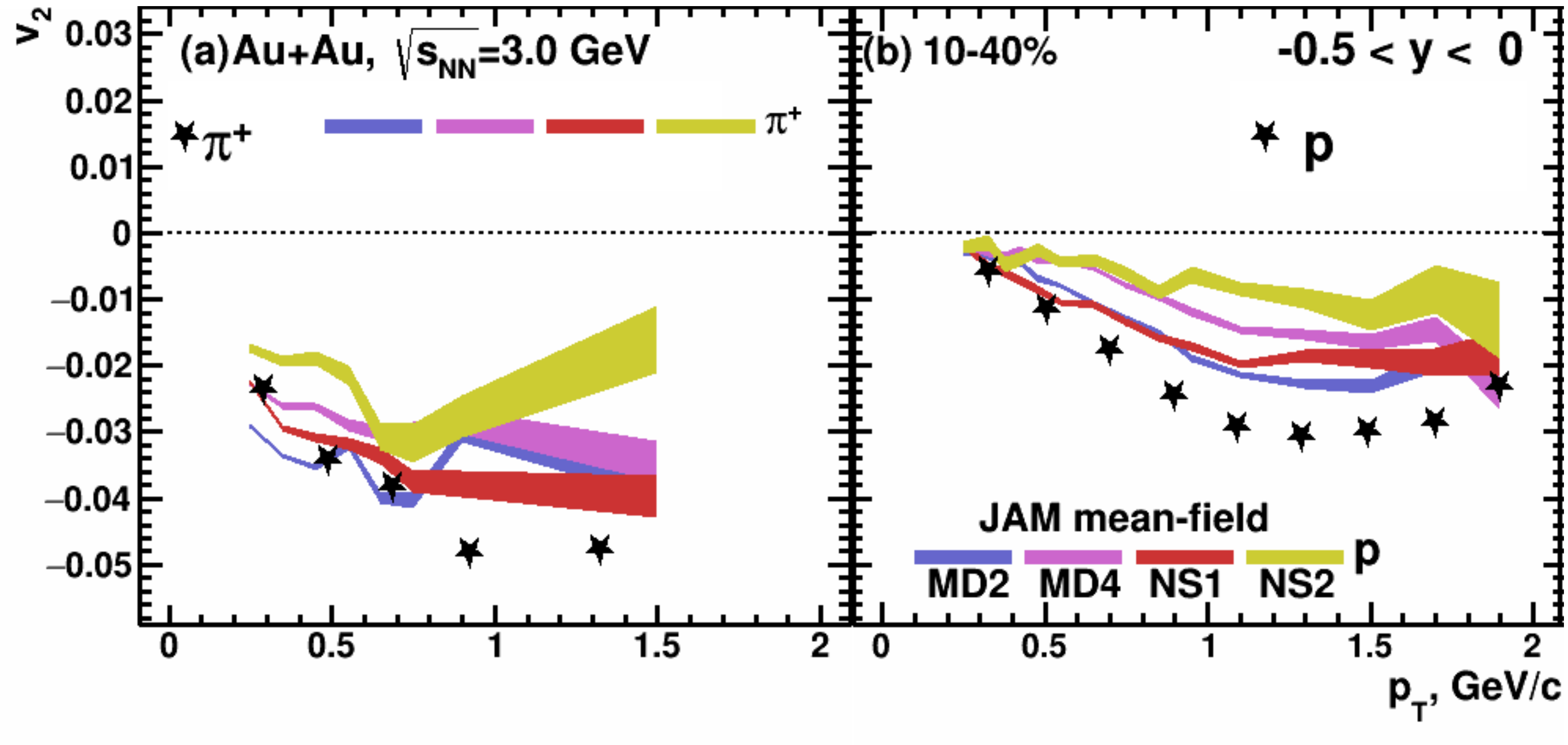


Experimental points are taken from:

M. Abdallah et al. [STAR Collaboration] *Phys.Lett.B* 827 (2022) 137003

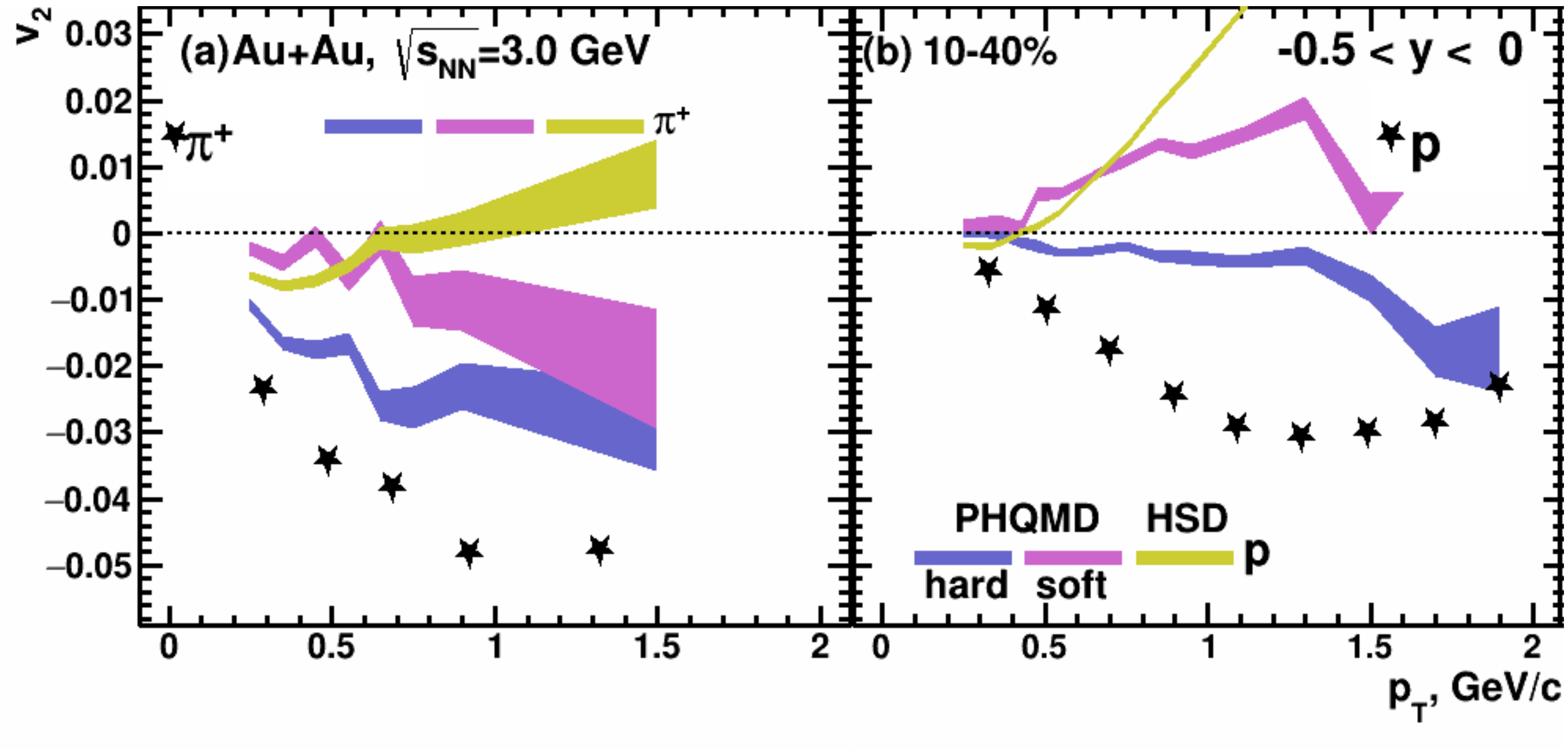
Both PHQMD and HSD cannot reproduce v_2 signal

$v_2(p_T)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



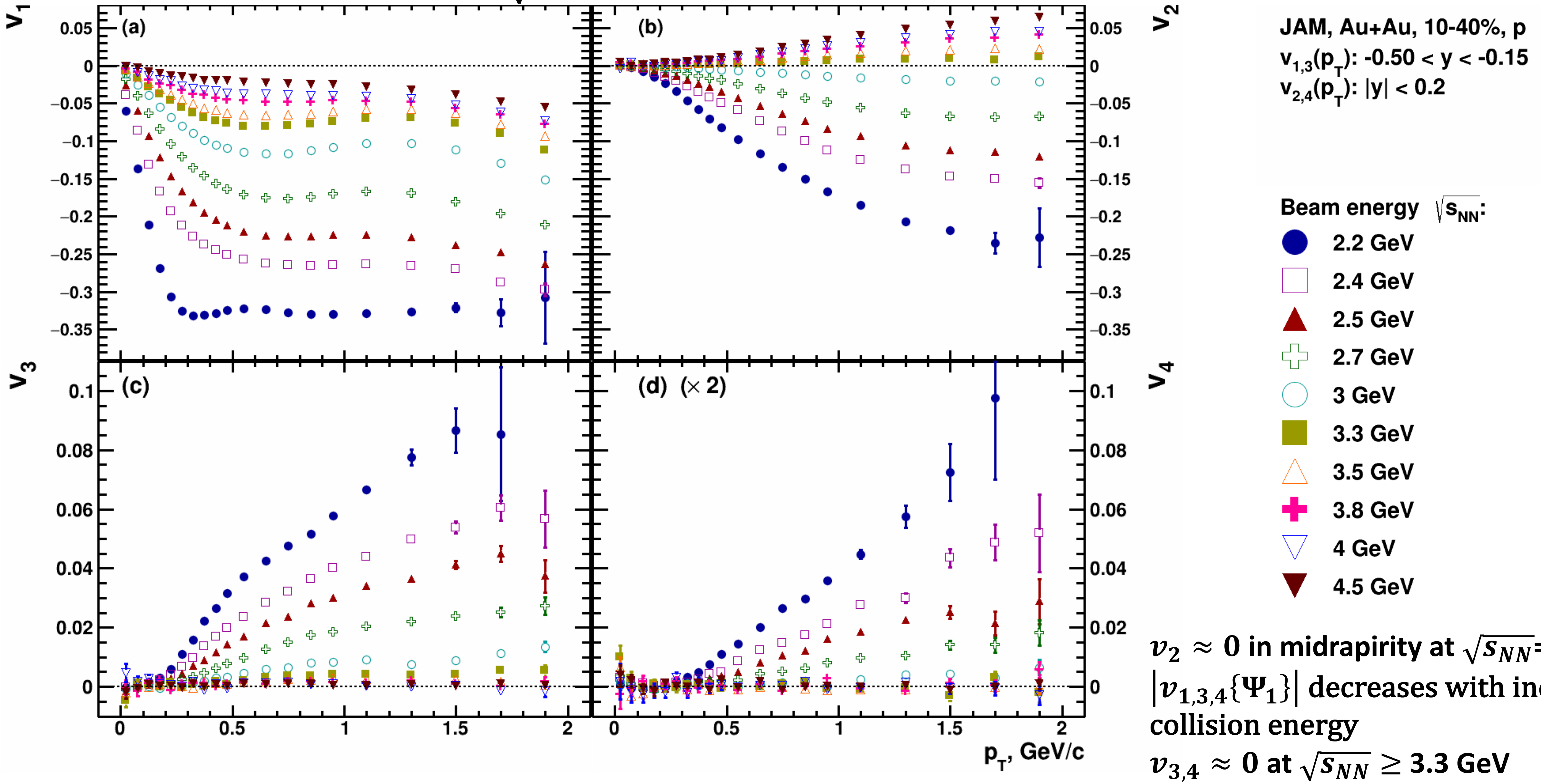
v_2 of pions and protons is more sensitive to different EOS than v_1

$v_2(p_T)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



PHQMD/HSD models cannot reproduce $v_2(p_T)$ of protons

$v_n(p_T)$ Au+Au $\sqrt{s_{NN}}$=2.4-4 GeV: JAM MD2

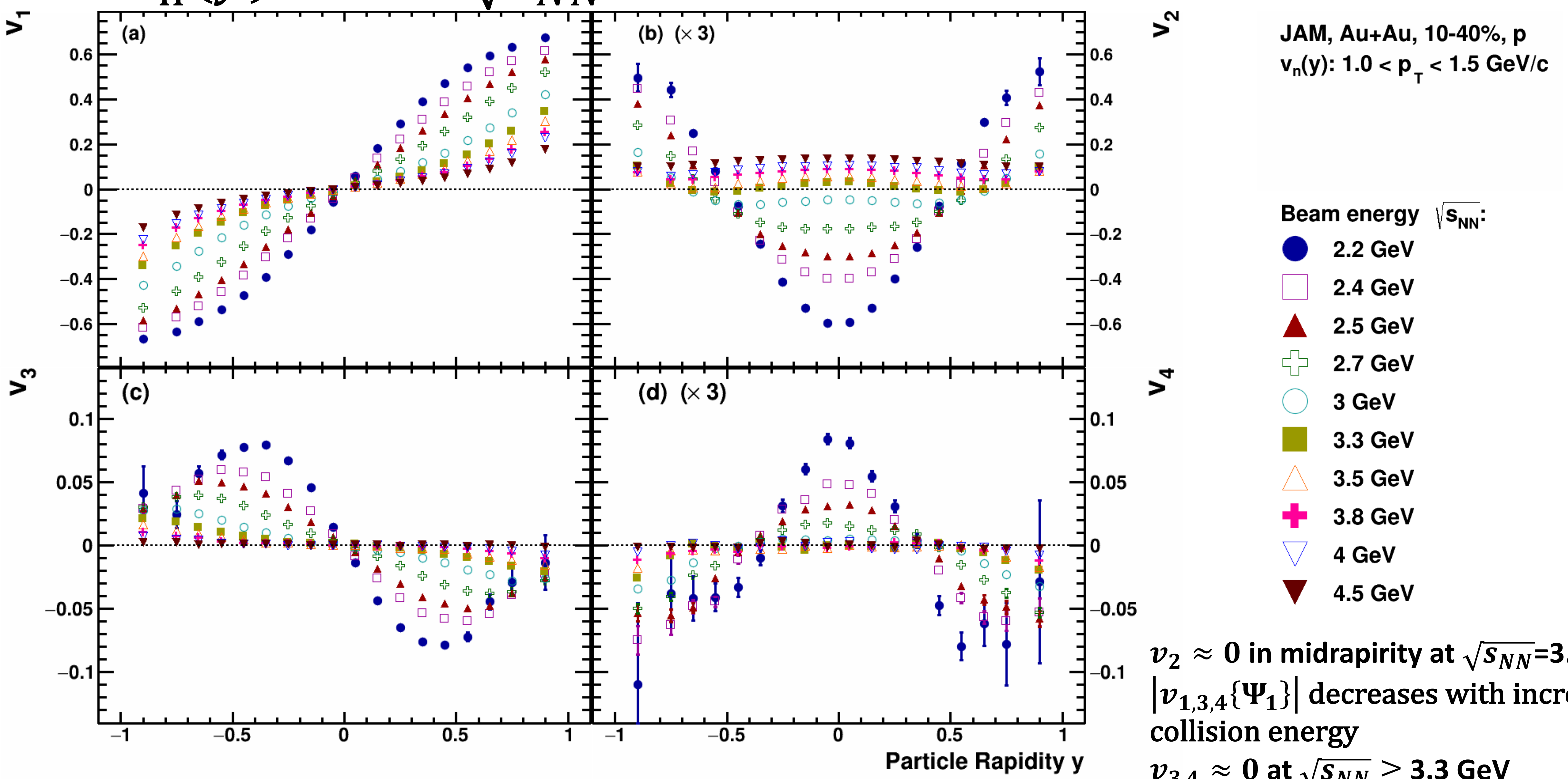


$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

$v_n(y)$ Au+Au $\sqrt{s_{NN}}$=2.4-4 GeV: JAM MD2

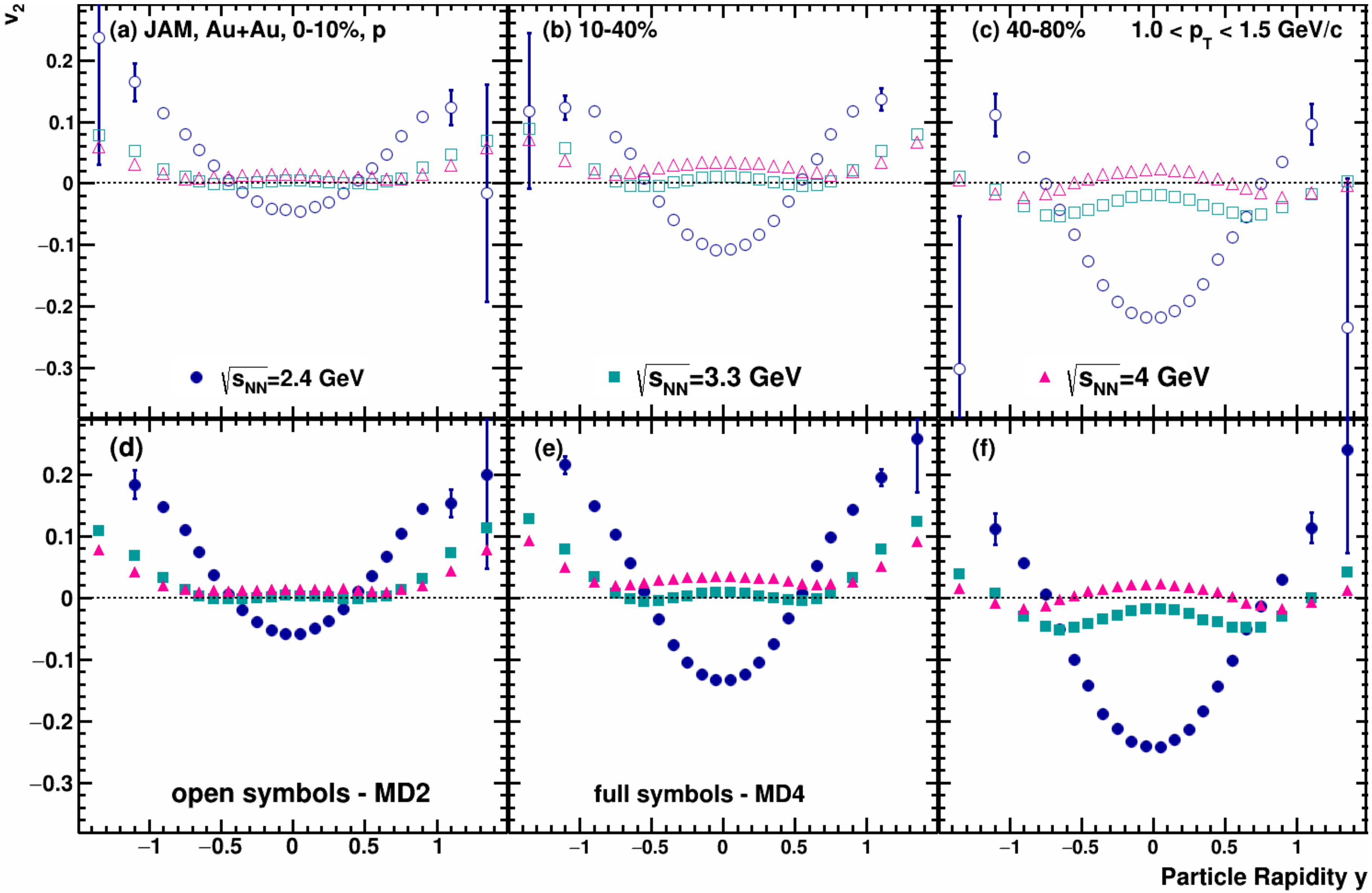


$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

$v_2(y)$ transition from out-of-plane to in-plane



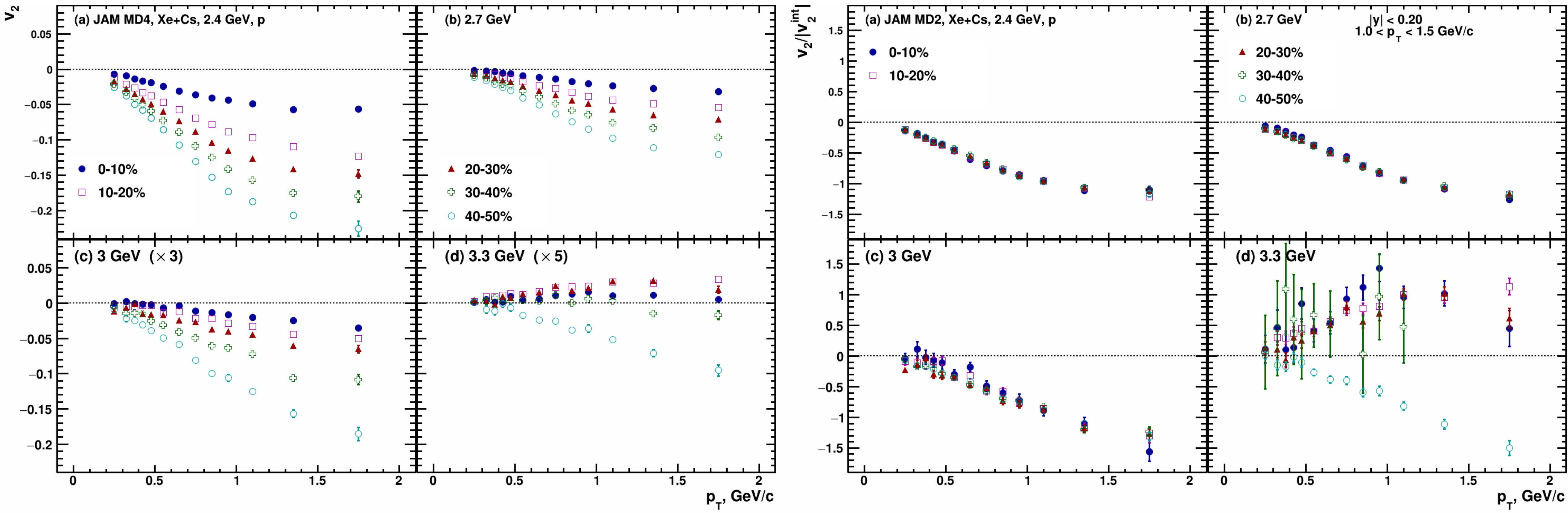
Protons:

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

- Weak dependence on EoS
- $v_2(p_T)$ strongly depends on centrality:
  - Transition from out-of-plane to in-plane depends on centrality
  - v_2<0 event at $\sqrt{s_{NN}}$=4 GeV in peripheral collisions

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

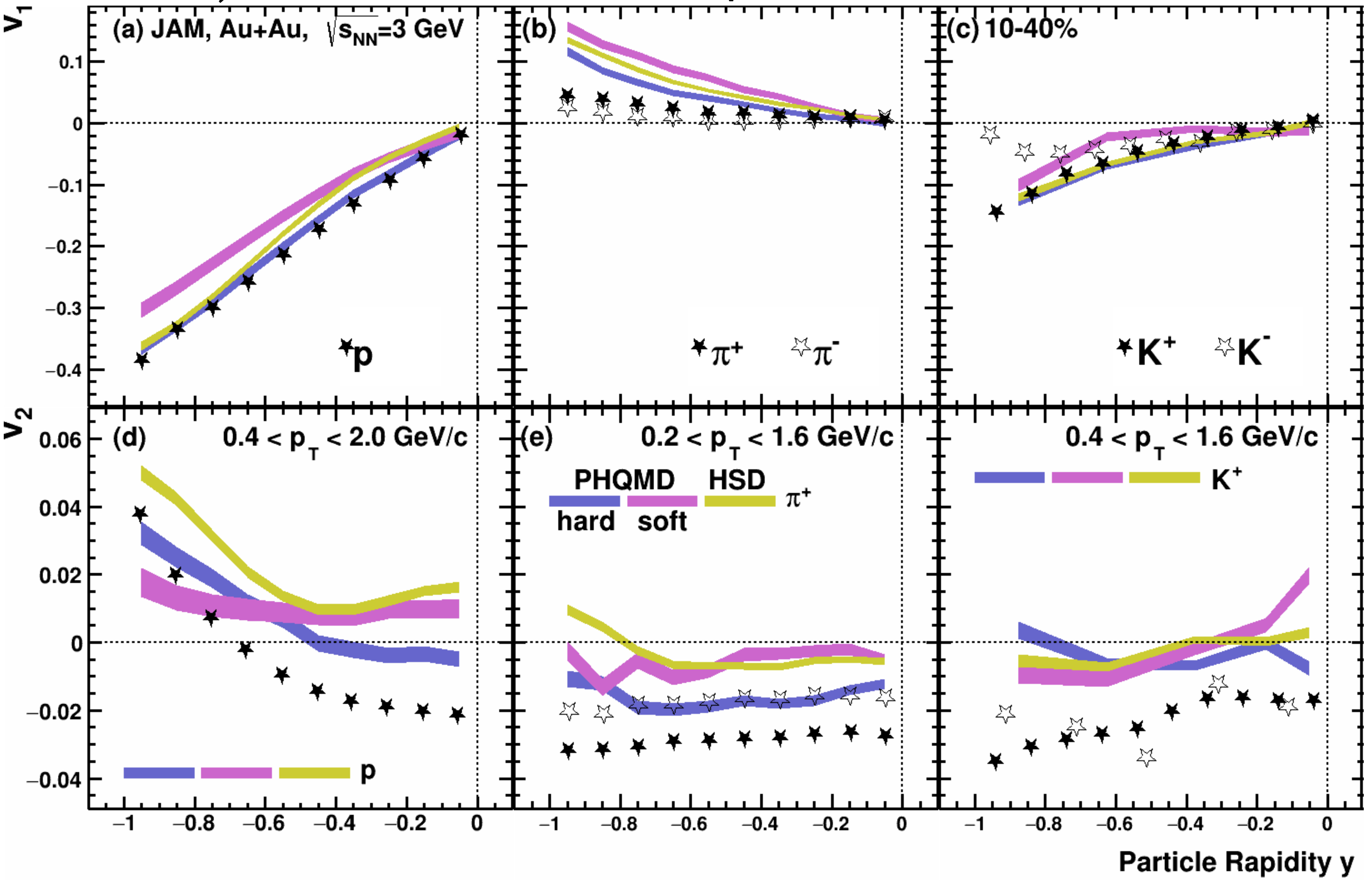
Summary and outlook

- **Anisotropic flow at $\sqrt{s_{NN}}$=4-11.5 GeV:**
  - Pure String/Hadronic Cascade models (no QGP phase) give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7-11.5 GeV
  - Models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$ =4.5 GeV
- **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 protons for v_n
  - JAM does not describe all particle species equally well
  - Higher harmonics more sensitive to the different EOS
- **Study of collision energy dependence of v_n:**
  - $|v_{1,3}|$ decreases with increasing collision energy
  - $v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV
  - $v_{3,4}\{\Psi_1\} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV
  - $v_2(p_T, y, \sqrt{s_{NN}})$ of protons depends on centrality
- Scaling relations can be used to compare results from BM@N with the existing experimental data for $\sqrt{s_{NN}} \leq 3$ GeV
- 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
- To perform more detailed study, different colliding systems, models and EOS are needed

Thank you for your attention!

Backup slides

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

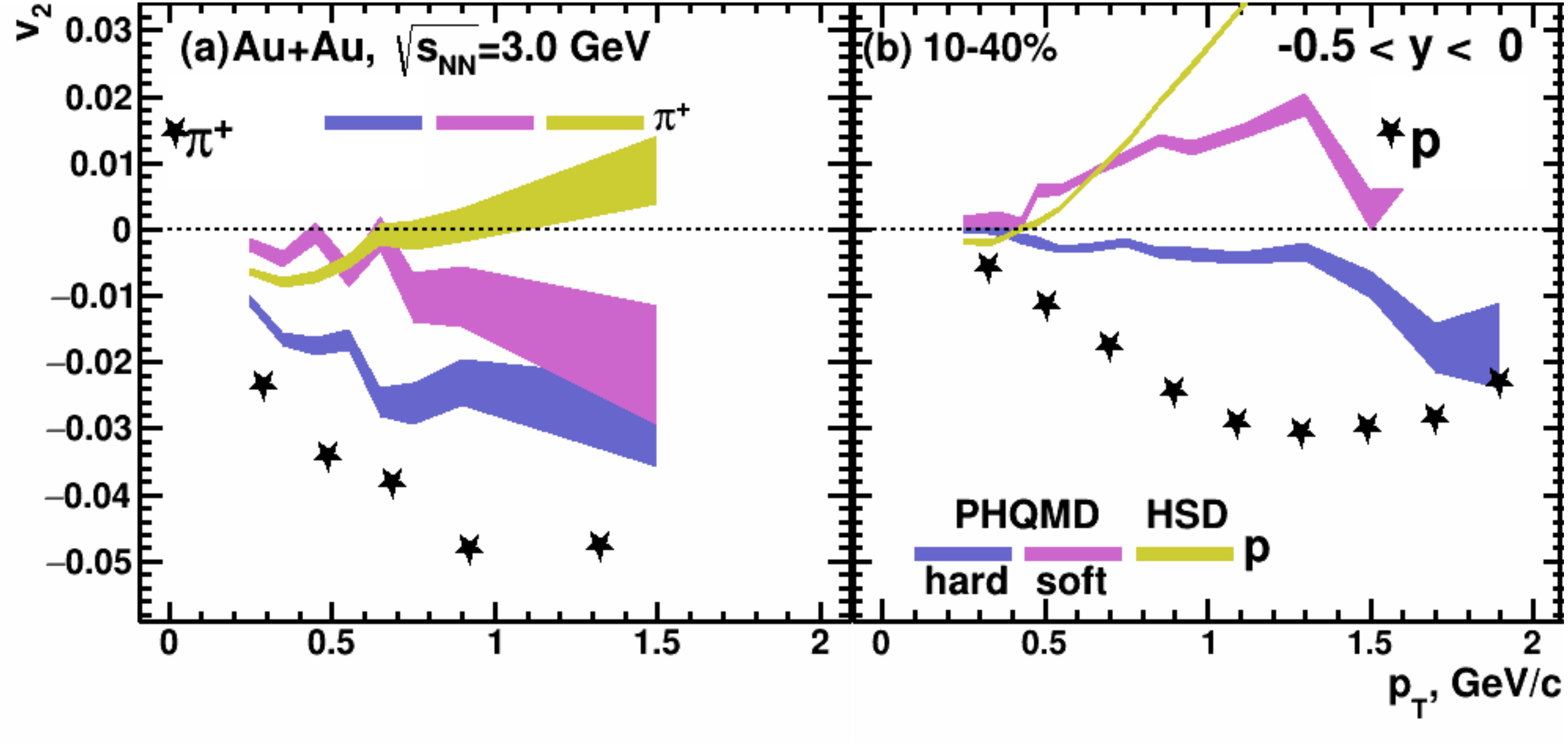


Experimental points are taken from:

M. Abdallah et al. [STAR Collaboration] *Phys.Lett.B* 827 (2022) 137003

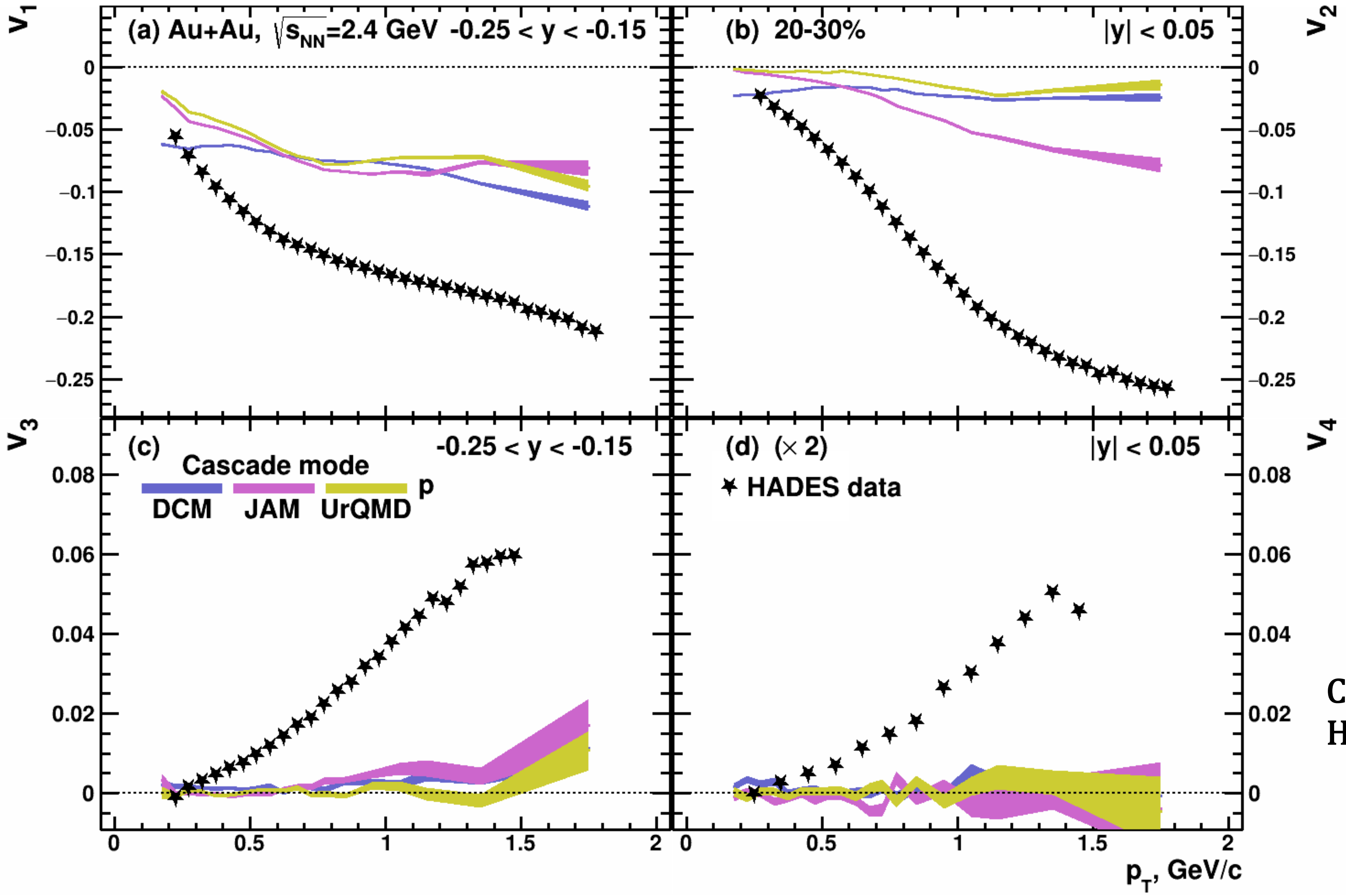
Both PHQMD and HSD cannot reproduce v_2 signal

$v_2(p_T)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



v_2 of pions and protons is more sensitive to different EOS than v_1

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

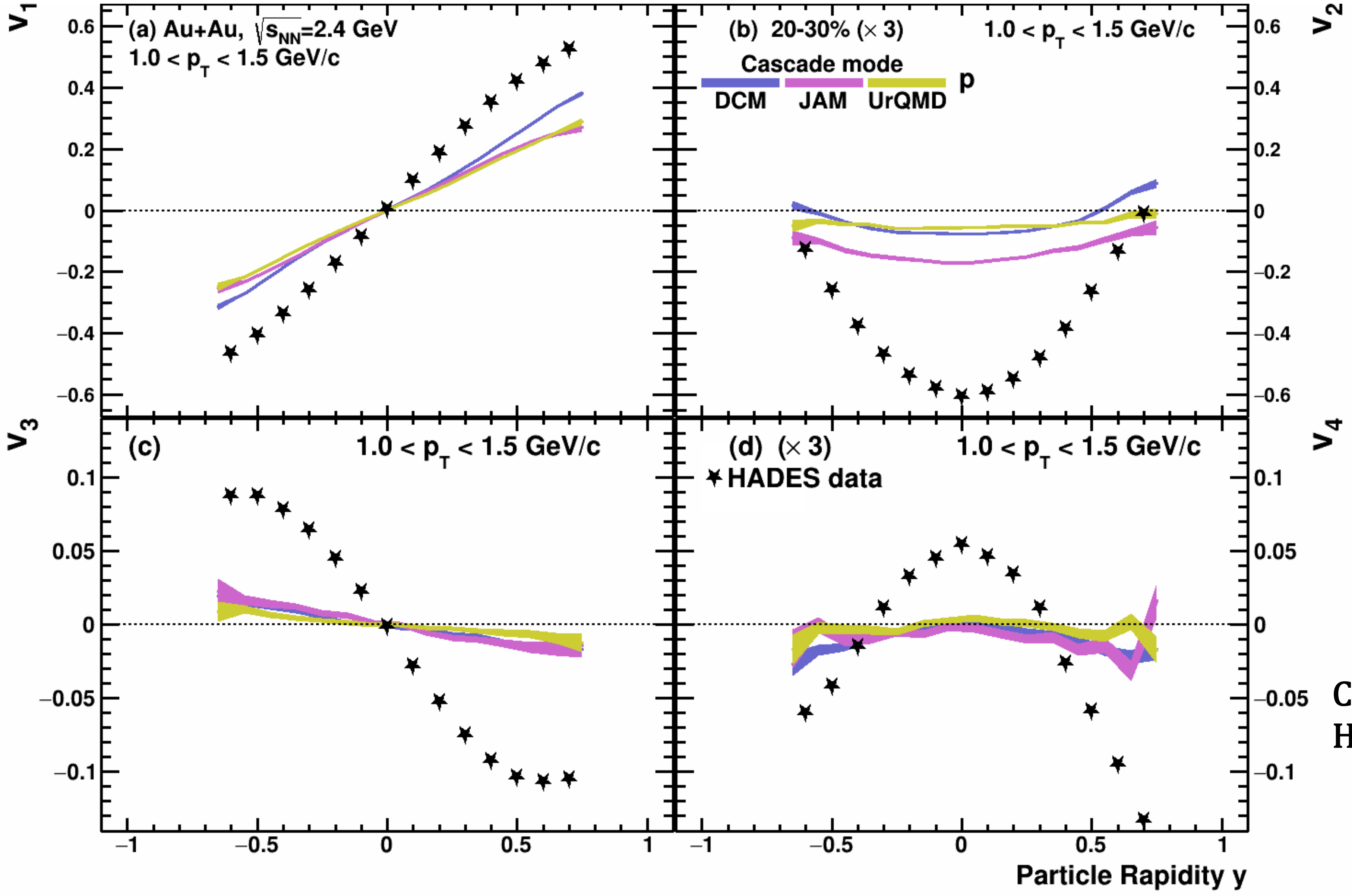


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{2,4}(p_T)$: -0.05 < y < 0.05

Cascade models fail to reproduce HADES experimental data

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

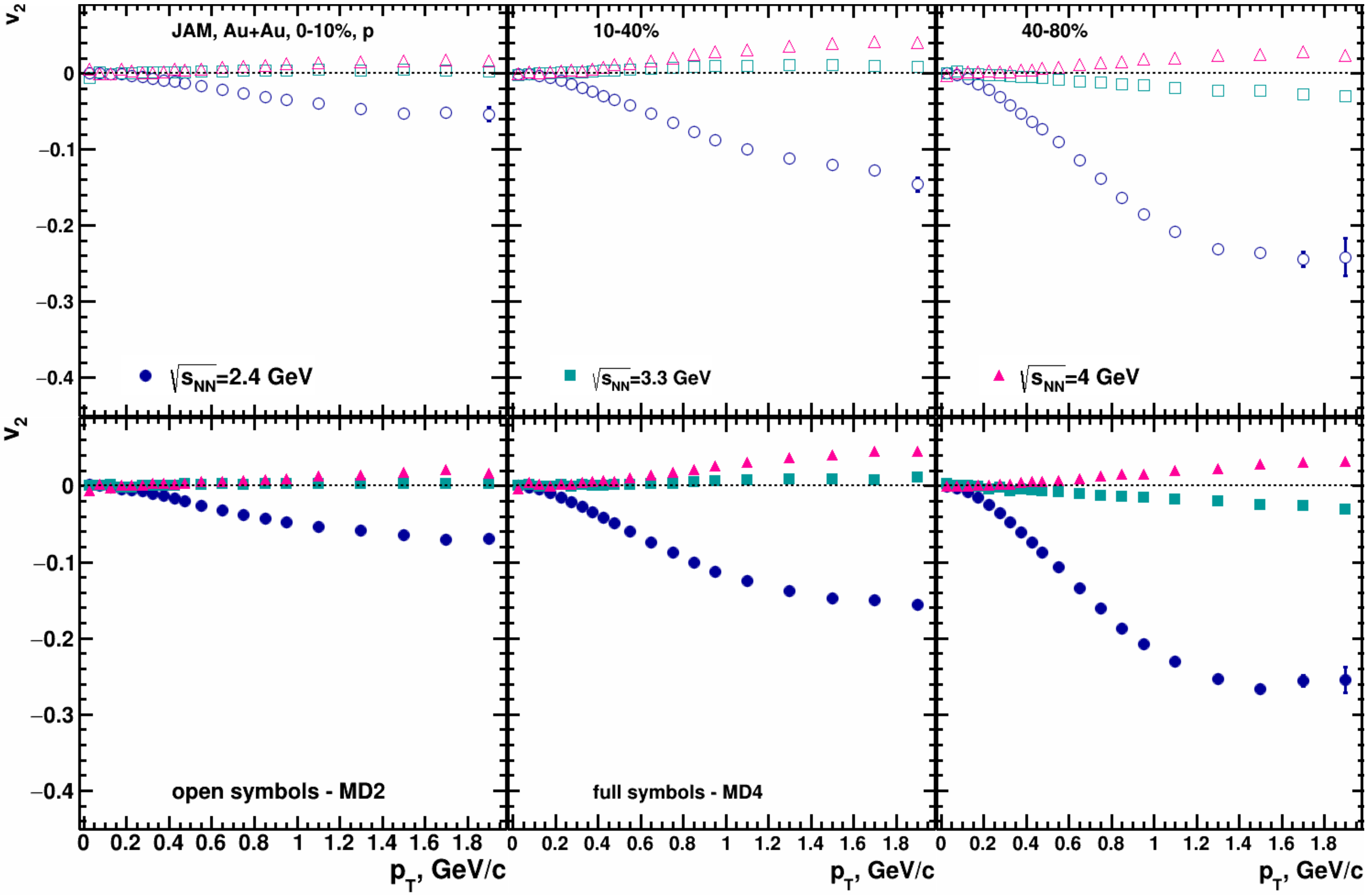


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

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

$v_2(p_T)$ transition from out-of-plane to in-plane

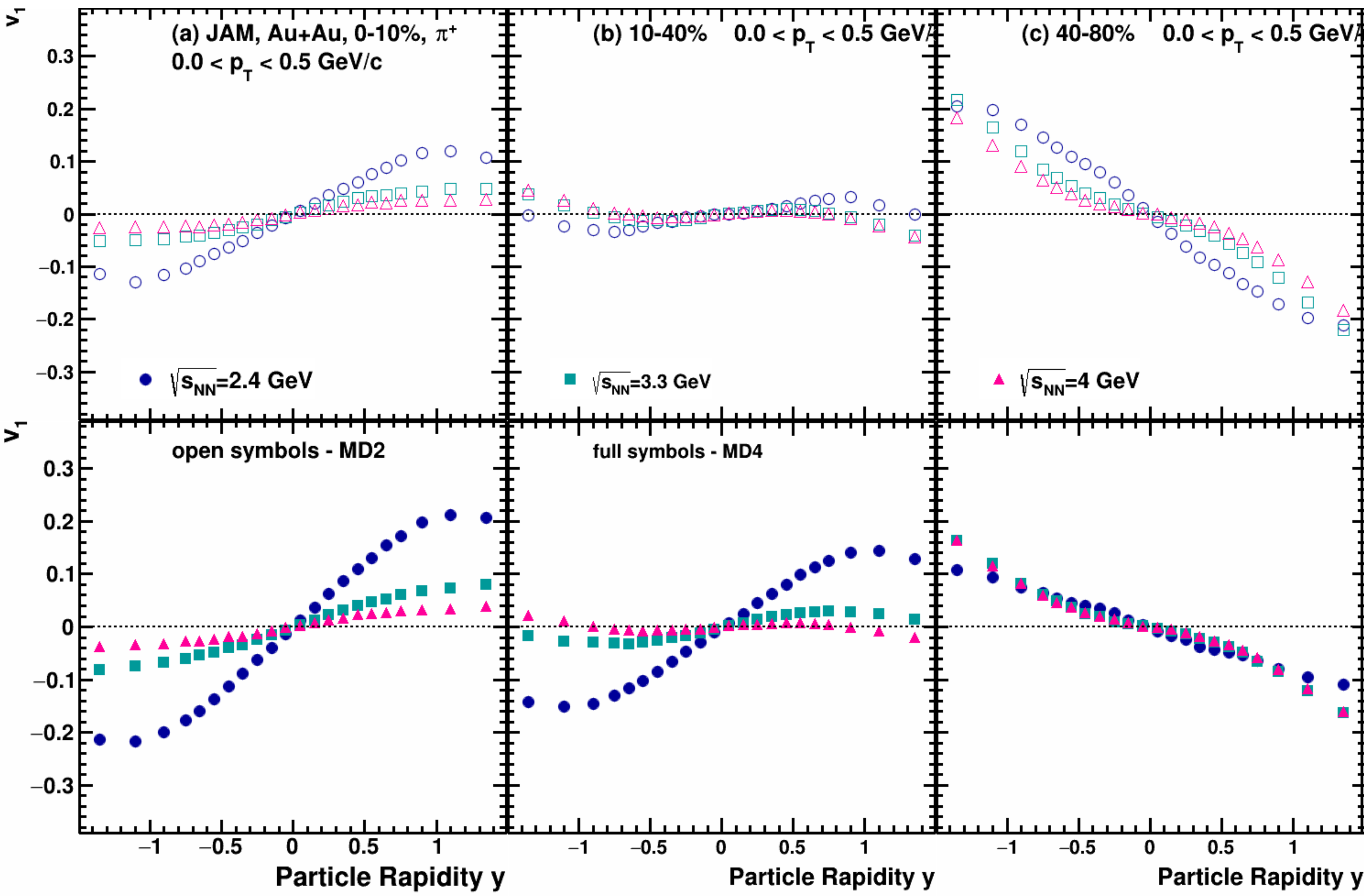


Protons:

$V_2(p_T)$: -0.2 < y < 0.2

- Weak dependence on EoS
- $v_2(p_T)$ strongly depends on centrality:
  - Transition from out-of-plane to in-plane depends on centrality
  - v_2<0 event at $\sqrt{s_{NN}}$=4 GeV in peripheral collisions

Centrality dependence of $v_1(y)$ pions



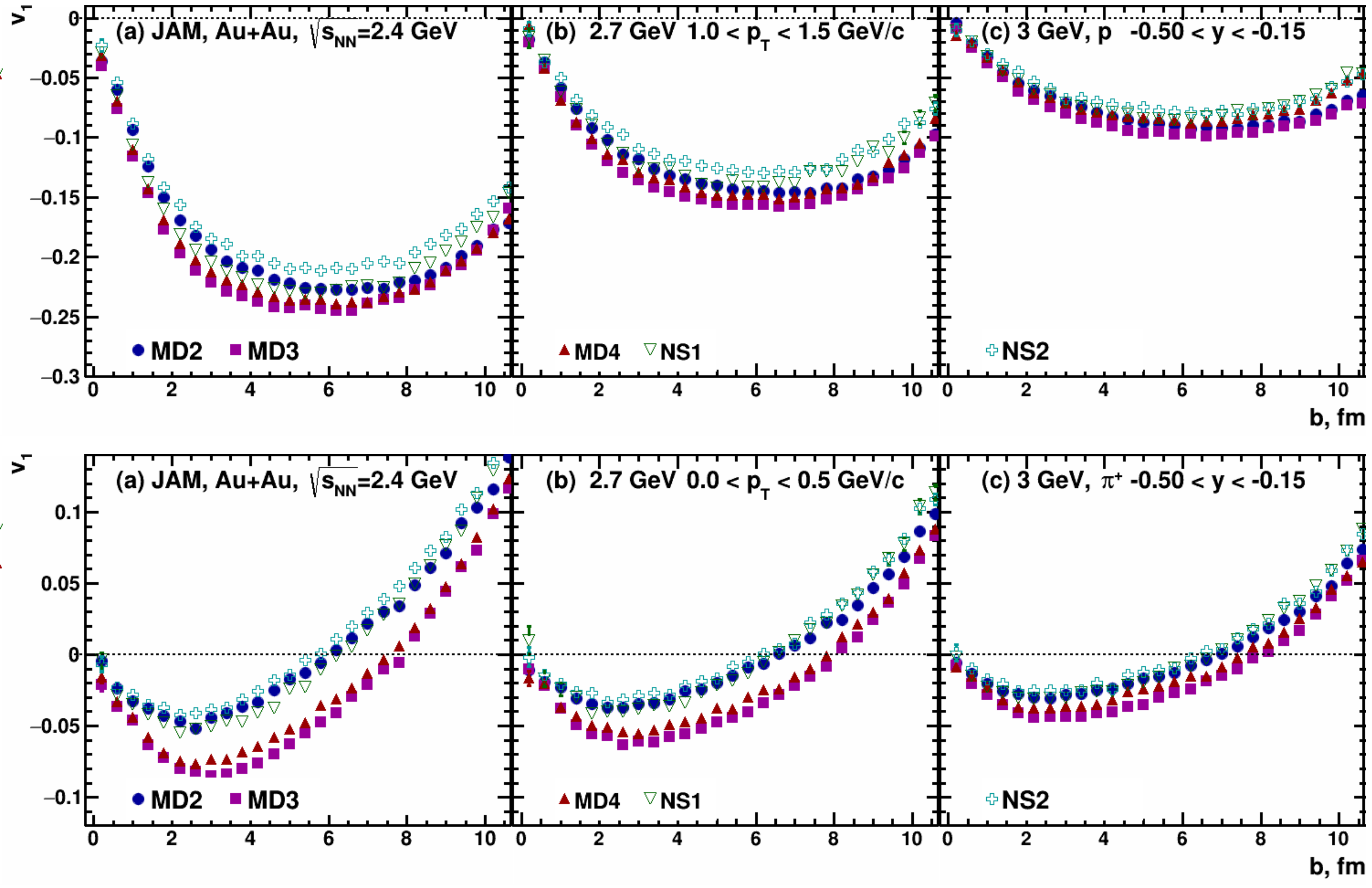
Pions:

$V_1(y)$: 0.2 < pT < 0.5 GeV/c

Strong dependence on EoS and centrality

More detailed study for different particle species are needed

Comparison of $v_1(b)$ for different EOS



MD2:
K=210 MeV, m^*/m=0.83

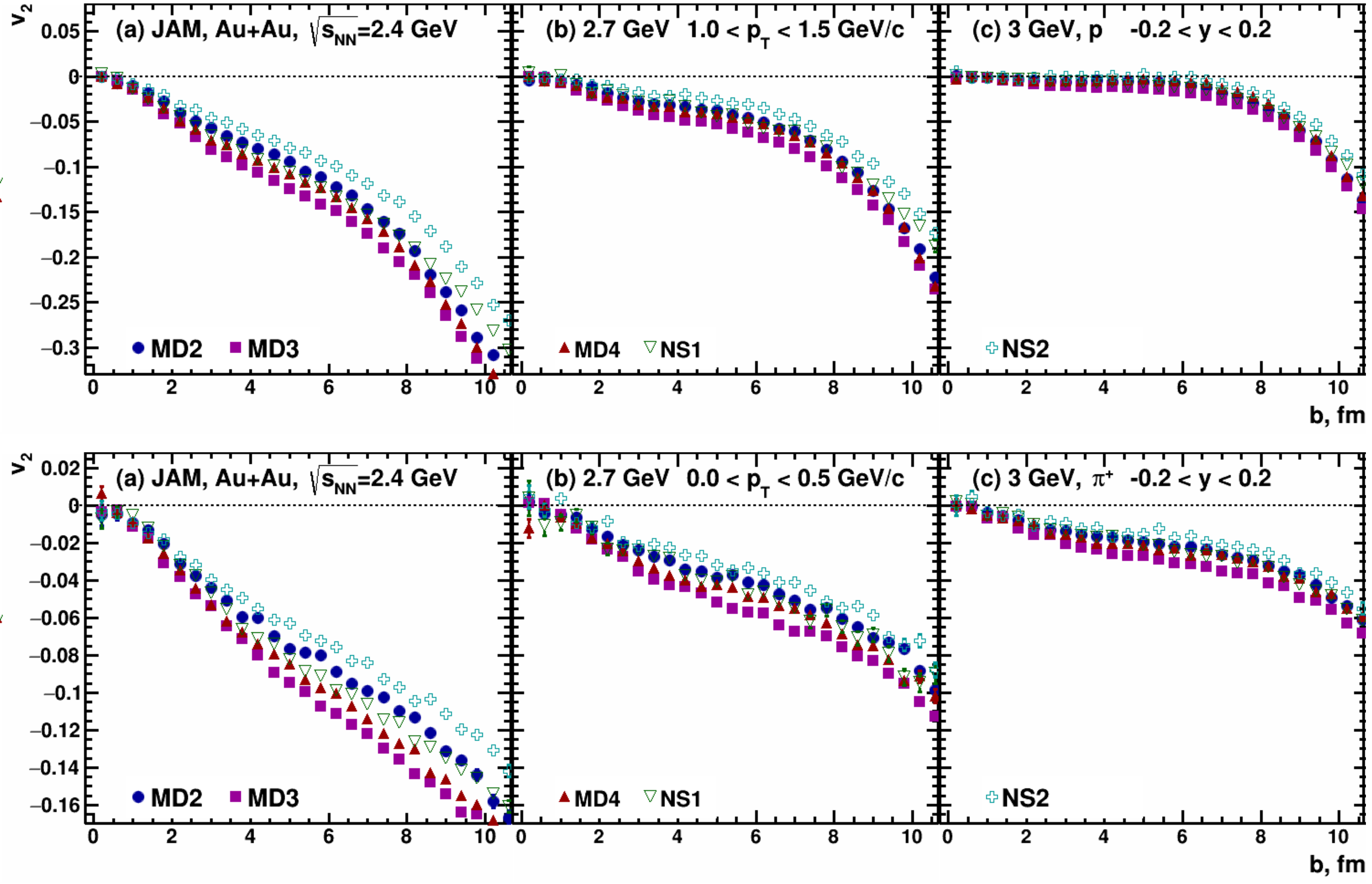
MD3:
K=380 MeV, m^*/m=0.65

MD4:
K=380 MeV, m^*/m=0.65

NS1:
K=380 MeV, m^*/m=0.83

NS2:
K=210 MeV, m^*/m=0.83

Comparison of $v_2(b)$ for different EOS



MD2:
K=210 MeV, m^*/m=0.83

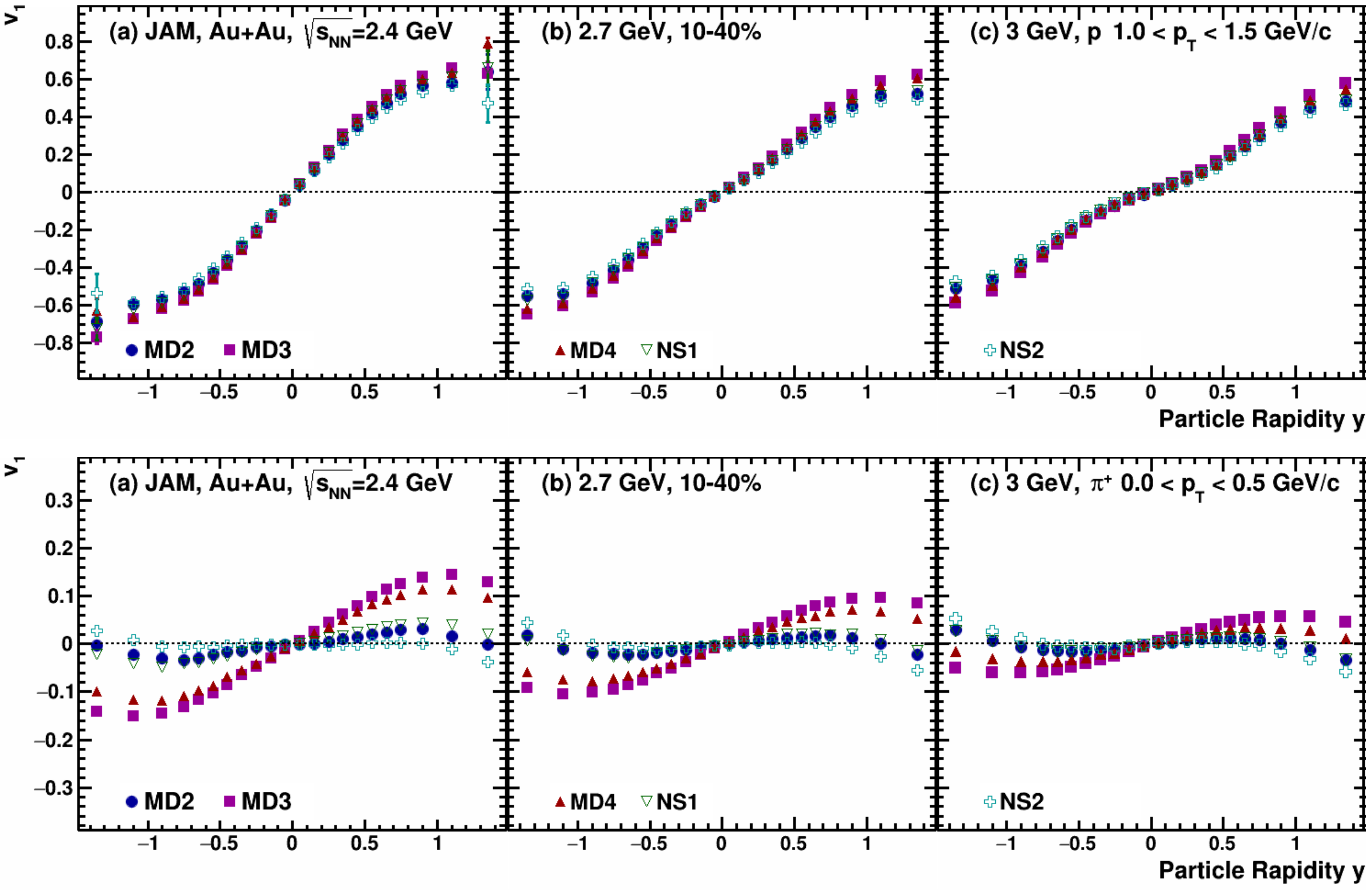
MD3:
K=380 MeV, m^*/m=0.65

MD4:
K=380 MeV, m^*/m=0.65

NS1:
K=380 MeV, m^*/m=0.83

NS2:
K=210 MeV, m^*/m=0.83

Comparison of $v_1(y)$ for different EOS



MD2:
K=210 MeV, m^*/m=0.83

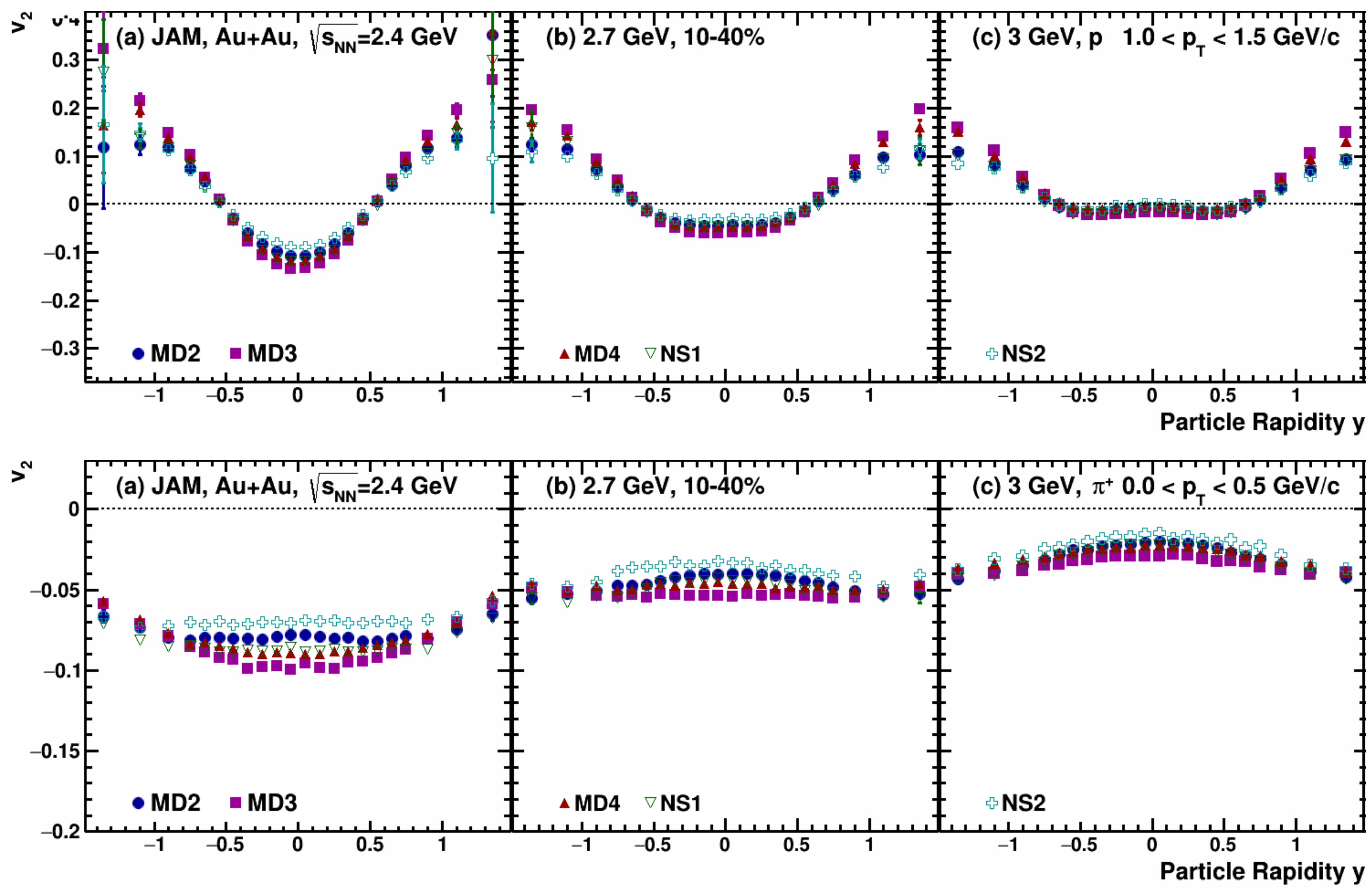
MD3:
K=380 MeV, m^*/m=0.65

MD4:
K=380 MeV, m^*/m=0.65

NS1:
K=380 MeV, m^*/m=0.83

NS2:
K=210 MeV, m^*/m=0.83

Comparison of $v_2(y)$ for different EOS



MD2:
K=210 MeV, m^*/m=0.83

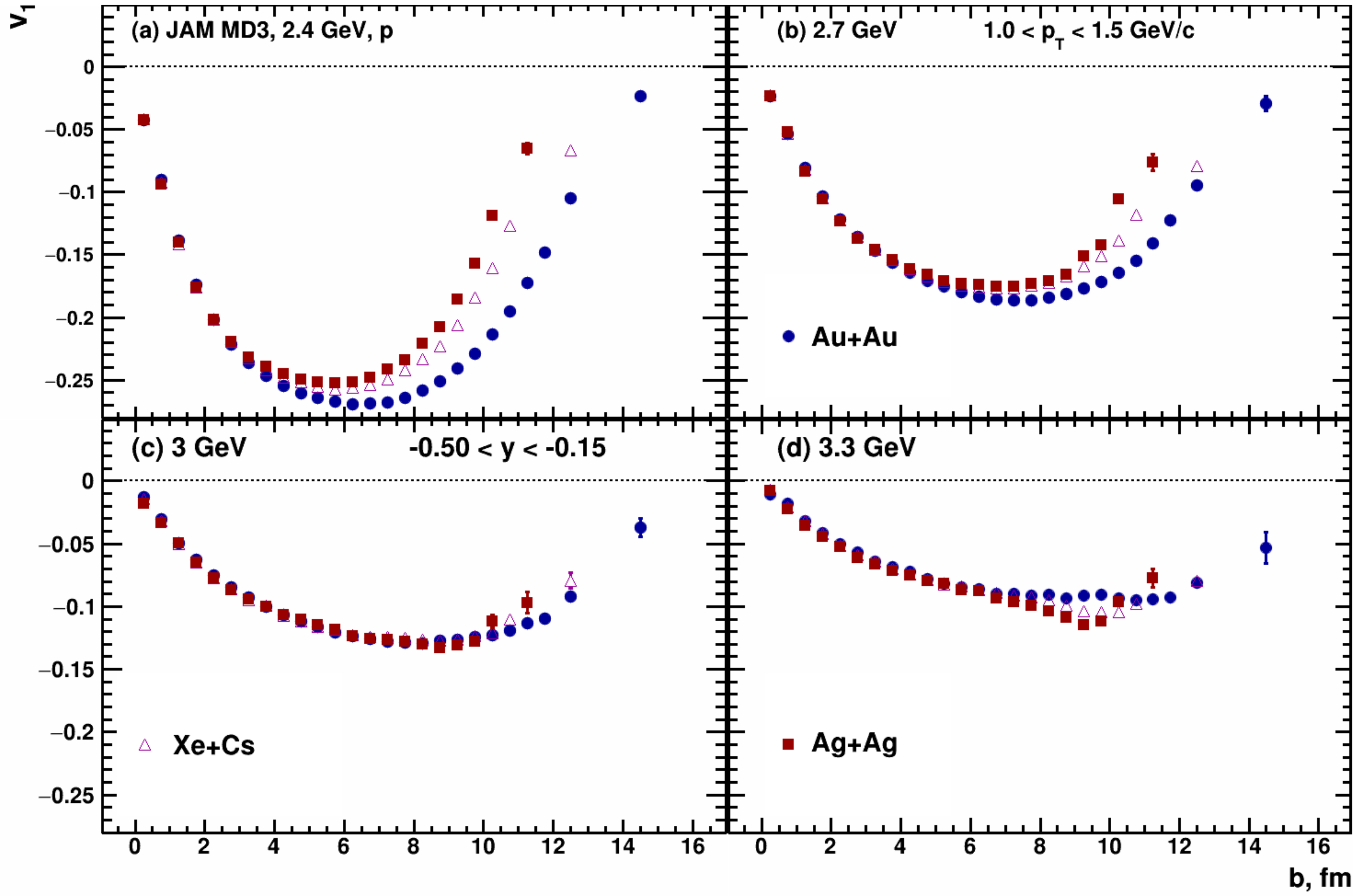
MD3:
K=380 MeV, m^*/m=0.65

MD4:
K=380 MeV, m^*/m=0.65

NS1:
K=380 MeV, m^*/m=0.83

NS2:
K=210 MeV, m^*/m=0.83

$v_1(b)$ Xe+Cs vs Au+Au - protons

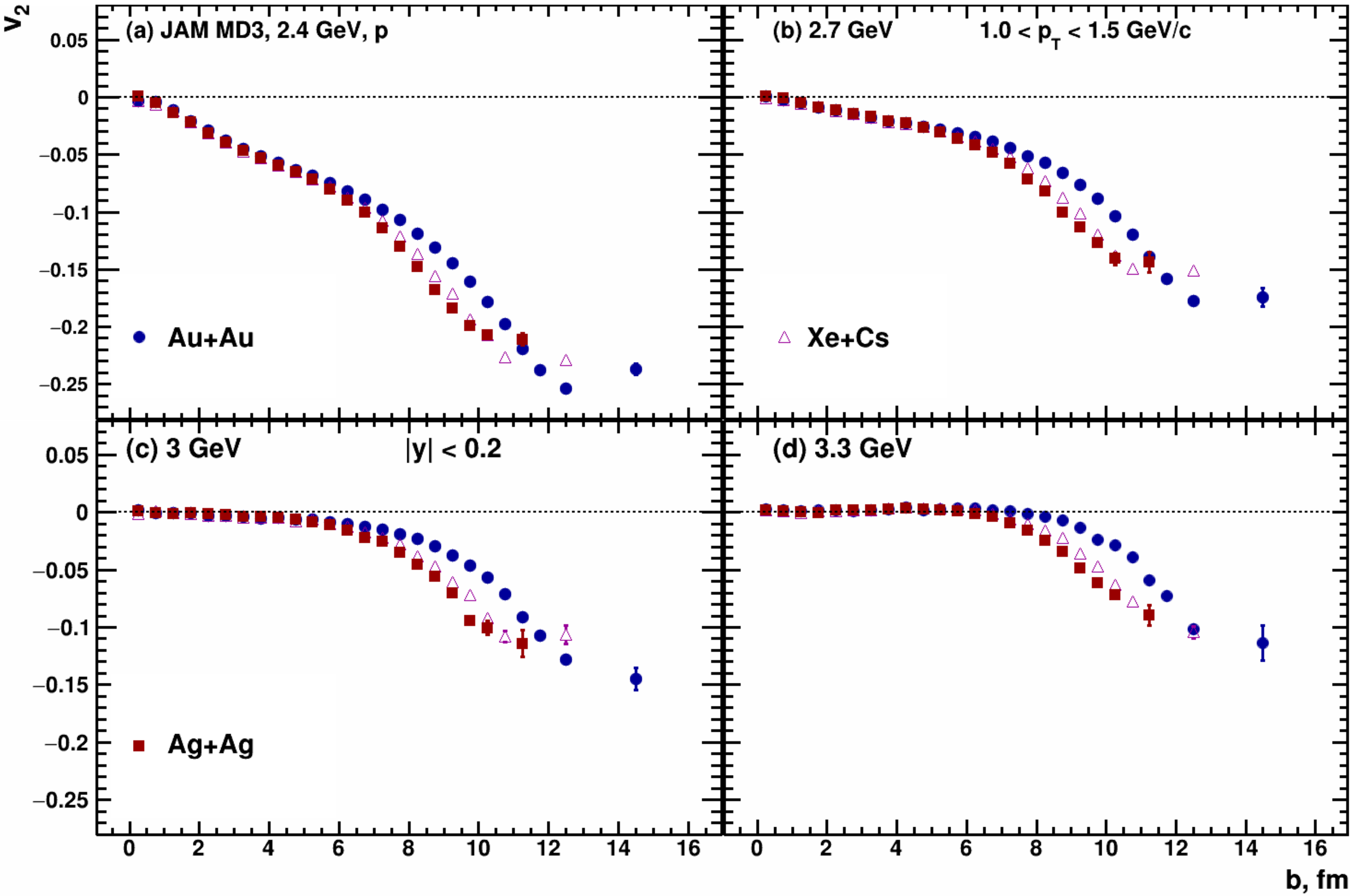


Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

$v_2(b)$ Xe+Cs vs Au+Au - protons

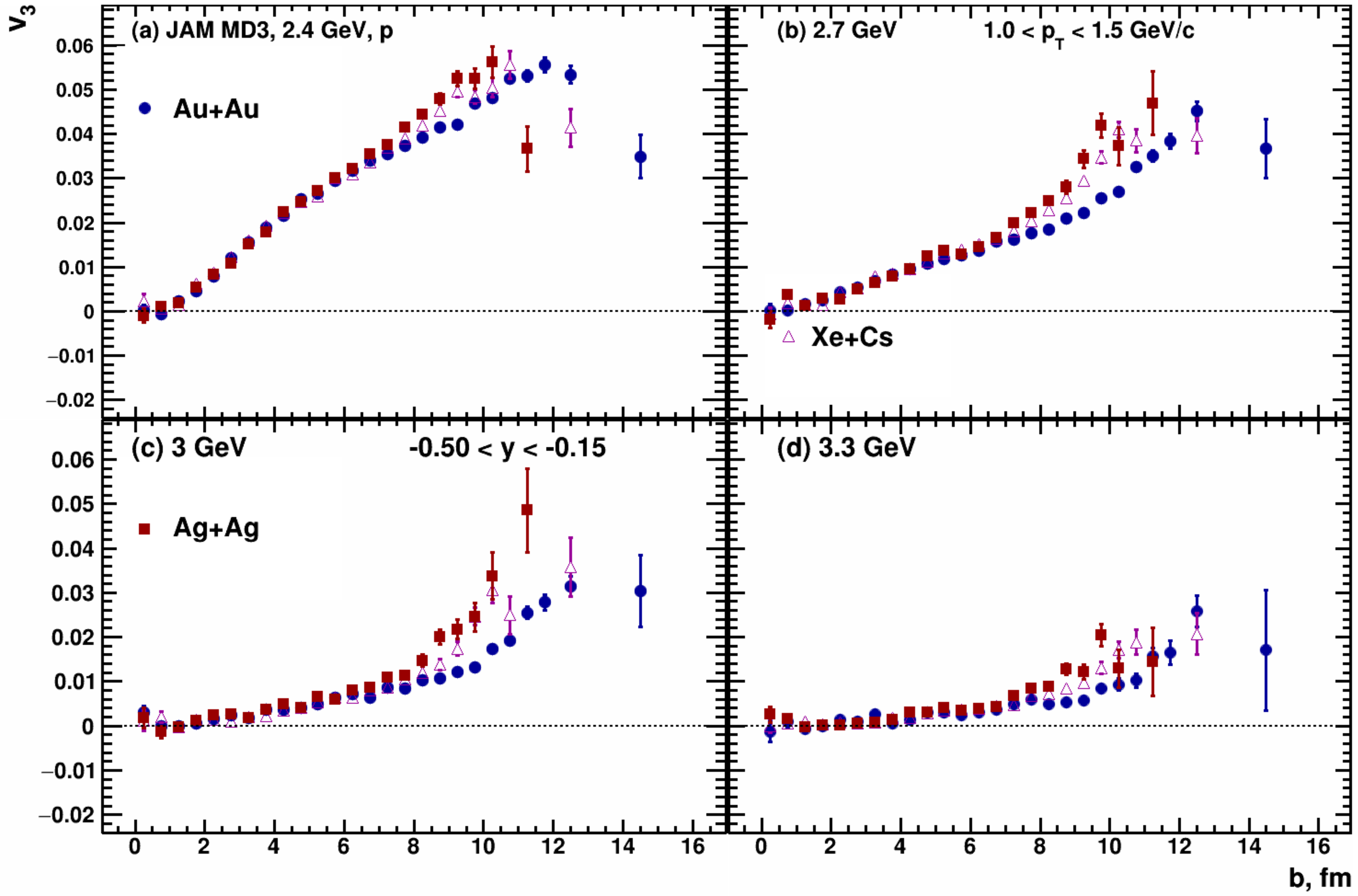


Kinematic cuts:

-0.2 < y < 0.2

1.0 < p_T < 1.5 GeV/c

$v_3(b)$ Xe+Cs vs Au+Au - protons

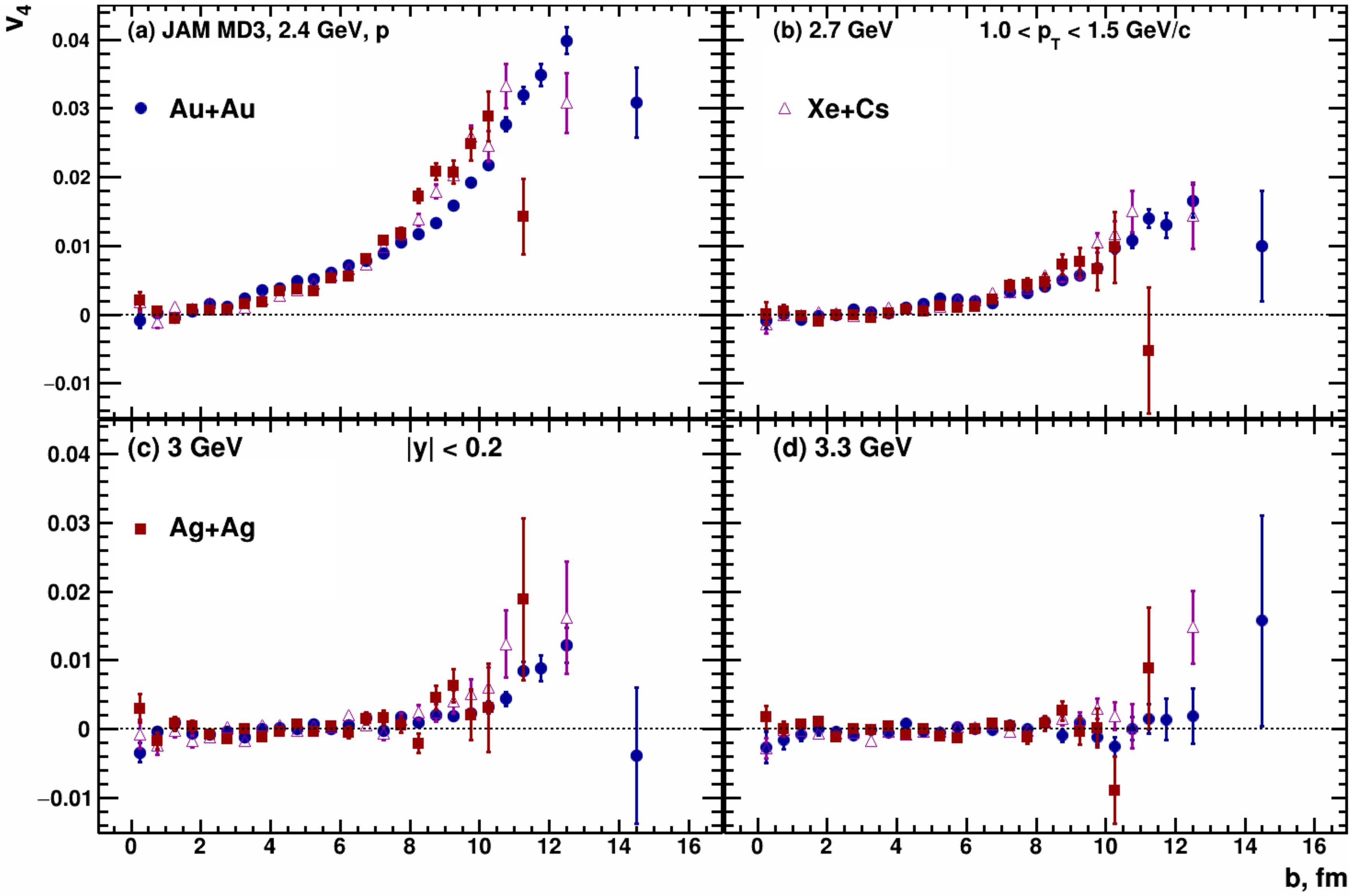


Kinematic cuts:

$-0.5 < y < -0.15$

$1.0 < p_T < 1.5$ GeV/c

$v_4(b)$ Xe+Cs vs Au+Au - protons

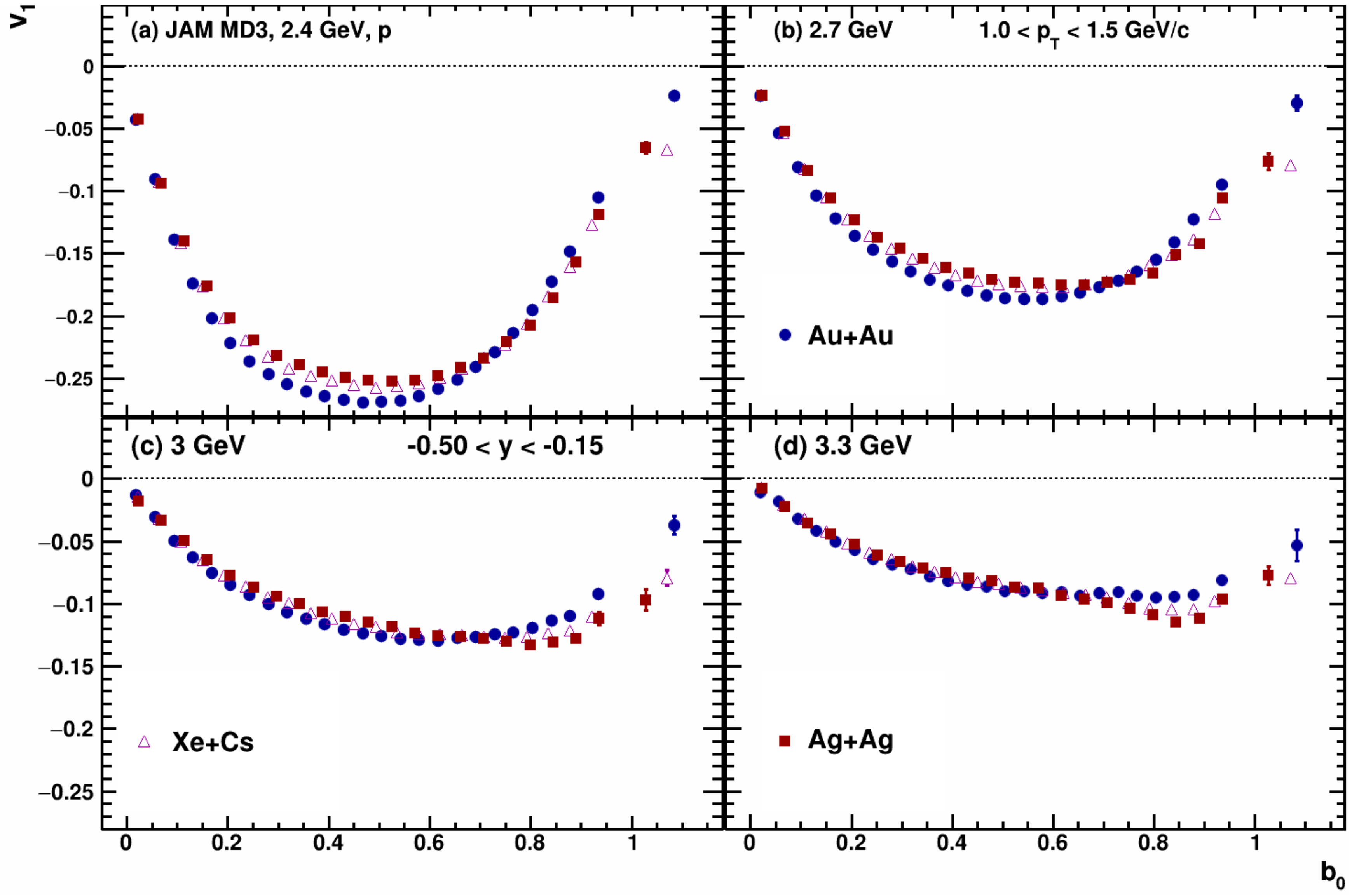


Kinematic cuts:

$-0.2 < y < 0.2$

$1.0 < p_T < 1.5$ GeV/c

$v_1(b_0)$ Xe+Cs vs Au+Au - protons



Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

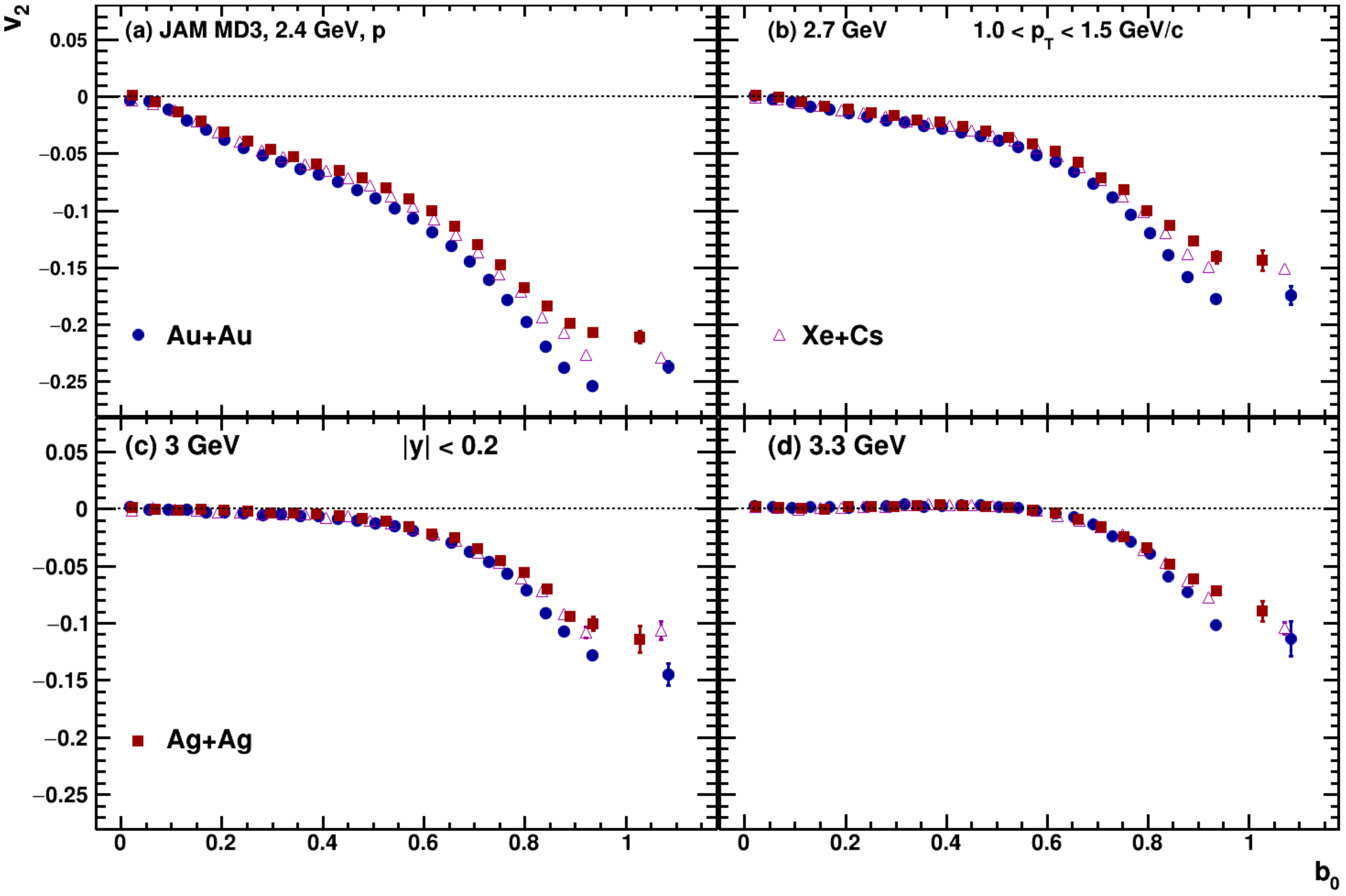
$$b_0 = {}^{b}/_{b_{max}}$$

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

$b_{max}(Xe + Cs) = 11.68$ fm

$b_{max}(Au + Au) = 13.38$ fm

$v_2(b_0)$ Xe+Cs vs Au+Au - protons



Kinematic cuts:

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$1.0 < p_T < 1.5$ GeV/c

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

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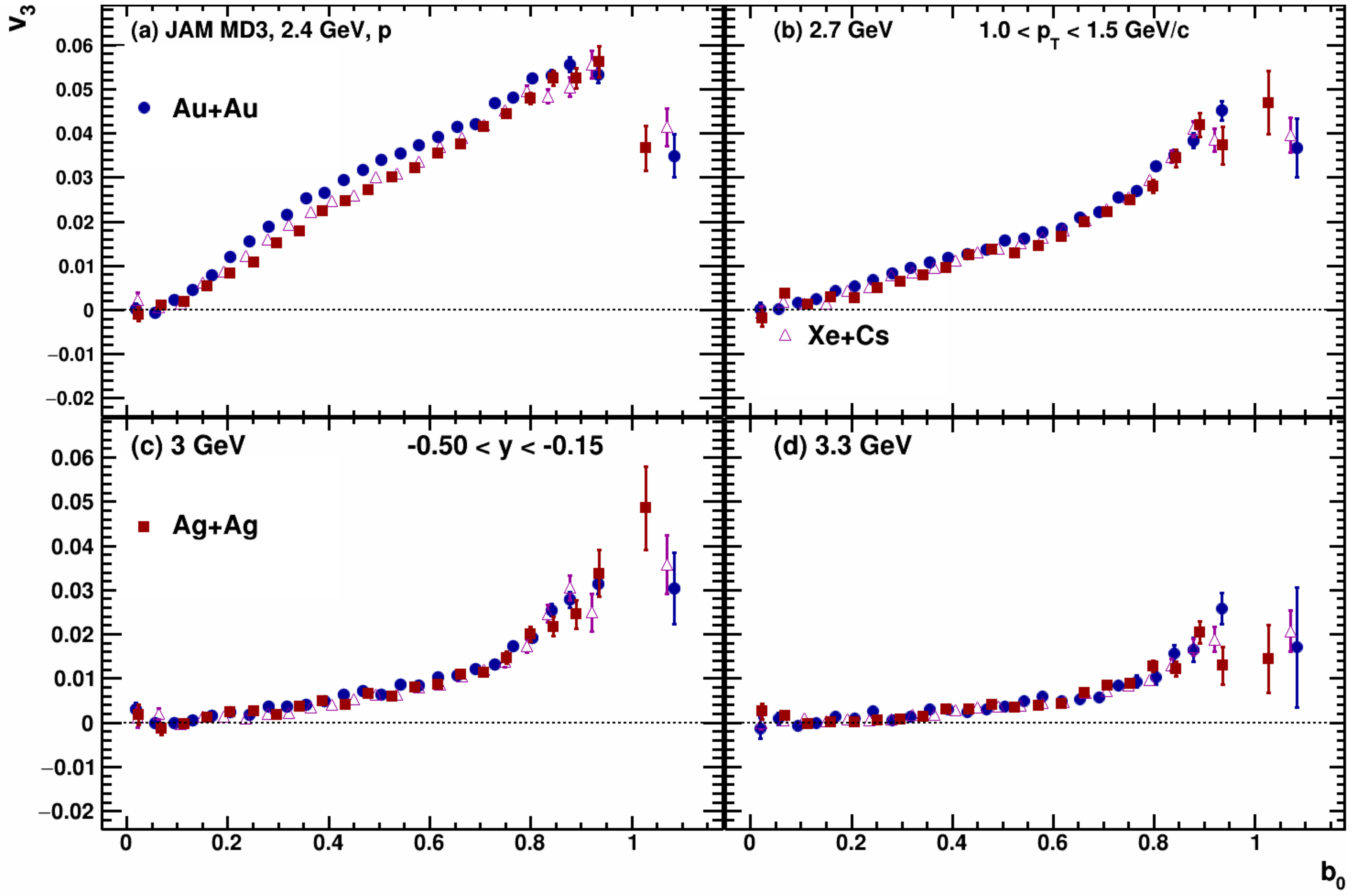
$b_{max}(Au + Au) = 13.38$ fm

$v_3(b_0)$ Xe+Cs vs Au+Au - protons



Kinematic cuts:

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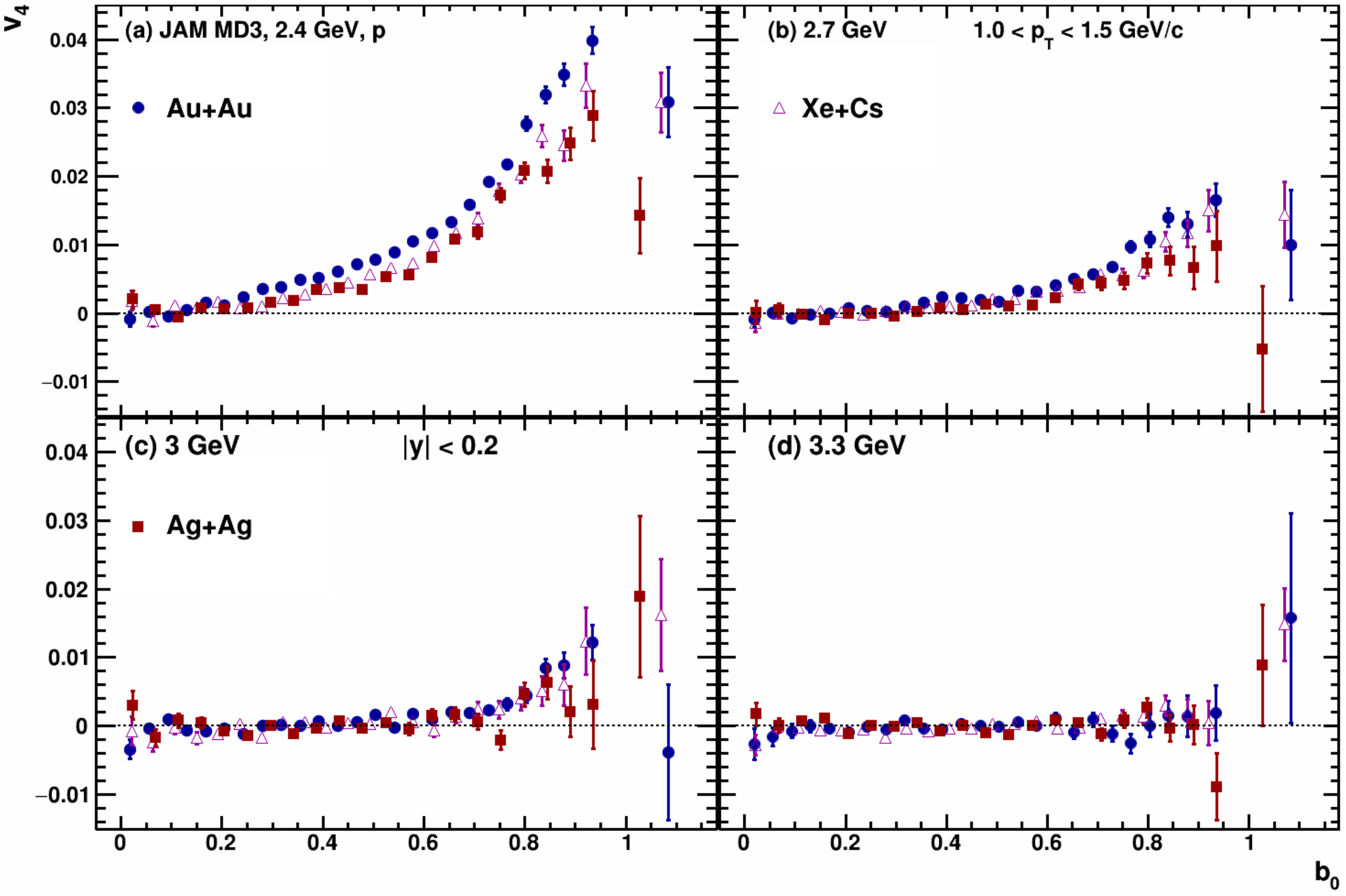
$$b_{max} = 1.15\left(A_{targ}^{1/3} + A_{proj}^{1/3}\right)$$

$b_{max}(Xe + Cs) = 11.68$ fm

$b_{max}(Au + Au) = 13.38$ fm

$v_4(b_0)$ Xe+Cs vs Au+Au - protons



Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

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

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

$b_{max}(Xe + Cs) = 11.68$ fm

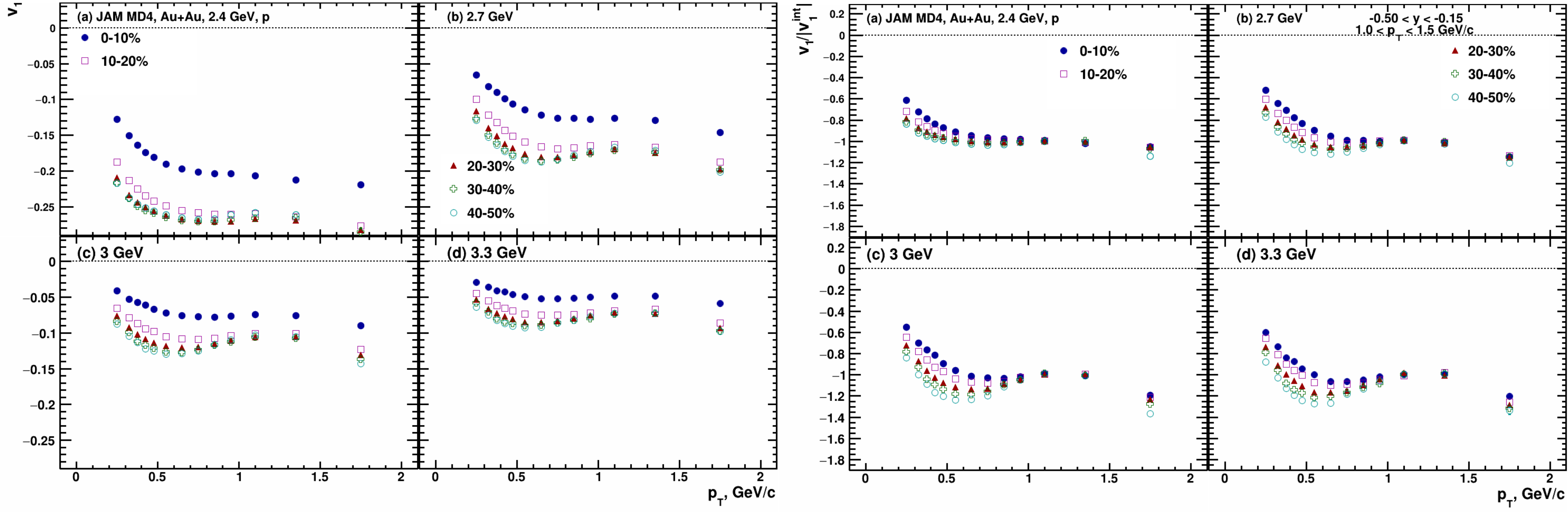
$b_{max}(Au + Au) = 13.38$ fm

$v_1(p_T)$ Au+Au - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

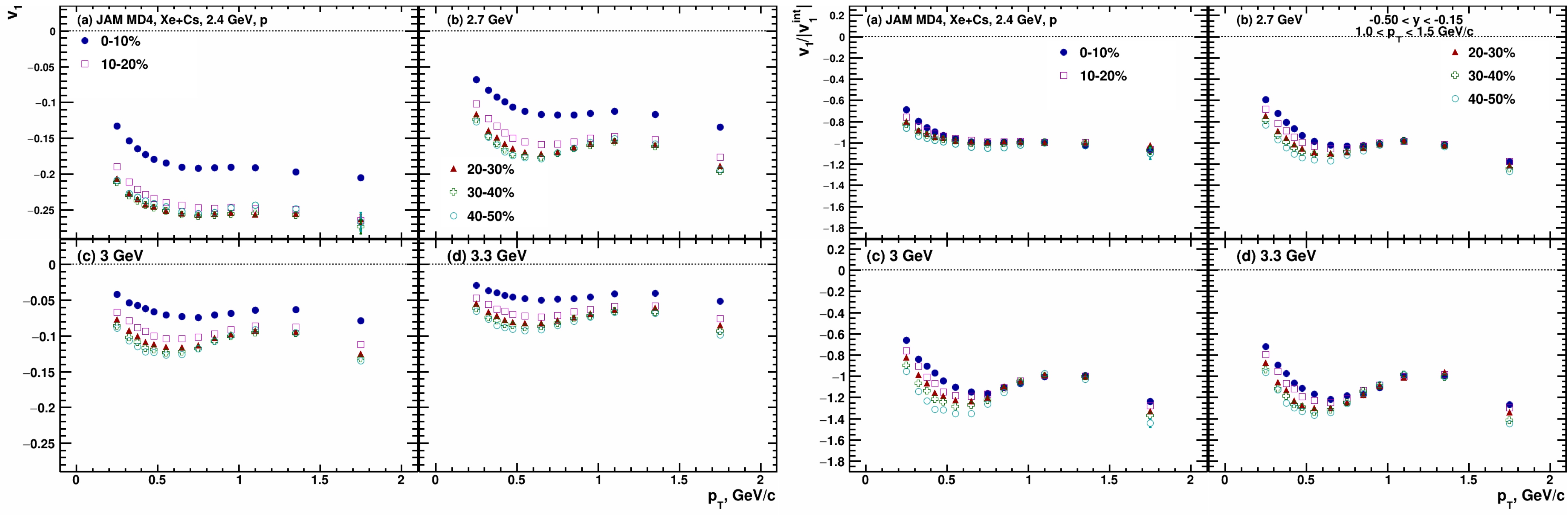


$v_1(p_T)$ Xe+Cs - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

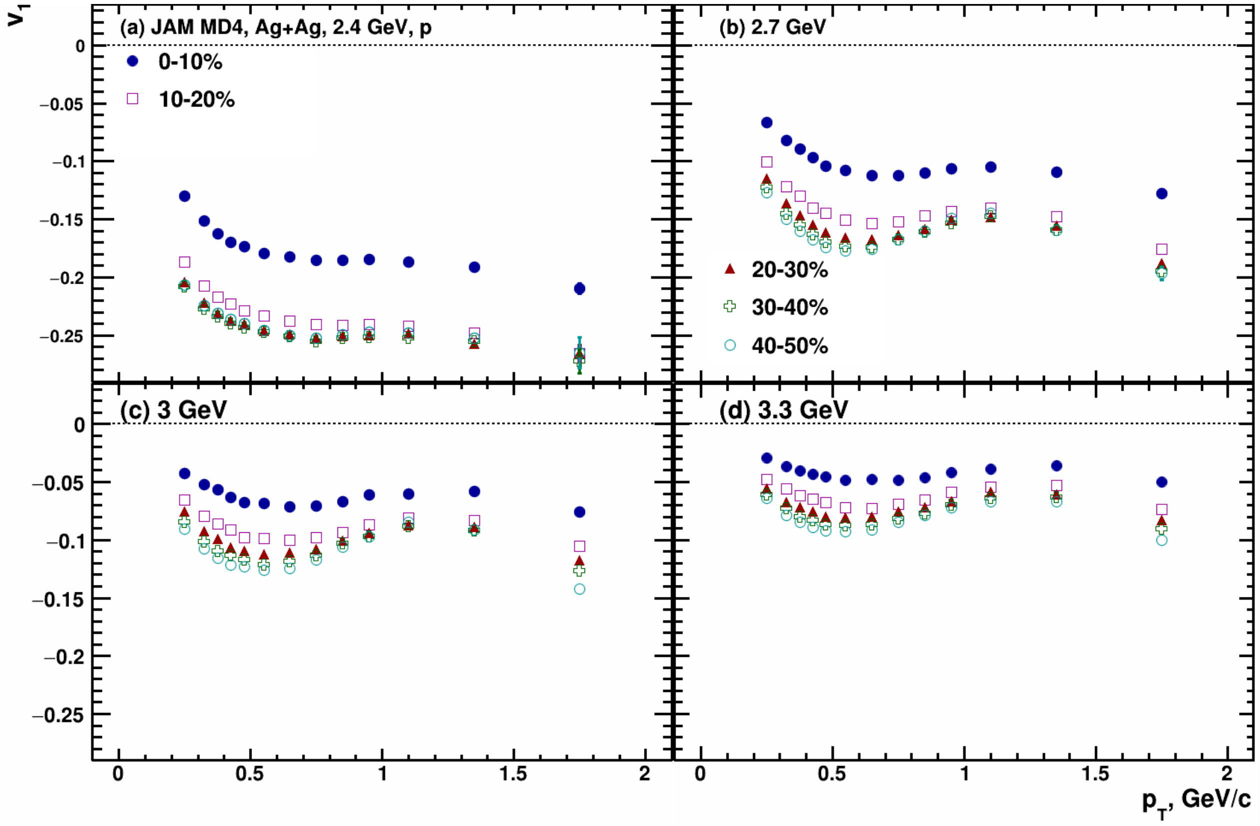


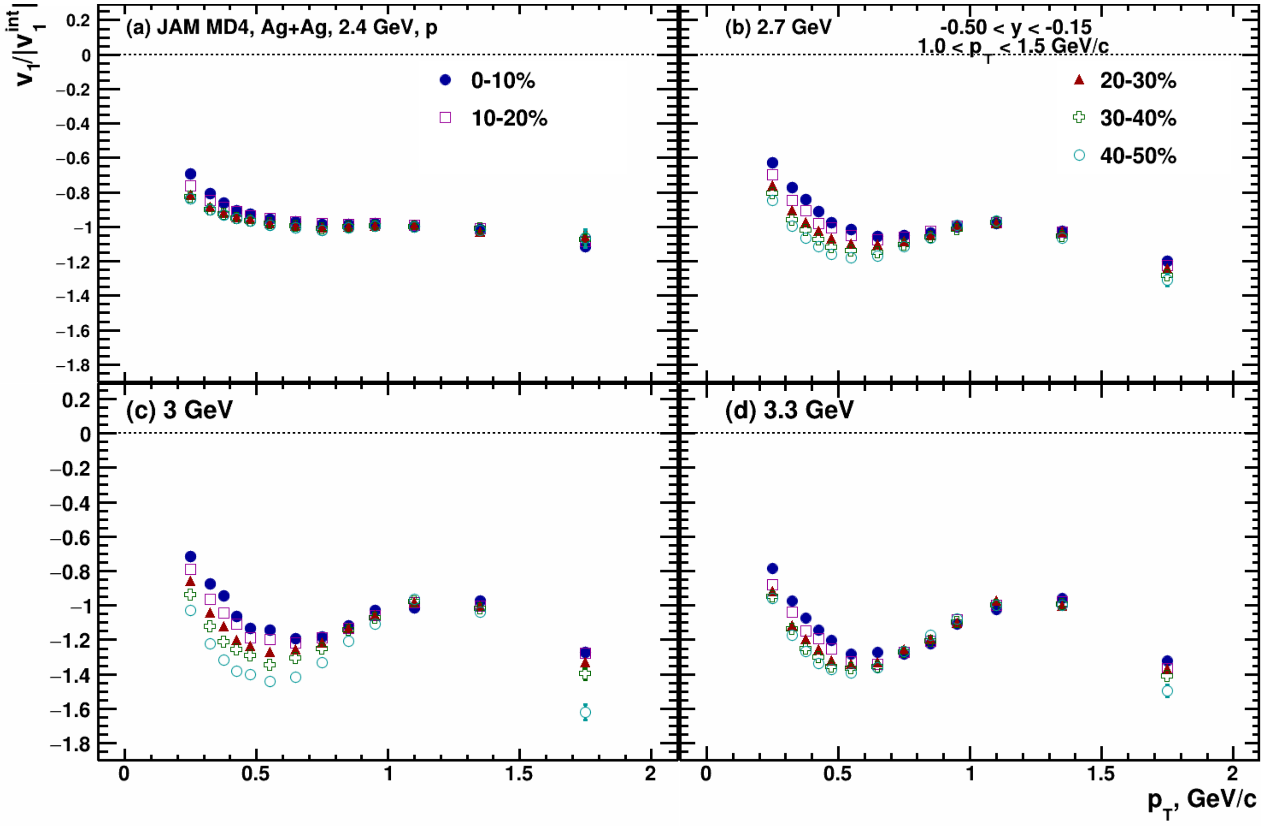
$v_1(p_T)$ Ag+Ag - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c



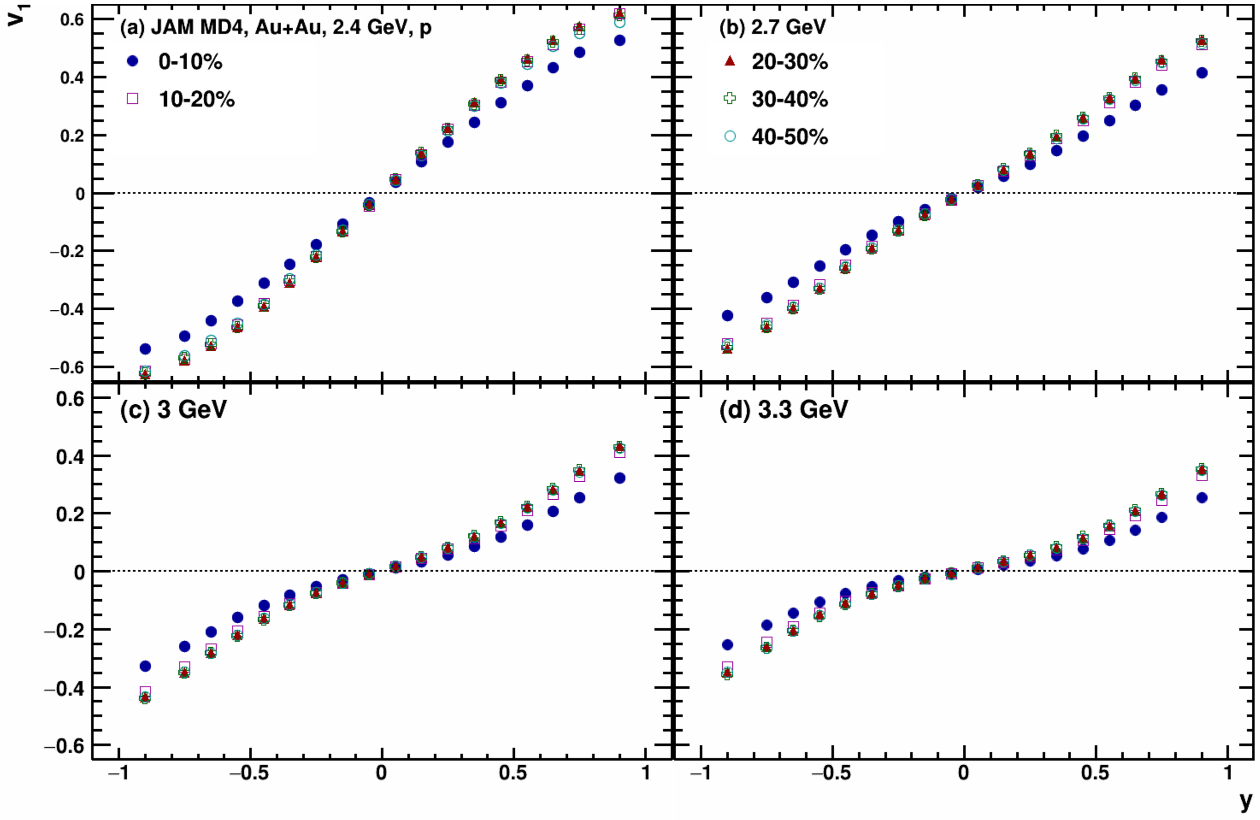


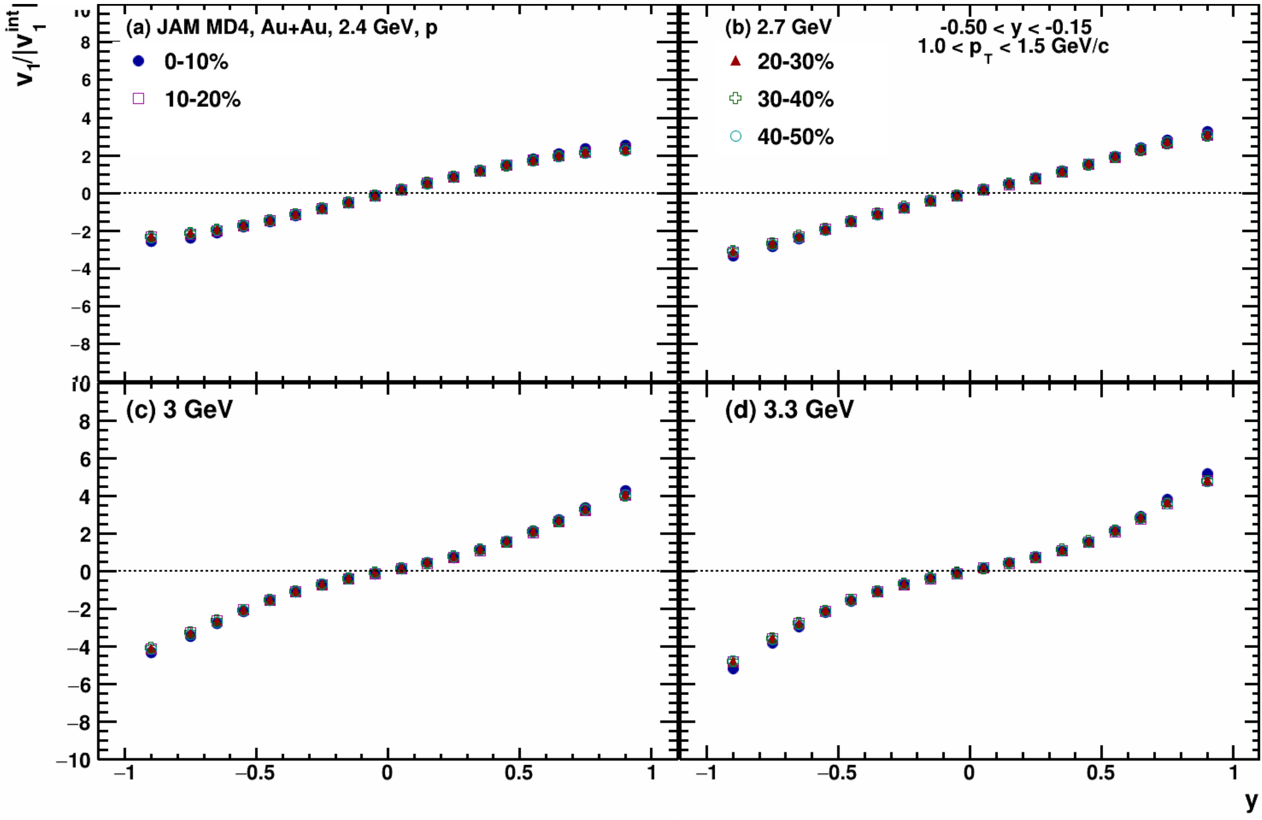
$v_1(y)$ Au+Au - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c



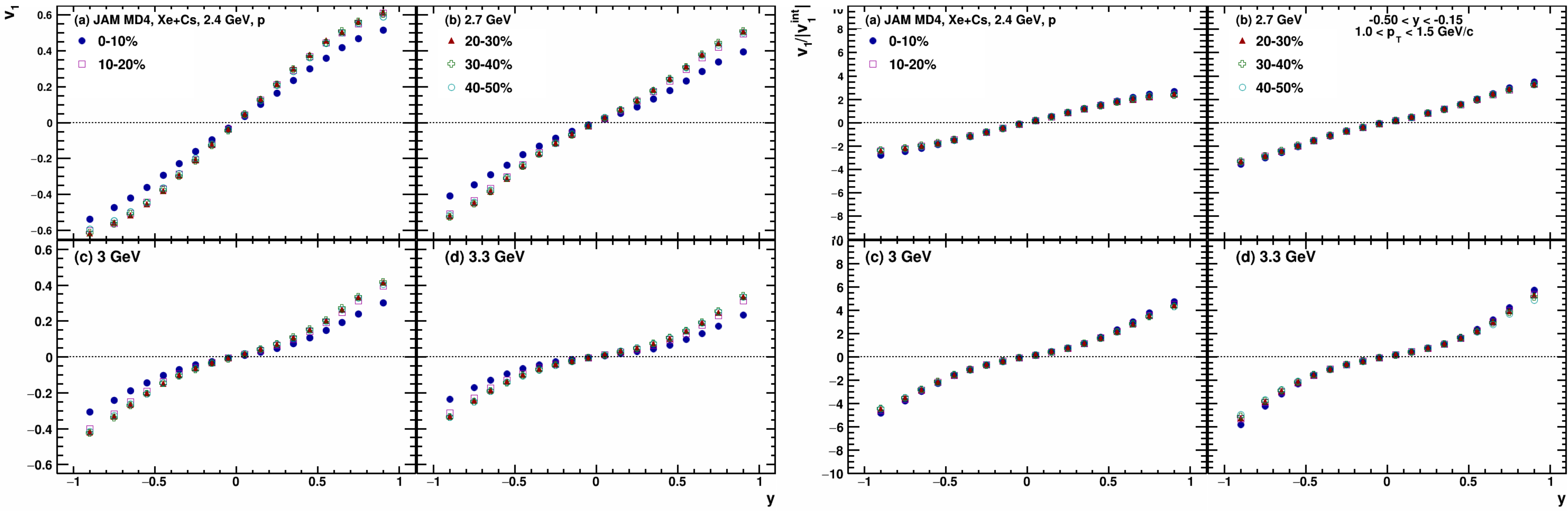


$v_1(y)$ Xe+Cs - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c

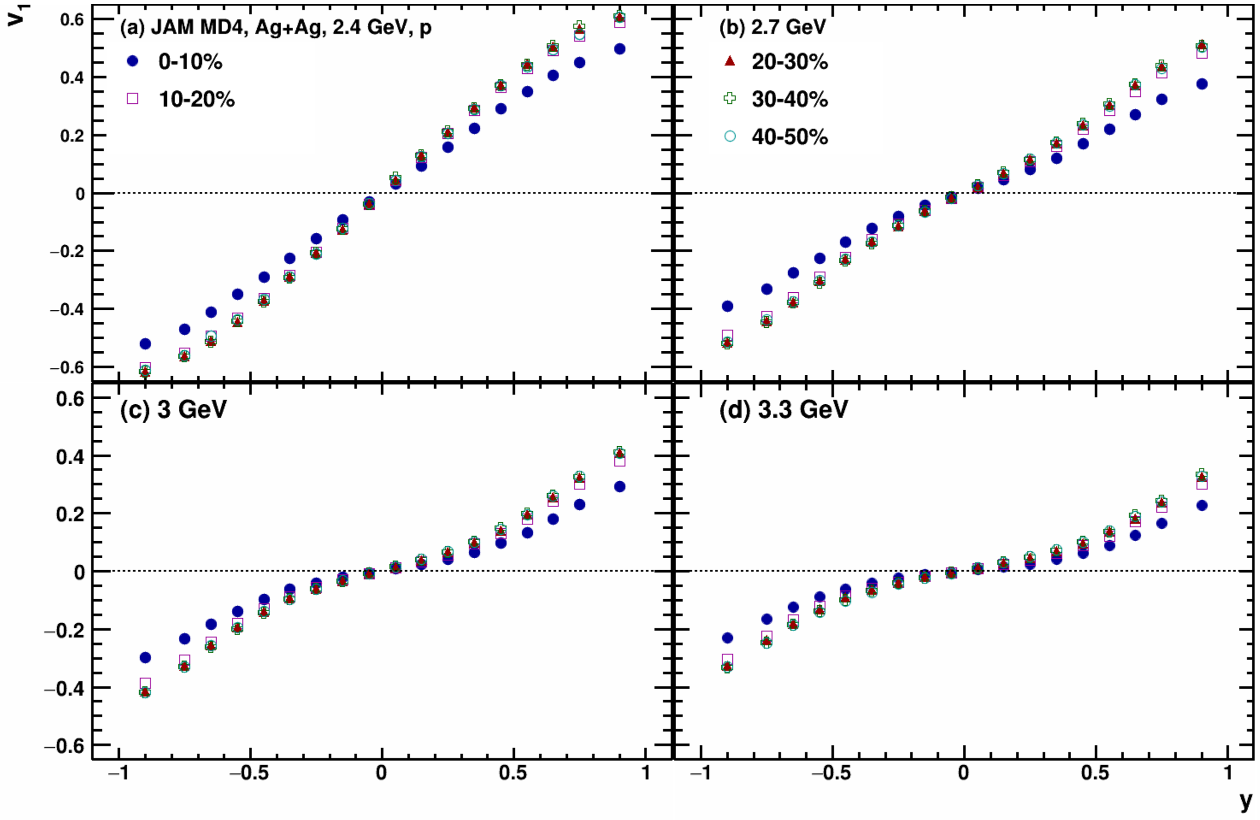


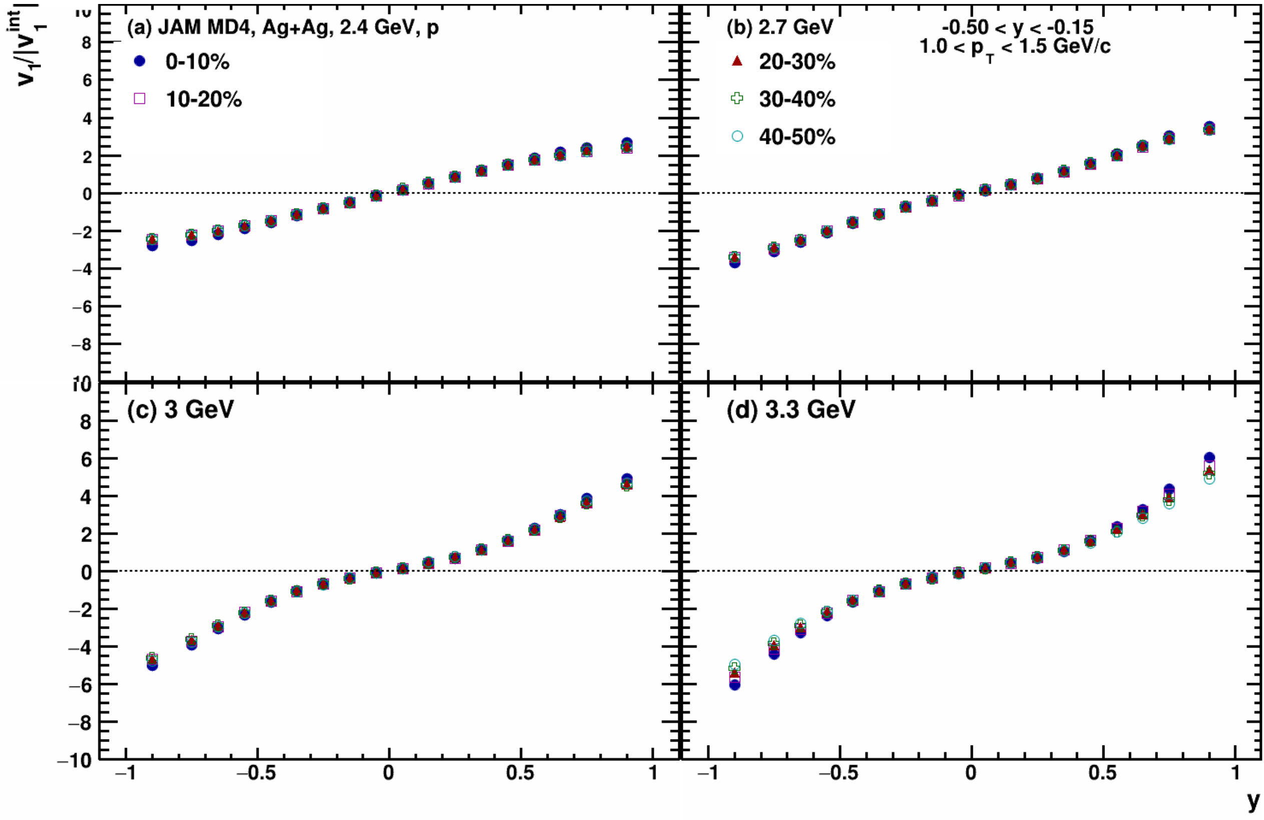
$v_1(y)$ Ag+Ag - protons

Kinematic cuts:

-0.5 < y < -0.15

1.0 < p_T < 1.5 GeV/c



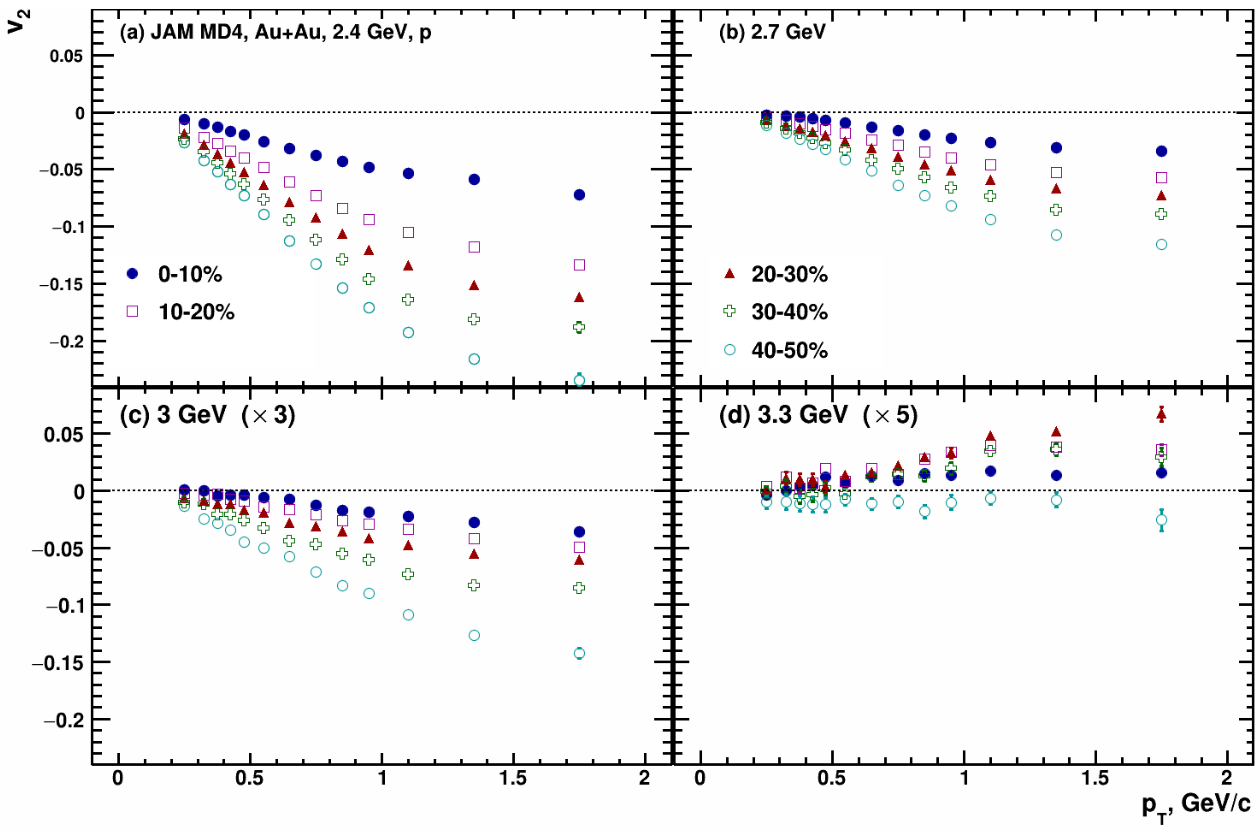


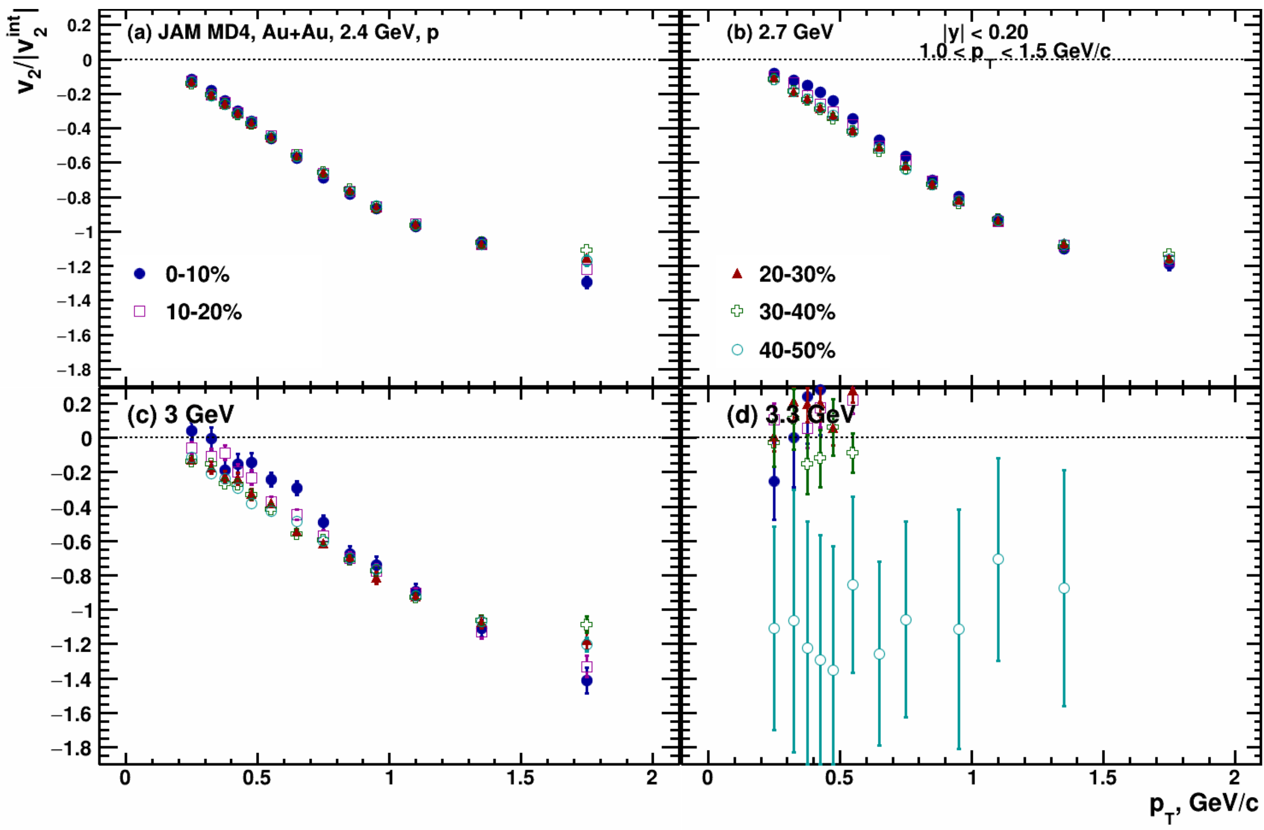
$v_2(p_T)$ Au+Au - protons

Kinematic cuts:

-0.2 < y < 0.2

1.0 < p_T < 1.5 GeV/c



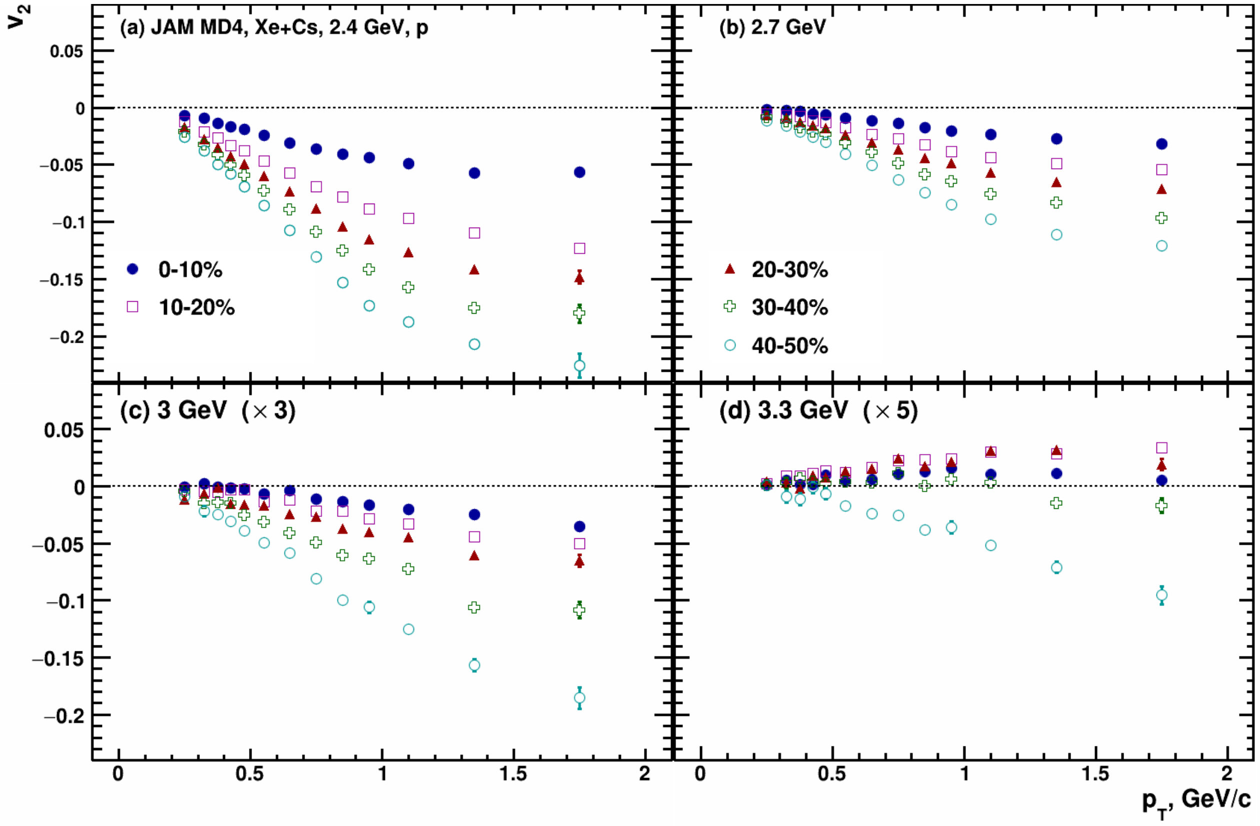


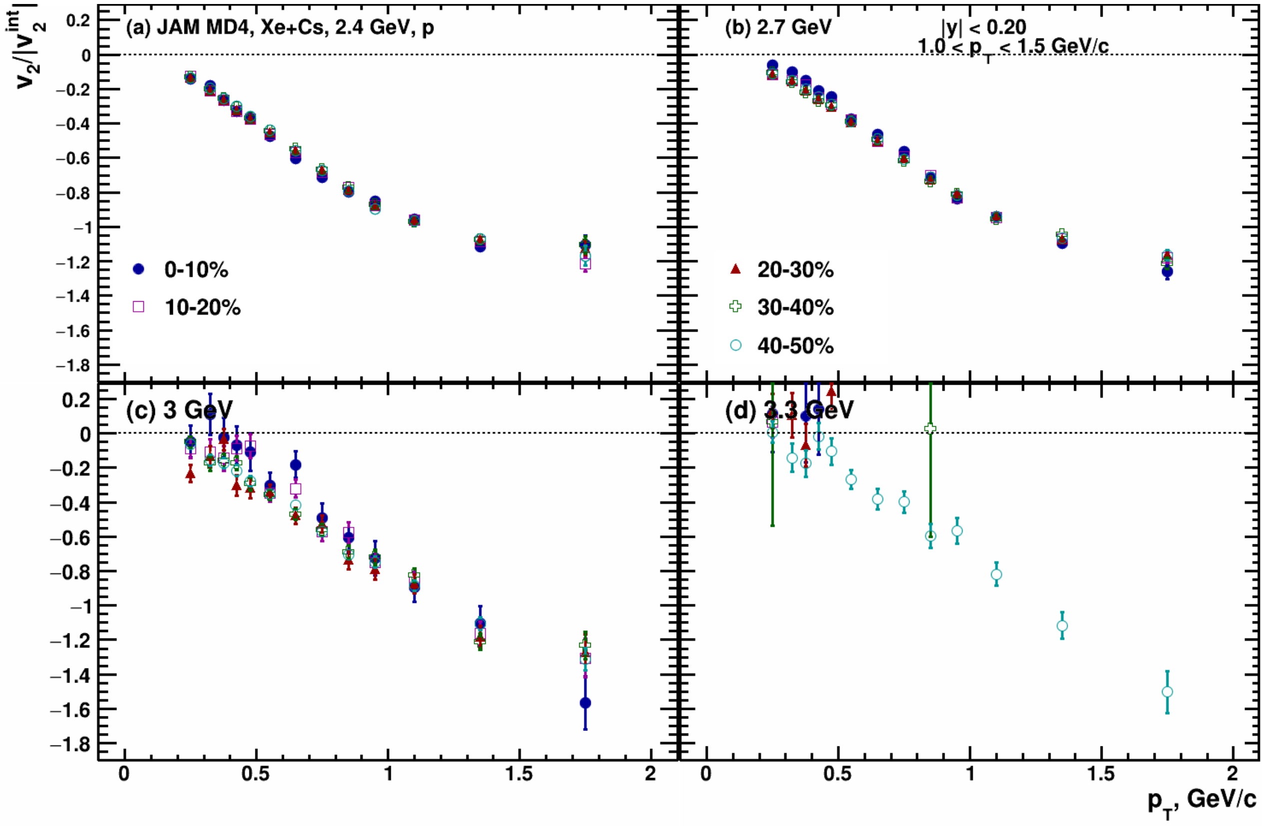
$v_2(p_T)$ Xe+Cs - protons

Kinematic cuts:

-0.2 < y < 0.2

1.0 < p_T < 1.5 GeV/c



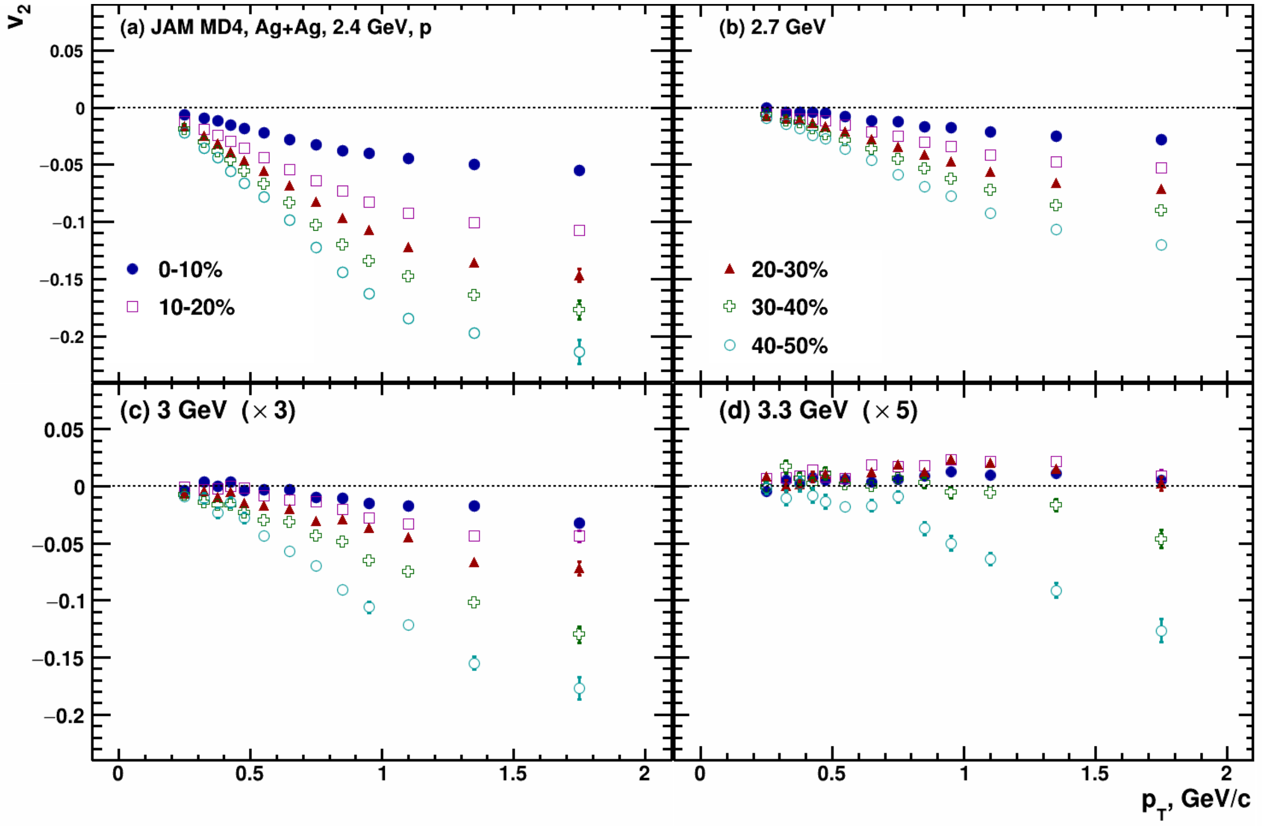


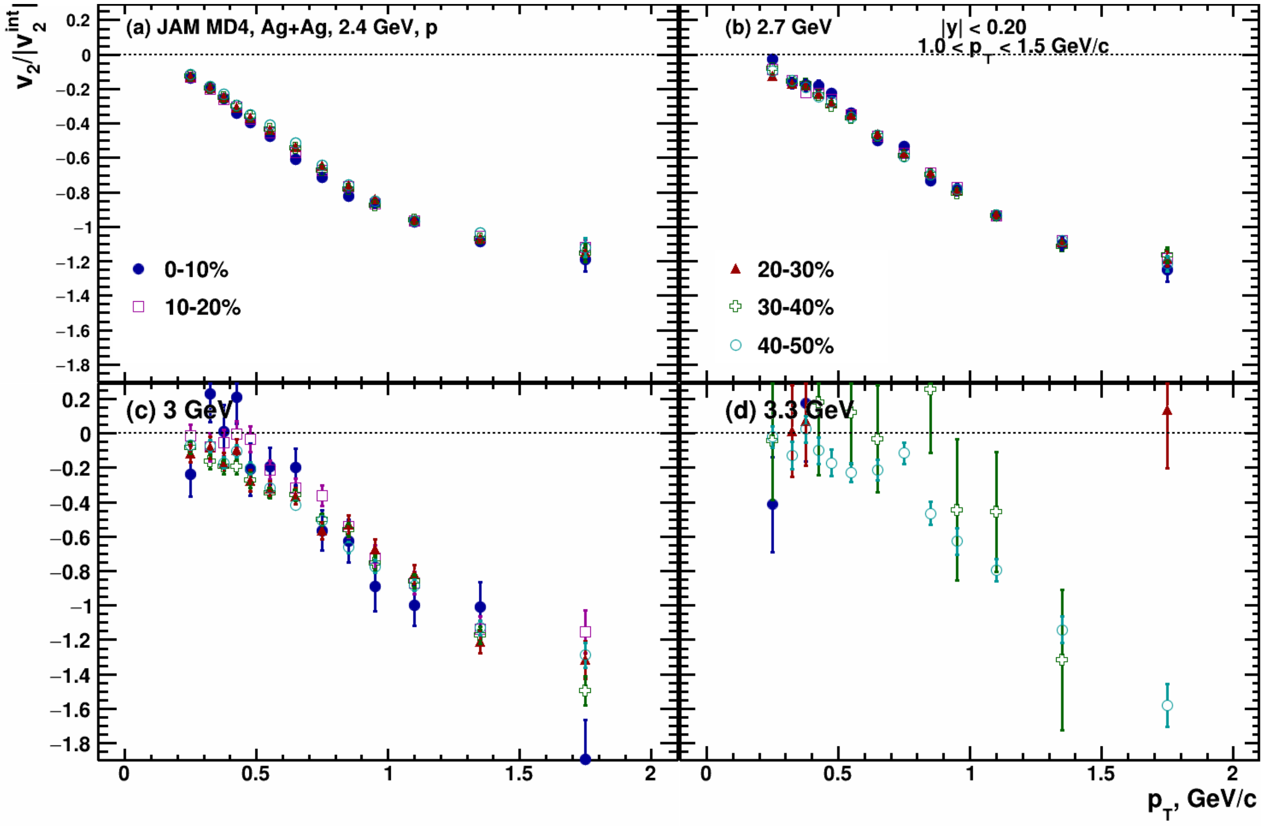
$v_2(p_T)$ Ag+Ag - protons

Kinematic cuts:

-0.2 < y < 0.2

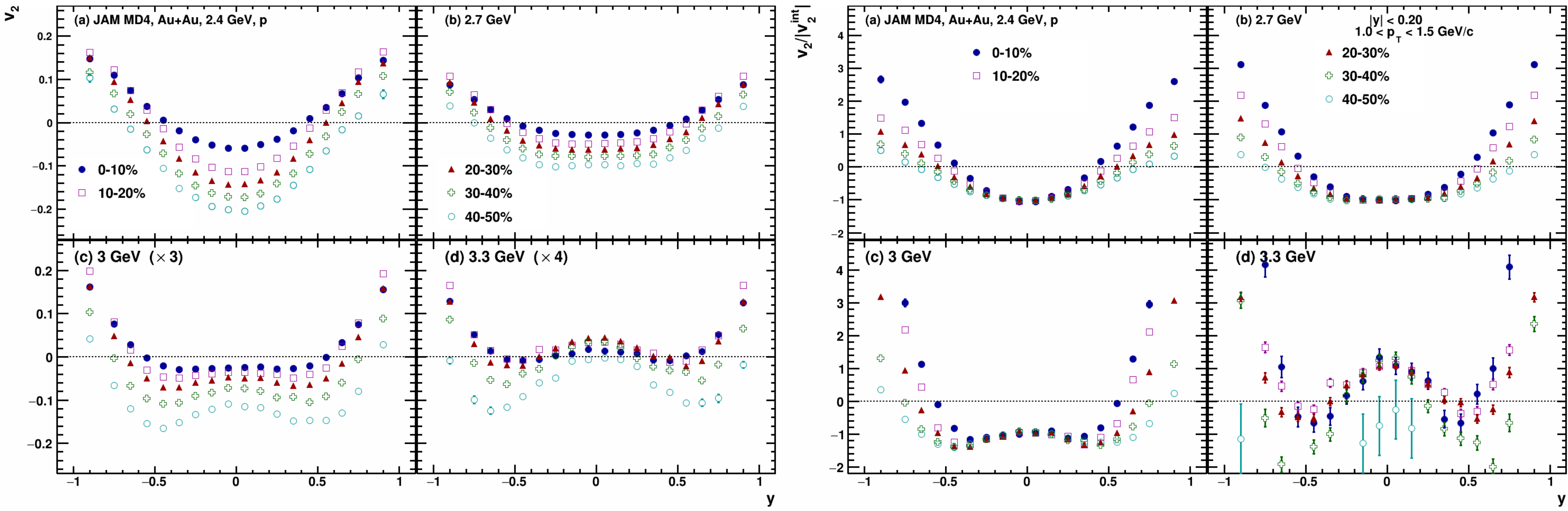
1.0 < p_T < 1.5 GeV/c





$v_2(y)$ Au+Au - protons

Kinematic cuts:
-0.2 < y < 0.2
$1.0 < p_T < 1.5$ GeV/c

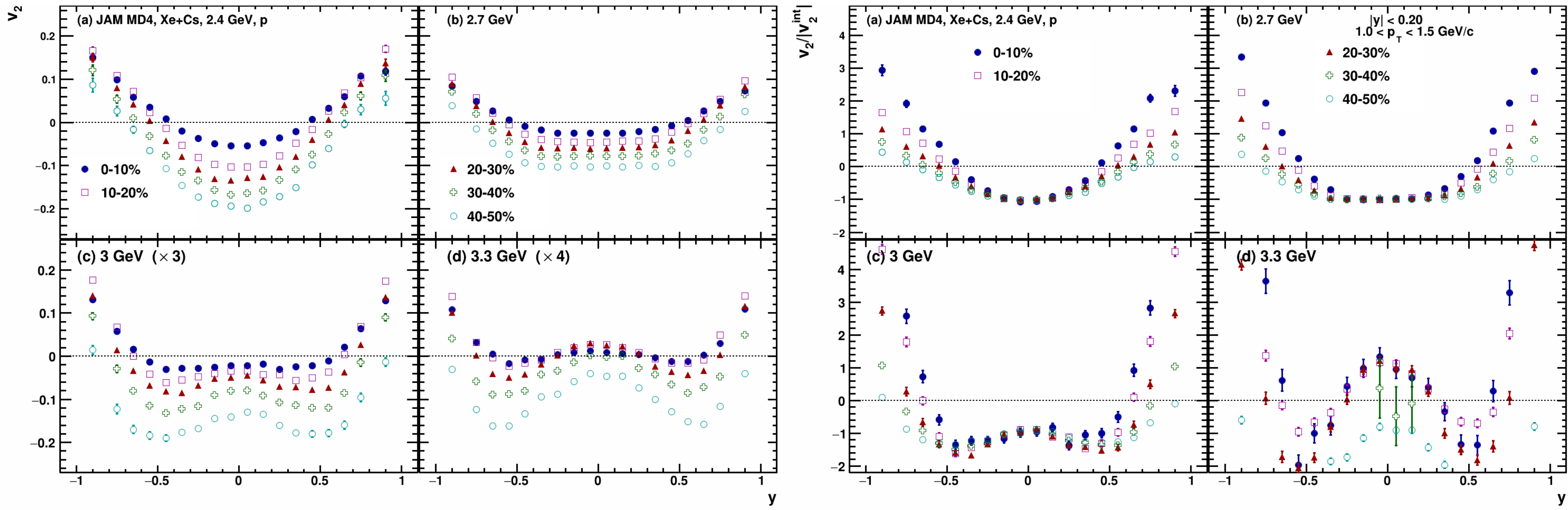


$v_2(y)$ Xe+Cs - protons

Kinematic cuts:

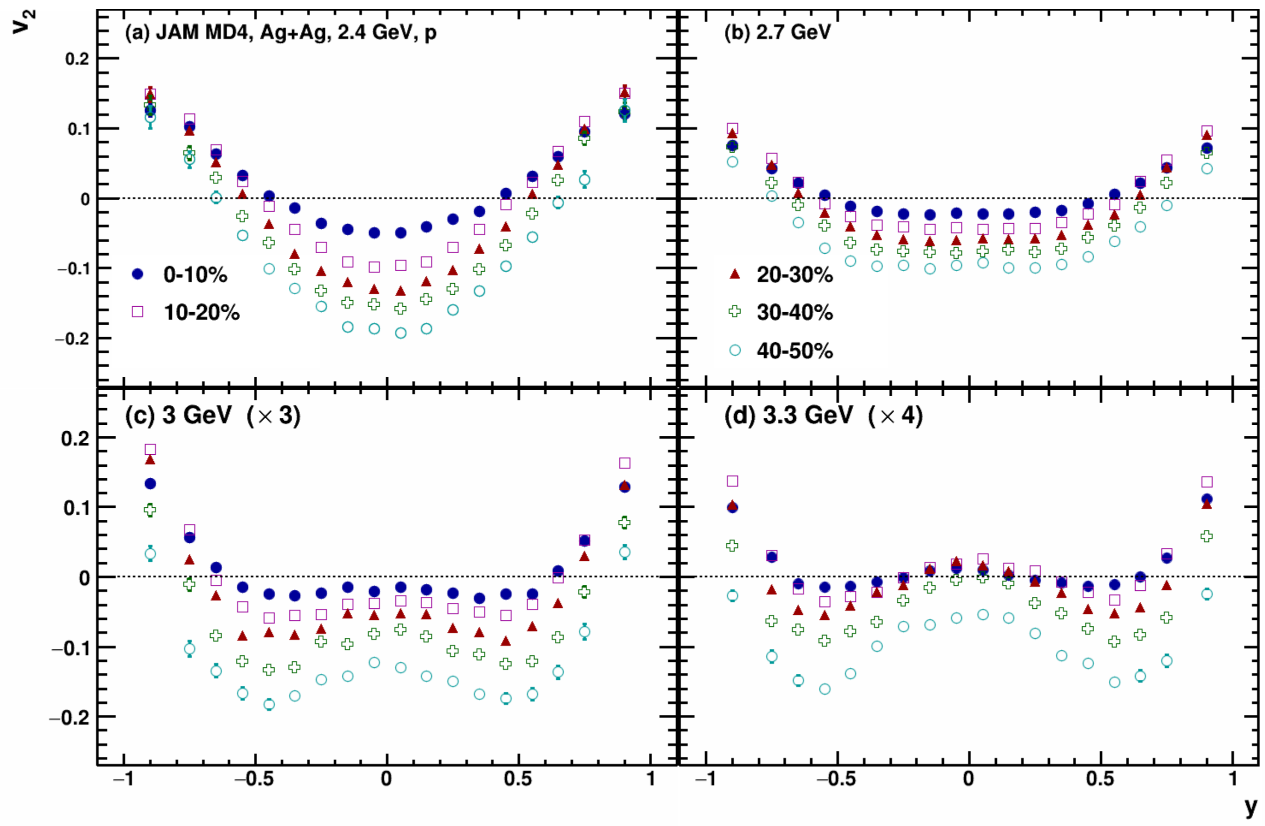
$-0.2 < y < 0.2$

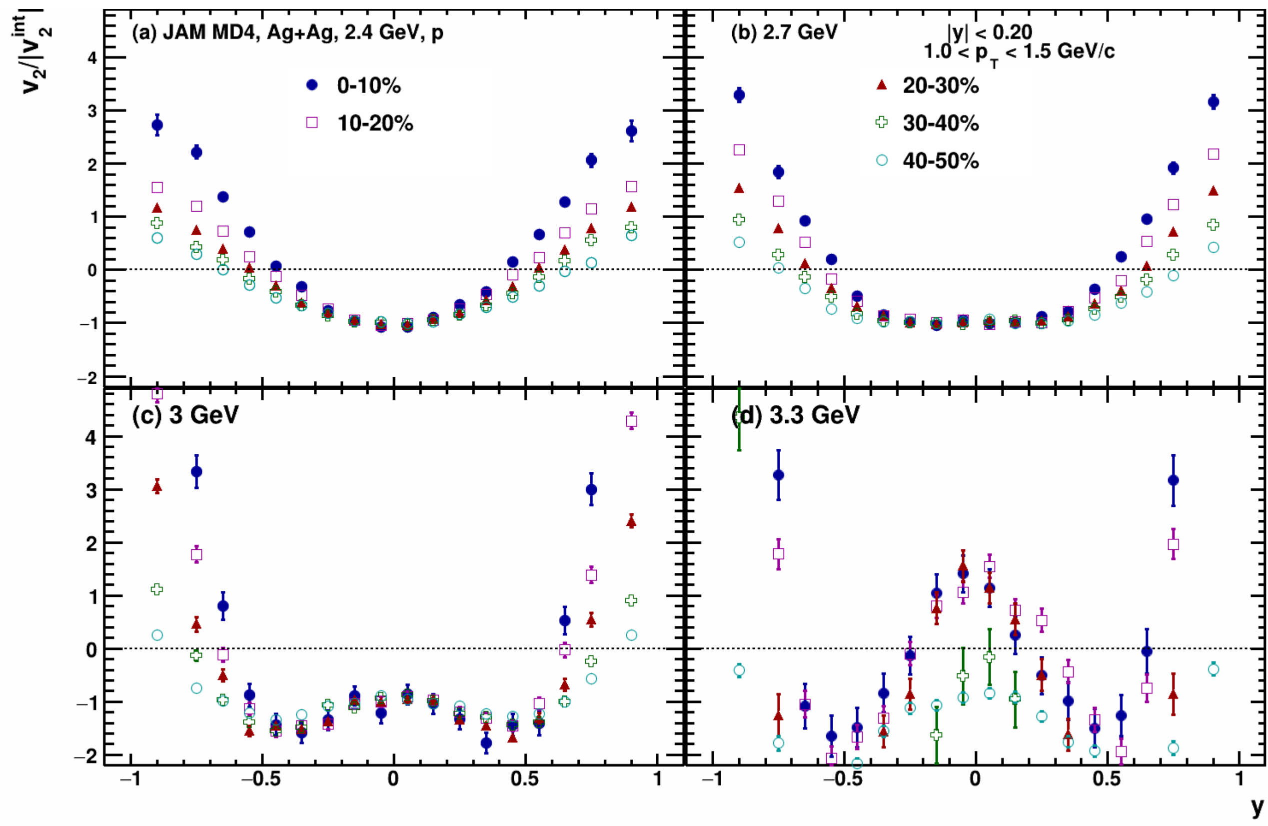
$1.0 < p_T < 1.5$ GeV/c



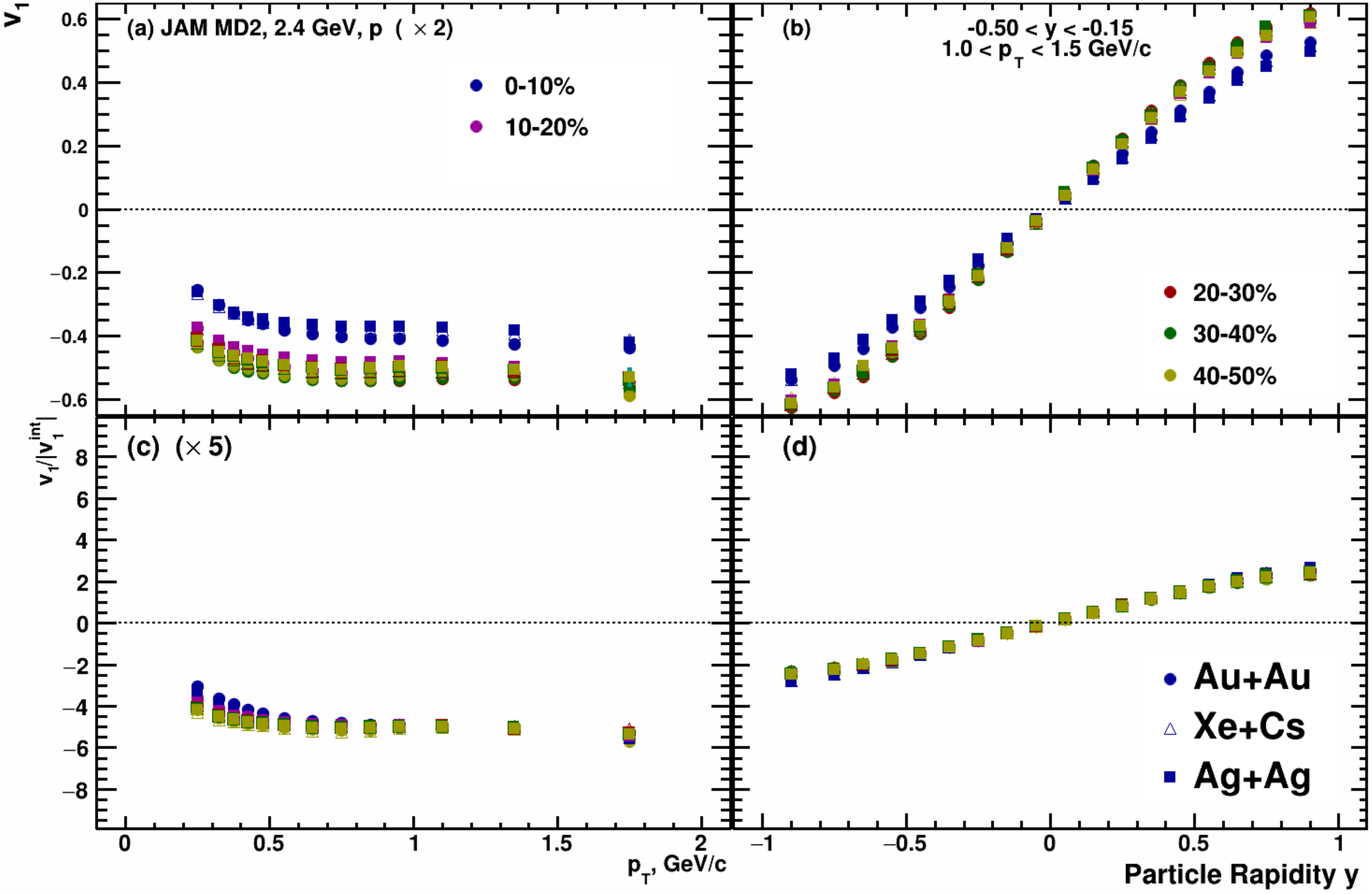
$v_2(y)$ Ag+Ag - protons

Kinematic cuts:
-0.2 < y < 0.2
$1.0 < p_T < 1.5$ GeV/c





$v_1(y)$ protons at $\sqrt{s_{NN}} = 2.4$ GeV

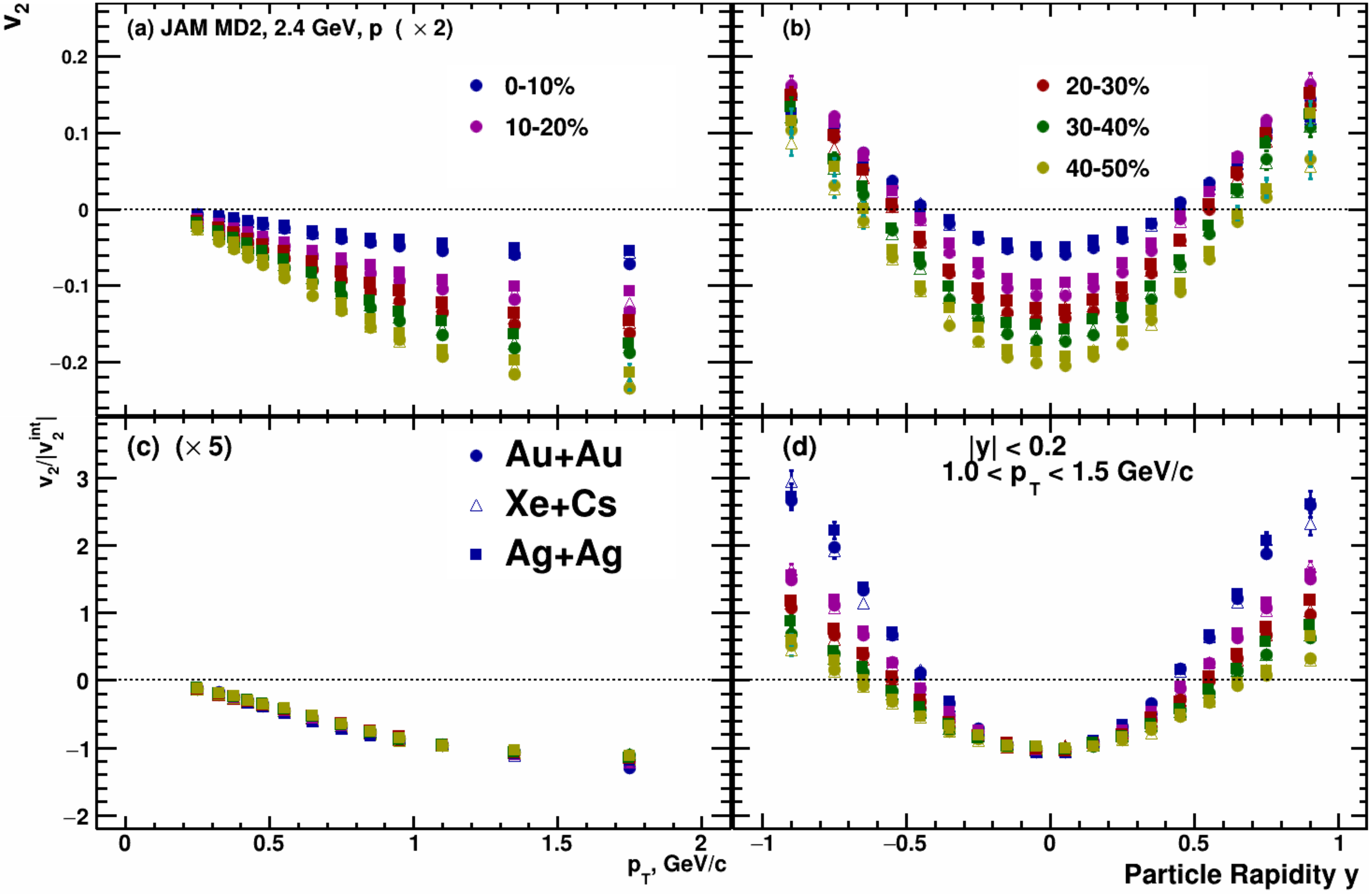


Kinematic cuts:

$-0.2 < y < 0.2$

$1.0 < p_T < 1.5$ GeV/c

$v_2(y)$ protons at $\sqrt{s_{NN}} = 2.4$ GeV



Kinematic cuts:

$-0.2 < y < 0.2$

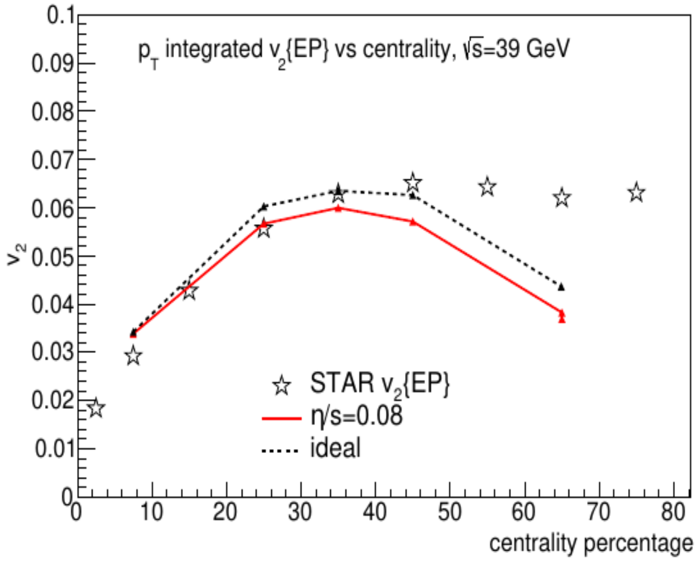
$1.0 < p_T < 1.5$ GeV/c

Hybrid models for anisotropic flow at RHIC/LHC

1. UrQMD + 3D viscous hydro model vHLLE+UrQMD

Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle
Parameters: from Iu. A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys. Rev. C91 (2015) no.6, 064901 – good description of STAR BES results for v_2 of inclusive charged hadrons (7.7-62.4 GeV)

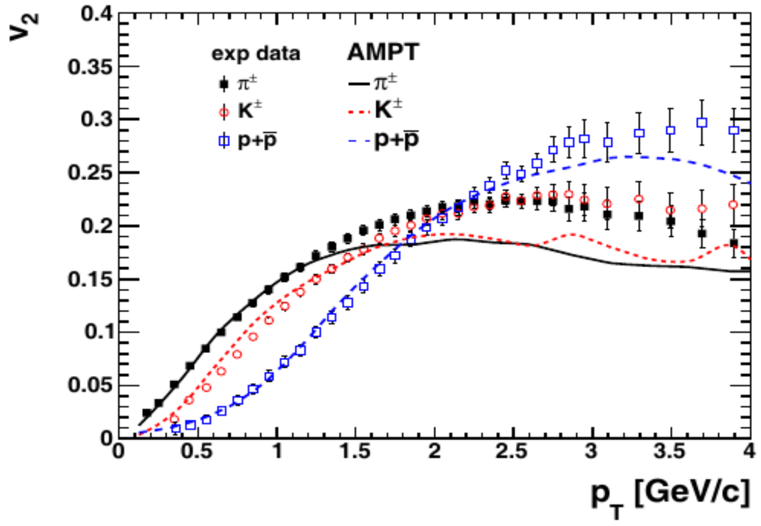
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)
Hadronic phase: model UrQMD



2. A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions

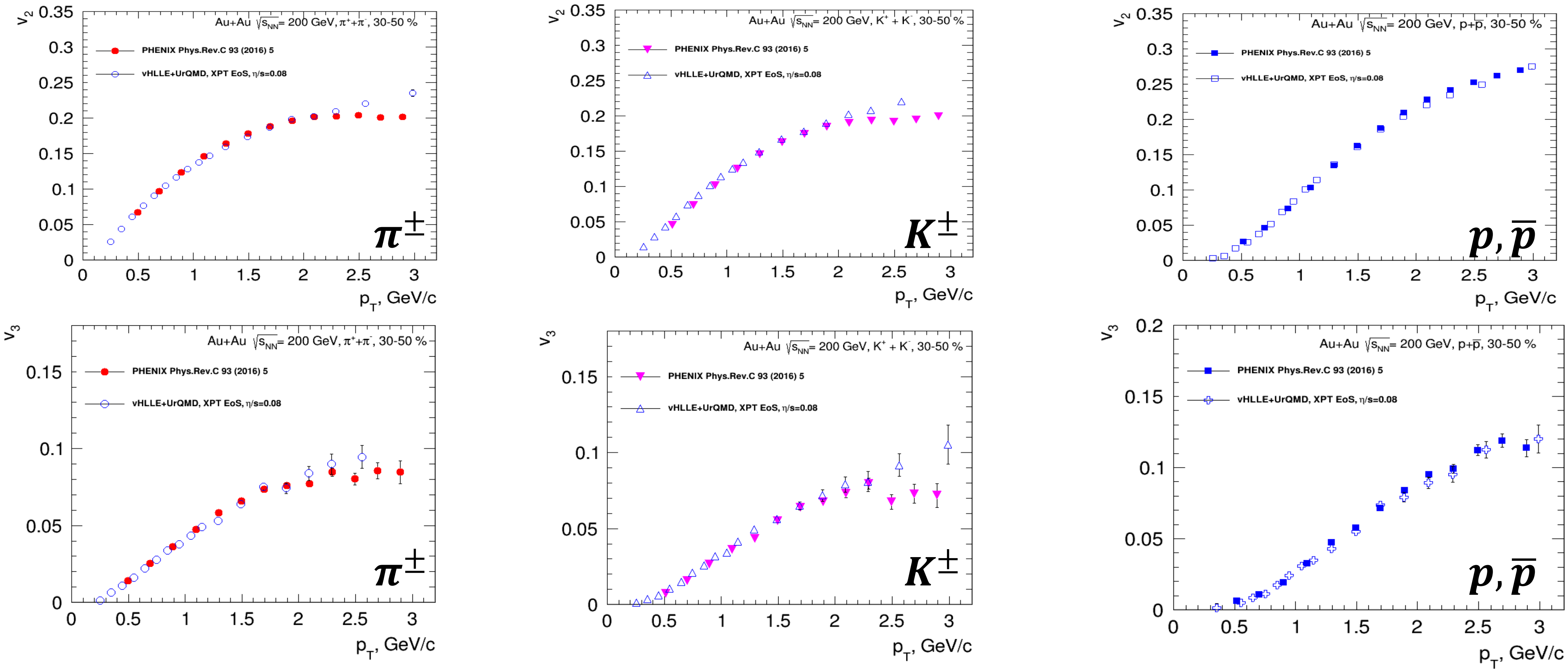
The main source code (Zi-Wei Lin):
https://myweb.ecu.edu/linz/ampt/v1.26t9b/v2.26t9b

Initial conditions: model HIJING
QGP phase: Zhang's parton cascade for modeling partonic scatterings
Hadronic phase: model ART



Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal:
Physical Review C 72, 064901 (2005).

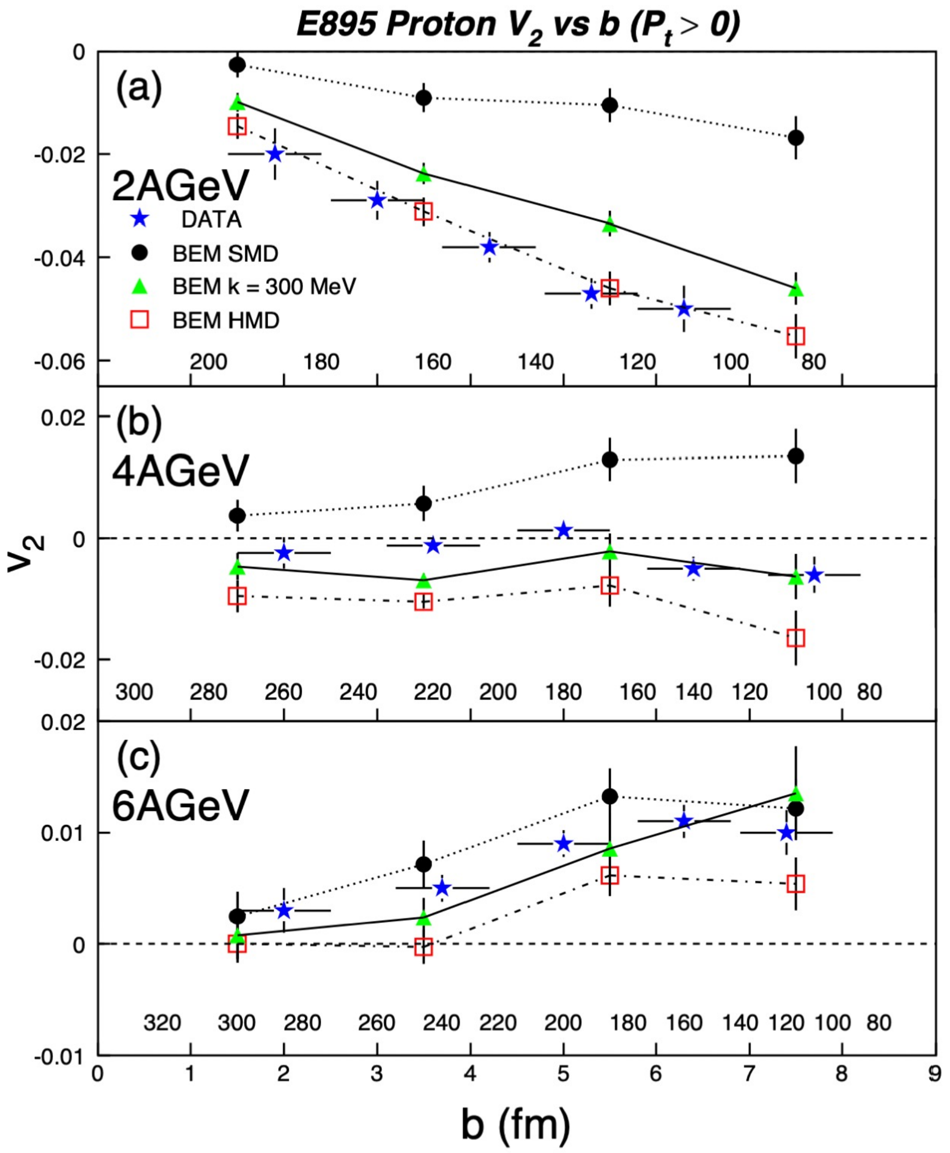
vHLLE+UrQMD: Elliptic and triangular flow in Au+Au collisions at 200 GeV



3D hydro model vHHLE + UrQMD (XPT EOS), η/s= 0.08 + param from Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data

Centrality dependence of v_2 protons at $\sqrt{s_{NN}}$=2.7-3.8 GeV



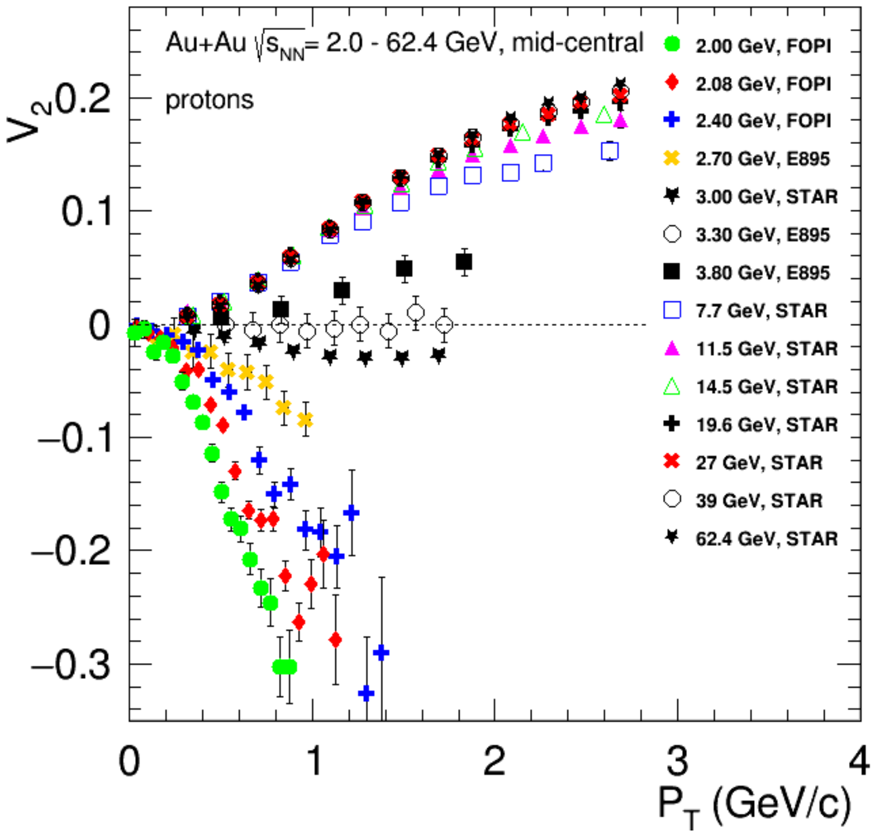
At $\sqrt{s_{NN}}$=3.3 GeV (E_{kin}=4 AGeV):

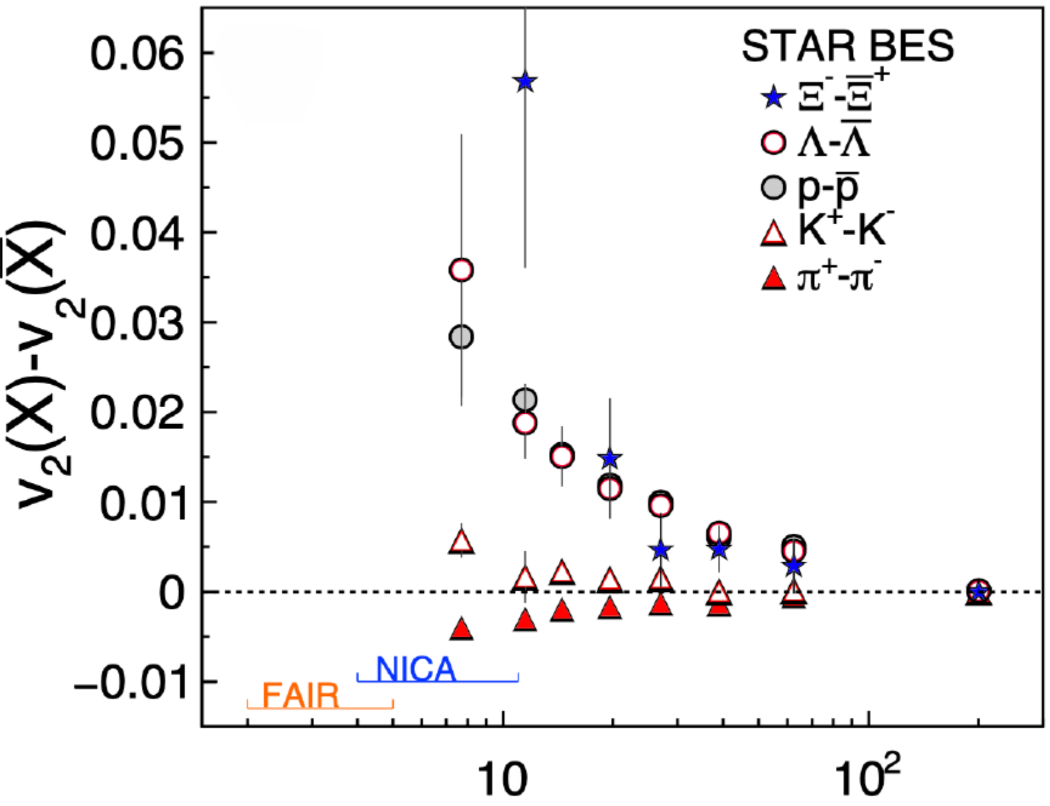
- Linear dependence of $v_2(b)$ breaks
- $v_2 \approx 0$ for central and mid-central collisions
- $v_2 < 0$ for peripheral collisions

Phys. Rev. C 66 (2002) 021901

Anisotropic collective flow at STAR BES

EPJ Web Conf. 204 (2019) 03009
Phys. Rev. C 88 (2013) 14902





- Small change in $v_2(p_T)$ for Au+Au $\sqrt{s_{NN}}$=7.7 – 62.4 GeV (STAR BES-I)
- Strong energy dependence of the difference in v_2 of particles and antiparticles