Anisotropic flow at Nuclotron-NICA energy range

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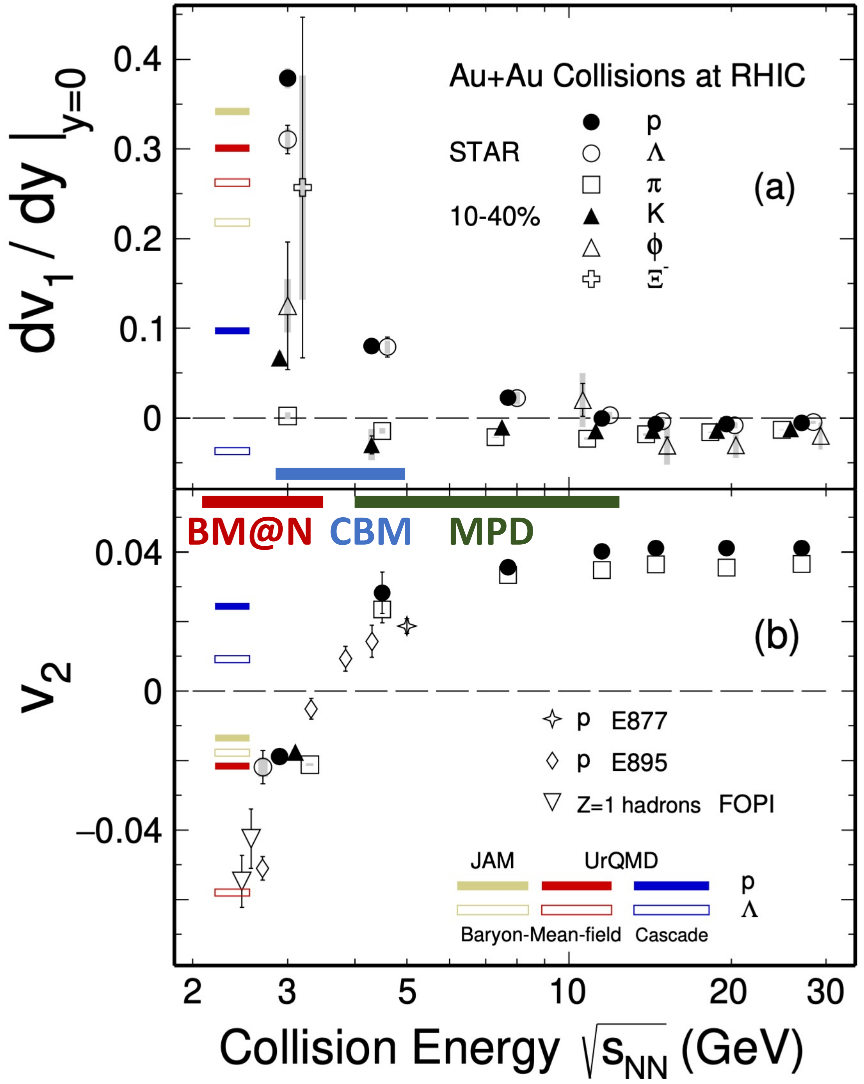
Outline

- 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-NICA energies?
- Summary and outlook

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

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



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

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:

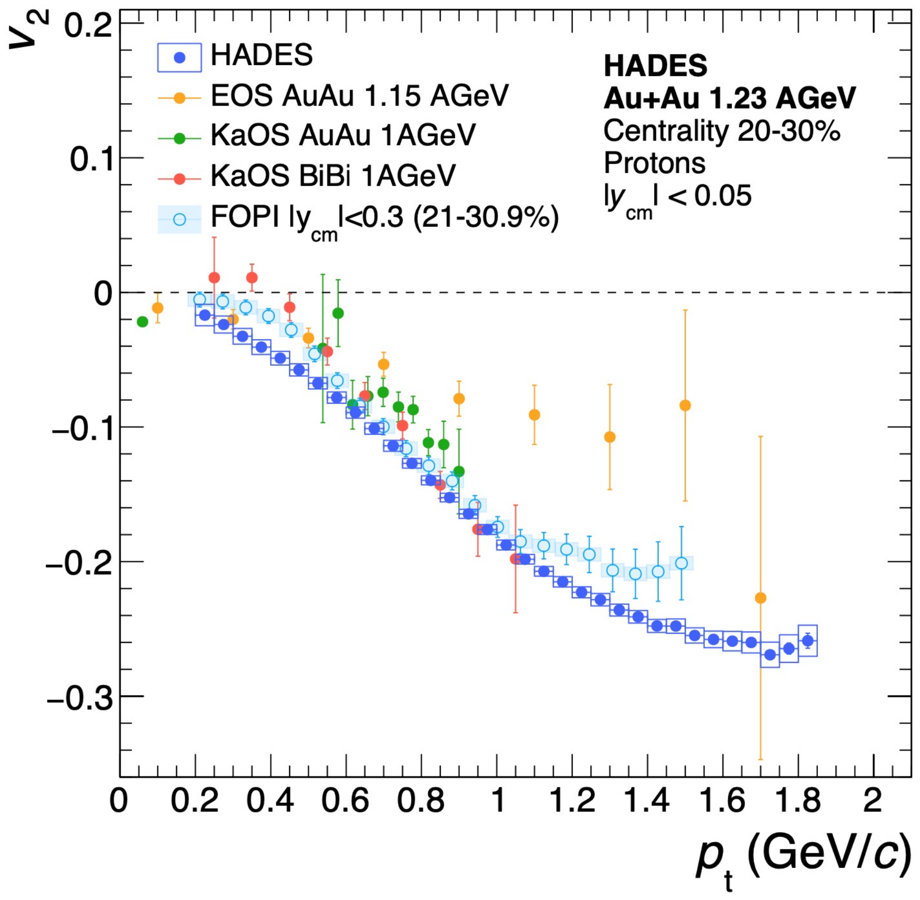
I. The ability of pressure developed early in the reaction zone and

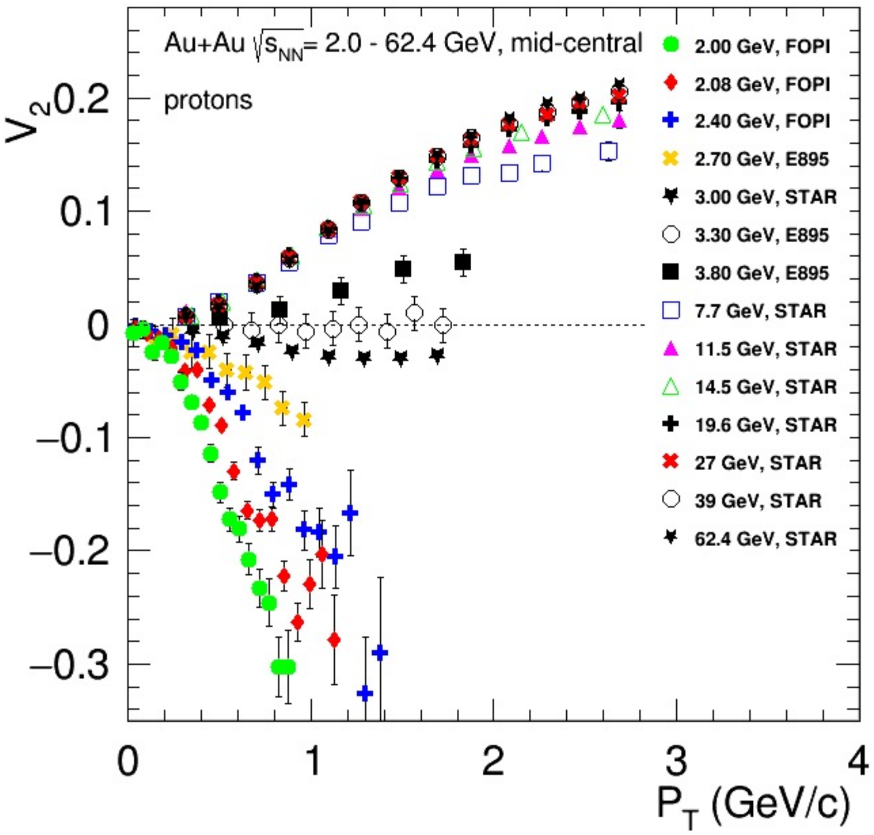
II. The passage time for removal of the shadowing by spectators

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), CBM ($\sqrt{s_{NN}}$=2.7-4.9 GeV), and MPD ($\sqrt{s_{NN}}$=4-11 GeV) energies

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





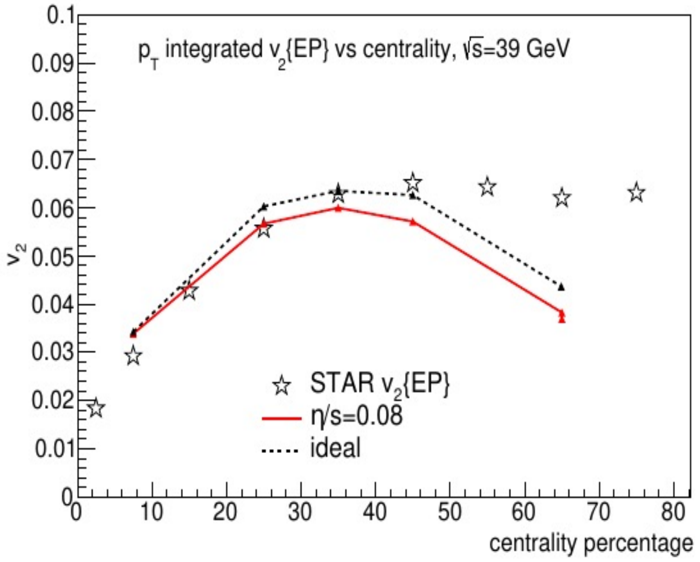
- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust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

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)

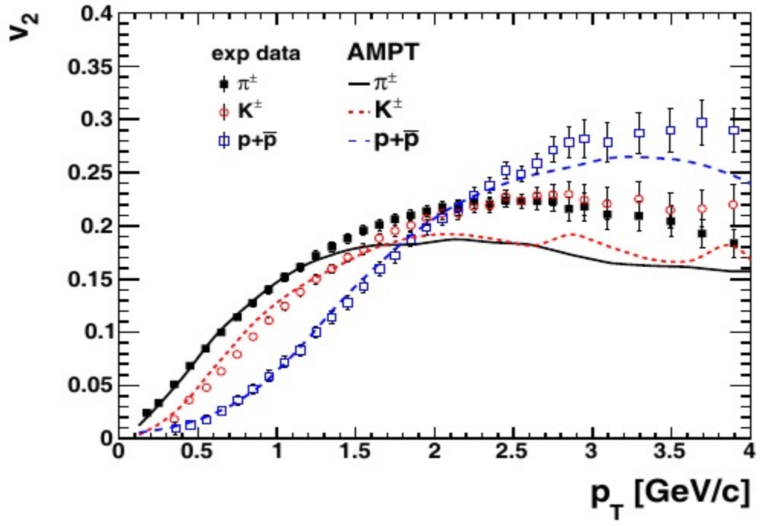
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)
Hadronic phase: model UrQMD



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

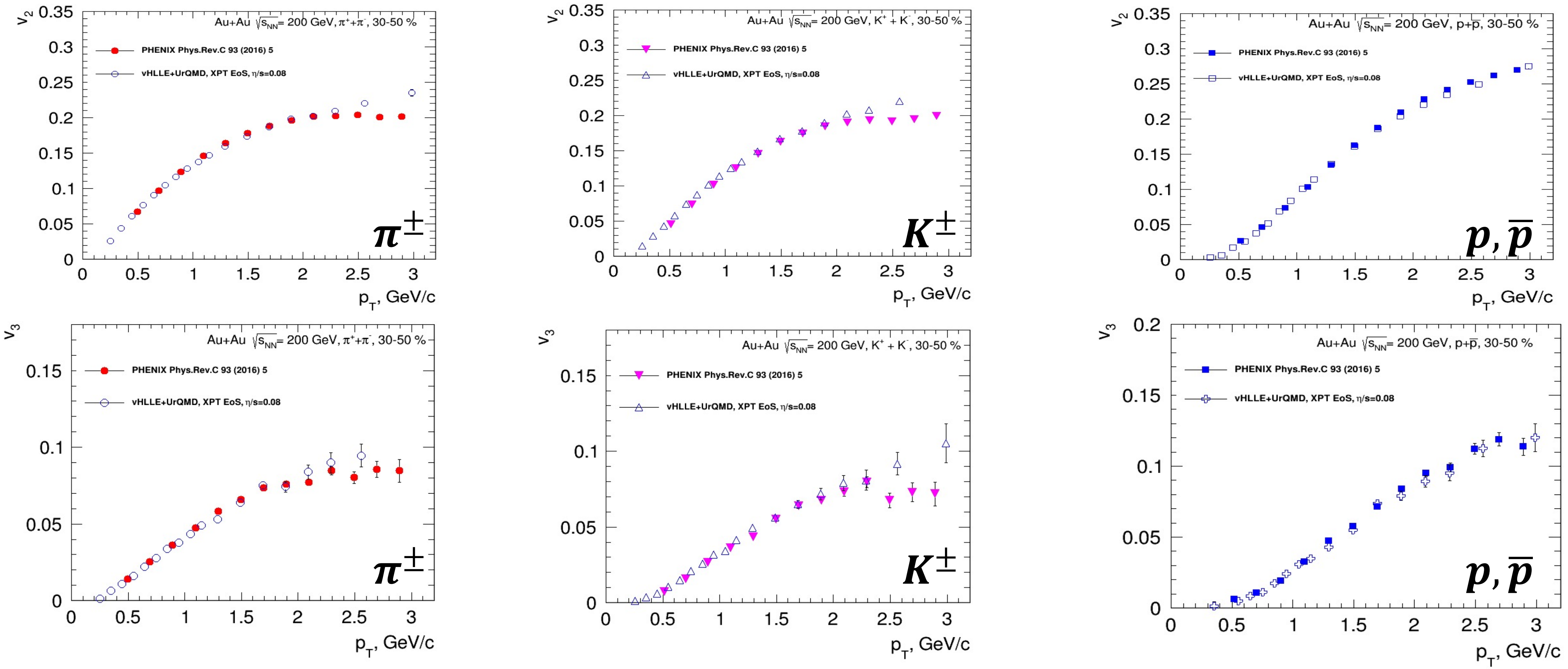
The main source code (Zi-Wei Lin):
https://myweb.ecu.edu/linz/ampt/v1.26t9b/v2.26t9b

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).

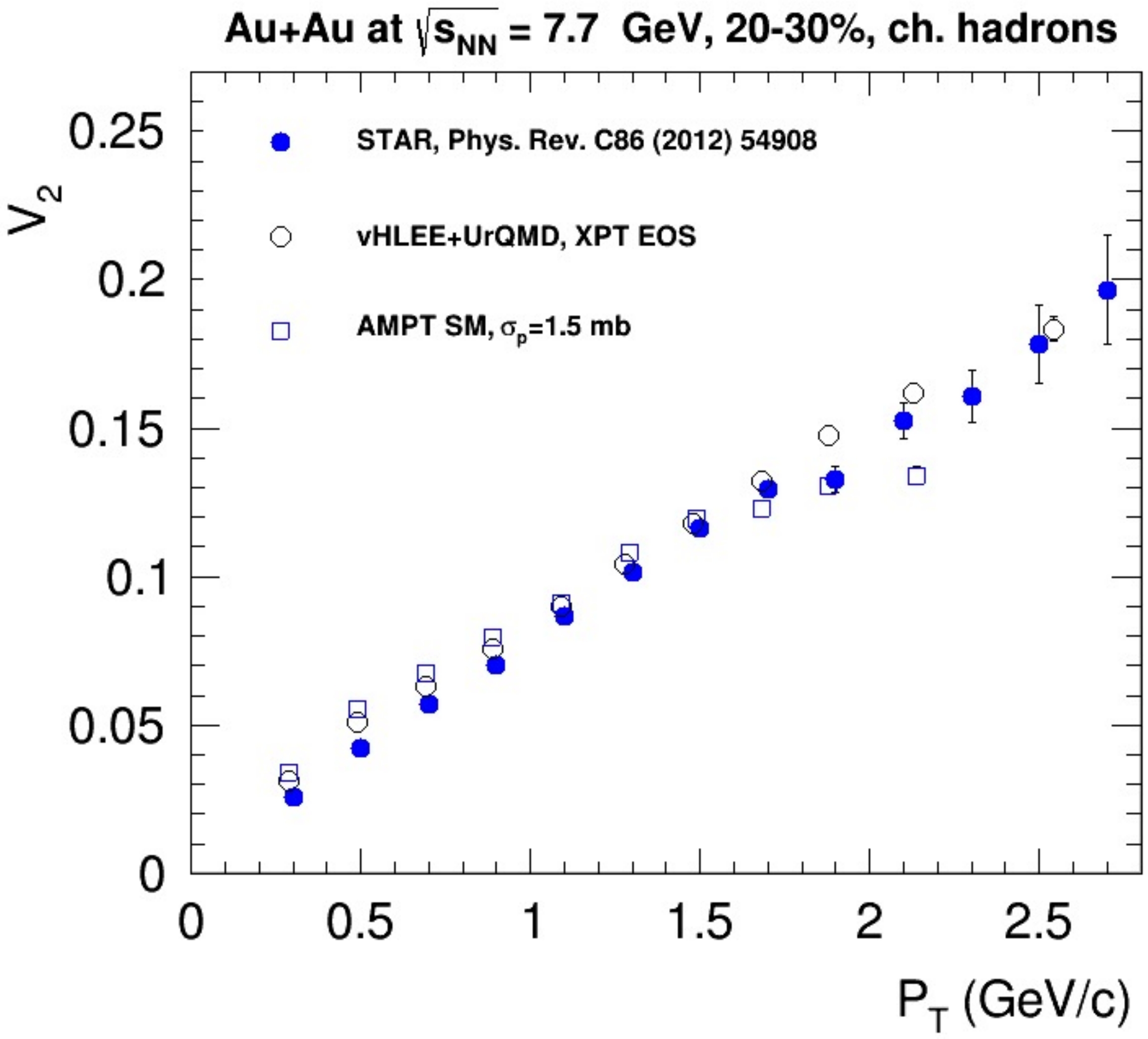
vHLLE+UrQMD: Elliptic and triangular flow in Au+Au collisions at 200 GeV

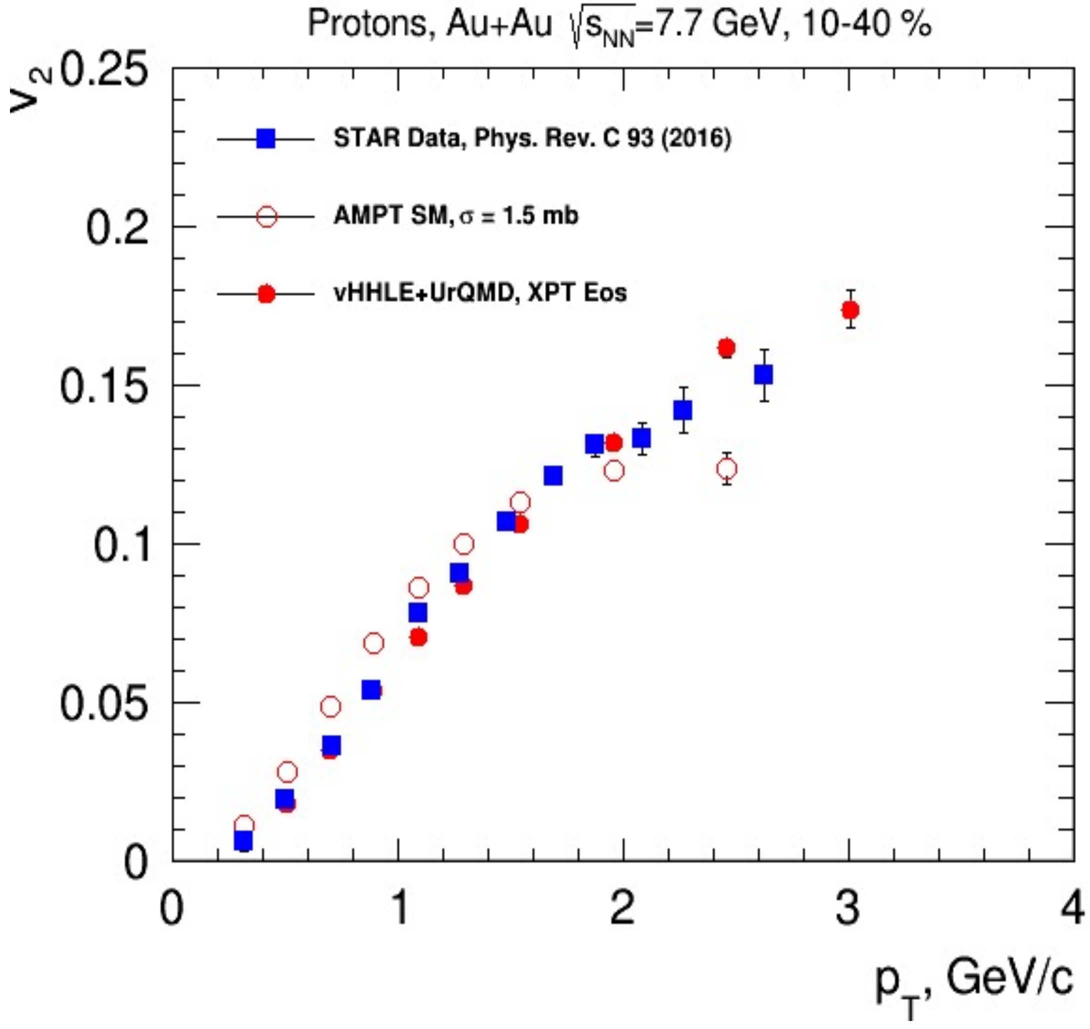


3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.08$ + param from Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

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

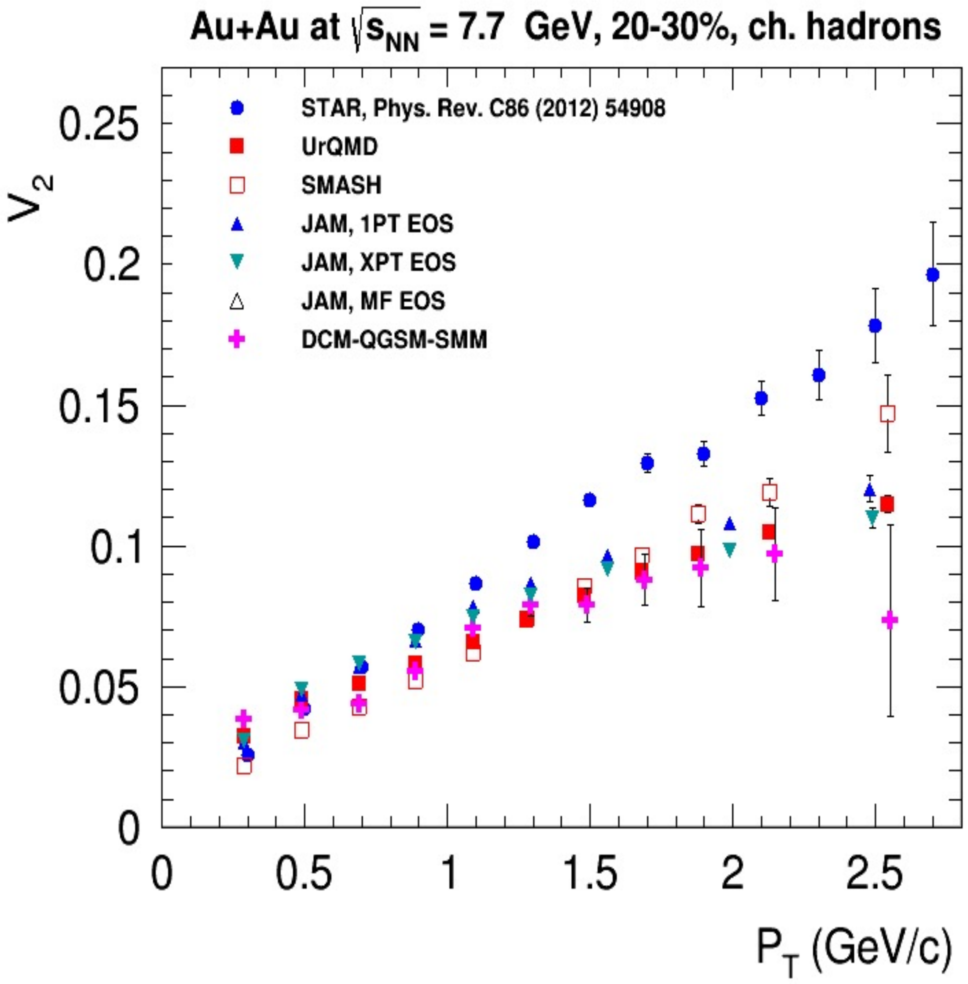
Elliptic flow at NICA energies: Models vs. Data comparison

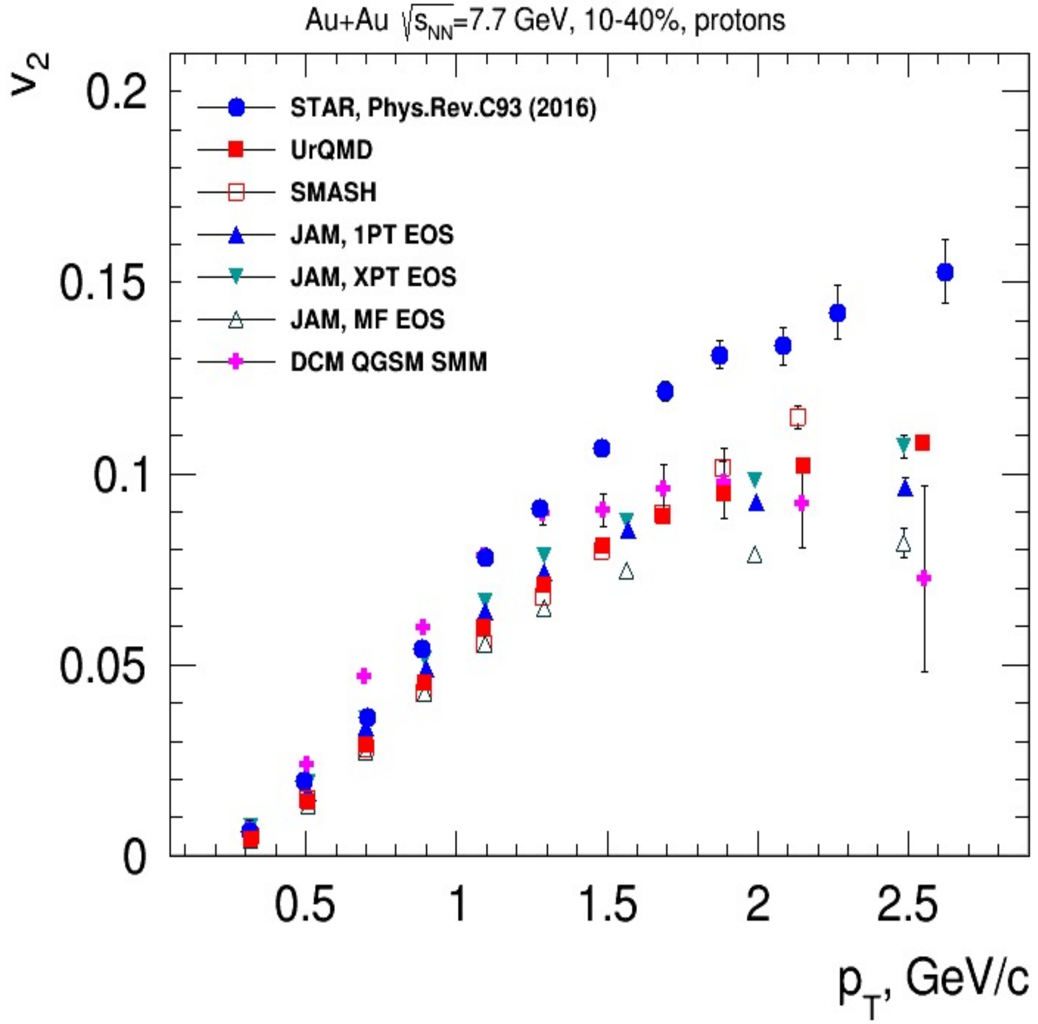




Good agreement between vHLLE+UrQMD ($\eta/s = 0.2$, XPT EOS), AMPT models and STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

Elliptic flow at NICA energies: Models vs. Data comparison

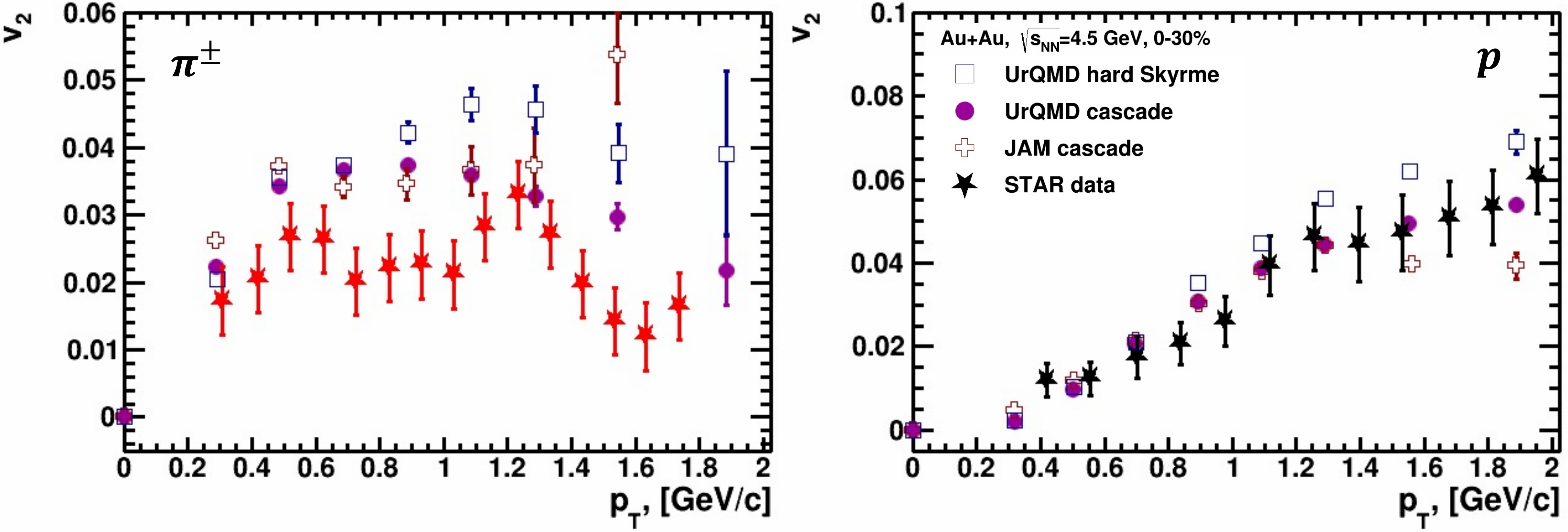




Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

Elliptic flow at NICA energies: Models vs. Data comparison

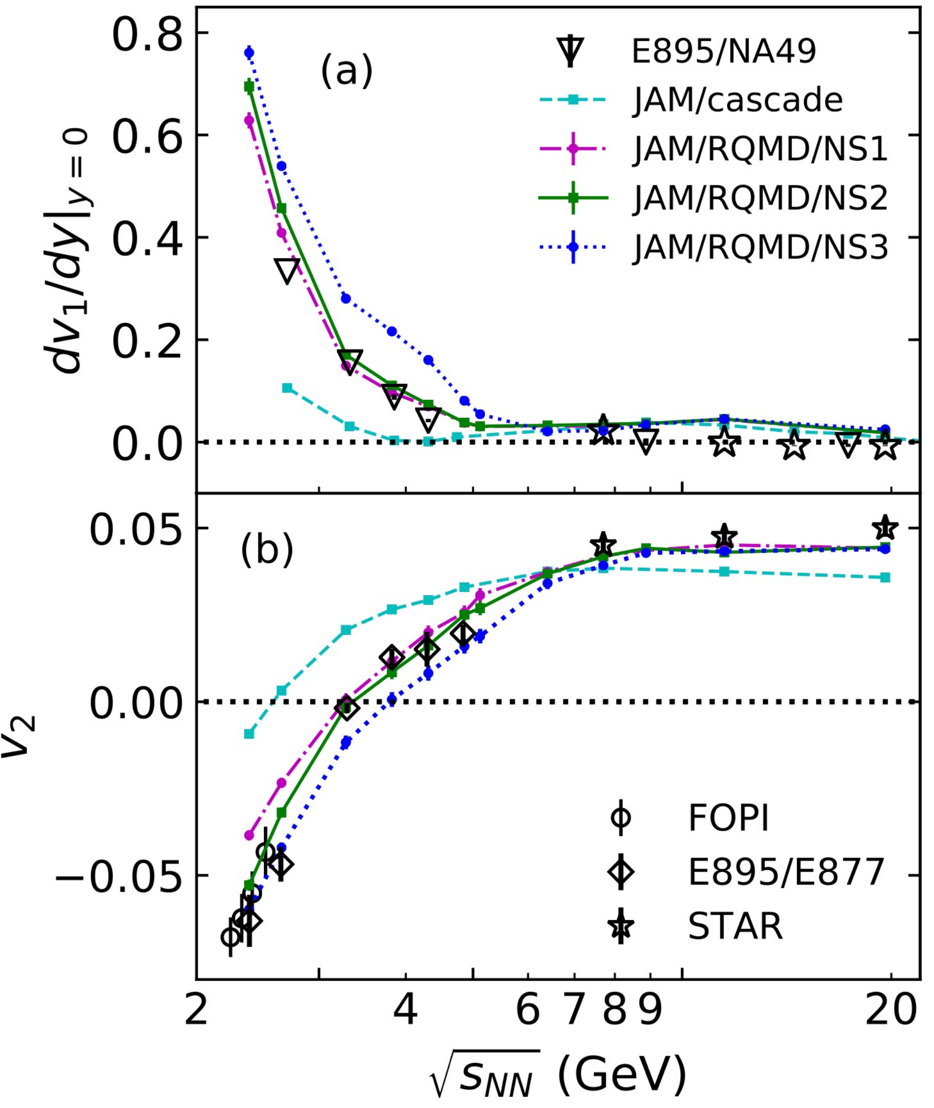
Experimental data is taken from: *Phys.Rev.C* 103 (2021) 3, 034908



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

Anisotropic flow study at $\sqrt{s_{NN}}$=2-4.5 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

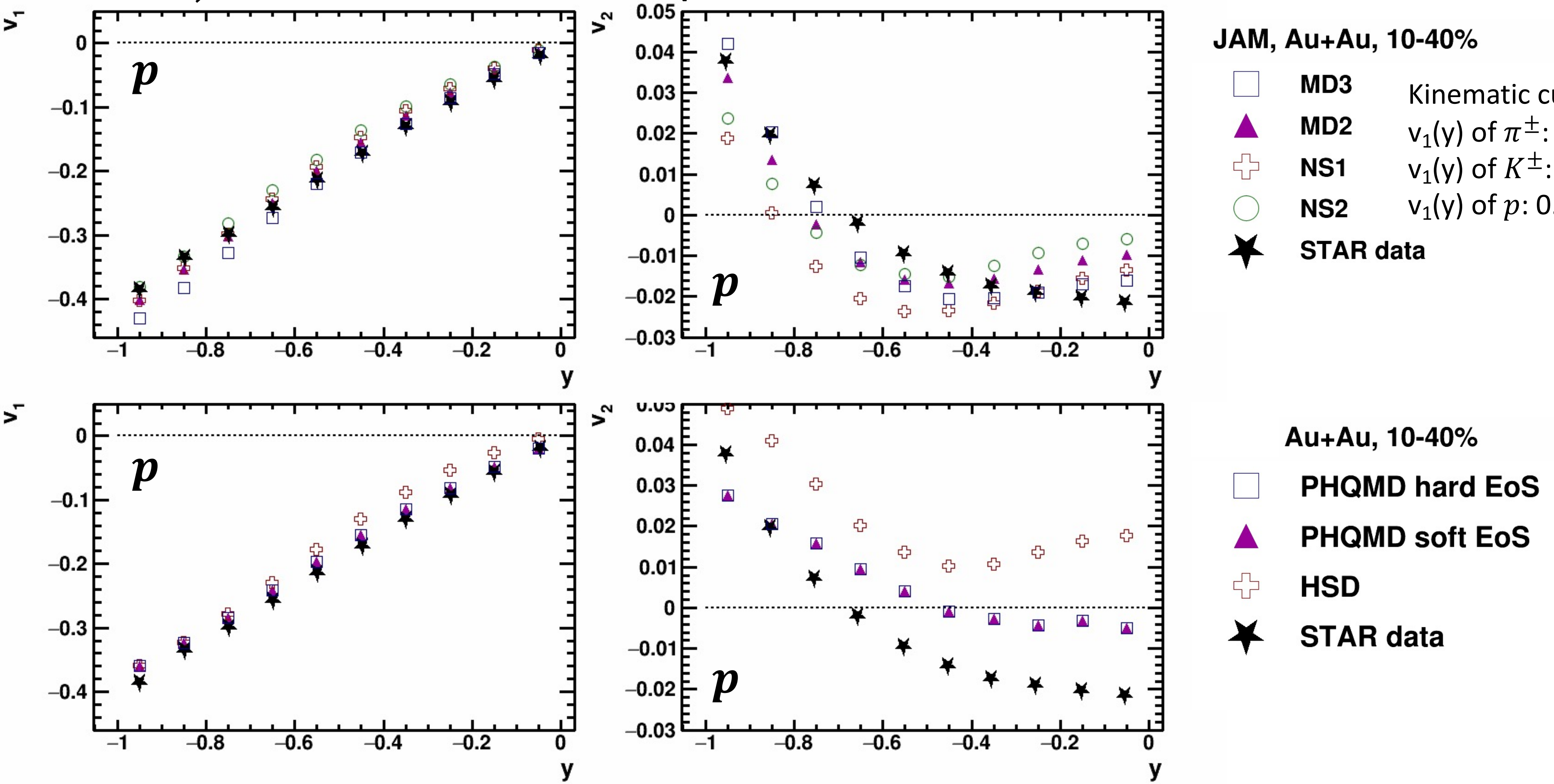
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

Different EOS were used:

- **MD3** (momentum-dependent potential): K=380 MeV, m^*/m=0.65
- **MD2** (momentum-dependent potential): K=210 MeV, m^*/m=0.8
- **MD4** (momentum-dependent potential): K=380 MeV, m^*/m=0.65
- **NS1**: K=230 MeV, m^*/m=0.8
- **NS2**: K=380 MeV, m^*/m=0.8

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

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

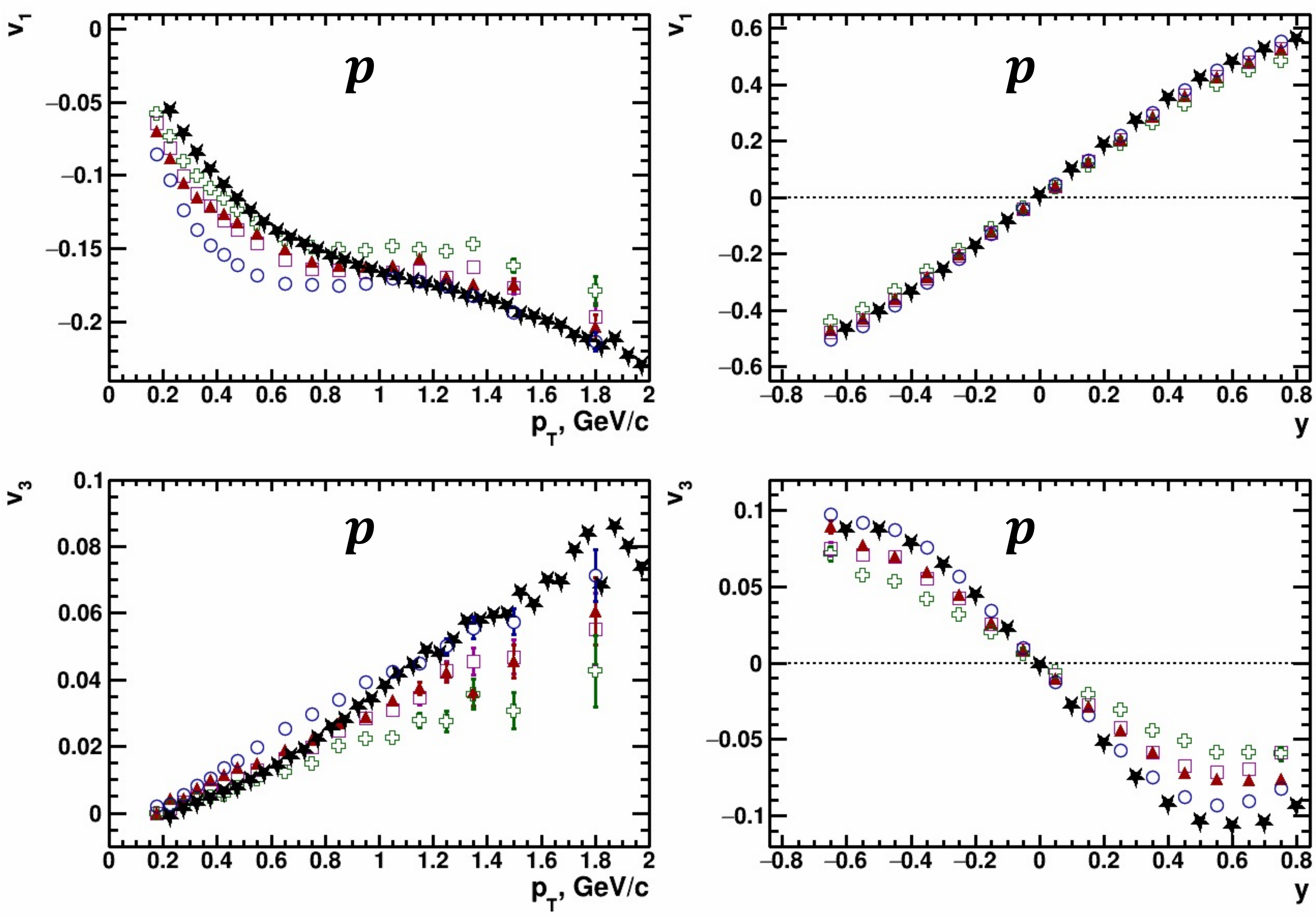


Kinematic cuts:
$v_1(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
$v_1(y)$ of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
$v_1(y)$ of p: 0.4 < pT < 2.0 GeV/c

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

Experimental data points were taken from:
M. Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]

$v_{1,3}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



JAM, Au+Au, 20-30% **(6<b<9 fm)**

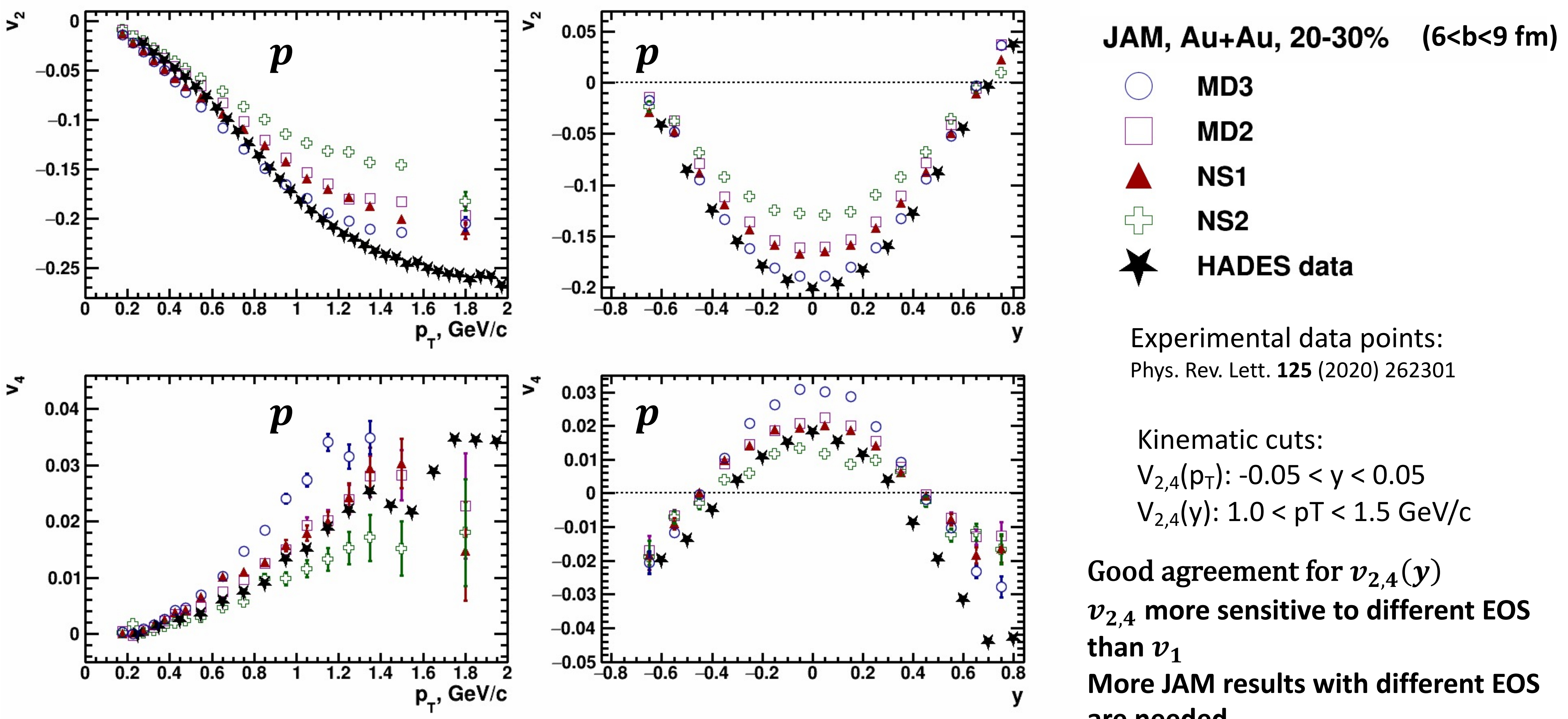
- **MD3**
- **MD2**
- **NS1**
- **NS2**
- **HADES data**

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

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

Good agreement for $v_{1,3}(y)$
$v_3(y)$ is more sensitive to different EOS than $v_1(y)$

$v_{2,4}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data

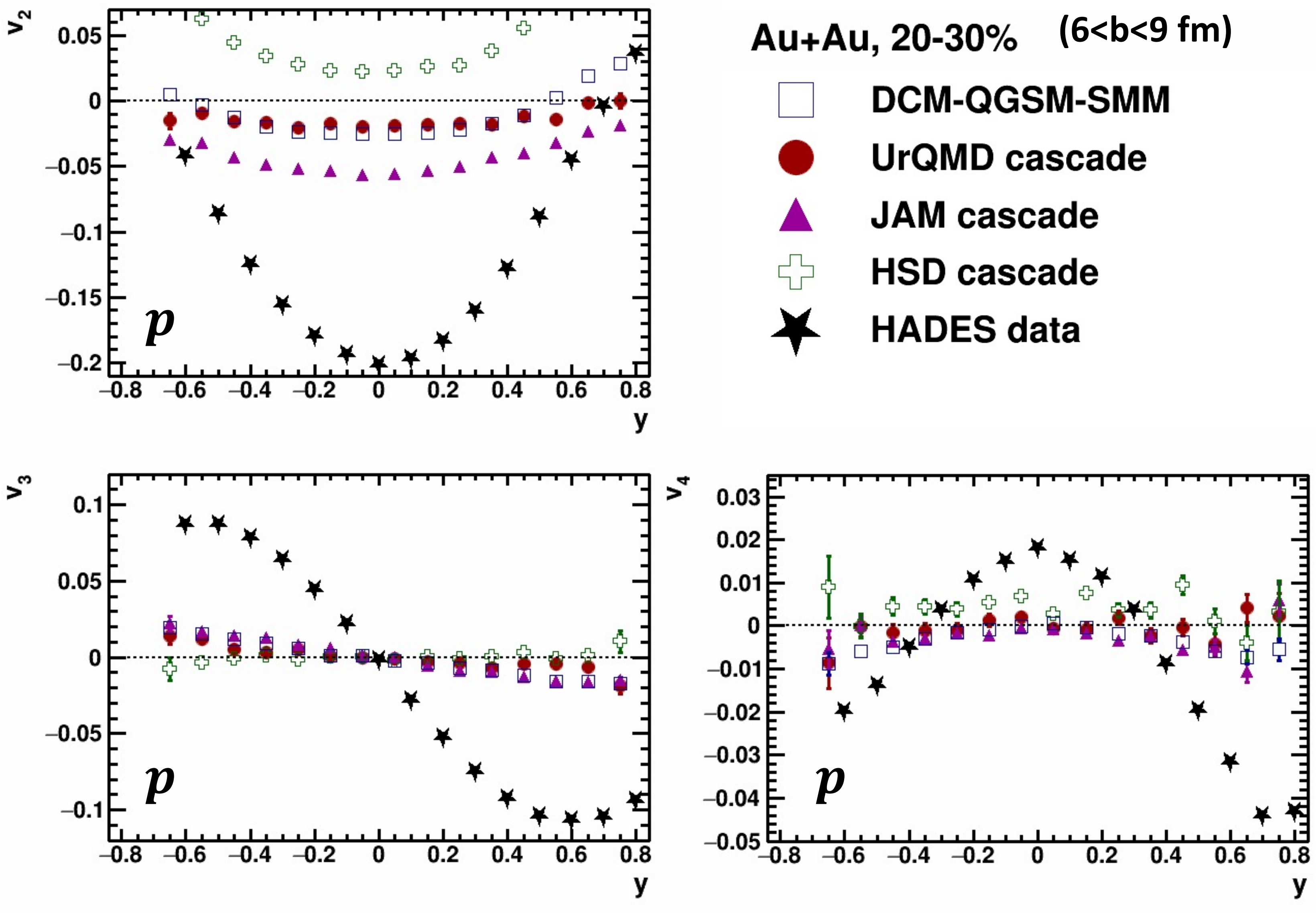


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{2,4}(p_T)$: -0.05 < y < 0.05
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Good agreement for $v_{2,4}(y)$
$v_{2,4}$ more sensitive to different EOS than v_1
More JAM results with different EOS are needed

$v_2(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models

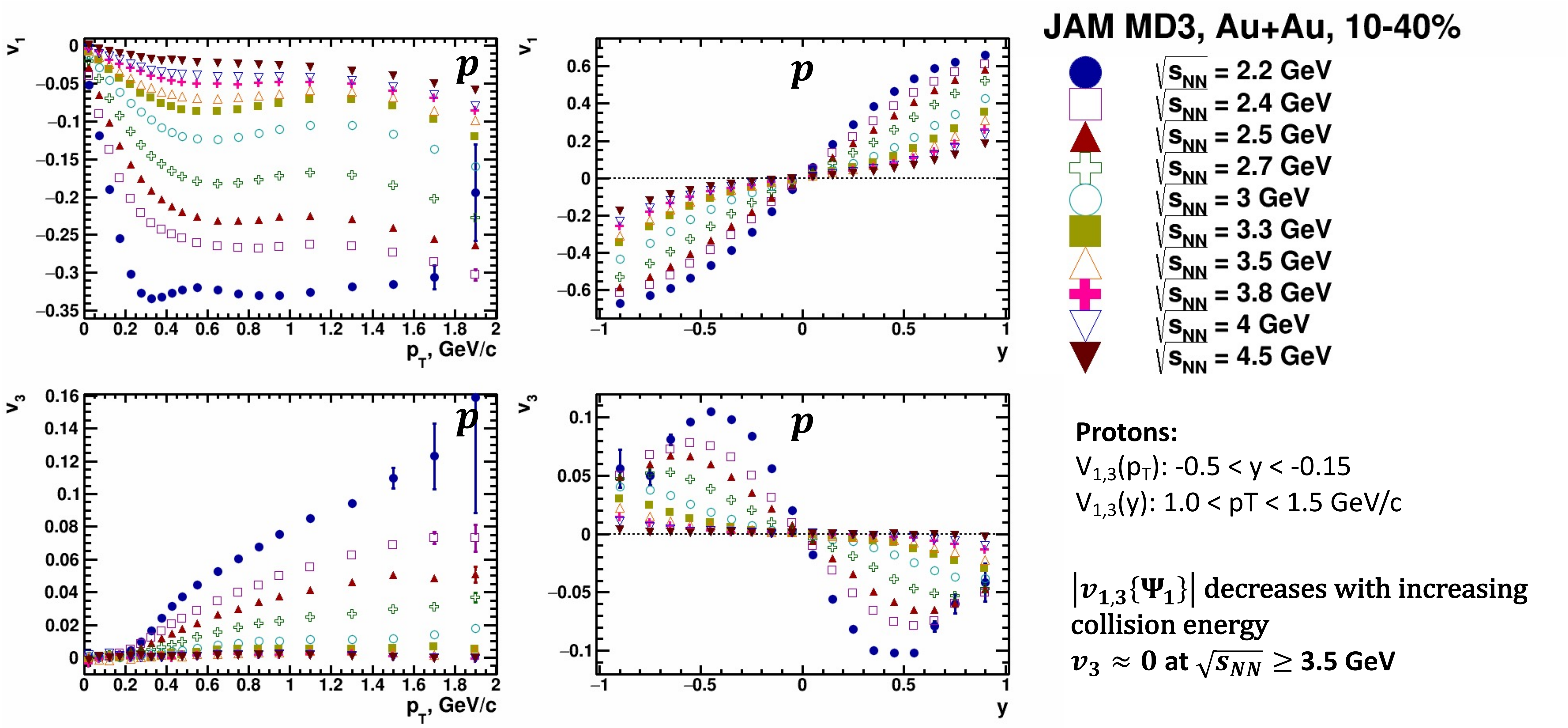


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{2,4}(p_T)$: -0.05 < y < 0.05
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Models with cascade mode cannot reproduce the experimental data

$v_{1,3}(p_T, y)$ Au+Au $\sqrt{s_{NN}}$=2.2-4.5 GeV: JAM



Protons:

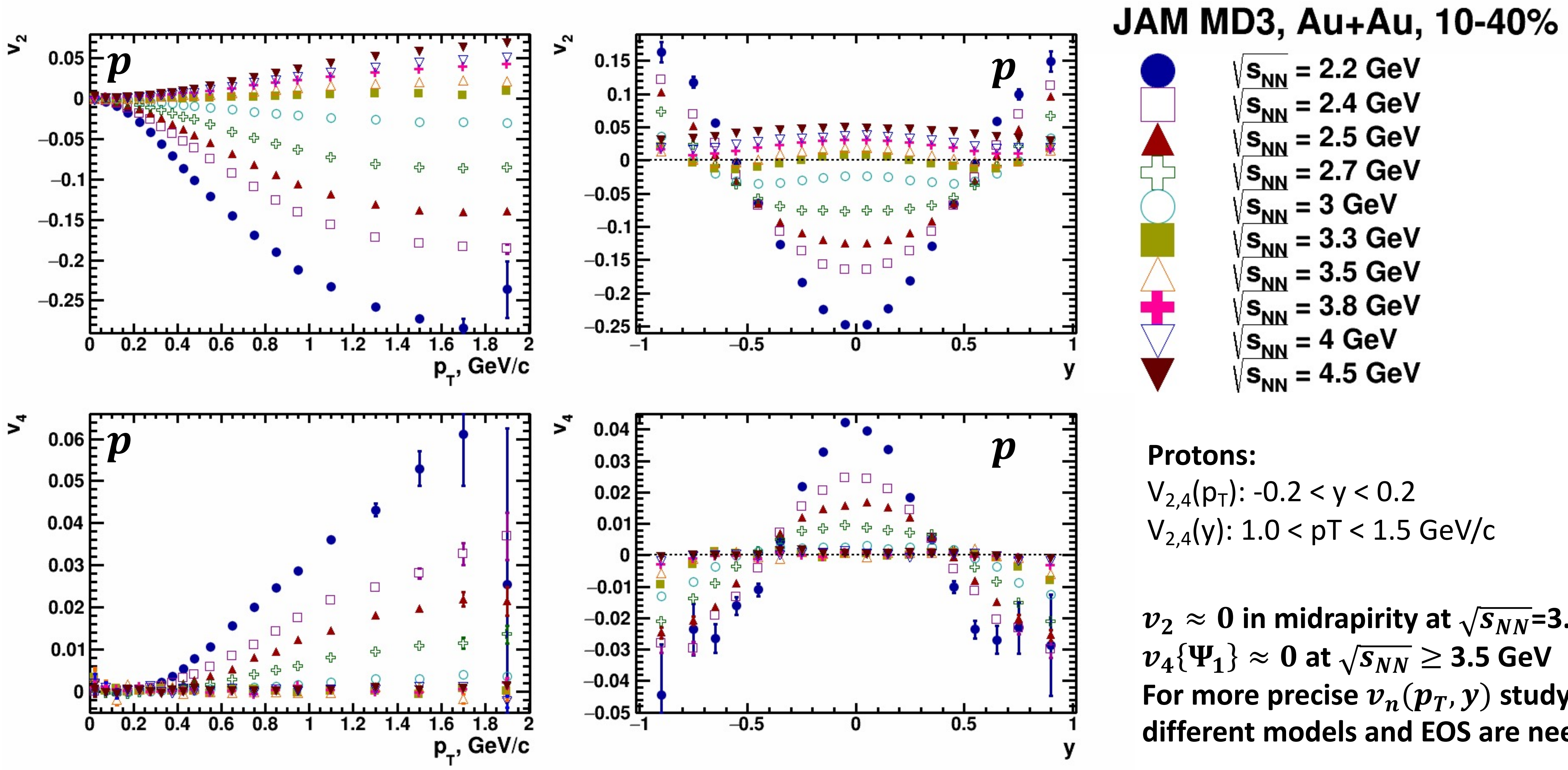
$V_{1,3}(p_T)$: -0.5 < y < -0.15

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

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

$v_3 \approx 0$ at $\sqrt{s_{NN}} \geq 3.5$ GeV

$v_{2,4}(p_T, y)$ Au+Au $\sqrt{s_{NN}}$=2.2-4.5 GeV: JAM



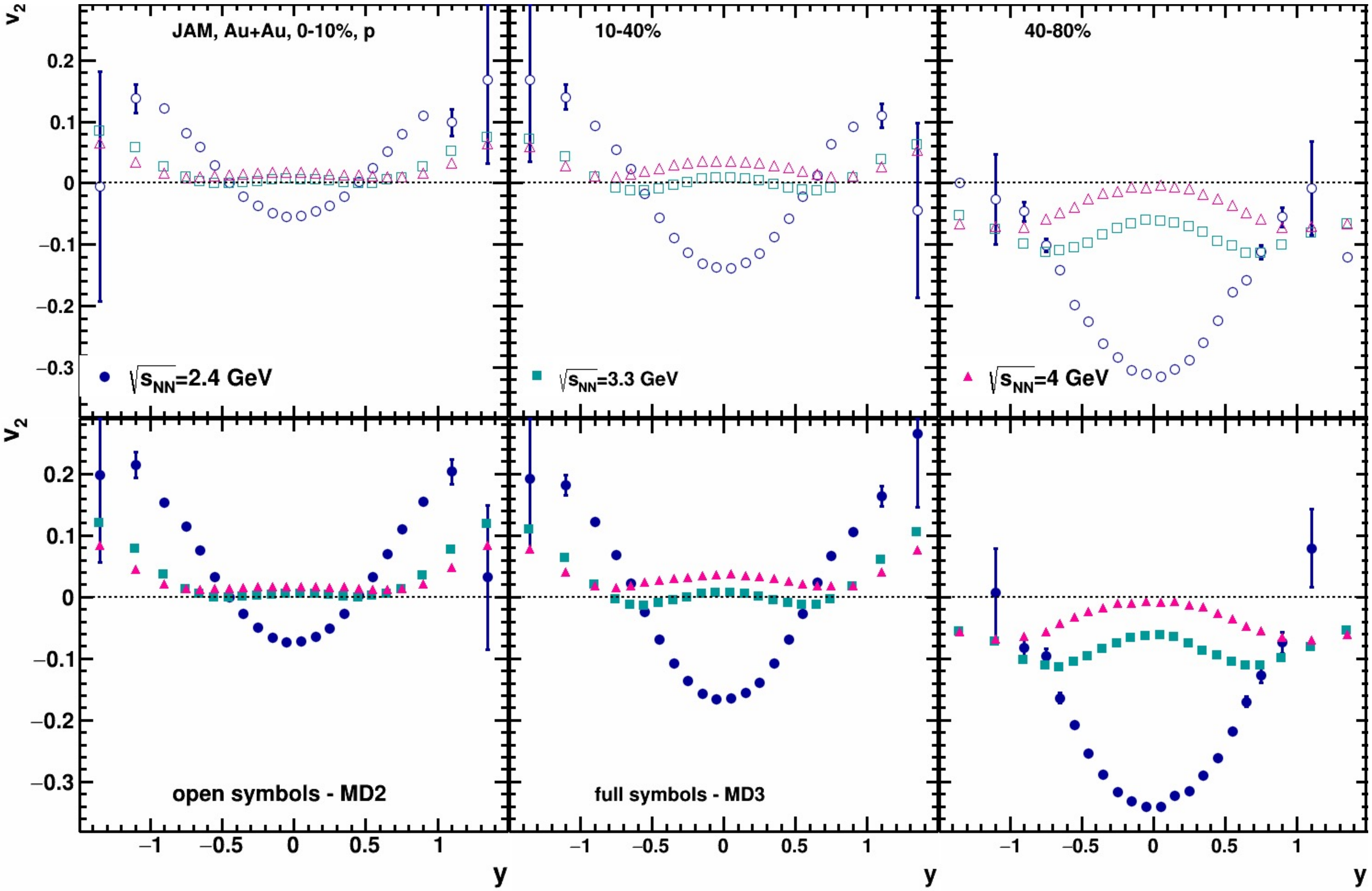
Protons:

$V_{2,4}(p_T)$: -0.2 < y < 0.2

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

$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV
$v_4\{\Psi_1\} \approx 0$ at $\sqrt{s_{NN}} \geq 3.5$ GeV
For more precise $v_n(p_T, y)$ study, different models and EOS are needed

$v_2(y)$ 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

Summary and outlook

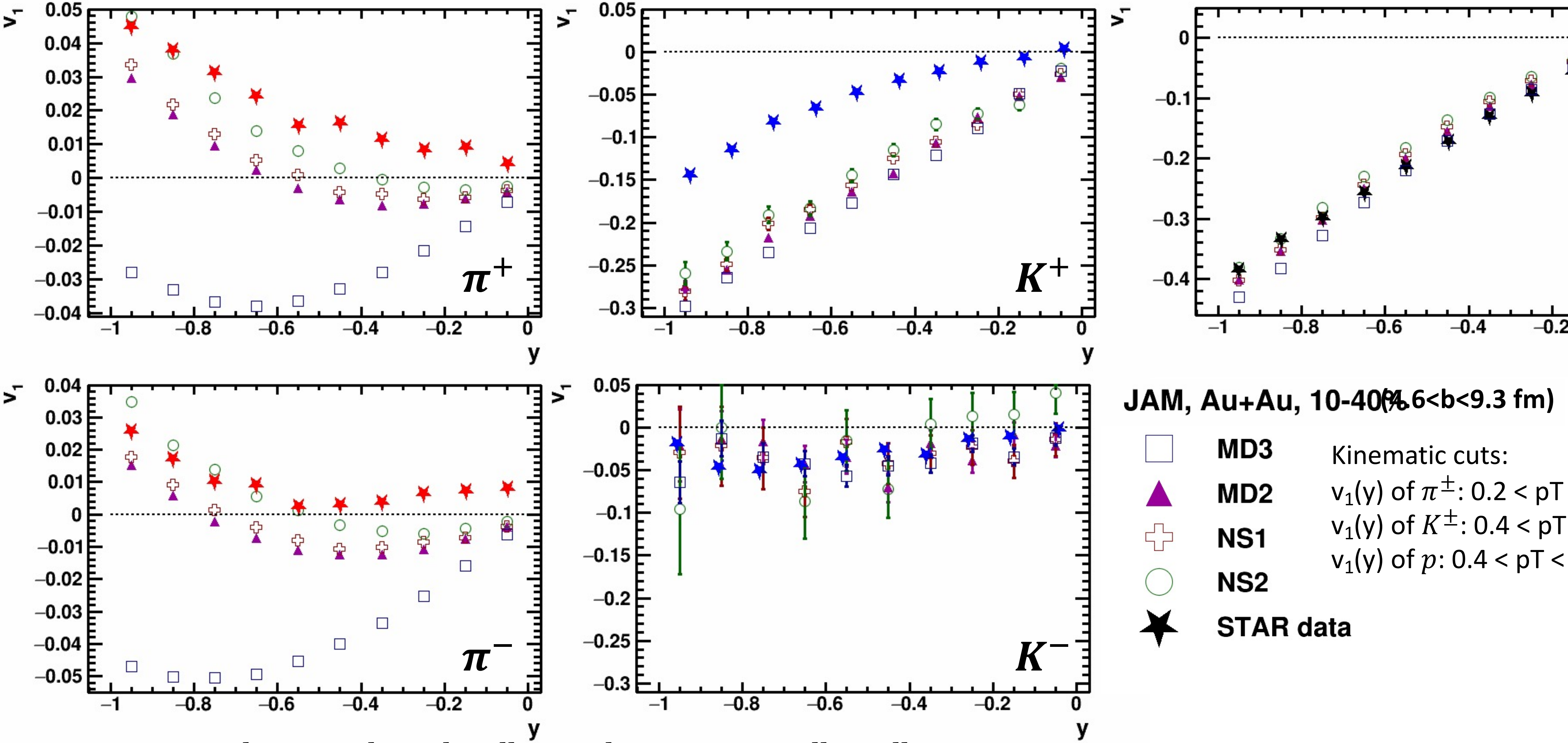
- **Anisotropic flow at $\sqrt{s_{NN}}$=4-11.5 GeV:**
  - Pure String/Hadronic Cascade models (no QGP phase) give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7-11.5 GeV
  - Models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$ =4.5 GeV
- **Comparison with STAR BES at $\sqrt{s_{NN}}$=4.5, 3 GeV and HADES at $\sqrt{s_{NN}}$=2.4 GeV:**
  - Good overall agreement with experimental data for protons for v_n
  - Models in cascade mode do not describe experimental data for v_n
  - 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 $\sqrt{s_{NN}} \geq 4$ GeV
  - $v_2(p_T, y, \sqrt{s_{NN}})$ of protons depends on centrality
- 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, detailed differential measurements with different colliding systems are needed

Thank you for your attention!

Backup slides

$v_1(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



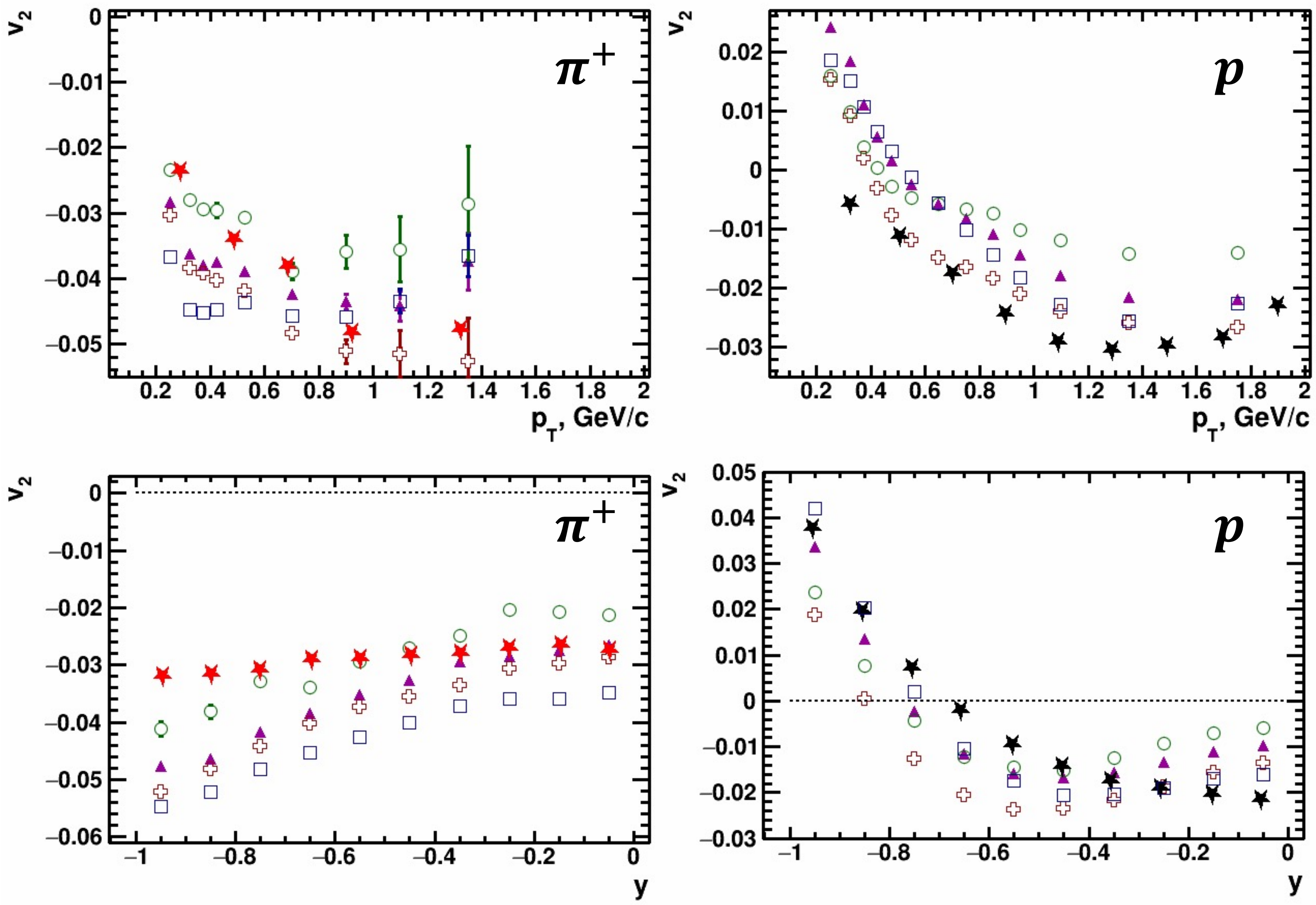
Kinematic cuts:
$v_1(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
$v_1(y)$ of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
$v_1(y)$ of p: 0.4 < pT < 2.0 GeV/c

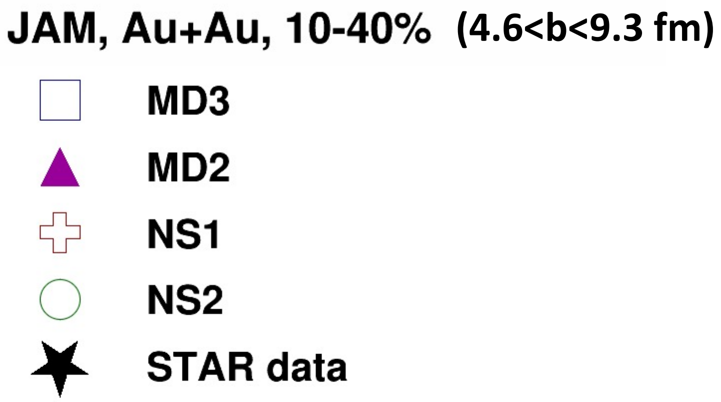
JAM does not describe all particle species equally well

v_1 of pions is most sensitive to different EOS

Experimental data points were taken from:
M. Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]

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





Experimental data points:

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

сократить

Kinematic cuts:

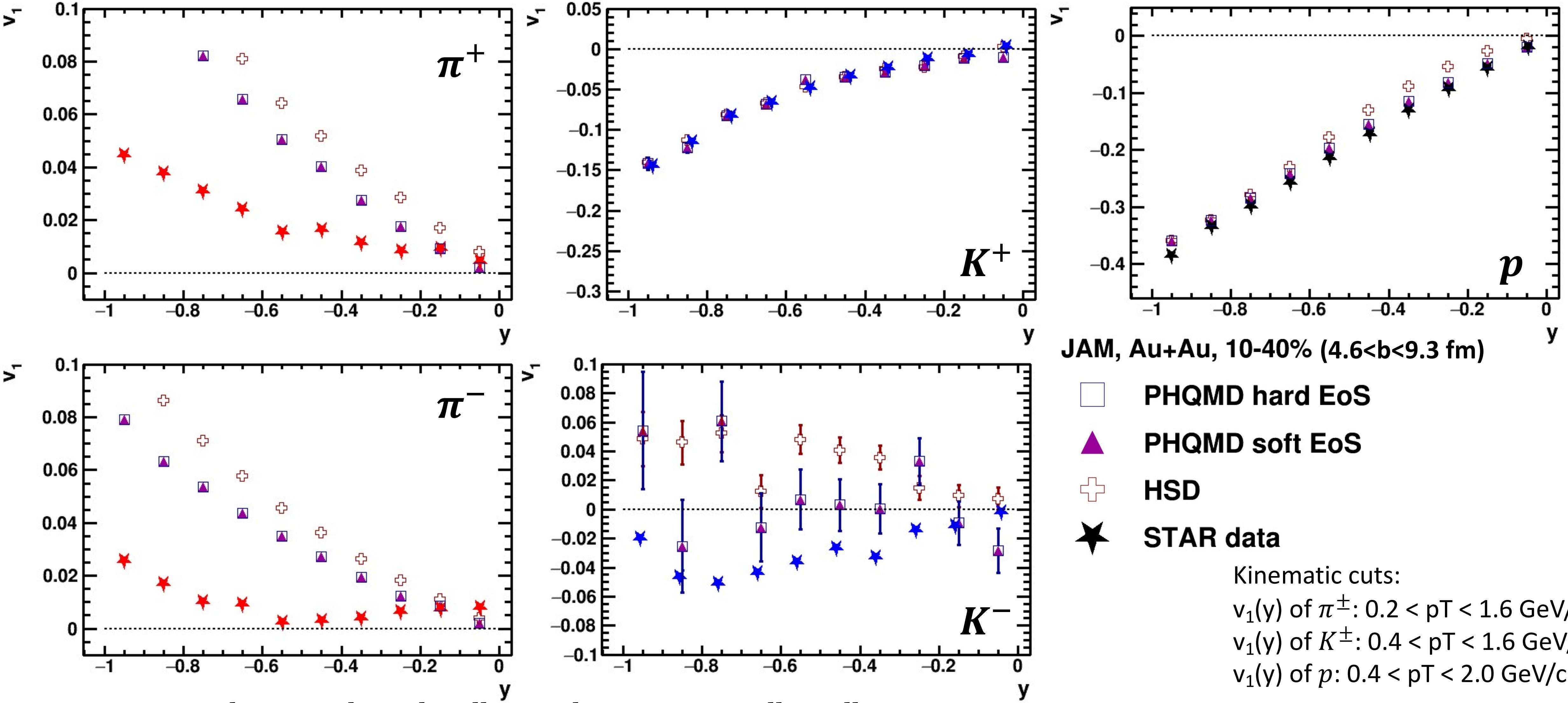
$v_2(p_T)$: -1 < y < 0

$v_2(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c

$v_2(y)$ of p: 0.4 < pT < 2.0 GeV/c

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

$v_1(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



Kinematic cuts:

$v_1(y)$ of $\pi^\pm$: 0.2 < pT < 1.6 GeV/c

$v_1(y)$ of $K^\pm$: 0.4 < pT < 1.6 GeV/c

$v_1(y)$ of p: 0.4 < pT < 2.0 GeV/c

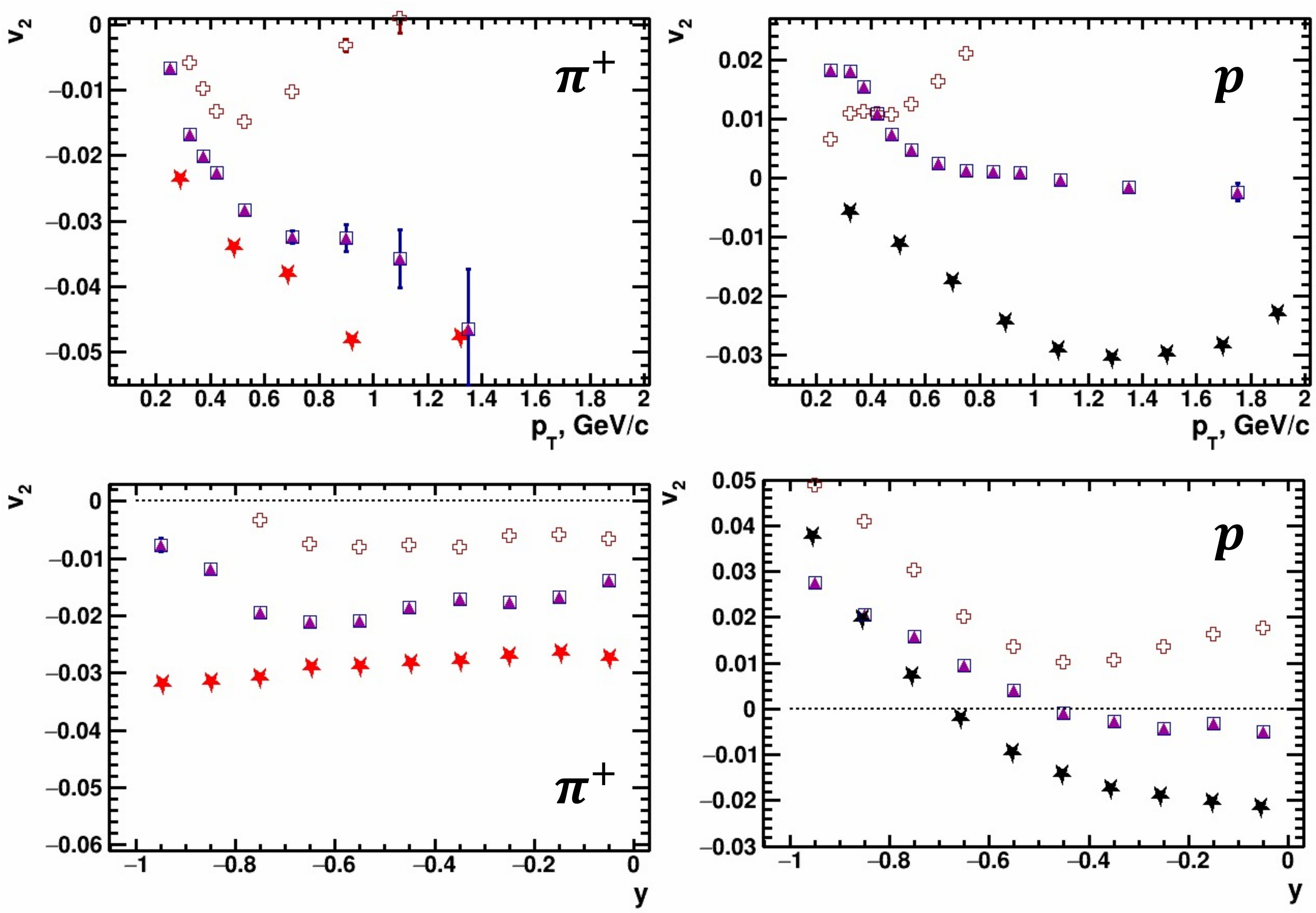
JAM does not describe all particle species equally well

v_1 of pions is most sensitive to different EOS

Experimental data points were taken from:

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

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



JAM, Au+Au, 10-40% (4.6<b<9.3 fm)

PHQMD hard EoS

PHQMD soft EoS

HSD

STAR data

Experimental data points:

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

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Kinematic cuts:

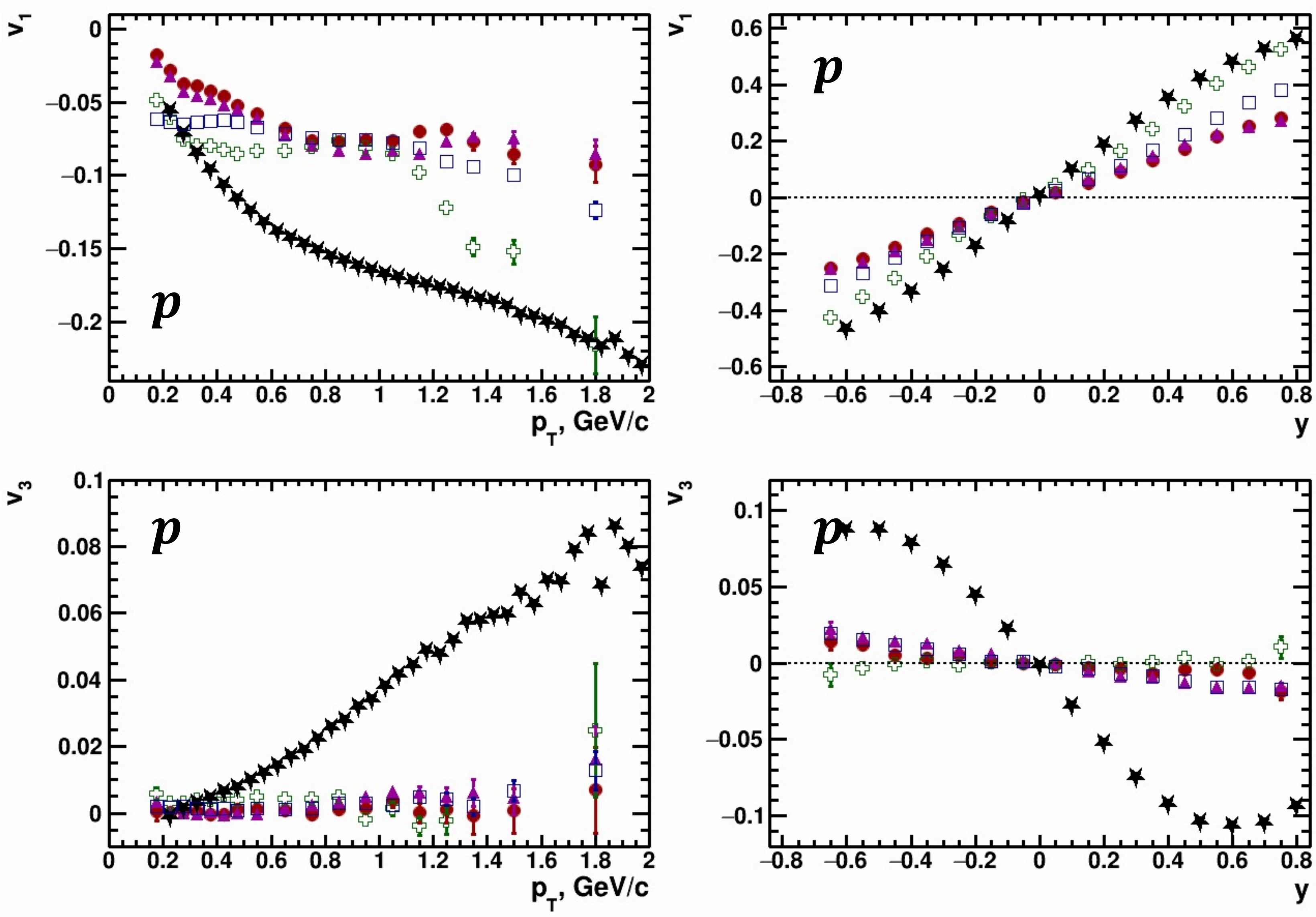
$v_2(p_T)$: -1 < y < 0

$v_2(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c

$v_2(y)$ of p: 0.4 < pT < 2.0 GeV/c

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

$v_{1,3}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models

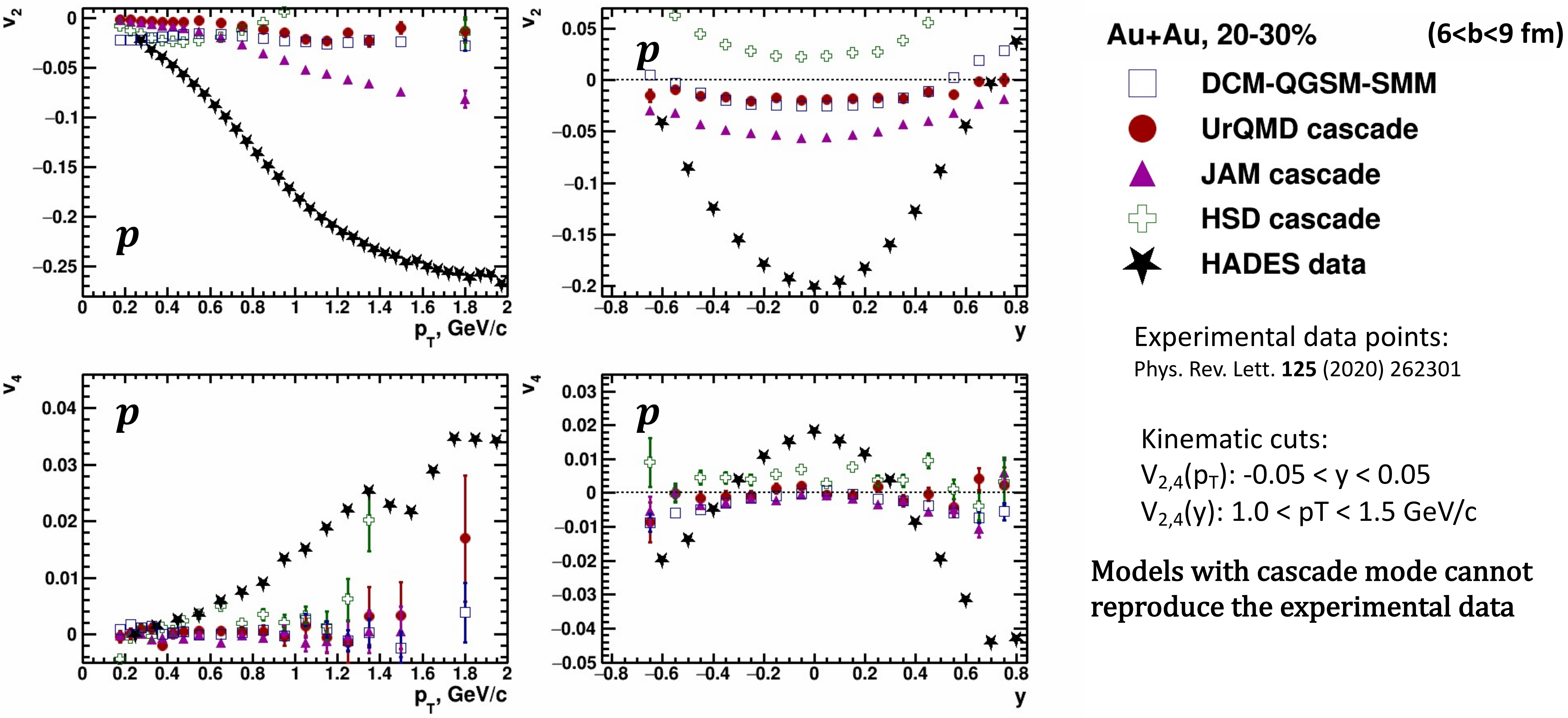


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

Models with cascade mode cannot reproduce the experimental data

$v_{2,4}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models

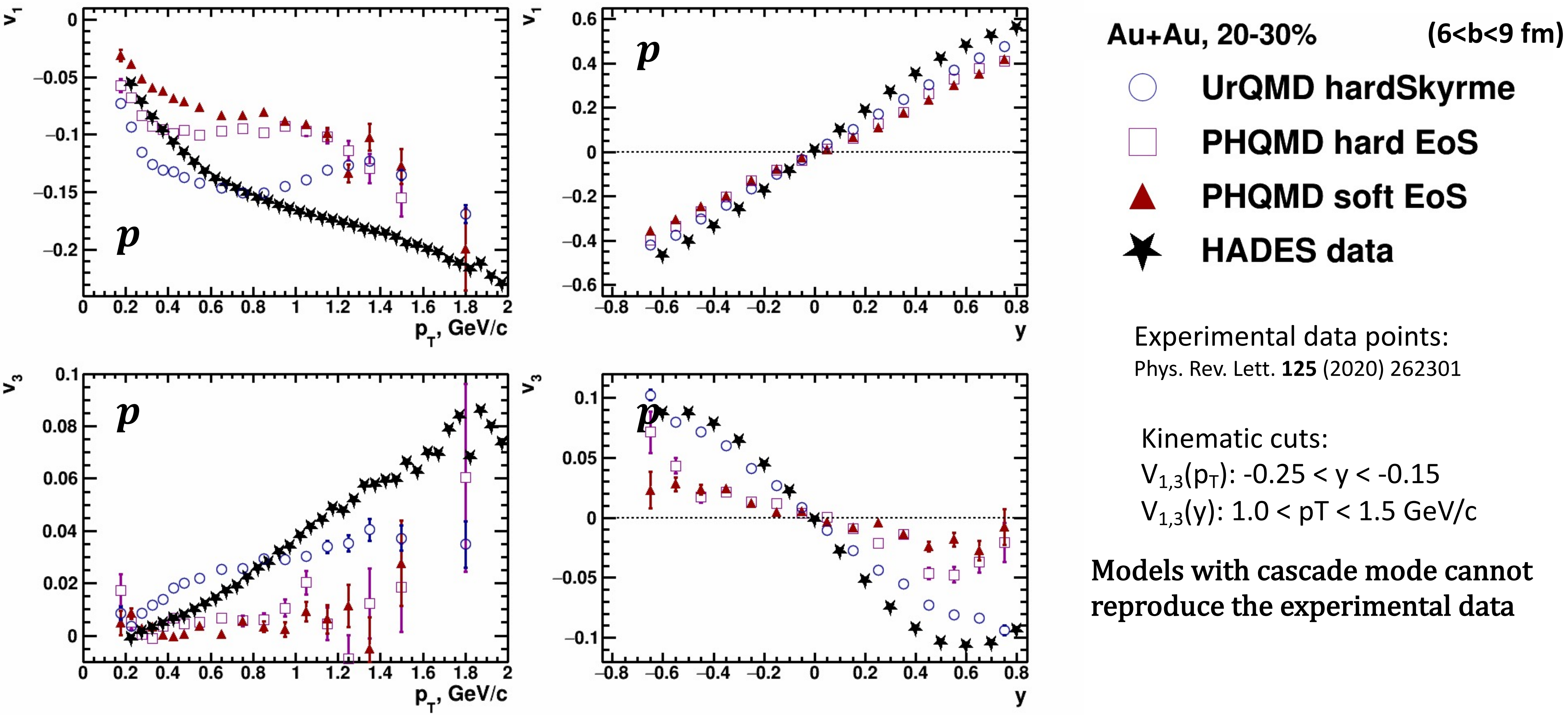


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{2,4}(p_T)$: -0.05 < y < 0.05
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Models with cascade mode cannot reproduce the experimental data

$v_{1,3}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: mean-field models



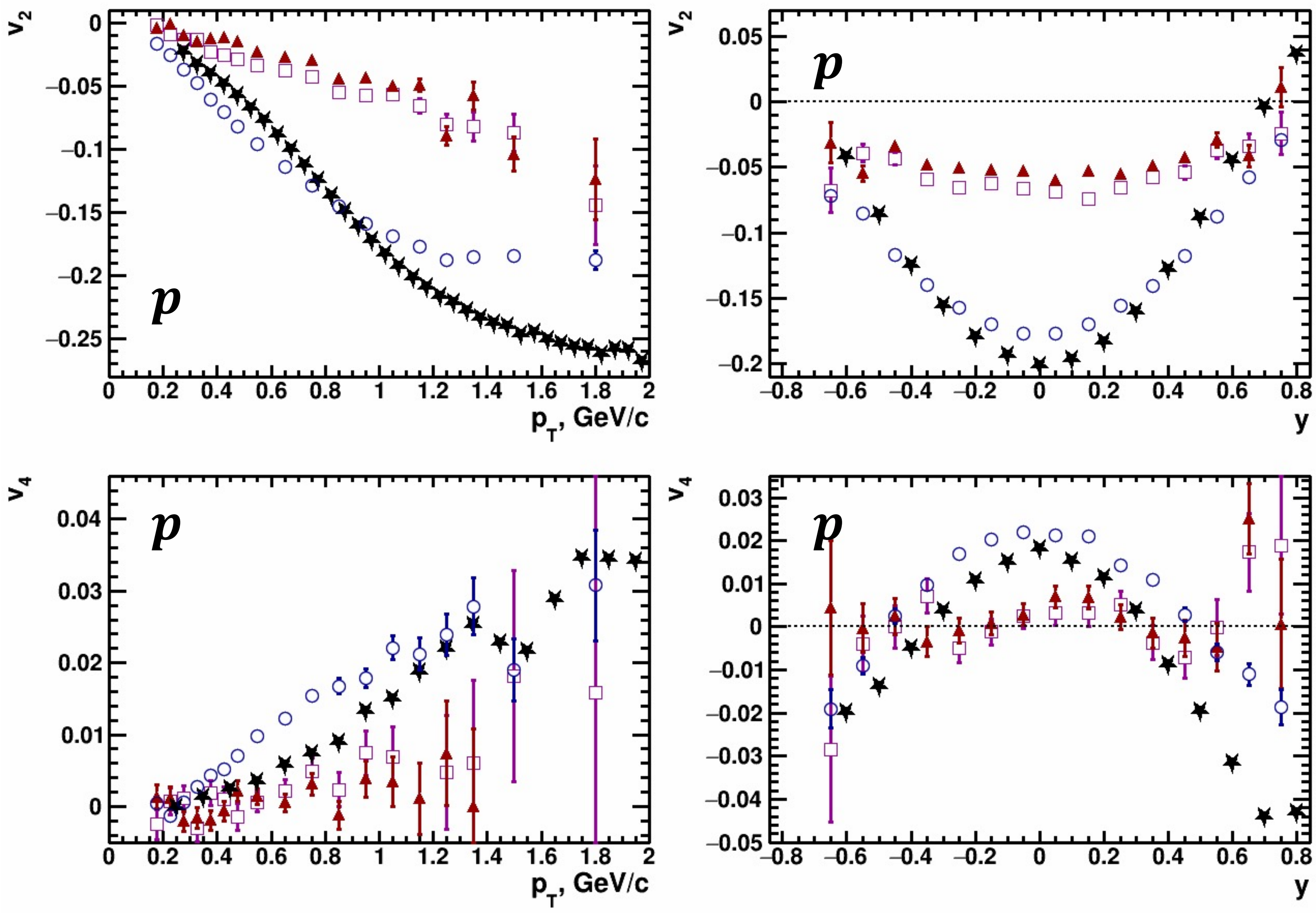
Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

Models with cascade mode cannot reproduce the experimental data

$v_{2,4}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: mean-field models

Только каскады



Au+Au, 20-30% **(6<b<9 fm)**

- UrQMD hardSkyrme
- PHQMD hard EoS
- PHQMD soft EoS
- HADES data

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

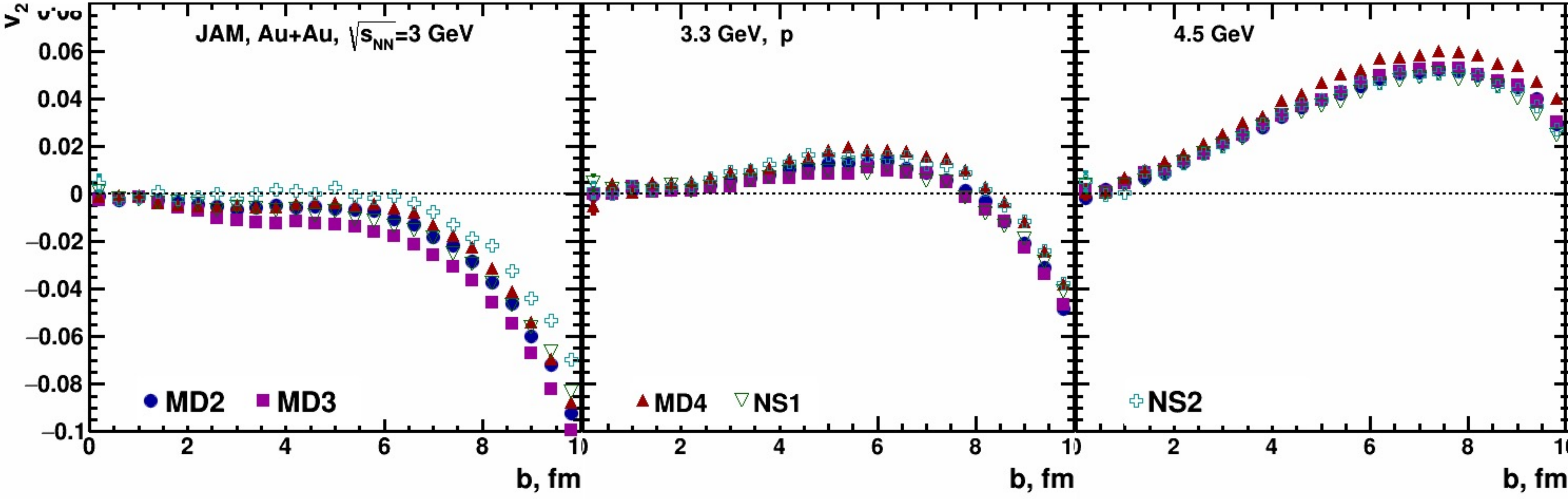
Kinematic cuts:
$V_{2,4}(p_T)$: -0.05 < y < 0.05
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Models with cascade mode cannot reproduce the experimental data

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

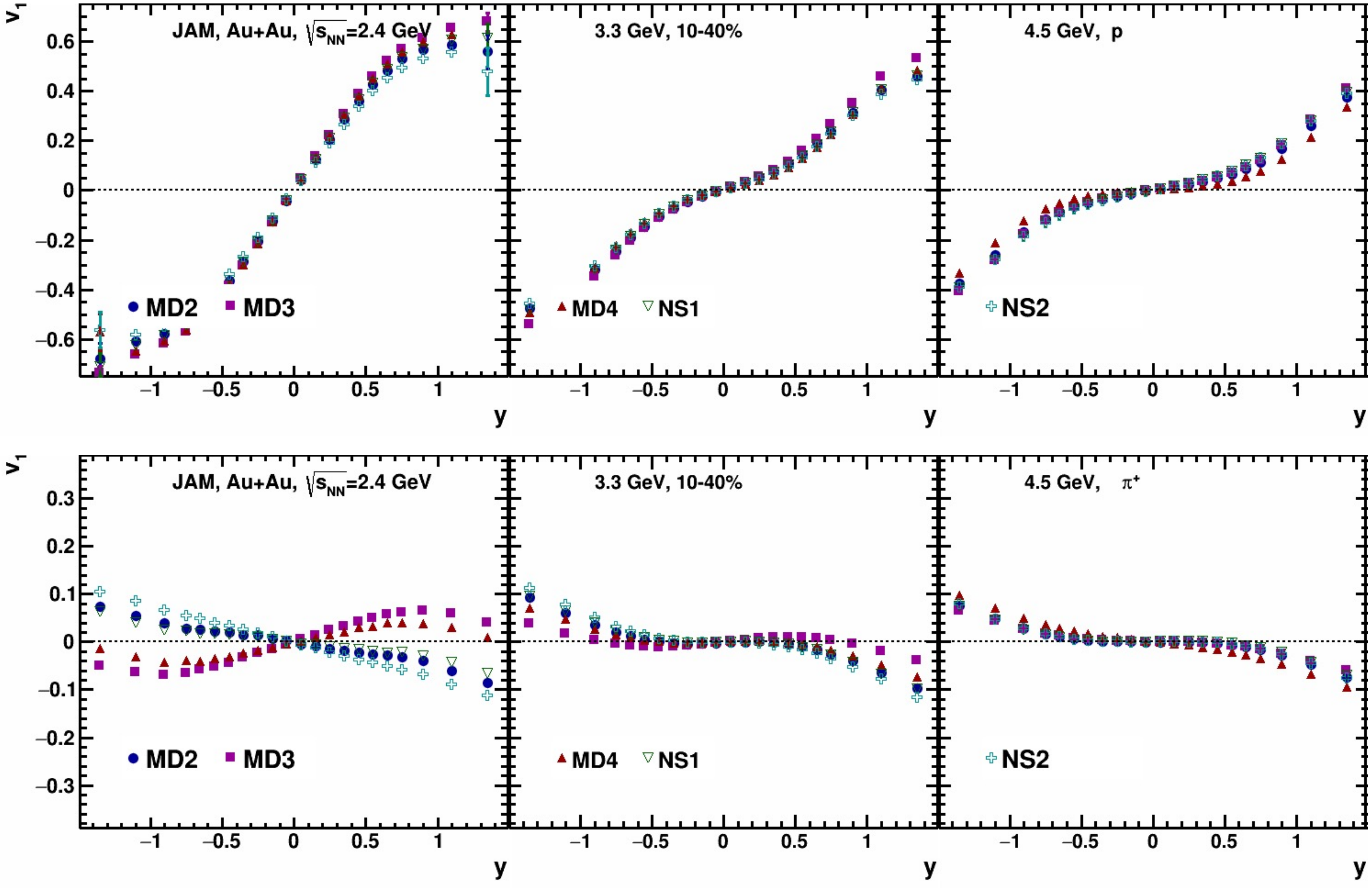
Protons:

$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c; |y|<0.2



Transition of v_2 from out-of-plane to in-plane depends on centrality and EoS

$v_1(y)$ transition from out-of-plane to in-plane



Protons:
$V_1(y)$: 1.0 < pT < 1.5 GeV/c
Pions:
$V_1(y)$: 0.2 < pT < 0.5 GeV/c

Выбрать то, что чувствительно
К EoS – найти такие переменные

- 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