Investigation of spectator-driven effects on anisotropic flow formation at the NICA energy range

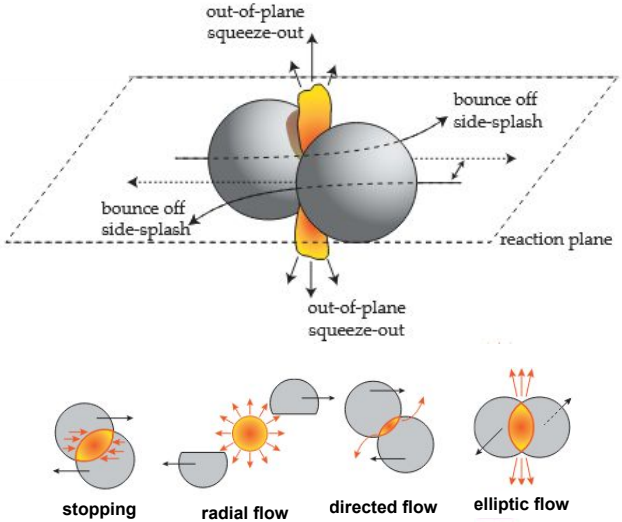
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(TPU, JINR LHEP, NRNU MEPhI)

The work has been supported by the Ministry of Science and Higher Education of the Russian Federation, Project **"Fundamental and applied research at the NICA (JINR) megascience experimental complex"** № FSWU-2025-0014

28.10.2026

Anisotropic flow

- Flow describes **anisotropy** in particle emission;
- Sensitive to early **pressure gradients** and **Equation of State (EoS)**



The anisotropic flow is **quantified as**:

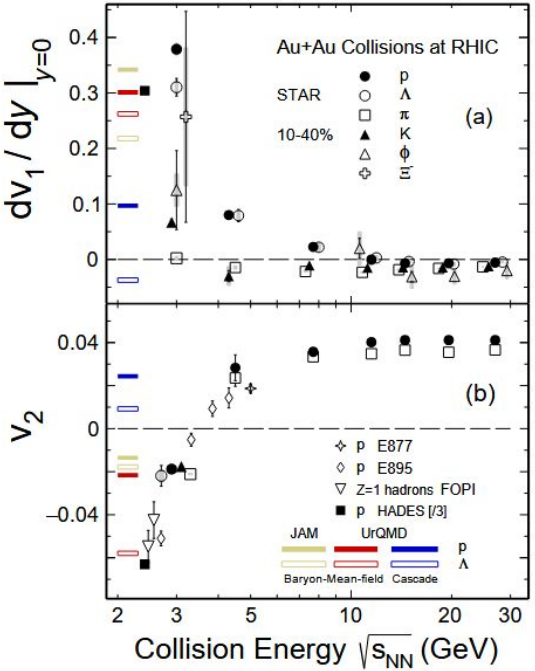
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]$$

Extraction of **azimuthal moments v_n**:

$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

Poskanzer & Voloshin, Phys. Rev. C 58, 1671 (1998)

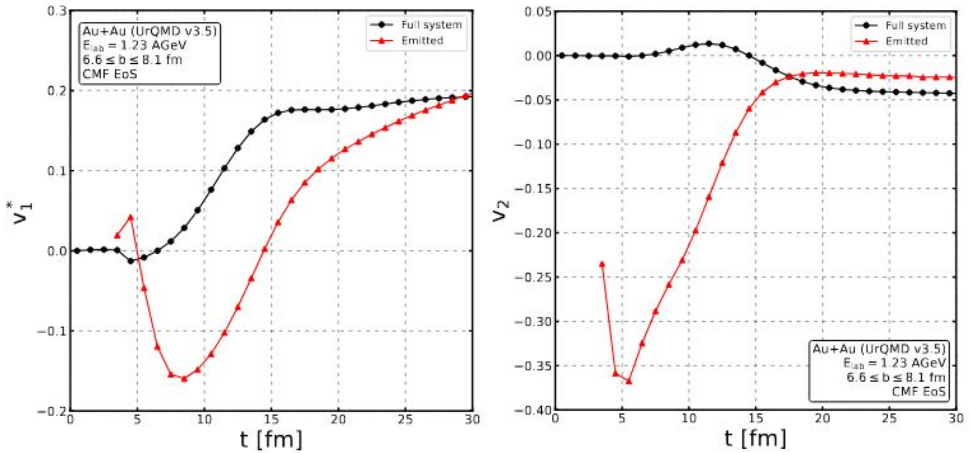
STAR Collaboration, Phys. Lett. B 827 (2022) 137003.



At NICA energies (**2 ÷ 11 GeV**), both **v_1** and **v_2 change strongly** with √sNN

System evolution and spectators influence at low $\sqrt{s_{NN}}$

- v_1 and v_2 **evolve rapidly** with time → complex behavior due to **spectator effects**;
- Different behavior for harmonics is observed for system evolution;



Reichert, T., et al., Phys. Lett. B 841 (2023) 137947.

It is interesting to investigate **the spectator-driven** effect on the formation of anisotropic flow:
1) For further EoS constraints;
2) Distinguishing spectator effects from other parameters.

JAM1 transport model

- Microscopic **QMD type** event-by-event transport model for relativistic heavy-ion collisions;
- In the baseline **cascade picture**, hadrons propagate between independent binary collisions;
- Inelastic scatterings excite resonances or strings; decay products can rescatter until freeze-out;
- Provides **wide variety** of options for customizing the simulation.

Main properties:

- Programming language: **Fortran77**;
- Relativistic potential: Yes;
- Potential options:
  1) Mean field;
  2) Sum of nucleon potentials;
  3) Electromagnetic potential;
  4) Momentum-dependent potential;
- Creation of **clusters**: At the **end** of the **simulation**;
- Description of **soft QCD** region: **Pythia**
- Wide range of **options** for **analysis** (turning spectators on/off; phase space in timesteps e.t.c.)

Download + Installation: [GutHub] (JAM1v9)

JAM1v9 Manual: [PDF]

Currently unsupported!



JAM2 transport model

- Download + Installation: [GitLab] (JAM2)
- Short manual (txt): [GitLab] (Manual.txt)

Main changes:

- **Fortran77 -> C++**;
- Pythia6 -> **Pythia8**;
- Inclusion of **new data** + **mean-field update** at √sNN = 2 – 20 GeV;
- **Speeding up** the computational time by introducing **expanding box** for collision term and potential evaluation;
- Main publications:
  - RQMD.RMF approach: Y.Nara, Physical Review C 100, 054902 (2019);
  - Momentum-dependent potential: Y. Nara, arXiv:2004.05550v2 (2020);
  - Mean-Field update: Y.Nara & A.Ohnishi, arXiv:2109.07594v3 (2022);

MC Production 41

Dataset:

- Model: JAM v2
- Equation of state:
  - **Skyrme potential** (RMF);
  - Momentum-Dependent: **MD2**;
- Collision systems:
  1) Xe+Xe; 2) Ag+Ag; 3) Au+Au; 4) U+U;
- Spectators: on/off for each case of energy and collision system;
- Energy: $\sqrt{s_{NN}}$ = 2.4 ÷ 4.5 GeV;
- Statistics per energy: ~30M

Event selection:

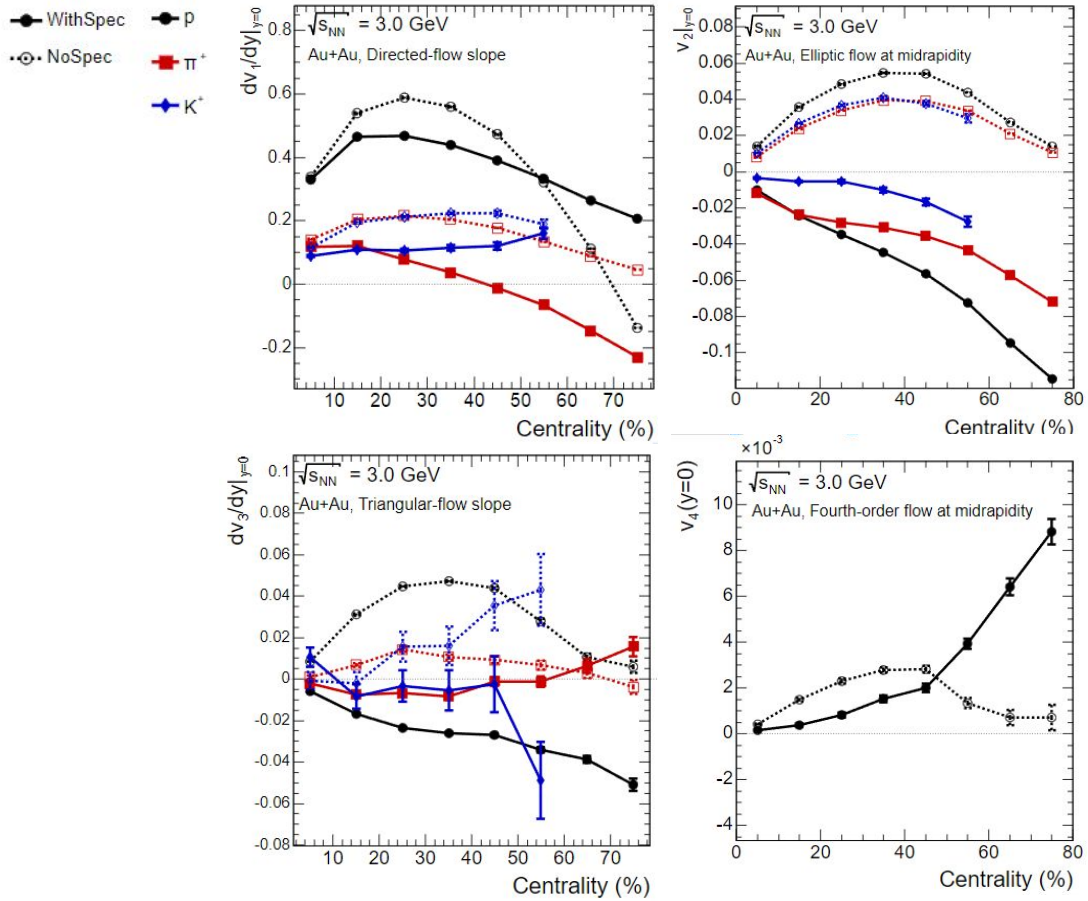
- Multiplicity-based centrality

Particle selection:

- Protons, pions, kaons (pdg cut)
- $|y| < 0.5$
  - Protons: $0.4 < p_T < 2.0$ GeV/c;
  - Pions: $0.2 < p_T < 1.6$ GeV/c;
  - Kaons: $0.4 < p_T < 2.0$ GeV/c

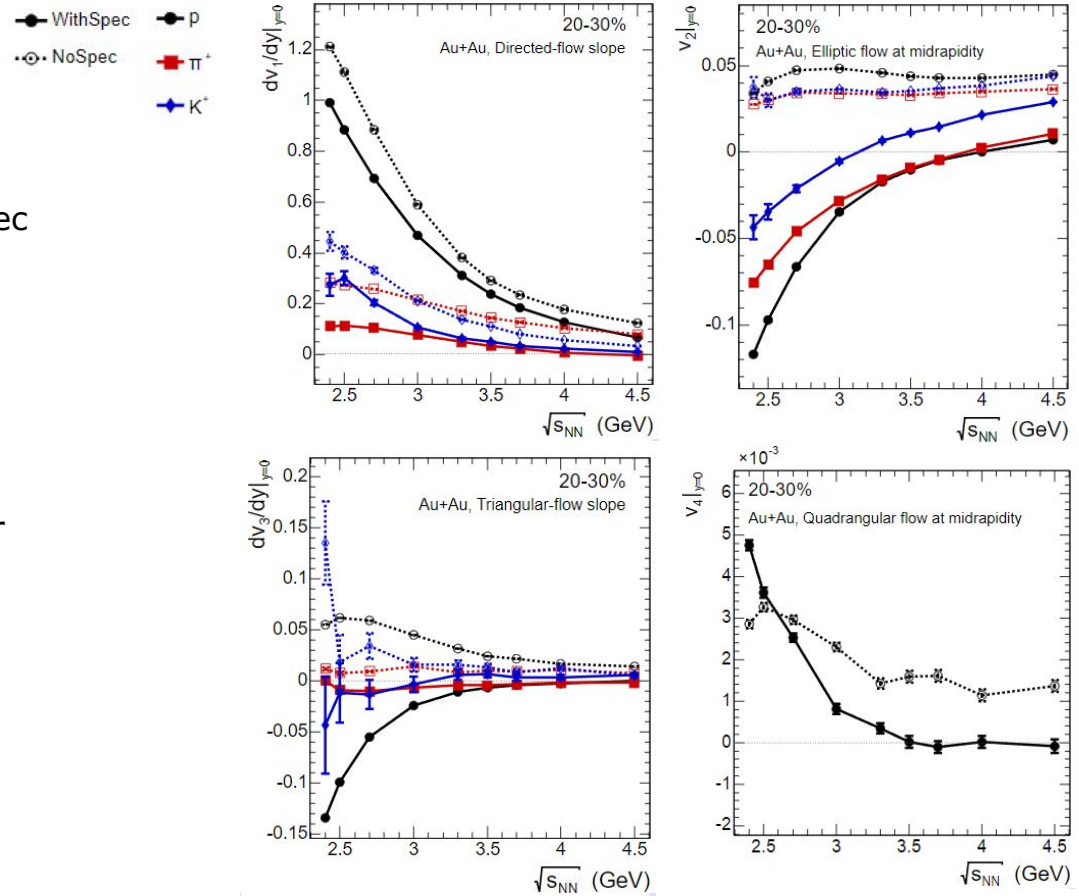
Centrality dependence

- Energy of **3.0 GeV** is chosen since:
  - Still **strong influence** of spectators;
  - **Higher statistics** for pions and kaons;
- Results for π^+ and π^- are similar -> shown for π^+;
- Results for K^- do not have enough statistics… -> shown for K^+
- Most difference is observed for **semi-central** and **peripheral** collisions of **heavy nuclei** -> Choosing **20-30%**
- v_3 slope and $v_2|_{y=0}$ without spectators **changes sign**
- For $v_4|_{y=0}$ only **protons** have enough statistics;
- Generally **stronger difference** for **protons** between WithSpec/NoSpec



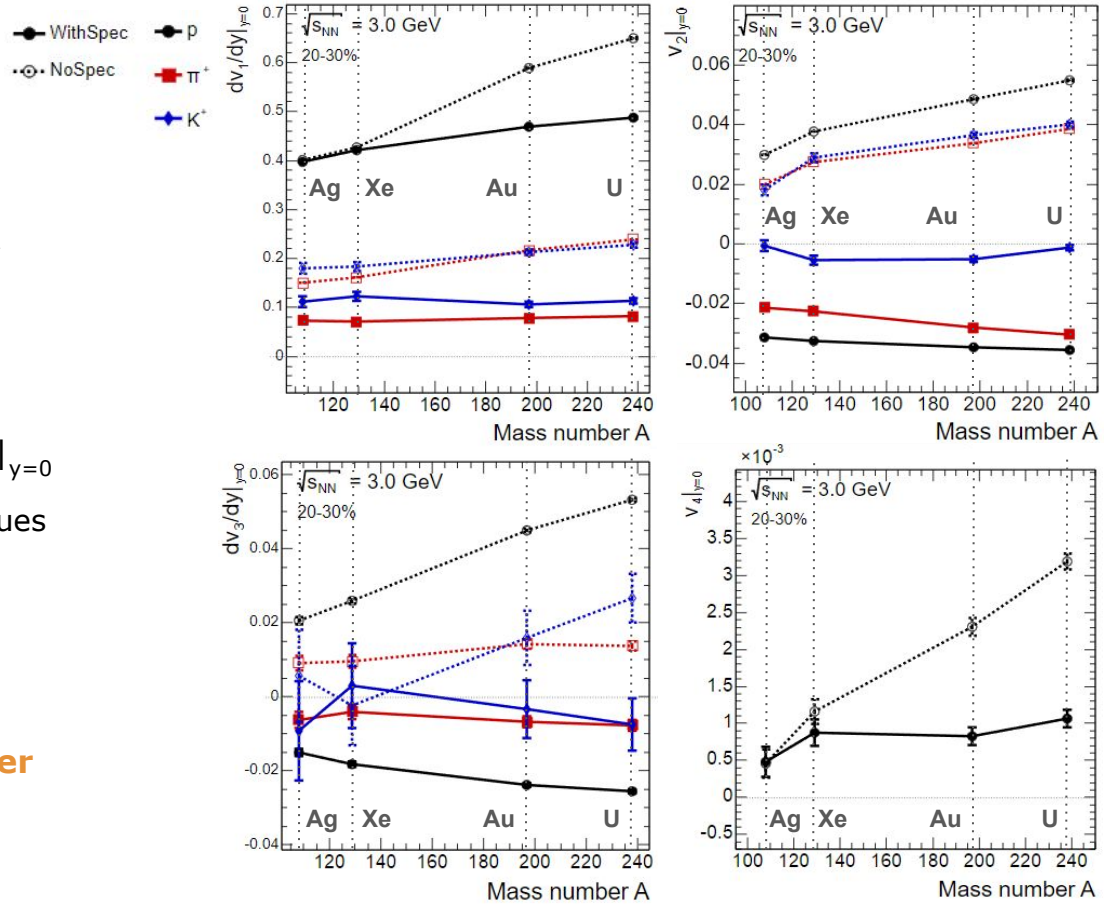
Energy dependence

- With **increase** of collision **energy** all anisotropic flows becomes **weaker**;
- For $dv_1/dy|_{y=0}$, $v_2|_{y=0}$ and $dv_3/dy|_{y=0}$ the higher difference between WithSpec/NoSpec is observed for **lower** collision **energies**;
- $v_2|_{y=0}$ and $dv_3/dy|_{y=0}$ **without spectators barely changes** with collision energy;
- Highest difference between WithSpec/NoSpec for $v_4|_{y=0}$ is observed for **higher collision energies**



System size dependence

- Difference of $dv_1/dy|_{y=0}$ between WithSpec/NoSpec **increases** for **heavier systems** for **protons**;
  - ↳ Not so much for **π⁺** and **K⁺**:
    - Slight increase without spectators;
    - Almost no change with spectators.
- WithSpec/NoSpec difference for $v_2|_{y=0}$ **changes** for **all** selected particle **types**;
- **Similar behaviour** is observed for $dv_3/dy|_{y=0}$
  - ↳ For **K⁺** for Xe+Xe collisions the values seems strange (probably not enough statistics…)
- WithSpec/NoSpec difference for $v_4|_{y=0}$ **changes strongly** with **system size**;
- All flow harmonics are significantly **stronger** for results **without spectators**.



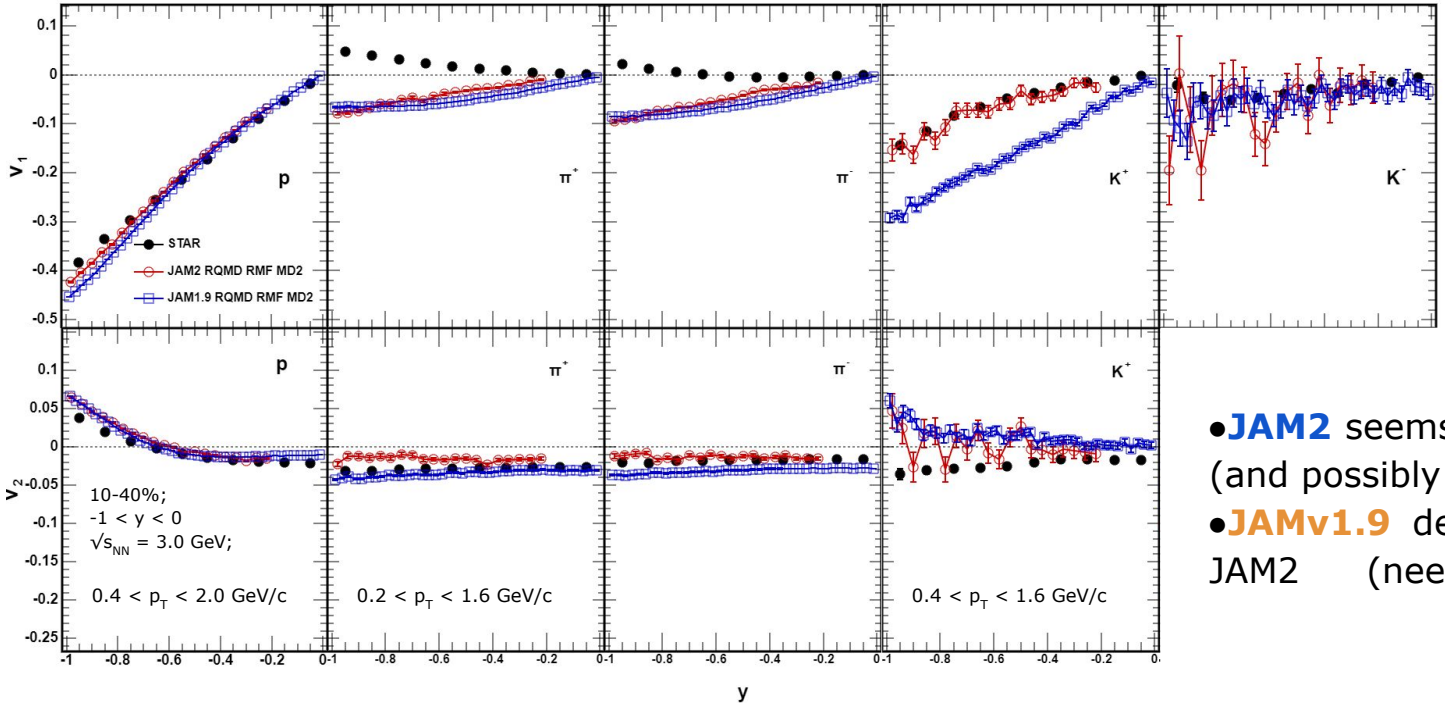
Summary

We studied spectator effects on anisotropic flow in Ag+Ag, Xe+Xe, Au+Au and U+U collisions at $\sqrt{s_{NN}}$ = 2.4–4.5 GeV using JAM2:

- Spectators strongly modify proton, pion and kaon flow, with pronounced effects in midcentral and peripheral collisions.
- Removing spectators changes the sign of midrapidity v_2 and the proton dv_3/dy slope at $\sqrt{s_{NN}}$ = 3.0 GeV.
- Spectator effects on dv_1/dy, v_2 and dv_3/dy generally decrease with increasing collision energy.
- Differences between calculations with and without spectators generally grow with system size, especially for protons.
- Proton v_4 remains sensitive to spectators across the studied energy range and shows a different energy dependence.

Back Up slides

Comparison with STAR data at 3.0 GeV



STAR Collaboration, arXiv:2108.00908 (2022)

- **Both** JAM versions describes $v_1(y)$ and $v_2(y)$ well for **protons**;
- **Both** JAM versions **fail** to describe $v_1(y)$ for **$\pi^{\pm}$** but describe $v_2(y)$;

- **JAM2** seems to **describe well** $v_1(y)$ (and possibly $v_2(y)$?) for **K^+**;
- **JAMv1.9** describes **K^- better** than JAM2 (need more statistics?)

Comparison with HADES data at $\sqrt{s_{NN}}$ = 2.4 GeV

Dataset:

- Model: JAM2
- Collision system: Au+Au
- Energy: $\sqrt{s_{NN}}$ = 2.4 GeV
- Statistics: ~800k

1) **Potential**: RQMD.RMF (relativistic mean field Skyrme)
   EoS: **MD2** (K = 380 MeV);
2) **Potential**: RQMDv2 (vector Skyrme)
   EoS: **MH2** (K = 380 MeV);

Event selection:

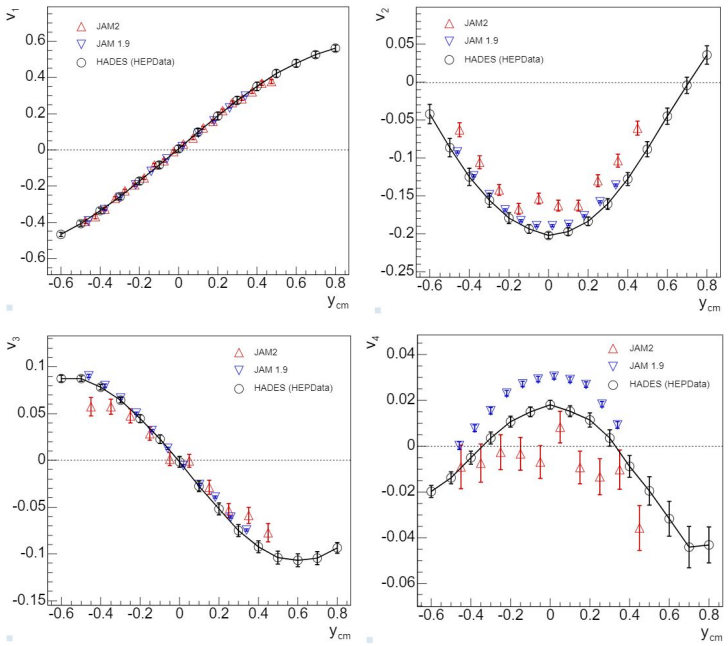
- Impact parameter based centrality

Particle selection:

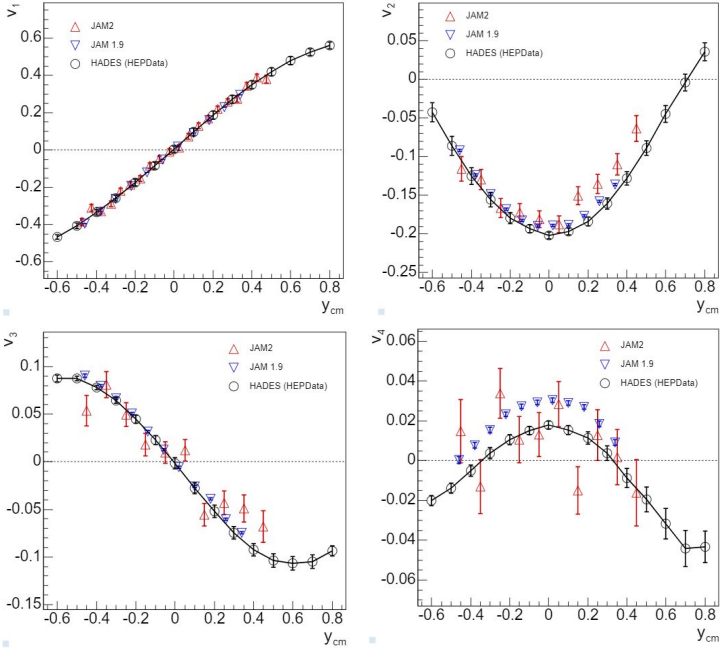
- Protons (pdg cut)
- $|y| < 0.5$
- $pT > 0.5$ GeV/c

$v_1(y)$ and $v_2(y)$

RQMDv2 with MH2



RQMD.RMF with MD2



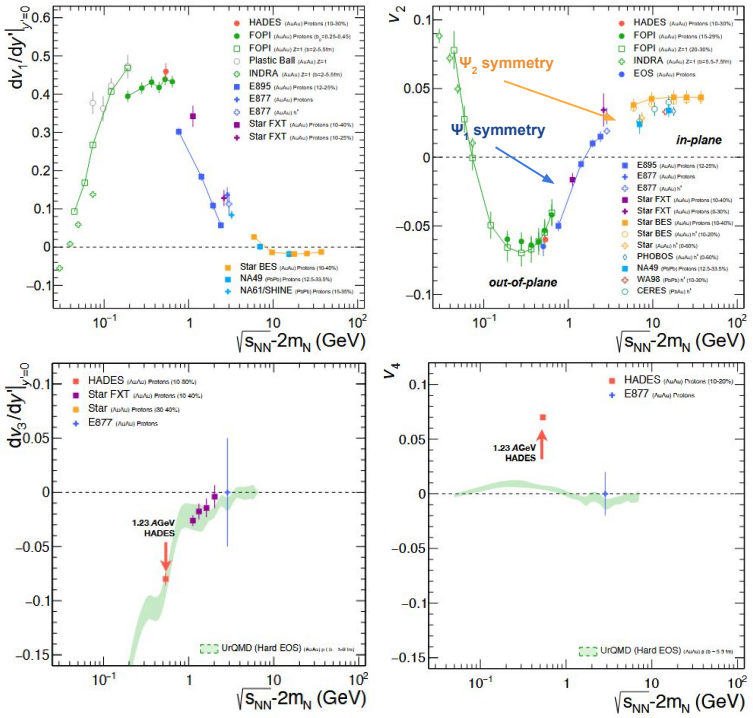
- **JAM2** describes $v_2(y)$ and $v_3(y)$ **worse** than **JAMv1.9** (tune parameters more precisely?);
- There is a possibility that JAM2 provides **better description** of $v_4(y)$ (need more statistics);
- $v_1(y)$ is in agreement with **both** versions;

HADES results on anisotropic flow correlations

B. Kardan, EMMI EOS Workshop II (2024).(URL)

HADES results:

- Provides results for **high order** flow harmonics (v_3, v_4);
- Show high sensitivity to EoS of **higher flow harmonics**;
- Transition of v_2 from **out-of-plane** to **in-plane** emission;
- Provide an insight on flow harmonics being **originated from v_2 (?)** Reichert, T., & Aichelin, J. arXiv:2411.12908 (2024)

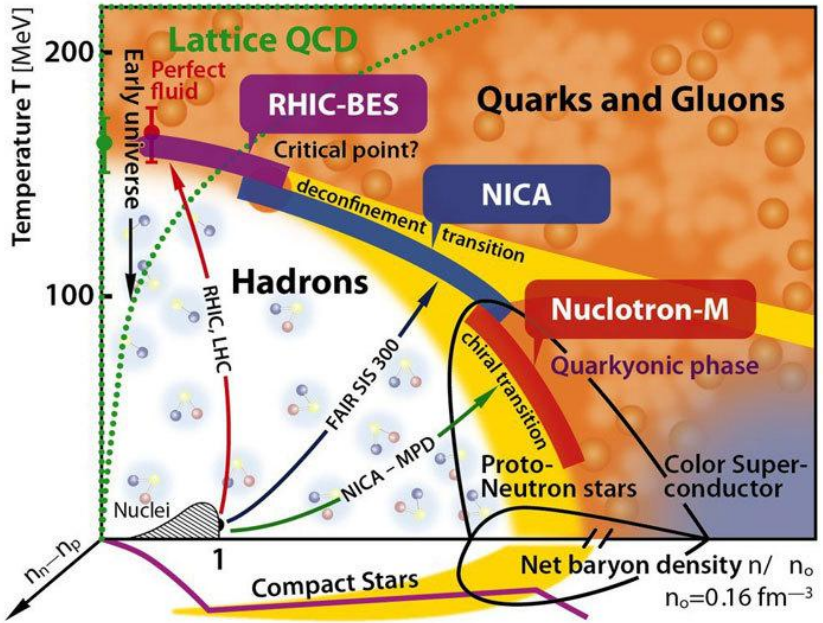


HADES, Eur. Phys. J. A 59, 80 (2023).

Relativistic heavy-ion collisions

- **The Goal:** Explore the high baryon density region of the QCD phase diagram to search for **first-order phase transition** and the **Critical Point (CEP)**.
- MPD experiments at NICA will collide heavy ions at center-of-mass energies $\sqrt{s_{NN}}$ = **2.4 – 11.5 GeV**.
  - This fills the gap between beam energy scans.

- **Low beam energies:**
  - Intermediate temperature (T);
  - **High net-baryon density**;
  - Analogous to the conditions found in the inner structure of neutron stars and neutron star mergers.

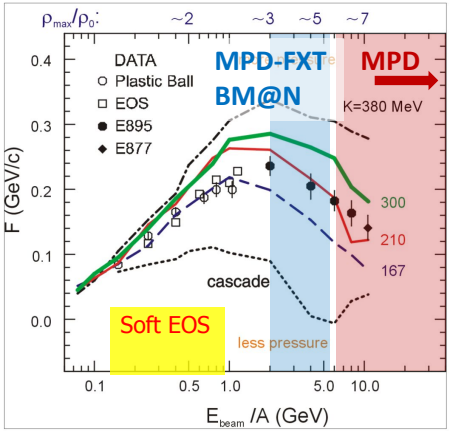


Sensitivity of anisotropic flow to the Equation of State (EoS)

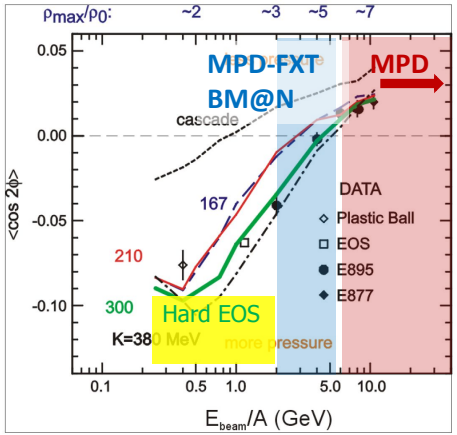
- **Anisotropic flow** is a **sensitive probe** of the pressure gradient built up in the **early, high-density** stage of the collision.
  - Stronger flow = Stiffer EoS (higher pressure)
  - Weaker flow = Softer EoS (lower pressure)
- The discrepancy in the interpretation:
  - Directed flow **v_1 suggests a soft EoS** ($K_0 \approx 210$ MeV).
  - Elliptic flow **v_2 suggests a stiff EoS** ($K_0 \approx 380$ MeV).

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

Directed flow v_1



Elliptic flow v_2



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

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

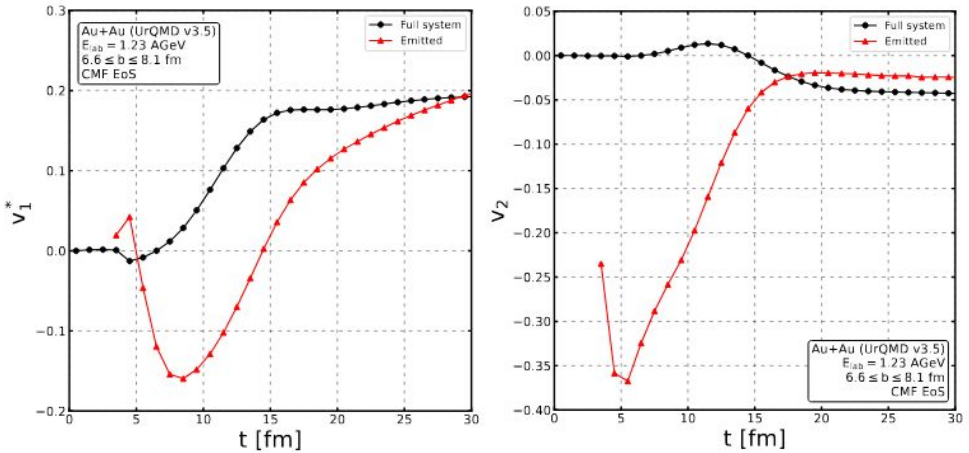
Nuclear incompressibility:

$$K_0 = 9\rho_0^2 \left.\frac{\partial^2(E/A)}{\partial\rho^2}\right|_{\rho=\rho_0}$$

HADES results on anisotropic flow correlations

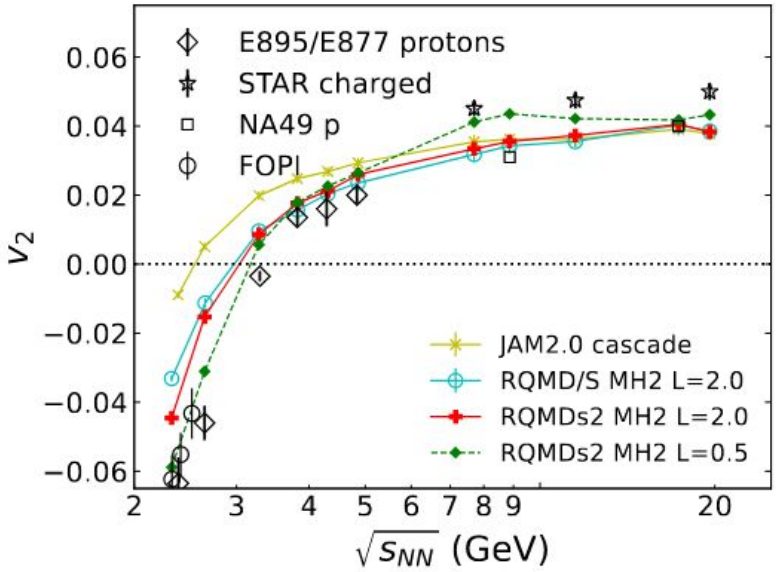
- v_1 and v_2 **evolve rapidly** with time → complex behavior (possibly due to **spectator effects**);
- Correlations (v_n – v_2) formed at **early stage** → **more robust** to late dynamics
- Harmonic flow correlations may allow for more **precise EoS extraction** from data

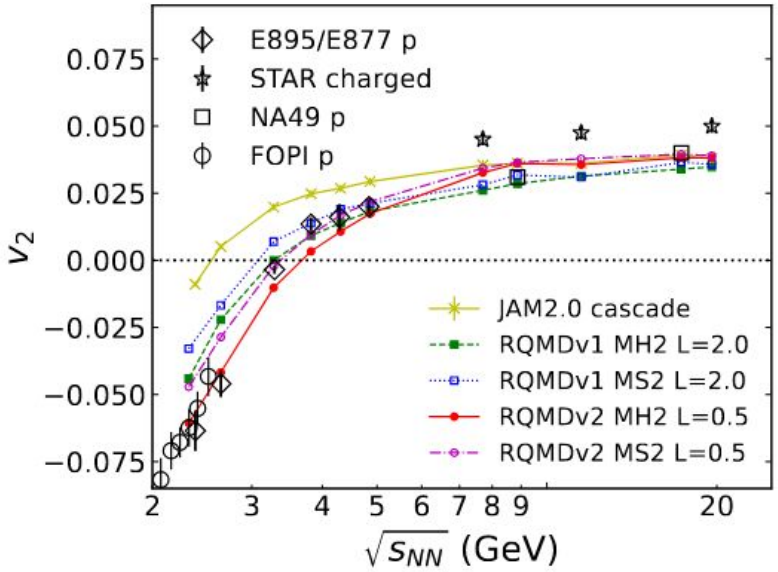
↳ It is interesting to investigate **the flow harmonics correlations**:
1) for **stricter EoS** constraints;
2) to check the idea of correlations **being independent** to spectator effects.



Reichert, T., et al., Phys. Lett. B 841 (2023) 137947.

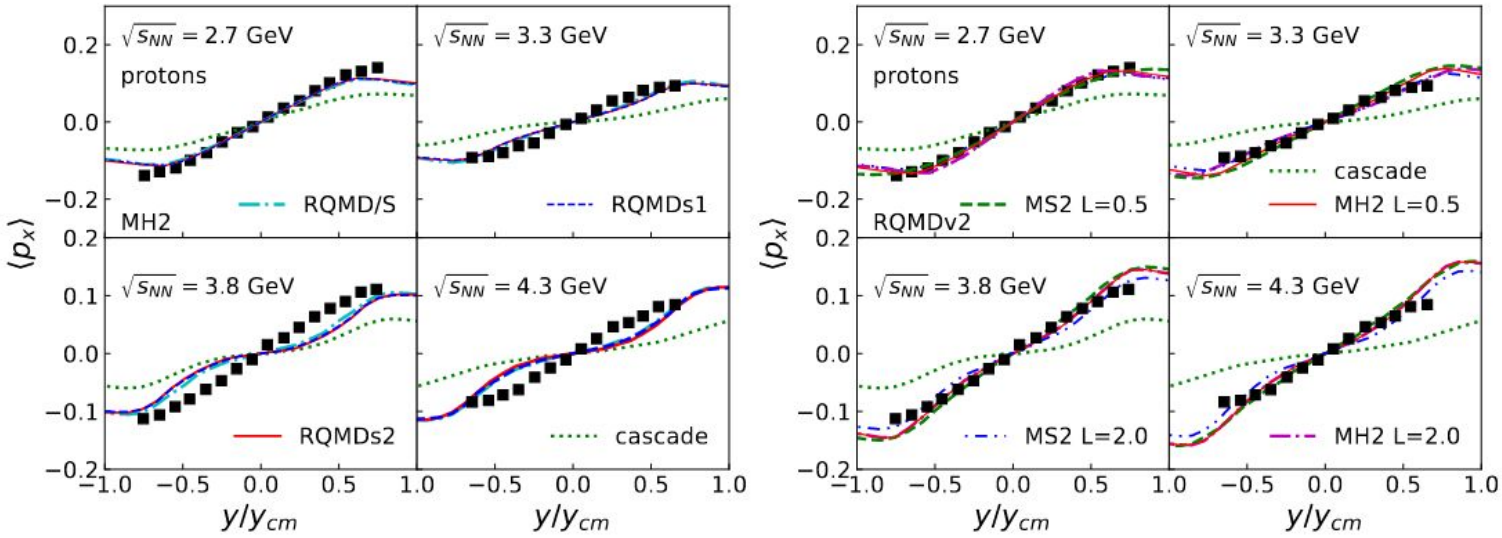
RQMD/S, RQMDs2, RQMDv1 and RQMDv2





Y. Nara, arXiv:2109.07594v3 (2022)

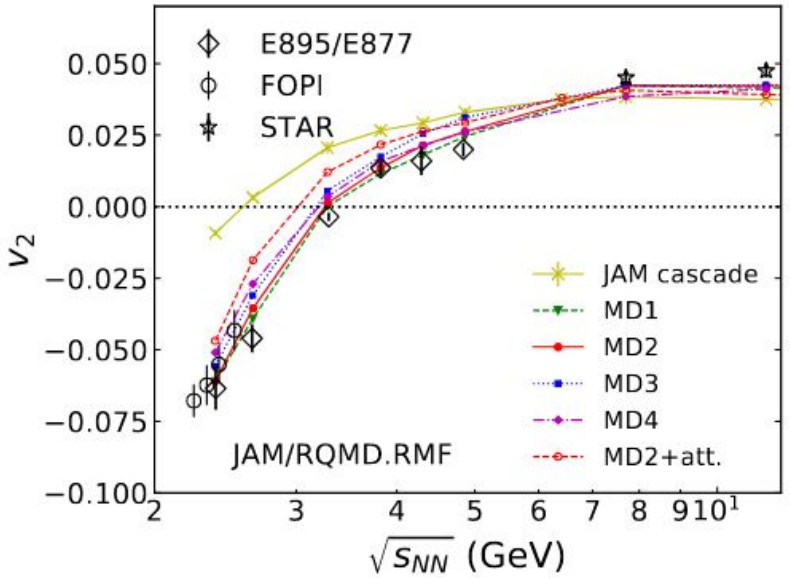
RQMD/S, RQMDs2, RQMDv1 and RQMDv2



Y. Nara, arXiv:2109.07594v3 (2022)

RQMD.RMF

		NS1	NS2	NS3	MD1	MD2	MD3	MD4
K	(MeV)	380	210	380	380	380	380	210
m^*/m		0.83	0.83	0.7	0.65	0.65	0.65	0.83
$U_{\rm opt}(\infty)$	(MeV)	95	98	200	95	30	−0.4	67
g_s		6.448	7.902	8.864	9.030	9.233	5.439	4.059
g_v		6.859	6.859	10.07	6.740	3.888	0.0	5.632
g_2	(1/fm)	−38.0	44.31	2.191	4.218	4.012	−15.59	−160.3
g_3		339.6	21.99	27.07	6.667	5.520	391.9	2684
$\bar{g}_s$		-	-	-	3.186	2.502	7.711	5.544
$\bar{g}_v$		-	-	-	8.896	10.43	11.22	3.926
Λ_s	(GeV)	-	-	-	0.641	0.4897	1.702	0.704
Λ_v	(GeV)	-	-	-	1.841	2.489	1.898	4.252

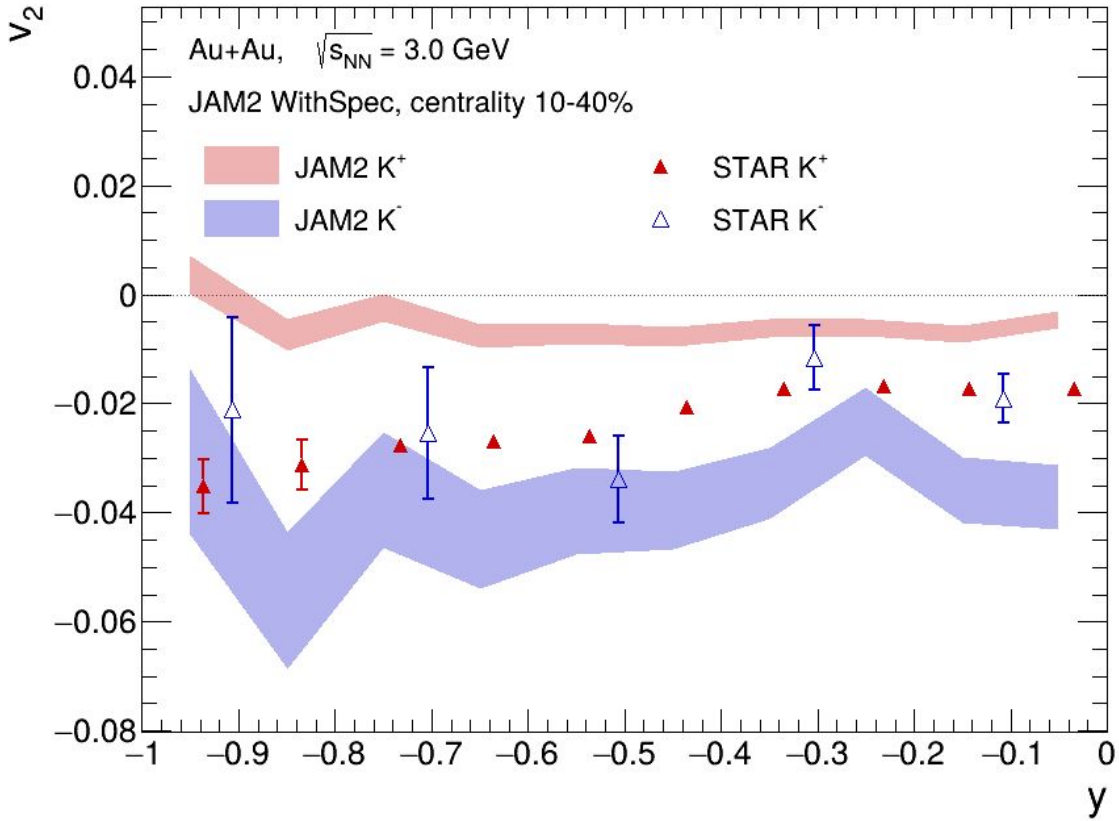


Y. Nara, arXiv:2004.05550v2 (2020)

Kaons in JAM2

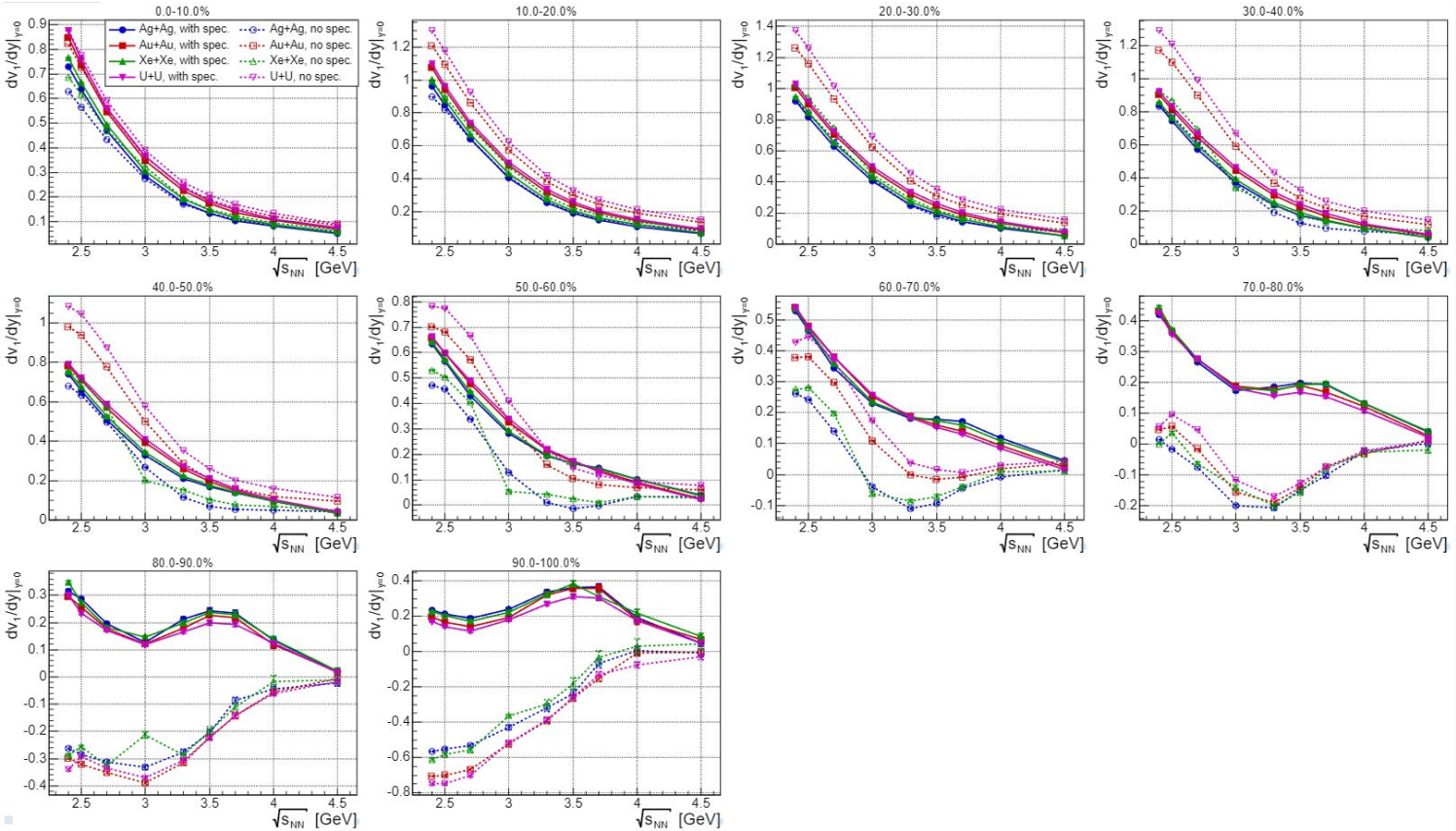
Prof. Nara:

"*JAM2 currently does not have any potential interaction for kaons. So kaons only suffer collisions.*
I guess one of the possible reasons for the different v2 may be that anti-kaon-nucleon cross section is much larger than the kaon-nucleon cross section."



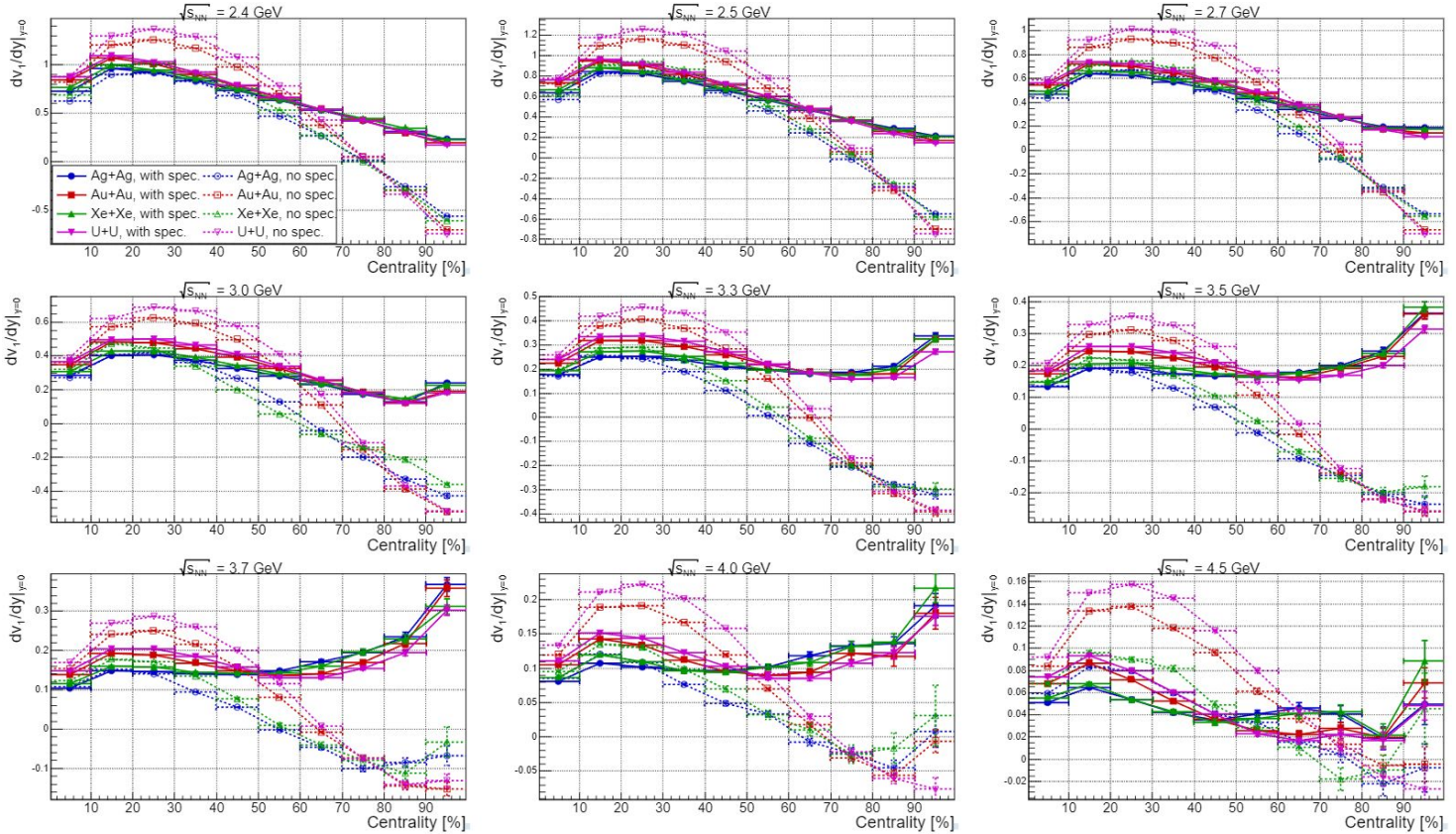
$dv_1/dy|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

- v_1 without spectators is **stronger** in **central** and **semi-central** collisions for heavy collision systems (Au+Au and U+U);
- For **lighter** systems -> **opposite**;
- For peripheral collisions v_1 becomes **weaker** without spectators



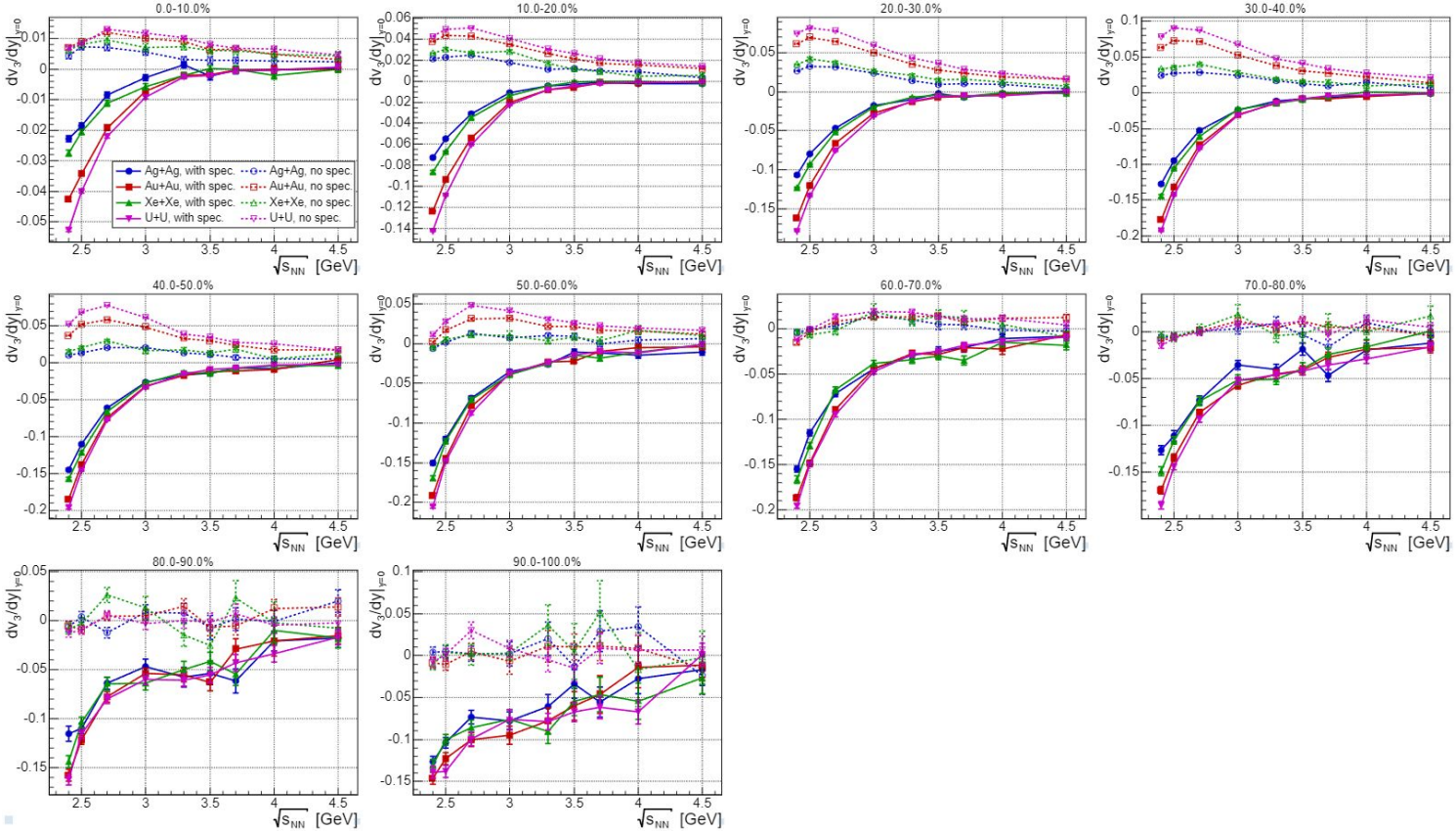
$dv_1/dy|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

- Most difference is observed for **semi-central** collisions of **heavy nuclei**;
- For light systems v_1 is generally weaker without spectators.



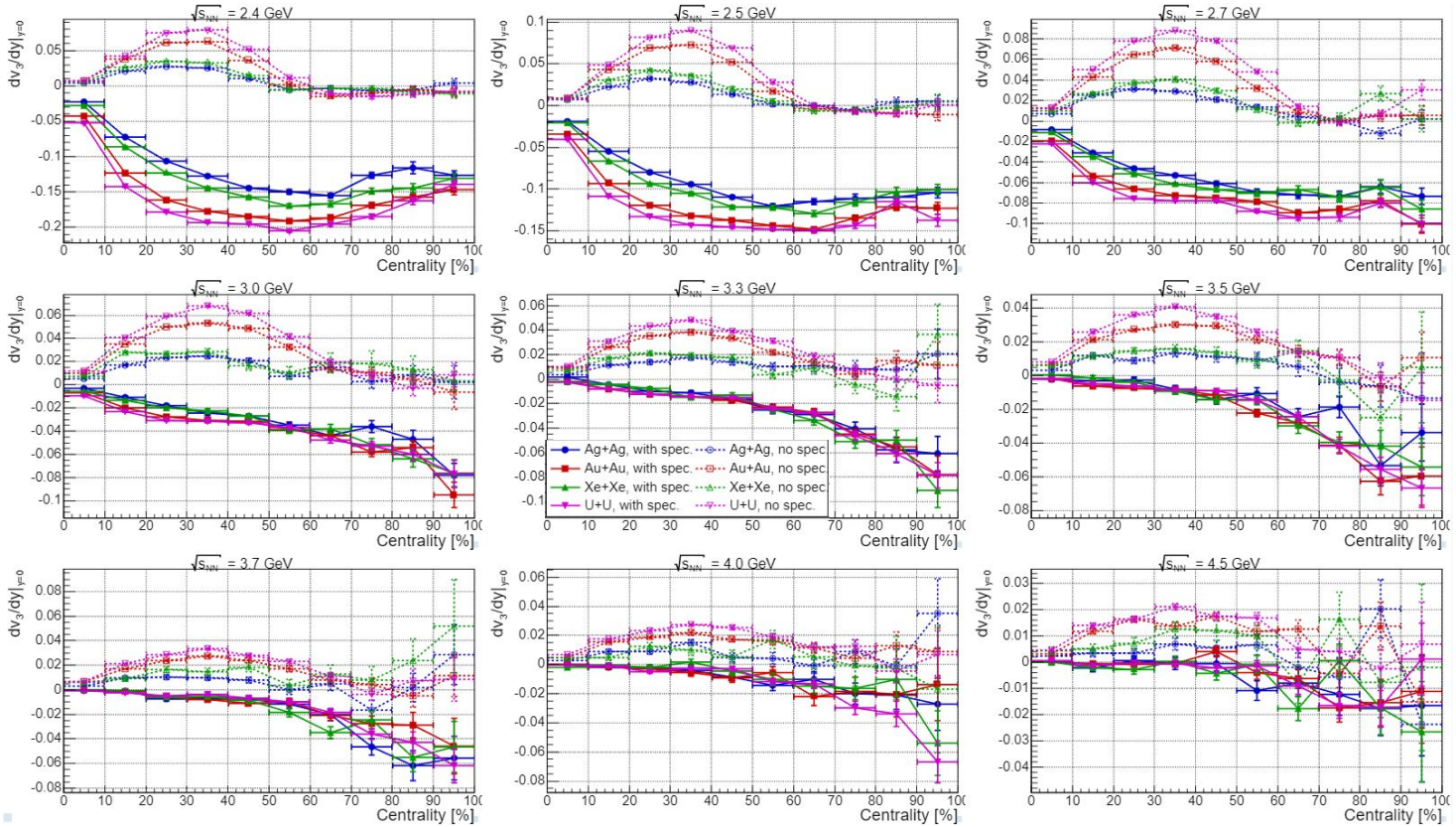
$dv_3/dy|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

- dv_3/dy without spectators **changes sign**;
- dv_3/dy becomes **less** in **abs. value** without spectators contribution;



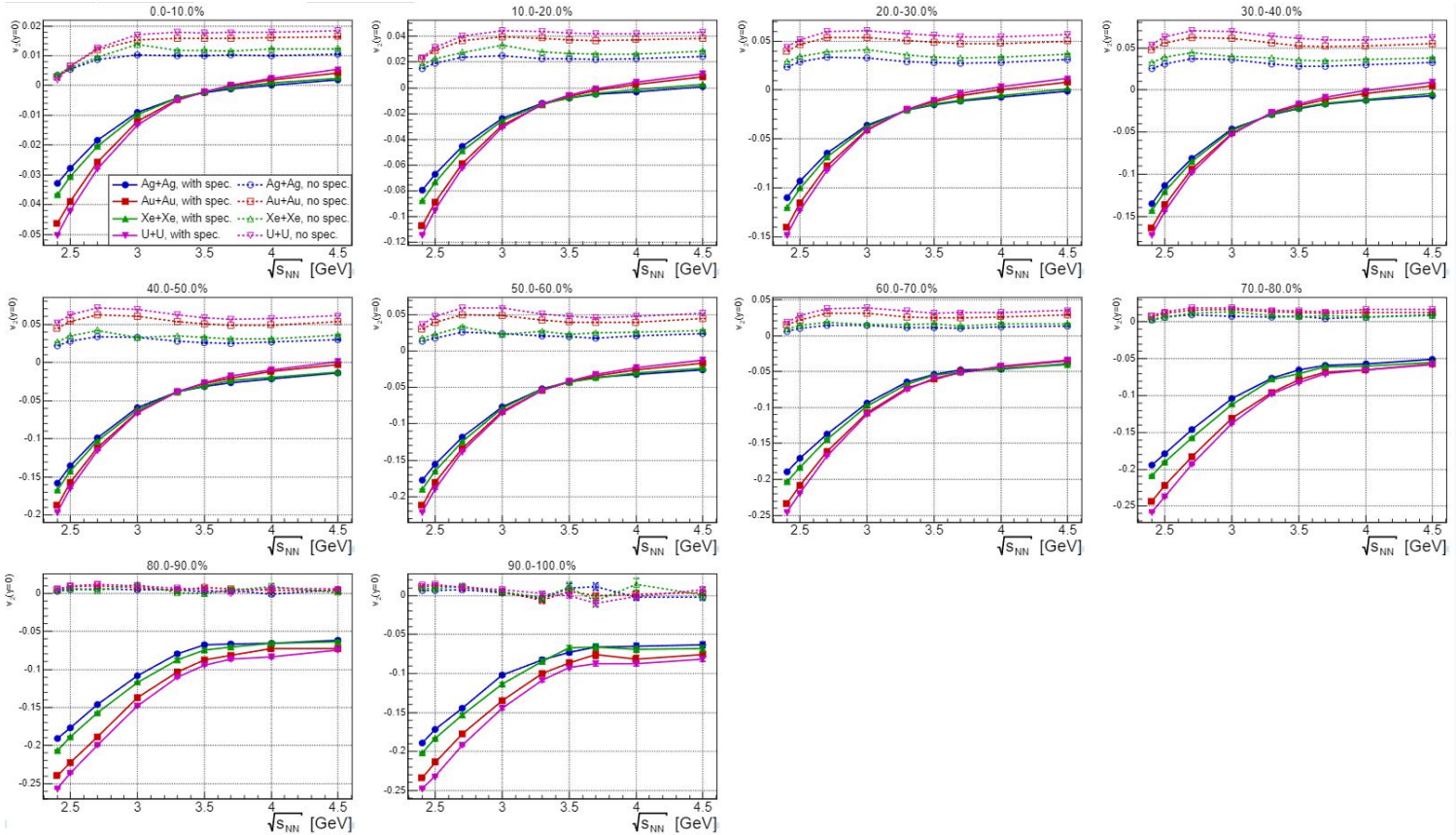
$dv_3/dy|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

- The significant difference is observed for **semi-central** and **peripheral** collisions of **all systems** for $\sqrt{s_{NN}} < 3.7$ GeV



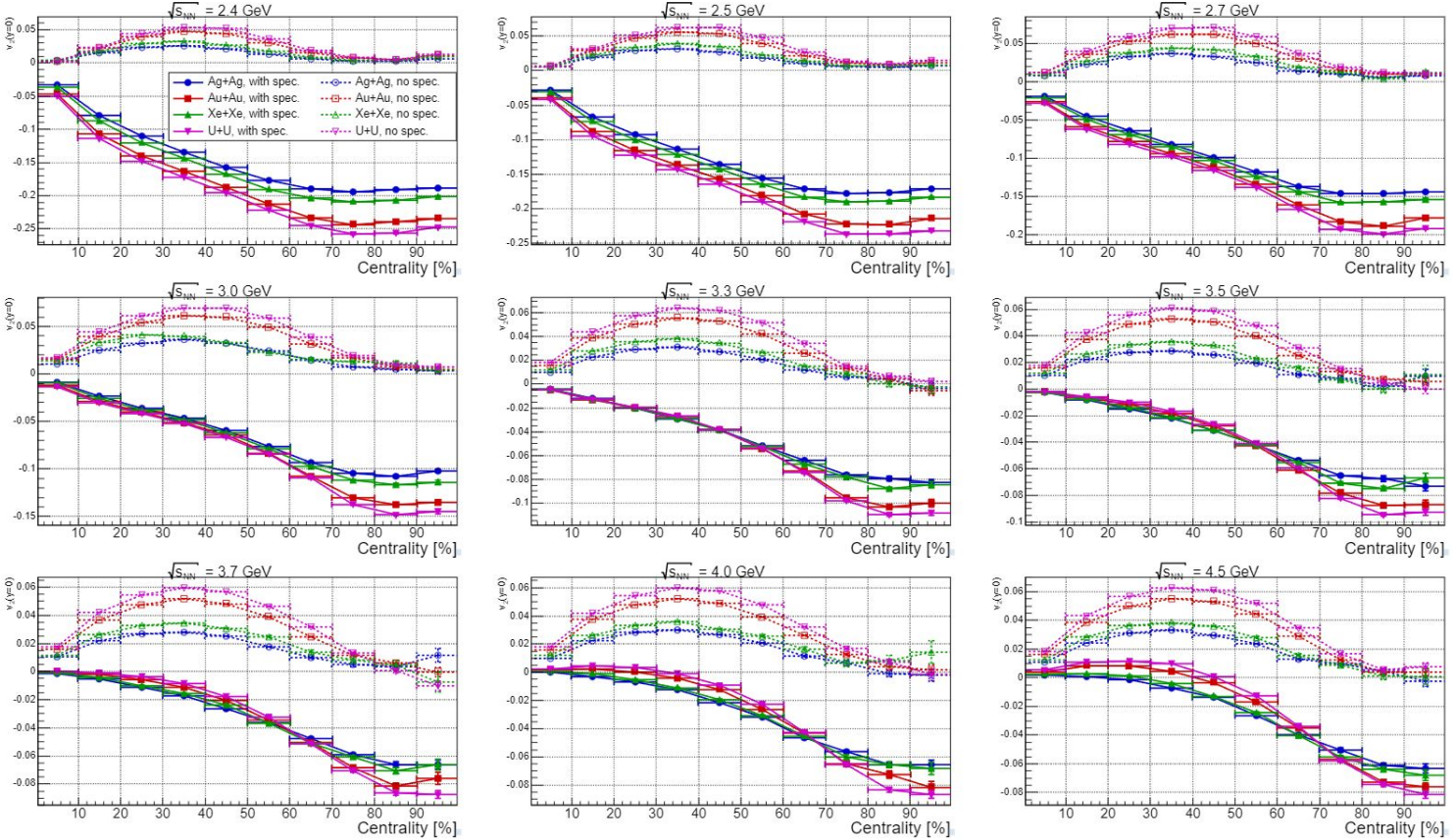
$v_2|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

- $v_2|_{y=0}$ without spectators also **changes sign**;
- $v_2|_{y=0}$ also becomes **less** in **abs. value** without spectators contribution;
- $v_2|_{y=0}$ without spectators almost **does not change** with collision energy.

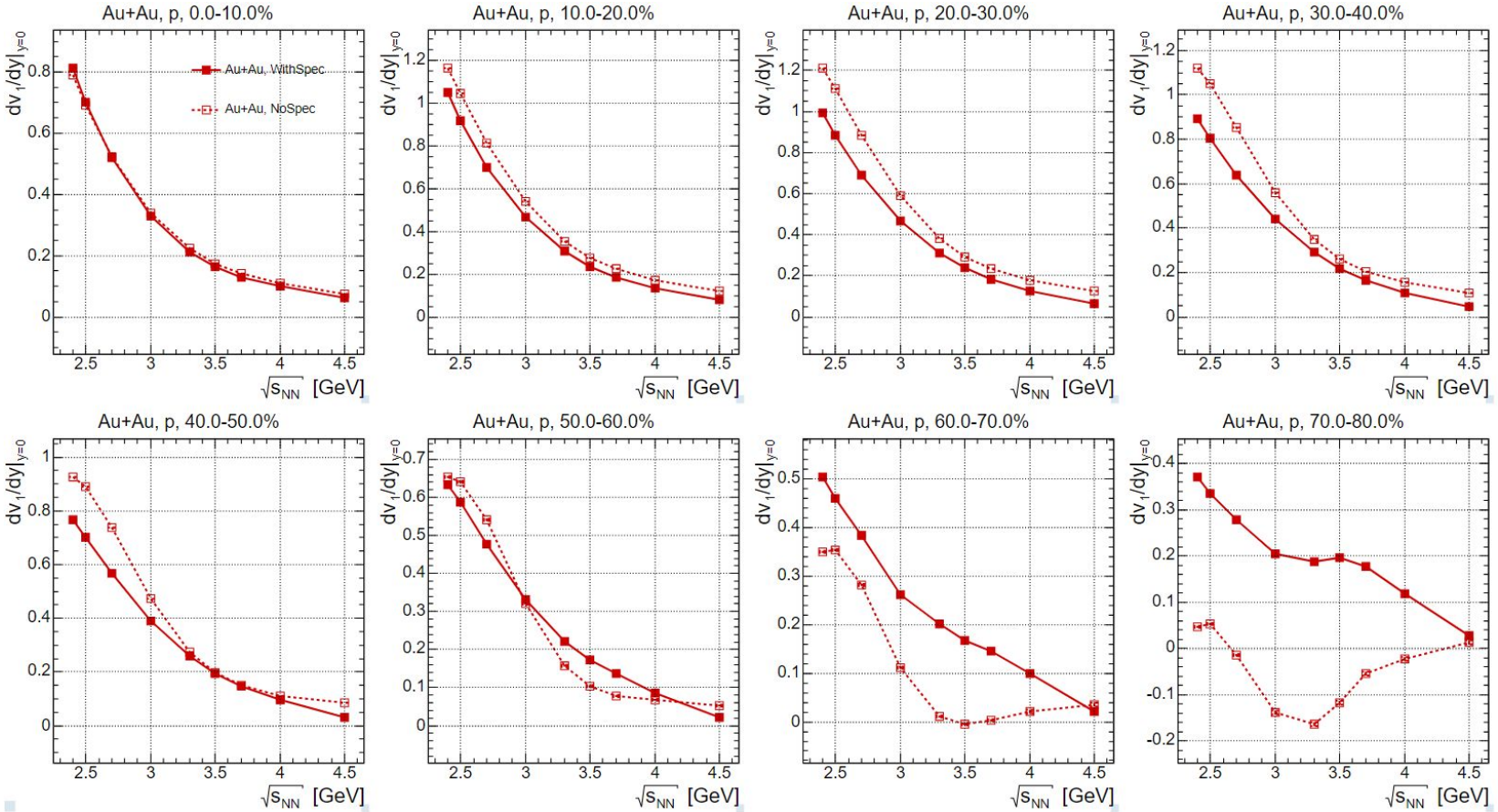


$v_2|_{y=0}$ for Au+Au, Ag+Ag, Xe+Xe and U+U

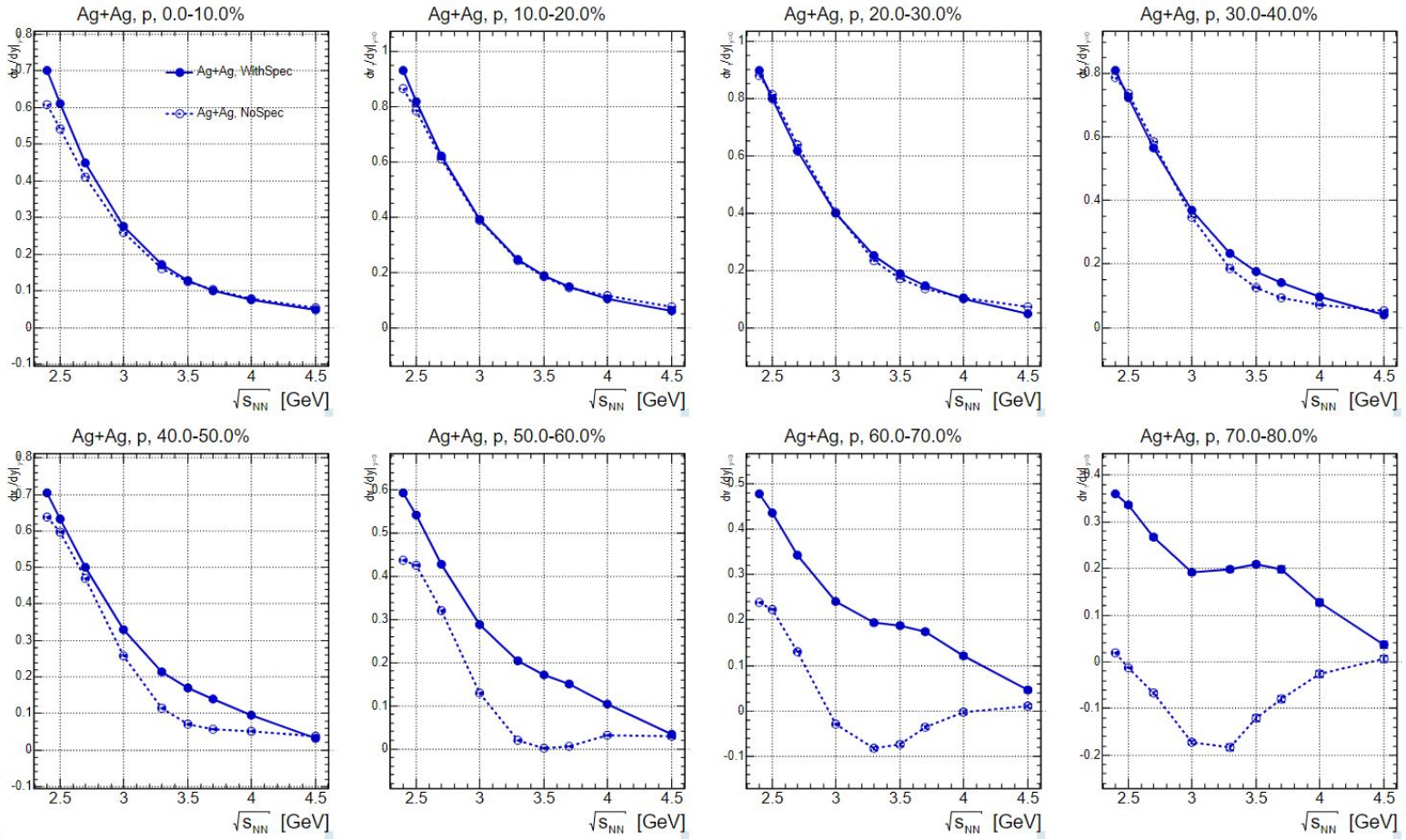
- $v_2|_{y=0}$ without spectators is highest at **semi-central collisions** (30-40%);
- With contribution of spectators the **dependence** is **changed**: absolute value of $v_2|_{y=0}$ grows for more peripheral collisions



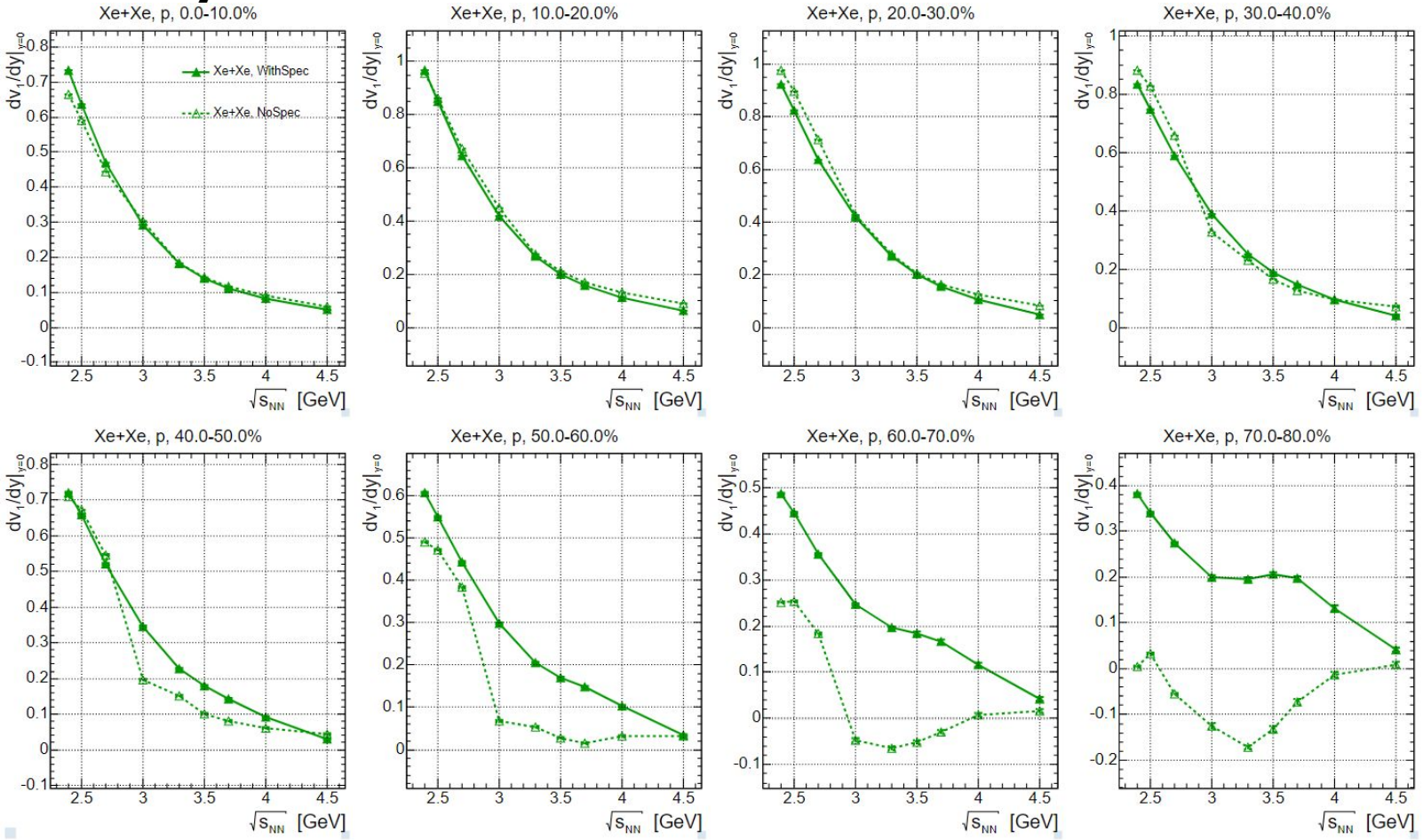
$dv_1/dy|_{y=0}$ for Au+Au (p)



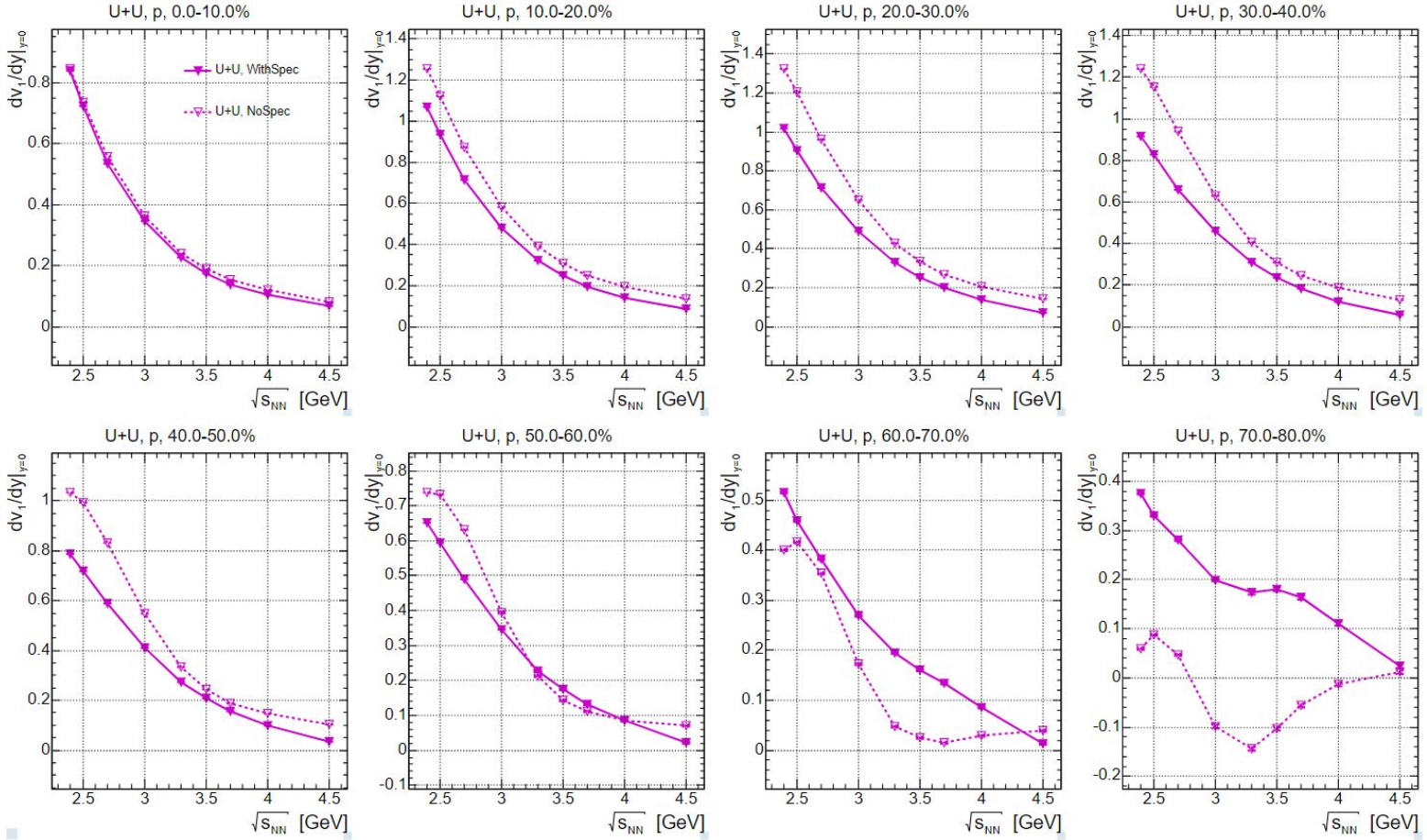
$dv_1/dy|_{y=0}$ for Ag+Ag (p)



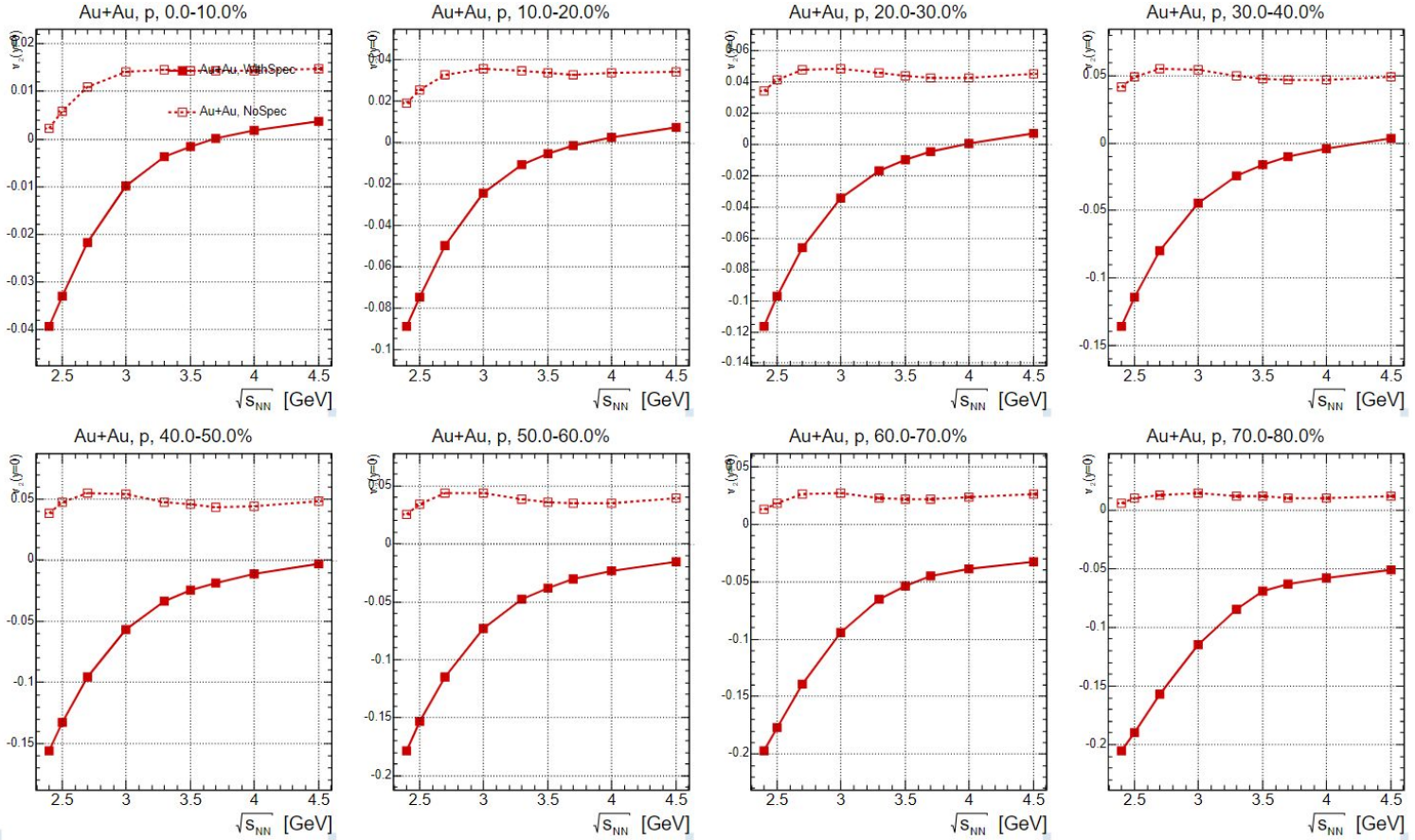
$dv_1/dy|_{y=0}$ for Xe+Xe (p)



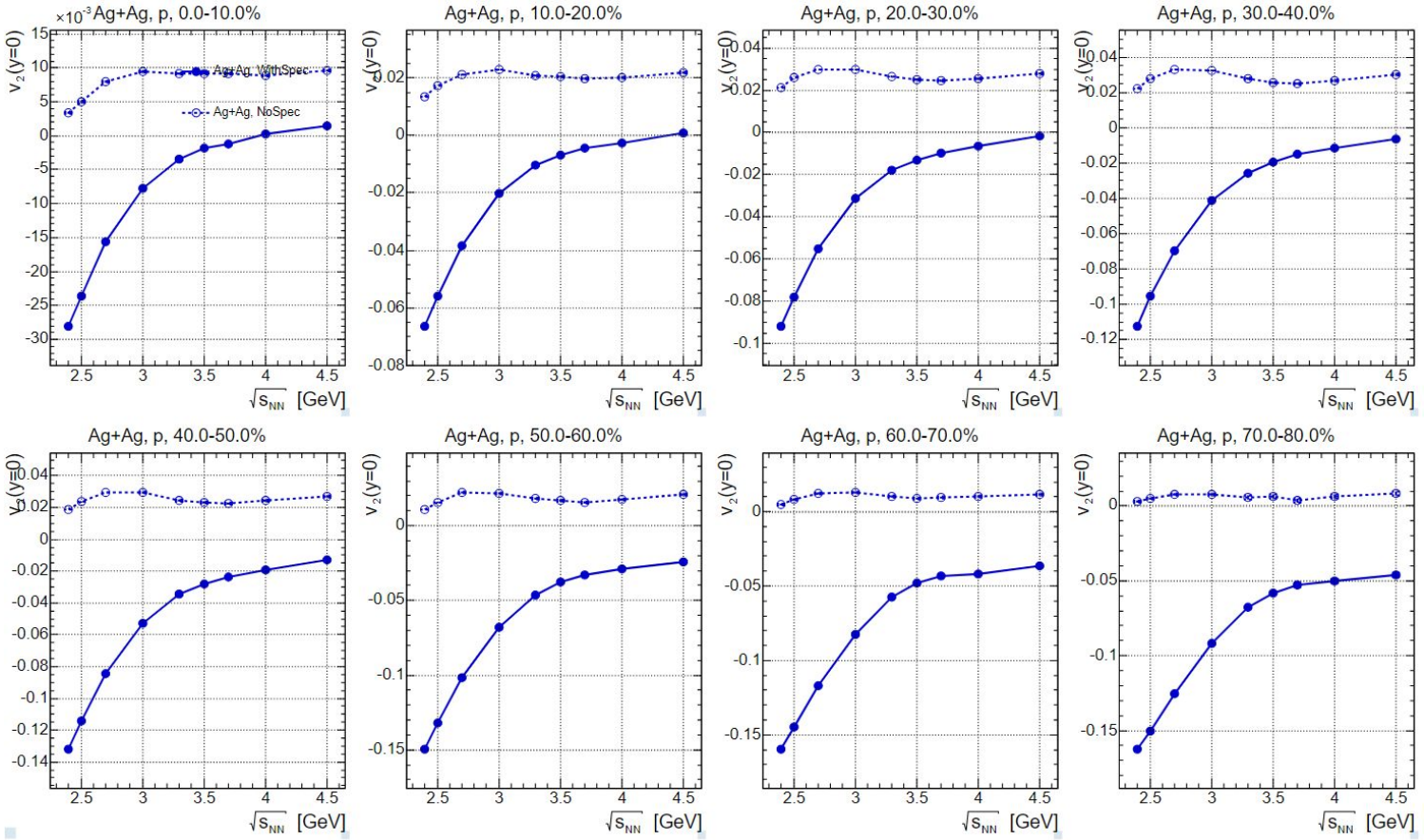
$dv_1/dy|_{y=0}$ for U+U (p)



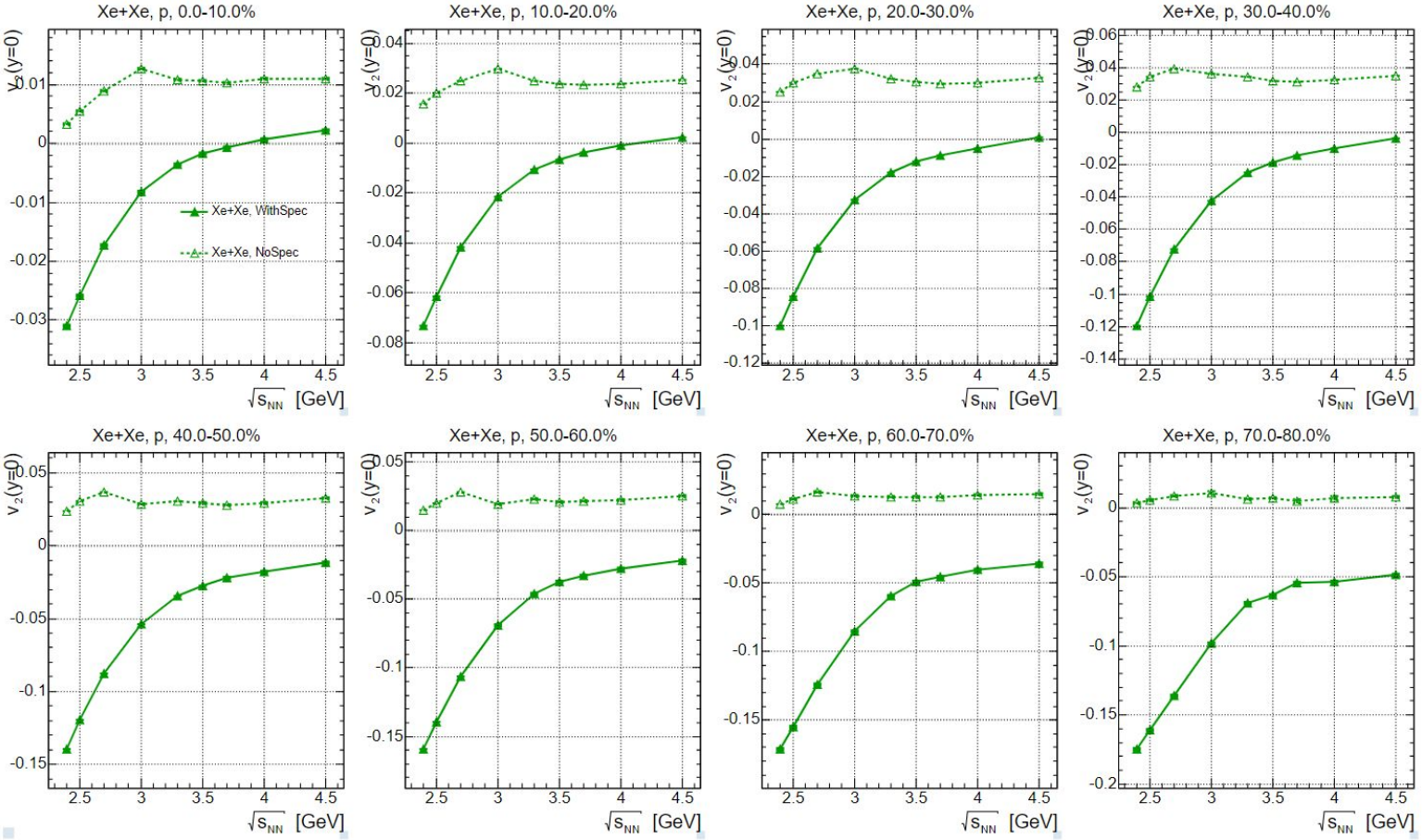
$v_2|_{y=0}$ for Au+Au (p)



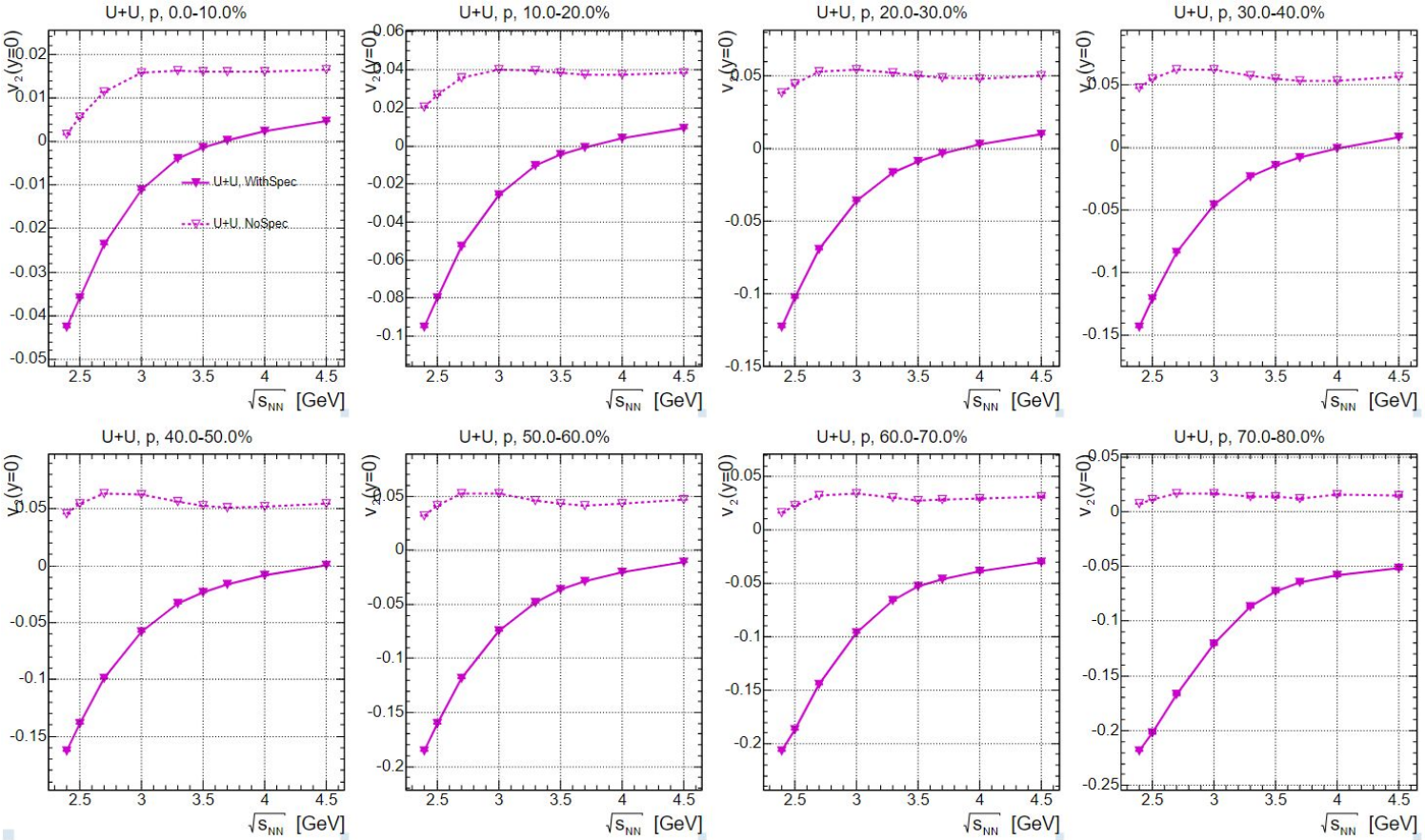
$v_2|_{y=0}$ for Ag+Ag (p)



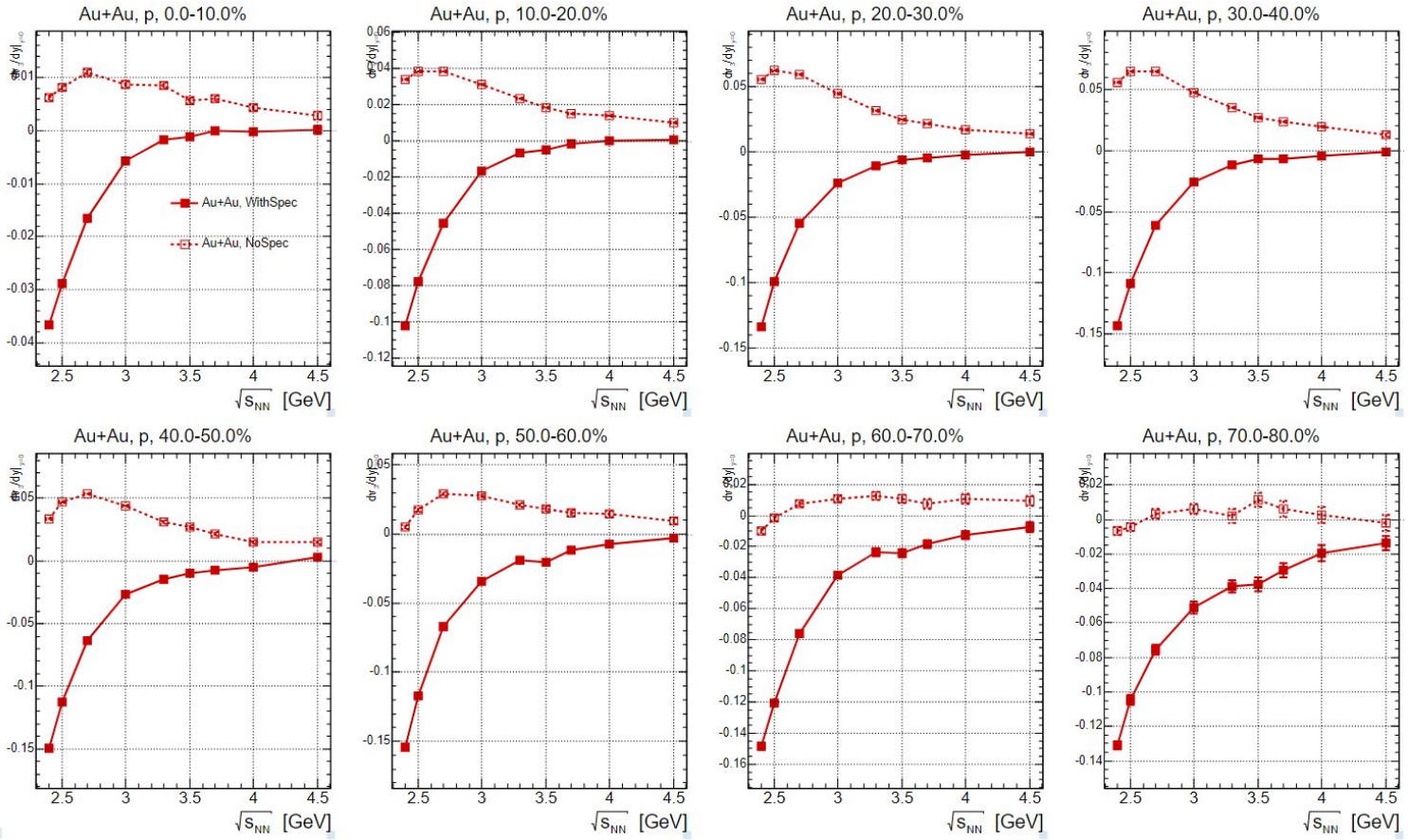
$v_2|_{y=0}$ for Xe+Xe (p)



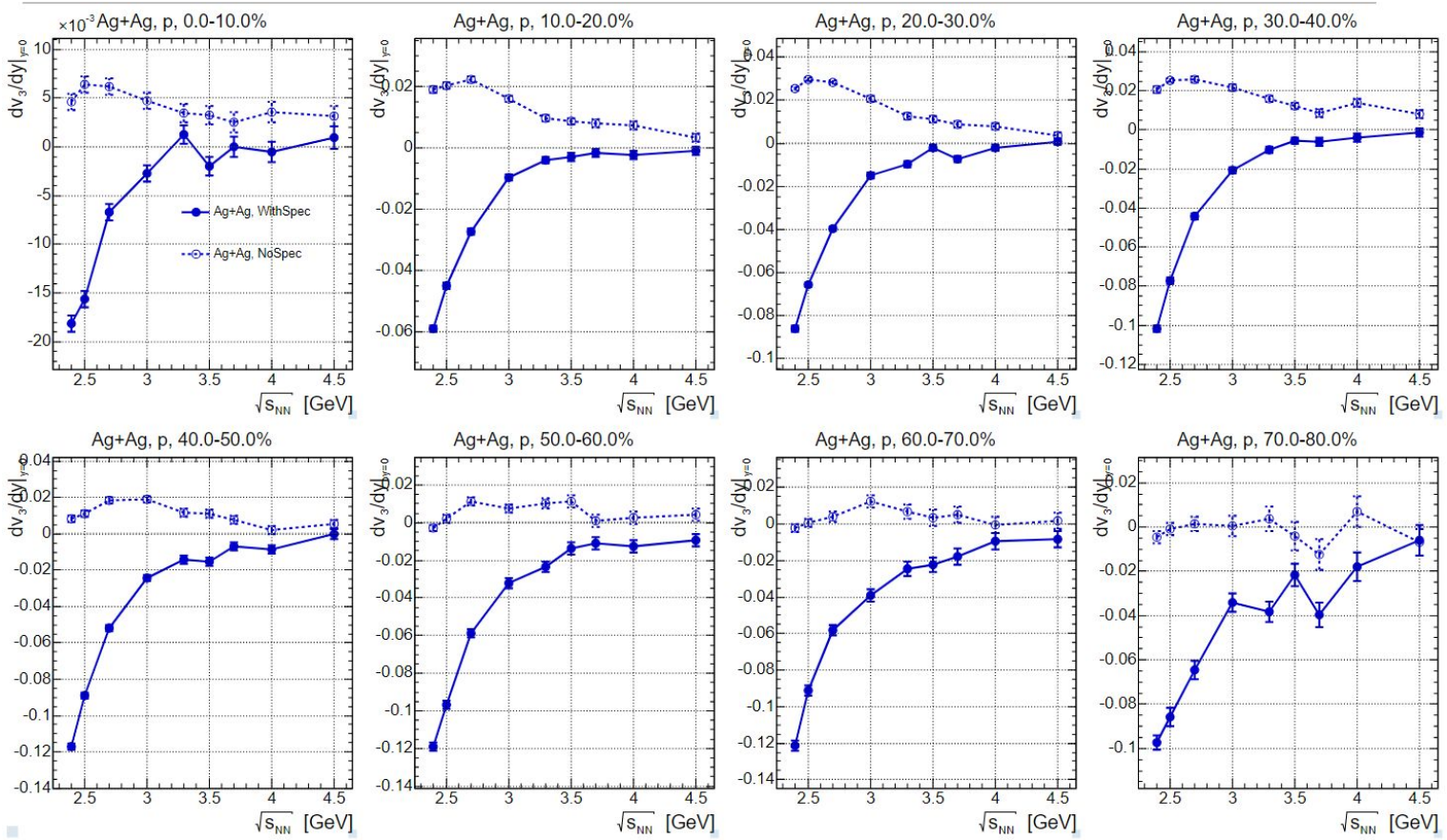
$v_2|_{y=0}$ for U+U (p)


U+U, p, 0.0-10.0%
U+U, p, 10.0-20.0%
U+U, p, 20.0-30.0%
U+U, p, 30.0-40.0%
U+U, p, 40.0-50.0%
U+U, p, 50.0-60.0%
U+U, p, 60.0-70.0%
U+U, p, 70.0-80.0%
$v_2(y=0)$
$\sqrt{s_{NN}}$ [GeV]
U+U, WithSpec
U+U, NoSpec

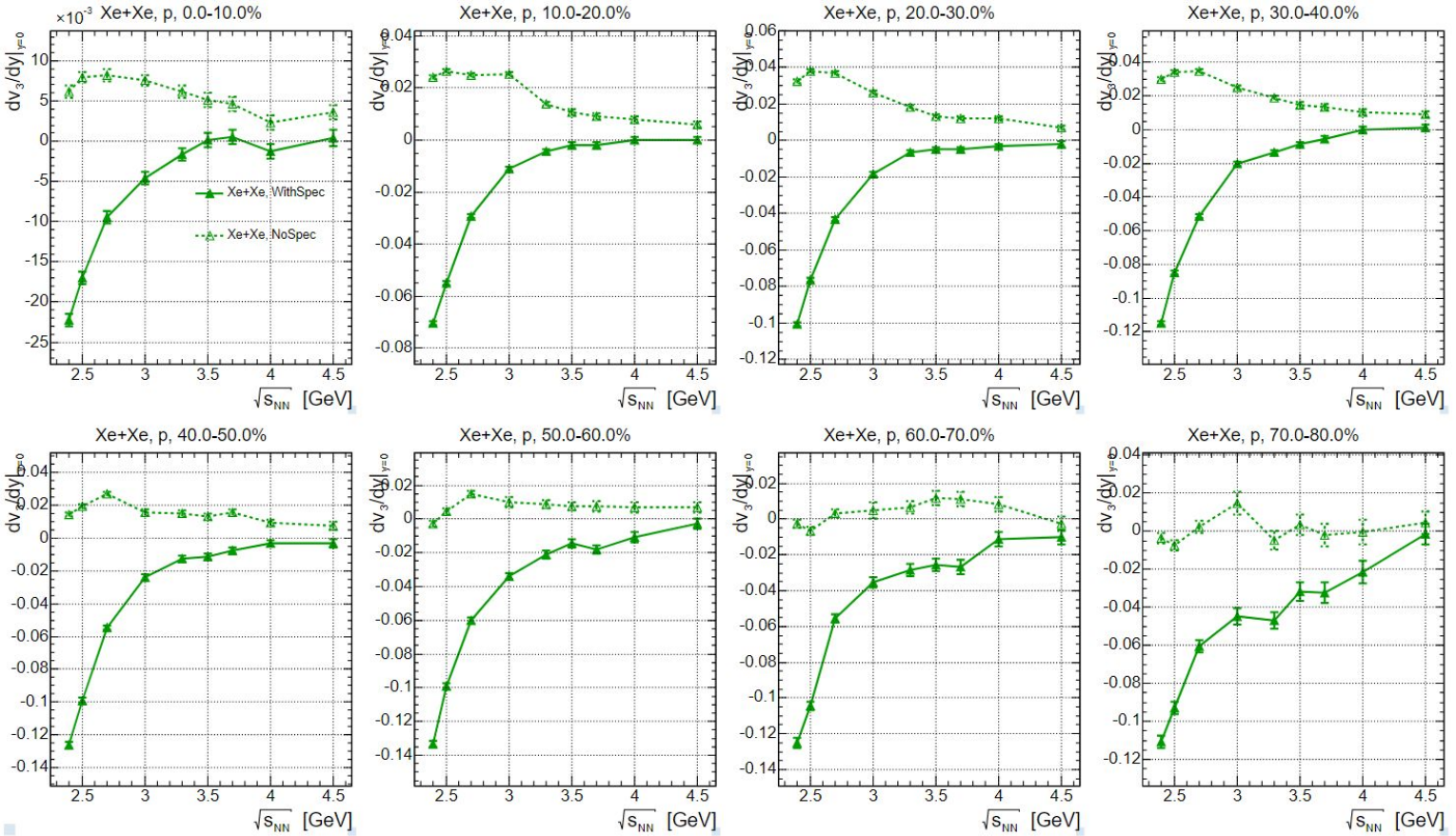
$dv_3/dy|_{y=0}$ for Au+Au (p)



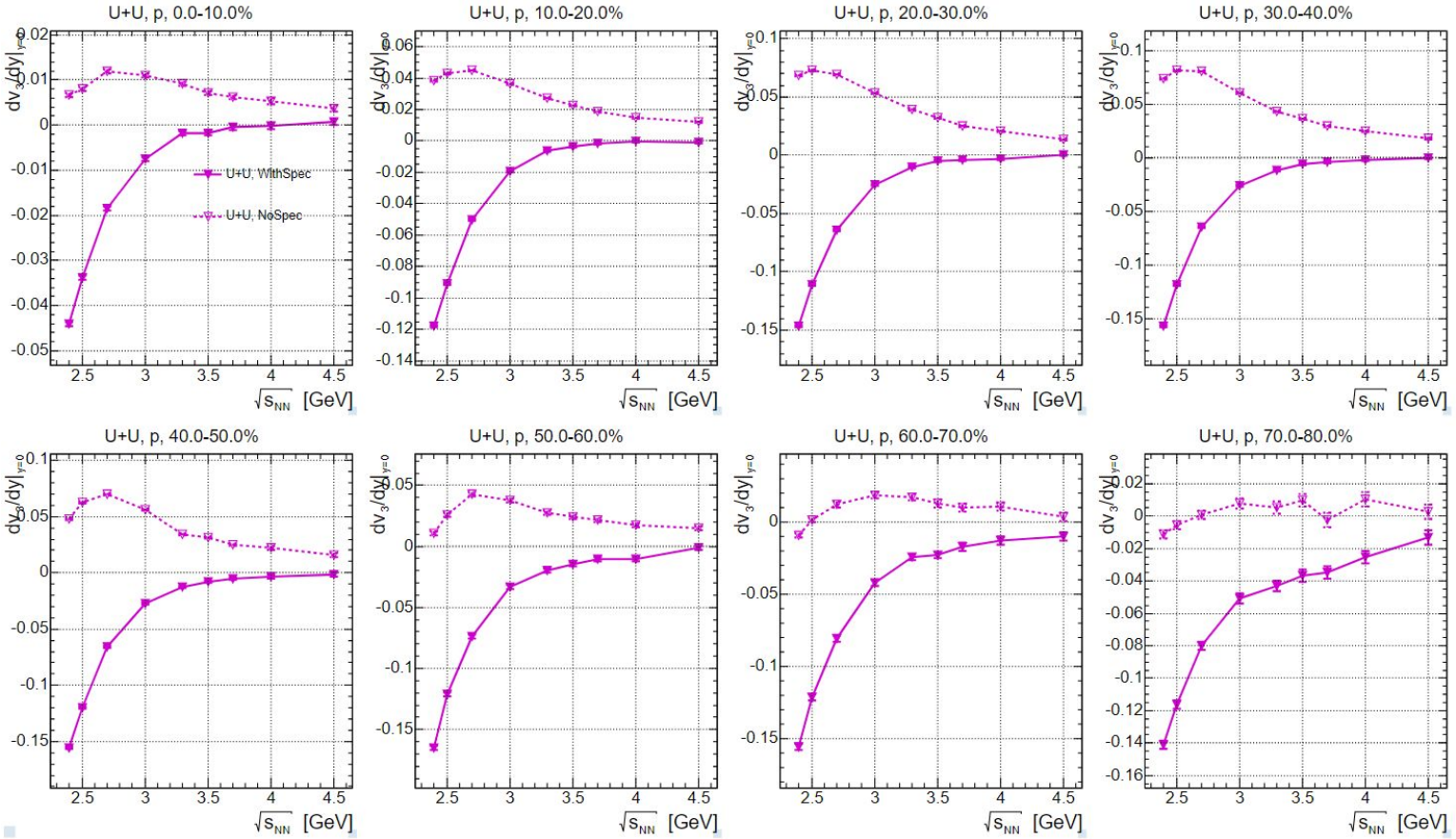
$dv_3/dy|_{y=0}$ for Ag+Ag (p)



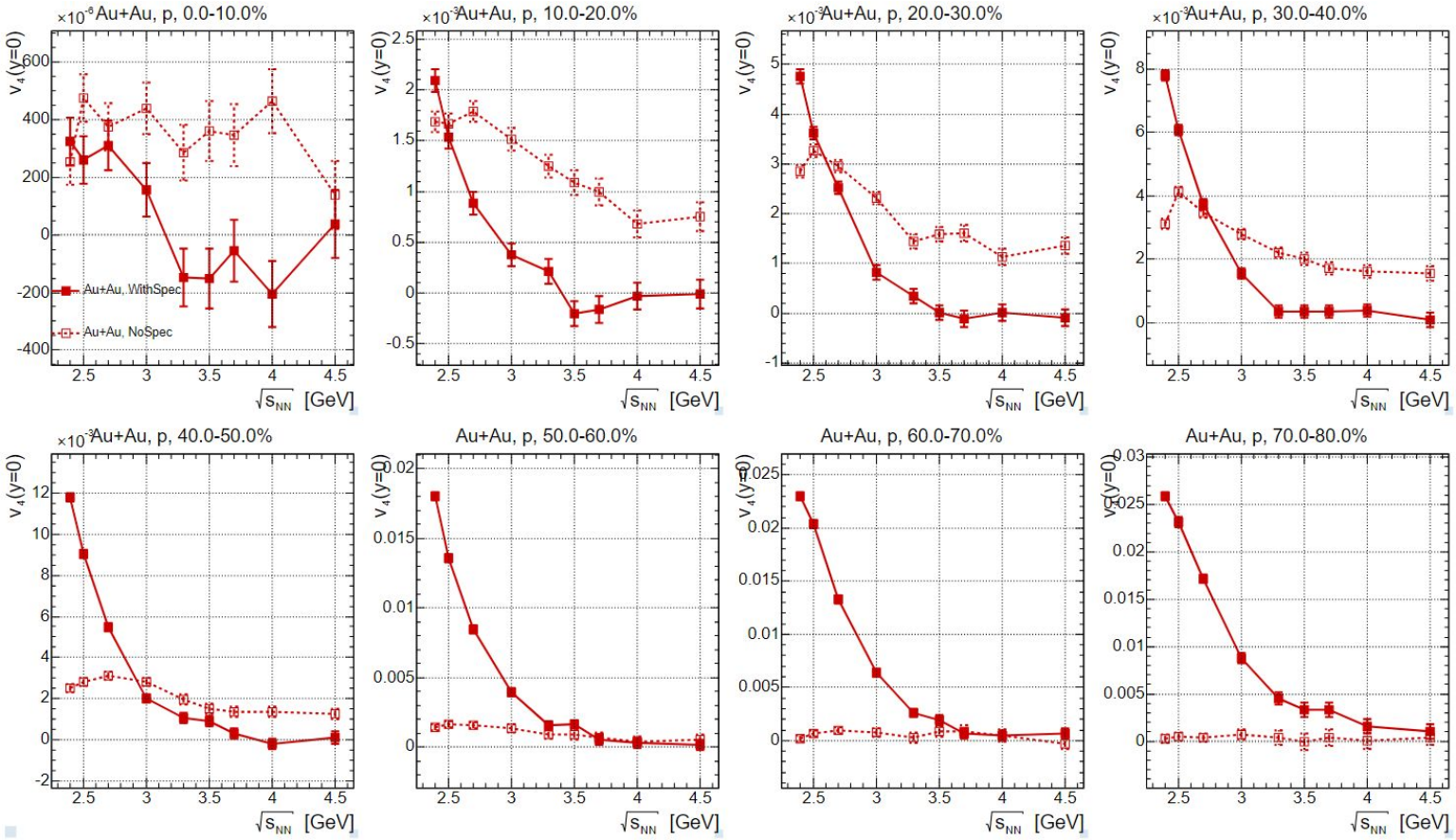
$dv_3/dy|_{y=0}$ for Xe+Xe (p)



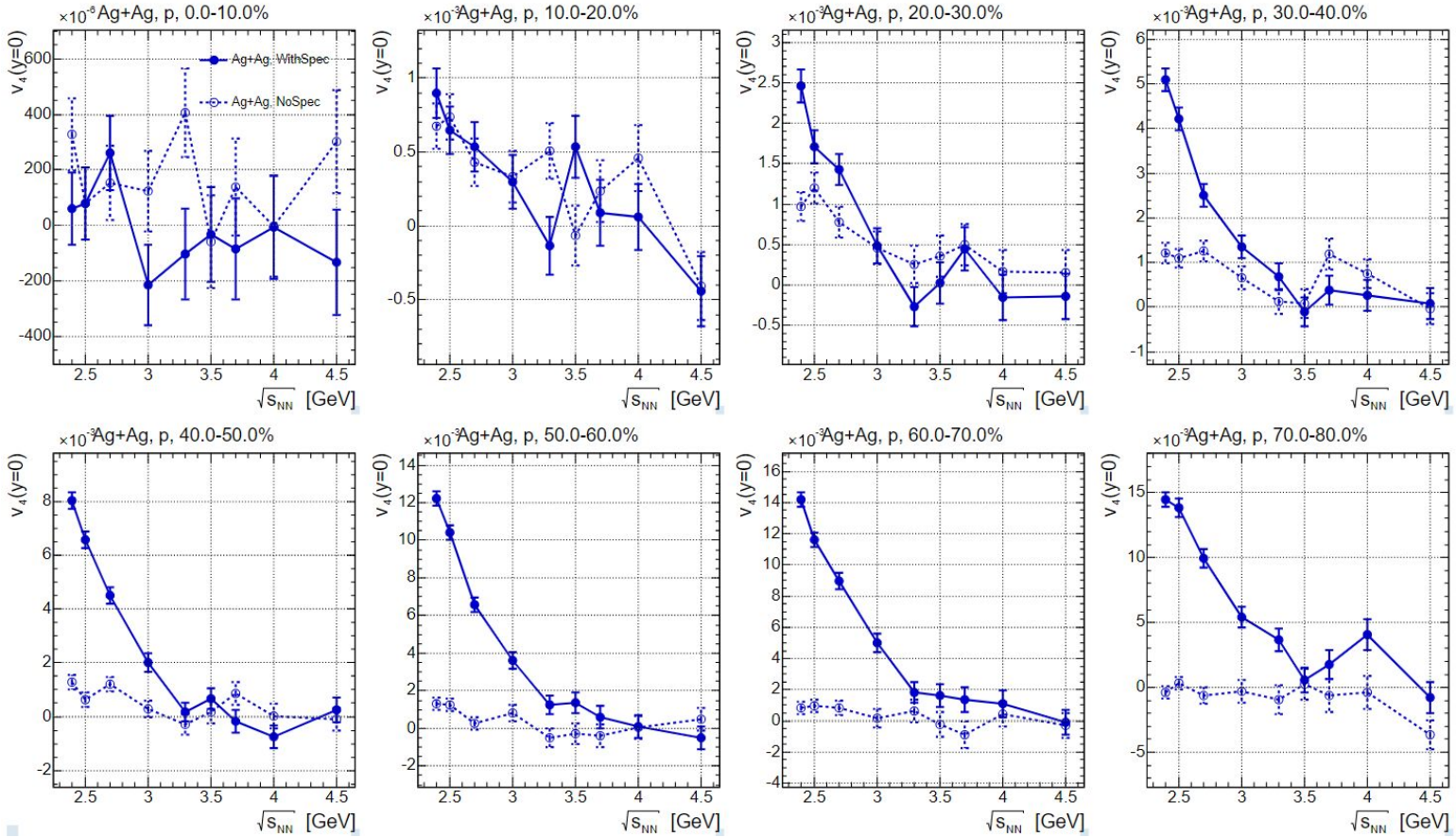
$dv_3/dy|_{y=0}$ for U+U (p)



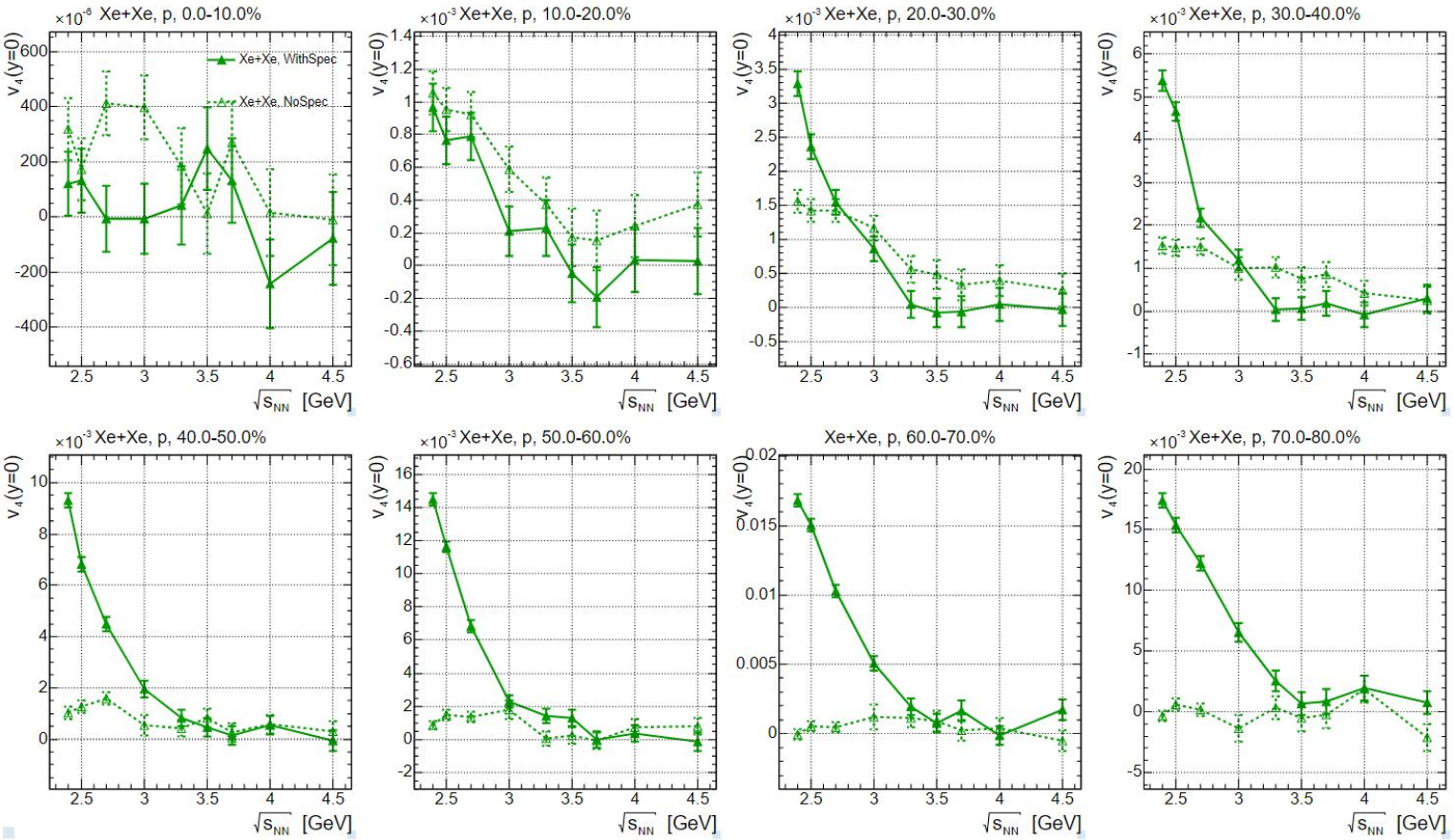
$v_4|_{y=0}$ for Au+Au (p)



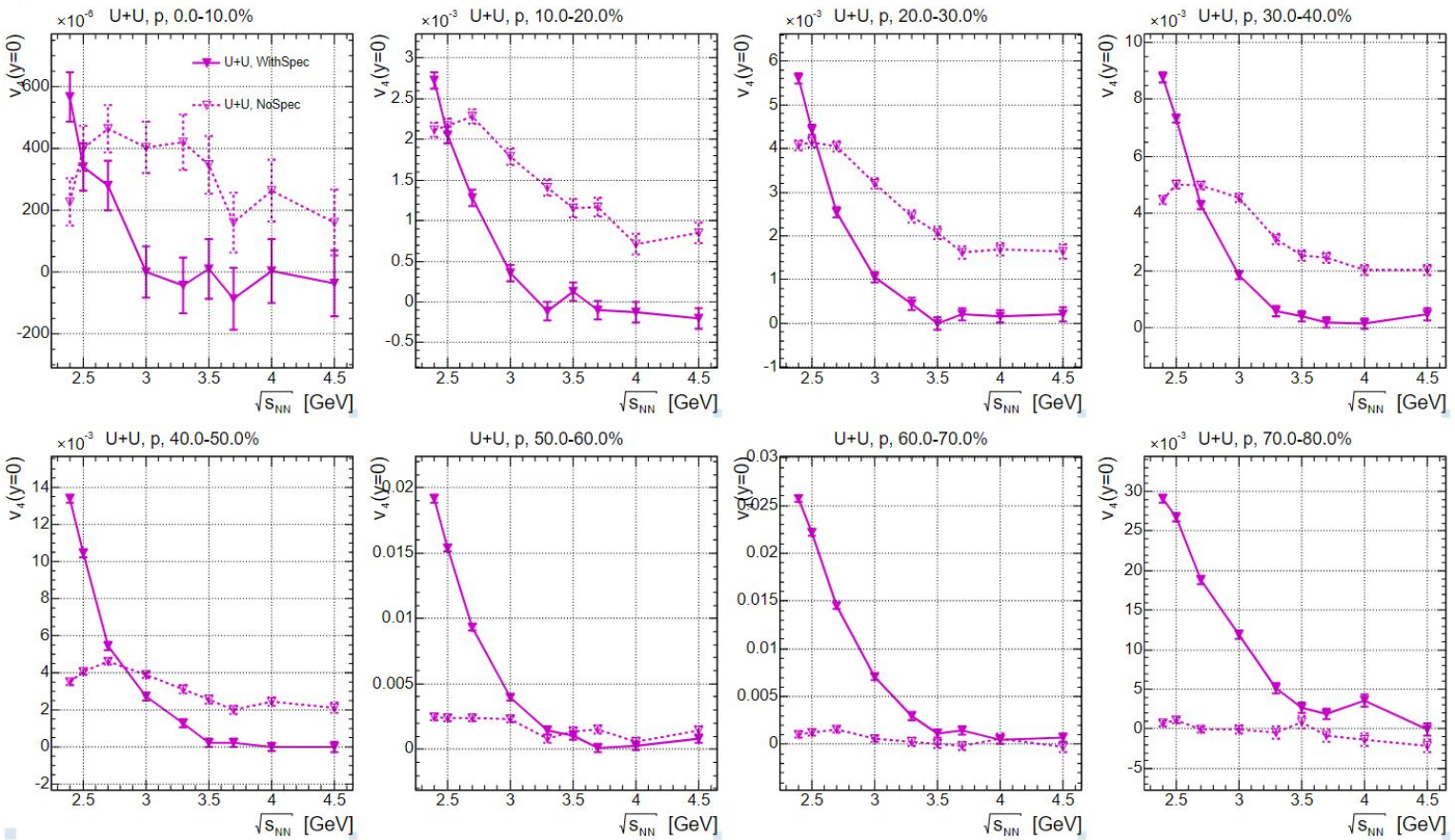
$v_4|_{y=0}$ for Ag+Ag (p)



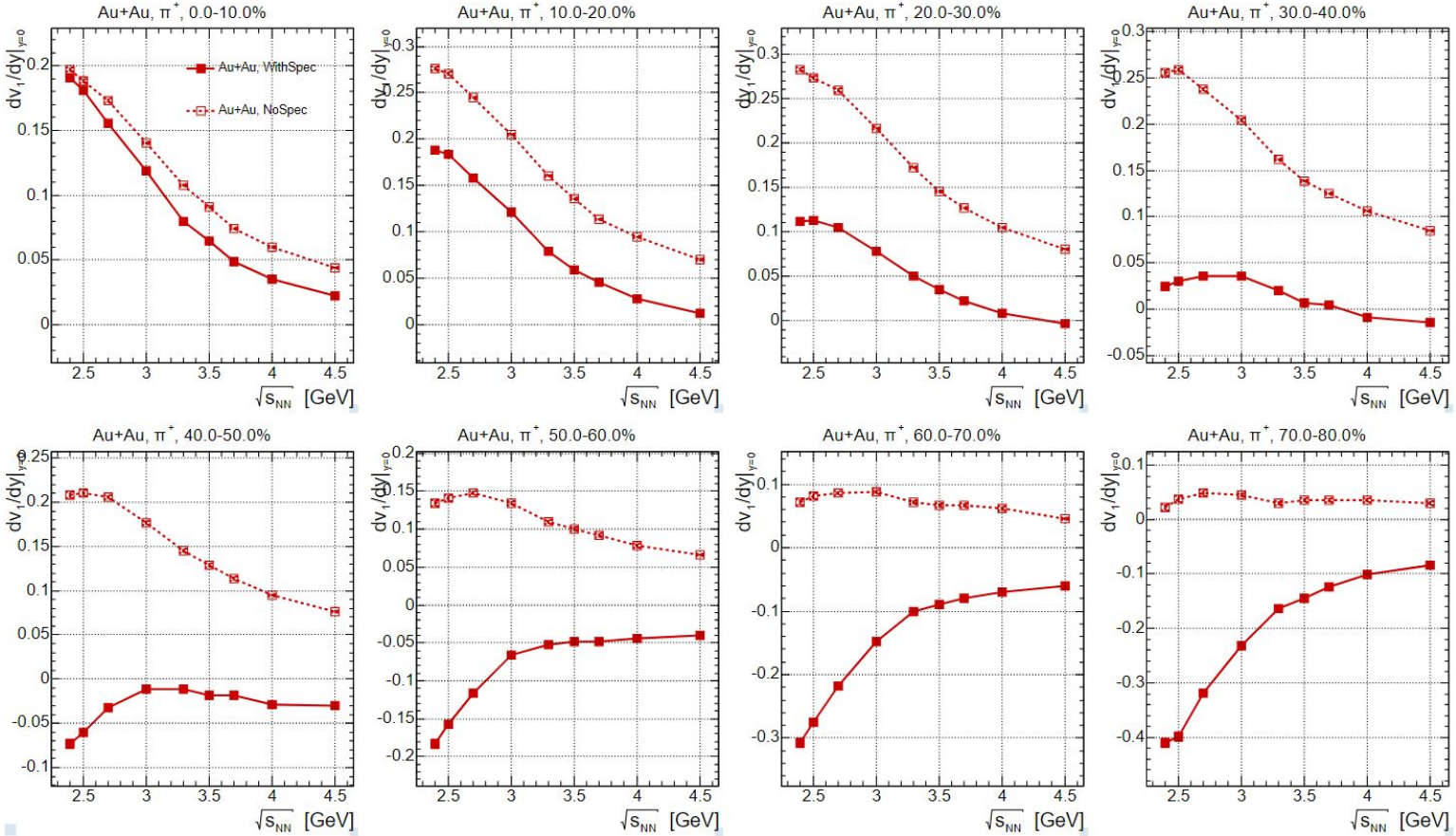
$v_4|_{y=0}$ for Xe+Xe (p)



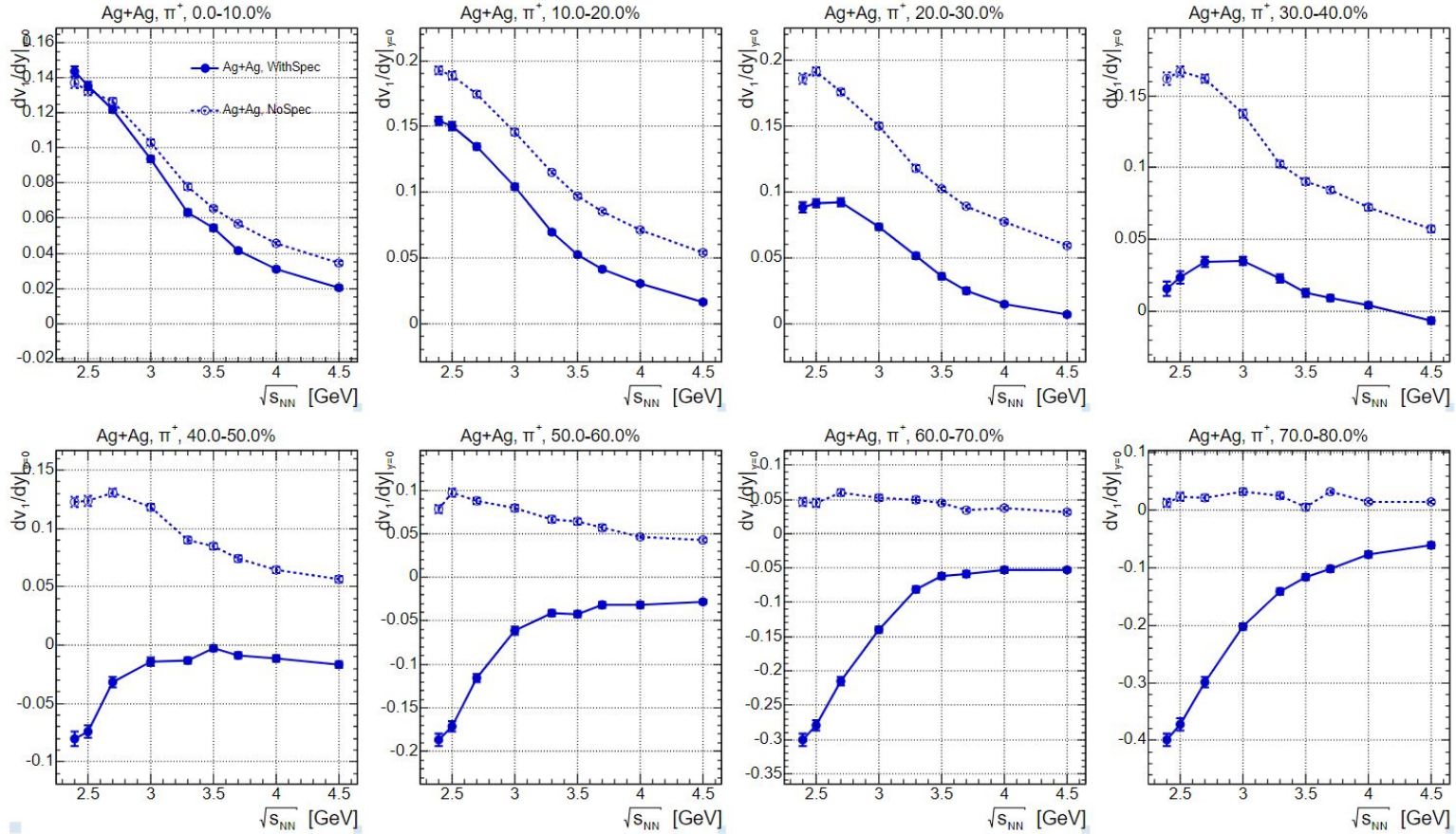
$v_4|_{y=0}$ for U+U (p)


U+U, p, 0.0-10.0%
U+U, WithSpec
U+U, NoSpec
U+U, p, 10.0-20.0%
U+U, p, 20.0-30.0%
U+U, p, 30.0-40.0%
U+U, p, 40.0-50.0%
U+U, p, 50.0-60.0%
U+U, p, 60.0-70.0%
U+U, p, 70.0-80.0%
$v_4(y=0)$
$\sqrt{s_{NN}}$ [GeV]

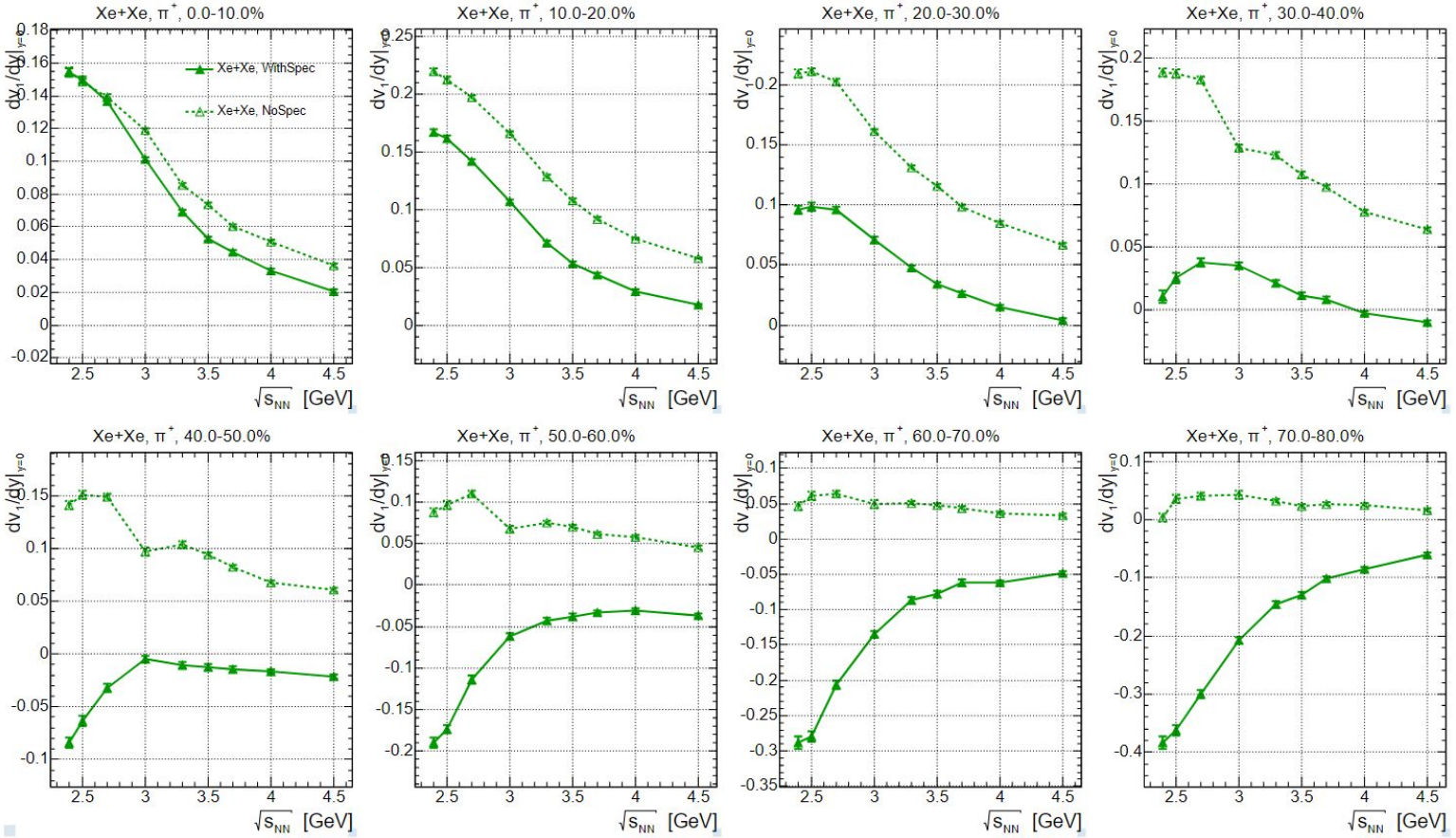
$dv_1/dy|_{y=0}$ for Au+Au (π^+)



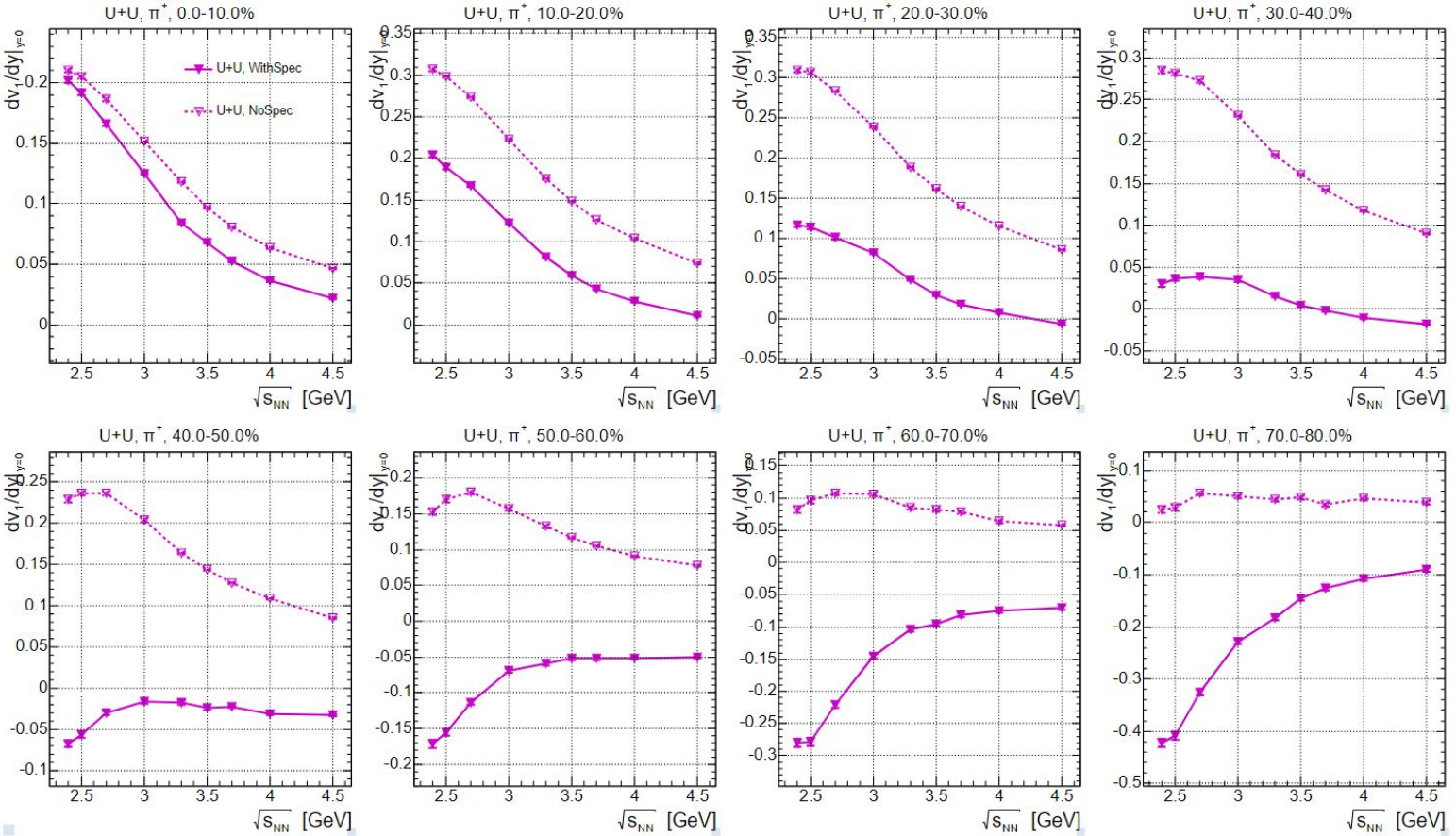
$dv_1/dy|_{y=0}$ for Ag+Ag (π^+)



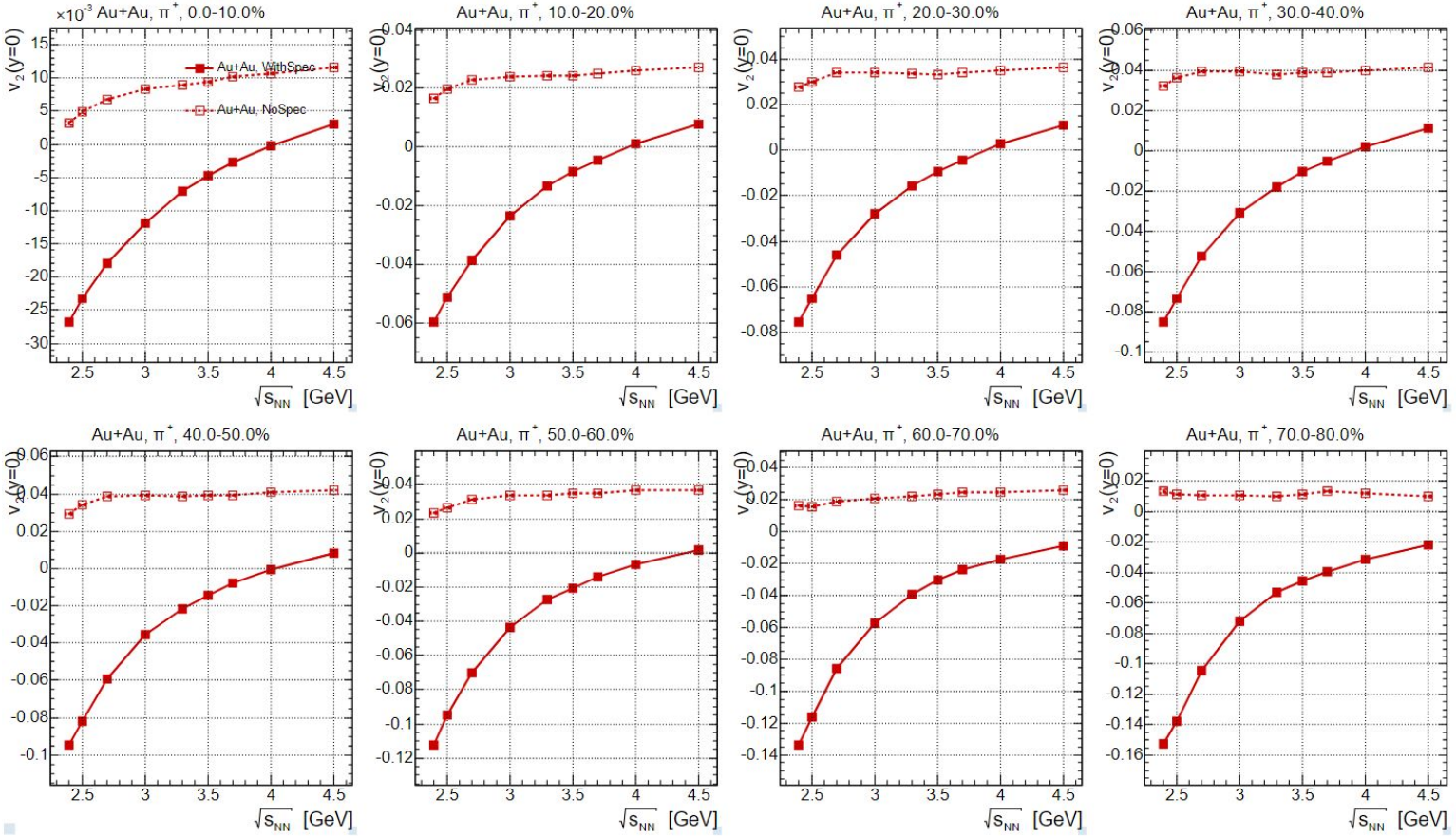
$dv_1/dy|_{y=0}$ for Xe+Xe (π^+)



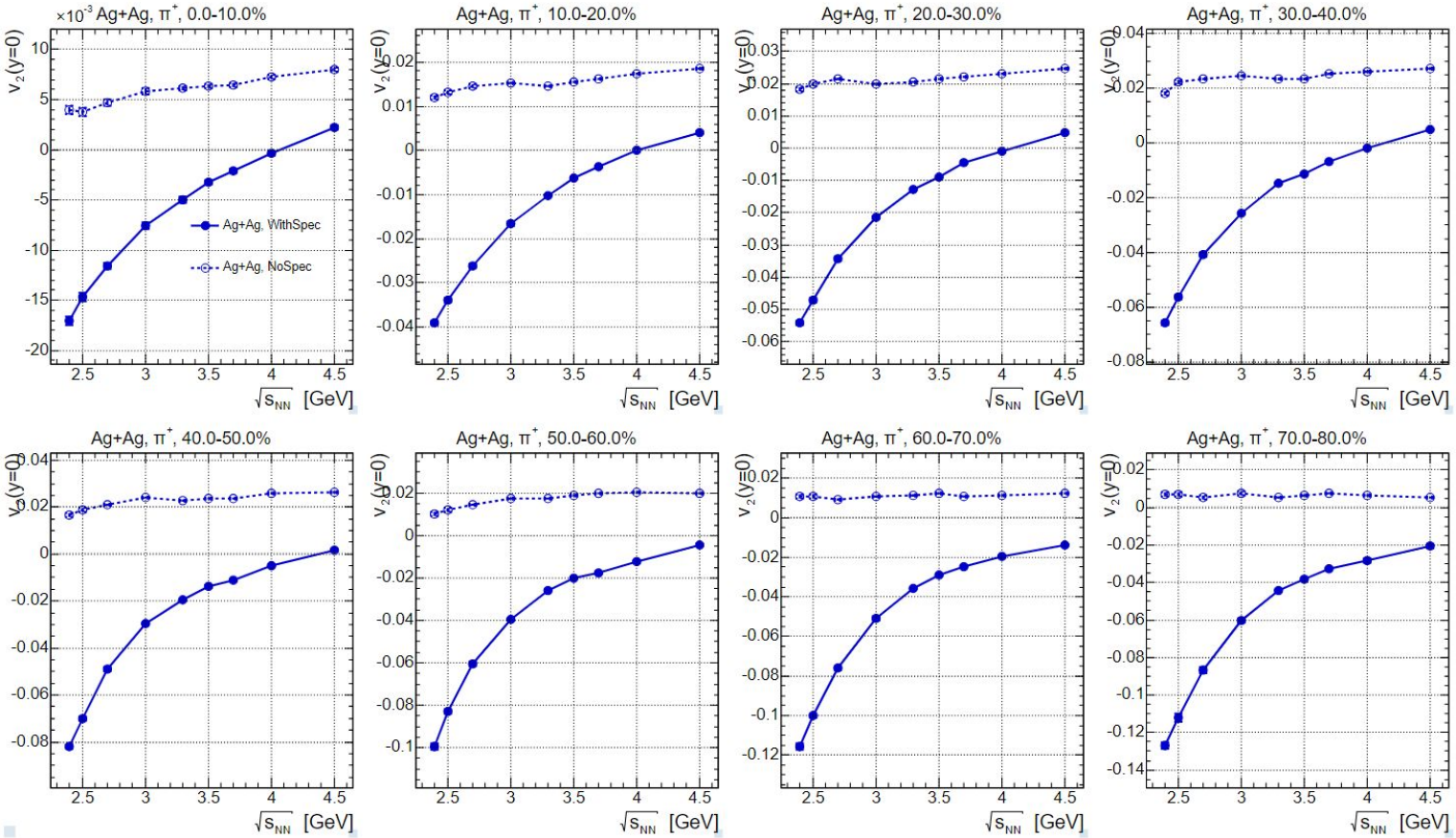
$dv_1/dy|_{y=0}$ for U+U (π^+)



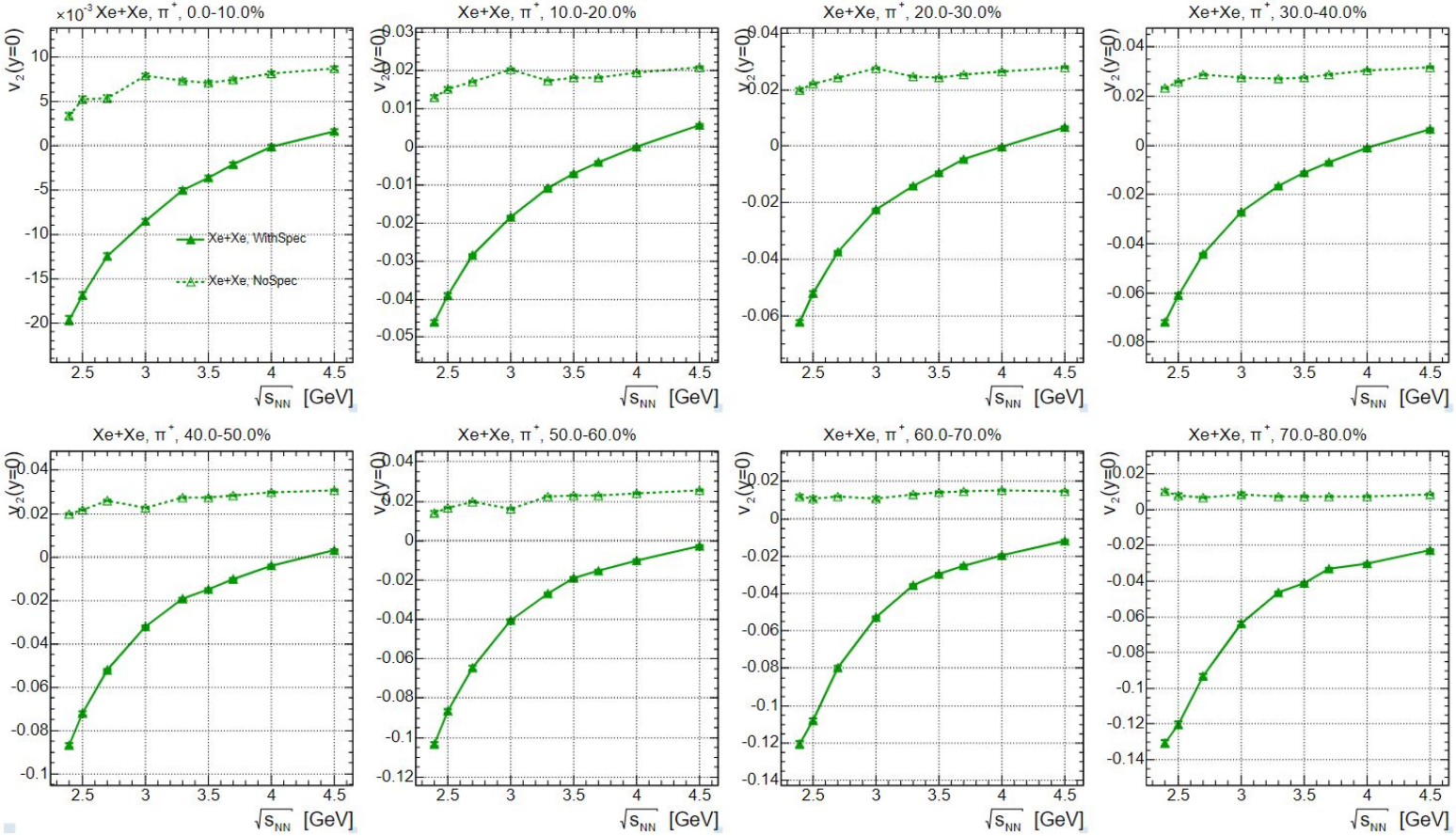
$v_2|_{y=0}$ for Au+Au (π^+)



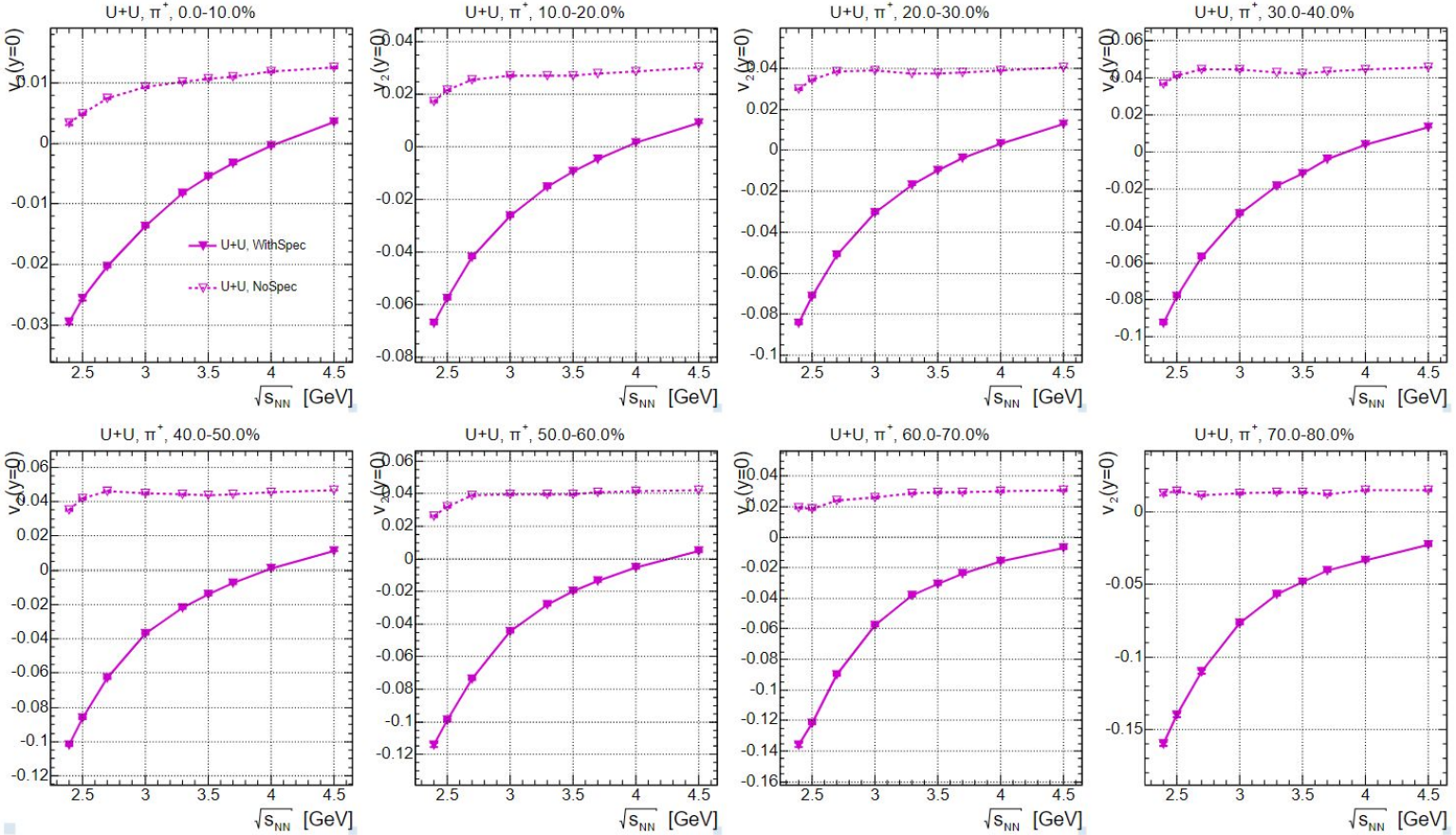
$v_2|_{y=0}$ for Ag+Ag (π^+)



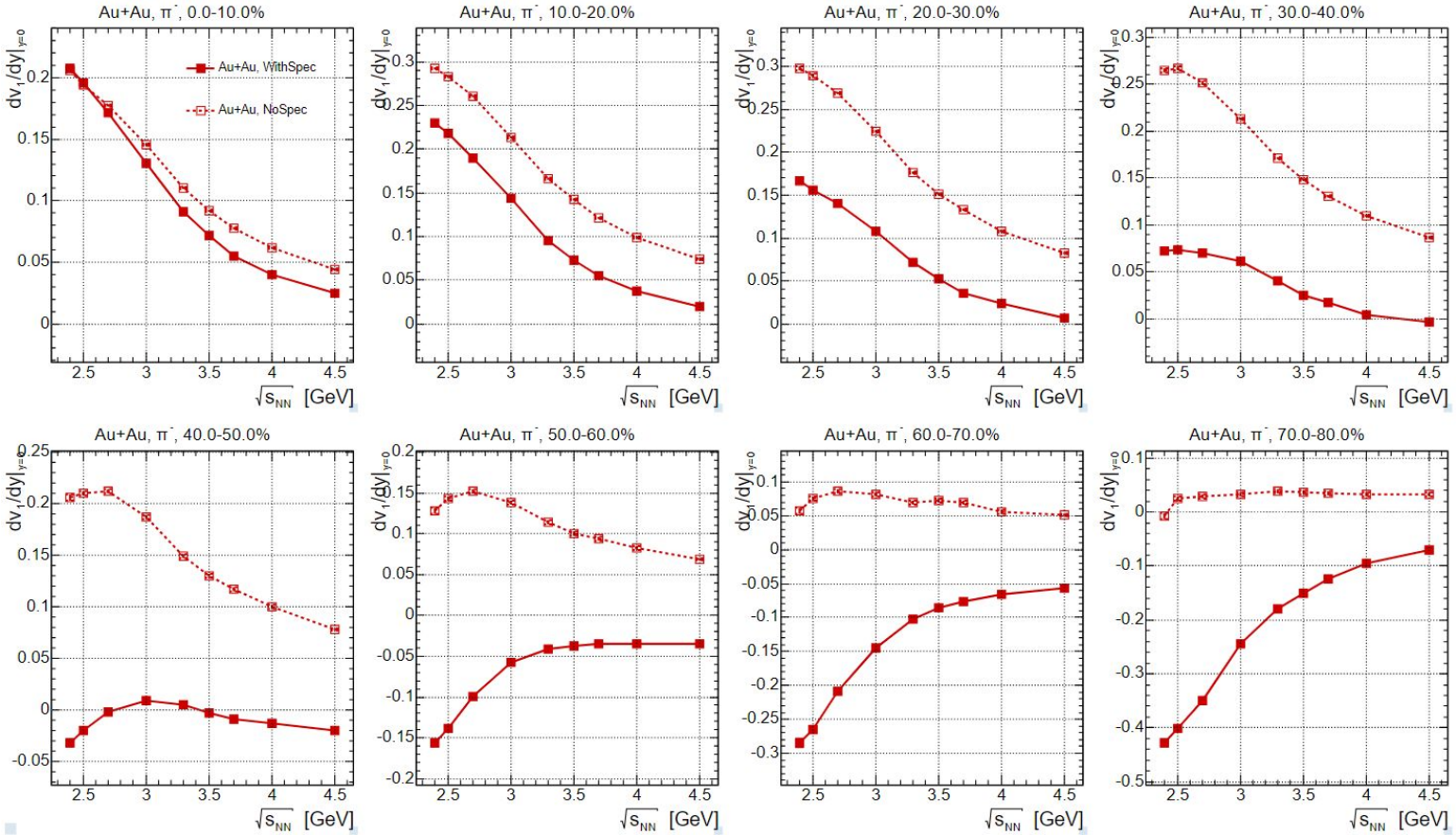
$v_2|_{y=0}$ for Xe+Xe (π^+)



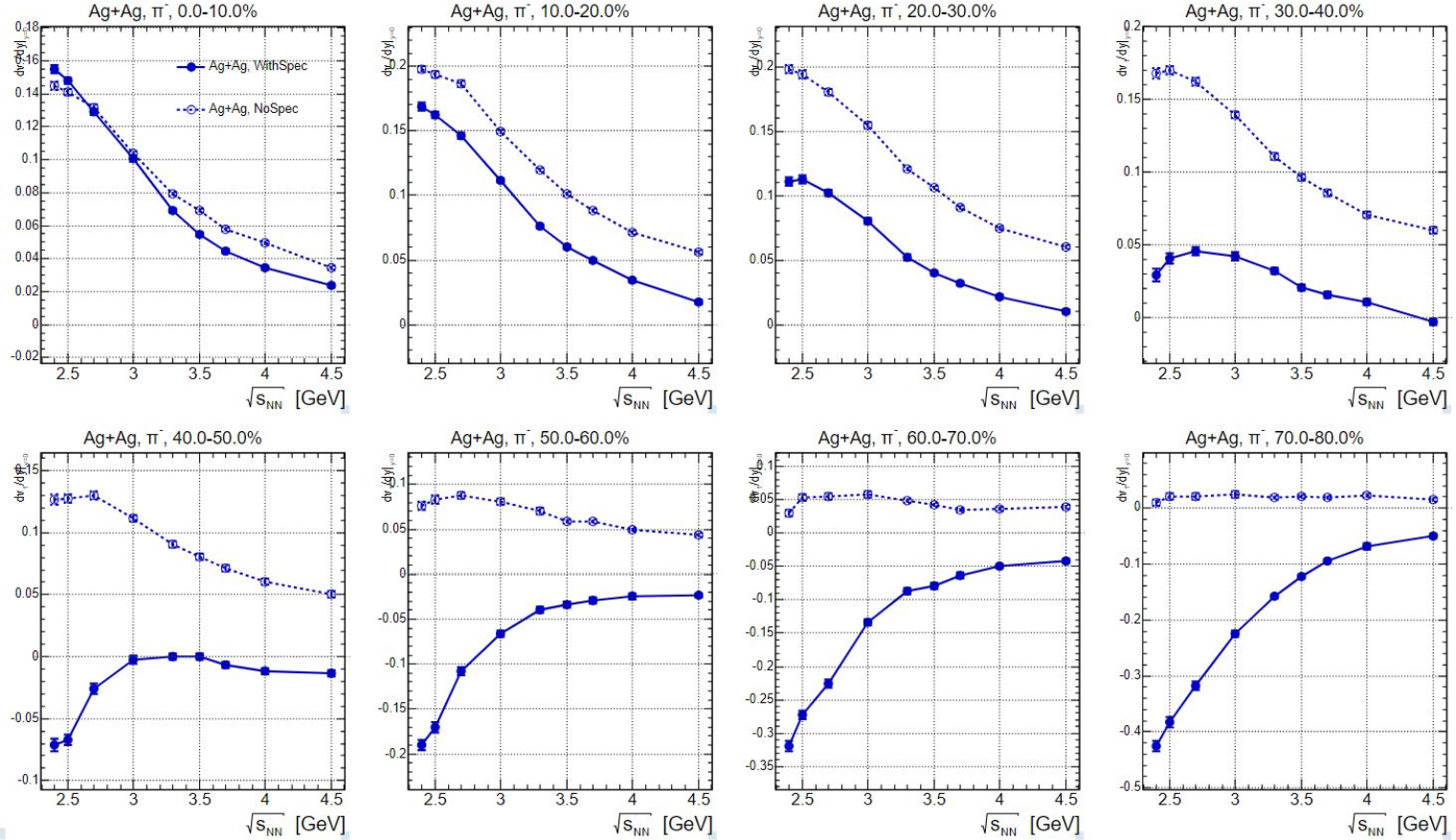
$v_2|_{y=0}$ for U+U (π^+)



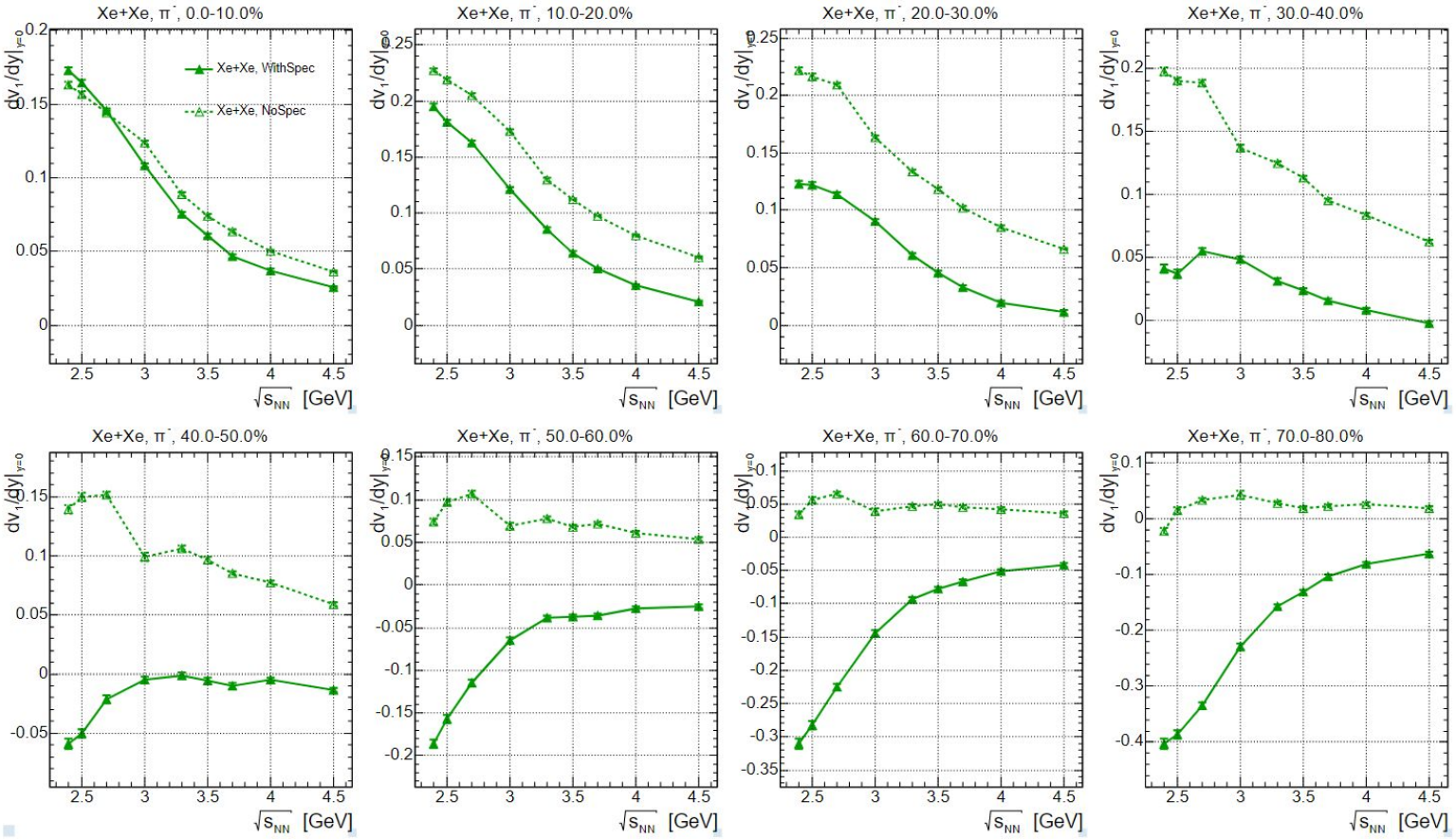
$dv_1/dy|_{y=0}$ for Au+Au (π^-)



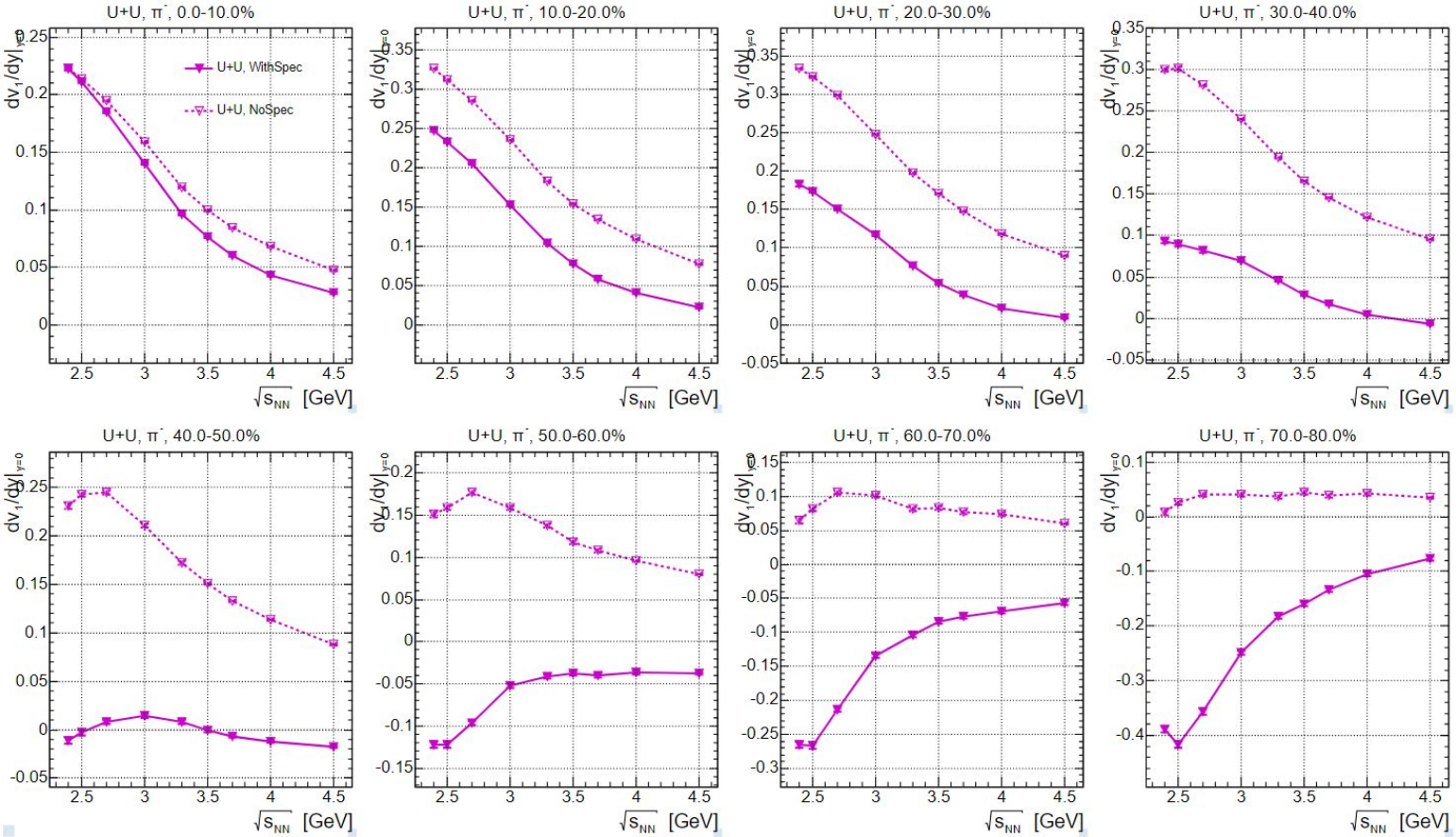
$dv_1/dy|_{y=0}$ for Ag+Ag (π^-)



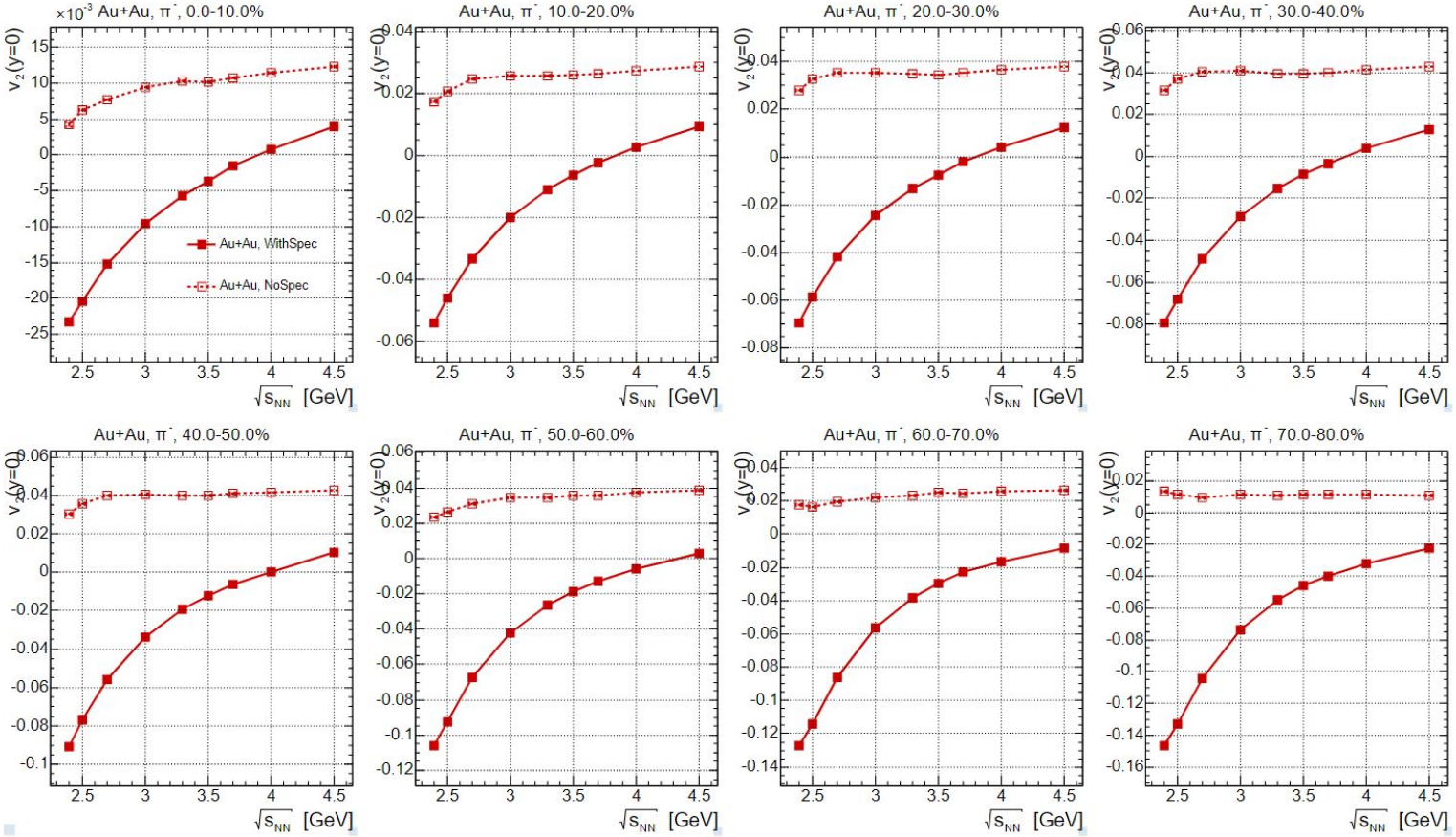
$dv_1/dy|_{y=0}$ for Xe+Xe (π^-)



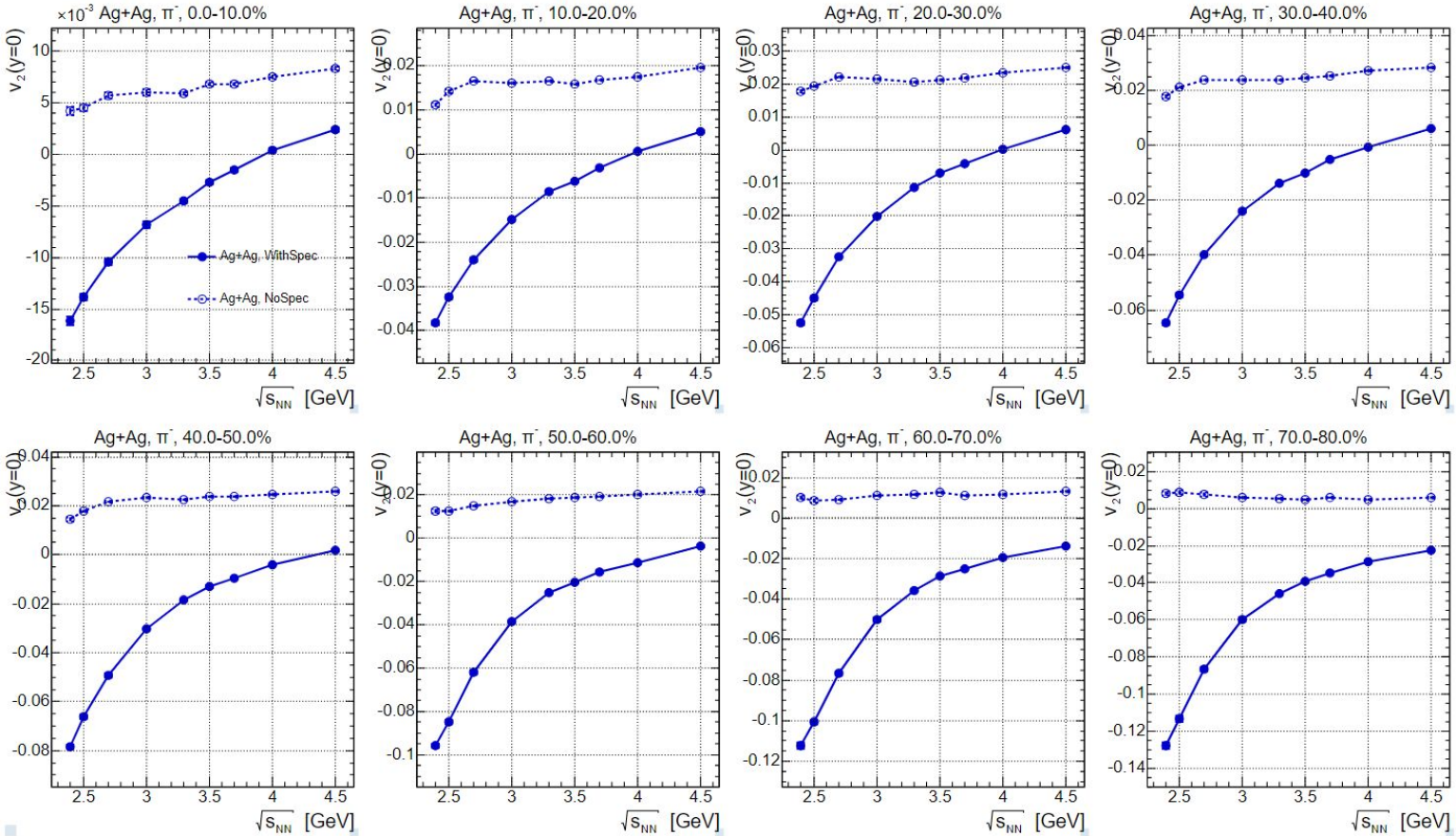
$dv_1/dy|_{y=0}$ for U+U (π^-)



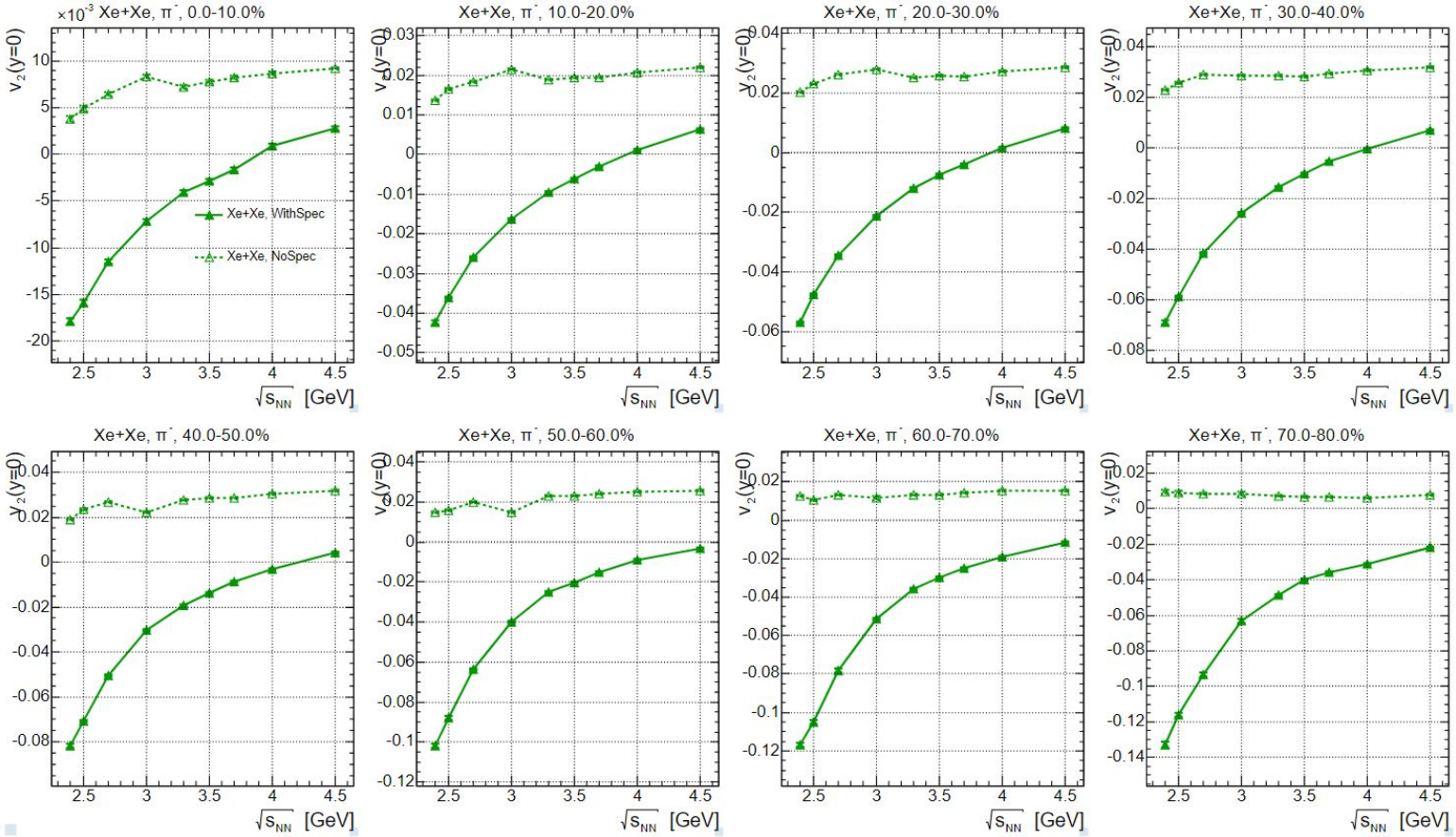
$v_2|_{y=0}$ for Au+Au (π^-)



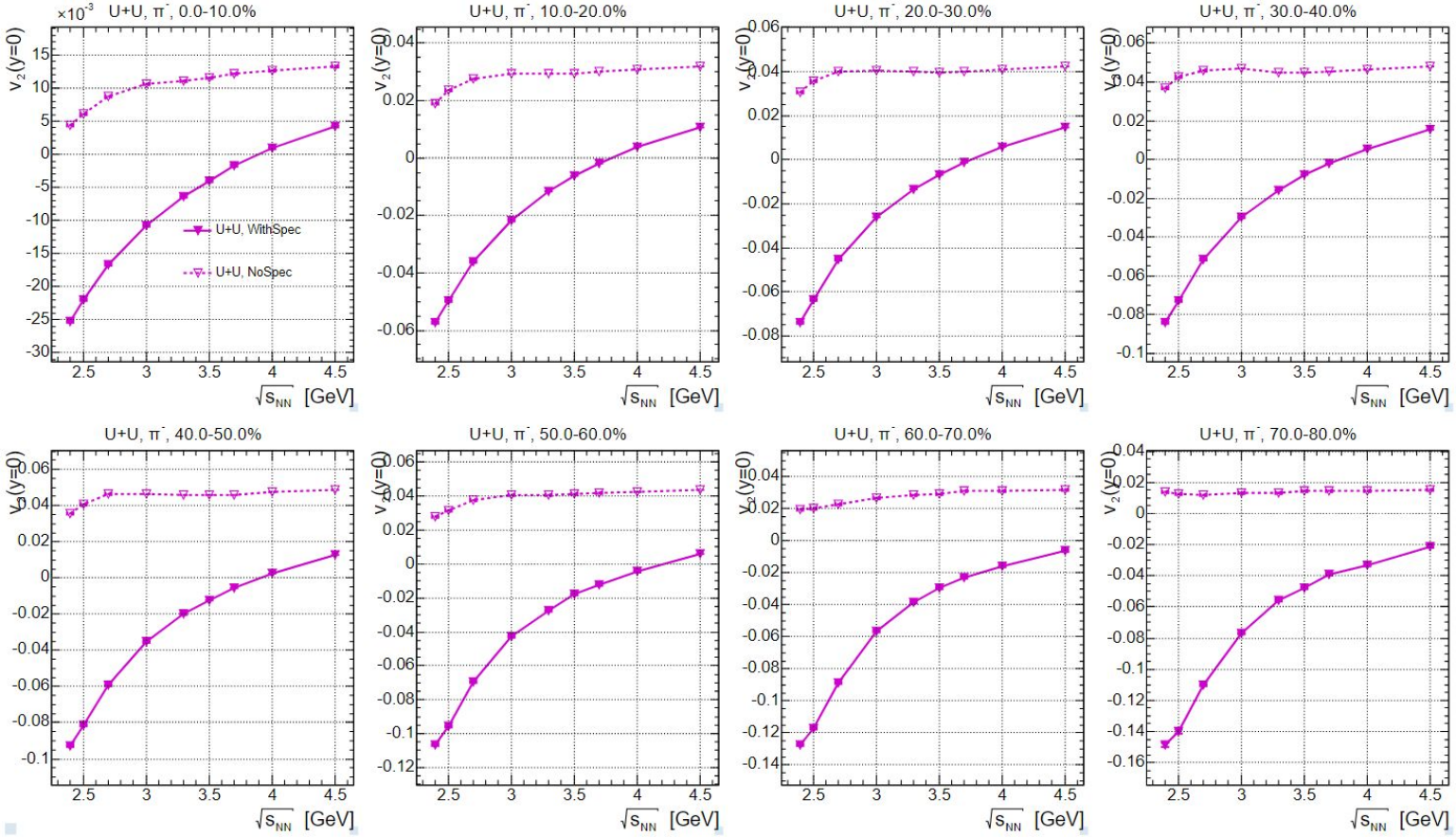
$v_2|_{y=0}$ for Ag+Ag (π^-)



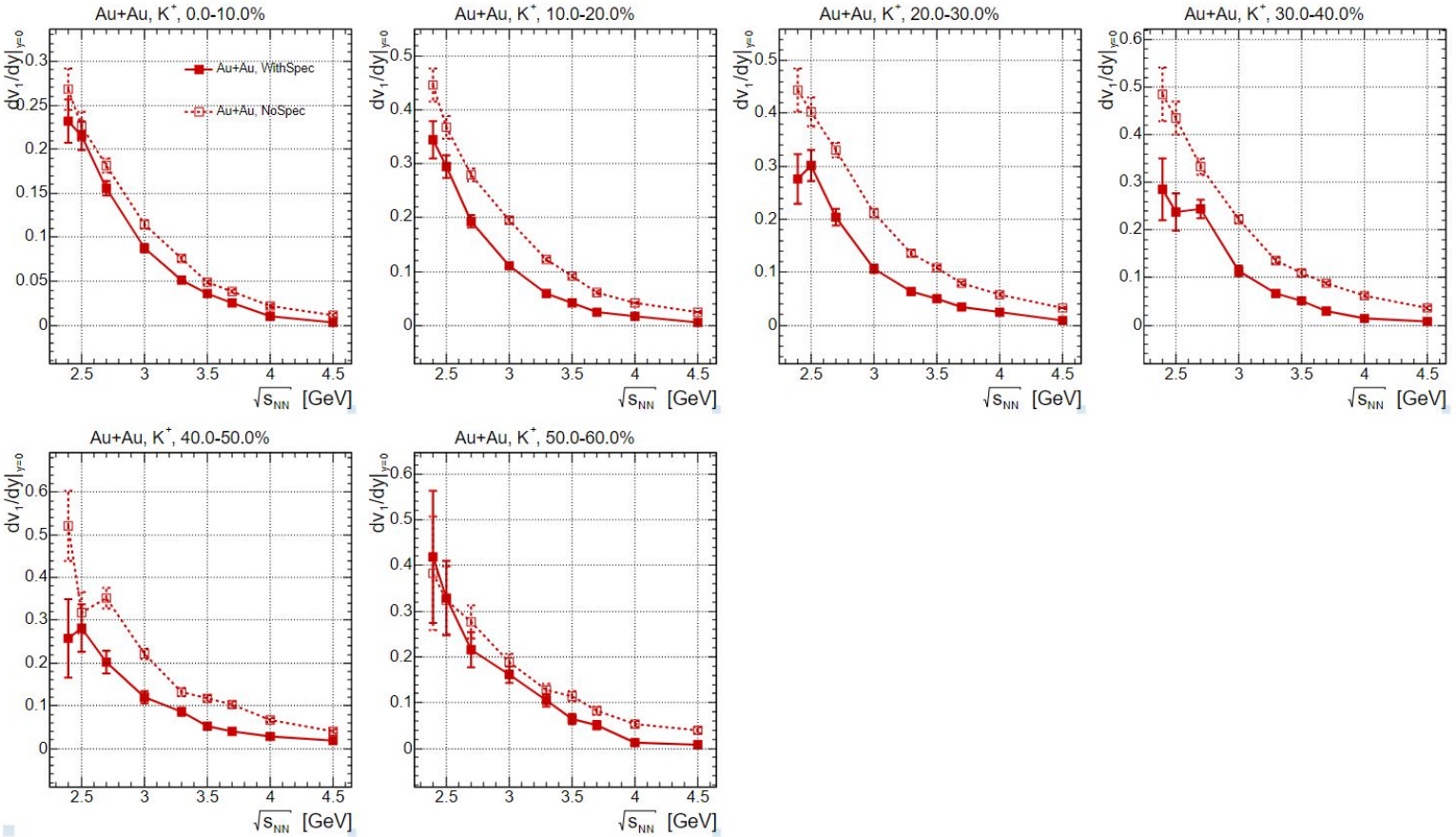
$v_2|_{y=0}$ for Xe+Xe (π^-)



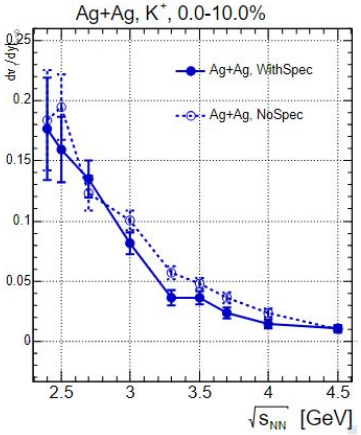
$v_2|_{y=0}$ for U+U (π^-)

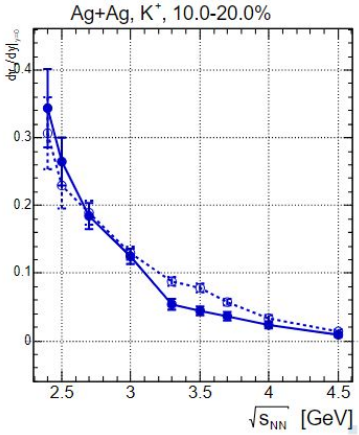


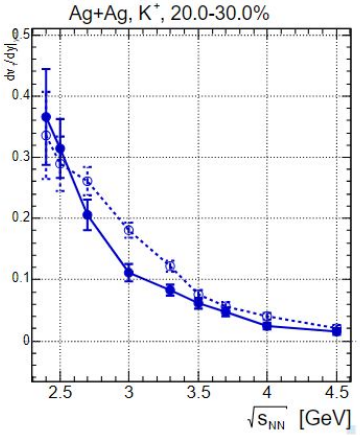
$dv_1/dy|_{y=0}$ for Au+Au (K^+)

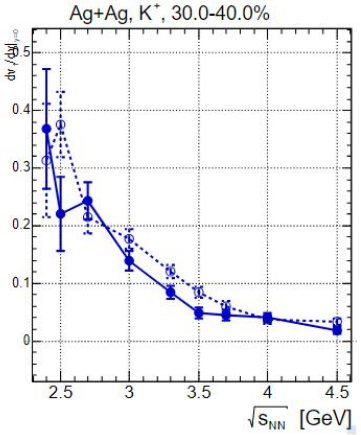


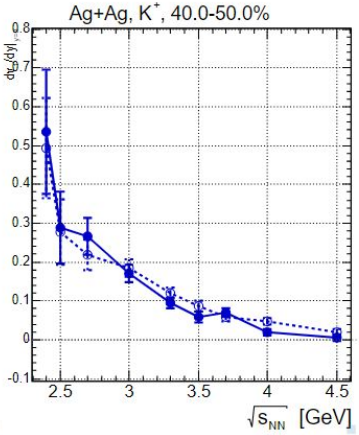
$dv_1/dy|_{y=0}$ for Ag+Ag (K^+)

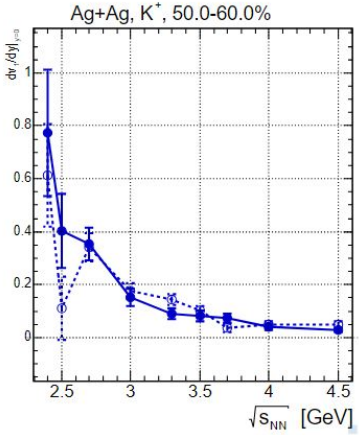




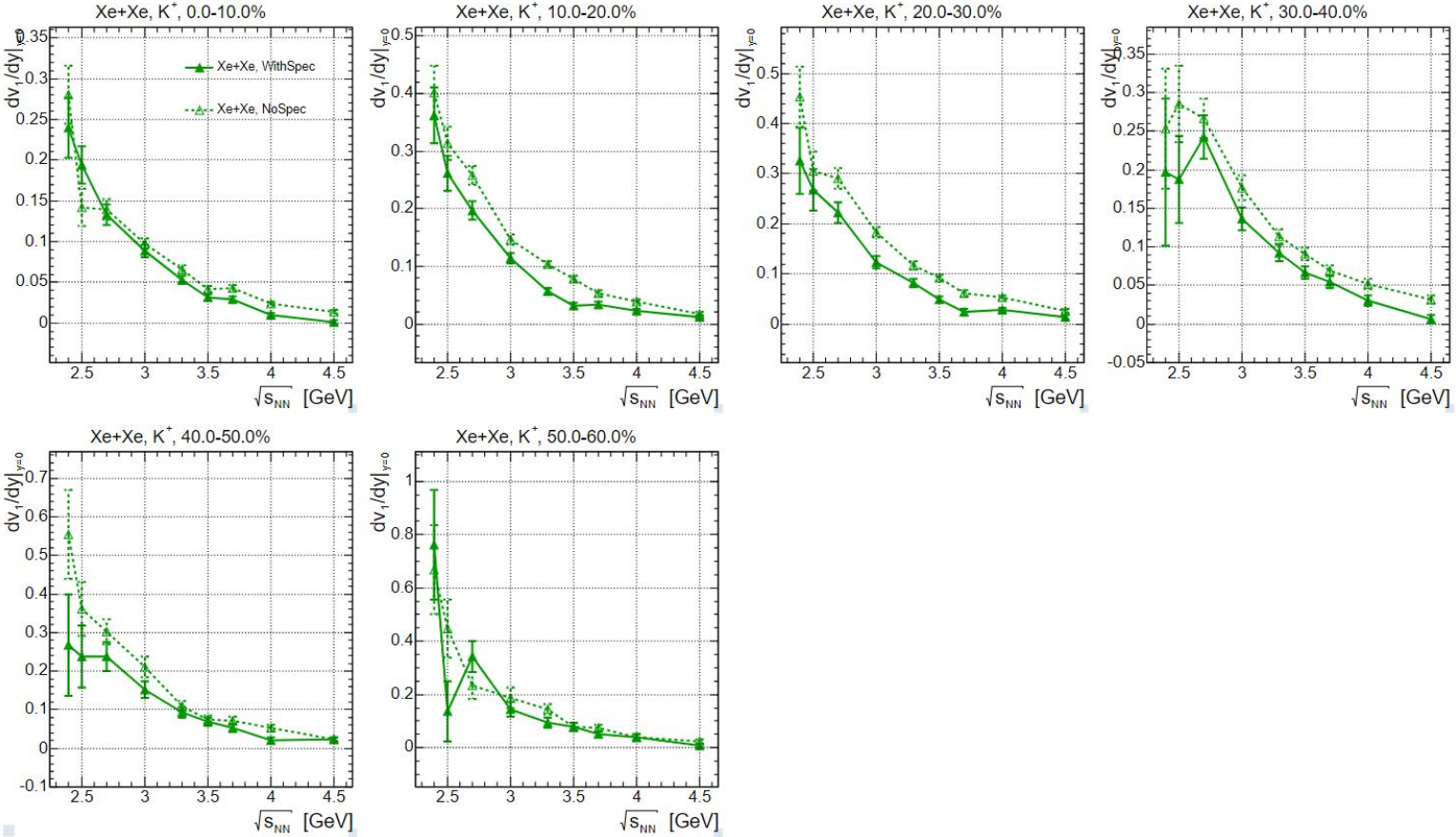








$dv_1/dy|_{y=0}$ for Xe+Xe (K^+)



$dv_1/dy|_{y=0}$ for U+U (K^+)

