Flow in the FXT region

The QCD Critical Point: Are We There Yet?

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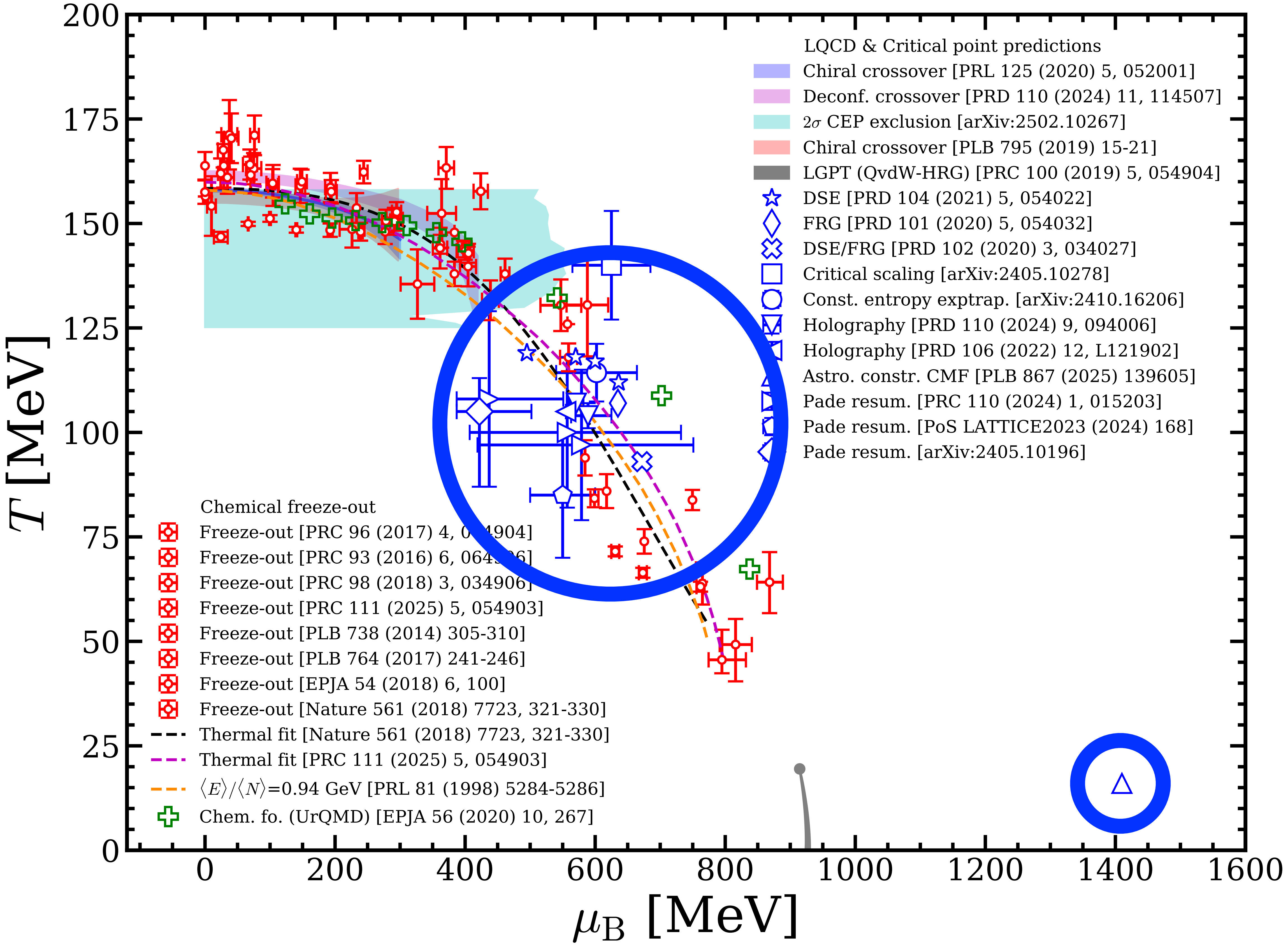
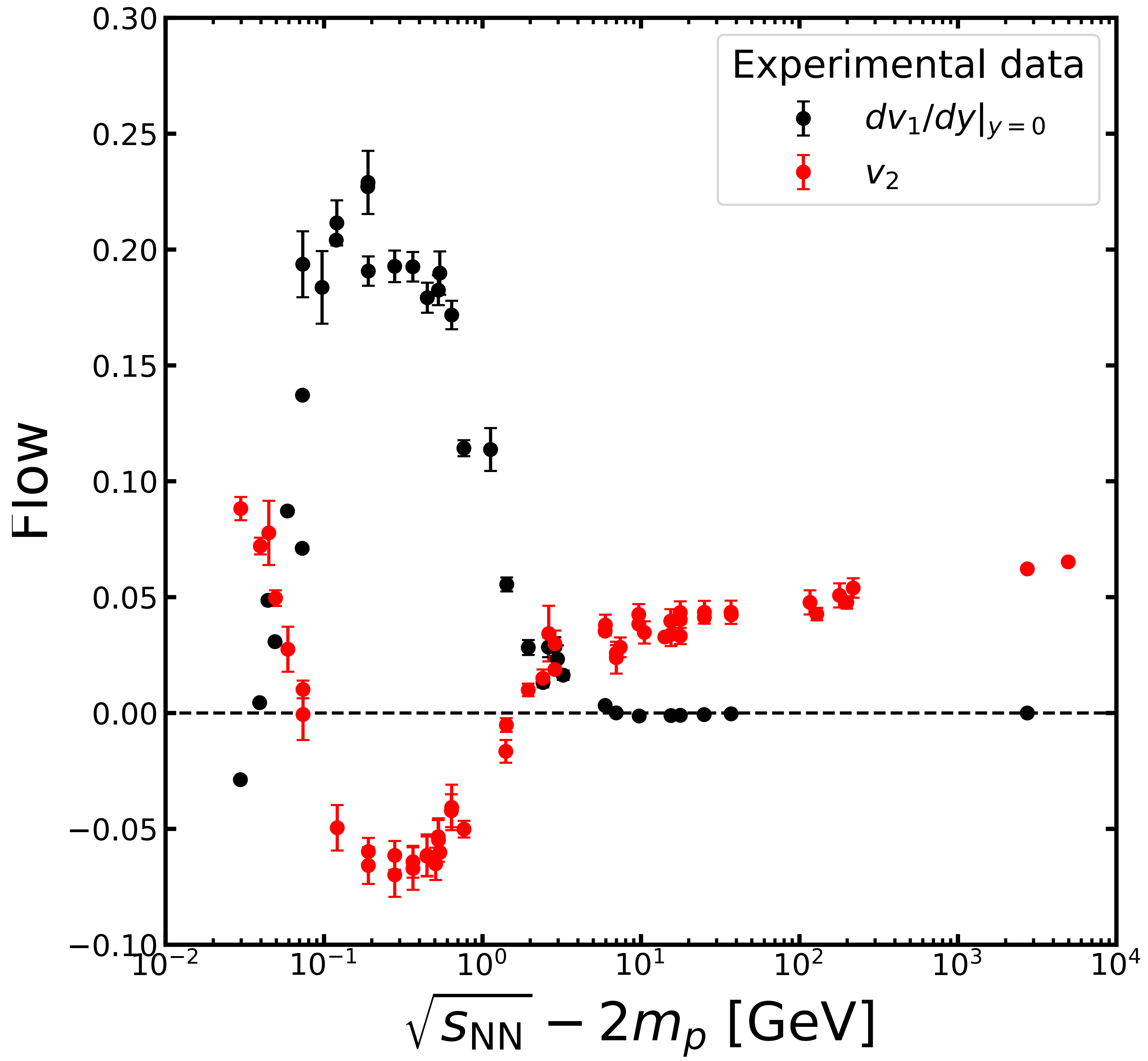
QCD critical point: Are we there yet?

Compilation of statements about the QCD phase diagram



Compilation of p_T-integrated flow measurements



$\mu_{B,\mathrm{c}} \in (400,\ 800)$ MeV, $\mathrm{T_c} \in (75,\ 125)$ MeV

corresponds to freeze-out parameters for $\sqrt{s} \in (4,\ 7)$ GeV

Flow varies a lot in this region:
- reflects rich (complex) physics
- opportunity to extract the EOS *IF* model systematics are understood

STAR data: what is available *now*

Published or “official” preliminary: differential measurements

FXT: $\sqrt{s} = 3.0 - 4.5\ \mathrm{GeV}$
Collider: $\sqrt{s} = 7.7 - 200\ \mathrm{GeV}$

Flow Harmonics: using reaction plane method (mostly to Ψ_1)

- v_2: p_T distributions for $-0.5 < y < 0$, rapidity distribution at 4 GeV, all particles, 10-40%
- v_1: rapidity distributions
- dv_1/dy: mostly protons + some $\pi,\ K,\ \Lambda$, antiparticles, mostly 10-40%
- v_3: rapidity distributions and slopes, p_T distributions (3 GeV only), protons, mostly 10-40% (at 3 GeV: peripheral, central), centrality distribution

Comparing models to data

- Energies above $\sqrt(s) = 10\ \mathrm{GeV}$:
  successful paradigm of using hydrodynamics; no such paradigm in the low energy region

- Transport models: UrQMD, SMASH, JAM:
  need: flexible potentials, momentum dependence, maybe in-medium cross sections?

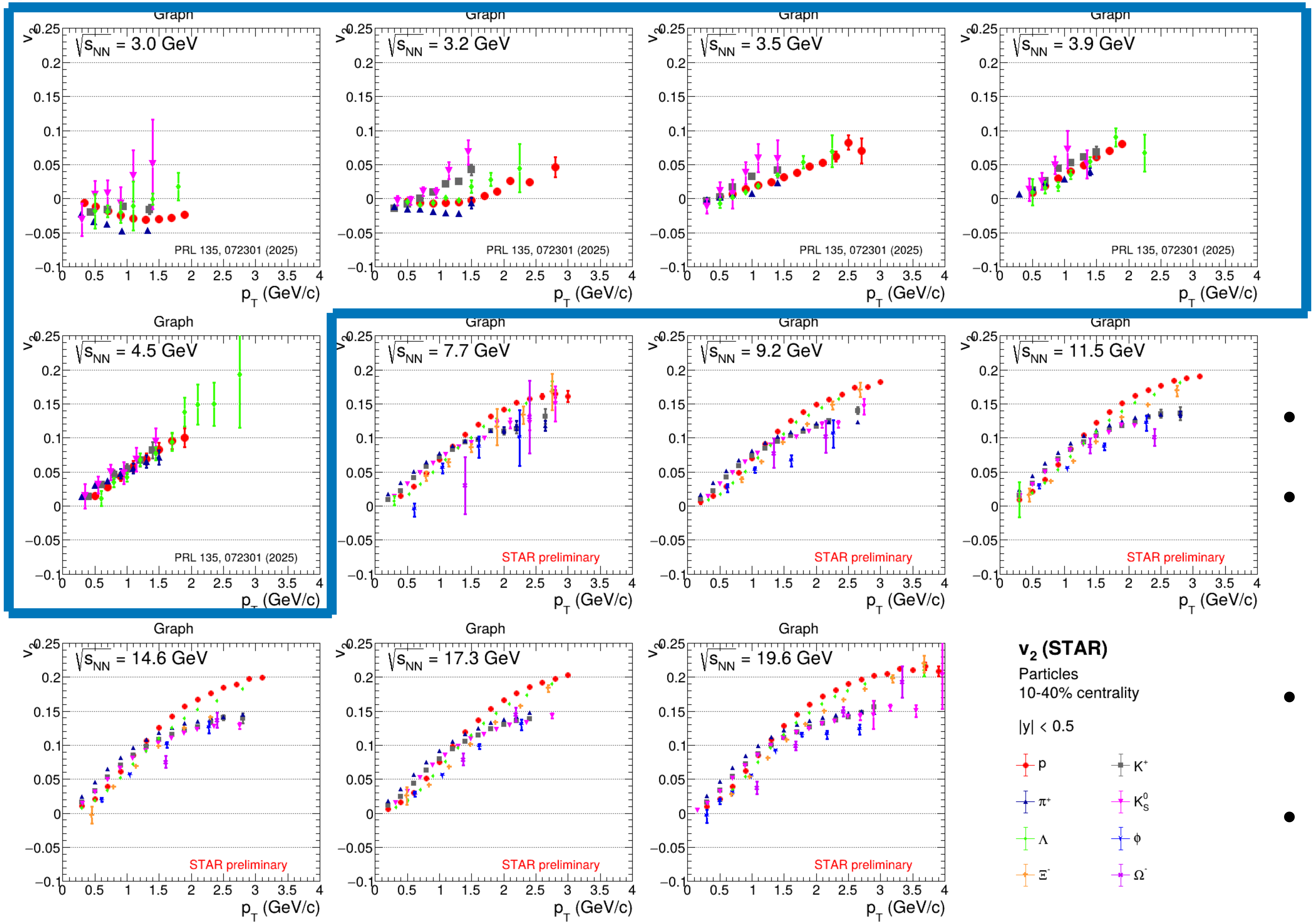
- Can we learn any physics by systematically comparing to models?
  need: reliability
  Experimentalists can help provide benchmarks
  Request for STAR from theoretical community: dN/dy of protons – we heard you!

- Wish from the experimentalists:
  Models with same ingredients give same results (e.g. cascade modes)
  Models available to extract physics: e.g., various forms of the potential

Goal: pinning down the location of the QCD CP / phase transition.
Are there specific observables?
Inferences from various sources should agree.

NCQ scaling of v_2: unscaled

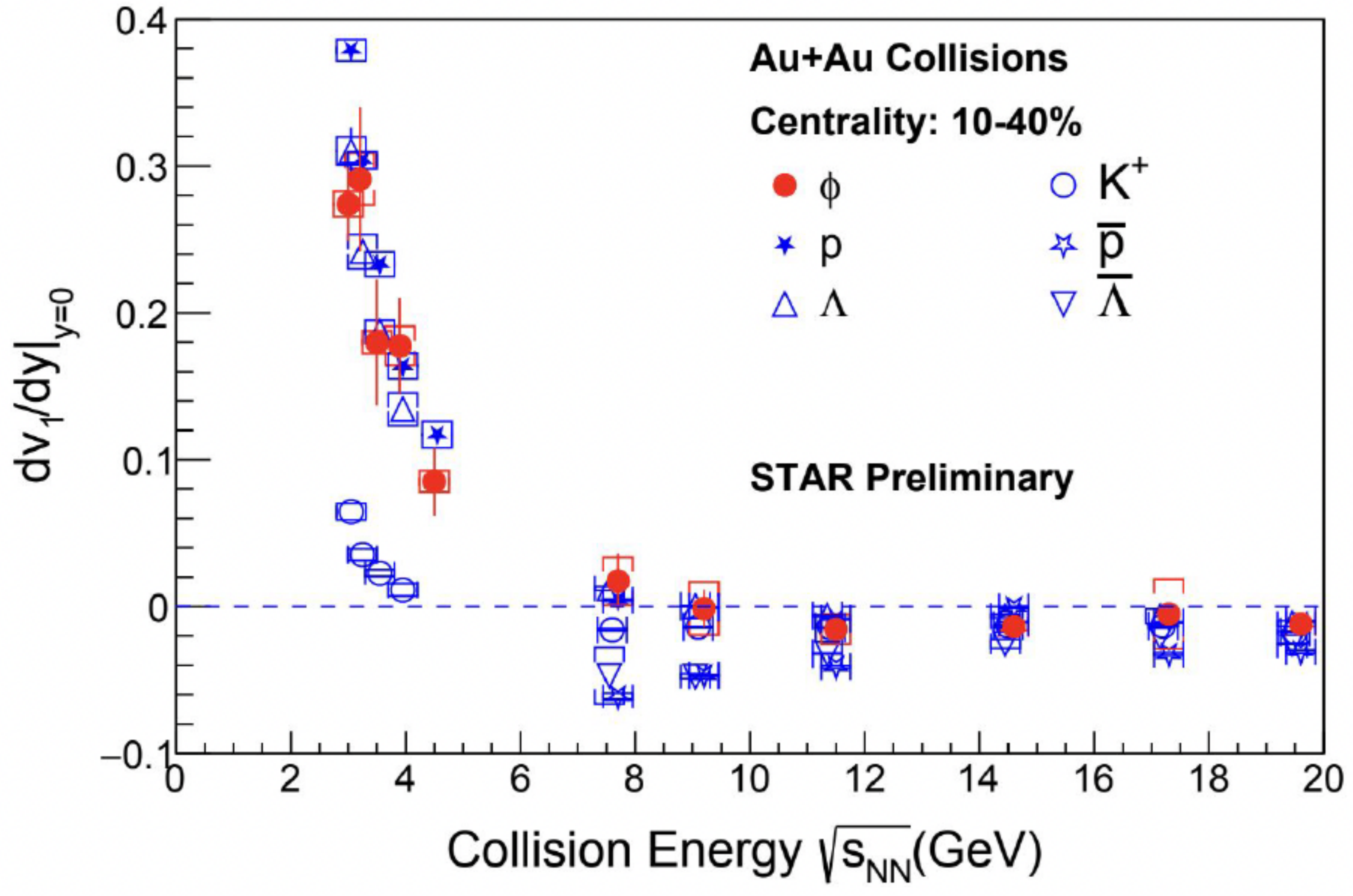
FXT

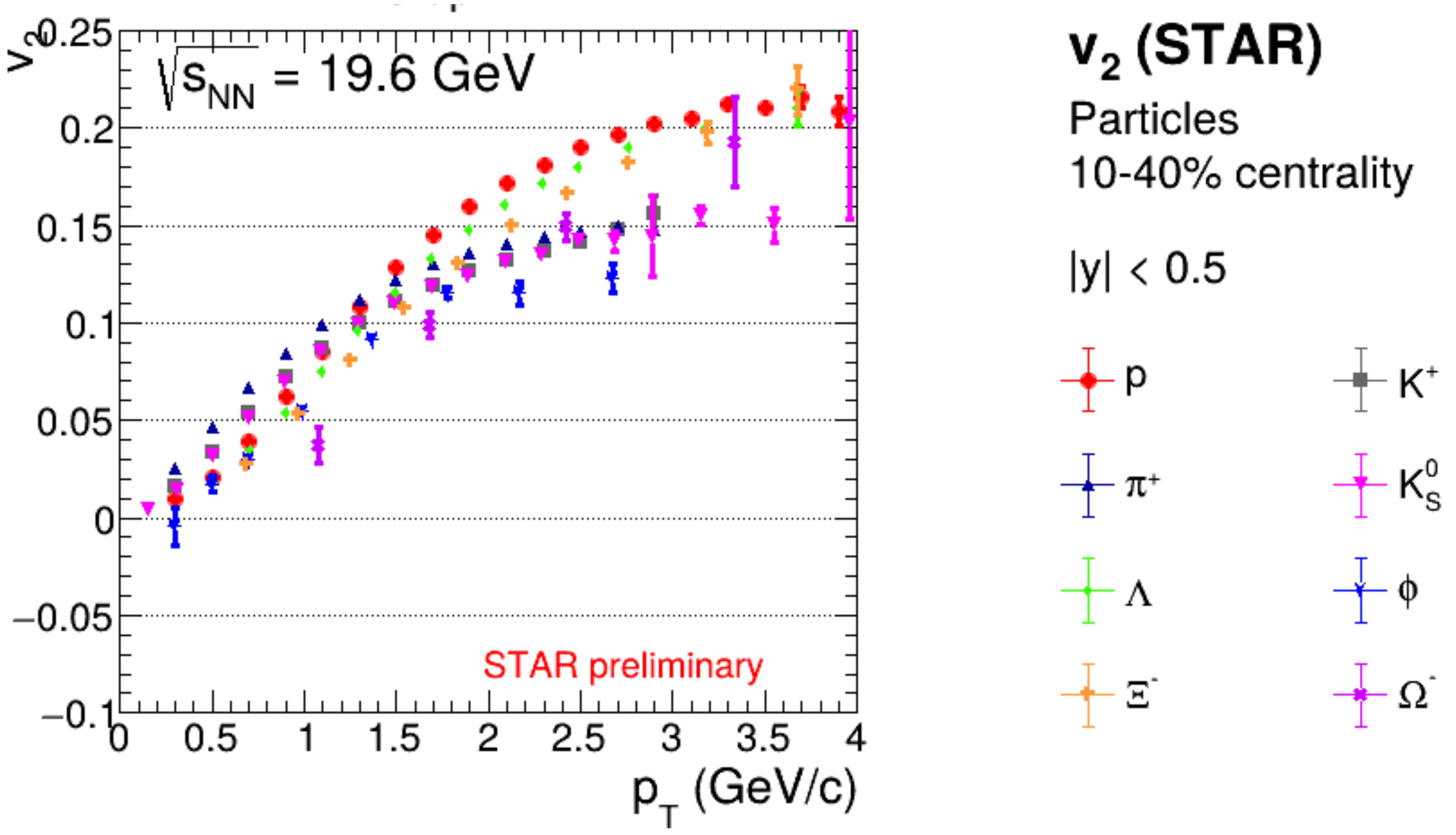


- Look for meson-baryon splitting
- Is NCQ scaling the hallmark of the (s)QGP?
  additive quark model ~ cross sections
- What is the cause of the failure of NCQ scaling below 7.7 GeV
- Tantalizingly close to 4.5 GeV mentioned as the CP

v_1 of mesons and baryons

Strong v_1 for protons; different crossing point for p and K





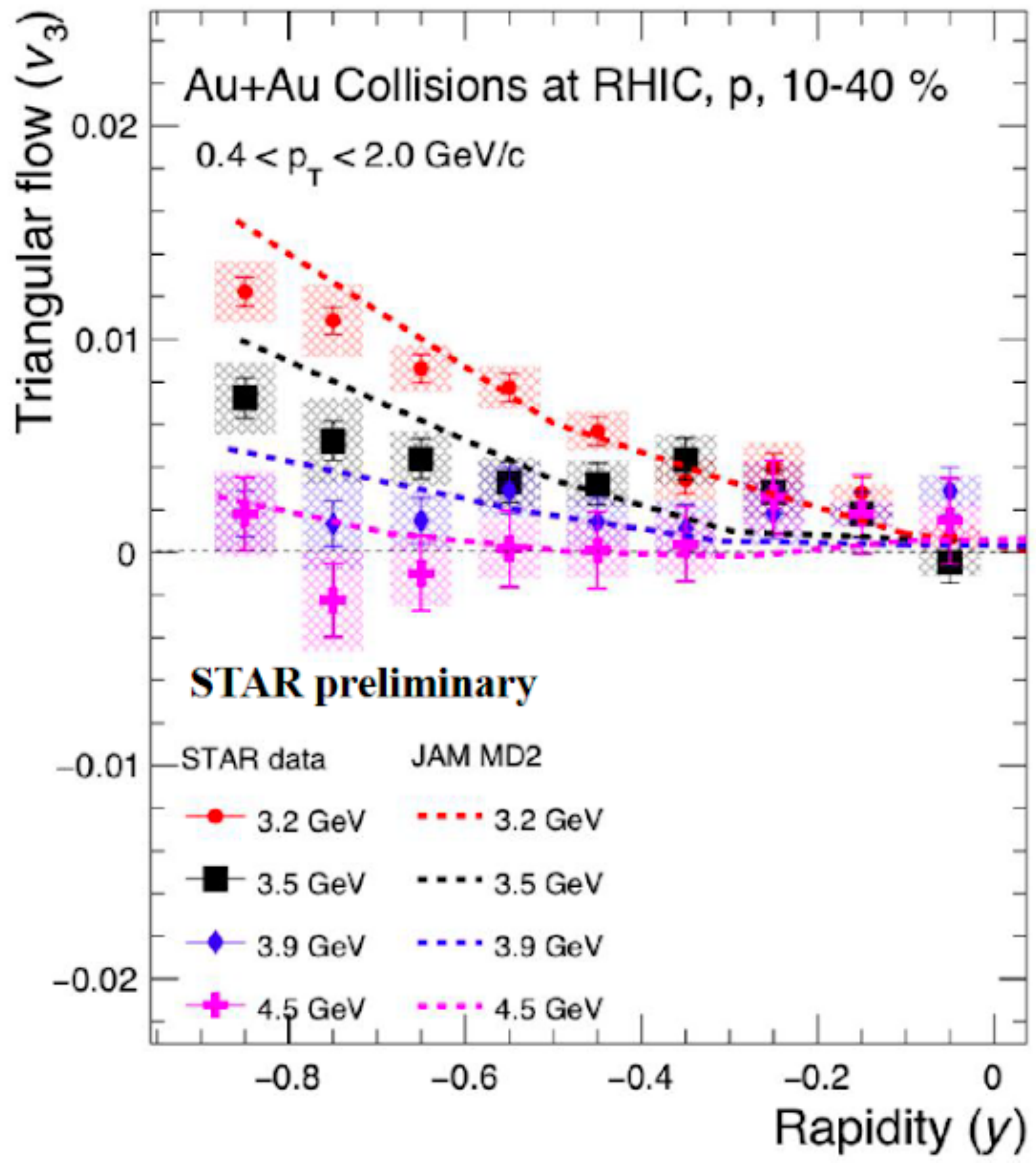
S. R. Sharma for the STAR Collaboration, QM 2025,
https://indico.cern.ch/event/1334113/contributions/6369544

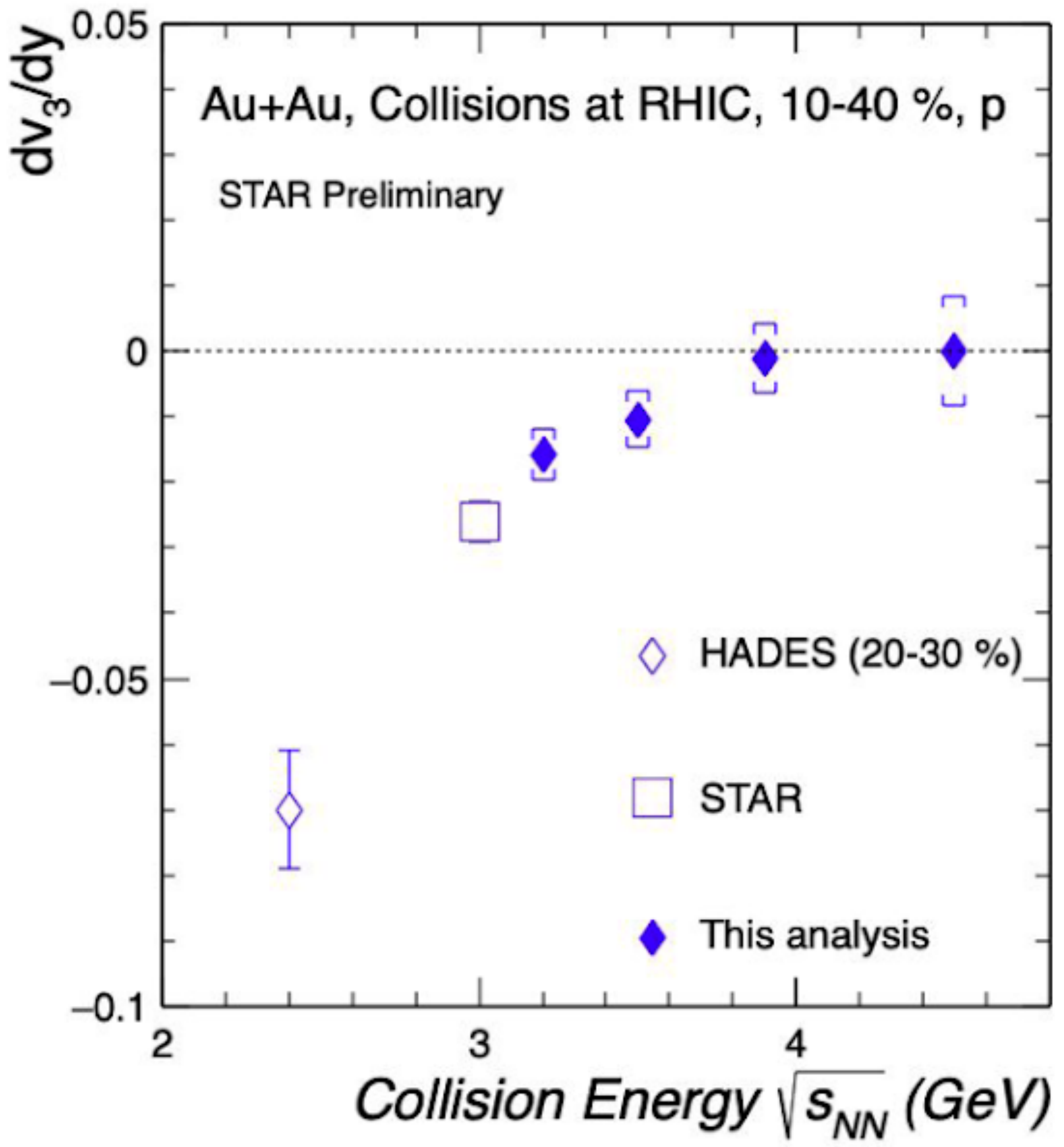
v_1 of ϕ: follows baryons
v_2 of ϕ: follows mesons

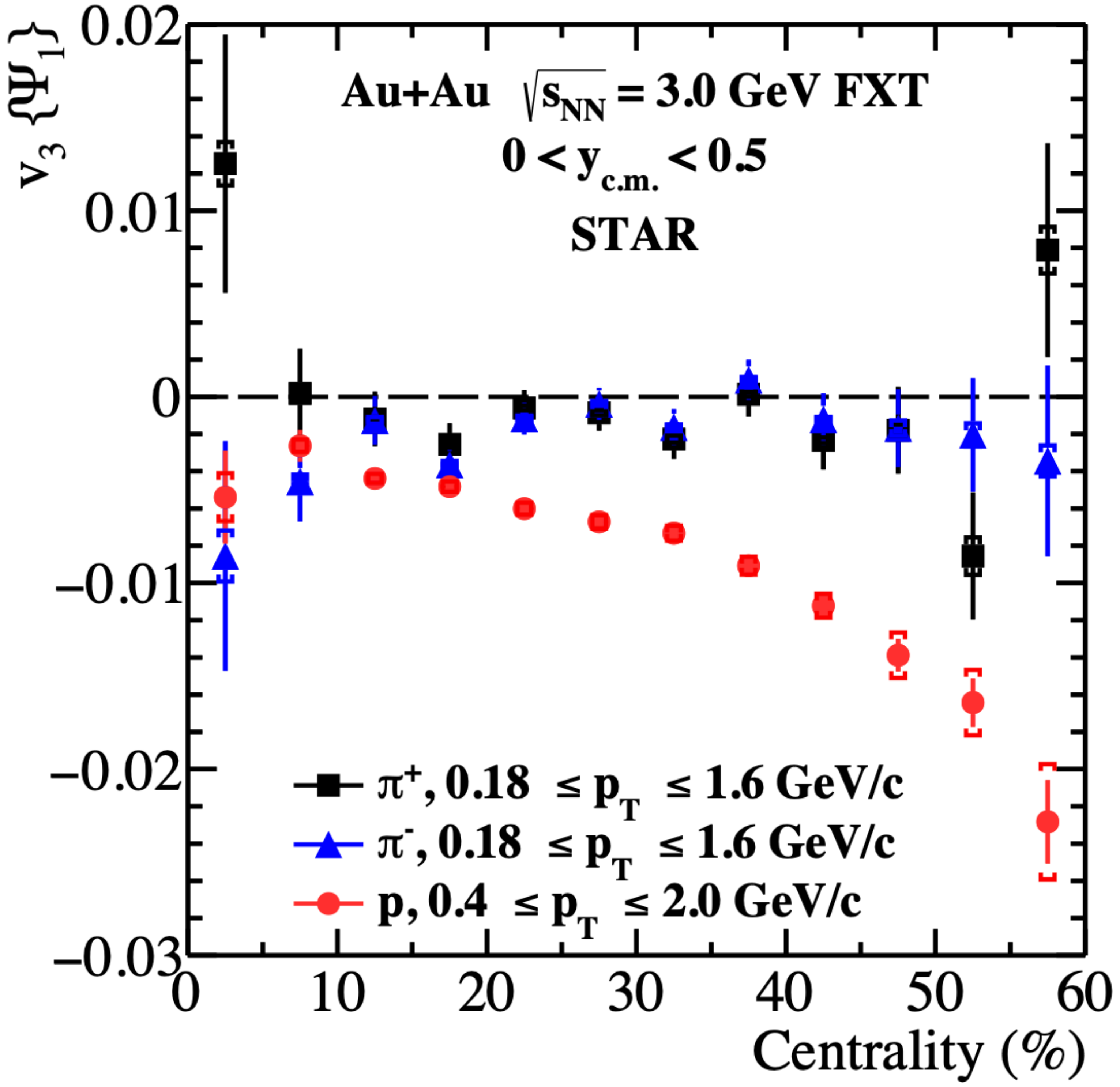
Can that be understood?

v_3 in the FXT range

Ψ_1-correlated proton v_3; signal gone at 4.5 GeV; no signal for pions (and kaons)





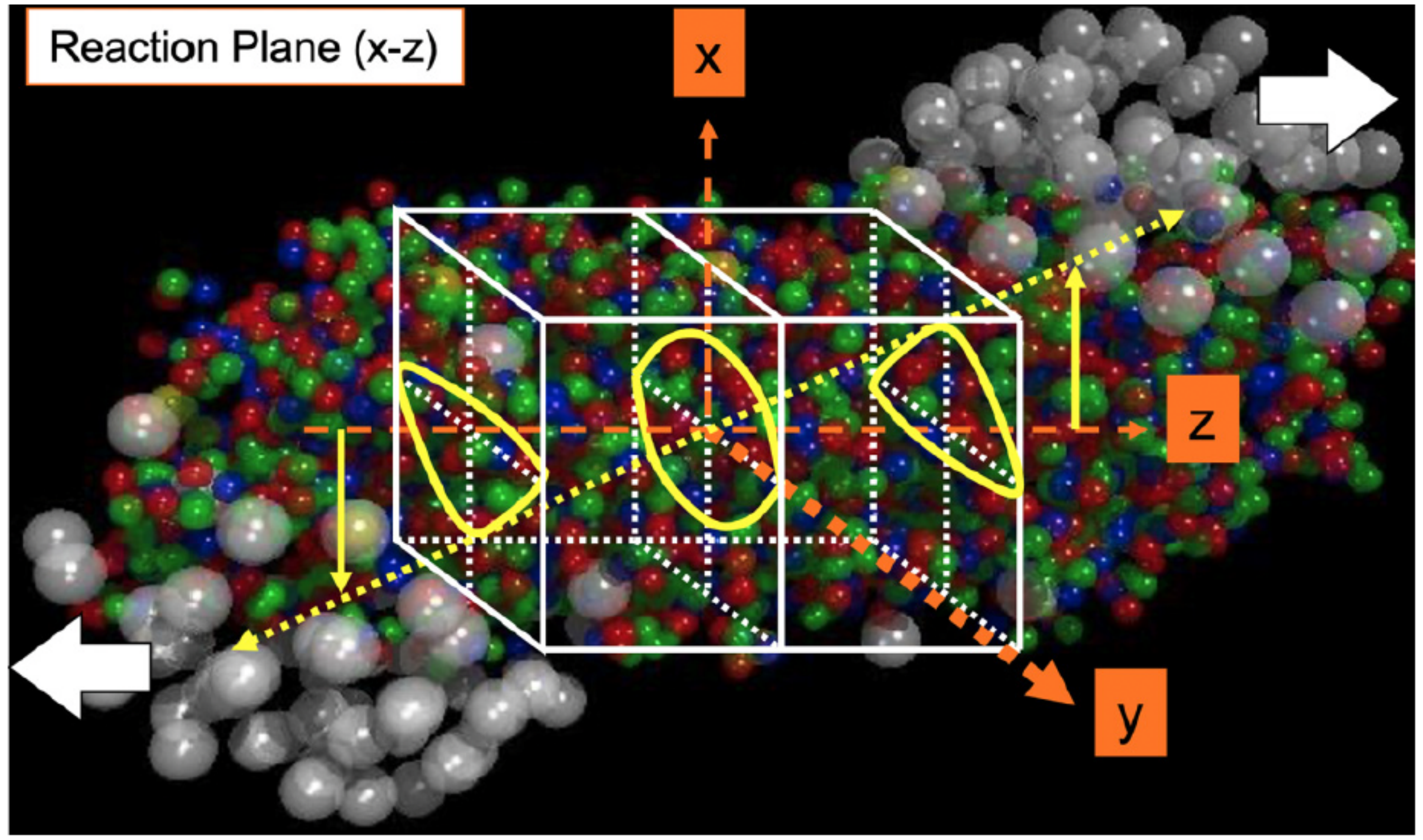


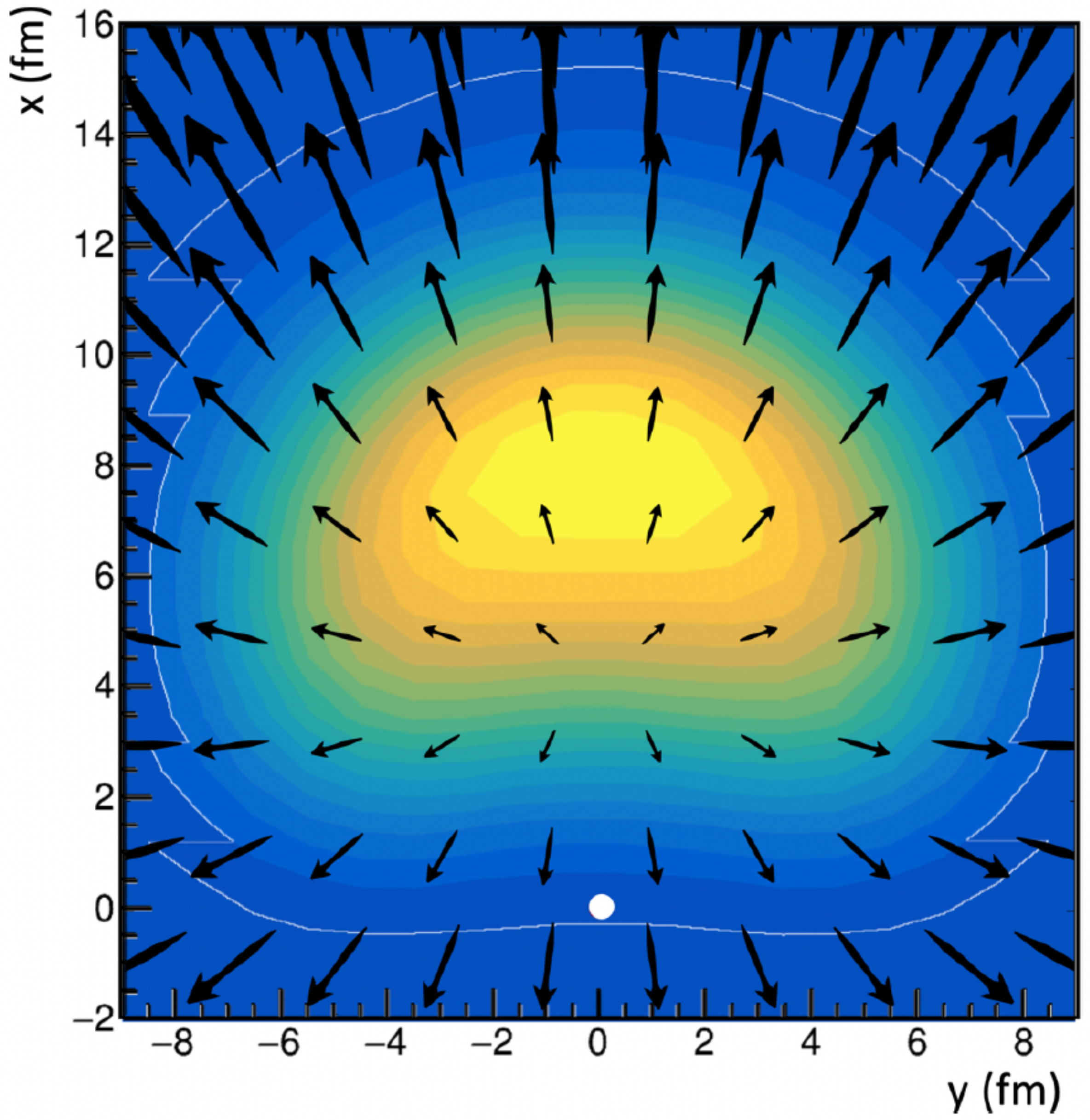
S. R. Sharma for the STAR Collaboration, QM 2025, https://indico.cern.ch/event/1334113/contributions/6369544

STAR, *Phys.Rev.C* 109 (2024) 4, 044914, arXiv: 2309.12610

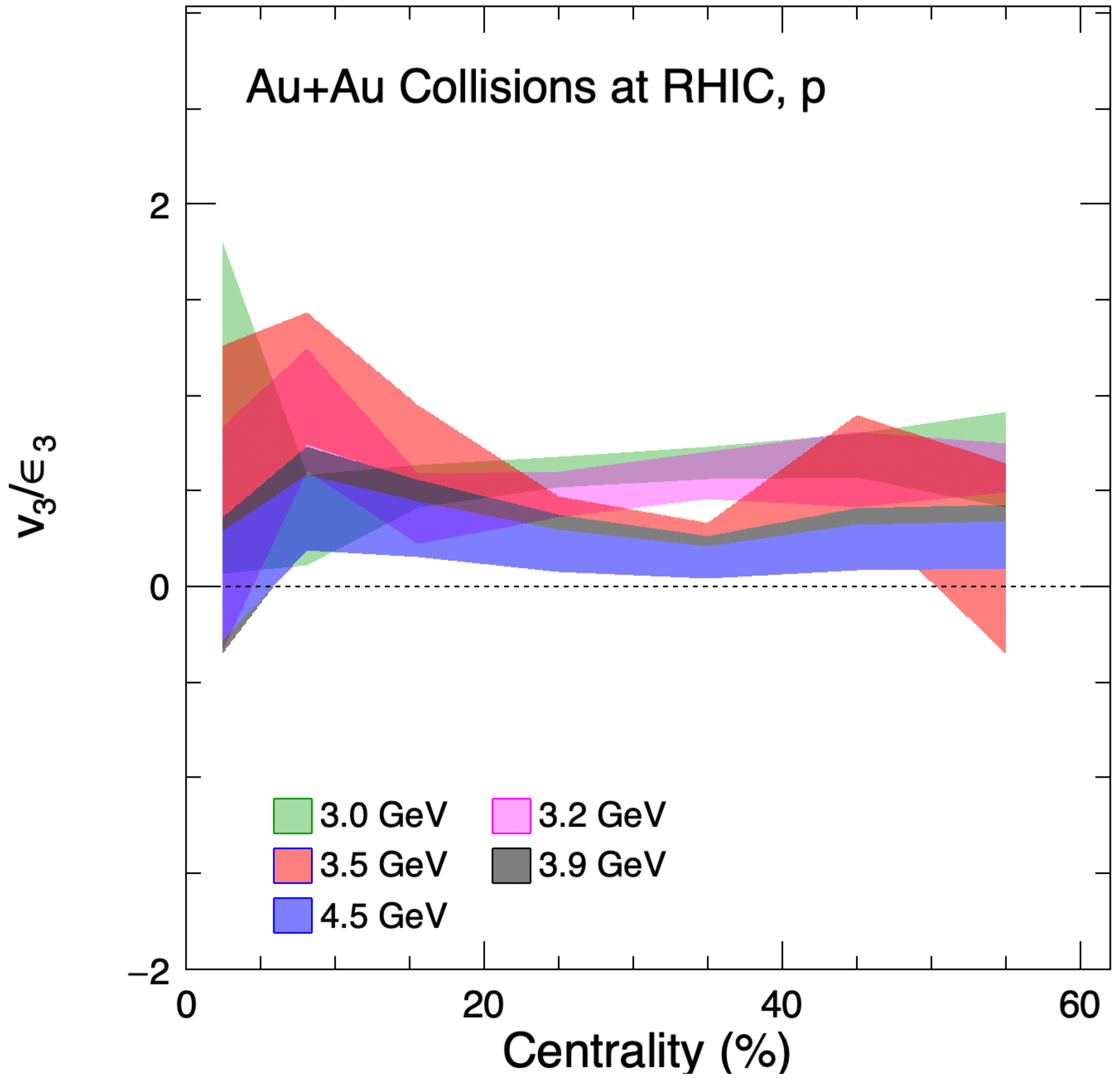
v_3 in the FXT range

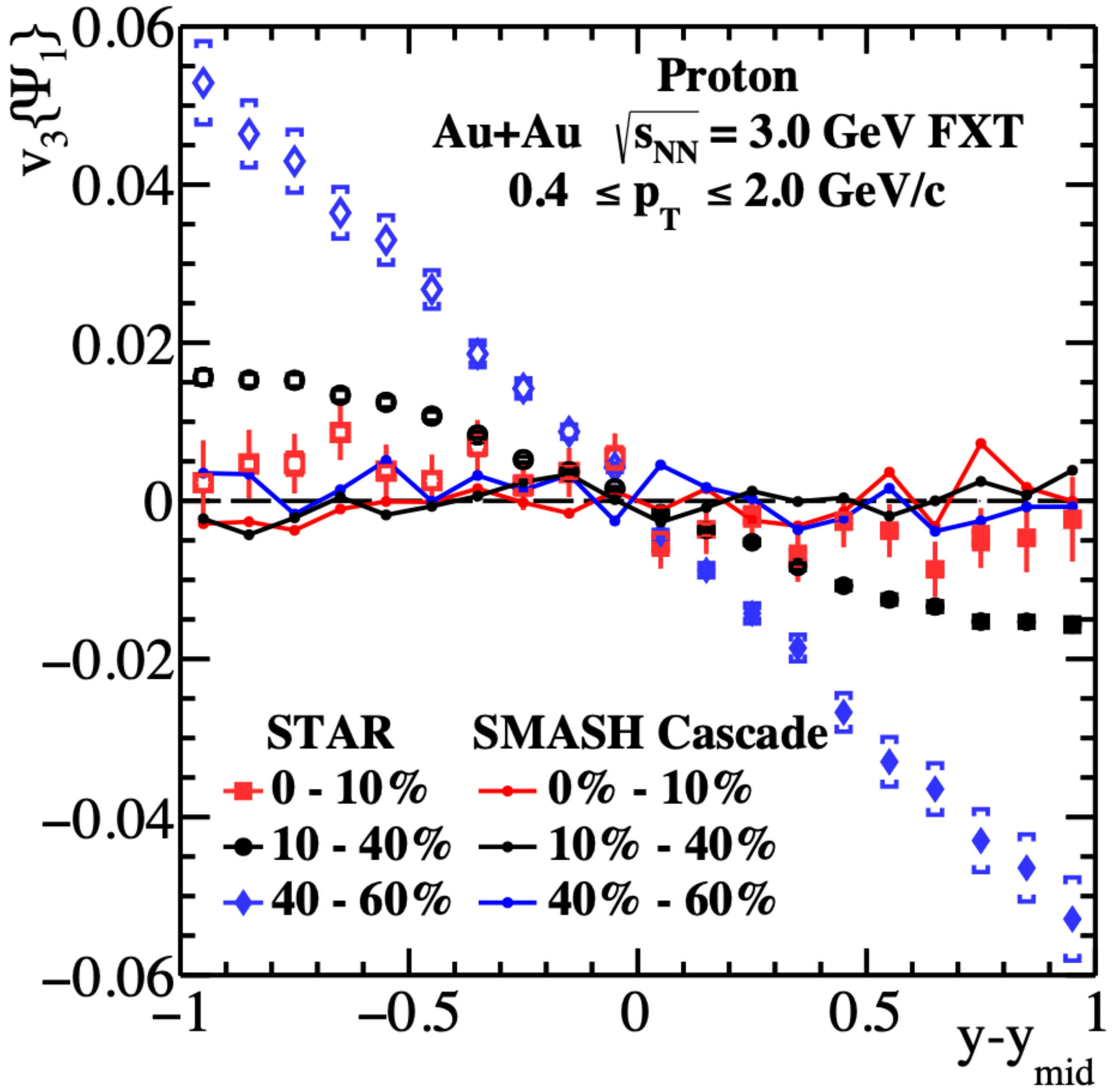
Where does the signal come from?





STAR, *Phys.Rev.C* 109 (2024) 4, 044914, arXiv: 2309.12610





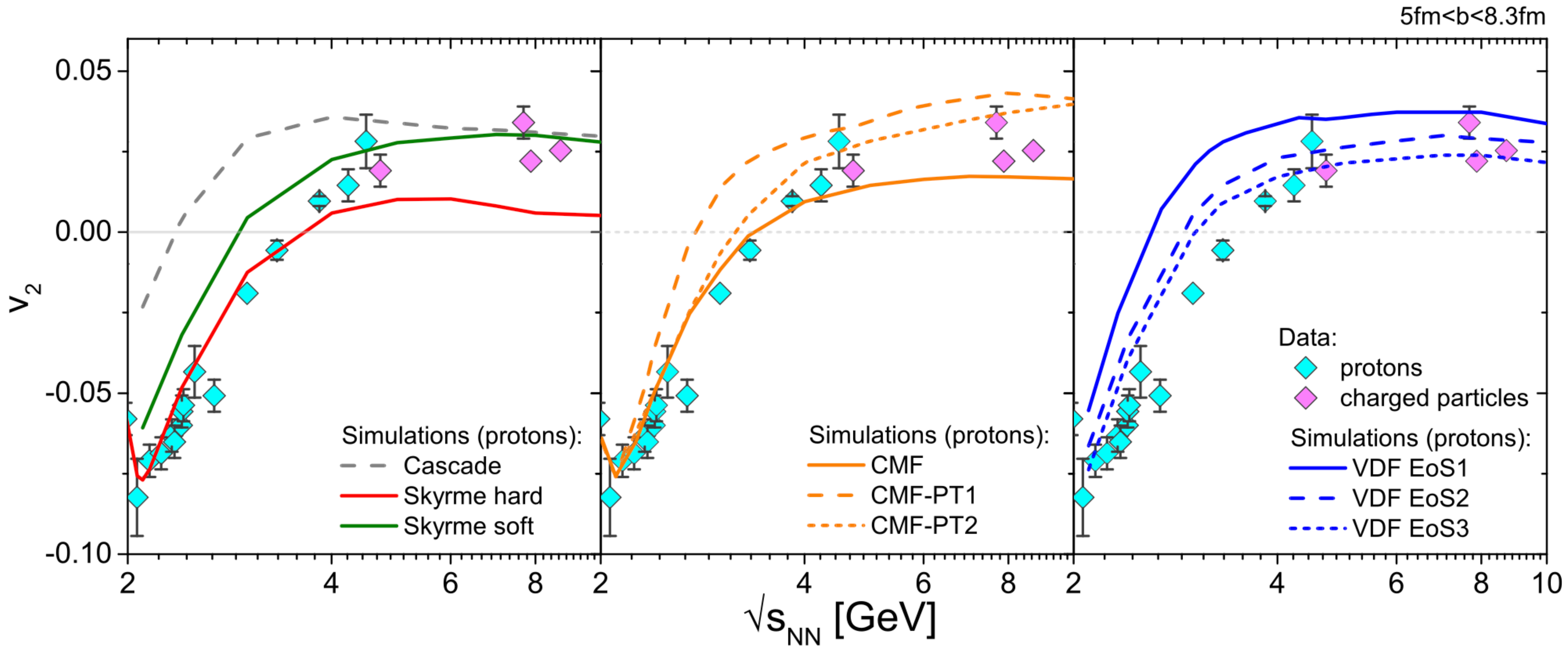
It follows triangularity: ~ 0 at 4.5 ➜ v_3 ~ 0 at 4.5

JAM Md2 potential form doesn't change

Very sensitive to the potential:
in contrast to v_1 and v_3, cascade does not generate v_3 (see later)

Experimental data vs. model predictions

J. Steinheimer et al. Eur.Phys.J.C 82 (2022) 10, 911

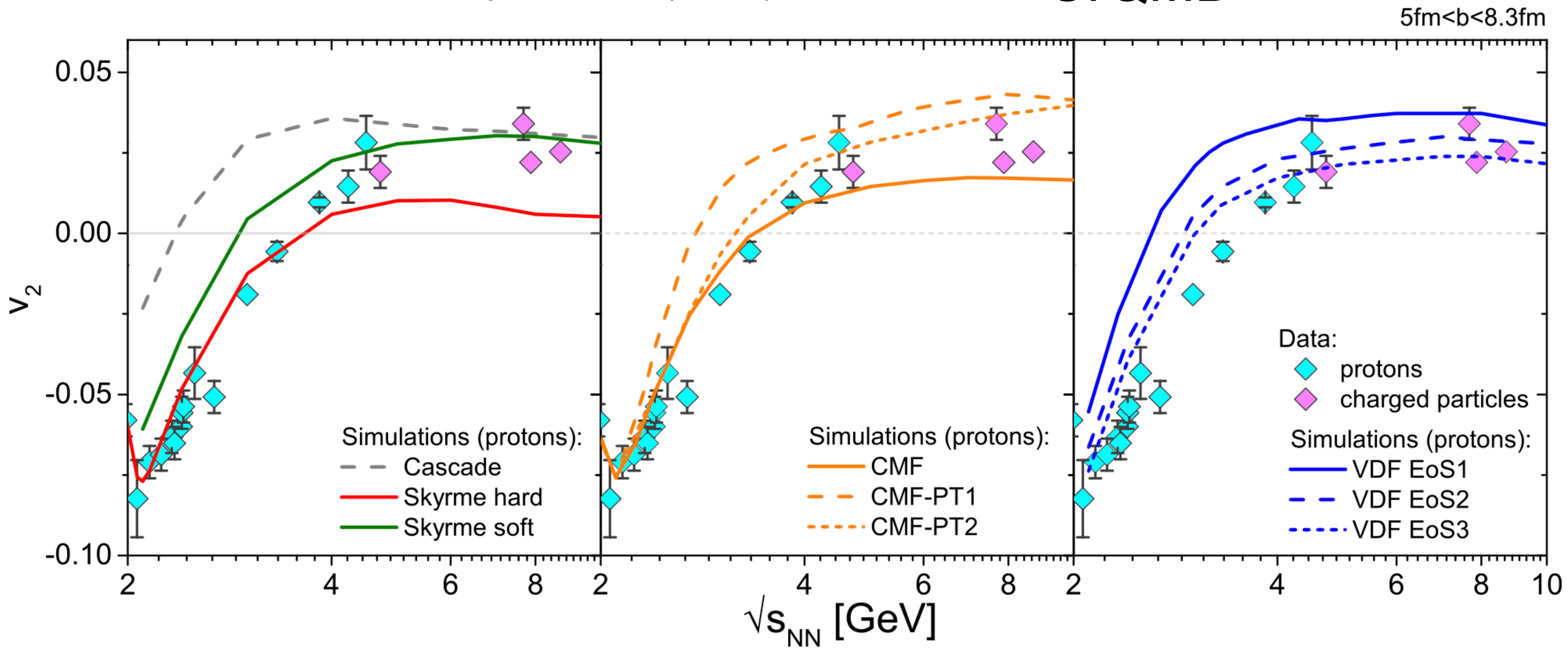


- 9 different EOSs in one framework (UrQMD)
- variations on the order of 1% change the extracted EOS

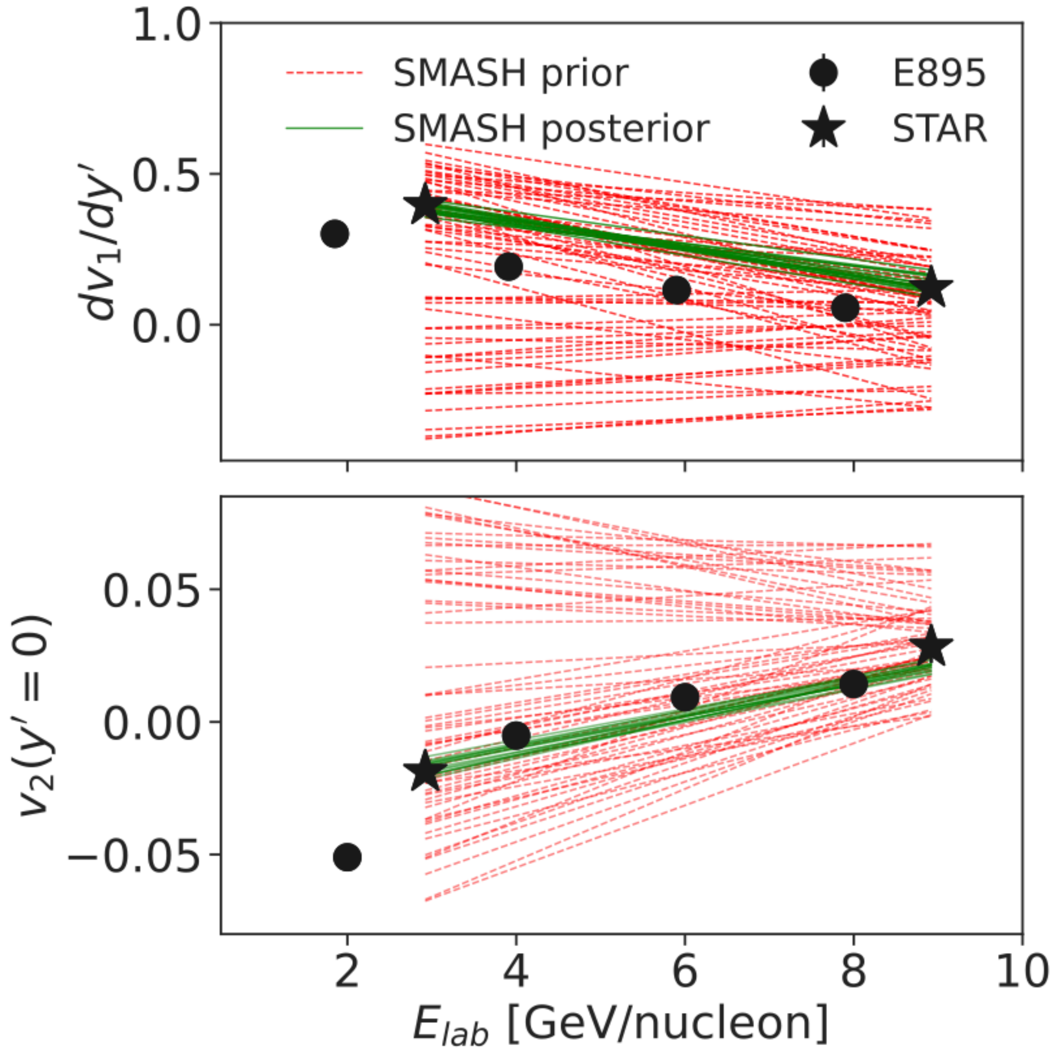
Experimental data vs. model predictions

J. Steinheimer et al. Eur.Phys.J.C 82 (2022) 10, 911

UrQMD

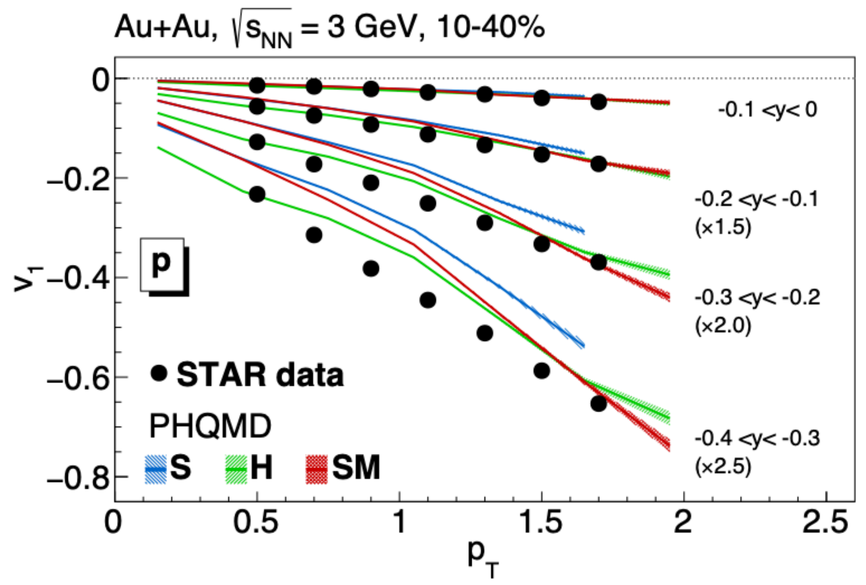


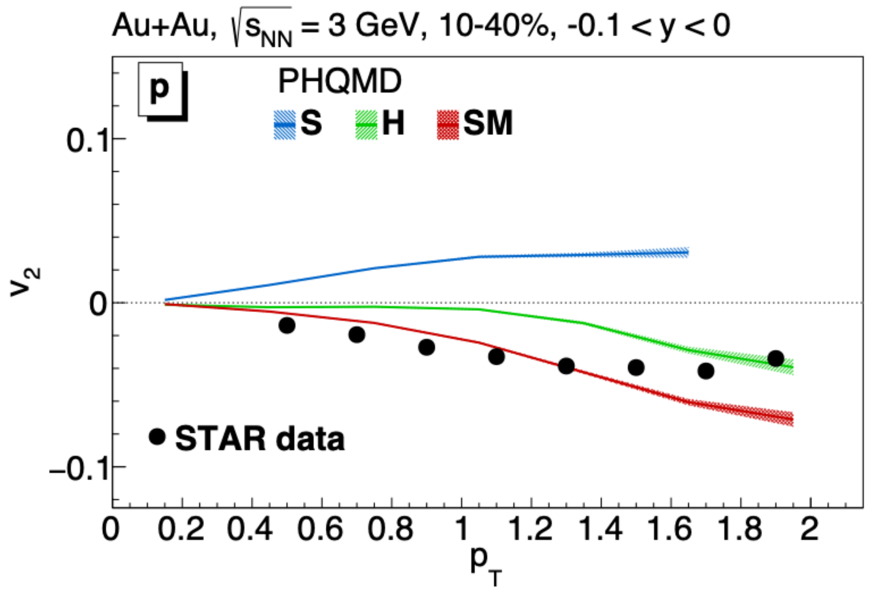
SMASH



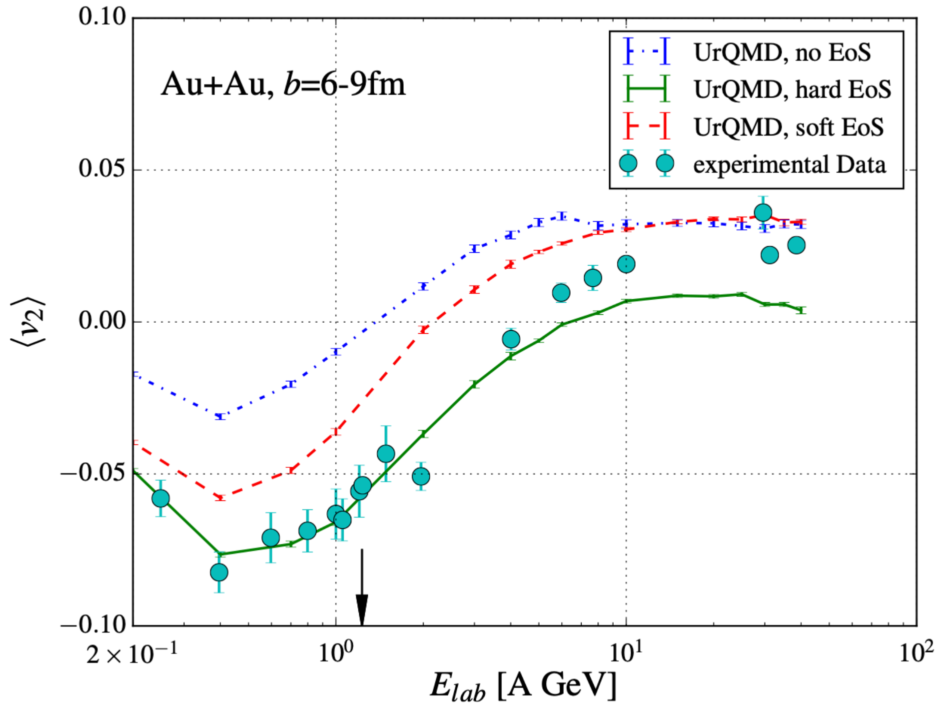
Phys.Rev.C 108 (2023) 3, 034908

PHQMD

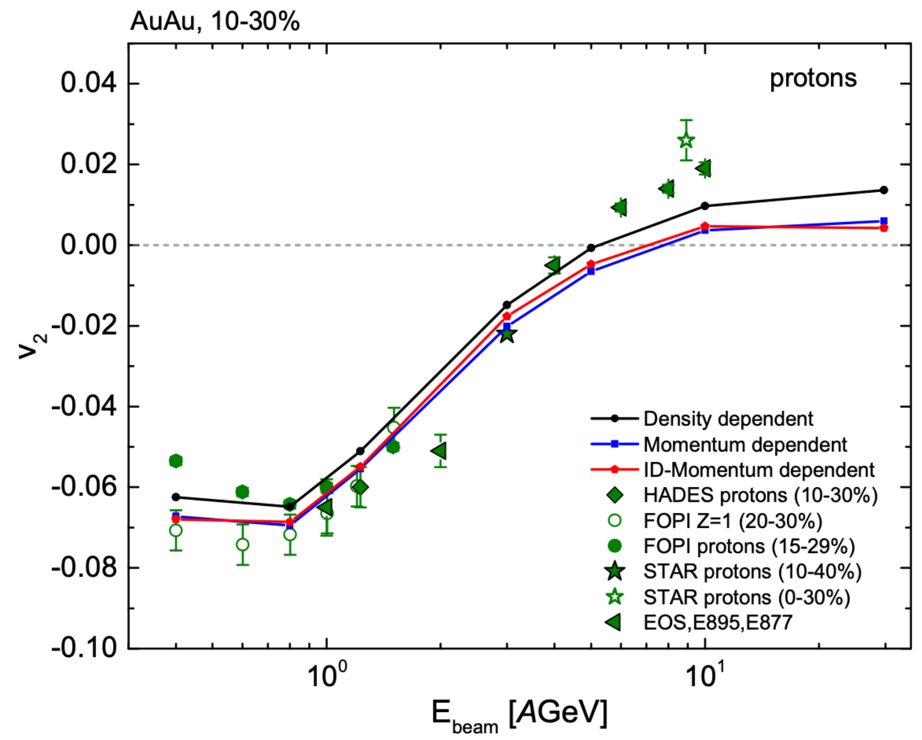


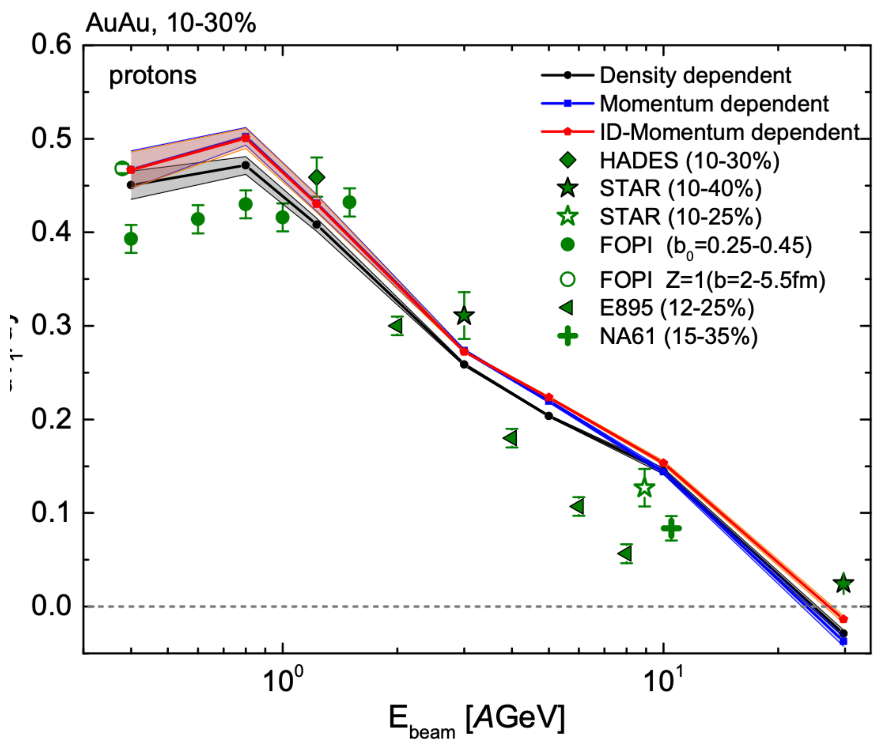


arXiv:2507.14255

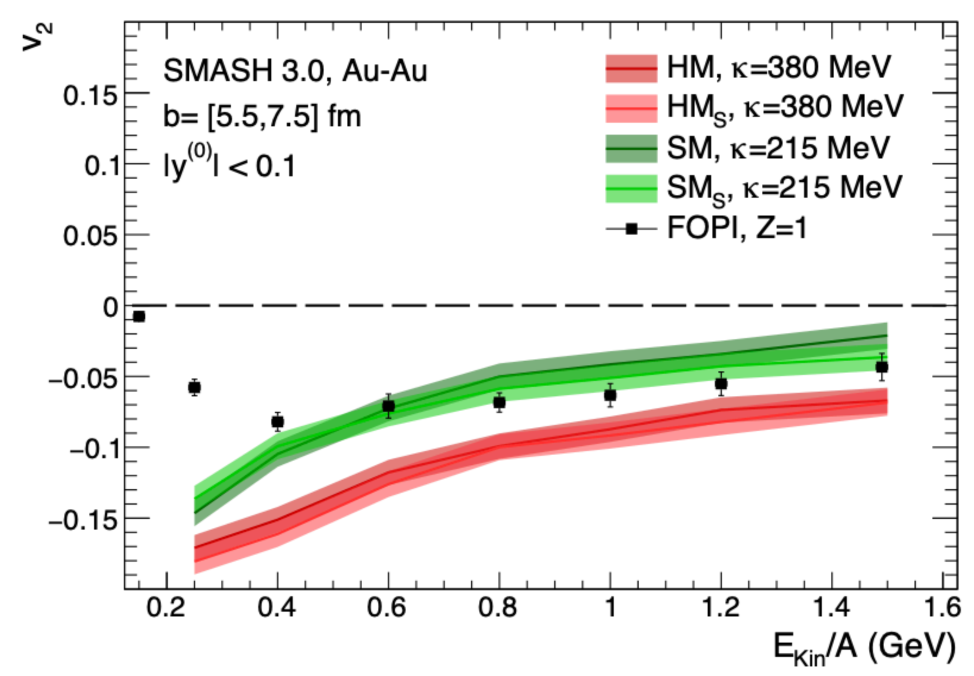


J.Phys.G 45 (2018) 8, 085101



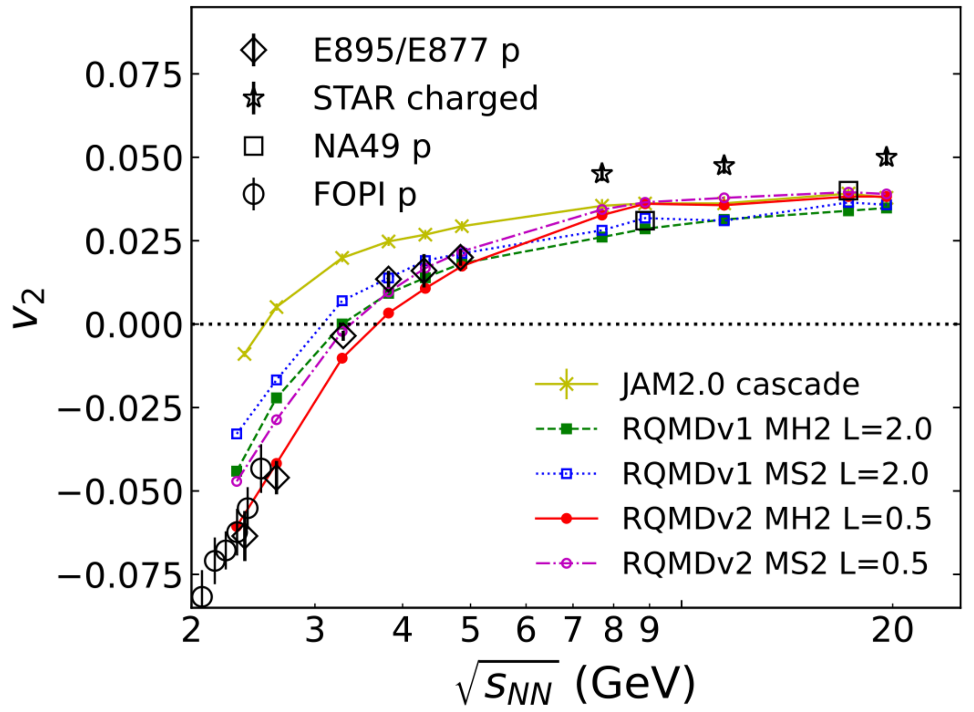


J.Phys.G 52 (2025) 3, 035103



Eur.Phys.J.A 60 (2024) 11, 232

JAM



Phys.Rev.C 105 (2022) 1, 014911

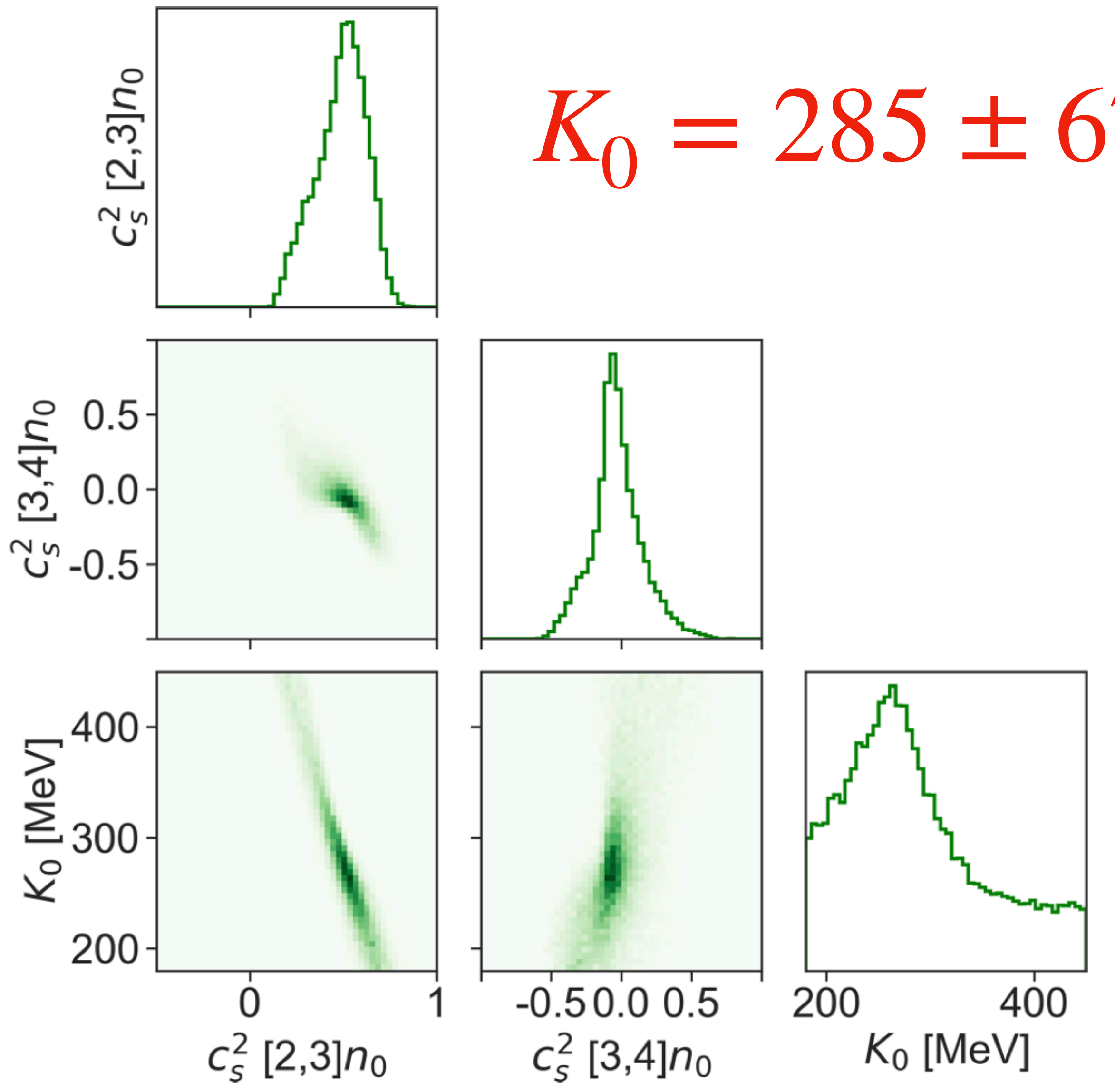
calls for:

1) benchmarking models (can we provide 1% precision?)

2) more differential studies (details, if not integrated out, can provide much needed tests)

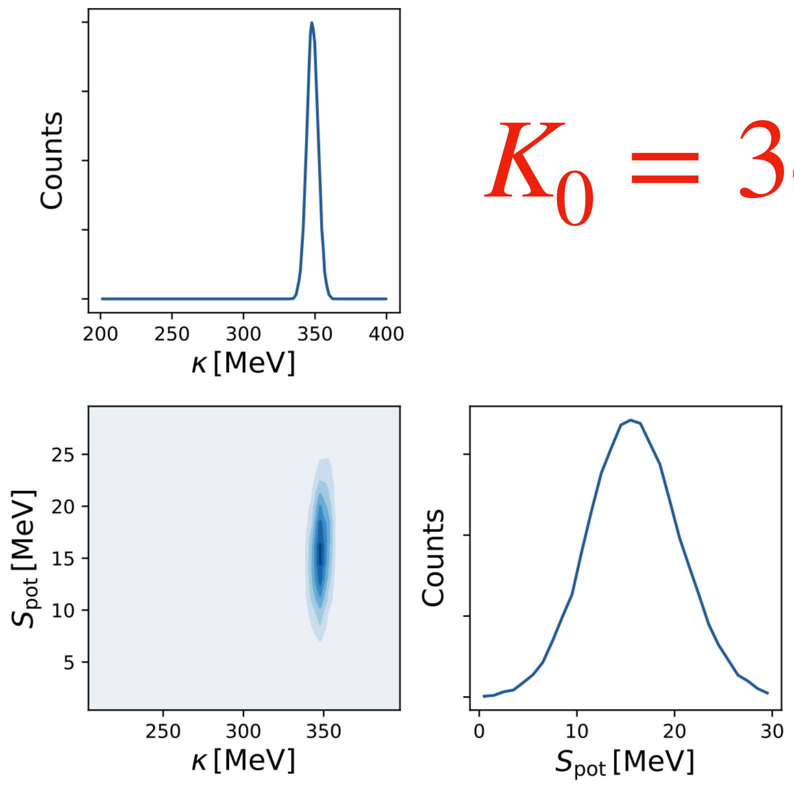
Bayesian analysis: yes, BUT

Two SMASH analyses extract completely different K_0



$K_0 = 285 \pm 67$ MeV

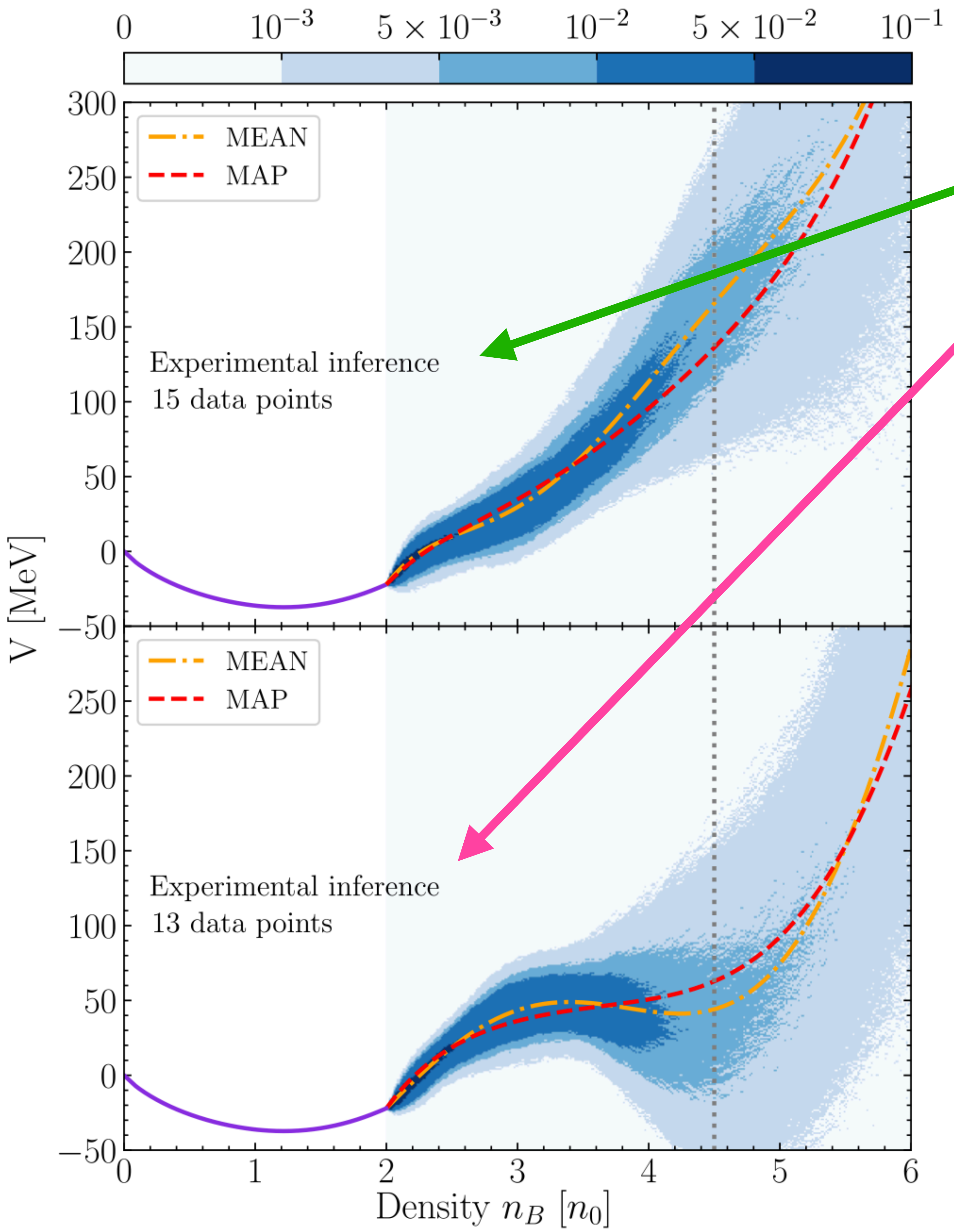
D. Oliinychenko et al. Phys.Rev.C 108 (2023) 3, 034908



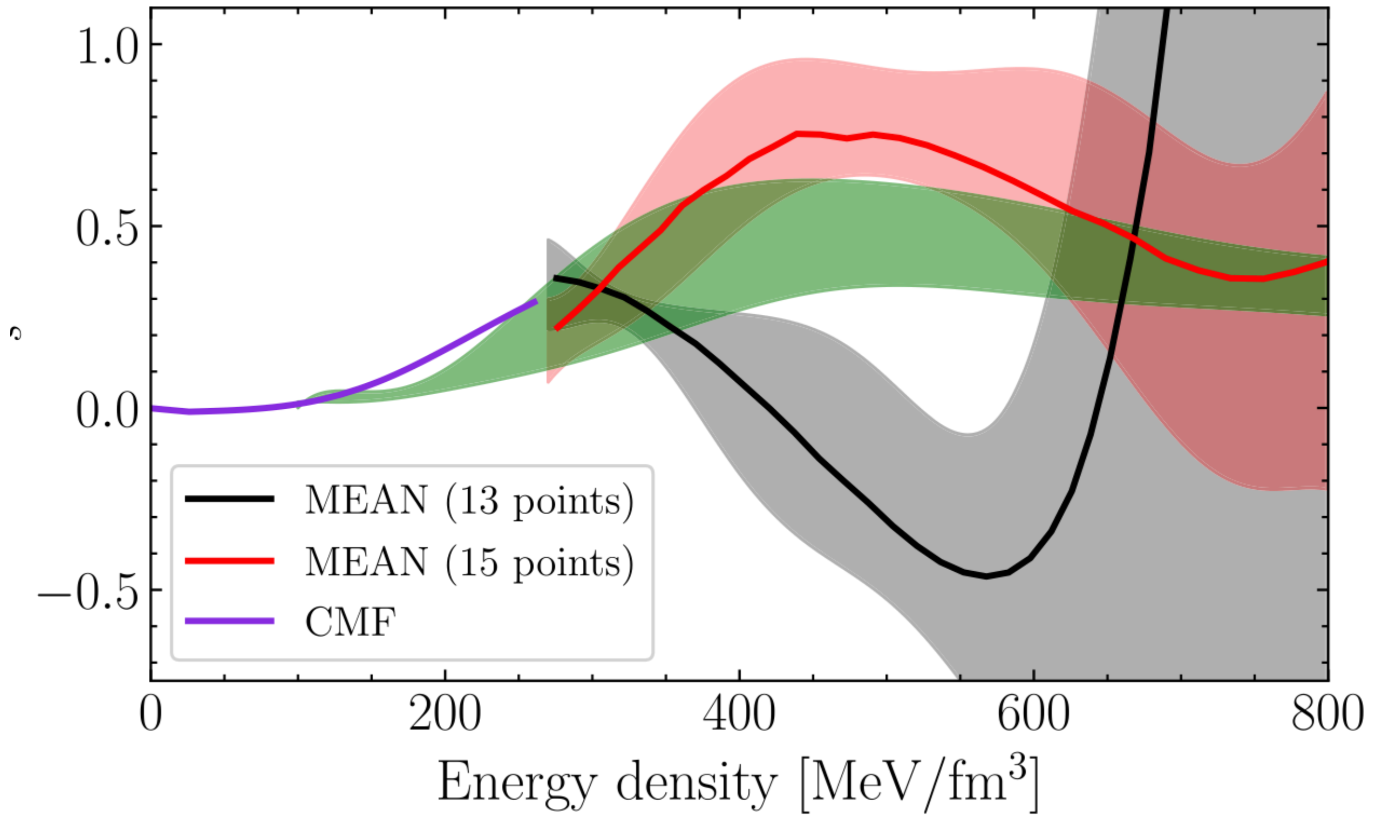
$K_0 = 348 \pm 4$ MeV

J. Mohs et al. Phys.Rev.C 112 (2025) 4, 044905

UrQMD results depend strongly on the data set



with and without $\langle m_T \rangle - m_0$ values at $\sqrt{s} = 3.83,\ 4.29$ GeV



M. Omana Kuttan et al. Phys.Rev.Lett. 131 (2023) 20, 202303

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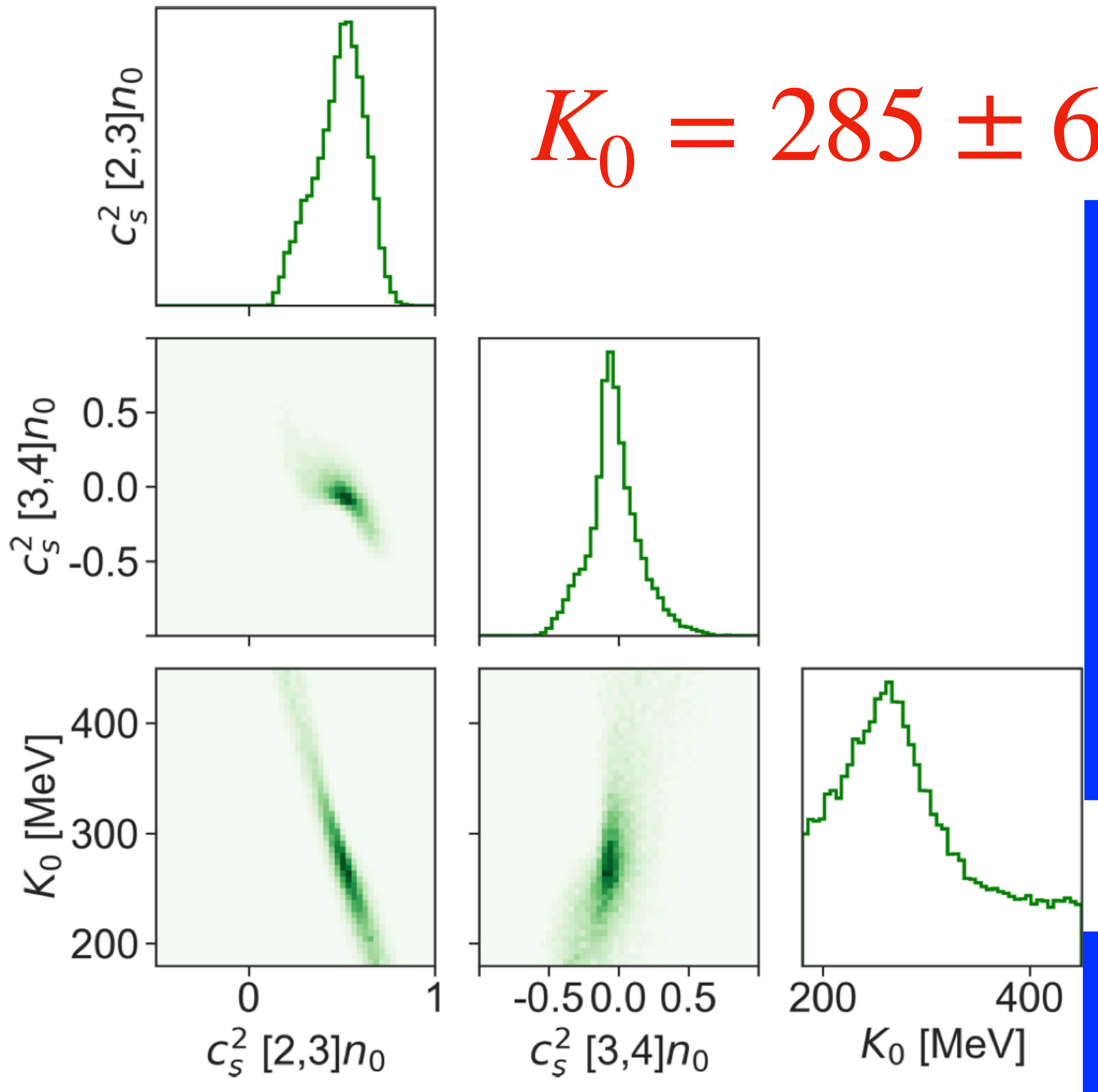

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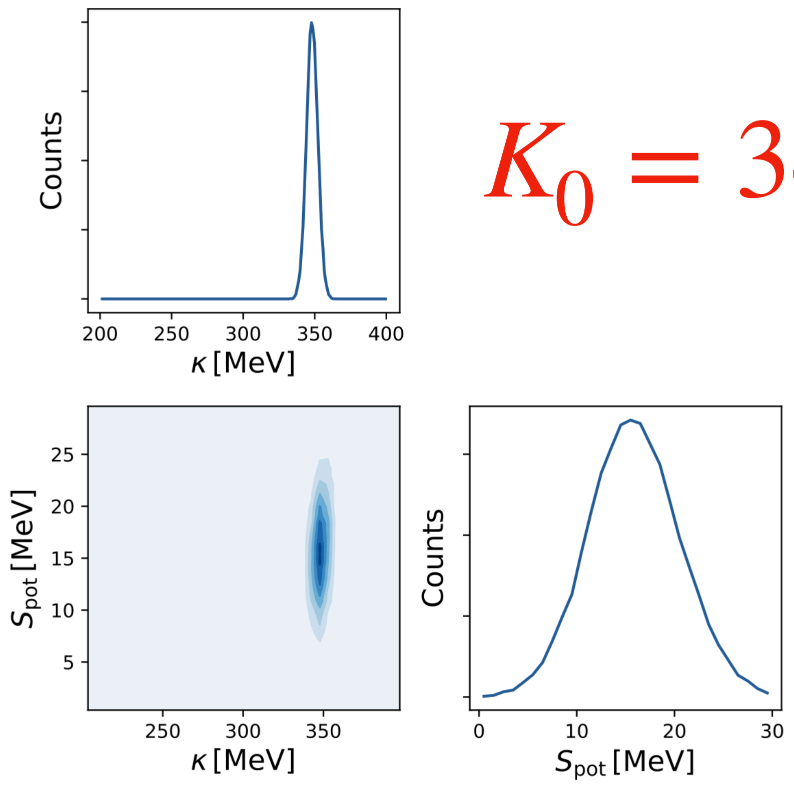
D. Oliinychenko et al. Phys.Rev.C 108 (



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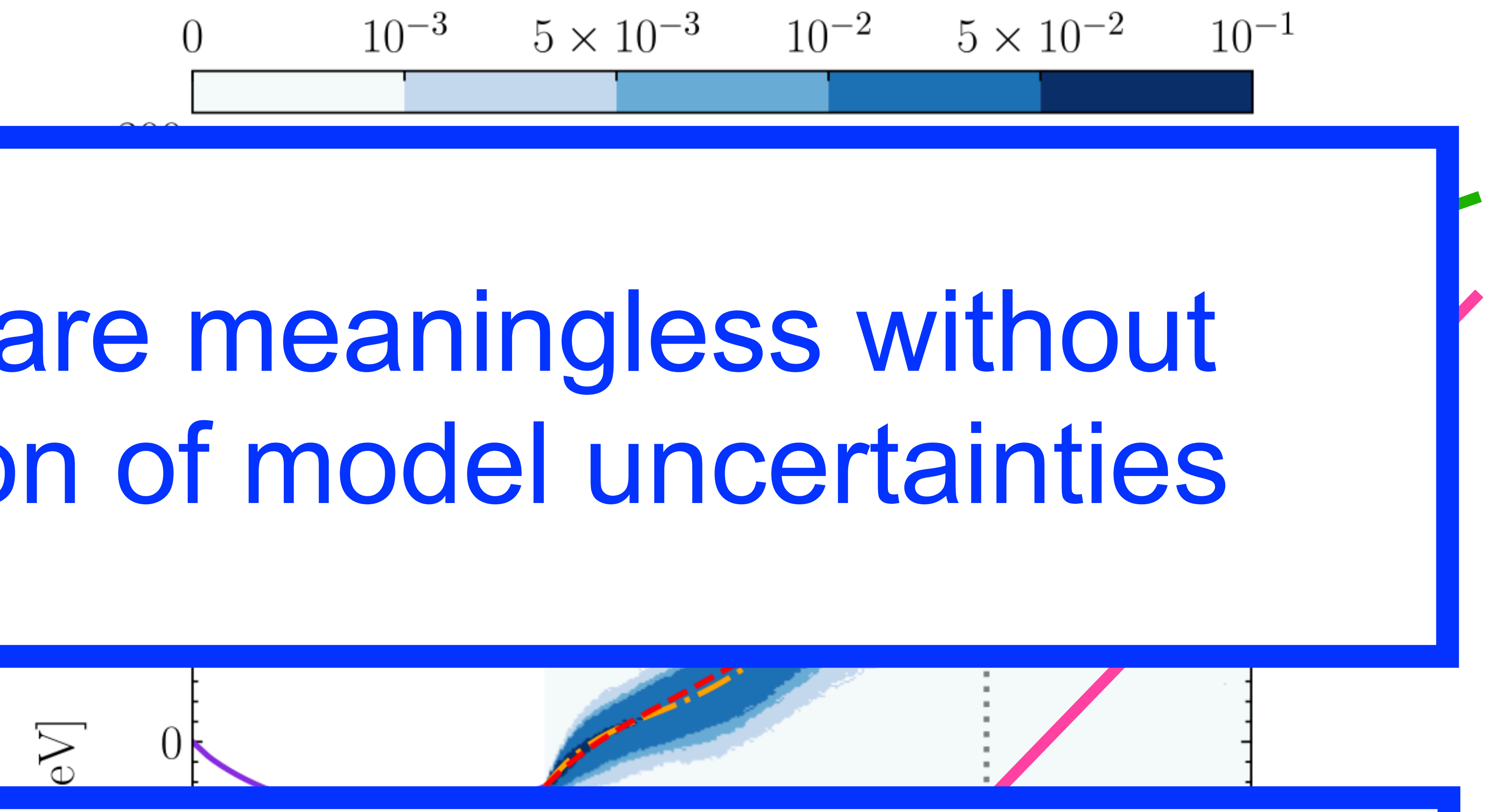

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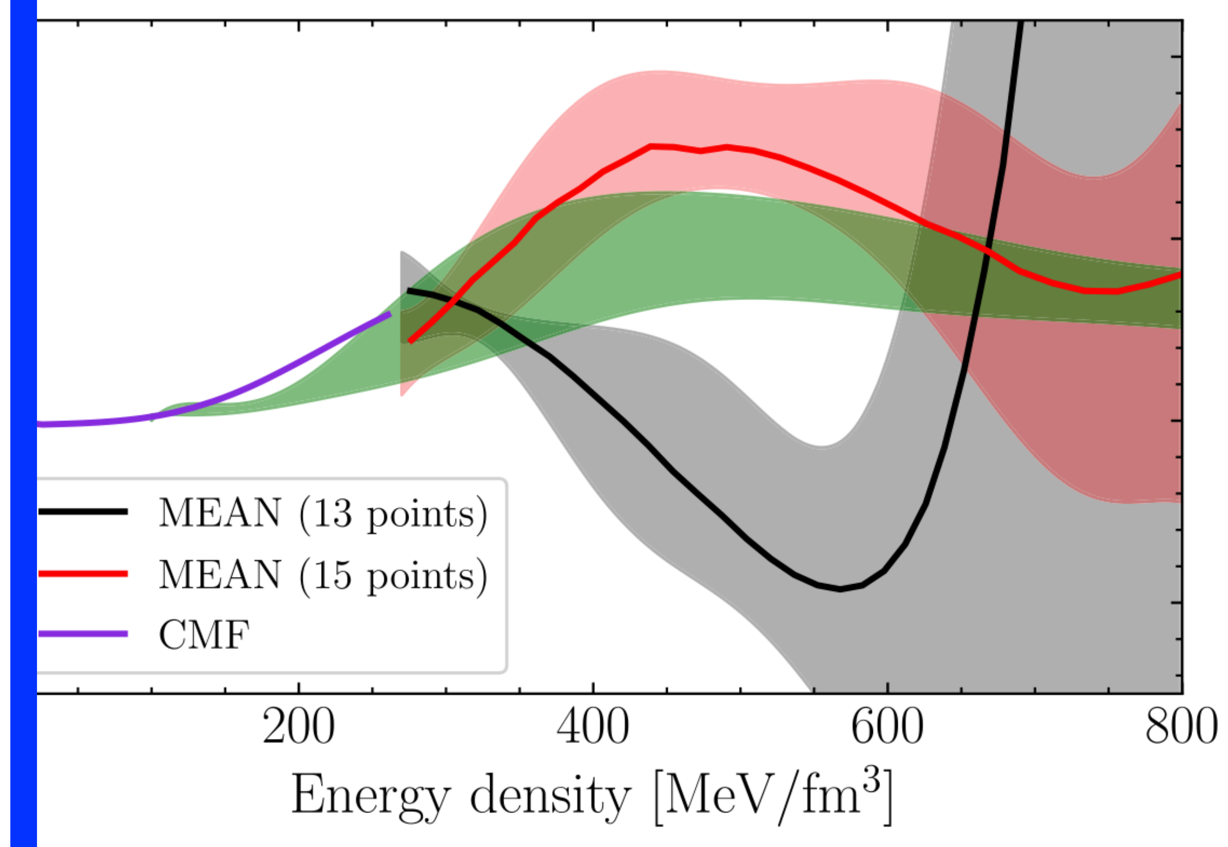


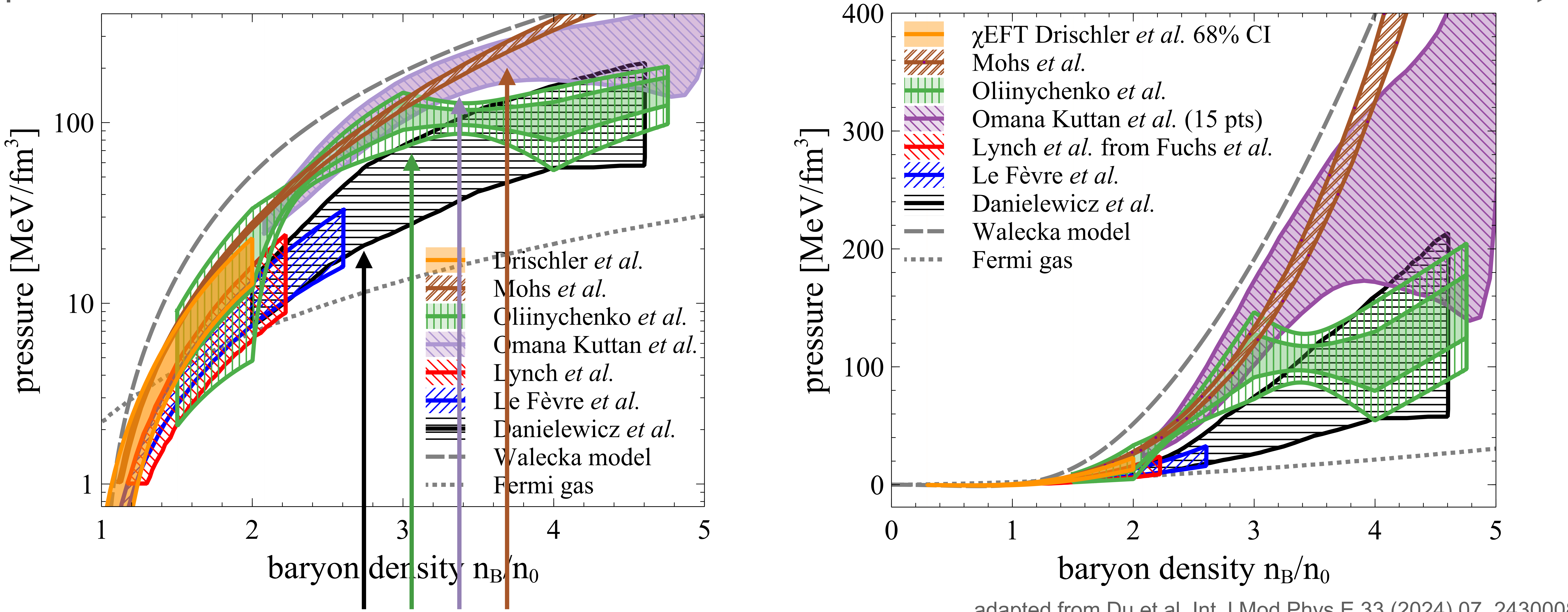
20, 202303

Results are meaningless without evaluation of model uncertainties

On the other hand, transport:

- Has good control of the initial state
- Handles non-equilibrium evolution
- No model interfaces (another source of uncertainty)

Good news: we understand the differences



adapted from Du et al, Int.J.Mod.Phys.E 33 (2024) 07, 2430008

Danielewicz et al: has p-dependence, but can't vary the EOS at high n_B

Oliinychenko et al: no p-dependence, but can vary the EOS at high n_B; however, did not vary above $4n_0$

Omana Kuttan et al: no p-dependence, but can vary the EOS at high n_B; observable choice not constraining at high n_B

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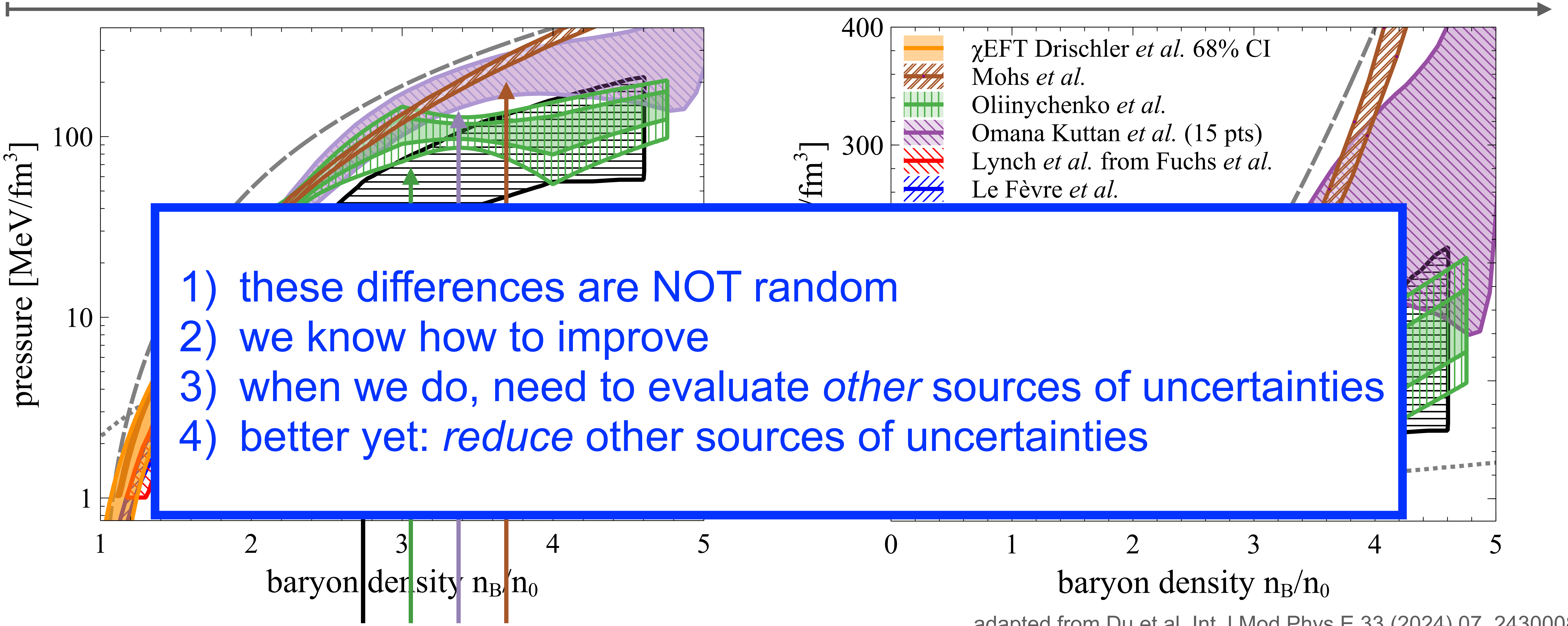

1) these differences are NOT random
2) we know how to improve
3) when we do, need to evaluate *other* sources of uncertainties
4) better yet: *reduce* other sources of uncertainties

adapted from Du et al, Int.J.Mod.Phys.E 33 (2024) 07, 2430008

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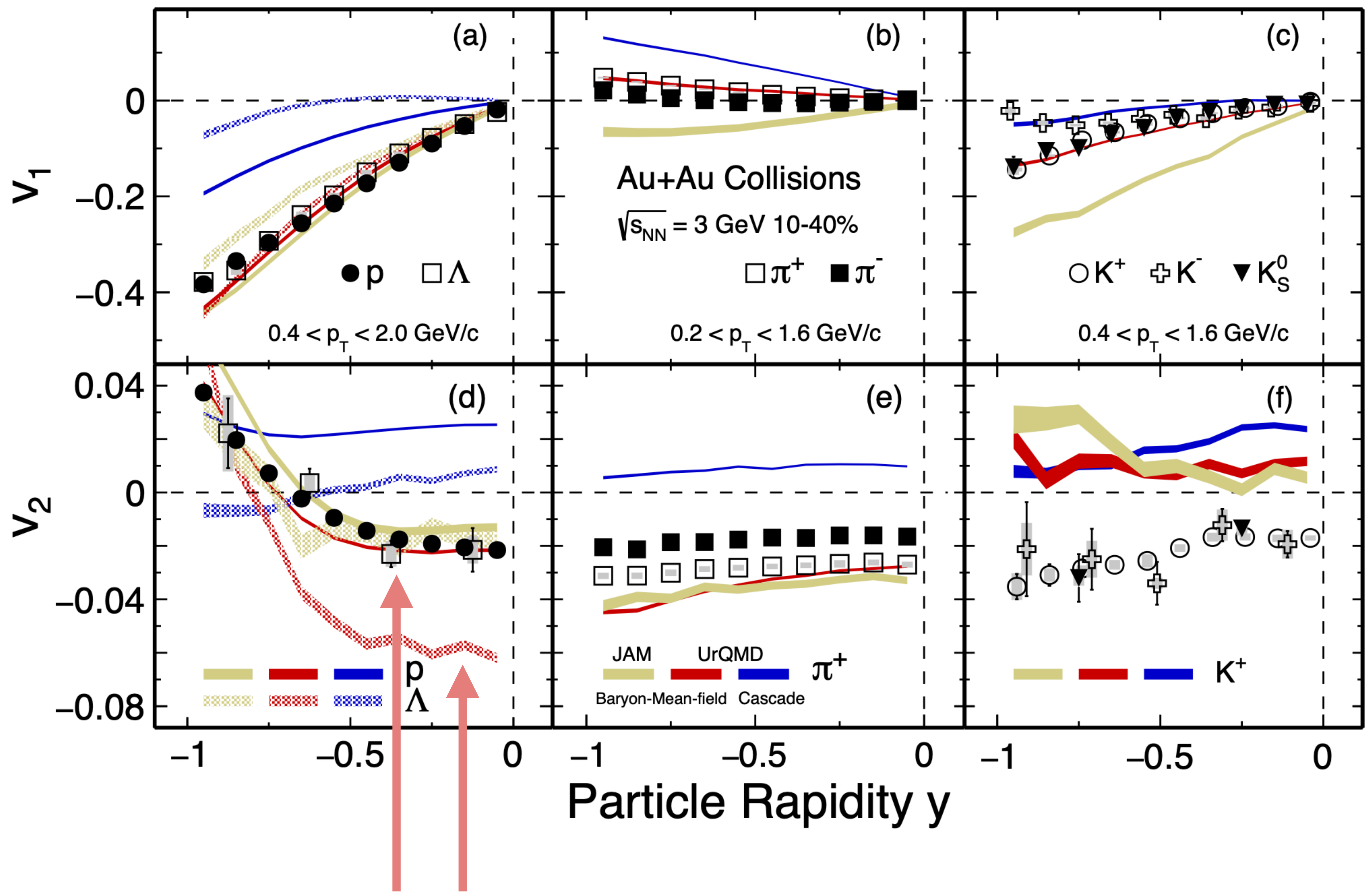
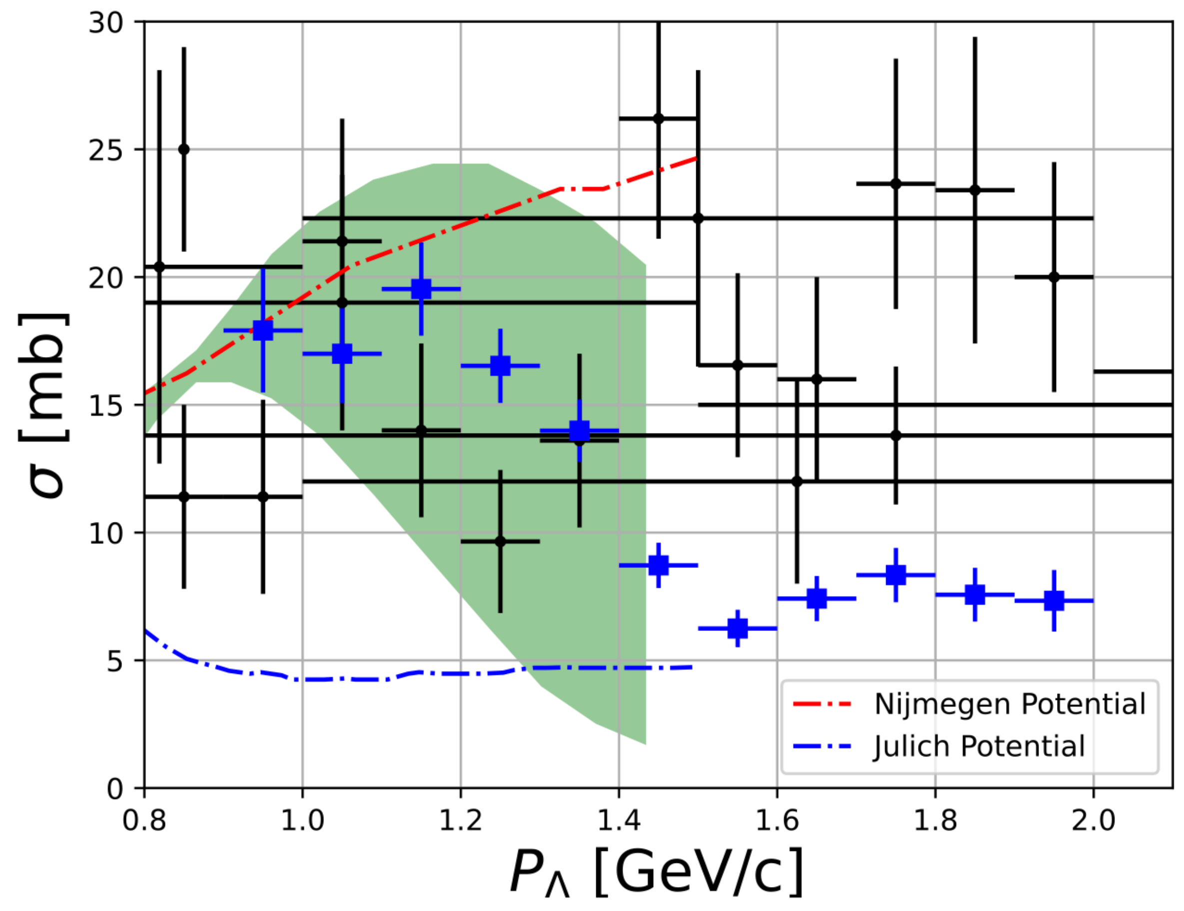
Importance of fundamental input

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

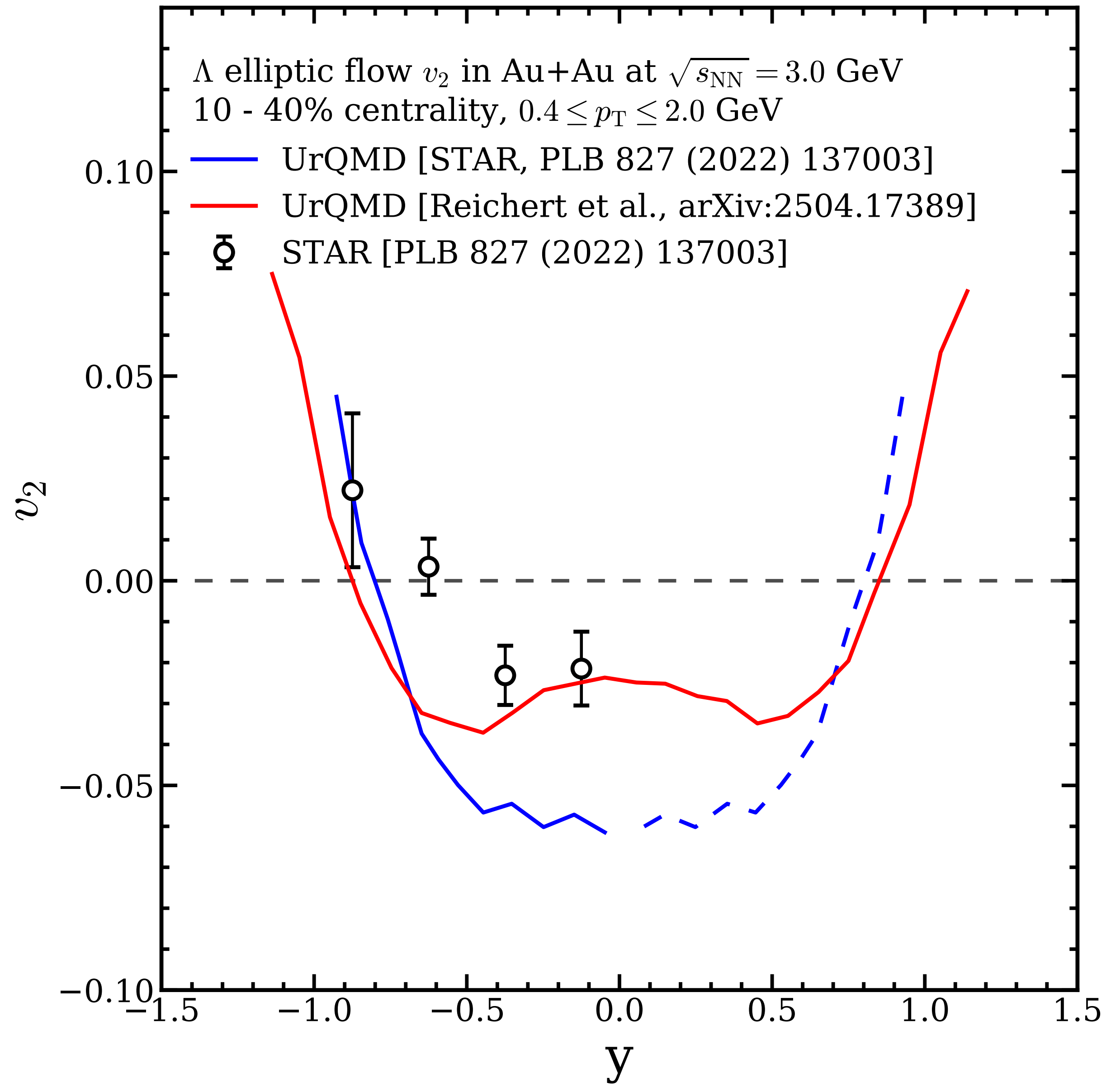


STAR data and model results differ by a factor of 2

Input to the model: ΛN cross section



CLAS, Phys.Rev.Lett. 127 (2021) 27, 272303



T. Reichert et al, arXiv:2504.17389

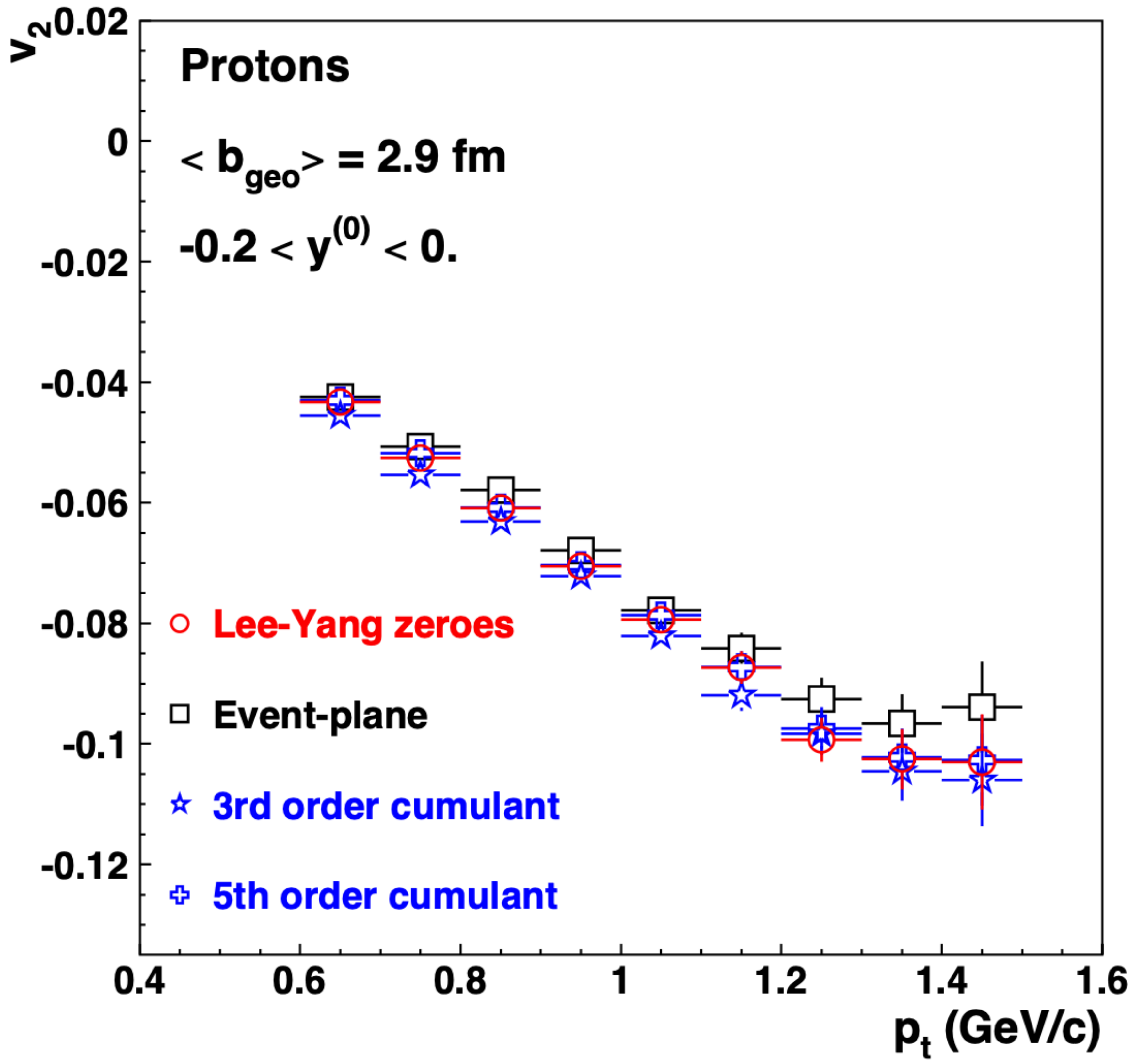
Λ flow is reproduced when employing more precise measurements of the ΛN cross section by CLAS

Importance of comparing apples to apples

How to measure flow?

- The theory method: $\Psi_{RP} \equiv 0$
- 1st order forward-spectator event plane
- *n*-th order event plane
- Q-vectors
- 2- and 4-particle cumulants
- Lee-Yang zeros

Use the same method in the measurement and in model analysis



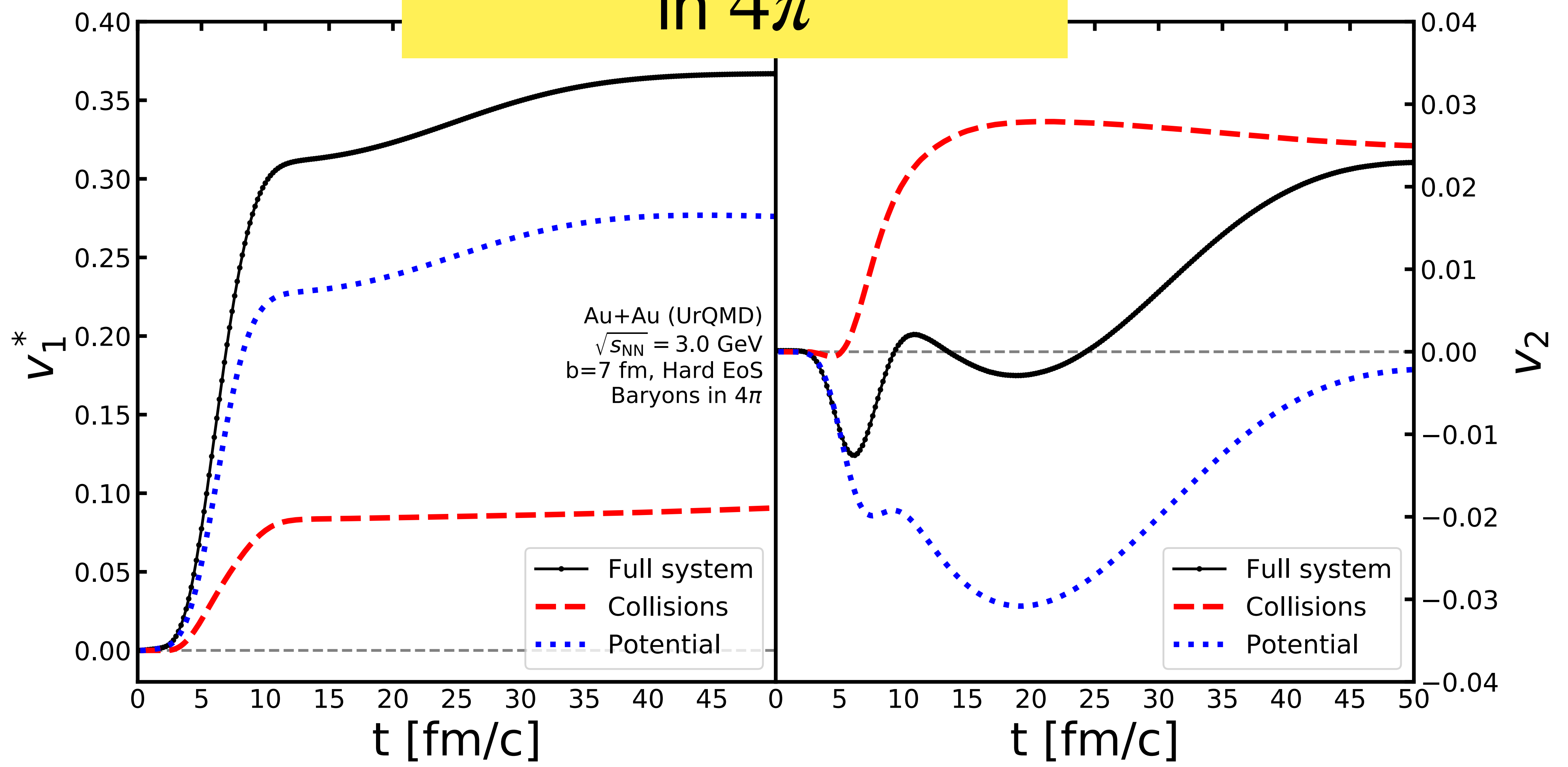
FOPI, Phys.Rev.C 72 (2005) 011901

Should we compare to fits or data points?

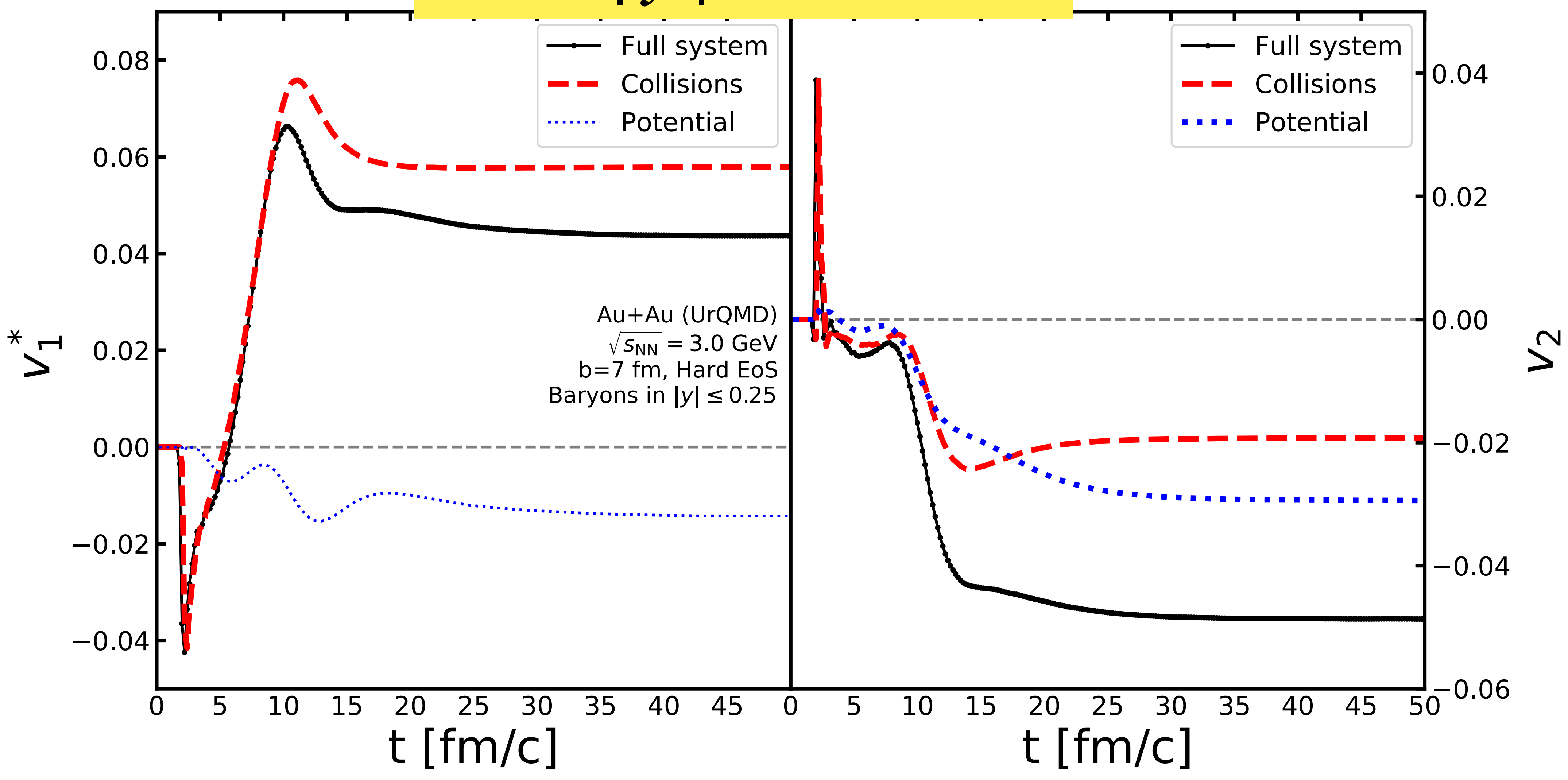
Fits are finicky! Let's move beyond $dv_1/dy\big|_{y=0}$ and $v_2(y=0)$

Understand the dynamics behind observables

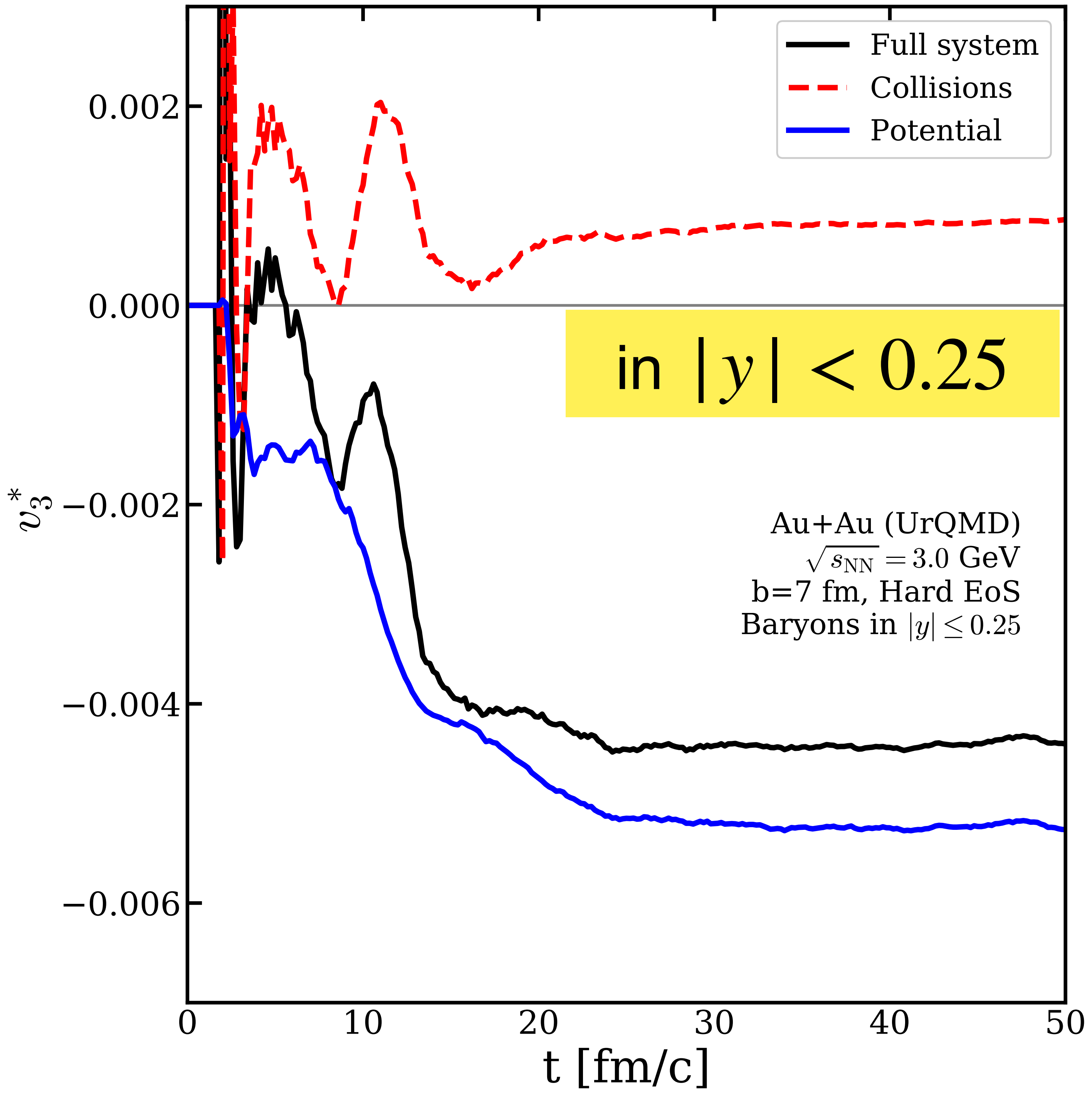
in 4π



in $|y| < 0.25$



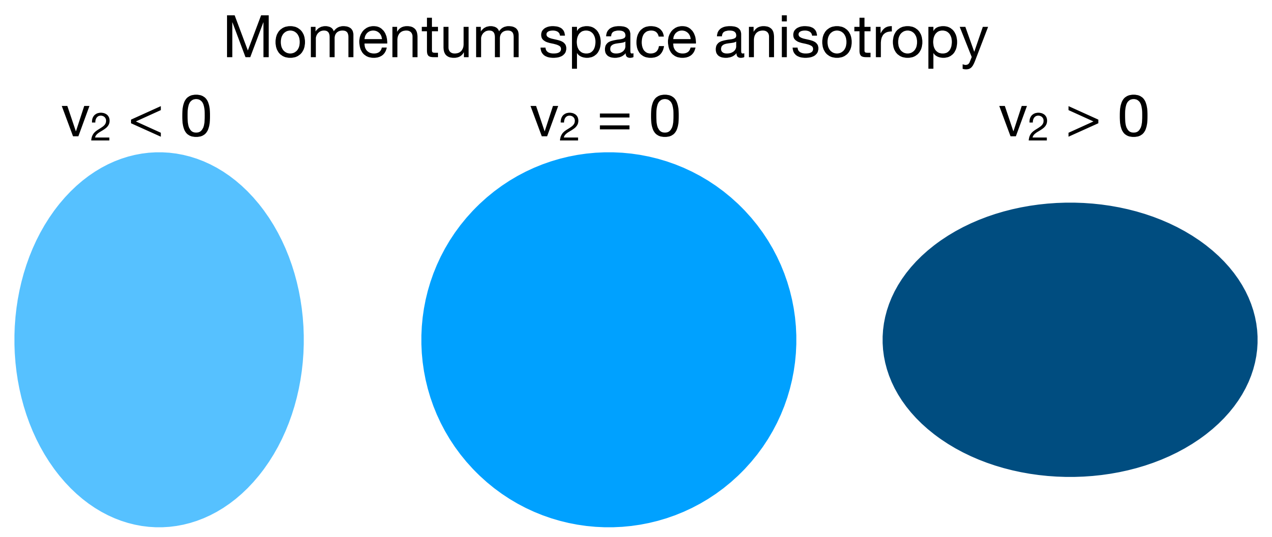
- Do we understand how both v1 and v2 are generated in transport models? We think we do!
- However, reality is more complicated than naive pictures suggest
- Midrapidity v_1 is mostly collisions, v_2 is 50:50 collisions and potential

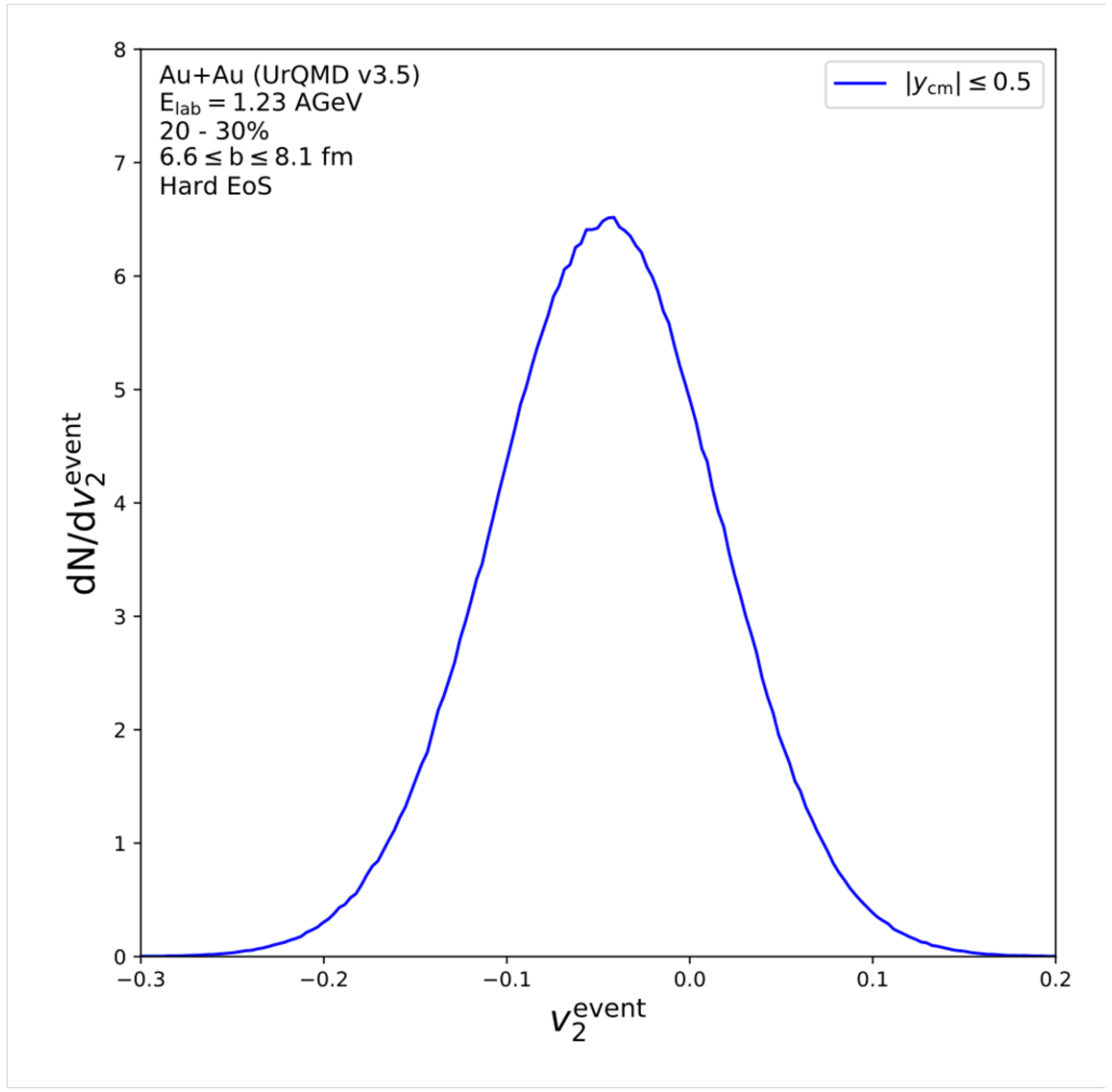


- Triangular flow data starts to become available
- Can we understand its generation?
- Interestingly, v_3 seems to be drastically driven by the EoS
- Go-to place to study the EoS?

T. Reichert and J. Aichelin, Phys.Rev.C 111 (2025) 5, 054916

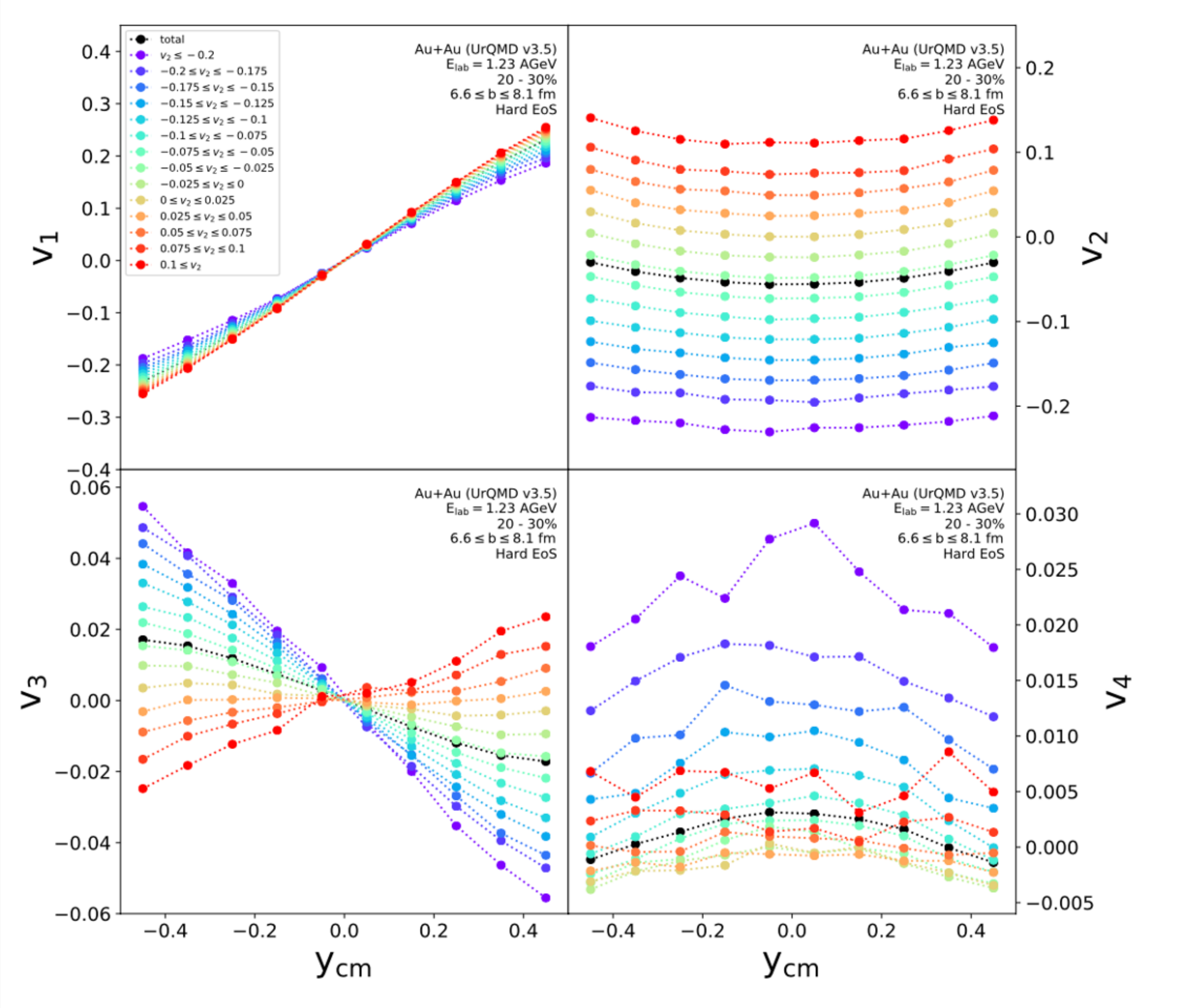
Differential observables



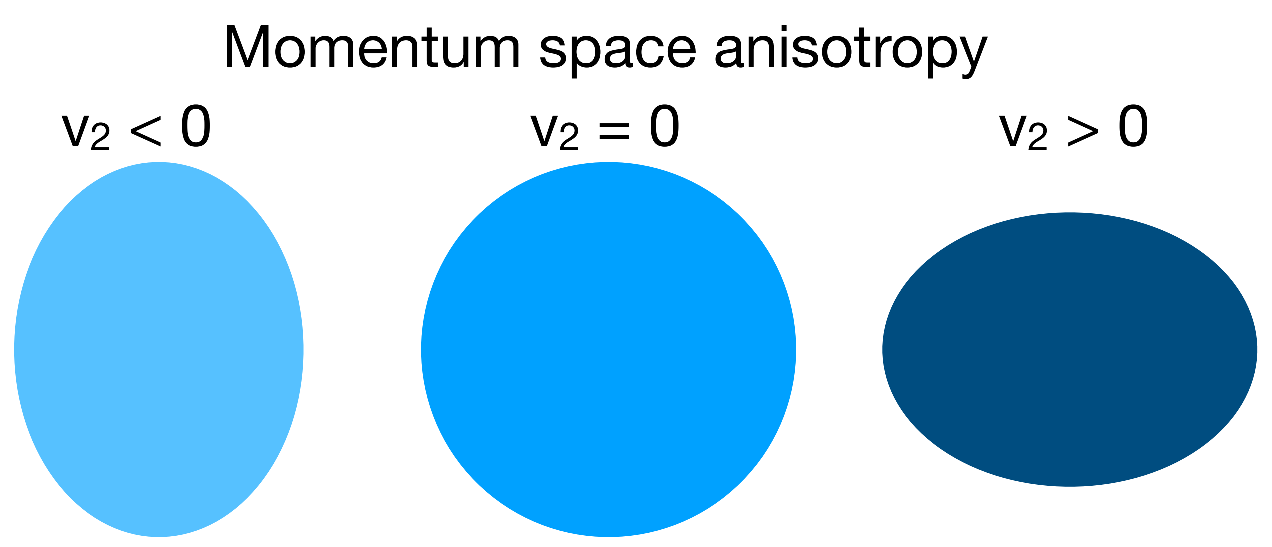


T. Reichert et al. Eur.Phys.J.C 82 (2022) 6, 510

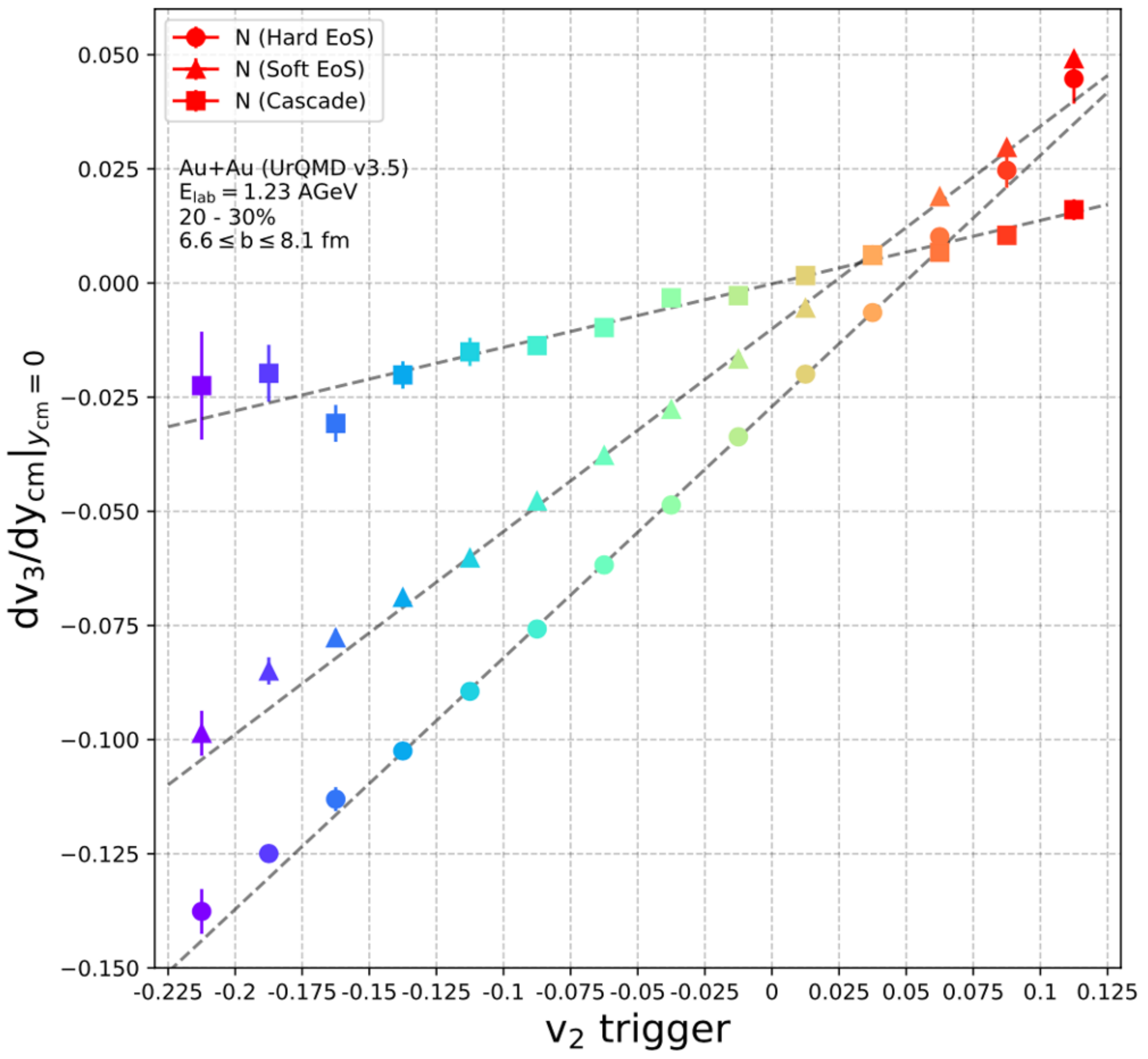
- Event-by-event elliptic flow at midrapidity fluctuates strongly
- Define event classes basen on $\langle v_2 \rangle^{\text{event}}_{|y|\leq 0.5}$
- Analyze v_1, …, v_4 as a function of rapidity in different “v_2 classes”



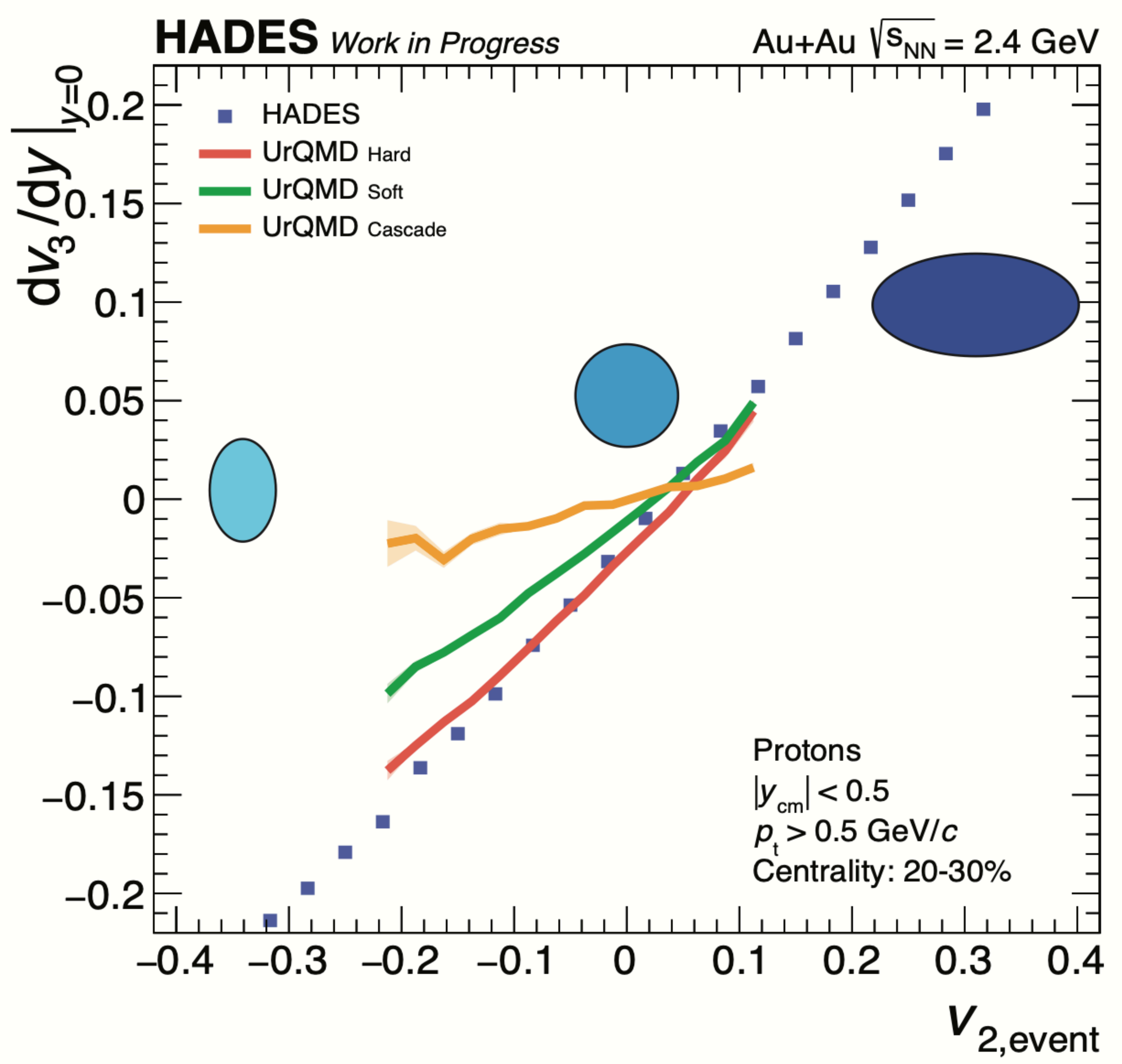
Differential observables: v_3



- Strong sensitivity to the employed EoS due to flow correlations
- Under investigation by HADES, insights from STAR would be valuable



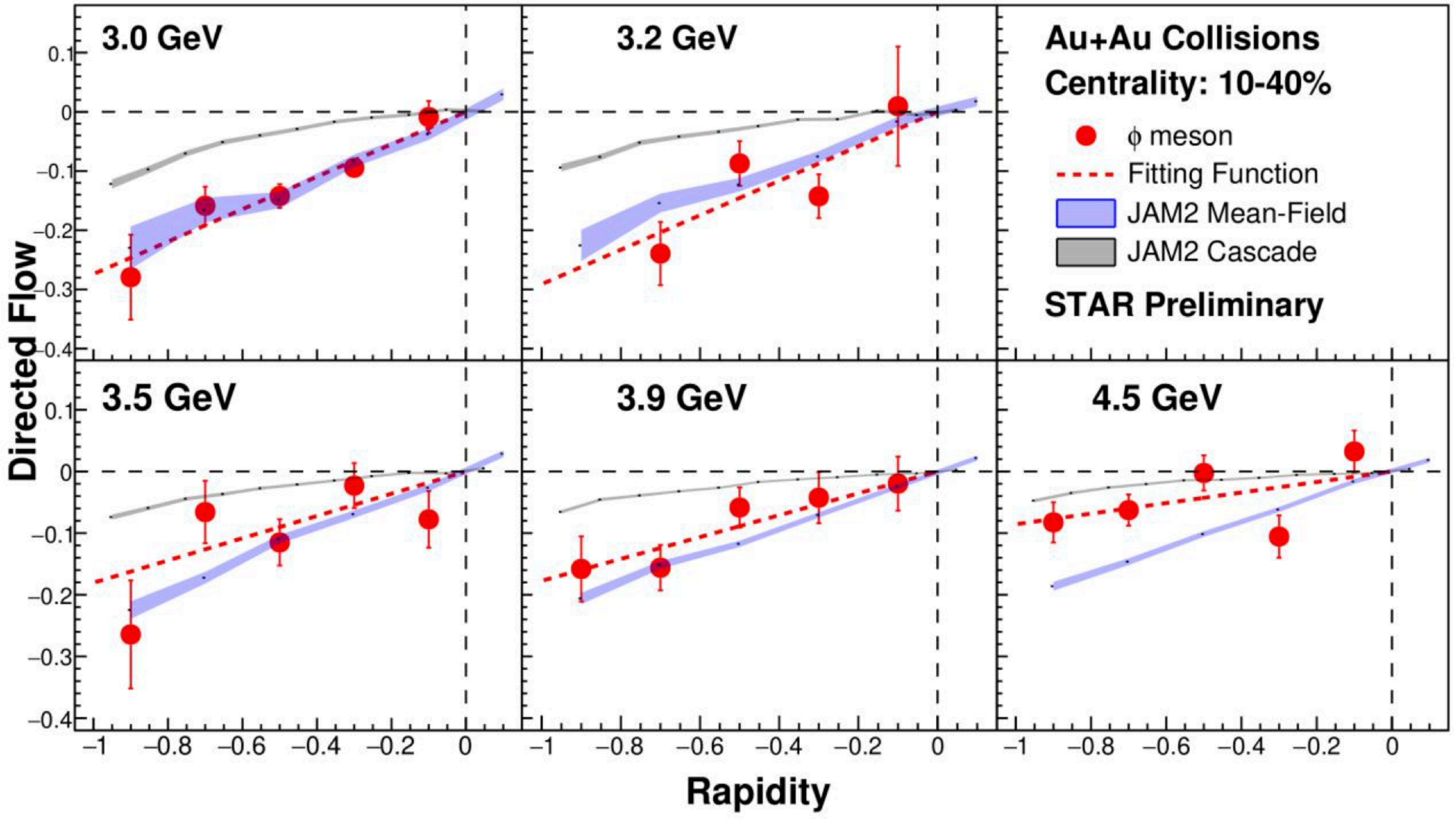
T. Reichert et al. Eur.Phys.J.C 82 (2022) 6, 510



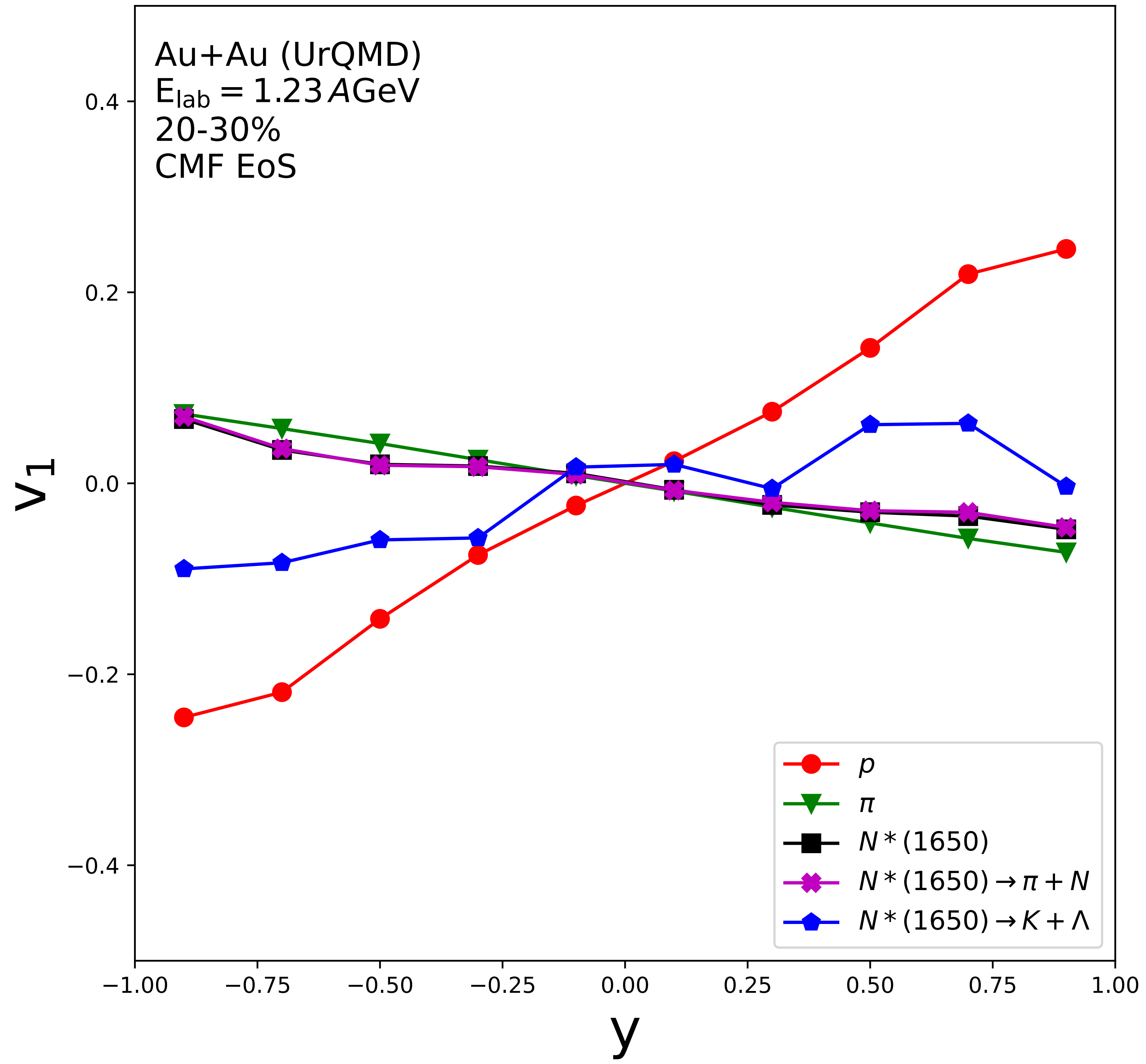
B. Kardan. Preliminary HADES data.
https://indico.cern.ch/event/1139644/contributions/5456429/

Flow of resonances

G. Zheng for STAR, QM25 poster, Preliminary



T. Reichert, work in progress



- ϕ directed flow follows baryons
- Quark coalescence?
- Production from heavy N*?

- Reconstruction effect
- $N^*(1650)$ provides a handle on the in-medium KN and ΛN cross section

Wishlist

1. @Transportlers:
   Please, do your best to scrutinize and eradicate model systematics. Discuss results in light of the capabilities of your model.

2. @Everybody:
   Please, in the appendix of your papers, put as much and as detailed information about the exact procedure of how you have a) measured and/or b) simulated your results. (@Experimentalists: please make sure you know what the models do.)

3. @Experimentalists: Please, triple differential d^3N/d^3p data is highly valuable and needed to shrink transport models' parameter freedom.

4. Bayesianing provides parameters that describe data. Bayesianing does not tell you whether your physics is correct.