Harmonic flow in the high baryon density regime

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In collaboration with J. Aichelin, I. Karpenko, J. Steinheimer, M. Bleicher

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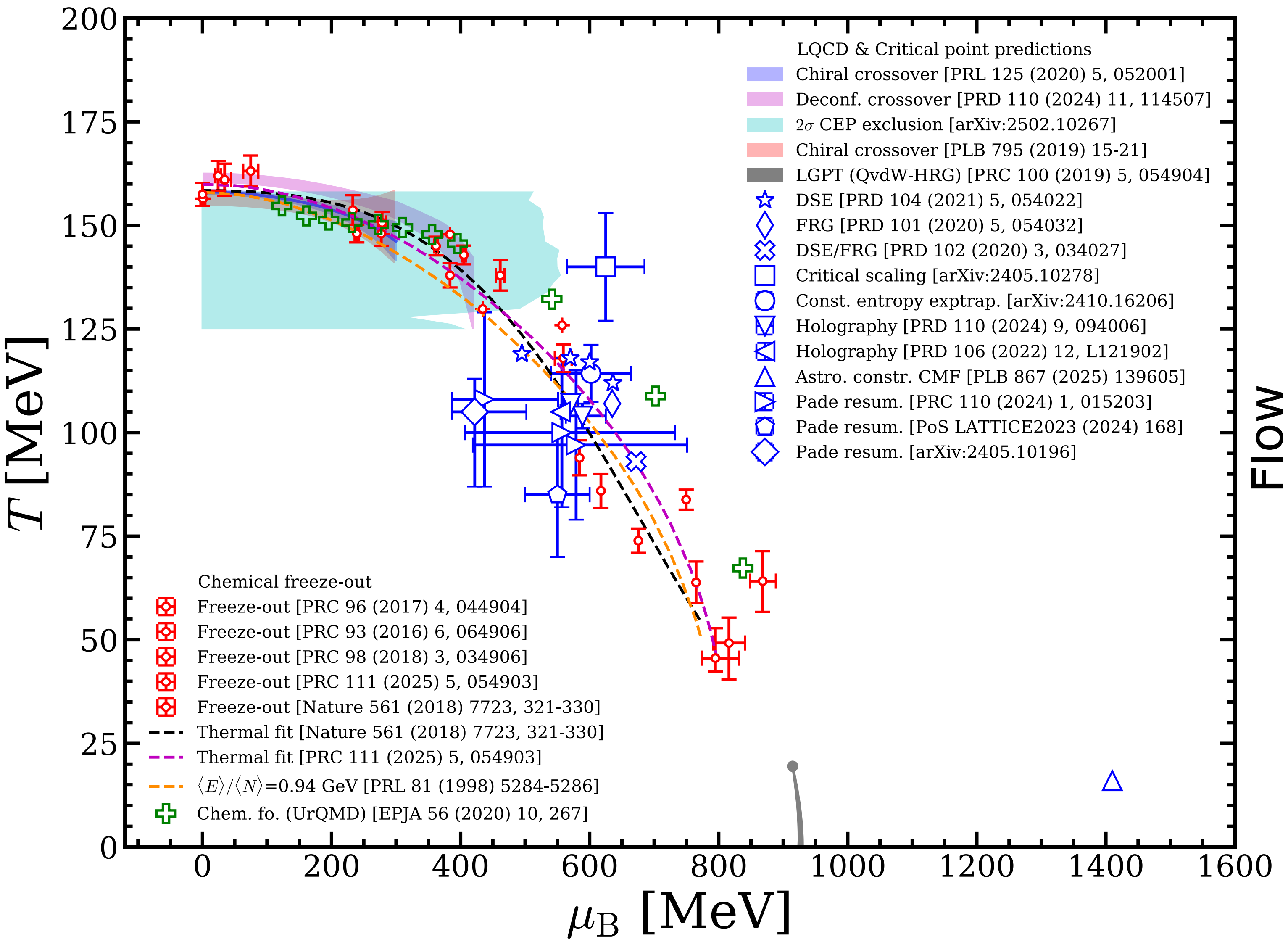
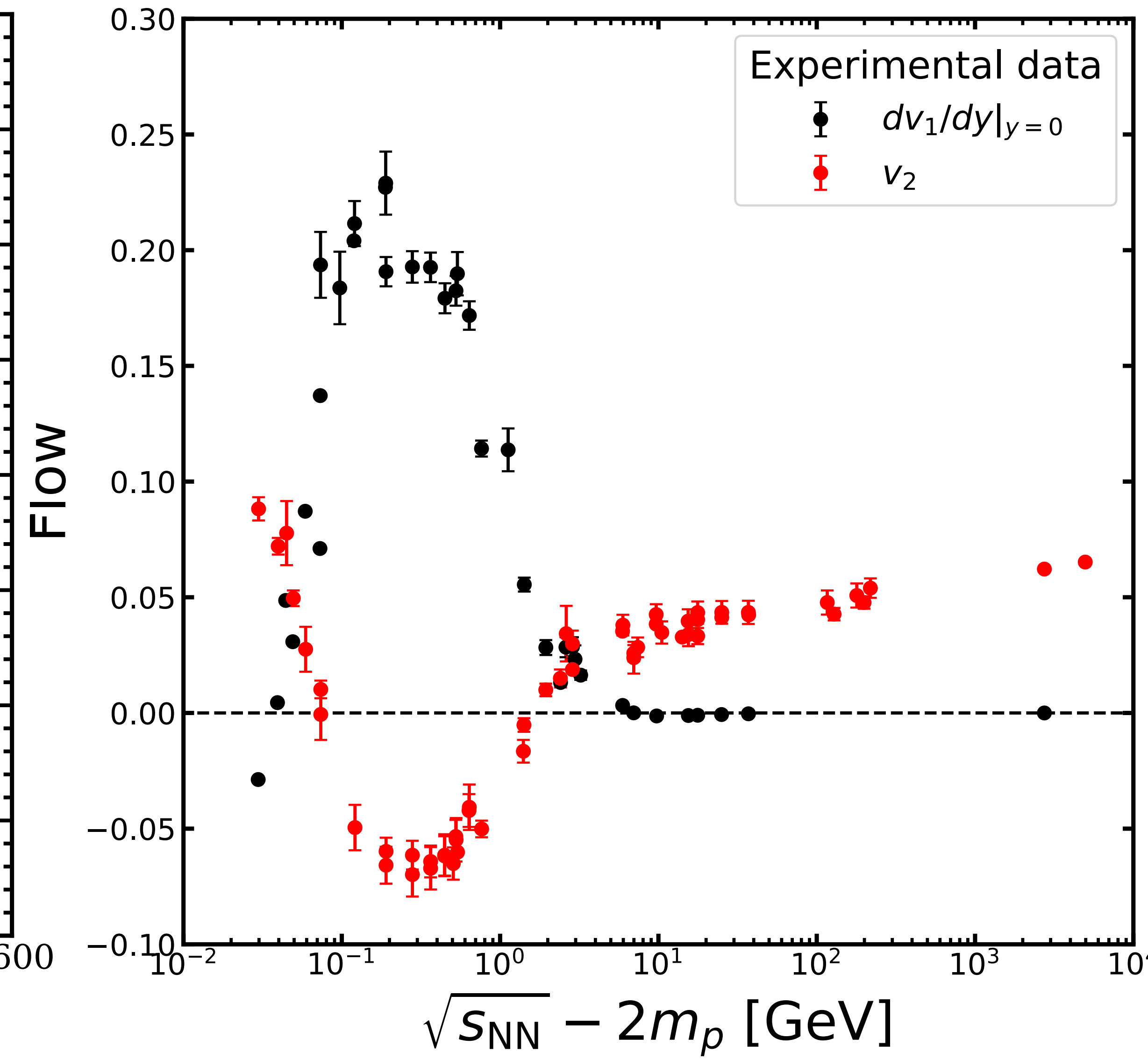
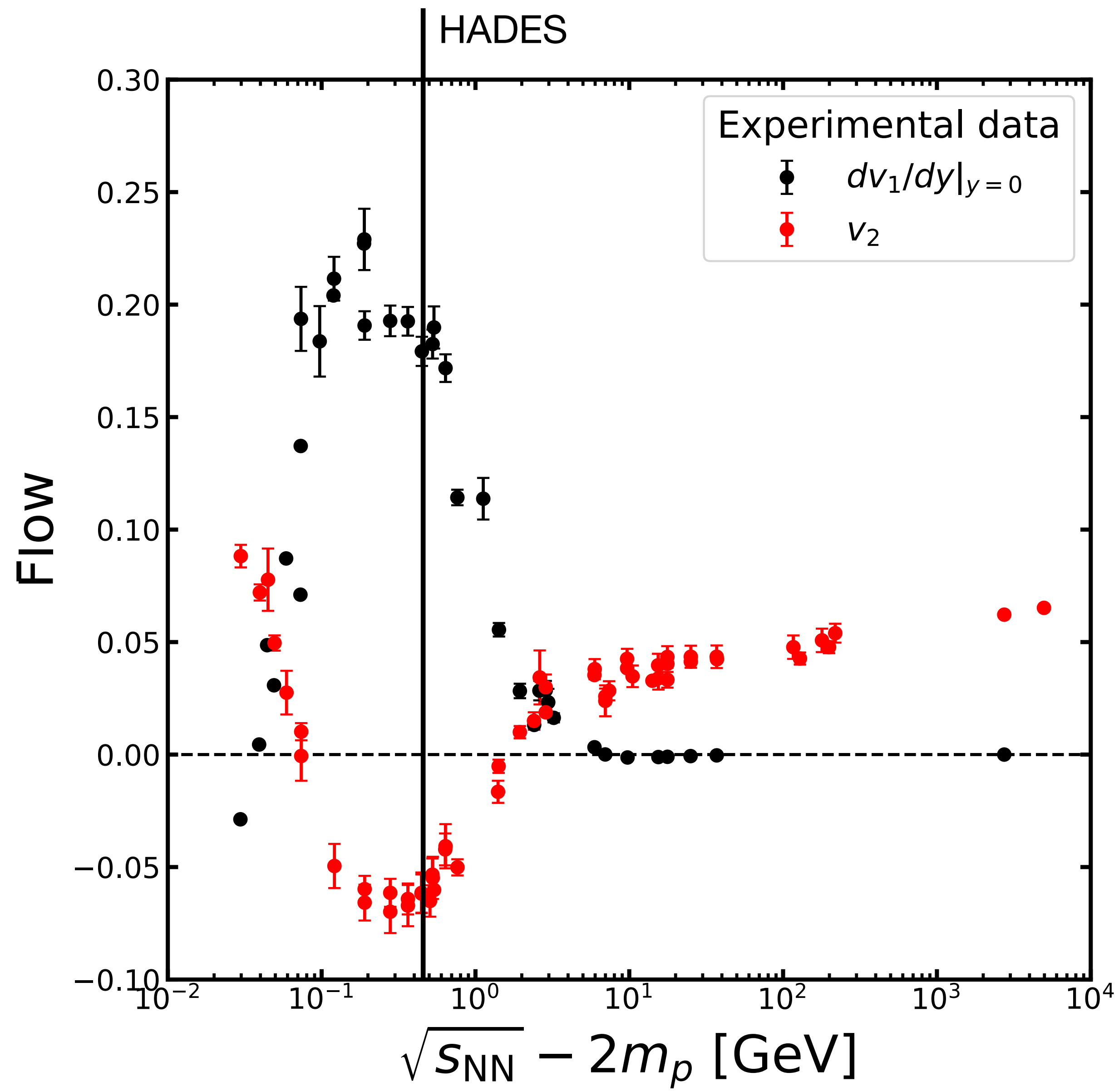
QCD phase diagram & Harmonic flow





- (Most) CEP predictions converge outside of lattice's reach
- Same √sNN region where integrated flow signal peaks / dips

QCD phase diagram & Harmonic flow

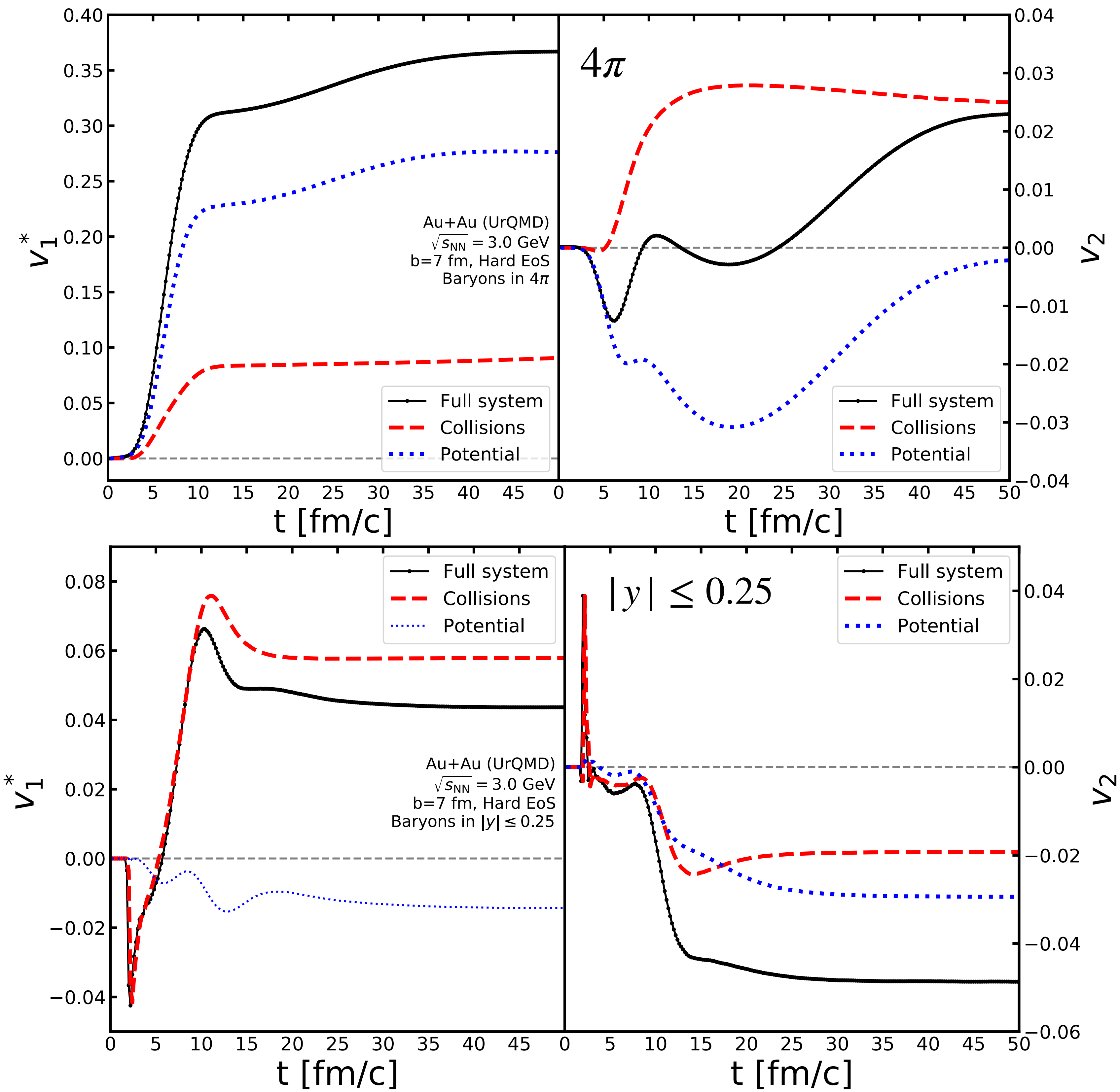


- Sizable values of v_2 and dv_1/dy at SIS18, SIS100, RHIC-FXT energies
- Driven by density gradients and pressure
- Ideal to study U(ρ) and the EOS
- However: Need to understand how EOS affects flow

- Squeeze-Out: Initial v_2 stronger out-of-plane
- Shadowing: Initial v_2 stronger in-plane, but absorbed by spectator

Generation of v_1 and v_2

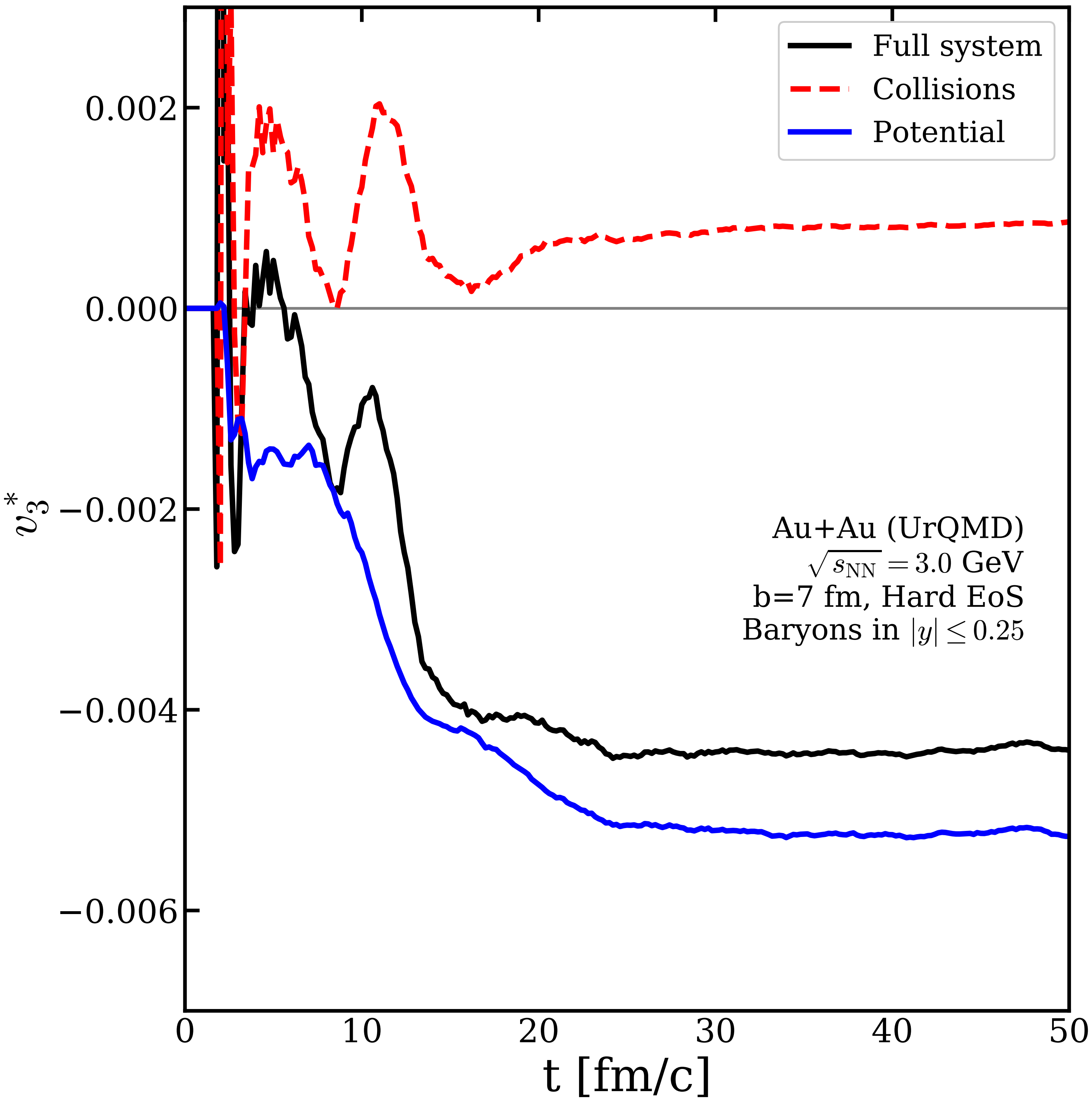
- Do we understand how both v_1 and v_2 are generated in transport models?
- We do! However, reality is more complicated than naive pictures suggest
- Midrapidity v_1 is mostly collisions
- Midrapidity v_2 is 50:50 collisions and potential



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

Generation of v_3

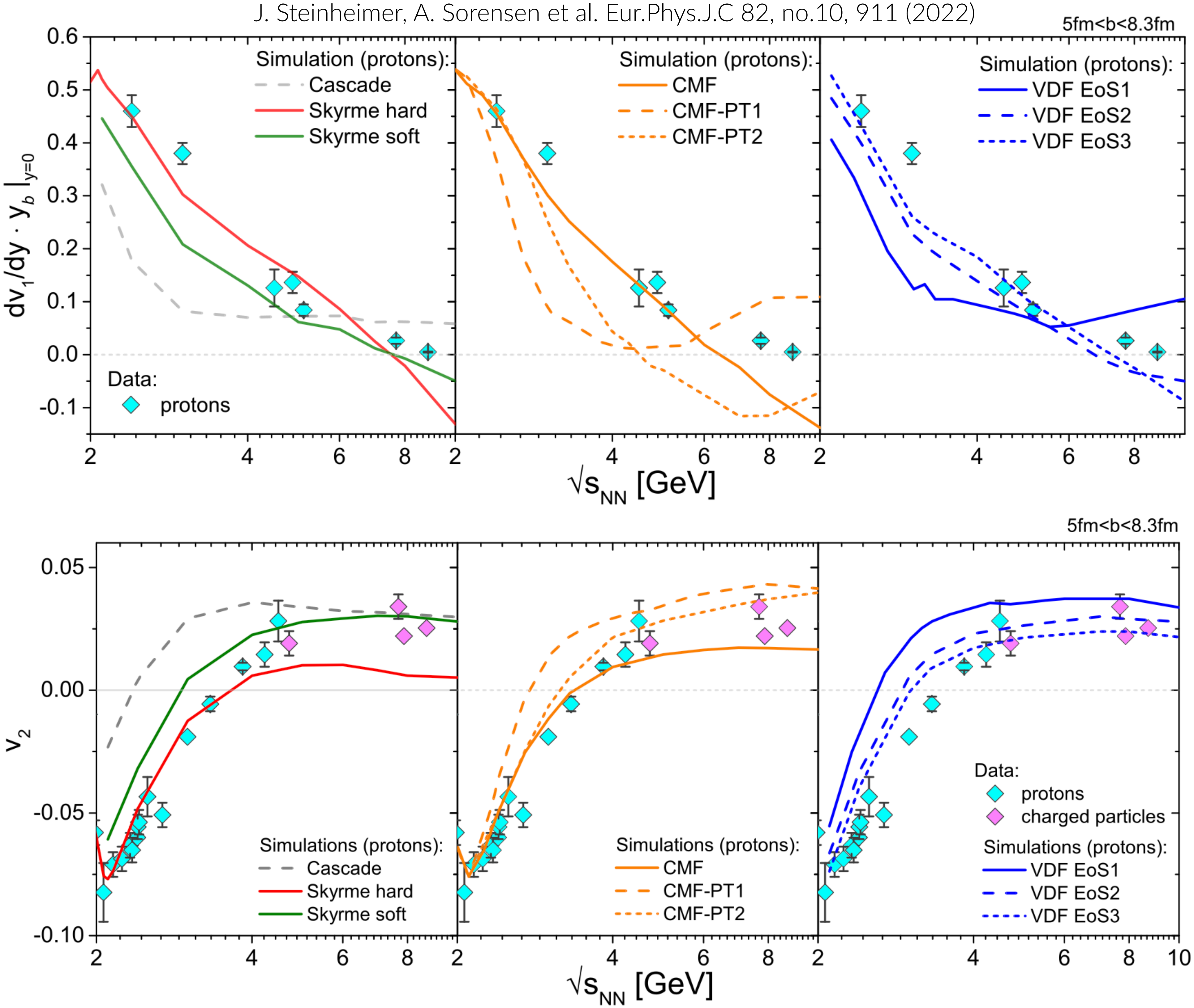
- Triangular flow results become available at more energies
- Can we understand its generation?
- Interestingly, v_3^* seems to be drastically driven by the EoS
- Go-To place to study the EoS



T. Reichert et al. Work in progress

Harmonic flow

J. Steinheimer, A. Sorensen et al. Eur.Phys.J.C 82, no.10, 911 (2022)



- Directed and elliptic flow show good sensitivity to employed EoS
- However, at each energy, the information is condensed into a single point
- Different model systematics, different experimental set-ups make EoS extraction difficult

➤ Find better observable!

EoS: hard or soft?

Most of the $\sqrt{s_{NN}} = 3$ GeV Au+Au data are best described by calculations using a soft momentum dependent EoS (SM),

Y. Zhou et al. arXiv:2507.14255 [nucl-th]

As one can see the solid black line gives the best description of the constraint which corresponds to an intermediate momentum dependence and a nuclear incompressibility of $K = 303$ MeV.

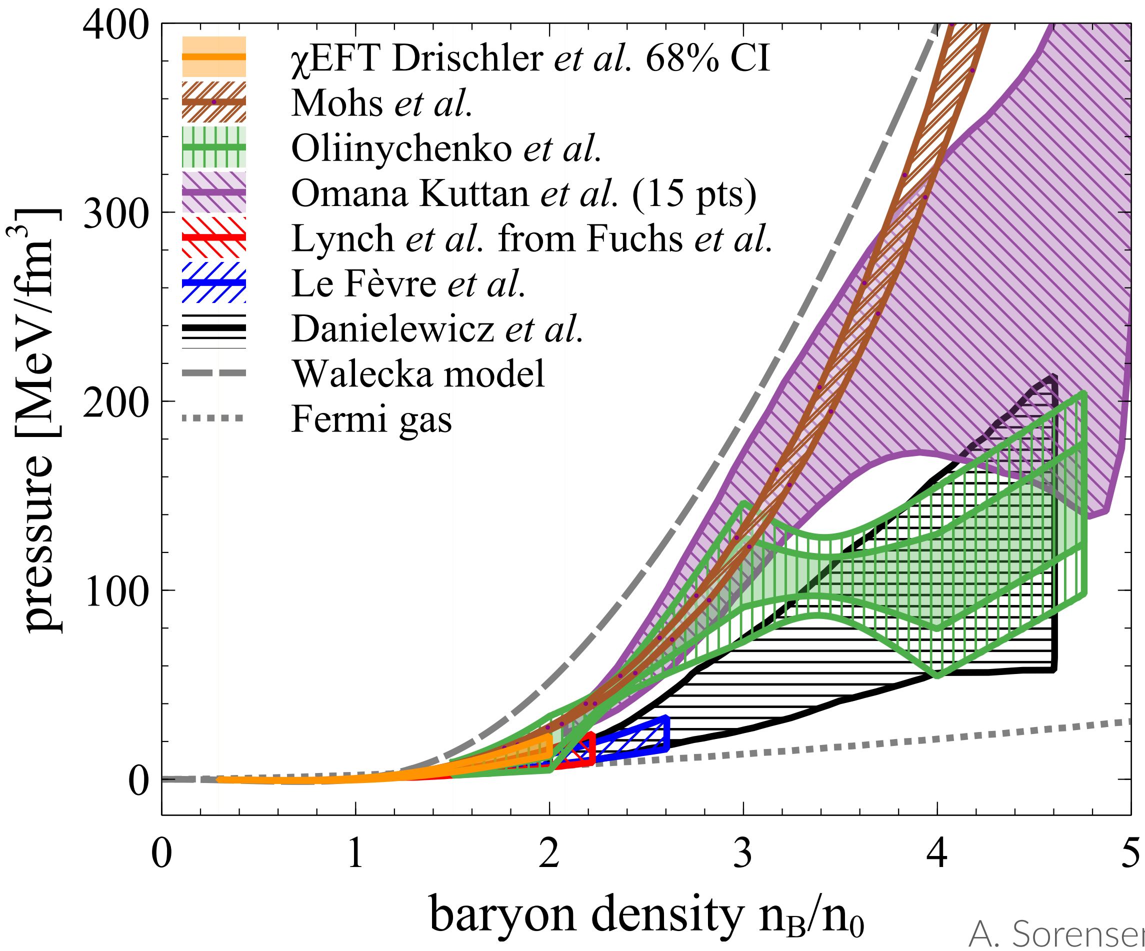
J. Steinheimer et al. Phys.Lett.B 867 (2025) 139605

Investigating the beam energy dependence of v_1 and v_2 we found that the data consistently favors a hard EoS for $E_{lab} < 5$ A GeV and a softening of the EoS for higher beam energies, consistent with findings in [8, 12].

P. Hillmann et al. J.Phys.G 45 (2018) 8, 085101

The results strongly depend on the model parameters; thus, we will not rule out the possible softening scenario within the current study.

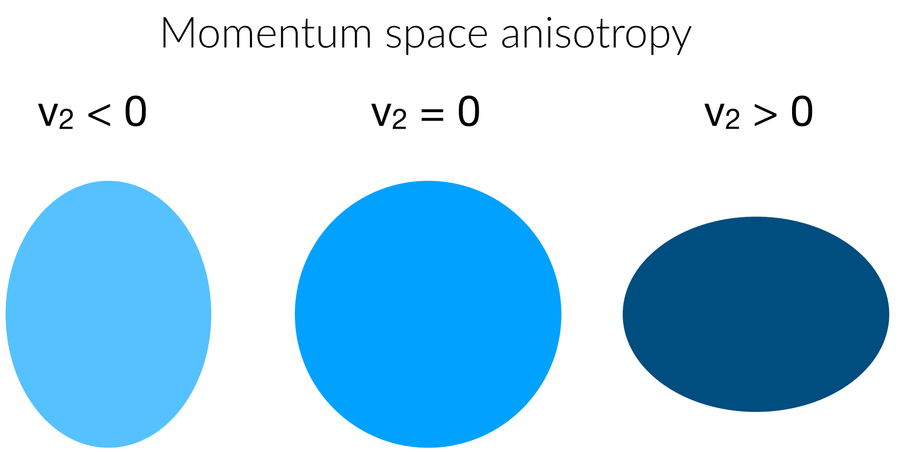
Y. Nara et al. Phys.Rev.C 105 (2022) 1, 014911



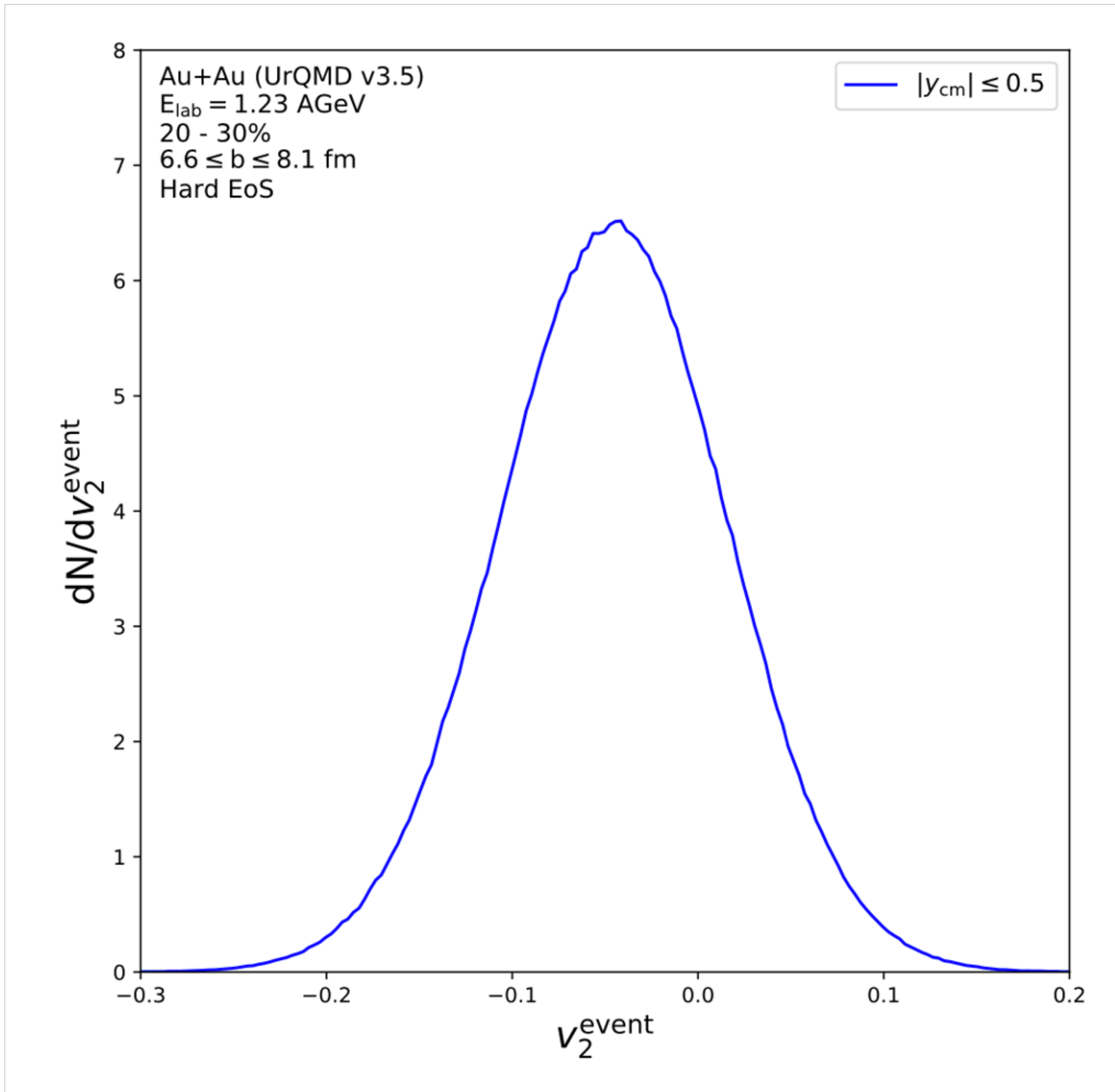
A. Sorensen adapted from:
L. Du et al. Int.J.Mod.Phys.E 33 (2024) 07, 2430008

- Despite all success the EoS remains (quantitatively) not well constrained above $2\rho_0$
- Bayesian inference didn't pin the EoS down yet, due to model dependencies

Flow correlations



- Event-by-event elliptic flow at midrapidity fluctuates strongly
- Average v_2 aligns with HADES data
- Event-wise elliptic flow can become very negative
- Event-wise elliptic flow can even turn positive
- Define event classes basen on $\langle v_2 \rangle^{event}_{|y|\leq 0.5}$



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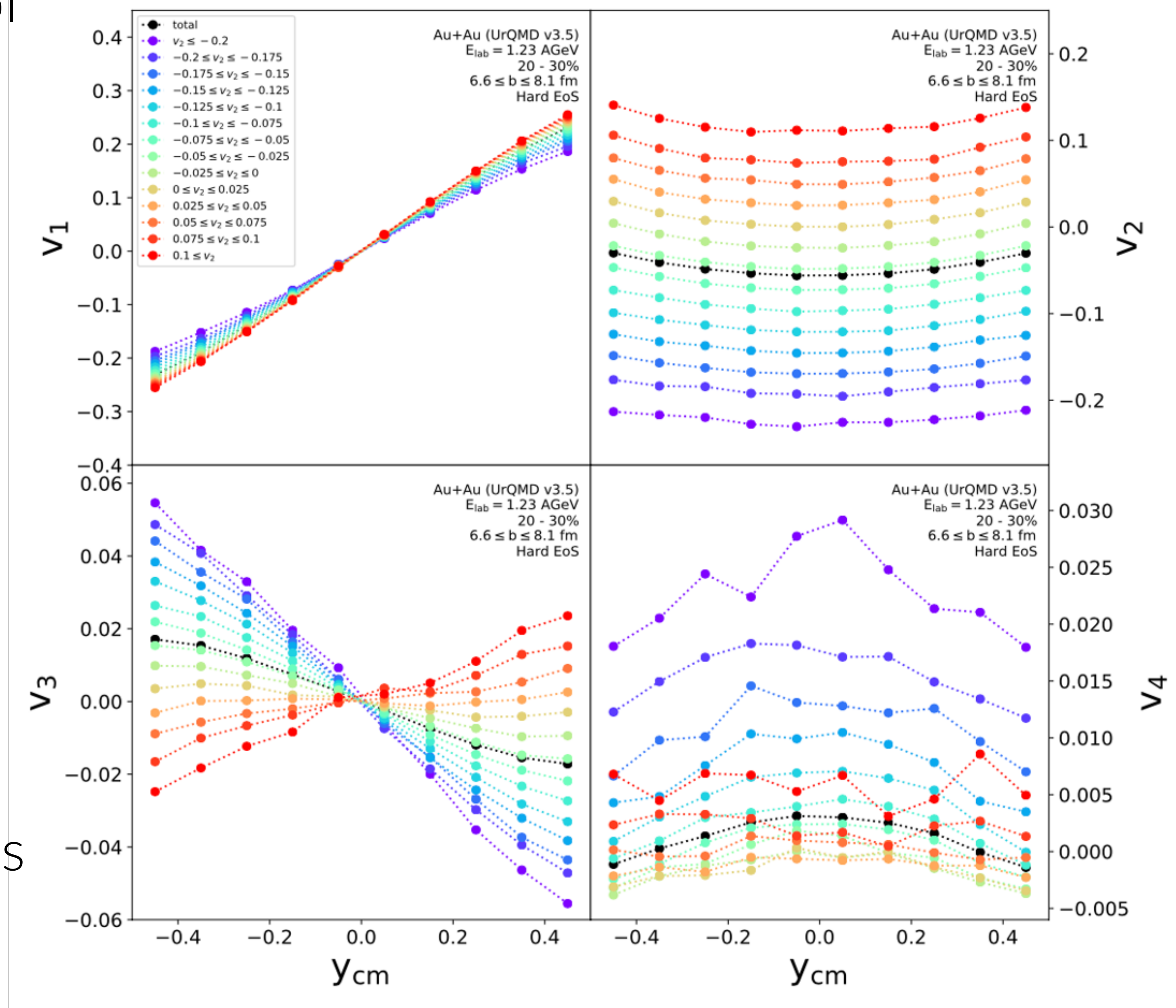
Flow correlations

- Analyze flow as function of rapidity in event classes
- Strong sensitivity of harmonic flow
- Directed flow increases
- Elliptic flow increases trivially
- Triangular flow switches sign
- Quadrangular flow changes shape



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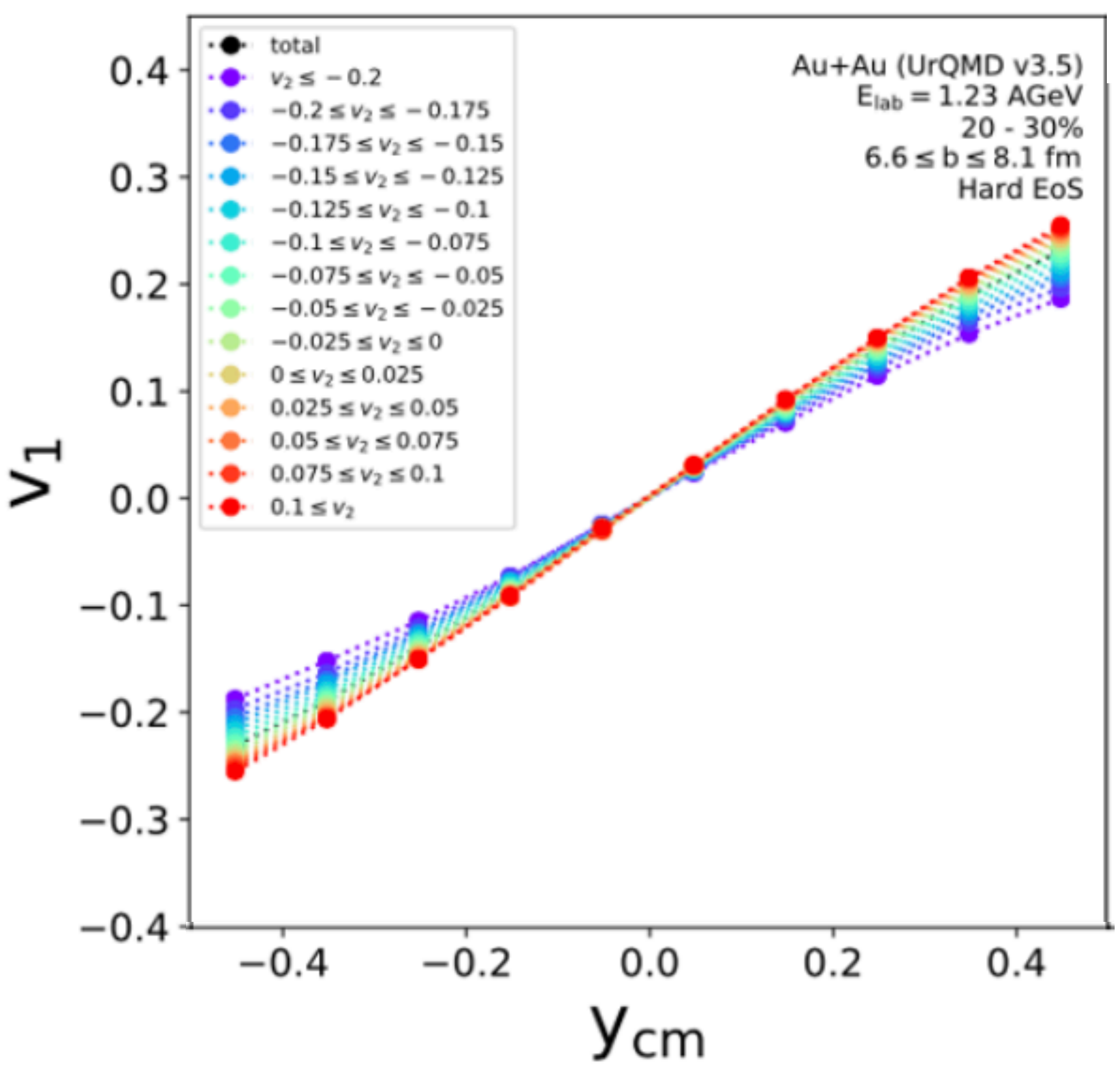
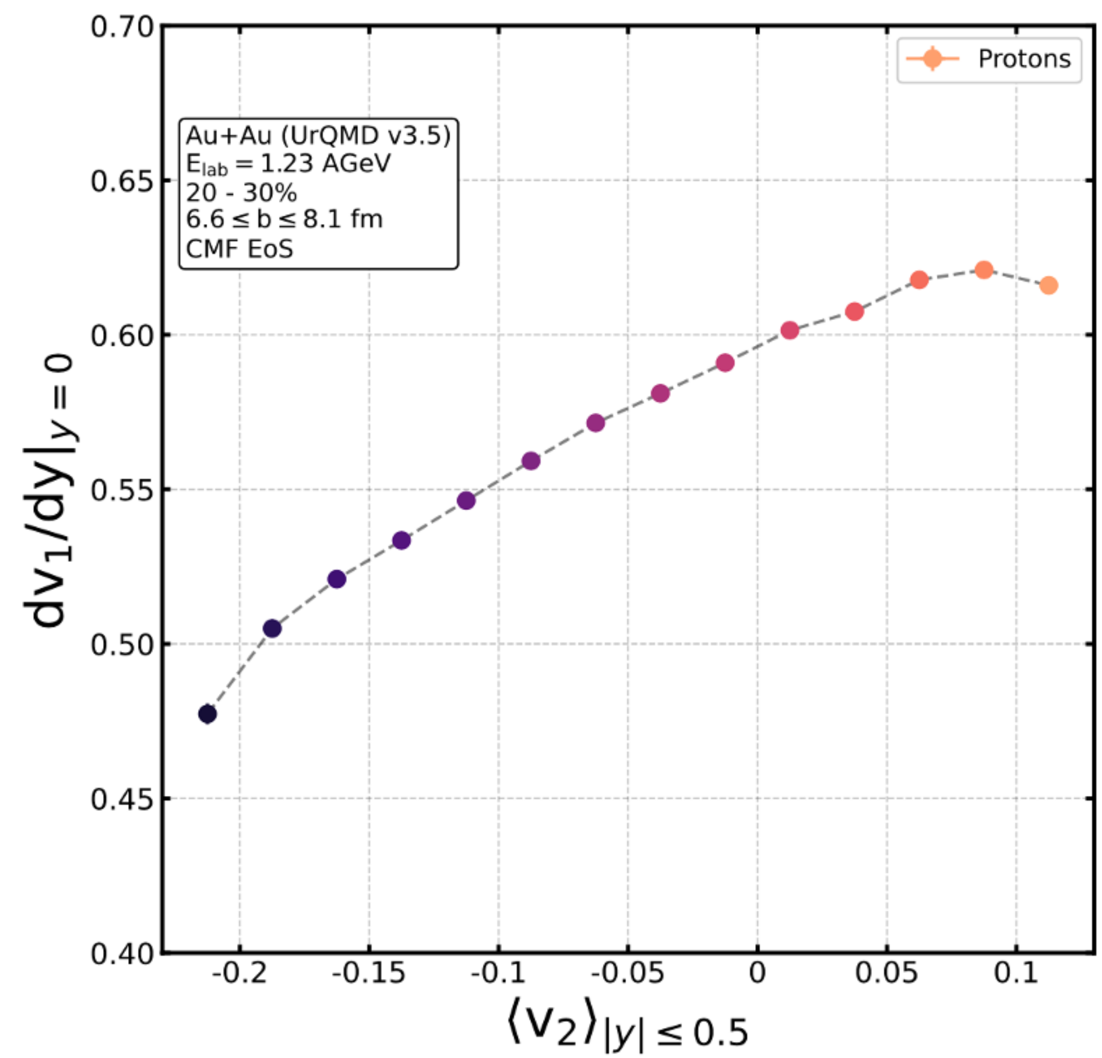
Flow correlations

- Slope of directed flow increases





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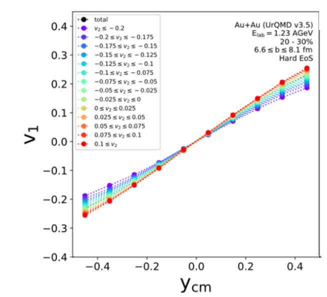
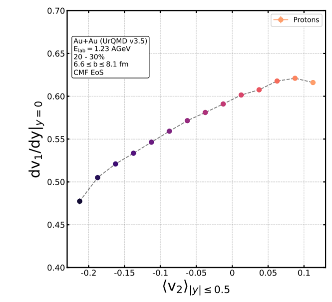
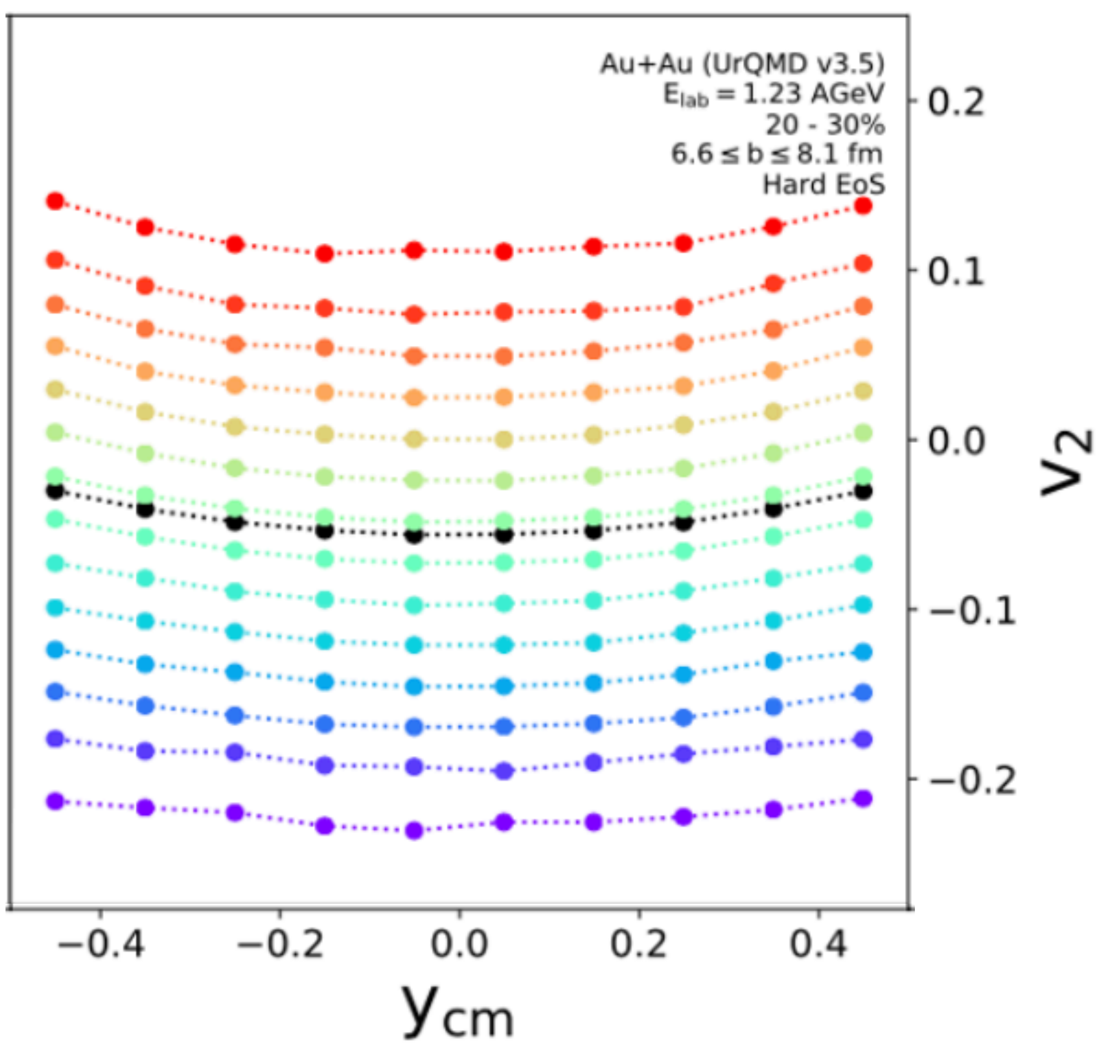
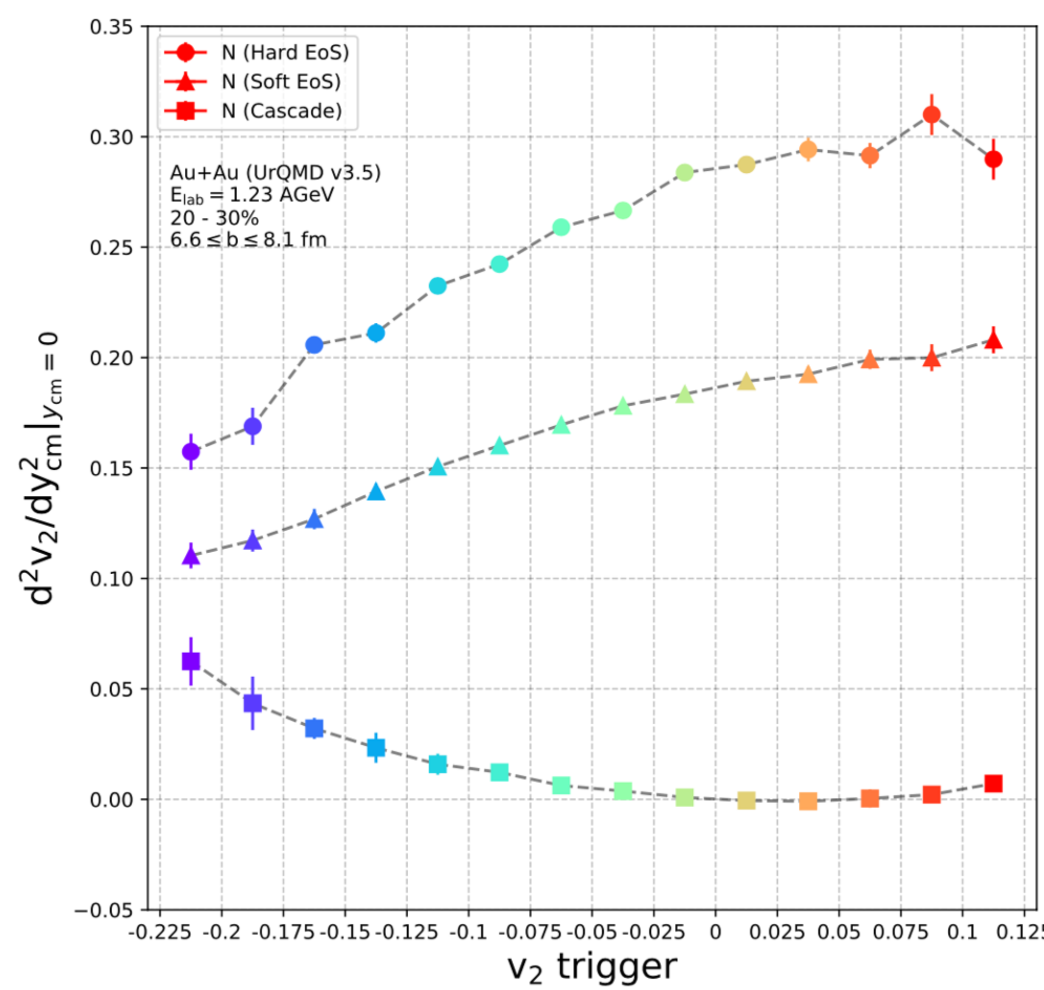




- Slope of directed flow increases
- Curvature of v_2 qualitatively different





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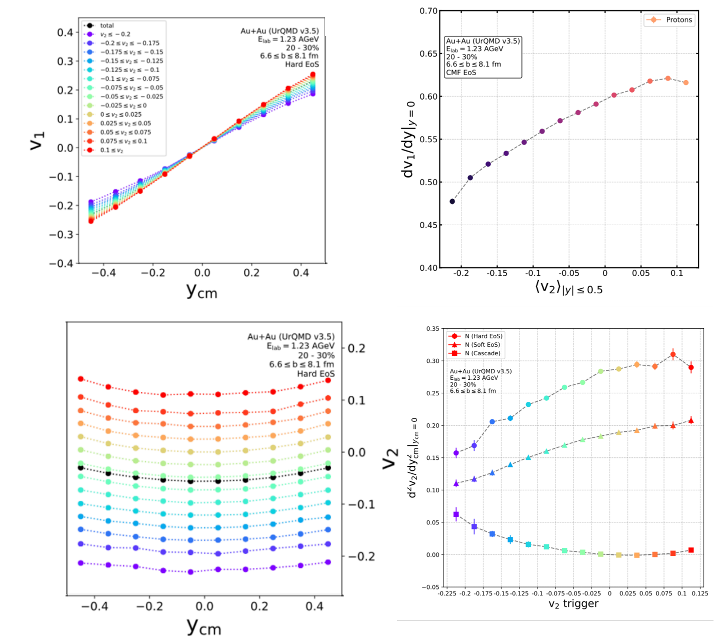
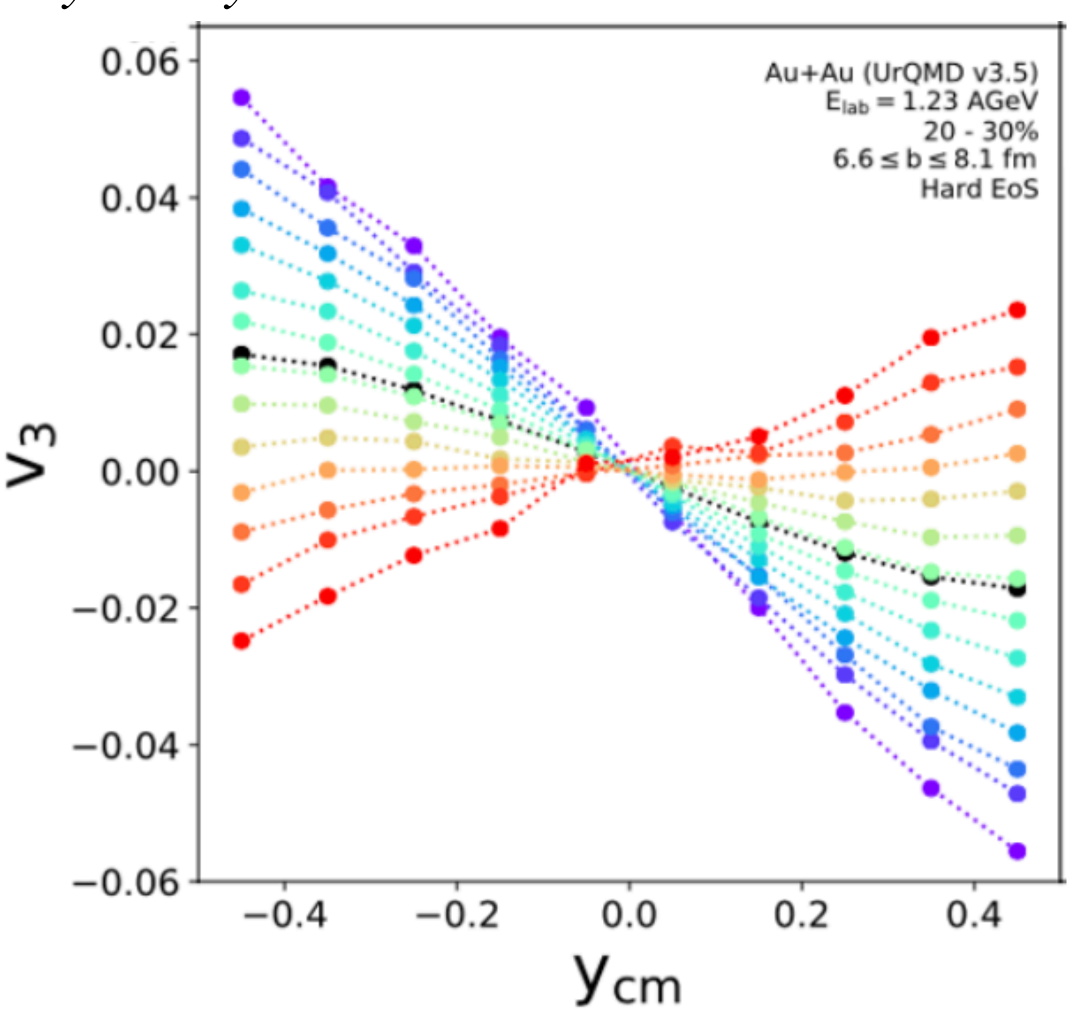
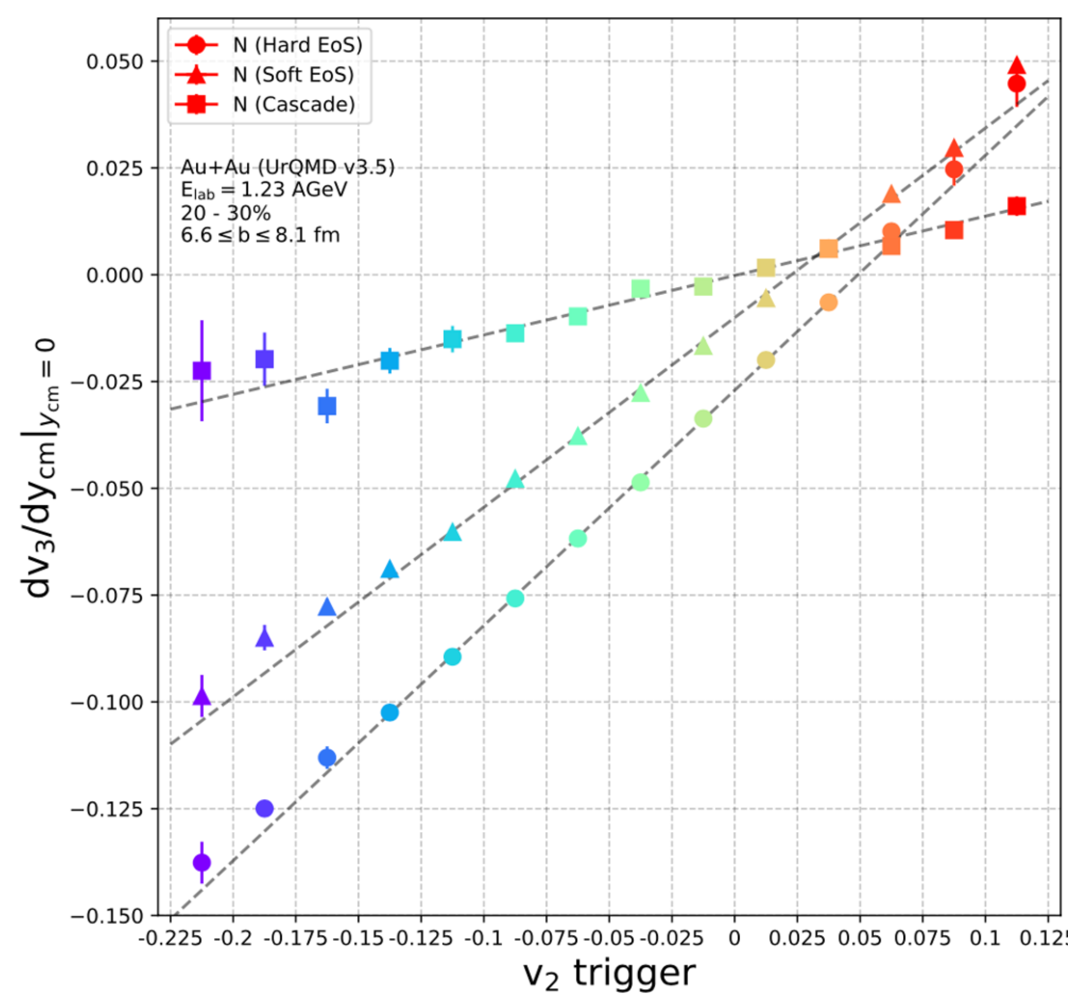
Flow correlations



- Slope of directed flow increases
- Curvature of v_2 qualitatively different
- Linear dependence of slope of v_3

$$\frac{dv_3}{dy} = \frac{dv_1}{dy} \cdot v_2$$





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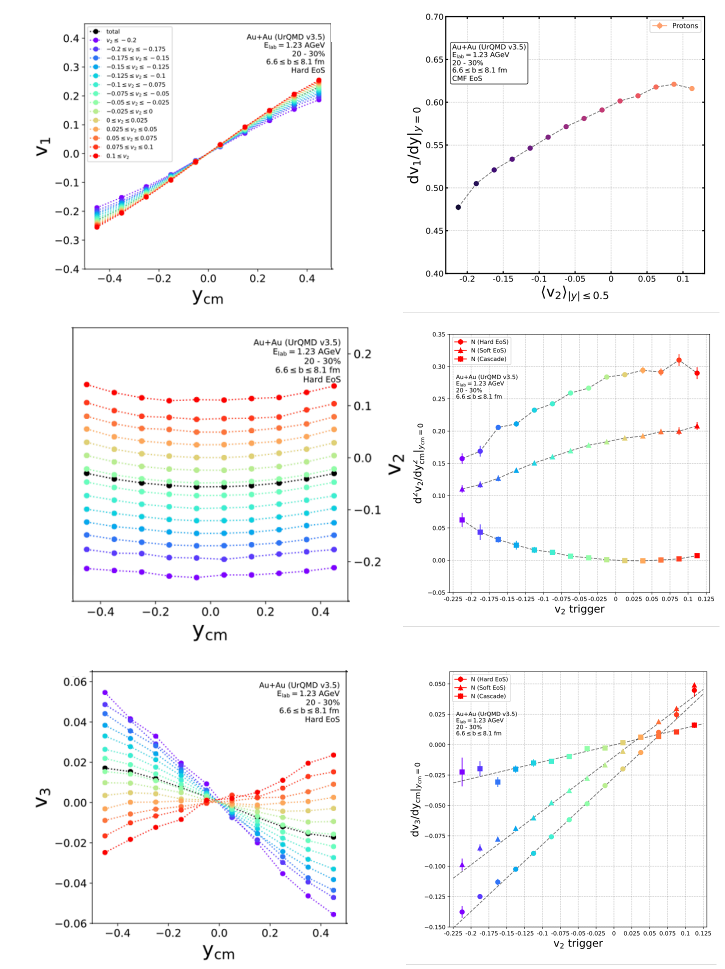
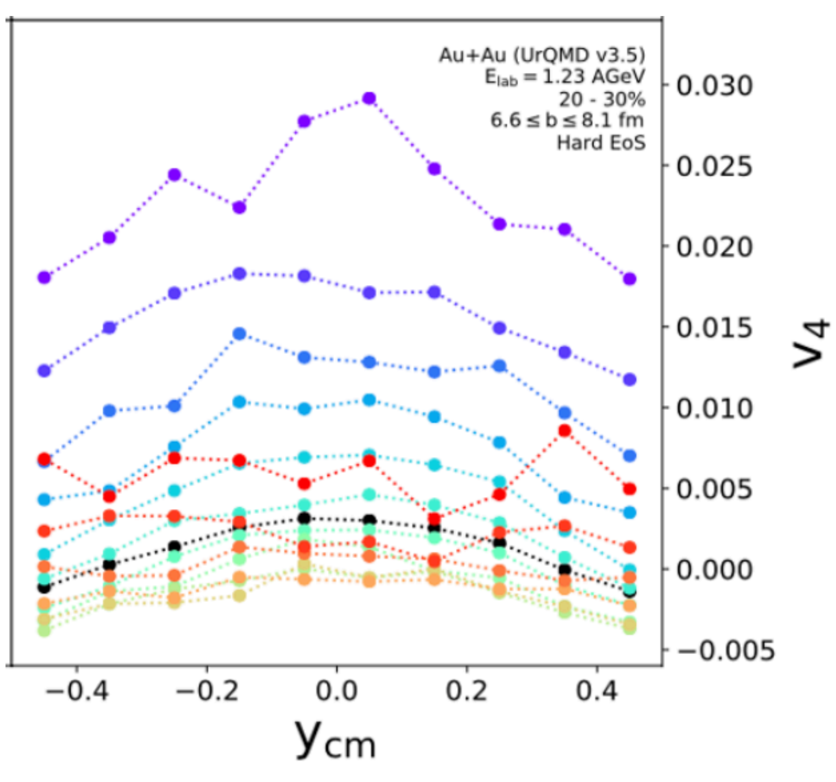
Flow correlations

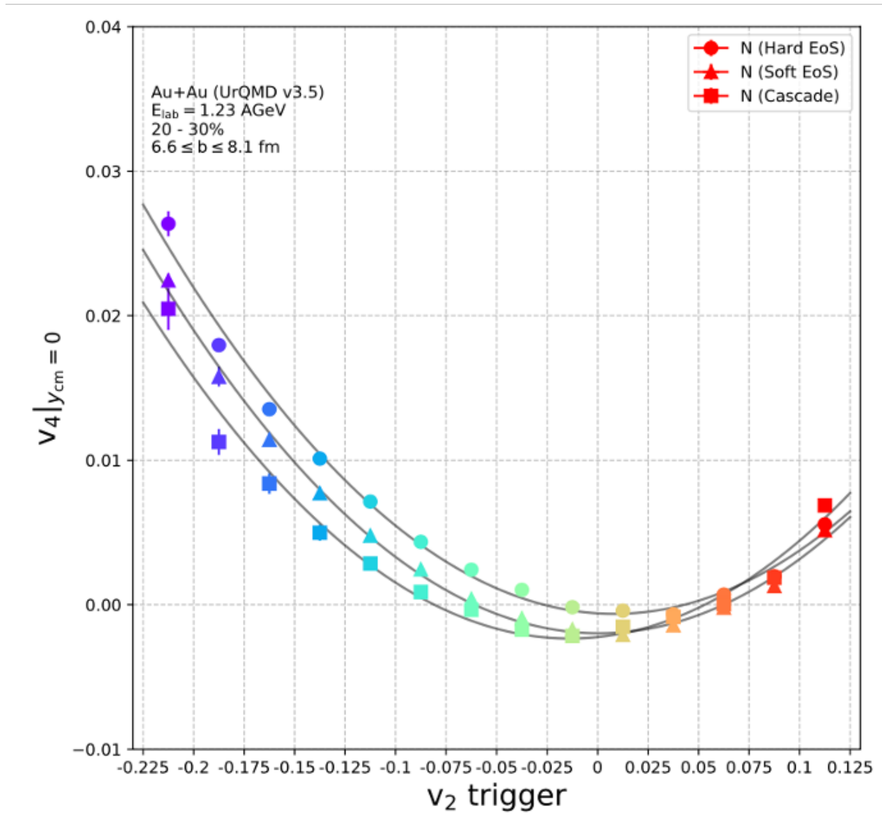


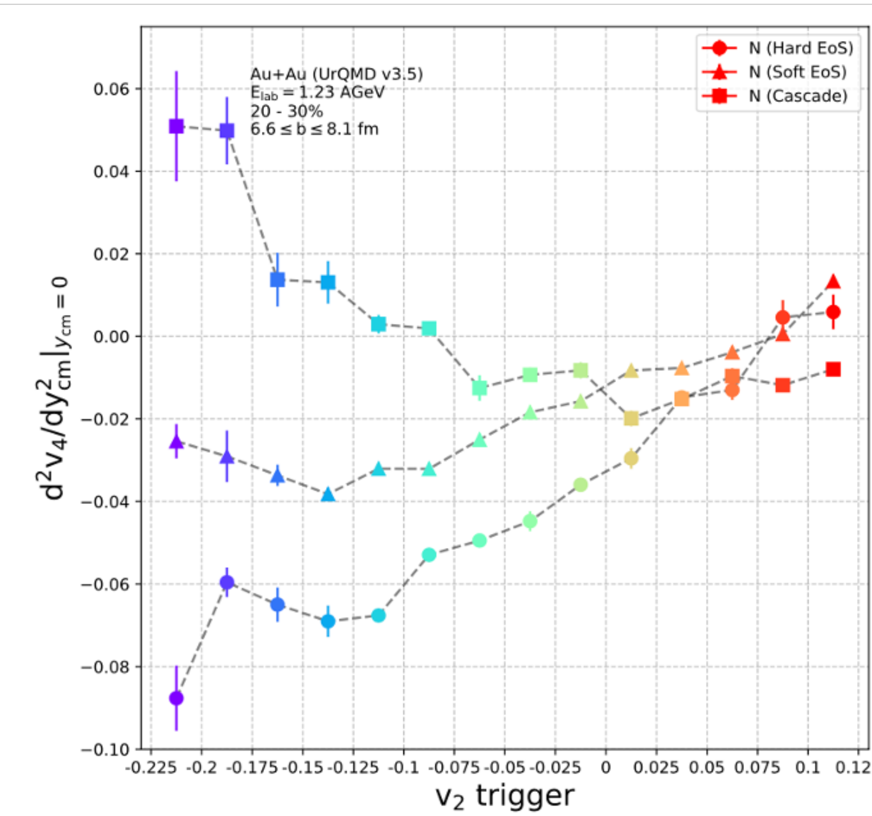
- Slope of directed flow increases
- Curvature of v_2 qualitatively different
- Linear dependence of slope of v_3

$$\frac{dv_3}{dy} = \frac{dv_1}{dy} \cdot v_2$$

- Value and curvature of v_4 also sensitive

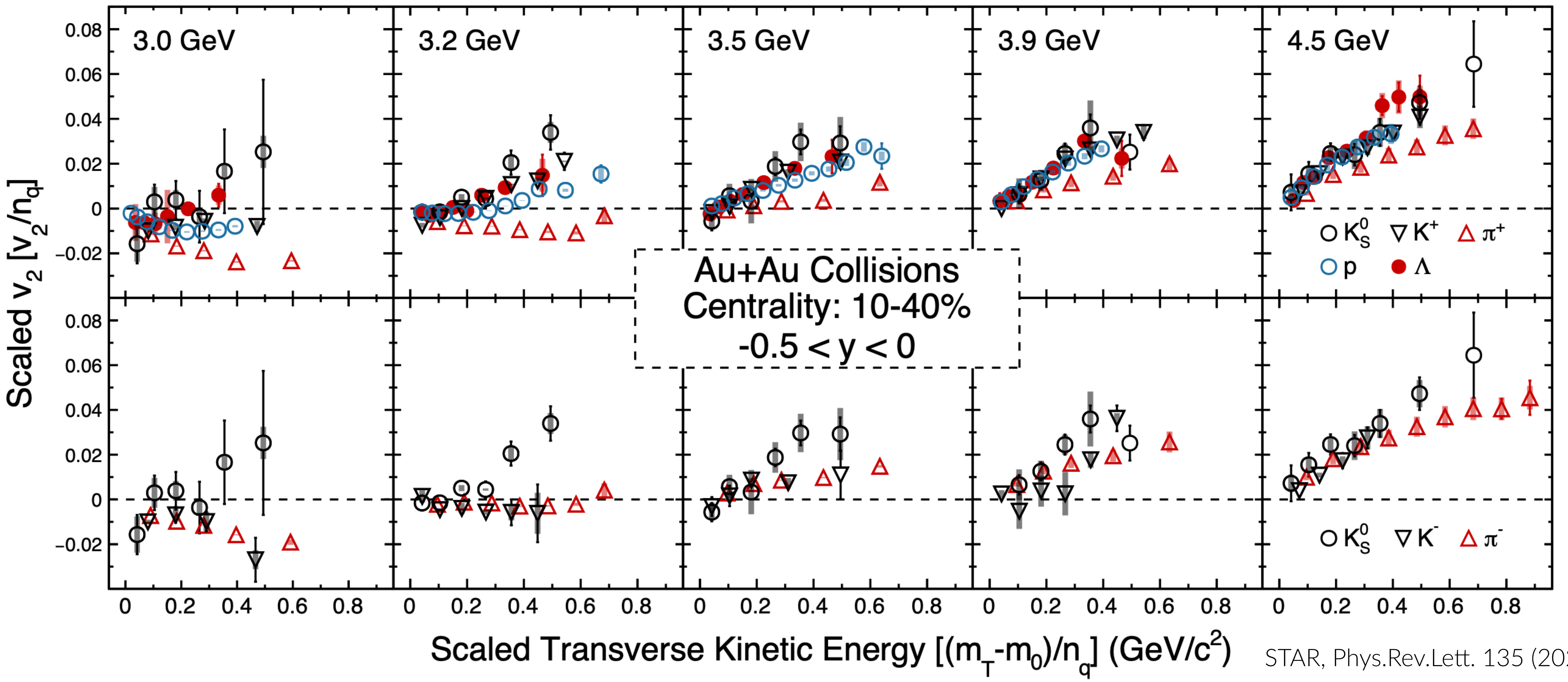






Breaking of (NCQ) scaling

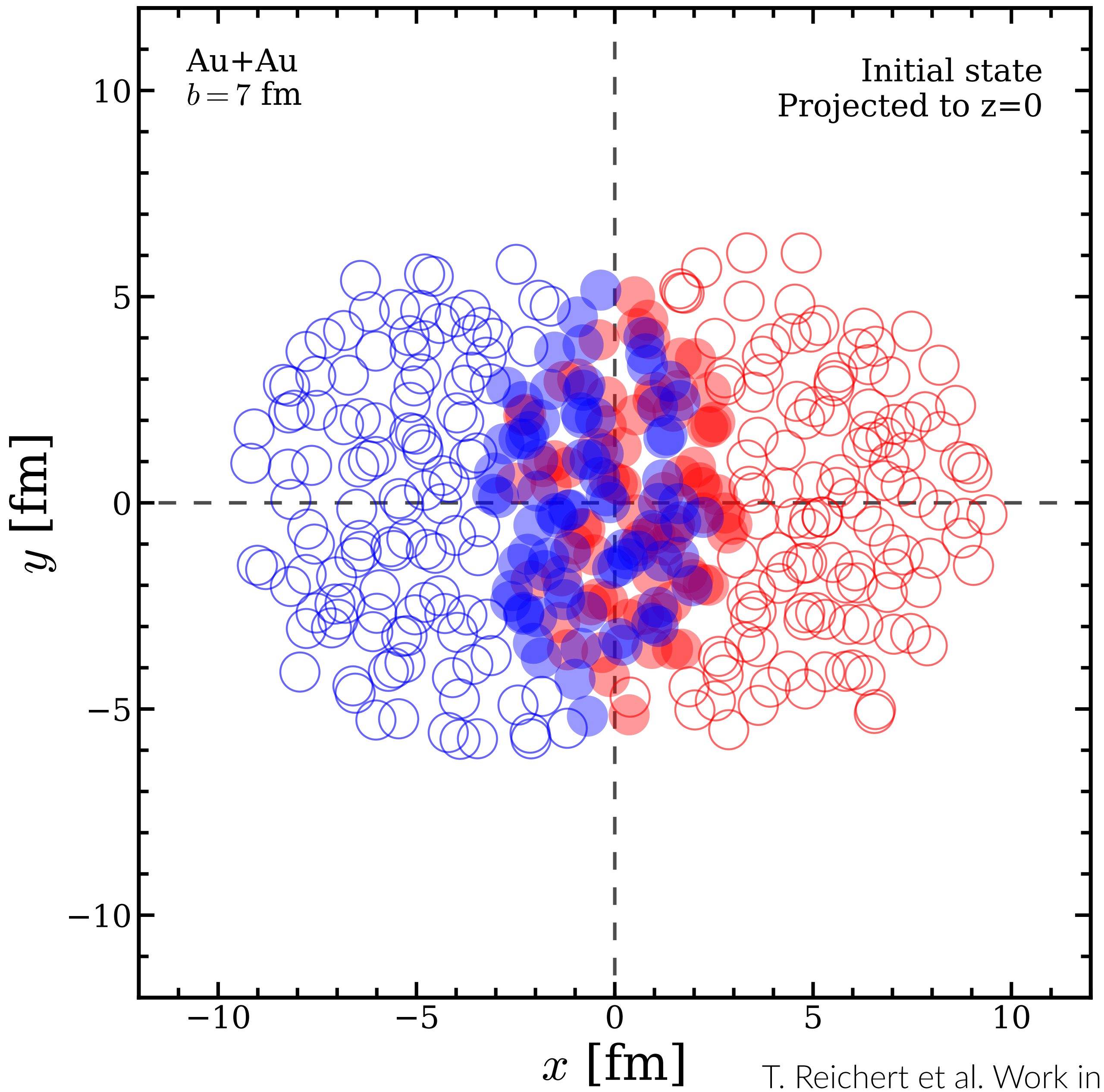
- Quark coalescence leads to NCQ scaling
- However, relative cross sections (AQM) also lead to scaling
- Even if NCQ scaling were present, in the negative v_2 regime it might be shadowed



STAR, Phys.Rev.Lett. 135 (2025) 7, 072301

Unshadowing flow

- Remove Glauber equivalent spectators from initial state
- Use frozen Fermi approx.
- Procedure automatically recovers real scenario at higher $\sqrt{s_{NN}}$
- Checked that dN/dy at y=0 remains unchanged, although beyond y=0 yields and spectra vary



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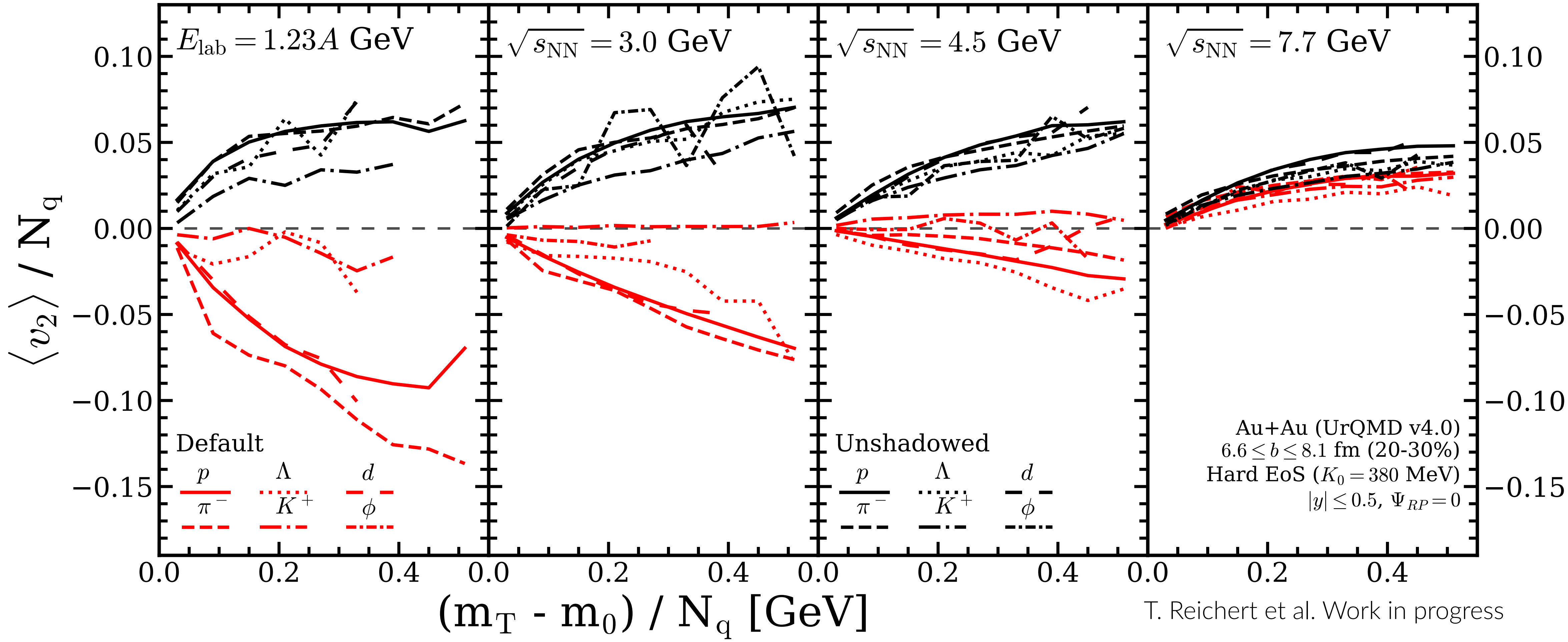
Unshadowing flow



- Partial recovering of „NCQ" scaling (UrQMD has no quarks)
- At least a fraction of „The onset of NCQ scaling" is due to shadowing
- Remember threshold effect in Kaon, Lambda, phi production

Analytic consideration

- NCQ scaling arises from $F_{\mathrm{M}}(\phi) \propto f_{\mathrm{q}}^{2}(\phi)$
- Rearranging terms with equal n yields $v_2^{\mathrm{M}}(2p_T) = 2v_2^{\mathrm{q}}(p_T)$
- Similar idea, however, including absorption on spectator
- $F_{\mathrm{M}}(\phi) \propto f_{\mathrm{q}}^{2}(\phi) \cdot P_{\mathrm{abs}}(\phi)$ yields $v_2^{\mathrm{M}}(2p_T) - v_2^{\mathrm{abs}} = 2v_2^{\mathrm{q}}(p_T)$ in leading order

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- With absorption probability

$$P_{\mathrm{abs}}(\phi) \propto \exp\left(-\int_{t_0}^{\infty} dt' \sigma_{abs}(\sqrt{s})\,|v_{rel}|\,\rho(\phi, t')\right)$$

- Ballistic Glauber or full fledged dynamical simulation as baseline

Summary

- Generation of v_1 and v_2 is complicated, having partial influence from shadowing and squeeze-out and freeze-out geometry
- Generation of v_3 is mostly determined by the EOS
- Strong v_2 fluctuations allow to classify events
- Large sensitivity in flow correlations using event classes
- (NCQ) scaling breaks down at low energies
- Unshadowed UrQMD attributes at least 50% of the non-scaling to shadowing
- Analytic correction could provide more insights

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