DECIPHERING FLOW AT SIS ENERGIES: A LOOK THROUGH THE KEYHOLE

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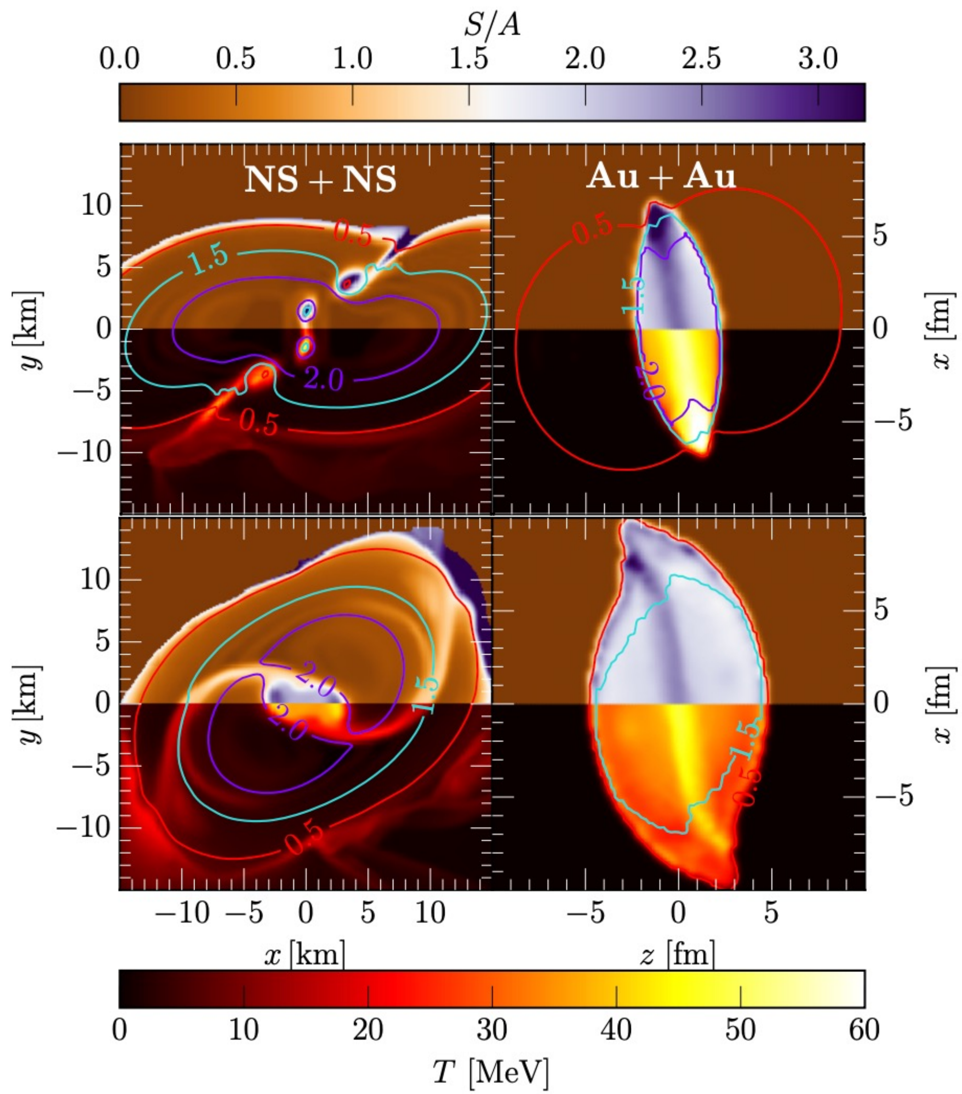
9th Non-Equilibrium Dynamics
Krabi, Thailand

Heavy Ion Collisions and Neutron Stars

- Remarkable resemblance
- Densities 2-6 ρ_0
- Vorticity $10^{40}\hbar$
- Measure Equation-of-State $P(\varepsilon)$ of nuclear matter
- Binary Neutron Star mergers
  - Gravitational waves
- Heavy Ion Collisions
  - Harmonic flow



E. Most, arXiv:2201.13150

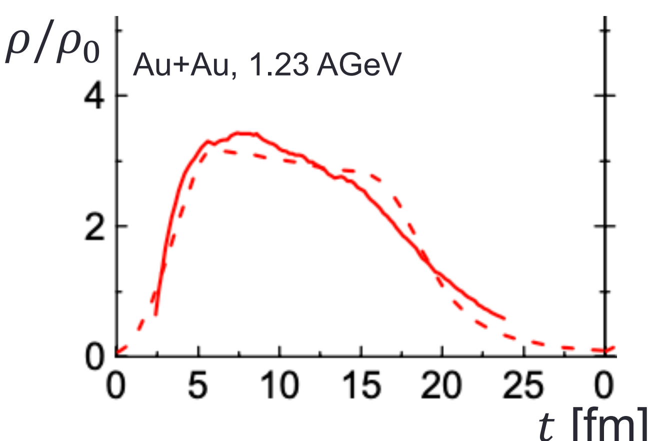
Ultra-relativistic Quantum Molecular Dynamics

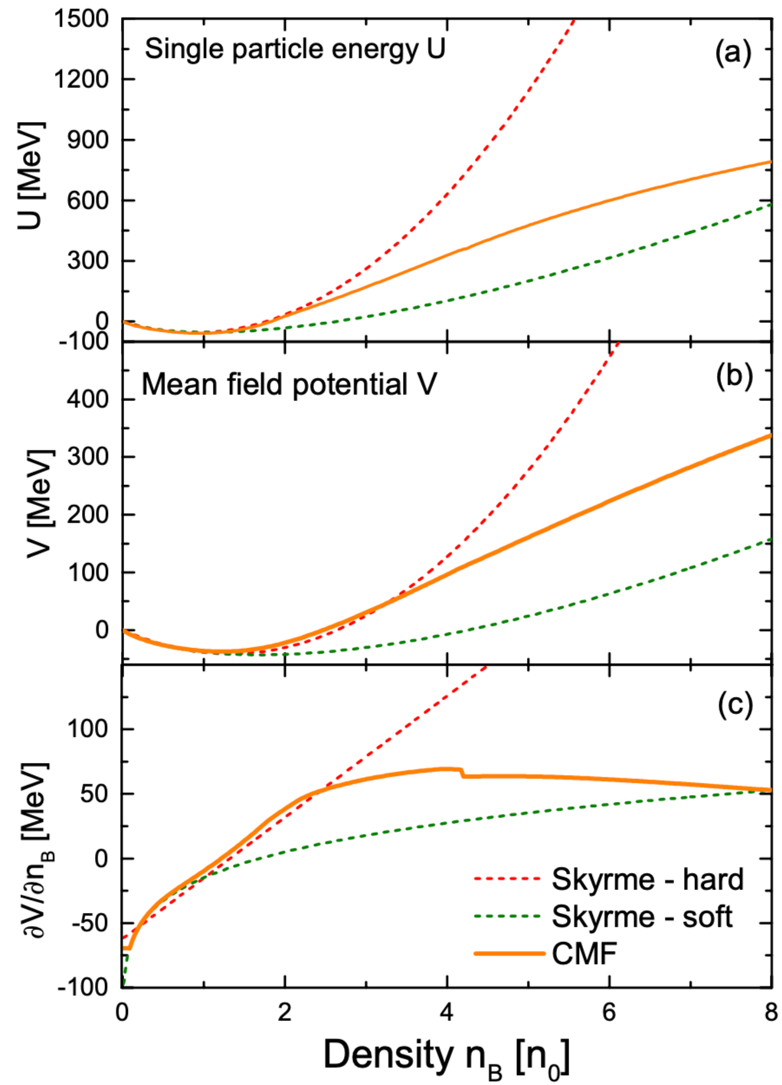
- Hadron/String transport approach
- Based on propagation of hadrons
- Rescattering among hadrons fully included
- String excitation and decay (LUND modell, PYTHIA)
- Solution for the time dependent n-body distribution of hadrons
- Collision term includes more than 100 hadrons up to 4 GeV in mass
- Soft/Hard or CMF EoS can be switched on

M. Bleicher et al. J.Phys. G25 (1999), 1859-1896

UrQMD with Chiral Mean Field EoS

- $m^*_{b\pm} = \sqrt{\left[(g^{(1)}_{\sigma b}\sigma + g^{(1)}_{\zeta b}\zeta)^2 + (m_0 + n_s m_s)^2\right]} \pm g^{(2)}_{\sigma b}\sigma \ ,$
- $V_{CMF} = E_{\text{field}}/A = E_{\text{CMF}}/A - E_{\text{FFG}}/A \ ,$
- CMF EoS hard up to $3\rho_0$ then soft
- Easy implementation of phase transition

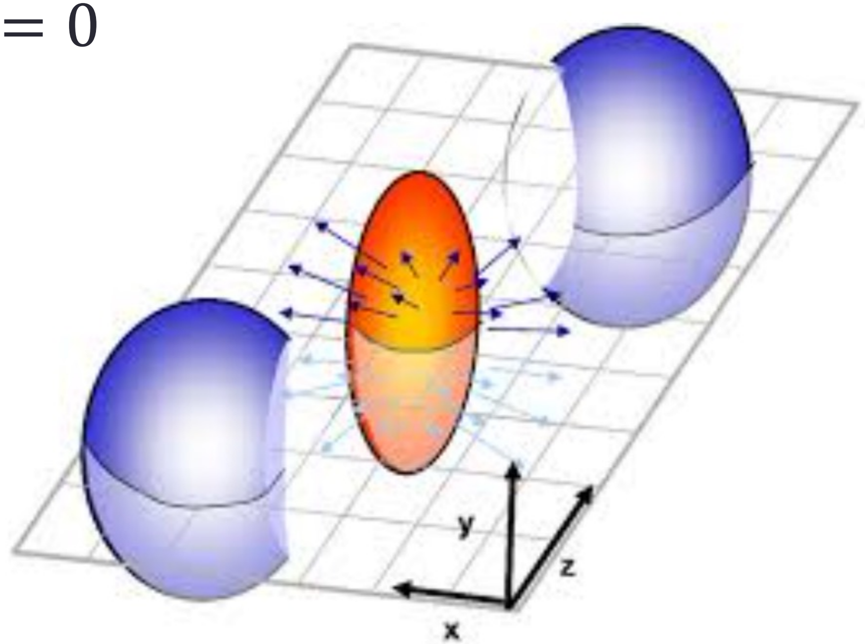




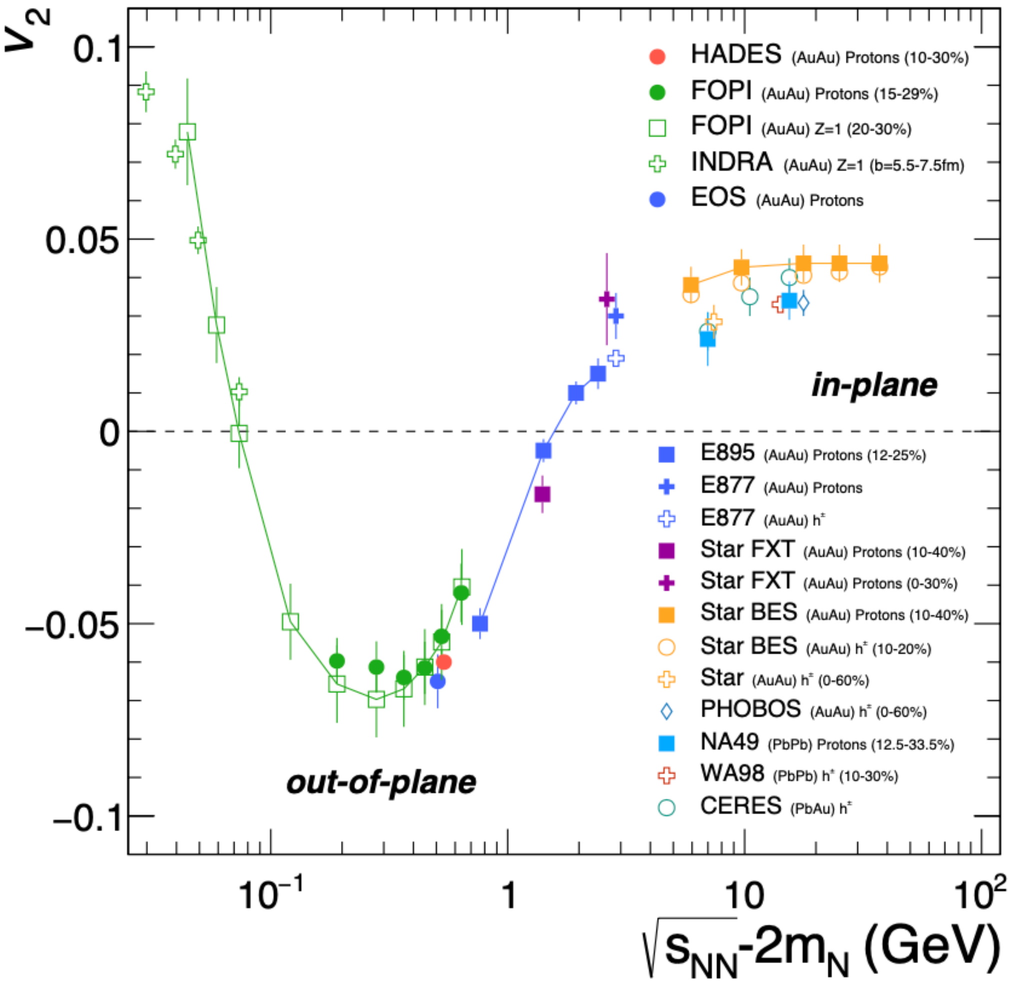
M. Omana Kuttan et al., arXiv:2201.01622

What is flow?

- Fourier series of azimuthal angle distribution
- $\frac{dN}{d\varphi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_{RP})) + \tilde{v}_n \sin(n(\varphi - \Psi_{RP}))$
- Experiment: difficult due to fluctuating reaction plane
- Simulation: $\Psi_{RP} = 0$ and $\tilde{v}_n = 0$
- v_1: Directed flow
- v_2: Elliptic flow



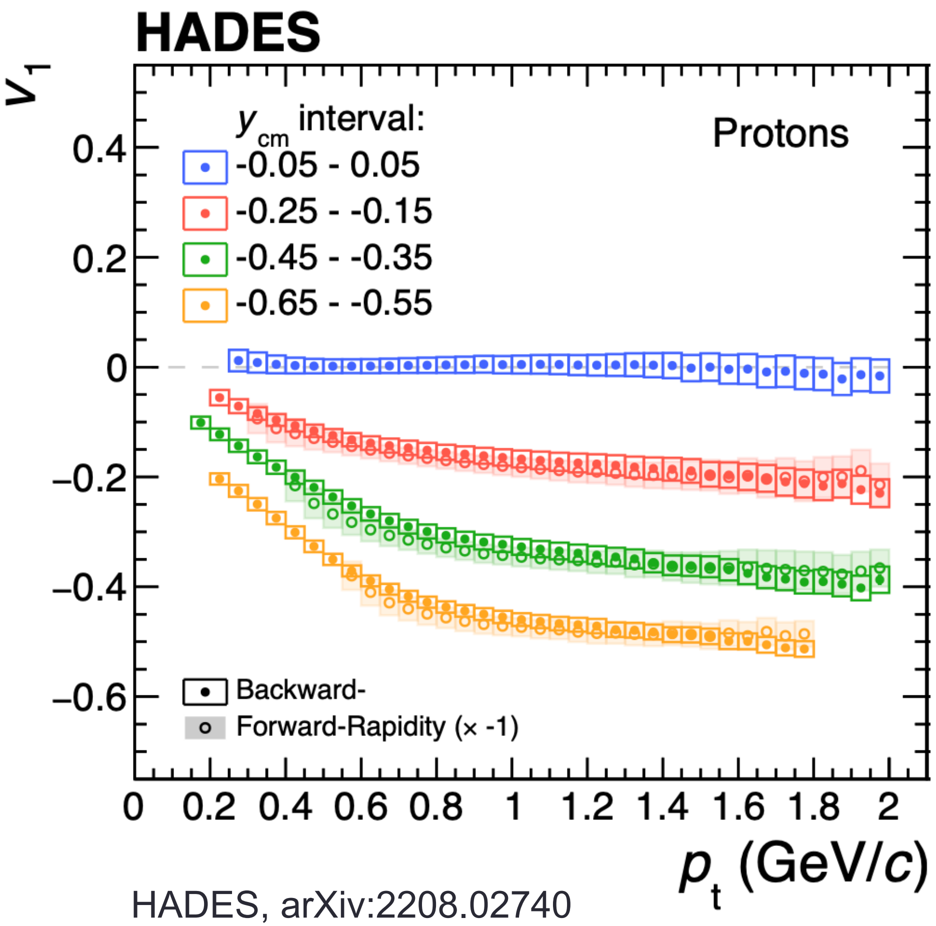
Elliptic flow versus energy



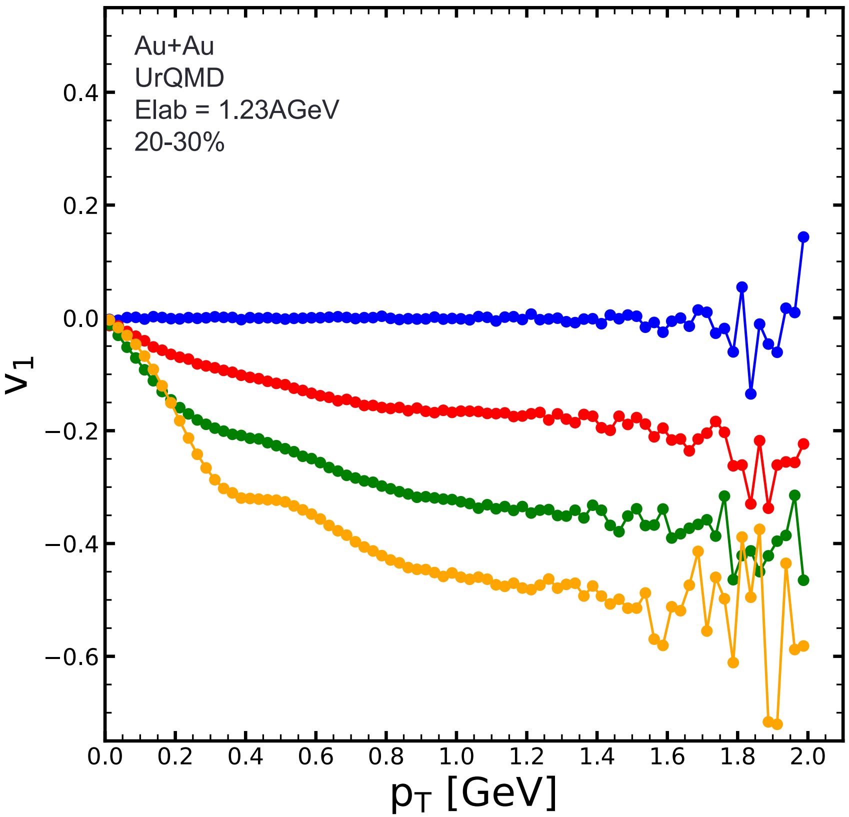
HADES, arXiv:2208.02740

- Elliptic flow is negative from $\sqrt{s_{NN}} = 2 - 4$ GeV
- Positive at higher energies
- Out-of-plane emission: Shadowing
- In-plane emission: Pressure gradient, transverse expansion

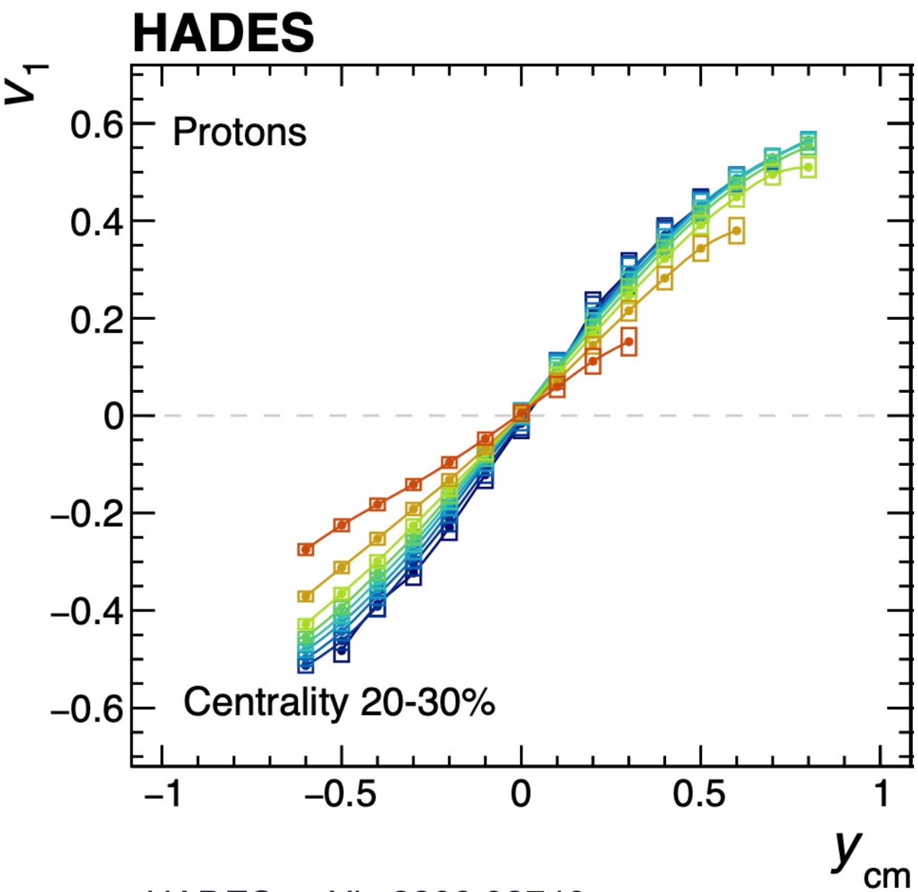
HADES vs UrQMD

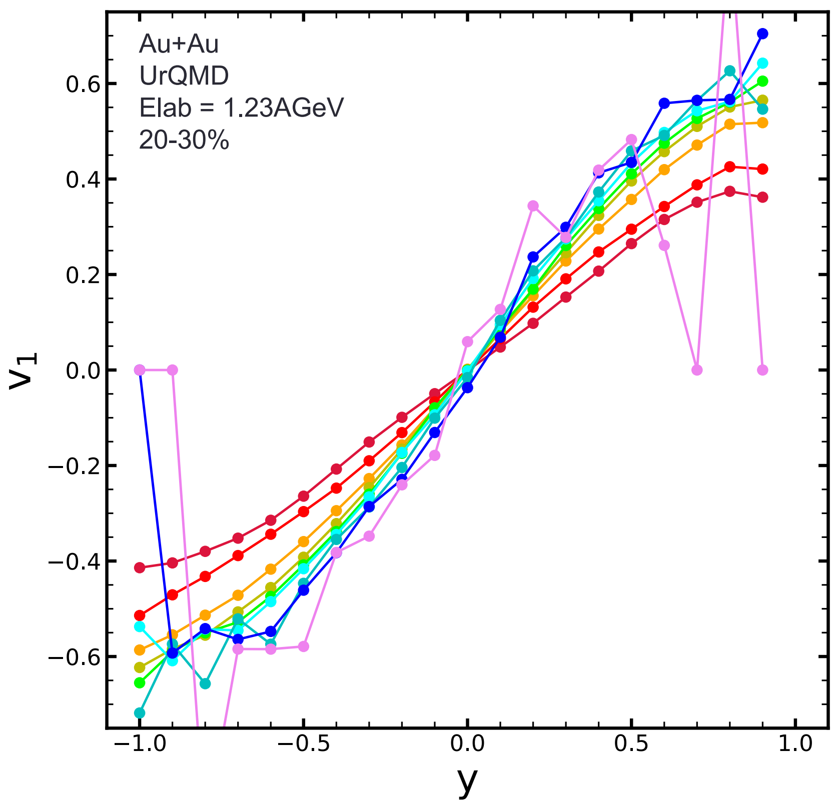


HADES, arXiv:2208.02740



HADES vs UrQMD

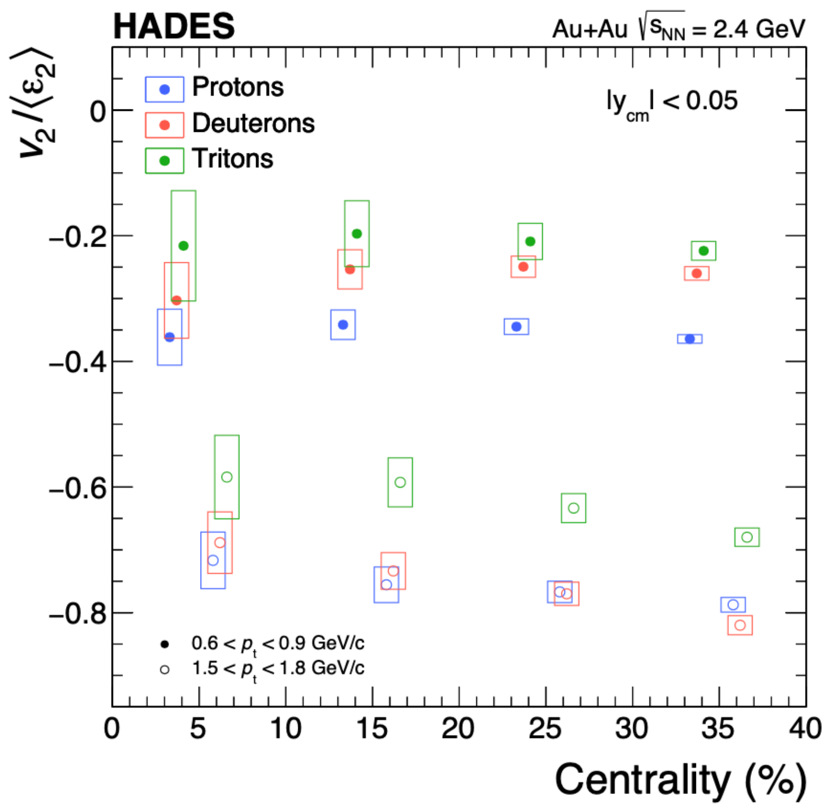




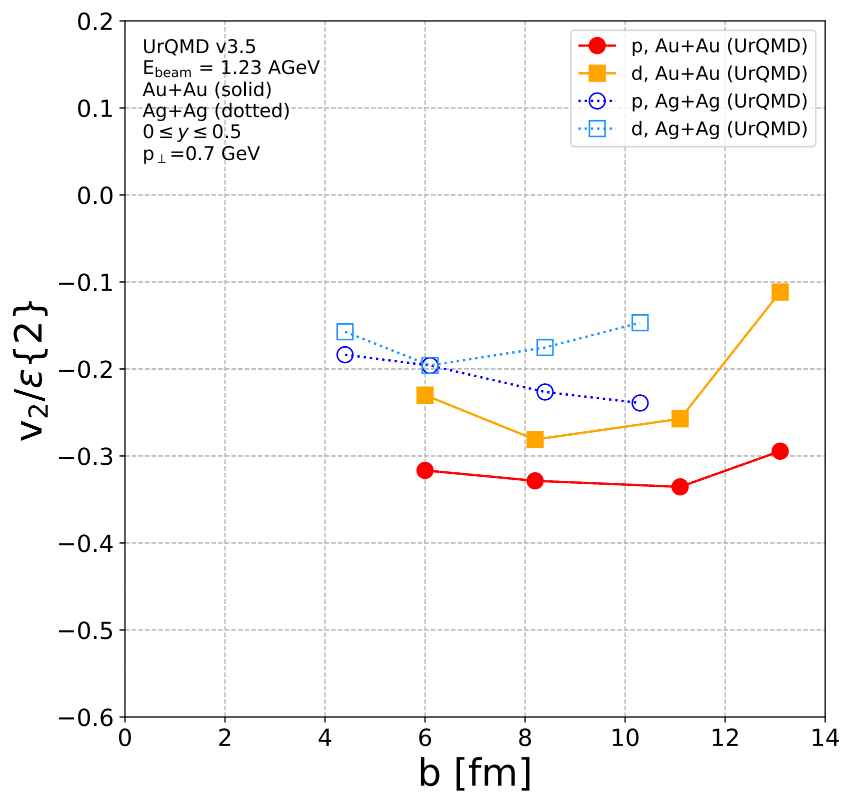
HADES, arXiv:2208.02740

Elliptic flow scaling with eccentricity

- LHC & RHIC: initial $\varepsilon_2 \rightarrow -\nabla n \rightarrow -\nabla P \rightarrow$ final v_2
- GSI: Negative scaling observed by HADES



HADES, arXiv:2208.02740

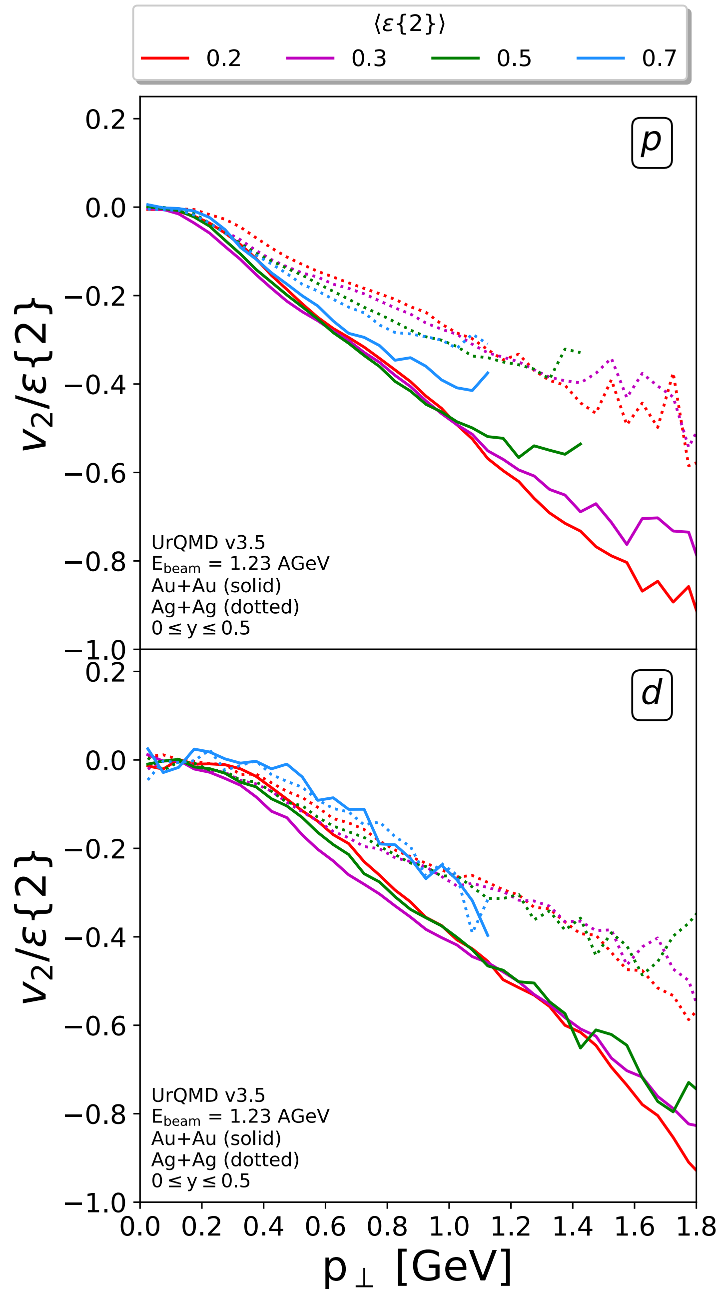


T. Reichert et al., arXiv:2208.10871

Flow scaling: p_T

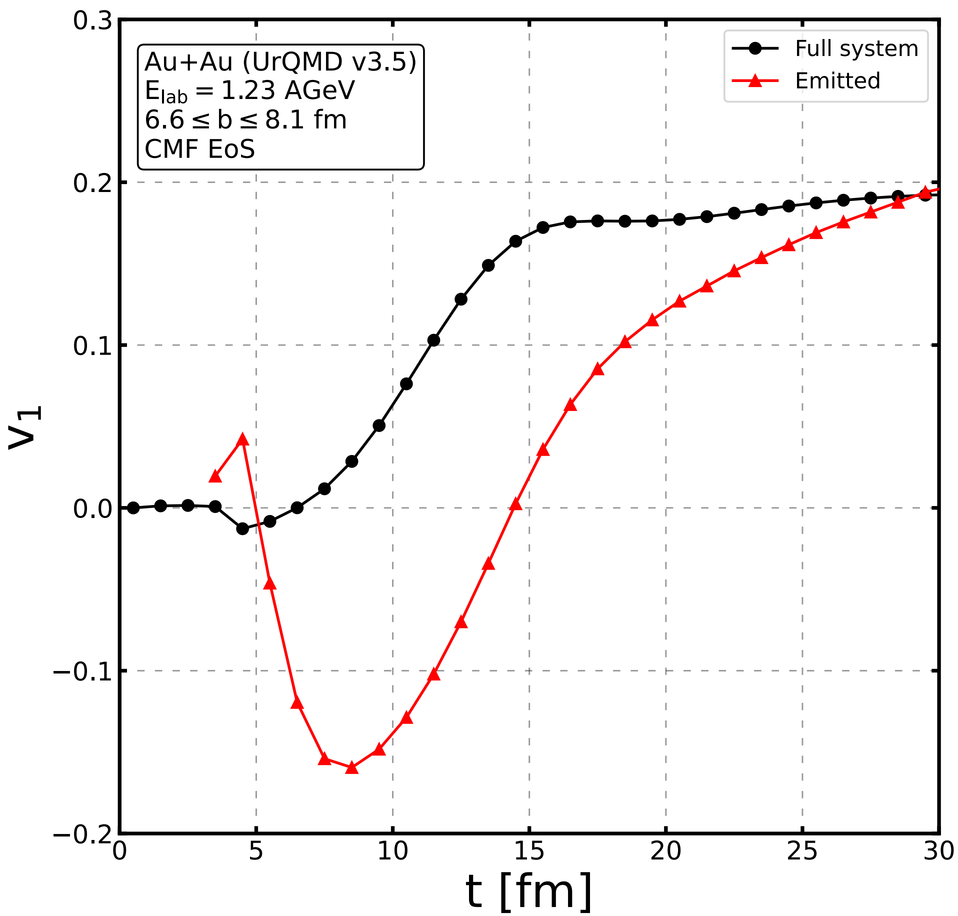
- v_2 scaling with ε_2 is negative
- p_T dependence observed
- Au collisions and Ag collisions behave similarly
- Similar shadowing strength at equal eccentricity

→ Probe hot and dense phase



T. Reichert et al., arXiv:2208.10871

Time development of v_1



Full system:

- Zero until compression is large
- Strong increase from 5 to 15 fm
- Saturates

Emitted:

- First negative (only unblocked direction)
- Then strongly increasing

T. Reichert et al., to be published

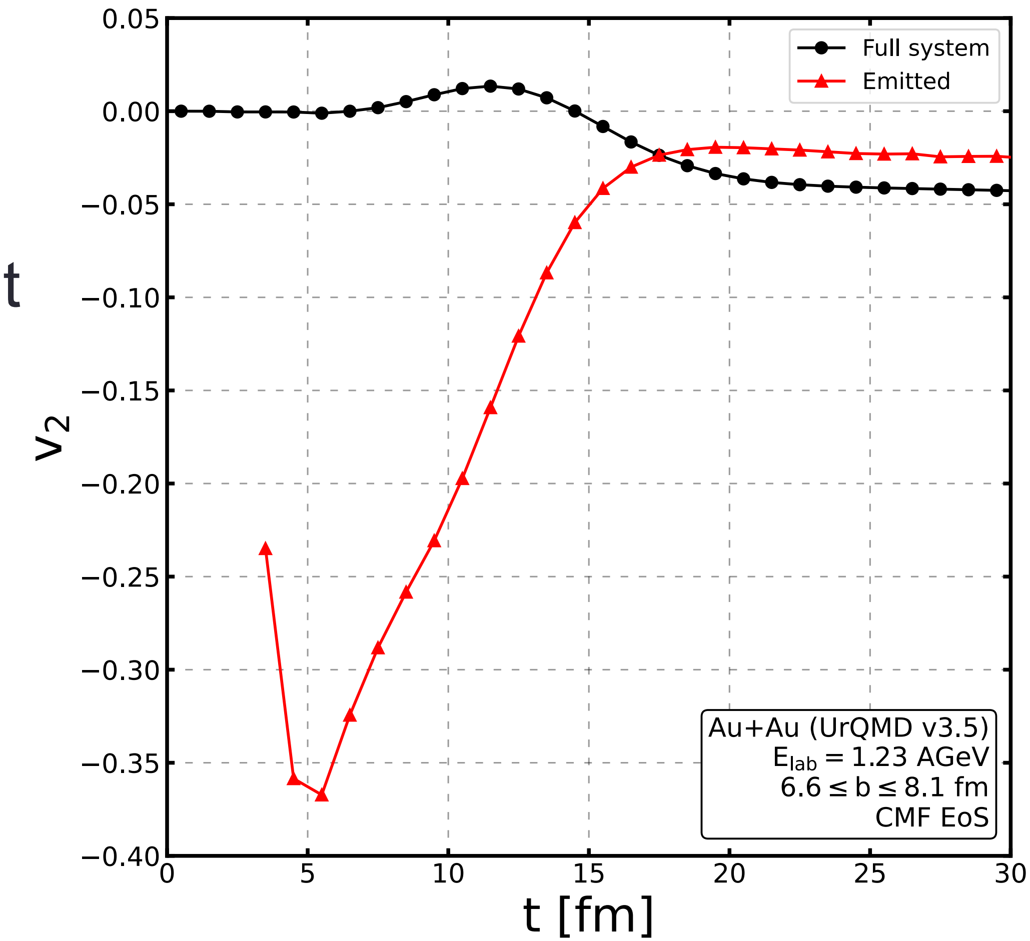
Time development of v_2

Full system:

- Zero until 7 fm
- Positive from 7 to 15 fm due to pressure gradient
- Momentum transfer to (semi-) spectators
- Turns negative

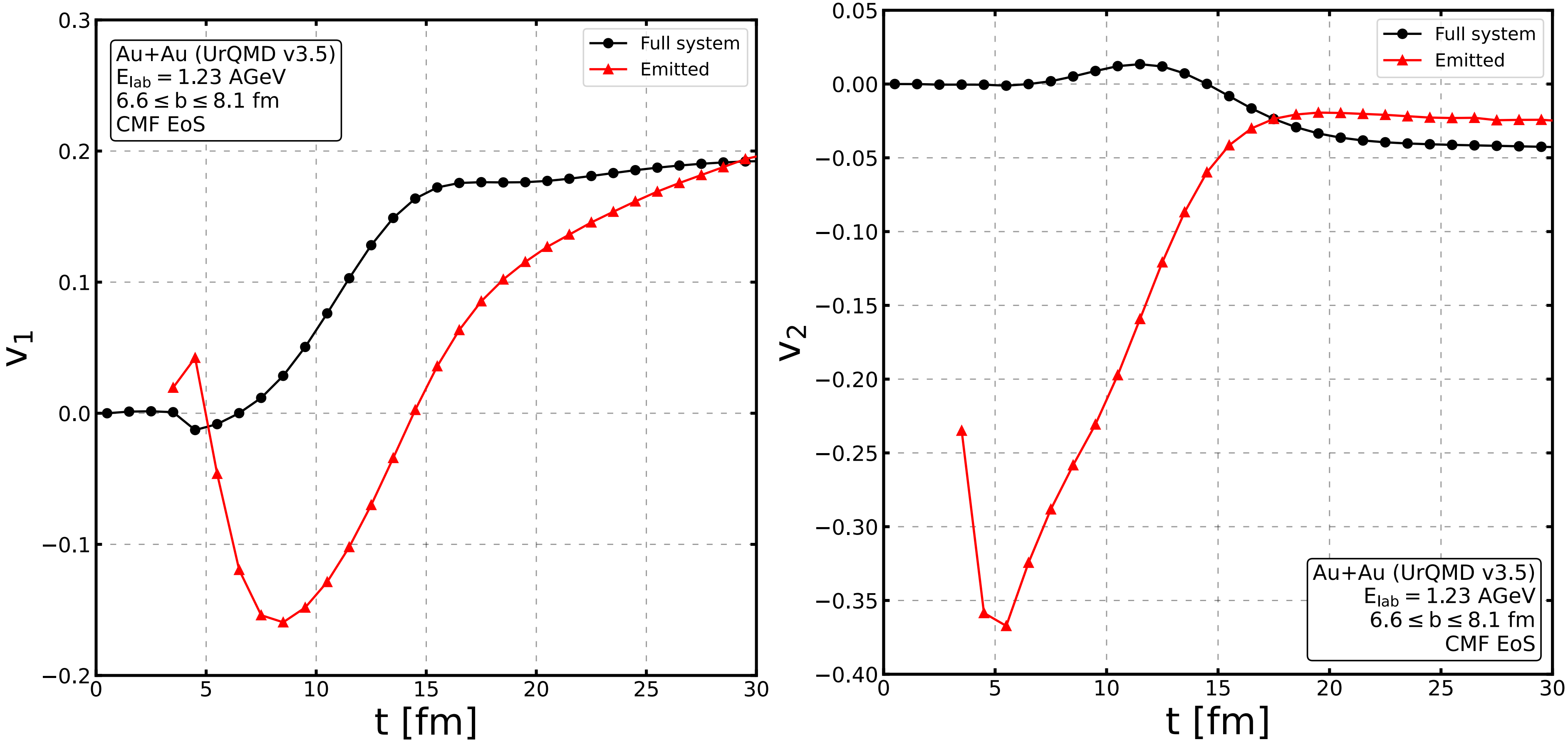
Emitted:

- First highly negative
- Increasing towards final value



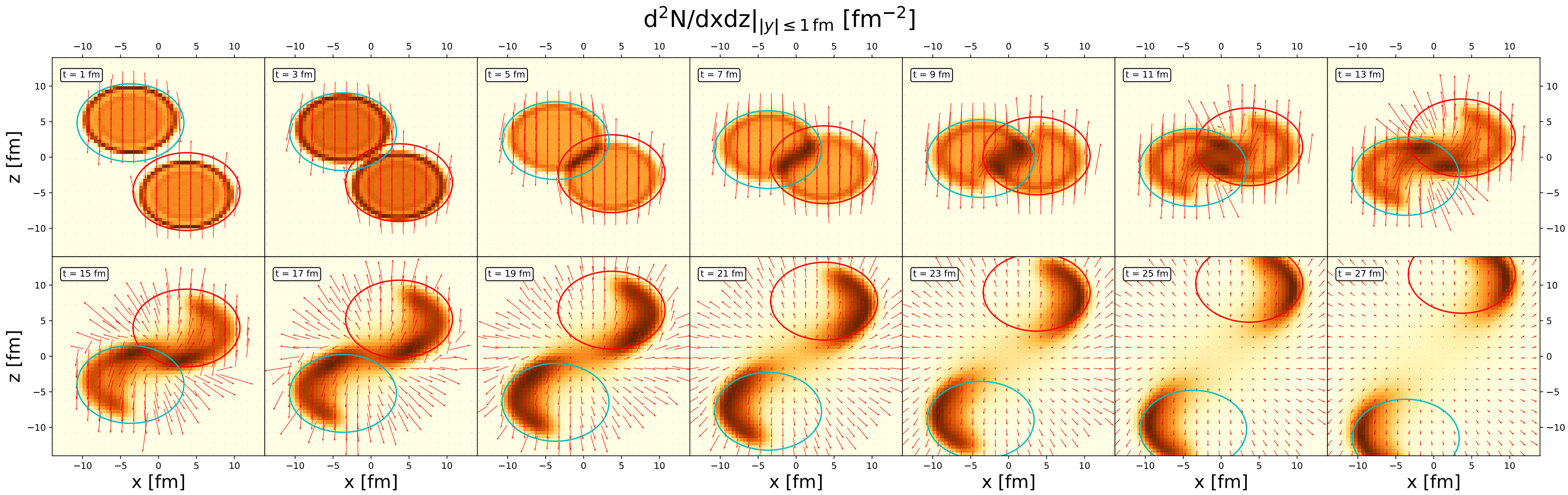
T. Reichert et al., to be published

Time development of v_1 and v_2



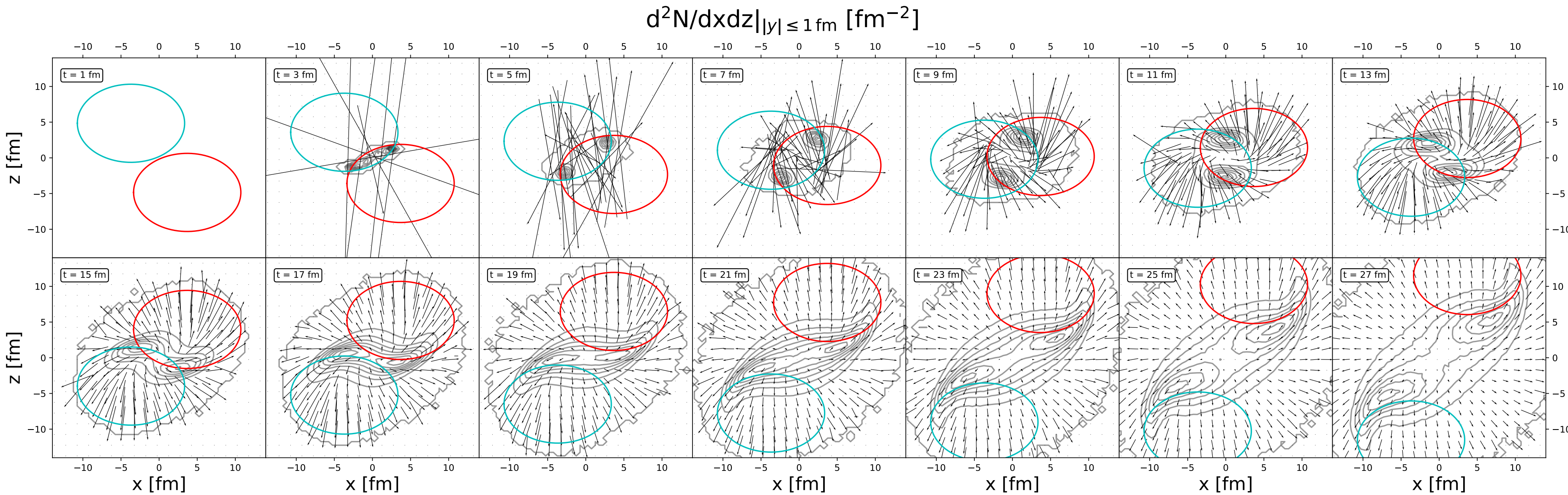
- Flow is directly sensitive to the EoS
- Tight connection between v_1 and v_2

Time evolution



- Full system from 0 to 28 fm
- Spherical expansion after 17 fm (residues have passed)

Time evolution

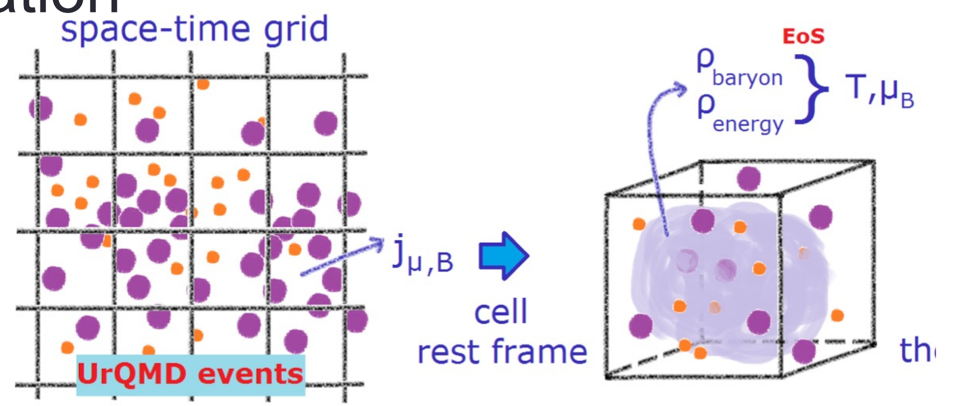


- Nucleons emitted at time t
- Different freeze-out contours at different times

Dileptons

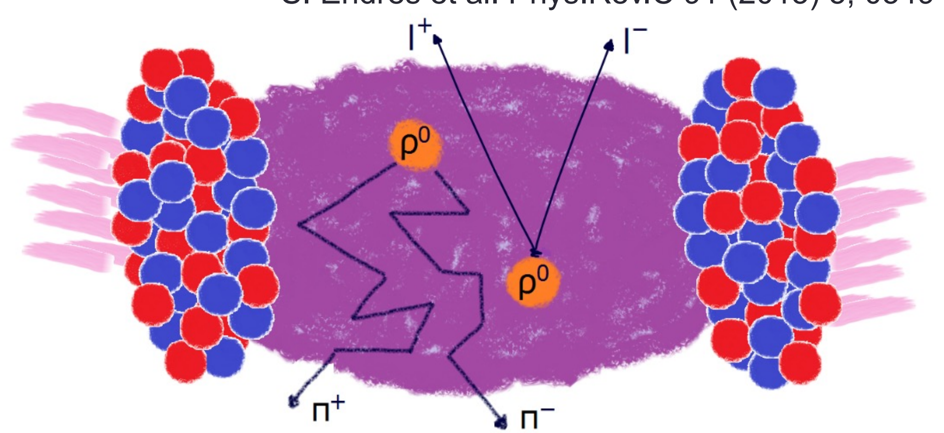
C. Gale et al. Nucl. Phys. B357 (1991) 65

- $$\frac{dN_{\ell^+\ell^-}}{d^4x\,d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{q^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\,\eta_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M,\vec{q})\,n_B(u\cdot q)$$
- Spectral and thermal information

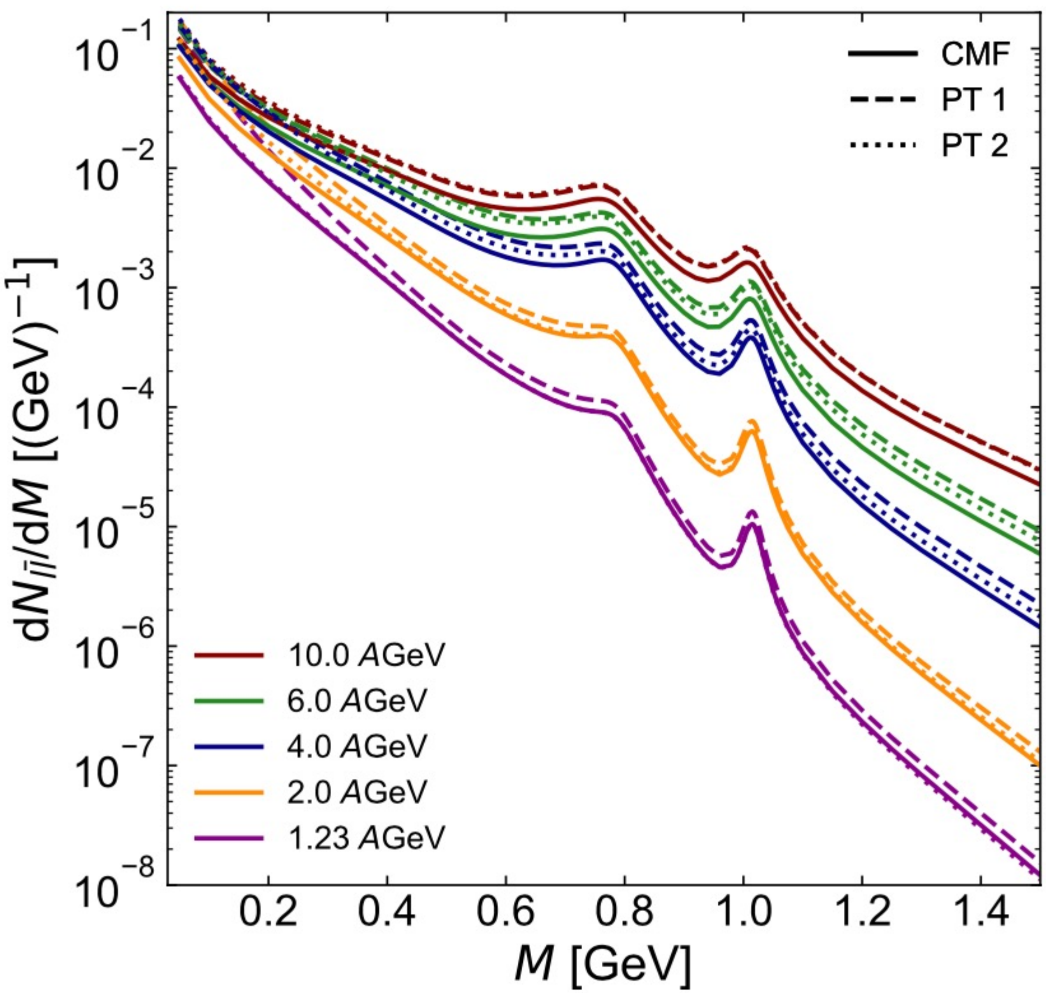


- UrQMD + coarse-graining
- Evaluate $\langle T^{\mu\nu}\rangle$ and $\langle j_B^{\mu}\rangle$ in each cell and obtain T, μ_B
- Calculate dileptons using Rapp spectral functions
- Shining method (collisional broadening included)

S. Endres et al. Phys.Rev.C 91 (2015) 5, 054911



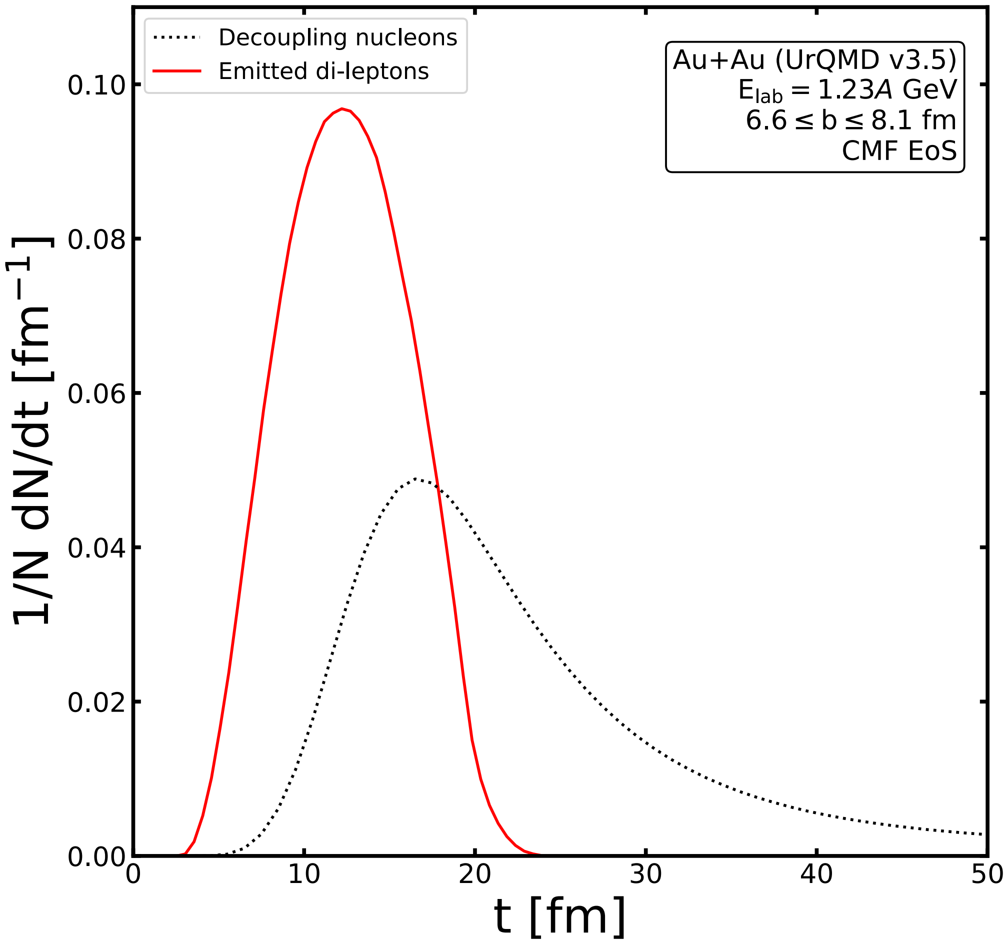
Dilepton spectra



O. Savchuk et al., arXiv:2209.05267

- Peaks of ω and ϕ visible
- ρ meson broadened at higher energies
- Enhancement with phase transition

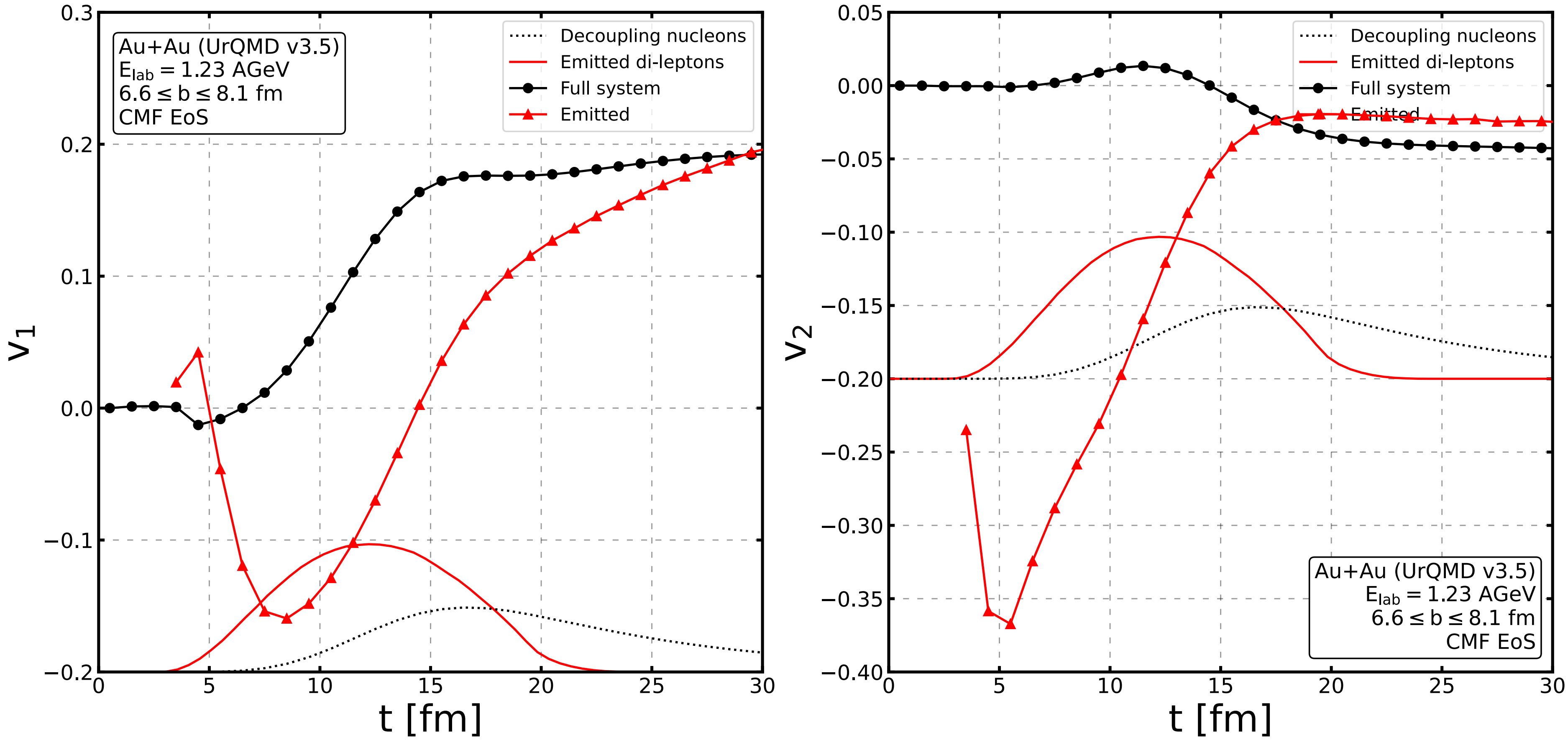
Decoupling time distribution



T. Reichert et al., to be published

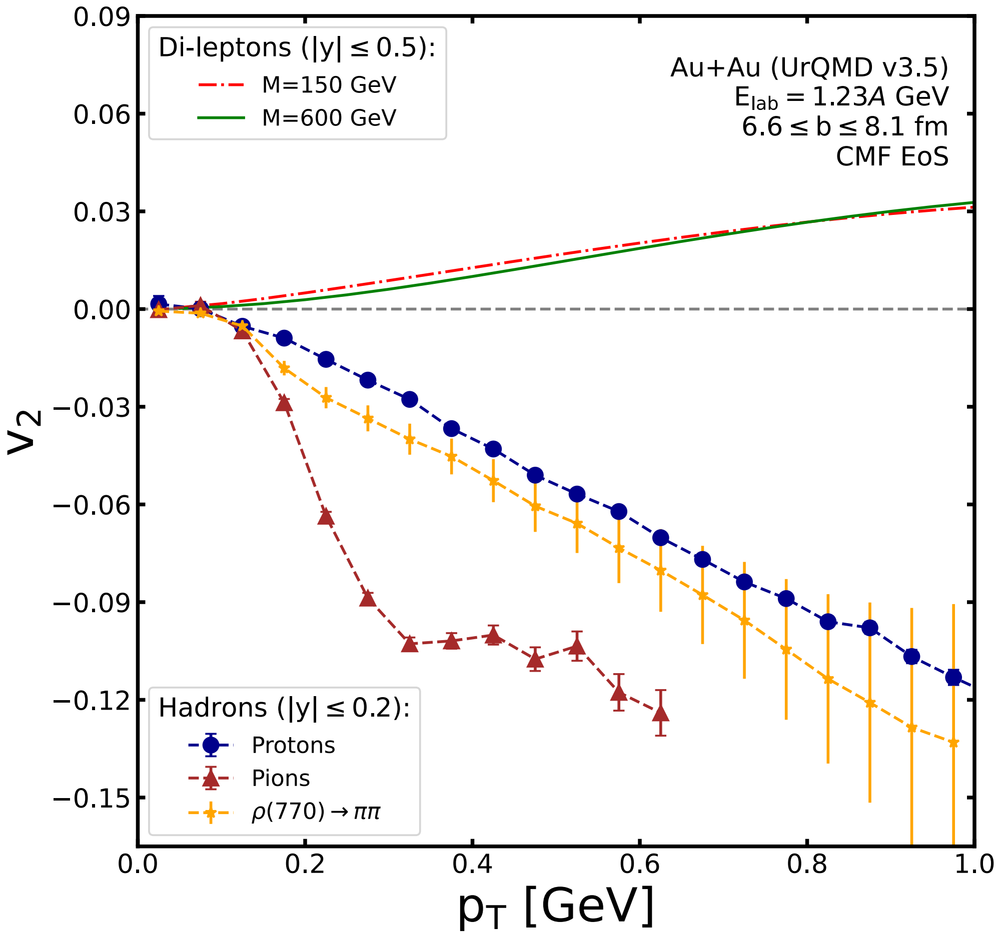
- Dileptons decouple mainly from 5 to 15 fm
- Narrow distribution
- Time when flow is positive
- Nucleons decouple from 10 to 35 fm
- Broad distribution

Decoupling time vs. flow



- Dileptons probe positive v_2 in hot and dense phase
- Hadrons probe negative v_2 at kinetic decoupling

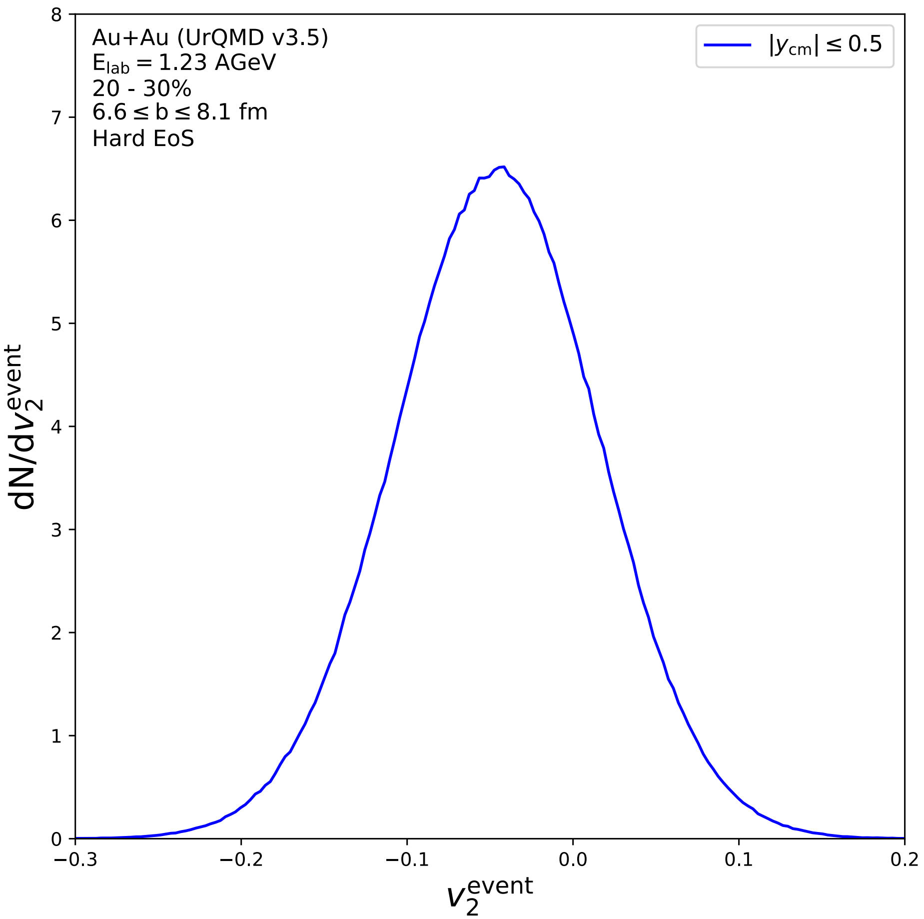
Elliptic flow: p_T dependence



T. Reichert et al., to be published

- Hadrons show negative v_2
- Simulation in line with HADES data
- Dileptons have positive v_2
- Dileptons show hydro-mass scaling
- Direct measurement of EoS

Elliptic flow fluctuation

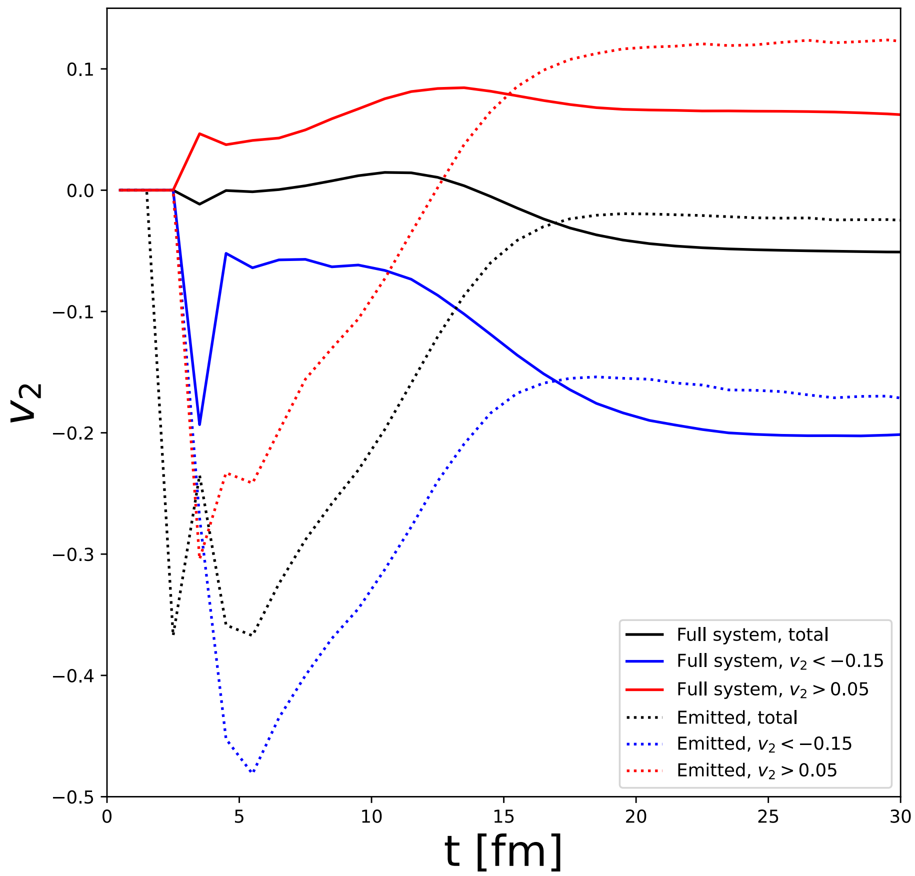


- Final v_2 fluctuates from -0.2 to 0.1
- Average $\langle v_2 \rangle \approx -0.05$ consistent with HADES data
- Where does the fluctuation come from?
- Connection to eccentricity?

→ Investigate how flow develops during time evolution

T. Reichert, Eur. Phys. J. C 82, no.6, 510 (2022)

What about the fluctuation?



- Initial positive v_2 corresponds to final positive v_2
- Initial negative v_2 corresponds to final negative v_2
- Initial ε_2 fluctuation exerts different pressure gradients
- Initial fluctuation in z-direction

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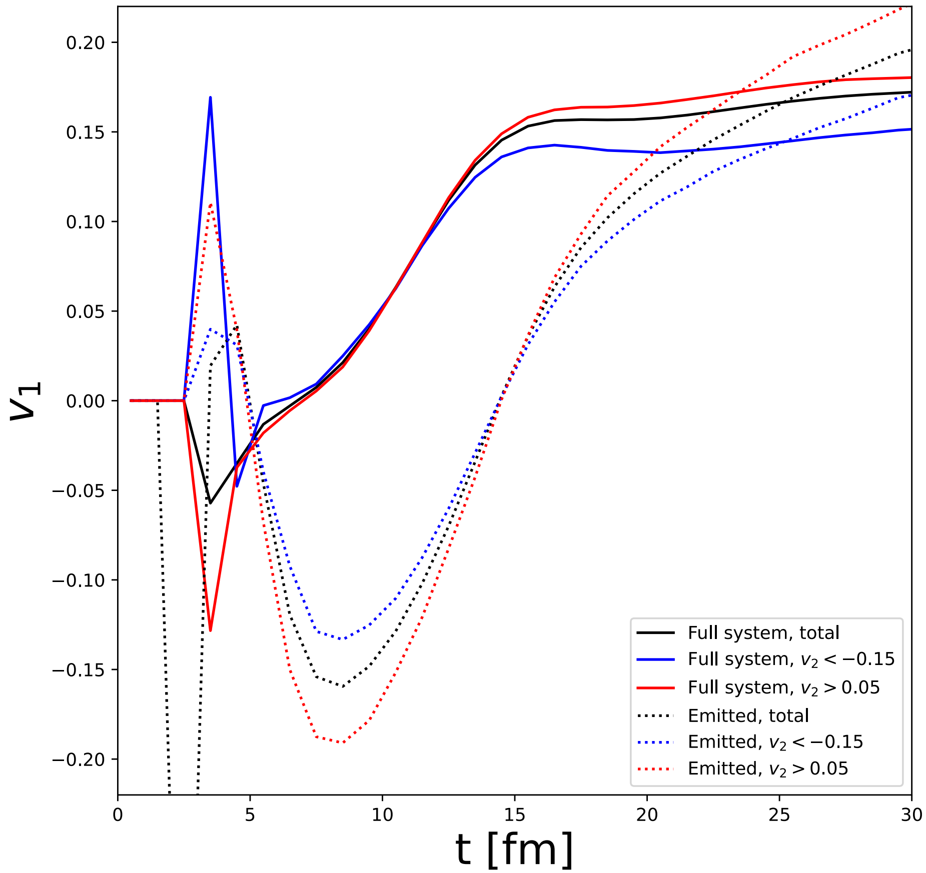
What about the fluctuation?



- More initial v_2 creates stronger bounce-off (v_1)
- Initial ε_2 fluctuation corresponds to fluctuation of shadowing strength
- Initial fluctuation in z-direction
- Tight connection of v_1 and v_2 even on event-by-event basis

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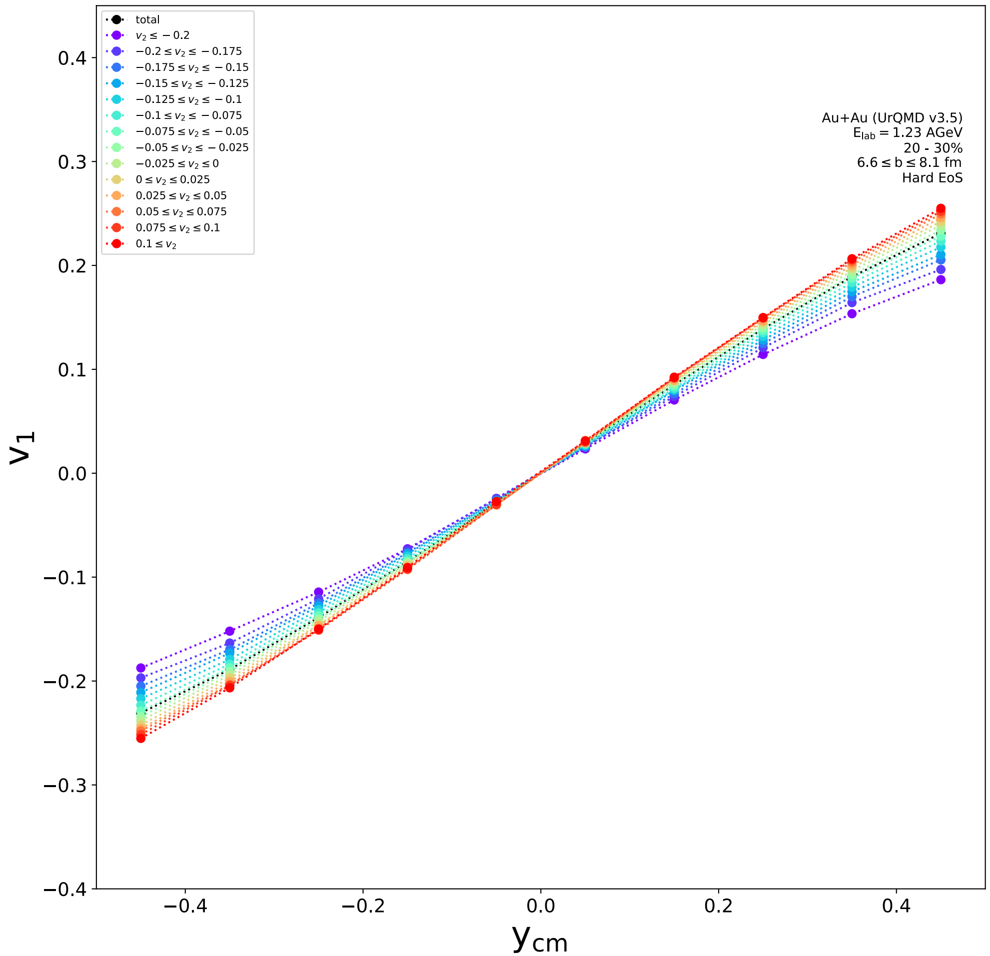
v_1 in different event classes



- Investigate v_1 to v_4 in different event classes
- Marginal influence on v_1, driven by bounce-off
- Positive correlation of final v_2 with v_1
- Slope at midrapidity mainly unaffected

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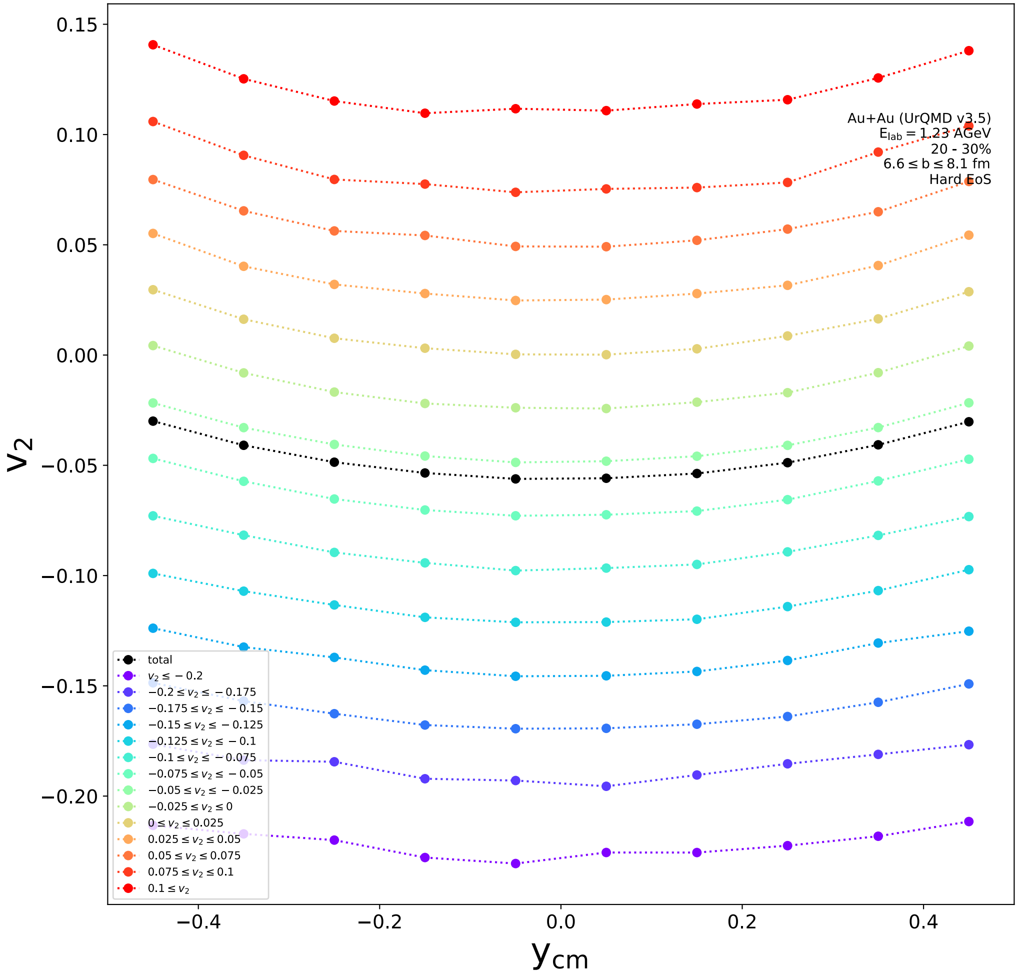
v_2 in different event classes



- Trivial self-correlation
- Shape is independent of trigger
- Trigger shifts linearly

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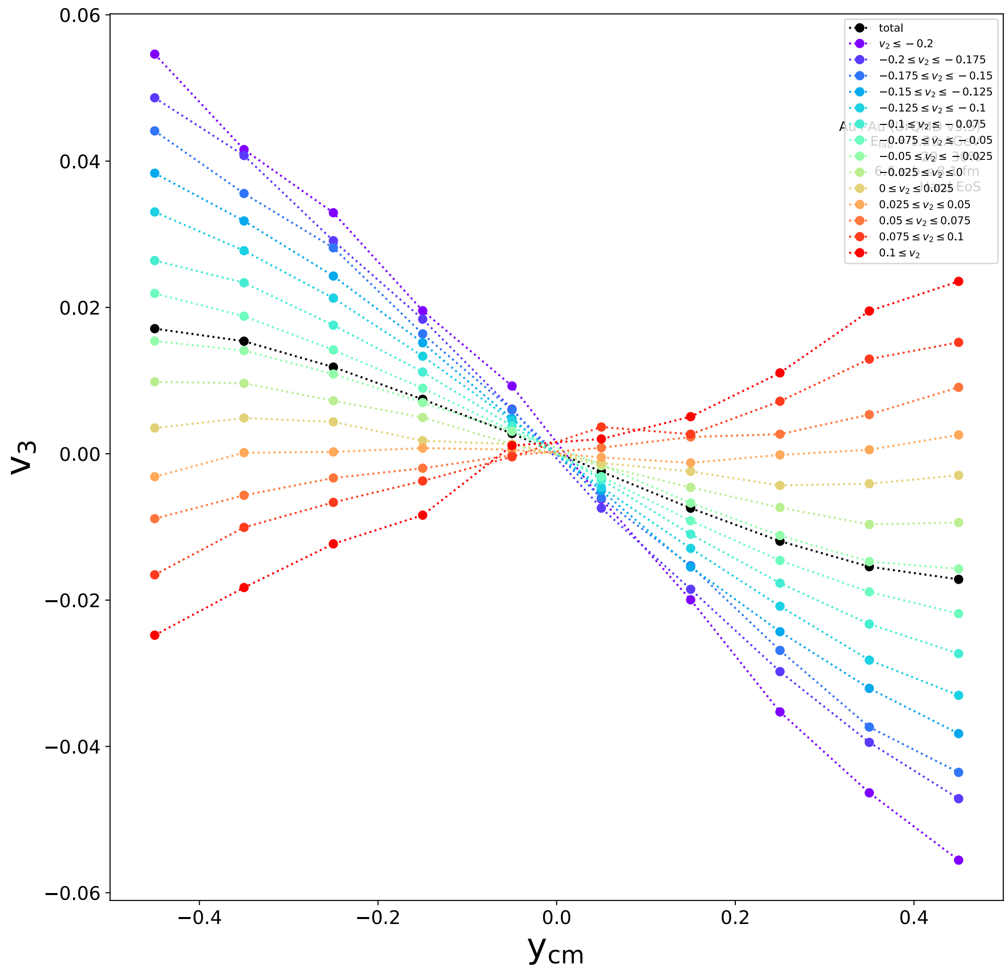
v_3 in different event classes



- Strong correlation
- Positive v_2 correlated to positive v_3 slope
- Negative v_2 correlated to negative v_3 slope
- Scaling $v_3 \propto v_1 \cdot v_2$?

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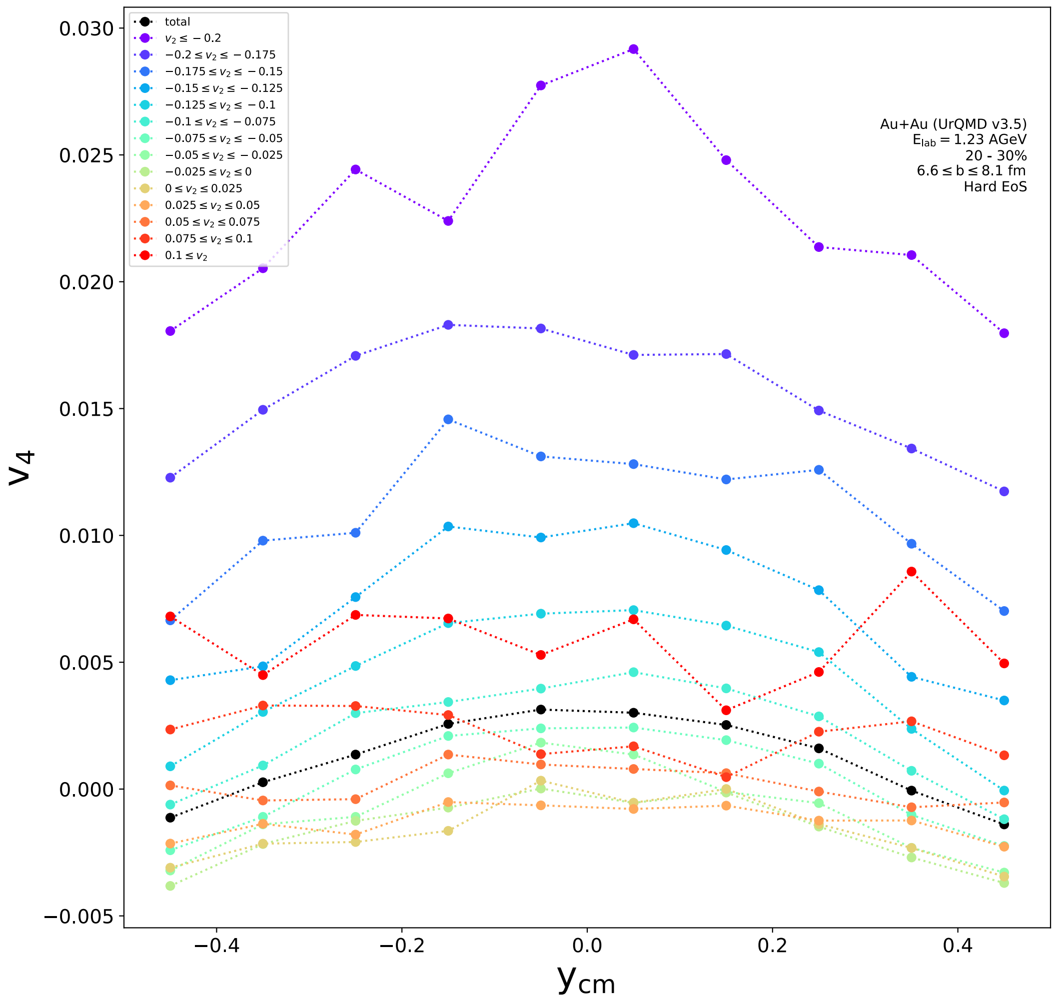
v_4 in different event classes



- Strong correlation
- Positive v_2 correlated to concave v_4 shape
- Negative v_2 correlated to convex v_4 shape
- Scaling $v_4 \propto v_2^2$

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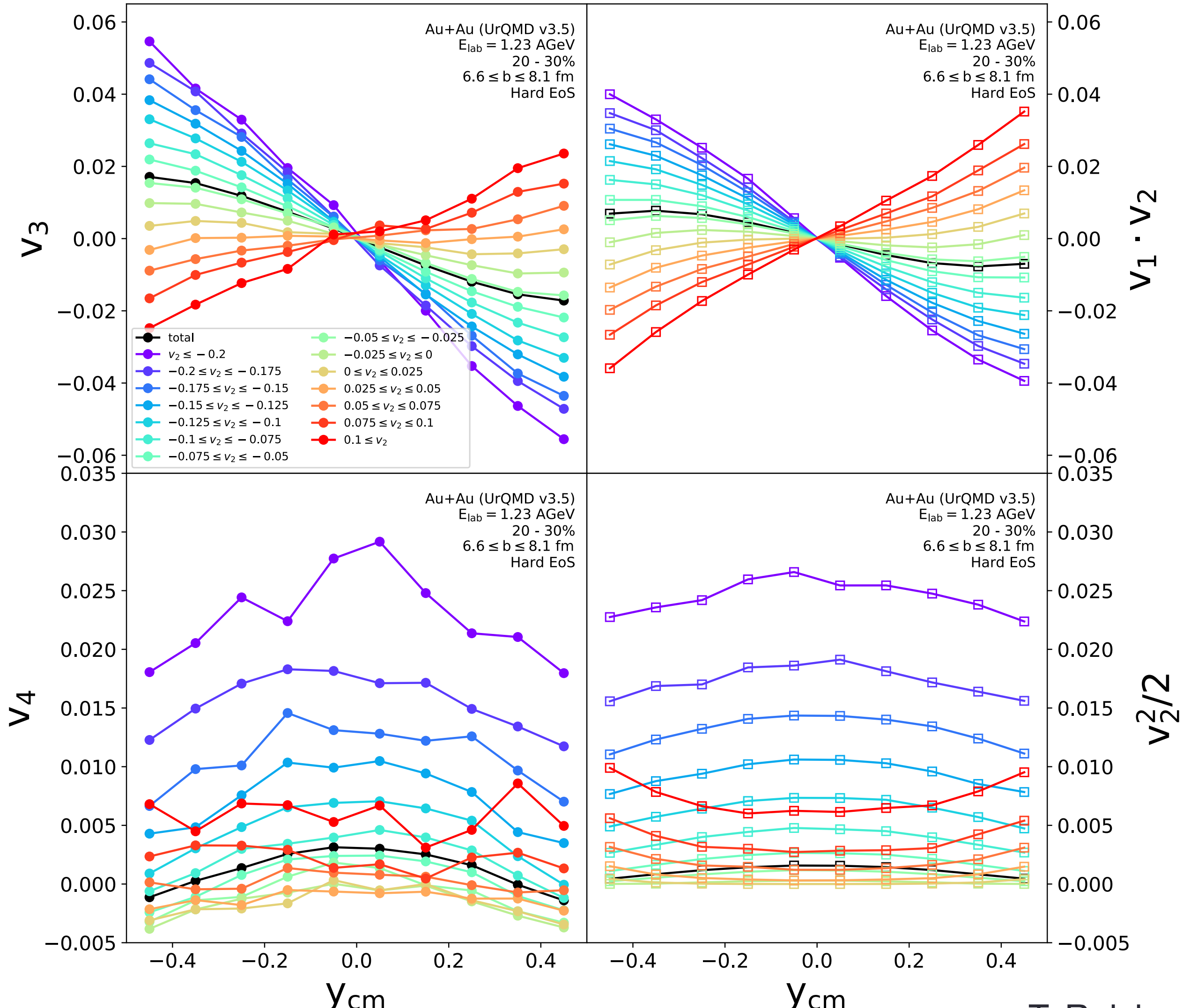
Flow scaling



- We understand flow development
- Thus scaling can be explained
- Initial ε_2 fluctuation drives built-up of v_1 and v_2
- Pressure gradient creates correlation: $v_3 \propto v_1 \cdot v_2$
- Measure EoS!

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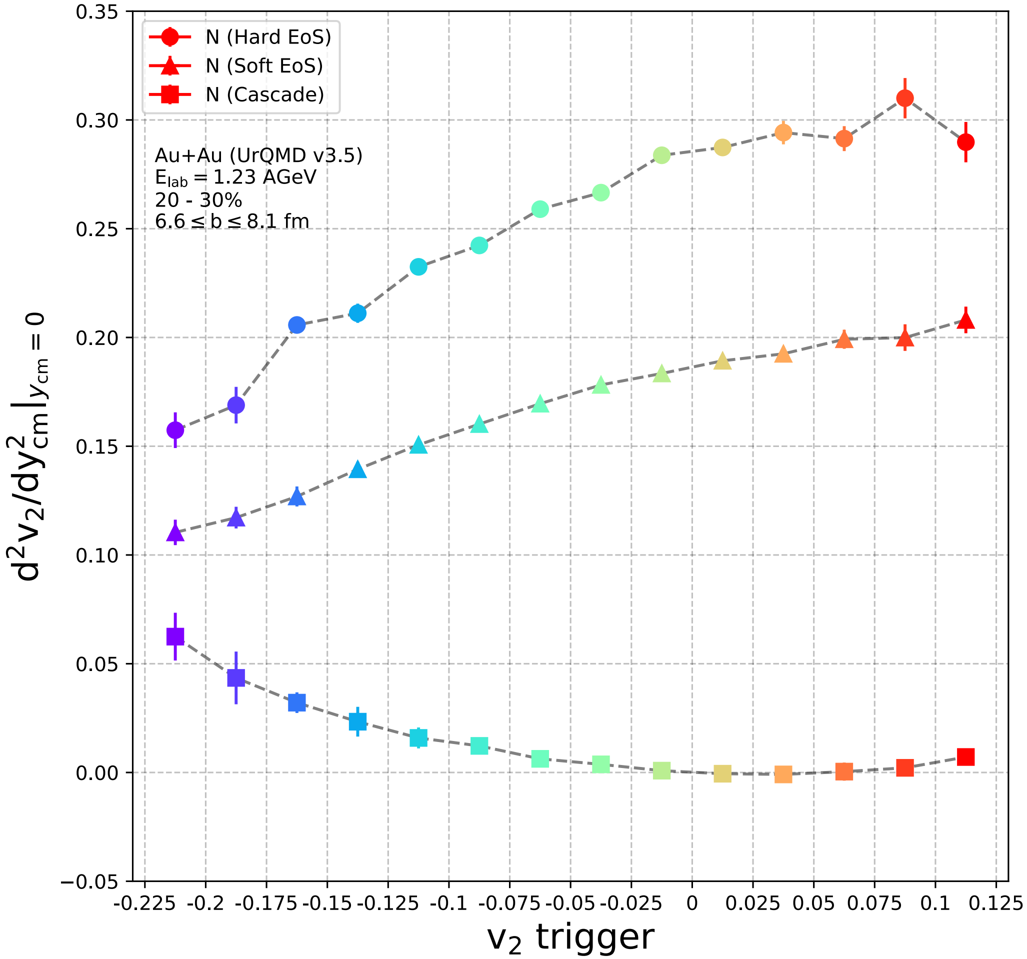
$\frac{d^2 v_2}{dy^2}$ vs event class



- Curvature sensitive to v_2 trigger and EoS
- With increasing stiffness of the EoS curvature increases
- Skyrme potential: curvature increases for larger v_2 triggers

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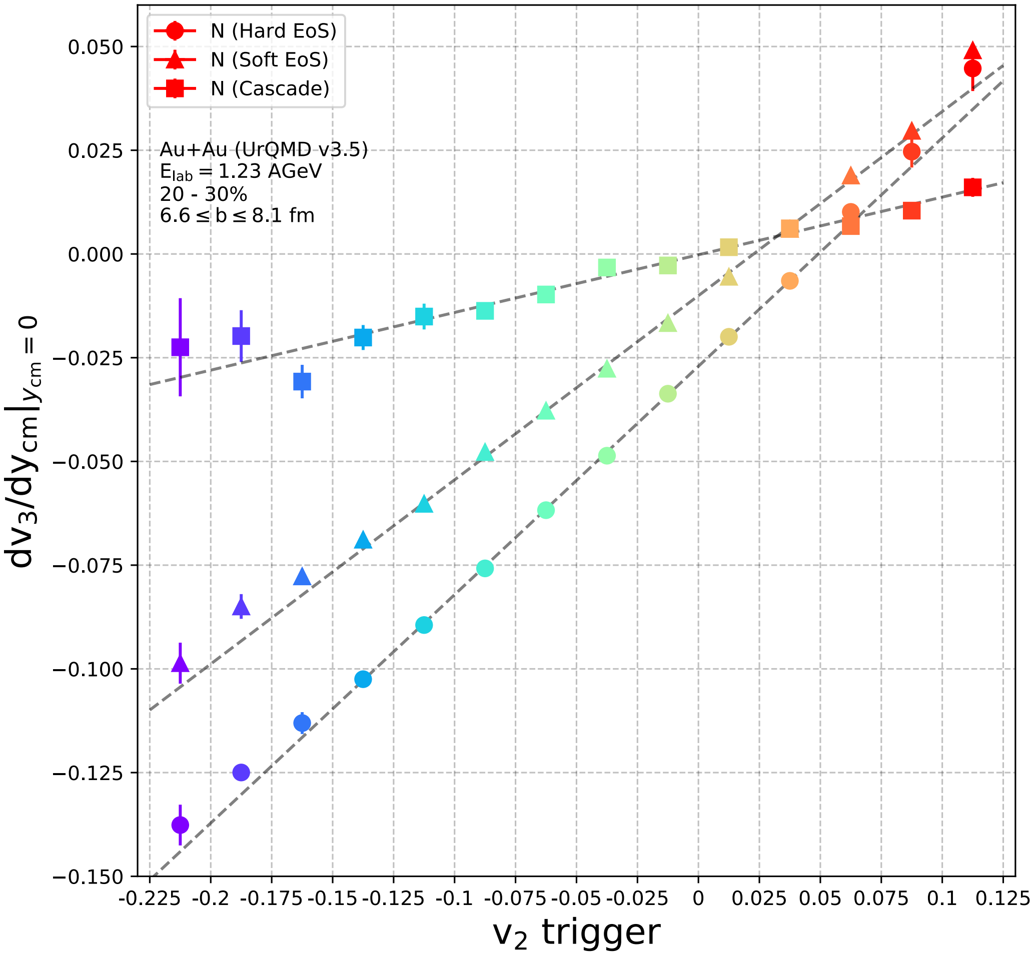
$\frac{dv_3}{dy}$ vs event class



- Clear linear dependence
- Pronounced sensitivity to EoS
- With increasing stiffness of the EoS, the incline becomes stronger
- Pin down EoS more precisely

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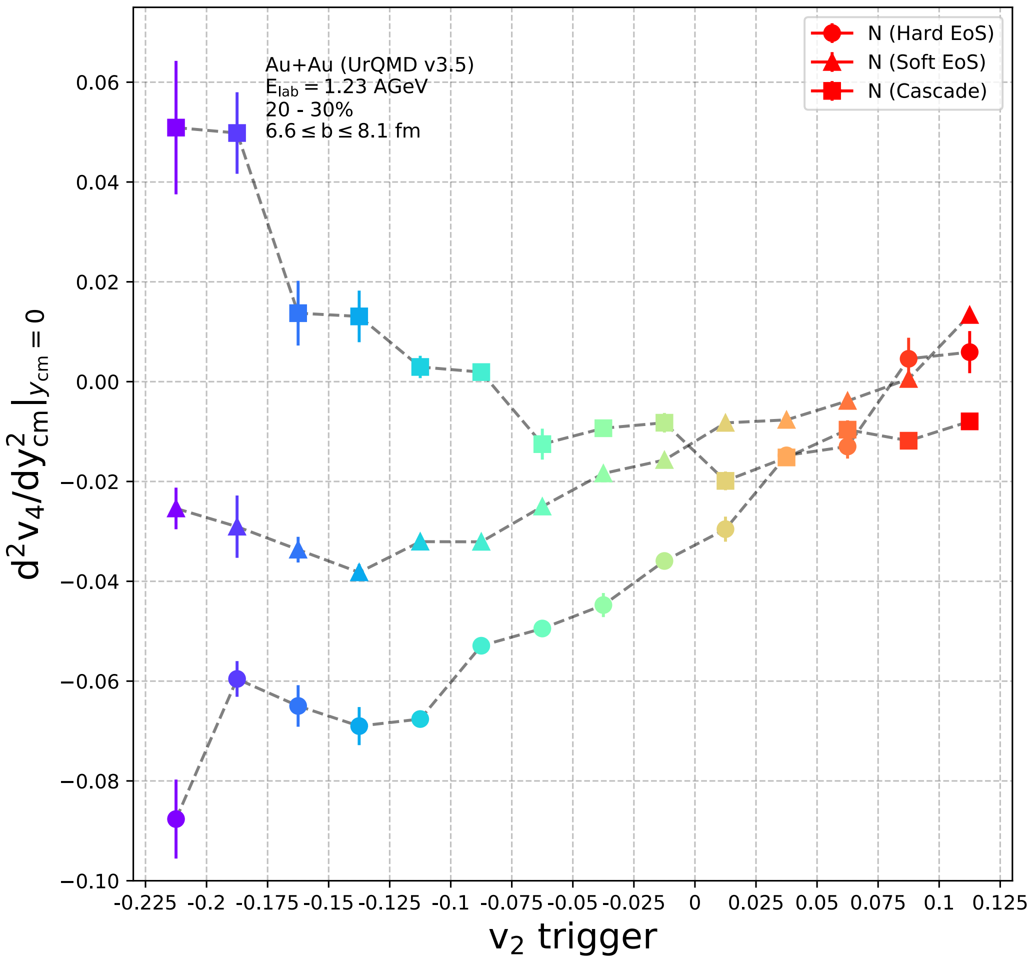
$\frac{d^2 v_4}{dy^2}$ vs event class



- Strong sensitivity even of v_4 curvature on v_2 trigger
- A harder EoS decreases the curvature in quadrangular flow
- Skyrme potentials: positive correlation of curvature with trigger

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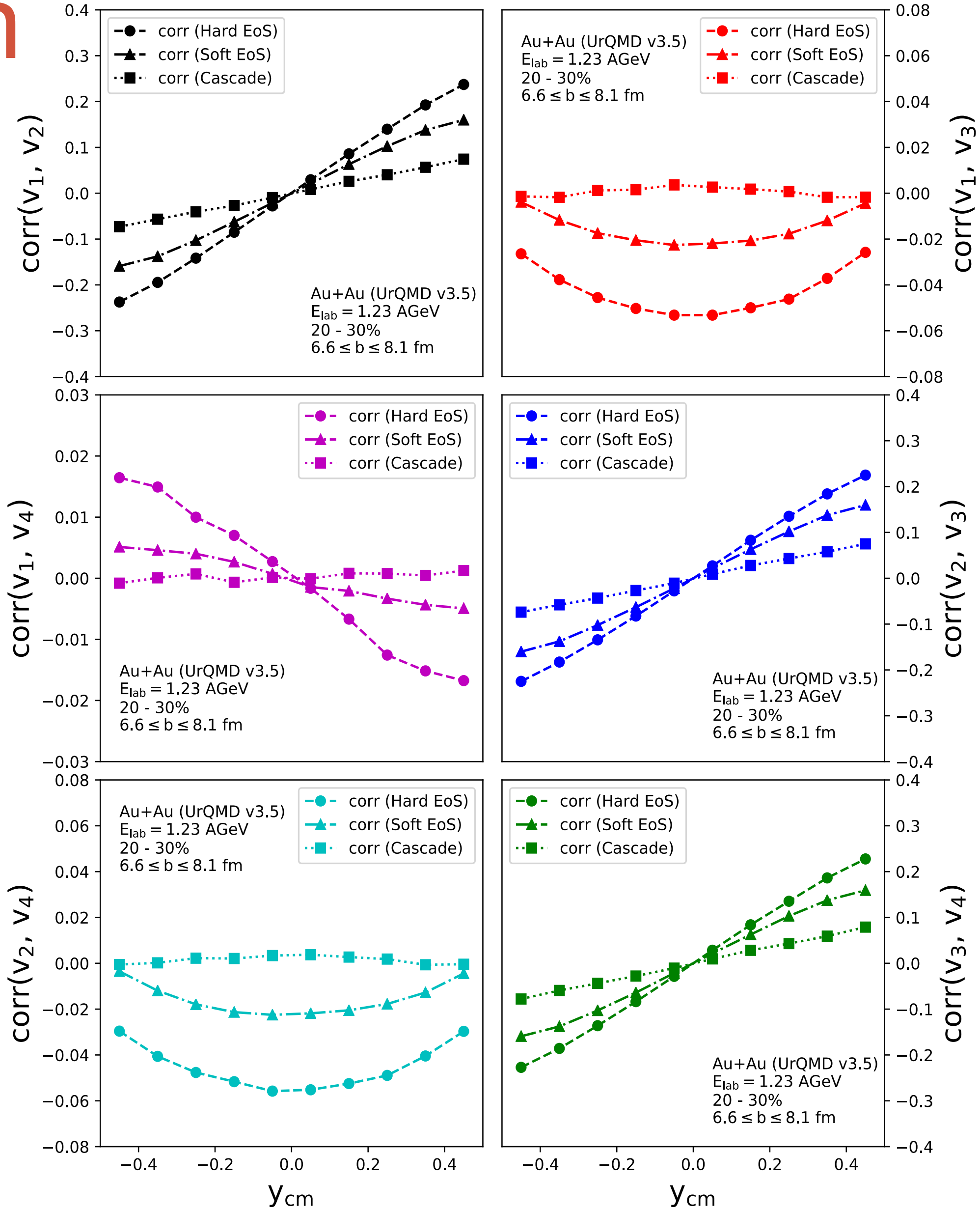
Pearson correlation

- Pearson correlation also non-zero
- However, Pearson measures only linear correlation
- Direct correlation via event selection is advantageous



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Summary

- v_2 at SIS at full overlap is positive due to pressure gradient exerted by Equation-of-State
- Final v_2 at SIS energies is negative due to immense shadowing, momentum transfer to (semi-) spectators
- Explains connection between v_1 and v_2
- Measurement via dileptons
- Fluctuation of v_2 can be explained
- Event classes allow to pin down EoS

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