HARMONIC FLOW CORRELATIONS AS A TESTING GROUND FOR THE NUCLEAR EOS

Tom Reichert
Institut für Theoretische Physik, Goethe-Universität Frankfurt
In collaboration with Apiwit Kittiratpattana, Oleh Savchuk, Jan Steinheimer, Marcus Bleicher, et al.

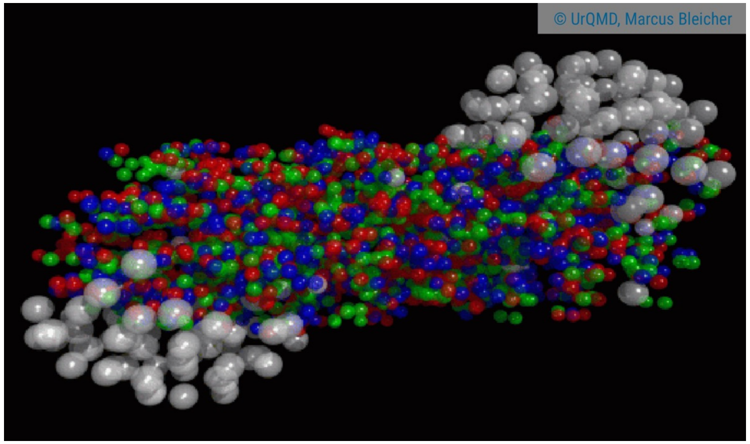
INT 22-84W – Dense Nuclear Matter Equation of State from Heavy-Ion Collisions
Dec 5-9, Seattle, USA

Helmholtz Forschungsakademie Hessen für FAIR

Institute for Theoretical Physics

treichert@itp.uni-frankfurt.de

Ultra-relativistic Quantum Molecular Dynamics

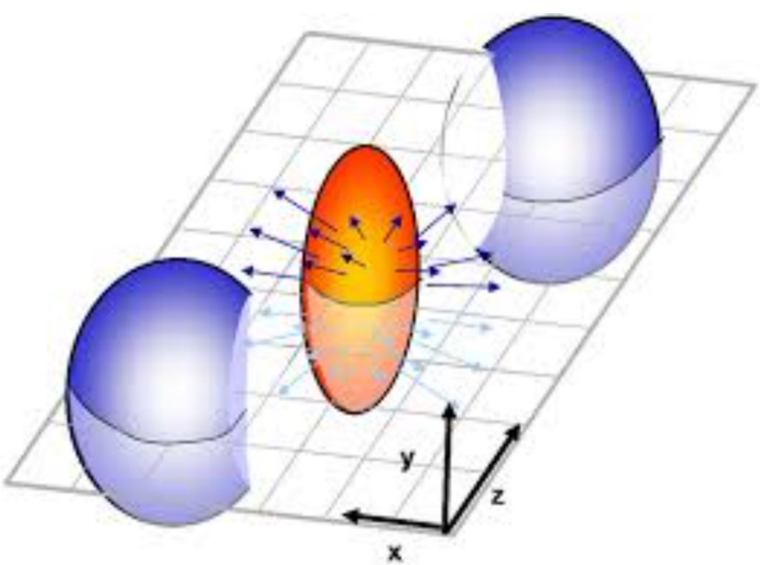


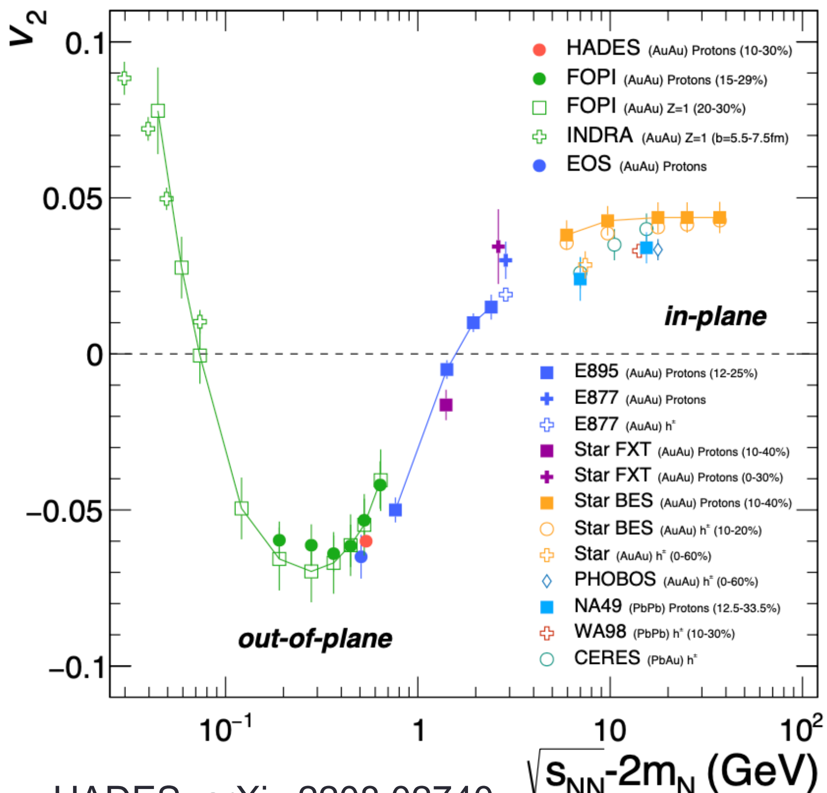
- Hadron/String transport approach
- Based on propagation of hadrons
- Rescattering among hadrons fully included
- String excitation and decay (LUND model, PYTHIA)
- Solution for the time dependent n-body distribution of hadrons
- Collision term includes more than 100 hadrons up to 4 GeV in mass
- Soft/Hard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

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

What is flow?

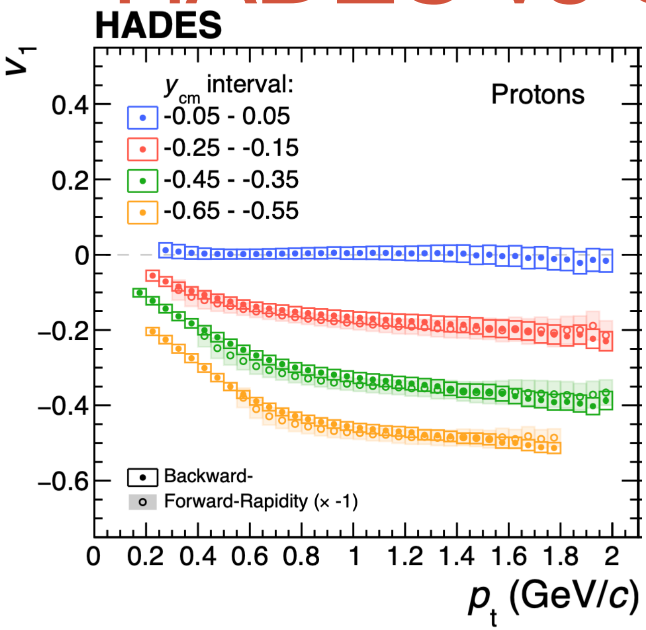
- Fourier series of azimuthal angle distribution
- $\frac{dN}{d\varphi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_{RP}))$
- Experiment: difficult due to fluctuating reaction plane
- HADES: fixed spectator plane
  → Simulation: $\Psi_{RP} = 0$

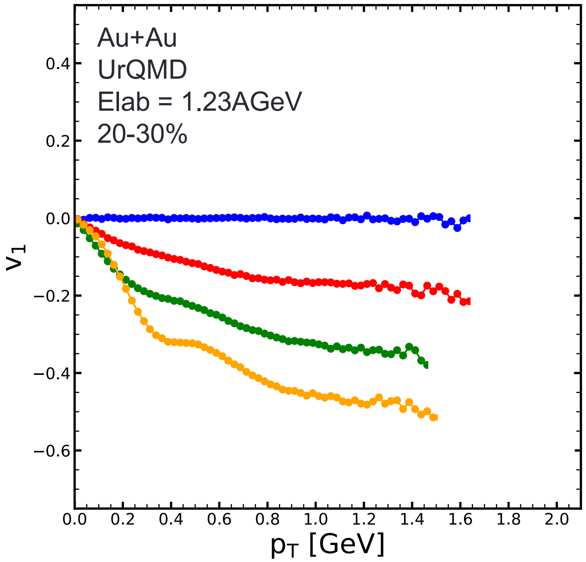


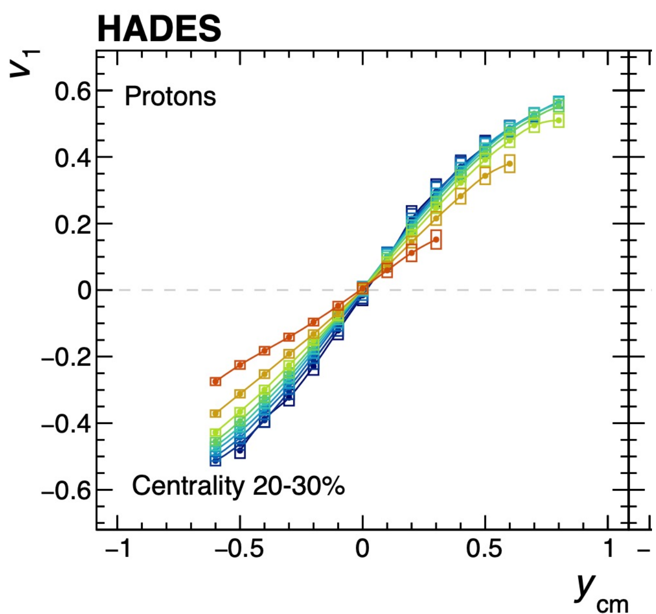


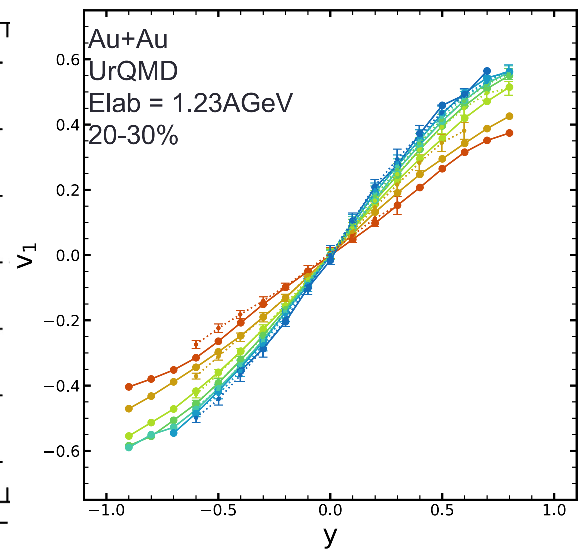
HADES, arXiv:2208.02740

HADES vs UrQMD









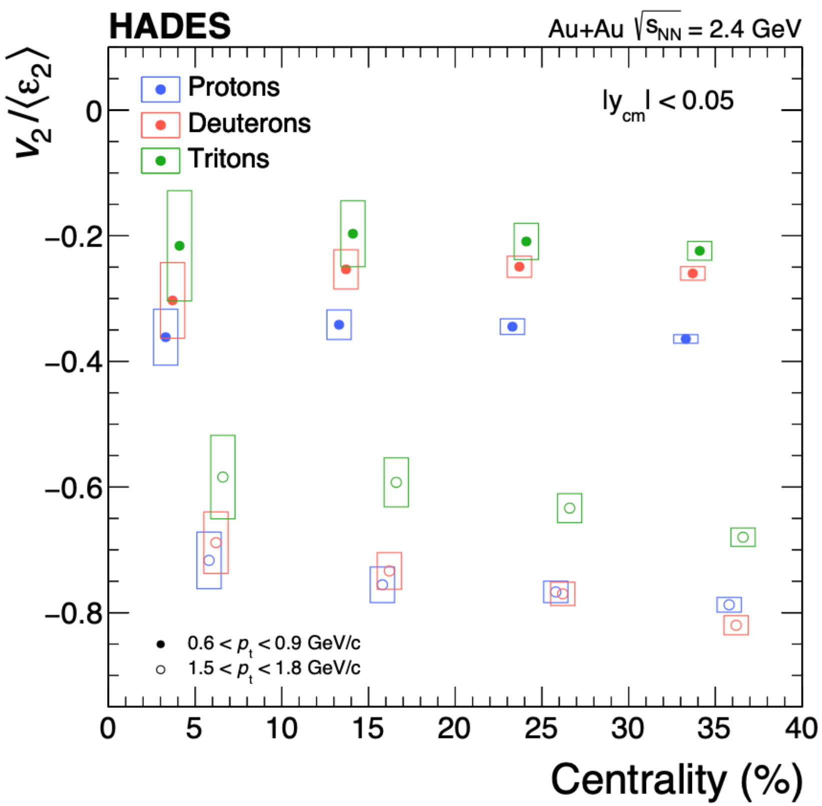
- Good description of HADES data

HADES, arXiv:2208.02740

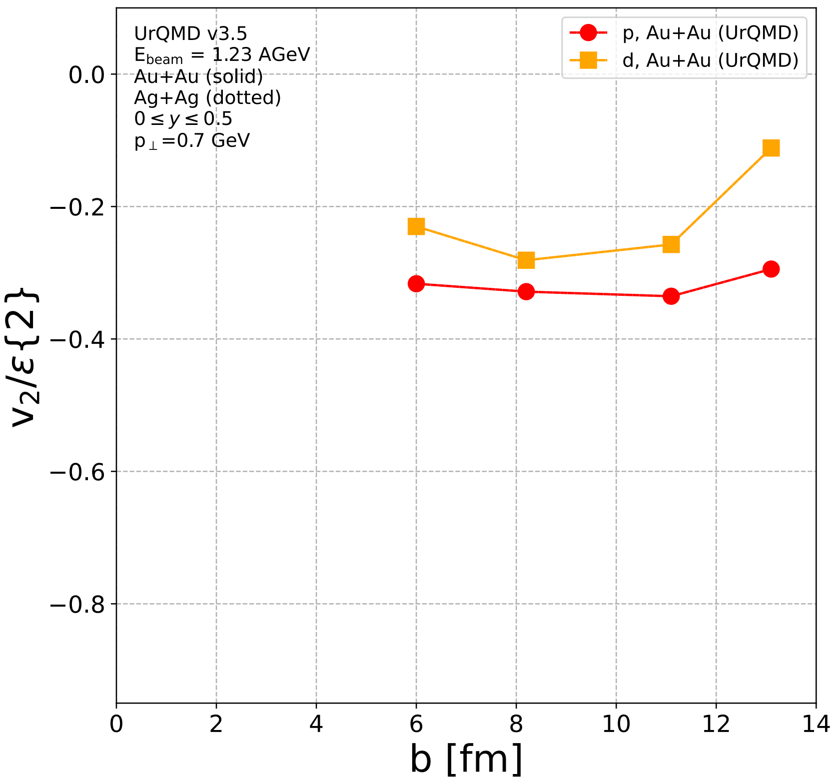
→ Talk by Behruz

Elliptic flow scaling with eccentricity

- LHC & RHIC: initial ε_2 → $-\nabla P$ → final v_2
- GSI: Negative scaling observed by HADES



HADES, arXiv:2208.02740



T. Reichert et al., arXiv:2208.10871

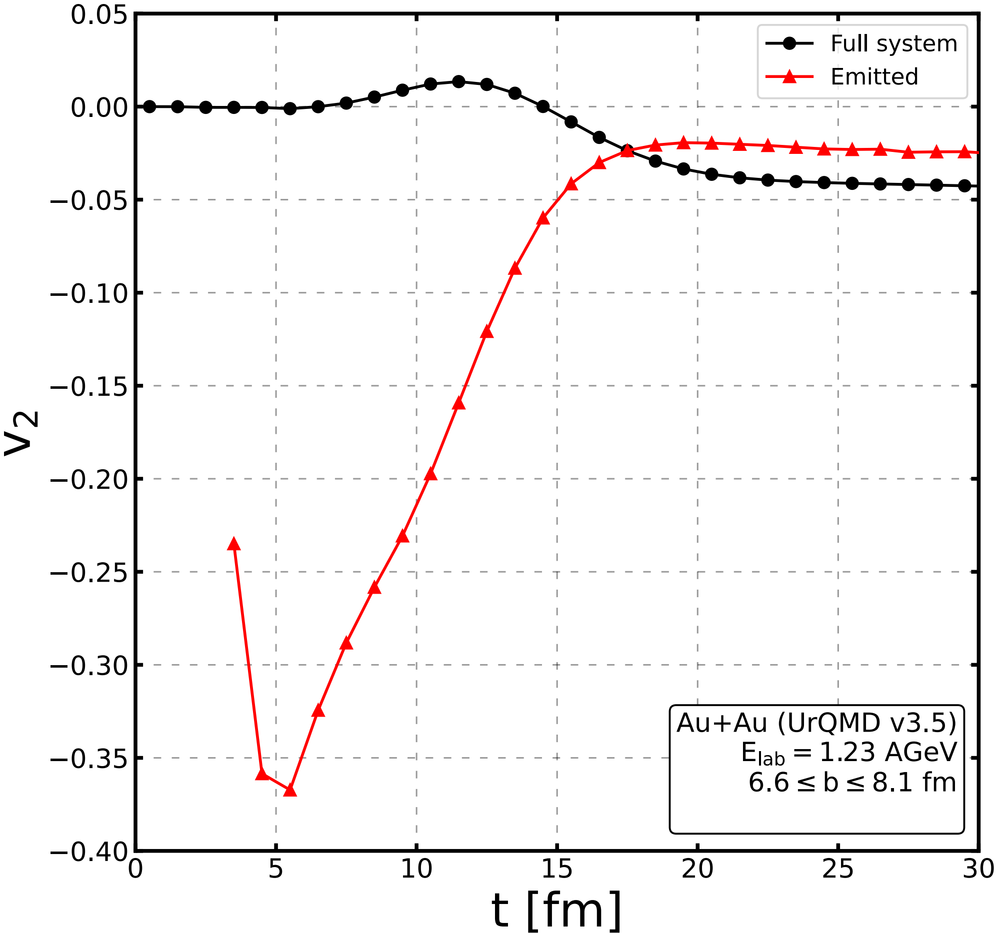
Time development of v_2

Full system:

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

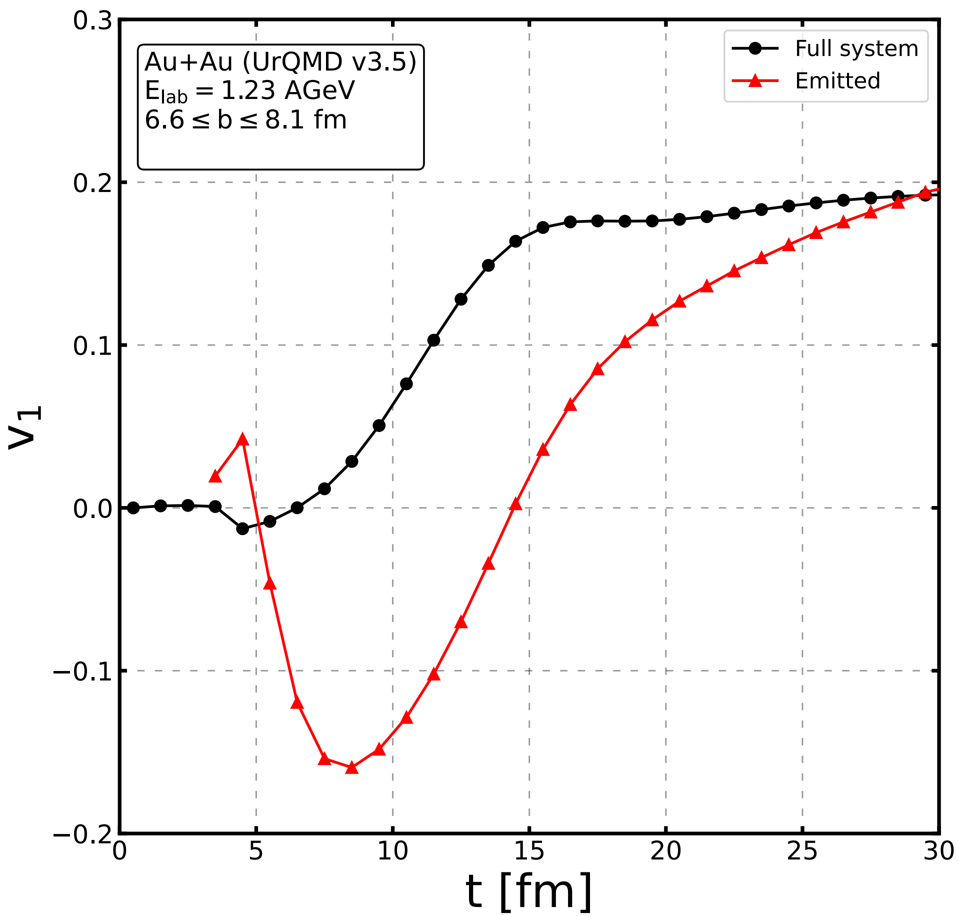
Emitted:

- First highly negative
- Increasing towards final value



T. Reichert et al., to be published

Time development of v_1



Full system:

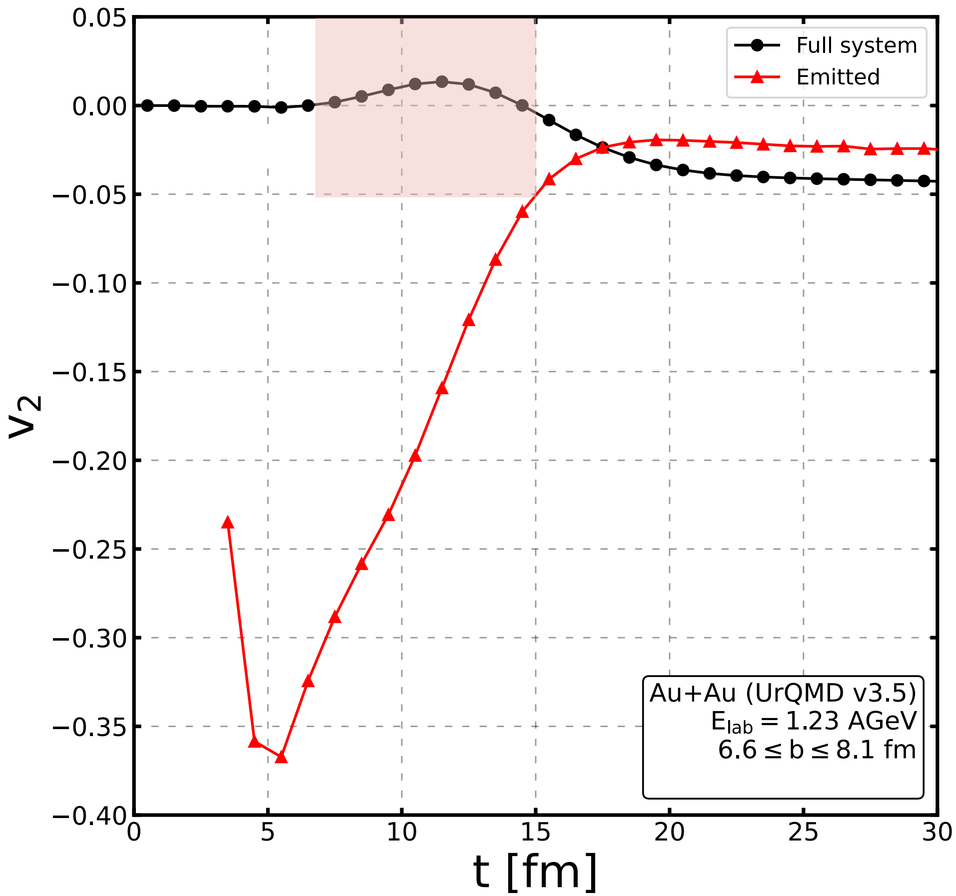
- Zero until compression transfers p_x momentum
- Strong increase from 5 to 15 fm
- Saturates

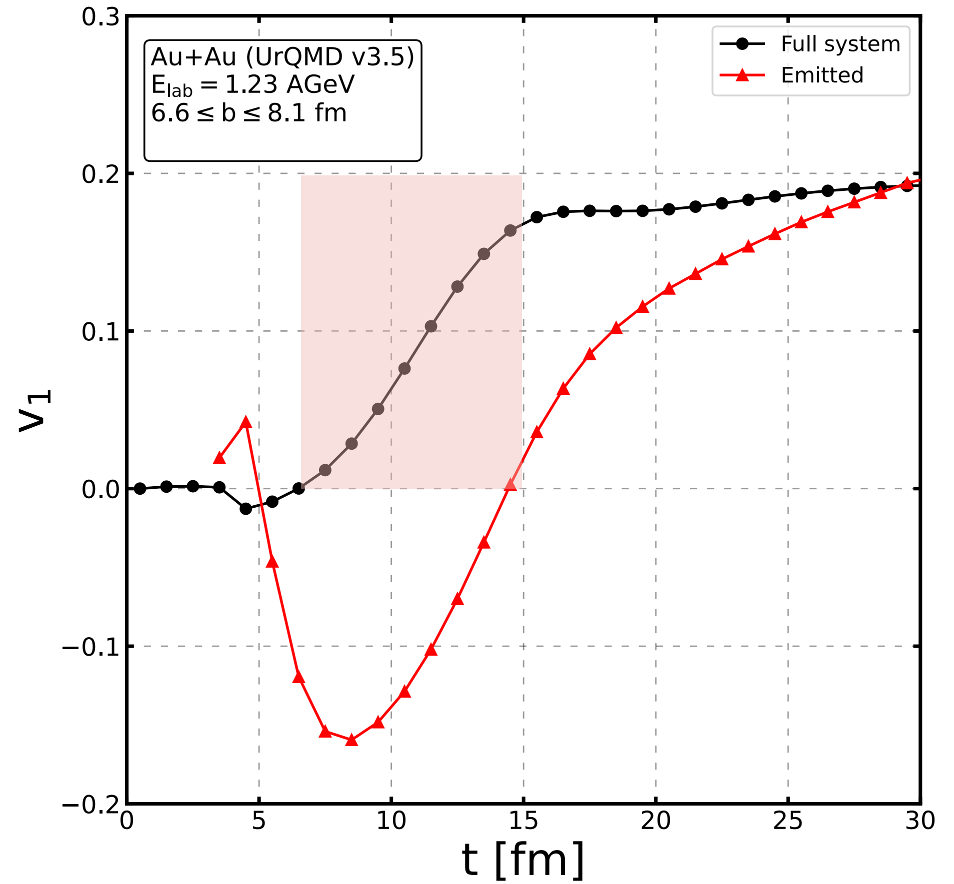
Emitted:

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

T. Reichert et al., to be published

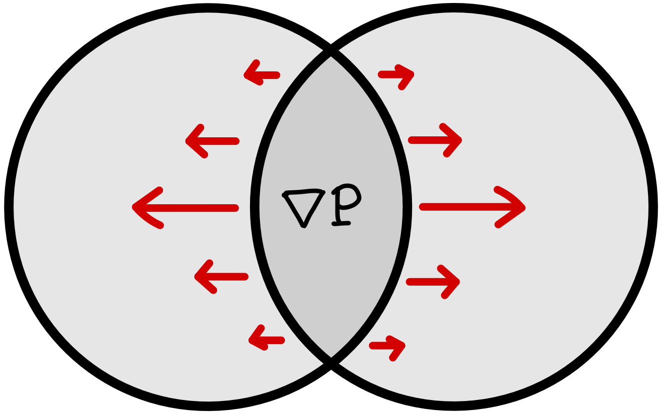
Time development of v_1 and v_2



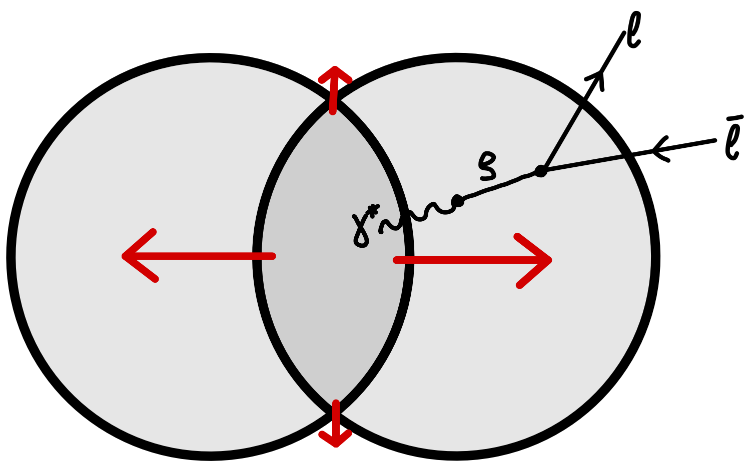


- Flow is directly sensitive to the EoS
- Tight connection between v_1 and v_2

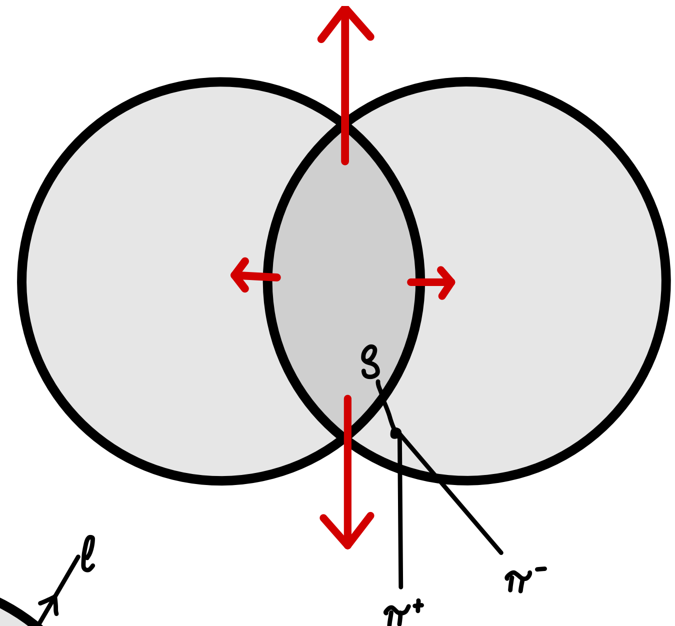
Time evolution



Bulk dynamics
t = 7-15 fm
Pos. v_2 creates pos. v_1



Dilepton emission
t = 12 fm
Observation of in-plane expansion



Hadron decoupling
t = 20-30 fm
Shadowing → neg. v_2

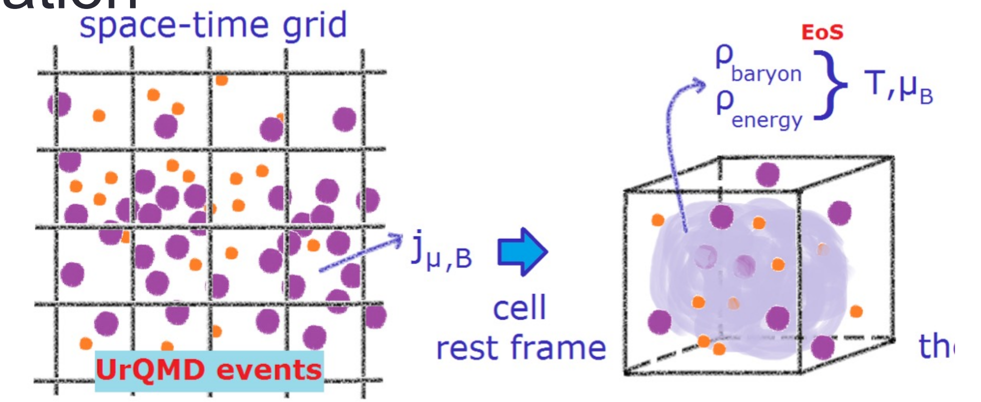
Measuring the influence EoS

Test 1: Dileptons

Dileptons

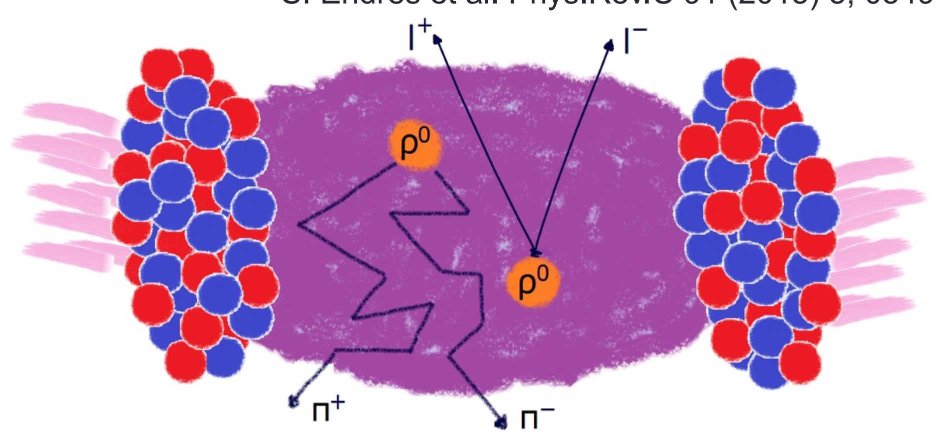
C. Gale et al. Nucl. Phys. B357 (1991) 65

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

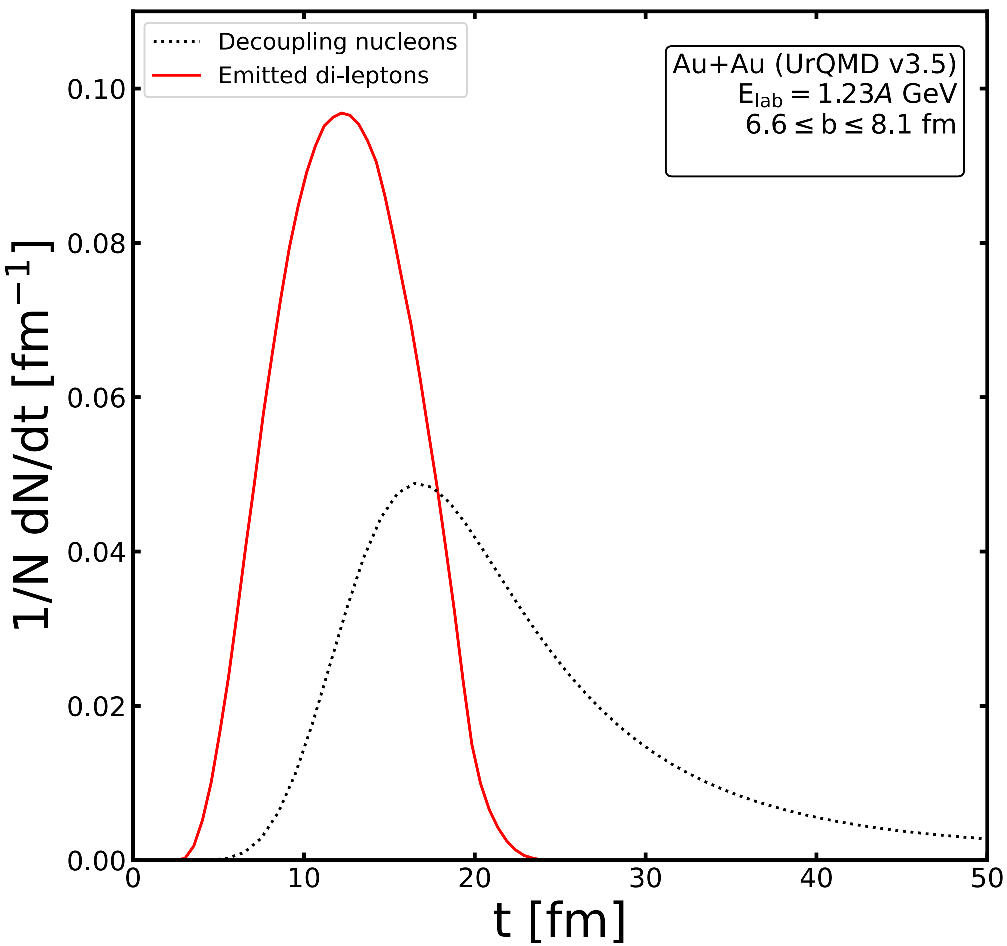


S. Endres et al. Phys.Rev.C 91 (2015) 5, 054911

- UrQMD + coarse-graining
- Evaluate $\langle T^{\mu\upsilon}\rangle$ 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)

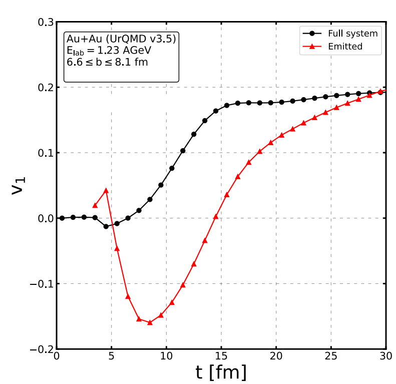


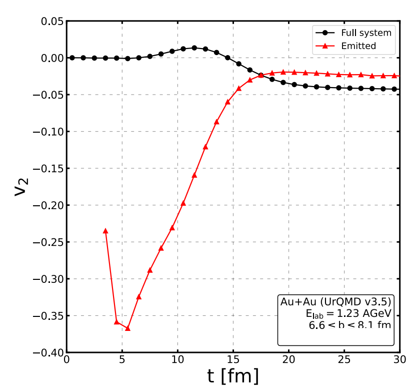
Decoupling time distribution



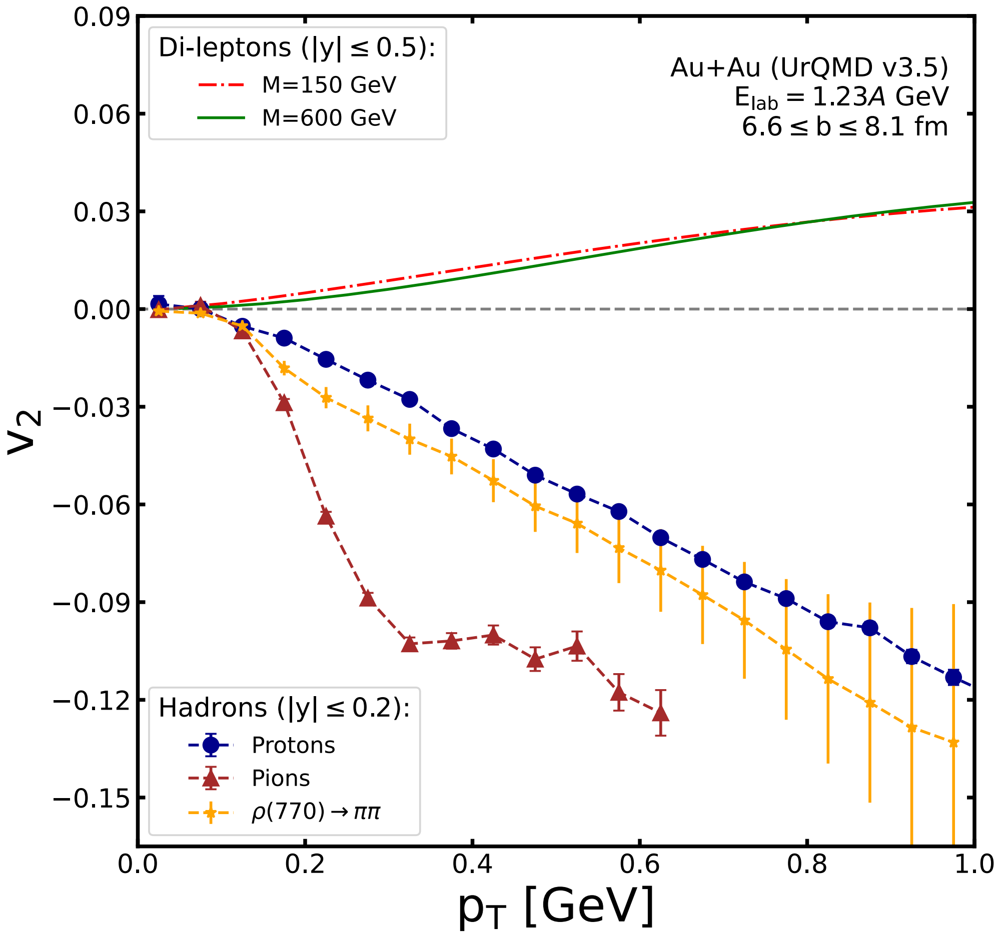
T. Reichert et al., to be published

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





Elliptic flow: p_T dependence



T. Reichert et al., to be published

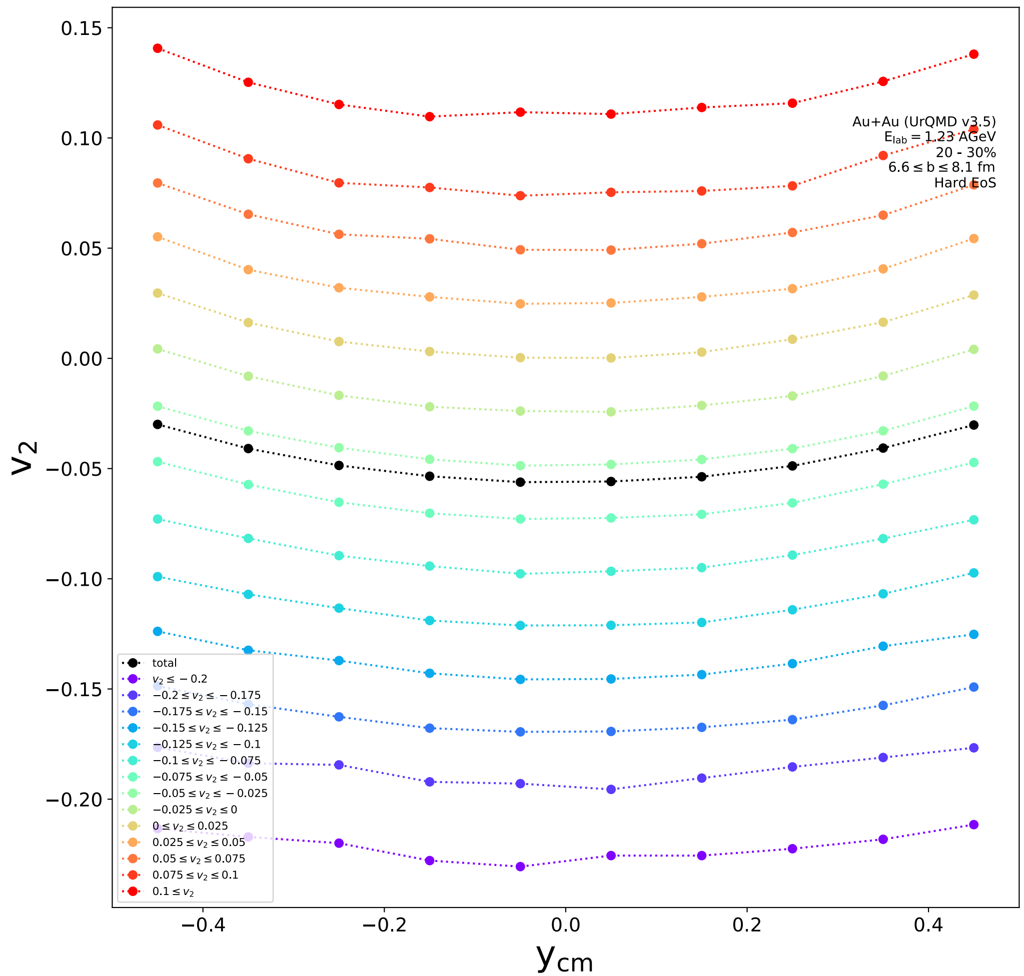
- Hadrons show negative v_2
- Simulation in line with HADES data
- Dileptons have positive v_2
- Dileptons show hydro-mass scaling
- Direct measurement of EoS

Measuring the influence EoS

Test 1: Dileptons

Test 2: Flow correlations

v_2 in different event classes

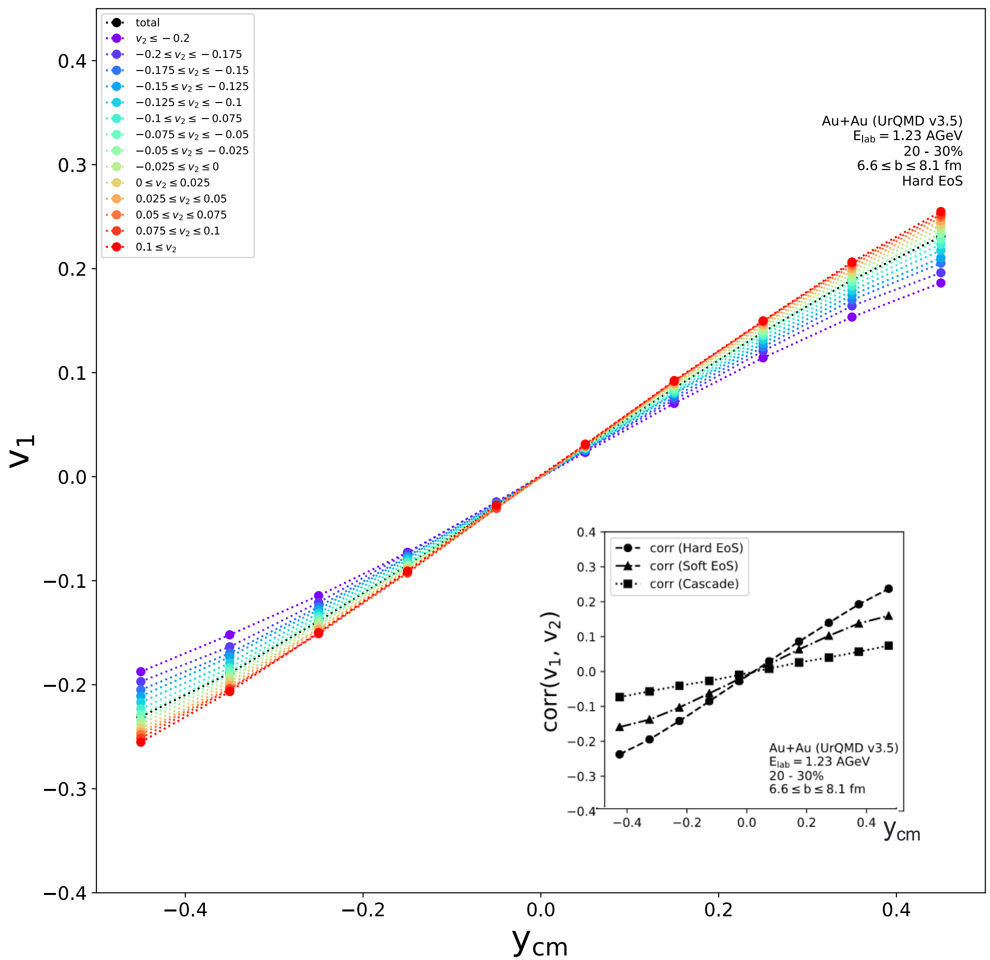


- Trigger on large variations of v_2 possible

- Expectation:
  - positive v_2 → larger v_1
  - negative v_2 → smaller v_1

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

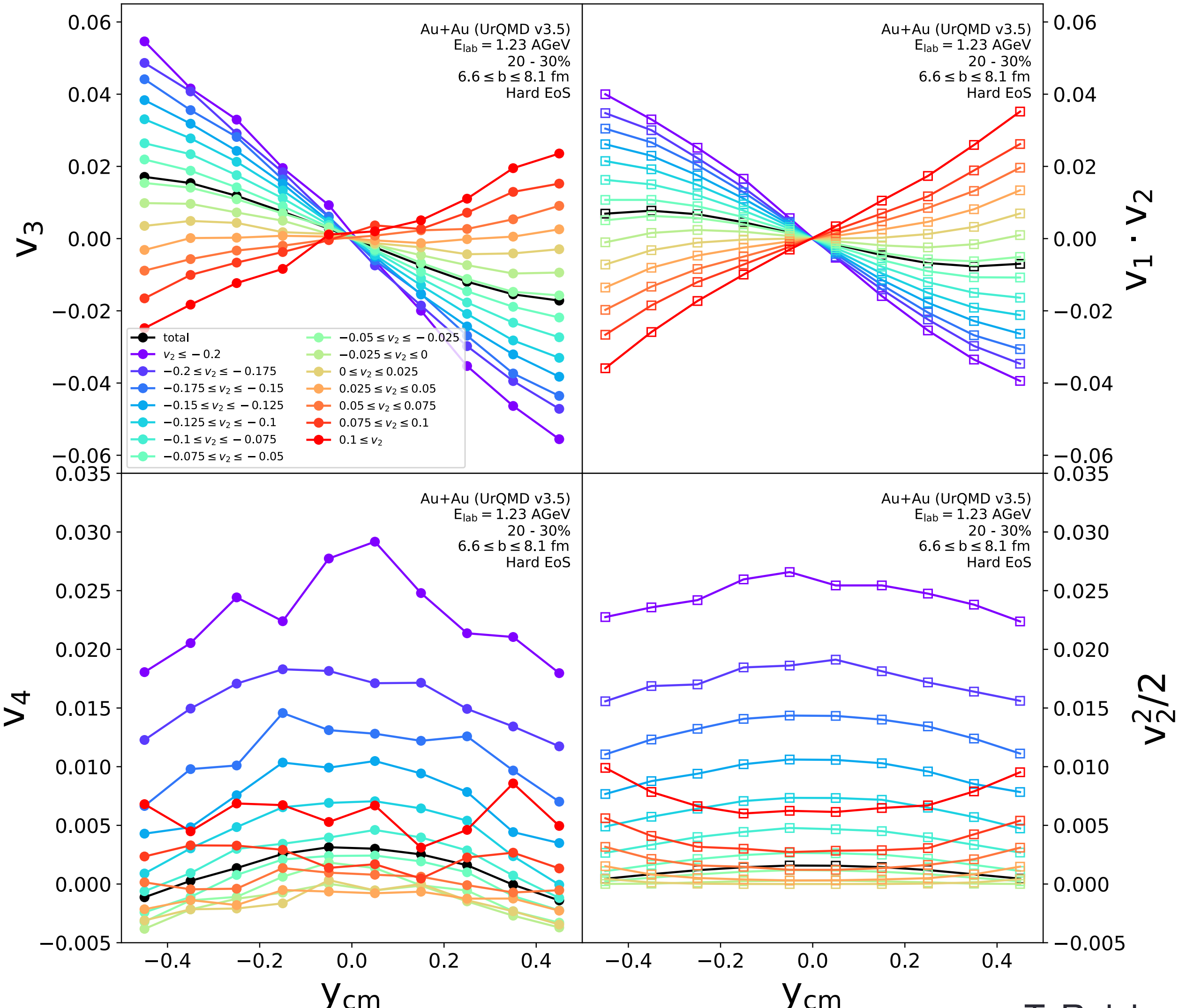
v_1 in different event classes



- Clear correlation:
  - Larger (positve) v_2
    → larger v_1
  - Smaller (negative) v_2
    → smaller v_1
- Strength of bounce-off defined by initial shape
- Proves picture of early in-plane expansion
- Investigate v_3 & v_4 in different event classes to find further correlations

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

Flow scaling

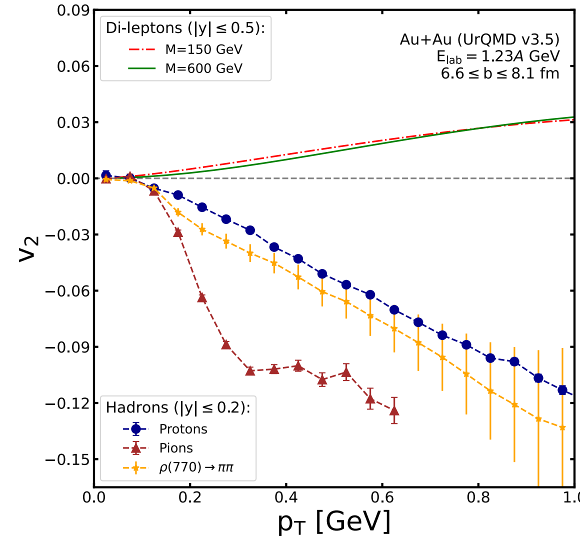


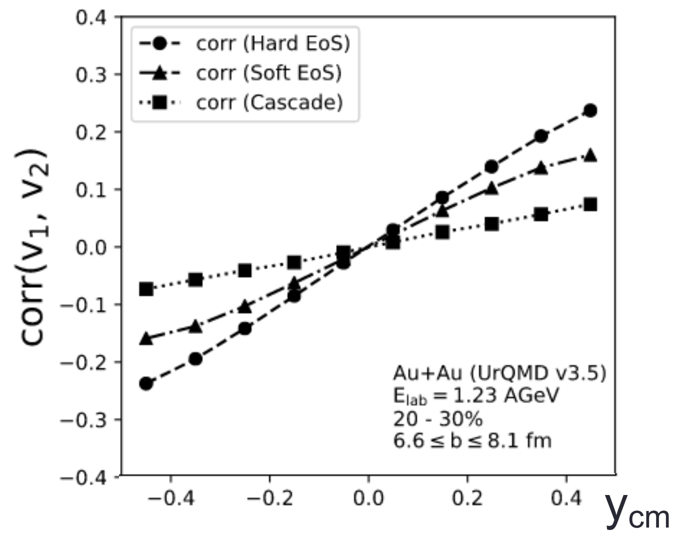
- We understand flow development
- Initial ε_2 fluctuation drives built-up of v_2 and v_1
- Pressure gradient creates correlation: $v_3 \propto v_1 \cdot v_2$
- Measure EoS!

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

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 correlation between v_2 and v_1
- Measurement via dileptons
- Event classes allow to pin down EoS





Helmholtz Forschungsakademie Hessen für FAIR

Institute for Theoretical Physics

treichert@itp.uni-frankfurt.de