STRONG-NA7 Workshop & HFHF Theory Retreat
28. Sep. – 4. Oct. 2023, Taormina, Italy

UNDERSTANDING HARMONIC FLOW OF PROTONS, LIGHT- & HYPERNUCLEI

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

FIAS Frankfurt Institute for Advanced Studies

Stiftung Polytechnische Gesellschaft Frankfurt am Main

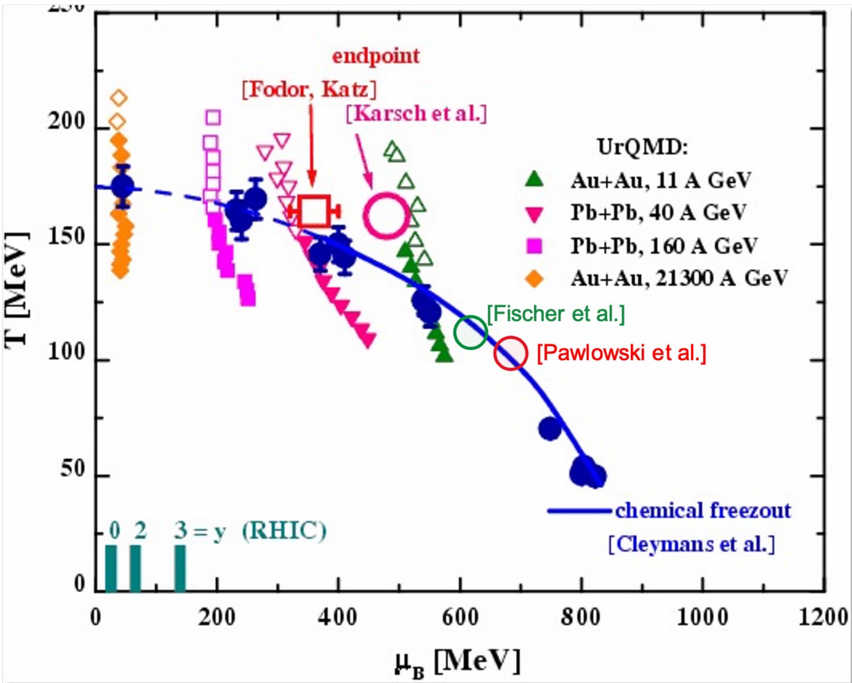
HFHF Helmholtz Forschungsakademie Hessen für FAIR

ITP Institute for Theoretical Physics

treichert@itp.uni-frankfurt.de

Overarching goal and outline

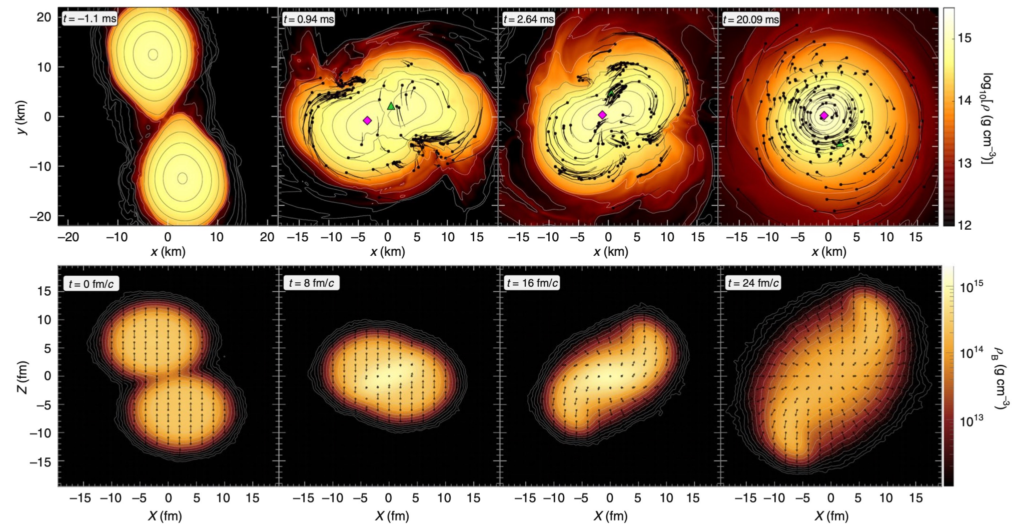
- Understanding the nature of the QCD phase diagram
- Bridge the gap from heavy-ion collisions to neutron stars



L. Bravina et al. JPG 1999
I. Arsene et al. PRC 2007

→ Talk: Christian Fischer

Neutron star simulation



Heavy-ion simulation (UrQMD)

HADES. Nature Phys. 15 (2019) 10, 1040-1045

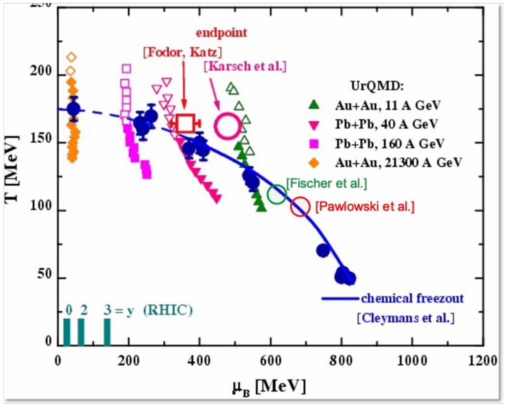
Overarching goal and outline

- Understanding the nature of the QCD phase diagram
- Bridge the gap from heavy-ion collisions to neutron stars
- Heavy-ions are collided at GSI, RHIC, LHC
- Compare to numerical simulations solving e.g. Boltzmann-Equation

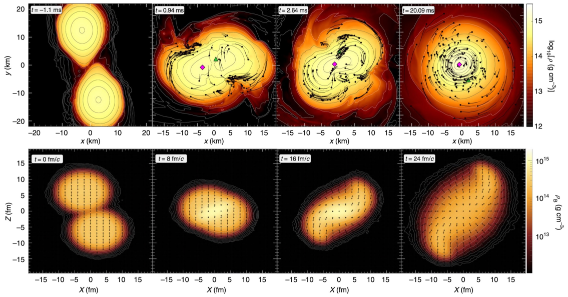
$$\frac{\partial f}{\partial t} + v \cdot \nabla_r f - \nabla U \cdot \nabla_p f$$

$$= -\int \frac{d^3p_2}{(2\pi)^3} \frac{d^3p_1'}{(2\pi)^3} \frac{d^3p_2'}{(2\pi)^3} \sigma v_{12} [f f_2 (1 - f_{1'})(1 - f_{2'})$$

$$- f_{1'} f_{2'} (1 - f)(1 - f_2)] \, (2\pi)^3 \delta^3 (p + p_2 - p_1' - p_2')$$

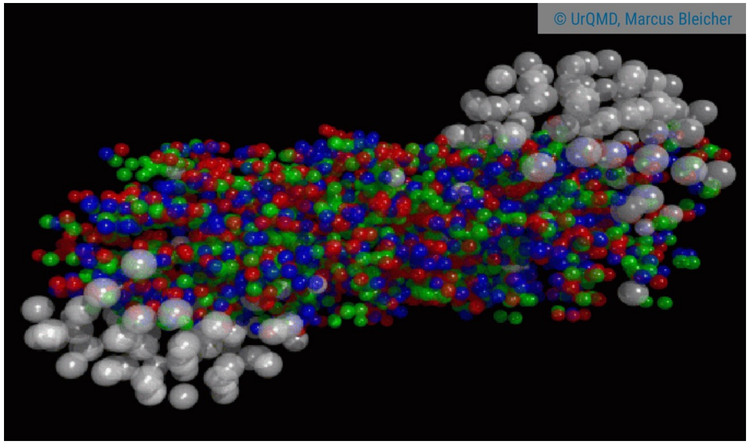


L. Bravina et al. JPG 1999
I. Arsene et al. PRC 2007



HADES. Nature Phys. 15 (2019) 10, 1040-1045

Ultra-relativistic Quantum Molecular Dynamics



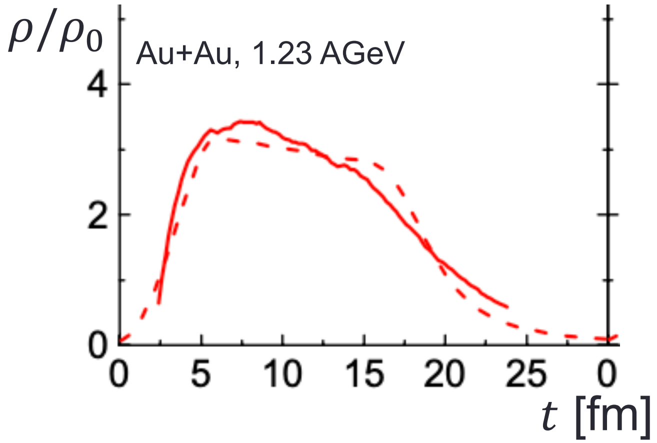
- Hadron/String transport approach
- Based on propagation of hadrons
- Rescattering among hadrons fully included
- String excitation and decay (LUND model, PYTHIA)
- Solution for the time dependent n-body distribution of hadrons
- Collision term includes more than 100 hadrons up to 4 GeV in mass
- Soft/Hard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

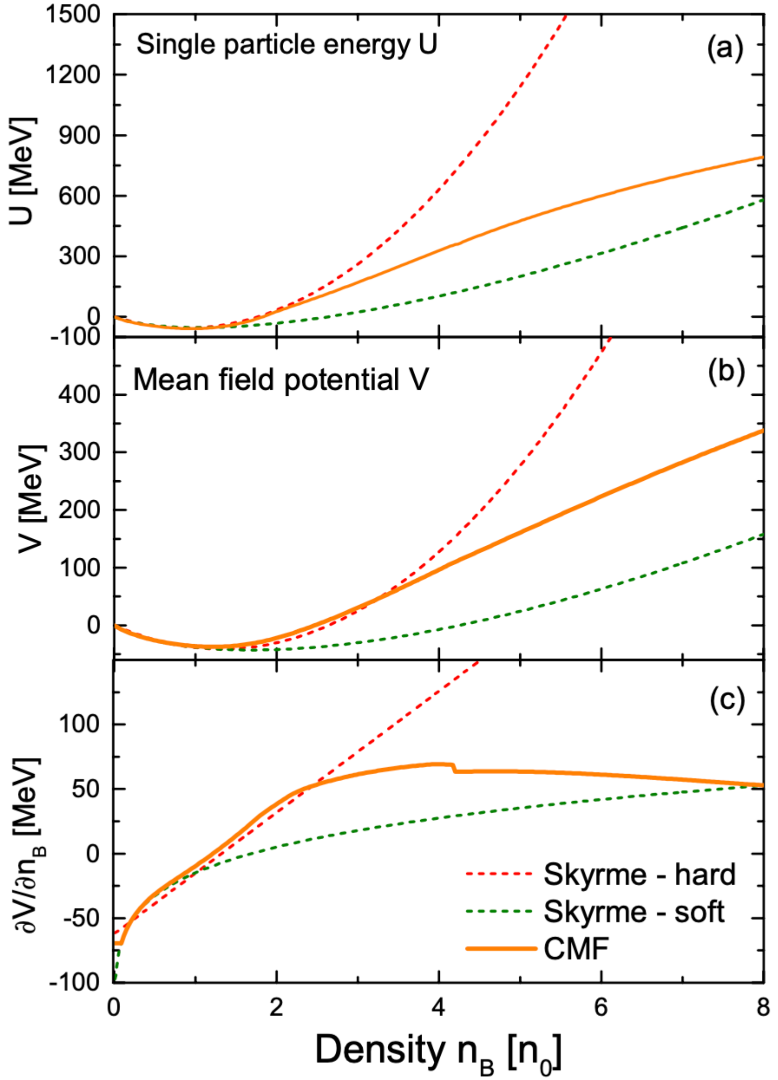
M. Bleicher et al. J.Phys. G25 (1999), 1859-1896

→ Talk: Marcus Bleicher

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



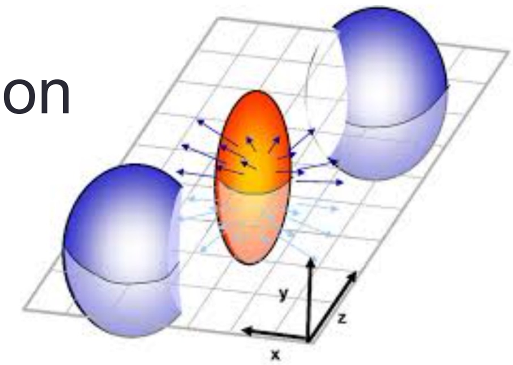


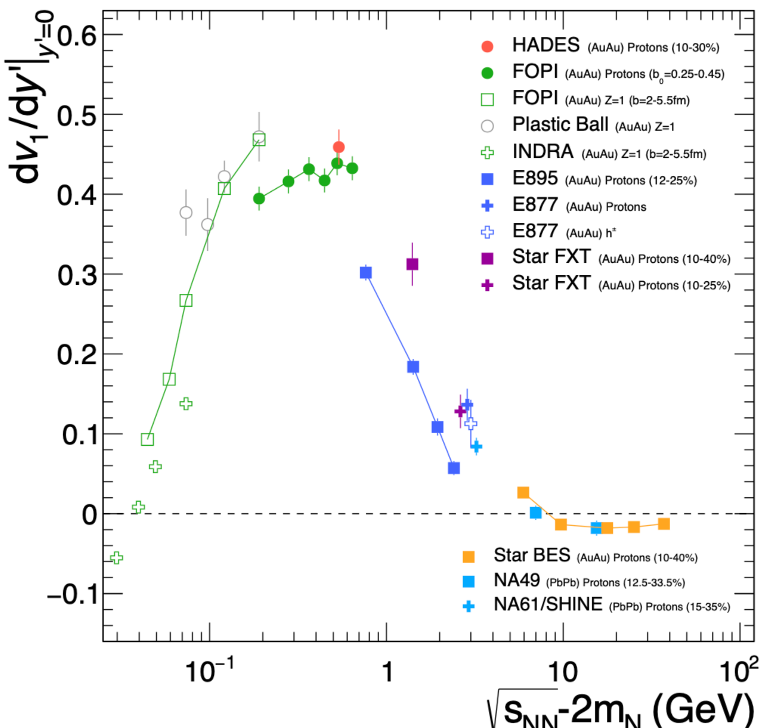
→ Talk: Jan Steinheimer

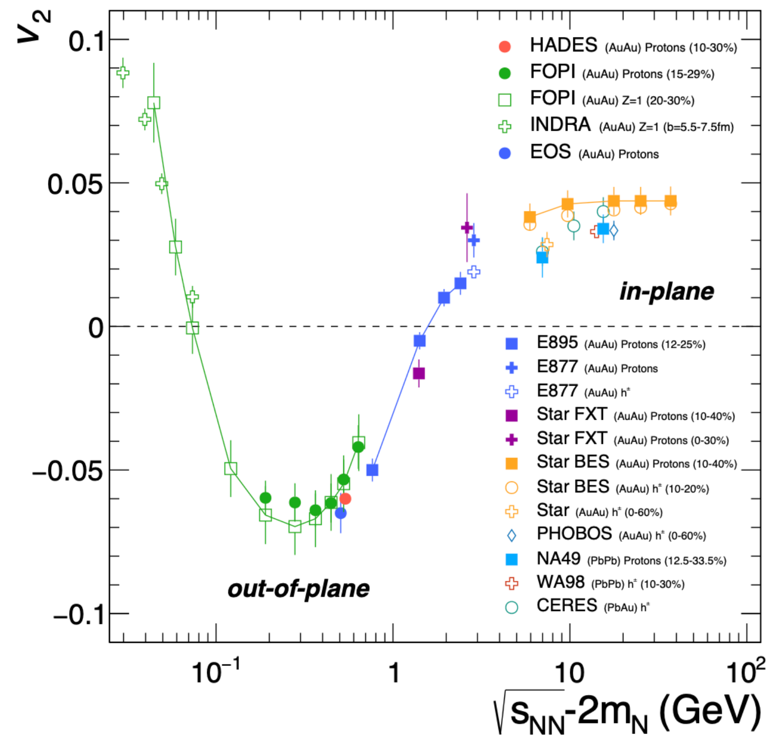
M. Omana Kuttan et al. Eur.Phys.J.C 82 (2022) 5, 427

Harmonic flow

- Fourier series of azimuthal angle distribution
- $\frac{dN}{d\varphi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_{RP}))$
- v_1: Directed flow, v_2: Elliptic flow



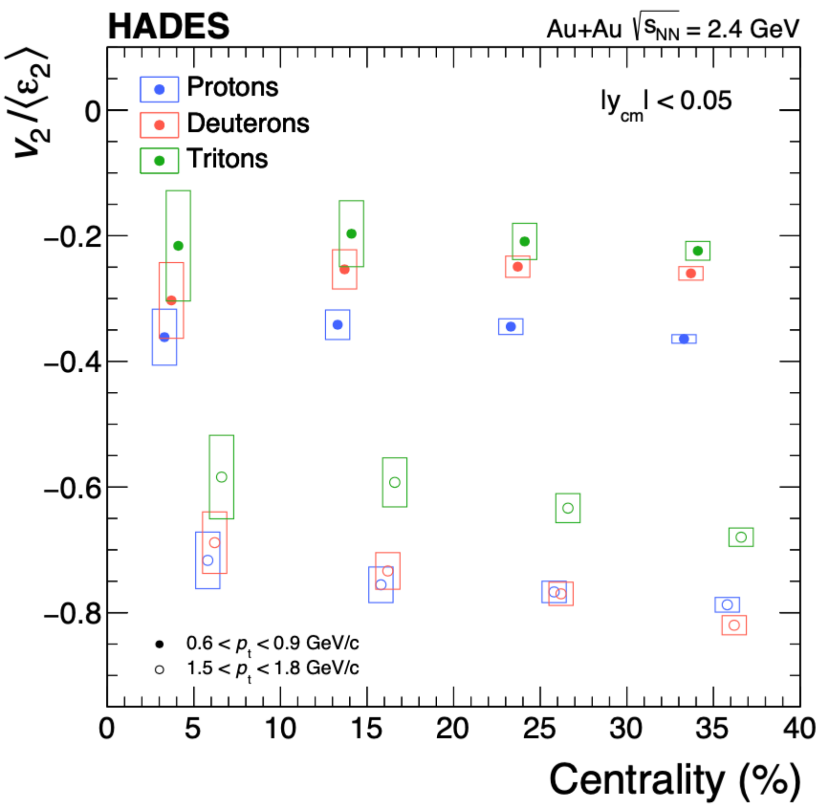




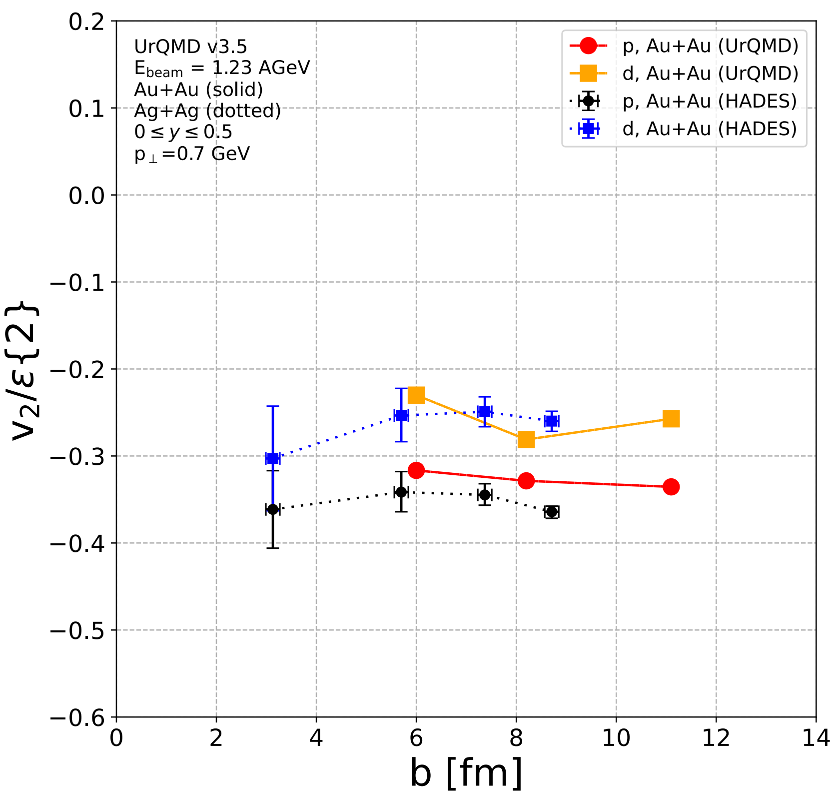
HADES. Eur.Phys.J.A 59 (2023) 4, 80

Elliptic flow scaling with eccentricity

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

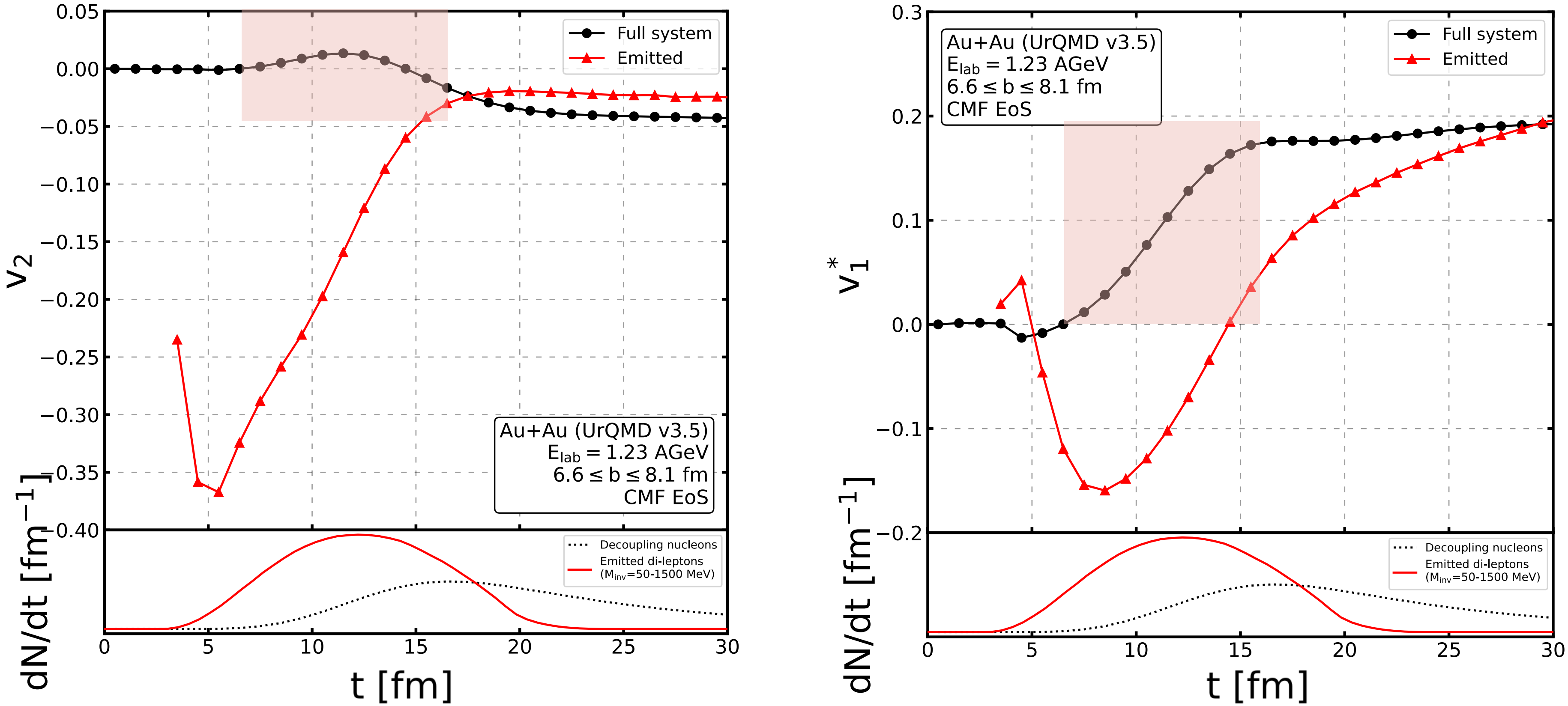


HADES. Eur.Phys.J.A 59 (2023) 4, 80



T. Reichert et al. J.Phys.G 49 (2022) 5, 055108

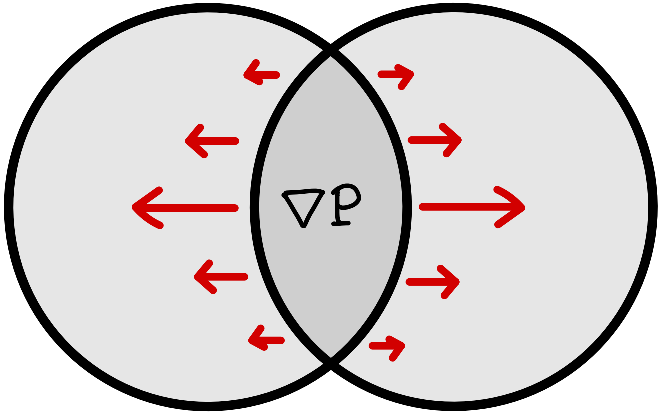
Time development of the flow



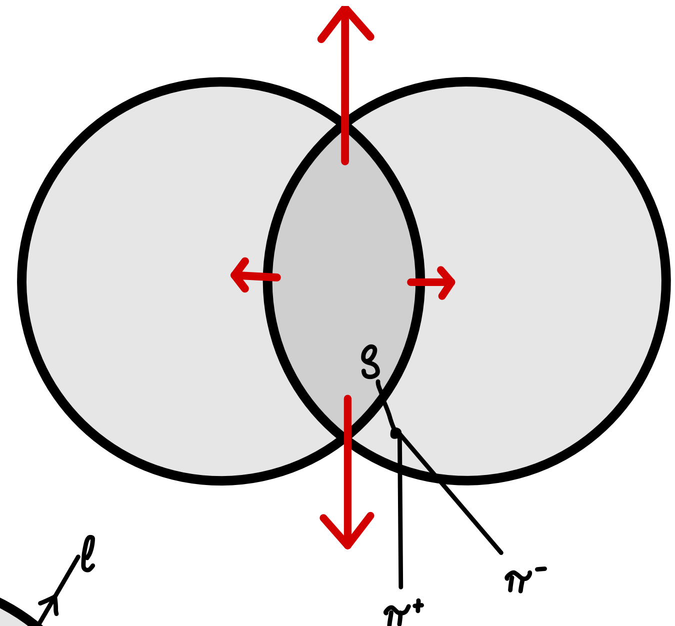
Reichert et al. Phys.Lett.B 841 (2023) 137947

- Flow is directly sensitive to the EoS
- Tight connection between v_1 and v_2
- Is the positive v_2 measureable?

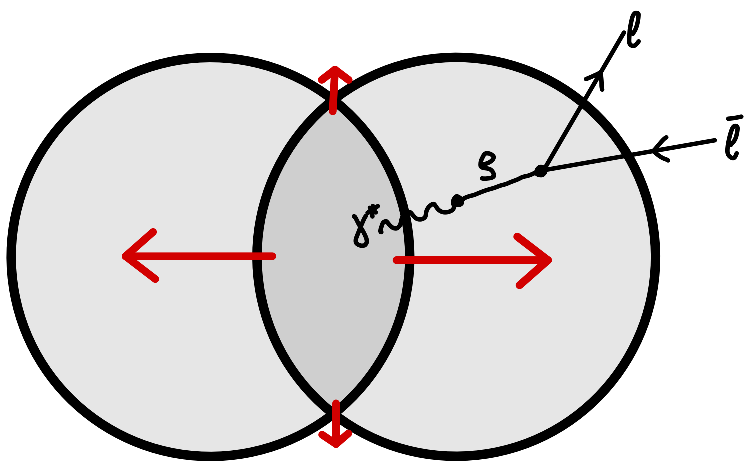
Time evolution



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



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

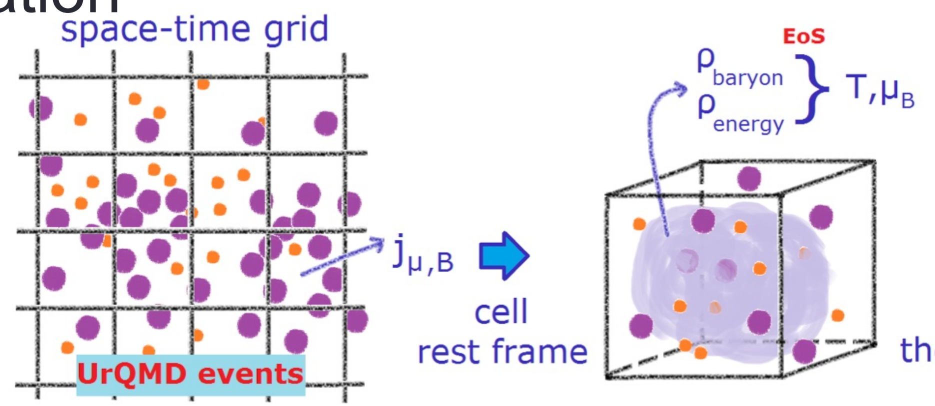


Dilepton emission
t = 12 fm
Observation of in-plane expansion

Dileptons

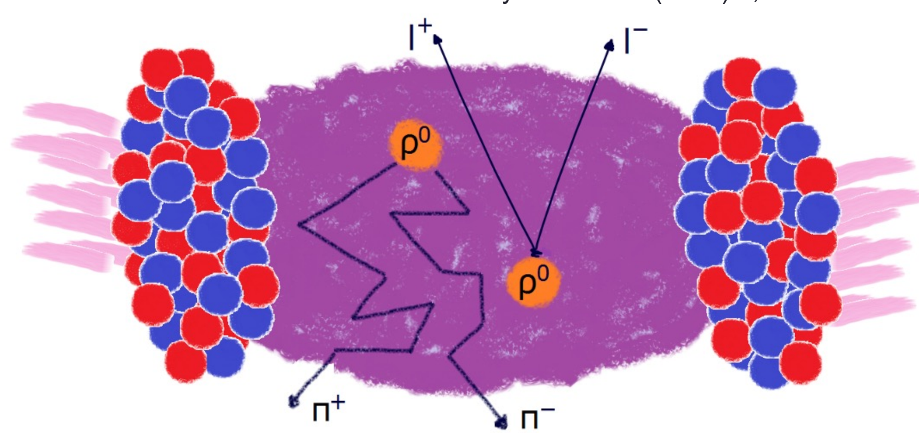
C. Gale et al. Nucl. Phys. B357 (1991) 65

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



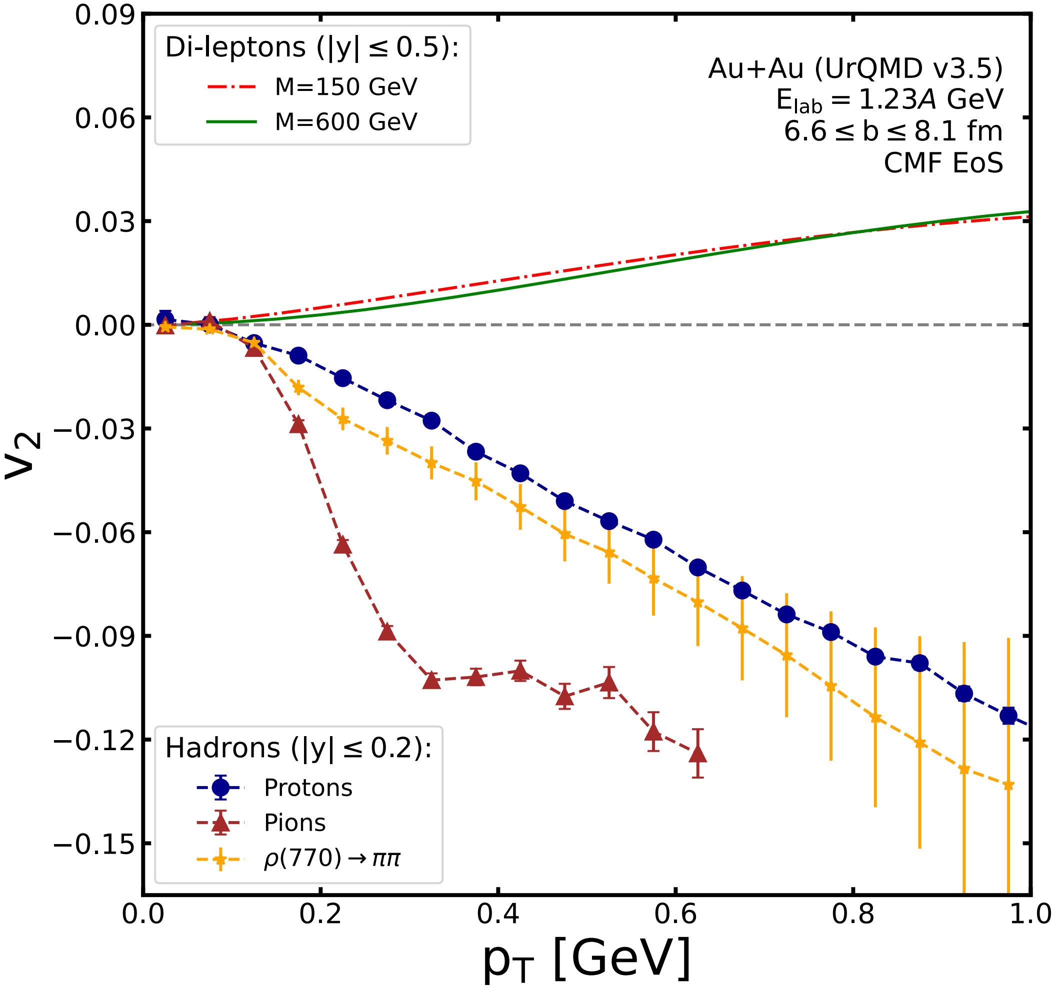
S. Endres et al. Phys.Rev.C 91 (2015) 5, 054911

- 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)



→ Talk: Hendrik van Hees
→ Talk: Renan Hirayama

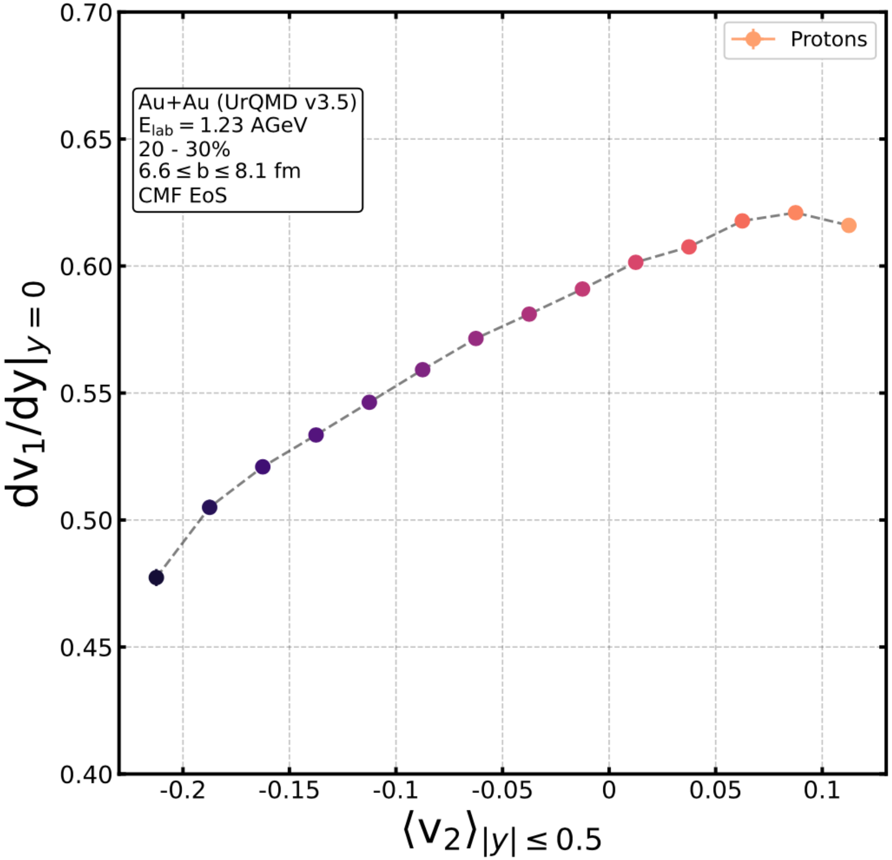
Measuring the initial flow and early EoS with Di-Leptons



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

- 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
- Direct correlation of v_2 and v_1

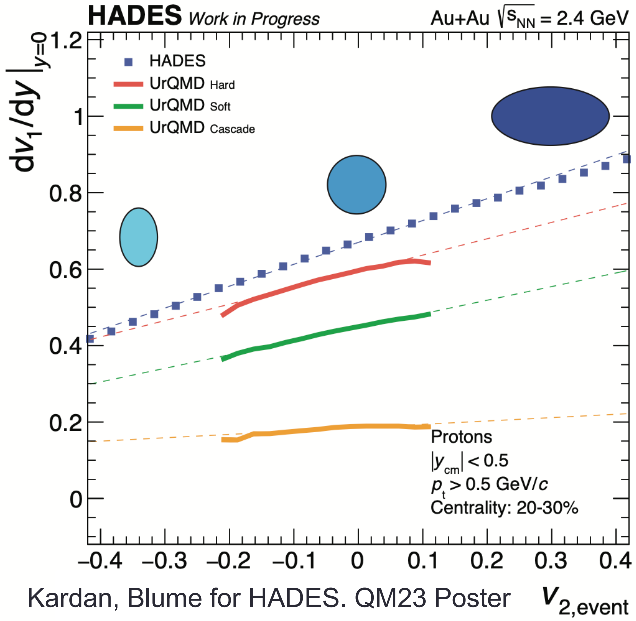
Measuring the initial flow and early EoS with Correlations



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

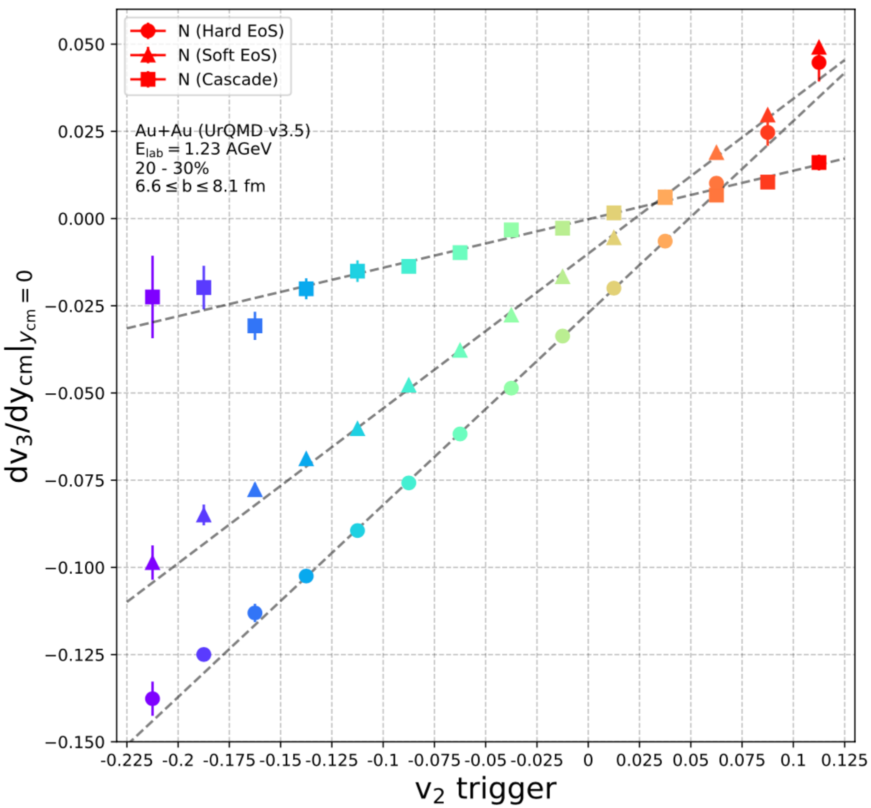
- HADES (prel!) data prefers hard EoS

- Select events based on integrated final v_2
- Measure dv_1/dy as function of v_2 trigger
- Strong correlation observed
- Explained by pressure gradient and shadowing



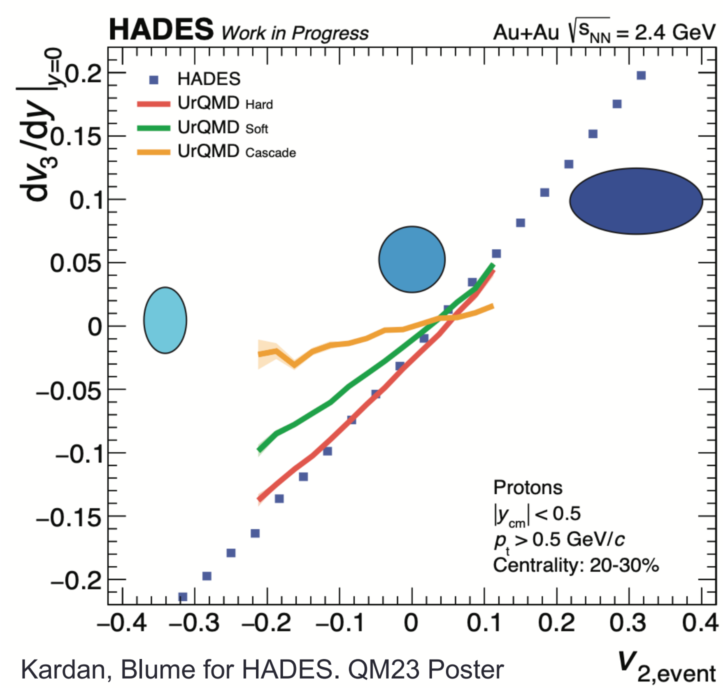
Kardan, Blume for HADES. QM23 Poster

Measuring the initial flow and early EoS with Correlations



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

- Select events based on integrated final v_2
- Measure dv_3/dy as function of v_2 trigger
- Strong sensitivity to stiffness of EoS



Kardan, Blume for HADES. QM23 Poster

- HADES (prel!) data prefers hard EoS

Light cluster and hypernuclei

- Light clusters

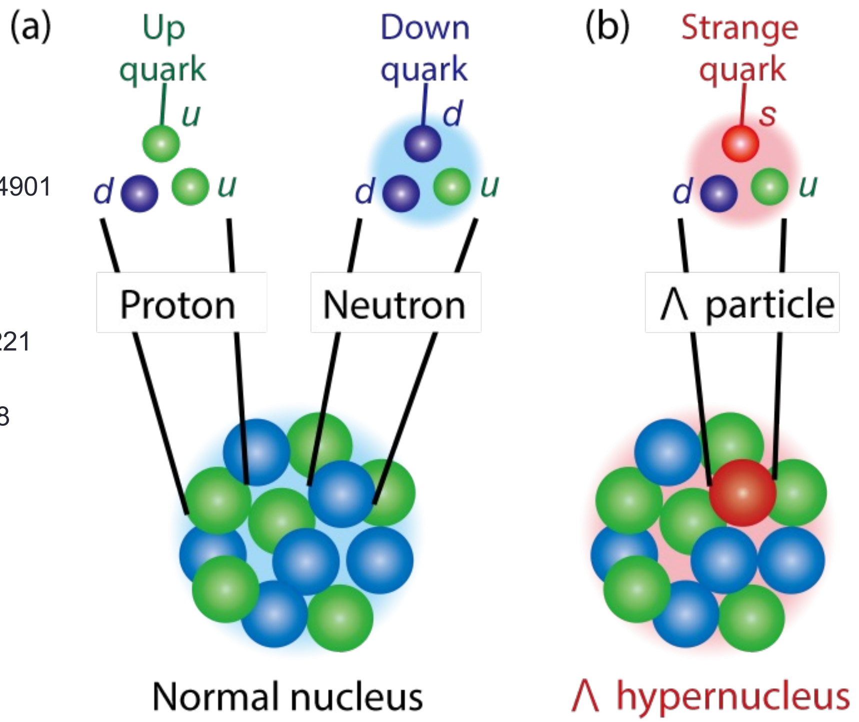
→ Deuteron (pn), Triton (pnn), ^{3}He (ppn), ^{4}He (ppnn)

- Hypernuclei

→ Hypertriton (pnΛ), $^4{}_\Lambda$H (pnnΛ)

- Production?
  - Coalescence S. Sombun et al. Phys.Rev.C 99 (2019) 1, 014901
  - Potential J. Aichelin, et al. Phys.Rev.C 101 (2020) 4, 044905
  - Fragmentation Bondorf et al. Phys.Rept. 257 (1995) 133-221
  - Thermal P. Braun-Munzinger, et al. Phys.Lett.B 344 (1995) 43-48
  - Wigner Mattiello et al. Phys.Rev.C 55 (1997) 1443-1454
  - Kinetic Oliinychenko et al. Phys.Rev.C 99 (2019) 4, 044907

→ Talk: Apiwit Kittiratpattana
→ Talk: Gabriele Coci
→ Talk: Tim Neidig



Coalescence

- Clusters are weakly bound compared to momentum transfer (temperature)
- Clusters are formed after kinetic freeze-out
- Coalescence: Cluster is formed if correct constituents occupy certain phase space volume

$$\frac{\mathrm{d}N}{\mathrm{d}^3k} = g \int \mathrm{d}p_1^3 \mathrm{d}p_2^3 \mathrm{d}x_1^3 \mathrm{d}x_2^3 f_A(p_1, x_1) f_B(p_2, x_2) \rho_{AB}(\Delta x, \Delta p) \delta(k - (p_1 + p_2))$$

- Need realistic phase space distribution functions of nucleons

→ Use microscopic transport model keeping all n-body correlations

Box-Coalescence

1. Boost into local rest frame of each possible nucleon+nucleon pair with the correct isospin combination at kinetic freeze-out. If relative distance $\Delta x < \Delta x_{max}$ and relative momentum $\Delta p < \Delta p_{max}$ the two-nucleon system is marked a deuteron candidate.
2. Boost into local rest frame of deuteron+nucleon and check again if $\Delta x < \Delta x_{max}$ and $\Delta p < \Delta p_{max}$. A triton or ^{3}He is then formed with a probability of 1/12 at the position $r_{NNN} = (r_1 + r_2 + r_3)/3$ and with momentum $p_{NNN} = p_1 + p_2 + p_3$

S. Sombun et al. Phys.Rev.C 99 (2019) 1, 014901
P. Hillmann et al. J.Phys.G 49 (2022) 5, 055107
T. Reichert et al. Phys.Rev.C 107 (2023) 1, 014912

Statistical Multifragmentation

Bondorf et al. Phys.Rept. 257 (1995) 133-221
Steinheimer et al. Phys.Lett.B 714 (2012) 85-91
Botvina. Phys. Rev.C76 (2007) 024909

- Break up of thermal nuclear system
- Microcanonical ensembles
- Break up is modeled according to statistical weight of entropy of decay channel

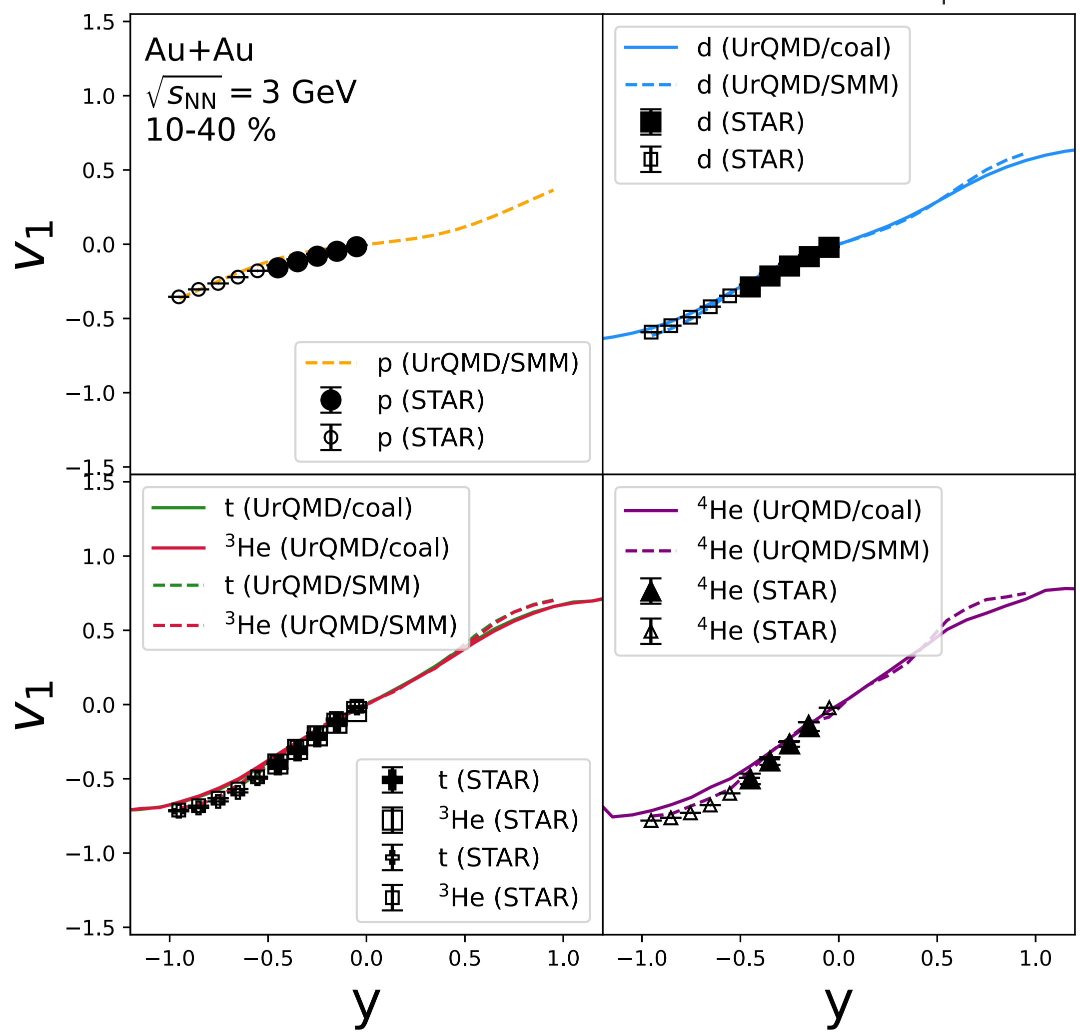
$$W_f \sim exp\left[S_f(A_0, Z_0, E^*, V)\right]$$

- Deexcitation via Fermi break up

Directed flow of light nuclei

- Data is described very good in large rapidity acceptance
- Coalescence and statistical multi-fragmentation yield similar results
- Prominent bounce-off visible in v_1
- v_1 of the clusters follows the v_1 of the nucleons

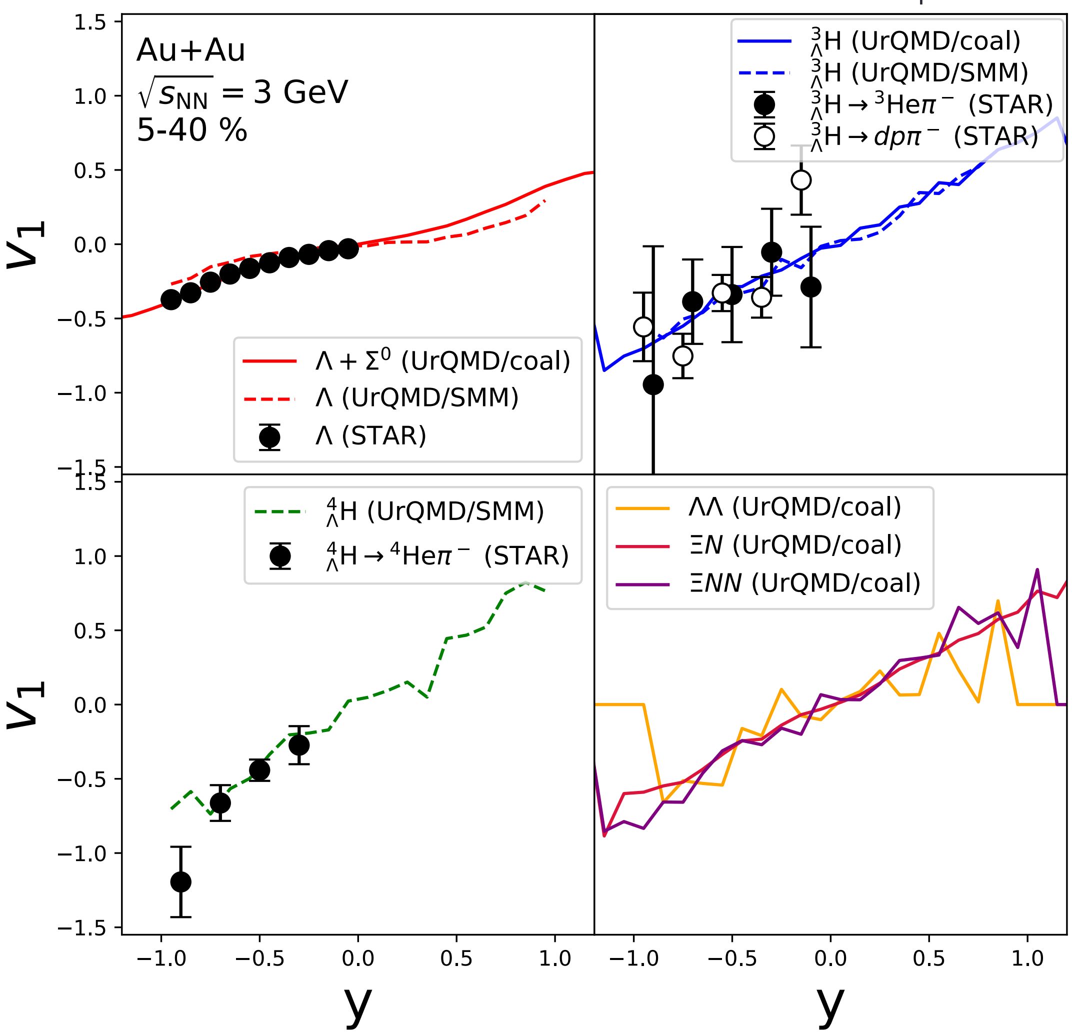
Reichert et al. to be published



Directed flow of hypernuclei

- Coalescence and multifragmentation describe v_1 of $\Lambda\Lambda$, ${}^{3}{}_{\Lambda}$H, ${}^{4}{}_{\Lambda}$H good
- v_1 of hypernuclei follows v_1 of the nucleons and Lambda hyperons
- Predict v_1 of exotic objects, $|\Lambda\Lambda\rangle, |\Xi N\rangle, |\Xi NN\rangle$
- Allows to constrain the YN interaction more precisely

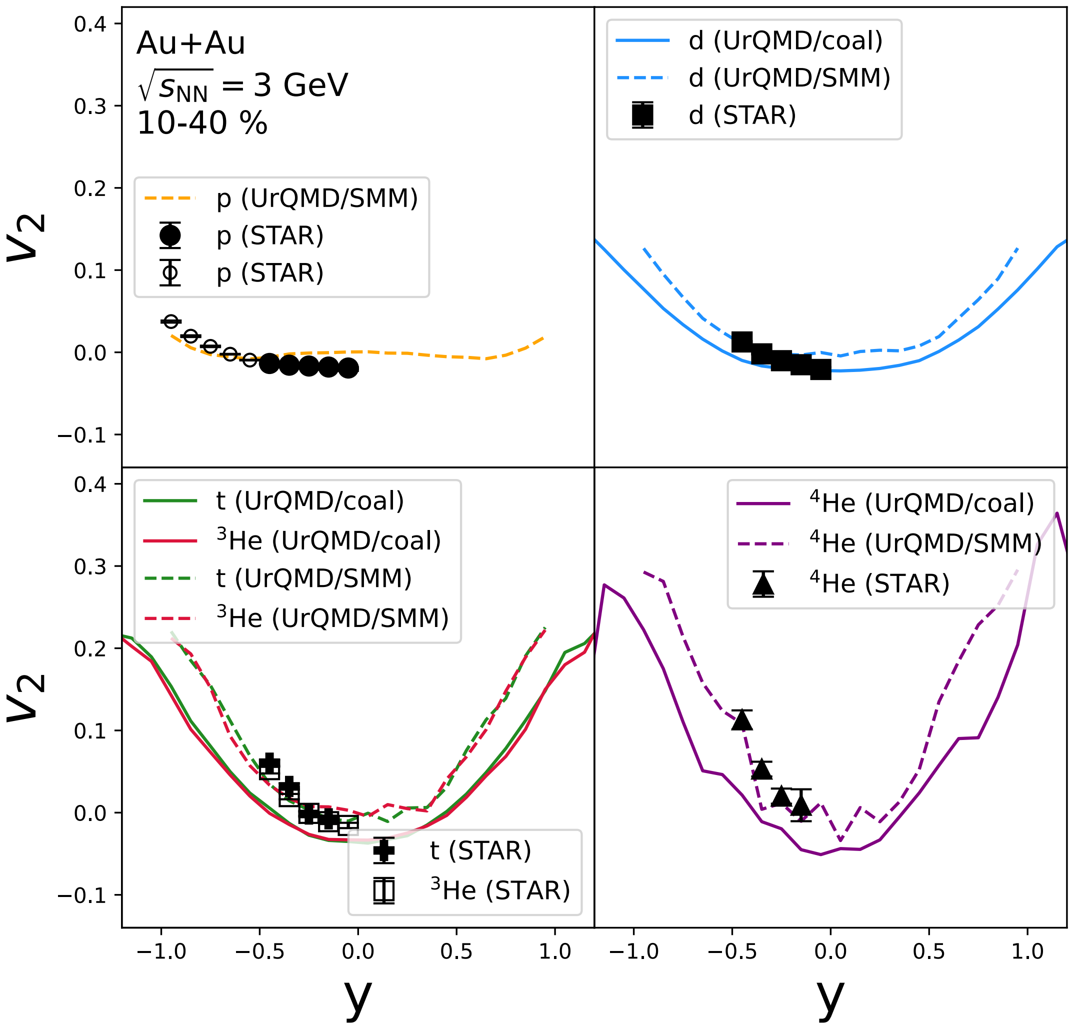
Reichert et al. to be published



Elliptic flow of light nuclei

- Data is very well described in large rapidity acceptance
- Coalescence yields a slightly smaller v_2 than multifragmentation
- v_2 of light clusters follow v_2 of the nucleons

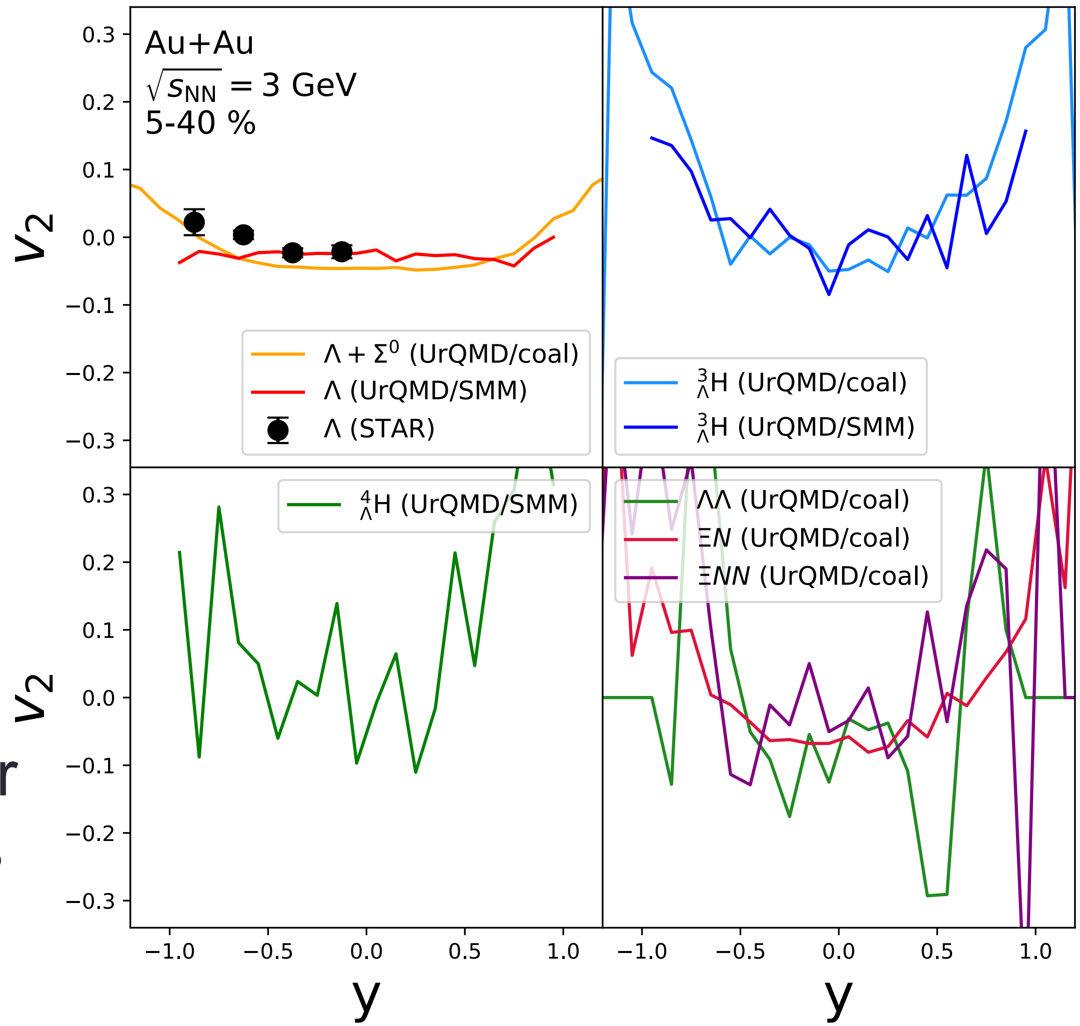
Reichert et al. to be published



Elliptic flow of hypernuclei

- Data is described very well
- Coalescence yields a smaller v_2 than multifragmentation
- Hints at intricate time evolution of v_2
- Constrain the YN interaction
- Benchmark potentials for neutron star calculations

Reichert et al. to be published



Summary

- Pressure gradient turns positive v_2 into positive v_1, therefore creating bounce-off
- Final v_2 is negative due to immense shadowing, momentum transfer to (semi-) spectators
- Measurement of initial v_2 possible with di-leptons
- Correlations of v_2- v_1, v_2- v_3 are sensitive to EoS
- Coalescence and Multifragmentation describe and predict flow of light- and hypernuclei
- v_1& v_2 pose opportunity to study YN interaction

SAMSON
FIAS Frankfurt Institute for Advanced Studies
Stiftung Polytechnische Gesellschaft Frankfurt am Main
HFHF Helmholtz Forschungsakademie Hessen für FAIR
ITP Institute for Theoretical Physics

treichert@itp.uni-frankfurt.de