FIAS Frankfurt Institute for Advanced Studies

HELMHOLTZ GEMEINSCHAFT

Collective Flow as a Signal of the Phase Transition

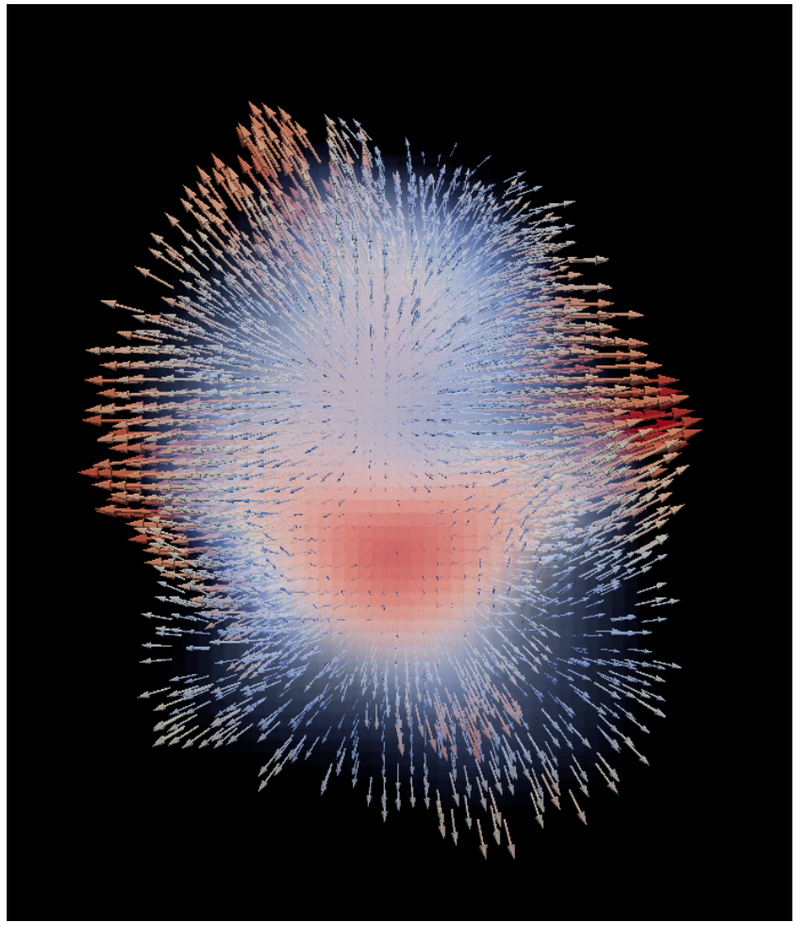
CBM Symposium, GSI, 9.4.14

Hannah Petersen

many thanks to Jussi Auvinen, Jan Steinheimer

Outline

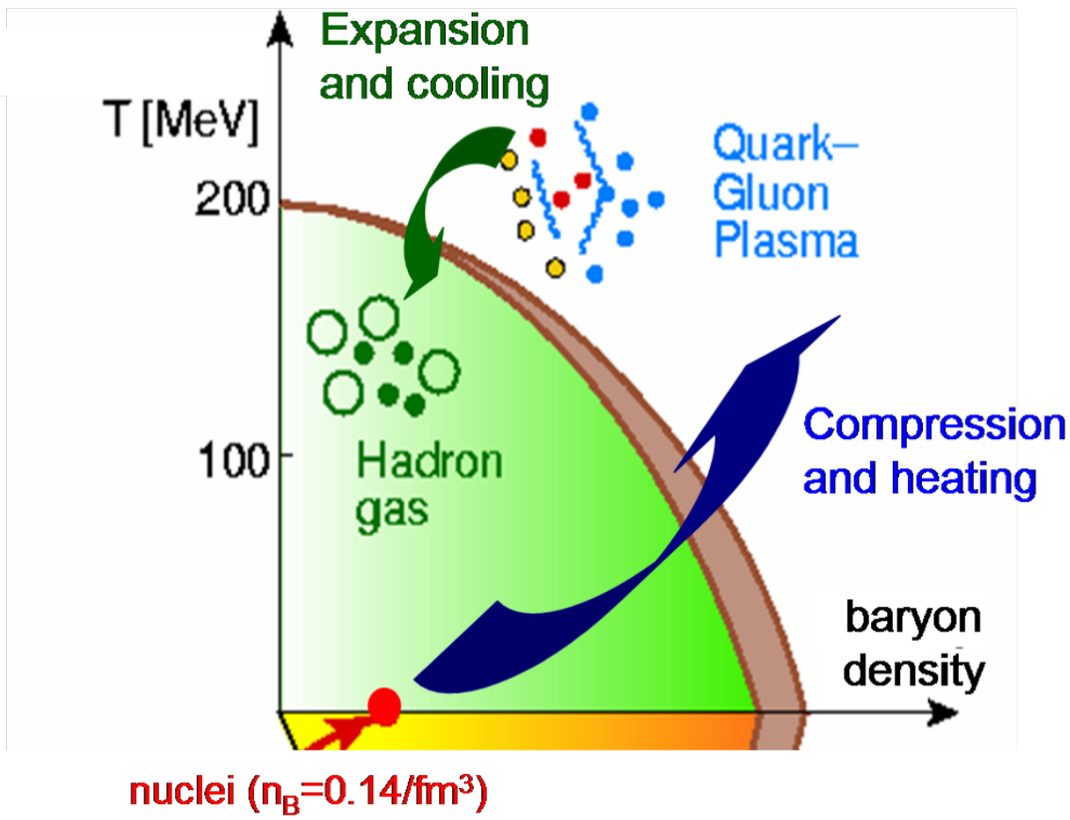
- The phase diagram of strongly interacting matter
- The dynamics of heavy ion reactions
  - UrQMD hybrid approach
- Collective Flow
  - Elliptic flow
    - A signal of the perfect liquid?
  - Triangular flow
    - A signal of fluctuations?
  - Directed flow
    - A signal of the softest point?



madai.us

The QCD Phase Diagram

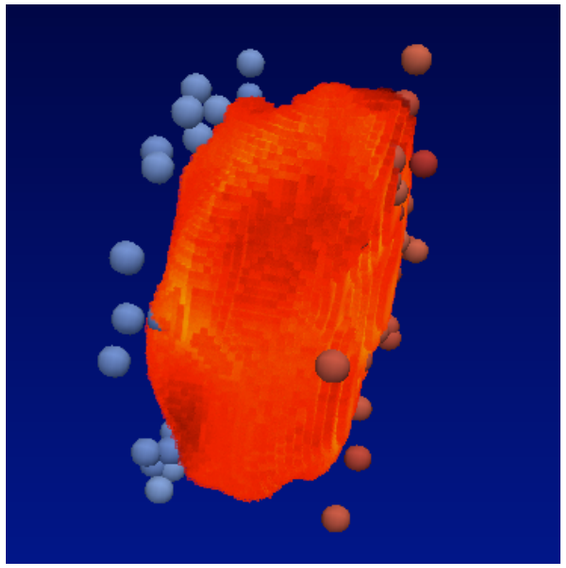
- Quantum chromodynamics has a **rich** phase structure
- Lattice QCD: thermodynamic properties predict change in **degrees of freedom**



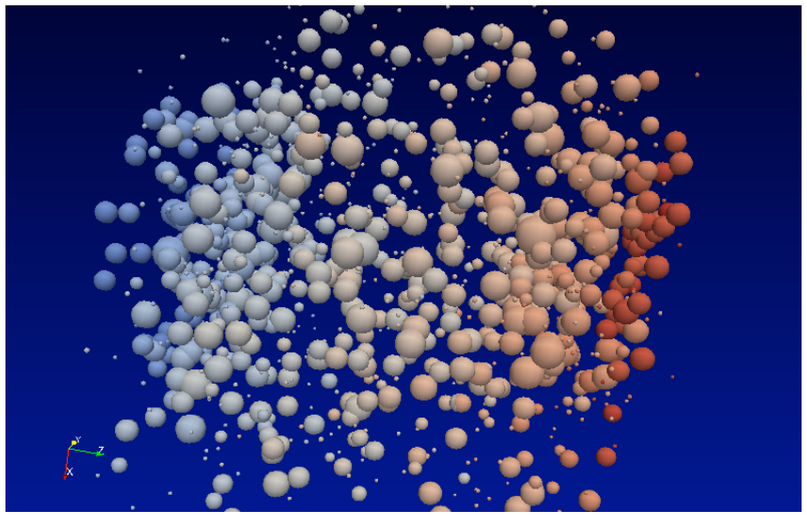
- **Questions** to be answered:
  - what is the temperature and the density?
  - what are the relevant degrees of freedom?
  - phase transition, critical point?
  - what are the transport properties?

- Collective flow is one of the most prominent observables

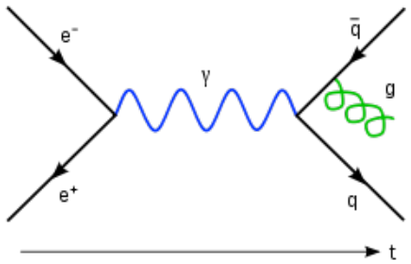
Theoretical Description



Dynamical description of heavy ion reactions

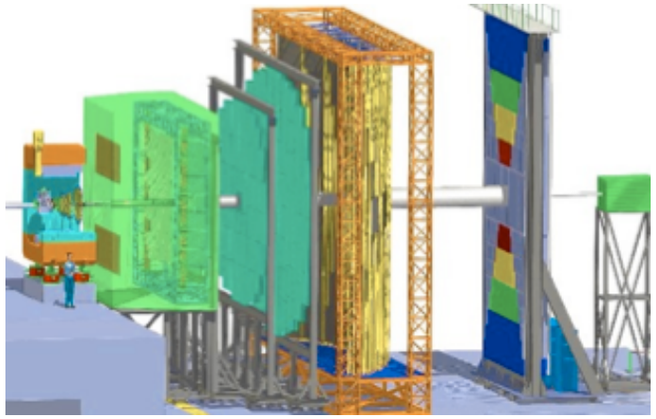


Fundamental field theory of strong interactions (QCD)



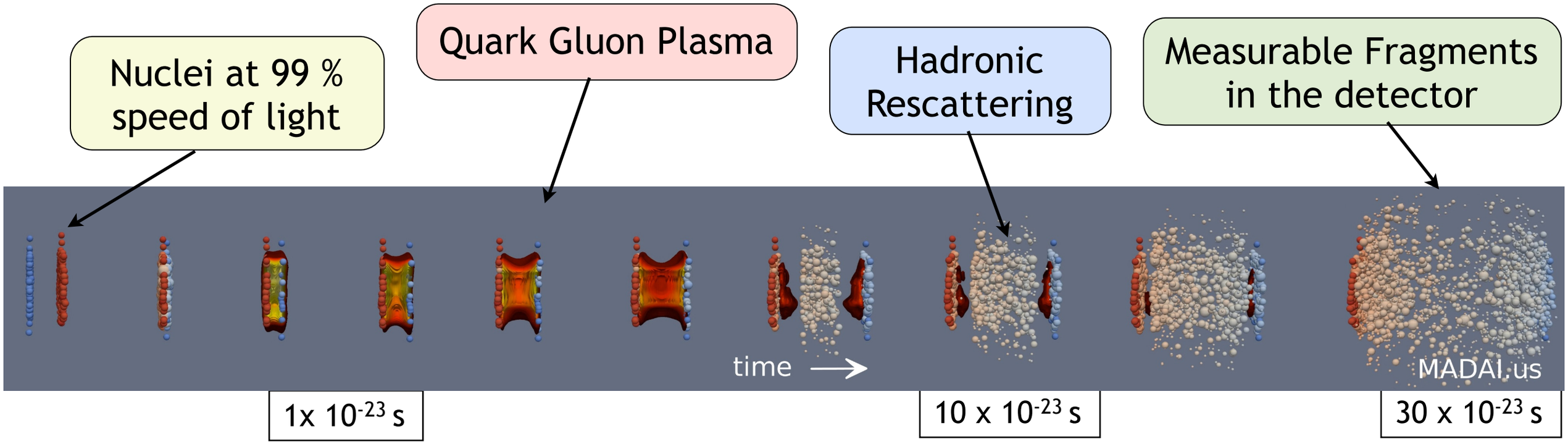
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Measurements in the detector (FAIR)



- **Theoretical models** are essential to gain insights about the properties of the quark gluon plasma, since the short timescale and small volume do not allow for a direct observation

Time Evolution of Heavy Ion Collisions

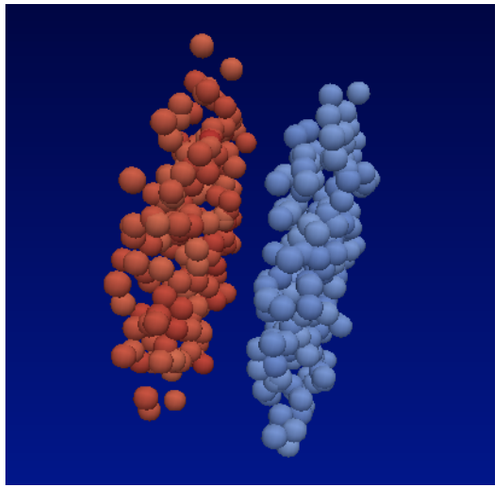


Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

Hybrid approaches are very successful for the description of the dynamics

HP, special issue JPG, arXiv:1404.1763

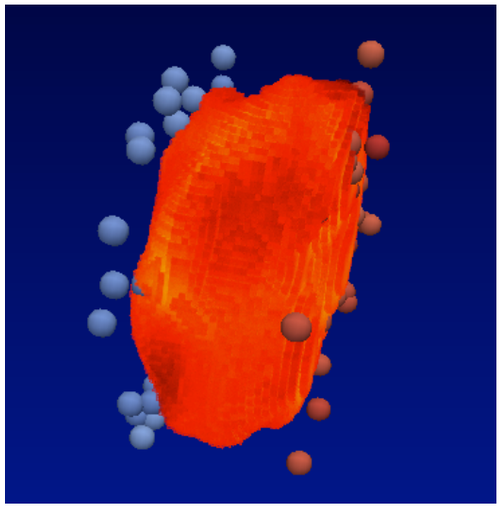
UrQMD Hybrid



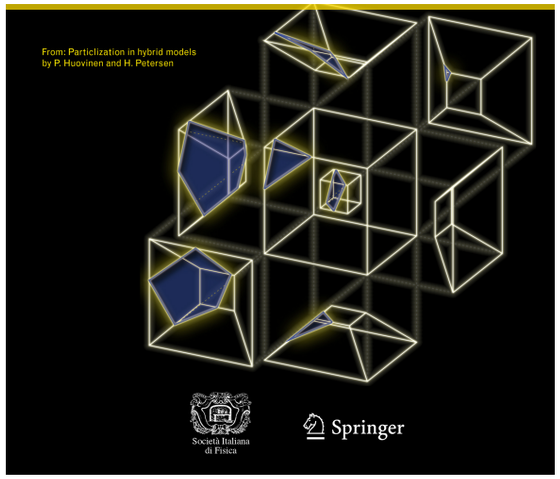
- Initial State:

H.P. et al, PRC78 (2008) 044901
P. Huovinen, H. P. EPJ A48 (2012) 171

  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally

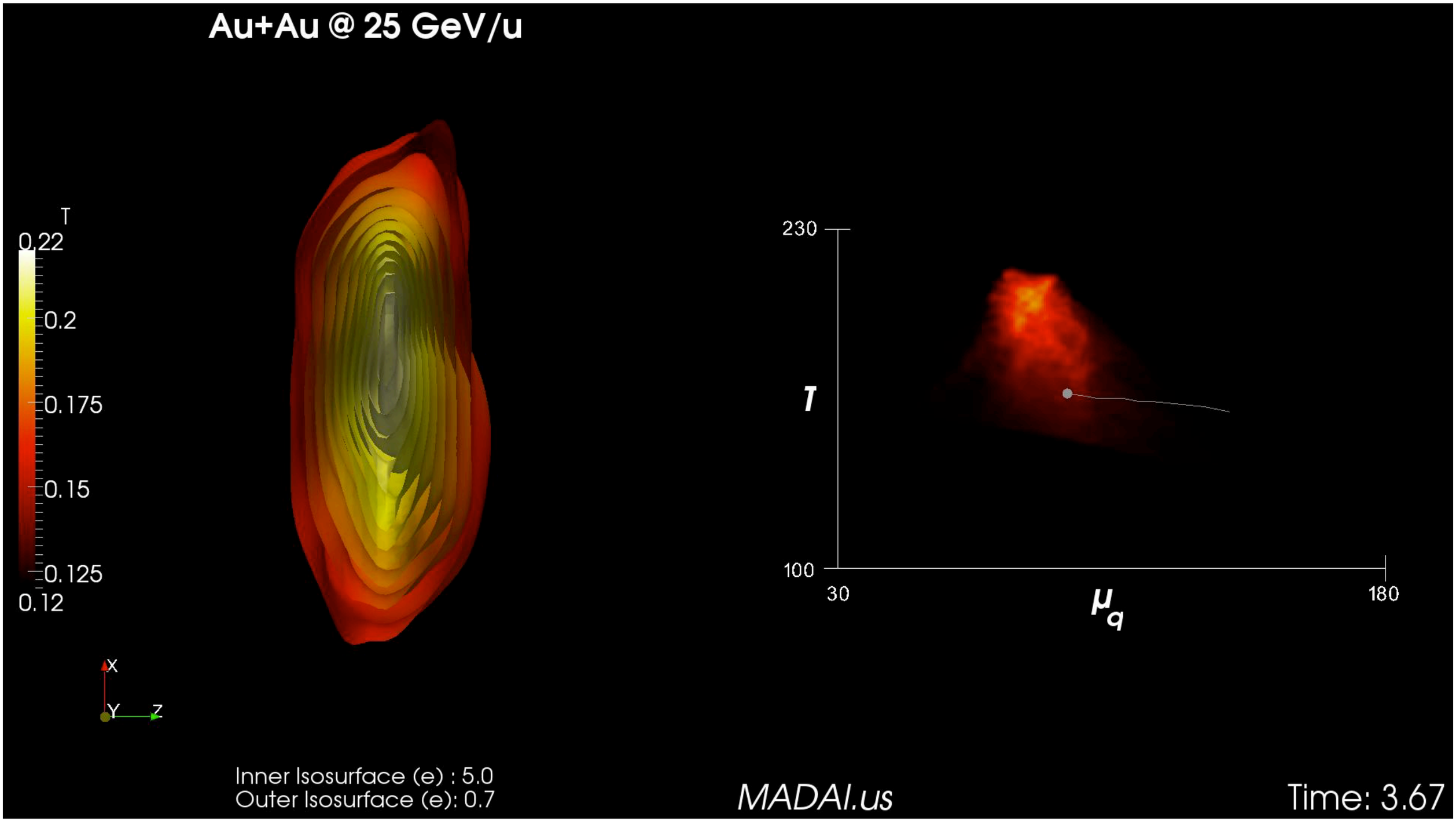


- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finit μ_B



- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within UrQMD

Au+Au @ 25 AGeV

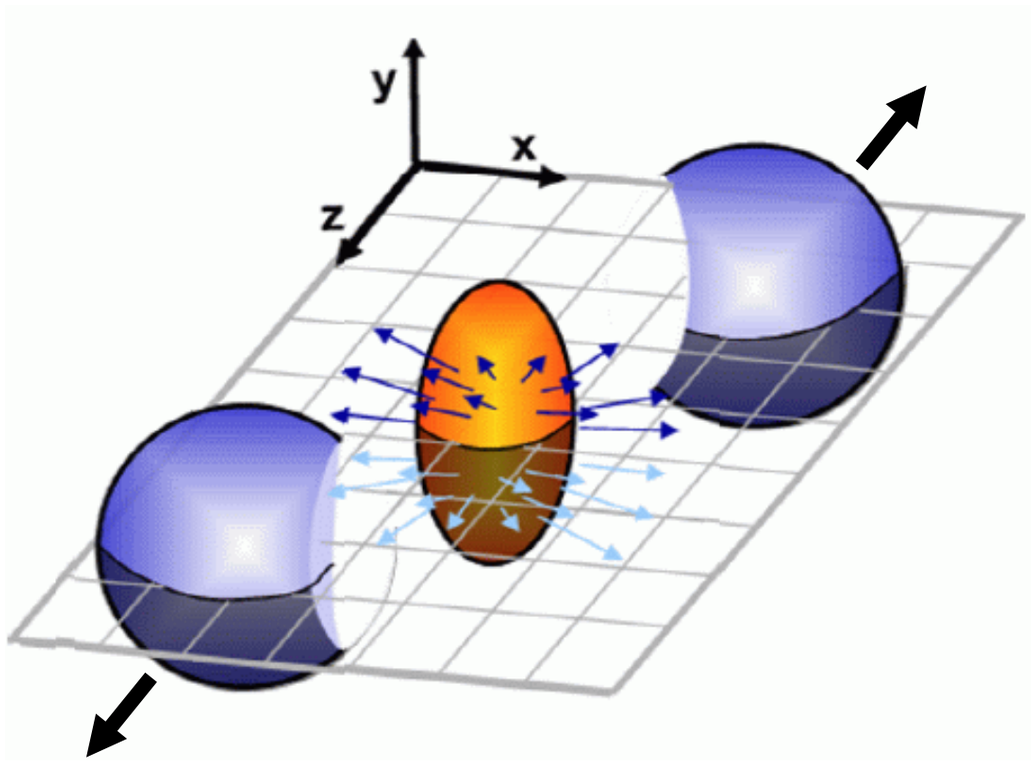

Au+Au @ 25 GeV/u
T
0.22
0.2
0.175
0.15
0.125
0.12
230
T
100
30
μ_q
180
X
Y
Z
Inner Isosurface (e) : 5.0
Outer Isosurface (e): 0.7
MADAI.us
Time: 3.67

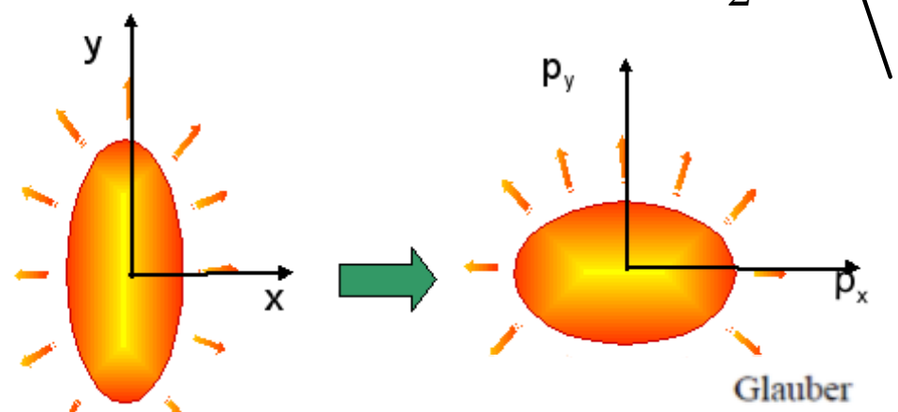
Elliptic Flow

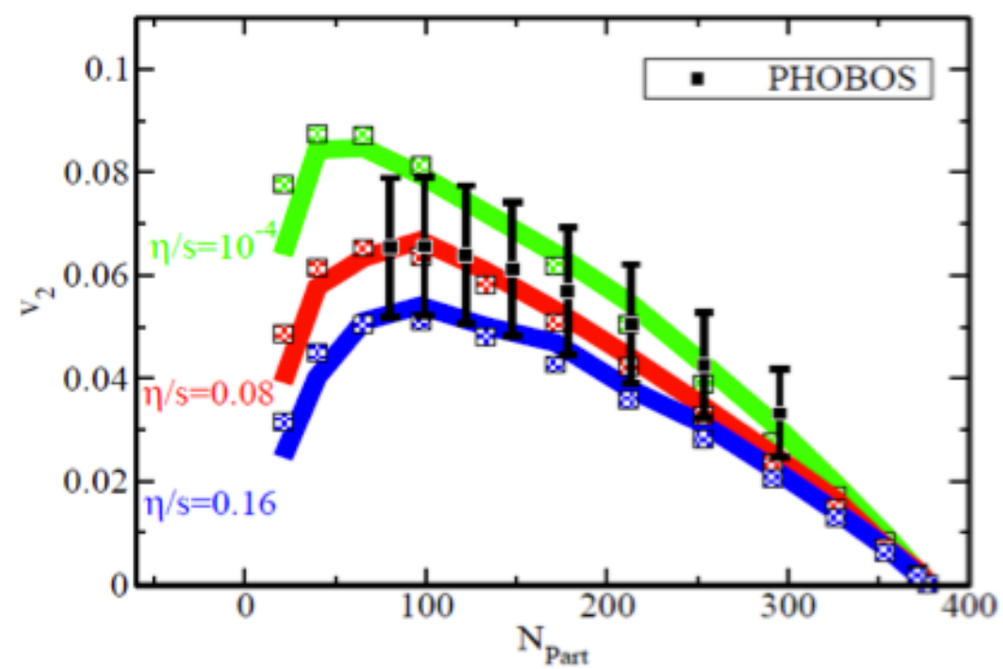
Elliptic Flow

Second coefficient of the Fourier expansion of the azimuthal particle distribution:

$$v_2 = \left\langle \left(\frac{p_x^2 - p_y^2}{p_T^2} \right) \right\rangle$$







M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

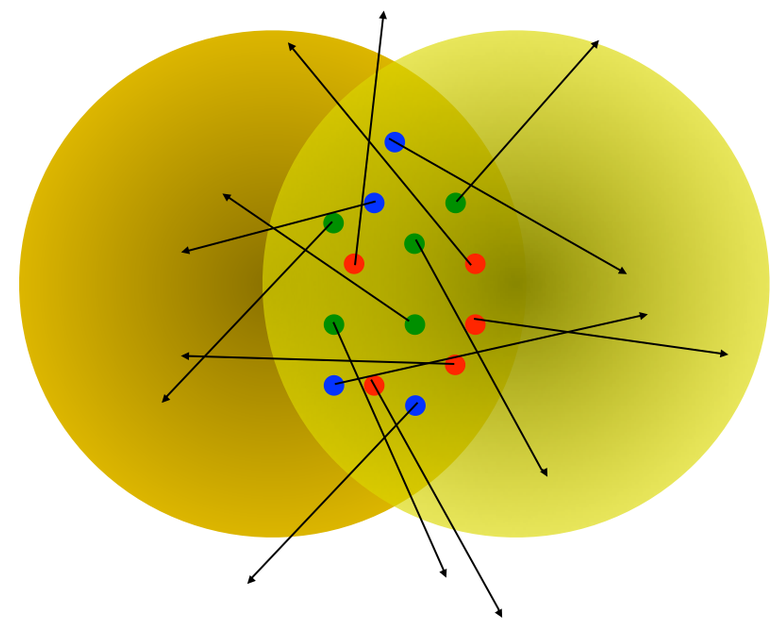
Coordinate space asymmetry
→ momentum space **anisotropy**

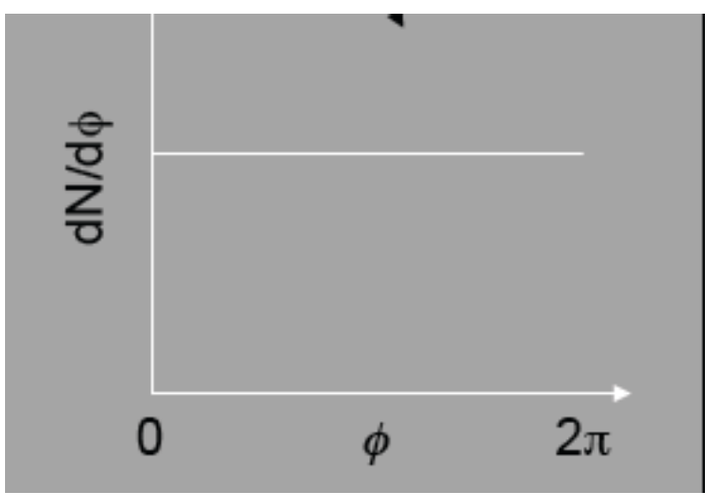
Relativistic fluid dynamics with very **low viscosity** describes elliptic flow at RHIC (and LHC)

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path λ→∞





Spatial anisotropy

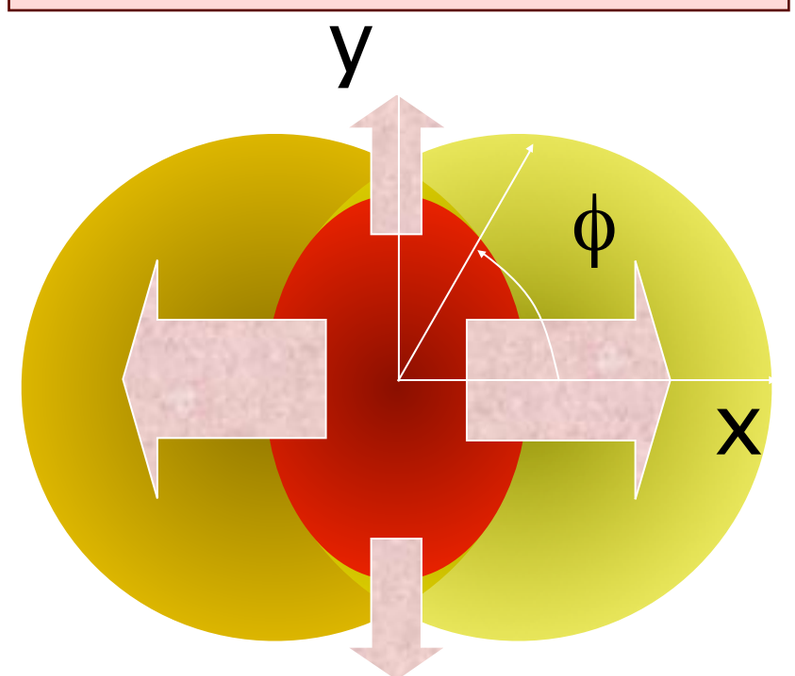
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

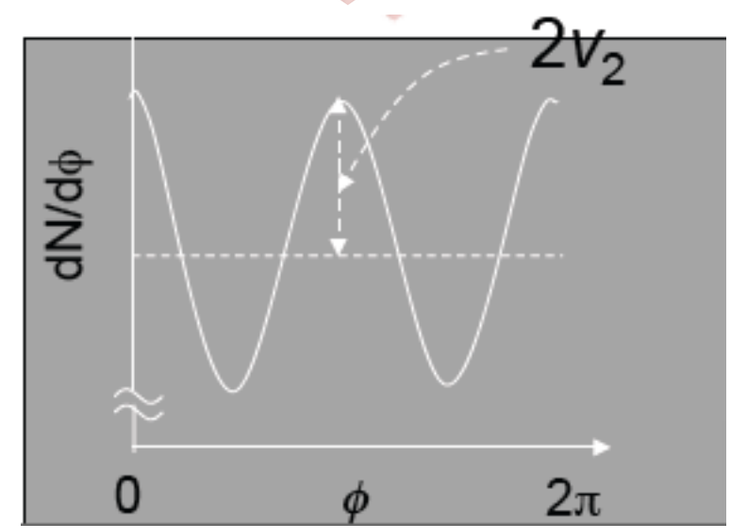
Interactions between particles

Momentum anisotropy

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

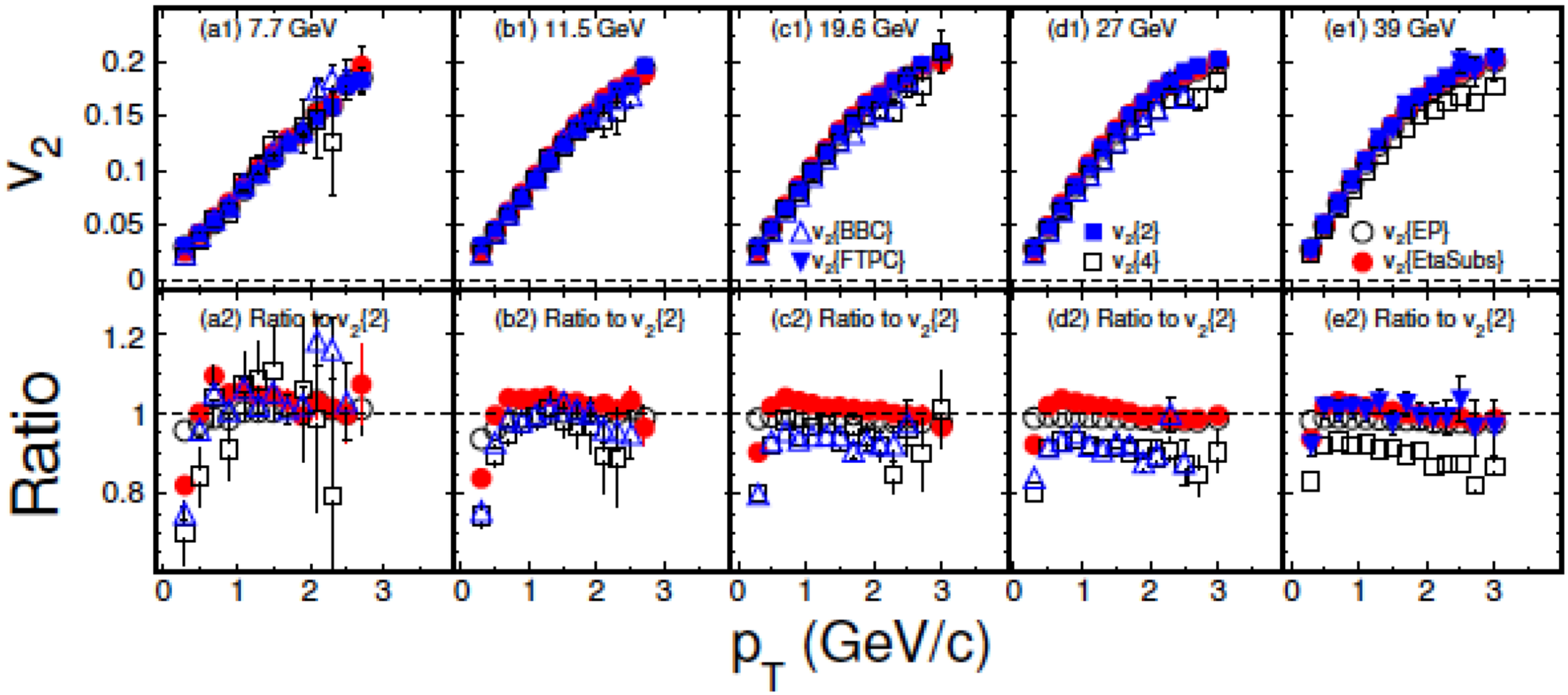
Hydrodynamic behaviour
mean free path λ→0





RHIC Beam Energy Scan

- Flow observables considered as evidence for QGP formation - does it disappear at lower energies?

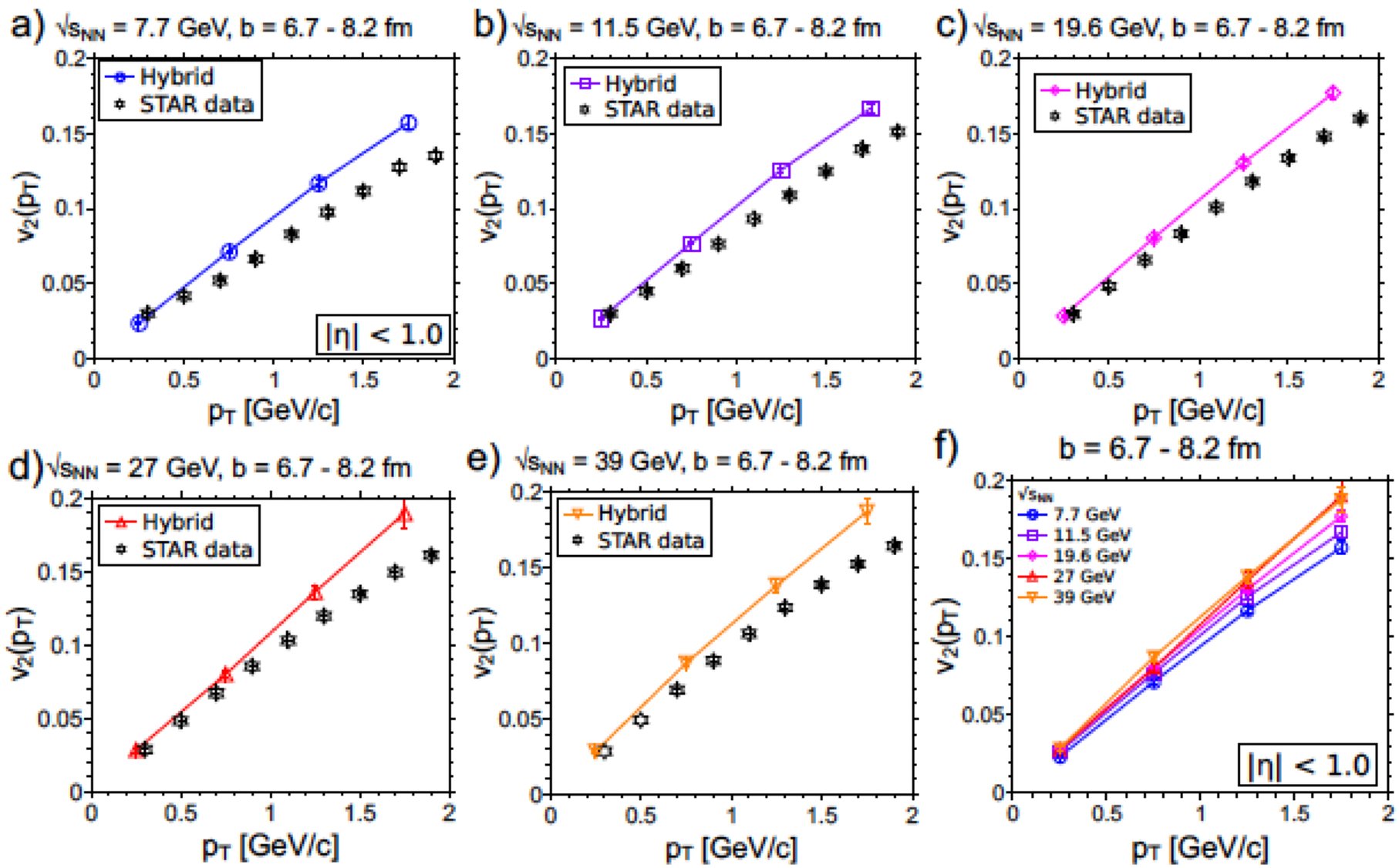


- Differential v_2 for charged hadrons almost identical for all beam energies

STAR, PRC 86 (2012) 054908

Differential Elliptic Flow

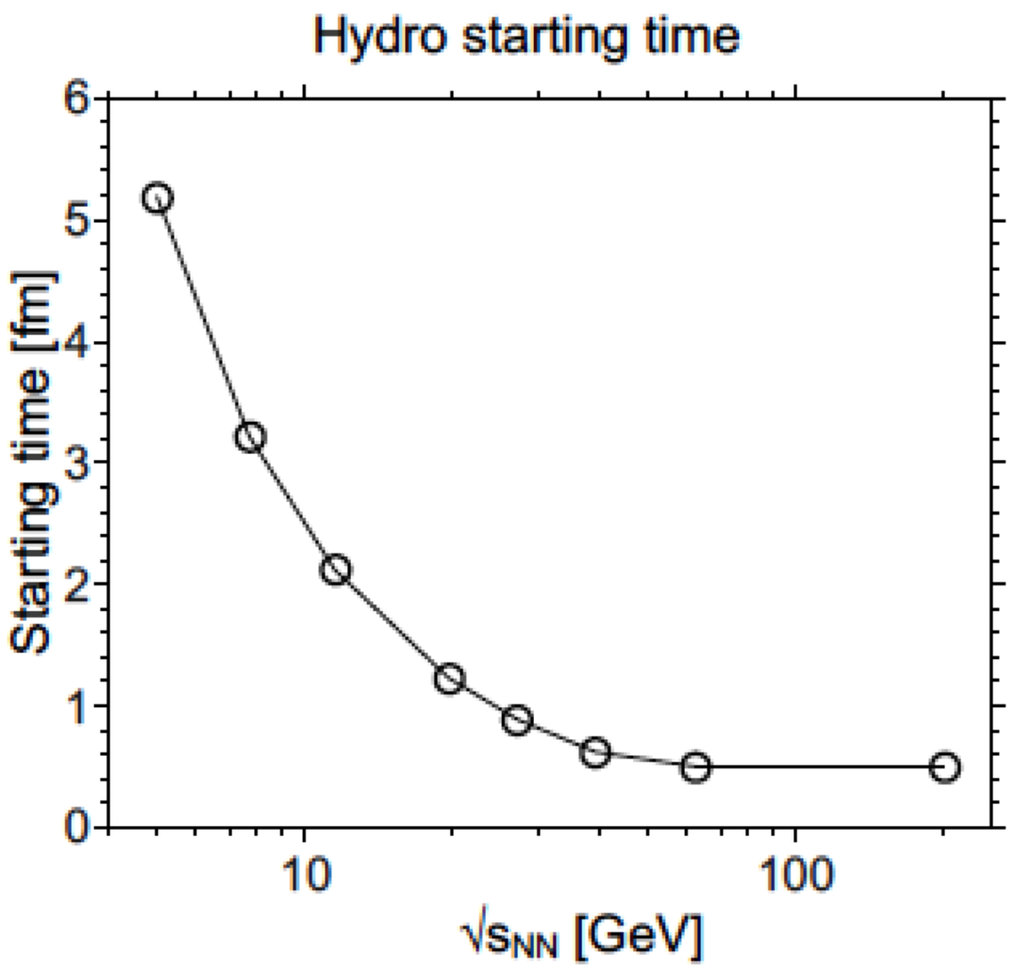
- Hybrid approach reproduces small energy dependence

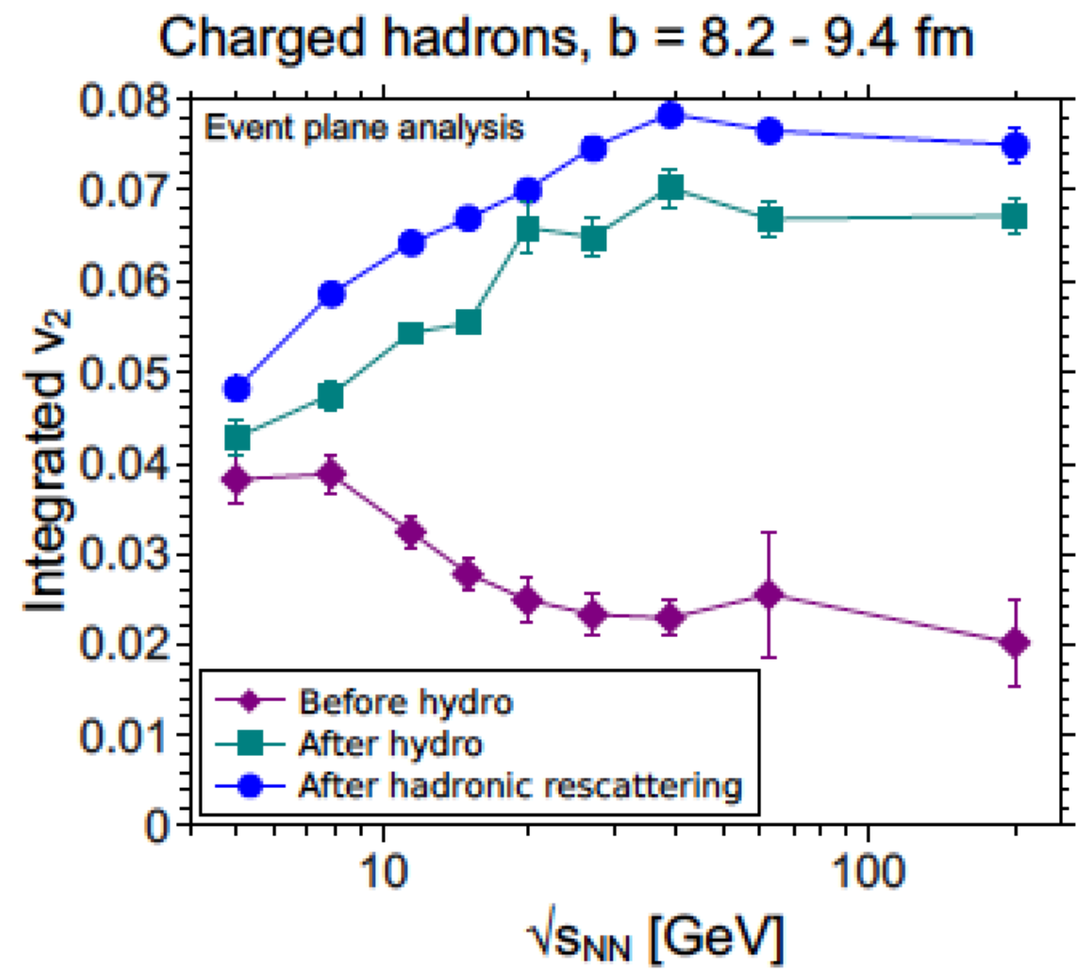


- Overestimation at higher p_T due to missing viscosity
- Sensitive to particlization switching criterion

J. Auvinen and HP, arXiv:1310.1764

Interplay of Hydro + Transport





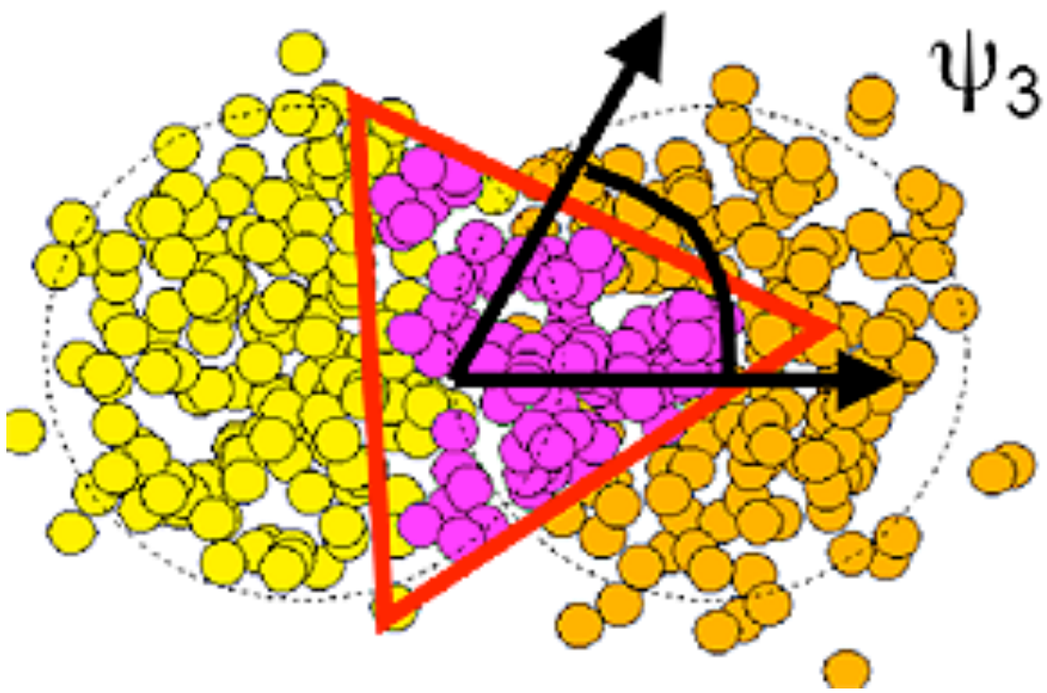
- Initial non-equilibrium evolution compensates for diminished hydrodynamic stage at lower beam energies
- Contribution of late stage hadronic rescattering ~10%

J. Auvinen and HP, arXiv:1310.1764

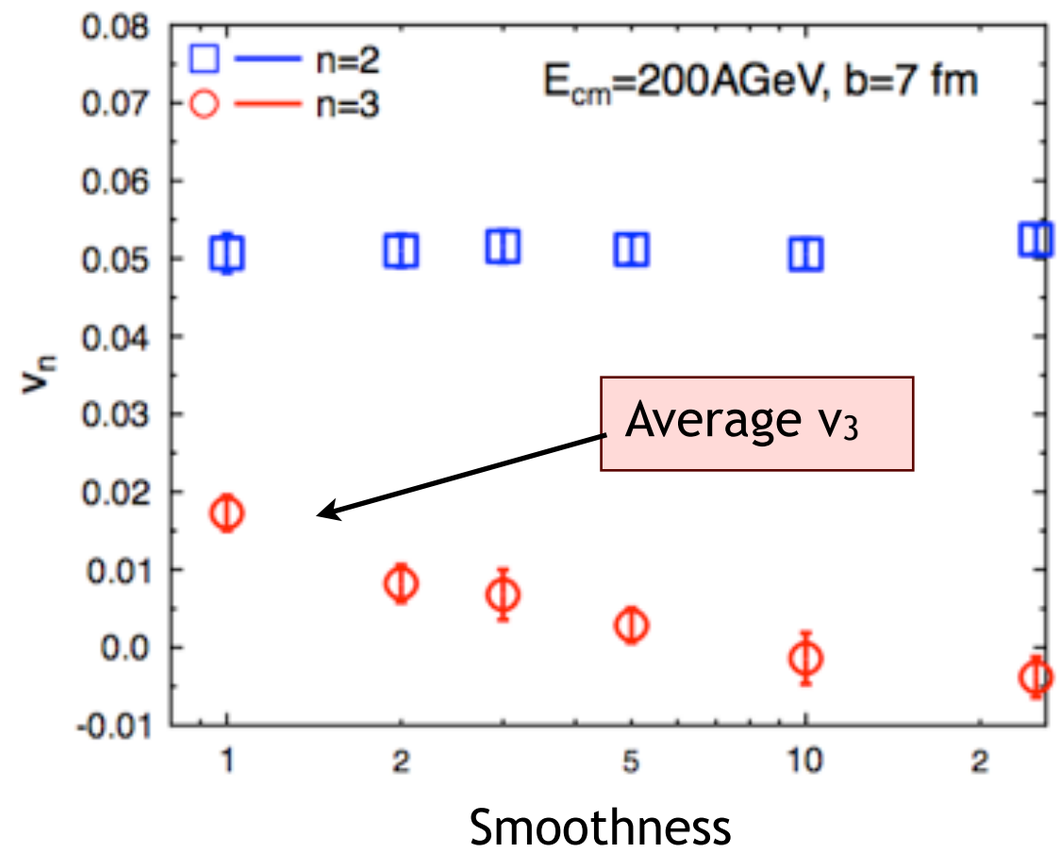
Triangular Flow

Triangular Flow

Initial State Fluctuations



Third Harmonic Coefficient



HP et al, JPG G39 (2012)

- Fluctuations introduce **higher order flow coefficients** that have been observed at the RHIC and LHC experiments
- A chance to disentangle initial state fluctuations from other e-by-e fluctuations related to phase transition?

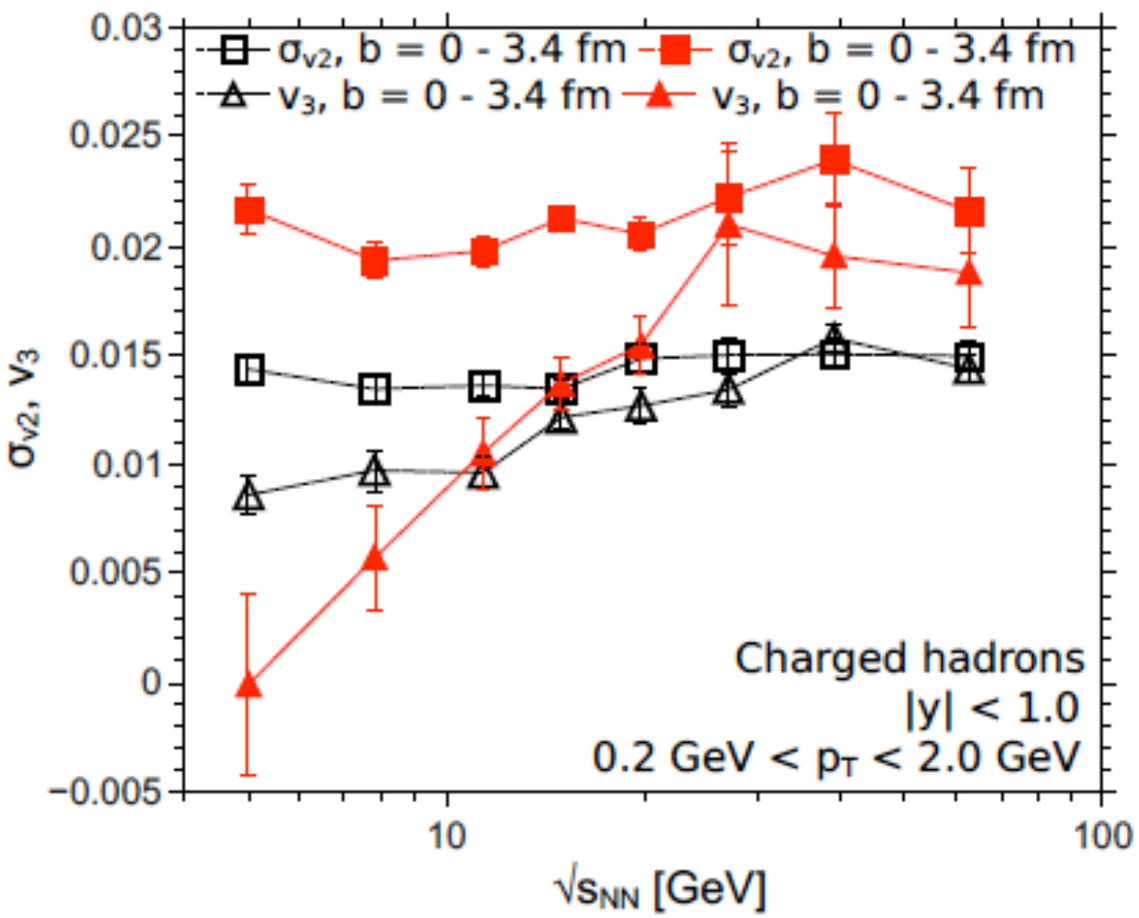
B. Alver and G. Roland, PRC 2010; Workshop summary: A. Adare, M. Luzum, HP, arxiv:1212.5388;

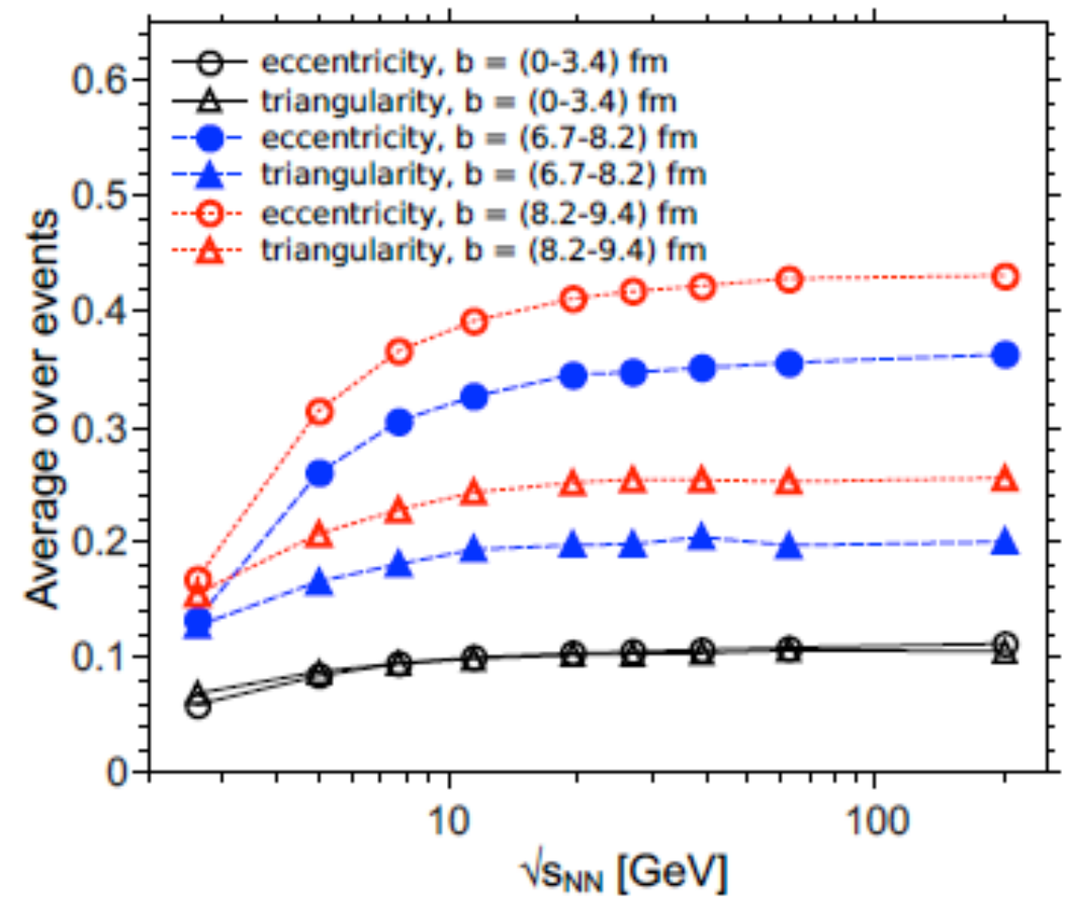
M. Luzum and HP arxiv:1312.5503 (to be published as IOP topical review)

Measuring Fluctuations

- At high energies:
  - v_3 is equal to σ_{v2}
- At lower energies v_3 vanishes

$$\sigma_{v2} = \sqrt{\frac{1}{2}(v_2\{\mathrm{EP}\}^2 - v_2\{\mathrm{RP}\}^2)}$$

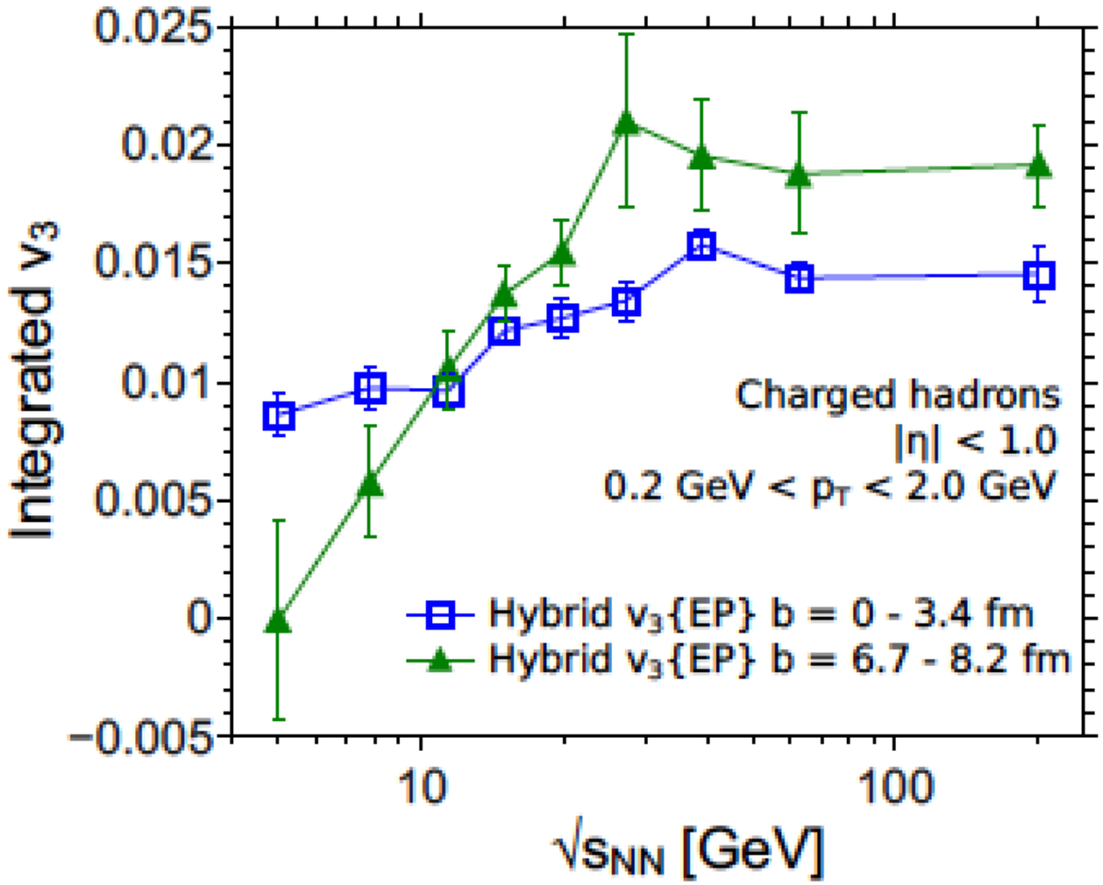


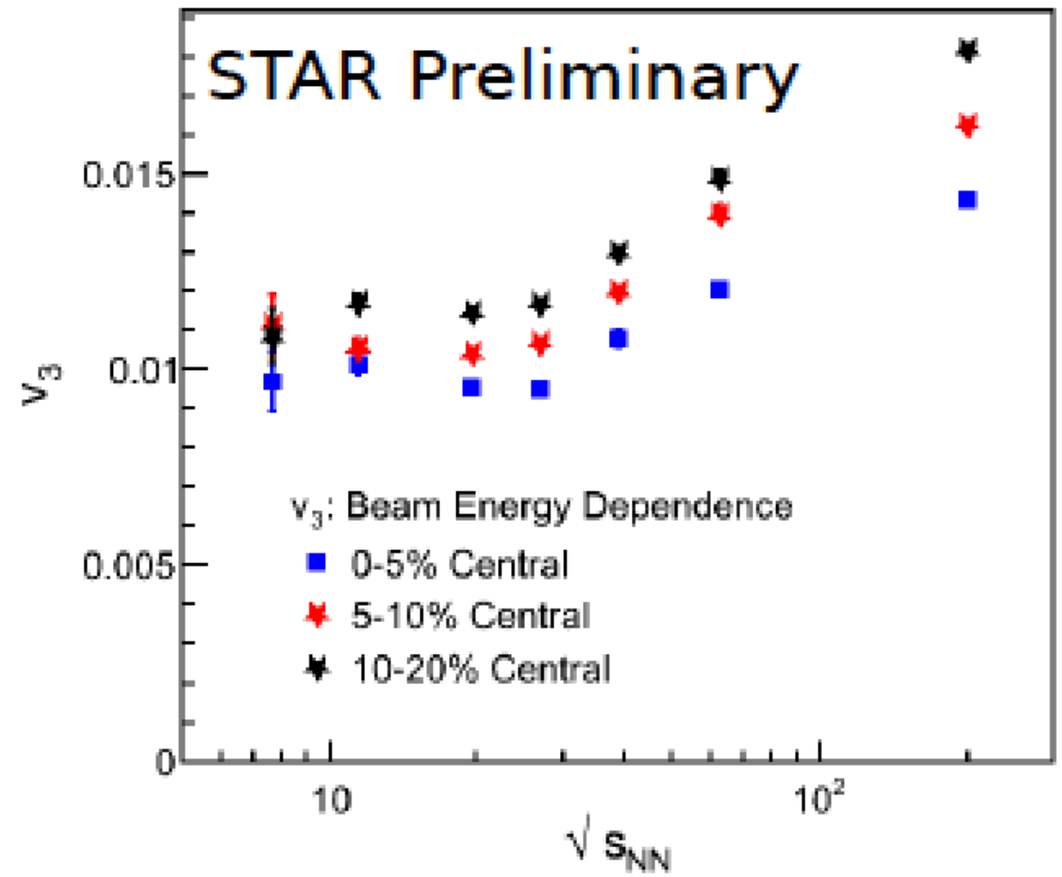


- Initial state geometry and fluctuations rather independent of beam energy

J. Auvinen and HP, arXiv:1310.1764

Triangular Flow

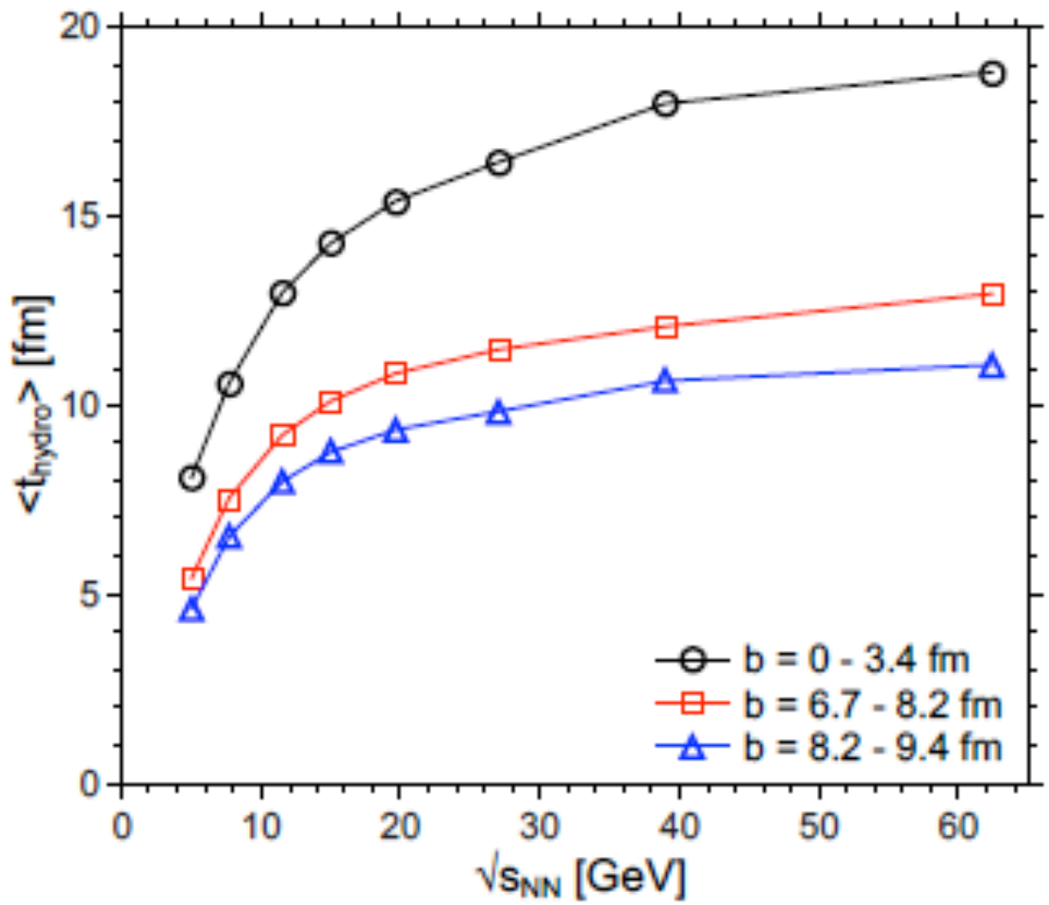


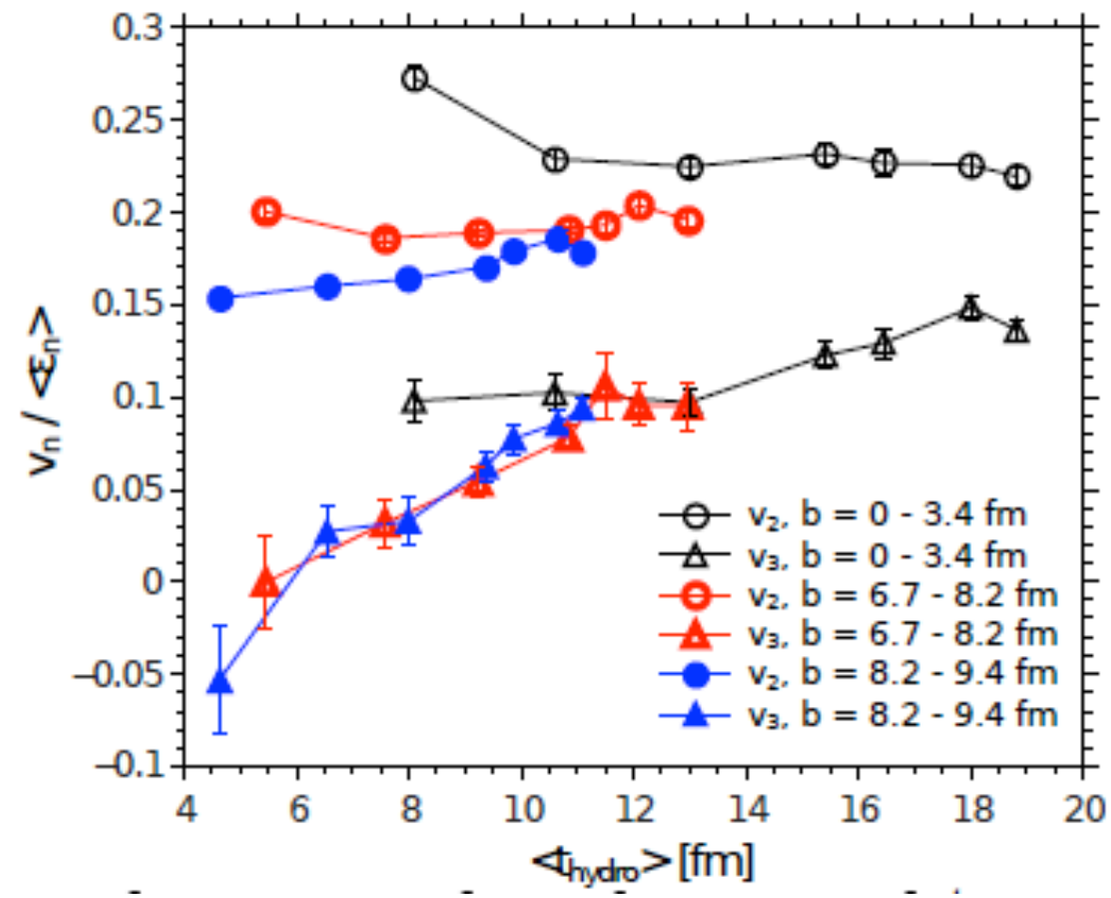


- Strong energy dependence in mid-central collisions
  - Transport not able to compensate for shortened hydro phase
- Agreement on the magnitude in central collisions

J. Auvinen and HP, arXiv:1310.1764

Sensitivity to ⟨t_{hydro}⟩





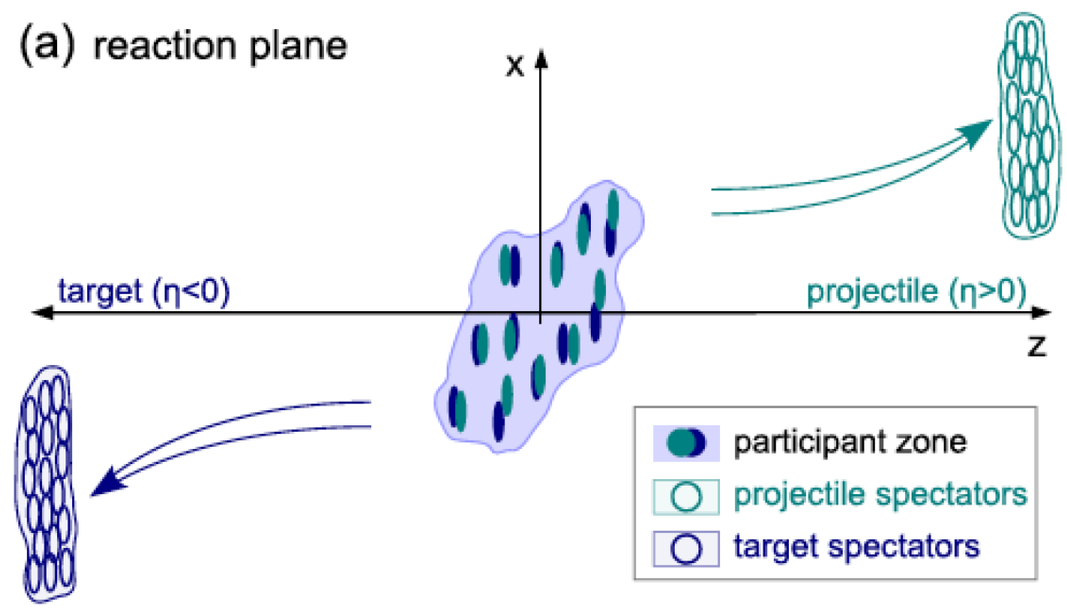
- v_3/ε_3 shows universal behaviour as a function of total duration of hydro phase
- v_2 does not follow scaling because of transport contribution

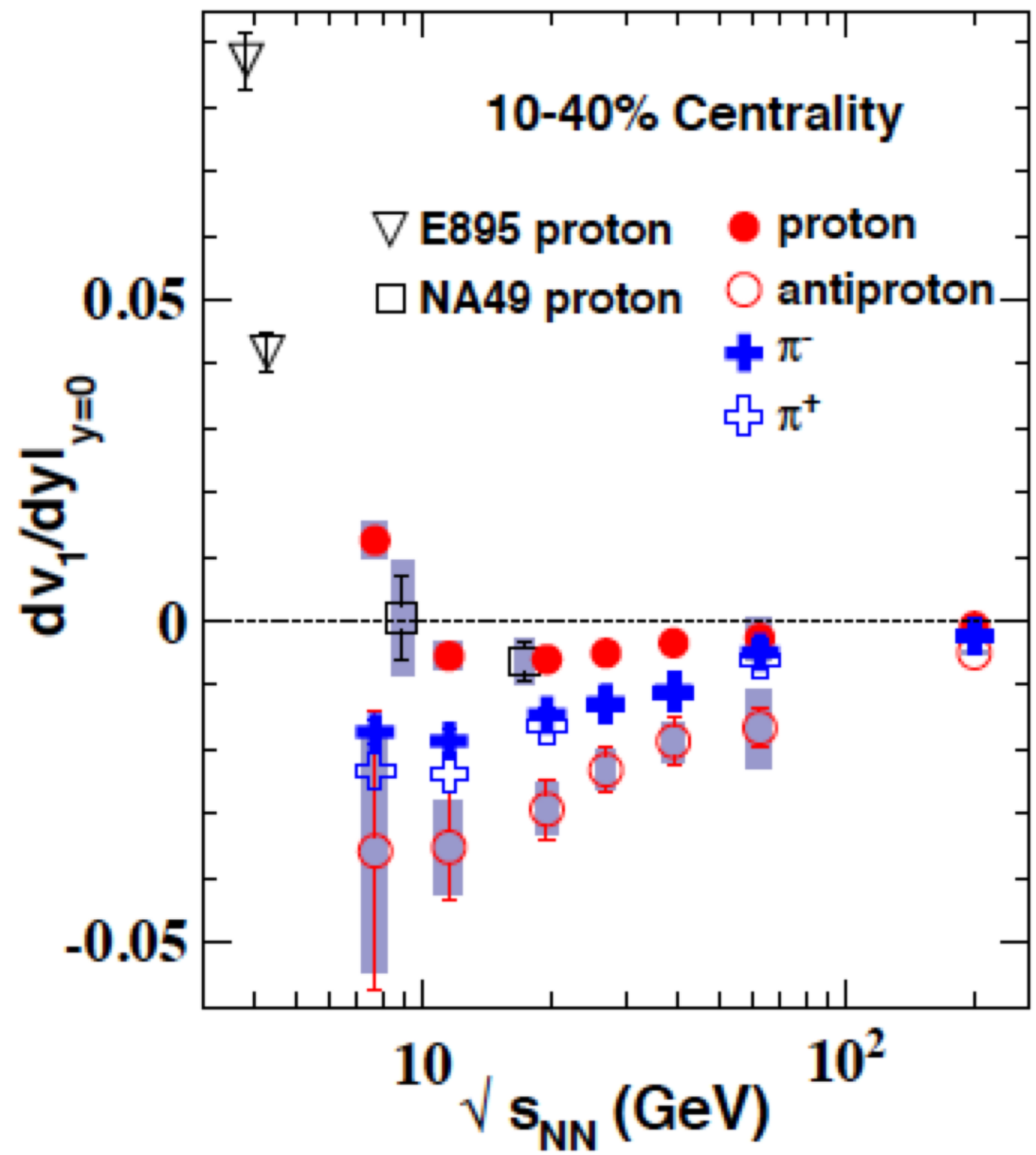
J. Auvinen and HP, arXiv:1310.1764

Directed Flow

Directed Flow

- Collective deflection of particles in reaction plane





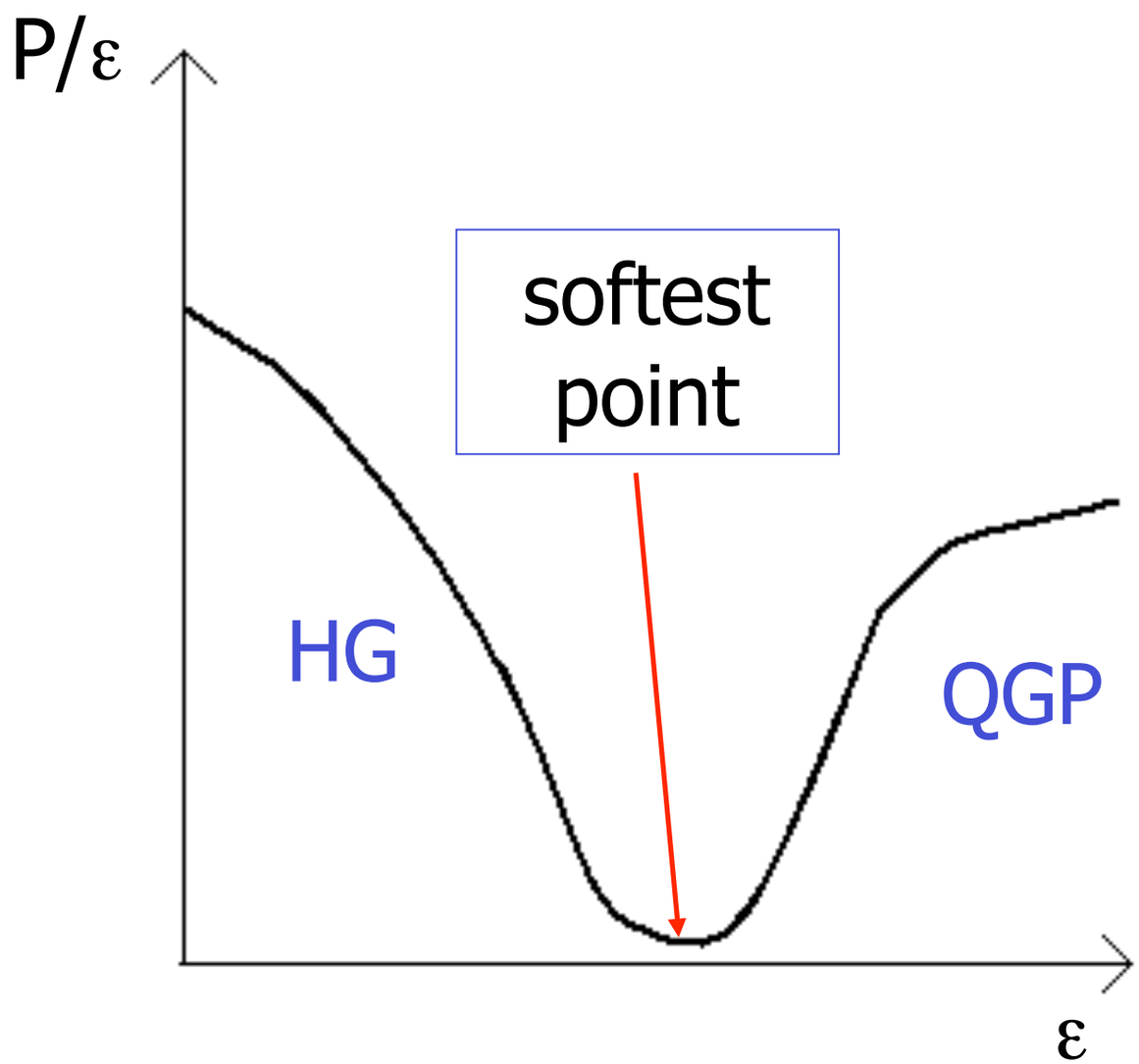
- Non-monotonic behavior of v1 slope
  - First order phase transition?

schematic view from ALICE, PRL 111, 232302 (2013)

STAR, arXiv:1401.3043

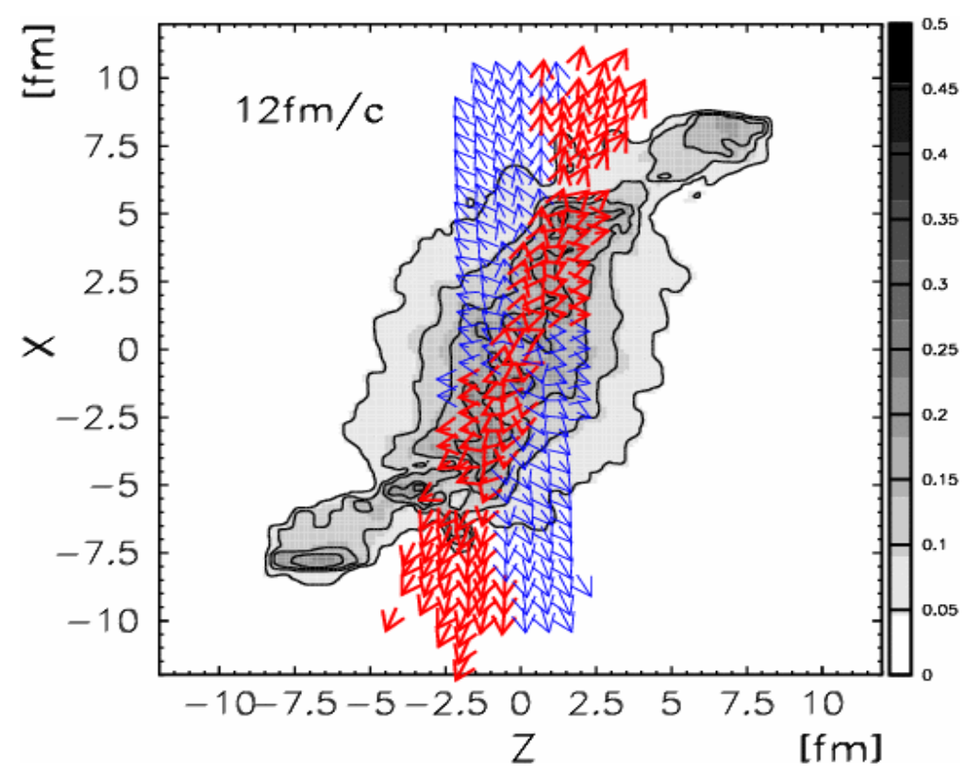
Equation of State

Schematic picture for a first order phase transition



Connection between pressure and flow via

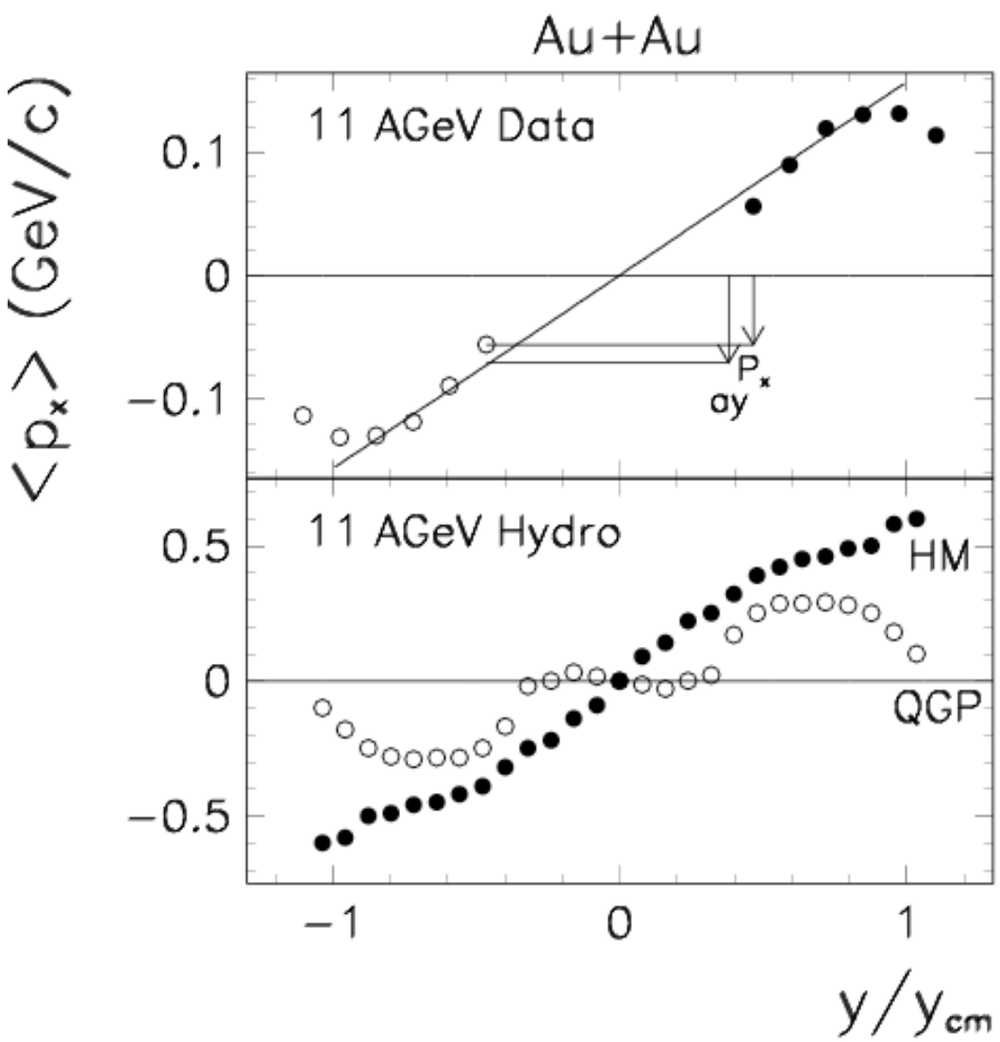
$$\vec{p_x} \sim \int_t \int_A P(\rho, \epsilon) dA dt$$

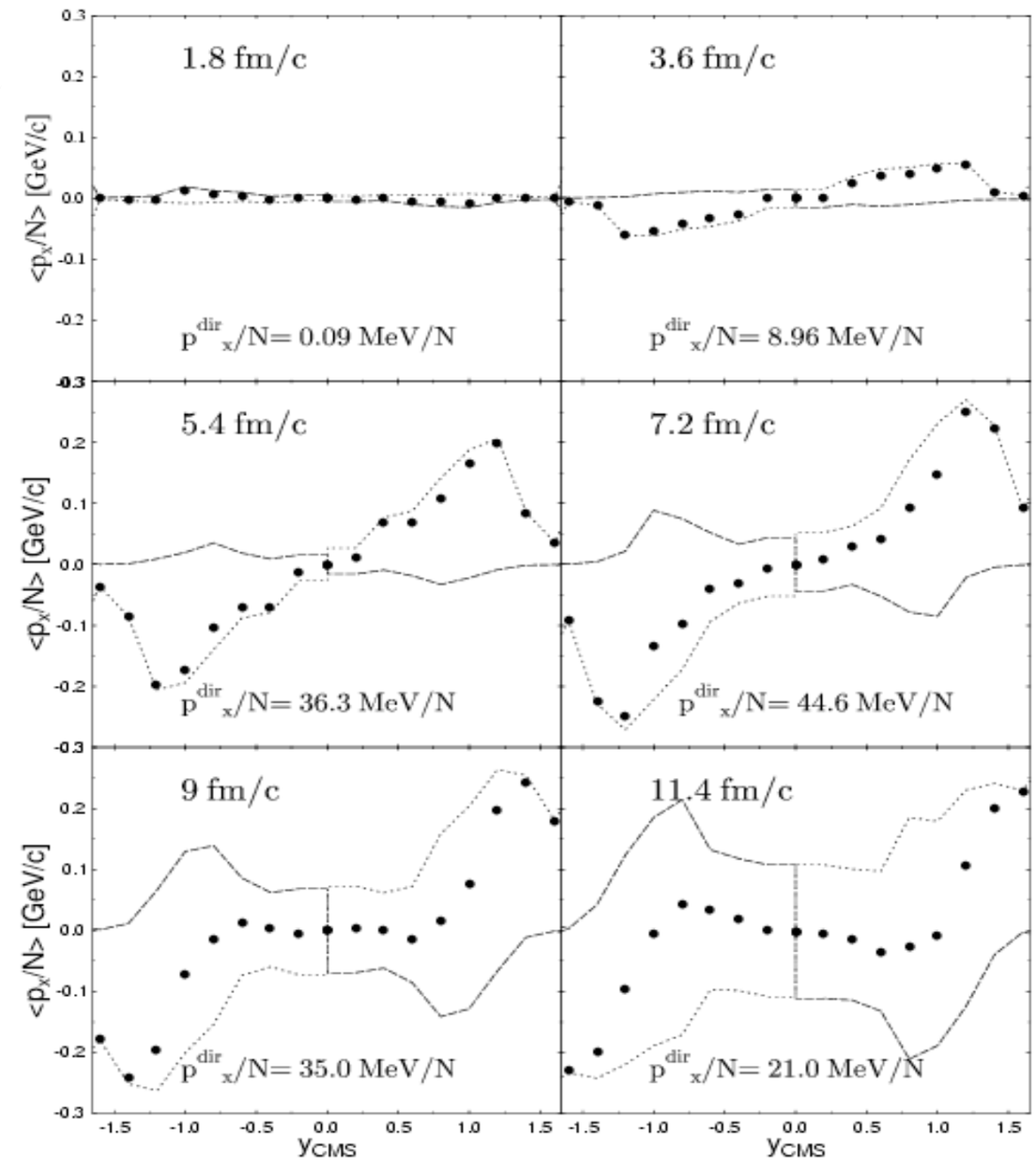


J.Brachmann et al., Phys.Rev. C, 61, 2000

Antiflow around Midrapidity

Prediction of antiflow,
if softening of the EoS leads to flow
in the „wrong“ direction





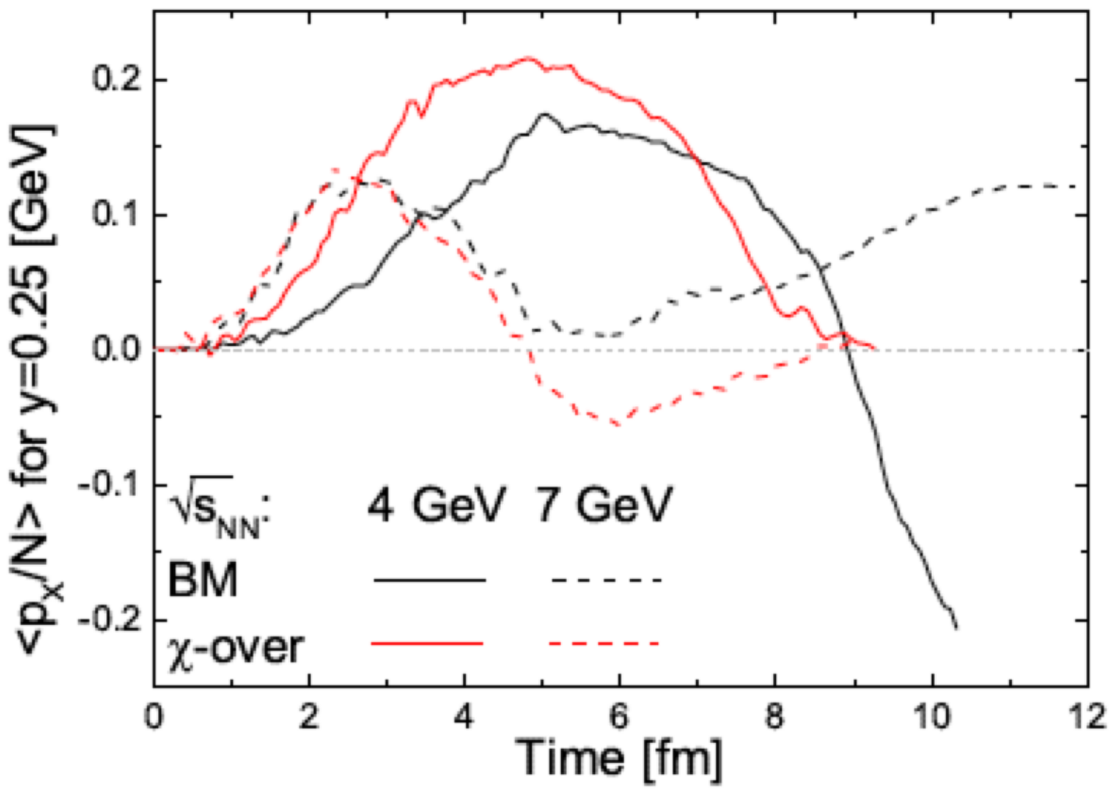
Note that this is all p_x^{dir}

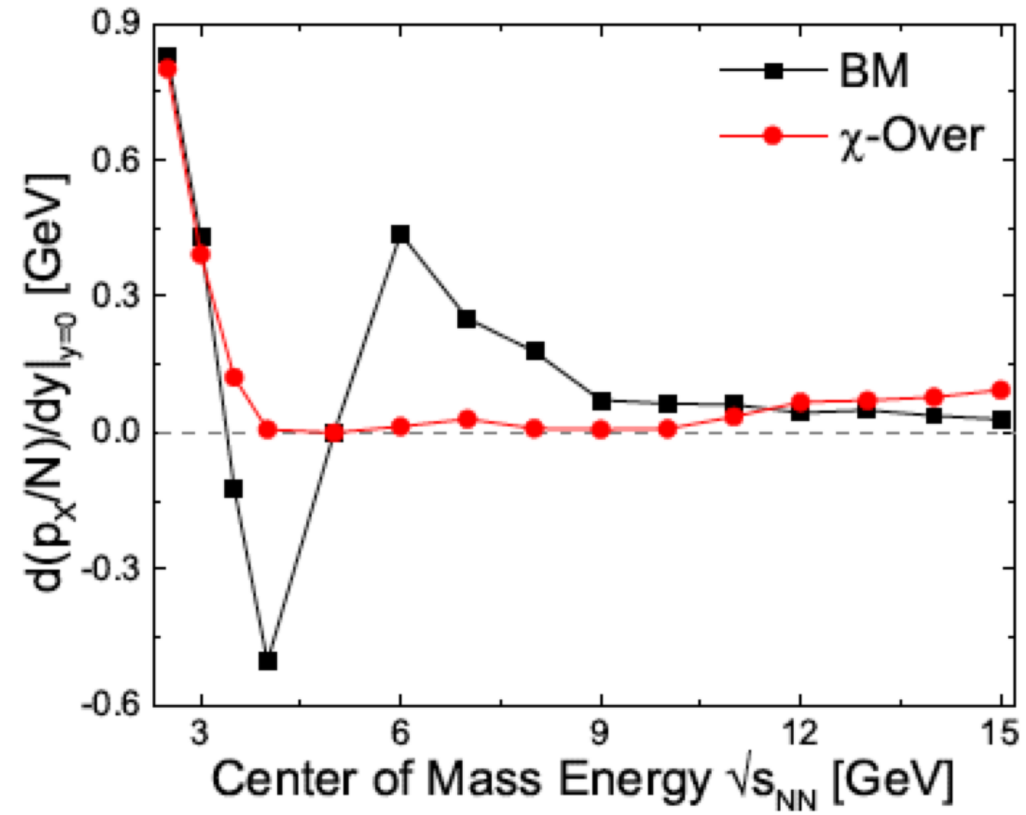
L.Csernai, Phys.Lett. B 458, 1999

J.Brachmann et al., Phys.Rev. C, 61, 2000

Fluid Calculation

- Negative slope is reproduced in fluid dynamic calculation

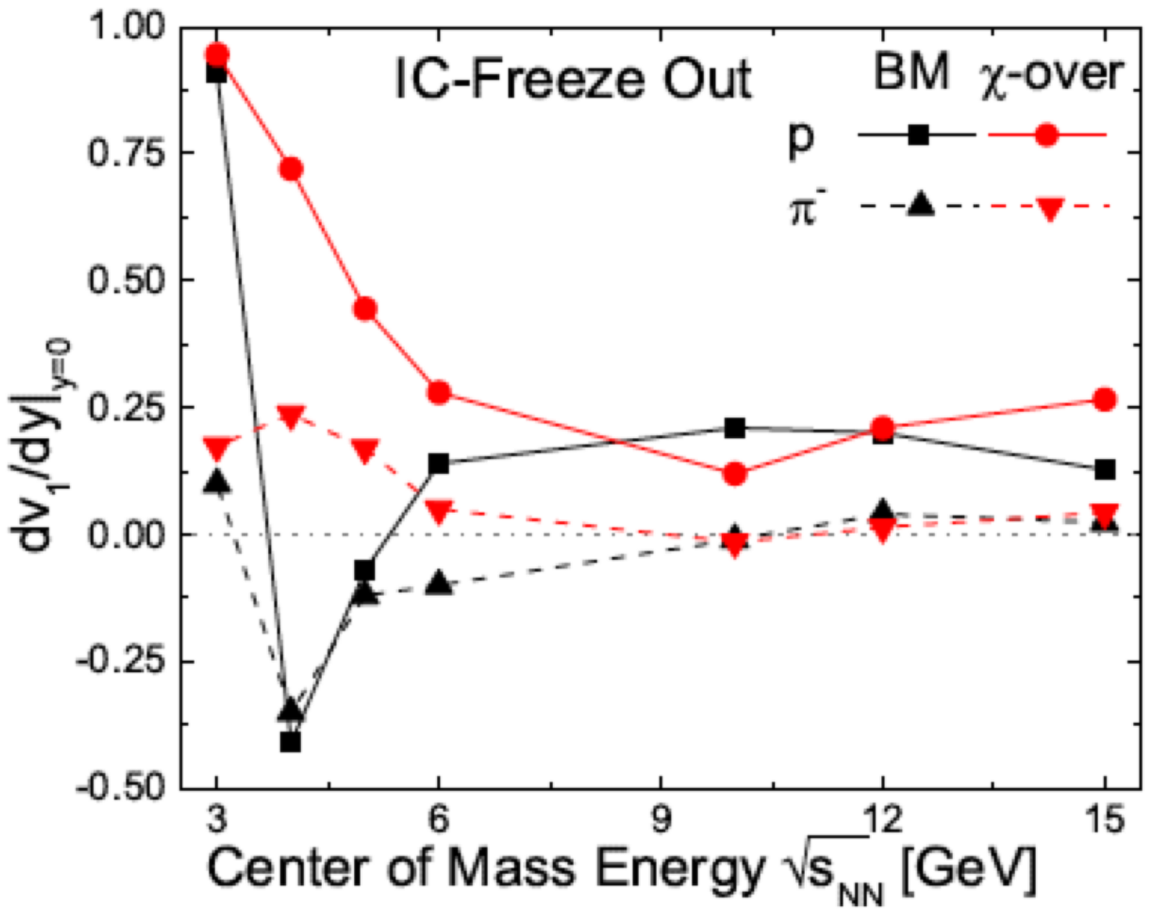


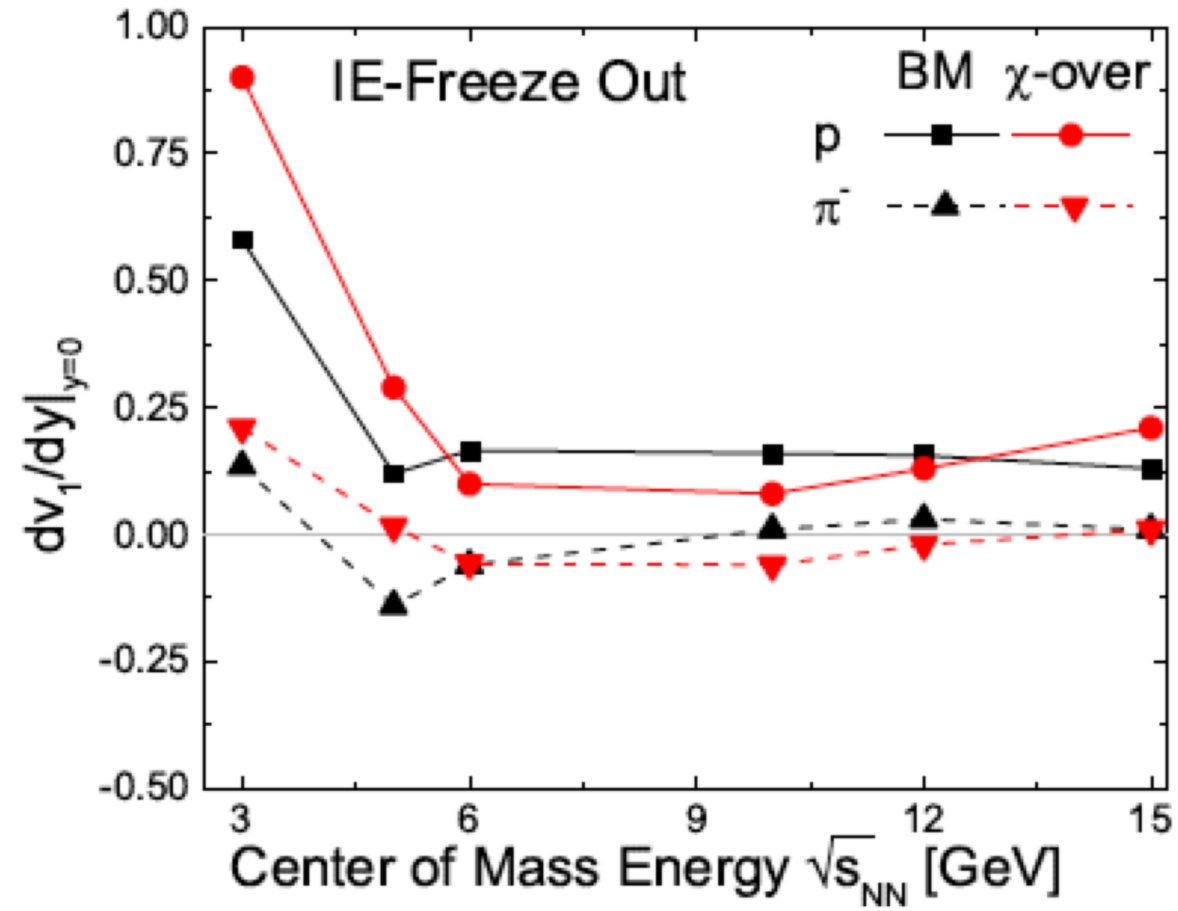


- Assumptions
  - Cold nuclear matter initialization (no pre-equilibrium transport)
  - Direct integration of momentum in x-direction without hadronic rescattering

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, arxiv:1402.7236

v1 Slope for Pions and Protons

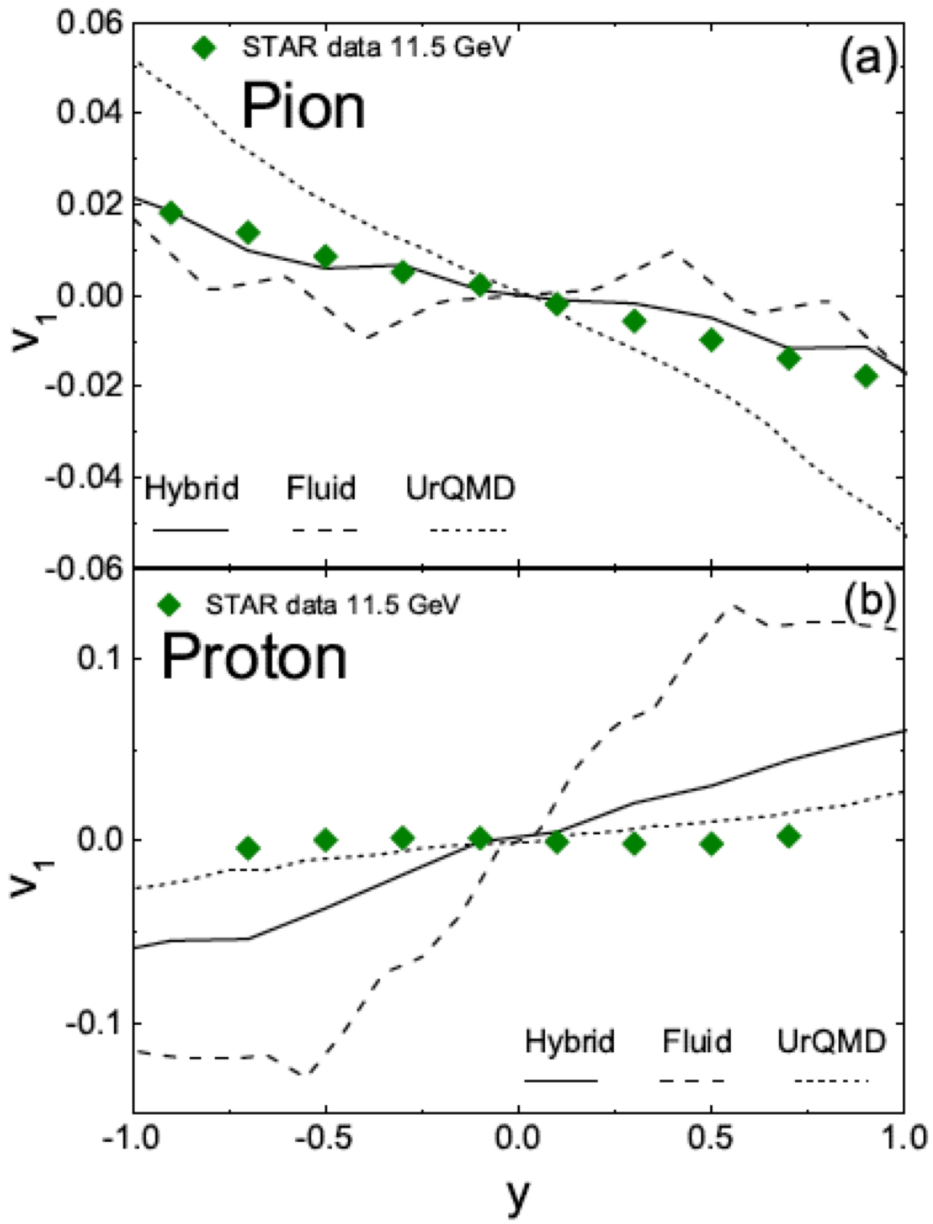


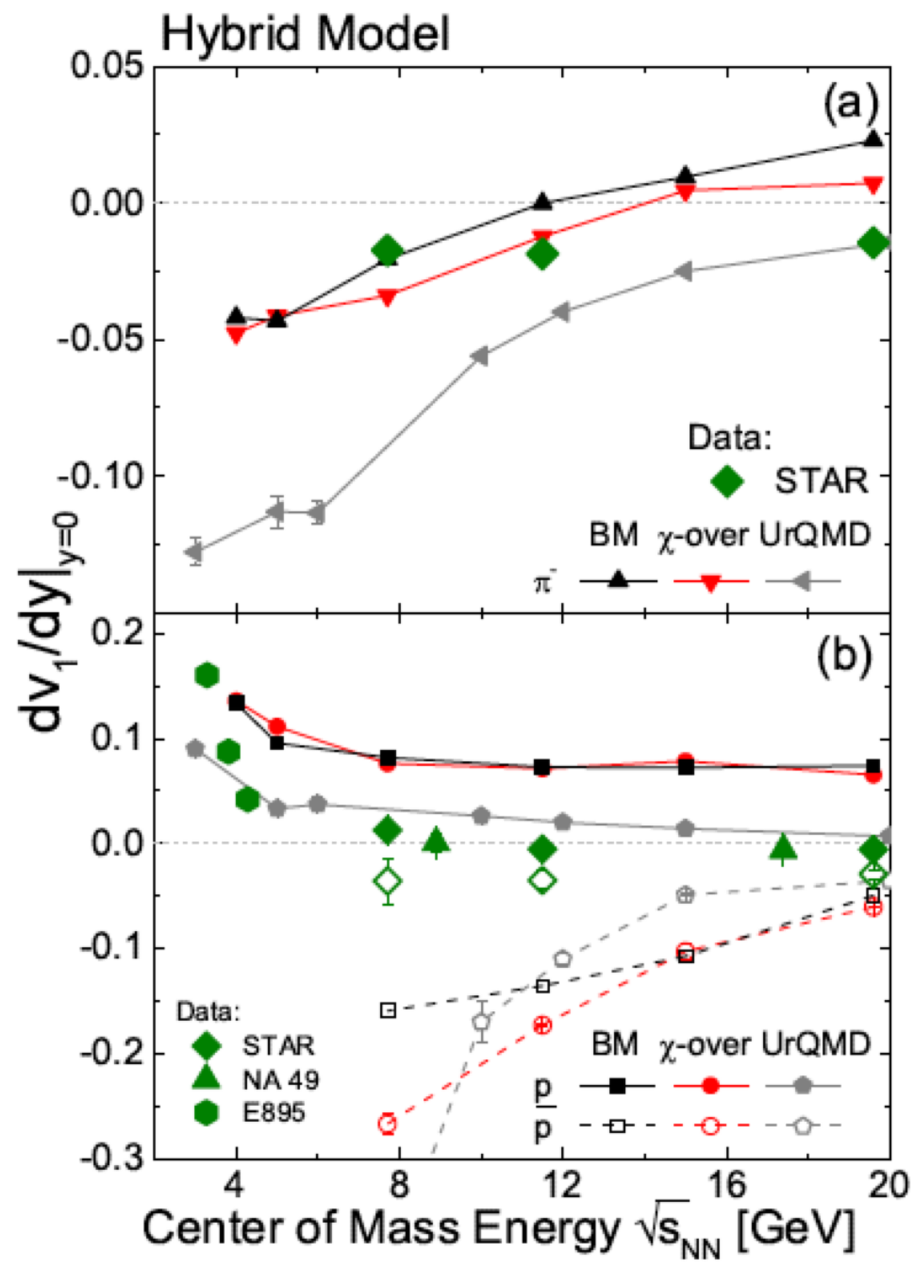


- Particlization added including hadronic rescattering
- Isochronous versus iso-energy density transition criterion
  - Drastic effect on dip structure

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, arxiv:1402.7236

Pions and Protons



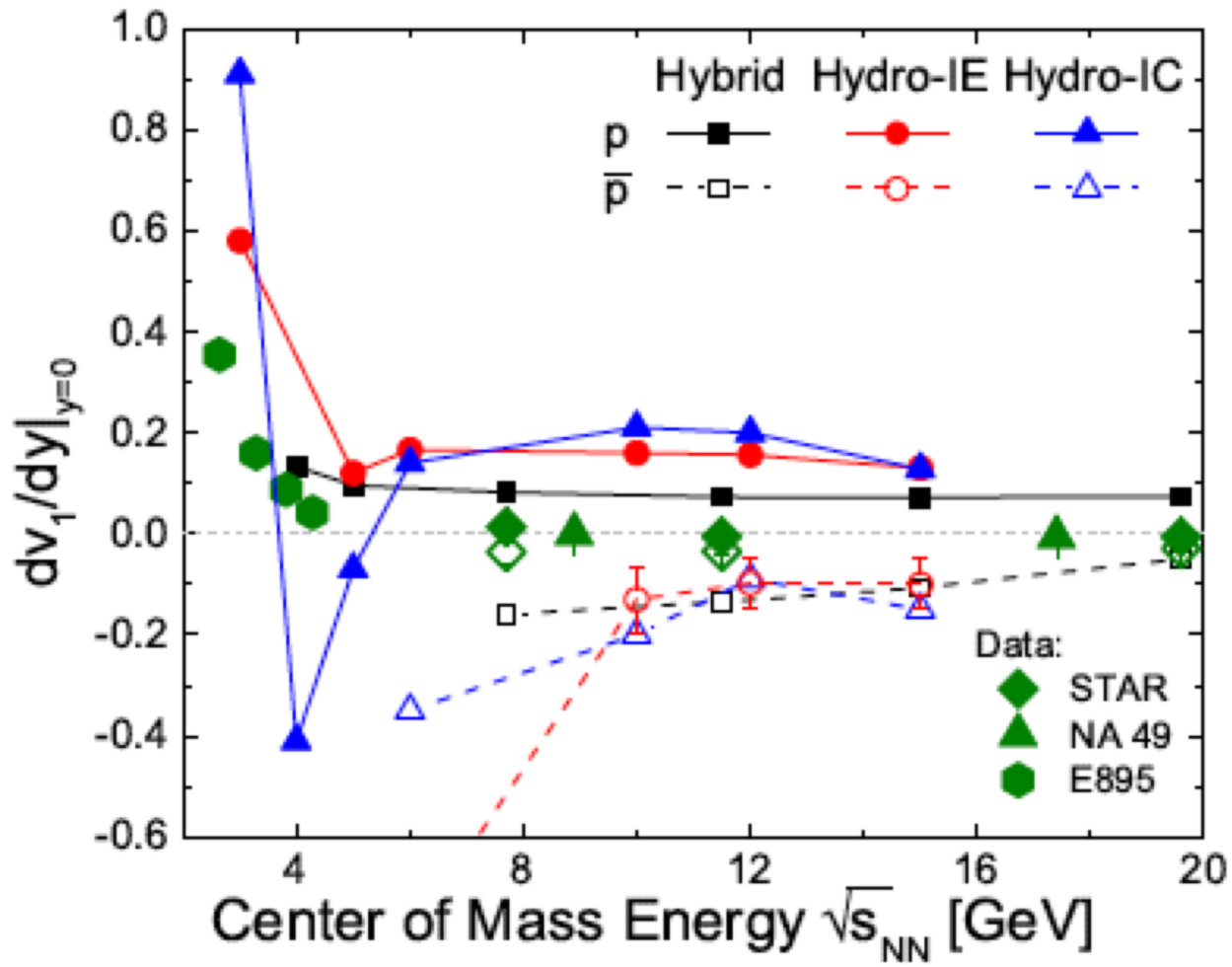


- More realistic hybrid approach does not show difference between first order phase transition and cross-over

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, arxiv:1402.7236

Comparison of Results

- Pure fluid with isochronous freeze-out shows dip at lower beam energies



- All other calculations show non-negative slope for all beam energies

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, arxiv:1402.7236

Summary

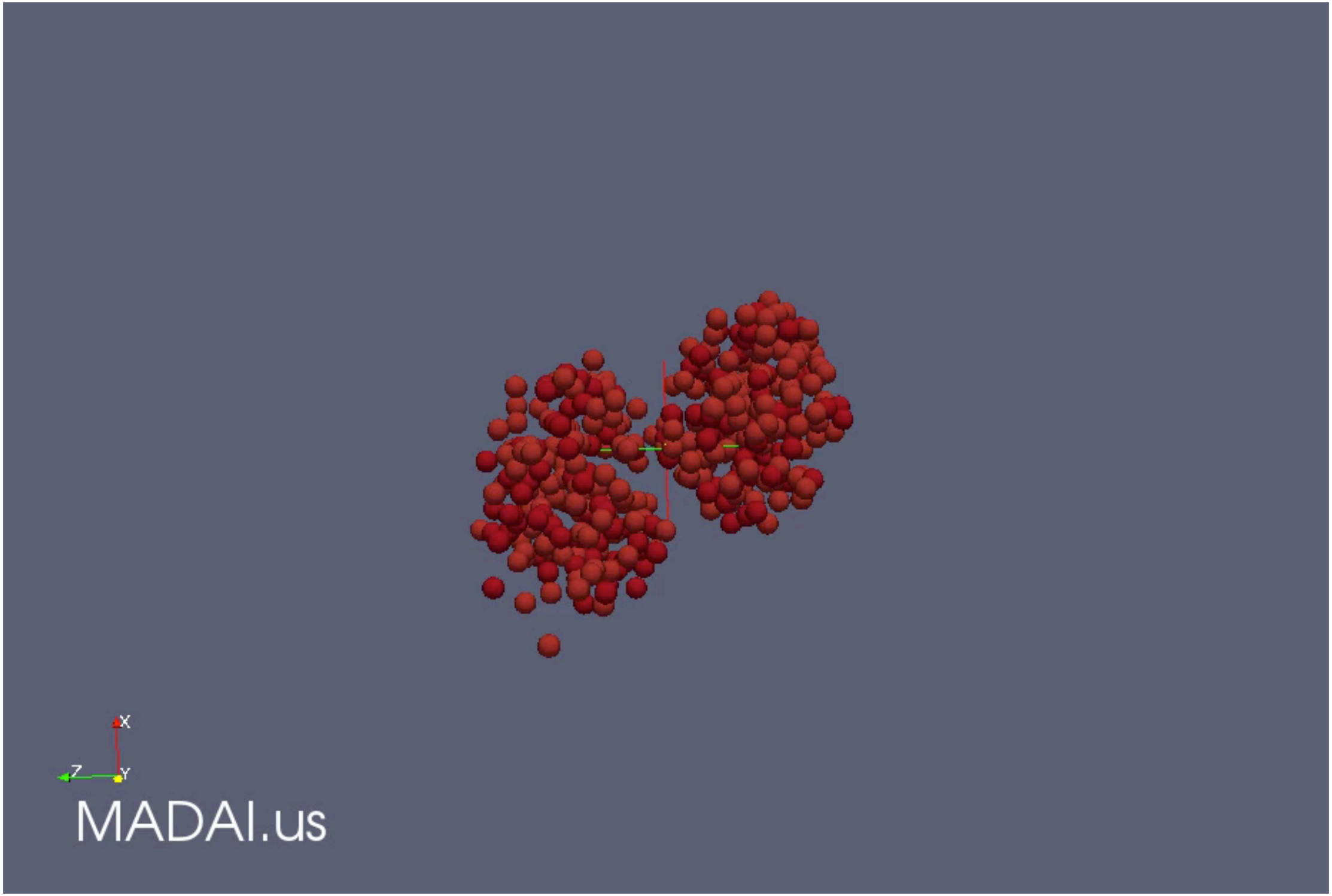
- Elliptic flow v_2 changes little as a function of beam energy; transport compensates for diminishing hydrodynamics
  - $v_2(p_T)$ overshoots the data; particlization condition might require adjustment (viscosity?)
- Triangular flow v_3 has much more notable energy dependence,
  - v_3 is the better indicator of the presence of low-viscous fluid
  - Chance to constrain initial state fluctuations (remove background for other e-by-e fluctuation measures)
- Directed flow v_1 found insensitive to the order of phase transition in hybrid approach
  - Old predictions can be reproduced
  - Rapidity slopes overestimated compared to STAR data

Outlook

New Transport Approach

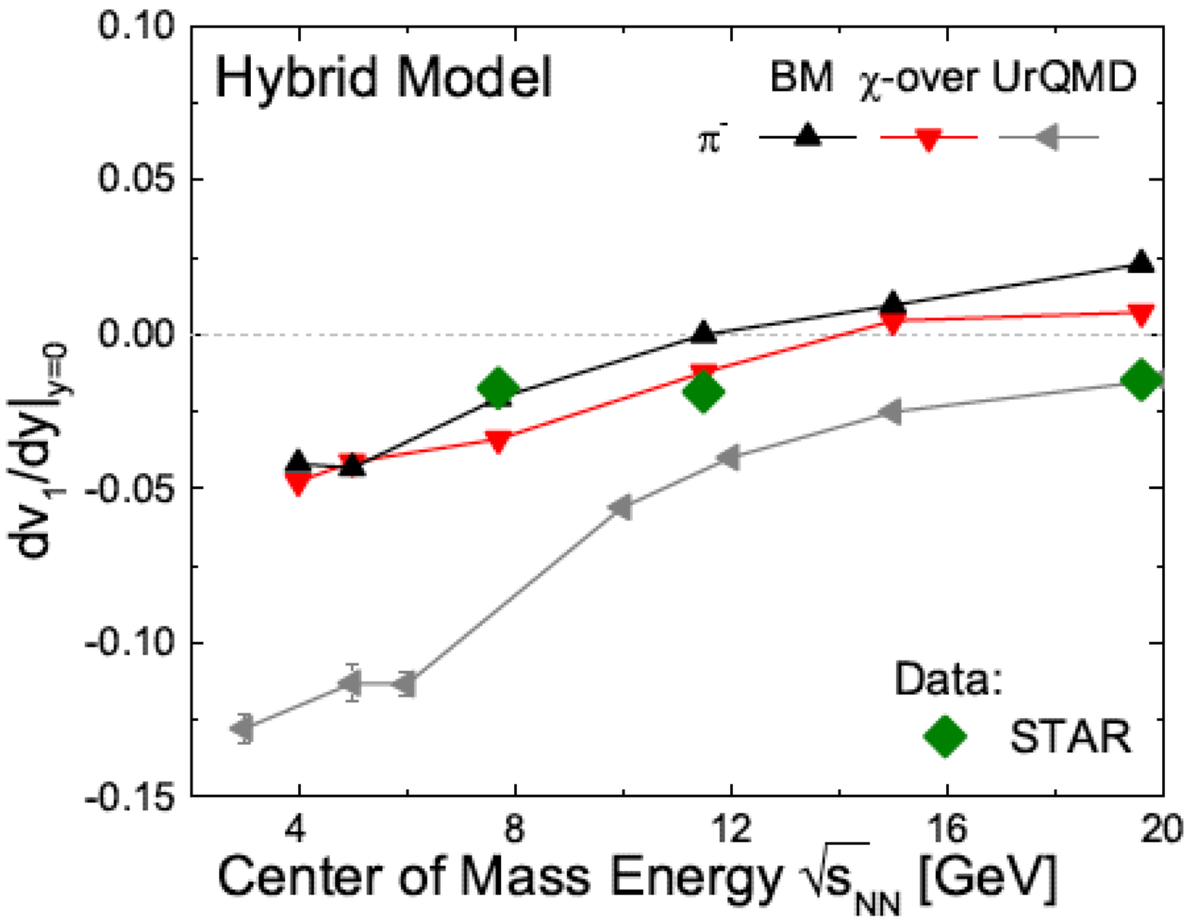
- Development of new hadron cascade hybrid approach with the following strategy:
  - Make sure that hadron dynamics is properly understood
  - Take that to higher densities (Hybrid, Multi-particle interactions,..)
  - C++, open source code, ROOT interface
  - Modular transparent structures
  - Eventually parallel and GPU programming
- Use input from new measurements of elementary reactions for cross-sections, resonances
- Make predictions for CBM at FAIR !

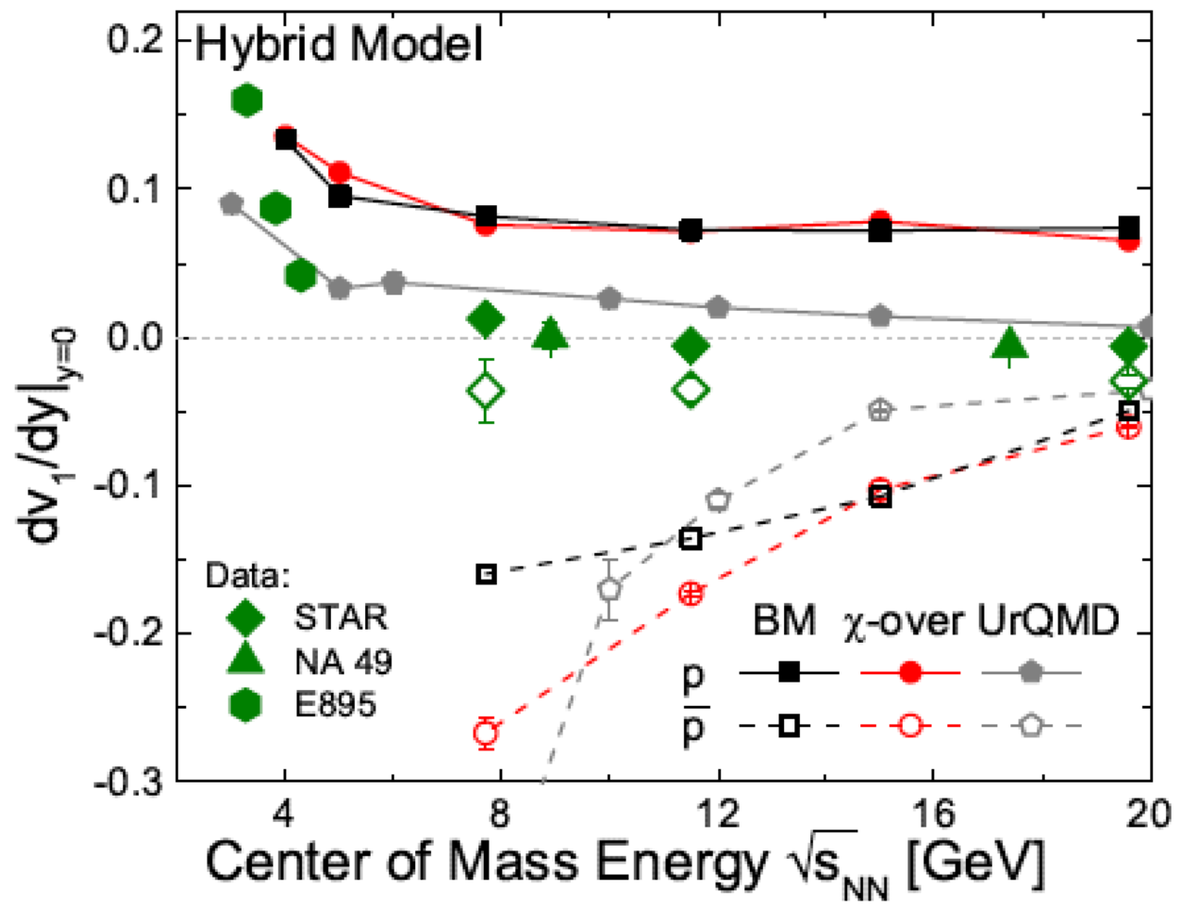
SMASH



Backup

Pions and Protons

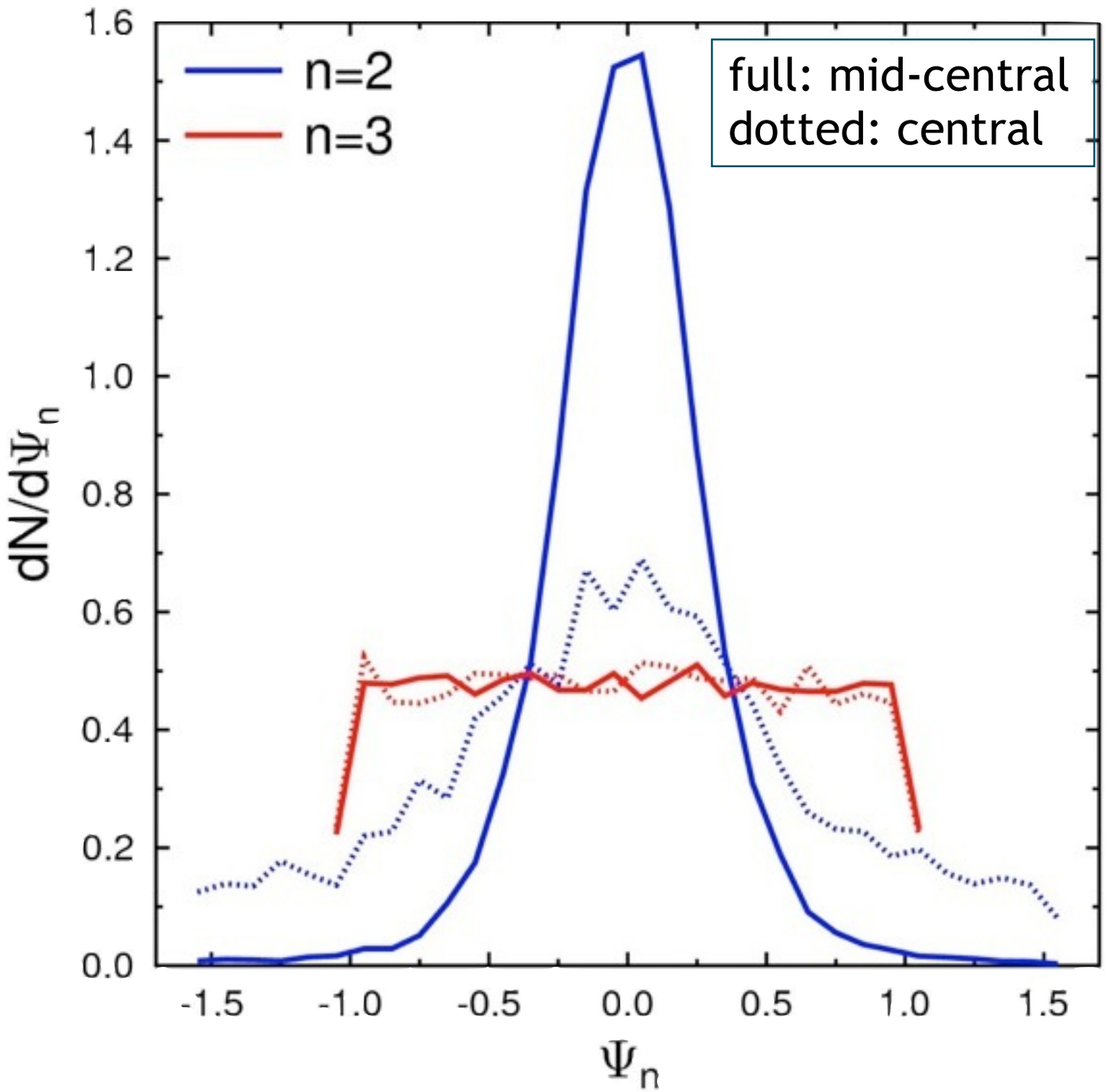




- More realistic hybrid approach does not show difference between first order phase transition and cross-over

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, arxiv:1402.7236

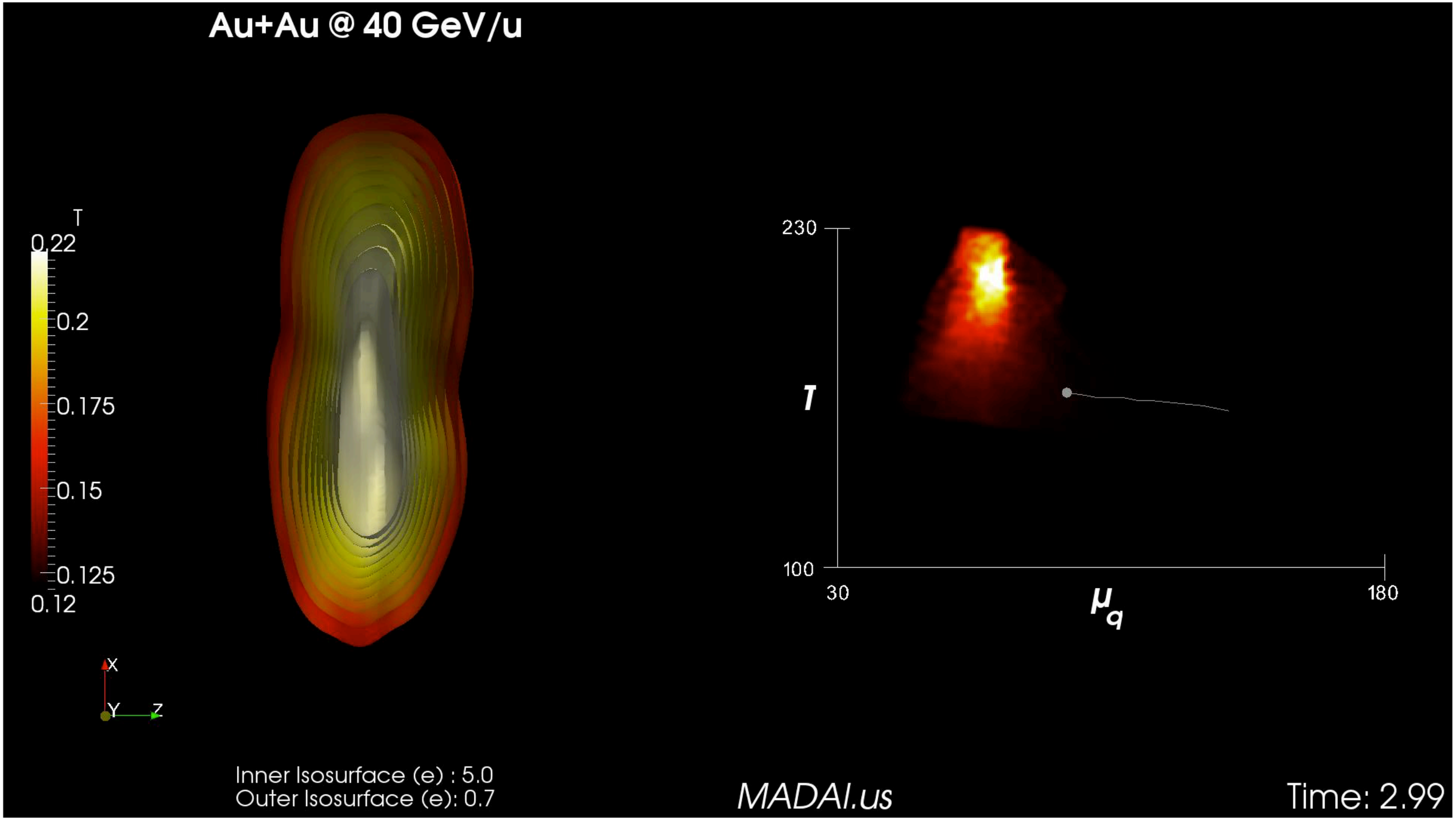
Event Plane Angles



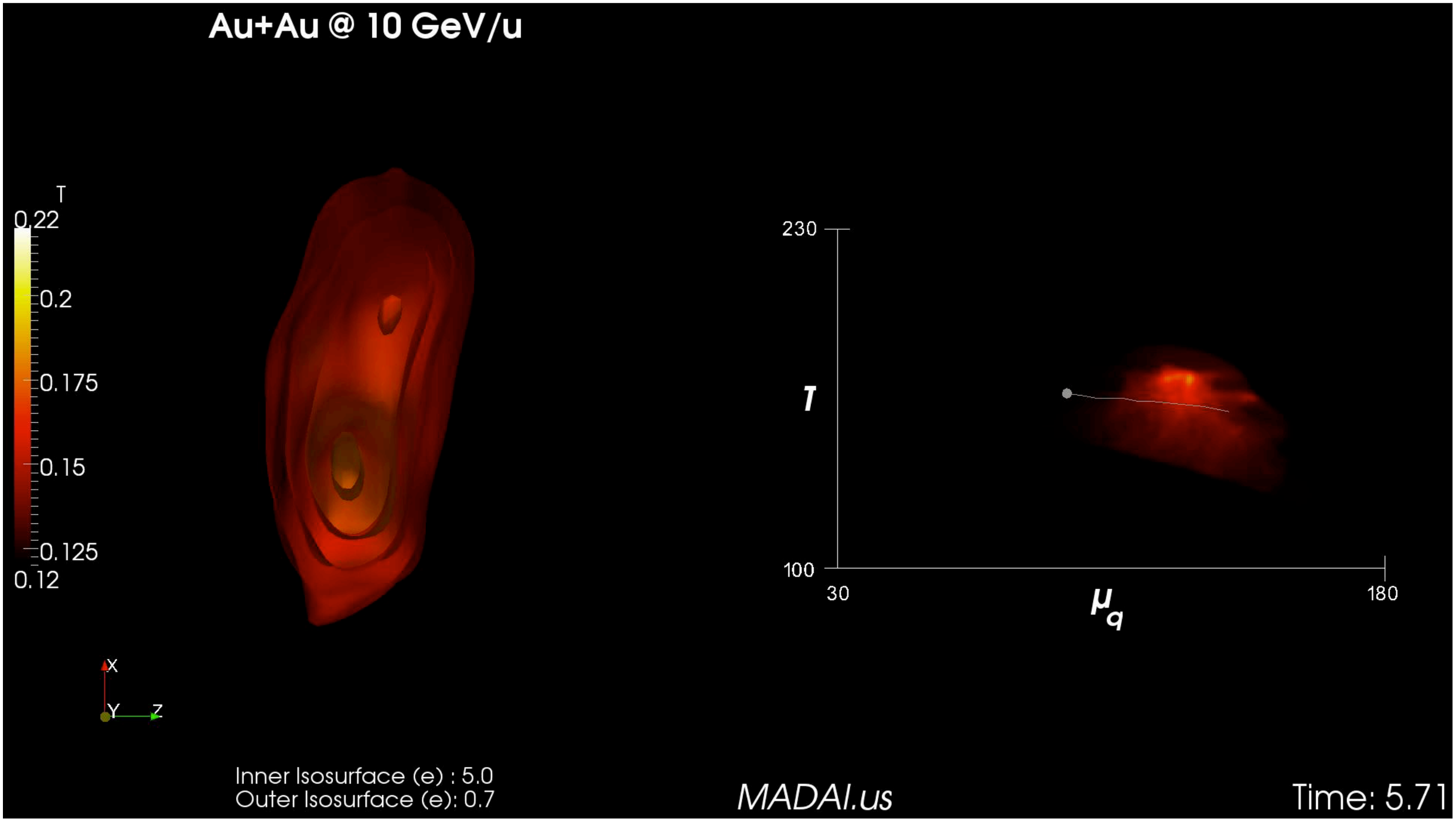
H.P. et al, Phys.Rev. C82 (2010) 041901

- Ψ_2 is **correlated** to reaction plane
- Ψ_3 distribution is **flat**
- **Only** fluctuations, no geometry in contrast to elliptic flow where both are mixed
- Triangular flow can be used for measuring granularity
- Distinguish fluctuations associated with CEP from other sources

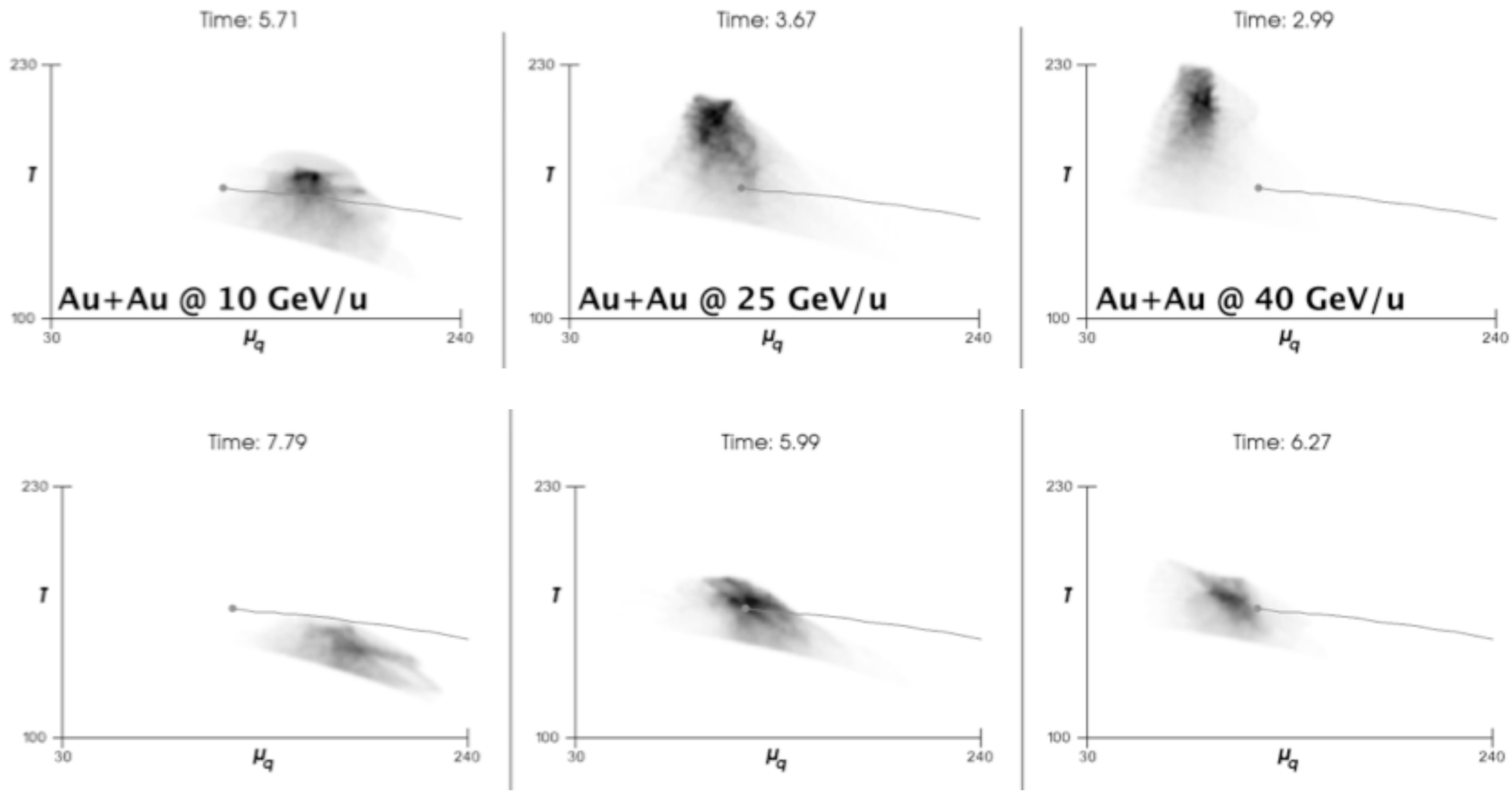
Evolution in the Phase Diagram



Au+Au @ 10 AGeV


Au+Au @ 10 GeV/u
T
0.22
0.2
0.175
0.15
0.125
0.12
230
T
100
30
μ_q
180
X
Y
Z
Inner Isosurface (e) : 5.0
Outer Isosurface (e): 0.7
MADAI.us
Time: 5.71

Exploring the Phase Diagram



S. Bass et al, arXiv:1202.0076, CPOD 2011

- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables for critical point or phase transition