HELMHOLTZ GEMEINSCHAFT

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Dynamical Modeling at Low Collision Energy and High μ_B

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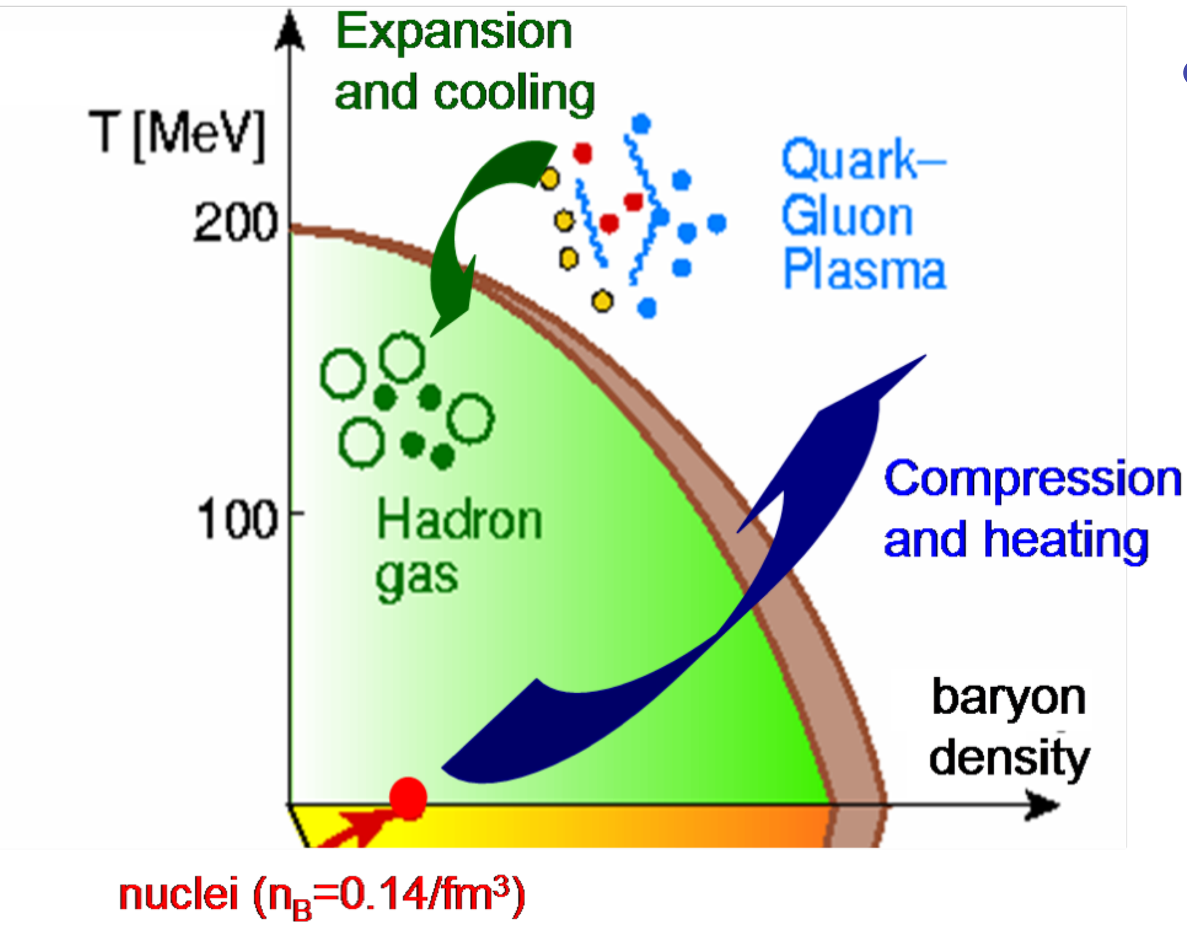
09/13/14, QCD Town Meeting, Philadelphia

FIAS Frankfurt Institute for Advanced Studies

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The QCD Phase Diagram

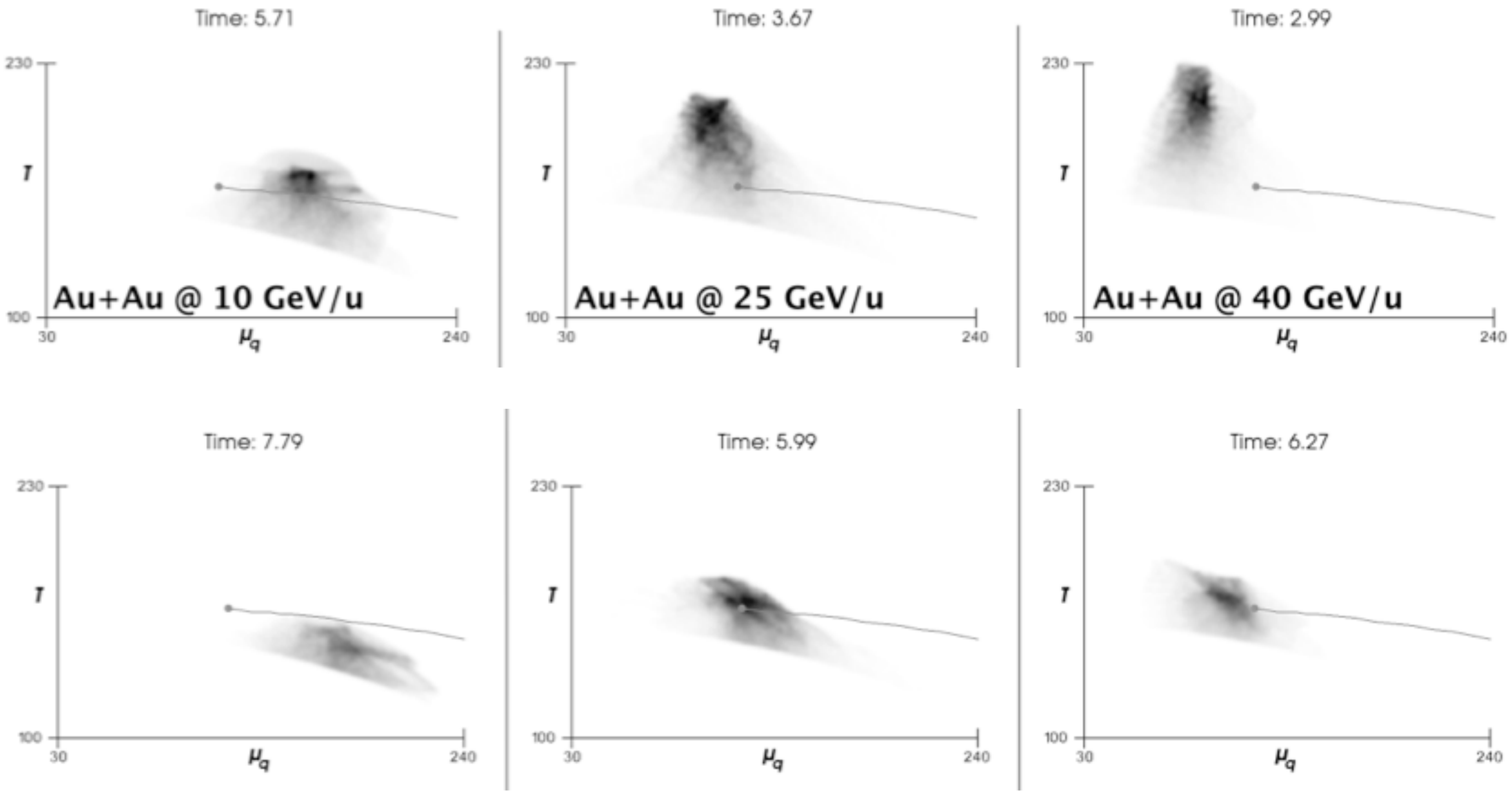
- Quantum chromodynamics has a **rich** phase structure
- Main goals of the beam energy scan program:



- **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? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- How far are we on the way to the answers?
- What additional developments are needed to answer these questions satisfactorily?

Exploring the Phase Diagram

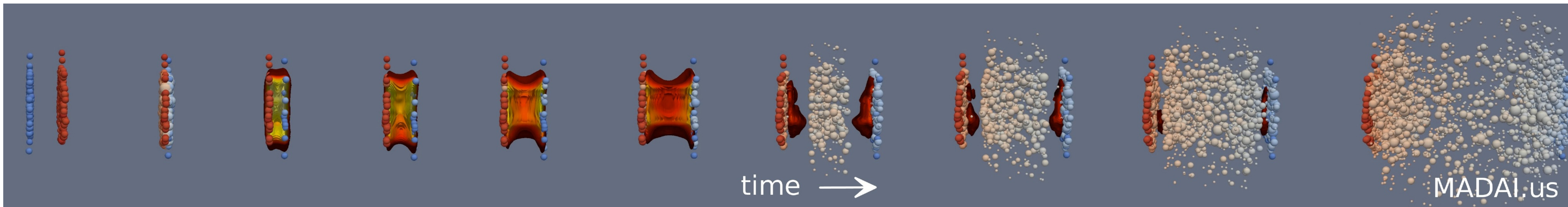


S. Bass et al, arXiv:1202.0076, CPOD 2011

- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables
- Detailed dynamical modeling required

‚Standard Model‘ at High Energies

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

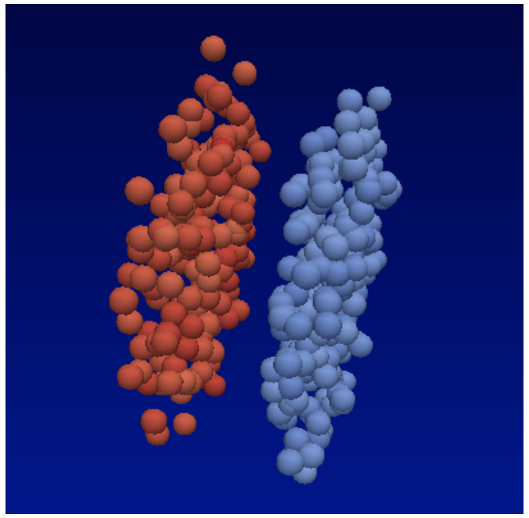


$1x\ 10^{-23}$ s 10×10^{-23} s 30×10^{-23} s

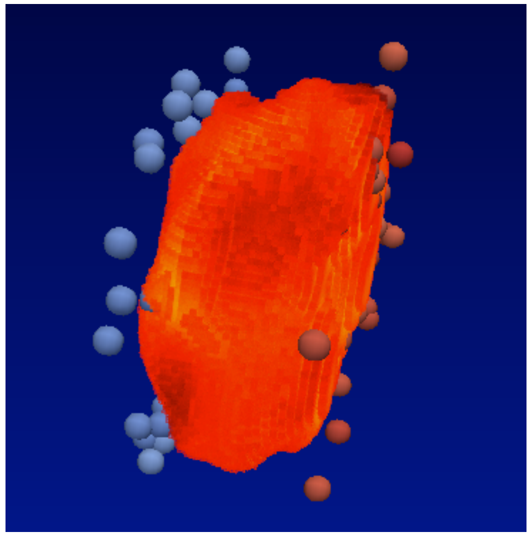
- Challenge at lower beam energies:
  - Finite net-baryon density (as conserved current and in EoS)
  - Dissipative effects/hadronic interactions gain importance
  - Non-equilibrium dynamics with a probably first order phase transition

Hybrid – Status

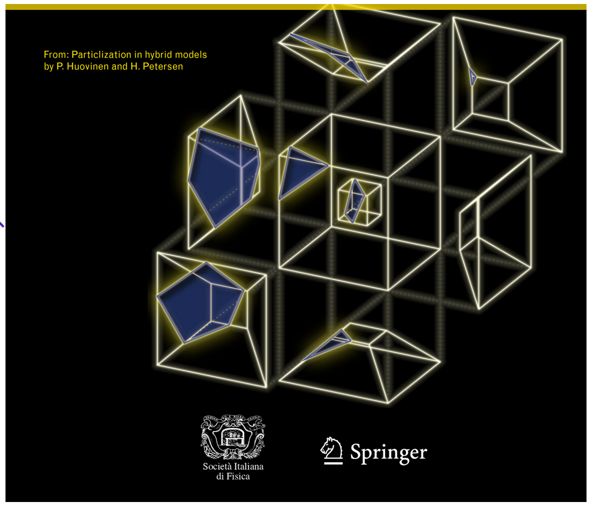
HP, special issue JPG, arXiv:1404.1763



- Initial State:
  - –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 finite μ_B
  - –Karpenko et al: 3+1d viscous hydrodynamics
- Final State:
  - –Hypersurface at constant energy density
  - –Hadronic rescattering and resonance decays within UrQMD



P. Huovinen, H.P. EPJ A48 (2012) 171

HP et al, PRC78 (2008) 044901, G. Gräf, J. Steinheimer and M. Bleicher, UrQMD-3.4 (urqmd.org)

Experiment – Status

- **BES I** program successfully completed
- There are **interesting structures** in the energy dependence of several observables such as
  - Mean transverse momentum of the particles,
  - Nuclear modification factor (R_{CP}) for hard particle production,
  - Cumulants of the net-proton distribution,
  - Directed flow of net-protons,
  - Elliptic flow for particles and antiparticles
  - Charge correlations as a function of the reaction plane

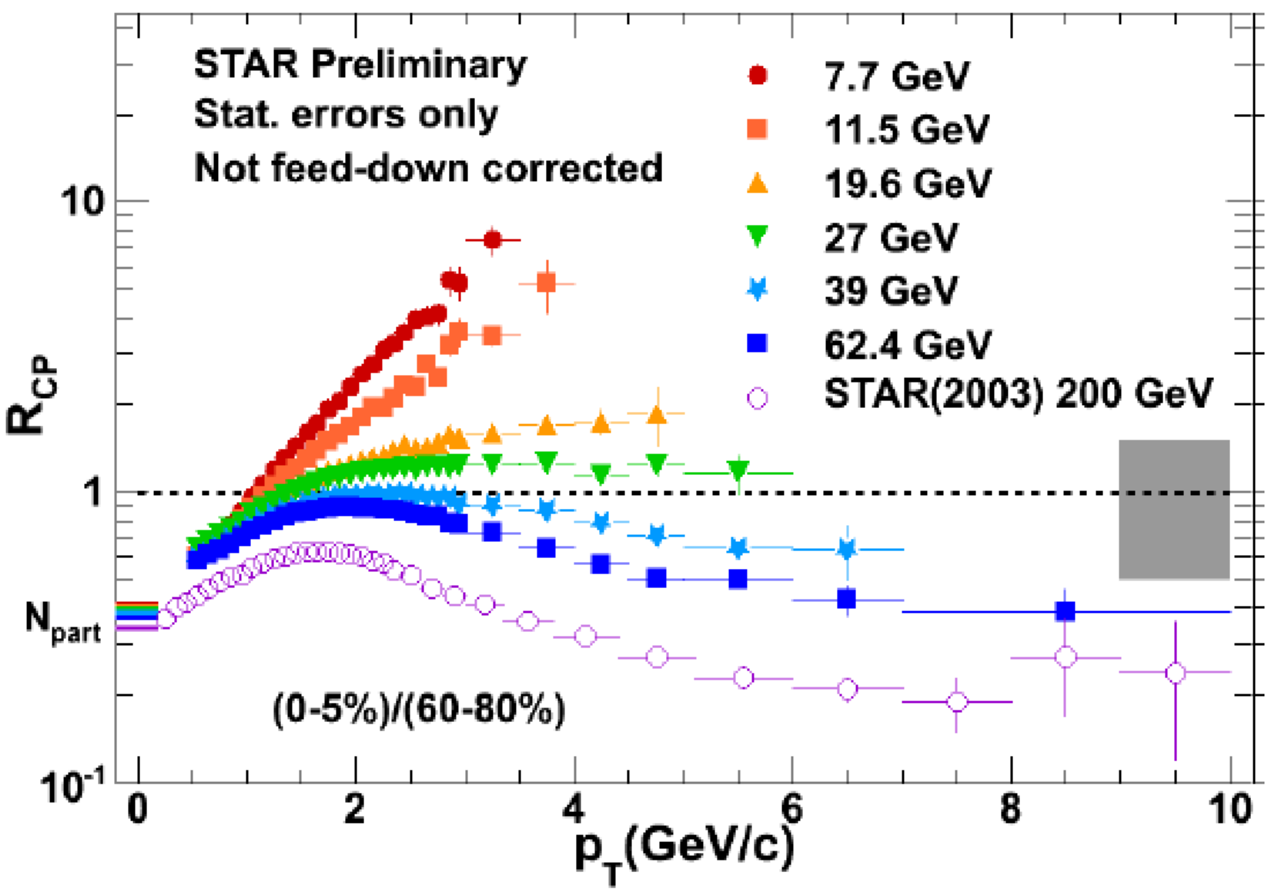
Which of these observables provide interesting insights about the **phase diagram** and do we understand all the ‚**trivial**' effects?

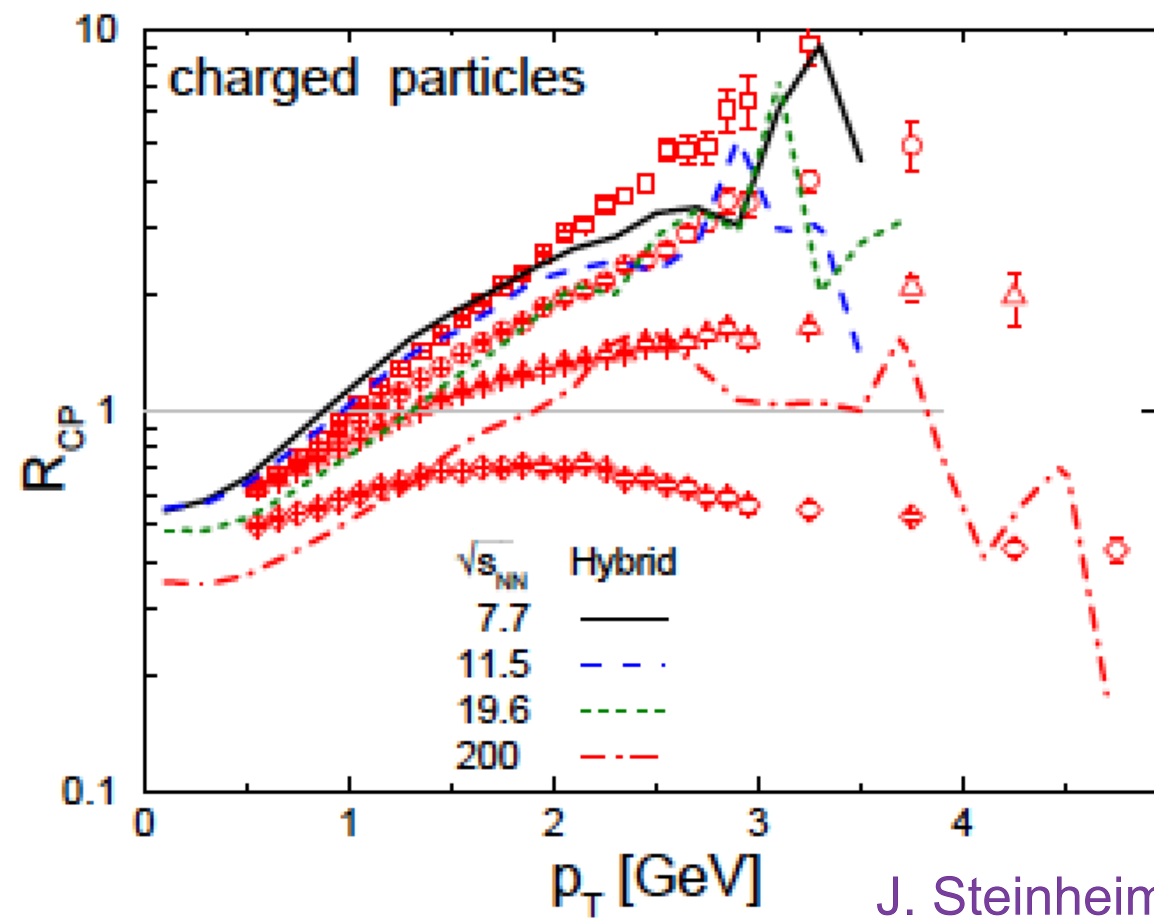
- Let us have a look at some specific examples…

R_{CP}

- Suppression of high p_T hadrons (jet quenching) signals deconfined phase at high energies

A. Schmah [STAR Collaboration], J. Phys. Conf. Ser. 426, 012007 (2013).



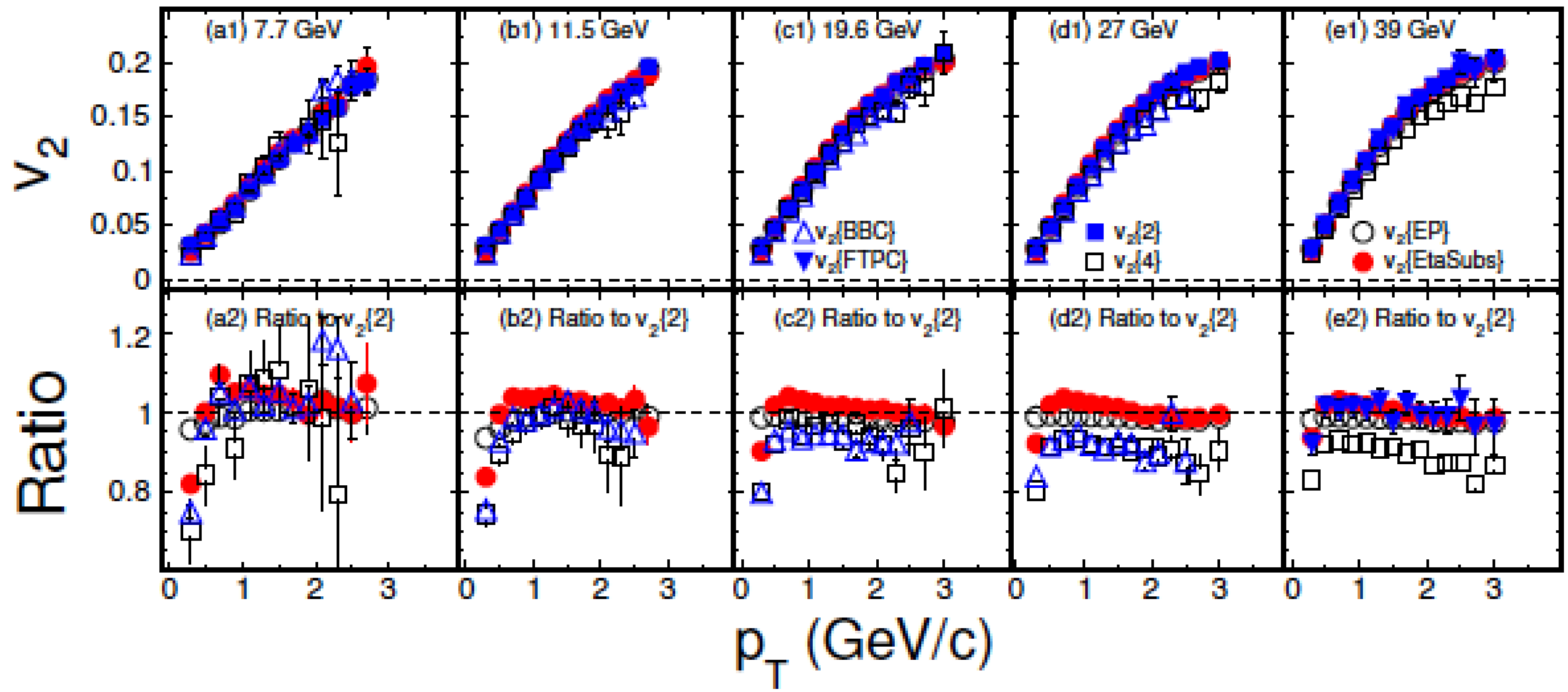


J. Steinheimer

- Qualitatively similar behavior in hybrid model without jets → Effects of radial flow
- Extension to high p_T and direct comparison of spectra necessary to disentangle soft and hard physics

Elliptic Flow

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

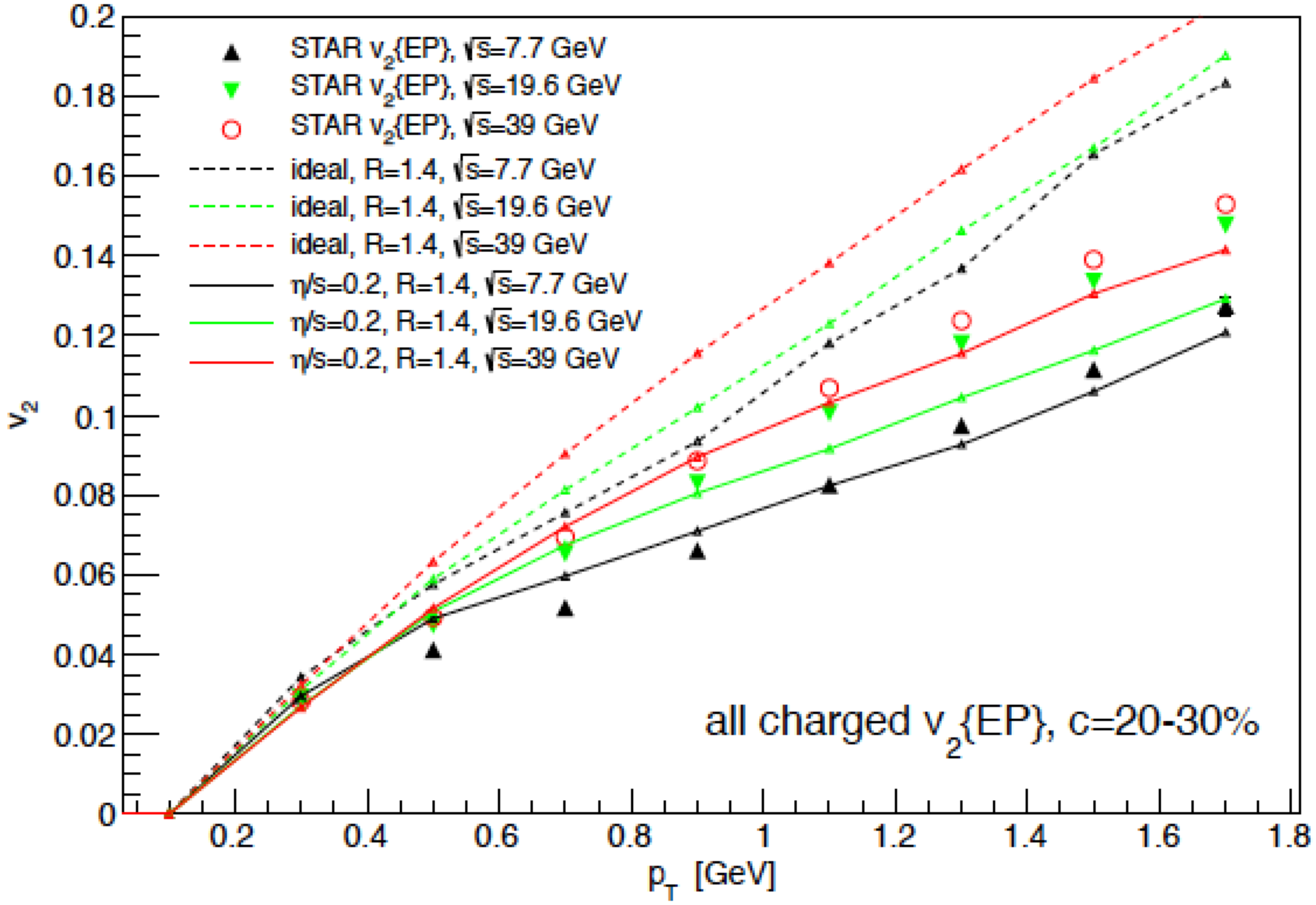


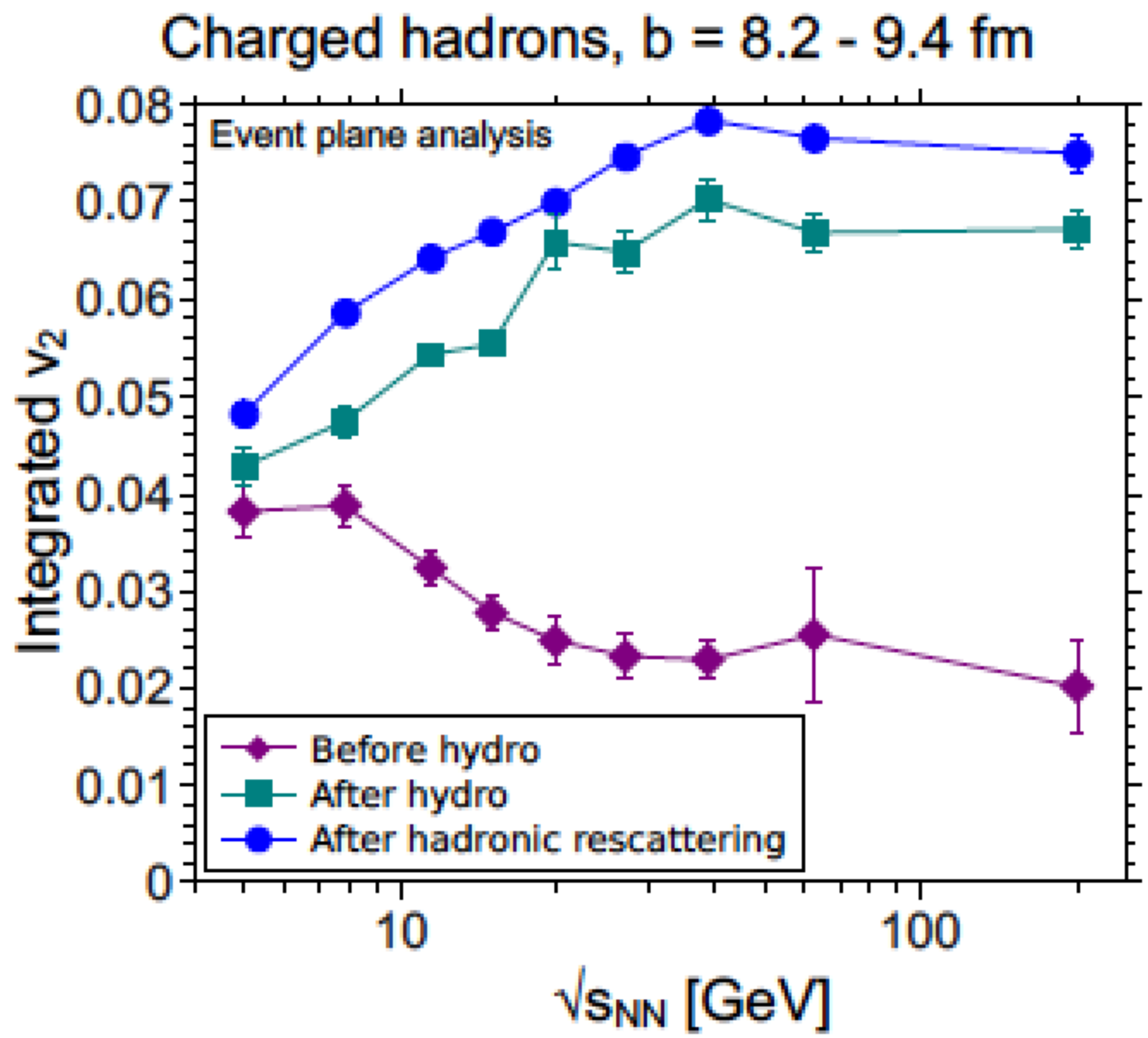
- Differential v_2 for charged hadrons almost identical for all beam energies

STAR, PRC 86 (2012) 054908

Viscous Hybrid

Karpenko et al, WPCF 14



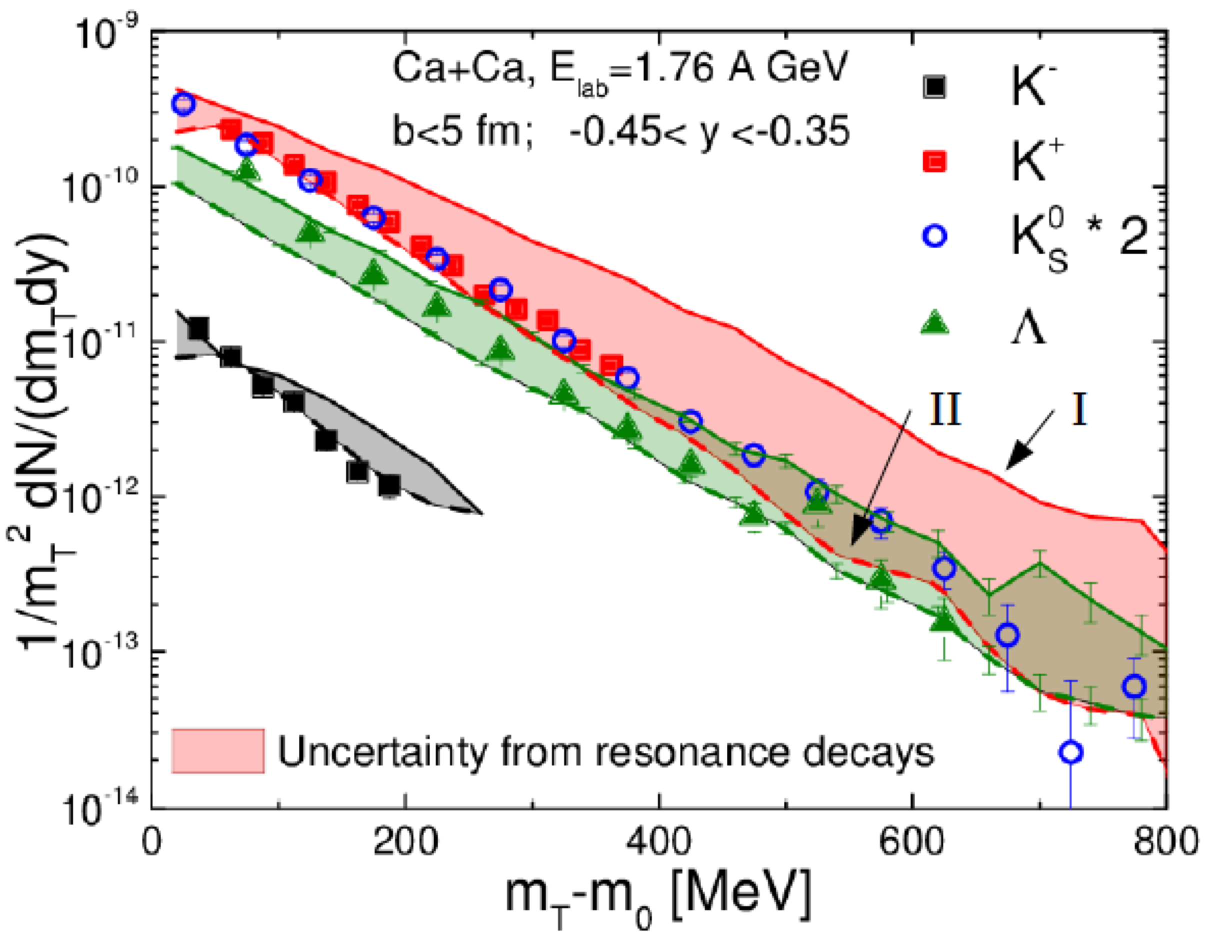


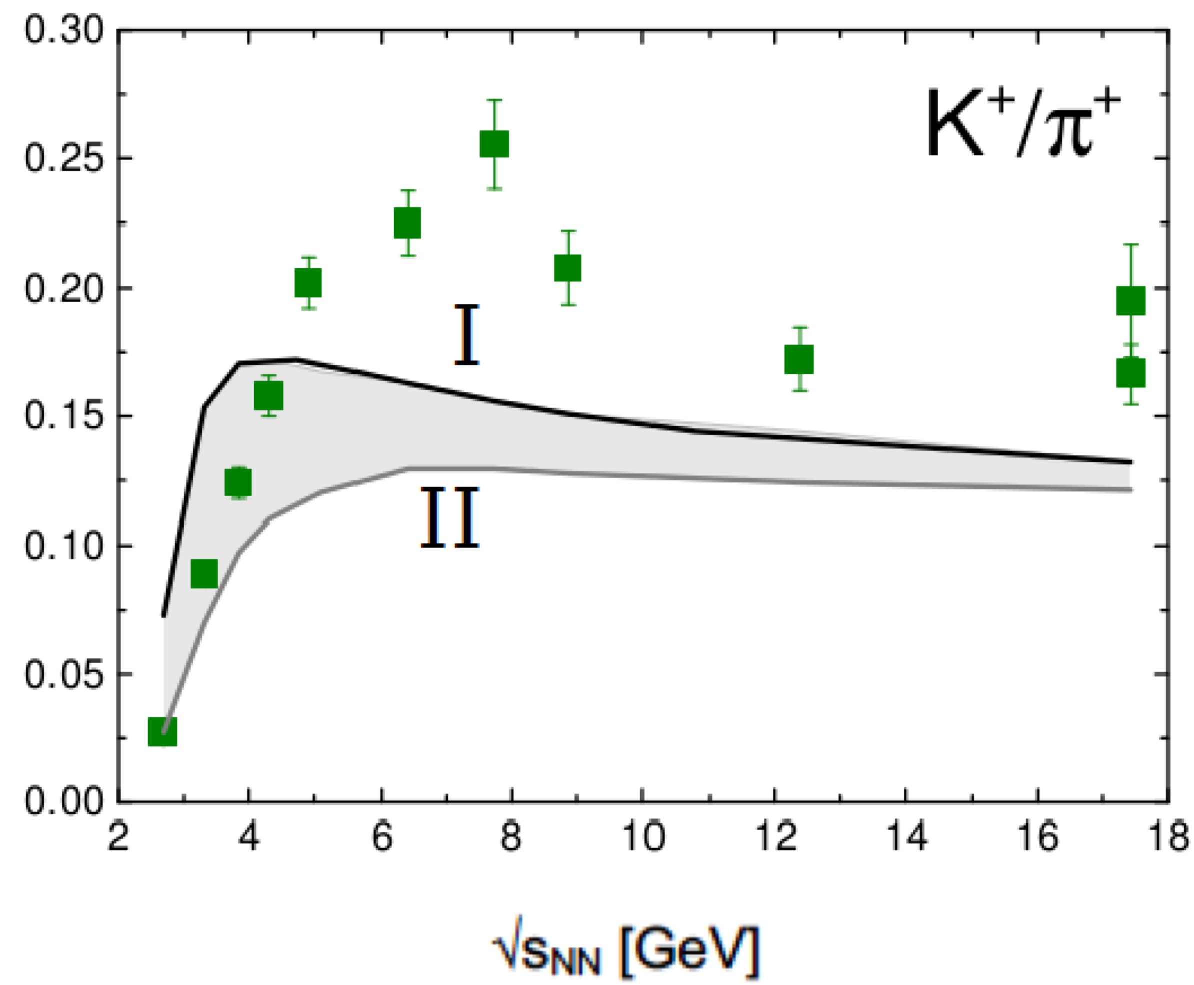
J. Auvinen and HP, PRC 88, 2013

- (Viscous) hybrid approach reproduces weak energy dependence
  - Initial non-equilibrium evolution largely compensates for shortened hydrodynamic stage at lower beam energies
- More detailed understanding of interplay of hydro and transport is required

K/π Ratio

- Transition from resonance dynamics to string excitation and fragmentation





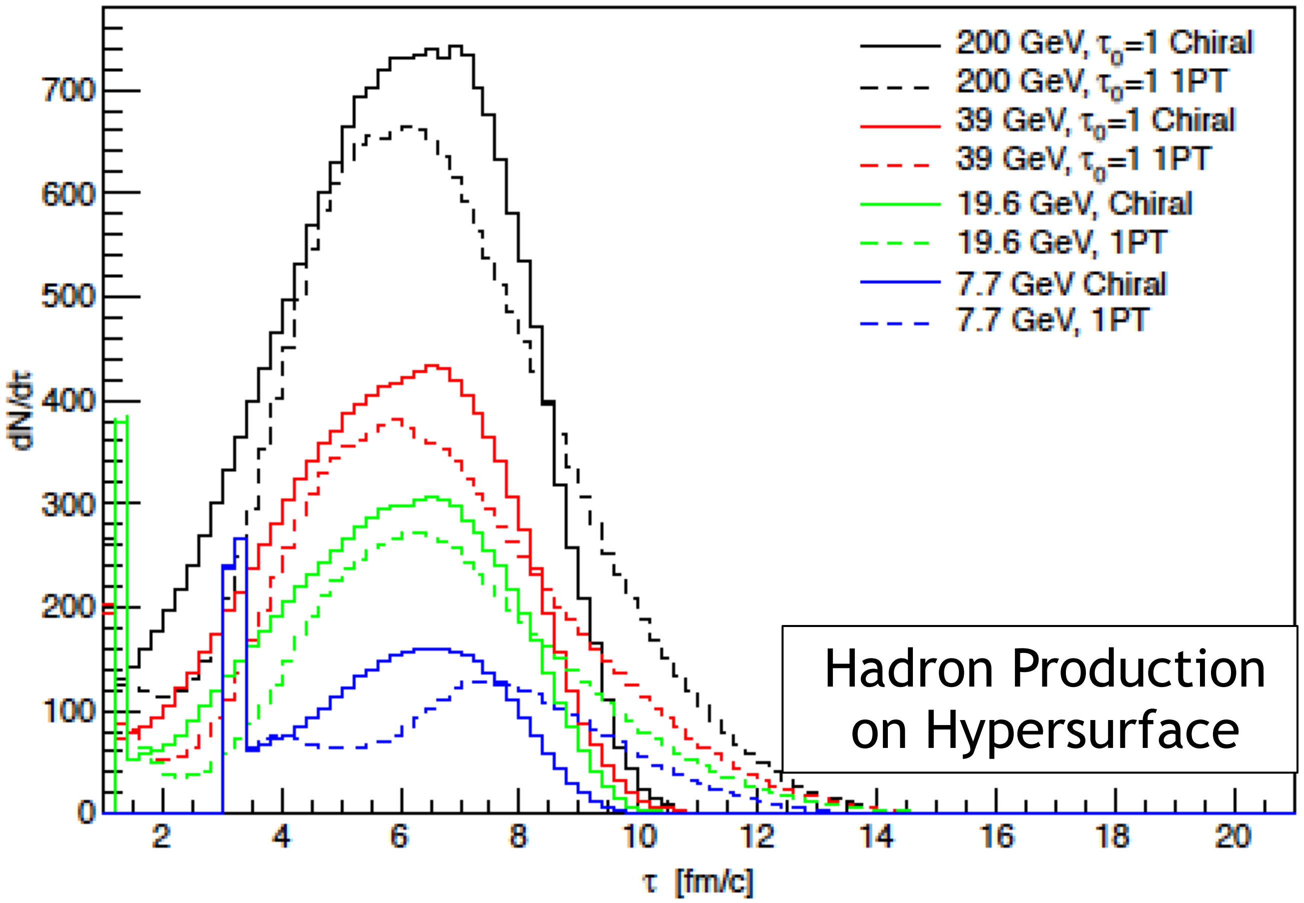
- Need assessment of uncertainties from resonance decays before understanding medium effects

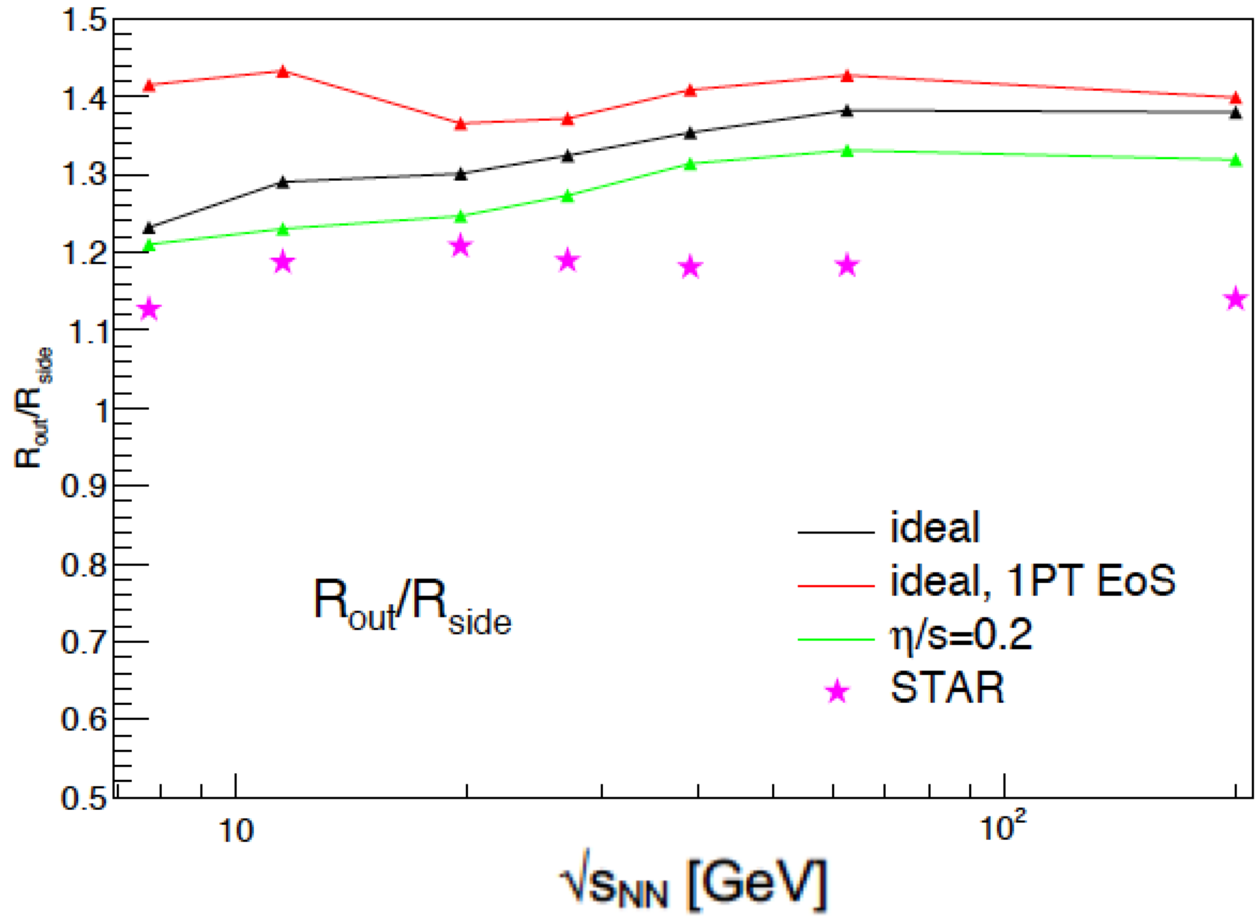
Gräf et al, in preparation

R_O/R_S Ratio

- Idea: Softest point increases the lifetime of the system

Y. Karpenko, WPCF 14

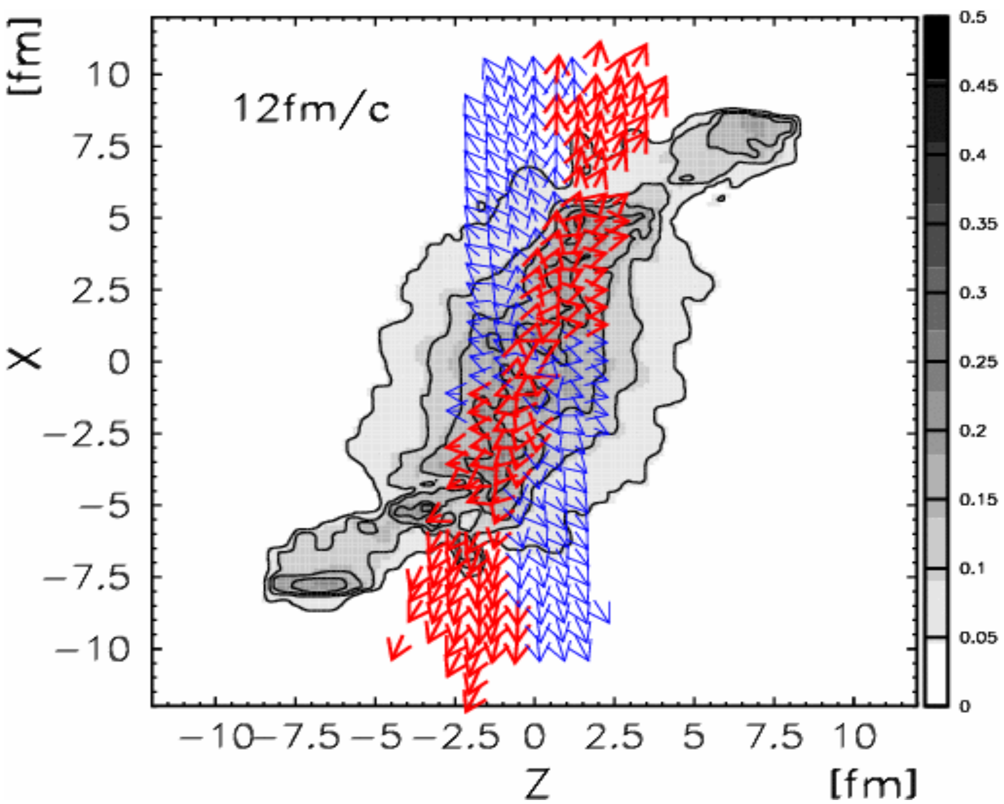




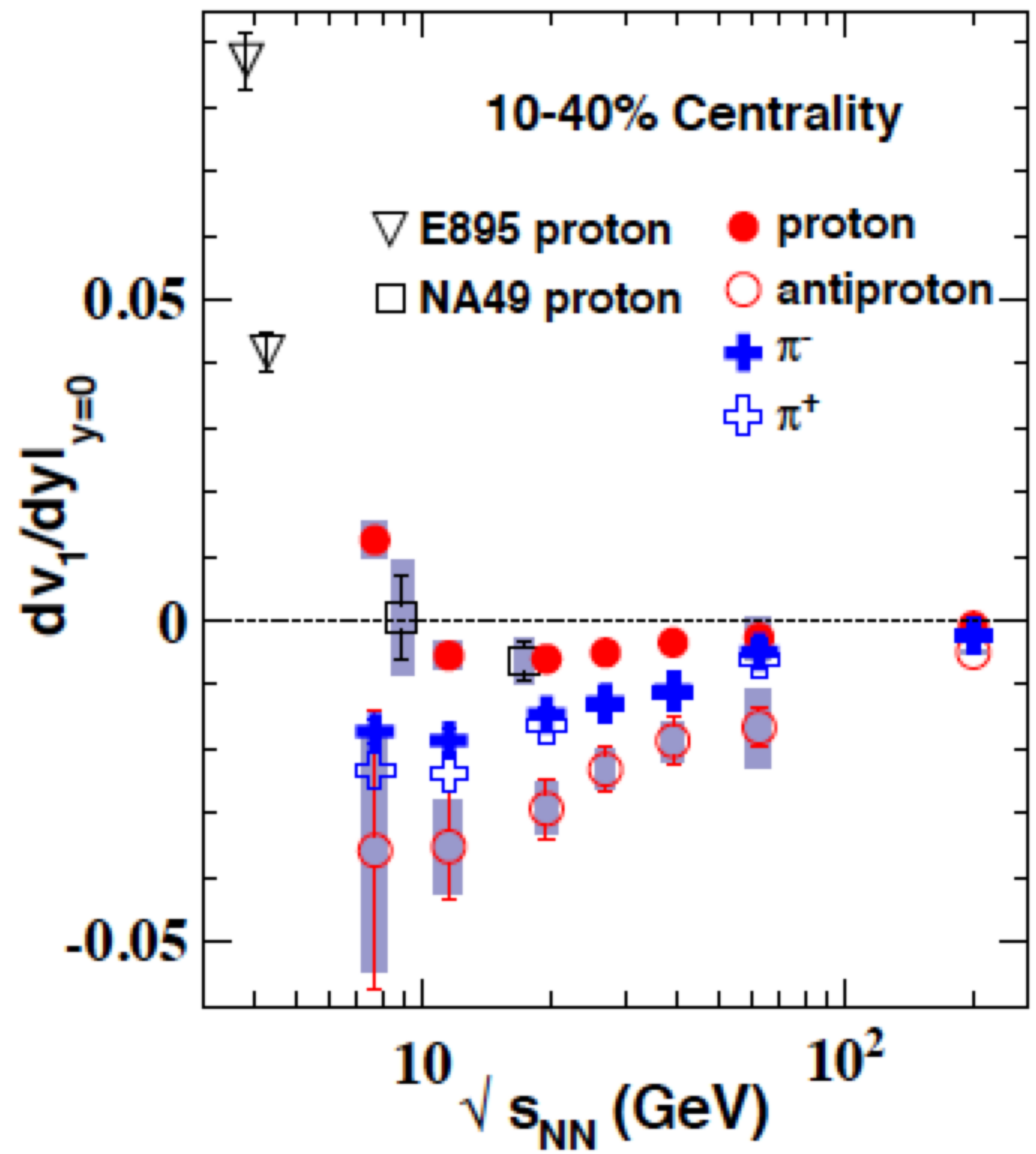
- Weak effect of EoS on HBT radii, finite viscosity has similar influence
- Open question: Cluster formation from phase separation

Directed Flow

- Collective deflection of particles in reaction plane



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

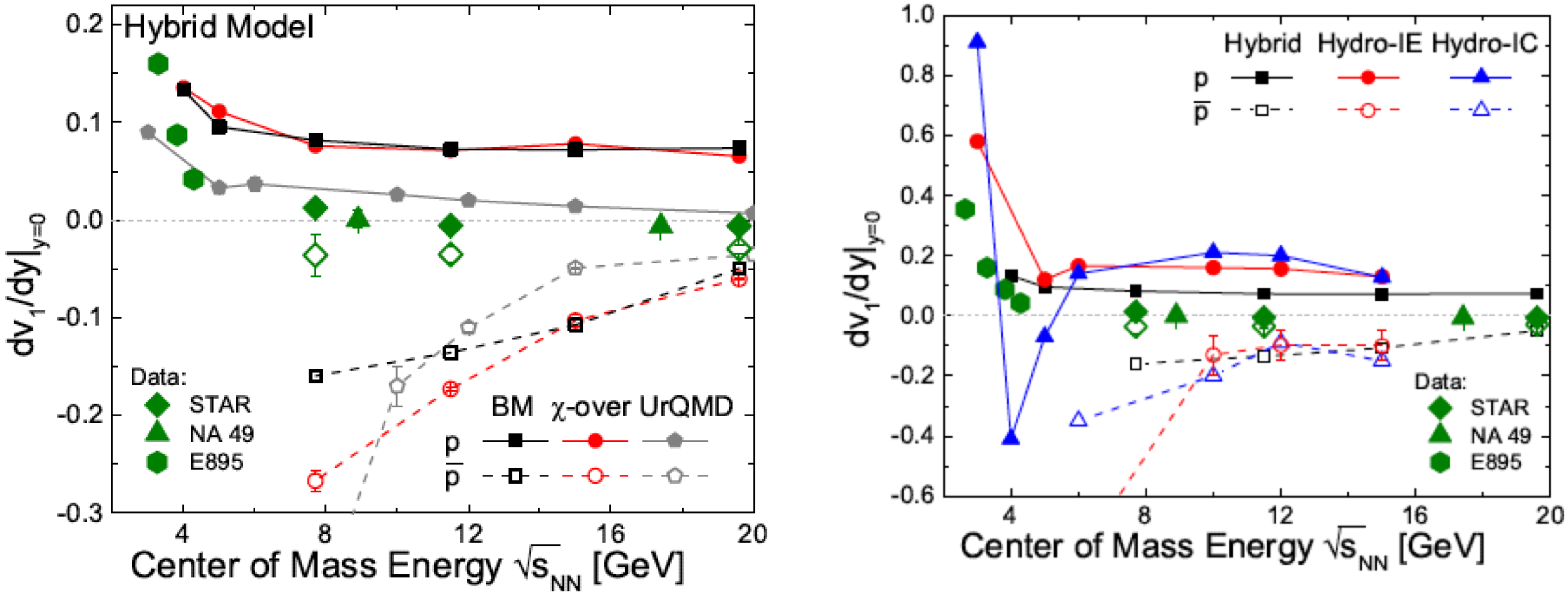


- Non-monotonic energy dependence of v1 slope
  - First order phase transition?

STAR, PRL 112, (2014) 162301

Directed Flow

- v_1 slope is not only sensitive to the EoS, but also to **freeze-out** transition criterion



- Dip structure only reproduced with pure fluid calculation with isochronous freeze-out and first order phase transition
- **Additional issues** that influence the energy dependence like nucleon potentials, interactions with spectators have to be sorted out

J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, PRC 89 (2014) 054913

Towards BES II

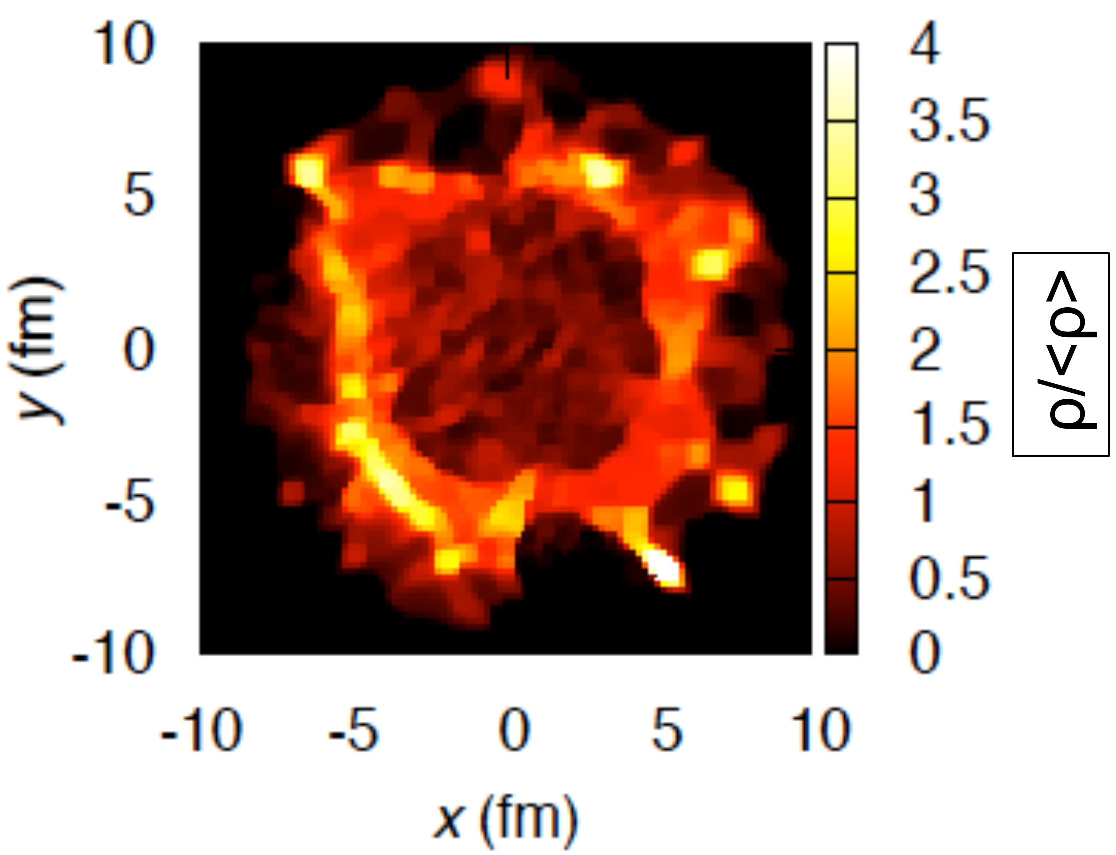
Theory – What is needed?

- Main questions:
  - Is there a phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T, \mu_B)$
- Answers require more detailed understanding of:
  - Transition from baryon-dominated to meson-dominated matter
  - Transition from hadron transport dynamics to fluid dynamics
    - Study of applicability limits as at higher energies (see p-Pb discussions)
  - Improved input on the equation of state including constraints e.g. from neutron stars
  - Fluctuations due to a critical point/phase transition need to be implemented in realistic non-equilibrium dynamics
    - Understand the sensitivities of correlation observables

Non-Equilibrium Dynamics

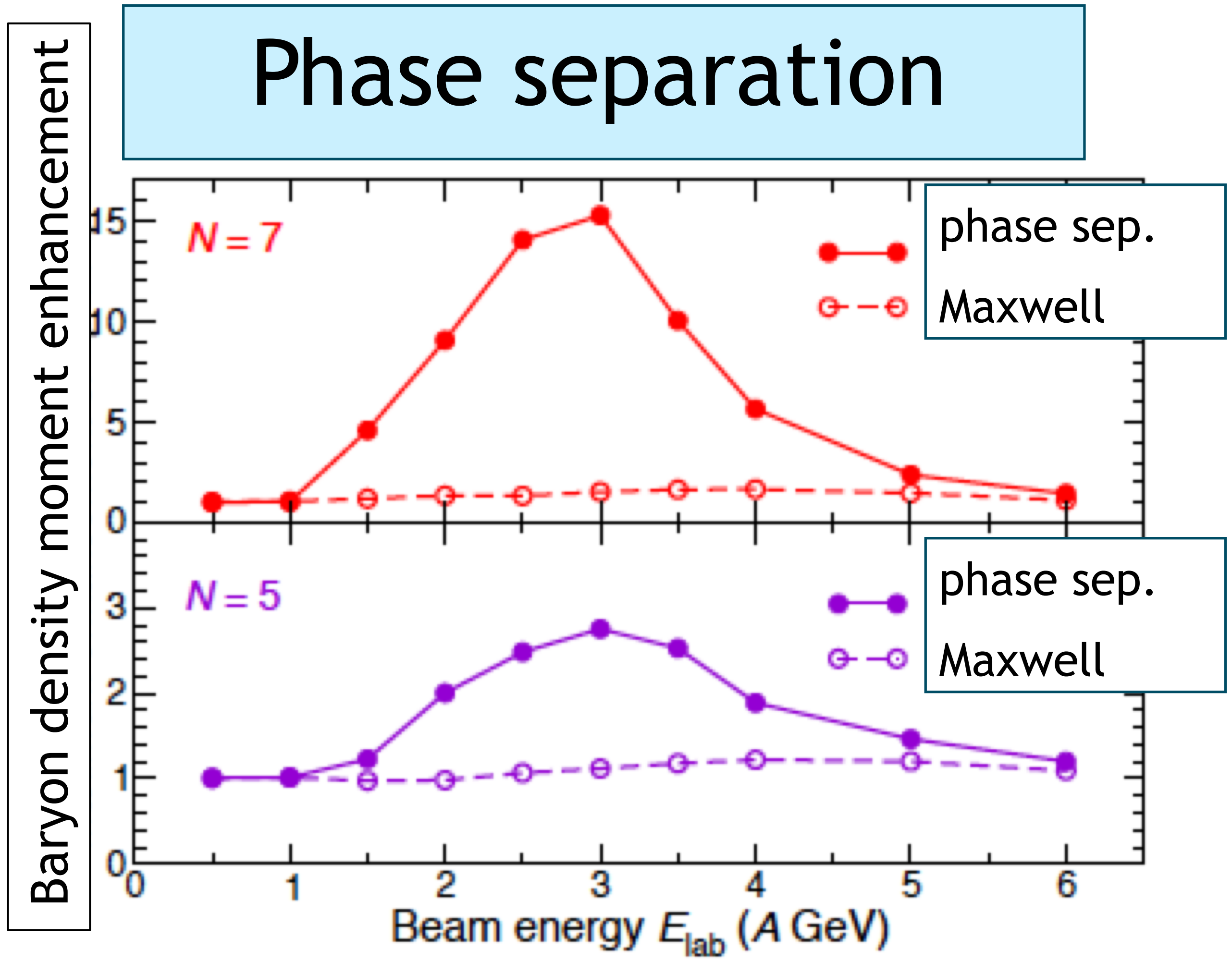
- First attempts to explore possible observables

Chiral fluid dynamics



Herold, Nahrgang et al, Nucl.Phys. A925 (2014) 14-24

Phase separation



Steinheimer, Randrup, PRL 109, 2012

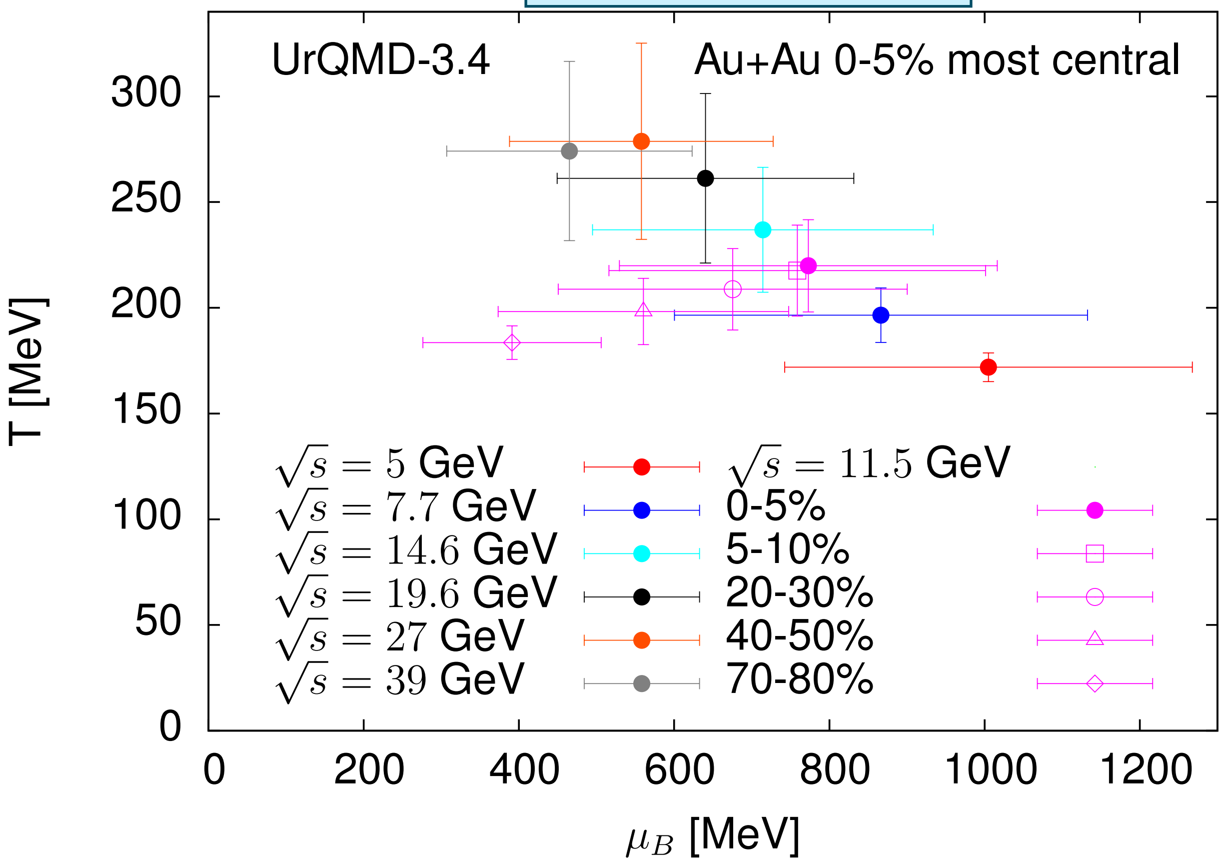
- How stable is droplet formation in net baryon density with respect to the EoS? Quantitative predictions are needed

Open Questions

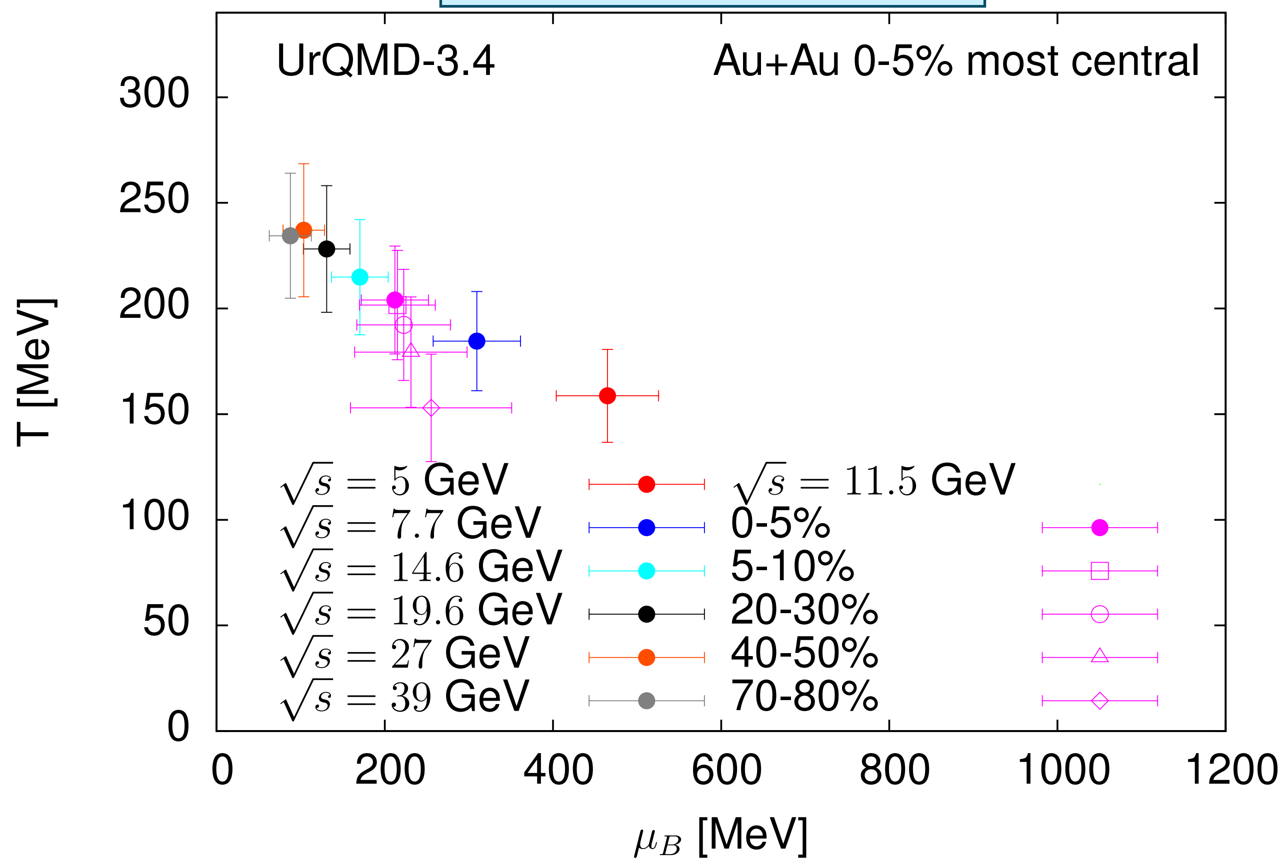
- **Initial Conditions:**
  - Understand the backgrounds and dynamical effects from **stopping** and constrain them independently in experiment
- **Equation of State:**
  - **Extrapolate the EoS** to regions of the baryon chemical potential where lattice calculations are not available and assess the uncertainties associated with using effective models for non-perturbative QCD
- **Transport Coefficients:**
  - The dependence of the **transport coefficients** on the baryon chemical potential must be calculated
- How do we **validate** a given dynamical treatment? What additional measurements need to be done in BES II to **constrain the model space**?

Experimental Access to Phase Diagram

Chiral EoS



Hadron Gas EoS



G. Gräf, J. Steinheimer, UrQMD-3.4 on urqmd.org

- Event-by-event fluctuations negligible, but sizable spread in **single** events → Different centralities increase spanned regions
- Absolute values are highly dependent on the Equation of State/ degrees of freedom
- Concentrate more on ε-ρ plane, since the densities are more relevant for the microscopic dynamics

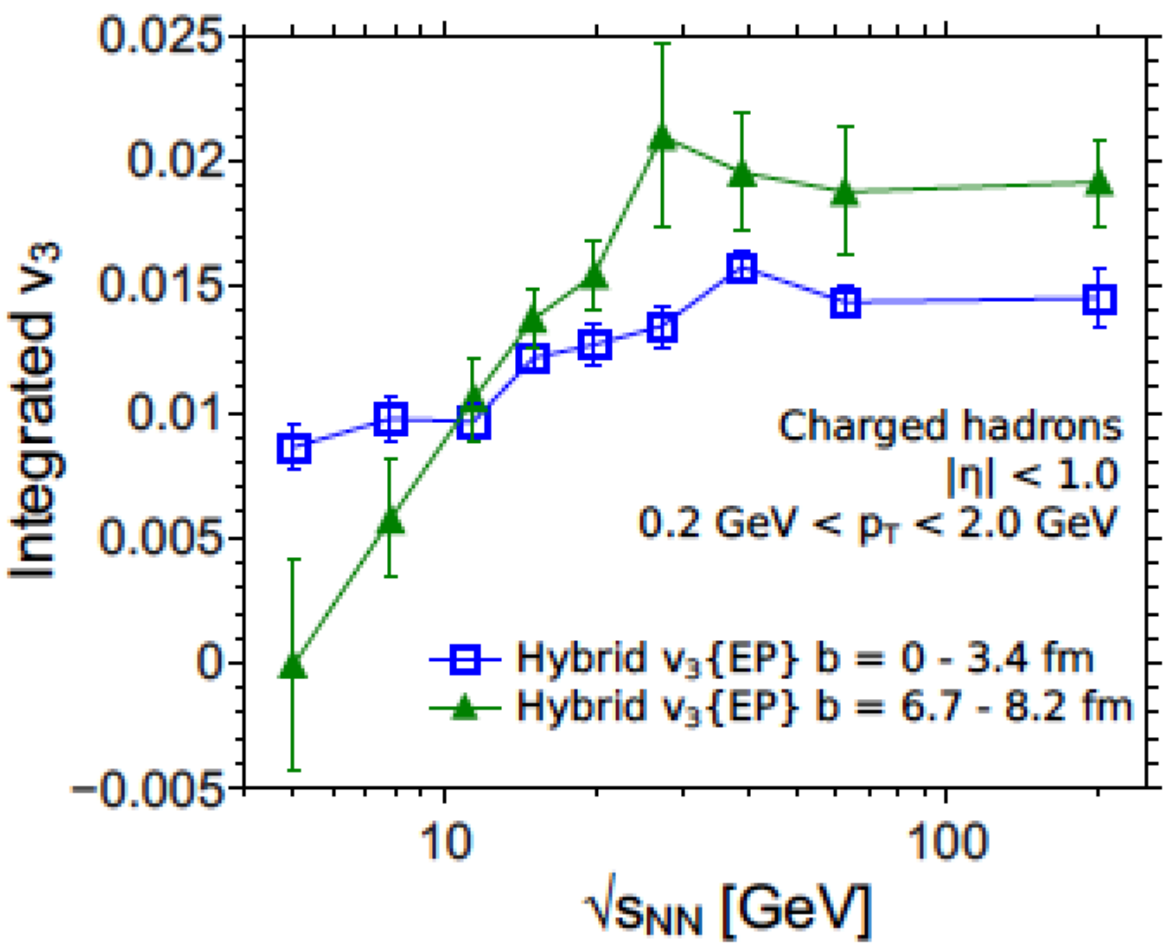
Experiment— What is needed?

- High statistics measurements of all bulk observables including particle identification
  - Multiplicities and p_T spectra
    - → Constrain entropy production and freeze-out transition
  - Flow coefficients v_1-v_3
    - → Constrain viscosity and the IC fluctuations
  - HBT correlations and tilt angles
    - → Insights about dynamics in coordinate space
  - Centrality dependence of directed flow
    - → Allows to distinguish potentials and spectator interaction from EoS during evolution

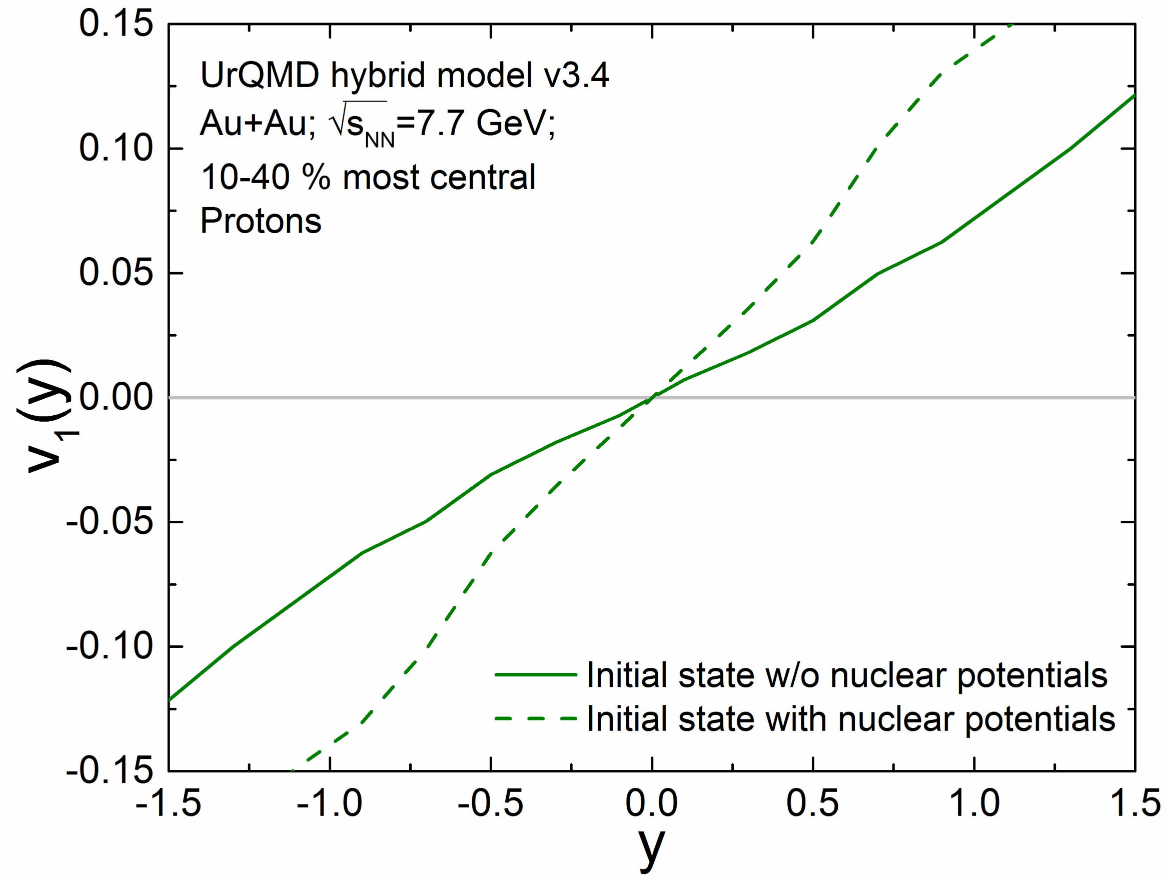
Anisotropic Flow

J. Auvinen and HP, arXiv:1310.1764

Triangular flow



Directed flow



- Systematic errors due to event plane have to be controlled
- A chance to disentangle IC fluctuations from e-by-e fluctuations related to phase transition

- Systematic studies of v1 are very promising to see effects of equation of state

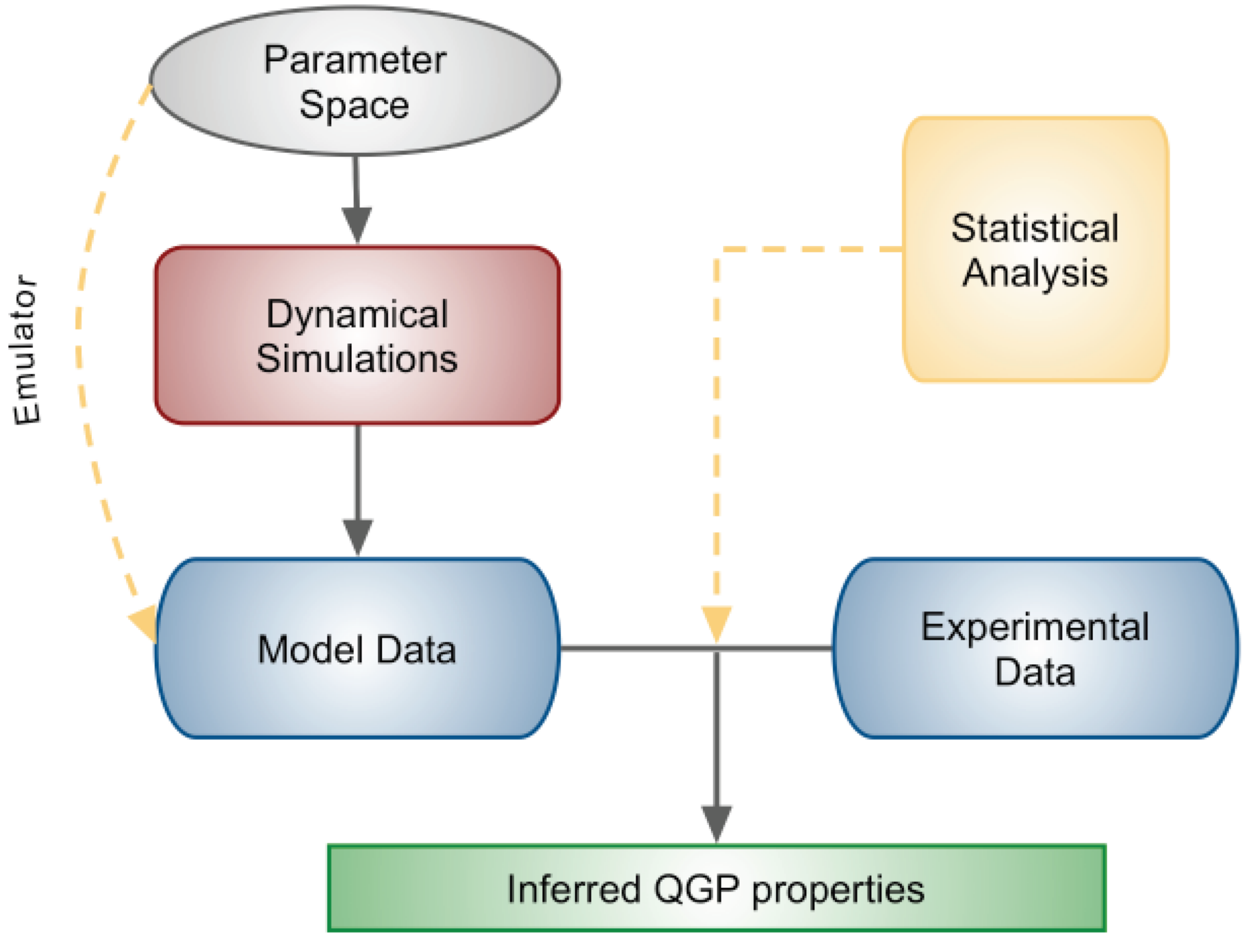
Model-to-Data-Comparisons

- Honest assessment of data and models including uncertainties is necessary
  → Many observables in one approach
  - Conscious decisions are required, if we want sensitivities or multi-parameter fits

Option 1:
Fix all parameters and explore sensitivity to one additional, e.g. EoS or viscosity

Option 2:
Multi-dimensional multi-parameter analysis -> requires statistical tools, databases and CPU hours

Option 3:
Something else? ...



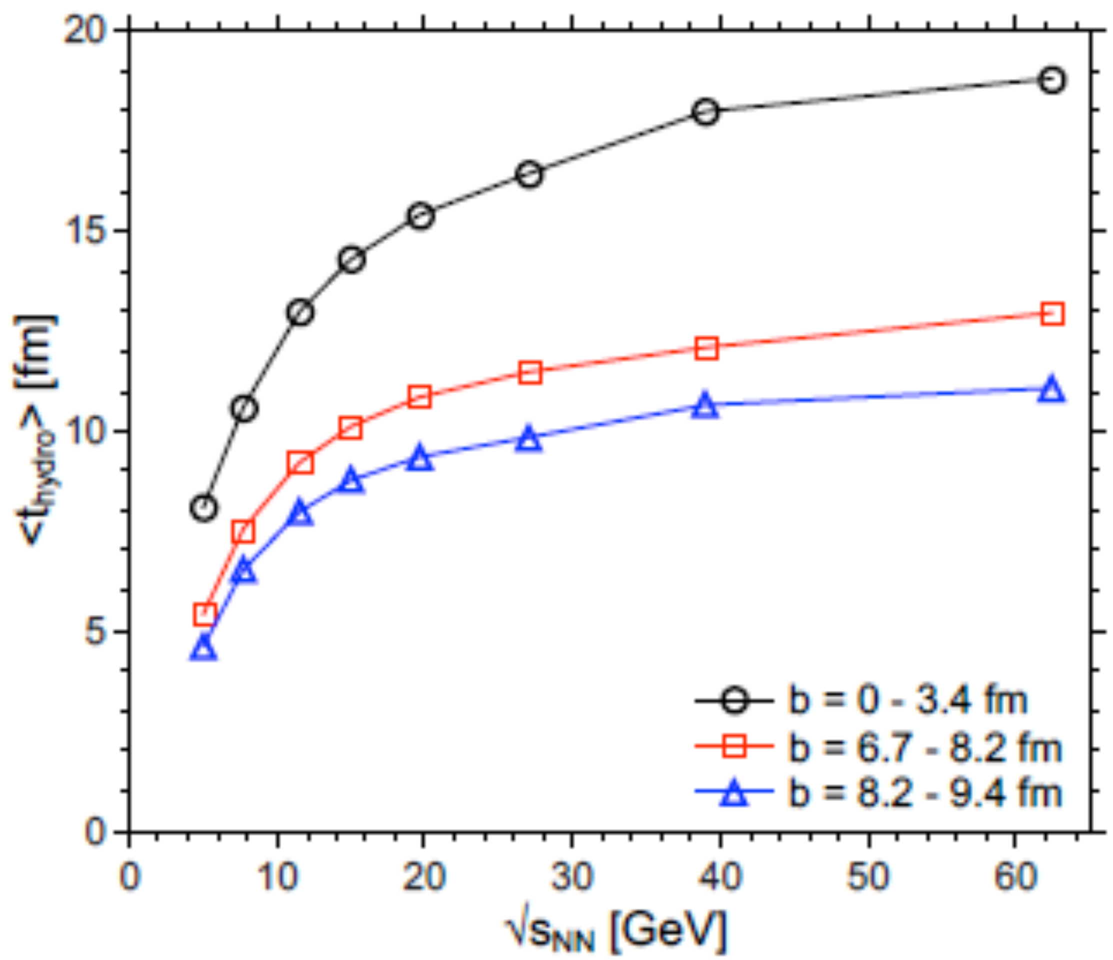
Summary

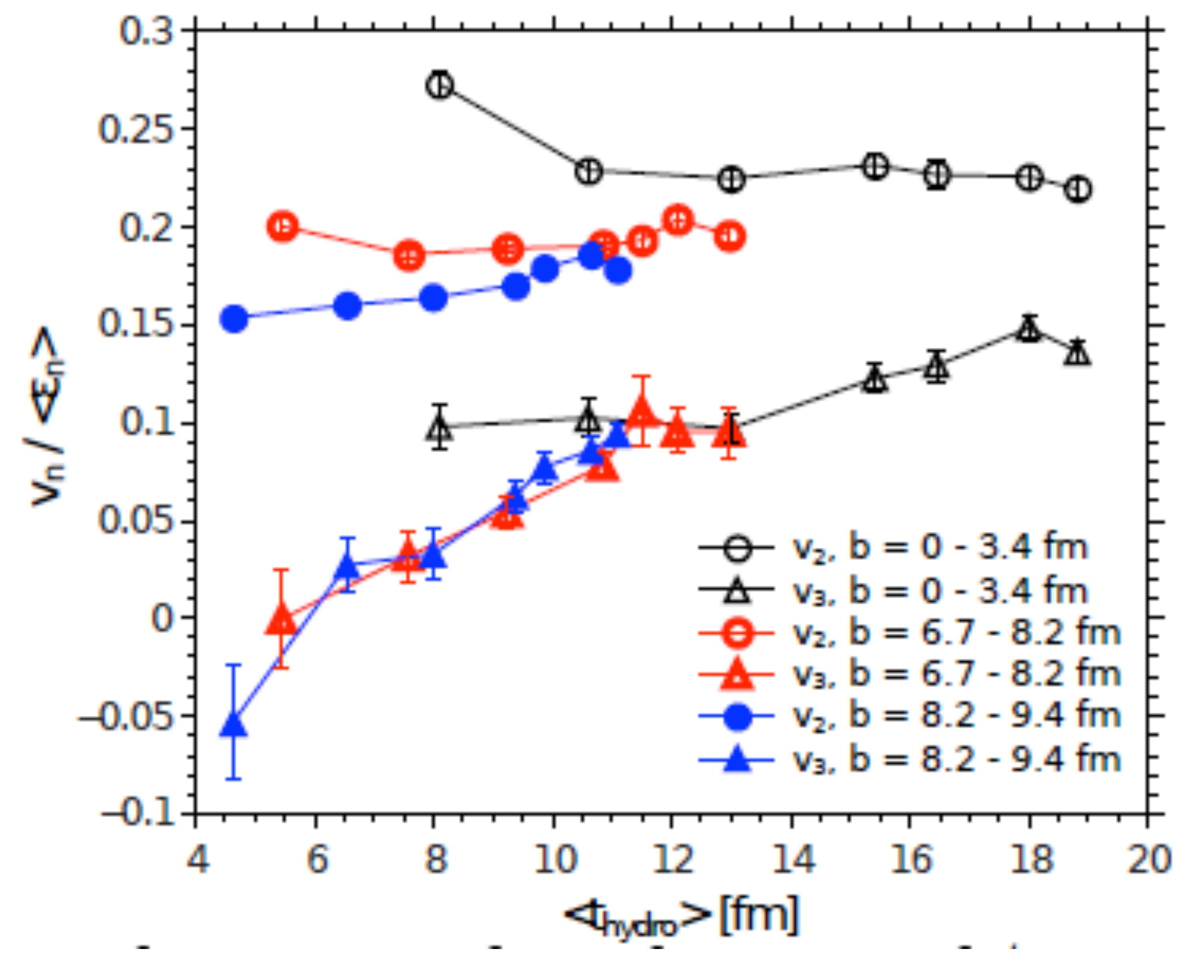
- Experiment Status:
  - BES I successful -> many exciting results that have revealed/ confirmed interesting structures as a function of beam energy
- Theory Status:
  - Hybrid models are applicable also at lower beam energies
  - Progress on dynamical modeling of non-equilibrium phase transition
- Necessary next steps:
  - Detailed high statistics measurements including PID needed to constrain model parameter space
  - Include ‚trivial' effects in dynamical models and describe many observables including an assessment of uncertainties
  - Quantitative predictions from non-equilibrium phase transitions

→ Insights about the QCD phase diagram

Backup

Sensitivity to 〈t_{hydro}〉

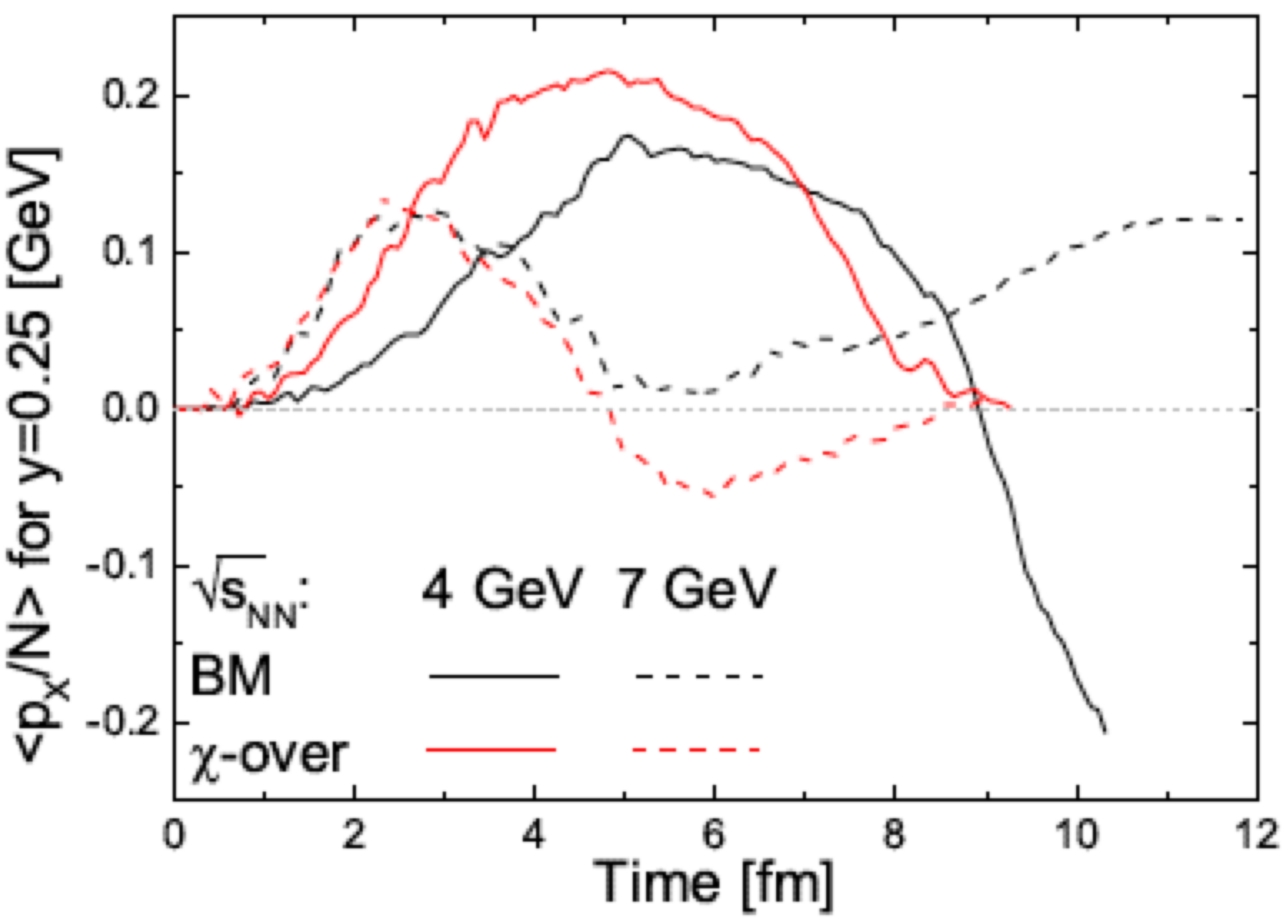


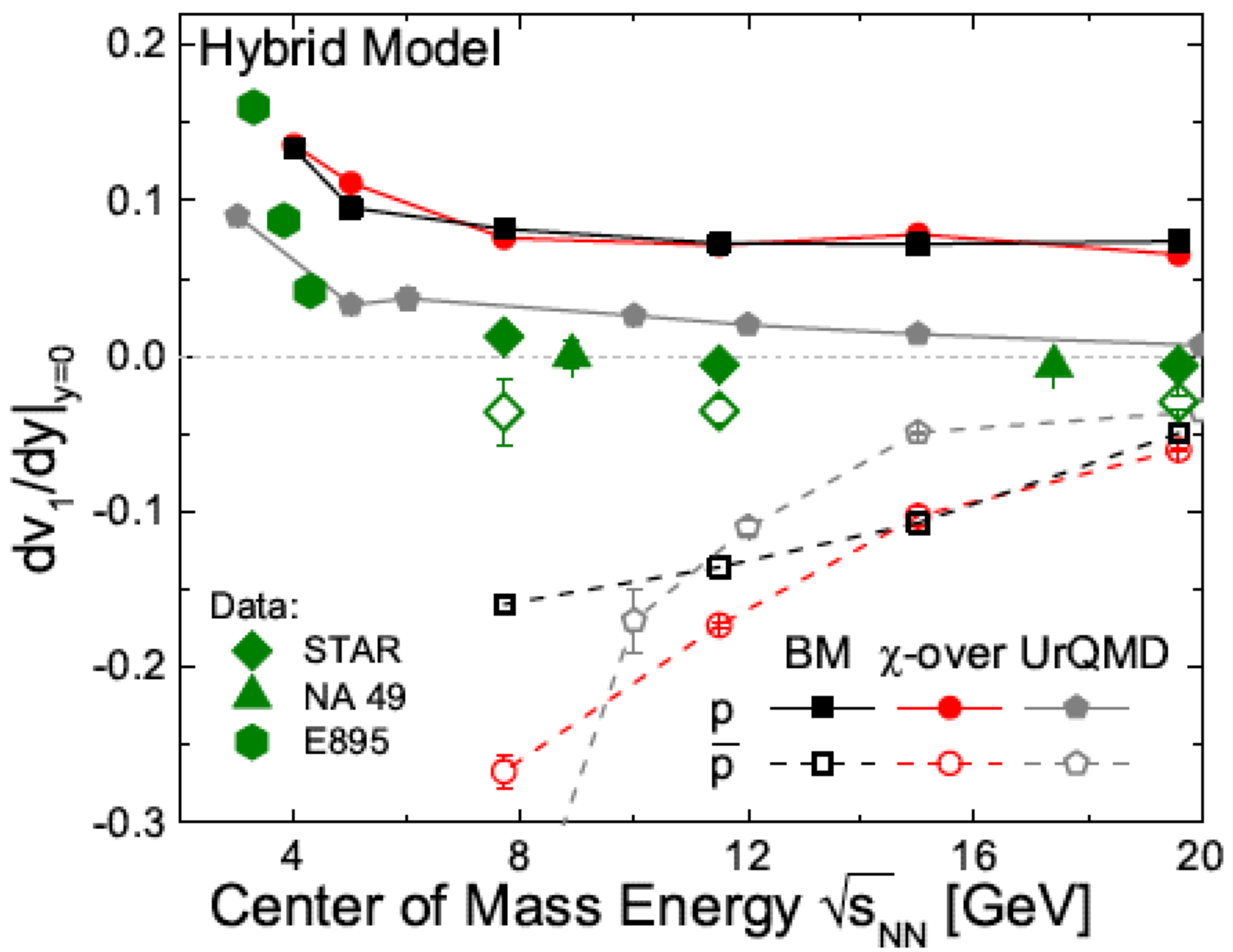


- v_3/ε_3 shows universal behaviour as a function of total duration of hydro phase
- v_2 does not follow scaling because of transport contribution

J. Auvinen and HP, arXiv:1310.1764

Time Evolution for v1





- 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