Event-by-Event Observables and Fluctuations

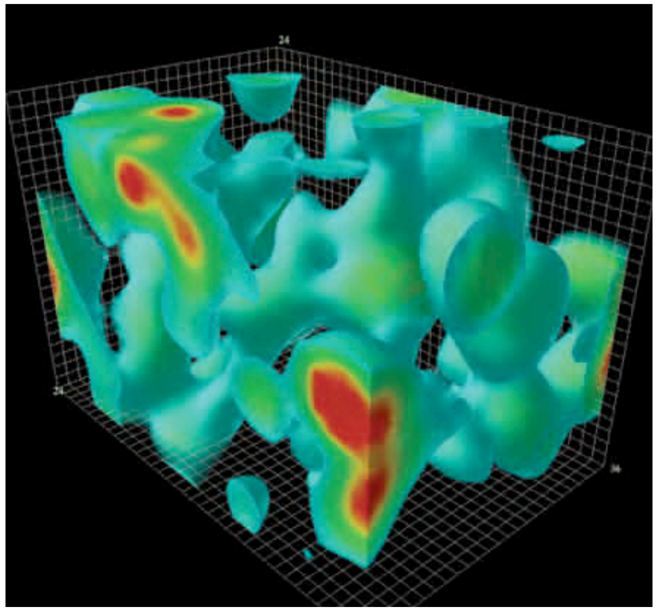
Quark Matter 2012, Washington DC
08/17/2012
Hannah Petersen, Duke University

What Causes Events to Differ?

The basic question:

Why do single collisions of indistinguishable ground state nuclei have different properties?

- Controllable Differences:
  - Changing the beam energy
  - Centrality selection
  - Choice of system
- BUT: Quantum fluctuations are unavoidable



The resulting challenge:

Fluctuations affect the probes of the quark gluon plasma

and opportunity:

Initial state fluctuations provide constraints on transport properties

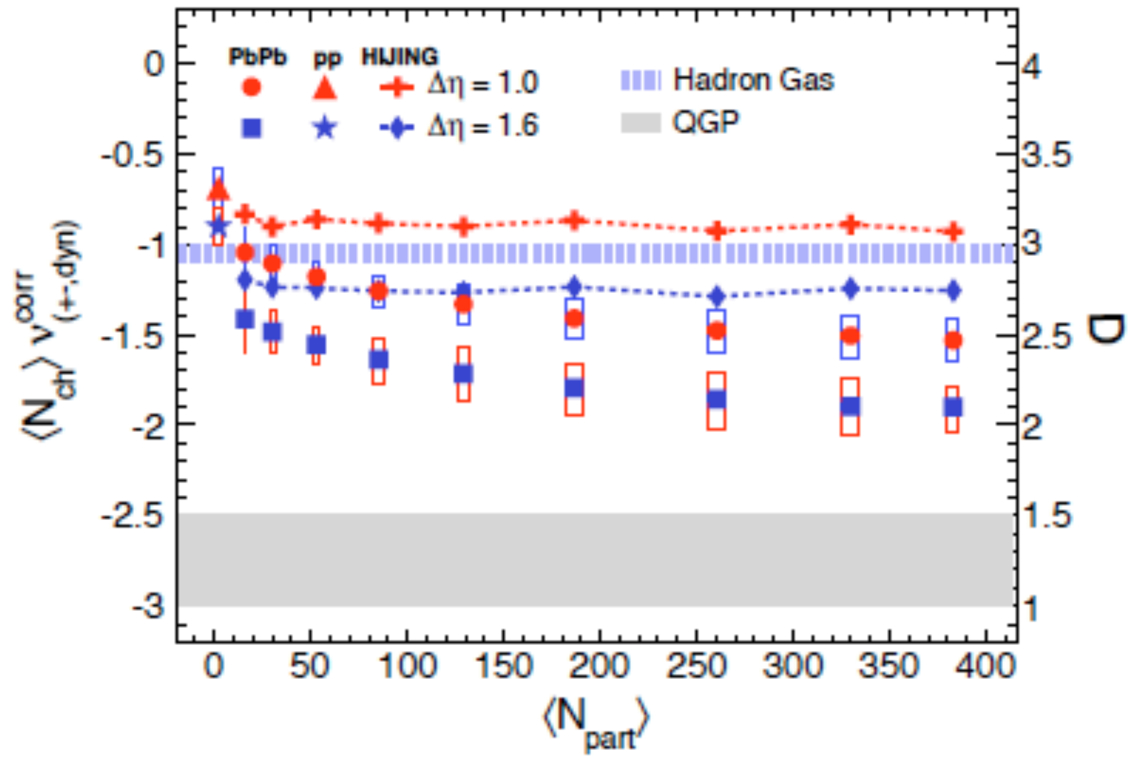
Heavy ion event-by-event measurements contribute towards determining these highly energetic nuclear initial states

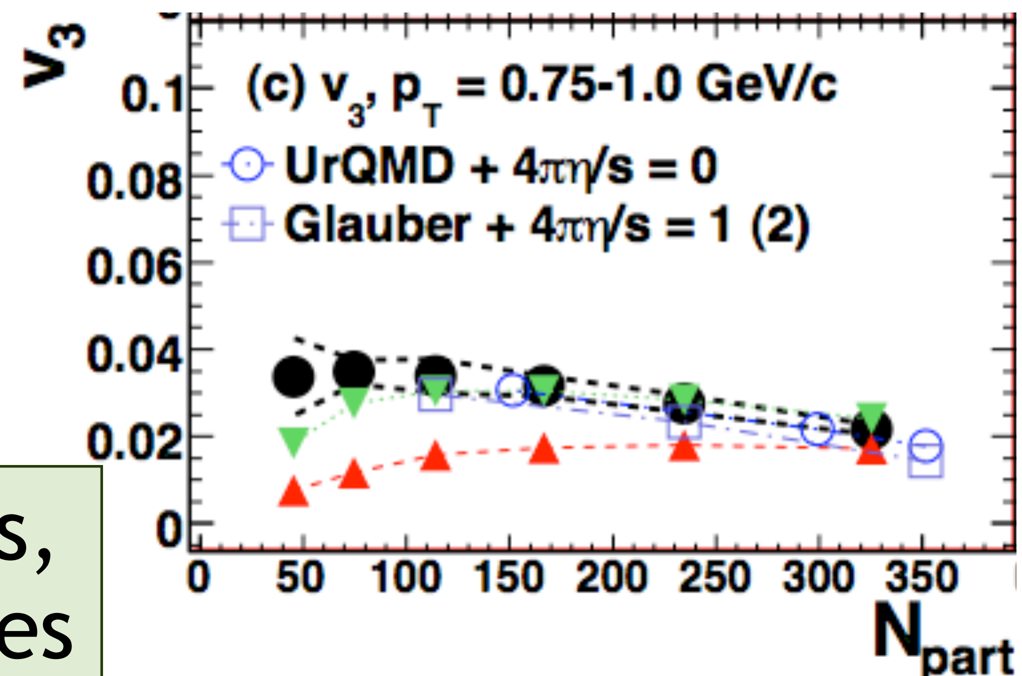
Fluctuation Observables

- 'Traditional' event-by-event fluctuations:
  - <p_T> fluctuations, conserved charge fluctuations, particle ratio fluctuations,..
- Higher moments of net proton distribution:
  - Skewness, kurtosis, 6th order cumulant,..
- Odd-numbered flow harmonics:
  - Event plane uncorrelated to reaction plane for rapidity-even v1, v3, v5
- Flow fluctuations:
  - Dynamical fluctuations of elliptic flow

There is a huge amount of measurements, calculations of many different observables in one approach are rare

ALICE, arxiv: 1207.6068

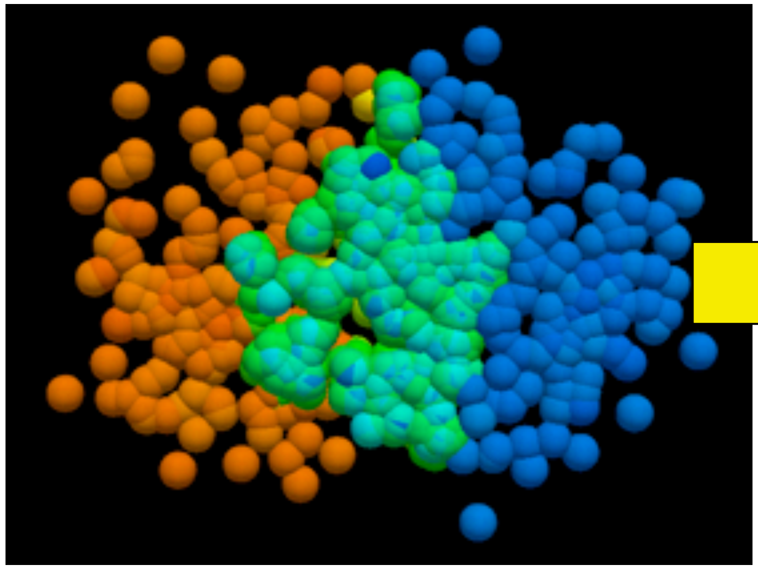




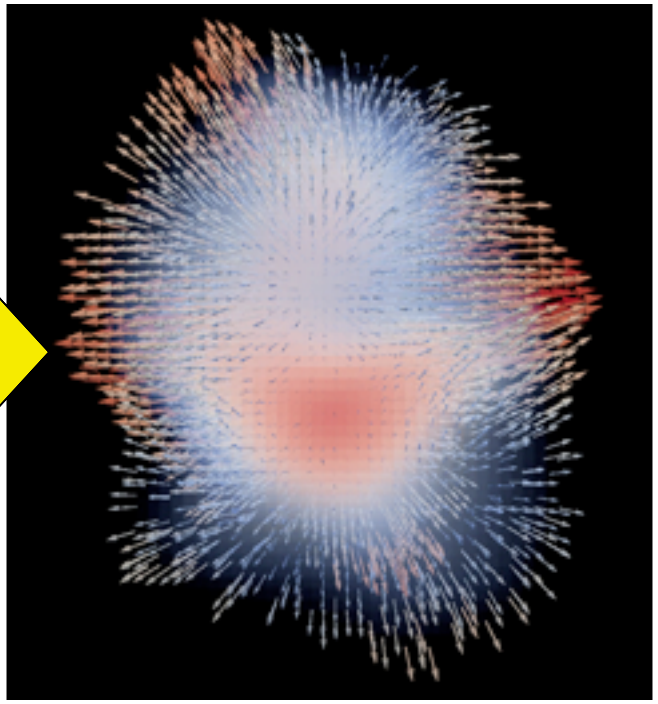
PHENIX, Phys.Rev.Lett. 107 (2011) 252301

Paradigm of Fluctuations and Higher v_n's

Initial State Fluctuations



Higher Flow Harmonics

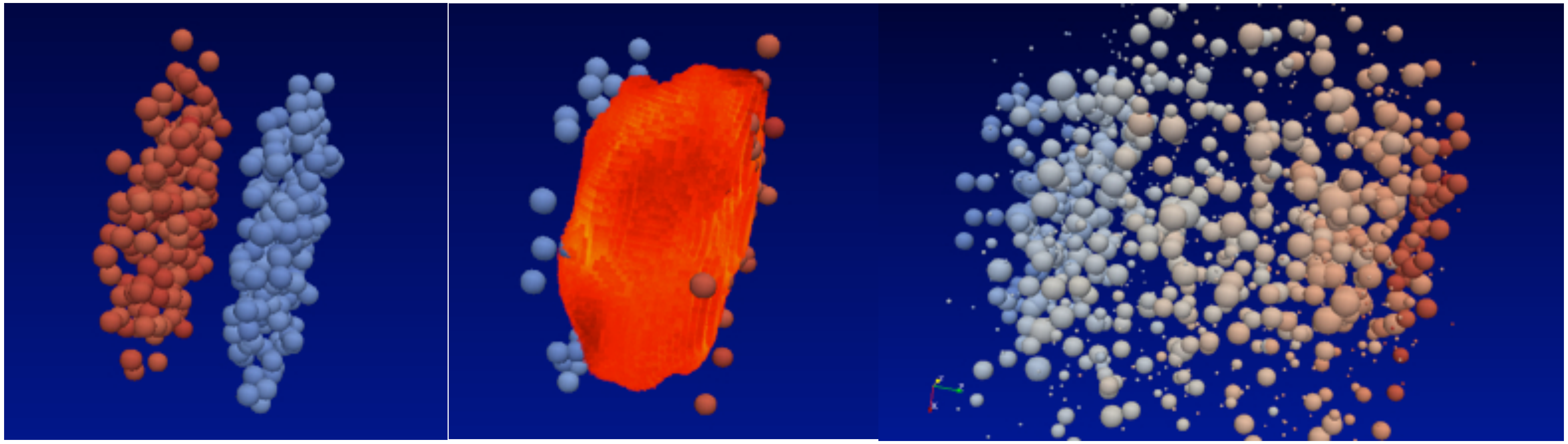


by MADAI.us

- Characterization of initial state profiles by **eccentricities**
- Hydrodynamic **response** and extraction of shear viscosity
- Final state momentum space analysis of **anisotropic flow** coefficients

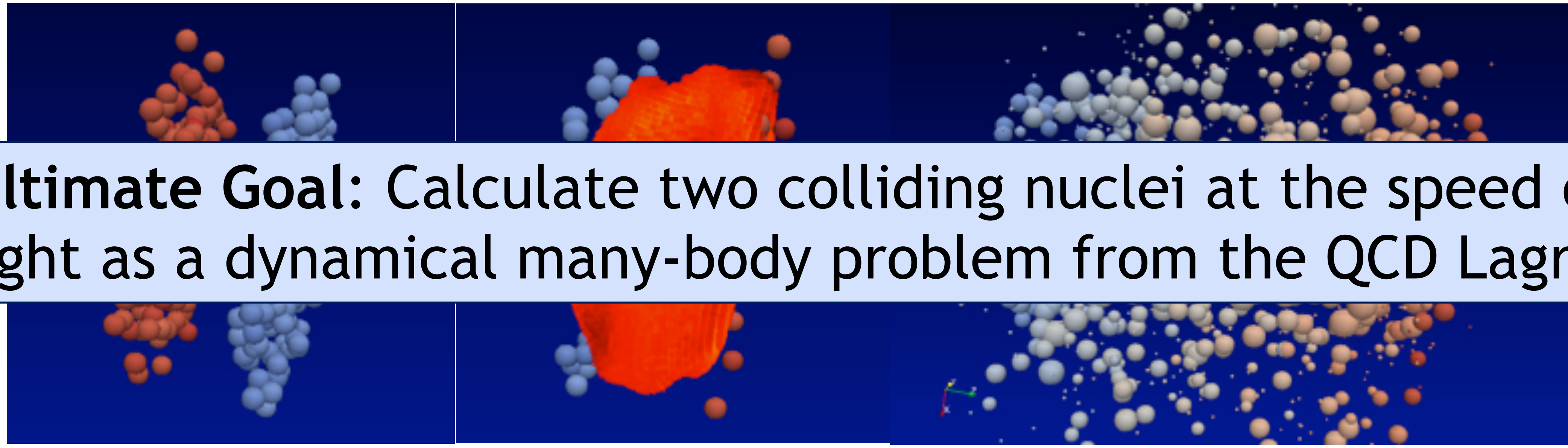
This topic has been covered in the plenary talks on Monday afternoon...

Full Event-by-Event Calculations



- Elements for a consistent description of the whole heavy ion reaction at highest RHIC and LHC energies:
  - Initial Conditions
  - Pre-equilibrium Evolution
  - Hydrodynamics
  - Hadronization
  - Hadronic Rescattering and Freeze-out
- How to do a meaningful comparison to experimental data?
- What is different at lower beam energies?

Full Event-by-Event Calculations



Ultimate Goal: Calculate two colliding nuclei at the speed of light as a dynamical many-body problem from the QCD Lagrangian

- Elements for a consistent description of the whole heavy ion reaction at highest RHIC and LHC energies:
  - Initial Conditions
  - Pre-equilibrium Evolution
  - Hydrodynamics
  - Hadronization
  - Hadronic Rescattering and F

E-by-e simulations are **necessary**:
- Bulk properties, fluctuation observables
- Background for hard probes, especially correlations

- How to do a meaningful comparison to experimental data?
- What is different at lower beam energies?

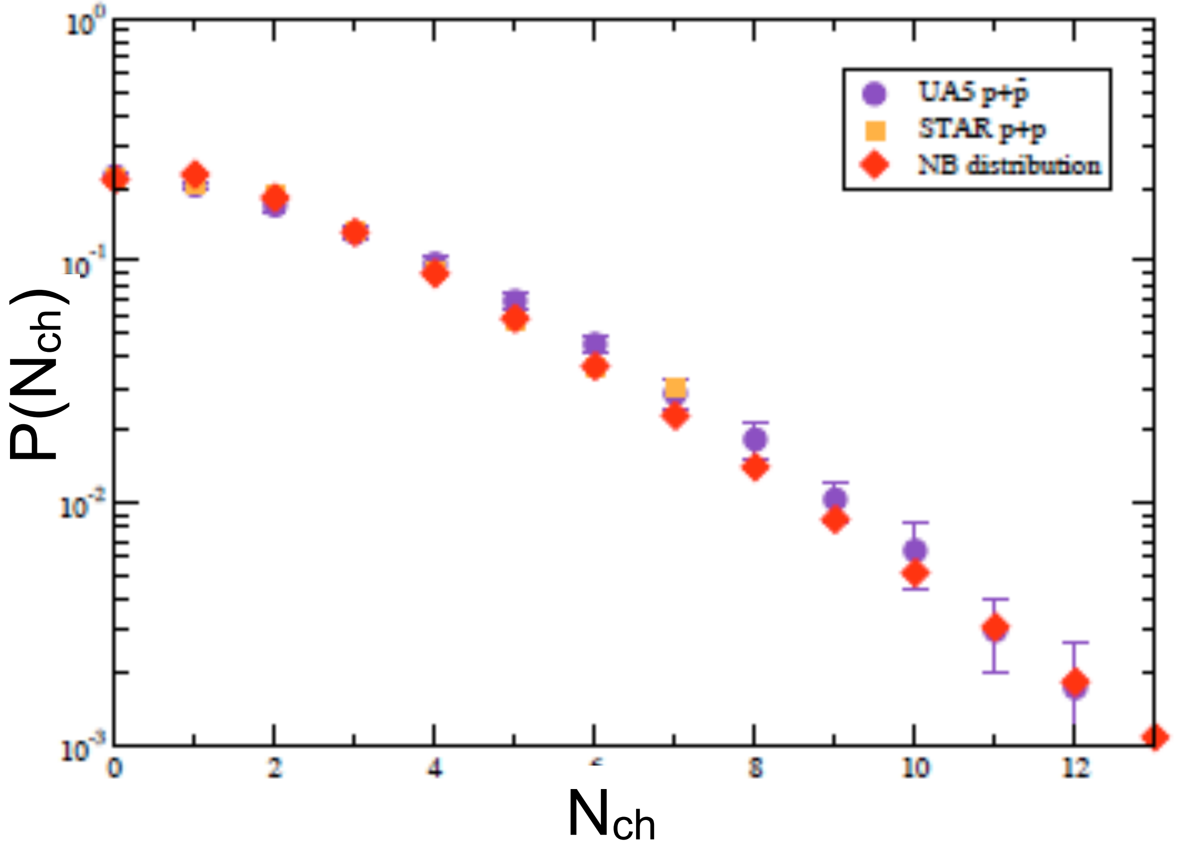
Initial State I

- Higher flow harmonics demonstrate need for initial state fluctuations on nucleon scale
- Find a reasonable **parametrization** that captures important features that are known to exist

- Nucleon degrees of freedom:
  - Fluctuations in nucleon **positions** and binary collisions
  - **Finite size** of the nucleons and NN correlations
  - **Energy deposition** per collision E.g.: Match known multiplicity distributions from p-p collisions

For example:
M. Rybczynski et al, Phys.Rev. C84 (2011) 064913,
M. Alvioli et al, Phys.Rev. C85 (2012) 034902

Negative Binomial multiplicity distributions in elementary collisions

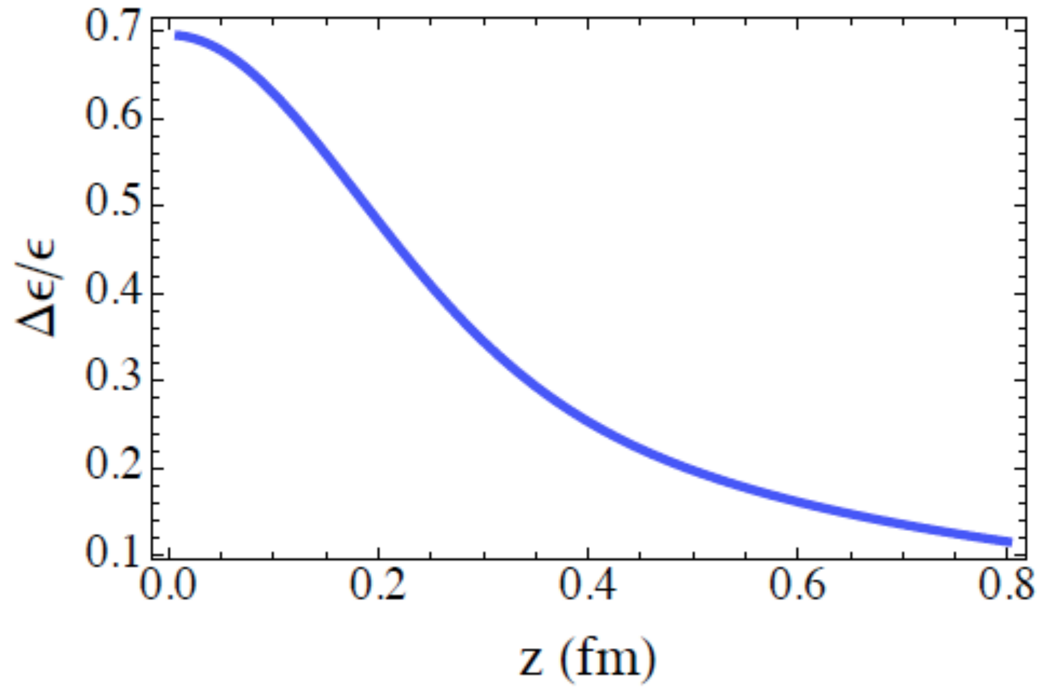


G.-Y. Qin, HP, S.A. Bass, B. Mueller, Phys.Rev. C82 (2010) 064903

Initial State II

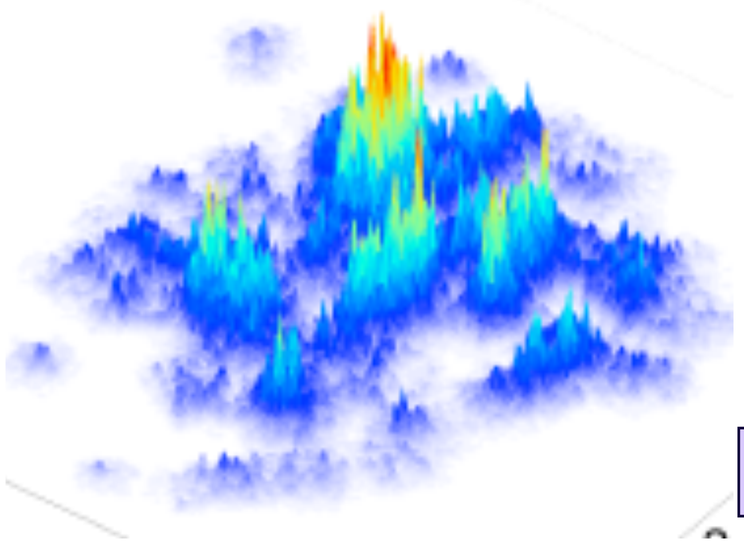
- Internal structure of the fluctuating gluon field:
  - Quantum fluctuations on smaller scales ~$1/Q_s$

Gaussian CGC model correlations



B. Mueller and A. Schaefer, PRD 85 (2012) 114030

Glasma, IP Sat Model



P3A B. Schenke

Schenke, Tribedy, Venugopalan, arXiv: 1202.6646, 1206.6805

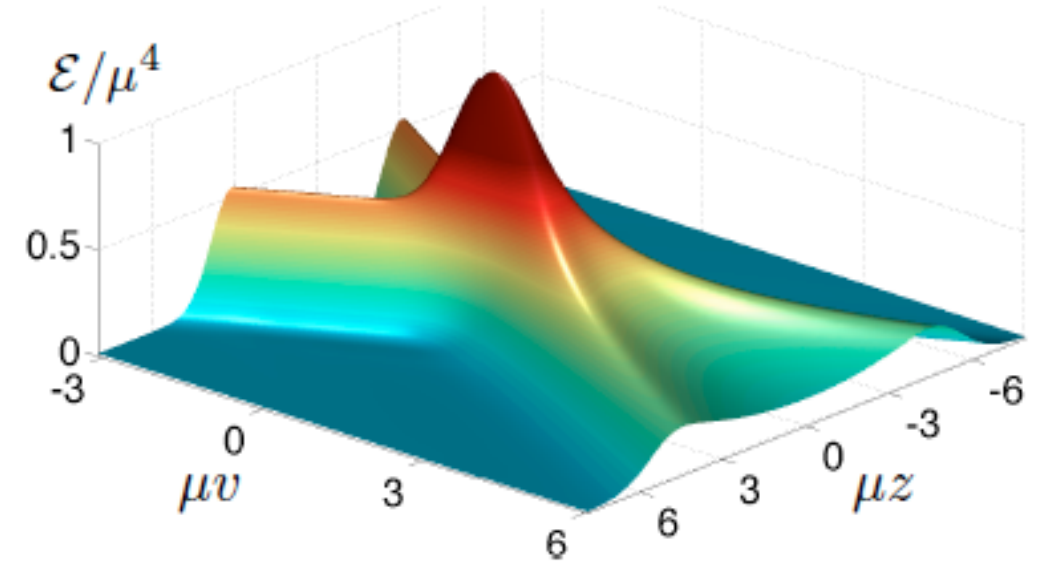
Related recent work:
A. Dumitru, Y. Nara, PRC85 (2012)
F. Gelis, T. Lappi, L. McLerran, NPA828 (2009)

- Precise **quantitative predictions** of the correlation length and scale of fluctuations associated with finer structures are needed
- Understand **sensitivity** of observables in more detail

Pre-equilibrium Evolution I

- Initial non-equilibrium evolution is **inevitable**
  - Leads to a nearly **thermalized** system on a short timescale
  - Provides full **energy-momentum tensor** including viscous corrections and initial flow components

- Qualitative attempts:
  - Plasma instabilities in anisotropic systems
    Dumitru, Nara, Strickland, Phys.Rev. D75 (2007) 025016
    Schlichting, arxiv:1207.1450
    Ipp et al PRD 84 (2011); Attems et al arxiv:1207.5795
  - Anisotropic hydrodynamics
    P3D
    Ryblewski, Florkowski, Phys.Rev. C85 (2012) 064901
    Martinez, Ryblewski, Strickland, Phys.Rev. C85 (2012) 064913
  - Colliding sheets in ADS/CFT
    Albacete, Kovchegov, Taliotis, JHEP 0807 (2008) 100
    Heller, Janik, Witaszczyk, PRD 85 (2012), PRL 108 (2012)
    Beuf, Heller, Janik, Peschanski, JHEP 0910 (2009) 043



P. Chesler, L. Yaffe, Phys.Rev.Lett. 106 (2011) 021601

P3D P. Chesler

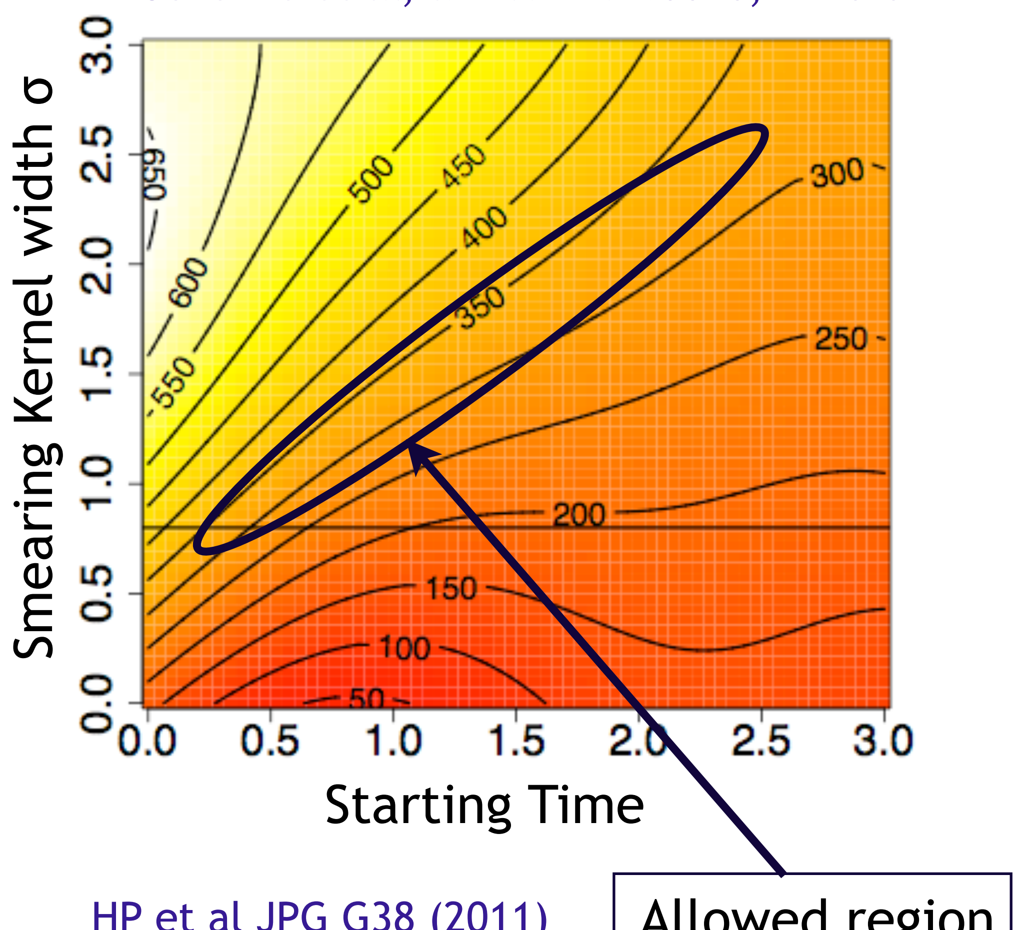
A first principle approach that determines **quantitatively** the initial energy-momentum tensor unambiguously is still missing

Pre-equilibrium Evolution II

- The **current options** in use by hydro groups:
  - Use parametrizations that attempt to capture the dynamics
  - Add free streaming to generate initial flow Broniowski et al, PRC 80 (2009) Qin et al, PRC 82 (2010)
  - Take favorite event generator (NEXUS, EPOS, UrQMD, AMPT,..) and enforce equilibrium Gardim et al, arXiv:1203.2882, Werner et al PRC 85 (2012), HP et al PRC 82 (2010), Pang et al, arXiv:1205.5019
  - Calculate classical Yang-Mills dynamics to simulate Glasma evolution Schenke et al, arXiv: 1202.6646, 1206.6805

All of these models contain **parameters**

Bulk observables restrict the initial state parameter space



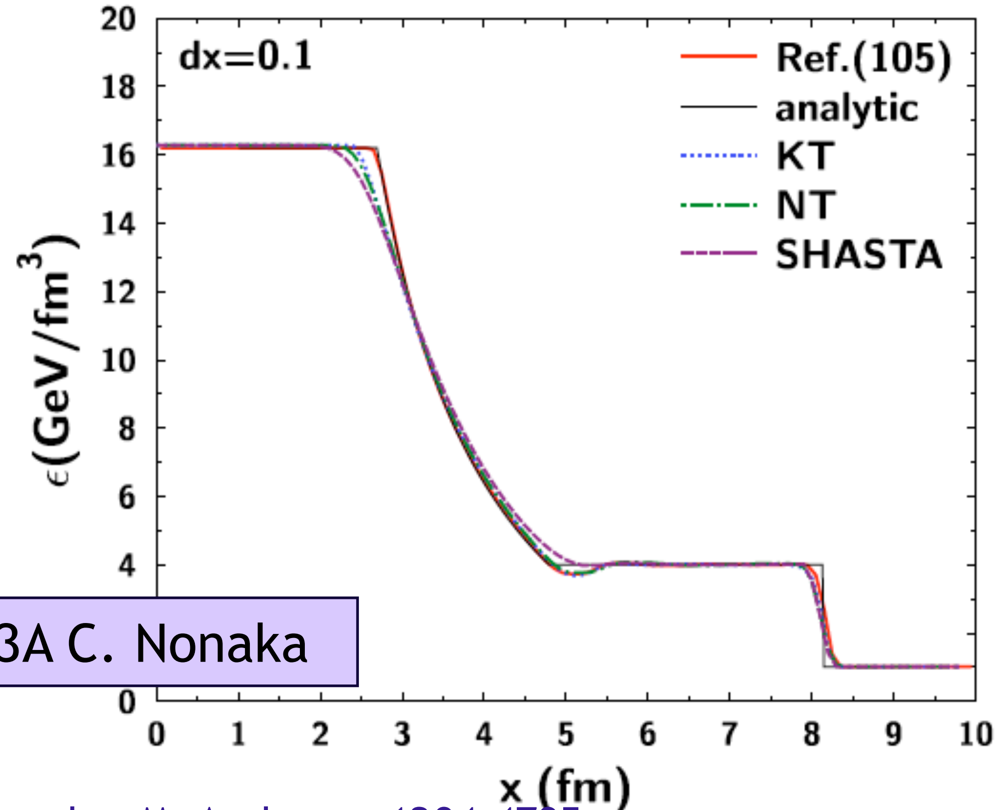
HP et al JPG G38 (2011)

Viscous Hydrodynamics

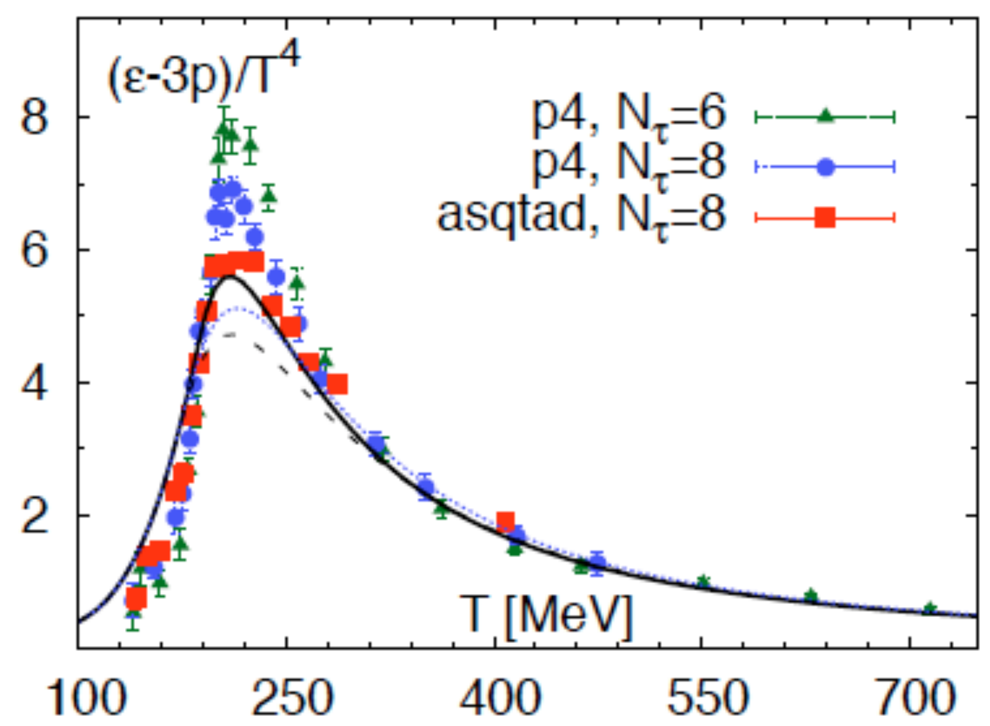
- **3+1d viscous** hydrodynamics is applied by many groups

  For example: McGill PRL106 (2011), MSU PRC85 (2012), Krakau PRC85 (2012), Nagoya in preparation
  - Stability against **shocks** is crucial for event-by-event calculations
  - Progress in development of **efficient** codes

J. Gerhard, V. Lindenstruth, M. Bleicher, arxiv: 1206.0919



C. Nonaka, M. Asakawa, 1204.4795



P. Huovinen, P. Petreczky, Nucl.Phys. A837 (2010) 26-53

- **Equation of state** that matches available lattice QCD data
  - What about finite baryo-chemical potential?
- **Hypersurface** finder that can resolve interesting structures

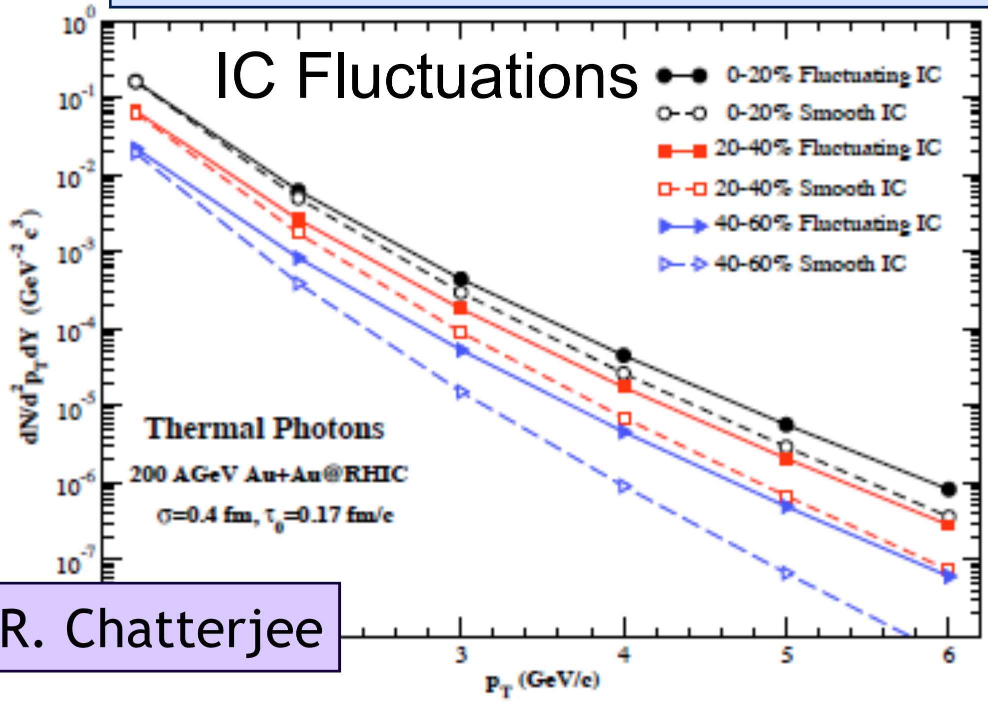
P. Huovinen, HP, 1206.3371

Adding Complexity

- The local equilibrium assumption breaks down
  - At high rapidities
  - At intermediate momenta
  - In peripheral collisions
  - At lower beam energies
  - During later stages of the reaction

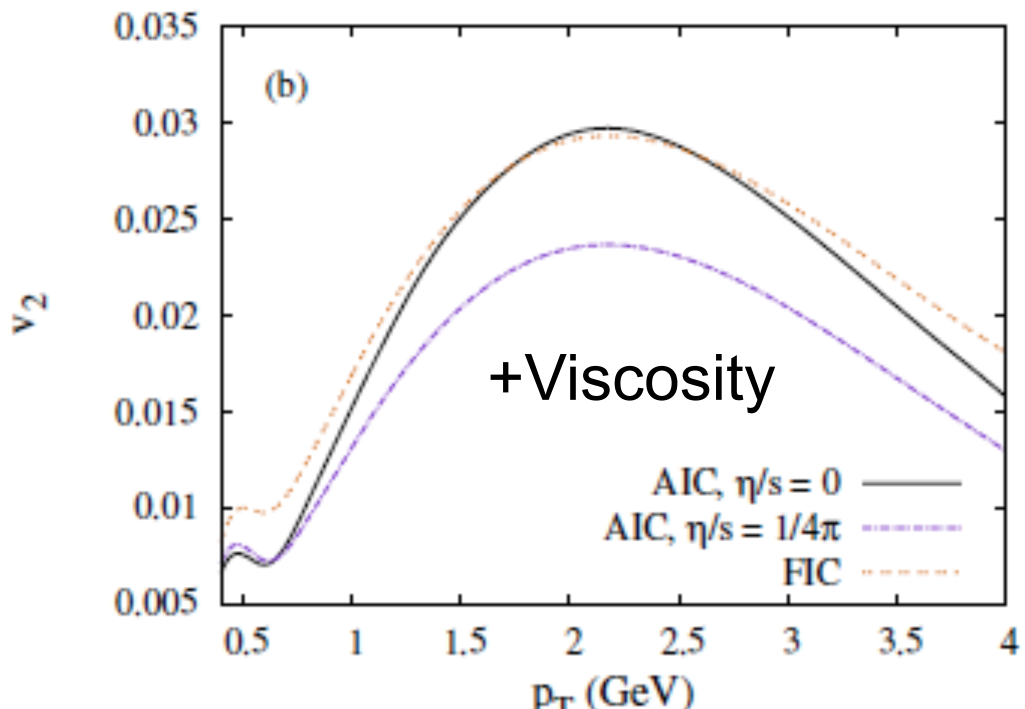
What is the phase-space dependence of transport properties?

Adding electromagnetic probes increases sensitivity to hot spots in the initial state



P6E R. Chatterjee

R. Chatterjee et al, Phys.Rev. C85 (2012) 064910

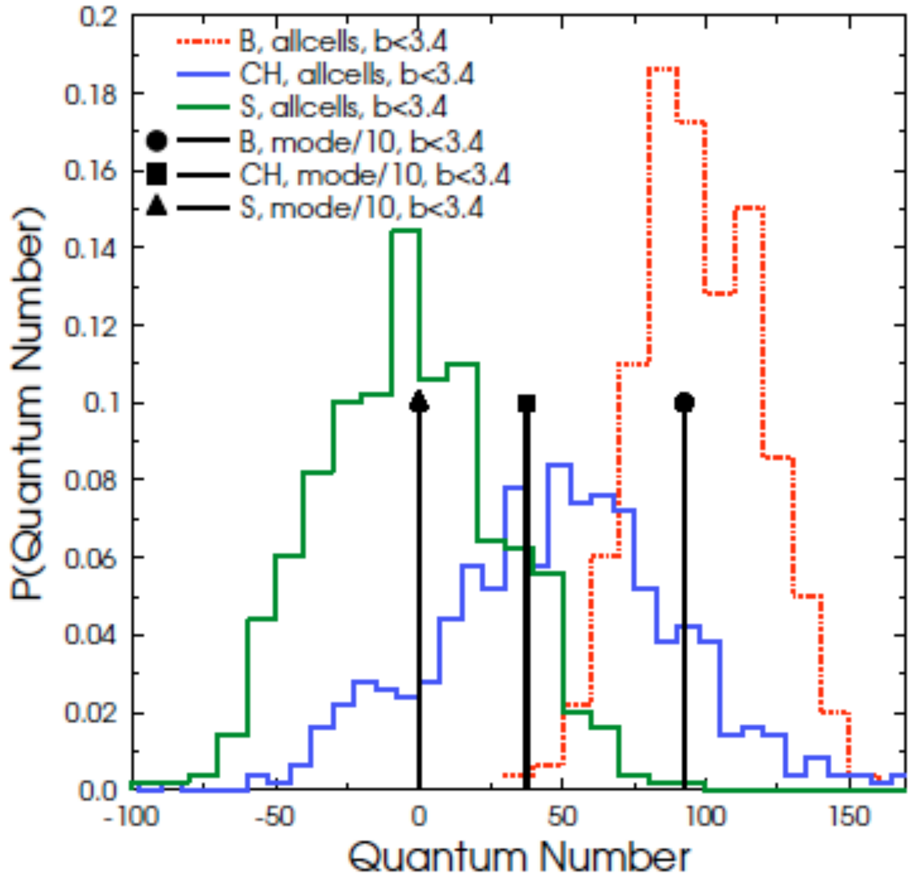


M. Dion et al, Phys.Rev. C84 (2011) 064901

Hadronization and Cooper-Frye

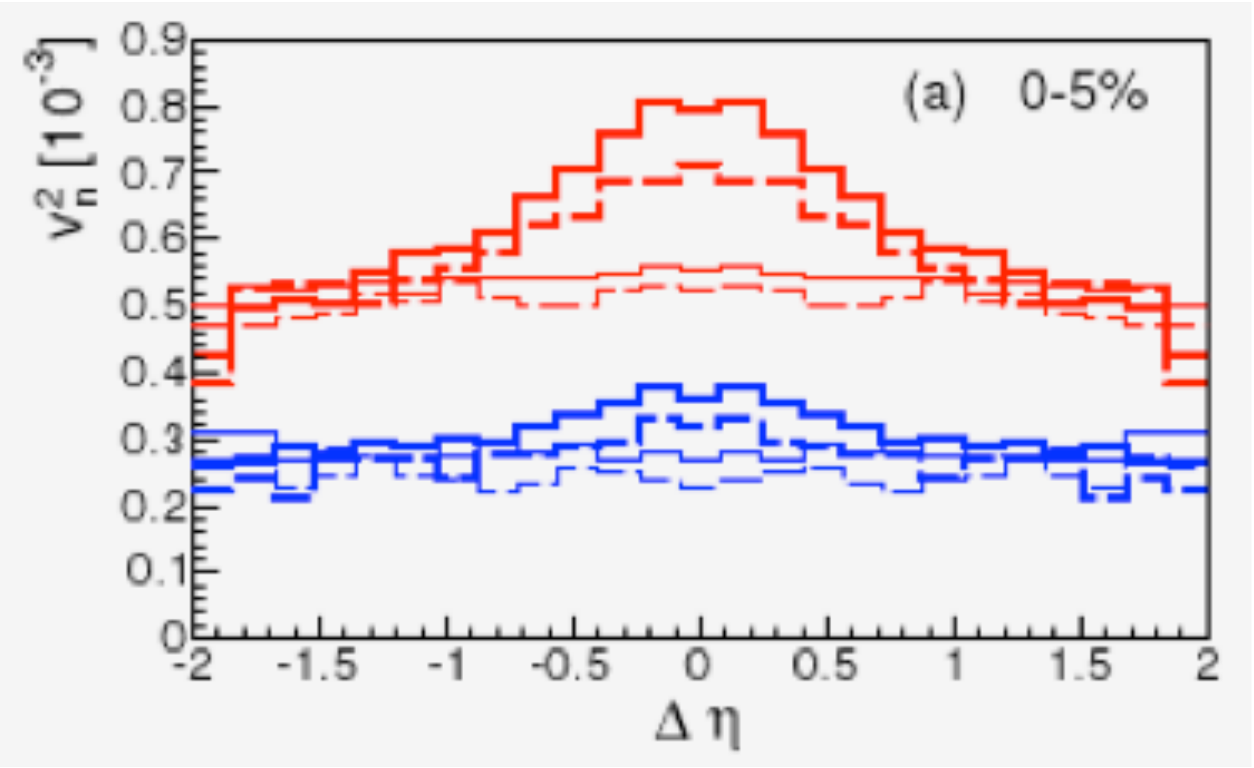
- Experiments observe **finite number** of hadrons in detectors
- **Hadronization** controlled by the equation of state
- Sampling of particles according to **Cooper-Frye** should:
  - Respect **conservation laws**, maybe even locally?
  - Introduces fluctuations on its own

Quantum number fluctuations



P. Huovinen, HP, arxiv: 1206.3371

Local charge conservation ->Bump in $v_n^2(\Delta\eta)$



P. Bozek, W. Broniowski, arxiv:1204.3580

P2C P. Bozek

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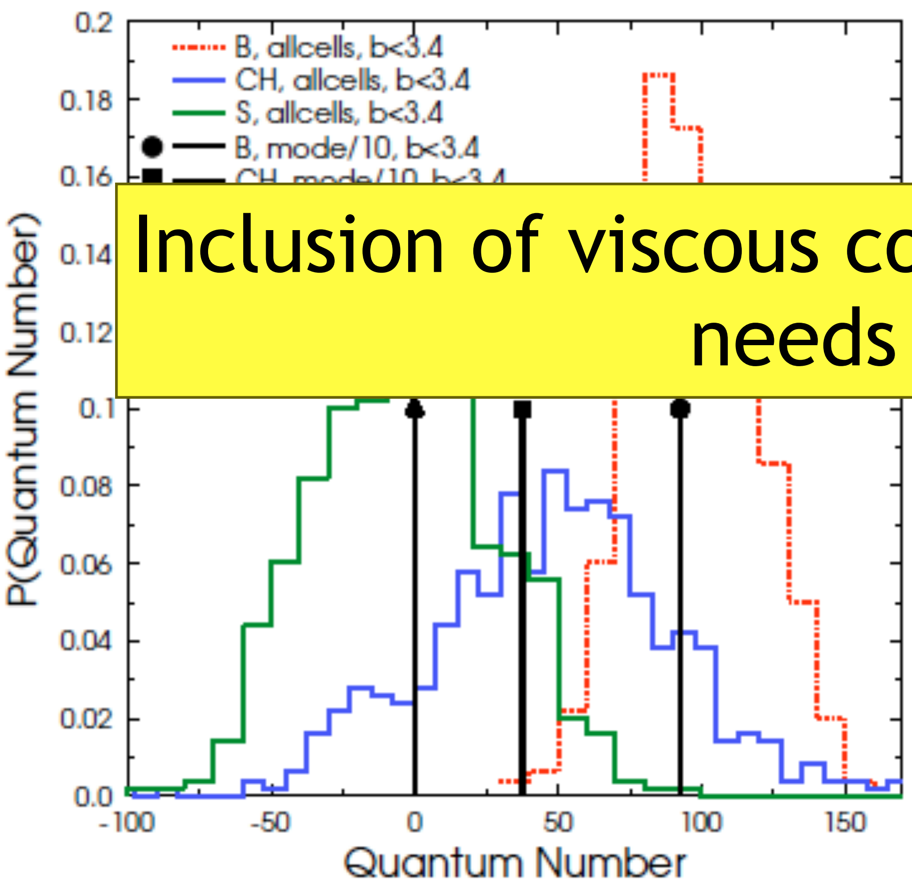

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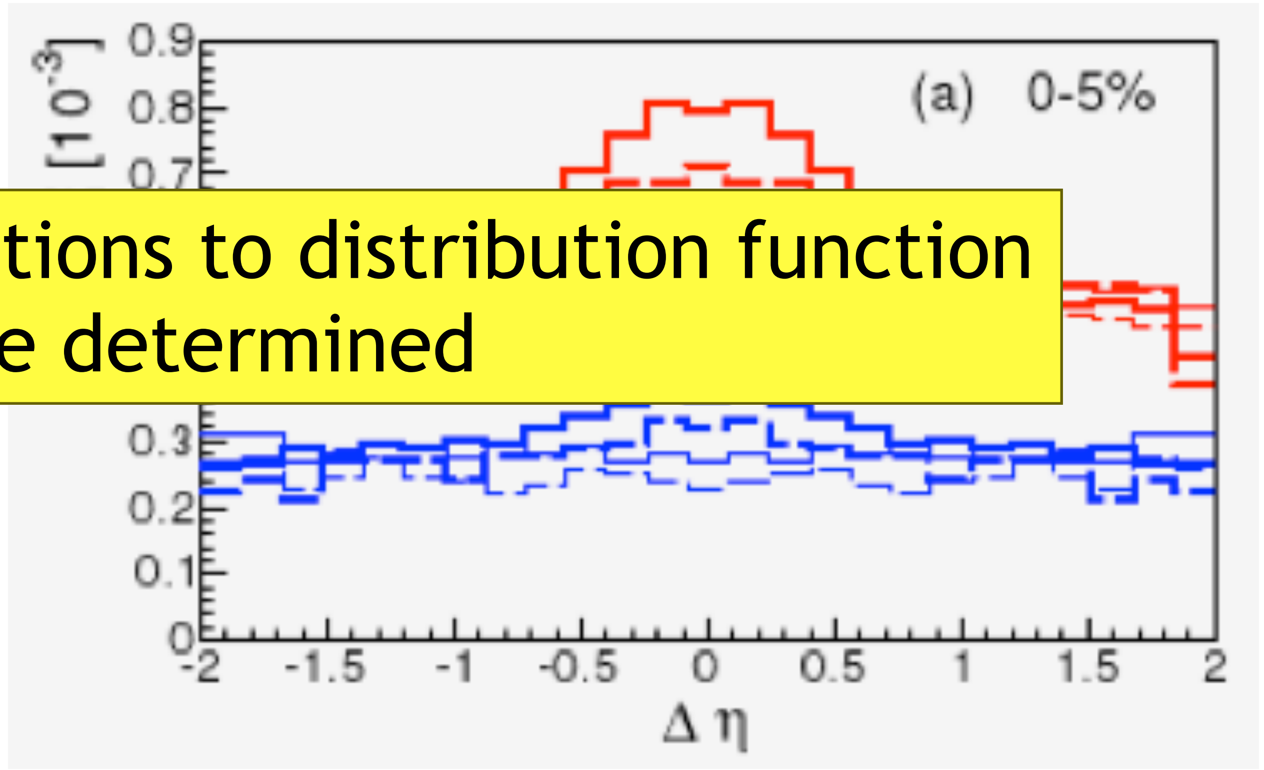


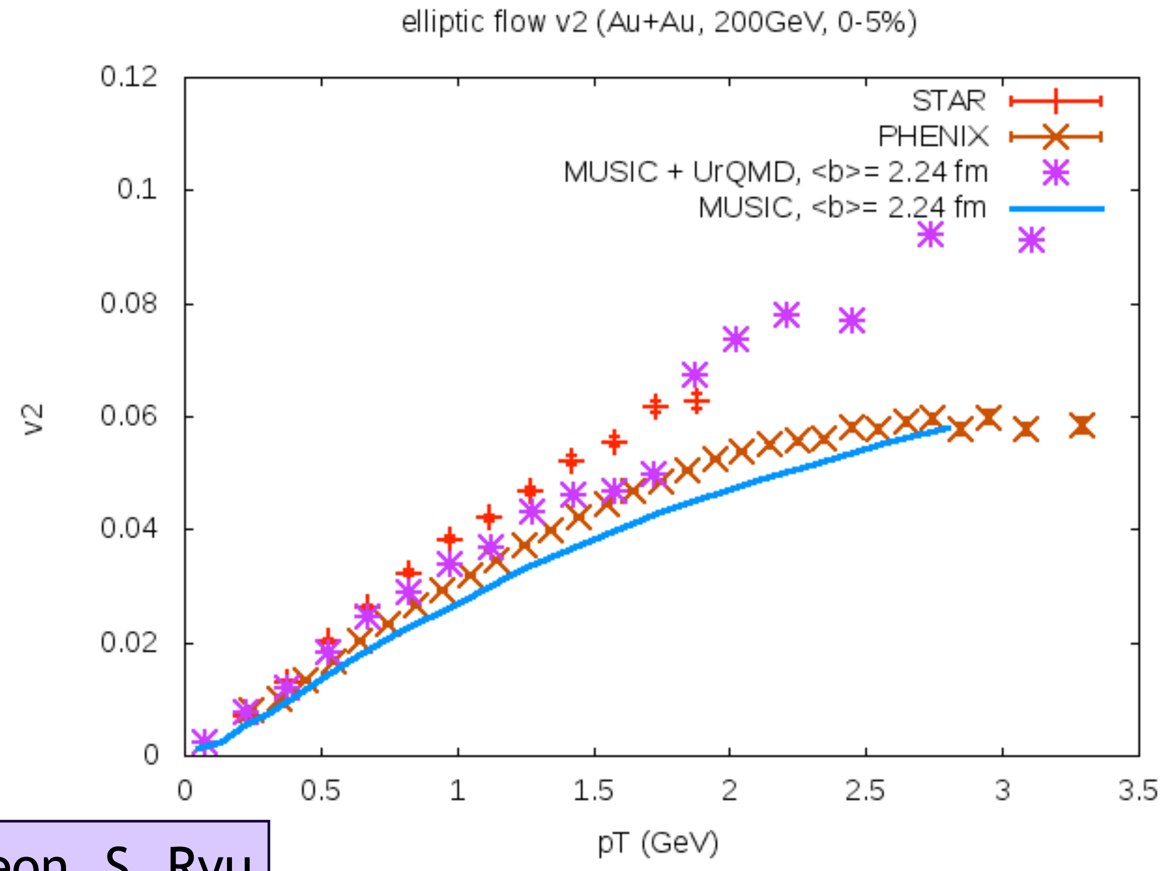
P. Bozek, W. Broniowski, arxiv:1204.3580

Inclusion of viscous corrections to distribution function needs to be determined

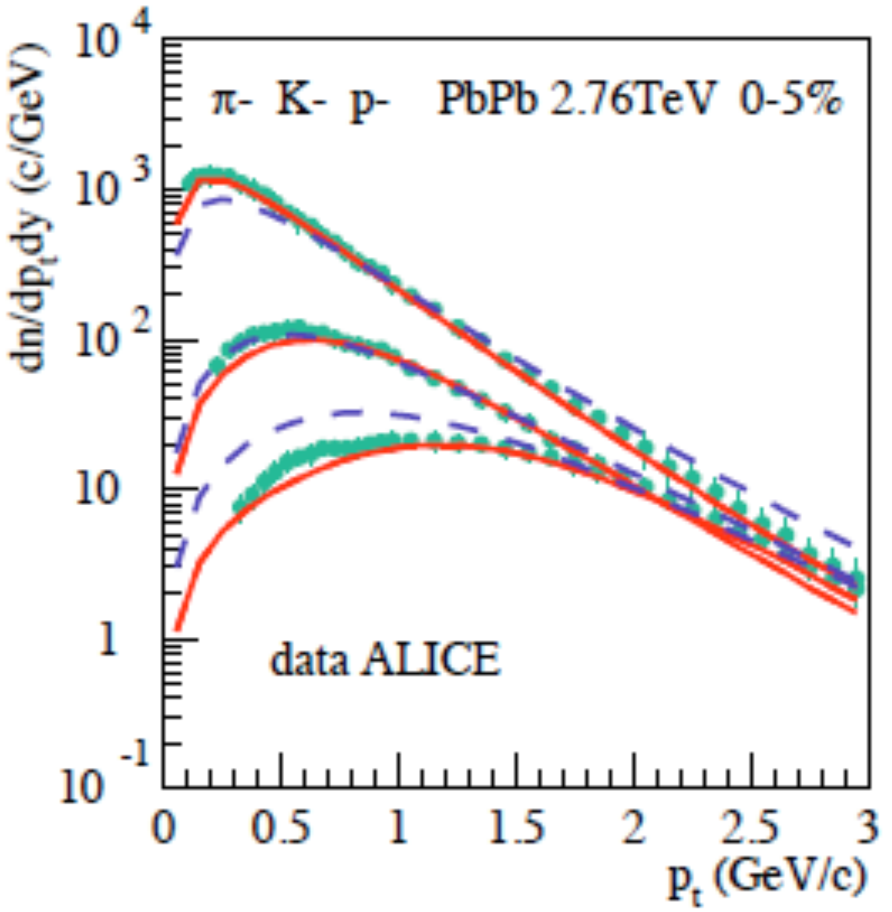
P2C P. Bozek

Final State Rescattering

- Reminder on why it matters:
  - Separation of chemical and kinetic **freeze-out**
  - Provides the only option to apply exact same analysis as in experiment
  - Influences the dynamics of **identified particles**:
    - Increase of mean transverse momentum by up to 30%
    - Mass splitting for anisotropic flow



P2A S. Jeon, S. Ryu



Werner et al, Phys.Rev. C85 (2012) 064907

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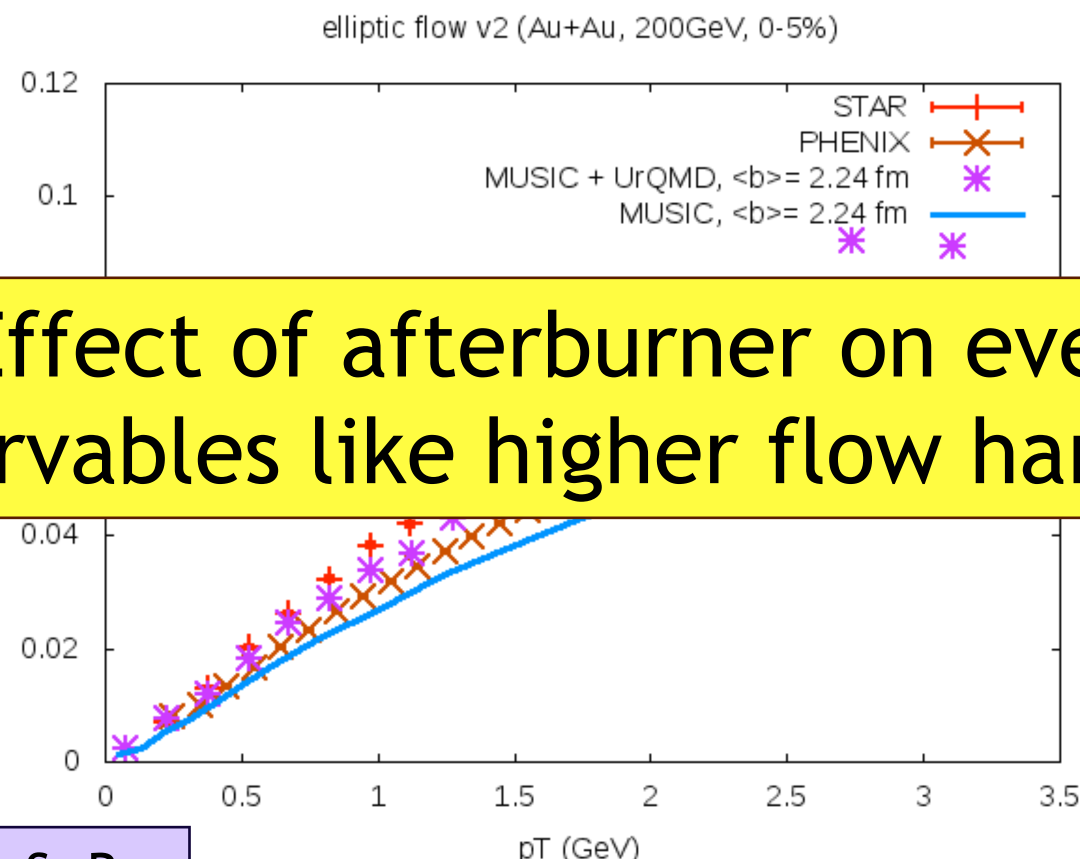
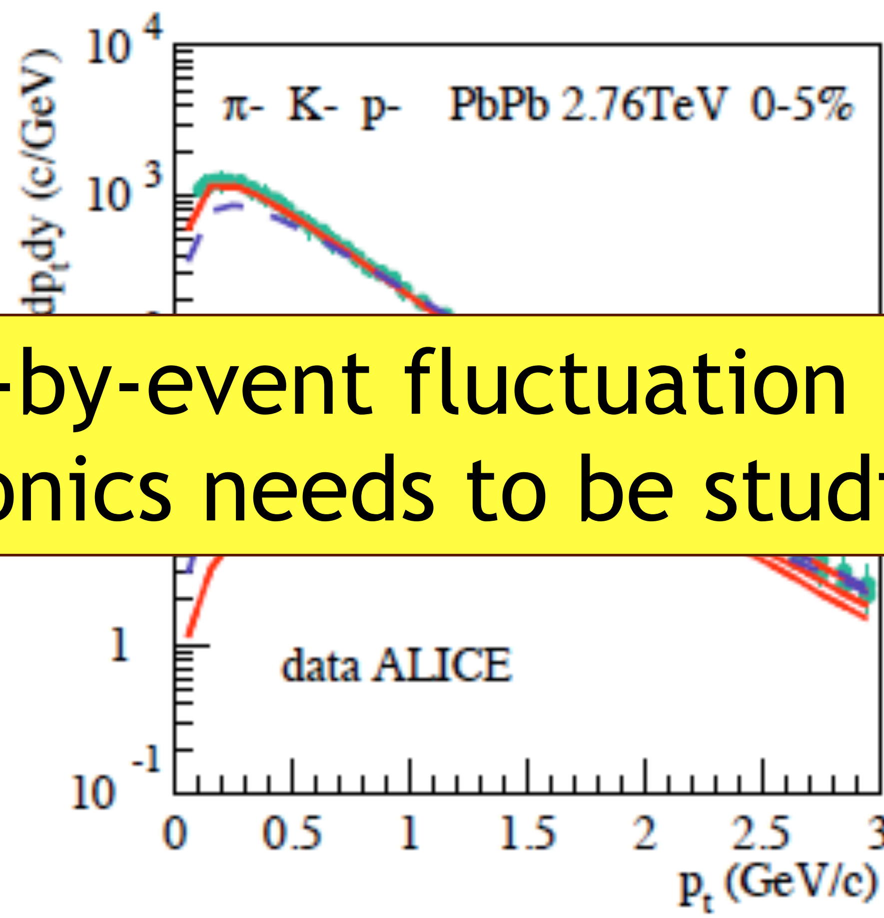




Effect of afterburner on event-by-event fluctuation observables like higher flow harmonics needs to be studied

P2A S. Jeon, S. Ryu

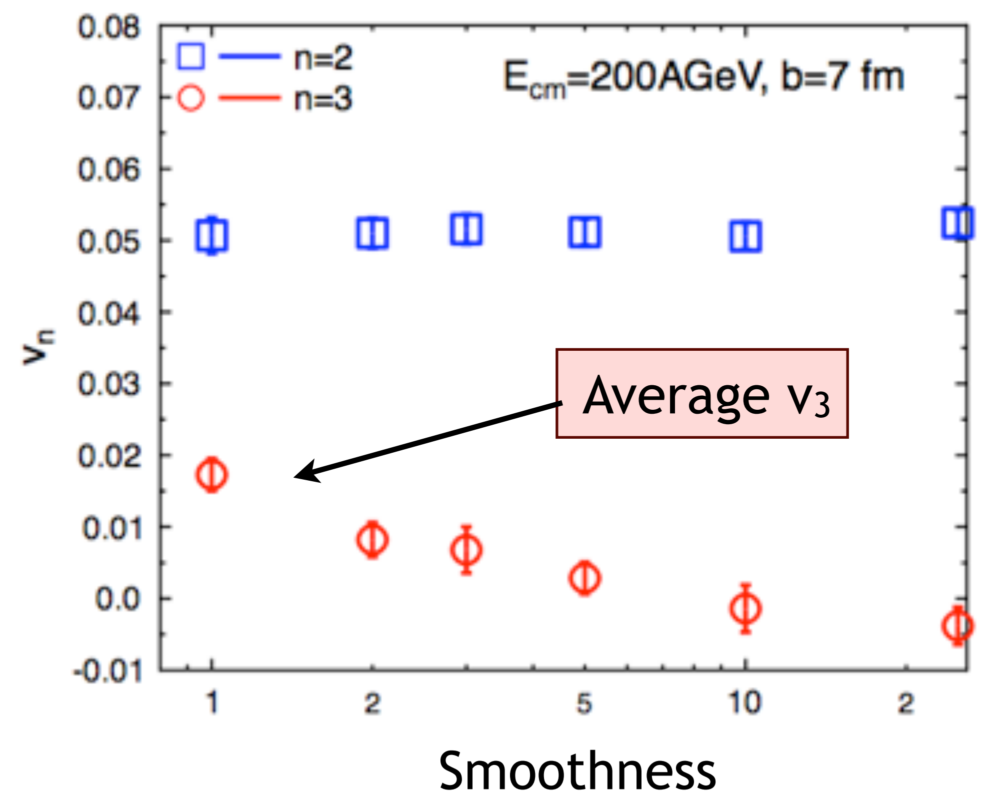
Werner et al, Phys.Rev. C85 (2012) 064907

Meaningful Comparisons

- Theory needs to pay attention to the **details**
  - Infinite statistics vs finite number of particles matters
  - Matching of centrality selection is crucial
  - Kinematic cuts can introduce large effects, especially on event-by-event observables
  - Matching the full procedure is computationally very expensive (~10^6 events are needed)
- Experimentalists help by providing details about analysis or even the tools to run it

Advantage of triangular flow over traditional e-by-e observables:

Average value is sensitive to fluctuations and needs less effort to calculate



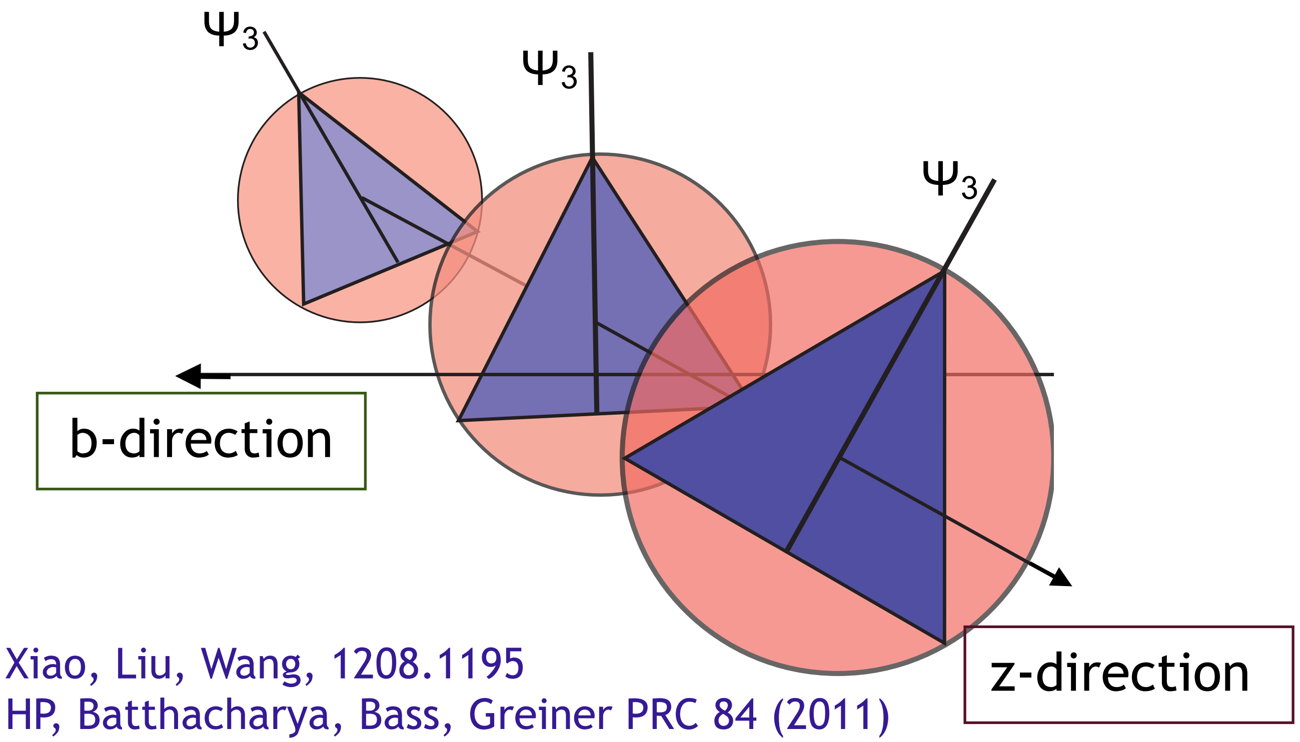
HP et al, JPG G39 (2012)

New Observables in Sight

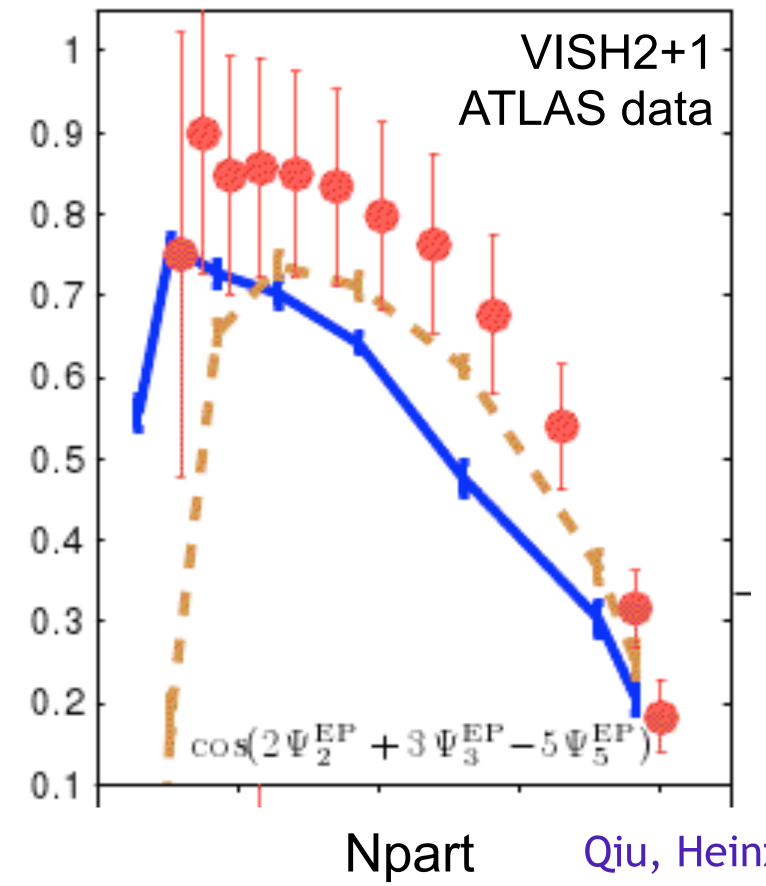
- 3-particle correlations and correlations between different **event planes** or planes in different kinematic regions
- $v_n(\Psi_m)$ with m≠n measurements

Qin, Mueller, PRC 85 (2012)
Bhalerao, Luzum, Ollitrault, PRC 84 (2011)
Jia, Mohapatra, 1203.5095; Jia, Teaney, 1205.3585

  – Useful to proof **consistency** in measurements, e.g. longitudinal correlation of event plane angles



Xiao, Liu, Wang, 1208.1195
HP, Batthacharya, Bass, Greiner PRC 84 (2011)

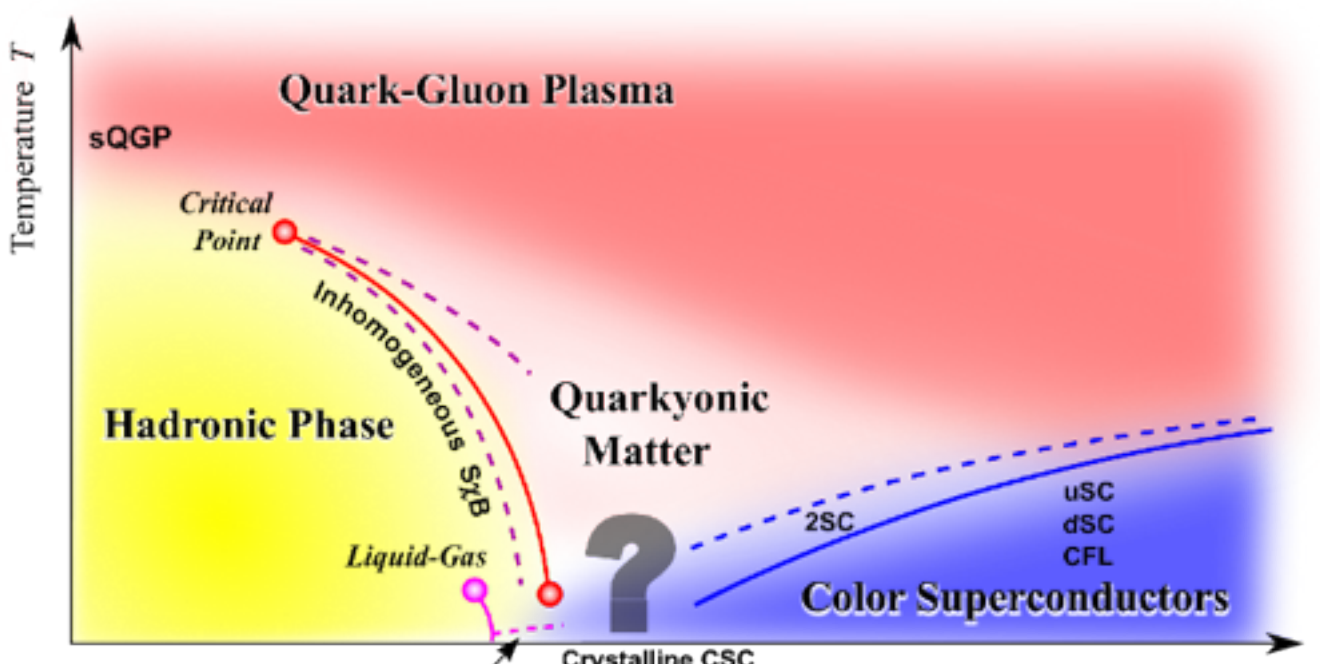


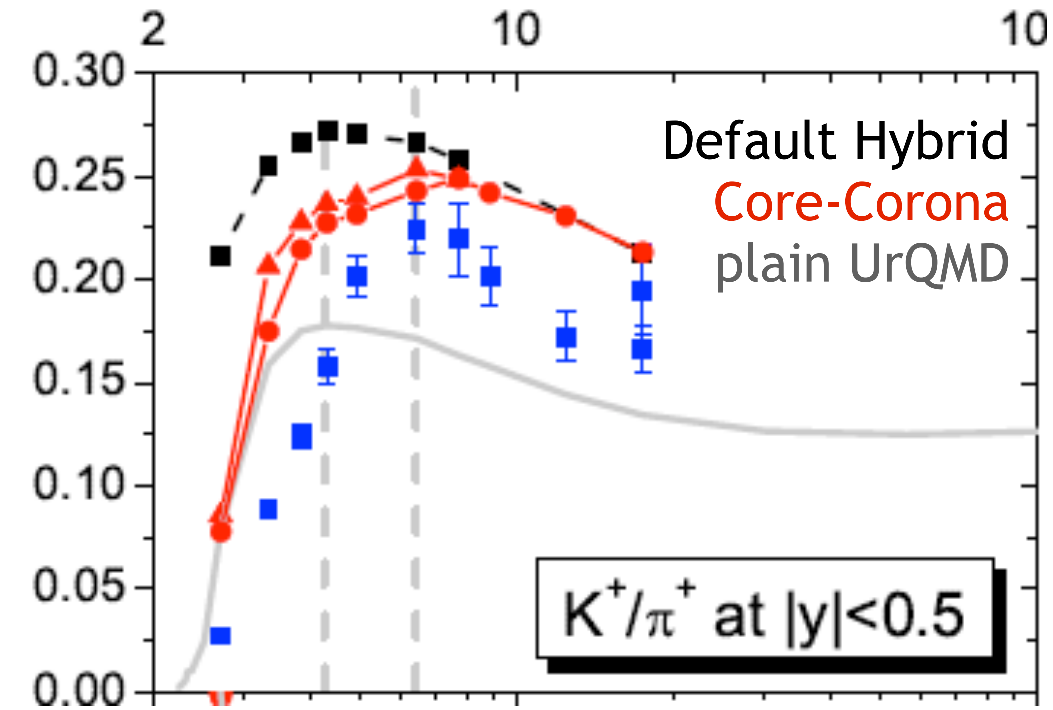
Qiu, Heinz, 1208.1200

Theory needs to keep up with experimental developments and **sort out** sensitivities of interest

Going to Lower Beam Energies I

- Differences in the evolution at lower beam energies:
  - Finite **net-baryochemical potential** needs to be taken into account in equation of state
  - **Conserved quantum numbers** need to be considered in evolution
  - **Dissipative effects** grow at lower energies (hadronic evolution gains importance)

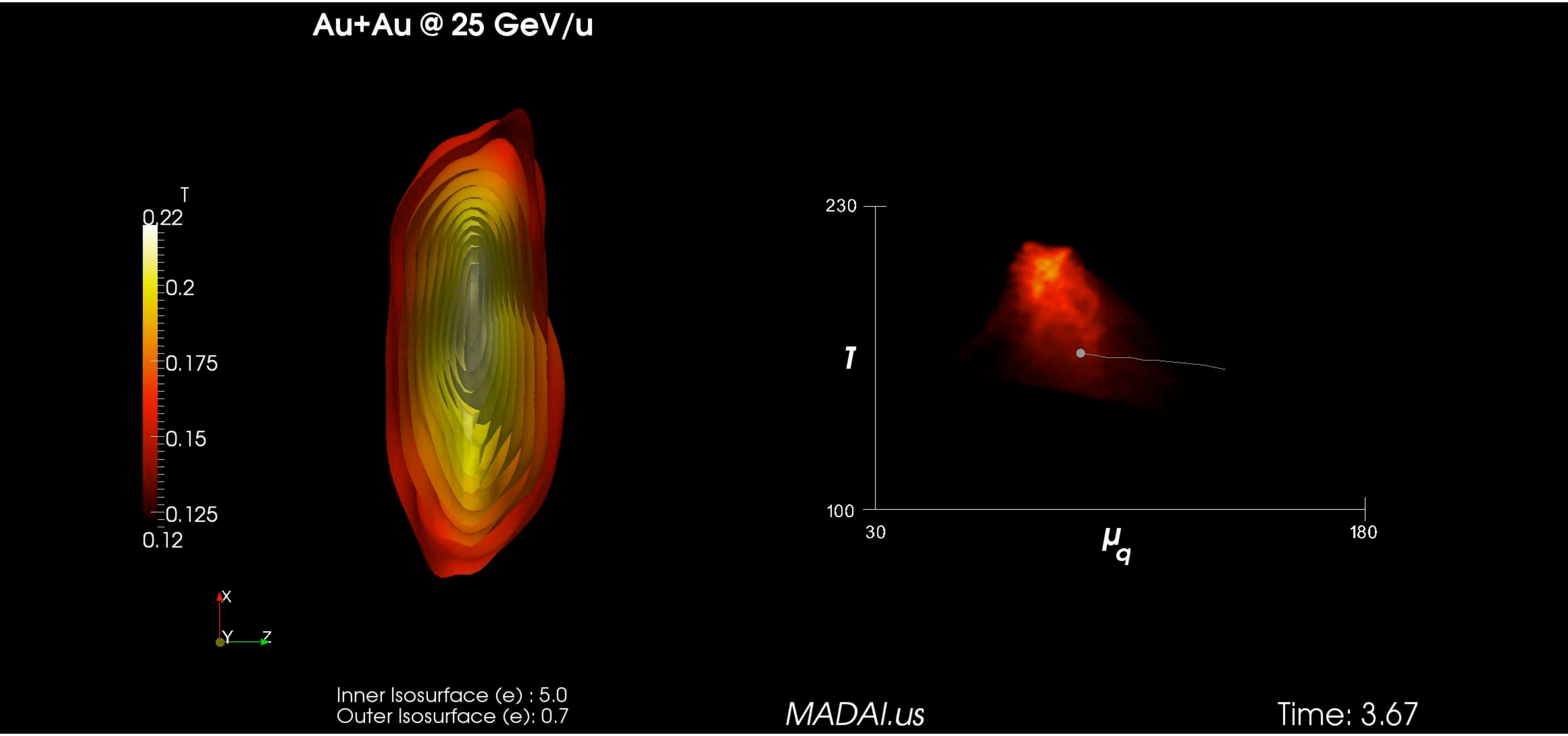




J. Steinheimer, M. Bleicher PRC84 (2011)

- Can a core-corona approach replace dynamical coupling of hydrodynamics and transport?
- Influence of splitting the system on event-by-event observables?

Exploring the Phase Diagram

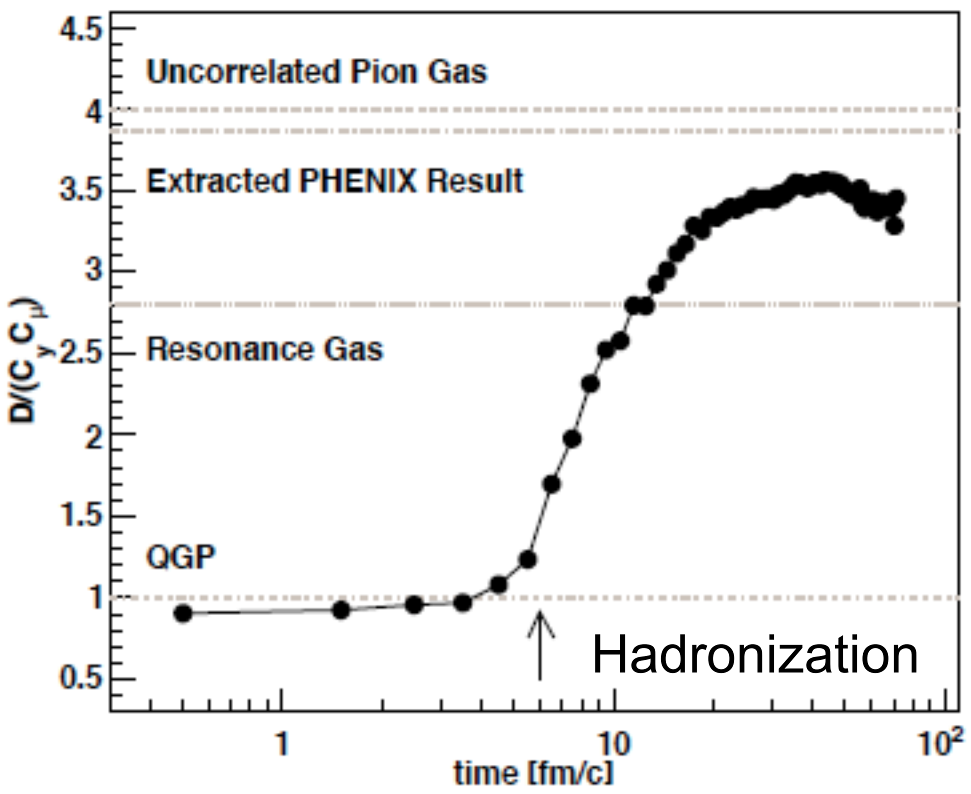


- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables for critical point or phase transition

Going to Lower Beam Energies II

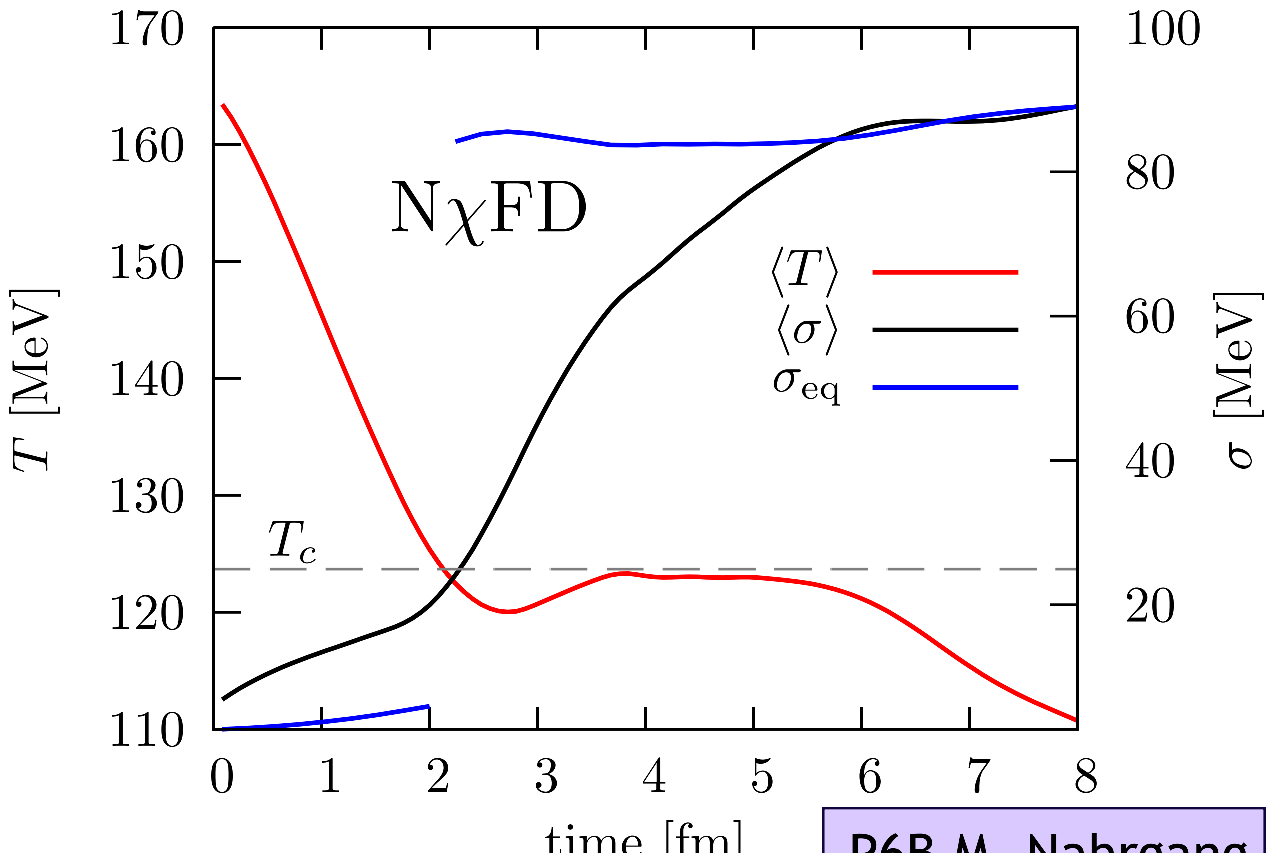
- Microscopic understanding of confinement transition is still missing
- Qualitative attempts to describe **non-equilibrium** phase transitions
- How to **disentangle** fluctuations associated with phase transition or critical point from other fluctuations, like initial state fluctuations?

qMD simulation for net charge fluctuations



S. Haussler, S. Scherer, M. Bleicher, PLB660 (2008) 197-201

Chiral Fluid Dynamics



P6B M. Nahrgang

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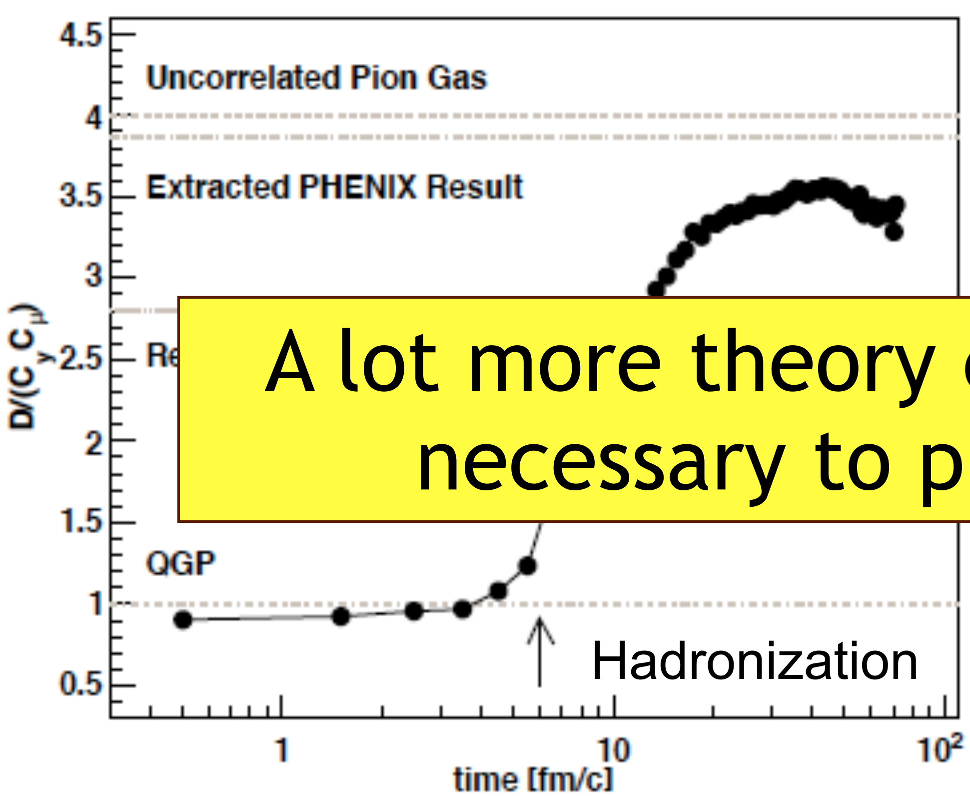

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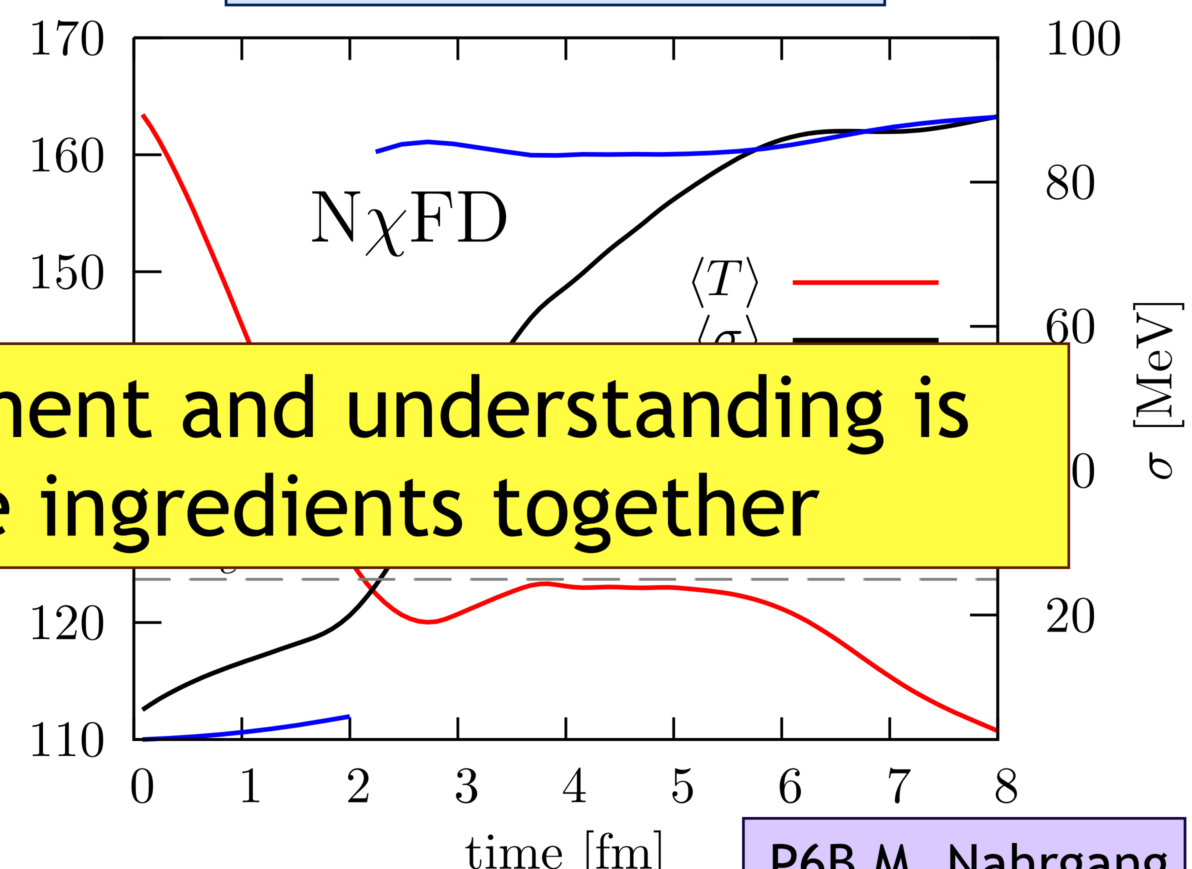


P6B M. Nahrgang

A lot more theory development and understanding is necessary to put all the ingredients together

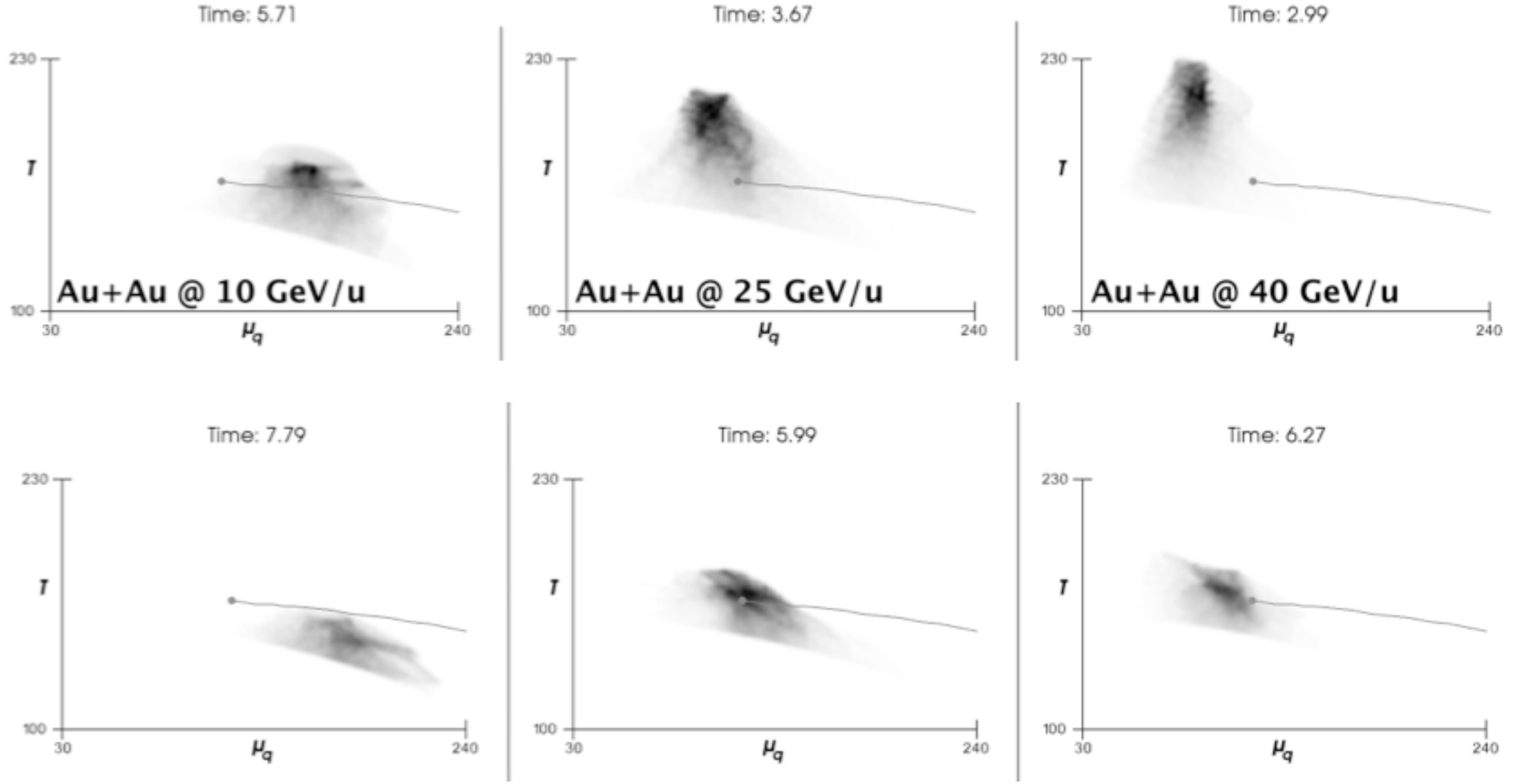
Summary

- **Initial Conditions/Pre-equilibrium Evolution:**
  - Take into account known sources of fluctuations
  - Predictions of the correlation length and scale of fluctuations
  - Initial energy-momentum tensor from first principles
- **Hydrodynamics:**
  - 3+1d viscous hydrodynamics is under control; faster, stable algorithms
  - Microscopic understanding of hadronization
- **Hadronic Rescattering and Freeze-out:**
  - Inclusion of viscous corrections to distribution function
  - Effect of afterburner on event-by-event fluctuation observables
- **Lower beam energies** require considerable theory development to disentangle different sources of fluctuations and understand non-equilibrium effects on phase transition

Event-by-event simulations of many observables in the same approach are crucial for the quantitative era of heavy ion physics!

Backup

Exploring the Phase Diagram



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

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