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 \( v_1 \), \( v_3 \), \( v_5 \)

- Flow fluctuations:
  - Dynamical fluctuations of elliptic flow

There is a huge amount of measurements, calculations of many different observables in one approach are rare
Paradigm of Fluctuations and Higher $v_n$'s

- 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...
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
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  - Hydrodynamics
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- How to do a meaningful comparison to experimental data?
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E-by-e simulations are **necessary**:
- Bulk properties, fluctuation observables
- Background for hard probes, especially correlations
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 $\sim 1/Q_s$

Glasma, IP Sat Model

Gaussian CGC model correlations

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

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
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
  
- Anisotropic hydrodynamics
  
- Colliding sheets in ADS/CFT

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
  - Take favorite event generator (NEXUS, EPOS, UrQMD, AMPT,..) and enforce equilibrium
  - Calculate classical Yang-Mills dynamics to simulate Glasma evolution

All of these models contain parameters

Bulk observables restrict the initial state parameter space

Allowed region
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

• Equation of state that matches available lattice QCD data
  – What about finite baryo-chemical potential?

• Hypersurface finder that can resolve interesting structures

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

IC Fluctuations

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

![Quantum number fluctuations graph]

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

![Local charge conservation graph]

P. Huovinen, HP, arxiv: 1206.3371

P. Bozek, W. Broniowski, arxiv:1204.3580

P2C P. Bozek
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Quantum number fluctuations

Local charge conservation \(\rightarrow\) Bump in \(v_n^2(\Delta\eta)\)

Inclusion of viscous corrections to distribution function needs to be determined

P. Huovinen, HP, arxiv:1206.3371
P. Bozek, W. Broniowski, arxiv:1204.3580

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

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

P2A S. Jeon, S. Ryu
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
New Observables in Sight

- 3-particle correlations and correlations between different event planes or planes in different kinematic regions

- $v_n(\Psi_m)$ with $m \neq n$ measurements
  - Useful to proof consistency in measurements, e.g. longitudinal correlation of event plane angles

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)

- Can a core-corona approach replace dynamical coupling of hydrodynamics and transport?
- Influence of splitting the system on event-by-event observables?
• Spread of the system in temperature and baryo-chemical potential has consequences on observables for critical point or phase transition
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

Chiral Fluid Dynamics

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

P6B M. Nahrgang
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?

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

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

Chiral Fluid Dynamics

P6B M. Nahrgang
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

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

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