Future theoretical breakthroughs due to flow and correlation measurements

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Heavy Ion Collisions

![Diagram of heavy ion collision process](image)

- **lumpy initial energy density**
- **QGP phase**: quark and gluon degrees of freedom
- **hadronization**
- **kinetic freeze-out**
- **collision overlap zone**
- **quantum fluctuations**

- **$\tau \sim 0$ fm/c**
- **$\tau \sim 1$ fm/c**
- **$\tau \sim 10$ fm/c**
- **$\tau \sim 10^{15}$ fm/c**

**Distributions and correlations of produced particles**
Why correlations and fluctuations are interesting

- Understand quark-gluon plasma fluid properties.
- Understand initial state and very early dynamics.
Understand quark gluon plasma fluid properties

- Evolution is space and time?
- Close-to or far-from local equilibrium?
- Do thermodynamic properties match lattice QCD?
- What transport properties describe a relativistic fluid properly?
  - shear viscosity $\eta$ and bulk viscosity $\zeta$
  - relaxation times $\tau_{\text{shear}}$ and $\tau_{\text{bulk}}$
  - more second order terms?
- Transport properties from first principles?
- Fluctuations in fluid fields described by a local Gibbs ensemble? Governed by local temperature $T(x)$ and fluid velocity $u^\mu(x)$?
- What other fields play a role? Chiral condensate $\sigma(x)$, baryon density $n_B(x)$, or electromagnetic fields?
- Spin diffusion? Anomalous fluid dynamics?
Understand initial state and very early time dynamics

- How precisely does the nuclear wave function describe the initial state?
- How does the concept of a parton distribution function have to be generalized?
- Can dynamic quantum fluctuations become macroscopic as a result of the expansion as in early time cosmology? Can we detect them?
- Can we constrain early time dynamics and “thermalization scenarios”? 

Experimental observables

- Particle number distribution
  
  \[ \frac{dN_j}{dpd\phi d\eta} \]

  - 1 discrete label particle "species" \( j \): mass, charges, spin
  - 3 continuous labels transverse momentum \( p \), angle \( \phi \) and rapidity \( \eta \)

- Information about event-by-event statistics in single particle spectrum
  
  \[ \left\langle \frac{dN_j}{dpd\phi d\eta} \right\rangle \quad (1 \text{ discr., } 3 \text{ cont.}) \]

  two-particle correlation function

  \[ \left\langle \frac{dN_{j_1}}{dp_1 d\phi_1 d\eta_1} \cdot \frac{dN_{j_2}}{dp_2 d\phi_2 d\eta_2} \right\rangle \quad (2 \text{ discr., } 6 \text{ cont.}) \]

  and higher order particle correlation functions

  \[ \left\langle \frac{dN_{j_1}}{dp_1 d\phi_1 d\eta_1} \cdots \frac{dN_{j_n}}{dp_n d\phi_n d\eta_n} \right\rangle \quad (n \text{ discr., } 3 \text{ n cont.}) \]
Expansion in harmonics

- Integrated observables
  - all charged particles
  - integrated over transverse momentum

- Expansion in azimuthal modes

\[
\frac{dN}{d\phi d\eta} = \frac{dN}{d\eta} \frac{1}{2\pi} \left[ 1 + \sum_m e^{im\phi} V_m(\eta) \right]
\]

or in azimuthal and rapidity modes

\[
\frac{dN}{d\phi d\eta} = \frac{dN}{d\eta} \frac{1}{2\pi} \left[ 1 + \sum_m \int_k e^{im\phi + ik\eta} \tilde{V}_m(k) \right]
\]

- Very many correlation functions possible, e. g.

\[
\langle V_2^*(\eta_1)V_2(\eta_2) \rangle, \quad \langle V_2^*(\eta_1)V_3^*(\eta_2)V_5(\eta_3) \rangle
\]

or more generally

\[
\langle V_{m_1}(\eta_1)V_{m_2}(\eta_2) \cdots V_{m_n}(\eta_n) \rangle
\]

- Also particle identified and momentum resolved...
Future theoretical breakthroughs

- Learn how to extract *space-time history* from experimental data
  → rapidity resolved correlation functions

- Distinguish *close-to* and *far-from equilibrium* quark gluon plasma
  → test fluctuation-dissipation relation
  → compare correlation and response functions

- Understand *baryon diffusion* and heat conduction in quark-gluon plasma
  → correlation functions of baryon minus anti-baryon numbers

- Quantify *charge transport* as a background to the *chiral magnetic effect*
  → correlation functions of net charges

- Understand the *nuclear wave function beyond PDFs*
  → access initial state fluctuations in energy-momentum tensor via fluid dynamic response

- Understand a *relativistic fluid* (quark-gluon plasma) from *first principles of quantum field theory*
  → sustained effort in interplay of experiment and theory
We need to invest into theory

- With more and more complex and differential observables the comparison between experiment and theory becomes more complex.
- Experimentalists must be enabled to directly compare to a *transparent and powerful standard model*
- Simple-to-use numerical implementation needed

Mode-by-mode fluid dynamics

- determine space-time history for smooth and symmetric events
- *response functions* for all kind of fluctuations around this
- construct map from initial to final state
- rapidity dependent perturbations
- baryon number & charge perturbations
- could add also electro-magnetic fields, chiral order parameter etc.
Improved statistics can help

- High Luminosity LHC can improve statistics significantly
- Higher order correlation functions
  - test collectivity in more detail
- More differential correlation functions
- Charge correlation functions
  - differential in azimuthal angle and rapidity
  - charge transport and electric conductivity
  - background to chiral magnetic effect
- Baryon number correlation functions
  - differential in azimuthal angle and rapidity
  - baryon diffusion / heat conductivity
  - background to critical fluctuations close to hypothetical critical end point