Future theoretical breakthroughs due to flow and correlation measurements

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High Luminosity LHC, CERN, October 31, 2017.

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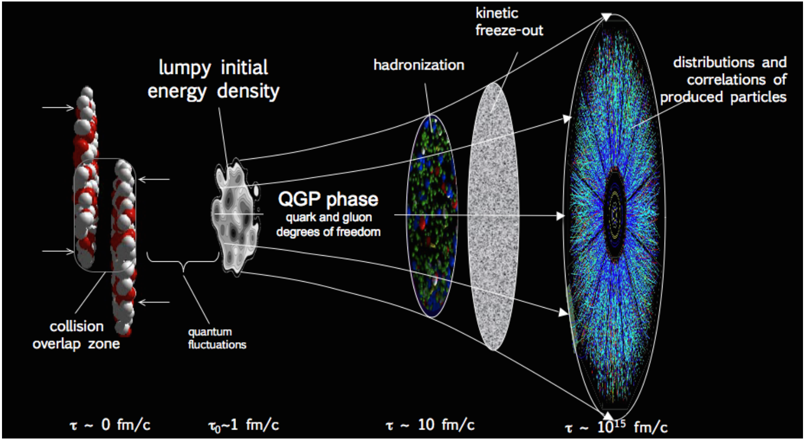
ISOQUANT SFB1225

Heavy Ion Collisions



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 η and bulk viscosity ζ
  - relaxation times τ_{shear} and τ_{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

$$\frac{dN_j}{dp d\phi d\eta}$$

  - 1 discrete label particle "species" j: mass, charges, spin
  - 3 continuous labels transverse momentum p, angle ϕ and rapidity η

- Information about event-by-event statistics in single particle spectrum

$$\left\langle \frac{dN_j}{dp d\phi d\eta} \right\rangle \qquad \text{(1 discr., 3 cont.)}$$

two-particle correlation function

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

and higher order particle correlation functions

$$\left\langle \frac{dN_{j_1}}{dp_1 d\phi_1 d\eta_1} \cdots \frac{dN_{j_n}}{dp_n d\phi_n d\eta_n} \right\rangle \qquad \text{(n discr., 3 n cont.)}$$

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.

$$\langle V_2^*(\eta_1)V_2(\eta_2)\rangle, \qquad \langle V_2^*(\eta_1)V_3^*(\eta_2)V_5(\eta_3)\rangle$$

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
  $\rightarrow$ rapidity resolved correlation functions
- Distinguish *close-to* and *far-from equilibrium* quark gluon plasma
  $\rightarrow$ test fluctuation-dissipation relation
  $\rightarrow$ compare correlation and response functions
- Understand *baryon diffusion* and heat conduction in quark-gluon plasma
  $\rightarrow$ correlation functions of baryon minus anti-baryon numbers
- Quantify *charge transport* as a background to the *chiral magnetic effect*
  $\rightarrow$correlation functions of net charges
- Understand the *nuclear wave function beyond PDFs*
  $\rightarrow$ 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*
  $\rightarrow$ 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