Heavy Ion Collisions: Theory overview

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Outline

This talk:

- Condensed matter physics of QCD
- Thermalization
- HI event characterization: from models to global analysis
- Small systems and limits of collectivity
- Jet quenching, EM probes
Why heavy ion collisions

- QCD prediction: deconfined phase at $T \gtrsim 150$ MeV
- QCD in the laboratory: fundamental (emergent) properties of QCD
- How: heavy ion collisions at various collider energies
- Not only rare events, global characteristics of collision

Simultaneously understand:
- Initial conditions, thermalization
- Spacetime evolution: hydrodynamics
- Hadronic phase
- Hard and electromagnetic probes from all stages
Introduction

Initial stages and thermalization

Global characterization of bulk

Small systems: limits of collectivity

Jets and EM probes

Conclusions
Initial state: small $x$ QCD

- Gluons ending in central rapidity region: multiple splittings from valence quarks
- Emission probability $\alpha_s \frac{dx}{x}$
  $\Rightarrow$ rapidity plateau for $\Delta y \ll 1/\alpha_s$
- Many gluons
  $\Rightarrow$ large phase space density

Weak coupling, but nonperturbative

- $\alpha_s$ small
- $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ large

True when typical momentum $Q_s \gg \Lambda_{QCD}$
$\Rightarrow$ gets better at large $\sqrt{s}$
Classical fields, kinetic theory, hydro

State of the art in QCD calculations for initial stages:

IPglasma Schenke et al 2012 –

- Classical color fields
- Nucleon- and subnucleon scale fluctuations
Classical fields, kinetic theory, hydro

State of the art in QCD calculations for initial stages:

- QCD kinetic theory ("EKT")
  - follow system to hydrodynamics

IPglasma Schenke et al 2012 –
  - Classical color fields
  - Nucleon- and subnucleon scale fluctuations

Keegan et al arXiv:1605.04287
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Hydrodynamical description of soft observables

Need:

- Initial conditions
- Hydrodynamical evolution:
  - Energy-momentum conservation \( \partial_\mu T^{\mu\nu} = 0 \)
  - Medium properties: EoS, transport coefficients
- Freezeout to particles

(E.g. viscosity \( \eta \))

Niemi et al arXiv:1504.02677
Hydrodynamical description of soft observables

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Calculate:
- $p_T$-spectra (yields, $\langle p_T \rangle$)
- Azimuthal harmonics ($v_n$'s)
- Reaction plane correlations
- ...

All of these for
- Identified particles
- Centrality classes

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Niemi et al arXiv:1504.02677
Viscosity extraction, data-driven hydro

State of the art Bernhard et al arXiv:1605.03954: Bayesian global fit

In particular: initial entropy density parametrized & fit

\[ s(x_T) \sim \left( \left( \frac{T_A(x_T) + T_B(x_T)}{2} \right)^p \right) \]

Data favors gluon saturation for particle production:
Viscosity extraction, data-driven hydro

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In particular: initial entropy density parametrized & fit

\[ s(x_T) \sim \left( \frac{(T_A(x_T))^p + (T_B(x_T))^p}{2} \right)^{\frac{1}{p}} \]

Result for QCD shear viscosity
Current challenges in hydro

Improvements still needed to exploit even larger data set

- **Rapidity dependence**
  - Parametric/string models
    - Pang et al., Denicol et al., Bozek et al 2015
  - How to compute in microscopic theory?

- **Viscous corrections to freezeout** \( \implies \) higher \( p_T \)
  - Hydrodynamics has integrated \( T^{\mu\nu} \)
  - At the end need to match to microscopic \( f(p) \).
  - How to do out of equilibrium? (with viscosity)

- **How low** \( (N_{ch}) \) **can you go?**
  . . .
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“Small systems”: pPb & pp at high $N_{\text{ch}}$
See H.I: parallel 1 this morning

### Observations

- Azimuthal correlations similar to AA
- Cumulant analysis: not a dijet correlation

\[
\phi \Delta \eta, \phi \Delta \phi \left( \begin{array}{c|c|c|c|c|c} \eta \Delta \phi \end{array} \right)
\]

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<tbody>
<tr>
<td>$\phi \Delta \eta$</td>
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Analyze as yield/trigger or $v_n$:

What is the origin?

- Collective flow as in AA?
- Initial state gluon correlations?

( $c_2\{4\}$: 4-particles, $\cos 2\varphi$ )
(Note sign change at $N_{\text{trk}} \sim 60$)
Flow in hydro

† Interactions/collectivity
† Temperature/pressure gradients
⇒ Anisotropic force
⇒ acceleration
⇒ anisotropy in momentum

Pb-Pb collision: large system
⇒ nucleon scale matters little
⇒ initial geometry known

Also pp, pPb collisions?
† Hydrodynamics for ∼ 50 particles?
† Initial geometry not controlled

E.g. Bozek et al
arXiv:1407.6478
How to sort out smaller systems?

- Higher cumulants: flow vs. “nonflow”
- Longitudinal correlations
  - Implemented in string models,
    E.g. L. G. Pang et al, G. Denicol et al, Bozek et al. 2015
  - Weak coupling: first steps
- Mass ordering: hadronization?

How much collectivity from QCD scattering + hadronization vs. hydrodynamics?

Event plane decorrelation:
Schenke et al arXiv:1605.07158
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Jet tomography
H.I. parallel 3 tomorrow

Dijet: calibration and probe

Quantify e.g. with dijet asymmetry

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]
Jet quenching: theory

Theory advances prompted by LHC data

- Structure of medium induced cascade: energy flow to soft gluons $\rightarrow$ large angles
  Blaizot, Dominguez, Iancu, Mehtar-Tani; Kurkela, Wiedemann
  ...

- NLO corrections to medium parameter $\hat{q}$
  Wu, Liou, Mueller, Mehtar-Tani,
  Blaizot, Dominguez, Iancu, ...

- Monte Carlo for medium cascade: JEWEL, Q-PYTHIA, Martini, YaJEM, PYQUEN, ...

![Graph showing dijet energy imbalance vs. angle $\theta$.]
Photons

Thermal photons & dileptons from plasma stage: only direct probe from deconfined phase

Problem: all these other sources of light...

Paquet et al arXiv:1509.06738

Edging towards solution of longstanding photon $v_2$ puzzle:

▶ Large yield: early plasma phase dominates
▶ Large $\cos 2\varphi$ asymmetry: late hadronic stage dominates

Difficult to get both
Open heavy flavor

“Open” = individual $c$, $b$ quarks in medium, not in bound states

At LHC:
$D$-meson $R_{AA} \approx$ light hadrons

(Recall $R_{AA} = \frac{1}{[\text{geometry}]} \frac{d\sigma_{AA}}{d\sigma_{pp}}$.)

But theory very different!

- Light: medium itself + quenched jets
- Heavy: $c$, $b$ quarks pushed by medium
  - flow
  - thermal noise

![Graph showing $D^0 R_{AA}$ vs $p_T$]
Heavy quarkonia

Quarkonia “melt” in quark-gluon plasma \( \Rightarrow \) thermometer!

So why is there less \( J/\psi \) suppression at LHC than at RHIC?

Thermometer complicated!

Need to understand:

- Production in pp & pA
- Dissociation in plasma (lattice)
- Propagation in medium (flow \( \Rightarrow p_T \))
- Regeneration from \( c \bar{c} \) pairs in dense medium \( \Rightarrow \) hadronization!

Making progress in all of these, but there is still work to do!
To summarize

- Progress in systematical extraction of fundamental properties of quark-gluon matter from experiment
- Still work to do, in nucleus-nucleus collisions:
  - Electromagnetic probes: additional constraint on evolution
  - Jets: interaction of colored particles with medium
- Proton-nucleus collisions more interesting than anybody believed when LHC started!
  - Understand “cold” nuclear matter effects for heavy quarks, high $p_T$ particles, electromagnetic probes
  - Onset of collective behavior in ever smaller systems