High-Density Systems: Introduction

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Relativistic Heavy-Ion Collisions

main goal: produce and study the quark-gluon-plasma

5. Individual hadrons freeze out
4. Hadron gas cooling with expansion
3. Quark Gluon Plasma thermalization, expansion
2. Pre-equilibrium state collision
1. Nuclei (initial condition)

however, one observes the system after it has gone through a complicated evolution involving different aspect of QCD
to understand each stage and the transition between them has been challenging
Outline

- **The Color Glass Condensate**
  an approximation of QCD to describe the nuclear wave function at small-\(x\), using classical fields

- **The Glasma**
  the pre-equilibrium phase, resulting of the collisions of two CGCs, during which classical fields decay into a particles

- **Finite temperature lattice QCD**
  a laboratory to study the transition from the deconfined phase into the hadronic phase, and to explore the QCD phase diagram

- **Bulk observables**
  properties of the collective behavior of the (thermalized ?) low-\(p_T\) particles (quarks/gluons then hadrons) composing the plasma

- **Hard Probes**
  rare high-\(p_T\) particles created at early times that have propagated through the evolving plasma
The Color Glass Condensate
Parton saturation

- a regime of the hadronic/nuclear wave function predicted in QCD

\[ x : \text{parton longitudinal momentum fraction} \]
\[ k_T : \text{parton transverse momentum} \]

QCD linear evolutions: \( k_T \gg Q_s \)

- DGLAP evolution to larger \( k_T \) (and a more dilute hadron)
- BFKL evolution to smaller \( x \) (and denser hadron)

dilute/dense separation characterized by the saturation scale \( Q_s(x) \)

QCD non-linear evolution: \( k_T \sim Q_s \) meaning \( x \ll 1 \)

\[ \rho \sim \frac{x f(x, k_T^2)}{\pi R^2} \]
\[ \sigma_{\text{rec}} \sim \frac{\alpha_s}{k^2} \]

- gluon density per unit area
- it grows with decreasing \( x \)
- recombination cross-section

recombinations important when \( \rho \sigma_{\text{rec}} > 1 \)

the saturation regime: for \( k^2 < Q_s^2 \) with \( Q_s^2 = \frac{\alpha_s x f(x, Q_s^2)}{\pi R^2} \)

the distribution of partons as a function of \( x \) and \( k_T \):

this regime is non-linear yet weakly coupled
\[ \alpha_s(Q_s^2) \ll 1 \]
The Color Glass Condensate

- the CGC: an effective theory to describe the saturation regime

McLerran and Venugopalan (1994)

lifetime of the fluctuations in the wave function \( \sim \frac{x P^+}{k^2} \) \( \Rightarrow \) \{ high-x partons \( \equiv \) static sources \( \rho \) \\ low-x partons \( \equiv \) dynamical fields \( \mathcal{A} \) \}

short-lived fluctuations

\[ |\text{hadron} \rangle = |qqq\rangle + |qqqg\rangle + \ldots + |qqq \ldots ggggg\rangle \Rightarrow |\text{hadron} \rangle = \int D\rho \ \Phi_x[\rho] |\rho\rangle = |\text{CGC} \rangle \]

valence partons as static random color source

effective wave function for the dressed hadron

separation between the long-lived high-x partons and the short-lived low-x gluons

classical Yang-Mills equations

\[ [D_\nu, F^{\nu\mu}]^a = \delta^\mu + \delta(x^-) \rho^a(x_\perp) \]

this effective description of the hadronic wave function applies only to the small-x part
Probing the CGC in p+A collisions

we would like to extract from data the only parameter in the theory, $Q_s^0$, we want to find out at what value of $x$ one should one stop using nuclear pdfs to describe the nuclear wave function and use the CGC instead

- typical values of $x$ being probed at forward rapidities ($y \sim 3$)

**RHIC** $x_d \sim 0.5 \quad x_A \sim 5 \times 10^{-3}$

deueron dominated by valence quarks

**nucleus dominated by early CGC evolution**

**LHC** $x_p \sim 0.1 \quad x_A \sim 10^{-5}$

the proton description should include both quarks and gluons

on the nucleus side, the CGC picture would be better tested
The suppression of $R_{dA}$

- The suppression of $R_{dA}$ was predicted

$$R_{dA} = \frac{1}{N_{coll}} \frac{dN_{dA \rightarrow hX}}{d^2kdy} \frac{dN_{pp \rightarrow hX}}{d^2kdy}$$

- What we learned
  
  Forward rapidities are needed to see the suppression
  $$Q_s^2 (0.01, Au) \sim 1 \text{ GeV}^2$$

  If forward rapidity data are included in npdfs fit, the resulting gluon distribution is over suppressed
The Glasma

![Diagram of the Glasma](image)
Collision of two CGCs

- the initial condition for the time evolution in heavy-ion collisions

before the collision:

\[ J^\mu = \delta^{\mu^+} \delta(x^-) \rho_1(x_\perp) + \delta^{\mu^-} \delta(x^+) \rho_2(x_\perp) \]

the distributions of \( \rho \) contain the small-x evolution of the nuclear wave function

\[ |\Phi_{x_1}[\rho_1]|^2, |\Phi_{x_2}[\rho_2]|^2 \]

- after the collision

compute the gluon field in the forward light-cone

\[ [D_\mu, F^{\mu\nu}] = J^\nu \quad \rightarrow \quad A_\mu[\rho_1, \rho_2] \]

the gluon field is a complicated function of the two classical color sources

the fields decay, once they are not strong (classical) anymore, a particle description is again appropriate
The field/particle composition

- the field after the collision is non trivial
  it has a strong component \( A^\mu \sim 1/g_s \), a particle-like component \( A^\mu \sim 1 \)
  and components of any strength in between

- the decay of the Glasma
  right after the collision, the strong component contains all modes
  then modes with \( p_T > 1/\tau \) are not part of the strong component anymore

- thermalization is still an outstanding problem? AdS/CFT?

  glasma:
  \[
  T^{\mu\nu} = \frac{1}{4} g^{\mu\nu} F^{\lambda\sigma} F_{\lambda\sigma} - F^{\mu\lambda} F^{\nu}_{\lambda}
  \]

  \[
  T^{\mu\nu}(\tau = 0^+) = \begin{pmatrix}
  \epsilon & \epsilon \\
  \epsilon & -\epsilon 
  \end{pmatrix}
  \]

  \[
  T^{\mu\nu}_{\text{hydro}} = \begin{pmatrix}
  \epsilon & p \\
  p & p \\
  \end{pmatrix}
  \]

Probing features of the Glasma

- possible with long-range rapidity correlations

in general, the following phases (QGP, ...) destroy the information coming from the initial CGC collisions, heavy-ion collisions are not great probes of parton saturation

nevertheless, some observables are still sensitive to the physics of the early stages

\[ \tau < \tau_{\text{freezeout}} \exp(-\Delta \eta / 2) \]
The ridge in A+A collisions

- the ridge is qualitatively understood within the CGC framework

if it is very extended in rapidity, the ridge is a manifestation of early-time phenomena:

$$\tau < \tau_{\text{freezeout}} \exp(-\Delta \eta/2)$$

- quantitative calculations are underway
P- and CP-odd effects

- topological charge fluctuations in the Glasma

Longitudinal E and B fields in the flux tubes with non-zero E.B Chern-Simons term

Consequence: fluctuating charge asymmetry with respect to reaction plane (although this is not the only possible mechanism)

Kharzeev, McLerran and Warringa (2008)
Finite temperature lattice QCD

Hadron Gas

Quark-Gluon Plasma
Recent results

- for some quantities, it is now possible to use a realistic pion mass

lattice QCD deals with a simpler QGP compared to heavy-ion collisions:
  it is static, fully-thermalized and baryon-less
Reproducing lattice results

- except around $T_c$, we know how to approximate QCD well enough

Hadron Resonance Gas model works until $0.9 \ T_c$

Hard-Thermal-Loop QGP works above $2 \ T_c$

can one build a model in which the transition between two regimes is smooth?

with/without AdS/CFT?

in actual RHIC, the medium is a dynamic fireball, with a deconfined core and a hadronic corona

Andersen, Su and Strickland (2010)
The QCD phase diagram

lattice QCD is successfully applied of zero baryon density

the chemical potential direction is also extensively studied: deconfinement phase transition, chiral symmetry restoration critical point, color superconductivity, …
Bulk Properties
The plasma flows like a fluid

the initial momentum distribution is isotropic

strong interactions induce pressure gradients

the expansion turns the space anisotropy into a momentum anisotropy

a complete causal formulation of relativistic viscous hydro was developed

viscous corrections are necessary for a quantitative data description

it was checked that they are small enough to validate the hydro approach

recently, the first 3+1d viscous hydro study was performed

Schenke, Jeon and Gale (2010)

however, to describe the hadronic phase, transport models are needed, a hybrid approach is necessary to realistically describe the bulk medium (core/corona)
Elliptic flow

$$v_2(p_T, b) = \frac{\int d\phi \cos(2\phi) \frac{d\sigma_{AA}}{d^2p_T d^2b}}{\int d\phi \frac{d\sigma_{AA}}{d^2p_T d^2b}}$$

a measure of the viscosity

viscous hydro calculations using CGC initial eccentricity describe the centrality and $p_T$ dependence using $\eta/s = 2/4\pi$

but:
contribution from hadronic corona?
uncertainties in initial conditions?

AdS/CFT bound:
$$\frac{\eta}{s} > \frac{1}{4\pi}$$

Luzum and Romatschke (2008)
Quark recombination

\[ p_B \approx 3p_Q \]

\[ p_M \approx 2p_Q \]

quark-number scaling of \( v_2 \)

\[
\frac{1}{2} v_2^M (p_T) = v_2^q \left( \frac{p_T}{2} \right)
\]

\[
\frac{1}{3} v_2^B (p_T) = v_2^q \left( \frac{p_T}{3} \right)
\]

data for different mesons and baryons lie on a universal curve
Triangular flow

$v_2$ has two components, a geometric one and one due to fluctuations (the geometric component vanishes in central collisions)

$v_3$ is only due to fluctuations

2+1d viscous hydro compared with data extracted from two-particle correlation measurements

Alver, Gombeaud, Luzum and Ollitrault (2010)

this alone may explain the away-side shoulder and perhaps even the ridge …
Hard Probes
status of pQCD calculations: 4 main groups (WHDG, ASW, AMY, HT) obtain results using different assumptions
The plasma is opaque

can such a strong stopping power happen in pQCD? or do we need strong-coupling dynamics? AdS/CFT?

there is no compelling extraction of $\hat{q}$ from the data
(first the different jet-quenching calculations have to converge)

but still $\hat{q} \simeq$ a few GeV$^2$/fm \quad (\Delta E \propto \hat{q}L^2)$
High-\(p_T\) azimuthal asymmetry

\[ v_2(p_T, b) = \frac{\int d\phi \cos(2\phi) \, d\sigma_{AA}/d^2p_T d^2b}{\int d\phi \, d\sigma_{AA}/d^2p_T d^2b} \]

- \(\bullet\) in-plane
- \(\bigcirc\) out-of-plane

pQCD: once parameters are adjusted to describe \(R_{AA}\), \(v_2\) cannot be reproduced

PHENIX collaboration

\[ \Delta E \propto L^2 \]

\[ \Delta E \propto L^3 \]
Heavy-quark energy loss

- it is also unclear if the perturbative QCD approach works

  high-p_T electrons from c and b decays indicate similar suppression for light and heavy quarks, but the dead-cone effect in pQCD implies a weaker suppression for heavier quarks

STAR data (2007)

trend: models underestimate the suppression

the measurements do not distinguish the charm and bottom quark contributions

in the future, separating the contributions from charm and bottom quarks will be helpful

note that there are complications with heavy quarks:

in-medium hadronization and dissociation, collisionnal energy loss, …
Jets in heavy-ion collisions

- A new sub-field which will appear with the LHC

Tools are already being developed in the context of RHIC

They will be needed at the LHC
Conclusions

• there are many topics I didn’t mention:
  electromagnetic probes
  strangeness
  quarkonia
  baryon production
  chemical equilibrium
  statistical hadronization
  HBT radii
  ...

• there will be 15 talks in the session, some explaining (and correcting) what I said, some covering the missing topics

  and I am sure the speakers will answer your questions