Theoretical Review of Ultra-Relativistic Heavy Ion Physics

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Topics:
- Color Glass Condensate
- Glasma
- Quark Gluon Plasma
- Quarkyonic Matter
- Topological Charge Fluctuations

Art due to S. Bass

CGC  Initial Singularity  Glasma  sQGP  Hadron Gas
What is the high energy limit of QCD?
What are the possible form of high energy density matter?
How do quarks and gluons originate in strongly interacting particles?
Cross sections for hadrons rise very slowly with energy

$$\sigma_{tot} \sim \ln^2 \left( \frac{E}{\Lambda_{QCD}} \right)$$

$$\Lambda_{QCD} \sim 200 \text{ MeV}$$

But the gluon density rises much more rapidly!

The high energy limit is the high gluon density limit.

Surely the density must saturate for fixed sizes of gluons at high energy.
Baryon:
3 quarks
3 quarks 1 gluon

.....
3 quarks and lots of gluons

Color Glass Condensate

Color: Gluons

Glass:
The partons which make the CGC fields are moving fast $\Rightarrow$ Lorentz time dilation $\Rightarrow$ fields evolve slowly compared to natural times scales

Condensate:

$$\frac{dN}{dy d^2p_T d^2x_T} = \rho$$

Phase space density

$$E = -\kappa \rho + \kappa' \alpha_S \rho^2$$

$\Rightarrow$ $\rho \sim 1/\alpha_S$

Coupling weak because density is high

Fields are coherent and classical
CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

Two sheets of colored glass collide
Glass melts into gluons and thermalize
QGP is made which expands into a mixed phase of QGP and hadrons

“Instantaneously” develop longitudinal color E and B fields
CGC Provides a Successful Phenomenology of:

Limiting Fragmentation
Growth and Scaling Properties of Gluon Distributions
Diffractive DIS and DIS Structure Functions
Multiplicities in Heavy Ion Collisions
Shadowing

Sophisticated theoretical formalism from first principles in QCD
Causality dictates:
\[ \tau \leq \tau_{\text{freeze-out}} \exp \left( -\frac{1}{2} |y_A - y_B| \right) \]

200 GeV Data

The Glasma, Long Range Correlations and the Ridge

Au+Au 200 GeV, 0 - 30%

PHOBOS preliminary

200 GeV Data

Analyzed 1.2M minbias 200 GeV Au+Au events, and 13M 62 GeV minbias events

(not shown) Included all tracks with \( p_T > 0.15 \text{ GeV/c} \), \(|\eta| < 1\), full \( \phi \)

note: 38-46% not shown

proton-proton

84-93%

75-84%

65-75%

55-65%

46-55%

28-38%

19-28%

9-19%

5.9%

0-5%

\( \Phi_\Lambda \), \( \eta_\Lambda \)

Shuryak
Dumitru, Gavin,
Gelis, Venugopalan
Moschelli
“Glittering” Glasmas

n-particle correlation can be expressed as

\[
\left\langle \frac{d^m N}{dy_1 d^2 p_{\perp 1} \cdots dy_n d^2 p_{\perp n}} \right\rangle = \frac{(n-1)!}{k^{n-1}} \left\langle \frac{dN}{dy_1 d^2 p_{\perp 1}} \right\rangle \cdots \left\langle \frac{dN}{dy_n d^2 p_{\perp n}} \right\rangle
\]

with \( k = \zeta_n \frac{(N_c^2 - 1)Q_S^2S_\perp}{2\pi} \) For \( k = 1 \), Bose-Einstein dist. For \( k = \infty \), Poisson Dist.

This is a negative binomial distribution which is known to describe well multiplicity distributions in hadronic and nuclear collisions

\[ \sigma^2 = \bar{n} + \frac{\bar{n}^2}{k} \]

Gelis, Lappi, McLerran

PHENIX

arXiv:0805.1521
Glasma Flux Tubes and Chern-Simons Number

Before: transverse E & B “Weizsacker-Williams fields

After: boost invariant flux tubes of size $1/Q_s$

Parallel color E & B fields

Chern-Simons topological charge

Lappi, McLerran

Kharzeev, Krasnitz, Venugopalan,

Krasnitz, Nara, Venugopalan; Lappi
P and CP violation: Chiral Magnetic Effect

Kharzeev, McLerran, Warringa

Topological fluctuations - sphaleron transitions in Glasma

External (QED) magnetic field

Possible experimental signal of charge separation (Voloshin)
The Unstable Glasma

• Small rapidity dependent quantum fluctuations of the LO Yang-Mills fields grow rapidly as

$$\sim e^{\sqrt{Q_S} \tau}$$

• $E_\perp$ and $B_\perp$ fields as large as $E_L$ and $B_L$ at time

$$\tau \sim \frac{1}{Q_S} \ln^2 \left( \frac{1}{\alpha_S} \right)$$

Possible mechanism for rapid isotropization

Problem: collisions can’t ‘catch up’

➢ Turbulent “thermalization” may lead to “anomalously” low viscosities

Asakawa, Bass, Muller; Dumitru, Nara, Schenke, Strickland

➢ Significant energy loss in Glasma because of synchrotron like radiation?

Shuryak, Zahed; Zakharov; Kharzeev
Thermalization:

Growth of Instabilities and Turbulance? Strong Coupling Dynamics?

System thermalizes and makes a very good fluid: Hydrodynamic simulations of flow induced by the collisions, and of particle distributions with transverse momenta $< 1$-2 GeV work very well. Estimates of viscosity give very small values

$$\frac{\eta}{S} > \frac{1}{4\pi} \quad \lambda T \sim \frac{1}{2\pi}$$

Strongly interacting QGP paradigm.

AdSCFT Modeling for qualitative understanding of the strong coupling limit

AdSCFT has allowed insight about the form of viscous corrections to relativistic hydrodynamics that allow for a consistent theoretical formulation and numerical implementation

Danielowicz, Gyulassy, Son, Starinets, Gubser

Romatschke and Romatschke, Muronga, Rischke

Klebanov
AdS/CFT and Jet Quenching:

Theoretical problem: No jets in strong coupling N=4:
- Electron positron annihilation
- Deep inelastic Jet production
- Cascade to low momentum modes occurs very quickly

A single hadron at high energy in strong coupling N=4:
- Distribution of partons \( \frac{dN}{dx} \sim \frac{1}{x^2} \)
- Saturated gluon density with phase space occupation \( \sim 1 \), not \( \frac{1}{\alpha} \)
- Leading twist contribution to deep inelastic scattering vanishes

Gylassy, Vitev
Rajagopal, Wiedmann; Yaffe; Mueller, Iancu and Hatta;
Maldacena; Kovchegov
Nevertheless:

Data on jet energy loss and heavy quark flow and energy loss is so stunning:

Heavy quark energy loss computations, Mach cones

Chasler and Yaffe;
Betz, Gyulassy, Noronha, Torrieri, Rischke
Large $N_c$:

Quark Loops do not affect the confinement potential

$$g^2 \mu_Q^2 \sim \alpha_N \mu_Q^2 / N_c$$

$e^{(\mu_B-M_B)/T} = 0$ if $\mu_B < M_B$

Baryon mass $\sim N_c$,

no baryons in low density phase

Pisarski, Hidaka, McLerran, Redlich, Sasaki