Recent Theoretical Developments in Strongly Coupled QCD

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Quark Matter 2012, Washington DC
Other talks on Holographic approach to QCD at this Conference

- Jet Energy Loss: P. Arnold, W. Horowitz (plenary), K. Rajagopal
- Thermalization: P. Chesler
Challenges for QCD in Heavy-Ion Collisions

- Time-dependent and many-body problem
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- Physics of different scales: High energy vs. Low $p_T$
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Entire history involves STRONGLY COUPLED dynamics
Recent Theoretical Developments in Strongly Coupled QCD

- Early Thermalization
- High $s$, Small $t$ Scattering Saturation
- Non Perturbative, Strongly Coupled QCD
- Strongly Coupled QGP
- Freeze-out, Hadronization
Recent Theoretical Developments in Strongly Coupled QCD

- Early Thermalization
- High $s$, Small $t$ Scattering Saturation
- $t \ll s$: Non-perturbative Regge behavior: $s^{\alpha_0 + \alpha' t}$
- Pomerons
- Unitarization
- (Anti) Shadowing
- Freeze-out, Hadronization
- Strongly Coupled QGP
- Non Perturbative, Strongly Coupled QCD
Recent Theoretical Developments in Strongly Coupled QCD

- Early Thermalization
  - Multiplicity production
  - Initial fluctuations
  - Fast thermalization: $\tau \sim 1$ fm

- Non Perturbative, Strongly Coupled QCD

- Strongly Coupled QGP

- High $s$, Small $t$ Scattering Saturation

- Freeze-out, Hadronization
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$\frac{n}{s}$, Flows and correlations
Jet quenching/fragmentation
Photons and dileptons
Heavy quarks
Recent Theoretical Developments in Strongly Coupled QCD

- Early Thermalization
- High $s$, Small $t$ Scattering Saturation
- Non-Perturbative, Strongly Coupled QCD
  - Hadronization dynamics
  - Heavy quark recombinations
  - Real time phase transition and phase fluctuations
- Strongly Coupled QGP
- Freeze-out, Hadronization
STRATEGIES

• Real time Lattice QCD ?

• AdS/CFT Correspondence or Holography

• Symmetry protected phenomena : Triangle anomaly
STRATEGIES

- Real time Lattice QCD?
- AdS/CFT Correspondence or Holography
- Symmetry protected phenomena: Triangle anomaly
Ideas of Holography

STATEMENT:

Strongly coupled gauge theory in large $N_c$ limit

is dual to

(Einstein) Gravity theory in a 5 dimensional space $AdS_5$
Ideas of Holography

We will highlight the ideas in intuitive ways,

and will simply review the results.
$AdS_5$

Extra (Energy) Dimension : $Z$

$$ds^2 = \frac{1}{z^2} (dz^2 + dx_{\mu} dx^{\mu})$$
AdS/CFT Correspondence (Holography)

$ds^2 = \frac{1}{z^2} (dz^2 + dx_\mu dx^\mu)$

**GRAVITY THEORY in AdS$_5$**

**GAUGE THEORY in $R^{1,3}$**
\[ ds^2 = \frac{1}{z^2} (dz^2 + dx_\mu dx^\mu) \]

**GRAVITY THEORY in AdS\(_5\)**

**GAUGE THEORY in R\(^{1,3}\)**
A peculiar property of $AdS_5$

\[ ds^2 = \frac{1}{z^2} \left( dz^2 + dx_\mu \, dx^\mu \right) \]
A peculiar property of $AdS_5$

$ds^2 = \frac{1}{z^2} (dz^2 + dx_\mu \, dx^\mu)$
A peculiar property of $AdS_5$

$AdS_5$

Energy $E \Leftrightarrow$ Position $Z$
\[ Z \leftrightarrow \text{Renormalization Scale: } \mu \]
Holography is an intrinsic property of Gravity

Brown-York $T^{\mu\nu}$ lives in boundary

Gravity Theory

There is no local Energy-Momentum
Justifications of the Extra Dimension

IN SUMMARY :

- It is like a box, not a truly extended dimension
- Extra dimension maps to the energy scale of the field theory
- Gravity has a holographic degrees of freedom
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Black-hole as a Quark Gluon Plasma

\[ Z = Z_H = T^{-1} \]

\[
\begin{align*}
    ds^2 &= \frac{1}{z^2 f(z)} dz^2 - \frac{f(z)}{z^2} dt^2 + \frac{1}{z^2} (\vec{d}x \cdot \vec{d}x) \\
    \text{Horizon} & \quad R^{1,3}
\end{align*}
\]
Black-hole as a Quark Gluon Plasma

\[ Z = Z_H = T^{-1} \]
Relevance in Heavy-Ion Physics

We will discuss three major applications:

- High energy $s$ and small momentum transfer $t$ scattering
- Initial thermalization
- Strongly coupled QGP and jet quenching
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Large $s$ and small $t$ scattering: **Holographic Pomeron**

( Janik-Peschanski, Rho-Sin-Zahed, Polchinski-Strassler )

**BASIC THEME:**

How do two hadrons interact in the **confining vacuum** when they pass-by with a **high rapidity** and with a **long transverse distance**
Large $s$ and small $t$ scattering: Holographic Pomeron

(Janik-Peschanski, Rho-Sin-Zahed, Polchinski-Strassler)

BASIC THEME:

When the distance is much larger than $\Lambda_{\text{QCD}}^{-1}$, the problem involves strongly coupled, non-perturbative dynamics.
Impact parameter: $b$

Proton at rest

$\Lambda_{QCD}^{-1}$

Proton at rest
Impact parameter: $b$

Amplitude $\sim e^{-\frac{b^2}{2\alpha'\chi}}$

Two protons moving with rapidity $\chi = \log s$
This leads to the Regge behavior $s^{\alpha_0 + \alpha't}$ with the total cross-section grows like

$$\sigma_T \sim s^{\alpha_0 - 1} \sim s^{0.08}$$

experimentally (Donnachie-Landshoff)

This $\sigma_T \sim s^{0.08}$ eventually violates the unitarity bound $\sigma_T \leq (\log s)^2$

The form $e^{-\frac{b^2}{2\alpha'\chi}}$ strongly suggests a Diffusion Equation (Gribov)

$$\partial_\chi K = D\nabla_\perp^2 K$$

with $D = \frac{\alpha'}{2}$
This leads to the **Regge behavior** \( s^{\alpha_0 + \alpha' t} \) with the total cross-section grows like \( \sigma_T \sim s^{\alpha_0 - 1} \sim s^{0.08} \) experimentally (Donnachie-Landshoff).

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with $D = \frac{\alpha'}{2}$.
What is diffusing and Why?
Multi-gluon wave-function quantum mechanically diffuses in rapidity space by branching

BFKL two-gluon exchange diagrams give intercept: \( \alpha_0 = 1 + \frac{4 \log 2 \alpha_s N_c}{\pi} \)

Diffusion constant: \( D = \frac{7 \zeta(3) \alpha_s N_c}{2\pi} \)

What is interesting is that there is a diffusion in sizes (virtuality) of dipoles
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Holographic diffusion of Pomerons
(Brewer-Polchinski-Strassler-Tan, Basar-Kharzeev-Yee-Zahed)

Diffused closed string Pomerons
Holographic Z
Transverse space: $x_T$

Diffusion constant: $D = \frac{\alpha'}{2}$, Diffusion time: $\log s$ (Same!)
For $\chi < \lambda (= g_{YM}^2 N_c)$ the Pomerons are of spin 2 (Brewer-Polchinski-Strassler-Tan), and for $\chi > \lambda$ they are of spin $D_{12}^{1/12} = \frac{1}{4}$ (Basar-Kharzeev-Yee-Zahed).

- Effective time is still $\chi \sim \log s$. Branching seems to work even in strong coupling.
- Holographic $z$ maps to the sizes (virtuality) of the Pomerons; another common point with BFKL.
- Saturation happens when this size becomes comparable to the Pomeron density (Stoffers-Zahed).
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World-sheet instantons and Micro Fire-ball

Micro Fire-ball from Unruh Temperature

World-sheet instanton of $\sim e^{-\frac{b^2}{2\alpha'\chi}}$
Tunneling through Vacuum

Color charged objects

Need to tunnel the distance $b$
Unitarization and multi-Pomerons

- One can satisfy the **unitarity bound**

\[ \sigma_T \leq (\log s)^2 \]

by exponentiating the single Pomeron amplitude via eikonalization

- Multi-Pomerons are large $N_c$ suppressed; this is going beyond leading large $N_c$ limit

- Presently we **don’t** know how to handle these multi-Pomerons in holographic models

- Presumably the onset of these multi-Pomerons is related to the holographic version of **saturation**
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$\chi = \log s$

Non Perturbative

Perturbative

Saturation

$Q_s(\chi)$

$\Lambda_{QCD}^2$

$Q^2$

DGLAP

JIMWLK

BFKL
$\chi = \log s$

Non Perturbative

Perturbative

Saturation

$Q_s(\chi)$

Multi-Pomeron

Single stringy Pomeron

AdS/CFT

$\Lambda_{QCD}^2$

$Q^2$

DGLAP

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BFKL
Initial Thermalization : Creating Black-holes

- **Colliding two planar shockwaves**
  (Janik-Peschanski, Albacete-Kovchegov-Taliotis, Chesler-Yaffe, Gubser-Pufu-Yarom, Kiritsis-Taliotis, Wu-Romatschke)

- **Falling thin mass shell**
  (Lin-Shuryak, Balasubramanian et al)

- **Boost invariant initial conditions**
  (Beuf-Heller-Janik-Peschanski-Witaszczyk)
(Initial) Thermalization (1) : Shock Waves

$R^3$

Thin moving energy plate
(Initial) Thermalization (1) : Shock Waves

$R^3$

Area $\sim$ Multiplicity

Black-hole (plasma) formed
Plot of Romatschke-Wu

\[ \epsilon \text{ [GeV/fm$^3$]} \]

- **RHIC Au+Au @ 200 GeV**
- **RHIC hydro**
- **LHC Pb+Pb @ 2.76 TeV**
- **LHC hydro**

\[ \tau \text{ [fm/c]} \]
(Initial) Thermalization (2) : Falling Mass Shell

$R^3$

Above : Black-hole metric

Thin Mass Shell Falling

Below : $AdS_5$
(Initial) Thermalization (2): Falling Mass Shell

$R^3$

Above: Black-hole metric

Black-hole Horizon
Deviation of spectral function from thermal state, \( R = \frac{\chi_{tx, tx} - \chi_{tx, tx}^{th}}{\chi_{tx, tx}^{th}} \), for different times.
Upper/lower curve: total/half thermalization time of entanglement entropy
\( R \): size of the probe
Thermalization of Correlation Functions
(Caron-Hout-Chesler-Teaney)
Plot of Chesler-Teaney
Plot of Heller-Janik-Witaszczyk

\[ F(w) = \frac{\tau}{w} \frac{dw}{d\tau} \quad , \quad w = T_{\text{eff}} \cdot \tau \]
Summary of results:

- Hydrodynamics fits in the description much earlier than the isotropization time: “Fast Thermalization”

- Various correlation functions with different sizes are studied: *Entanglement entropy* thermalizes slowly (*Balasubramanian, et al*)

- No delay in UV thermalization: *probably due to conformal nature*
Jet Quenching in Strongly Coupled QGP
Quark is a String (Gubser, Herzog et al.)

Drag: $\frac{dp}{dt} \sim -\sqrt{\lambda} T^2 \frac{p}{m_q}$
Plot of W.A. Horowitz

\[ \sqrt{s} = 2.76 \text{ ATeV; 0-20\%} \]

- B WHDG
- B AdS/CFT Drag

\( R_{AA} \)

\( p_T \) (GeV/c)
Heavy/Light Quark Diffusion

(Casalderrey-Solana-Teaney, Gubser, Myers-Starinets-Thompson)

\[ D \sim \frac{1}{\sqrt{\lambda T}} \]

\[ D \sim \frac{1}{T} \]

Heavy Quarks -> Radiations -> Light Quarks
Modeling $q\bar{q}$ Jets

(Chesler-Jensen-Karch-Yaffe)

$Z \sim \frac{1}{\sqrt{Q^2}}$: Virtuality

(Hatta-Iancu-Mueller)

Light-like geodesic

(Arnold-Vaman)

$Z$ 

Black-hole Horizon
Back Reaction: \( \frac{dE}{dt} \sim \frac{y^2}{N_c^2} T^2 \) (Shuryak-Yee-Zahed)
Massless Green's Function in Odd Dimensions

Massless Retarded Green's function is non-zero inside the whole lightcone
THREE CLAIMS

• $\Delta x \sim E^{1/3}$
  (Gubser-Gulotta-Pufu-Rocha, Hatta-lancu-Mueller, Chesler-Jensen-Karch-Yaffe)

• $\Delta x \sim E^{1/4}$ is more typical for finite size jets
  (Arnold-Vaman)

• $\Delta x \sim E^0$ for realistic $N_c = 3$ and $\gamma \gg 1$
  (Shuryak-Yee-Zahed)
Another strategy to strongly coupled system

Symmetry protected aspects of Triangle Anomaly
Triangle Anomaly

\[ \partial_\mu J_\mu^A = \frac{N_F}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = \frac{N_F}{4\pi^2} \vec{E} \cdot \vec{B} \]

\[ \langle J_A J_V J_V \rangle \quad \text{or simply} \quad \langle AVV \rangle \]
Triangle Anomaly

\[ \partial_\mu J^\mu_A = \frac{N_F}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = \frac{N_F}{4\pi^2} \vec{E} \cdot \vec{B} \]

The full consequences of \( \langle A\nabla V \rangle \) may not have been explored completely in various situations.
Chiral Magnetic Effect

Fukushima-Kharzeev-Warringa, Vilenkin

\[ \vec{J}_{V,A} = N_c e \vec{B} \frac{\mu}{2\pi^2} \]

Charge current along the magnetic field is induced by chemical potential.
Possible experimental consequence of chiral magnetic effect
Possible experimental consequence of chiral magnetic effect

\[ \vec{B} \]

\[ \vec{J} \]

\[ Q_5 \]

SPHALERONS

CHIRAL MAGNETIC EFFECT

REACTION PLANE

NON-CENTRAL COLLISION
Possible experimental consequence of chiral magnetic effect

\[ \vec{B} \]

[Diagram showing components of the chiral magnetic effect]

CHIRAL MAGNETIC EFFECT

\[ \vec{J} \]

Q_5

SPHALERONS

REACTION PLANE

NON-CENTRAL COLLISION
Possible experimental consequence of chiral magnetic effect

SAME CHARGE CORRELATIONS: \[ \cos (\phi_1 + \phi_2) \approx -1 < 0 \] (S. Voloshin)

\[ \vec{B} \]

NON-CENTRAL COLLISION
Possible experimental consequence of chiral magnetic effect

OPPOSITE CHARGE CORRELATIONS: \( \cos(\phi_1 + \phi_2) \approx +1 > 0 \) (S. Voloshin)
Experiments in STAR and PHENIX at RHIC

<\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})>

\( (p_{T,\alpha} + p_{T,\beta})/2 \) (GeV/c)

PHENIX preliminary
Au+Au 200 GeV 10-30%
\( \Phi_{RRH} \) \( \eta = 1.0 \sim 2.8 \)

\[\begin{align*}
&\text{STAR} \quad \text{AuAu 200 GeV} \\
&\text{Centrality 30-50%} \\
&\text{same charge} \quad \text{red line} \\
&\text{opp charge} \quad \text{blue line}
\end{align*}\]
Experiments in ALICE at LHC

\[ \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle \times 10^{-3} \]

Opp. Same charge
- ALICE Pb-Pb @ \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
- STAR Au-Au @ \( \sqrt{s_{NN}} = 0.2 \text{ TeV} \)

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It seems very plausible but still not a proof due to other background effects
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Other more rigid prediction from triangle anomaly?
CHIRAL MAGNETIC WAVE (Kharzeev-HUY)

New propagating charge waves along magnetic field originating from triangle anomaly

\[ \omega = \mp v_\chi k - iD_L k^2 + \cdots \quad , \quad v_\chi = \frac{N_c eB}{4\pi^2} \left( \frac{\partial \mu}{\partial Q} \right) \]
Why do we have waves?

\[ \vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A \], \hspace{1cm} \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V

CHIRAL MAGNETIC EFFECT
Why do we have waves?

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\( Q_5 > 0 \)

\( Q > 0 \)

\( \vec{B} \)

CHIRAL SEPARATION EFFECT

Recent Theoretical Developments in Strongly Coupled QCD
Possible experimental consequences of chiral magnetic waves

Charge dependent elliptic flow $v_2$ of pions

(Burnier-Kharzeev-Liao-HUY)

$v_2(\pi^-) > v_2(\pi^+)$

Talk by Gang Wang, STAR Coll.
Essential physics mechanism

\[ \mathbf{Q} = Q_L + Q_R > 0 \]

\[ Q_A = Q_L - Q_R = 0 \]

NON-CENTRAL COLLISION
Essential physics mechanism

\[ \vec{B} \]

\[ v_x \]

CHIRAL MAGNETIC WAVE

\[ Q_L \]

\[ Q_R \]

NON-CENTRAL COLLISION

Recent Theoretical Developments in Strongly Coupled QCD
Essential physics mechanism

$\vec{B}$

$Q_L$

$Q_R$

$\vec{J}$

CHIRAL MAGNETIC EFFECT

NON-CENTRAL COLLISION
Essential physics mechanism

$\vec{B}$

NON-CENTRAL COLLISION
Essential physics mechanism

\[ \vec{B} \]

NON-CENTRAL COLLISION
Charge dependent elliptic flow

Theory from Burnier et al, 1103.1307; 1208.2537 and Data from Gang Wang’s talk

\[ v_{2}^{\pm} = v_{2} \mp A \times r \] ,  \[ A \equiv \frac{N_{+} - N_{-}}{N_{+} + N_{-}} \]
For $p$ ($K^+$) and $\bar{p}$ ($K^-$), cross sections in the after-burner phase are quite different

$$\sigma(\bar{p}) > \sigma(p), \quad \sigma(K^-) > \sigma(K^+)$$

that may wash out or even reverse the effect
Future Directions?

- Holographic understanding of hadronization, probably beyond large $N_c$ limit
- Holographic version of 2D reduction of high energy scattering (Lipatov, Verlinde-Verlinde)
- Better understanding of unitarization and multi-Pomerons in holography
- Better understanding of multiplicity generation in holographic Pomeron picture
- New effects from triangle anomaly at second order hydrodynamics (Kharzeev-Yee)
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