Recent Theoretical Developments in Strongly Coupled QCD

Ho-Ung Yee

University of Illinois at Chicago/RIKEN-BNL Research Center

August 17, 2012

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
Challenges for QCD in Heavy-Ion Collisions

- Time-dependent and many-body problem
- Physics of different scales: High energy vs. Low $p_T$
Challenges for QCD in Heavy-Ion Collisions

- Time-dependent and many-body problem
- Physics of different scales: High energy vs. Low $p_T$
- Indirect measurements: Things mix
Challenges for QCD in Heavy-Ion Collisions

- Time-dependent and many-body problem
- Physics of different scales: High energy vs. Low $p_T$
- Indirect measurements: Things mix
- Precision measurements at RHIC and LHC
Challenges for QCD in Heavy-Ion Collisions

- Time-dependent and many-body problem
- Physics of different scales: High energy vs. Low $\rho_T$
- Indirect measurements: Things mix
- Precision measurements at RHIC and LHC

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: $s^{\alpha_0 + \alpha_1 t}$
  - Pomerons
  - Unitarization
  - (Anti) Shadowing
- Non Perturbative, Strongly Coupled QCD
- Strongly Coupled QGP
- Freeze-out, Hadronization
Ho-Ung Yee

Recent Theoretical Developments in Strongly Coupled QCD

Early Thermalization

- Multiplicity production
- Initial fluctuations
- Fast thermalization: $\tau \sim 1\,\text{fm}$

Non Perturbative, Strongly Coupled QCD

High $s$, Small $t$ Scattering Saturation

Strongly Coupled QGP

Freeze-out, Hadronization
Recent Theoretical Developments in Strongly Coupled QCD

- Early Thermalization
- High $s$, Small $t$ Scattering Saturation
- Non Perturbative, Strongly Coupled QCD
- Strongly Coupled QGP
- Freezing-out, Hadronization

$\frac{n_s}{s}$, 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.
$\text{AdS}_5$

Extra (Energy) Dimension : $Z$

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

$4 \text{ Dimensional Minkowsk Space}$

$R^{1,3}$
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 $R^{1,3}$**

**How come is this possible?**
A peculiar property of $AdS_5$

$AdS_5$

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

$AdS_5$

GRAVITATIONAL POTENTIAL from WARPING FACTOR

WARPING FACTOR

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

$R^{1,3}$

$Z=0$
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
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
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
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
Black-hole as a Quark Gluon Plasma

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

\[ ds^2 = \frac{1}{z^2 f(z)} dz^2 - \frac{f(z)}{z^2} dt^2 + \frac{1}{z^2} (\vec{dx} \vec{dx}) \]
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
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
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
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: $b$

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

Proton at rest  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)

$$\partial \chi K = D \nabla^2 \perp K$$

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

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)

\[
\partial_{\chi} K = D \nabla^2_{\perp} K
\]

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)

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)

$$\partial_\chi K = D\nabla^2 K$$

with $D = \frac{\alpha'}{2}$
What is diffusing and Why?
Perturbative BFKL-Mueller picture of Dipoles

Seed Dipole

Diffused Dipoles

$b$
Multi-gluon wave-function \textbf{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 \textbf{sizes} (virtuality) of dipoles.
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.
• 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
Holographic diffusion of Pomerons
(Brewer-Polchinski-Strassler-Tan, Basar-Kharzeev-Yee-Zahed)

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 \cite{Brewer-Polchinski-Strassler-Tan}, and for $\chi > \lambda$ they are of spin $\frac{D}{12} = \frac{1}{4}$ \cite{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 \cite{Stoffers-Zahed}.
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 $\frac{D_{\perp}}{12} = \frac{1}{4}$ (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)
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 $\frac{D_1}{12} = \frac{1}{4}$ (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).
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 $\frac{D_1}{12} = \frac{1}{4}$ (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).
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

Need to tunnel the distance $b$

Vacuum wall

Color charged objects
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
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**
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
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**
$\chi = \log s$

Non Perturbative

$\Lambda_{QCD}^2$

$Q^2$

Perturbative

Saturation

$Q_s(\chi)$

DGLAP

JIMWLK

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

\[ \varepsilon \, [\text{GeV/fm}^3] \]

- 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

$\mathbb{R}^3$

- 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

$Z$
Deviation of spectral function from thermal state, \[ R = \frac{\chi_{tx, tx} - \chi_{th}^{tx, tx}}{\chi_{th}^{tx, tx} - \chi_{th}^{tx, tx}} \], for different times
Plot of Balasubramanian et al.

Upper/lower curve: total/half thermalization time of entanglement entropy

$R$: size of the probe
Thermalization of Correlation Functions
(Caron-Hout-Chesler-Teaney)

$R^3$

Time

Matter perturbation

Increasing Black-hole Horizon
Plot of Chesler-Teaney

\begin{center}
\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot}
\end{figure}
\end{center}

- $E/E_f$
- $P_{\perp}/E_f$
- $P_{||}/E_f$
- $\pi T_f v$

- $T_1/T_f$
- $T_2/T_f$ (time-like)
- $T_2/T_f$ (light-like)
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

\[ R_{AA} \]

- **B WHDG**
- **B AdS/CFT Drag**

\[ \sqrt{s} = 2.76 \text{ ATeV}; \ 0-20\% \]
Heavy/Light Quark Diffusion

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

$D \sim \frac{1}{\sqrt{\lambda T}}$

Heavy Quarks

Radiations

Light Quarks

$D \sim \frac{1}{T}$
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: \( \frac{dE}{dt} \sim \frac{\gamma^2}{N_c^2} T^2 \)

(Shuryak-Yee-Zahed)
Massless Green's Function in Odd Dimensions

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

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

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

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

Symmetry protected aspects of Triangle Anomaly
Triangle Anomaly

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

\[ \langle J_A J_V J_V \rangle \quad \text{or simply} \quad \langle AVV \rangle \]
The full consequences of $\langle AVV \rangle$ may not have been explored completely in various situations.
Charge current along the magnetic field is induced by chemical potential.

\[
\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V
\]
Possible experimental consequence of chiral magnetic effect

\[ \vec{B} \]

\[ Q_5 \]

SPHALERONS

REACTION PLANE

NON-CENTRAL COLLISION
Possible experimental consequence of chiral magnetic effect

\[ \vec{B} \]

\[ \vec{J} \]

CHIRAL MAGNETIC EFFECT

SPHALEONS

Q_5

REACTION PLANE

NON-CENTRAL COLLISION
Possible experimental consequence of chiral magnetic effect
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

\[ \langle \cos(\phi_\alpha - 2\psi_{RP}) \rangle \]

\[ \frac{(p_{t,\alpha} + p_{t,\beta})}{2} \text{ (GeV/c)} \]

PHENIX preliminary
Au+Au 200 GeV 10–30%
\( \phi_{DDH} \) (1.0 – 2.8)

- (+,−) pair
- (+,+) pair
- (−,−) pair

PHENIX preliminary
Au+Au 200 GeV 10–30%
\( \phi_{BDT-MPC} \) (3.0 – 3.9)

- (+,−) pair
- (+,+) pair
- (−,−) pair

30–50%
\( \phi_{LH} \) (1.0 – 2.8)

- STAR ++
- STAR ++,−

30–50%
\( \phi_{BDT-MPC} \) (3.0 – 3.9)

- STAR ++
- STAR ++,−

\[ <p_t> = \frac{(p_{T1} + p_{T2})}{2} \text{ (GeV/c)} \]
Experiments in ALICE at LHC

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

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

Preliminary
It seems very plausible but still not a proof due to other background effects
It seems very plausible but still not a proof due to other background effects.

Other more rigid prediction from triangle anomaly?
New propagating charge waves along magnetic field originating from triangle anomaly

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

\[ \vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A, \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V \]
Why do we have waves?

\[ \vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A, \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V \]
Why do we have waves?

\[ \mathbf{J}_V = \frac{N_c e B}{2\pi^2} \mu_A \quad , \quad \mathbf{J}_A = \frac{N_c e B}{2\pi^2} \mu_V \]
Why do we have waves?

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

$\vec{B}$

$Q = Q_L + Q_R > 0$

$Q_A = Q_L - Q_R = 0$

NON-CENTRAL COLLISION
Essential physics mechanism

CHIRAL MAGNETIC WAVE

Q_L

Q_R

NON-CENTRAL COLLISION

\vec{B}

v_x

- v_x
Essential physics mechanism

\[
\vec{B}
\]

\[
Q_L \quad \vec{j} \quad Q_R
\]

CHIRAL MAGNETIC EFFECT

NON-CENTRAL COLLISION

Ho-Ung Yee
Recent Theoretical Developments in Strongly Coupled QCD
Essential physics mechanism

NON-CENTRAL COLLISION
Essential physics mechanism
Charge dependent elliptic flow

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

\[ v_{2}^{\pm} = v_{2} \mp A \ast r \quad , \quad A \equiv \frac{N_{+} - N_{-}}{N_{+} + N_{-}} \]
\( v_2^{\pm} \) for other hadrons

For \( p (K^+) \) and \( \bar{p} (K^-) \), cross sections in the after-burner phase are quite different

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

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)
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)
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](#))
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)
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)