Prospects with Heavy Ions at the LHC
So far at RHIC:

- Elliptic Flow \( \rightarrow \) Near-perfect Fluid
- High \( p_T \) Suppression \( \rightarrow \) Strongly-coupled QGP
- Jet Quenching \( \rightarrow \) Strongly-coupled QGP
- Away-side of jet \( \rightarrow \) Energy dissipation/propagation in medium
  - Medium properties?
- Near-side Ridge \( \rightarrow \) Something new, unresolved
  - Heating of the system
  - Longitudinal expansion?
  - Initial parton distributions?
  - Initial parton bremsstrahlung + flow?

RHIC and LHC:

Cover 2 – 3 decades of energy (\( \sqrt{s_{NN}} \sim 20 \text{ GeV} – 5.5 \text{ TeV} \))
What are the properties of hot QCD in this temperature range (\( T \sim 150 – 600 \text{ MeV} \)?)
BIG Physics Questions for RHIC & LHC Heavy Ions

- How does the system evolve/decohere from its initial state?
  - Initial state saturation / color glass?
  - Rapid thermalization - how?
- What are the properties & constituents (vs. T) of the QGP?
  - e.g., screening length, bulk/shear viscosity, $v_s$, diff. coeff.,….
- How do partons lose energy in the QGP?
- How does the QGP respond to large energy deposition ("jet heating")
  - Response of medium (e.g. away-side, near-side ridge)?
- How does hadronization take place?
### Simple Expectations - Heavy Ion Physics at the LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (GeV)</td>
<td>17</td>
<td>200</td>
<td>5500</td>
</tr>
<tr>
<td>$t_{\text{form}}$ (fm/c)</td>
<td>1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>$T / T_c$</td>
<td>1.1</td>
<td>1.9</td>
<td>3.0 - 4.2</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm$^3$)</td>
<td>3</td>
<td>5</td>
<td>15-60</td>
</tr>
<tr>
<td>$\tau_{\text{QGP}}$ (fm/c)</td>
<td>≤ 2</td>
<td>2-4</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

- RHIC is factor 28 times larger than SPS.
- RHIC is 3.0 - 4.2 times hotter than SPS.
- RHIC is 15-60 times denser than SPS.
- RHIC is longer-lived than SPS.
Significant increase in hard scattering yields at LHC:

- jets & large $p_T$ processes

- $\sigma_{bb} (\text{LHC}) \sim 100 \sigma_{bb} (\text{RHIC})$

- $\sigma_{cc} (\text{LHC}) \sim 10 \sigma_{cc} (\text{RHIC})$
**How Will LHC Heavy Ions Contribute?**

- How does the system evolve/decohere from its initial state?
  - LHC extends reach to very low-x phenomena
- What are the properties & constituents (vs. T) of the QGP?
  - LHC extends reach to higher T
  - LHC extends abundance & diversity of probes
    (e.g. flow of heavy quarks & quarkonia – $v_2$ scaling?)
- How do partons lose energy in the QGP?
  - LHC extends reach in mass, flavor, and $p_T$ of hard probes
    (different parton probes, jets, Z-bosons, heavy quarks, quarkonia)
- How does the QGP respond to “jet heating” – response of medium
  (e.g. away-side, near-side ridge)?
  - Trigger on hard probes (above) of different mass, flavor and $p_T$
- How does hadronization take place?
  - Investigate intermediate $p_T$ (5 – 15 GeV/c) hadron production
  - Investigate fragmentation process in detail (hadrochemistry in jets)
  - Investigate production of “new” scalar and vector particles
LHC Heavy Ion Collider Program

• LHC to start $\sqrt{s} = 14$ TeV $p + p$ operation in Spring 2008

• LHC Heavy Ion operation
  - $\sqrt{s_{NN}} = 5.5$ TeV Pb + Pb
  - Anticipate 1 month per year

• Detectors
  - ATLAS
  - CMS
  - ALICE
**LHC Heavy Ion Collider Experiments**

**ATLAS** – Multi-purpose, large acceptance system. Designed for large $p_T$ with extensive calorimetry for detailed jet studies.

**CMS** – Multi-purpose, large acceptance system. Designed for large $p_T$ with calorimetry for detailed jet studies.

**ALICE** – Dedicated heavy ion experiment. Large suite of detectors for tracking and PID from 100 MeV/c to 100 GeV/c. Proposed calorimetry for jet trigger and studies.
AdS/CFT
(and all theories)

Meets

Heavy Ions at the LHC
Prospects for AdS/CFT with LHC Heavy Ions

LHC ions will investigate $v_2$ for light & heavy particles ($\pi, \ldots, \phi, \Omega, \ldots, B, D, J/\psi, \ldots$)

From PHENIX non-$\gamma$ e-data, transport models require:
- small heavy quark relaxation time
- small diffusion coefficient $D_{HQ} \times (2\pi T) \sim 4 - 6$
- constrain viscosity/entropy
- $\eta/s \sim (1.5 - 3) / 4\pi$
- within factor 2 - 3 of AdS/CFT conjectured lower bound
- consistent with light hadron $v_2$ analysis

* Kovtun, Son, Starinets, hep-th/0405231

John Harris (Yale) AdS/CFT Strings Intersect Beams at Columbia, 26 Oct. 2007
Prospects for AdS/CFT with LHC Heavy Ions

What about the $v_2$ “Quark Scaling” at intermediate $p_T$?

My naïvete: how does this work?
– Early flow & constituent quark scaling?

John Harris (Yale) AdS/CFT Strings Intersect Beams at Columbia, 26 Oct. 2007
Prospects for AdS/CFT with LHC Heavy Ions

What is the dynamical origin of parton energy loss (quenching, suppression)?

What happens to the radiation? Interference effects? Dist. relative to parton?

How does parton lose energy?

What is dependence on mass, flavor and energy of parton?

\[ \Delta E_{\text{gluon}} > \Delta E_{\text{quark, } m=0} > \Delta E_{\text{quark, } m>0} \]

What about recoil energy of collisional E-loss?

One parameterization of energy loss \( \hat{q} = \frac{\mu^2}{\Lambda} \)

John Harris (Yale)  AdS/CFT Strings Intersect Beams at Columbia, 26 Oct. 2007
Jets & High $p_T$ Particles with LHC Heavy Ions

Jet Physics

- **Jets**: measure parton $E$ & $E$-loss, jet-tag (B vs. light quark, gluon)
- **long. & transverse mod. of jet**
- **$\gamma$-jet, $Z^0$-jet, di-jet**: parton $E$ & $E$-loss
- **Hadrochemistry in Jets**
  
  fragmentation function mod.
  
  light flavored mesons – gluons parents
  
  D-mesons – quark parents ($m_c \sim 0$)
  
  B-mesons – quark parents ($m_b > 0$)
\[ q = 5 - 15 \text{ GeV}^2 / \text{fm} \text{ from RHIC } R_{AA} \text{ Data} \rightarrow \text{ LHC? } \]

\[ R_{AA}(p_T) ? \]
AdS$_5$/CFT – Parton Energy Loss Results & Future!

Hot gauge theory lives on boundary

AdS$_5$–Schwarzschild

Black-hole horizon

Heavy quark is end of string on boundary

String provides drag (energy loss)

Calculating the Jet Quenching Parameter from AdS/CFT

H. Liu, K. Rajagopal and U. A. Wiedemann

John Harris (Yale) AdS/CFT Strings Intersect Beams at Columbia, 26 Oct. 2007
**AdS$_5$/CFT – Parton Energy Loss Results & Future!**

Future for AdS/CFT:
What is the velocity dependence of energy loss?
What is the mass & flavor (q, g) dependence of energy loss?
What is radiated from the partons?

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A Near-side “Ridge” Appears at RHIC!

Di-hadron correlations

Trigger Jet (near-side)

Near-side ridge

Jets: scale with # of binary collisions

Ridge: exists to highest $p_T$ (trig) $\rightarrow$ correlated with jets

But ridge spectra $\sim$ same as medium (‘bulk-like’, seen for mesons/baryons)$\rightarrow$ thermal spectra + flow origin? jet-heating?........
Possible “Ridge” Mechanisms So Far

References to proposed explanations so far:

- Radiated gluons, broadened by
  - Color magnetic fields, Majumder et al, hep-ph/0611035
- Medium heating + recombination, Chiu & Hwa, PRC72, 034903
- Radial flow + trigger particle bias, Voloshin, N.P. A749, 287, Shuryak nuc-th/07063531
Response of the Medium in AdS/CFT

The wake of a quark moving through a strongly-coupled $N=4$ supersymmetric Yang-Mills plasma

hep-ph/0706.0368

Paul M. Chesler and Laurence G. Yaffe
Department of Physics, University of Washington, Seattle, WA 98195, USA
(Dated: July 31, 2007)

The energy density wake produced by a heavy quark moving through a strongly coupled $N=4$ supersymmetric Yang-Mills plasma is computed using gauge/string duality.

Sonic booms and diffusion wakes generated by a heavy quark in thermal AdS/CFT

hep-th/0706.4302

Steven S. Gubser and Silviu S. Pufu
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

Amos Yaron
Ludwig-Maximilians-Universität, Department für Physik, Theresienstrasse 37, 80333 München, Germany
(Dated: June 28, 2007)

We evaluate the Poynting vector generated by a heavy quark moving through a thermal state of $N=4$ gauge theory using AdS/CFT. A significant diffusion wake is observed as well as a Mach cone. We discuss the ratio of the energy going into sound modes to the energy coming in from the wake.

Questions for AdS/CFT:
Dependence on mass, flavor and velocity?

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Heavy Flavors at the LHC

**c\bar{c} and b\bar{b} rates (ALICE PPR)**

<table>
<thead>
<tr>
<th>system</th>
<th>NN x-sect (mb)</th>
<th>shadowing</th>
<th>total multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>p + p, 14 TeV</td>
<td>11.2 / 0.5</td>
<td>1 / 1</td>
<td>0.16 / 0.007</td>
</tr>
<tr>
<td>Pb + Pb, 5.5 TeV (5%)</td>
<td>6.6 / 0.2</td>
<td>0.65 / 0.85</td>
<td>115 / 4.6</td>
</tr>
</tbody>
</table>

$R_{AA}$ of D and B-mesons to large $p_T$ at LHC

AdS/CFT – dE/dx of heavy quarks

- Chesler & Yaffe, hep-th/07060368.
- Horowitz & Gyulassy, nuc-th/07062336.
- ….
Color Screening of the Medium?

**J/ψ and Υ Physics**

- Melting of quarkonium states:
  - initial $T$
  - suppression / regeneration
  - color screening of medium?

**Graphs**

- SPS
- RHIC
- LHC
- Opposite sign dimuon invariant mass (GeV/c$^2$)

John Harris (Yale)       AdS/CFT Strings Intersect Beams at Columbia, 26 Oct. 2007
An AdS/CFT calculation of screening in a hot wind

Hong Liu, Krishna Rajagopal, and Urs Achim Wiedemann

1 Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2 Nuclear Science Division, MS 70R319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
3 Department of Physics, CERN, Theory Division, CH-1211 Geneva 23, Switzerland

One of the challenges in relating experimental measurements of the suppression of the number of $J/\psi$ mesons produced in heavy ion collisions to lattice QCD calculations is that whereas the lattice calculations treat $J/\psi$ mesons at rest, in a heavy ion collision a $c\bar{c}$ pair can have a significant velocity with respect to the hot fluid produced in the collision. The putative $J/\psi$ finds itself in a hot wind. We present the first rigorous non-perturbative calculation of the consequences of a wind velocity $v$ on the screening length $L_s$ for a heavy quark-antiquark pair in hot $\mathcal{N} = 4$ supersymmetric QCD. We find $L_s(v,T) = f(v)[1-v^2]^{1/4}/\pi T$ with $f(v)$ only mildly dependent on $v$ and the wind direction. This $L_s(v,T) \sim L_s(0,T)/\sqrt{\gamma}$ velocity scaling, if realized in QCD, provides a significant additional source of $J/\Psi$ suppression at transverse momenta which are high but within experimental reach.

Screening length in plasma winds

E. Caceres, M. Natsume, T. Okamura, hep-th/0607233

ABSTRACT: We study the screening length $L_s$ of a heavy quark-antiquark pair in strongly coupled gauge theory plasmas flowing at velocity $v$. Using the AdS/CFT correspondence we investigate, analytically, the screening length in the ultra-relativistic limit. We develop a procedure that allows us to find the scaling exponent for a large class of backgrounds. We find that for conformal theories the screening length is (boosted energy density)$^{-1/d}$. As examples of conformal backgrounds we study R-charged black holes and Schwarzschild-anti-deSitter black holes in $(d+1)$-dimensions. For non-conformal theories, we find that the exponent deviates from $-1/d$. As examples we study the non-extremal Klebanov-Tseytlin and Dp-brane geometries. We find an interesting relation between the deviation of the scaling exponent from the conformal value and the speed of sound.
Medium Modification of Fragmentation from Jets

Fragmentation along jet axis: $z = \frac{p_{\text{hadron}}}{p_{\text{parton}}}$

Introduce $\xi = \ln\left(\frac{E_{\text{jet}}}{p_{\text{hadron}}}\right) \sim \ln\left(\frac{1}{z}\right)$:

$dN^h_{\xi,\tau}(\xi, \tau)$

- OPAL, $\sqrt{s} = 192–209$ GeV
- in vacuum, $E_{\text{jet}} = 100$ GeV
- in medium, $E_{\text{jet}} = 100$ GeV
- TASSO, $\sqrt{s} = 14$ GeV
- in vacuum, $E_{\text{jet}} = 7$ GeV
- in medium, $E_{\text{jet}} = 7$ GeV

Black line = radiative E-loss
Dashed line = flat
Collisional E-loss?

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Medium Modifications and Jet Hadrochemistry

Parton energy loss can alter: parton’s color charge (flavor, baryon # ?)

\[ J_{AA} \rightarrow R_{AA} \text{ in jet cone} \]

100 GeV jet in central Pb+Pb

Sapeta & Wiedemann, hep-ph/07073894

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**Hadronization, Fragmentation, Medium Modification**

**Fragmentation** at lower $z$ in jets

**Hadronization** of lower $p_T$ particles from colored medium.

Both impacted by medium properties

Microscopic hadronization process?

**Bourrely & Soffer, hep-ph/0305070:**
Each flavor parton - contributes differently to fragmentation function.

- loses different amounts of energy in medium.

Study $z = p_{hadron}/p_{jet}$

Requires high $p_T$ identified particles

Jets, Intra- & inter-jet particle correlations

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**The Quark-Gluon Plasma at the LHC**

**At LHC:**

- Is the QCD phase diagram feature-less at $1 - 4 \, T_c$?
- What happens as we go up in $T$ (e.g. coupling)?
- Are there new phenomena?
- What’s the range of theoretical validities (non-pQCD, pQCD, strings)?

Measure/understand parton energy loss at the fundamental level

- Establish flavor (gluon and quark mass) dependence
- Use jets and/or photons to establish hard-scattered parton energy
- Jet modifications - longitudinal & transverse “heating”
- Medium response to jet-heating (near- and away-side)

Measure/use open charm and beauty decays (also as jet-tags)
- $c\bar{c}$ and $b\bar{b}$ states (screening, suppression, enhancement)

Direct Photon Radiation?

Developments in theory (lattice, hydro, parton E-loss, string theory…)

“the next frontier!”

John Harris (Yale)    AdS/CFT Strings Intersect Beams
AdS/CFT Meets Heavy Ions at the LHC......

Summary of Physics Questions for both

What is:

- the velocity dependence of energy loss?
- the flavor (q, g) dependence of energy loss?
- radiated from partons in energy loss?
- the response of the medium?
- the color screening of the medium?
- the particle type dep. of viscosity (flow)?
- the basis for quark scaling of $v_2$ at inter. $p_T$
- hadronization mechanism?
Thanks for Discussions / Contributions to This Presentation!!

Miklos Gyulassy
Dima Kharzeev
Peter Jacobs
Urs Wiedemann