Evidence for a Quark-Gluon Plasma at RHIC - Part 2
Space-time Evolution of RHIC Collisions

- Hard Scattering + Thermalization ($< 1 \text{ fm/c}$)
- QGP ($\sim$ few fm/c)
- Freeze-out ($\sim 10 \text{ fm/c}$)
- Hadronization

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“Chemical” equilibration (particle yields & ratios):

Particles yields represent equilibrium abundances

→ universal hadronization temperature

Small net baryon density \((K^+/K^-; \bar{B}/B\) ratios) \(\rightarrow \mu_B \sim 25 - 40\) MeV

Chemical Freezeout Conditions \(\rightarrow T = 177\) MeV, \(\mu_B = 29\) MeV \(\rightarrow T \sim T_{\text{critical}}\) (QCD)
**QCD Phase Diagram**

At RHIC:

$T = 177 \text{ MeV}$

$T \sim T_{\text{critical}} \ (\text{QCD})$
Particles are thermally distributed and flow collectively, at universal hadronization temperature $T = 177$ MeV!
Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.
Probing Hot QCD Matter with Hard-Scattered Probes

leading particle

hadrons

leading particle

hadrons
High Momentum Hadrons Suppressed - Photons Not

Deviations from binary scaling of hard collisions:

Photons

Hadrons factor 4 – 5 suppression
Final State Suppression / Initial State Enhancement!

- The hadron spectra at RHIC from p+p, Au+Au and d+Au collisions establish existence of early parton energy loss, a new final-state effect, from strongly interacting, dense QCD matter in central Au-Au collisions.
Energy Loss of Hard Scattered Parton

Energy loss requires large \( \langle \hat{q} \rangle \approx 5 - 10 \text{ GeV}^2/\text{fm} \)

(Dainese, Loizides, Paic, hep-ph/0406201)

\( p_T = 4.5 - 10 \text{ GeV/c} \)

Much larger energy loss than expected from pQCD

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Non-photonic electrons come from semi-leptonic decays of heavy quarks:

- $c \rightarrow e^+ + \text{anything}$ (B.R. = 9.6%)  
  - $D^0 \rightarrow e^+ + \text{anything}$ (B.R. = 6.87%)  
  - $D^\pm \rightarrow e^\pm + \text{anything}$ (B.R. = 17.2%)
- $b \rightarrow e^+ + \text{anything}$ (B.R. = 10.9%)  
  - $B^\pm \rightarrow e^\pm + \text{anything}$ (B.R. = 10.2%)  
- plus small contribution from Drell-Yan for $p_T < 10$ GeV/c
**$R_{AA}$ of Heavy Quarks from Non-photonic Electron**

$R_{AA} = \frac{\left(\frac{d^3 N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3 \sigma}{dp^3}\right)_{pp}}$

Suppression observed:
- ~0.4-0.6 in 40-80% centrality
- ~0.3-0.4 in 10-40%
- ~0.2 in 0-5%

Max suppression at $p_T \sim 5$-6 GeV

Theories currently cannot describe the data!

Heavy quarks suppressed like light quarks

Only c contribution describes $R_{AA}$ but not p + p spectra

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Hard Scattering (Jets) as a Probe of Dense Matter II

Can we see jets in high energy Au+Au?

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**STAR** Hard Scattering: Two-Particle Azimuthal Correlations

**Technique:**

\[
C_2(\Delta \Phi) = \frac{1}{N_{\text{trigger}}} \frac{1}{\text{efficiency}} \int d(\Delta \eta) N(\Delta \Phi, \Delta \eta)
\]

Azimuthal correlation function

Trigger particle
\[ p_T > 4 \text{ GeV}/c \]

Associate tracks
\[ 2 < p_T < p_T(\text{trigger}) \]

Di-jets from \( p + p \) at 200 GeV
**Technique:**

\[
C_2 (\Delta \Phi) = \frac{1}{N_{\text{trigger}} \text{ efficiency}} \int d(\Delta \eta) N(\Delta \Phi, \Delta \eta)
\]

Azimuthal correlation function

- **Trigger particle**
  \[ p_T > 4 \text{ GeV/c} \]
- **Associate tracks**
  \[ 2 < p_T < p_T(\text{trigger}) \]

*Short range $\eta$ correlation:*
  - jets + elliptic flow

*Long range $\eta$ correlation:*
  - elliptic flow

**130 GeV Au + Au, central trigger**

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Relative Charge Dependence

Compare ++ and - - correlations to +- correlations

<table>
<thead>
<tr>
<th>System</th>
<th>(+-)/(++ &amp; --)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>2.7+-0.6</td>
</tr>
<tr>
<td>0-10% Au+Au</td>
<td>2.4+-0.6</td>
</tr>
<tr>
<td>Jetset</td>
<td>2.6+-0.7</td>
</tr>
</tbody>
</table>

Strong dynamical charge correlations in jet fragmentation → “charge ordering”


\[ p_T > 4 \text{ GeV/c} \text{ particle production mechanism same in central Au+Au & pp} \]

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Assume (then compare):

high $p_T$ triggered $Au+Au$ event
is a superposition:
high $p_T$ triggered $p+p$ event +
elliptic flow of $AuAu$ event

- $v_2$ from reaction plane
  analysis
- $A$ from fit in non-jet
  region ($0.75 < |\Delta \phi| < 2.24$)
Hammering the Nail in the Coffin

Au + Au
away-side correlation quenched!

d + Au
“di-jet” correlations similar to p + p

Quenching of Away-side “jet” is final state effect

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High Pt hadrons
suppressed in central Au + Au
enhanced in d + Au

Back-to-back Jets
Di-jets in p + p, d + Au
(all centralities)
Away-side jets quenched
in central Au + Au
→ emission from surface
→ strongly interacting medium
The suppression of high $p_T$ hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium.
Where Does the Energy Go?

Jet correlations in proton-proton reactions.
Away-side jet disappears for particles $p_T > 2$ GeV.

Jet correlations in central Gold-Gold. Away-side jet reappears for particles $p_T > 200$ MeV.

Azimuthal Angular Correlations

Lost energy of away-side jet is redistributed to rather large angles!

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Response of the Medium

Measure low-$p_T$ associated hadrons

- Shapes of jets are modified by the medium
  - Mach cone?
  - Cerenkov?
  - Color wakes? ..... Other....

Properties of the medium can be determined from these shapes!
- Sound velocity
- Di-electric constant

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**Mach Cone Resulting from Fast Parton in Medium**

**Figure 1.** (a) A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point (the black circle at point B) from which sound waves start propagating as spherical waves (the dashed circle). The companion quenched jet is moving to the left, heating the matter and thus creating a cylinder of excited matter (shaded area). The head of the jet is a “nonhydrodynamical core” of the QCD gluonic shower, formed by the original hard parton (black dot A). The solid arrow shows a direction of flow normal to the shock cone at the angle $\theta_M$, the dashed arrows show the direction of the flow after shocks hit the edge of the fireball. (b) Dependence of the Mach cone angle $\theta$ (rad) for

F. Antinori and E.V. Shuryak, arXiv:nucl-th/0507046

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Summary of Results Covered

Extreme initial densities –
\[ \varepsilon \geq 5 \text{ GeV/fm}^3 \]
\[ \sim 30 - 100 \times \text{nuclear density} \]
\[ > 15,000 \text{ quarks } + \overline{\text{quarks}} \text{ in final state} \]

Jet energy loss –
large gluon densities \( \rightarrow \) strongly coupled QGP

Strongly-coupled system of quarks and gluons (sQGP) formed at RHIC

Equilibrium particle abundances –
Universal hadronization \( T \sim T_{\text{crit}} \)
Rapid u, d, s equilibration near \( T_{\text{crit}} \)

Quark coalescence /flow \( \rightarrow \) constituent quark degrees of freedom

Ideal hydrodynamic flow \( \rightarrow \) “perfect fluid”
- Early thermalization & Quark-Gluon EOS
In the Spirit of Erice and this Course:

A Mere Experimentalist
Will Dare to “Mention” String Theory

INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

THE LOGIC OF NATURE, COMPLEXITY AND NEW PHYSICS:
From String Theory to Quark-Gluon Plasma,…..

44th Course – ERICE-SICILY: 29 AUGUST – 7 SEPTEMBER 2006

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### AdS$_5$/CFT Papers in Past Years “Relevant for RHIC”

**References:**

AdS$_5$/CFT

- Analogy between black hole physics and equilibrium thermodynamics
- Solutions called black branes (translationally invariant horizons)
- Black branes possess hydrodynamic characteristics Similar to fluids – viscosity, diffusion constants,....

MULTIPLICITY
Entropy ↔ Black Hole Area

DISSIPATION
Viscosity ↔ Graviton Absorption

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Use strongly coupled $N = 4$ SUSY YM theory.

Derive a quantum lower viscosity bound: $\eta/s > 1/4\pi$

2-d Rel Hydro describes STAR $v_2$ data

where $\eta/s \leq 0.1$ - near this lower bound!
Jet Quenching in the Medium

Figure 1: The $AdS_5$-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [25]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by the quark’s fundamental charge and interacting with the thermal medium.

We would be remiss not to attempt a comparison to implications of RHIC data. Taking $N_c = 3$ and $\alpha_{\text{SYM}} = \frac{1}{2}$, reasonable for temperatures not far above the QCD phase transition, we shall use $\lambda = 6\pi$ to make estimates. From (15), we find $\hat{q} = 3.2, \; 7.5, \; 14.7 \; \text{GeV}^2/\text{fm}$ for $T = 300, \; 400, \; 500 \; \text{MeV}$. In a heavy ion collision, $\hat{q}$ decreases with time $\tau$ as the hot fluid expands and cools. The time-averaged $\hat{q}$ which has been determined in comparison with RHIC data is $\bar{q} \equiv \frac{2}{(L_f)^2} \int_{\tau_0}^{\tau_0 + L_f -} \tau \hat{q}(\tau) \; d\tau$, found to be of order $10 \text{ GeV}^2/\text{fm}$ [4, 5]. If we assume a one-dimensional string.
“Suddenly in Last 3 Months” – A Deluge of AdS\textsubscript{5}/CFT Papers on RHIC Measurements – Part 1

References:

More AdS$_5$/CFT Papers on RHIC Measurements

References:

Charmonium Suppression - Deconfinement

Color screening of $c\bar{c}$ pair would result in $J/\psi$ ($c\bar{c}$) suppression!

$T_{\text{RHIC}} > T_{\text{melt}(\chi_c)}, T_{\text{melt}(\Psi')}, T_{\text{melt}(\Upsilon(3S))}$
Charmonium Suppression - Deconfinement

Color screening of c\bar{c} pair results in J/\psi (c\bar{c}) suppression!

\[ R_{AA} = \frac{N_{	ext{c\bar{c}}}}{N_{\text{hadrons}}} \]

PHENIX Preliminary
Au+Au

- EKS98 1mb, 200GeV, y=2
- Au+Au 200GeV, |y|<0.35
- EKS98 1mb, 200GeV, y=0
- Au+Au 200GeV, 1.2<|y|<2.2

Late News

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Charmonium Suppression - Deconfinement

Color screening models exhibit more $J/\psi$ (c$\bar{c}$) suppression than observed!

Suppression models

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Capella, hep-ph/0505032, 1mb
Grandchamp, hep-ph/0306077
Kostyuk, hep-ph/0305277
Zhu, nucl-th/0411093

PHENIX Preliminary
Au+Au

$R_{AA}$ vs $N_{\text{part}}$

0 50 100 150 200 250 300 350

0 0.2 0.4 0.6 0.8 1.0 1.2

Au+Au 200GeV, $|y|<0.35$
Au+Au 200GeV, 1.2<$|y|<$2.2
Charmonium Suppression - Deconfinement

Color screening models plus recombination of \( c\bar{c} \) pairs closer to \( J/\psi \) (\( c\bar{c} \)) data!

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Quarkonium – Thermometer of Dense QCD

$T_{\text{RHIC}} > T_{\text{melt}}(\chi_c), T_{\text{melt}}(\Psi'), T_{\text{melt}}(\Upsilon(3S))$

$T_{\text{LHC}} > T_{\text{melt}}(J/\Psi), T_{\text{melt}}(\chi_b), T_{\text{melt}}(\Upsilon(2S))$

$T_{\text{melt}}(\Psi') < T_{\text{melt}}(\Upsilon(3S)) < T_{\text{melt}}(J/\Psi) \approx T_{\text{melt}}(\Upsilon(2S)) < T_{\text{RHIC}} < T_{\text{melt}}(\Upsilon(1S))$
**Hard Scattering Processes at the LHC**

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Significant increase in hard scattering yields at LHC:

- jets & large $p_T$ processes

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

- $\sigma_{cc} (\text{LHC}) \sim 10 \sigma_{cc} (\text{RHIC})$

LO pQCD by I. Vitev, hep-ph/0212109
One dedicated HI experiment: ALICE
Two pp experiments with HI program:
ATLAS and CMS
ALICE Set-up

- HMPID
- Muon Arm
- TRD
- PHOS
- PMD
- TOF
- ITS
- TPC

Size: 16 x 26 meters
Weight: 10,000 tons
Questions at RHIC (and Extending to the LHC)

- **What are the degrees of freedom in the evolution?**
  - Can we determine the constituents as a function of energy density (or T)?

**sQGP & its evolution**

- Initial T? Deconfinement $T_c$?
  - (Quarkonium melting)
- Constituents (partons, quasi-bound states, pre-hadrons...)
- Parton density (jet tomography, flavor, intra-, inter-jet correlations)
- Response to energy deposition
- Bulk properties
- Equation of State
- Chiral symmetry restoration?
Deconfined QGP?
  \( \bar{c}c, \bar{b}b \) suppression & melting sequence

Chiral symmetry restoration?

Thermalized heavy flavors?
  Open charm, beauty, multiply-strange baryon production & flow

Establish properties of the sQGP medium
  Constituents?
  Transport properties (speed of sound, diffusion...)
  Flavor dependence of suppression & propagation
  Light vector mesons (mass and width modifications in medium)

Direct Photon Radiation?

New phenomena…….

LHC & 40 x luminosity of RHIC & e-ion collider!

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

“the adventure continues!”

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Jamie Nagle
Thomas Ullrich