Exploring the Quark-Gluon Plasma at RHIC & LHC – Today’s Perspective
**Modifications to $\alpha_s$**

Heavy quark-antiquark coupling at finite $T$ from lattice QCD

Constituents - Hadrons, dressed quarks, quasi-hadrons, resonances?

Coupling strength varies; investigates (de-)confinement, hadronization, & intermediate objects.

low $Q^2$ - high $Q^2$
Modifications to $\alpha_s$

Nobel Prize 2005

D. Gross
H.D. Politzer
F. Wilczek

QCD Asymptotic Freedom (1973)

“Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma.”

David Gross, Nobel Lecture (RMP 05)
Phase Diagram of QCD Matter

Early universe

RHIC

LHC

T ≈ 170 MeV

Critical point?

quark-gluon plasma

color superconductor

hadron gas

nucleon gas

nuclei

neutron stars

CFL

vacuum

baryon density

see: Alford, Rajagopal, Reddy, Wilczek

Phys. Rev. D64 (2001) 074017

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Quark-Gluon Plasma (Soup)

Standard Model $\rightarrow$ Lattice Gauge Calculations predict QCD Deconfinement phase transition at $T_c \sim 175$ MeV ($\epsilon_c \sim 0.5$ GeV / fm$^3$)

Cosmology $\rightarrow$ Quark-hadron phase transition in early Universe

- Can we make the primordial quark-gluon soup in the lab?
- Establish properties of QCD at high T (and density?)

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Ultra-Relativistic Heavy Ion Collisions

Gold nucleus
diameter = 14 fm

 Interaction of Au nuclei complete
in $\tau \leq$ few tenths fm/c

$\gamma = 100$
(Lorenz contracted)

$\tau = (14 \text{ fm/c}) / \gamma \sim 0.1 \text{ fm/c}$

General Orientation
Hadron (baryons, mesons) masses $\sim 1 \text{ GeV}$
Hadron sizes $\sim 10^{-15}$ meters ($1 \text{ fm} \equiv 1 \text{ fermi}$)

RHIC Collisions
$E_{cm} = 200 \text{ GeV/nn-pair}$
Total $E_{cm} = 40 \text{ TeV}$
Ultra-Relativistic Heavy Ion Collision at RHIC
On the “First Day” (at RHIC)

Initial Observations:

Large produced particle multiplicities ed. - “less than expected! → gluon-saturation?”

\[ \frac{d n_{\text{ch}}}{d \eta} \big|_{\eta=0} = 670, \ N_{\text{total}} \sim 7500 \]

\( > 15,000 \) q + \( \bar{q} \) in final state, \( > 92\% \) are produced quarks

Large energy densities \((d n/d \eta, dE_{\perp}/d \eta)\)

\[ \varepsilon \geq 5 \ \text{GeV/fm}^3 \quad \varepsilon \geq 5 - 15 \varepsilon_{\text{critical}} \]

30 – 100 x nuclear density

Large collective flow ed. - “completely unexpected!”

\[ \rightarrow \text{Due to large early pressure gradients, energy & gluon densities} \]

\[ \rightarrow \text{Requires hydrodynamics and quark-gluon equation of state} \]

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

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How do RHIC Collisions Evolve?

1) Superposition of independent p+p:

momenta random relative to reaction plane
How do RHIC Collisions Evolve?

1) Superposition of independent p+p:
   - momenta random relative to reaction plane

2) Evolution as a bulk system
   - Pressure gradients (larger in-plane) push bulk “out” → flow
   - “zero” pressure in surrounding vacuum
   - more, faster particles seen in-plane
Azimuthal Angular Distributions

1) Superposition of independent p+p:
   momenta random
   relative to reaction plane

2) Evolution as a **bulk system**
   Pressure gradients (larger in-plane)
   push bulk “out” → flow
   more, faster particles
   seen in-plane

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On the First Day at RHIC - Azimuthal Distributions

STAR, PRL90 032301 (2003)

Normalized Counts

$\phi_{lab}$ - $\Psi_{plane}$ (rad)

b ≈ 6.5 fm
b ≈ 4 fm

“central” collisions

Top view

Beams-eye view

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On the First Day at RHIC - Azimuthal Distributions

STAR, PRL\textbf{90} 032301 (2003)

\begin{equation*}
\begin{split}
    b & \approx 4 \text{ fm} \\
    b & \approx 6.5 \text{ fm} \\
    b & \approx 10 \text{ fm}
\end{split}
\end{equation*}

Peripheral collisions

Top view

Beams-eye view

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Elliptic Flow Saturates

Hydrodynamic Limit

- Azimuthal asymmetry of charged particles:
  \[ \frac{dn}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]

Mass dependence of \( v_2 \)

Requires -

- Early thermalization (0.6 fm/c)
- Ideal hydrodynamics (zero viscosity) → “nearly perfect fluid”
- \( \varepsilon \sim 25 \text{ GeV/fm}^3 \) (\( >> \varepsilon_{\text{critical}} \))
- Quark-Gluon Equ. of State
**Identified Hadron Elliptic Flow Complicated**

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons

$$\frac{d^2n}{dp_Tdp_\phi} \sim 1 + 2v_2(p_T)\cos(2\phi)$$

- **Baryons**
- **Mesons**

If the flow established at quark level, it is predicted to be *simple* →

$$KE_T \rightarrow KE_T / n_q, \quad v_2 \rightarrow v_2 / n_q, \quad n_q = (2, 3 \text{ quarks}) \text{ for (meson, baryon)}$$

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If baryons and mesons form from independently flowing quarks then quarks are deconfined for a brief moment (~ $10^{-23}$ s), then hadronization!
Transport in gases of strongly-coupled atoms

RHIC fluid behaves like this –

*a strongly coupled fluid.*

Universality of classical strongly-coupled systems?
→ Atoms, sQGP, …… AdS/CFT……
AdS$_5$/CFT – a 5D Correspondence of 4D Systems

- Analogy between black hole physics and equilibrium thermodynamics
- Solutions possess hydrodynamic characteristics
  Similar to fluids – viscosity, diffusion constants, ….

MULTIPLICITY

Entropy ↔ Black Hole Surface Area

DISSIPATION

Viscosity ↔ Graviton Absorption

Use strongly coupled N = 4 SUSY YM theory.

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

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Quantum lower viscosity bound: $\eta/s > 1/4\pi$ (Kovtun, Son, Starinets)

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

2-d Rel Hydro describes STAR $v_2$ data with $\eta/s \leq 0.1$ near lower bound!
“The RHIC fluid may be the least viscous fluid ever seen”

The American Institute of Physics announced the RHIC quark-gluon liquid as the top physics story of 2005!

see http://www.aip.org/pnu/2005/
“Chemical” equilibration (particle yields & ratios):

Particles yields represent equilibrium abundances → universal hadronization temperature

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

Chemical Freezeout Conditions → \(T = 177 \text{ MeV}, \mu_B = 29 \text{ MeV} \rightarrow T \sim T_{\text{critical (QCD)}}\)
Particles are thermally distributed and flow collectively, at universal hadronization temperature $T = 177 \text{ MeV}$!
On the “Second” Day (~ Year) at RHIC
Probing Hot QCD Matter with Hard-Scattered Probes

→ parton energy loss: modification of jets and leading particles & jet-correlations
High Momentum Hadrons Suppressed - Photons Not

Deviations from binary scaling of hard collisions:

\[ R_{AA} = \frac{N_{\pi/\gamma}^{AA}}{N_{coll}^p N_{\pi/\gamma}^{pp}} \]

Deviation from binary scaling of hard collisions:

PHENIX Au+Au (central collisions):
- Direct \( \gamma \)
- \( \pi^0 \) Preliminary
- \( \eta \)
- GLV parton energy loss (\( dN/dy = 1100 \))

Photons

Hadrons

factor 4 – 5 suppression

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Dynamical Origin of High $p_T$ Hadron Suppression?

How does parton lose energy?

What happens to the radiation?

What is the dependence on the type of parton?

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

For collisional energy loss what about recoil energy?

One parameterization of energy loss →

$\hat{q} = \frac{\mu^2}{\Lambda}$
Parameterization of Parton Energy Loss

\[ \hat{q} = 5 - 15 \text{ GeV}^2/\text{fm} \]

from RHIC \( R_{AA} \) Data
Interpretation of the Parton Energy Loss

Energy loss requires large $\langle \hat{q} \rangle \approx 5 - 15 \text{ GeV}^2/\text{fm}$

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

R. Baier, Nucl Phys A715, 209c

RHIC data

$s$QGP

QGP

Pion gas

Cold nuclear matter

R. Baier, Nucl Phys A715, 209c
Heavy Quark Suppression

- Using fixed order next-to-leading log (FONL) cross sections for charm and beauty

Armesto, Cacciari, Dainese, Salgado, Wiedemann, PLB637:362, 2006

Insufficient suppression from theoretical models!
AdS$_5$/CFT *Again!* - Initial Results on Jet Quenching

### Calculating the Jet Quenching Parameter from AdS/CFT

H. Liu, Krishna Rajagopal, and Urs Achim Wiedemann

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2 Nuclear Science Division, MS 70R219, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
3 Department of Physics and Astronomy, University of Stony Brook, NY 11794, USA
4 RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

(Dated: May 16, 2006)


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*Heavy quark is end of string on boundary*

*Hot gauge theory lives on boundary*

*String provides drag (energy loss)*

*Black-hole horizon*

*AdS$_5$ - Schwarzschild*

*AdS$_5$/CFT*


transition, we shall use $\lambda = 6\pi$ to make estimates. From (15), we find $\bar{q} = 3.2$, 7.5, 14.7 GeV$^2$/fm for $T = 300$, 400, 500 MeV. In a heavy ion collision, $\bar{q}$ decreases with time $\tau$ as the hot fluid expands and cools. The time-averaged $\bar{q}$ which has been determined in comparison with RHIC data is $\bar{q} \equiv \frac{2}{(L/L_0)^2} \int_{-L_0}^{L_0} \tau \bar{q}(\tau) \, d\tau$, found to be of order 10 GeV$^2$/fm [4, 5]. If we assume a one-
Hard Scattering (Jets) as a Probe of Dense Matter II

Can we see jets in high energy Au+Au?
Where Does the Energy Go?

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

Azimuthal Angular Correlations
Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet disappears for particles $p_T > 2$ GeV

Azimuthal Angular Correlations
Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet reappears in particles $p_T > 200$ MeV

Color wakes?
J. Ruppert & B. Müller

Mach cone from sonic boom?
H. Stoecker
J. Casalderrey-Solana & E. Shuryak

Cherenkov-like gluon radiation?
I. Dremin
A. Majumder, X.-N. Wang

Lost energy of away-side jet is redistributed to rather large angles!
A Near-side “Ridge” Appears!

Di-hadron correlations

Trigger Jet (near-side)

Near-side ridge

Jets: scale with # of binary collisions

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

But ridge spectra same as medium (‘bulk-like’, seen for mesons/baryons)

→ thermal spectra + flow origin? or jet-heating?

3 < $p_T$ (trigger) < 4 GeV

$p_T$ (assoc.) > 2 GeV

J. Putschke, STAR, QM

J. Putschke, STAR, QM
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 nucl-th/0312065, N.P. A749, 287

• Initial parton scatter + Jet-medium interactions, C.Y. Wong, hep-ph/07072385
The suppression of high $p_T$ hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium.!
Conclusions about a QGP at RHIC (for reference)

- **Large** $\varepsilon > \varepsilon_c$ ($T > T_c$) **system** – QCD vacuum “melts” – NOT hadrons
- **Thermalized system of quarks and gluons** – NOT just q & g scattering
  - Large elliptic & radial flow $\rightarrow$ fluid flow (“perfect”!)
  - Heavy quark (charm) flow (not shown)
  - Particle ratios fit by thermal model $\rightarrow$ $T = 177$ MeV $\sim T_c$ (lattice QCD)
- **System governed by quark & gluon Equation of State** – NOT hadronic
  - Flow depends upon particle (constituent quark & gluon) masses
    $\rightarrow$ QGP EoS, quark coalescence
- **Deconfined system of quarks and gluons** – NOT hadrons
  - Flow already at quark level, charmonium suppression (tbd)
- **NOT a Weakly-interacting QGP** (predicted by Lattice QCD)
  - Strongly interacting quarks and gluons $\rightarrow$ ….degrees of freedom (tbd)
- **Strongly-interacting QGP** (NOT predicted by Lattice QCD)
  - Suppression of high $p_T$ hadrons, away-side jet quenched
  - Large opacity (energy loss) $\rightarrow$ extreme gluon/energy densities
    $\rightarrow$ strongly-interacting QGP (sQGP)
Future!
Geneva with Large Hadron Collider Superimposed

Starts in Spring 2008
### Simple Expectations - Heavy Ion Physics at the LHC

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

- Significant increase in hard scattering yields at LHC:
  - jets & large $p_T$ processes
  - $\sigma_{bb}$ (LHC) $\sim 100 \sigma_{bb}$ (RHIC)
  - $\sigma_{cc}$ (LHC) $\sim 10 \sigma_{cc}$ (RHIC)

LO pQCD by I. Vitev, hep-ph/0212109

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The Future of RHI's at the LHC:
Dedicated HI experiment - ALICE
Two pp experiments with HI program:
ATLAS and CMS
ALICE Set-up

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

**Size:** 16 x 26 meters
**Weight:** 10,000 tons
John Harris (Yale)  Hadron 07 - Frascati, Italy, 8 -13 Oct. 2007

ALICE today
The Quark-Gluon Plasma at RHIC & LHC – Today’s Perspective

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 (\( T \sim 150 – 600 \text{ MeV} \))?
The Quark-Gluon Plasma at RHIC & LHC –
Today’s Perspective

At LHC:

Is the QCD phase diagram feature-less at 1 – 4 Tc?
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 (T_i, screening/suppression, enhancement?)

Direct Photon Radiation?

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

“the next frontier!”

John Harris (Yale)
Miklos Gyulassy
Peter Jacobs
Mike Lisa
Thomas Ullrich
Urs Wiedemann