Search for Quark-Gluon Plasma from RHIC to LHC:

Hard Probes at RHIC & What to “Expect” at LHC!
Jets & High $p_T$ Particles in Proton-Proton Collisions

Hard probes ⇒ early times

Calculable in pQCD:
“QCD Factorization”

\[
E \frac{d^3 \sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d \hat{\sigma}_{ab \rightarrow cd}}{d t} \otimes D_{h/c}(z_c, Q^2)
\]
**Jets & High $p_T$ Particles**

*Nucleus-Nucleus Collisions*

Fragmentation:

\[ z = \frac{p_{\text{hadron}}}{p_{\text{parton}}} \]

Same as pp case except:

- Partons propagate in medium

$k_T$ "radiative corrections"
- Pre- and post-scattering
- Di-jet: $\Delta \phi \neq \pi$

\[ n_{ch}^{\text{in jet}} : \text{increases} \]
\[ \langle z^{\text{in jet}} \rangle : \text{decreases} \]

Gyulassy et al., nucl-th/0302077

John Harris (Yale)
At RHIC - High Momentum Hadrons Are Suppressed, Photons Not

Deviations from binary scaling of hard collisions:

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

John Harris (Yale)       LNF Spring School, Frascati 12 – 16 May 2008

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

Photons
Hadrons factor 4 – 5 suppression
RHIC - Compare Au + Au with d + Au (control experiment)

Hadron spectra at RHIC in p+p, Au+Au & d+Au establish existence of *early parton energy loss* from strongly interacting QCD matter in central Au-Au collisions.
Dynamical Origin of High $p_T$ Hadron Suppression?

How does parton lose energy?

What happens to the radiation?

How does $\Delta E$ depend 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

\[ \widehat{q} = 5 - 15 \text{ GeV}^2/\text{fm} \] from RHIC \( R_{AA} \) Data
Interpretation of the Parton Energy Loss at RHIC

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

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

$$\hat{q}_{pQCD} = \frac{4\pi^2 \alpha_s N_C}{N_C^2 - 1} \rho_{\text{medium}}[xG(x, \hat{q}L)]$$

**Equilibrated gluon gas:**

$\rho_{\text{medium}} \sim T^3$

energy density $\varepsilon \sim T^4$

$\rightarrow$ $\hat{q} = c \varepsilon^{\frac{3}{4}}$

`Equilibrated gluon gas:`

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Equilibrated gluon gas:

$\rho_{\text{medium}} \sim T^3$

energy density $\varepsilon \sim T^4$

$\rightarrow$ $\hat{q} = c \varepsilon^{\frac{3}{4}}$

John Harris (Yale)
AdS$_5$/CFT Again! - Initial Results on Jet Quenching

Hot gauge theory lives on boundary

Heavy quark is end of string on boundary

String provides drag (energy loss)

Calculating the Jet Quenching Parameter from AdS/CFT

Hong Liu, Krishna Rajagopal, and Urs Achim Wiedemann

1Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2Nuclear Science Division, MS 70R219, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
3Department of Physics and Astronomy, University of Stony Brook, NY 11794, USA
4RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

(Dated: May 16, 2006)


transition, we shall use $\lambda = 6\pi$ to make estimates. From (15), we find $\bar{q} = 3.2, 7.5, 14.7 \text{ GeV}^2/\text{fm}$ for $T = 300, 400, 500 \text{ MeV}$. 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 $\bar{q} \equiv \frac{2}{(T_{\text{RHIC}}^{+})^2} \int_{\tau_0}^{\tau_{\text{RHIC}}^{+}} \tau \bar{q}(\tau) \, d\tau$, found to be of order $10 \text{ GeV}^2/\text{fm}$ [4, 3]. If we assume a one-
\( R_{AA} \) of Heavy Quarks from Non-photonic Electrons

- Non-photonic electrons come from semi-leptonic decays of heavy quarks
  - \( c \rightarrow e^+ + \) anything \( (\text{B.R.} = 9.6\%) \)
  - \( D^0 \rightarrow e^+ + \) anything \( (\text{B.R.} = 6.87\%) \)
  - \( D^\pm \rightarrow e^\pm + \) anything \( (\text{B.R.} = 17.2\%) \)
  - \( b \rightarrow e^+ + \) anything \( (\text{B.R.} = 10.9\%) \)
  - \( B^\pm \rightarrow e^\pm + \) anything \( (\text{B.R.} = 10.2\%) \)
  - plus small contribution from Drell-Yan
    for \( p_T < 10 \text{ GeV/c} \)

Heavy quarks thought too massive to be attenuated by medium!
**Dead Cone Effect** for Heavy Quarks


Gluon radiation from a massive parton is suppressed at small angles

\[ \Theta < \frac{m_q}{E_q} \]

(result of causality since \( v_q < c \))

Energy loss is therefore reduced.

Heavy quarks up to \( \sim 10 - 20 \text{ GeV/c} \)
**RHIC - $R_{AA}$ of Heavy Quarks from Non-photonic Electrons**

Suppression observed

$\sim 0.4-0.6$ in 40-80% centrality

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

STAR, nucl-ex/060712
**RHIC - $R_{AA}$ of Heavy Quarks from Non-photonic Electrons**

**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!

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

Heavy quarks suppressed like light quarks

**STAR, nucl-ex/060712**
RHIC - 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!
Heavy Quark Suppression and Elliptic Flow

large suppression &
large $v_2$ of electrons
→ charm thermalization?

• transport models require
  - small heavy quark relaxation time
  - small diffusion coefficient
  $D_{HQ} \times (2\pi T) \sim 4-6$

• These constrain viscosity/entropy
  - $\eta/s \sim (1.5 - 3) / 4\pi$
    within factor 2 - 3 of conjectured lower bound
  - consistent with light hadron $v_2$

PHENIX, nucl-ex/0611018
Hard Scattering (Jets) as a Probe of Dense Matter

Can we see jets in high energy Au+Au?
**STAR**  Hard Scattering: Two-Particle Azimuthal Correlations

**Technique:**

Azimuthal correlation function

Trigger particle

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

Associate tracks

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

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

*di-jets from p + p at 200 GeV*
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**

- $p_T > 4$ GeV/c

**Associate tracks**

- $2 < p_T < p_T(\text{trigger})$

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

short range $\eta$ correlation:

- jets + elliptic flow

long range $\eta$ correlation:

- elliptic flow

John Harris (Yale)  LNF Spring School, Frascati 12 – 16 May 2008
Relative Charge Dependence

Compare ++ and -- correlations to +- 

<table>
<thead>
<tr>
<th>System</th>
<th>(+-)/(++ &amp; --)</th>
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<td>2.7±0.6</td>
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<td>Jetset</td>
<td>2.6±0.7</td>
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</table>

STAR Preliminary @ 200 GeV/c
0-10% most central Au+Au
p+p minimum bias
4<p_T(trig)<6 GeV/c
2<p_T(assoc.)<p_T(trig)

John Harris (Yale) LNF Spring School, Frascati 12 – 16 May 2008
**Relative Charge Dependence**

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

$p_T > 4$ GeV/c particle production mechanism same in central Au+Au & pp

Using p+p to Study Au+Au Jet Correlations at RHIC

Assume:

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

$C_2(Au+Au) = C_2(p+p) + A*(1 + 2v_2^2 \cos(2\Delta \phi))$

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

Peripheral Au + Au
Away-side jet
Central Au + Au
disappears

STAR 200 GeV/c
peripheral & central Au+Au
p+p minimum bias
4 < $p_T$(trig) < 6 GeV/c
2 < $p_T$(assoc.) < $p_T$(trig)
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
Where Does the Energy Go?

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

Azimuthal Angular Correlations

4 < p_T(trig) < 6 GeV/c
Jet correlations in central Gold-Gold.

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

Azimuthal Angular Correlations

$4 < p_T(\text{trig}) < 6$ GeV/c
Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet reappears in particles $p_T > 0.2$ GeV

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

John Harris (Yale)   LNF Spring School, Frascati 12 – 16 May 2008
A Closer Look at the Away-Side of Jets

Measure low-\(p_T\) associated hadrons
Shapes of jets are modified by the medium

John Harris (Yale) LNF Spring School, Frascati 12 – 16 May 2008
Response of the Medium?

Possibilities:

- **Deflected jets**

- **Cerenkov radiation**

- **Mach cone from hydrodynamics**

- **Mach cone from color wakes**
  - P. Chesler & L. Yaffe, hep-ph/0706.0368

- **Mach cone from AdS/CFT**
  - Properties of the medium can be determined from these shapes!
    - Sound velocity
    - Di-electric constant
The suppression of high $p_T$ hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium!
Response of the Medium in AdS/CFT

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

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 $\mathcal{N}=4$ supersymmetric Yang-Mills plasma is computed using gauge/string duality.

Also see: Gubser, Pufu, Yarom, hep-th/0706.0213

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A Real Test of “Theories” in the Future from Heavy Flavors at RHIC & LHC?

W. Horowitz, M. Gyulassy, arXiv:0804.4330v1

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Explaining the AdS/CFT Equivalence

1) Weakly Coupled (classical) gravity in Anti-deSitter Space (AdS)

2) Maldacena’s Conjecture

3) Strongly Coupled (Conformal) Gauge Field Theories (CFT)
Summary of Hard Scattering at RHIC

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

John Harris (Yale)

LNF Spring School, Frascati 12 – 16 May 2008
A Couple More RHIC Results of Interest

- Observation of Thermal Photons
- Charmonium Suppression
**Thermal Photons at RHIC**

PHENIX, arXiv: 0804.4168v1

Dashed curves are binary-scaled pp data

Solid curves are binary-scaled pp data + thermal

$T = 221 \pm 23\,\text{(stat)} \pm 18\,\text{(sys)} \, \text{MeV}$

This spectrum fit by hydrodynamics with $T_{\text{init}} \sim 300 - 600 \, \text{MeV}$ at $0.6 - 0.15 \, \text{fm/c}$

Dashed curves are binary-scaled pp data

pp data and 3 different NLO calculations

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LNF Spring School, Frascati 12 – 16 May 2008
Charmonium Suppression at RHIC

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

$J/\psi$ suppressed but less than expected?

Perhaps, regeneration!

(more to do!)

John Harris (Yale)
H. Satz’ lecture

at LHC:

Large heavy flavor cross sections

Measure melting order of $c\bar{c}$:
$\Psi'$, $\chi_c$, $J/\psi$

Also $b\bar{b}$:
$\Upsilon'$, $\Upsilon$, $\Upsilon''$

Karsch hep-lat/0502014v2

Graph showing cross sections for different temperatures:
- $T < T_c$
- $T_{\psi'} < T < T_{\chi}$
- $T_{\chi} < T < T_{\psi}$
- $T > T_{\psi}$
LHC Heavy Ions
**Heavy Ion Physics at the LHC**

**LHC Heavy Ions** –
- guided by pQCD predictions
- expectations (detector simulations) based on RHIC extrapolations and theory
- lesson from RHIC – guided by theory + versatility + “expect the unexpected”

**Soft Physics at LHC** –
- smooth extrapolation from SPS → RHIC → LHC?
- expansion will be different ($v_2$, HBT, $T_{\text{chem}}$ & $T_{\text{kin}}$, strange/charm particles & resonances)
Heavy Ion Physics at the LHC

**LHC Heavy Ions** –
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- expansion will be different ($v_2$, HBT, $T_{\text{chem}}$ & $T_{\text{kin}}$, strange/charm particles & resonances)

**Hard Probes at LHC** –
- significant increase in hard cross sections
  \[ \frac{\sigma_{\text{hard}}}{\sigma_{\text{total}}} \approx 2\% \text{ at SPS} \]
  \[ 50\% \text{ at RHIC} \]
  \[ 98\% \text{ at LHC} \]
- “real” jets, large $p_T$ processes
- abundance of heavy flavors
- probe early times, calculable → precision studies!

\[ \sigma_{bb} (\text{LHC}) \sim 100 \sigma_{bb} (\text{RHIC}) \]
\[ \sigma_{cc} (\text{LHC}) \sim 10 \sigma_{cc} (\text{RHIC}) \]

John Harris (Yale)  
LNF Spring School, Frascati 12 – 16 May 2008
Jet-finding – Much Work Already at LEP & Tevatron

John Harris (Yale)
LNF Spring School, Frascati 12 – 16 May 2008
Jet-finding - Learning from the Tevatron

\( p + p \) experience (CDF)
- most of energy within \( R = 0.3 \)

\[ R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

fraction of energy outside \( R = 0.3 \)

John Harris (Yale)
Jet-finding Approach with Heavy Ions

\( p + p \) experience (CDF)
- most of energy within \( R = 0.3 \)

A + A approach (current attempts)
- suppress “soft” heavy ion background by
  - \( p_T \) cut: \( p_T > 1 - 2 \text{ GeV}/c \)
  - use small jet cones \( R = 0.3 - 0.4 \)
- estimate remaining background by
  - \( E_{byE} \) out-of-cone background energy

Issues to understand:
- effects of acceptance
- event-by-event fluctuations
- elliptic flow
- other effects of real data!

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LHC Heavy Ion Programs

Heavy Ion Data-taking
Pb + Pb at $\sqrt{s_{NN}} = 5.5$ TeV
Overview:

ATLAS has a broad heavy ion physics program - excels at jet and photon measurements

Jets
- reconstruct jets in a large kinematical range, $E_T > 40$ GeV and $|\eta|<5$
- perform key fragmentation measurements
- jet shape and FF modifications
- multi-jet studies

Photons
- isolate / measure photons in large range, $E_T > 10$ GeV and $|\eta|<2.5$
- unique calorimeter design allows additional rejection beyond isolation
Example of Anticipated Jet Measurements

Reconstructed spectra not corrected for efficiency and energy resolution.

\[ \frac{dN}{d\eta} = 2700 \quad \text{Top 0.5% } \sigma_{AA} \]
**Overview:**

CMS has a broad heavy ion physics program:
- precision tracking $|\eta| < 2.5$
- muon identification $|\eta| < 2.5$
- high-res calorimetry $|\eta| < 5$
- forward coverage

CMS expects to excel at:
- photon-tagged jet measurements (FF modifications)
- quarkonium measurements
Fragmentation Functions in CMS

E_{T,\gamma} > 70\text{GeV}

E_{T,\gamma} > 100\text{GeV}

Courtesy: C. Roland and CMS

John Harris (Yale)  LNF Spring School, Frascati 12 – 16 May 2008
A Little More About ALICE
the Dedicated Heavy Ion Experiment
(a huge Italian involvement, including Frascati!)

~ 1000 Members
~ 30 Countries
~ 100 Institutes
A View of ALICE Under Construction
An ALICE PbPb Event

\[ p_T > 1 \text{ GeV} \]
**ALICE Physics Measurements**

**Soft Probes – “ala RHIC”**
- Expansion dynamics different from RHIC due to timescales, densities
- All soft physics measurements as at RHIC so far (+ extended PID)
- Day 1 physics +

**Hard Probes – Jet Quenching**
- Jets, $\gamma$, pi-zeros, leading particles to large $p_T$

**Hard Probes – Heavy Quarks**
- Displaced vertices ($D^o \rightarrow K^- \pi^+$) from TPC/ITS
- Electrons in Transition Radiation Detector (TRD)

**Hard Probes – Quarkonia**
- $J/\psi$, $\Upsilon$, $\Upsilon'$ (excellent), $\Upsilon''$ (2-3 yrs), $\psi'$ ???
**ALICE EMCal**

**Approved for funding Jan. 2008**

- 10 ½ Super-Modules
- 7 ½ SM from US
- 3 SM from Italy (Frascati, Catania)
  & France (Grenoble, Nantes)

**Construct / install: 2009 → 2011**

Lead-scintillator sampling calorimeter

\[ \Delta \eta = 1.4, \quad \Delta \phi = 110^\circ \]

Shashlik geometry, APD photosensor

\(~13K\) towers \((\Delta \eta \times \Delta \phi \sim 0.014 \times 0.014)\)

Energy resolution = \(10.6\%/\sqrt{E} + 2.1\%\)

over-takes tracking above \(~30\) GeV

\(\pi^0/\gamma\) discrimination to \(p_T \sim 30\) GeV

John Harris (Yale)
Hard Probe Capabilities of ALICE with EMCal

EMCal improves detector capabilities:
- Fast trigger ~10 -100 enhancement of jets
- Improves jet reconstruction (plus TPC)
- Good $\gamma/\pi^0$ discrimination increases coverage
- Good electron/hadron discrimination

EMCal extends the physics of ALICE:

$10^4$/year in minbias Pb+Pb:
- inclusive jets: $E_T \sim 200$ GeV
- dijets: $E_T \sim 170$ GeV
- $\pi^0$: $p_T \sim 75$ GeV
- inclusive $\gamma$: $p_T \sim 45$ GeV
- inclusive $e$: $p_T \sim 30$ GeV

Thanks – Peter Jacobs
Jet energy determination:

- $R_c = 0.4$
- $p_T > 1 \text{ GeV/c}$

Charged particles for FF $\xi$:

- $R_c = 0.7$
- $p_T > 0 \text{ GeV/c}$

More studies of background are needed & underway!

J. Putschke, ECT 2008

Annual ALICE run statistics:

- $<E_{\text{input}}> \sim 175 \text{ GeV}$
- Pb+Pb 0-10%: $<\hat{\epsilon}> = 50 \text{ GeV}^2/\text{fm}$

Large background corrections, 5% sys. uncertainty assumed

J. Putschke, ECT 2008
Synopsis of Experimental Results –

- Successfully heated matter to temperature $T > 2 \times 10^{12}$ K (200 MeV)
- This is > 100,000 times hotter than the core of Sun
- This is more than hot enough to make a Quark-Gluon Soup

What are its characteristics?

- It flows like a liquid, better than any we know or have made
- It behaves like a soup of quarks (and gluons)
- It is opaque to the most energetic probes (fast quarks)

**RHIC and new Large Hadron Collider (LHC) at CERN in Geneva:**

Cover 2 – 3 decades of energy ($\sqrt{s_{NN}} \sim 20$ GeV – 5.5 TeV)
To discover the properties of hot QCD at $T \sim 150 – 600$ MeV)
Many Things to Do with Heavy Ions at the LHC!

Day 1 – Elliptic Flow
Multiplicities (just to check the models) and spectra
Flavor (Gluon and Quark mass) dependence of parton energy loss
Use jets and/or photons to establish hard-scattered parton energy
Jet and high pt particle correlations
Jet modifications - longitudinal & transverse “heating” – due to medium
Medium response to jet-heating (near- and away-side)
Separate open charm and beauty decays
cc and bb states (screening, suppression, enhancement?)
Direct Photon Radiation?
..........to name a few............
New phenomena........
Developments in theory (lattice, hydro, parton E-loss, string theory...)

“The next frontier!”
Special Thanks for Contributions to This Presentation!!

Miklos Gyulassy
Peter Jacobs
Thomas Ullrich
Urs Wiedemann
The End