Report From the High Temperature Frontier

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August 10, 2011

Division of Particles and Fields
of the American Physical Society
Brown University
August 8-13, 2011
What are the properties of hot QCD matter?

- **thermodynamic (equilibrium)**
  - $T$, $P$, $\rho$
  - Equation Of State (relation between $T$, $P$, $V$, energy density)
  - $v_{\text{sound}}$, static screening length

- **transport properties (non-equilibrium)**
  - particle number, energy, momentum, charge
  - diffusion, sound, viscosity, conductivity

In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, $\lambda_D$
also the case for strong, rather than EM force

*measuring these is new for nuclear/particle physics!

*Nature is nasty to us: does a time integral…*
Heat nuclei at both RHIC and LHC

Compare to:

p+p – no medium
p/d+A – cold nuclear matter effects

Au+Au at 200 GeV per NN

Pb+Pb at 2.76 TeV per NN

5 active experiments:
STAR, PHENIX
ALICE, ATLAS, CMS
Temperature reached? thermal radiation

Low mass, high $p_T$ $e^+e^-$ → nearly real photons
Large enhancement above $p+p$ in the thermal region

pQCD $\gamma$ spectrum (QCD Compton scattering) agrees with $p+p$ data
**direct photons: \( T_{\text{init}} > T_c \)**

- **Exponential fit in \( p_T \):**
  \[
  T_{\text{avg}} = 221 \pm 23 \pm 18 \text{ MeV}
  \]

- **Hydrodynamics models reproduce data (different \( \tau_0 \)):**
  \( T_{\text{init}} \geq 300 \text{ MeV} \)
  > 4 trillion degrees!

**NB:** \( T_c \sim 170 \text{ MeV} \)

\( T_{\text{init}} \) at LHC \( \sim 30\% \) higher
(by more indirect measures)
Now we are on the map

\[ T_c \sim 170 \pm 10 \text{ MeV} \]
\[ \varepsilon \sim 3 \text{ GeV/fm}^3 \]

RHIC puts us here
… what have we learned about QGP?
QCD matter at $T = 300-600$ MeV (at RHIC)

- Collective flow with low viscosity/entropy ratio: "perfect liquid"
  How low? Strong coupling...

- Opacity very high
  Plasma ~ stops quarks & gluons
  How and why? Strong coupling...

- Even heavy quarks lose energy & flow
  Not expected from pQCD; mechanism?
  -> strong coupling
  High mass scatterers?

- J/$\psi$ suppression indicates color screening
  How much?

Example of the viscosity of milk. Liquids with higher viscosities will not make such a splash when poured at the same velocity.

Non photonic electrons

$\pi^0, \eta$
Strong coupling: forefront issue in other fields!

Quark gluon plasma is like other systems with STRONG COUPLING – all exhibit liquid properties & phase transitions

Cold atoms: coldest & hottest matter on earth are alike!

Dusty plasmas & warm, dense plasmas have liquid and even crystalline phases

In all these cases have a competition:

Attractive forces ↔ repulsive force or kinetic energy

Result: many-body interactions; quasiparticles exist?
$e^+e^-$ excess at low mass, low $p_T$

Excess at $M_{ee} < 2-3 \ T_c$

Non-perturbative radiation (lQCD)?

Rate boosted by correlations in medium?

Pre-equilibrium emission?

PRC81, 034911 (2010)
NEW RESULTS FROM HEAVY ION COLLISIONS AT RHIC AND THE LHC
Critical point search: low energy Au+Au @ RHIC

Tools:
Fluctuations, partonic collective flows
Fluctuations as Critical Point Signature

Event-by-event net-baryon fluctuation ratios from STAR are so far consistent with the Hadron Resonance Gas

Hadron freezeout not (yet) near critical point

Calculations of higher moments from LQCD deviate from HRG calculations and may provide conclusive evidence for critical point if observed in data
Pb+Pb at LHC $\Rightarrow$ similar flow as at RHIC

ALICE

STAR at RHIC

\[ p_T = 1.7 \text{ GeV} \]

\[ p_T = 0.7 \text{ GeV} \]

\[ \nu_2 \text{ saturates } @ \approx 39 \text{ GeV} \]

@ LHC \( T_{\text{init}} \approx 30\% \text{ higher} \)

\( \eta/s(t) \text{ sampled differently} \)
Thermal photons also flow!

Flow magnitude is surprising. Can “extras” explain it?
Initial nucleon positions fluctuate (& flow)
Perfect liquid? What’s the viscosity of QGP?

- Use hydro with lattice EOS
- Set initial energy density to reproduce observed particle multiplicity
- Use various values of $\eta/s$
  - Quantum mechanical lower bound is $1/4\pi$
    - determined with help from AdS/CFT
- Constrain with data
  - (Account for hadronic state viscous effects with a hadron cascade afterburner)
Fluctuations, flow and the quest for $\eta/s$

$v_2$ described by both Glauber and CGC but different values of $\eta/s$.

$v_3$ described only by Glauber breaks degeneracy.

2 models with different fluctuations, eccentricity, $\rho$ distribution.

Theory calculation: Alver et al. PRC82,034913

Theory calculation: Alver et al. PRC82,034913

Stefan Bathe for PHENIX, QM2011
Energy loss in QGP

$R_{AA} = \frac{\text{AuAu}}{\text{pp}} \times N_{\text{coll}}$

ALICE

CMS Preliminary
$PbPb \sqrt{s_{NN}} = 2.76 \text{ TeV}$
$\int L \, dt = 7 \mu\text{b}^{-1}$

$R_{AA}$

ALICE, charged particles, Pb-Pb
$\sqrt{s_{NN}} = 2.76 \text{ TeV}$, 0-5%, $|\eta| < 0.8$

ALICE Preliminary

$\cdot$ pronounced $p_T$ dependence of $R_{AA}$ at LHC

→ sensitivity to details of the energy loss distribution
Reconstruct jets in heavy ion collisions

Requiring a narrow jet $\rightarrow$ same suppression as leading hadron

PHENIX Preliminary
- $0-20\%$
- $\pi^0 \ 0-10\%, \langle z \rangle = 0.7$ (PRL 101, 162301)

Hard to reconcile if $\text{eloss} = \text{splitting inside jet cone}$
Much zippier jets in Pb+Pb at LHC!

Similar $R_{AA}$ as RHIC for 100 GeV $\rightarrow$ 250 GeV jets; $R$ independent

Energy loss $\rightarrow$ jet asymmetry; no decorrelation, Fragm.Fn. same!

CMS finds excess soft particles in interjet region...
Is there a relevant screening length?

- Plasma: interactions among charges of multiple particles spreads charge into characteristic (Debye) length, $\lambda_D$
- Particles inside Debye sphere screen each other
- Strongly coupled plasmas: few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
  Sometimes even even crystals!
- *Test with heavy quark bound states*
  Do they survive?
  All? None? Some? Which size?
- Are residual correlations important?

![Graph showing temperature bands with corresponding energies and particle states](image.png)
To quantify color screening in quark gluon plasma:
study as function of $\sqrt{s}$, $p_T$, $r_{onium}$

Also MUST measure $J/\psi$ in d+A/p+A for cold matter effects:
gluon shadowing, energy loss

$J/\psi \ R_{AA}$ ~same from 17.5-200 GeV!

2.76 TeV direct $J/\psi$ lower at mid-$y$, inclusive above at forward $y$

No clear suppression pattern with $\varepsilon$, $T$!

Why more suppression at $y=2$?
Breakup in hadron gas?
Final state coalescence of $q\bar{q}$?
New questions from RHIC & LHC data!

1. At what scales is the coupling strong?
2. How is equilibration achieved so rapidly?
3. Nature of QCD matter at low T but high $\rho$?
4. What is the mechanism for quark/gluon-plasma interactions? For the plasma response?
   Is collisional energy loss significant?
5. Is there a relevant (color) screening length?
6. Are there quasiparticles in the quark gluon plasma? If so, when and what are they?
Next step for experiments:

- Do even $b$ quarks come to a screeching halt? $M_b \approx 4.2 \text{ GeV/c}^2$
- What does $b$ fate tell us about interactions inside?
- Higher luminosity to access rarer (i.e. heavier) probes
- Add silicon microvertex detectors to both PHENIX and STAR
  Displaced vertex to separate $c,b$; reconstruct $D$ & $B$ mesons
- Vertex detectors in place @ LHC
- Address Q 1,4,6
After 2015: Upgrade PHENIX

Focused on capabilities to answer compelling questions
Don’t try to do everything

- Compact detector covering $-1 < \eta < 4$  
  x50 acceptance for quarkonia, jets
- Measure jets, electrons and photons in mid-rapidity $\rightarrow$ Measure QGP properties
- Gluon saturation physics at forward region ($\eta > 1$)
- First eRHIC detector (not yet optimized)
Conclusions

- $T > T_c$; now study quark gluon plasma properties
  QGP behaves as a strongly coupled liquid
- Flow (pressure gradients) build up & saturate below 39 GeV
  Soft photons flow too!
- $\eta/s$ near quantum limit; similar @ LHC and RHIC
  Uncertainties being reduced by higher harmonics of flow
- Parton energy loss large at low $p_T$ @ LHC and RHIC
  At high $p_T$, hadron suppression less, but still substantial
  Jets suppressed from 10-250 GeV, but dijet correlation & fragmentation unchanged. WHERE is the lost energy??!!
- Need to understand onium suppression patterns in terms of medium effects on the correlation -> screening length
- The data raise entirely new questions!
  Answer by running time and p+A at LHC
  Upgrades at RHIC for heavy quark & jet probes of plasma
• backup slides
Flow subtraction/correction with measured $v_n$ for central-central 2-particle correlation

mach-cone is mostly gone
remaining medium effect seen
(correlated pair yield by absolute normalization)
Calculating transport in QGP

weak coupling limit
perturbative QCD
kinetic theory, cascades
interaction of particles

\[ \infty \] strong coupling limit
not easy! Try a pure field...
gravity ⇔ supersym 4-d
(AdS/CFT)

2 \rightarrow 3,3 \rightarrow 2, n \rightarrow 2 \ldots
Lepton pair emission ↔ EM correlator

Emission rate of dileptons per volume

\[
\frac{dR_{\mu\mu}}{d^4q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M)}{M^2} \text{Im}\Pi_{\text{em},\mu}(M, q; T) f^B(q_0, T)
\]

\[f^B(q_0, T) = \frac{1}{(e^{q_0/T} - 1)}\]

\[L(M) = \sqrt{1 - \frac{4m_i^2}{M^2}(1 + \frac{2m_i^2}{M^2})}\]

\(\gamma^* \to e^+ e^-\) decay

EM correlator

Medium property

Boltzmann factor

Temperature

Hadronic contribution

Vector Meson Dominance

Medium modification of meson

Chiral restoration

Thermal radiation from partonic phase (QGP)

\[\text{Im}\Pi_{\text{em}}^\text{vac}(M) = \left\{ \begin{array}{ll}
\sum_{V=\rho,\omega,\phi} \left(\frac{m_V^2}{g_V}\right)^2 \text{Im}\Pi_{D}(M) \\
-\frac{M^2}{12\pi} \left(1 + \frac{\alpha_s(M)}{\pi} + \ldots\right) N_c \sum_{q=u,d,s} (e_q)^2
\end{array} \right.\]

\(\bar{q}q\) annihilation

From emission rate of dileptons, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

Yasuyuki Akiba - PHENIX QM09
Suppression pattern ingredients

- Color screening

- Initial state effects
  Shadowing or saturation of incoming gluon distribution
  Initial state energy loss
  (calibrate with p+A or d+A)

- Final state effects
  Breakup of quarkonia due to co-moving hadrons
  Coalescence of q and qbar at hadronization
  (calibrate with A, centrality dependence)

arXiv:1010.1246
Expect if c-cbar pairs numerous or correlated

Open charm flows but J/ψ does not

So, c̅c coalescence in final state @ RHIC is not large

Higher at LHC?
**b-bar bound states**

- Coalescence *could* be important at LHC

More c-cbar pairs produced. Use b-bar to probe...

\[ \Upsilon (2S, 3S) \] suppressed

- Does partial screening preserve correlations, enhancing likelihood of final state coalescence?

- arXiv:1010.2735 (Aarts, et al): \[ \Upsilon \text{unchanged to } 2.09T_c \]

\[ \chi_b \text{ modified from 1-1.5T}_c, \text{ then free} \]
Prompt (CMS) vs. inclusive (ATLAS) J/\psi

- at high p_T, prompt J/\psi < inclusive?
  (b states less suppressed)

- recall:
  √s dependence is weak
  LHC less suppressed!

Final state coalescence?
susceptibilities & net-baryon fluctuations

\[ S_\sigma = \frac{[B^3]}{[B^2]} = \frac{T \chi_B^{(3)}}{\chi_B^{(2)}} , \]

\[ \kappa \sigma^2 = \frac{[B^4]}{[B^2]} = \frac{T^2 \chi_B^{(4)}}{\chi_B^{(2)}} , \]

\[ \frac{\kappa \sigma}{S} = \frac{[B^4]}{[B^3]} = \frac{T \chi_B^{(4)}}{\chi_B^{(3)}} , \]

Relation between the baryon susceptibilities, \( \chi_B \), and cumulants of the net-baryon fluctuations.
Elliptic flow scales with quark number

implication: valence quarks, not hadrons, are relevant DOF coalesce into hadrons when $T$ falls below $T_c$ consistent with success of hydro with lattice EOS, but…

what gives? dressed quarks are born of flowing field?

Nb: strongly interacting liquids lack well-defined, long-lived quasi-particles
minimum $\eta$ at phase boundary?

Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

minimum observed in other strongly coupled systems – kinetic part of $\eta$ decreases with $\Gamma$ while potential part increases

strongly coupled dusty plasma

B. Liu and J. Goree,
Insights, given first LHC results

- **Quarkonia energy dependence not understood!**
  Need charmonium and bottomonium states at $>1 \sqrt{s}$ at RHIC
  + guidance from lattice QCD!

- **Jet results from LHC very surprising!**
  Steep path length dependence of energy loss
  also suggested by PHENIX high $p_T v_2$; AdS/CFT is right?
  Little modification of “jet” fragmentation function
  looks different at RHIC (different jet definition, energy)
  Lost energy goes to low $p_T$ particles at large angle
  is dissipation slower at RHIC? Due to medium or probe?
  Little modification of di-jet angular correlation
  appears to be similar at RHIC

- Need full, calorimetric reconstruction of jets in wide $y$ range at RHIC to disentangle probe effects/medium effects/initial state
HCal improvement to Jet Energy Measurement

- tracking $p < 10$ GeV/c required to avoid fake jets

- No fake jet due to tracking background
- Catch neutral energy
- No asymmetric tail in measured energy $\Rightarrow$ Essential for $A_J$ measurement
HCal for jet measurement

With 10 GeV tracking cut off, only tiny fraction of jet can be reconstructed

With 20 GeV tracking cut off, still less than 1/3 of jet is reconstructed at proper energy

• For di-jet asymmetry ($A_j$) measurement, the tail is the killer
• Hcal eliminates the tail.
• Hcal is not the cost driver of sPHENIX
Beam Energy Scan

Large acceptance $\rightarrow$ Energy scan of rare probes at lower beam energy

- Jets
- High $p_T$ single hadrons
- Open heavy flavor
- Quarkonia
  repeat energy scan of 20 – 200 GeV with large acceptance detector to characterize the suppression as a function of $\sqrt{s}$
- Photon-hadron, Photon-jets
  Probe Energy loss and QGP response in lower beam energy
Direct photon flow ingredients

- Key cross checks:
  - $\gamma^{inc}$ are really $\gamma$’s:
  - check using $\gamma \rightarrow e^+e^-$
  - $R_\gamma$ for virtual vs. real $\gamma$

[Graph showing $\gamma^{inc} v_2$ with external conversion method]

[Graph showing $R_\gamma = \frac{N(\gamma^{inc})}{N(\gamma^{BG})}$ vs. $p_T$]
heavy quark suppression & flow?

Collisional energy loss?
$v_2$ decrease with $p_T$?
role of b quarks?

PRL.98: 172301,2007
arXiV: 1005.1627
Mysteries in heavy ion physics

- Energy loss mechanism
  - LHC 40 GeV jets opposing 100 GeV jets look “normal”
    - no broadening or decorrelation
    - no evidence for collinear radiation from the parton
  - RHIC low energy jets appear to show medium effects
    - but, “jet” is defined differently
  - c & b to probe role of collisional energy loss
  - quantify path length dependence

- J/ψ suppression and color screening
  - amazingly similar from √s=17-200 GeV; but initial states differ
    - not SO different at LHC
  - Other states γ & √s dependence (e.g. ψ’)
  - d+Au for initial state; 130 GeV Au+Au eventually?
To answer these questions

**Questions**
- Quarks strongly coupled Interaction mechanisms
- Quasiparticles in medium
- Screening Length
- Thermal Behavior Thermalization time

**Observables**
- Jets, Dijets, \( \gamma \)-Jet (FF, radiation)
- Charm/Beauty Jets
- \( J/\psi \) at multiple energies
- Upsilon (all states)
- Direct \( \gamma^* \) flow

**Needs**
- Large Acceptance
- High Rate
- Electron ID
- Photon ID
- Excellent Jet Capabilities (HCAL)
How does this happen?
Cost estimate

Carry over from existing PHENIX:
- VTX and FVTX
- EMCal in Forward Arm and perhaps barrel
- DAQ
- Infrastructure (LV, HV, Safety systems…)

What is new:
- 2-3T solenoid ($R = 60-100 \text{ cm}$)
- Preshower detector
- Barrel EMCal (maybe new)
- Hadronic Calorimetry
- Additional tracking layers of Si at $\sim 40\text{ cm}$
- Forward Arm with RICH and GEM tracker

Other
- Forward magnet
- Forward HCAL
- Barrel tracking layer $\sim 60\text{ cm}$

\[ \{ \begin{align*} 
&\text{20M} \\
&\text{8-10M} \\
&\text{5-7M} \\
&\text{10M}
\end{align*} \]

Can be built incrementally

Total Project Cost $53-62\text{M}$
- Approx $\frac{1}{2}$ replacement cost of existing $130\text{M}$ PHENIX detector
- DOE contribution estimated to be 60\% of total $32-44\text{M}$
- Forward detector is key for eRHIC physics (part of eRHIC project?)

All cost estimate include overhead and contingency
sPHENIX acceptance

+ DAQ/Trigger: 50B events / year!
Our big picture plan
Thermal photons (virtual)

Observe excess photons beyond pQCD in AA collisions. In thermal $p_T$ region.
Dielectron production in $0.5 < m_{ee} < 1$ GeV

Significant excess in central collisions.

Dominantly at low $p_T$

We are investigating using Run-10 data with the HBD

NSAC milestone DM6
Beam Energy Scan in PHENIX

Is there a critical point separating 1\textsuperscript{st} order phase transition & smooth cross-over?

- Quark-number scaling of $V_2$
  - saturation of flow vs collision energy
  - find $\eta/s$ minimum at critical point from flow
- Critical point searches via:
  - fluctuations in $<p_T>$ & multiplicity
  - $K/\pi$, $\pi/p$, $p\bar{p}/p$ chemical equilibrium
  - $R_{AA}$ vs $\sqrt{s}$, ....

![Graphs and diagrams related to beam energy scan in PHENIX](image-url)
Dense gluonic matter (d+Au, forward y): large effects observed

\[ \sqrt{s} = 200 \text{ GeV} \text{ p+p, d+Au} \rightarrow h + \pi^0 + X \]

Di-hadron suppression at low x

\[ x_{\text{Au}}^{\text{frag}} = \frac{<p_{T1}> e^{-<\eta_1>} + <p_{T2}> e^{-<\eta_2>}}{\sqrt{s}} \]

Shadowing/absorption stronger than linear w/nuclear thickness

\[ J_{dA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{dA}^{\text{pair}}}{\sigma_{dA}} / \frac{\sigma_{pp}^{\text{pair}}}{\sigma_{pp}} \]
Viscosity/Entropy (natural units)

He near $\lambda$-point

String theory limit
Calculate the correlator on the lattice

→ non-perturbative contributions to thermal dilepton rates at low mass

• For small energy, $\omega/T < (1-2)$ spectral function > free form

• For $\omega/T \approx 1$ thermal dilepton rate ~ order of magnitude > leading order Born rate

• for $\omega/T > \sim (2-4)$ the spectral function is close to the free form

From fit to lattice spectral fn. in Phys.Rev.D.83.034504 (2011)
Heavy quark diffusion

Ding, et al.
arXiv: 1107.0311

**Figure 3.** Uncertainties of output spectral functions in $PS$ (left) and $V_{tt}$ (right) channels at all available temperatures. The shaded areas are errors of output spectral functions from Jackknife and the solid lines inside the shaded areas are mean values of spectral functions.

**J/ψ:** Not yes/no!

Is the correlation gone @ $T > 1.5 \ T_c$?

What happens at 1.0-1.2$T_c$?

Is there observable evidence of partial screening?

Association of both $J/ψ$ and $η_c$ at $T \geq 1.46 \ T_c$. 

**Answer:**

- **J/ψ:** Not yes/no!
- **Correlation:**
  - Gone @ $T > 1.5 \ T_c$?
  - What happens at 1.0-1.2$T_c$?
  - Is there observable evidence of partial screening?

**Significance:**

The plots illustrate the behavior of spectral functions in different temperature regimes, which are crucial for understanding the dynamics of heavy quark diffusion in the QCD plasma. 

**Further Analysis:**

The association of $J/ψ$ and $η_c$ at $T \geq 1.46 \ T_c$ suggests a non-trivial interplay between these states, which could provide insights into the quark-gluon plasma's properties and its transition to hadrons.
Matter flows like a ~ideal liquid

- huge pressure buildup
- large anisotropy → rapid equilibration

Hydrodynamics reproduces elliptic flow of q-\overline{q} and 3q states
Mass dependence requires soft EOS, NOT gas of hadrons

only works if viscosity/entropy is near the minimum for a quantum system (1/4π)
“perfect” liquid (D. Teaney, PRC68, 2003)
# Beam Energy Scan at RHIC

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<th>Status</th>
<th>Experiment</th>
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<td>TBD</td>
<td>STAR</td>
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<tr>
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<td>analyzed</td>
<td>STAR PHENIX (limited statistics)</td>
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don’t give up! ask lattice QCD

Karsch, et al.

coupling drops off for $r > 0.3$ fm
High $m_{\text{eff}} \rightarrow$ large collisional energy loss

Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks ($m_q = 200$ MeV). The results for the numerator $\Delta E_Q$ and the denominator $\Delta E_q$ are the same as used for plotting Fig. 2.
Collective motion & elliptic flow ($v_2$)

\[
dN/d\phi \sim 1 + 2 v_2(p_T) \cos (2\phi) + \ldots
\]

hydrodynamics works!

Almond shape overlap region in coordinate space

momentum space