The little bang: understanding the Quark Gluon Plasma

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QCD Phase Diagram

\[ \mu_B \text{ (MeV)} \]

\[ T_{ch} \text{ (MeV)} \]

\[ \text{Au+Au Collisions} \]

Quark-Gluon Plasma

Hadron Gas

arXiv:1701.07065

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How to make a Quark Gluon Plasma

Heat

nucleon boundary irrelevant

Compress
The phase transition in the laboratory

Initial State

QGP

Freeze-out

Hydrodynamical flow

Jet quenching


https://physics.aps.org/articles/v7/97
Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, \( U+U \)
\( \sqrt{s_{NN}} = 9 - 200 \) GeV

Geneva, Switzerland
8.6km diameter
p+p, Pb+Pb
2.76 GeV, 5.5 TeV
**Trigger detectors:** When do we have a collision?

**Tracking detectors:** Where did the particle go?

**Identification detectors:** What kind of particle is it?

**Calorimeters:** How much energy does the particle have?

- **Size:** 16 x 26 meters
- **Weight:** 10,000 tons
- **Detectors:** 18

- **ACORDE**
- **ITS**
- **FMD T0 & V0**
- **TRGCH**
- **MFUON**
- **TRIGHER**
- **ZDC ~116m from L.P.**
- **V0**
- **T0**
- **TOF**
- **TPC**
- **FMD**
- **HMPID**
- **PMD**
- **ZDC ~116m from L.P.**
- **PHOS**
- **DIPOLE MAGNET**
- **ABSORBER**
p+p collisions

3D image of each collision
Pb+Pb collisions

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QGP Energy Density
How can we estimate the energy density?

- Transverse energy ($E_T$)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- $\tau = $ formation time
- Energy density $\epsilon$

$$\epsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d \eta}$$

- QGP formation for $\epsilon > 0.5$ GeV/fm$^3$
Energy density

\[ \epsilon \tau_0 \approx 1 \text{ fm/c} \]

ALICE Pb–Pb √s_{NN} = 2.76 TeV

\[ \epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy} \]

Standard estimate \( \tau_0 \approx 1 \text{ fm/c} \)

RHIC

QGP formation

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QGP Chemistry
Chemistry - equilibrium

T~170 MeV

- Ratios of particles expected from model
- Even strange quarks are at equilibrium!
Phase diagram of nuclear matter

Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun.
QGP Thermometers
Measuring temperature

![Graph showing the relationship between intensity and wavelength for different temperatures. The graph includes a light bulb and a color spectrum.]
Thermal photons

PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Inverse slope: $T = 221 \pm 19$ (stat) $\pm 19$ (syst) MeV

ALICE collaboration: Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Inverse slope: $T = 304 \pm 51$ MeV

QCD processes
Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is extremely hot and dense.
Building a quarkonium-thermometer

Clear hierarchy in $R_{AA}$ of different quarkonium states
Building a quarkonium-thermometer

CMS-PAS HIN-11-011

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- Prompt $J/\psi$ (Preliminary)
- $\Upsilon(1S)$
- $\Upsilon(2S)$

Note: $6.5<p_T<30$ GeV for $J/\psi$ and $\psi(2s)$

CMS Preliminary

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- Inclusive $\psi(2S)$ ($6.5 < p_T < 30$ GeV/c, $|y| < 1.6$)
- $\Upsilon(3S)$ ($|y| < 2.4$), 95% upper limit
- $\Upsilon(2S)$ ($|y| < 2.4$)
- Prompt $J/\psi$ ($6.5 < p_T < 30$ GeV/c, $|y| < 2.4$)
- $\Upsilon(1S)$ ($|y| < 2.4$)

Expected in terms of binding energy
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arXiv:1701.07065

Au+Au Collisions

$T_{\text{ch}}$ (MeV)

$\mu_B$ (MeV)

00-05%
30-40%
60-80%

Grand Canonical Ensemble (Yield Fit)

Cleymans et al.
Andronic et al.

trajectory of system

$\sim 600$
QGP Spectroscopy
Probing the Quark Gluon Plasma

Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived $\rightarrow$ need a probe created in the collision
We expect the medium to be dense $\rightarrow$ absorb/modify probe
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-\(p_T\) probes (jets) are suppressed, this is evidence of jet quenching

\[
R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma^{pp}/dp_Td\eta}
\]

Enhancement

Suppression
Nuclear modification factor

- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb
• **Electromagnetic probes** – consistent with no modification – medium is transparent to them

• **Strong probes** – significant suppression – medium is opaque to them - even heavy quarks!
Careers in high energy physics

• You should consider high energy physics if...
  - You like programming and working with computers
  - You're a people person – and don't mind working with 1000 people
  - You like to travel around the world – and work
  - You enjoy giving talks

• Common career options for people with a Ph.D. in high energy physics
  - Academia – research and teaching universities
  - Research at a National Laboratory
  - National security
  - Finance
  - Computer programming
What I spend my time doing

- Programming (C++) - analyzing data
- Writing and giving talks – 3 research talks, 1 seminar, 2 posters, 1 software tutorial, and lots of talks (>30) at internal meetings in 2010
- Hardware work: assembling & testing the detector
- Outreach: blogging for ALICE, giving tours of PHENIX to the public...
- Writing papers and conference proceedings
- Reviewing the work of my collaborators
- Reading papers
- Taking shifts – including being on call 24/7
- Teaching, advising students (undergrad & grad)
- Committee work
Resources

- US LHC blog and Facebook page
- Experiments
  - Relativistic Heavy Ion Collider: STAR PHENIX
  - Large Hadron Collider: ALICE ATLAS CMS LHCb TOTEM
- Event displays and pretty pictures from ALICE
- Really cool ATLAS event animation
- Links to articles in the press on PHENIX
- Scientific American article
<table>
<thead>
<tr>
<th><strong>US Universities with graduate programs in experimental heavy ion physics</strong></th>
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<tr>
<td><strong>Relativistic Heavy Ion Collider</strong></td>
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<td><strong>• STAR</strong></td>
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<td>University of California at Davis</td>
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<td>University of California Los Angelos</td>
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<td>University of Houston</td>
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<td>University of Illinois at Chicago</td>
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<td>Creighton University (masters only)</td>
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<td>Yale University</td>
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</tbody>
</table>
US Universities with graduate programs in experimental heavy ion physics

Large Hadron Collider

• ALICE
  - University of Texas Austin
  - Chicago State University
  - Ohio State University
  - Wayne State University
  - University of Texas Houston
  - University of Tennessee Knoxville
  - Yale University
  - Creighton University (masters only)
  - Purdue University

• CMS
  - University of California Davis
  - University of Illinois Chicago
  - University of Kansas
  - University of Maryland
  - University of Iowa
  - Rutgers University

• ATLAS
  - Columbia University
p+Pb as a control

\[ R_{pPb} \]

\begin{align*}
\Omega &= 0.55 \\
0-1\% &
\end{align*}

\[ \begin{array}{c}
\bullet -2. < y^* \leq -1.5 \\
\diamond -0.5 < y^* \leq 0.5 \\
+ 2 < y^* \leq 2.5 \\
\end{array} \]

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

ATLAS

CMS Preliminary

\[ N_{\text{coll}}=6.9 \]

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

\[ R_{pPb} (|h_{CM}|<1) \]

\[ p\text{Pb} \mid S_{NN} = 5.02 \text{ TeV, charged particles} \]
Suppression of quarkonia in $p+Pb$
Suppression of quarkonia in d+Au

arXiv:1315.5516, to be publ PRL

PHENIX

$|y| < 0.35$, $\sqrt{s_{NN}} = 200$ GeV d+Au
Baryon anomaly: $\Lambda/K^0_S$

Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV, $|y|<0.75$

Preliminary

only stat. errors shown
Nuclear modification factor ($R_{AA}$)

\[
R_{AA}(p_T) = \frac{\langle 1/N_{coll} \rangle (1/N_{evt}^{pp}) d^2N_{ch}^{AA} / d\eta dp_T}{\langle N_{coll} \rangle (1/N_{evt}^{pp}) d^2N_{ch}^{pp} / d\eta dp_T}
\]
Charm nuclear modification factor

\[ R_{AA} \]

\[ \text{Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ \text{ALICE Preliminary} \]

\[ D^0 R_{AA} \] 0-20% CC
\[ D^+ R_{AA} \] 0-20% CC
\[ \pi^\pm R_{AA} \] 0-20% CC