Probing the quark gluon plasma

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Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/
Quark Gluon Plasma – a liquid of quarks and gluons created at temperatures above \(~170 \text{ MeV} (2 \cdot 10^{12} \text{K})\) – over a million times hotter than the core of the sun
How to make a Quark Gluon Plasma

nucleus

Heat

Compress

nucleon boundary irrelevant

CGP
The phase transition in the laboratory

Phase Transition/Cross-Over
Chemical Freeze-Out (inel. collisions cease)
Thermal Freeze-Out (el. collisions cease)

Collision
pre-equilibrium
QGP
Hadron Gas

$\tau_0$

$T_c$

$T_{ch}$

$T_{fo}$

time
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, $p+Pb$, Pb+Pb
$\sqrt{s_{NN}} = 2.76$ GeV, 5.5 TeV

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Comparison of colliders

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (GeV)</td>
<td>9-200</td>
<td>2760, 5500</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta$</td>
<td>~1200</td>
<td>~1600</td>
</tr>
<tr>
<td>$T/T_c$</td>
<td>1.9</td>
<td>3.0-4.2</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm$^3$)</td>
<td>5</td>
<td>~15</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>2-4</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

*center of mass energy*

*number of particles*

*temperature*

*energy density*

*lifetime of QGP*

**RHIC and LHC:**
Cover 2 –3 decades of energy ($\sqrt{s_{NN}} = 9$ GeV –5.5 TeV)
To discover the properties of hot nuclear matter at $T \sim 150$ –600 MeV
p+p collisions

3D image of each collision
Pb+Pb collisions
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 → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe
**Jets**

Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles.

\[ p + p \rightarrow \text{dijet} \]
Jet reconstruction

- Identify all of the particles in the jet $\rightarrow$ parton energy, momentum
- Difficult in heavy ion collisions – but possible!
Jets

nucleus

nucleus

ATLAS

Calorimeter Towers


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Quenched jets

- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
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

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Nuclear modification factor $R_{AA}$

- **Electromagnetic probes** – consistent with no modification – medium is transparent to them
- **Strong probes** – significant suppression – medium is opaque to them

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Nuclear modification factor $R_{AA}$ at LHC

Like for charged particles, high-$p_T$ jet $R_{AA}$ flat at $\approx 0.5$
p+Pb as a control

$R_{pPb}$

$\Omega=0.55$

-2. < $y^* \leq$ -1.5
-0.5 < $y^* \leq$ 0.5
2 < $y^* \leq$ 2.5

ATLAS

CMS

CMS Preliminary

$N_{coll}=6.9$

$pPb, \sqrt{s_{NN}}=5.02$ TeV, charged particles

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Measuring temperature
Thermal photons

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

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

QCD processes

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Building a quarkonium-thermometer

Clear hierarchy in $R_{AA}$ of different quarkonium states

Note: $6.5 < T < 30$ GeV for $J/\psi$ and $\psi(2s)$
Suppression of quarkonia in p+Pb
Suppression of quarkonia in d+Au

arXiv:1315.5516, to be publ PRL
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 transparent to colored probes and translucent to electromagnetic probes...
- ...And extremely hot and dense.