Hard probes of the Quark Gluon Plasma

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Tsukuba Global Science Week
28-30 September 2014
Colored spheres: quarks
White spheres: hadrons, i.e. bound quarks

In a nuclear collision, a Quark-Gluon Plasma (liquid) is formed
⇒ Study this new state of matter
Probing the Quark-Gluon Plasma

Probe beam
- Not feasible:
  - Short life time
  - Small size (~10 fm)

Use self-generated probe:
- quarks, gluons from hard scattering
- large transverse momentum
RHIC and LHC

RHIC, Brookhaven
Au+Au $\sqrt{s_{NN}} = 200$ GeV

LHC, Geneva
Pb+Pb $\sqrt{s_{NN}} = 2760$ GeV

First run: 2000
STAR, PHENIX, PHOBOS, BRAHMS

First run: 2009/2010
Currently under maintenance
Restart 2015 with higher energy:
pp $\sqrt{s} = 13$ TeV, PbPb $\sqrt{s_{NN}} = 5.12$ TeV
ALICE, ATLAS, CMS, (LHCb)
Collision centrality

Nuclei are large compared to the range of strong force

Peripheral collision

Central collision

b finite

b~0 fm

This talk: concentrate on central collisions
Centrality continued

Experimental measure of centrality: multiplicity

Need to take into account volume of collision zone for production rates
Testing volume ($N_{\text{coll}}$) scaling in Au+Au

Direct $\gamma$ spectra

Scaled by $N_{\text{coll}}$

Direct $\gamma$ in A+A scales with $N_{\text{coll}}$

A+A initial production is incoherent superposition of p+p for hard probes

PHENIX, PRL 94, 232301
$\pi^0$ $R_{AA}$ – high-$p_T$ suppression

Hard partons lose energy in the hot matter.

$\gamma$: $R_{AA} = 1$

$\pi^0$: $R_{AA} \approx 0.2$

Hadrons: energy loss
Getting a sense for the numbers – RHIC

\[ \pi^0 \text{ spectra} \]

Ball-park numbers: \( \Delta E/E \approx 0.2 \), or \( \Delta E \approx 3 \text{ GeV} \) for central collisions at RHIC

Oversimplified calculation:
- Fit pp with power law
- Apply energy shift or relative E loss

Not even a model!
From RHIC to LHC

RHIC: 200 GeV per nucleon pair
LHC: 2.76 TeV

Energy ~14 x higher

LHC: spectrum less steep, larger $p_T$ reach

$$\frac{l}{2\pi p_T} \frac{dN}{dp_T} \propto p_T^{-n}$$

RHIC: $n \sim 8.2$
LHC: $n \sim 6.4$

Fractional energy loss:

$$R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$

$R_{AA}$ depends on $n$, steeper spectra, smaller $R_{AA}$
From RHIC to LHC

RHIC: $n \sim 8.2$

$LHC: n \sim 6.4$

$\left(1 - 0.23\right)^{6.2} = 0.20$

$\left(1 - 0.23\right)^{4.4} = 0.32$

Energy loss at LHC is larger than at RHIC
($R_{AA}$ is similar due to flatter spectra)
Towards a more complete picture

- **Geometry:** couple energy loss model to model of evolution of the density (hydrodynamics)
- Energy loss not single-valued, but a distribution
- Energy loss is partonic, not hadronic
  - Full modeling: medium modified shower
  - Simple ansatz for leading hadrons: energy loss followed by fragmentation
  - Quark/gluon differences
Medium-induced radiation

Key parameter:
Transport coefficient

\[ \hat{q} \equiv \frac{\langle q_{\perp}^2 \rangle}{\lambda} \]

Mean transverse kick per unit path length

\[ \Delta E_{med} \sim \alpha_s \hat{q} L^2 \]

Depends on density \( \rho \) through mean free path \( \lambda \)

\[ \lambda \propto \frac{1}{\rho} \]
Fitting the model to the data

\[ \chi^2 \text{ of data wrt model} \]

Clear minimum: found best value for transport coefficient

Factor \(~2\) larger at LHC than RHIC
Comparing several models

RHIC:
\[ \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/fm \]
(T=370 MeV)

LHC:
\[ \hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/fm \]
(T=470 MeV)

Expect factor 2.2 from multiplicity + nuclear size

\[ \hat{q} \] values from different models agree
\[ \hat{q} / T^3 \] larger at RHIC than LHC
Transport coefficient and viscosity

Transport coefficient: momentum transfer per unit path length

\[ \hat{q} = \frac{\langle q^2 \rangle}{\lambda} = \rho \int dq_\perp^2 q_\perp^2 \frac{d^2 \sigma}{dq_\perp^2} \]

\[ \rho \propto T^3 \quad \hat{q} \quad \text{basically measures the density} \]

Viscosity: \( \eta \propto \rho \langle p \rangle \lambda \)

General relation:

\[ \frac{\hat{q}}{T^3} \propto \left( \frac{\eta}{s} \right)^{-1} \]

Expect \( \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \) for a QCD medium

Majumder, Muller and Wang, PRL99, 192301
Relation transport coefficient and viscosity

(Scaled) viscosity slightly larger at LHC

Increase of $\eta/s$ and decrease of $q/T^3$ with collision energy are probably due to a common origin, e.g. running $\alpha_S$

Results agree reasonably well with expectation:

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{q}$$
Conclusion

- High-$p_T$ particles are a ‘hard probe’ of the Quark Gluon Plasma
- Use these to find the transport coefficient of the QGP:
  - RHIC: $\hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/fm$
  - LHC: $\hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/fm$
- Increase from RHIC to LHC slightly smaller than expected
- Similar effect observed in viscosity $\eta$
- Probably common origin, e.g. running $\alpha_S$

Next step: use other observables, e.g. jets, to test and improve energy loss models
Extra slides
Geometry

Density profile

Profile at $\tau \sim \tau_{\text{form}}$ known

Density along parton path

Longitudinal expansion dilutes medium
$\Rightarrow$ Important effect

Space-time evolution is taken into account in modeling
A simplified approach

\[
\left. \frac{dN}{dp_T} \right|_{\text{hadr}} = \frac{dN}{dE} \bigg|_{\text{jets}} \otimes P(\Delta E) \otimes D(p_{T,\text{hadr}} / E_{\text{jet}})
\]

This is where the information about the medium is

\[P(\Delta E)\] combines geometry with the intrinsic process – Unavoidable for many observables

Notes:
• This is the simplest ansatz – most calculation to date use it (except some MCs)
• Jet, \(\gamma\)-jet measurements ‘fix’ \(E\), removing one of the convolutions

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Systematic comparison of energy loss models with data
Medium modeled by Hydro (2+1D, 3+1D)
$p_T$ dependence matches reasonably well
CUJET: $\alpha_s$ is medium parameter
Lower at LHC

HT: transport coeff is parameter
Higher at LHC
Nuclear geometry: $N_{\text{part}}$, $N_{\text{coll}}$

Two limiting possibilities:
- Each nucleon only \textit{interacts once}, ‘wounded nucleons’
  \[ N_{\text{part}} = n_A + n_B \] (ex: $4 + 5 = 9 + \ldots$)
  Relevant for \textit{soft production}; long timescales: $\sigma \propto N_{\text{part}}$
- Nucleons \textit{interact with all} nucleons they encounter
  \[ N_{\text{coll}} = n_A \times n_B \] (ex: $4 \times 5 = 20 + \ldots$)
  Relevant for \textit{hard processes}; short timescales: $\sigma \propto N_{\text{bin}}$
Nuclear modification factor $R_{AA}$

$$R_{AA} = \frac{\left. dN/dp_T \right|_{A+A}}{N_{coll} \left. dN/dp_T \right|_{p+p}}$$

Measured $R_{AA}$ is a ratio of yields at a given $p_T$

The physical mechanism is energy loss; shift of yield to lower $p_T$

The full range of physical pictures can be captured with an energy loss distribution $P(\Delta E)$
Nuclear modification factor

\[ R_{AA} = \frac{dN / dp_T \bigg|_{Pb+Pb}}{N_{coll} \ dN / dp_T \bigg|_{p+p}} \]

Suppression factor 2-6
Significant \( p_T \)-dependence
Similar at RHIC and LHC?

So what does it mean?