QGP Physics – From Fixed Target to LHC

8. Hard Scattering, Jets, and Jet Quenching

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SS 2011
More than 99% of all particles (the bulk) have transverse momenta less than 2 GeV/c.

High-$p_T$ particles in A+A can be used as a probe of the created medium.
Jet Quenching: Basic Idea

Expectation:
Simple scaling from p+p to p+A (no suppression)

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling from p+p to A+A for direct photons (no suppression)
What Can We Hope to Learn from Particles at High $p_T$ and Jets?

- In heavy-ion physics, particles at high $p_T$ and jets are of great interest because
  - they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
  - their initial production rate can be calculated with perturbative QCD

- Observables related to jet quenching may help to
  - characterize the new state of matter above $T_c$
  - understand the mechanism of parton energy loss

- Basic logic

\[
\text{QGP} \quad \leftrightarrow \quad \text{Suppression of hadrons at high } p_T
\]
How Can We Study Jet Quenching?

- Measurement of particle multiplicities at high $p_T$
- Measurement of two-particle angular correlations
- Jet reconstruction on an event-by-event basis
  - Challenging in central nucleus-nucleus collisions at RHIC due to large particle multiplicity from the underlying event
  - Situation improves significantly for Pb+Pb at the LHC due to the increased cross section for jet production
Hard Scattering in p+p
Theoretical Description of High-$p_T$ Particle Production: Perturbative QCD

- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from $e^+e^-$ collisions

Leading hadron:

$$\langle z \rangle = \langle \frac{p_{\text{hadron}}}{p_{\text{parton}}} \rangle \approx 0.25$$

Factorization:

$$d\sigma = \sum_{a, b, c} f_a \otimes f_b \otimes d\hat{\sigma}_{ab} \otimes D_c^{\text{Hadron}}$$
Hadron Production in Leading Order QCD

\[ E \frac{d^3 \sigma}{dp^3} = K \sum_{a,b,c,d=q,ar{q},g} \int_{x_{a,\text{min}}}^{1} dx_a \int_{x_{b,\text{min}}}^{1} dx_b \ f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \frac{d\sigma_{ab\rightarrow cd}}{d\hat{t}} \frac{1}{\pi z_c} D_{h/c}(z_c, Q^2) \]

- Phenomenological factor which takes higher order contributions into account
- Parton distributions (functions of \( x_{\text{Bjorken}} \) and momentum transfer \( Q^2 \))
- Fragmentation function

Elementary QCD parton-parton cross section

\[ z_c = p_{T,Hadron}/p_{T,c} \]
### Point Cross Sections at Leading Order

| Process          | \( \sum |\mathcal{M}|^2/g^4 \)                           | \( \theta^* = \pi/2 \) |
|------------------|------------------------------------------------------|-------------------------|
| \( q q' \rightarrow q q' \) | \( \frac{4}{9} \frac{s^2 + u^2}{t^2} \)             | 2.22                    |
| \( q \bar{q}' \rightarrow q \bar{q}' \) | \( \frac{4}{9} \frac{s^2 + u^2}{t^2} \)             | 2.22                    |
| \( q q \rightarrow q q \)       | \( \frac{4}{9} \left( \frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} \right) - \frac{8}{27} \frac{s^2}{u^t} \) | 3.26                    |
| \( q \bar{q} \rightarrow q' \bar{q}' \) | \( \frac{4}{9} \frac{t^2 + u^2}{s^2} \)             | 0.22                    |
| \( q \bar{q} \rightarrow q \bar{q} \) | \( \frac{4}{9} \left( \frac{s^2 + u^2}{t^2} + \frac{t^2 + u^2}{s^2} \right) - \frac{8}{27} \frac{u^2}{s^t} \) | 2.59                    |
| \( q \bar{q} \rightarrow g g \) | \( \frac{32}{27} \frac{t^2 + u^2}{t^u} - \frac{8}{3} \frac{t^2 + u^2}{s^2} \) | 1.04                    |
| \( g g \rightarrow q \bar{q} \) | \( \frac{1}{6} \frac{t^2 + u^2}{t^u} - \frac{3}{8} \frac{t^2 + u^2}{s^2} \) | 0.15                    |
| \( g q \rightarrow g q \) | \( -\frac{4}{9} \frac{s^2 + u^2}{s^u} + \frac{u^2 + s^2}{t^2} \) | 6.11                    |
| \( g g \rightarrow g g \) | \( \frac{9}{2} \left( 3 - \frac{t^u}{s^2} - \frac{s^u}{t^2} - \frac{s^t}{u^2} \right) \) | 30.4                    |

Relative importance at equal parton luminosities
Parton Distributions: High Precision Data from HERA

HERA: $e^\pm p$ scattering

H1 and ZEUS, JHEP 1001:109, 2010 (→ link)
Website with combined HERA results (→ link)

\[
d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}_{ab} \otimes D_c^{Hadron}
\]

Bjorken-$x$
**Parton Distributions for Nuclei**

- \( x < 0.1 \): “shadowing region”
- \( 0.1 < x < 0.3 \): “anti-shadowing”
- \( 0.3 < x < 0.7 \): “EMC effect”
- \( 0.7 < x < 1.0 \): Fermi-motion of nucleons in nuclei

Nuclear gluon pdf’s at low \( x \) poorly constrained experimentally

**Eskola et al., arXiv:0902.4154v2 [hep-ph]**
Example: Gluon and u-Quark Fragmentation Functions

Fragmentation functions:
Number density for the production of a hadron $h$ with fractional energy $z$ in the fragmentation of a parton (e.g. determined from $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$ )
Jet Quenching
Jet Quenching History


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Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The $dE/dx$ is roughly proportional to the square of the plasma temperature. For this effect, an interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

- Energy loss via elastic scattering was later believed to have only a minor effect on jets
- Radiative energy loss was discussed in the literature from 1992 on by Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigne, Schiff, Levai, Vitev, Zhakarov, Wang, Salgado, Wiedemann, …
Analogy:
Energy loss of Charged Particles in Normal Matter

- $\mu^+ \text{ on Cu: }$ Radiational energy loss („bremsstrahlung“) starts to dominate over collisional energy loss („Bethe-Bloch formula“) for $p >> 100 \text{ GeV/c}$
- For energetic quarks and gluons in QCD matter, radiative energy loss via induced gluon emission is/was expected to be the dominant process
Parton Energy Loss

Radiative energy loss dominant (\(?)\):
\[
\frac{dE_{\text{rad}}}{dx} \gg \frac{dE_{\text{coll}}}{dx}
\]

\[\Delta E \propto \alpha_s C_F \hat{q} L^2\]

\(\mu^2\) : Typical momentum transfer from the medium to the parton
\(\lambda\) : Mean free path

Energy loss \(\Delta E\) in a static medium of length \(L\) for \(E \to \infty\) (BDMPS results)

\(L^2\) dependence:
Non-abelian nature of QCD + quantumm. interference

\[C_F = \begin{cases} 
3 & \text{for gluon jets} \\
4/3 & \text{for quark jets} 
\end{cases}\]

Review: U. Wiedemann, arXiv:0908.2306 (→ link)
Energy loss in the GLV Formalism for Pb+Pb at the LHC

Central Pb+Pb at $\sqrt{s_{NN}} = 5500$ GeV: $L \approx 6$ fm, $dN^g/dy = 2000, 3000, 4000$

$\Delta E_{\text{gluon}} / \Delta E_{\text{quark}} = 9/4$ only in the limit $E \to \infty$
In many parton energy-loss models the fragmentation of the quark and gluon jets is assumed to happen in the vacuum like in p+p. Parton energy loss can then be conveniently included in a pQCD calculation via modified fragmentation functions:

Consider fixed parton energy loss $\varepsilon$: 

$$\frac{dn}{dx} = \frac{dn}{dz} \cdot \frac{dz}{dx} = D_{h/q}(z, Q^2) \cdot \frac{1}{1 - \varepsilon}$$

Average over energy loss probability:

$$D_{h/q}^{med}(x, Q^2) = \int_0^1 d\varepsilon P(\varepsilon) D_{h/q} \left( \frac{x}{1 - \varepsilon}, Q^2 \right) \frac{1}{1 - \varepsilon}$$

Hadrons resulting from gluon bremsstrahlung neglected.

Prob. distr. for parton energy loss $\varepsilon$ ("Quenching weight")
The Discovery of Jet Quenching at RHIC
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (I)

\[ R_{AB} = \frac{\frac{dN}{dp_T}|_{A+B}}{\langle T_{AB} \rangle \times \frac{d\sigma_{inv}}{dp_T}|_{p+p}}, \]

where \( \langle T_{AB} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{inel}^{NN}} \)

- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (see slide 22)
- Evidence for parton energy loss


Direct photons follow $T_{AB}$ scaling as expected for a hard probe not affected by the medium.
QGP Physics – J. Stachel / K. Reygers: 8
Hard Scattering, Jets, and Jet Quenching

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (III)

Indication for a small Cronin enhancement for pions in d+Au

No pion suppression in min. bias d+Au collisions
⇒ pion suppression is a final state effect caused by the created medium
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (IV)

- No jet correlation around 180° in central Au+Au
- Consistent with jet quenching picture

Trigger particle: $p_T > 4$ GeV/c
Associated particle: $p_T > 2$ GeV/c
Further Experimental Results Related to Jet Quenching
$\pi^0 R_{AA}$ with Higher Statistics (Run 4)

$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB} \rangle \times d\sigma_{\text{inv}}/dp_T|_{p+p}},$

where $\langle T_{AB} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}^{NN}$
Simple Interpretation of the Constant $R_{AA}$

$\pi^0$ spectrum without energy loss:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \frac{1}{p_T^n}$$

$\pi^0$ spectra at RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) described with $n \approx 8$

Constant fractional energy loss:

$$\varepsilon_{\text{loss}} := -\frac{\Delta p_T}{p_T}, \text{ i.e., } p_T' = (1 - \varepsilon_{\text{loss}})p_T$$

(However, QCD expectation is $\varepsilon_{\text{loss}} \sim \log(p_T)/p_T$)

This leads to:

$$R_{AA} = (1 - \varepsilon_{\text{loss}})^{n-2} \Rightarrow \varepsilon_{\text{loss}} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

$R_{AA}$ depends on the parton energy loss and the shape of the $p_T$ spectrum

In this simplistic view the constant $R_{AA} \approx 0.25$ implies a constant fractional energy loss of about 20% in central Au+Au collisions at 200 GeV
The rather flat $R_{AA}$ at RHIC can be interpreted as an accidental cancellation between

1) The fraction of high-$p_T$ gluons to quarks
2) The hardening of the parton spectrum (increase of $n(p_T)$)
3) The decrease in energy loss as a function of $p_T$
Particle Species Dependence of $R_{AA}$

**PHENIX** $\text{Au+Au, } \sqrt{s_{\text{NN}}} = 200$ GeV, 0-10% most central

- direct $\gamma$ (prelim.)
- $\pi^0$ (PRL101, 232301)
- $\eta$ (PRC82, 011902)
- $\phi$ (PRC83, 024909)
- $J/\psi$ 0-20% cent. (PRL98, 232301)
- $\omega$ 0-20% cent. (arXiv:1105.3467)
- $e^+_{HF}$ (arXiv:1005.1627)
- $K^+$ (arXiv:1102.0753)
- $p$ (arXiv:1102.0753)

**Axes:** $R_{AA}$ vs. $p_T$ (GeV/c)
$\sqrt{s_{NN}}$ Dependence: $\pi^0 R_{AA}$ for Heavy Nuclei at $\sqrt{s_{NN}} = 17.3$, 62.4, and 200 GeV

Onset of suppression between $\sqrt{s_{NN}} \approx 20$ GeV and 62.4 GeV
Dependence on the Size of the Nucleus:

$\sqrt{s_{NN}}$ Dependence of the $\pi^0$ $R_{AA}$ for Cu+Cu ($A = 63$)

62.4 and 200 GeV

$\pi^0$ production less suppressed than in Au+Au

22.4 GeV

- No suppression
- Enhancement consistent with a calculation that describes Cronin effect in p+A

Same conclusion as for heavier nuclei:
Parton energy loss starts to prevail over Cronin enhancement between $\sqrt{s_{NN}} = 22.4$ GeV and 62.4 GeV

Further Results from Two-Particle Correlations (I): Away-Side Jets Visible Again For Higher Jet $p_T$

- Charged hadron correlation
- Trigger particle: $p_T > 8$ GeV/c
- Associated particle: $p_T > 6$ GeV/c

For higher jet energies the correlation at $\Delta \phi = 180^\circ$ in central Au+Au is not fully suppressed anymore
Hierarchy Expected for Different Types of Partons

\[ \Delta E_{\text{Gluon}} > \Delta E_{\text{Quark}, m=0} > \Delta E_{\text{Quark}, m \neq 0} \]

larger color factor for gluons:

\[ C_F = \begin{cases} 
3 & \text{for gluon jets} \\
4/3 & \text{for quark jets}
\end{cases} \]

Dead cone effect:
Heavy quarks (c, b) are slower and radiate fewer gluons

\[
\omega \left. \frac{dI}{dw} \right|_{\text{HEAVY}} = \frac{\omega \left. \frac{dI}{dw} \right|_{\text{LIGHT}}}{\left( 1 + \left( \frac{m_Q}{E_Q} \right)^2 \frac{1}{\theta^2} \right)^2}
\]

Dokshitzer & Kharzeev, PLB 519(2001)199
$R_{AA}$ for Electrons from c- and b-Quark Decays

$\Delta E_{\text{Gluon}} > \Delta E_{\text{Quark},m=0} > \Delta E_{\text{Quark},m\neq0}$ not observed!
Radiative vs. Collisional (i.e., Elastic) Energy Loss: Maybe $\Delta E_{\text{collisional}}$ More Important Than Initially Thought?

- $\Delta E_{\text{radiative}} > \Delta E_{\text{collisional}}$ for $u, d$ as well as $c$ quarks with $E > 10$ GeV
- $\Delta E_{\text{radiative}} \approx \Delta E_{\text{collisional}}$ for $b$ quarks

Wicks, Horowitz, Djordjevic, Gyulassy, Nucl. Phys. A784, 426-442
$R_{AA}$ for Electrons from Heavy Quarks: Not Understood with Current Energy Loss Models

- Radiative energy loss not sufficient to describe excess electron $R_{AA}$
- Including elastic scattering improves the situation only slightly
Results from the LHC: 1. Spectra
Data test density dependence of light quark and gluon energy loss:
\[ dN_{\text{ch}} / d\eta \mid_{\text{PbPb@2.76TeV}} \approx 2 \ dN_{\text{ch}} / d\eta \mid_{\text{AuAu@0.2TeV}} \]

The relatively small difference between \( R_{AA} \) at RHIC and LHC is a challenge to theory.
$R_{AA}$ for Charged Particles up to $p_T = 100 \text{ GeV}/c$

$R_{AA}$ rises with $p_T$ up to $R_{AA} \approx 0.5$.

The increase of $R_{AA}$ is consistent with the expected $\Delta p_T/p_T \sim \log(p_T/p_T)$.
Verification of $T_{AB}$ Scaling with Hard Photons

$R_{AA} \approx 1$ for isolated photons (CMS) verifies the expected $T_{AB}$ (or $N_{coll}$) scaling for hard processes.

Compton (isolated)

bremsstrahlung, fragmentation (not isolated)
The reaction plane dependence of $R_{AA}$ constrains the path length dependence of parton energy loss.

The reaction plane dependence of $R_{AA}$ at RHIC poses a problem to perturbative energy loss models (PHENIX, Phys.Rev.Lett.105:142301,2010).
Results from the LHC: 2. Jets
Jet Event in a p+p Collision at $\sqrt{s} = 63$ GeV

Lego plot shows energy vs. pseudorapidity $\eta$ and azimuthal angle $\phi$

Jets were discovered in e+e- in the late 1970's and then also observed in p+p
Evolution of a Jet Event

Hard Process $\rightarrow$ Parton Cascade $\rightarrow$ Hadronization

- Describable with pQCD
- Not describable with pQCD (only phenomenological models)
Jet-Finding Algorithms

- Objective: reconstruct energy and direction of initial parton
- Must be unambiguously applicable at the level of experimental data (tracks/towers) and in perturbative QCD calculation (parton level)
- Starting point: list of calorimeter towers and/or charged hadron tracks
- Two classes of algorithms:
  - Cone algorithm: traditional choice in hadron-hadron collisions
  - Sequential recombination: traditional choice in $e^+e^-$ collisions ($k_T$ algorithm, anti-$k_T$ algorithm)

Cone algorithm:

- Successively merge “particles” in order of relative transverse momentum (“run parton cascade backwards”).
- Termination of merging controlled by a parameter $D$

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

Typical choice in p+p: $R = 0.7$
Why is Jet Reconstruction Difficult in Central Au+Au Collisions at RHIC?

Central Au+Au collision at $\sqrt{s_{NN}} = 130$ GeV:

$$\left. \frac{dE_T}{d\eta} \right|_{\eta=0} \approx 500 \text{ GeV}$$

Consider jet cone with radius $R$:

$$R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$$

Total transverse energy in this cone:

$$E_{T,\text{cone}} = \frac{d^2 E_T}{d\eta d\phi} \cdot \pi R^2$$

$$= \frac{1}{2\pi} \left. \frac{dE_T}{d\eta} \right|_{\eta=0} \cdot \pi R^2 \approx 40 \text{ GeV}$$

- Background energy large compared to jet energy in A+A at RHIC.
- Increased jet cross section helps at LHC.
Two-Jet Event in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV (ATLAS)
Jet-$E_T$ Spectrum and Jet $R_{AA}$ in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Jet $R_{CP} \approx 0.5$ in central Pb+Pb ($R = 0.4$)
Points to Take Home

- High-$p_T$ particles can be regarded as a probe of the medium created in heavy-ion collisions.
- The suppression of high-$p_T$ particles in A+A collisions can be described by parton energy loss in a medium of high color charge density.
- Many open issues in parton energy loss theory:
  - Reaction plane dependence of $R_{AA}$
  - Heavy-quark energy loss
  - Similar $R_{AA}$ at RHIC and LHC
  - ...
- Full jet reconstruction is challenging at RHIC due to large backgrounds.
- The increased jet cross section allows to study parton energy loss in Pb+Pb collisions with full jet reconstruction at the LHC.