QGP Physics – from Fixed Target to LHC

9. Hard scattering, Jets, and Jet Quenching

PD Dr. Klaus Reygers, Dr. Kai Schweda
Physikalisches Institut, Universität Heidelberg
SS 2013
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

\[ \text{QGP} \underset{\text{Suppression of hadrons at high } p_T}{\overset{\text{Basic logic}}{\rightleftharpoons}} \]
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

\[
\langle z \rangle = \left\langle \frac{p_{\text{hadron}}}{p_{\text{parton}}} \right\rangle \\
\approx 0.25
\]

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

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

- Inv. Cross section
- Parton distributions (functions of \( x_{\text{Bjorken}} \) and momentum transfer \( Q^2 \))
- Phenomenological factor which takes higher order contributions into account
- Fragmentation function
- Elementary QCD parton-parton cross section

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

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

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

HERA: $e^\pm p$ scattering

H1 and ZEUS

$\frac{d\sigma}{d^2Q^2} = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}_{ab} \otimes D_c^{\text{Hadron}}$

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

K. Reygers, K. Schweda | QGP physics SS2013 | 9. Hard scattering, Jets, and Jet Quenching
Parton Distributions for Nuclei

\[ x < 0.1: \text{“shadowing region”} \]

\[ 0.1 < x < 0.3: \text{“anti-shadowing”} \]

\[ 0.3 < x < 0.7: \text{“EMC effect”} \]

\[ 0.7 < x < 1.0: \text{Fermi-motion of nucleons in nuclei} \]

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

\[ R_g^{\text{Pb}}(x, Q^2=1.69\text{ GeV}^2) \]

\[ R_g^{\text{Pb}}(x, Q^2=100\text{ GeV}^2) \]

Eskola et al.,

[arXiv:0902.4154v2 [hep-ph]]
Example: Gluon and u-Quark Fragmentation Functions

Albino, Kniehl, Kramer, Nucl. Phys. B 725 (2005), 181

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 $e^+ e^- \rightarrow Z^0 \rightarrow q\bar{q}$)
Heavy Quark Fragmentation

- Heavy quark jets fragment hard into leading heavy meson
- Qualitatively different than g/uds → π
- Qualitative argument: heavy quark Q only marginally slowed down when picking up a light quark to form a heavy meson

J.D. Bjorken, Phys Rev D17, 171 (1978)
Jet Quenching
Jet Quenching History


J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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

- $\mu^+$ on Cu: Radiational energy loss („bremsstrahlung“) starts to dominate over collisional energy loss („Bethe-Bloch formula“) for $p >> 100$ 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
Collisional vs. Radiative Parton energy loss

Collisional energy loss:
- Elastic scatterings with medium constituents
- Dominates at low particle momenta

Radiative energy loss:
- Inelastic scatterings within the medium
- Dominates at higher momenta
Parton Energy Loss

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

Medium parameter
\[ \hat{q} = \frac{\mu^2}{\lambda} \]
- \( \mu^2 \): 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)

Energy loss for gluon jets larger than for quark jets

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

Review: U. Wiedemann, arXiv:0908.2306 (→ link)

K. Reygers, K. Schweda | QGP physics SS2013 | 9. Hard scattering, Jets, and Jet Quenching
Parton Energy Loss: Qualitative Discussion

Consider electric charge passing through matter. At sufficiently high energy it loses energy via bremsstrahlung. At very high energies, the charge scatters coherently off many medium constituents, leading to destructive interference. This so-called Landau-Pomeranchuk-Migdal (LPM) effect greatly reduces the radiative energy loss.

Formation time of a radiated gluon: \[ t_c \approx \frac{\omega}{k_T^2} \]

The gluon acquires additional transverse momentum if it scatters with medium constituents within its formation time (or formation length \( z_c \)):

\[ k_T^2 \approx \hat{q} z_c = \frac{\mu^2}{\lambda} z_c \]

This results in a medium-modified formation length: \[ z_c \approx \frac{\omega}{k_T^2} \approx \sqrt{\frac{\omega}{\hat{q}}} \]

\( \lambda < z_c \): Coherent scattering with destructive interference

\( \lambda > z_c \): incoherence
Parton Energy Loss: Qualitative Discussion

For fixed medium thickness $L$, $z_c = L$ defines a critical energy $\omega_c$: 

$$\omega_c = \hat{q}L^2$$

Gluons can be emitted with energies up to this critical energy.
Parton Energy Loss: Qualitative Discussion

There are three regimes for radiative energy loss:

1. Incoherent regime ($\lambda > z_c$):
   \[- \frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \frac{E}{\lambda}\]

2. Coherent regime ($\lambda < z_c$) with $L > z_c$ (saturated LPM regime)
   \[- \frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \sqrt{\frac{E}{\hat{q}}}\]

3. Coherent regime ($\lambda < z_c$) with $L < z_c$
   \[- \frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \hat{q}L\]
Parton Energy Loss: Qualitative Discussion

\[ \frac{-1}{\sqrt{E}} \frac{dE}{dz} \]

\[ \text{coherent (LPM)} \]

\[ L_c \quad L \]
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, $dN_g/dy = 2000, 3000, 4000$

\[ \frac{\Delta E_{\text{gluon}}}{\Delta E_{\text{quark}}} = \frac{9}{4} \text{ only in the limit } E \to \infty \]
Medium-Modified Fragmentation Functions

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:

\[ z = \frac{E_h}{(1 - \varepsilon)E_q}, \quad x = \frac{E_h}{E_q} \]

Prob. distr. for parton energy loss \( \varepsilon \) (“Quenching weight”)

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:

\[ D_{h/q}^{\text{med}}(x, Q^2) = \frac{1}{0} \int d\varepsilon \, P(\varepsilon) \, D_{h/q}(x, Q^2) \cdot \frac{1}{1 - \varepsilon} \]

Hadrons resulting from gluon bremsstrahlung neglected
The Discovery of Jet Quenching at RHIC
Hard scattering, Jets, and Jet Quenching

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

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

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

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

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

Centrality Dependence of the $\pi^0$ and direct $\gamma$ $R_{AA}$:

Direct photons follow $T_{AB}$ scaling as expected for a hard probe not affected by the medium.
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (III)

Possible explanation for the Cronin effect: multiple soft scattering in the initial state

No pion suppression in min. bias $d+Au$ collisions  
$\Rightarrow$ 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

Au+Au peripheral

Au+Au central

background and ellip. flow subtracted

$\Delta \phi$ (radians)
Further RHIC 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.
Interpretation of the Rather Flat $R_{AA}$ at RHIC

Horowitz, Gyulassy, arXiv:1104.4958

Upper panel:
Red: Fraction $f$ of gluon jets as a function of jet $p_T$.
Black: fraction of $\pi^0$ from gluons as a fct. of pion $p_T$.

Lower panel:
Partonic spectral index $n(p_T)$:

$$n(p_T) = - \frac{d \log(\frac{dN_{\text{parton}}}{dydp_T})}{d \log(p_T)}$$

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 $p_T$
$\sqrt{s_{NN}}$ Dependence: $\pi^0 R_{AA}$ for Heavy Nuclei at $\sqrt{s_{NN}} = 17.3, 62.4, \text{ and } 200 \text{ GeV}$

Onset of suppression between $\sqrt{s_{NN}} = \sim 20 \text{ GeV}$ and 62.4 GeV

Particle Species Dependence of $R_{AA}$

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

- direct $\gamma$ (prelim.)
- $\pi^0$ (PRL101, 232301)
- $\eta$ (PRC82, 011902)
- $\phi$ (PRC83, 024090)
- 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)
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: $p_T > 8 \text{ GeV}/c$
- Associated particle: $p_T > 6 \text{ GeV}/c$

For higher jet energies the correlation at $\Delta \phi = 180^\circ$ in central Au+Au is not fully suppressed anymore
Hierarchical 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) radiate fewer gluons

Emission of gluons at small angles suppressed.

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

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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{PHENIX data\cite{PHENIX}.}
\end{figure}

\textbf{PHENIX}


\begin{equation}
R_{AA} \leq 0-10 \%
\end{equation}

\textbf{Au+Au @ \sqrt{s_{NN}} = 200 GeV}

\textbf{e^+ and e^- from c and b decays as strongly suppressed as pions:}

\[ \Delta E_{\text{Gluon}} > \Delta E_{\text{Quark}, m=0} > \Delta E_{\text{Quark}, m \neq 0} \text{ not observed!} \]
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
Increase of Hard Scattering Yields with $\sqrt{s}$
Charged Hadron $R_{AA}$ in Pb-Pb at $\sqrt{s} = 2.76$ TeV

$R_{AA} = \frac{\frac{dN}{dp_T}(A + A)}{\langle T_{AA} \rangle \times \frac{d\sigma}{dp_T}(p + p)}$

$\langle T_{AA} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}}$

from Glaubers calculation

- Expect $R_{AA} = 1$ in the hard scattering regime without nuclear effects ($p_T > 2$ GeV/c)
- Suppression by a factor 7 at $p_T \approx 6$-7 GeV/c
- Rise of $R_{AA}$ for $p_T > 7$ GeV/c indicates decrease of relative parton energy loss $\Delta E/E$ with increasing $E$
Charged Hadron $R_{AA}$ at high $p_T$

- Rise of $R_{AA}$ with $p_T$ for the first time established at the LHC
- Large $p_T$ reach helps unveil dependence of parton energy loss on initial parton energy

**Graph:**
- SPS 17.3 GeV (PbPb)
- RHIC 200 GeV (AuAu)
- LHC 2.76 TeV (PbPb)
- Comparison of $R_{AA}$ with different $p_T$ values

**Data Points:**
- CMS (0-5%)
- ALICE (0-5%)
- PBS (2000-4000)

**Legend:**
- GLV: $dN/dy = 400$
- GLV: $dN/dy = 1400$
- GLV: $dN/dy = 2000-4000$
- YaJEM-D
-elastic, small $P_{\text{inc}}$
-elastic, large $P_{\text{inc}}$
- CMS (0-5%)
- ALICE (0-5%)
-PQM: $\langle \hat{q} \rangle = 30 - 80 \text{ GeV}^2$/fm

**Note:**
- CMS, arXiv:1202.2554v1
p+Pb at $\sqrt{s} = 5.02$ TeV: No Suppression

Absence of suppression in p-Pb confirms that suppression in Pb-Pb is a final-state effect

\[ R_{pPb} = \frac{dN/dp_T(p+Pb)}{\langle T_{pPb} \rangle \times d\sigma/dp_T(p+p)} \]

\[ \langle T_{pPb} \rangle = \langle N_{coll} \rangle / \sigma_{pp}^{inel} \]

pp reference interpolated from measurements at $\sqrt{s} = 2.76$ and 7 TeV

Verification of $T_{AB}$ Scaling with Hard Photons

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

Compton (isolated) and bremsstrahlung, fragmentation (not isolated)

CMS: PLB 710, 256 (2012)
PHENIX: PRL 109, 152302 (2012)
Z bosons in Pb+Pb follow $T_{AB}$ scaling

Good agreement with Pythia shape normalized to $\sigma_{NNLO}$ & scaled by $N_{coll}$

$Z \rightarrow e^+e^-$
Summary of Single Particle $R_{AA}$ results
$v_2 > 0$ at Large $p_T$: Parton Energy Loss

$v_2$ expected due to different path lengths in the QGP in plane and out-of-plane

ALICE, Physics Letters B 719 (2013) 18

ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
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)
$R_{AA}$ for Identified Particles in Central Pb+Pb

- $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ for $3 < p_T < 8$ GeV/c
- Similar $p$, $K$ and $\pi$ $R_{AA}$ for $p_T > 8$ GeV/c

Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,\text{hadron}} > 8$ GeV/c?
D Meson $R_{AA}$: Charm Quark Energy Loss Surprisingly Similar to Quark and Gluon Energy Loss

Radiative parton energy loss:

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

- Color factor
- Dead cone effect

- Strong suppression also for D mesons (which cannot be explained by shadowing)
- Suppression of D mesons and pions surprisingly similar
  - Pions mainly from gluons
  - Dead cone effect for c and b
- Little indication for expected hierarchy
  (however, need to carefully consider also the steepness of the initial parton spectra)
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

CERN ISR, ca. 1982
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:**

Sum content in cone with radius

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

Typical choice in p+p:

\[ R = 0.7 \]

**$k_T$ algorithm:**

Successively merge “particles” in order of relative transverse momentum (“run parton cascade backwards”).

Termination of merging controlled by a parameter $D$
**$k_T$ jet algorithm**

- Algorithms starts with a list of preclusters (calorimeter cells, particles, or partons)
- Calculate $p_T$ and rapidity $y$ for each precluster
- For each precluster define $d_i = p_T^2, i$
- For each pair $(i,j)$ of preclusters define

$$d_{i,j} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta R_{i,j}^2}{D^2}$$

$$= \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{D^2}$$

- For $D = 1$ and $\Delta R_{ij}^2 << 1$, $d_{ij}$ is the minimal transverse momentum $k_T$ (squared) of one vector with respect to the other
- Find minimum $d_{\text{min}}$ of all $d_i$ and $d_{ij}$
- Merge preclusters $i$ and $j$ if $d_{\text{min}}$ is a $d_{ij}$
- Else: Remove precluster $i$ with $d_{\text{min}} = d_i$ from list of preclusters and add it to the list of jets
- Repeat until list of preclusters is empty
Anti-$k_T$ algorithm

- Jets reconstructed with the $k_T$ algorithm don't have a well defined shape/area
- This makes the subtraction of the energy from the underlying event difficult
- Therefore, the anti-$k_T$ algorithm is the standard choice for the LHC experiments

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta_{i,j}^2}{R^2}, \quad d_i = p_{T,i}^{2p}$$

- $p = 1 : k_T$ algorithm
- $p = -1 : \text{anti-$k_T$ algorithm}$
Anti-$k_T$ algorithm vs. $k_T$ algorithm

arXiv:0802.1189
Why is Jet Reconstruction Difficult in Central Au+Au Collisions at RHIC?

\[ E_T = \sum_i E_i \sin \vartheta_i, \quad dE_T/d\eta \approx \langle m_T \rangle \cdot dN_{ch}/d\eta \]

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:

\[ E_{T,\text{cone}} = \left. \frac{d^2 E_T}{d\eta d\phi} \right|_{\eta=0} \cdot \pi R^2 \]

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

- 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)
Dijet Energy Asymmetry in Pb+Pb

- ATLAS and CMS find large asymmetry in energy of dijets in Pb+Pb
- Observations
  - Dijets in Pb+Pb still back-to-back [no angular decorrelation]
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 ($R = 0.4$)

K. Reygers, K. Schweda | QGP physics SS2013 | 9. Hard scattering, Jets, and Jet Quenching
CMS Jet Results in Pb+Pb

- Single particle $R_{AA}$ and jet $R_{AA}$ consistent
  $z = p_T(\text{track})/p_T(\text{jet}) = 0.4 - 0.6$ for charged particles with $p_T = 50-100$ GeV

- $b$-quark jet suppression similar to light quark jet suppression
Modification of Jet Fragmentation in central Pb+Pb

\[ z = \frac{p_T^{\text{ch}} \cos \Delta \alpha}{p_T^{\text{jet}}} \]

\[ R_D(z) = \frac{D(z)_{0-10\%}}{D(z)_{60-80\%}} \]

ATLAS Preliminary

Pb+Pb \( \sqrt{s_{NN}} = 2.76 \) TeV

\( L_{\text{int}} = 0.14 \) nb\(^{-1} \)

anti-\( k_T \) \( R = 0.4 \)

\( p_T^{\text{jet}} > 100 \) GeV

0-10\%/60-80\%
Gamma-Jet Correlations

[Image of CMS experiment data and a diagram showing a photon (191 GeV) and a jet (98 GeV)]
Gamma-Jet Correlations

\[ p_T^\gamma > 60 \text{ GeV/c} \quad |\eta^\gamma| < 1.44 \]

Average fraction of isolated photons with an associated jet above 30 GeV/c

\[ p_T^{\text{Jet}} > 30 \text{ GeV/c} \quad |\eta^{\text{Jet}}| < 1.6 \]

Average ratio of jet \( p_T \) to photon \( p_T \)

\[ \Delta \phi_{j\gamma} > \frac{7}{8} \pi \]

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

\[ \int L \, dt = 150 \mu \text{b}^{-1} \]
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