Observation and Studies of Jet Quenching in Pb+Pb collisions at 2.76 TeV

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Overview

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- Introduction to heavy-ion collisions and jet quenching
- Details of analysis techniques
- Dijet imbalance results from calorimeters
- Track-Jet correlations in search of missing energy
Motivation for Heavy Ions

- Study QCD at extreme temperatures and densities ($\mu$s after Big Bang)
- Explore properties of new form of matter (QGP) proposed at high energy densities: above 1 GeV/fm$^3$
- Already at RHIC, conservative estimates of energy density in the early system are well above predicted crossover
- But our ‘QGP’ doesn’t look like an ideal gas of deconfined quarks and gluons. So what are the properties of the strongly interacting matter produced at RHIC/LHC?
Summary of Results from RHIC

200 GeV Au+Au collisions (BNL, 2000-present)

Experimental Signature

• Early onset of collective behavior characterized by ‘hydrodynamic’ flowing medium

• Dramatic modification of high-p_T particle production relative to p+p reference (jet quenching)

Property of sQGP

‘Ideal fluid’: vanishing shear viscosity and mean free path

Partonic energy loss proportional to medium properties (e.g. gluon density, transport coefficient)
Jet Quenching = Tomographic QGP Probe

This is the goal, studied more indirectly at RHIC.

“gluon density” $dN_g/dy$

“scattering power” $<q>$

vacuum splitting functions

medium splitting functions
• $\pi^0$ cross section measured in p+p and central (small impact parameter) Au+Au collisions @ 200 GeV

• Yields of high-$p_T$ hadrons is suppressed by factor $\sim 5$ compared to p+p expectation*

* p+p data scaled by number of binary collisions $N_{coll}$

Compiled by D. D'Enterria
Springer Verlag. Landolt-Boernstein Vol. 1-23A
Dihadron correlations at RHIC

• Correlation of charged hadrons with:

\[ 2 \text{ GeV/c} < p_{T,\text{partner}} < p_{T,\text{trigger}} \]
\[ 4 \text{ GeV/c} < p_{T,\text{trigger}} < 6 \text{ GeV/c} \]

• Near-side peak shows little modification

• Away-side jet correlation nearly extinguished in this \( p_T \) range

STAR Collaboration
Strong jet quenching evident at RHIC, but direct jet reconstruction is challenging due to fluctuations in soft background
• At $\sqrt{s_{NN}} = 2.76$ TeV, copious high-$E_T$ jets ($\sim 100$ GeV) give much larger separation between hard and soft scales

• Even looking at event displays in first days, significant imbalance was apparent in dijets

Beginning of a **new era** at LHC!

For the first time, we can clearly identify modified dijet partners.
CMS Detector

- Hadronic Forward Calorimeter (HF)
- Pixel and Silicon-Strip Tracker
- ECAL + HCAL inside 3.8 T solenoid
- Beam Scintillator Counters (BSC)
• 2010 has been a successful year at LHC

• After delivering over 40 pb\(^{-1}\) of p+p data, LHC delivered over 8 µb\(^{-1}\) of Pb+Pb

• For rare processes, this is ‘equivalent’ to \(\sim\)300 nb\(^{-1}\) of p+p

6.7 µb\(^{-1}\) used in this dijet analysis
Jet Trigger

- Level-1 Single Jet 30 GeV (uncorrected energy)
- HLT Single Jet 50 GeV (uncorrected energy)
- Fully efficient for corrected energy above 100 GeV

Minimum Bias Trigger

- HF or BSC firing in coincidence on both sides
- > 97% efficient

Collision Rate: 1-210 Hz, Jet50U Rate: < 1 Hz
Event Selection

107k good jet-triggered collision events after all selections
Events are classified according to the percentile of the Pb+Pb inelastic cross section based on total deposited HF energy.
Jet Algorithm

1. Calculate background in ieta slices
2. Run IC5 jet finder on subtracted towers
3. Re-calculate background excluding jets
4. Re-run IC5 jet finder on subtracted towers

Intro to Heavy Ions
Analysis Methods
Calorimeter jet imbalance
Energy balance in charged tracks
Simulated Data Samples

- **PYTHIA**: D6T tune, modified isospin (Pb\(^{208}\)\(^{82}\))
- **PYTHIA + DATA**: embedding PYTHIA dijet event into real data background
- **PYTHIA + HYDJET\(^*\)**: embedding PYTHIA dijet event into simulated PbPb background

\(^*\) HYDJET is a two-component heavy-ion generator: parameterized hydrodynamic soft-particle production + \(N_{\text{hard}} \times \text{PYTHIA (}\hat{p}_T > 7 \text{ GeV/c)}\)
Jet Energy Scale and Resolution

- Intro to Heavy Ions
- Analysis Methods
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Residual Energy Scale

Energy Resolution

- Pb Pb
- Pb Pb
- Pb

PLOTS:

(a) 50-100% CMS
(b) 20-30%
(c) 0-10%
(d) 50-100%
(e) 20-30%
(f) 0-10%

- PYTHIA+DATA
- Leading Jet Response
- Subleading Jet Response
- Resolution in p+p
Jet-Finding Efficiency

Dijet Selections

- Leading jet $p_{T,1} > 120 \text{ GeV}/c$, $|\eta_1| < 2$
- Subleading jet $p_{T,2} > 50 \text{ GeV}/c$, $|\eta_2| < 2$
- Opening angle $\Delta\phi_{12} > 2\pi/3$

# of Events

- 4216
- 3684
- 3514
Leading Jet Spectra

Shape of leading jet $p_T$ spectrum not strongly modified compared to PYTHIA
Dijet Azimuthal Decorrelation

Intro to Heavy Ions
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Δφ > 2π/3
Slightly fewer back-to-back jets in data than ‘unquenched’ jets embedded into HI background.

Number of nucleons participating in collisions (1+1 → 208+208)

median Δφ value in PYTHIA (dominated by 3-jet events)
Quantify dijet energy imbalance by asymmetry ratio:

\[ A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

- Removes uncertainties in overall jet energy scale
- Limit on \( p_{T,2} \) puts a \( p_T \)-dependent upper limit on \( A_j \)

\[ \text{e.g. } \frac{(120-50)}{(120+50)} = 0.41 \]
Dijet Energy Imbalance

- Intro to Heavy Ions
- Analysis Methods
- Calorimeter Jet Imbalance
- Energy balance in charged tracks

Graphs showing event fractions for different collision types and conditions:
- **pp** collisions
- **PbPb** collisions

Equation:

\[ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]
Dijet ‘Balanced’ Fraction

- Includes all events with a qualifying leading jet (i.e. even apparent ‘mono-jet’ events)

- Dramatic suppression of balanced jets with increasing centrality

- Number of nucleons participating in collisions (1+1 → 208+208)

- Median $A_j$ value in PYTHIA (dominated by 3-jet events)

- Data from CMS: $\int L \, dt = 6.7 \, \mu{b}^{-1}$

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

- PYTHIA and PYTHIA+DATA
Fractional imbalance varies little with leading jet $p_T$, though the present errors do not rule out a constant $\Delta p_T$. 

### LeadJet $p_T$ dependence

- **Intro to Heavy Ions**
- **Analysis Methods**
- **Calorimeter Jet Imbalance**
- **Energy balance in charged tracks**
For the < 10% of unbalanced PYTHIA dijets ($A_j > 0.3$), a 3rd jet provides most of momentum balance.
Where does energy go?

- Large dijet energy imbalance seen in calorimeters.
- By using track information, we have an opportunity to do the first in-depth studies of where the energy goes (low-$p_T$, large angle)
  - Explore fragmentation properties with angular correlations of tracks to jet axes after subtracting combinatorial background
  - Explore global momentum balance of tracks -- missing $p_T$ projected along dijet axis -- in various $p_T$ ranges
• Find tracks “associated” with the jets using jet-by-jet subtraction of Pb+Pb underlying event

• Study associated track distributions versus $p_T$ and $\Delta R$

• Uncertainties in background subtraction limit this method to $p_T > 1$ GeV/c and $\Delta R < 0.8$
- Background evaluated within R=0.8 cone symmetric about $\eta$
- Avoids $\phi$-dependent variations due to detector effects and hydrodynamic flow
- Single jets required to be in $0.8 < |\eta| < 1.6$
Track-Jet Correlation Result

Jet asymmetry in calorimeters is mirrored in tracks
Track-Jet Correlation Result

MC

Data

Significantly more energy in large-$\Delta R$ tracks below 4 GeV/c
Calculate projection of $p_T$ on leading jet axis and average over selected tracks:

$$p_T^\parallel = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$

This was calculated for all tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$ and also for tracks in various $p_T$ ranges.

This allows us to see which $p_T$ range carries the balance of the jet momentum.
Missing-\(p_T\) Results

In central Pb+Pb data, much more of the balance is carried by tracks below 2 GeV.

High-\(p_T\) (> 8 GeV) excess towards leading jet balanced by tracks below 8 GeV.

Excess away from leading jet.

Excess towards leading jet.

MC

Data

balanced jets

unbalanced jets
In PYTHIA, balance is found out-of-cone as well, but at higher $p_T$ (third jets!)

For data, in-cone excess of high-$p_T$ tracks is balanced by out-of-cone low-$p_T$ tracks
Summary

- Large dijet momentum imbalance, increasing with centrality.
- Imbalance extends to highest jet energies measured ($p_{T,1} > 200 \text{ GeV/c}$)
- Imbalance in calorimeter measurement reflected also in charged tracks
- Momentum balance recovered by including tracks at low-$p_T$ and at large angle
- In data (but not PYTHIA) a large fraction of the balance is carried by tracks with $p_T < 2.0 \text{ GeV/c}$ and $\Delta R > 0.8$
Conclusions

• LHC energies bring new era to jet quenching studies: unambiguous identification of both partners in copious, asymmetric dijets.

• This is just the beginning! Future studies: medium-modified fragmentation functions, flavor-dependence of jet quenching (e.g. via gamma-jet correlations, multi-jet events, heavy flavor tagged jets)

• More powerful, quantitative constraints on transport properties of QCD matter will be possible via data-model comparisons
BACKUP SLIDES
\[ \rho_{T,1} > 100 \text{ GeV} \]
\[ \rho_{T,2} > 25 \text{ GeV} \]
\[ \Delta \phi_{1,2} > \pi/2 \]
\[ |\eta_{\text{jet}}| < 2.8 \]
Event Selection

Beam-Gas, Beam-Halo, Beam-Scraping

Ultra-Peripheral Collisions

Inelastic, Hadronic Collisions after all applied selections

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

# of 1st layer pixel hits

Sum HF energy (TeV)

Beam-Gas
ECAL APD hit cleaning

\[^{p_T} > 20\ \text{GeV}\]

\[^{p_T} > 3\ \text{GeV}\]

HCAL noise cleaning

doi:10.1088/1748-0221/5/03/T03014.
Underlying Event in Jet Cone

![Diagrams showing estimated PU vs. p_T for leading jet corrected, HF energy (p_T > 70 GeV), and estimated PU - fitted mean.](image_url)
Data-Driven Efficiency

Absolute Efficiency $0.0 < |\eta| < 0.8$, 0 - 10 Pct Centrality

![Graph showing absolute efficiency as a function of $p_T$ for different data sets with error bars.](image)

- Pion Data
- Mixed Data
- HYDJet
Tracking Performance

Absolute Efficiency 5-10% Centrality

Fake Reconstruction Fraction 5-10% Centrality
In-Cone MPT vs. J-T Corr

[Graph showing comparisons between In-Cone MPT and J-T Correlation with data points and regions highlighted for different momentum values.]