HOT LEAD

Measurement of angular and momentum distributions of charged particles with and around jets in Pb+Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$TeV with the ATLAS detector

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Introduction

- We need to know about:
  - Heavy ion collision dynamics
  - Quark gluon plasma
  - Jet quenching
  - The ATLAS detector

- In order to understand:
  - The experimental results
Not The Math We Deserve But The Math We Need

- $D(P_T, r) = \frac{1}{N_{jet}} \left( \frac{1}{2\pi dr} \right) \left( \frac{dn_{ch}(p_T,r)}{dp_T} \right)$
- $R_{D(P_T,r)} = \frac{D(p_T,r)_{Pb+Pb}}{D(p_T,r)_{pp}}$
- $\Delta D(P_T, r) = D(p_T,r)_{Pb+Pb} - D(p_T,r)_{pp}$

- $r$ is the radius from the jet axis
- $N_{jet}$: # of jets in consideration
- $n_{ch}(P_T, r)$: # of charged particles with a given $P_T$ at a distance $r$ from the jet axis
- $R_{D(P_T,r)}$: ratio of yields for PbPb and pp collisions
- $\Delta D(P_T, r)$: absolute difference in charged particle yields between PbPb and pp
The experiment uses 5.02 TeV/nucleon center of mass energy

\[ \left( \frac{m}{q} \right)_{Pb} = 2.52 \left( \frac{m}{q} \right)_{p} \]

2.51 TeV/nucleon Pb has the same cyclotron radius as 6.32 TeV protons

Near the 6.5 TeV/beam limit of the LHC at the time
Quark Gluon Plasma

- High energy, unconfined quarks
  - Quark soup
  - Extremely hot, dense, short lived

(Kawagoe 2014)
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Jet Quenching

- Jets form in the collision of heavy ions the same way they do in p-p interactions
- When they pass through this hot, dense material, they shed energy, producing a larger number of lower energy particles

The ATLAS Detector

- Relevant detectors
  - Inner detector
  - Calorimeter
- Other systems
  - Trigger
  - Data Acquisition

(Ky & Van, 2015)
**ATLAS Inner Detector**

- Contained within a solenoid B field
- **Pixel Detector**
  - Detects charge
  - Initial curve of path gives momentum
- **Semiconductor tracker**
  - Surrounds pixel detector
  - 4 layers give accurate path info
- **Transition Radiation Detector**
  - Gives more info on particle type
- Covers $|\eta| < 2.5$, $\theta > 9.3^\circ$

https://atlas.cern/Discover/Detector/Inner-Detector
ATLAS
Calorimeters

- LAr calorimeter
  - Barrel calorimeter surrounding the inner detector
- EM calorimeter
  - Dense plates measuring energy
- Zero Degree Calorimeter
  - 140 m down the beam line
  - Covers $|\eta| > 8.3$, $\phi < 0.028^\circ$
  - Spectator neutrons mostly
Trigger Systems

- **Physical (L1)**
  - Digitizes calorimeter signals, bins them, and calibrates transverse energy
  - Counts electron, photons and taus
  - Sums energy of the jet and sends it to the software trigger

- **Software (HLT)**
  - Required at least one of the following: (1) a total-energy L1 trigger selecting more-central collisions and (2) a ZDC coincidence trigger at L1 and a veto on the total-energy trigger, with the additional requirement of at least one track in the HLT, selecting peripheral collisions.
Not The Math We Deserve But The Math We Need (Reprise)

- $D(P_T, r) = \frac{1}{N_{jet}} \left( \frac{1}{2\pi dr} \right) \left( \frac{dn_{ch}(p_T,r)}{dp_T} \right)$
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- $N_{jet}$: # of jets in consideration
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Systematic Errors

- Sources of error add in quadrature
  - JES, JER, Tracking, Unfolding, MC non-closure, and UE
  - Error sources are comparable between high and low centrality for Pb Pb
  - Clearly Pb collisions give higher Uncertainty than pp, especially at larger $r$

ATLAS
Jet and Track Selection

- Discard particles where $\tau < 3 \times 10^{-10} s$
- Discard muons
- Discard Jets where a nearby jet ($\Delta R > 1.0$) has a larger $p_T$
- Discard tracks from particles with $p_T < 1.0$ GeV to suppress secondary particle contribution
- Jets must have a transverse momentum between 126 and 316 GeV
Data Quality

- \(1.8 \times 10^7\) events for each type of collision
- Pb+Pb collisions binned according to centrality: 0-10\%, 10-20\%, 20-30\%, 30-40\%, 40-60\% and 60-80\%.
- >80\%(glancing blows) are ignored
- Tracking efficiency is at least 80\% for Pb+Pb jets below |\(\eta\)| = .3, but drops to 67\% when 1.0 < |\(\eta\)| < 2.0
• Substantial difference between pp and Pb+Pb

• More pronounced at lower $p_T$ and for higher energy jets

• Positive values imply a larger number of charge particles per jet for PbPb jets

• Similar patterns across all momenta, but note the error bars increasing with increasing transverse momentum
Higher energy jets can raise the yield ratio at larger r

- Jets in Pb+Pb collisions have a larger number of low $p_T$ charged particles per jet around the edges
- pp Jets have higher yields for high $p_T$ particles at low r
- Pb+Pb Jets are more of a mist, pp are more of super soaker stream
- Jet quenching spreads out the jets

Higher centrality (impact parameter) causes yield ratio to tend towards 1

- Less QGP in the way
- Less jet quenching
- $p_T^{jet}$ does not change the distribution of charged particles

Note the very low yield ratios for $10 \text{ GeV} < p_T < 63.1 \text{ GeV}$

- Yield ratios below 1 demonstrate that pp jets have more energetic particles in the center
These measurements quantify the effect of jet quenching on the angular spread of charged particles from a jet. Provide constraints for properties of QGP.
References


Thank you!
Appendix

- G. Roland, K. Safarik, P. Steinberg, Heavy-ion collisions at the LHC, Progress in Particle and Nuclear Physics (2014), http://dx.doi.org/10.1016/j.ppnp.2014.05.001
Not The Math We Deserve
But The Math We Need

- Let’s talk pseudorapidity: $\eta$
  - Shorthand for direction of jets relative to the beamline
  - Used to describe the locations of individual detectors in ATLAS (and other, lesser experiments) in a way that conveys the ratio of transverse to longitudinal momentum quickly
  - Particles travelling near $\eta = \infty$ are lost with the exiting beam

$$\eta = -\ln(\tan\left(\frac{\theta}{2}\right)) = \frac{1}{2} \ln\left(\frac{|p| + p_L}{|p| - p_L}\right)$$
Definitions

- Centrality: How dead on the PbPb collision was. 0% is perfect overlap, most of the measurements here require centrality of 10% or less
- JER: Jet Energy Resolution. Stems from limitations of the calorimeters
- JES: Jet Energy Scale. Jets from Pb may be substantially different than MC modelling predicts.
- Tracking uncertainty: you lose track of particles sometimes. This increases uncertainty about total energy and momentum
- UE: Underlying Event
- Unfolding uncertainty: When using Bayesian unfolding to re-bin data, there is some residual uncertainty about whether an individual data point was in the wrong bin to start with
HLT Trigger (Software trigger)

Minimum bias (MB) events were recorded using a logical OR of two triggers: (1) a total-energy L1 trigger selecting more-central collisions and (2) a ZDC coincidence trigger at L1 and a veto on the total-energy trigger, with the additional requirement of at least one track in the HLT, selecting peripheral collisions. The total-energy trigger required the total transverse energy measured in the calorimeter system to be greater than 50 GeV. Jet events were selected by the HLT, seeded by a jet identified by the L1 jet trigger in pp collisions or by the total-energy trigger with a threshold of 50 GeV in Pb + Pb collisions. The L1 jet trigger utilized in pp collisions required a jet with transverse momentum greater than 20 GeV. The HLT jet trigger uses a jet reconstruction procedure similar to that in the offline analysis as discussed in Sec. IV. It selected events containing jets with a transverse energy of at least 75 GeV in Pb + Pb collisions and at least 85 GeV in pp collisions.