Jet suppression in Pb+Pb collisions with the ATLAS detector

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Jets in Heavy Ion Collisions

- Jets provide a powerful tool to probe the hot and dense medium created in HI collisions.
- RHIC's measurements of single high $p_T$ particles: the first evidence for jet quenching.
- Need to do the full jet reconstruction to understand the quenching in more details.

- The first ATLAS Pb+Pb paper: significant increase of the number of collisions with a large di-jet asymmetry with increasing collision centrality: arXiv:1011.6182, Phys. Rev. Let. 105, 252303
- How do partons loose energy in QGP?
- Better understanding of QCD in the limit of high densities and temperatures.
- How does the medium modify the parton showers?
Jets in Heavy Ion Collisions

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- RHIC's measurements of single high $p_T$ particles: the first evidence for jet quenching.
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I. Vitev et al., JHEP11 (2008) 093
N. Armesto et al., JHEP0802 (2008) 048: 
The ATLAS Detector

- ATLAS, a general-purpose p-p experiment, is also an excellent detector for heavy ion physics!
- Large pseudorapidity coverage and full azimuthal acceptance.
- Fine granularity and longitudinal segmentation.
- Precise inner detector in a 2T solenoid field.
- Extensive system of muon chambers placed inside a 1T toroid field.
Centrality

- Characterize centrality by percentile of total cross-section using total $E_T$.
- Measured in Forward Calorimeter (3.2<|η|<4.9).
- Centrality → number of participants $N_{\text{part}}$ and binary collisions $N_{\text{coll}}$.

**ATLAS calorimeter**
Jet Reconstruction at ATLAS

- Reconstruction algorithm: anti-$k_t$ with $R=0.2$, 0.3 and 0.4.
- Input: calorimeter towers $0.1 \times 0.1$ ($\Delta \eta \times \Delta \phi$).
- Event-by-event background subtraction:
  \[
  E_{T_j}^{\text{sub}} = E_{T_j} - A_j \rho_i(\eta_j) \left( 1 + 2v_{2i} \cos \left[ 2 \left( \phi_j - \Psi_2 \right) \right] \right)
  \]
- Anti-$k_t$ reconstruction prior to a background subtraction.
- Underlying event estimated for each longitudinal layer and $\eta$ slice separately.
- We exclude jet candidates with $D = \frac{E_{T_{\text{max}}}^{\text{tower}}}{\langle E_{T_{\text{tower}}} \rangle} > 4$ to avoid biasing subtraction from jets but no jet rejection based on $D$.
- Additional iteration step to remove residual effect of the jets on the background estimation.
- Jets corrected for flow contribution.
Performance of the Jet Reconstruction

- Performance is evaluated using pp hard scattering events from Pythia overlying on top of HIJING MB events without quenching.

- JER is well described by 
  \[ \sigma (\Delta E_T)/E_T = 1/E_T (a \sqrt{E_T} + b + c.E_T) \]
  where parameter \( b \) is consistent with the result from the fluctuation analysis.

- The performance have been also verified using data overlay with similar results.
Data and MC

- Three data sets were used:
  - Pb+Pb data recorded in 2011 with integrated luminosity of 0.14 nb$^{-1}$.
  - Pb+Pb data recorded in 2010 with integrated luminosity of 7 μb$^{-1}$.
  - High level jet triggers (HLT) seeded by L1 minimum bias (MB) triggers were used to select events in 2011 and only MB triggers for 2010 data.

- Jet trigger algorithm required a R=0.2 jet with $E_T > 20$ GeV.

- All events were required to satisfy MB events selection: good timing and vertex.

- MC Pythia di-jet events embedded into MC HIJING and data overlay were used for performance evaluation.
Measurement of an inclusive jet production is the important probe of jet quenching.

The jet suppression was quantified by different variables:

- $R_{CP}$ – central to peripheral ratio, defined as

$$R_{CP} = \frac{1/N_{coll}^{cent}}{1/N_{coll}} \frac{1/N_{evnt}^{cent} dN/dE_T}{1/N_{evnt}^{periph} dN/dE_T}$$

- We measured the $R_{CP}$ for different jet radii to study the role of radiative energy loss.
- SVD unfolding was used to account for effect of bin migration caused by detector and UE effects.

- Small effect on R=0.2 jets.
- $R_{CP}$ is reduced for R=0.4 by a factor of two for low $E_T$ jets.
Centrality Dependence of Jet $R_{CP}$

- Factor of 2 suppression in central with respect to peripheral collisions.
- Increasing suppression with increasing centrality.
  - The increase is linear for high $p_T$, quick turns on at low $p_T$.
  - Similar result is observed also for other jet radii.
Jet $R_{CP}$ as a Function of Jet $p_T$

The jet suppression factor shows small variation with the jet $p_T$. 

\[ R_{CP} \text{ as a Function of } p_T \]

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

\[ \int L \, dt = 7 \mu b^{-1} \]

ATLAS

anti-$k_t$ $R = 0.2$

10 - 20%

50 - 60%

30 - 40%

0 - 10%

\[ p_T \text{ [GeV]} \]
Jet $R_{CP}$ as a Function of Jet Radius

Weak dependence on jet radius is observed. A small difference is present only at very low $p_T$. 

**ATLAS**  
\[ \text{Pb+Pb} \sqrt{s_{NN}} = 2.76 \text{ TeV} \]  
\[ \int L \, dt = 7 \, \mu b^{-1} \]
$R_{CP} - R$ dependence

Less suppression for jets with larger $R$. 

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

$\int L \, dt = 7 \mu \text{b}^{-1}$

**ATLAS**

- $R = 0.3$
- $R = 0.4$
- $R = 0.5$

Less suppression for jets with larger $R$. 
Azimuthal dependence of jet yields

- Path length dependence of jet suppression
- Ratios of yields in different slices of $\Delta \varphi = \varphi^{jet} - \Psi_2$ with respect to $\Delta \varphi = 0 - \pi/8$

\(~15\%\) reduction in plane yields with respect to out of plane yields.
Jet $v_2$

- $v_2^{\text{jet, meas}} = 0.016 \pm 0.002$
  - 5 - 10 \%
  - $\int L dt = 0.14 \text{ nb}^{-1}$
  - Pb+Pb $s_{NN} = 2.76 \text{ TeV}$

- $v_2^{\text{jet, meas}} = 0.032 \pm 0.002$
  - 10 - 20 \%
  - anti-$k_T R = 0.2$
  - $60 < p_T < 80 \text{ GeV}$

- $v_2^{\text{jet, meas}} = 0.042 \pm 0.002$
  - 20 - 30 \%

- $v_2^{\text{jet, meas}} = 0.041 \pm 0.002$
  - 30 - 40 \%

- $v_2^{\text{jet, meas}} = 0.034 \pm 0.003$
  - 40 - 50 \%

- $v_2^{\text{jet, meas}} = 0.027 \pm 0.004$
  - 50 - 60 \%

- $v_2^{\text{jet, meas}} = 0.027 \pm 0.004$
  - 50 - 60 \%

- 20 - 30 \%
  - $\int L dt = 0.14 \text{ nb}^{-1}$
  - Pb+Pb $s_{NN} = 2.76 \text{ TeV}$

- 30 - 40 \%

- 50 - 60 \%

- $p_T$ [GeV]

- $p_T$ [GeV]

- Weak $p_T$ dependence

- Consistent result with the measurement using single high-$p_T$ particles
Jet Structure

- We measured two sets of fragmentation distributions describing the jet structure:

\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(p_T)}{\Delta p_T} \quad D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(z)}{\Delta z} \]

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

- Spectra of charged particles in jets
- Fragmentation function

- D(z) and D(p_T) distributions have similar shape in all centrality bin.
- Ratios are needed to study centrality dependence.
D(z) centrality dependence

~15% suppression at intermediate z (~0.1) and 25% enhancement at very low z (~0.02).

No strong modification at large z (↔ leading parton) in central collisions with respect to peripheral ones.

Shaded bands uncorrelated or partially correlated systematic errors: regularization, JES, JER, tracking efficiency, non-zero central to peripheral ration of D(z) and D(\(p_T\)) in MC.

Solid lines 100% correlated systematic errors: tracking efficiency.
D(\(p_T\)) centrality dependence

Shaded bands: uncorrelated or partially correlated systematic errors

Solid lines: 100% correlated systematic errors

Similar behaviour as for D(z) distribution.
Conclusions

- Energy imbalance in the di-jet system is strongly increasing with increasing centrality.
- Suppression by a factor of 2 is observed in jet yield in central with respect to peripheral collisions.
- The dependence of the $R_{CP}$ is very weak on jet $p_T$
- Less suppression is observed for jets with larger R parameters.
- Azimuthal dependence of jet yields exhibits a clear path length dependence.
- Study of jet internal structure shows increasing size of modifications of fragmentation functions with increasing centrality.
Backup
**R_{CP} – Systematics**

**JES:** Relative energy scale differences between central and peripheral.

**JER:** Possible disagreement between data and MC in UE fluctuations.

**Efficiency:** cover possible MC/data differences, 5% for pT < 100 GeV

**Xini:** Sensitivity to power in power law: +0.5, -0.5

**R_{coll}:** sensitive to centrality determination, σ_{NN}

Regularization: Sensitivity to choice of k:+/-1
Subtracted $E_T$

Mean subtracted energy as a function of asymmetry

-no asymmetry dependence
-amount of subtracted energy for leading and sub-leading jet is comparable
Study of Background Fluctuations

- Study physics of underlying event fluctuations → it can provide a basic information about correlations in the underlying event.
- Independent validation of JER.
- The size of fluctuations is characterized by standard deviation \( \sigma = \sqrt{\langle E_T^2 \rangle - \langle E_T \rangle^2} \) and plotted as a function of FCal \( \Sigma E_T \).
- A very good agreement between data and MC.
Fluctuations are measured in single towers and also in larger windows comparable to the area of jet:

- 7x7 towers \( \sim R = 0.4 \) jets.
- 4x3 towers \( \sim R = 0.2 \) jets.

An agreement between data and MC is better than 5% for \( R = 0.2 \) jets.

Fluctuations in data are at most 5% higher than in MC for \( R = 0.4 \) jets.

Fluctuations are higher in MC in the most central events.
Detail study of Underlying Event

- Data and MC are compared in a narrow bin of FCal $\Sigma E_T$:

- HIJING over-predicts the size of upward fluctuations.
- HIJING over-predicts the size of downward fluctuations in central collisions.
- Where the spread in fluctuations is larger in data than in MC it is because data has larger downward fluctuations.
Azimuthal dependence of jet yields: JES and JER

**ATLAS simulation**

- $45 < p_T < 60$ GeV
- $60 < p_T < 80$ GeV
- $80 < p_T < 110$ GeV

- $\Delta p_T / p_T$
- $\sigma[\Delta p_T / p_T]$

- anti-$k_t$, $R = 0.2$
- 10 - 20%
Azimuthal dependence of jet yields: Systematic uncertainties
Fragmentation analysis: analysis setup

- Seven centrality bins and three jet $p_T$ ranges: $p_T > 85$ ($R=0.2$), $92$ ($R=0.3$), $100$ GeV ($R=0.4$).
- Charged particles with $p_T > 2$ GeV in cone of 0.4 around the jet axis were used.
- Jet required to be isolated (to avoid biases from split jets).
- b-jet candidates were excluded from the analysis.
- Jet $p_T$ was corrected to reduce the effect of the jet up-feeding due to JER.
- “fake” jets (from UE fluctuations) were identified and rejected by requirement of matching calorimeter jet to a track jet or electro-magnetic cluster > 7 GeV.
  - Measurement is restricted to $|\eta| < 2.1$.
  - We operate on trigger and jet reconstruction efficiency plateau for selected jet energies.
  - Residual fake rate is negligible for selected jet energies.
SVD unfolding was used to correct detector effects and to reduce the effect of statistical fluctuations.

D(z) unfolding accounts for track momentum and jet energy resolution, $D(\rho_T)$ for track momentum resolution.

**ATLAS Preliminary**

$Pb+Pb \sqrt{s_{NN}}=2.76$ TeV

$L_{int} = 0.14$ nb$^{-1}$

anti-$k_T$ $R = 0.4$

- 0-10% Raw $\times 10$

- 0-10% Unfolded $\times 10$

- 60-80% Raw

- 60-80% Unfolded

**ATLAS Preliminary**

$Pb+Pb \sqrt{s_{NN}}=2.76$ TeV

$L_{int} = 0.14$ nb$^{-1}$

anti-$k_T$ $R = 0.4$

- Raw

- Unfolded
Performance of the Track Reconstruction

- Performance was evaluated using Pythia particles embedded into HIJING MB events.

- Very good description of detector response by MC.