Measurements of jet suppression with ATLAS

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Jet suppression

If we assume:

- Standard collinear factorization of hard cross section
- Parton density set by nucleon PDFs times density of nucleons in geometric overlap region

Number of expected jets per event of a given centrality

\[
\langle T_{AA} \rangle_{\text{cent}} \times \frac{d^2 \sigma_{jet}^{pp}}{dp_T dy}
\]

\[
R_{AA} = \frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}} \langle T_{AA} \rangle_{\text{cent}} \times \frac{d^2 \sigma_{jet}^{pp}}{dp_T dy}
\]

Is a test of ordinary QCD factorization in AA collisions

Tests magnitude of factorization breaking via final-state interactions: jet quenching
Single jet measurements

- Given new $p+Pb$ measurements it is even more important we understand difference between peripheral and no nuclear effects
  - Updated measurements of color neutral probes
- Measure absolute magnitude of suppression with respect to unquenched reference, $R_{AA}$
- What do we know from existing measurements:
  - Jets are generally suppressed relative to peripheral by a factor of two
  - This suppression does not show a strong $p_T$ dependence
  - Larger radius jets show less suppression
- Improve precision of measurement to identify trends
  - Improvements over previous $R_{CP}$ measurement
  - Measure more differentially
    - Rapidity dependence, finer centrality bins
At more forward rapidity (lower points) the spectrum becomes steeper, e.g. at 100 GeV power law index drops from -5.8 to -6.6
At 200 GeV, -6.7 to 8 over the rapidity range measured here (0 — 2.1)

Also, at increasingly forward rapidities, jet production dominated by hard scattering with outgoing quarks which have a different parton shower, may lose less energy (naive color factor) yielding a higher $R_{AA}$

Which effect wins out? Answer likely depends on kinematic region…
The ATLAS detector

Detector characteristics

- **Width:** 44m
- **Diameter:** 22m
- **Weight:** 7000t

CERN AC - ATLAS V1997
Geometry from electroweak probes: $W$ and $Z$

**in situ** determination of $T_{AA}$

**$W$**

![Graph showing data for $W$ particles](image)

$\langle N_{\text{coll}} \rangle / N_{\text{events}}$ vs. $\langle N_{\text{part}} \rangle$

- $W^+$ NLO
- $W^-$ NLO
- $W^+$ LO

Integration: $\int L dt = 0.14 - 0.15 \text{ nb}^{-1}$

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

**$Z$**

![Graph showing data for $Z$ particles](image)

$\langle N_{\text{coll}} \rangle / N_{\text{events}}$ vs. $\langle N_{\text{part}} \rangle$

- $Z \rightarrow ee$
- $Z \rightarrow ll$
- $Z \rightarrow \mu\mu$

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

Data 2011 $L_{\text{int}} = 0.15 \text{ nb}^{-1}$

Binary scaled Pb+Pb data compared to NLO
Geometry from electroweak probes: $\gamma$

$|\eta| < 1.37$

$1.52 < |\eta| < 2.37$

$T_{AA}$ scaled Pb+Pb compared with cross sections from JETPHOX
Control over geometry

- Have multiple checks in data that rates for hard processes scale with the expected geometric enhancement
- $T_{AA}$ is controlled experimentally to $\sim 10\%$
  - At the level of expected NPDF effects
- Significant departures of $R_{AA} = 1$ for jets ($< 10\%$) cannot be explained without significant final state interactions
Improvements over $R_{CP}$ measurement

- Now using 2011 Pb+Pb data and 2013 pp data
  - Factor of 20 improvement in statistics
- Using overlay procedure to evaluate response and perform unfolding
  - Previously had embedded PYTHIA jets into HIJING simulation
  - Now embedding into real Pb+Pb data
    - Sample contains UE contribution that is identical to data
    - Contains ALL UE fluctuations/correlations
- Improvements to background subtraction procedure
- Exhaustive studies of jet energy scale (JES)
  - Determine response and uncertainties using direct balance methods in $\gamma/Z+$jet events in high statistics 8 TeV pp data
  - Evaluated response to jets of different flavor and parton showers produced by different generators
  - Determined effects on JES when measuring jets modified due to quenching using measurements of fragmentation function
Jet production in Pb+Pb collisions

Centrality variation at fixed rapidity ($|y| < 2.1$)

Rapidity variation at fixed centrality (0—10 %)

Dashed lines are $pp$ reference

Suppression evident from fact that points fall below reference
Jet suppression: $R_{AA}$ vs $p_T$

**ATLAS Preliminary**

- anti-$k_t$, $R = 0.4$ jets
- $\sqrt{s_{NN}} = 2.76$ TeV
- 2011 Pb+Pb data, $L_{int} = 0.14$ nb$^{-1}$
- 2013 $pp$ data, $L_{int} = 4.0$ pb$^{-1}$

**Centrality variation at fixed rapidity**

- $|y| < 2.1$
- $|y| < 0.8$
- $1.2 < |y| < 2.1$
Jet suppression: $R_{AA}$ vs $p_T$

Now showing different centrality bins
Jet suppression: $R_{AA} \text{ vs } y$

May see hints of some variation with $|y|$ but nothing significant
Jet suppression: $R_{AA}$ vs $y$

May see hints of some variation with $|y|$ but nothing significant.
Jet suppression: $R_{AA}$ vs $N_{\text{part}}$

Smooth behavior with $N_{\text{part}}$, maximal suppression in 0—1% is 0.4

$R_{AA}$ vs $N_{\text{part}}$

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

$63 < p_T < 80$ GeV

$80 < p_T < 100$ GeV

$100 < p_T < 126$ GeV

$126 < p_T < 158$ GeV

2011 Pb+Pb data, $L_{\text{int}} = 0.14$ nb$^{-1}$

2013 $pp$ data, $L_{\text{int}} = 4.0$ pb$^{-1}$
Conclusions

- ATLAS has measured the $R_{AA}$ for jets over wide range of jet $p_T$, rapidity and collision centrality
- Jets are suppressed by more than a factor of two in central collisions with respect to $pp$ collisions
- This suppression shows a weak dependence on $p_T$
  - For central collisions the $R_{AA}$ changes from 0.47 to 0.56 from 50 to 350 GeV.
- Do not see a large rapidity dependence
  - Magnitudes of effects contributing to this need to be sorted out via comparisons to theoretical calculations accounting for both
Extras
Measuring quenched jets

We know we have a centrality dependent modification to the fragmentation function

Have extensively studied how our ability to measure a jet’s energy changes when it has a different fragmentation function

Most significant effects from depletion of jet’s energy at mid-\( z \) (0.4-0.2)

<table>
<thead>
<tr>
<th>centrality</th>
<th>( \int \Delta D(z)dz )</th>
<th>( \int z\Delta D(z)dz )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>(-1.7^{+0.6}_{-0.8})</td>
<td>(-0.14^{+0.04}_{-0.06})</td>
</tr>
<tr>
<td>10-20%</td>
<td>(-1.6^{+0.7}_{-0.8})</td>
<td>(-0.12^{+0.05}_{-0.06})</td>
</tr>
<tr>
<td>20-30%</td>
<td>(-1.3^{+0.6}_{-0.6})</td>
<td>(-0.12^{+0.04}_{-0.06})</td>
</tr>
<tr>
<td>30-40%</td>
<td>(-1.3^{+0.6}_{-0.7})</td>
<td>(-0.10^{+0.04}_{-0.05})</td>
</tr>
<tr>
<td>40-50%</td>
<td>(-0.6^{+0.6}_{-0.8})</td>
<td>(-0.07^{+0.04}_{-0.06})</td>
</tr>
<tr>
<td>50-60%</td>
<td>(-1.2^{+0.9}_{-0.7})</td>
<td>(-0.08^{+0.06}_{-0.06})</td>
</tr>
</tbody>
</table>

Pyquen can be configured to produce fragmentation functions that differ from those from Pythia in a way that is similar to the measured centrality-dependent variation
Jet suppression and collision geometry

- Jets in the direction of the event plane are less suppressed
- $\cos(2\Delta\phi)$ modulation of yield of 1-5%

hep-ex/1306.6469
Jet suppression and collision geometry

- Compare ratio of yields at $\Delta \phi=0$ and $\pi/2$ to expectation from pure second harmonic modulation
- Almost no room for different modulation (e.g. $\cos^2 2\Delta \phi$) which may be expected from non-linear path length dependence
- Need calculation with full realistic geometry

[Graphs showing data points and expected trends]

hep-ex/1306.6469
Jet yields and cross sections

\[ \frac{\mathrm{d}^2 \sigma}{\mathrm{d}p_T \mathrm{d}y} \] [ nb/GeV ]

\[ y > T_p \]

\[ N_{\text{jet}} \] (evt)

\[ \langle T_A \rangle \]

\[ L = 2.76 \text{ TeV} \]

\[ s = 0.4 \text{ jets}, \langle T_A \rangle = 0.14 \text{ nb}^{-1} \]

\[ L = 4.0 \text{ pb}^{-1} \]

\[ |y| < 2.1 \] (x 10^8)

\[ |y| < 0.3 \] (x 10^6)

\[ 0.3 \leq |y| \leq 0.8 \] (x 10^4)

\[ 0.8 \leq |y| \leq 1.2 \] (x 10^2)

\[ 1.2 \leq |y| \leq 2.1 \] (x 10^0)

\[ 0 - 10 \% ( \times 10^8) \]

\[ 10 - 20 \% ( \times 10^7) \]

\[ 20 - 30 \% ( \times 10^6) \]

\[ 30 - 40 \% ( \times 10^5) \]

\[ 40 - 50 \% ( \times 10^4) \]

\[ 50 - 60 \% ( \times 10^3) \]

\[ 60 - 70 \% ( \times 10^2) \]

\[ 70 - 80 \% ( \times 10^1) \]
Comparison with published $R_{\text{CP}}$

- 2010 stat. $\oplus$ sys. error, $L_{\text{int}} = 7 \, \mu\text{b}^{-1}$
- 2011 stat. $\oplus$ sys. error, $L_{\text{int}} = 140 \, \mu\text{b}^{-1}$

$|y| < 2.1$  
$0 - 10 \%$

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

$R_{\text{CP}}$ vs $p_T$ [GeV]

ATLAS Preliminary