Jet measurements in heavy ion collisions with the ATLAS detector

Martin Spousta
on behalf of the ATLAS Collaboration

Charles University,
Prague

The European Physical Society Conference on High Energy Physics
July 5-12, 2017, Venice, Italy
Introduction

• Jet production and properties are modified in heavy ion collisions
• Study of jets in Pb+Pb collisions should tell us about e.g.:
  – properties of de-confined matter created in heavy ion collisions
  – radiation of energetic color charges in this de-confined medium
• Study of jets in p+Pb collisions should tell us about e.g.:
  – initial state effects
  – correlations between soft and hard processes

• LHC heavy ion runs & ATLAS:
  – Run 1: Pb+Pb: √s_{NN} = 2.76 TeV, L_{int} = 0.15 nb^{-1}
    \quad pp: √s = 2.76 TeV, L_{int} = 4.2 pb^{-1}
    \quad p+Pb: √s_{NN} = 5.02 TeV, L_{int} = 29 nb^{-1}
  – Run 2: Pb+Pb: √s_{NN} = 5.02 TeV, L_{int} = 0.5 nb^{-1}
    \quad pp: √s = 5.02 TeV, L_{int} = 28 nb^{-1}
Inclusive jet suppression in Pb+Pb collisions

\[ R_{AA} = \frac{1}{N_{\text{evnt}}} \frac{d^2 N_{\text{jet}}^{PbPb}}{dp_T dy} \Bigg|_{\text{cent}} \times \langle T_{AA} \rangle_{\text{cent}} \times \frac{d^2 \sigma_{\text{jet}}^{pp}}{dp_T dy} \]

- Jet yield in heavy ion collisions
- Number of expected jets per event of a given centrality
- Nuclear thickness function
- Jet cross-section in \( pp \) collisions

Nuclear modification factor quantifies the magnitude of the jet suppression which is dominantly due to final state interactions with constituents of the medium.
Jet $R_{AA}$: $p_T$-dependence, $\sqrt{s_{NN}} = 2.76$ TeV

- A factor of two suppression of jet yield in 0-10% central collisions (○○○).

- A modest grow of jet $R_{AA}$ with increasing jet $p_T$.

- Still significant suppression even for 60-80% centrality bin (○○○).

- Practically no rapidity dependence.
Quantifying jet $R_{AA}$ in the $p_T$ range of **100 GeV to 1 TeV** and for $|y|<2.8$.

Jet $R_{AA}$: $p_T$-dependence, 2.76 TeV versus 5.02 TeV

**ATLAS** Preliminary
anti-$k_t$ $R = 0.4$ jets

- ATLAS, $\sqrt{s_{NN}} = 5.02$ TeV, this analysis
- ATLAS, $\sqrt{s_{NN}} = 2.76$ TeV, arXiv: 1411.2357

2015 Pb+Pb data, 0.49 nb$^{-1}$
2015 $pp$ data, 25 pb$^{-1}$

• **Same magnitude** of $R_{AA}$ within systematic uncertainties seen at the two different center-of-mass energies.
Jet $R_{AA}$: y-dependence, $\sqrt{s_{NN}} = 5.02$ TeV

- Vertical-axis: ratio of $R_{AA}$ in a given rapidity to the $R_{AA}$ for jets with $|y|<0.3$.
- With increasing jet $p_T$, $R_{AA}$ getting smaller in the forward region as compared to the mid-rapidity region (predicted in arXiv:1504.05169).

ATLAS Preliminary

$R_{AA}(y)/R_{AA}(y<0.3)$

0 - 10% $\quad 0.6 < p_T < 200$ GeV

200% $p_T < 251$ GeV

251% $p_T < 316$ GeV

316% $p_T < 562$ GeV

2015 Pb+Pb data, 0.49 nb$^{-1}$

2015 pp data, 25 pb$^{-1}$
Jet fragmentation at 2.76 TeV

rapidity of jet

\[ R_D(z) = \frac{D(z)|_{\text{cent}}}{D(z)|_{pp}} \]

\[ D(z) = \frac{1}{N_{jet}} \frac{dN}{dz} \]

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

EPJC 77 (2017) no.6, 379

now published

EPS-HEP 2017
Jet fragmentation at 2.76 TeV

Centrality dependence
- Enhancement at low $z$ and at high $z$
- Suppression at intermediate $z$

Rapidity dependence
- No rapidity dependence except for the highest $z$ values (hint of a smaller enhancement for more forward jets)

Jet $p_T$ dependence
- No significant dependence on jet $p_T$ (not shown here)
Jet fragmentation at 2.76 TeV

To quantify the flow of particles: \( N^{\text{ch}} = \int_{p_T,\text{min}}^{p_T,\text{max}} \left( D(p_T)|_{\text{cent}} - D(p_T)|_{\text{pp}} \right) \, dp_T \)

... quantifies number of missing/extra particles

Also measured was first moment (see backup)
Jet fragmentation 
at 5.02 TeV

- Ratios of $D(z)$ distributions for tracks with $p_T > 4$ GeV.
- 5.02 TeV measurement agrees with 2.76 TeV measurement at the comparable z domain.
Jet fragmentation in p+Pb at 5.02 TeV

- Ratios of $D(z)$ and $D(p_T)$ distributions measured in 5.02 TeV p+Pb collisions.
- No modifications of the jet internal structure seen in the p+Pb environment.
Dijet production

- Fully **particle-level corrected** dijet asymmetry measurement
- Uses 2D bayesian unfolding to correct for the detector effects in $p_{T1}$ and $p_{T2}$ simultaneously
- Energy loss **very different for two jets** in the system
Clear centrality dependence.

0-10%: most probable value ~0.5.

60-80%: consistent with pp.

Pronounced jet pt dependence, high-pt jets almost unmodified.

\[ x_J = \frac{p_T,1}{p_T,2} \]
Gamma-jet production

- Good agreement between PYTHIA8 and $pp$ data
- Not unfolded for the detector response
Gamma-jet production

- Clear modification (downward shift) due to the parton energy loss of the balancing jet.
- Not shown is centrality dependence – smaller effect in less central collisions

\[ x_{J\gamma} = \frac{p_{T,\text{jet}}}{p_{\gamma}} \]
Other published jet results with Pb+Pb collisions (2013+)

- Jet $R_{CP}$ (PLB 719 (2013) 220)
- Azimuthal angle dependence of inclusive jets (PRL 111 (2013) no.15, 152301)
- Jet fragmentation I. (PLB 739 (2014) 320)
- Small angle jet pairs (PLB 751 (2015) 376)

Central-to-peripheral ratio of nearby jet yield

**ATLAS**
Pb+Pb 2011

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

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

$E_{T}^{llest} > 80$ GeV

$0.8 < \Delta R < 1.6$

$E_{T}^{nbr}$ [GeV]

$\rho_{R_{\Delta R}}$

5 - 10% anti-$k_t$ $R = 0.2$

20 - 30% $L dt = 0.14$ nb$^{-1}$

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

40 - 50%
Other jet results with p+Pb and \textit{pp} collisions

- Jet production in p+Pb (PLB 748 (2015) 392)
- Jet and forward $E_T$ correlations in \textit{pp} (PLB 756 (2016) 10)

Forward UE production \textbf{depleted} if $x$-target is large, but only a modest variation with varying $x$-projectile (not shown)
• Jet $R_{AA}$ measured differentially in centrality, rapidity and up to 1 TeV

• Jet internal structure measured differentially centrality, jet pt and rapidity in $pp$, Pb+Pb, and $p$+Pb collisions

• Fully corrected di-jet measurement exhibits very pronounced difference between Pb+Pb and $pp$ collisions

• Uncorrected photon-jet measurement exhibits a significant suppression of balancing jet
Backup slides
Jet cross-section in pp collisions

2.76 TeV
5.02 TeV
Jet yields in Pb+Pb collisions

$2.76$ TeV

$5.02$ TeV

$\langle T_{AA}\rangle$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d\phi_T d\rho_T}$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d p_T dy}$

$\langle T_{AA}\rangle$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d\phi_T d\rho_T}$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d p_T dy}$

$\langle T_{AA}\rangle$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d\phi_T d\rho_T}$ $\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{d p_T dy}$

$|y| < 2.1$

$|y| < 0.3$ ($\times 10^8$)

$0.3 \leq |y| < 0.8$ ($\times 10^8$)

$0.8 \leq |y| < 1.2$ ($\times 10^8$)

$1.2 \leq |y| < 2.1$ ($\times 10^8$)

$|y| < 2.8$

$0-10\%$ ($\times 10^6$)

$20-30\%$ ($\times 10^6$)

$30-40\%$ ($\times 10^6$)

$60-80\%$ ($\times 10^6$)

$pp$ data

ATLAS Preliminary

anti-$k_t$, $R=0.4$ jets, $\sqrt{s_{NN}}=5.02$ TeV

2015 Pb+Pb data, 0.49 nb$^{-1}$

2015 $pp$ data, 25 pb$^{-1}$
Correlations between soft and hard production in $pp$

- **What is measured**: correlation between the dijet kinematics and the magnitude of the UE in the forward region in $pp$ collisions

- **Motivation**: modeling of particle production, reference measurement to better understand the centrality in p+Pb

$(\langle \Sigma E_T \rangle$ of UE in the forward region (-4.9<$\eta$<-3.2) (p$_{T1}$+p$_{T2}$)/2 of dijet
Correlations between soft and hard production in $pp$

- **What is measured**: correlation between the dijet kinematics and the magnitude of the UE in the forward region in $pp$ collisions

- **Motivation**: modeling of particle production, reference measurement to better understand the centrality in p+Pb

Anti-correlation between “soft production” and “hard production”
Correlations between soft and hard production in $pp$

Anti-correlation is stronger when $\eta_{\text{dijet}}$ approaches the $\Sigma E_T$ measuring region...

...this can be evaluated as a function of $x$-target and $x$-projectile (~ Bjorken $x$)
Correlations between soft and hard production in $pp$

\[ x_{\text{proj/trag}} = \frac{p_{\text{T}}^{\text{avg}}}{\sqrt{s}} \left( e^+ + e^+ \right) \]

Forward UE production depleted if $x$-target is large

... but only a modest variation with varying $x$- projectile

The target is the analogue of the nucleus in $p+Pb$ collisions, projectile analogue of proton ...

small sensitivity of $\Sigma E_T$ to $x$-projectile suggests that effects seen in $p+Pb$ jets are not due to trivial anti-correlation in individual nucleon-nucleon collisions (e.g. “energy conservation”).
Correlations between soft and hard production in $pp$

$$x_{\text{proj/trag}} = \frac{\left<p_T^\text{avg}\right>}{\sqrt{s}} \left(e^{-\eta_1} + e^{+\eta_2}\right)$$

$\sum E_T$

$\eta_1 = +1.5$

$\eta_2 = +0.5$

$r \leftarrow \eta \rightarrow +\infty$
Correlations between soft and hard production in $pp$

$$x_{\text{proj/frag}} = \frac{p_T^{\text{avg}}}{\sqrt{s}} (e^+_{-\eta_1} + e^+_{-\eta_2})$$

$\Sigma E_T$

$\eta_1 = +1.5$

$\eta_2 = +0.5$

$-\infty \leftarrow \eta \quad \eta \rightarrow +\infty$
Correlations between soft and hard production in \( pp \)

\[
x_{\text{proj/trag}} = \frac{p_T^{\text{avg}}}{\sqrt{s}} \left( e^+ \eta_1 + e^+ \eta_2 \right)
\]

Forward UE production depleted if \( x\)-target is large

\( \langle \Sigma E_T \rangle / \langle \Sigma E_T \rangle_{\text{ref}} \)

\( ATLAS \)

\( pp, \sqrt{s} = 2.76 \text{ TeV} \)

\( \langle \Sigma E_T \rangle_{\text{ref}} = \langle \Sigma E_T \rangle(p_T^{\text{avg}} = 50-63 \text{ GeV}, |\eta| < 0.3) \)

\( x_{\text{proj}} / x_{\text{trag}} \)

\( x_{\text{proj}} \)

\( x_{\text{trag}} \)

\( \text{MC / Data} \)

\( X_{\text{proj}} \)

\( X_{\text{trag}} \)

\( \text{Data, 4.0 pb}^{-1} \)

\( \text{PYTHIA 6 AUET2B} \)

\( \text{PYTHIA 8 AU2} \)

\( \text{HERWIG++ UE-EE-3} \)

... but only a modest variation with varying \( x\)-projectile
Correlations between soft and hard production in $pp$

(a) $p+$Pb collision

$$\Sigma E_T$$

$$\eta_1 = +1.5$$

$$\eta_2 = +0.5$$

(b) $pp$ collision

$$\Sigma E_T$$

$$\eta_1 = +1.5$$

$$\eta_2 = +0.5$$
Correlations between soft and hard production in $pp$

- Anti-correlation can be evaluated also as a function of $x$-projectile and $x$-target.

- Example of configurations:
  
  \[
  x_{\text{proj/trag}} = \frac{p_{\text{avg}}}{\sqrt{s}} \left( e^{+\eta_1} + e^{-\eta_2} \right)
  \]
\[ R_{p\text{Pb}} \text{ for jets: While the } R_{p\text{Pb}} \text{ is consistent with unity when evaluated inclusively in centrality (left), it is } \textbf{not unity when evaluated differentially in the centrality} \text{ (right).} \]
**Inclusive jets**

- $R_{CP} / R_{pPb}$ scales with the total momentum of a jet for jets in the positive forward region suggesting a **dependence on $x$ of parton in proton**.

- How much of the centrality dependence (= dependence on $\Sigma E_T$ in the negative forward region) comes from the dependence of $\Sigma E_T$ on $x$ in individual NN collision?
Jet yields and $R_{pPb}$

- 0-90% $R_{pPb}$ compared to NLO with EPS09 nPDFs
- $R_{pPb}$ does not differ much from unity if measured inclusively in centrality, **but** ...
Jet $R_{pPb}$ and $R_{CP}$

$R_{CP}$ strongly varies with centrality exhibiting decrease with increasing $p_T$ in all three centrality bins.

If $R_{pPb}$ is unity and $R_{CP}$ decreases then there must be enhancement in peripheral collisions wrt to pp. Indeed, this is observed.

The use of Glauber-Gribov only amplifies these effects.
Jet $R_{pPb}$ and $R_{CP}$

**ATLAS**

2013 $p+Pb$ data, 27.8 nb$^{-1}$

anti-$k_t$, $R=0.4$, $\sqrt{s_{NN}} = 5.02$ TeV

0-10% / 60-90%

$R_{CP}$

$p_T \times \cosh(<y^*>)$ [GeV]
Inclusive jet suppression

- Detailed estimation of jet energy scale uncertainty.
- Using *in situ* techniques ($\gamma$+jet and $Z$+jet) and limits on the impact of modified fragmentation on jet energy scale.
- Same level of rigor as in precision pQCD measurement should be a standard for precision HI measurements in the run II.
Jet $R_{AA}$

$R_{AA}$ versus $|y|$ for different $p_T$ bins:

- $0 < p_T < 80$ GeV
- $80 < p_T < 100$ GeV
- $100 < p_T < 126$ GeV
- $126 < p_T < 158$ GeV

ATLAS data:
- $\sqrt{s_{NN}} = 2.76$ TeV
- 2011 Pb+Pb data, 0.14 nb$^{-1}$
- 2013 pp data, 4.0 pb$^{-1}$

Color coding for different $p_T$ ranges:
- 1 - 5% (red)
- 20 - 30% (blue)
- 60 - 70% (green)
Jet $R_{AA}$

- Anti-$k_t$ $R = 0.4$ jets
- $\sqrt{s_{NN}} = 2.76$ TeV
- $63 < p_T < 80$ GeV, $|y| < 2.1$

- $80 < p_T < 100$ GeV, $|y| < 2.1$

- 2011 Pb+Pb data, 0.14 nb$^{-1}$
- 2013 $pp$ data, 4.0 pb$^{-1}$
- $100 < p_T < 126$ GeV, $|y| < 2.1$
- $126 < p_T < 158$ GeV, $|y| < 2.1$
$R_D(z)$ in Pb+Pb for $R=0.4$ jets
$R_{D(\text{pt})}$ in Pb+Pb for $R=0.4$ jets

A clear evolution with centrality

ATLAS
Pb+Pb $\sqrt{s_{\text{NN}}}=2.76$ TeV
0.14 nb$^{-1}$

anti-$k_T$ $R=0.4$
$p_T^{\text{jet}}>100$ GeV
0-10%/60-80%

Data
Systematic Uncertainty
10-20%/60-80%

20-30%/60-80%

30-40%/60-80%

40-50%/60-80%

50-60%/60-80%

EPS-HEP 2017
Jet fragmentation – flow of particles

• To quantify the flow of particles:

\[ N_{\text{ch}} = \int_{p_T,\text{min}}^{p_T,\text{max}} \left( D(p_T)|_{\text{cent}} - D(p_T)|_{\text{pp}} \right) \, dp_T \]

... as a function of \( N_{\text{part}} \)

Tells us how many extra/missing particles is present in a given \( p_T \) range
To quantify the flow of momentum:

\[ \langle \hat{p}_T \rangle_{N_{\text{part}}} = \int_{p_T^{\text{min}}}^{p_T^{\text{max}}} \left( \frac{D(p_T)}{dN_{\text{part}}} \right)_{\text{cent}} - \left( \frac{D(p_T)}{dN_{\text{part}}} \right)_{\text{pp}} \] 

... as a function of \( N_{\text{part}} \)

Tells us how much \( p_T \) is carried by extra/missing particles in a given \( p_T \) range
Sign of a larger enhancement at high $z$ in the mid-rapidity region as compared to the forward rapidity region (explanation for this proposed in arXiv:1504.05169).
Jet event shape correlations

• Study the dependence of the dijet asymmetry on the **angle between the leading jet and second order event plane** => help constraining the **path length dependence** of the jet quenching.

• Evaluating second Fourier coefficient of mean $A_J$:

$$\langle A_J(\phi^{\text{Lead}} - \Psi_2) = A_J^0 \left( 1 + 2c_2^{\text{obs}} \cos(2 \times |\phi^{\text{Lead}} - \Psi_2|) \right)$$

![Graph showing the distribution of $A_J$](image-url)
Jet event shape correlations

\[ c_2 = \frac{c_2^{\text{obs}}}{\text{Res}\{2\Psi_2\}} \]

\( c_2 \) small (<2%), negative indicating slightly larger \( A_J \) for leading jets oriented out-of-plane than for jets oriented in-plane.
Jet and event shape correlations, system size from a simple model

Simple geometric picture: The colliding nucleons are treated as disks in the transverse plane. The mean in-plane and out-of-plane sizes are obtained as $2R_{Pb} - \langle b_{imp} \rangle$ and $\sqrt{4R_{Pb}^2 - \langle b_{imp} \rangle^2}$ respectively, where $R_{Pb}$ is the radius of the Pb nucleus (7.4 fm) and $\langle b_{imp} \rangle$ is the mean impact parameter for the given centrality interval.
Jet and event shape correlations

\[ \text{ATLAS Preliminary} \]
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
\[ R = 0.2 \]

Centrality (0-10)\%:

\[ (1/N_{\text{lead}}) dN/dA_j \]

Centrality (10-20)\%:

Centrality (20-30)\%:

\[ \langle A_j \rangle \]

\[ c^2_{\text{obs}} = -0.0047 \pm 0.0024 \]

\[ c^2_{\text{obs}} = -0.0030 \pm 0.0028 \]

\[ c^2_{\text{obs}} = -0.0083 \pm 0.0035 \]
Jet and event shape correlations, $c_2$ differentially in $q_2$
Neighboring jet production

- Neighboring jet production quantified using quantity previously measured at Tevatron

\[ R_{\Delta R} = \frac{1}{dN_{\text{jet}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{dN_{\text{jet},i}^{\text{nbr}}}{dE_T^{\text{test}}} (E_{T}^{\text{test}}, E_{T,\text{min}}^{\text{nbr}}, \Delta R) \]

... the rate of neighboring jets that accompany a given test jet.

- To quantify the centrality dependence the central-to-peripheral ratios, \( \rho(R_{\Delta R}) \), also evaluated.
Correction flow for neighboring jet yields

\[ \text{Unfolded} = k \times (\text{Raw} - \text{Combinatorics}) \]
Central-to-peripheral ratios

Central to peripheral ratio of $R_{\Delta R}$ as a function of test jet $E_T$.

$\rightarrow$ suppression factor of about 0.5
$\rightarrow$ suppression rather flat with $E_T$

$\} \text{ similar trends as in the inclusive jet } R_{CP}$
Central-to-peripheral ratios

Central to peripheral ratio of $R_{\Delta R}$ as a function of neighboring jet $E_T$. Decrease of suppression with increasing jet $E_T$ may be expected for the configuration of magnitude of neighboring jet $E_T$ approaching the magnitude of test jet $E_T$ (the per-test jet normalization in the $R_{\Delta R}$ effectively removes the suppression).