Measurement of jet structure and substructure in heavy ion collisions with ATLAS

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Jet splitting and parton shower in QGP

- How is the parton shower modified in the deconfined medium?
  - Is the fragmentation process modified?
  - What is the role of jet momentum?
  - Can we see medium response to the fast partons?
  - Previous jet measurements suggest transfer energy out-of the jet cone.

- How does jets with multi-pronged structure loose energy?
  - Can we see color coherence/decoherence effects?
  - It may help to disentangle the contributions of path length and fluctuations to the quenching.
Jet fragmentation

- Measurement of fragmentation functions and their ratios:

\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T} \quad D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz} \]

\[ z \equiv p_T \cos \Delta R / p_T^{\text{jet}} \]

- Fully corrected for detector effects.

\[ R_{D(z)} \equiv \frac{D(z)_{\text{PbPb}}}{D(z)_{pp}} \]

Shower in medium

Shower in vacuum
Jet $p_T$ dependence to the FF modification

No dependence on jet $p_T$ observed at high $z$ for jets up to 400 GeV.

Enhancement of soft fragments increases for high $p_T$ jets.
Expanding the measurement to large angles

\[ D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{\text{d}^2 n_{\text{ch}}(r)}{\text{d}r \text{d}p_T} \]

where \( r < 0.8 \) with respect to jet axis

- Ratios and differences are evaluated:
  \[ R_D(p_T, r) = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{\text{pp}}} \]
  \[ \Delta D(p_T, r) = D(p_T, r)_{\text{Pb+Pb}} - D(p_T, r)_{\text{pp}} \]

- Measurement corrected for UE contributions and for track and jet momentum and angular resolutions.
Radial profile

- Sharp fall-off with $r$ with increasing track $p_T$.
- Change of shapes in central Pb+Pb collisions compared to $pp$ reference.
Jets are broader in more central collisions at low $p_T$.

Significant suppression of yields of particles $p_T > 4$ GeV outside the jet core.
Smallest modification seen in the jet core.

The enhancement increases with decreasing $p_T$.

The suppression decreases with increasing $p_T$.

Minimal modification for particles with $p_T$ of ~4 GeV.
Absolute size of modifications

The largest excess in terms of number of extra particles is in the cone!
- Up to ~5 extra particles per unit area per GeV.

\[ \Delta D(p_T, r) = D(p_T, r)_{\text{Pb+Pb}} - D(p_T, r)_{\text{pp}} \]
Integrals of $D(p_T, r)$ distributions

\[ \Theta(r) = \int_{1 \text{ GeV}}^{4 \text{ GeV}} D(p_T, r) dp_T \]

\[ \Delta\Theta(r) = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp} \]
Integrals of $D(p_T, r)$ distributions

$$\Theta(r) = \int_1^{4 \text{ GeV}} D(p_T, r) dp_T$$

$$\Delta\Theta(r) = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}$$

- Significant jet $p_T$ dependence to the enhancement is observed
  - Consistent with inclusive jet fragmentation measurement.
Expanding the measurement to large angles

- Does the jet suppression depend on jet structure?
- Can be addressed by measurement of jet $R_{AA}$ as a function of their sub-structure using sub-jets.

Reclustered large-$R$ jets

- Cal. towers & UE subtraction
- $R=0.2$ jets $p_T > 35$ GeV
- re-clustering with anti-$k_t$ $R=1.0$
- Splitting scale $\sqrt{d_{12}}$
- re-clustering with $k_t$ algorithm
- Sub-jets

Different jets than the conventional $R=1.0$.
Trimming & 35 GeV threshold remove all the soft component.

"Conventional" jet
Re-clustered jet
Observables and analysis procedure

- Measurement of yields of re-clustered $R=1.0$ jets as function of $p_T$ and and $k_t$ splitting scale:
  $$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

- Jet suppression is evaluated using nuclear modification factor $R_{AA}$

- Yields are corrected for detector effects using 2D Bayesian unfolding.
  - Corrects also for presence of the combinatorial contribution.

**ATLAS Preliminary**

Pb+Pb 1.72 nb$^{-1}$, pp 257 pb$^{-1}$

$\sqrt{s_{NN}} = 5.02$ TeV

$|y|<2.0$, $200 < p_{t} < 251$ GeV

Reclustered $R = 1.0$ jets

**Raw sub-jet multiplicity**
Observables and analysis procedure

- Measurement of yields of re-clustered $R=1.0$ jets as function of $p_T$ and $k_t$

$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

- Jet suppression is evaluated using nuclear modification factor $R_{AA}$

- Yields are corrected for detector effects using 2D Bayesian unfolding.
  - Corrects also for presence of the combinatorial contribution.

Single sub-jet: $\sqrt{d_{12}} = 0$
Clear centrality dependence of the yields and suppression with respect to $pp$ cross-section.
Suppression by factor of 2 in the most central collisions.
Small but continuous increase of the $R_{AA}$ with $p_T$. 
$R_{AA}$ of Inclusive yields

- Qualitatively similar to suppression of conventional $R=0.4$ jets but a larger suppression.
- Models predict a smaller suppression for larger $R$ jets.
- Re-clustering remove the energy radiated between $R=0.2$ sub-jets.
The lowest $\sqrt{d_{12}}$ interval populated by jets with single “isolated” sub-jet.

Yields suppressed in more central collisions with respect to $pp$ collisions.
Significant change of the $R_{AA}$ magnitude between jets with single sub-jet and and those with more complex substructure.

The $R_{AA}$ sharply decreases with increasing $\sqrt{d_{12}}$ followed by flattening.
A continuous increase of the suppression with increasing centrality.

The jets with single sub-jet are less suppressed with respect to those with higher sub-jet multiplicity.

In agreement with previous measurements if suppression of nearby jets.
Jet $p_T$ dependence

- $R=1.0$ with a single “isolated” sub-jet shows similar trends as inclusive measurement but smaller suppression.
Less $p_T$ dependence seen for $R_{AA}$ for re-clustered jets with a complex substructure.

Both spectra shapes and quenching affects the $R_{AA}$.
Conclusions

- Suppression of higher $p_T$ particles outside the jet core.
- The largest excess in terms of number of extra particles is in the cone.

- Measurement of re-clustered $R=1.0$ jets shows significant variation of $R_{AA}$ with the $p_T$ scale of the hardest splitting.
- Significance difference in quenching or jets with multi-prong structure compared to those with single sub-jet.

**ATLAS HI Public results:**
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
Jet response depends on parton flavour.
Steeper FF when approaching the $z \sim 1$.
Worsening of track momentum resolution at high $p_T$.
Difference in the jet energy resolution in $pp$ and Pb+Pb at lower $p_T$.

Difference in response for quark and gluon jets:

$arXiv:1406.0076$
Aspects of measurement @ high-$p_T$

- Jet response depends on parton flavour.
- Steeper FF when approaching the $z \sim 1$.
- Worsening of track momentum resolution at high $p_T$.
- Difference in the jet energy resolution in $pp$ and Pb+Pb at lower $p_T$.

Need for 2D unfolding

Impact of the unfolding

The $D(p_T, r)$ are further corrected for position resolution by bin-by-bin correction.
No modification of parton shower is observed in $p$+Pb system.
UE in FF measurement

ATLAS
Pb+Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, 0.49 nb$^{-1}$, 0-10%
anti-$k_T$, $R=0.4$ jets, $126 < p_T^{ch} < 158 \text{ GeV}$

ATLAS
Pb+Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, 0.49 nb$^{-1}$, 30-40%
anti-$k_T$, $R=0.4$ jets, $126 < p_T^{ch} < 158 \text{ GeV}$

ATLAS
Pb+Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, 0.49 nb$^{-1}$, 60-80%
anti-$k_T$, $R=0.4$ jets, $126 < p_T^{ch} < 158 \text{ GeV}$

arXiv:1805.05424
Tracking efficiency

ATLAS Simulation

$pp \quad \sqrt{s} = 5.02 \text{ TeV}$

$|y^{\text{jet}}| < 0.3$

anti-$k_{\perp}, R=0.4$

Tracking efficiency

ATLAS Simulation

$Pb+Pb \quad \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$|y^{\text{jet}}| < 0.3$

anti-$k_{\perp}, R=0.4$

- 0-10%, $126 \text{ GeV} < p_{T}^{\text{jet}} < 158 \text{ GeV}$
- 0-10%, $251 \text{ GeV} < p_{T}^{\text{jet}} < 316 \text{ GeV}$
- 60-80%, $126 \text{ GeV} < p_{T}^{\text{jet}} < 158 \text{ GeV}$
- 60-80%, $251 \text{ GeV} < p_{T}^{\text{jet}} < 316 \text{ GeV}$
Modification of jet fragmentation in Pb+Pb

Increasing modification to FF with increasing centrality.
Enhancements of yields of hard and soft fragments.
Hybrid model (arXiv:1707.05245) consistent at high $z$, disagreement at low $z$ due to simplistic medium response modeling.

EQ model is able to describe the high-$z$ excess.

SCETg model is able to qualitatively described the low-$z$ excess.
Integrals of $D(p_T)$ distributions

Jet $p_T$ dependence to the enhancement.

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

arXiv:1805.05424
Rapidity dependence

Measured as ratio of $R_{D(z)}$ in different jet $y$ bins to the $R_{D(z)}$ in $|y|<0.3$.

Still statistically limited.

No significant rapidity dependence to the modification.

Sign of depletion at high $z$. 

arXiv:1805.05424
Both models are able to describe the rapidity dependence in data.

Comparison to EQ and Hybrid model.
Is there dependence on collision energy?

- Comparison to the result at 2.76 TeV.

No dependence on the collision energy. Similar to other jet observables.
Jet $p_T$ dependence of $R_{D(p_T,r)}$

Similar observation as for $r$-inclusive measurement:

Yield of soft fragments more enhanced for higher $p_T$ jets.

No significant dependence of yields for fragments with intermediate $p_T$. 

**ATLAS**

Pb+Pb $\sqrt{s}_{NN} = 5.02$ TeV, 0.49 nb$^{-1}$

$pp$ $\sqrt{s} = 5.02$ TeV, 25 pb$^{-1}$

anti-$k_t$, $R=0.4$

$1.6 < p_{T,1} < 2.5$ GeV

$6.3 < p_{T,2} < 10.0$ GeV
Modification of Radial Profile

Jets are broader in more central collisions at low $p_T$.
Significant suppression of yields of particles $>4$ GeV outside the jet core.

Continuous modifications with centrality:
Increase of yields of soft fragments with $r$.
Decrease of yields of higher-$p_T$ particles with $r$. 
Integrals of $D(p_T, r)$ distributions

Integrated “jet shape”

$$P(r) = \int_{0}^{r} \int_{1 \text{ GeV}}^{4 \text{ GeV}} D(p_T, r') dp_T dr'$$

$$R_P(r) = \frac{P(r)_{Pb+Pb}}{P(r)_{pp}}$$

- Linear increase of the excess with $r$ towards $r = 0.5$ with flattening at larger radial distances.
- Significant jet $p_T$ dependence to the enhancement is observed.
Integrals of $D(p_T, r)$ distributions

**ATLAS**

\[
\Delta \Theta(r) = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}
\]

Significant jet $p_T$ dependence to the enhancement is observed

Consistent with inclusive jet fragmentation measurement.

\[
\Theta(r) = \int_{1 \text{ GeV}}^{4 \text{ GeV}} D(p_T, r) dp_T
\]

\[
\Delta \Theta(r) = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}
\]
Yields of Re-clustered jets vs splitting scale

Significant change of the $R_{AA}$ magnitude between jets with single sub-jet and those with more complex substructure.

The $R_{AA}$ sharply decreases with increasing $\sqrt{s_{NN}}$, followed by flattening.

Consistent with previous ATLAS result reporting suppression to conditional yields of nearby jets.
Integrals of $D(p_T)$ distributions

Jet $p_T$ dependence to the enhancement.

Response of the medium to the high-$p_T$ parton?

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