Inclusive jet measurements in pp and Pb-Pb collisions with ALICE

James Mulligan (Yale University), on behalf of the ALICE Collaboration

Oct 3 2018
Aix-Les-Bains, France
Jet yields are suppressed in heavy-ion collisions

\[ R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{\text{event}}} \frac{d^2 N}{dp_T d\eta}}{\frac{d^2 \sigma}{dp_T d\eta}} \bigg|_{\text{pp}} \]

Inclusive jet measurements show that jets in central Pb-Pb collisions lose on average ~10-20% of their energy, depending on \( p_{T,\text{jet}} \).

The energy loss fraction gradually decreases as \( p_{T,\text{jet}} \) increases.

ALICE Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

Anti-\( k_T \) \( R = 0.2 \) \( |\eta_{\text{jet}}| < 0.5 \)

\( p_{T,\text{ch}}^{\text{lead}} > 5 \text{ GeV/c} \)

- ALICE 0 - 10%
- PLB 746 (2015) 1
- CMS 0 - 10%
- PRC 96 (2017) 015202
- ATLAS 0 - 10%
- PRL 114 (2015) 072302

ATLAS scaled from \( R = 0.4 \) to \( R = 0.2 \) using \( R_{CP} \) ratios in PLB 719 (2013) 220
How well do we understand jet $R_{AA}$?

Can we distinguish jet energy loss models using jet $R_{AA}$?

• All models have strong quenching, decreasing with $p_T$
• There are slight differences in the absolute level of quenching, and the $p_T$-dependence of quenching

What about at low $p_T$? → Strongest $p_T$-dependence

ATLAS jet $R_{AA}$ measurement at 5.02 TeV from $p_T = 100$-$1000$ GeV

High precision!

arxiv 1805.05424
How well do we understand jet $R_{AA}$?

Can we distinguish the $R$-dependence of jet energy loss?

- Do we recover induced gluon radiation and/or medium recoil? (Less suppression as $R$ increases)
- Or do smaller $R$ jets tend to be more collimated, and therefore less quenched? (More suppression as $R$ increases)

Can we achieve sufficient experimental precision to distinguish whether jet $R_{AA}$ increases or decreases with jet $R$?
Do measurements show an $R$-dependence?

- **ALICE charged jets**
  - No modification in ratio $R=0.2/R=0.3$
  - CMS jet $R_{AA}$
    - No significant modification $R=0.2-0.4$
  - ATLAS $R_{CP}$
    - Significant modification for $R=0.2-0.5$
  - Jet shapes (ALICE, CMS)
    - show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from $R=0.2-0.5$, ...

\[ \sigma(R=0.2)/\sigma(R=0.3) \]

\[ \begin{align*}
\text{ALICE} \\
\text{Pb-Pb} & \quad s_{NN}=2.76 \text{ TeV} \\
\text{Anti-}k_T & \\
\rho_{\text{track}} & > 0.15 \text{ GeV/c} \\
\text{Leading track} & \quad \rho_T > 5 \text{ GeV/c}
\end{align*} \]
Do measurements show an $R$-dependence?

- **ALICE charged jets**
  - No significant modification $R=0.2/0.3$

- **CMS jet $R_{AA}$**
  - No significant modification $R=0.2-0.4$

- **ATLAS $R_{CP}$**
  - Significant modification for $R=0.2-0.5$

- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from $R=0.2-0.5$, …
Do measurements show an $R$-dependence?

- **ALICE charged jets**
  - No significant modification $R=0.2/R=0.3$
- **CMS jet $R_{AA}$**
  - No significant modification $R=0.2-0.4$
- **ATLAS $R_{CP}$**
  - Significant modification for $R=0.2-0.5$
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from $R=0.2-0.5$, …
Do measurements show an $R$-dependence?

- ALICE charged jets
  - No significant modification $R=0.2/R=0.3$
- CMS jet $R_{AA}$
  - No significant modification $R=0.2-0.4$
- ATLAS $R_{CP}$
  - Significant modification for $R=0.2-0.5$
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from $R=0.2-0.5$, ...

**Measurements do not provide a clear picture**
Measuring jets in ALICE

ALICE reconstructs jets at mid-rapidity ($\eta < 0.7$) in pp, p-Pb, Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 - 13$ TeV.

Charged particle jets (charged jets)
- High-precision tracking down to $p_{T,\text{track}} = 150$ MeV/$c$

Jets (full jets)
- Addition of particle information from the EM calorimeter down to $p_{T,\text{cluster}} = 300$ MeV/$c$

EMCal $\varphi$ acceptance: $108^\circ$
Measuring jets in ALICE

Most ALICE jet measurements use charged particle jets

Today, I will focus on full jets (charged + neutral)

- Full jets allow a direct comparison to theory
- But significant experimental complication!
  - And reduced statistics due to limited coverage
Measuring jets in ALICE

Most ALICE jet measurements use charged particle jets

Today, I will focus on full jets (charged + neutral)

- Full jets allow a direct comparison to theory
- But significant experimental complication!
  - And reduced statistics due to limited coverage

Inclusive jet measurement in pp, Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

1. Measure jet $R_{AA}$ for $R=0.2-0.4$
2. Measure Pb-Pb jet cross-section ratio
Analysis strategy

• **Three main pieces to the analysis:**
  - Measure the jet $p_T$ — combine track $p_T$ and EMCal $p_T$
  - Subtract the combinatorial background event-by-event
  - Correct the jet $p_T$ for detector and resolution effects

• **Improvements relative to the 2.76 TeV ALICE analysis**
  - Extend to $R=0.4$
    - Allows examination of modification to jet shape
  - Refine analysis technique
    - Better understanding of our tracking and calorimetry
    - Utilization of embedding-based jet $p_T$ correction
Results — pp jet cross-section

We measure the inclusive pp jet cross-section for $p_{T,jet} = 20-140$ GeV/c at 5.02 TeV as a reference for jet $R_{AA}$.
The measurement is consistent with POWHEG + Pythia8
Results — Pb-Pb jet spectra

We measure the Pb-Pb jet spectrum in 0-10% centrality for $p_{T,\text{jet}} = 40$-140 GeV/c.
Results — Jet $R_{AA}$

The first full jet $R_{AA}$ measurement at $p_{T,\text{jet}} < 100$ GeV/c at 5.02 TeV

Similar suppression observed in $R=0.2$ and $R=0.4$
Results — Jet $R_{AA}$

ALICE $R=0.4$ jet $R_{AA}$ is consistent with ATLAS $R=0.4$ jet $R_{AA}$

ALICE Preliminary
Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
pp $\sqrt{s_{NN}} = 5.02$ TeV
Anti-$k_T$ $R = 0.4 \ \ |\eta_{jet}| < 0.3$
$p_T^{lead,ch} > 7$ GeV/c

arxiv 1805.05424
Charged particle jets and full jets are consistent

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
ALICE Preliminary
POWHEG+Pythia8 reference

Anti-$k_T$ $R = 0.2$ | $|\eta_{\text{jet}}^{\text{full}}| < 0.5$, $|\eta_{\text{jet}}^{\text{ch}}| < 0.7$
$p_{T,\text{lead, ch}} > 5$ GeV/c

$R_{AA}$

Full jets
Charged jets
Correlated uncertainty
Shape uncertainty
Correlated uncertainty
Shape uncertainty

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
ALICE Preliminary
POWHEG+Pythia8 reference

Anti-$k_T$ $R = 0.3$ | $|\eta_{\text{jet}}^{\text{full}}| < 0.4$, $|\eta_{\text{jet}}^{\text{ch}}| < 0.6$
$p_{T,\text{lead, ch}} > 5$ GeV/c

$R_{AA}$

Full jets
Charged jets
Correlated uncertainty
Shape uncertainty
Correlated uncertainty
Shape uncertainty
Results — Jet $R_{AA}$

ALICE full jet $R_{AA}$ at 5.02 TeV is similar to 2.76 TeV for $R=0.2$, with hint of increase.

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Preliminary

Anti-$k_T$ $R = 0.2$, $|\eta_{jet}| < 0.5$

$P_{T,lead,ch} > 5$ GeV/c

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

Correlated uncertainty
Shape uncertainty

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

Correlated uncertainty
Shape uncertainty
Results — Jet $R_{AA}$

Measurements compared to theoretical predictions:

**LBT** provided in arxiv:1809.02525

*PRC 91 (0549098)*

**SCET$_G$** provided by Haitao Li

*arxiv:1801.00008*

*PLB 769 (242)*

**Hybrid model** provided by Daniel Pablos

*JHEP 10 (2014) 19*

*JHEP 03 (2017) 135*

*JHEP 03 (2016) 53*

*JHEP 03 (2018) 10*

**JEWEL** (generated internally, Ritsuya Hosokawa)

*JHEP 03 (2013) 80*

*JHEP 07 (2017) 141*

*EPJ C (2016) 76:695*
Results — Jet $R_{AA}$

All models qualitatively describe the $R_{AA}$

But quantitatively, most models have slight tension with the data
Results: Jet cross-section ratio

The ratio of jet cross-sections $R=0.2 / R=0.4$ in pp provides a baseline for Pb-Pb.

In pp, the jet cross-section ratio is also useful to disentangle hadronization and underlying event effects.
Results: Jet cross-section ratio

No modification in Pb-Pb is observed compared to pp

Generally consistent with previous measurements at 2.76 TeV showing no significant modification in $R \sim 0.2 - 0.4$
Results: Jet cross-section ratio

No modification in Pb-Pb is observed compared to pp

Models predict some modification, but our resolution is not good enough to distinguish them

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Preliminary

$\text{Anti-}k_T \quad |\eta_{jet}^{R=0.2}| < 0.5 \quad |\eta_{jet}^{R=0.4}| < 0.3$

$p_T^{\text{lead,ch}} > 7$ GeV/c
Discussion

1. The measured jet $R_{AA}$ contains sufficient precision to distinguish models at low $p_T$, to an extent
   - However, the models use different input spectra, different medium evolution, different hadronization, different leading track biases, and different ways of fixing model parameters...
   - What does it mean for a model to be “consistent” or “inconsistent” with measured $R_{AA}$?

2. With the current statistical precision and systematics, we cannot experimentally distinguish $R$-dependence of models
   - Increased statistics will improve the statistical and unfolding uncertainties — not clear to what extent
   - ATLAS/CMS can measure jet $R_{AA}$ for $R=0.2$-$0.4$ at high-$p_T$ with high precision at 5.02 TeV — this may distinguish the $R$-dependence of models (e.g. pQCD vs. Hybrid model)
Summary

New pp and Pb-Pb inclusive full jet measurements from ALICE at 5.02 TeV

Jet $R_{AA}$ with measured pp reference for $R = 0.2, 0.4$
Thank you!
Backup
Leading track requirement

Suppress combinatorial jets by requiring jets to contain a 5 GeV/c charged track.

POWHEG+Pythia8 $\sqrt{s} = 5.02$ TeV
Biased: $p_{T}^{\text{lead,ch}} > 5$ GeV/c

ALICE Simulation
R=0.2 / R=0.3 jet cross-section ratio

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
ALICE Preliminary
Anti-$k_T$ $|\eta^{R=0.2}_{\text{jet}}| < 0.5, \quad |\eta^{R=0.3}_{\text{jet}}| < 0.4$
$p_T^{\text{lead,ch}} > 5$ GeV/c

$\frac{d^2\sigma^{R=0.2}}{dp_T^{\text{jet}} d\eta^{R=0.2}_{\text{jet}}} / \frac{d^2\sigma^{R=0.3}}{dp_T^{\text{jet}} d\eta^{R=0.3}_{\text{jet}}}$

- 0 - 10% Pb-Pb
- Correlated uncertainty
- Shape uncertainty
- POWHEG+Pythia8
- Scale + PDF uncertainty
- JEWEL, recoils on, 4MomSub
- JEWEL, recoils off
Jet cross-section ratio, charged jets

\[ \frac{\sigma(R=0.2)}{\sigma(R=0.3)} = f(p_{T,\text{ch jet}}) \]

ALICE Pb-Pb 0 - 10% \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

Charged jets Anti-\( k_T \)

\[ | \eta_{\text{jet}}^{0.2} | < 0.7 \quad | \eta_{\text{jet}}^{0.3} | < 0.6 \]

\( p_{T,\text{lead}} > 5 \text{ GeV/c} \)

ALICE Preliminary