Jets in Nuclear Collisions

Anne M. Sickles
there are a lot of new jet results!

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A lot of talks—this overview is incomplete!
jet quenching observed from the earliest days of heavy ion running at the both RHIC and LHC

jets in nuclear collisions—past

our task today is not to demonstrate that jets are still quenched, but to understand how these jets are modified and what that means about the inner workings of the QGP

this demands controlled, systematic measurements & systematic theory
inclusive jets in PbPb collisions

jet quenching from 50 GeV $\rightarrow$ 1 TeV

what do we know about how particles make up these jets?
The fragmentation functions are defined as:

\[ D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{d n_{\text{ch}}}{d z} \]

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

\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{d n_{\text{ch}}}{d p_T} \]

Jet energy measurement is correlated with how the jet fragments!

ATLAS
Simulation
\( \sqrt{s} = 7 \text{ TeV} \)
anti-\( k_T \) \( R=0.4 \) Jets
EM+JES Calibration \( |\eta| < 0.8 \)

PYTHIA MC11
HERWIG++
PYTHIA Perugia2011
response matrix in $p_{T,\text{meas}}, p_{T,\text{true}}, z_{\text{meas}}, z_{\text{true}}$

measured

$\langle z \rangle$

$\langle p_{T,\text{jet}} \rangle$

unfolded

particle $z$

track $z$

$\langle p_{T,\text{jet}} \rangle$

2-dimensional unfolding

large JER centrality dependence to JER due to UE fluctuations

smaller UE effect similar unfolding change in pp & PbPb

$\langle p_{T,\text{jet}} \rangle$: 126 - 158 GeV

$\langle p_{T,\text{jet}} \rangle$: 251-316 GeV

Martin Rybar, Wednesday

1805.05424
how do we look at jets?

Yi Chen, Wednesday afternoon

Level of detail

Full jet
Large structure
Constituent

$R_{AA}$  jet mass  fragmentation functions
also run in the mode in which it keeps track of the scattering c

production. For the jet mass measurement, low-momentum fra

loss of energy and momentum out of the di-jet system, and is ex

Fig. 8: Ratio between fully-corrected jet mass distributio

Fig. 6: Fully-corrected jet mass distribution for anti-

PYTHIA (tune Perugia 2011) at

collisions and minimum bias p–Pb collisions. The ratio is co

energy loss. In JEWEL each scattering of the leading parton w

0.2

0.1

0.1

0

ALICE

PYTHIA Perugia 2011

p

NN

< 80 GeV/

M

= 2.76 TeV

ch jet

ch jet

R

p

p

NN

< 80 GeV/

< 120 GeV/

< 120 GeV/

NN

M

= 5.02 TeV

ch jet

ch jet

ALICE: mass from charged particles

ATLAS: mass from calorimeter towers

no significant mass modification observed in PbPb within the uncertainties

Martin Spousta, Wednesday
**soft drop**: recluster the jet with Cambridge-Aachen then go through the constituents and exclude the softer leg unless

\[ z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left( \frac{\Delta R_{ij}}{R_0} \right)^\beta \]

Larkoski et al. 1402.2657

**n_{SD}**: number of splittings which satisfy the soft drop condition

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**Data/MC**

ALICE Preliminary

PbPb \( \sqrt{s_{NN}} = 2.76\text{ TeV} \)

Anti-\( K_T \) charged jets, \( R = 0.4 \)

\( 80 < p_{T,jets} < 120 \text{ GeV/c} \)

SoftDrop \( z_{\text{cut}} = 0.1 \beta = 0 \)

- Data
- Shape Uncertainty
- PYTHIA Embedded

ALI-PREL-155677
soft drop: reclustering the jet with Cambridge-Aachen then go through the constituents and exclude the softer leg unless:

\[ z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left( \frac{\Delta R_{ij}}{R_0} \right)^\beta \]

Larkoski et al. 1402.2657

exclude jet if final 2 subjets are at \( \Delta R_{12} < 0.1 \) (30%)

calculate mass from these two subjets
the role of jet parton flavor
• why rapidity?

• fraction of quark jets increases with $|y|$ at fixed jet $p_T$

• jet $p_T$ spectra become steeper with increasing $|y|$

rapidity selected spectra in pp collisions

\[ \frac{d^2\sigma}{dp_T dy} \] 2015 pp data, 25 pb$^{-1}$

anti-$k_t$, $R=0.4$ jets

$\sqrt{s} = 5.02$ TeV

$|y| < 2.8, 1.2 < |y| < 1.6, 0.8 < |y| < 1.2, 0.3 < |y| < 0.8, |y| < 0.3$
• why rapidity?

• fraction of quark jets increases with $|y|$ at fixed jet $p_T$

• jet $p_T$ spectra become steeper with increasing $|y|$

• decrease RAA with $|y|$

• quarks jets should lose less energy than gluon jets

• increase RAA with $|y|$
and fragmentation functions?

**quark** jets have more high z particles than **gluon** jets

**OPAL**

Figure 6: (a) Corrected distributions of charged particle scaled energy, $x_E = E/E_{jet}$, for 40.1 GeV gluon jets and 45.6 GeV uds quark jets. (b) The ratio of the gluon to quark jet $x_E$ distributions for 40.1 GeV jets. The total uncertainties are shown by vertical lines. The experimental statistical uncertainties are indicated by small horizontal bars. (The uncertainties are too small to be seen for the uds jets.) The predictions of various parton shower Monte Carlo event generators are also shown. These data are tabulated in Table 2.

no significant rapidity dependence to modification of fragmentation functions
- photon-jet events dominated by \( q + g \rightarrow q + \gamma \) process
- changes the flavor mix with respect to inclusive jets
- significant difference between inclusive and \( \gamma \)-tagged fragmentation functions

\[
\frac{1}{N_{\text{jet}}}(dN/dz) \]

**ATLAS** Preliminary
\( pp, 26 \text{ pb}^{-1}, 5.02 \text{ TeV} \)

- Data, \( \gamma \)-tagged jets
- \text{PYTHIA 8 A14 NNPDF23LO}
- Data, inclusive jet (\( p_T^{\text{jet}} = 80-110 \text{ GeV} \))

\[
\text{Ratio to } \gamma+\text{jet Data}
\]

**Figure 3**: Fragmentation function in \( pp \) events as a function of charged particle \( p_T \) (left) or \( z \) (right). Results are shown for the measured distribution for photon-tagged jets (black), the analogous generator-level distribution in \( p_T^{\text{jet}} \) events (green), and for the measured distribution for inclusive jets in a similar jet \( p_T \) range (red). The shaded bands correspond to the total systematic uncertainties on the data.

- \( p_T^{\gamma} \): 79.6-125 GeV
- \( p_T \): 63.1-144 GeV

Dennis Perepelitsa, Wednesday morning
Photon-jet fragmentation functions

 photon $p_T$: 79.6-125 GeV  
 jet $p_T$: 63.1-144 GeV

 $\xi_{\text{jet}} = \ln(1/z)$

 photon $p_T$: > 60 GeV  
 jet $p_T$: > 30 GeV

 $z$ range:

- 0-10%: 0.5-1
- 10-30%: 1-1.5
- 30-50%: 1.5-2
- 50-100%: 2-4

Ratio of PbPb to pp:

- 0-10%: 1
- 10-30%: 2
- 30-50%: 3
- 50-100%: 4

ATLAS Preliminary

0-30% Pb+Pb / pp  

Kaya Tatar, Tuesday

CMS: 1801.04895

ATLAS-CONF-2017-074
**photon-tagged fragmentation functions**

**photon p_T**: 79.6-125 GeV  
**jet p_T**: 63.1-144 GeV

**γ-hadron correlations at 200 GeV AuAu collisions**

Joe Osborn, Wednesday

- **γ-tagged jets**: 5.02 TeV  
  - 0-30% Pb+Pb / pp
- **inclusive jets**: 2.76 TeV  
  - (0-10%)

**ATLAS** Preliminary

- Low p_T enhancement begins at a similar p_T to inclusive jets and at a similar p_T between LHC and RHIC
- Looking forward to precision measurements with reconstructed jets at sPHENIX!
Figure 1:

Top: The differential jet shape, radial distribution of tracks in a jet opposite the photon

Middle: 50-100% PbPb / pp, 30-50% PbPb / pp, 10-30% PbPb / pp, 0-10% PbPb / pp (full crosses), pp (open crosses) collisions, and

Bottom: The ratios of the PbPb over pp distributions.

The ratios of the MC/pp

PbPb / pp (x10)

0-10% (+4)

30-50% (+2)

10-30% (+2)

50-100% (+6)

CMS: 1801.04895

Kaya Tatar, Tuesday

shape measurements of jets opposite a photon
**photon p\(_T\): 100-158 GeV**

**ATLAS** Preliminary
*pp* 5.02 TeV, 25 pb\(^{-1}\)
*Pb+Pb*, 0.49 nb\(^{-1}\)

\(p_T^\gamma = 100-158\) GeV

increasing centrality → increasing shift to low \(x_{J\gamma}\)

peak for nearly balanced pairs

---

ATLAS-CONF-2018-009, D Perepelitsa, Wednesday
20-30% Pb+Pb $p_T^{\gamma} = 79.6-100$ GeV

0-10% Pb+Pb $p_T^{\gamma} = 100-158$ GeV

**QM '17**

uncorrected Pb+Pb data to smeared Pythia: bulk shift...

**QM '18**

unfolded Pb+Pb-pp comparison: jets lose small/large amounts of energy!

Dennis Perepelitsa, Wednesday morning
D⁰s reconstructed in jets

15 < jet \(p_T < 30 \text{ GeV/c}\)

CMS Preliminary

Prompt J/\(\psi\)

\[ 4 < p_T^{D} < 20 \text{ GeV/c} \]

\[ |y|^{D} < 2 \]

\[ |p_{T,jet}^{D}| > 60 \text{ GeV/c} \]

\[ |\eta|^{D} < 1.6 \]


looking forward D to measurements with higher luminosity and the ALICE upgrades

Barbara Trzeciak, Tuesday

Papers at IPAC2018
https://ipac18.org
http://ipac2018.vrws.de

MOPMF039
First Xenon-Xenon Collisions in the LHC

MOPMF038
Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

TUPAF020
Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon

TUPAF024
Impedance and Instability Studies in LEIR With Xenon

Future interest in lighter species?
ALICE, ATLAS & CMS successfully took data for the very short XeXe run

jets and high pt charged particles in XeXe quenched according to ~Npart/multiplicity informs discussion of light ions in the future
The suppression of charged hadrons is measured using the nuclear modification factor, \( R_{\text{AA}} \), that the underlying event in Pb+Pb and Xe+Xe collisions may be similar. Thus inferences may be made comparing observables sensitive to jet quenching between different collision systems. In this note, Xe+Xe data are shown in circles, while the Pb+Pb distribution is shown for comparison in diamonds. The Xe+Xe data are smeared to Pb+Pb, and the Pb+Pb systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The Pb+Pb systematic uncertainties are shown here.

\[
\chi_J = \frac{p_{T2}}{p_{T1}}
\]

\( A_J = (p_T^{\text{lead}} - p_T^{\text{sublead}}) / (p_T^{\text{lead}} + p_T^{\text{sublead}}) \)

ATLAS Preliminary

anti-\( k_t \), \( R = 0.4 \) jets

- Xe+Xe, \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV
- Pb+Pb, \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV
- Xe+Xe smeared to Pb+Pb

\( 2.05 < \Sigma E_{T,\text{FCal}} < 2.99 \) TeV

looking forward to doing this comparison over a wider kinematic range at RHIC with sPHENIX!
lighter ions could provide more jets at the LHC

This would be on the assumption that a fill would be kept forever until one beam was exhausted (and other loss mechanisms are neglected). Real gain/fill will be less.

In reality, one also gains from longer luminosity lifetime and less time spent refilling the machine.

We will try to quantify this better in future.
Jet Rates and Physics Reach Scientific Objective and Performance

Figure 1.22 summarizes the current and future state of hard probes measurements in $A + A$ collisions in terms of their statistical reach, showing the most up to date $R_{AA}$ measurements of hard probes in central Au+Au events by the PHENIX Collaboration plotted against statistical projections for sPHENIX channels measured after the first two years of data-taking. While these existing measurements have greatly expanded our knowledge of the QGP created at RHIC, the overall kinematic reach is constrained to $<20$ GeV even for the highest statistics measurements. Figure 1.23 shows the expected range in $p_T$ for sPHENIX as compared to measurements at the LHC. Due to the superior acceptance, detector capability and collider performance, sPHENIX will greatly expand the previous kinematic range studied at RHIC energies (in the case of inclusive jets, the data could extend to 80 GeV/c, four times the range of the current PHENIX $p_T$ measurements) and will allow access to new measurements entirely (such as fully reconstructed $b$-tagged jets).

looking forward to sPHENIX in 2023

measurements we are making now will help us understand sPHENIX data when it comes
looking forward

• as a community, much experience with modified jets in AA collisions

• at this conference: many innovate & systematic measurements

• what we need going forward:
  
  • consistent theory calculations over a wide range of observables and an understanding of what we learn from them
  
  • great to see the **wealth of theory comparisons** in talks/papers/notes and the **release of JETSCAPE**

• focus on high quality measurements that are comparable between experiments (now and in the future) and with theory

**both of these are necessary to make sure that we get the full benefit of the tremendous resources (time and money) that we are putting into heavy ion running over the next decade**
backup
Ratios of fragmentation functions in PbPb / pp

Excess 1-4 GeV particles in PbPb compared to pp

ATLAS

- 0-10% Pb+Pb, \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 0.49 \text{ nb}^{-1} \)
- 10-20% pp, \( \sqrt{s} = 5.02 \text{ TeV}, 0.25 \text{ pb}^{-1} \)
- 20-30% anti-\( k \), \( R = 0.4 \) jets, \( |y|^{\text{jet}} < 2.1 \)
- 30-40% 
- 40-60% 
- 60-80%

\[ N^{\text{ch}} \left( 1.0-4.2 \text{ GeV} \right) \]

\[ p_T^{\text{jet}} \text{ [GeV]} \]

\[ R_D \left( p_T \right) \]

\[ p_T \text{ [GeV]} \]

\[ 10^2 \]

\[ 1 \]

\[ 0.5 \]

\[ -0.5 \]

\[ 2 \times 10^2 \]

\[ 3 \times 10^2 \]

\[ 4 \times 10^2 \]

\[ 2.5 \]

\[ 2 \]

\[ 1.5 \]

\[ 1 \]

\[ 0.5 \]

\[ 10^2 \]

\[ 1 \]

\[ 10 \]

\[ 0.5 \]
low momentum particles: broad angular distribution which extends far outside the jet