Jets
Overview

• Jet quenching in a nutshell
  – Partons lose energy in the medium
  – This lost energy makes jets broader and softer

• Towards quantitative understanding
  – Measurement details matter
  – Cold nuclear matter effects?
Jets – the cartoon

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe
Quenched jets: what we're trying to study

- Softer constituents
- Broader radius

Ways to study jets

- Single particle
- Di-hadron (multi-hadron) correlations
- Fully reconstructed jets

PRL 105 (2010) 252303
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-$p_T$ probes (jets) are suppressed, this is evidence of jet quenching

\[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta} \]

Enhancement

Suppression
Nuclear modification factor $R_{AA}$

**RHIC**

**LHC**

- **Electromagnetic probes** – consistent with no modification – medium is transparent to them
- **Strong probes** – significant suppression – medium is opaque to them
Nuclear modification factor $R_{AA}$

**Single particles**

- Electromagnetic probes – consistent with no modification – medium is transparent to them
- Strong probes – significant suppression – medium is opaque to them

**Jets**

- CMS "PRELIMINARY PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- $L \ dt = 7-150 \mu b^{-1}$
Jet Collaboration: For a 10 GeV quark traveling 4 fm
\[ \hat{q} \approx 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \text{ at } \tau_0 = 0.6 \text{ fm/c in Au+Au at } \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \rightarrow \text{loses 2.2 Gev} \]

\[ \hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} \text{ in Pb+Pb collisions at } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \rightarrow \text{loses 2.8 Gev} \]

\[ \hat{q} = \frac{Q^2}{L} \]

\( Q = \) Momentum transfer from parton to medium

\( L = \) path length
p+Pb as a control

\[ R_{pPb} \]

ATLAS
\( p+Pb \text{ } 1 \mu b^{-1} \)
\( |s_{NN}|=5.02 \text{ TeV} \)

- ATLAS \( |y^{*}|<0.5 \), Glauber, 0-90%
- ALICE \( |\eta_{CM}|<0.3 \), MinBias
- CMS \( |\eta_{CM}|<1 \)

\textbf{ATLAS}
CERN-EP-2016-077
arXiv:1605.06436
Di-jet asymmetry

$$A_j = \frac{p_T^{\text{Leading jet}} - p_T^{\text{Subleading jet}}}{p_T^{\text{Leading jet}} + p_T^{\text{Subleading jet}}}$$
Di-jet asymmetry

Au+Au di-jets more imbalanced than p+p for $p_T^{cut}>2\text{ GeV/c}$

Au+Au $A_J \sim p+p A_J$ for matched di-jets ($R=0.4$)

Central Au+Au
anti-$k_T$, $R=0.4$

STAR Preliminary

Kolja Kauder, RHIC/AGS
User's Meeting 2016

arXiv:1609.03878

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Anti-$k_T$ $R=0.4$, $p_T^{Lead}>20\text{ GeV}$ & $p_T^{SubLead}>10\text{ GeV}$ with $p_T^{cut}>2\text{ GeV/c}$
Fragmentation functions

\[ z = \frac{p_T}{E_{\text{jet}}} \]

**CMS**

PRC 90 (2014) 024908

High \( p_T \)

Low \( p_T \)
Dihadron correlations

\[ \frac{1}{N} \frac{dN}{d\Delta \phi} \]

- \( 0 < \phi^T - \psi < \pi/12 \)
- \( \pi/12 < \phi^T - \psi < 2\pi/12 \)
- \( 2\pi/12 < \phi^T - \psi < 3\pi/12 \)
- \( 3\pi/12 < \phi^T - \psi < 4\pi/12 \)
- \( 4\pi/12 < \phi^T - \psi < 5\pi/12 \)
- \( 5\pi/12 < \phi^T - \psi < 6\pi/12 \)

- \( 1.5 < p_T^T < 2.0 \text{ GeV/c} \)
- \( 6.0 < p_T^T < 4.0 \text{ GeV/c} \)

- \( 4.0 < p_T^T < 6.0 \text{ GeV/c} \)

- \( \Delta \phi \) (radians)


Christine Nattrass (UTK), Hot Quarks, September 2016
Dihadron correlations


Christine Nattrass (UTK), Hot Quarks, September 2016
What is a jet?

A jet is what a jet finder finds.
Jets in principle

- Jet measures partons
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and collinear safe

\[\text{Jet 1} \quad \text{Jet 2}\]

\[\text{Hard scattering} \quad \text{Parton shower} \quad \text{Hadronization}\]
Full jet ratios in pp
$\sqrt{s} = 2.76$ TeV, $R = 0.2, 0.4$ Inclusive

Hadronization is important even in pp collisions!

arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026
Jet finding algorithms

- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input

Bias & Background
Signal

- Harder
- Correlated with rxn plane
- Low $p_T$ modifications
- Flavor modifications?

Background

- Softer
- Correlated with rxn plane
- Large fluctuations/hot spots
- Combinatorial background
- Degraded energy resolution
Bias

- Modified jets probably look more like the medium
- Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996), ]
- Gluon jets reconstructed with $k_T$ algorithm have more particles than jets reconstructed with anti-$k_T$ algorithm [Phys. Rev. D 45, 1448 (1992)]
- Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]
What you see depends on where you look

\[ z = \frac{p_T}{E_{\text{jet}}} \]

High \( p_T \)

Low \( p_T \)

\[ \xi = \ln(1/z) \]
Focus on high $p_T$

- **Pros:**
  - Reduces combinatorial background

- **Cons:**
  - Cuts signal where we expect modifications
  - Could bias towards partons which have not interacted
  - Biases sample towards quarks
Focus on smaller angles

- **Pros**
  - Background is smaller
  - Background fluctuations smaller

- **Cons:**
  - Modifications expected at higher R
  - Biases sample towards quarks
ALICE/STAR

Combinatorial “jets”

- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track $p_T > 5$ GeV/c
  - Suppresses combinatorial “jets”
  - Biases fragmentation
- No threshold on constituents
- Limited to small $R$

Measured spectra:

$$p_{T,jet}^{unc} = p_{T,jet}^{rec} - \rho \cdot A$$

Where $p_{T,jet}^{rec}, A$ comes from FastJet anti-$k_T$ algorithm
Fake Jets: After the background subtraction, some local fluctuations remain! Fluctuations will deteriorate the jet resolution in central events.


### ATLAS

- **Iterative procedure**
  - **Calorimeter jets:** Reconstruct jets with $R=0.2$. $v_2$ modulated $\langle Bkgd \rangle$ estimated by energy in calorimeters excluding jets with at least one tower with $E_{\text{tower}} > \langle E_{\text{tower}} \rangle$.
  - **Track jets:** Use tracks with $p_T > 4$ GeV/c.
  - Calorimeter jets from above with $E > 25$ GeV and track jets with $p_T > 10$ GeV/c used to estimate background again.
  - Calorimeter tracks matching one track with $p_T > 7$ GeV/c or containing a high energy cluster $E > 7$ GeV are used for analysis down to $E_{\text{jet}} = 20$ GeV.

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**Definitely imposes a bias, especially at 20 GeV!**
**We should treat that bias as a tool, not a handicap.**

Event mixing

- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
- Requires normalization at low $p_T$
- All physical correlations treated like jets

Alexander Schmah, Hard Probes 2015
Cold Nuclear Matter effects

- Indications of modification at forward rapidities from dihadron correlations [Phys. Rev. Lett. 107, 172301 (2011)]
Conclusions

• What to remember
  – A jet is not a parton
  – All jet measurements are biased
  – Background subtraction/suppression methods are important
  – Beware Cold Nuclear Matter effects!

• Challenges to the field
  – Cross check between experiments using the same method
  – Experimentalists: explain method/measurement to theorists!
  – Theorists: don't ignore the method!

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