An experimental review of Jets and charged hadrons

Matthew Nguyen
Q: Why jets?
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A: To get closer to the parton energy
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Avoid (or control) kinematic biases

... and the (poorly known) non-perturbative FFs
But which parton?

- Ambiguous even in pp
  - Multijets, initial and final state radiation
  - Beam remnants, multi-parton interactions

→ Particle-level jets

- A+A
  - Large (flowing) UE
  - Jet-medium interactions
Q: Why probe the QGP w/ jets?

- Novel mechanisms
- Different regimes of applicability, different scales

A: To understand the transport properties of the medium in detail, we must understand how parton showers are modified in the QGP to the extent that we can model the entire process.

Casalderrey-Solana, Milhano, Weidemann
*J.Phys. G38 (2011) 035006*

Majumder – Hard Probes 2015
Roadmap

- Single jet: $R_{AA}$, $v_2$
- Inter-jet: Dijets, recoil jets
- Intra-jet: ‘FFs’, jet shapes, substructure
- “Detour”: p(d)+A
- Extra-jet: Energy flow
Jet spectra: $R_{AA}$

- Flattish $R_{AA}$ →
  - i.e., not very far from a constant fractional shift*
  - some slope expected from increasing quark-gluon ratio
- ~ Reasonably described by models that get hadron $R_{AA}$
- Reasonable agreement across experiments given measurement differences (more work needed)

* Not to be equated w/ fractional e-loss if jet-by-jet fluctuations are important (which they are!)
Rapidity dependence of $R_{AA}$

- $R_{AA}$ is dead flat vs. rapidity
- With increasing rapidity:
  - Jet spectrum steepens ($R_{AA}$ should decrease)
  - Quark-to-gluon ratio rises ($R_{AA}$ should increase)
- Fortuitous cancellation?
- Forward jets would offer improved sensitivity (but difficult to measure)
- See: Spousta & Cole arXiv:1504.05169
- Forward jets a focus of CMS HL-LHC upgrades
\( p_T \) Shift: \( \delta p_T/p_T \) (\( S_{\text{loss}} \))

- \( R_{AA} \) sensitive to underlying spectral shape
- \( p_T \) shift more useful to compare across \( \sqrt{s} \)
- Scaling:
  - multiplicity
    - (or Bjorken energy density)
  - number of participant nucleons or quarks
- Energy loss mainly driven by energy density
Jet $v_2$

- Relatively large $\Rightarrow$ up to 10% more jets in-plane than out-of-plane
- Qualitative agreement between ALICE and ATLAS
- Well described by AMPT and by JEWEL

ALICE: arXiv:1509.07334
ATLAS: PRL 111 152301 (2013)
Variation of dijet $p_T$ asymmetry small compared to inclusive jet $v_2$.

What is the correspondence between these two quantities?

Naïve $\Delta E = \text{const} \cdot L^2 + \text{MC Glauber tuned to match jet } R_{AA} \text{ and } v_2$, shows this result is not unexpected.\(^1\,^2\)

(Real) model comparisons?

\(^1\)Credit: Yetkin Yilmaz
\(^2\)Blame: This speaker
Dijet $p_T$ asymmetry

$x_J = \text{subleading jet } p_T / \text{leading jet } p_T$

- ATLAS has fully unfolded detector resolution effects for dijet $p_T$ asymmetry
- Difference between Pb+Pb and pp diminishes with leading jet $p_T$
Dijet $p_T$ asymmetry

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- ATLAS has fully unfolded detector resolution effects for dijet $p_T$ asymmetry
- Difference between Pb+Pb and pp diminishes with leading jet $p_T$
- Qualitatively different message than CMS $\rightarrow$ to be followed up
Recoil jets (from hadrons)

- Charged jets opposite a high $p_T$ hadron (20-50 GeV/c)
- Low $p_T$ hadron trigger class jets used for UE subtraction
- Selects a particular population of jets
  - Near-side fragmentation bias (similar to hadron-hadron)
  - Surface / unquenched bias
- Biases evolve with $p_{T,\text{jet}}$

$I_{AA} = \text{ratio of recoil jet spectrum in central PbPb to PYTHIA}$

ALICE arXiv:1506.03984
R dependence: inclusive vs. recoil

\[ \langle p_T^{\text{charged jet}} \rangle \approx 0.65 \langle p_T^{\text{full jet}} \rangle \]

- A different population of jets is selected in the two cases
- Interesting interplay between jet selection and pathlength
Recoil jets at RHIC

- Similar measurement to ALICE, except
  - $I_{CP}$ instead of $I_{AA}$
  - 9-30 GeV/c charged hadrons instead of 20-50 GeV/c
- STAR does see a reduced suppression with increasing cone size
- Caution: trigger condition may sample different pathlengths for different $\sqrt{s}$
- Nevertheless, difference between RHIC and LHC is intriguing
Dijet imbalance at RHIC

\[ A_J = \frac{p_T^{\text{Lead}}(p_T^{\text{cut}} > 2 \text{ GeV}) > 20 \text{ GeV} - p_T^{\text{SubLead}}(p_T^{\text{cut}} > 2 \text{ GeV}) > 10 \text{ GeV}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}} \]

- With constituent cut of 2 GeV/c anomalous imbalance is observed

Central Au+Au anti-\( k_T \), \( R=0.4 \)

Preliminary
Dijet imbalance at RHIC

\[ A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}} \]

- With constituent cut of 2 GeV/c anomalous imbalance is observed
- For matched dijets w/o constituent cut, imbalance disappears!
- Is this a very particular population of jets or is quenching very different at RHIC and LHC energies (or both)?
Looking inside jets

Jet fragmentation (longitudinal)

Jet shape (transverse)

- Excess at low $p_T$ and large angle clearly a feature of jet quenching
- Modest modification of jet structure at small angle & medium to high $p_T$
- To what extent is this due to quenching changing the q/g fraction?
Jet production and fragmentation in p+A

- Jet spectra not very modified (w/i errors), all expt’s agree
- The jury is still out on jet fragmentation $\rightarrow$ urgent need for 5 TeV pp reference data (w/ matching parton luminosity)
Jet quenching in p+\(A\)?)

Dijet angular (de)correlation

- CMS pPb 35 nb\(^{-1}\)
- \(\sqrt{s_{_{NN}}} = 5.02\) TeV

\[
\sigma(\Delta\phi_{1,2})
\]

| \(E_T^{4<|\eta|<5.2}\) (GeV) |
|------------------|
| 0 | 0.18 |
| 10 | 0.2 |
| 20 | 0.22 |
| 30 | 0.24 |
| 40 | 0.26 |
| 50 | 0.28 |
| 60 | 0.2 |

Dijet \(p_T\) (im)balance

- \(p_{T,1} > 120, p_{T,2} > 30\) GeV/c
- \(|\eta| < 3, \Delta\phi_{1,2} > 2\pi/3\)

\[
\langle \frac{p_{T,2}}{p_{T,1}} \rangle
\]

| \(E_T^{4<|\eta|<5.2}\) (GeV) |
|------------------|
| 0 | 0.65 |
| 10 | 0.67 |
| 20 | 0.7 |
| 30 | 0.75 |
| 40 | 0.8 |
| 50 | 0.8 |
| 60 | 0.8 |

No sign yet of angular decorrelation or anomalous \(p_T\) imbalance
Jet quenching in p+A?

- Already in 50-100% dijet asymmetry is not much different than in pPb (dE_T/dη per participant in min. bias pPb more like 70-100% PbPb)
- More data will help map out turn off (or not) of final state effects in PbPb
Nuclear PDFs from p+A

- Nuclear effects distort the dijet rapidity distribution
- Relative normalization insensitive to jet reconstruction systematics
- Best constraint yet on the nuclear glue from the LHC
- With Run 2: dijet $\eta$ vs dijet mass to probe both $x_p/x_Pb$ and $Q^2$
Centrality dependence of hard probes in p+A

- Unexpected “centrality” dependence
- $R_{CP}$ scales w/ jet energy for forward jets
- Forward (p-going): jet energy $\sim$ Bjorken $x_p$
- Anti-correlation btwn $x_p$ and $E_T$ on A-going side

ATLAS PLB 748 (2015) 392-413
PHENIX arXiv:1509.04657
Centrality dependence of hard probes in p+A

- Several proposed mechanisms/models

- Based on measurements in pp, not a trivial consequence of energy conservation
  ATLAS-CONF-2015-019

- Can we measure energy loss in “central” p+A or study the impact parameter dependence of nPDFs in a well-controlled manner?

- Underscores one of the physics cases for an Electron-Ion Collider
END DETOUR
Jet substructure

pp @ 7 TeV

\[ g = \sum_{i \in \text{jet}} \frac{p_{T}^{i}}{p_{T}^{\text{jet}}} |r_{i}| \]

\( r_{i} \) is distance between constituent \( i \) and jet axis

- Radial moment (girth) is a \( p_{T} \)-weighted width of the jet: collimated jets have lower \( g \)
- Reasonably well described by recent PYTHIA Perugia tune

Also measured by ALICE: dispersion \( p_{T}D \), and leading-subleading track
Jet substructure

\[ g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i| \]

\( r_i \) is distance between constituent \( i \) and jet axis

- Jets shift towards lower \( g \) i.e., more collimated
- Similar trend in JEWEL (recoil turned off)
Jet substructure

Pb-Pb @ 2.76 TeV

\[ g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T} |r_i| \]

\( r_i \) is distance between constituent \( i \) and jet axis

- Jets shift towards lower \( g \) i.e., more collimated
- Similar trend in JEWEL (recoil turned off)
- PbPb jets more quark-like

- Collimation or preferential gluon quenching (or both)?

→ Substructure observables should discriminate not only quenching mechanisms, but flavor selection effects (and their interference)
No strong modification of jet hadrochemistry (baryon/meson) in jets
Clean separation between fragmentation and recombination regimes
Quenched energy flow

Two approaches used by CMS:

- Jet track correlations
- Missing $p_T$||

Also, top-down approach of ATLAS via “neighboring jets”

“Sideband” region
$1.5<|\Delta\eta|<2.5$

arXiv:1506.08656
Angular (re)distribution

Jet-track correlations

- Broad angular distribution of low $p_T$ jet ‘fragments’
- Also seen for leading jets
  → Departure from a pure surface bias picture
Radial profile of jet (+ radiation + nearby jet) momentum out to 1 unit of $\Delta r$!

- Sizable modification of momentum flow, ratio increasing with angle
Jet shapes to large angle
Leading vs. subleading

- At first glance subleading jet looks less modified than leading in PbPb
- Driven by the difference between leading and subleading in pp
  → Handle reference comparisons with care
**Missing $p_T\parallel$: In/out of cone**

![Graph](image)

- **Take-home message (ca. 2011):** Dijet balance only recovered at low $p_T$ and large angle

- **But what does large angle mean, if pp shows a similar pattern?**
Missing $p_T^{\parallel}$ in pp

- Large angle balance already present in pp, depends on jet selection
- Large $A_J$ selection enhances large angle radiation (e.g., harder 3rd jet)
- What is the more useful reference for asymmetric dijets in PbPb?
Missing $p_T^{||}$: pp vs. PbPb

- Familiar shift of energy to lower $p_T$ “fragments”
- No large angular redistribution of total energy flow w.r.t. to pp
Changing R selects a different population of jets → structure of missing $p_T$ changes, incorporating nearby radiation into jets

Still, only modest change to cumulative balance compared to pp

… Incidental or fundamental?
So where does the energy go?

Q: Does the quenched energy go to large angle?
A: Well, the core appears more collimated, but yes it must, otherwise we would recover all the dijet imbalance provided we sum over all constituents in the cone (which is at least not true at the LHC)

Q: Ok, so where exactly does it go?
A: Compared to what? So far we don’t have a comparison sample of jets with the same initial parton energy. High statistics $\gamma$+jet will go a long way here. Confronting models will be key.
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Take home message: Beware of take home messages
Thanks for your attention!

And thanks for useful discussions, plots, etc:
François Arleo, Oliver Busch, Zvi Citron, Leticia Cunquiero, Olga Evdokimov, Ali Hanks, Peter Jacobs, Chris McGinn, Hannu Paukkunen, Dennis Perpelitsa, Hallie Trauger and Yetkin Yilmaz
Backup
(My) conclusions (so far)

- Jets are now fully part of the HI toolbox
- Overall spectra modification and reaction plane dependence more or less under control, but…
  - Inter-experiment consistency only somewhat established
  - Better sensitivity to flavor dependence is desirable
- Intra-jet structure only lightly modified … but more so at low $p_T$ / collision energy?
- Interesting results on large angle energy flow
- Ditto for nuclear effects in small systems
- But do we really understand our reference(s)?
  - High-luminosity pp a no-brainer
  - High statistics $\gamma$+jet should shed some light
- For complex observables urgent need for (more) full event modeling on top of realistic pQCD / hadronization
What does the future hold?

• Near/medium term: **High statistics data**
  - Full exploitation of recoded & upcoming RHIC data, recently exceeding luminosity expectations
  - LHC Run 2 (3) promising 10x (100x) the stats
  ➔ Repeat all measurements, but for γ+jet

• Medium/long term: **Upgrades**
  - A high-rate ALICE detector
  - Phase 1 & 2 upgrades of ATLAS and CMS

• Long term: **Future facilities**
  - A jet (and upsilon) detector at RHIC
  - An EIC that can really pin down nPDFs?
ATLAS neighboring jets

\[ \rho_{R,\text{NN}} \]

\[ \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]
\[ L_{\text{int}} = 0.14 \text{ nb}^{-1} \]

\[ E_T^{\text{test}} > 80 \text{ GeV} \]
\[ 0.8 < \Delta R < 1.6 \]

\[ E_T^{\text{nbr}} \text{ [GeV]} \]

\[ E_T^{\text{test}} > 90 \text{ GeV} \]
\[ 0.8 < \Delta R < 1.6 \]

\[ E_T^{\text{nbr}} \text{ [GeV]} \]

\[ E_T^{\text{test}} > 110 \text{ GeV} \]
\[ 0.8 < \Delta R < 1.6 \]

\[ E_T^{\text{nbr}} \text{ [GeV]} \]

\[ \text{anti-}k, \ d=0.4 \]

arXiv:1506.08656
ALICE dijet in pPb

\[ p\text{-Pb } \sqrt{s_{\text{NN}}}=5.02 \text{ TeV } 0\text{-}40\% \text{ (V0A)} \]

Anti-\( k_T \) \( R=0.4; |\Delta \phi_{\text{dijet}}| < \pi/3 \)

\[ 15 < p_{T,\text{assoc jet}}^{\text{ch}} < p_{T,\text{jet}}^{\text{ch+ne}} \text{ GeV/c} \]
ALICE charged jets in pPb

**Figure**

- **ALICE p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- Charged jets, anti-\( k_T \), \(|\eta_{lab}| < 0.5\)
- Reference: Scaled pp jets 7 TeV

**Graphs**

1. **Resolution parameter** \( R = 0.2 \)
   - \( p_{T, \text{ch jet}} \) (GeV/c)
2. **Resolution parameter** \( R = 0.4 \)
   - \( p_{T, \text{ch jet}} \) (GeV/c)

**Citation**

ATLAS pPb jet fragmentation

ATLAS-CONF-2015-022
Rapidity dependence of $R_{AA}$

$R_{AA}$, ATLAS

- anti-$k_t$, $R = 0.4$ jets
- $|S_{NN}| = 2.76$ TeV
- 2011 Pb+Pb data, 0.14 nb$^{-1}$
- 2013 $pp$ data, 4.0 pb$^{-1}$

$|y| < 2.1$

- 0 - 10%$
- 30 - 40%
- 60 - 80%

$0.3 < |y| < 0.8$

$1.2 < |y| < 2.1$

$R_{AA}$ vs $p_T$ [GeV]

Jet broadening – match to 

R=0.2

For the same R=0.4, $p_{T,1}>20$, $p_{T,2}>10$ GeV jets, balance can not be restored within R=0.2 $\rightarrow$ Broadening
Jet softening – match to $p_T^{\text{Cut}} = 1\text{GeV}/c$

$p_T^{\text{Cut}} = 1\text{GeV}/c$ not sufficient to restore balance
→ signs of jet softening between 1 and 2 GeV/c
Dijet angular decorrelation?

No azimuthal decorrelation observed
Similar message from CMS and ATLAS

STAR does see a broadening*
(*Not yet fully corrected)

Is something fundamentally different at RHIC and LHC energies?
Jet calibration in heavy ions

In-situ calibrations in pp
- Relative scale: dijets
- Absolute scale: $\gamma/Z$+jet

Extension to PbPb
- In-situ calibrations via cross-calibration
- Moderate add’l uncertainty due to quenching

Precision jet measurements are feasible in heavy ions

Also ALICE underlying event fluctuations: JHEP 1203 (2012) 053