Jet Spectra in pp, pA, and AA Collisions

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Little Bangs, Both Big and Small

7 TeV pp Multijet Event

2.76 TeV PbPb Dijet Event

Jets provide direct access to parton kinematics BUT:

- Generally clearer connections than PbPb
- Multiparton interactions (MPI) smear quark-jet connections
- Full jet evolution still not totally understood

- Jet-Medium interactions obfuscate jet-quark connections
- Large (and flowing!) underlying event
Some Thoughts on Jets in Pb+Pb

- The Jet $R_{AA}$ does not seem to depend on:
  - Jet cone size (or even e.g. full jet vs charged jet)
  - Jet flavor ($b / c(?)/ light$), at high-$p_T$
  - Jet pseudorapidity
  - (Large) Collision species, e.g. Cu+Au & Pb+Pb
  - Depends weakly on jet $p_T$

- Is there a tension in the Meson <-> jet correspondence?
  - Meson $R_{AA}$ seems to trend quickly toward unity
  - Jet $R_{AA}$ asymptotes toward unity eventually??

- Large cones ($R > 1$) needed to recover the jet energy
Inclusive Jets in PbPb Collisions, so far...

- Jets are quenched – even out to very large $p_T$
  - Suppression independent of rapidity and flavor

\[ R_{AA} \]

\[ (\text{GeV/c}) \]

\[ N_{\text{part}} \]

CMS

166 $\mu$b$^{-1}$ (PbPb 2.76 TeV)

anti-$k_t$ $R = 0.3$

Inclusive jet $R_{AA}$ (0-5%) $|\eta| < 2$

b-jet $R_{AA}$ (0-10%) $|\eta| < 2$

arXiv: 1312.4198, 1609.05383

9/26/16
Kurt Jung (UIC), Hard Probes 2016, Wuhan, China
5 TeV Jet $R_{AA}$

- Finally a true pp reference
- Interplay between full jet, charged jet and cone size seen via comparisons to ATLAS
Jet radius dependence of $R_{AA}$

- Dependence on jet radius parameter is negligible
  - Cone-size dependence useful to test both vacuum QCD fragmentation expectations and quenching
  - Quenching affects $R=0.2$->0.4 similarly
  - Large cone sizes $>1.4$ needed to fully recover energy (seen in jet-track corr.)
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See poster by: Raghav Elayavalli

arXiv: 1609.05383
Jets in Cu+Au

- Cu+Au $R_{AA}$ tells same story as Au+Au or Pb+Pb
  - Suppression slightly reduced from Pb+Pb LHC
  - Cu+Au @ 200 GeV -> Pb+Pb @ 2.76 TeV = add’l 15% suppression?
  - Note $R_{AA}$ convolutes energy loss with spectrum shape

See talk by: Sergey Zharko (Sat. AM)
Thoughts on **Dijets in PbPb**

- Classic picture of “leading jet = unmodified jet” may be incorrect at LHC (but probably ok at RHIC!)
  - Better baselines (e.g. EW probes) needed to properly determine full extent of quenching

- Angular spread of jet constituent particles is likely different at LHC and at RHIC

- Have to be very careful when discussing dijet distributions for PbPb – pp or PbPb/pp
  - Quenching smears the relative jet parton $p_T$
Dijets at the LHC

\[ A_J = \frac{\rho_{T,1} - \rho_{T,2}}{\rho_{T,1} + \rho_{T,2}} \]

- Centrality-dependent dijet asymmetry observed as early as 2010 at LHC
  - Clear deviation of \( A_J \) toward quenching
Large angles needed to fully recover the energy

- Typically energy contained in low-$p_T$ particles ($< 1$ GeV/c)
Di-jets in PbPb Collisions, so far…

\[ p_{T,1} > 120; p_{T,2} > 50 \text{ GeV} \]
\[ |\eta_1, \eta_2| < 0.6; \Delta \phi_{1,2} > 5\pi/6 \]

- Shape of energy recovery is similar in pp and PbPb
- Indications that low-\( p_T \) particles are pushed further from dijet axis than high-\( p_T \) particles

- Large angles needed to fully recover the energy
  - Typically energy contained in low-\( p_T \) particles (\(< 1 \text{ GeV/c}\))

Missing Dijet momentum recovered via rings of \( \Delta R \)

arXiv: 1509.09029
• New STAR measurement of dijet $A_J$
  – Hints of quenching for $R=0.2$ jets
  – Quenching fully recovered by $R=0.4$: consistent $A_J$ distributions between pp and AuAu
Jet Track Correlations

- Shift in constituent particle distribution between balanced and unbalanced jets
  - Subleading jet low-\(p_T\) constituents pushed farther away for quenched jets
  - Leading jet particle distributions consistent between quenched/unquenched sample

\(A_J < 0.22, \ p_{T,1} > 120 \ \text{GeV}, \ p_{T,2} > 50 \ \text{GeV}\)

\(A_J > 0.22, \ p_{T,1} > 120 \ \text{GeV}, \ p_{T,2} > 50 \ \text{GeV}\)

See talk by: Dragos Velicanu (Sat. PM)

arXiv: 1609.02466

\(\Delta \phi\)

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Jet Track Correlations

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- Leading jet constituents are modified, even for balanced dijets (!)
  - Assumption that leading jet is unmodified may not be true at LHC energies
  - Need a better reference for jet suppression than another jet
Jet Track Correlations

\[ A_J < 0.22, \ p_{T,1} > 120 \text{ GeV}, \ p_{T,2} > 50 \text{ GeV} \]

- Leading jet constituents are modified, even for balanced dijets (!)
  - JEWEL predicts this phenomenon looking at dijet surface bias
Electroweak Boson References in PbPb

CMS-PAS-HIN-15-013

Z+Jet Energy Modification

See talk by K. Tatar (Sat. PM)

CMS Preliminary

\[ \frac{dN_{Z}}{dx_{Z}} \]

- Z+Jet events suggest minor shift in jet energy relative to Z-boson
  - Increase of Z \( p_T \) shifts jet distribution away from 30 GeV cutoff resulting in smaller \( \langle X_{JZ} \rangle \)
  - Observed effect consistent with jet quenching
- Distributions in pp consistent with MADGRAPH predictions
Electroweak Boson References in PbPb

\[ \langle X_{J\gamma} \rangle \text{ in PbPb smaller than in pp} \]
- Sizeable shift in jet energy for central events
- Photon \( p_T \) dependence is fairly minor

See talks by:
Chris McGinn (Sat. PM)
Brian Cole (Sat. PM)
Electroweak Boson References in PbPb

- $<X_{J\gamma}>$ in central PbPb reduced from pp
  - Relative shift in quenched jets similar between both new electroweak references: photons and Z-Bosons
Investigate properties of leading order heavy-flavor jet production
- Inclusive flavored jet has large gluon splitting (NLO) component
- Observe modification consistent with inclusive-jet measurements
Di-b-jets

- Investigate properties of leading order heavy flavor jet production
- Observe modification consistent with inclusive-jet measurements

CMS-PAS-HIN-16-005

25.8 pb⁻¹ (5.02 TeV pp) + 404 µb⁻¹ (5.02 TeV PbPb)

CMS
Preliminary

CMS
Preliminary

Inclusive dijets

\( p_T, 1 > 100 \text{ GeV}, p_T, 2 > 40 \text{ GeV}, d\phi > 2\pi/3 \)

\( \langle x_j \rangle \)

\( \langle N_{\text{part}} \rangle \)

\( \langle N_{\text{part}} \rangle (N_{\text{coll}} - \text{weighted}) \)

See talk by: Cheng-Chieh Peng (Sun. AM)

Kurt Jung (UIC), Hard Probes 2016, Wuhan, China

9/26/16
Thoughts on **Jets in pA**

- Centrality definitions in pA can be biased by assuming Glauber scaling works properly
  - Jets in particular can dramatically affect centrality classification

\[
<N_{\text{trk}}> = \text{“Central” medium light fragmentation} + \text{“Peripheral” medium heavy fragmentation}
\]

- Would be good to see \(Q_{\text{PbPb}}\) studies to confirm/validate the ALICE centrality estimation procedure

- New pp data allows tight nPDF constraints using dijets large regions of \(Q^2\)-x phase space
  - Would be great to check di-b-jets in pPb = gluon nPDF
• pPb jets are not quenched
  – No large initial state effects observed, even vs flavor
Jets in pA Collisions, so far...

- pPb jets are not quenched
  - Same story observed at RHIC energies
• Centrality dependence is a bit of a mystery
  – $R_{CP}$ values hugely “suppressed” at high-$p_T$ -> centrality bias?
ALICE pPb Inclusive Jet Result

(Centrality calculated in bins of ZDC energy + scaled $<N_{\text{coll}}>$)

- ALICE measure a different jet $R_{pA}$ centrality dependence than PHENIX and ATLAS
  - Centrality definition based on ZDC + normalized multiplicity in the forward calorimeter ("Hybrid" method)
- Observe virtually no centrality dependence of jet $R_{pA}$, consistent with inclusive-centrality measurements
- Note limited pseudorapidity region: $|\eta_{\text{lab}}| < 0.5$ not heavily modified
Di-jets in pA Collisions, so far...

- New tool for constraining nuclear PDFs
  - Strong dijet pseudorapidity ↔ Bjorken-x correlation
  - Forced to use NLO simulation – 5 TeV pp data not yet available at publication time
Gluon distributions constrained by dijet pseudorapidity distributions
  – Deviations in EMC region from EPS09 -> good agreement with DSSZ

CMS-PAS-16-003

See talk by: Yen-Jie Lee (Sun. AM)
Summary

• Can we use **new references** to control energy-loss baselines?
  – Consistent picture shown by Electroweak, Flavored, Virtuality Probes: Jet quenching only very apparent at most central events
  – EW + $R_{AA}$ + Theory suggest $\langle \Delta E \rangle \sim 10$-15 GeV at 100 GeV jets

• Can we go **searching for quenched energy**?
  – Quenched energy pushed out to $\sim 1.4$ in $\Delta R$, contained in particles of $p_T < 2$ GeV at LHC, but fully recovered by $\Delta R \sim 0.4$ at RHIC

• Can we **gain control of centrality** in small systems?
  – Centrality needs to be carefully calibrated – prefer centrality definitions without Glauber MC and using ZDC

• Can we **further constrain nPDFs** using jets?
  – Yes – especially with new 5 TeV pp data. Adding new constraint to the gluon nPDFs using hadron colliders at large $x$
Flavored Jets in pA Collisions

- b-Jet and c-Jet $R_{pA}^{Pythia}$ find no discrepancy from unity
- Flavored jet measurements tell a similar story as the inclusive jets
  - Favors pQCD models where mass-dependent effects are negligible at jet $p_T >> b$-quark mass
Possible culprit for Centrality Bias

Forward jet recoil contaminates centrality selection using bins of forward calorimeter energy

- Affects shape of centrality distribution such that central events are redefined as peripheral

Because fits to Glauber MC are not great (from jet recoil bias), $\langle N_{\text{coll}} \rangle$ estimation overnormalizes central events and undernormalizes peripheral events
Analyses

• CMS
  – Updated Jet RAA (1609.05383)
  – Bjet Pairs in PbPb (HIN-16-005)
  – Finalized jet-track correlations (1609.02466)
  – Dijets in pPb @ 5 TeV with updated pp ref (HIN-16-003)

• ATLAS
  – 2.76 TeV Dijet Asymmetry (1011.6182)
  – 2.76 TeV Jet RAA (1411.2357)
  – 5 TeV pPb jet RpA (1412.4092)
  – 5 TeV Photon-Jet Asymmetry (Preliminary)

• ALICE
  – Inclusive charged jet RAA @ 5 TeV (Preliminary)
  – Jet RpA @ 5 TeV (1603.03402)

• PHENIX
  – d+Au jet RpA (1509.04657)
  – Jets in Cu+Au (Preliminary)

• STAR
  – Dijet $A_J$ in Au+Au and pp at 200 GeV (1609.03878)