Heavy Ion Experimental 2

Hard Probes
(focus on jets)

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NNPSS

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Hard Probes

• Unlike bulk observables: multiplicity, flow...
• Hard probes penetrate the medium
  – Heavy flavor quarks & high momentum partons
  – Modifications reveal interaction:

Illustration: Alan Stonebraker http://physics.aps.org/articles/v1/2

Ultracold neutral plasma
Jets are suppressed!

- Initial RHIC results used high $p_T$ hadrons as a proxy for jets
- Suppression of high $p_T$ hadrons observed -> Jet Quenching
- Direct photons do not interact via strong force; give $R_{AA} = 1$
- Di-hadron away-side suppressed compared to pp and dAu

![Graph showing suppression of jets and di-hadron away-side suppression compared to pp and dAu in RHIC experiments.](image-url)
“T-Shirt Plot”

- Suppression also observed at LHC
- Electroweak probes give \( R_{AA} = 1 \)
Questions for Jets in the QGP

- Is the fragmentation pp like?
- What is the effect of small systems on jets?
- Where does the lost energy go?
- What happens to dijet pairs?
- How does temperature effect quenching?
- Does the pathlength effect quenching?
- Are jets effected by the medium?
Collision System Dependence

• Pion suppression in a variety of collision species compared at similar $N_{\text{part}}$

Phys. Rev. Lett. 101, 232301

Phys. Rev. Lett. 101, 162301
Energy Dependence

- Suppression effect not present at lower collision energies
Energy Density Dependence

- Expect energy loss, $\Delta E/E$ to differ between RHIC and LHC
  - $R_{AA}$ is insensitive to variations in energy loss
- Try fractional momentum loss $S_{\text{loss}} = \delta p_T/p_T$
- $S_{\text{loss}}$ scales with energy density not geometry

M. Connors DNP 2015
Pathlength Dependence at RHIC

- Suppression of pions has pathlength dependence
- Toward out of plane:
  - Larger L → More Eloss

Relation between $R_{AA}(\varphi)$ and $v_2$:

$$R_{AA}(\varphi) = R_{AA} \left( 1 + 2v_2 \cos 2(\varphi - \psi) \right)$$
Heavy Flavor Energy Loss

- Constrain models with $R_{AA}$ and pathlength effect via $v_2$
- High $p_T v_2$ due to pathlength dependent energy loss

![Graphs showing $R_{AA}$ and $v_2$ vs $p_T$](arXiv:1804.09083)
Jet Quenching

- $R_{AA}$ for reconstructed jets also less than 1 out to high $p_T$
- Non-zero $v_2$ indicates pathlength dependent energy loss
Pop Quiz

• Q. What is a proton?
• A. A particle comprised of valence quarks: 2 up and 1 down... Mass of ~938 MeV.... Stable for $>10^{29}$ years... spin of $\frac{1}{2}$...

Q. What is a Jet?
A. It depends...
What’s your definition?

Jet: colorless states

the collimated spray of particles that results from the branching of the original hard parton and subsequent hadronization of the fragments
Jet Definition for QCD

• Snowmass Accord: fermilab-conf-90-249

ABSTRACT

In order to reduce uncertainties in the comparison of jet cross section measurements, we are proposing a standard jet definition to be adopted for QCD measurements involving light quarks and gluons. This definition involves the use of a cone in the $\eta - \phi$ metric with a radius of 0.7 units.

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Tevatron 1990
How to find jets

How many jets do you see?
How Many Jets are in Heavy Ion Collisions?

Seeing versus Defining Jets

Jets are what we seeClearly 2 jets here

Do you really want to ask yourself this question in Au+Au?
Maybe not so so Crazy

- Jets boldly stand out of background at LHC
- Modification of di-jet balance visible
Some Jet Finding Algorithms

MC: proton-proton - single event

- $k_t$, R=1
- Cam/Aachen, R=1
- SISCon, R=1, f=0.75
- anti-$k_t$, R=1
An Important Jet Finding Parameter

What Matters is R!

To first approx.

various algs. moderately different but R can matter a lot more

QCD & Searches, G. Salam (p. 19)

Jet quality

Physics of quality

Small v. large jet radius (R)

Small jet radius

Large jet radius

single parton @ LO: jet radius irrelevant
What R is better?

Small jet radius

Large jet radius

perturbative fragmentation: large jet radius better
(it captures more)
What R is better?

Small jet radius

Large jet radius

non-perturbative fragmentation: **large jet radius better**
(it captures more)
What R is better?

underlying ev. & pileup “noise”: **small jet radius better** (it captures less)
Removing the Background

- Sometimes referred to as “fake jets” in PHENIX
- ALICE & STAR median $\rho$ subtraction
- Iterative subtraction in $\eta$-rings
- Need to account for fluctuating background!
Unfolding

- PYTHIA jets through GEANT of your detector to make a response matrix to map detector jet to truth jet $p_T$
- Unfolding methods: Bayesian, SVD, $\chi^2$ (bin by bin)

\[
\begin{align*}
  y_j^{\text{reco}} &= \sum_{i=0}^{N} R_{ij} y_i^{\text{true}} \\
  y_i^{\text{true}} &= \sum_{i=0}^{N} R_{ij}^{-1} y_j^{\text{reco}}.
\end{align*}
\]
How to Measure Jets

- Measure your particles
- Choose your Algorithm and R
- Run FastJet
- Measure your background and remove it from your jets
- Unfold for detector effects
- Obtain a fully corrected jet spectrum
Di-Jets

- Dijet Asymmetry

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]
pQCD Factorization

$\Delta f_{a,b} = \text{polarized quark and gluon distribution functions}$

$\Delta \sigma_{pp} = \sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes \Delta \hat{\sigma}_{f_a f_b \rightarrow fX} \otimes D^h_f(z)$

Initial State nPDF pQCD Final State $\Delta E$

$D^h_f = \text{fragmentation function for } f \rightarrow h(z)$

Partonic cross section from pQCD

$\Delta \sigma_{pp} \rightarrow hX$
Jets at the LHC

• Fragmentation functions with modified jets
• $z = p_{Th}/p_{T\text{jet}}$

CMS Phys. Rev. C 90, 024908
Studying Jets in Heavy Ion Collisions

High $p_T$ Particles

-what you want
~what you get

M. Connors DNP 2015
Photon Tagged Jets

- Photons do not interact strongly
- $R_{AA} \approx 1$ implies no medium effect
- Fragmentation Function: $dN/dz$
  - $z = p_h/p_{jet}$

\[ \gamma \text{ energy} \approx \text{jet energy} \]
Measurements with Jet Probes

Spectra and $R_{AA}$
- Is AA just a superposition of pp collisions?

$$R_{AA} = \frac{dN_{jet}^{AA} / dp_T}{\left<N_{coll}\right> dN_{jet}^{pp} / dp_T} \frac{N_{evt}^{pp}}{N_{evt}^{AA}}$$

Correlations
- Energy deposition as a function of angle

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$

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\textbf{\( \gamma \)-h correlations: Fragmentation Function}

\[ p_T^\gamma \approx p_T^{jet} \quad z_T = \frac{p_T^h}{p_T^\gamma} \quad \implies \quad D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T} \]

- Photon \( p_T \) approximates parton/jet \( p_T \)
  - potential imbalance due to \( k_T \)
- Modified Fragmentation function
- Selects quark jets
  - pp results consistent with TASSO measure of quark FF
- Modified FF in Au+Au

\begin{itemize}
  \item \( p+\text{Au+Au} \rightarrow \gamma + h + X \)
  \item PHENIX Au+Au 0-40\% @ 200 GeV
    - global sys = \( \pm 8.8\% \)
  \item PHENIX \( p+p \)
    - global sys = \( \pm 8\% \)
\end{itemize}

(PRL 111, 032301)

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\( \gamma \)-h correlations: FF Modification

- \( I_{AA} \) quantifies the FF modification
- Suppression at low \( \xi \) and enhancement at high \( \xi \)
- Qualitative agreement with models
  - Similar conclusion from STAR jet-h results
- More enhancement at wider angles
- LHC can study effect at higher \( s_{NN} \) and access higher parton energies

\[
\begin{align*}
  &\text{0-40\% Au+Au @ 200 GeV} \\
  &\text{PHENIX Au+Au 0-40\% @ 200 GeV} \\
  &8.8\% \pm \text{global sys} = 6\%
\end{align*}
\]

\( 5 < p_T < 9 \text{ GeV/c} \times 0.5 < p_T'' < 7 \text{ GeV/c} \)

\[
\frac{dN}{d\Delta \phi} \mid_{\Delta \phi < \pi/6} \quad \frac{dN}{d\Delta \phi} \mid_{\Delta \phi < \pi/3} \quad \frac{dN}{d\Delta \phi} \mid_{\Delta \phi < \pi/2}
\]

\[
\begin{align*}
  &I_{AA} \mid_{\Delta \phi < \pi/2} \\
  &I_{AA} \mid_{\Delta \phi < \pi/3} \\
  &I_{AA} \mid_{\Delta \phi < \pi/6}
\end{align*}
\]

\(0\% \cdot \frac{1}{N_{\text{true}}} \cdot \Delta N/d\Delta \phi\)

\( M_{\pi} \)

\( \Delta \phi \leq 7 \text{ GeV/c} \)

\( H_{\text{PHENIX}} \)

\( h + X \gamma \rightarrow /\text{Au+Au} \)

\( p + p \)

\( \phi \Delta \mid_{|y| < 0.35} \)

\( |p_T| < 9 \text{ GeV/c} \times 0.5 < |p_T''| < 7 \text{ GeV/c} \)

\( \text{BW-MLLA in medium E} \)

\( \text{YaJEM 9-12 GeV/c} \)

\( |\Delta \phi/\pi| < \frac{1}{2} \pi \)

\( |\Delta \phi/\pi| < \frac{1}{2} \pi \)

\( |\Delta \phi/\pi| < \frac{1}{2} \pi \)

\( \text{arXiv:1212.3323} \)

Phenix PRL 111, 032301
Studying Jets in Heavy Ion Collisions

High $p_T$ Particles

-what you want
~what you get

M. Connors DNP 2015
Photon Tagged Jets at the LHC

- Exciting to see these measurements achieved

**Figure 6**: Ratio of the fragmentation function for jets azimuthally balanced with a high-$p_T$ photon, between that in 30–80% Pb+Pb collisions and pp collisions (left panels) and 0–30% Pb+Pb collisions and pp collisions (right panels). Results are shown as a function of charged particle $p_T$ (top panels) or $z$ (bottom panels). Hatched bands and vertical bars show the total systematic and statistical uncertainties, respectively, for each measurement.

**Figure 1**: Top: The centrality dependence of the $x$ distribution for jets associated with an iso-tagged photon for PbPb (full crosses) and pp (open crosses) collisions. The pp results are smeared appropriately for each PbPb centrality bin, and data for each centrality bin are shifted vertically as indicated, for clarity. Bottom: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.

- Photon $p_T$: 79.6-125 GeV
- Jet $p_T$: 63.1-144 GeV

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

- Photon $p_T$: $> 60$ GeV
- Jet $p_T$: $> 30$ GeV

- ATLAS Preliminary
  - 0-30% Pb+Pb / pp

- CMS: 1801.04895

- Photon $p_T$: $> 60$ GeV
- Jet $p_T$: $> 30$ GeV
MinBias dAu consistent with pp

Interesting centrality dependence observed

PHENIX PRL 116, 122301 (2016)
Pions in small systems

- Pions in small systems also show similar effect
- Theoretical explanations: shrinking proton and others...not final state energy loss effect
• Increased statistical precision of data is providing more powerful constraints on nPDF
Where does the lost energy go? LHC

- Shows enhanced particles out to 1 radian

\[ \rho(r) = \frac{1}{\delta r N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks}}(r_{a}, r_{b}) p_{T}^{\text{track}}}{p_{T}^{\text{jet}}} \]

- A\text{,} J Inclusive
  - pp 5.3 pb\(^{-1}\) (2.76 TeV)
  - PbPb 166 \(\mu\)b\(^{-1}\) (2.76 TeV)

Leading Jet Shape
- anti-\(k_{T}\) R = 0.3, \(|l_{\text{jet}}| < 1.6\)
- \(120 < p_{T,1} < 300, p_{T,2} > 50\) GeV/c, \(\Delta \phi_{1,2} > 5\pi/6\)

Jet shapes to large angle

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?
Where does the energy go? RHIC

- Surface bias jet with high $p_T$ constituent & study away-side jet
- Enhanced low momentum particle production
- Width appears broader but large uncertainties

Jet-hadron Correlations

<table>
<thead>
<tr>
<th>$p_T^{jet,rec}$ (GeV/c)</th>
<th>$\Sigma D_{AA}$ (GeV/c)</th>
<th>Detector uncertainty (GeV/c)</th>
<th>$v_2$ and $v_3$ uncertainty (GeV/c)</th>
<th>Jet energy scale uncertainty (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–15</td>
<td>$-0.6 \pm 0.2$</td>
<td>$+0.2$</td>
<td>$+3.7$</td>
<td>$+2.3$</td>
</tr>
</tbody>
</table>
LHC vs RHIC Jets

- Similar level of suppression
- Enhancement of low momentum particles at broader angles at LHC
- RHIC more sensitive to surface bias effects
Physics Conclusions

What is the effect of small systems on jets?
- Strong suppression is not a CNM effect

Where does the lost energy go?
- Low momentum particles at large angles

Is the fragmentation pp like?
- No: Modified fragmentation functions measured
- Yes: Jet substructure is pp like
- Yes: Jet composition is the pp like

Does the pathlength effect quenching?
- Yes! Suppression depends on in- or out-of-plane
- Beware of surface bias effects

What happens to dijet pairs?
- Energy imbalance due to different path lengths

How does temperature effect quenching?
- Fractional Eloss depends on energy density
- LHC-RHIC complementarity constrains models

Are jets effected by the medium?
- Yes, jets lose energy and appear to be quenched by the medium
LHC and RHIC Jet Complementarity

- LHC has more jets
- RHIC jets are more influenced by the QGP
- Different temperatures of the QGP
From September 2014 Town Hall meeting
• I believe there are still surprises to be discovered but perhaps in the details
• Currently embarking on an era of photon tagged jets, jet substructure and precise heavy flavor measurements
sPHENIX

- Upgrade to PHENIX
- Plan to start taking data in 2023

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 \(< 20 \text{ GeV} \) 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 \( p_T^{-0} \) measurements) and will allow access to new measurements entirely (such as fully reconstructed b-tagged jets).
Over Simplification of Quarkonia Melting

- **"Thermometer"**: different states dissociate at different temperatures → sequential suppression

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b$ (MeV)</td>
<td>$\sim 640$</td>
<td>$\sim 60$</td>
<td>$\sim 1100$</td>
<td>$\sim 500$</td>
<td>$\sim 200$</td>
</tr>
</tbody>
</table>

$r_{q\bar{q}} \sim 1 / E_{\text{binding}} > r_D \sim 1 / T$

05/18/2018
Rongrong Ma (BNL), QM2018
Theory Comparisons

• Amount of experimental measurements with the dawn of the LHC is impressive and continually growing (Xe+Xe)

• Models need to describe all stages of the collision to fully explain the increasingly precise data

• Theory Collaborations

http://jet.lbl.gov/documents-1/report-on-status-of-qhat
JETSCAPE
Take home messages

• Jets are a useful probes of the QGP
• Reconstructed Jets are a robust observable
• We have learned a lot about jets in the QGP without reconstructing jets
• Reconstructed jets allow us to study modifications to the substructure of the jets
• Photon tagged jets are a golden probe for studying energy loss in the QGP
• RHIC and LHC are complimentary facilities
  – Run 2 underway at LHC
  – sPHENIX starts data taking in 2023
  – Theory collaborations bridge gap in apples to apples comparisons
Tool Box

• JETSCAPE
  
  www.github.com/JETSCAPE/JETSCAPE

• Jet finding algorithms: FastJet
  
  ▸ M. Cacciari, G. Salam, G. Soyez (see http://fastjet.fr/)

• Unfolding: RooUnfold

• Review of Jet Measurements:
  – Connors et al, arxiv:1705.01974