Vision on Key Measurements Past, Present and Future

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Heavy-ion Jet Substructure Workshop
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Early Key Measurements at RHIC (2001-3)

**Strong suppression of high $p_T$ hadrons**

**Modification of the leading fragment**

**Disappearance of the away-side peak**

**Fate of associated hadron in the near- and away-side**

PRL 88 (2002) 022301

(1033 citations)

Di-hadron Correlation


(779 citations)
Early Key Measurements at LHC (2010)

Dijet Momentum Imbalance

Jet quenching with jet
Energy flow out of the jet cone

Missing Transverse Momentum

Quenched energy carried by low $p_T$ particle out of the jet cone
Key Results on Jet Energy Loss (2013)

- **ATLAS**
  - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
  - $\int L \, dt = 7 \mu$b$^{-1}$
  - 0-10% Centrality

- **CMS**
  - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
  - $\int L \, dt = 150 \mu$b$^{-1}$

Slow recovery of the quenched energy

"Absolute Energy Loss"
Key Results on Jet Structure (2014)

Jet Transverse Structure

- Significant modification of average jet substructure when compared the jets in PbPb to the pp reference at the same $p_T$.
- Jet structures, defined by clustering and background subtraction algorithms, are modified in PbPb collisions.

Jet Longitudinal Structure

- CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV
- $L dt = 150 \ \mu$b$^{-1}$
- anti-$k_T$ jets: $R = 0.3$

- ATLAS Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- $0.14 \ \text{nb}^{-1}$
- anti-$k_T$ $R = 0.4$
- $p_T^{\text{jet}} > 100$ GeV/c
- $0.3 < |\eta| < 2$
- $p_T^{\text{track}} > 1$ GeV/c

PLB 730 (2014) 243-263
PLB 739 (2014) 320-342
Ungroomed Charged Jet Mass

No significant modification of jet mass with respect to PYTHIA

Groomed Subjet $p_T$ Sharing

Significant modification of $Z_g$ at LHC

No significant modification $Z_g$ at RHIC (See Raghav’s talk)
Progress Over the Last ~18 Years

2001 Leading Fragment
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-2014 Parton Flavor Dependence of Eloss
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- 2017 Jet Substructure Dependence of Eloss
- 2014 Parton Flavor Dependence of Eloss
2019
Present Status
Density Fluctuation of CMB and QGP

Power spectrum of the Big Bang

Fourier analysis of many little bangs

Inflation

Sound Wave

Geometry

Baryon

Planck

Cross-checks

Multipole moment, $\ell$

Angular scale

$D[\mu K]$

$\ell$

$\sqrt{s_{NN}} = 2.76$ TeV

0-0.2% centrality

$V_{n}^{2part,|\Delta n|>2}$

Geometry

Cross-checks

$0.3 < p_T < 3$ GeV/c

JHEP 02 (2014) 088

JET TOOLS 2019
Near Perfect Fluid

Shear viscosity to entropy ratio

\[ \frac{\eta}{s} \]

- H$_2$O
- Helium
- Ultracold Fermi Gas
- Quark-Gluon Plasma

Calculation from AdS/CFT

Bayesian Analysis (Duke)
PRC94 (2016) no.2, 024907

Temperature
Near Perfect Fluid

Shear viscosity to entropy ratio

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- \( H_2O \)
- Helium
- Ultracold Fermi Gas
- Quark-Gluon Plasma
- Upsilon
- Light hadron

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Temperature
Agreement between Hard and Soft Probes

Shear viscosity to entropy ratio

\[ \frac{\eta}{s} \]

- \( H_2O \)
- Helium
- Ultracold Fermi Gas
- Quark-Gluon Plasma
- Heavy Quarks
- Upsilon
- Light hadron

Calculation from AdS/CFT

Bayesian Analysis (Duke)
PRC94 (2016) no.2, 024907
Precision Measurement of Hadron $R_{AA}$

- Extraction of jet quenching parameters from hadron spectra
- Large uncertainty from model dependence
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JETSCAPE Collaboration Preliminary

- PHENIX 2008 (0-5%)
- PHENIX 2012 (0-5%)
- $\hat{q}_0 = 0.8, 1.0, 1.2, 1.4, 1.7 \text{GeV}^2/fm$

CMS

- CMS 5.02 TeV
- ALICE 2.76 TeV
- CMS 2.76 TeV
- ATLAS 2.76 TeV

p = 100 GeV

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Vision on Key Measurements
Extraction with hadron spectra can not provide a full picture

To fully utilize the jet as a probe of the QGP:

Need the full understanding of the jet quenching mechanism which include: how the medium modifies the jets and how the jets modify the medium

Q: Why do we need more accuracy?
Quark Gluon Plasma Substructure

Quarks and Gluons

QGP Fluid
“Quark Soup”

AdS/CFT low viscosity goo

Short Wavelength

Long Wavelength
Quark Gluon Plasma Substructure

Quarks and Gluons

QGP Fluid
“Quark Soup”

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What is the structure of QGP at intermediate length scale?

Can we come out with concrete observables and an estimated size of the effects from the jet tool workshop?
Jet Quenching vs. Time

Jet Quenching

Delayed Quenching w/o Monopole

End of Jet Quenching?

Contribute to the understanding of starting time of the jet quenching (QGP)
Jet Quenching vs. Time

Jet Quenching

Delayed Quenching w/o Monopole

End of Jet Quenching?

QCD transport theory (pre-hydro)

Contribute to the understanding of starting time of the jet quenching (QGP)
Currently, we can not separate the three curves using hadron $R_{AA}$ and $v_2$. Jet substructure involving partons with different formation time could help.
Future Measurements
Can we extract QGP properties from jet substructures?

To make an organized effort toward success:

1. Make a complete survey on jet spectra and substructure (choose the basis wisely)

2. Make human understandable measurements which are sensitivity to one dominant effect

3. Need direct (or a concrete strategy) comparisons between the expectations from RHIC and LHC energies
Example 1: Jet $R_{AA}$ vs. $R$
Example 2: Medium Response

Tan Luo, Xin-Nian Wang

Measure the **near-side associated yield** with photon-jet and Z-jet

Ex: Z-hadron correlation, “Z fragmentation function”
3. Complementarity between RHIC & LHC

Change the initial temperature by 100-200 MeV

- Exciting opportunity to extract properties of QGP vs. Temperature
- Could simultaneously vary the QGP geometry by centrality selection

Complications (or opportunity):

- **Spectra slope**: Steeper jet $p_T$ Spectra at RHIC (larger sensitivity to quenching)
- Smaller **initial state radiation** at RHIC at LHC (larger sensitivity at RHIC to dijet / photon-jet azimuthal decorrelation)
- Sampling different part of **nPDF**: led to different quark/gluon composition (RHIC has more quark jets) and purity of photons (RHIC isolated photon has less fragmentation contamination)
- **Larger nuclei passing time** at RHIC than LHC: possible complications from cold nuclear effects at RHIC
- **Au+Au vs. Pb+Pb** (seriously, what’s the point?)
Collective behavior is observed in small systems down to pp
Not observed (yet) in high multiplicity $e^+e^-$
Have we detected jet quenching in small system?
• No suppression observed in pPb collisions from those observables
• Also centrality / activity dependent results:
  Charged Particle $Q_{pPb}$ from ALICE, $R_{dAu}$ in PHOBOS and CMS dijet:
  need higher accuracy and better event classification
Sizable $v_2$ at high $p_T$ in identified hadrons!

- Effect of residual non-flow? Selection bias?
- Indication that CGC and/or Escape Mechanism effects in pPb?

**Crucial elements:**

- Exp: How can we do better in centrality classification?
- Theory: what do we expect? How big is the modification in $R_{AA}$, photon-jet asymmetry and jet substructure in 0.001% pPb collisions?
- What is a good reference?

**Ex:** ref from event generators which are tuned to describe $e^+e^-$ well
In addition, $e^+e^-$ data are the best testing ground for the new jet substructure observables proposed in the jet tool workshop.

Could serve as a validation of the theoretical approach in vacuum and a reference to pp, pA and AA collisions.
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Connection to Electron Ion Collider

Hadronization effect due to the presence of cold nuclear matter

- Full extraction of parton distribution functions and the origin of spin
- Eloss in cold nuclear matter: $O(10)$ smaller effect than hot QCD
- Very clean environment in $e+A$
  Probably hadronization is the main non-perturbative effect
- Difficulty: relatively lower jet $p_T$ reach
Summary

• Jet tool workshop:
  • Show that jet substructure observable could be sensitive to QGP properties
  • Agree on how to do a complete survey on jet spectra and jet substructure measurements
  • Design “smoking gun” observables which are sensitive to a dominant mechanism
  • Show how to utilize the RHIC and LHC data to extract QGP properties vs. Temperature

• Efforts on archived e^+e^- data:
  • Validation of the event generators vs. event multiplicity
  • A testing ground for new ideas from the jet tools workshop
  • Potentially a new reference to the hadron-hadron collisions

• Connection to EIC:
  • Hot QCD experience could help for the extraction of cold QCD matter properties
  • Understanding of cold QCD could help refine the interpretation of hot QCD results
• Backup slides
Jet Longitudinal Structure

Jet shape
“the jet energy distribution” vs. r

Jet Fragmentation function
how transverse momentum is distributed inside the jet cone

Jet shape
“the jet energy distribution” vs. r

Jet Quenching
Medium Response

Energy
pp
PbPb

\[ \rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})} \]

\[ \xi_{\text{jet}} = \ln \frac{|p_{\text{jet}}|^2}{p_{\text{trk}} \cdot p_{\text{jet}}} \]