Experimental results of jet physics in heavy-ion collisions

The 8th Asian Triangle Heavy-Ion Conference (ATHIC 2021)
Invited Session 4: Hard Probes

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Jets in QCD matter

In vacuum (e.g. $p+p$)

In A+A collisions

Bullet in air

Bullet in water

Experimental jet results in AA – Saehanseul Oh
Jets in QCD matter

- **Jets in vacuum**
  - Hard-scattered parton fragments into final state particles \(\rightarrow\) Algorithmic recombination into a Jet
  - Jets in vacuum are well understood in pQCD framework

- **Jets in heavy-ion collisions**
  - Hard-scattered partons are produced at the very early stages of collisions \(\rightarrow\) Interact with QGP as they traverse it
  - Any modifications to jet observables are due to the interaction with the QCD medium \(\rightarrow\) Jet quenching

In vacuum (e.g. \(p+p\))

In A+A collisions

Experimental jet results in AA – Saehanseul Oh
What questions are we trying to answer?

• How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
• How can we use jets to probe the microstructure of the QGP?
• What is the resolution scale of the medium? How can we measure that?
• What can we learn from the mass dependence of jet quenching?
• ...
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Jet observables

- Each jet observable is connected to one or multiple questions – We can probe different aspects of jet quenching
- We measure the same physics in multiple ways – Consistency
Jets in QCD matter

What questions are we trying to answer?

• How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
• How can we use jets to probe the microstructure of the QGP?
• What is the resolution scale of the medium? How can we measure that?
• How to connect measurements and calculations for QCD properties?
• What can we learn from the mass dependence of jet quenching?

What have we found so far?

Jet observables

• Jet energy loss
• Jet substructure modification
• Jet deflection

Jet observables

• Each jet observable is connected to one or multiple questions
  – We can probe different aspects of jet quenching
  – We measure the same physics in multiple ways
  – Consistency?
Jet spectra
Inclusive jet spectra

\[ R_{AA} = \frac{1}{N_{\text{event}}} \frac{d^2 N}{dp_T, n_{\text{jet}} d\eta_{\text{jet}}} \bigg|_{\text{AA}} \],

\[ \langle T_{AA} \rangle \frac{d^2 \sigma}{dp_T, n_{\text{jet}} d\eta_{\text{jet}}} \bigg|_{pp} \]

⇒ Basic measurements of jet yield suppression

CMS, 2.76 TeV, PRC 96 (2017) 015202

ATLAS, 5.02 TeV, PLB 790 (2019) 108-128

ALICE, 5.02 TeV, PRC 101 (2020) 034911

• Most models reasonably describe data – more differential measurements needed

Experimental jet results in AA – Saehanseul Oh
Inclusive jet spectra

\[ Jet \ R_{AA} = \frac{1}{N_{\text{event}}} \frac{d^2N}{dp_{T,\text{jet}}d\eta_{\text{jet}}} \frac{\langle T_{AA} \rangle}{\frac{d^2\sigma}{dp_{T,\text{jet}}d\eta_{\text{jet}}}} \]

- No clear \( R \) dependence or collision energy dependence at the LHC at standard \( R \)
- Consistent \( R_{AA} \) values from different collaborations (Different \( \eta_{\text{jet}} \), systematics)
- What about at RHIC energies?
Inclusive jet spectra

\[
R_{AA} = \frac{\frac{1}{N_{\text{event}}} \frac{d^2 N}{dp_{T,\text{jet} \cdot d\eta_{\text{jet}}}}_{\text{AA}}}{\langle T_{\text{AA}} \rangle \frac{d^2 \sigma}{dp_{T,\text{jet} \cdot d\eta_{\text{jet}}}}_{\text{pp}}}
\]

- Inclusive charged-particle jet spectra at 200 GeV Au+Au collisions with respect to PYTHIA
Inclusive jet spectra

- Jet $R_{CP}$ – Comparison between central and peripheral collisions

- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

Experimental jet results in AA – Saehanseul Oh
Inclusive jet spectra

- Jet $R_{CP}$ – Comparison between central and peripheral collisions

- Consistent and similar level of jet yield suppression observed at different collision energies and different $R$

- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

STAR, 0.2 TeV, PRC 102 (2020) 054913

Experimental jet results in AA – Saehanseul Oh
Semi-inclusive jet spectra

- Semi-inclusive jet measurements
  - Jets in the recoil region of high-$p_T$ trigger particles
  - Correlated vs. uncorrelated contributions with respect to the trigger particle → Effective removal of the latter
  - Capability to access lower $p_{T,jet}$

Experimental jet results in AA – Saehanseul Oh

Semi-inclusive jet spectra

- $I_{CP}, I_{AA}$ = The ratio of recoil jet yields in central to peripheral or $pp$ distributions

- Similar level of suppression via $I_{CP}$ to charged-particle jet $R_{CP}$ at 200 GeV

Experimental jet results in AA – Saehanseul Oh
In addition to $R_{AA}$ or $l_{AA}$, jet yield suppression can be quantified with $-\Delta \rho_T$.
Inclusive and semi-inclusive jet spectra

- In addition to $R_{AA}$ or $I_{AA}$, jet yield suppression can be quantified with $-\Delta p_T$

- At RHIC, similar energy loss for different channels of measurements
- At the LHC with higher $p_{T,\text{jet}}$, indication of larger energy loss than RHIC for $h+\text{jet}$ measurements
- Further $-\Delta p_T$ quantification for other spectrum measurements is needed

Experimental jet results in AA – Saehanseul Oh
Inclusive jet spectra at larger jet $R$

- Jet $R_{AA}$ at higher jet $R$ – Wider jets more suppressed? Quenched energy toward larger $R$?

- No strong dependence on jet radius persists at large $R$ ($=1.0$) and high $p_T^{jet}$ (1 TeV/c)

- Significant tension between models – Further constraints on the underlying jet quenching mechanisms
Jet substructure observables
Jet substructure observables

- Given the jet energy loss in the medium, how is the shower modified when a jet traverses the medium?

- Do these jets quench differently in QCD medium? What is the resolution scale of the medium?
Groomed jet substructure

- Jet grooming via SoftDrop: \( \frac{\min(p_{T,1}p_{T,2})}{p_{T,1}+p_{T,2}} > z_{\text{cut}} \left( \frac{\Delta R}{R} \right)^\beta \)

- Comparison between A+A and smeared pp results

- Steeper \( z_g \) distributions in central Pb+Pb collisions – parton splitting process is modified by the medium
Groomed jet substructure

- Background fluctuations in heavy-ion environment result in an incorrect splitting being identified by the grooming algorithm.
- Smaller $R$ jets, increased $z_{cut}$ in SD, using semi-central collisions.

- $z_g$ distributions in Pb+Pb collisions are consistent with those of $pp$ collisions within experimental uncertainties.

Experimental jet results in AA – Saehanseul Oh
Groomed jet substructure

- Background fluctuations in heavy-ion environment result in an incorrect splitting being identified by the grooming algorithm.
- Smaller $R$ jets, increased $z_{\text{cut}}$ in SD, using semi-central collisions.
- Suppression (enhancement) of large (small) angles – Qualitative description by models.
Jet substructure with subjets

- Reclustering jets with smaller resolution parameter ($r < R$) with the original jet constituents
- Subjets are proxy for the hardest shower splitting
Jet substructure with subjets

- Reclustering jets with smaller resolution parameter \((r < R)\) with the original jet constituents
- Subjets are proxy for the hardest shower splitting

\(\theta_{SJ} = \text{Distance between two hardest subjets}\)

Is jet quenching different for two \(\theta_{SJ}\) classes?
Jet substructure with subjets

**HardCore jets**

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

**Matched jets**
No significant difference between $\theta_{SJ}$ classes

- No observational evidence of characteristic signature of coherent or de-coherent energy loss
- Larger resolution/coherence length of the medium
Jet substructure with subjets

\[ \sqrt{d_{12}} = \min(p_{T,1}^2, p_{T,2}^2) \times \Delta R_{12}^2 \]

- Small \( \sqrt{d_{12}} \) dependence for jets with a complex substructure, i.e. \( \sqrt{d_{12}} > 0 \) jets
- Significant difference in jet quenching between jets with a single subjet and jets with multi-prong structure

\[ \sqrt{d_{12}} = 0 \rightarrow \text{Single isolated subjet} \]
Other jet observables
Jet acoplanarity

- Angular decorrelations between a trigger particle and its recoil jet – Are we seeing discrete scattering centers or effectively continuous medium?

- Narrowing in central Pb+Pb collisions ⇐ due to negative radiative correction to $\langle p_T^2 \rangle$? (Zakharov, EPJC 81 (2021) 57)
J/ψ in jets

- Jets containing a prompt (or inclusive) J/ψ
  - J/ψ produced with a larger degree of surrounding jet activity are more suppressed – Need to incorporate jet quenching + J/ψ suppression?
  - Further results coming at RHIC energies

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J/ψ in jets

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Experimental jet results in AA – Saehanseul Oh
There are more results deserved to be mentioned...
jets provide unique tools to study hot dense QCD medium
- Jets in vacuum and in-medium: theoretically well controlled in many aspects (but not all)
- Broad kinematic reach: probe the medium over a wide range in scale
- Complex structure: many complementary observables that probe similar physics – require consistent picture

experimental jet results
- Jet $R_{AA}$ and $I_{AA}$ show consistent values for different $R$ and collision energy
- Parton splitting process is modified by the medium
- Jet classification based on subjet distance can shed light on medium resolution scale
- Further results expected to be presented at QM 2022, and more data coming with LHC Run 3, and RHIC 2023-2025 run with advanced detectors
Thank you!
Jet substructure with subjets

- ATLAS measurements using reclustered large-R jets

\[
\sqrt{d_{12}} = \min\left(p_{T,1}^2, p_{T,2}^2\right) \times \Delta R_{12}^2
\]

with two jets before the final clustering step
Jet substructure with subjets

- ATLAS measurements using reclustered large-$R$ jets

- Reclustered jets are different to the conventional $R = 1.0$ jets

-Trimming and 35 GeV/c threshold remove soft components
Jet substructure with subjets

Utilizing subjets, i.e. reclustering

ATLAS, 5.02 TeV

- Small $\sqrt{d_{12}}$ dependence for jets with a complex substructure, i.e. $\sqrt{d_{12}} > 0$ jets
- Significant difference in jet quenching between jets with a single subjet and jets with multi-prong structure