An overview of recent RHIC and LHC Jet Measurements

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Jets: Theorist View

JETS: Colored partons from the hard scatter (2→n)
- Fragmentation via gluon radiation
- Hadronization: “spray” of colorless hadrons

Parton Level: Calculable with pQCD
Underlying Event: Beam remnants ➔ Soft Background


... and many more
Jets: Experimentalist View

Back-to-back asymmetric jets

Snow Mass Acord:
Experimental and theoretical definitions of jets must match!
Underlying event is the hardest to match.
Diagnosing medium: pass a QCD-sensitive internal probe through it, then look for any modifications due to the medium.
To learn about the medium:

• Look at elementary/smaller collision systems
  – Measure an observable (e.g., in this case jet production)

• Look at Heavy Ion collisions
  – Measure the same observable as we do in elementary/smaller system
  – Compare them, is there something new?
A Simple Physics Observable:

Yield in A+A Events

\[ R_{AA} \equiv \frac{N_{\text{bin}}(\text{Yield in p+p Events})}{\text{Yield in A+A Events}} \]

When reference measurement is not available look instead to smaller systems like peripheral events and construct the Rcp.

If no “effects”:
- \( R < 1 \) in regime of soft physics
- \( R = 1 \) at high-\( p_T \) where hard scattering dominates
Jet $R_{AA}$ @ LHC

Jets appeared to be quenched in a collision energy independent way!

Jet $R_{AA}$ radius dependence @ LHC

No strong dependence on jet radius!

What about larger radii?

No strong dependence on jet radius persists at high pt and large R!

CMS, arXiv:2102.13080
The choice of $\Delta E$ can emulate the RAA suppression. 
Same shape of spectra: No R dependence: Same RAA for the same $\Delta E$
Theoretical Challenges: Rigorous calculations of jet variables “Model building of in-medium modifications...”

• Jewel (Jet Evolution With Energy Loss): K. Zapp et. Al. Medium recoil parton (Parton shower with microscopic description of interactions with medium – random process of scattering is used to modify the formation time of the radiated gluon.)

• Q-Pythia: N. Armesto et. Al.

MC implementation in Pythia of medium-induced gluon radiation through an additive term in the vacuum splitting functions.

• Many others .... Martini (S. Jeon), YaJEM (T. Renk) PYQUEN (Lokhtin, Snigriev), PQM (Dainese, Loizides, Paic), HIJING (Gyulassy, Wang)...

Analytic Calculations: Vitev et. al., Borghini et al.
SCET$_G$: Splitting function (large angle radiation)
CCNU: recoil parton + hydro dynamical evolution

Not a complete list...

Measure various jet observables that have different sensitivities!
Confronting LHC large jets with realistic calculations: CMS arXiv:2102.13080

Significant tension remains in view of the large jets.

Further constraints on the underlying jet quenching mechanisms.
No strong dependence on jet radius in low pt kinematic range!

STAR, Phys. Rev. C 102 (2020) 054913

When we don’t have precision pp reference:
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Similar magnitude of suppression at RHIC and the LHC

STAR, Phys. Rev. C 102 (2020) 054913
A Simple Physics Observable – Nuclear Modification Factor:

High $p_T$ $\pi^{\pm}$ suppressed in peripheral events

Geometric biases (on initial $nn$ impact parameter) $\rightarrow$ Centrality selection biases.

A Simple Physics Observable – Nuclear modification Factor:
We need to be careful but there is hope!

High $p_T$ $h^\pm$ suppressed in peripheral events

Geometric biases (on initial $nn$ impact parameter) $\rightarrow$ Centrality selection biases.

Peripheral $Z$ boson yields are also suppressed

New data driven methods to study this bias!
Heavy Flavour Dependence

Bottom and charm tagged jets are selected on displaced vertices.

**3+ Body Secondary Vertex Tagging:**
- light vs c

Feed into template shapes
- charm jet contribution extracted

**Corrected Secondary Vertex Mass:**
- c vs b

![Diagram](image)
Heavy Flavour Dependence

Suppression of $b$ quarks in PbPb, while no apparent suppression in pPb collisions

Explore with future RHIC data!

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Caveat: b/c jet might not be original!

Huang, Kang, Vitev et al.

At high pt region, mass effect can be neglected

Explore multi tags such as c/b jet with D/B and γ.

\[ \text{R}_{\text{gluon}}: \text{fraction of g} \rightarrow \text{b} \]
\[ \text{R}_b: \text{fraction of b} \rightarrow \text{b} \]
\[ \text{R}_{\text{other}}: \text{fraction of q} \rightarrow \text{b} \]
Jet Morphology: Angular and Momentum Structures

At small angles: Most of the $p_T$ and carried with high $p_T$ constituents

At large angles: Small fraction of $p_T$ and carried with softer constituents

Jets are quenched! How? Need to explore jet inner-workings.
Many Jet Shape Observables:

- **Jet Mass**
  \[ M = \sqrt{E^2 - p_T^2 - p_Z^2}, \]
  Measures how spread out the constituents of the jet are.

- **Momentum dispersion** \( p_T^D \): (Energy Sharing)
  \[ p_T^D = \sqrt{\sum_i p_T^2, i / \sum_i p_T, i} \]
  Measures 2nd moment of the constituent \( p_T \) distribution in the jet and is connected to how hard or soft the jet fragmentation is.

- **Radial moment**
  \[ g = \sum_i \frac{p_T, i}{p_T, jet} |\Delta R_i| \]
  Measures 1st radial moment or angularity and is sensitive to collimation / broadening of a jet.

- **LeSub**:
  \[ LeSub = p_{T,track}^{lead} - p_{T,track}^{sublead} \]

- **Fragmentation function (FF)**:
  \[ FF(z) = \frac{1}{N_{jet}} \frac{dN}{dz} \]

- **Differential jet shape**:
  \[ \rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{jets}} \sum_{\text{tracks} \in (r_a, r_b)} \frac{\Sigma \text{tracks} p_{T}^{trk}}{p_{T}^{jets}} \]

- **Jet Charge**:
  \[ Q^\kappa = \frac{1}{(p_T^{jet})^\kappa} \sum_{i \in \text{jet}} q_i (p_T^i)^\kappa. \]

Not an inclusive list but examples of jet substructure measurements that are currently being used as tools to disentangle different kinds of jets and study the effects of QGP.
Jet Mass @ RHIC

Baseline for measurements in heavy-ion collisions at RHIC

Well-described by the RHIC-tuned PYTHIA-6 Perugia 2012, others fail providing crucial input for further RHIC tunes.

STAR, arXiv:2103.13286,
Jet Mass @ LHC

Well-described by the LHC-tuned PYTHIA-6 Perugia 2011,

Tension between data & quenching models!

An example in pp: Quark-gluon discrimination

Compared to gluon jets, quark jets in vacuum have:
1. Fewer constituents
2. Narrower shape
3. Harder fragmentation function and less symmetric energy sharing among constituents

1. Multiplicity: Total, Charged, Neutral → Particle-Flow in CMS
2. Width Variables

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}
\]

obtained by diagonalizing

\[
\frac{1}{\sum_i p_{T,i}^2} \sum_i p_{T,i}^2 \left( \frac{(\Delta \phi_i)^2}{(\Delta \eta_i \Delta \phi_i)} \frac{(\Delta \phi_i \Delta \eta_i)}{(\Delta \eta_i)^2} \right)
\]

3. Energy Sharing Variable: \( p_T D \)

\[
p_T D = \sqrt{\frac{\sum_i p_{T,i}^2}{\sum_i p_{T,i}}} \]

\( p_T D = 1 \) single jet constituent
\( p_T D = 0 \infty \) number of jet constituents.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

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Quark-gluon discrimination:

Likelihood based discriminator obtained by combining 3 variables:
- Total multiplicity
- Minor axis
- $p_T^D$  

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Quark-gluon discrimination:

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https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

quark/gluon discrimination is difficult, but not impossible in pp

Might not be directly applicable to AA but combine it with other taggers.
Can we learn something about Quark vs Gluon jets through observables alone?

pp distributions are well represented by Pythia!
Can we learn something about Quark vs Gluon jets through observables alone?

Discrepancies between PbPb distributions and Pythia!

JHEP10(2018)139
Can we learn something about Quark vs Gluon jets through observables alone?

Fragmentation resembles that of quark jets in vacuum. A useful bias to investigate at RHIC energies.
Jet Charge: Another approach for Quark/Gluon-like jets

\[ Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{i \in \text{jet}} q_i (p_T^i)^\kappa. \]

\( \kappa \) parameter adjusts sensitivity of jet-charge to high/low \( p_T \) tracks

\( \kappa = 0.5 \rightarrow \) most sensitive to parton charge initiating jet! [according to theory]

quark/gluon jet fractions extracted with template-fitting method

• Use PYTHIA and PYTHIA+HYDJET for pp/PbPb model
Quark/Gluon-like Jet Fractions

No significant modification of quark/gluon jet fraction in PbPb
Contradicts expectations of some jet quenching models
Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis

\[ \rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (r_a, r_b)} p_{T}^{\text{trk}}}{p_{T}^{\text{jets}}} \]

Averaged over many jets
Change in Jet Morphology as seen with CMS @ LHC:

**Jet Shapes:** Structure of reconstructed jets modified towards an excess of particles far from the jet axis.

**Fragmentation Functions:** Structure of reconstructed jets is modified towards an excess of particles at low $p_T$. 

*Note:* All graphs are labeled with references to their source papers.
Jet Shapes @ LHC:

Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis.

Jet Shapes of $\gamma + \text{jet}$: Structure of reconstructed mostly quark-jets is modified towards an excess of particles from the jet axis.
Jet Shapes @ RHIC:

Event plane dependence is studied with low kinematic range jets.

- Hints of low-$p_T$ tracks pushed toward farther distances in out-of-plane relative to in-plane
- Above 2 GeV/$c$, results are consistent with each other
  Less steep than @ LHC energies
Flavored Jet Shapes @ LHC:

CMS $\sqrt{s} = 5.02$ TeV, $\int L dt = 27.4$ pb$^{-1}$, anti-$k_T$ jet (R=0.4), $p_T^{\text{jet}} > 120$ GeV, $|\eta_{\text{jet}}| < 1.6$

Inclusive jets $\rho(\Delta r)$

$b$ jets $\rho(\Delta r)$

$\rho(\Delta r)$ vs $\Delta r$

Primary Vertex $L_{xyz}$

Secondary Vertex

Important reference for the future studies of flavor effects for parton interactions with QGP.
Simulations show different jet shape predictions at large angular distances, where nonperturbative contributions are likely to dominate.
Flavored Jet Shapes @ LHC

The radial distributions of the total charged-particle yields:

- Larger radial distances are only well-estimated by HERWIG++

Constraints on pQCD calculations for flavor dependencies in parton
D⁰ Radial distributions @ LHC

Hint of a diffusion of charm quarks in the medium created in heavy ion collision

*Phys. Rev. Lett. 125 (2020) 102001*
**D⁰ Radial distributions @ RHIC**

Access to lower p_T

D⁰ meson angular correlation as the proxy.

**D⁰**-hadron (D⁰ → π±K∓)

Similar width and yield to light-flavor correlations

Charm-quark interaction with the medium is similar to light-flavor interaction with the medium.

*STAR, Phys. Rev. C 102 (2020) 14905*
**J/ψ in a jet @ LHC & RHIC**

More suppression at low $z$:

J/ψ produced with a large degree of surrounding jet activity are more highly suppressed than those produced in isolation.

More J/ψ in jets in data:

J/ψ populate lower values of $z$ than predicted by PYTHIA at LHC & RHIC → Further tuning of models/calculation.
Utilize tools developed for pp - Jet Grooming: the systematic removal of a subset of the jet constituents → remove soft and wide-angle radiation from the jet

High-$p_T$ regime: $p_T > 2m/R$

Decay is collimated i.e., $qq$ are in the same jet.

Grooming systematically removes jet constituents in order to reduce contamination from initial-state radiation (ISR), underlying event (UE), and multiple parton-parton/proton-proton collisions (MPI/pileup).
Utilizing Jet Grooming

large-angle soft radiation and bkg removed by grooming!

\[ z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \]

- Splitting functions appear to be universal.
- Calculation shows weak dependence on the jet of the vacuum jet splitting function

Utilizing Jet Grooming @ LHC

large-angle soft radiation and bkg removed by grooming!

Two hard subjets (large Zg) more suppressed than the ones with a single core (small Zg)
(Or small Zg is enhanced)

Momentum sharing between two leading subjets

Modification of splitting of inclusive jet measurements!
Utilizing Jet Grooming @ RHIC

Good agreement between data and RHIC-tuned PYTHIA 6
Utilizing Jet Grooming @ RHIC

large-angle soft radiation and bkg removed by grooming!

\[ z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \]

Contrast to LHC results

\( \rightarrow \) Different population of jets, time of split, kinematics, dilution, …

No significant splitting modification on near-or away-side at RHIC

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Conclusions

Jet Tomography has been explored with multiple jet substructure & constituent observables at various kinematic ranges @ RHIC & LHC.

Need to characterize medium parton interactions in detail with experiments and theory simultaneously!

Requires continuous interaction between Experiment & Theory

With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.

— John von Neumann —