Jet production and correlations in heavy ion collisions

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Heavy Ion Collisions

- Heavy Ion collisions can produce a state of deconfined nuclear matter called the Quark Gluon Plasma (QGP)

- Enables the study of properties of the strong force normally hidden behind confinement

- Through the comparison of yields in heavy ion collisions to $pp$ one can understand the properties of interactions with the QGP
Jets as Probe of the Quark Gluon Plasma

- Jets are correlated cones of particles produced through the evolution of high $p_T$ partons produced in hard QCD interactions
  - Produced early in the collision

- In heavy ion collisions the partons interact with the nuclear medium resulting in an effect known as jet quenching
Nuclear Modification of jet production at LHC

Partons produced in hard scattering lose energy as they traverse the nuclear medium resulting in ‘jet quenching’

Significant energy loss for $R = 0.4$ jets is observed across centrality.

$$R_{AA} = \frac{1}{N_{evt}} \frac{dN_{PbPb}}{dp_T dy} = \frac{1}{N_{evt}} \frac{dN_{PbPb}}{dp_T dy}$$

2015 data: Pb+Pb 0.49 nb$^{-1}$, pp 25 pb$^{-1}$
Nuclear Modification of jet Production at LHC

➢ ALICE has measured the $R_{AA}$ for $R = 0.2$ and $R = 0.4$ jets down to lower $p_{T,\text{Jet}}$ in central Pb+Pb

➢ Observes no evidence for size dependence to suppression between $R = 0.2$ and $R = 0.4$ jets
Nuclear modification factor: Radius Scan

- Sensitive to balance between increasing radiative sources and recovering re-distributed energy
- No modification from $R_{AA}^{0.2}$ is observed for 30-90% events out to 400 GeV
- Potential for minor enhancement of large R Jets is observed 0-30% events in 400-500 GeV
- CMS observes no radius dependence to the $R_{AA}$ in 0-10% central Pb+Pb for 500 GeV < $p_T^{jet}$ < 1 TeV
  - Potential relative suppression observed for large R jets in 10-30%
Nuclear modification factor: Radius Scan

- Sensitive to balance between increasing radiative sources and recovering re-distributed energy
- No modification from $R_{AA}$ is observed for $30-90\%$ events out to $400$ GeV
- Potential for minor enhancement of large $R$ Jets is observed in $0-30\%$ events in $400-500$ GeV
- CMS observes no radius dependence to jet energy loss in $0-10\%$ central Pb+Pb for $500$ GeV $< p_T^{\text{Jet}} < 1$ TeV
- Potential suppression observed for $10-30\%$

It enables simultaneous comparisons of model calculations across jet Radii.
➢ Similar level of jet and charged hadron suppression observed at RHIC and LHC energies
➢ Different underlying spectral shapes at 200 GeV versus 2.76 TeV

➢ No clear evidence for jet size or $p_T$ dependence to the $R_{CP}$ observed by STAR

Look forward to future jet measurements from sPHENIX!
Nuclear Modification of Jets in Cu+Au

- Clear centrality dependence to modification
- No significant $p_T$ dependence observed
- Similar suppression as seen in 0-20% Cu+Au events as observed in Au+Au ($R_{CP}$) and Pb+Pb ($R_{AA}$) collisions
Global Bayesian Analyses

Theory collaborations use $R_{AA}$ measurements from both RHIC and LHC experiments in Bayesian analyses to extract insight on the QGP properties

- Recent publications by Weiyao Ke and Xin-Nian Wang, as well as the JETSCAPE collaboration highlight extractions of jet transport coefficient $\hat{q}$

[Graph showing $\hat{q}_T/T^3$ vs $T$ for different $p$ values]
Probing Jet Energy Loss

• Dijet Momentum Balance
  ➢ Sensitive to path length dependent energy loss and fluctuations

• Jet $v_n$
  ➢ Path length dependent energy loss can cause enhanced jet yield in-plane vs. out-of-plane: positive $v_2$
  ➢ $v_{3+}$ can give insight to the role of initial state fluctuations to jet quenching
Back-to-back dijet pairs in $pp$ collisions strongly favor symmetric momentum.

In Pb+Pb collisions observe significant enhancement of asymmetric dijets.

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$
DiJet Momentum Balance

\[ x_J = \frac{p_{T,2}}{p_{T,1}} \]

Observe significant suppression of symmetric dijets in Central Pb+Pb across jet \( p_T \)

- subleading jet loses more energy than the leading jet potentially due to traversing a larger distance in the medium

\[ x_J = \frac{p_{T,2}}{p_{T,1}} \]
Jet $v_2$

ATLAS observes for $R = 0.2$ Jets a significant 1-4% jet $v_2$ on inclusive jet $p_T$

$\triangleright v_2$ is enhanced in more elliptical initial states (mid central, peripheral)
Jet $v_2$

- Jets observed at 5.02 TeV by ATLAS observe similar $v_2$ to charged hadrons at 5.02 TeV by CMS.
- ALICE measured systematically larger Jet $v_2$ in 0-5% events at $\sqrt{s_{NN}} = 2.76$ TeV than other measurements.
Jet $\nu_3$

No evidence observed in ATLAS or CMS for non-zero $\nu_3$
Summary and Outlook:

➢ Many exciting measurements of jet production and correlations from both LHC and RHIC experiments
  • Too many to have covered here

➢ Ongoing developments and improvements in theory allows for comparisons providing insight to the properties of interactions with the QGP

➢ Look forward to results using high luminosity run 3 LHC data and from the future sPHENIX experiment
  ➢ See Yeonju Go’s talk in this session
backups
Dijet momentum balance: 2.76 TeV

- At $\sqrt{s_{NN}} = 2.76$ TeV ATLAS observed an enhancement of dijets with $x_J \approx 0.5$ for $p_{T,1} > 100$ GeV

- By 126 GeV the observed peak has faded and the distribution is consistent with flat for $x_J > 0.5$
$\rho$ is proportional to track momentum density in a radius window.

Clear depletion of momentum near the core of the jet for the subleading jet.

Clear enhancement of momentum carried near the edges of the subleading jet compared to the leading jet.

Quenched jets observe significant broadening.