Probing Hadronization via Measurement of EECs in $pp$ Collisions at STAR

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Jets and Hadronization

- Jets are proxies for hard-scattered partons
- Clustered from final state particles using a jet finding algorithm
- Testing energy evolution of parton shower in time.

Formation Time: \( t_f \propto \frac{1}{\Delta R^2} \)

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Energy Energy Correlators (EEC)

- Use all final state charged particles, and examine how energy is distributed as a function of their separation.
- Allows for study of jet evolution using final state jet constituents as they are, no additional grooming after jet-finding.
Energy Energy Correlators (EEC)

\[
\text{ENC}(R_L) = \left( \prod_{k=1}^{N} \int d\Omega_{\vec{n}_k} \right) \delta(R_L - \Delta \hat{R}_L)
\]

\[
\frac{1}{(E_{\text{jet}})^N} \langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N) \rangle
\]

Normalized EEC = \[ \frac{1}{\Sigma_{\text{Jets}} \Sigma_{i \neq j} E_i E_j / p_{T,\text{Jet}}^2} \]

\[ d \left( \Sigma_{\text{Jets}} \Sigma_{i \neq j} \frac{E_i E_j}{p_{T,\text{Jet}}^2} \right) d (\Delta R) \]

Note: Energy assumes pion mass

- Use all final state charged particles, and examine how energy is distributed as a function of their separation
- Allows for study of jet evolution using final state jet constituents as they are, no additional clustering or grooming after jet-finding

Chen et al. 2020, PRD 102, 5
Relate This to Jet Evolution

Normalized EEC = \frac{1}{\sum_{jets} \sum_{i\neq j} \frac{E_i E_j}{p_{T,jet}^2}} \frac{d \left( \sum_{jets} \sum_{i\neq j} \frac{E_i E_j}{p_{T,jet}^2} \right)}{d (\Delta R)}

*Constant of proportionality is dependent on initiating parton flavor/mass

- Behavior at low $\Delta R$ corresponds to a random distribution of hadrons, while behavior at high $\Delta R$ is influenced by parton shower—Study Transition Region

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$p_T^{Jet}$ Correction Method

- Inform correction via use of PYTHIA6 (Truth) and PYTHIA6 + GEANT Embedded in min-bias data (Reconstructed)
- Match jets between Truth and Reconstructed samples within a $\Delta R$ of 0.4 and then match constituents inside of jets within a $\Delta R$ of 0.02 and form response matrix

- Preliminary results use a correction procedure in which $p_{T,jet}$ is the only variable in which a response matrix is formed
  - Detailed in arXiv:2309.05761
  - Planning to expand to full three-dimensional unfolding
First EEC Measurement at RHIC

15 < Full Jet $p_T < 20$ GeV/c

$\text{Normalized EEC}$

$\Delta R$

$\text{p+p, } \sqrt{s} = 200$ GeV
Constituent $p_T > 0.2$ GeV/c
Jet $R = 0.4$, $|\eta_{\text{jet}}| < 0.6$
$15 < \text{Jet } p_T < 20$ GeV/c

30 < Full Jet $p_T < 50$ GeV/c

$\text{Normalized EEC}$

$\Delta R$

$\text{p+p, } \sqrt{s} = 200$ GeV
Constituent $p_T > 0.2$ GeV/c
Jet $R = 0.4$, $|\eta_{\text{jet}}| < 0.6$
$30 < \text{Jet } p_T < 50$ GeV/c
Monte-Carlo Comparison

- PYTHIA 8 Detroit Tune describes behavior well

Aguilar et al., PRD 105, 016011

\[ \frac{15 < \text{Jet } p_T < 20 \text{ GeV/c}}{\text{Normalized EEC}} \]

\[ \frac{30 < \text{Jet } p_T < 50 \text{ GeV/c}}{\text{Normalized EEC}} \]

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Theoretical Comparison ($R = 0.4$)

- **Theoretical comparison calculated in the Perturbative Region ($3 \text{ GeV} < p_T < 0.6$ with $15 < p_T^{\text{jet}} < 20 \text{ GeV/c}$)

- Behavior agrees well with directly calculable theoretical expectations!

- Low angle behavior compared with toy model of hadrons, assuming uniform energy distribution

- Transition region moves to lower angles with increasing momentum – want to quantify this


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$p_T$-Shifted Distributions

- Shift Corrected Result on x axis by average $p_{T,\text{jet}}$ in a given bin
- As location of transition $\propto \frac{\Lambda_{\text{QCD}}}{p_{T,\text{jet}}}$, this will collapse it onto a single point
- In this case, average momentum is determined via PYTHIA and applied post-correction

< $p_{T,\text{jet}}$> $\Delta R_{\text{Turnover}} \sim 2 - 3$ GeV
Comparison with ALICE and CMS Results

- Also measured by CMS and ALICE

\[ p_{T,\text{Jet}} \rightarrow \Delta R_{\text{Transition}} \]

- Can further test universality of \text{Turnover} \propto \frac{\Lambda_{\text{QCD}}}{p_{T,\text{Jet}}} \text{ by scaling with } p_{T,\text{Jet}}

CMS: \text{Lu, BOOST 2023}  
ALICE: \text{Fan, Quark Matter 2023}
Comparison with ALICE and CMS Results

- STAR Result is roughly consistent with both CMS and ALICE results – across a large gap in jet momentum
- EEC scaled to have value at peak be one to more directly compare peak locations
- Quark, gluon fragmentation differences ➞ transition shift
Impact of Quark/Gluon Fraction

- Observed turnover region for ALICE result occurs at larger $\langle p_{T,\text{jet}} \rangle$ $\Delta R_{\text{Turnover}}$
- This is largely due to difference in quark/gluon fraction as gluons fragment to larger angles
- Magnitude of effect can be approximated in simulation:

\[
\begin{align*}
R &= 0.4 \\
\left|\eta_{\text{jet}}\right| &< 0.6 \\
\text{Constituent } p_T &> 0.2 \text{ GeV/c}
\end{align*}
\]

\[
\sqrt{s} = 200 \text{ GeV} \quad \text{Quark Dominated}
\]

\[
\sqrt{s} = 13 \text{ TeV} \quad \text{Gluon Dominated}
\]

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Outlook

• New Unfolding method will allow for more accurate measurement of $p_{T,\text{jet}}$-shifted distributions

• **Like** and **Opposite** Sign Charged Correlators will further elucidate fragmentation
  
  *Lee, Moult (2023): arXiv:2308.00746*

• Future applications in heavy ions
  
  *Andres et al. Phys. Rev. Lett. 130 (2023) 26, 262301*

• Higher order correlation functions
  
  • **See talk by Ananya!**
Conclusions

- EEC is an exciting observable that probes jet evolution across both perturbative and non-perturbative regions

- Dependence on jet $p_T$ provides insight into hadronization via the transition region
  - Universality expected in theory observed alongside separation of quark/gluon peaks

- **First measurement of EEC at RHIC**
  - Paper in Progress
Backup
Systematic Uncertainties – Detector Effects Simulation

Impact of Detector on EEC outside of $p_T^{Jet}$

- Treat Percentage difference between Truth and Detector level for MATCHED Jets as an uncertainty

- Approximates Detector effects assuming jet $p_T$ was corrected successfully

- Hovers around unity in hadron, quark/gluon and Transition regions, do not need to correct in addition to $p_T^{Jet}$

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PYTHIA Simulation – Quark and gluon fraction at different center of mass energies

Fraction of Quarks and Gluons that make up the EEC distribution at two different center of mass energies as a function of jet momentum, taking into account number of correlations and energy weighting.
As shape correction needed is small, systematic uncertainties determined for the correction procedure are small.

**Hadronic Correction**
- Varied from 100% to 50%

**Tower Scale Variation**
- Varied $\pm$ 3.8%

**Tracking Efficiency**
- 4% Uncertainty

**Maximum Detector Variation**
- Previous Slide
Theoretical Comparison (R = 0.6)

- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{p_T^{\text{Jet Low}}} < \Delta R < \text{Jet R}$) received directly from Kyle Lee, MIT.
- Behavior agrees well with directly calculable theoretical expectations!
As $p_T$ correction needed is small, systematic errors determined for the correction procedure is small.

To capture range for variation, compare with maximum Geant variation within corrected $p_T$, the percentage difference between measured and truth level distributions for matched jets.
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