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

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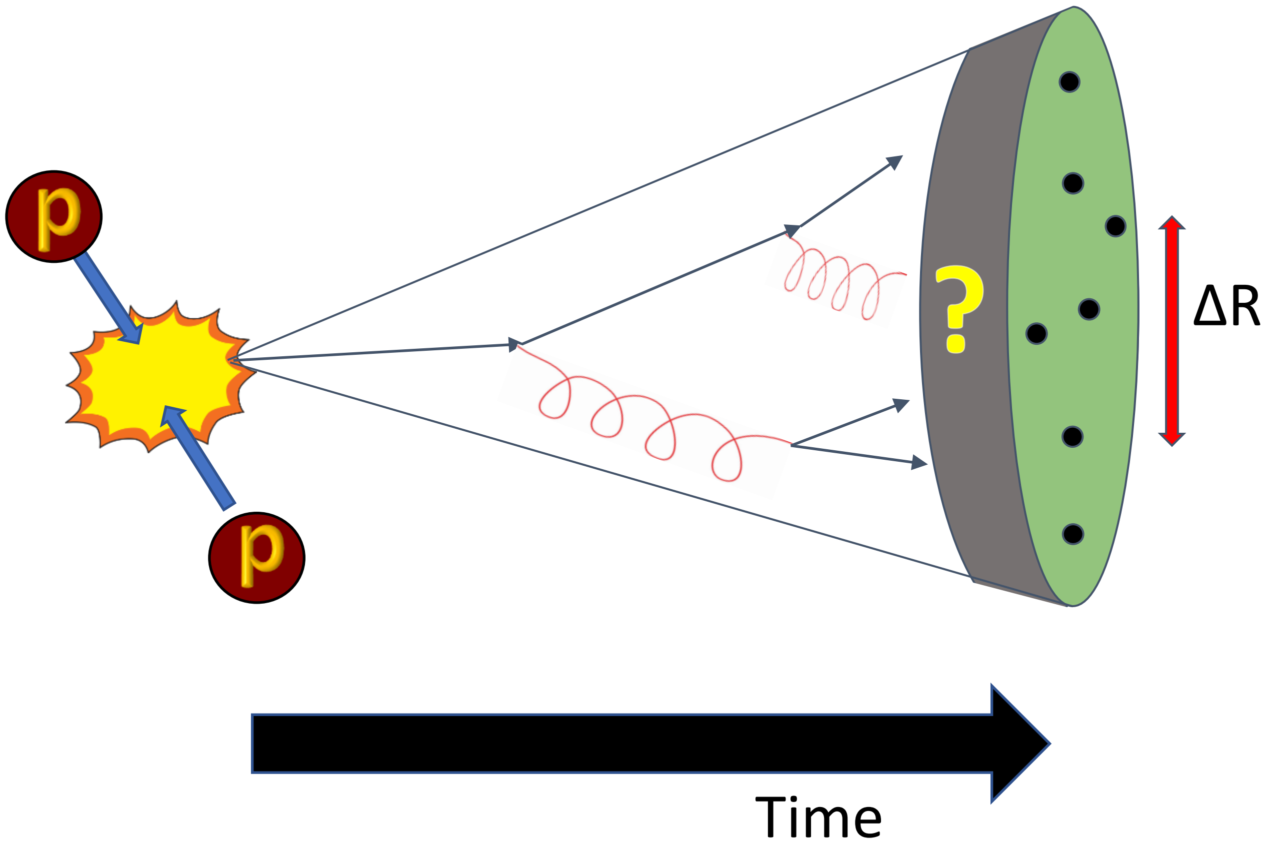
Jets and Hadronization

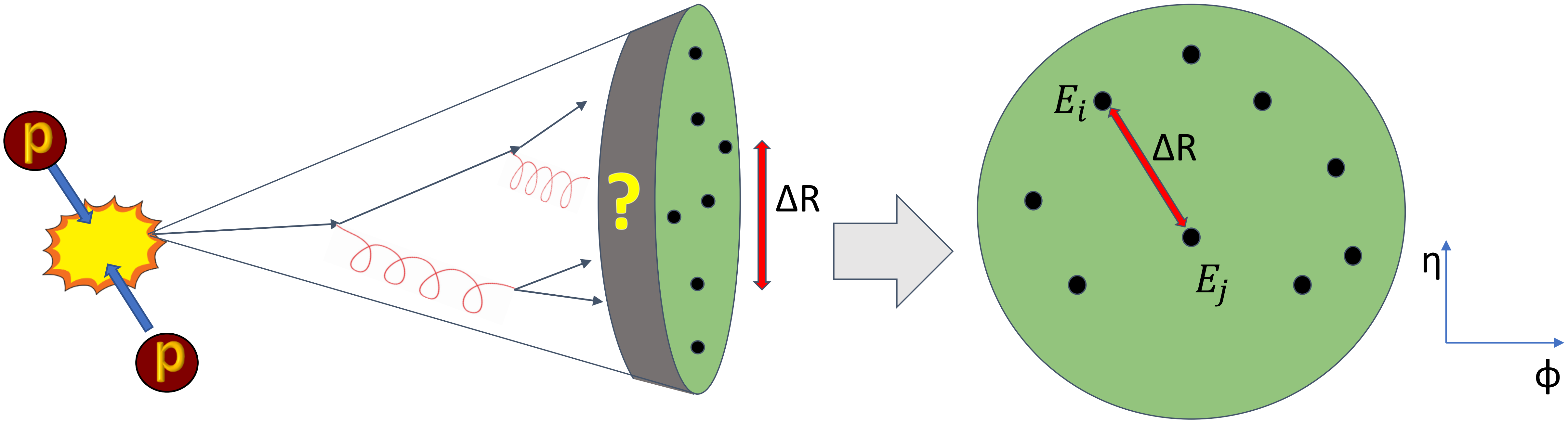


- **Jets are proxies for hard-scattered partons**
- Clustered from final state particles using a jet finding algorithm
- Testing energy evolution of parton shower in time.

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

Cacciari et al. JHEP 0804:063 (2008)

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)

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta(R_L - \Delta\hat{R}_L) \cdot \frac{1}{(E_{\mathrm{jet}})^N}\langle\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$$

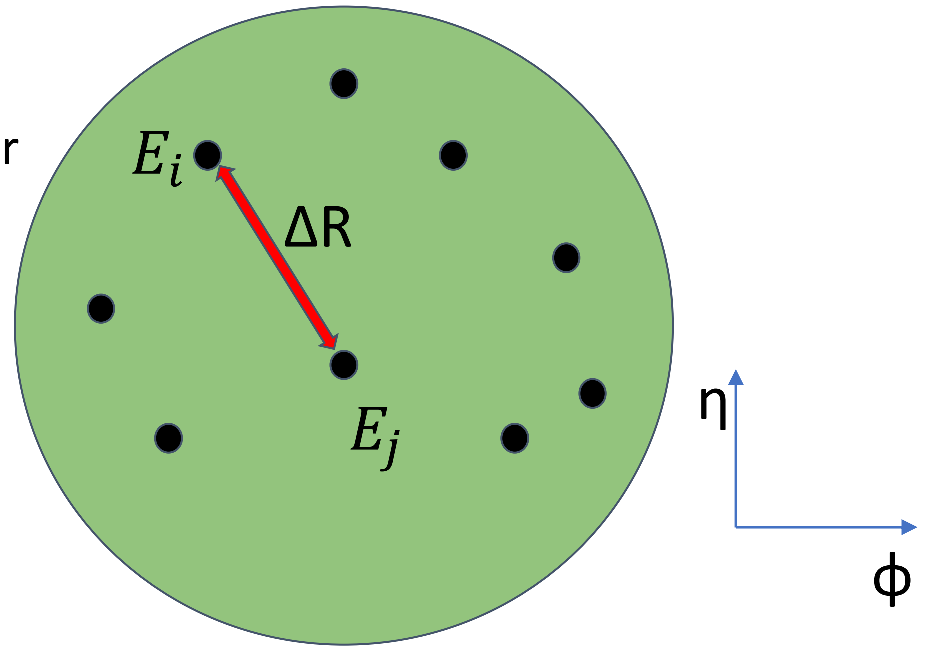
Chen et al. 2020, PRD 102, 5

Theoretical Definition of projected N-Point Correlator

$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{{p_{T,Jet}}^2}}\frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{{p_{T,Jet}}^2}\right)}{d\,(\Delta R)}$$

Experimental Construction of Two-Point Correlator

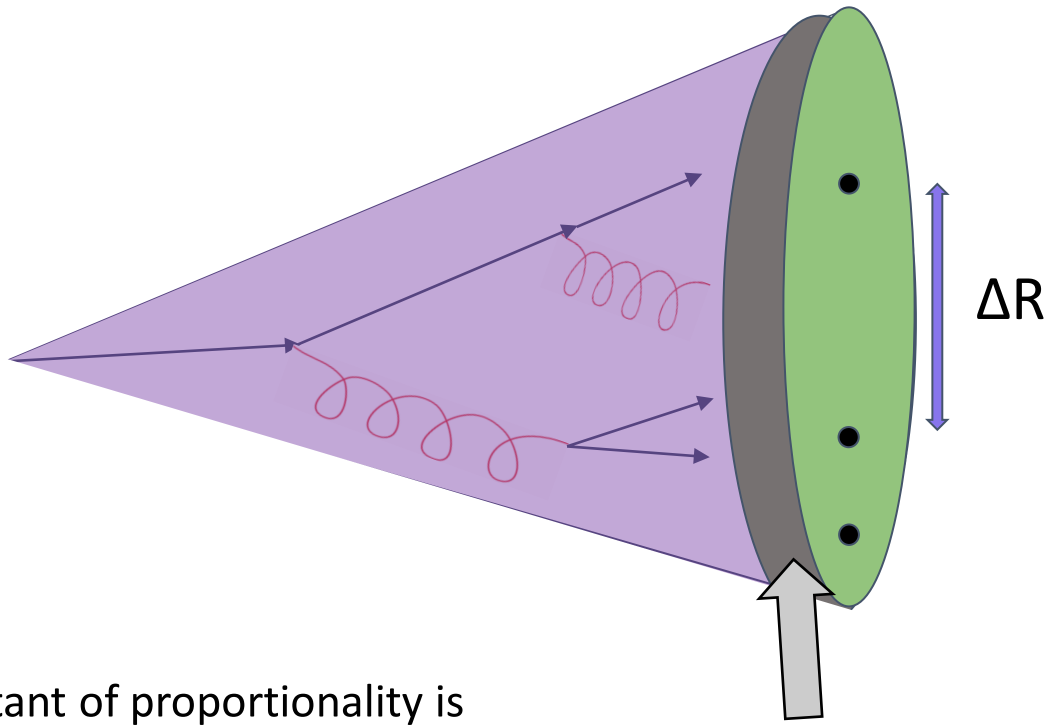
Note: Energy assumes pion mass

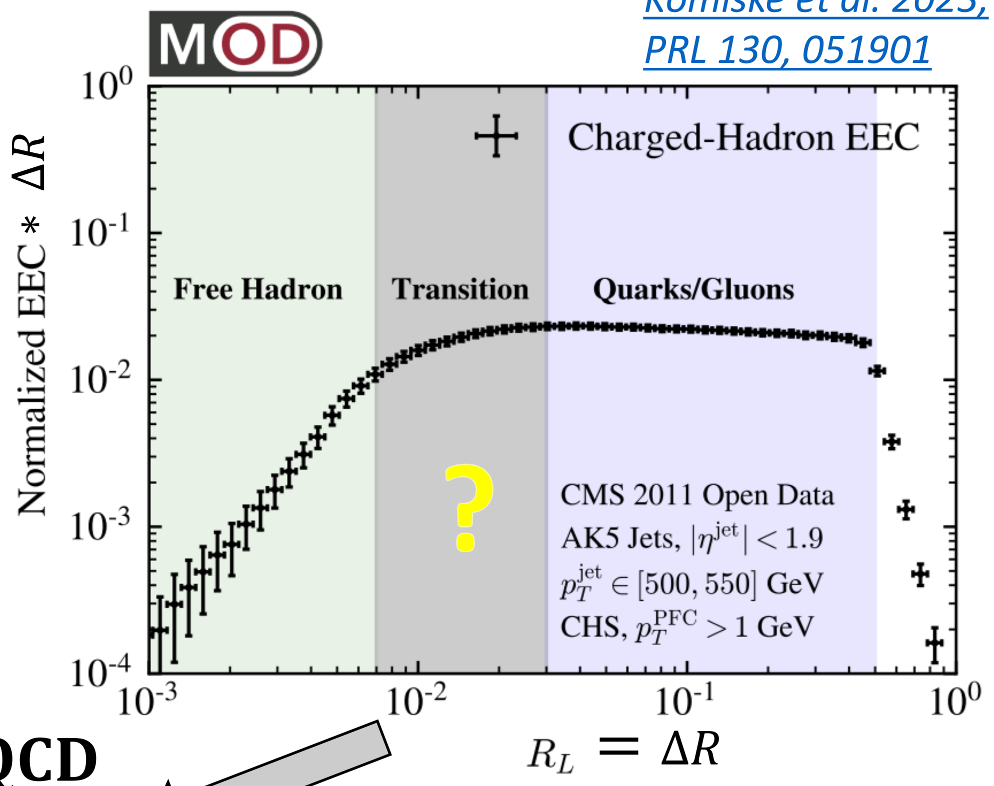


- Use all final state charged particles, and examine how energy is distributed as a function of their separation
- **Allows for study of jet evolution using final state jet constituents as they are**, no additional clustering or grooming after jet-finding

Relate This to Jet Evolution

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





[Komiske et al. 2023, PRL 130, 051901]

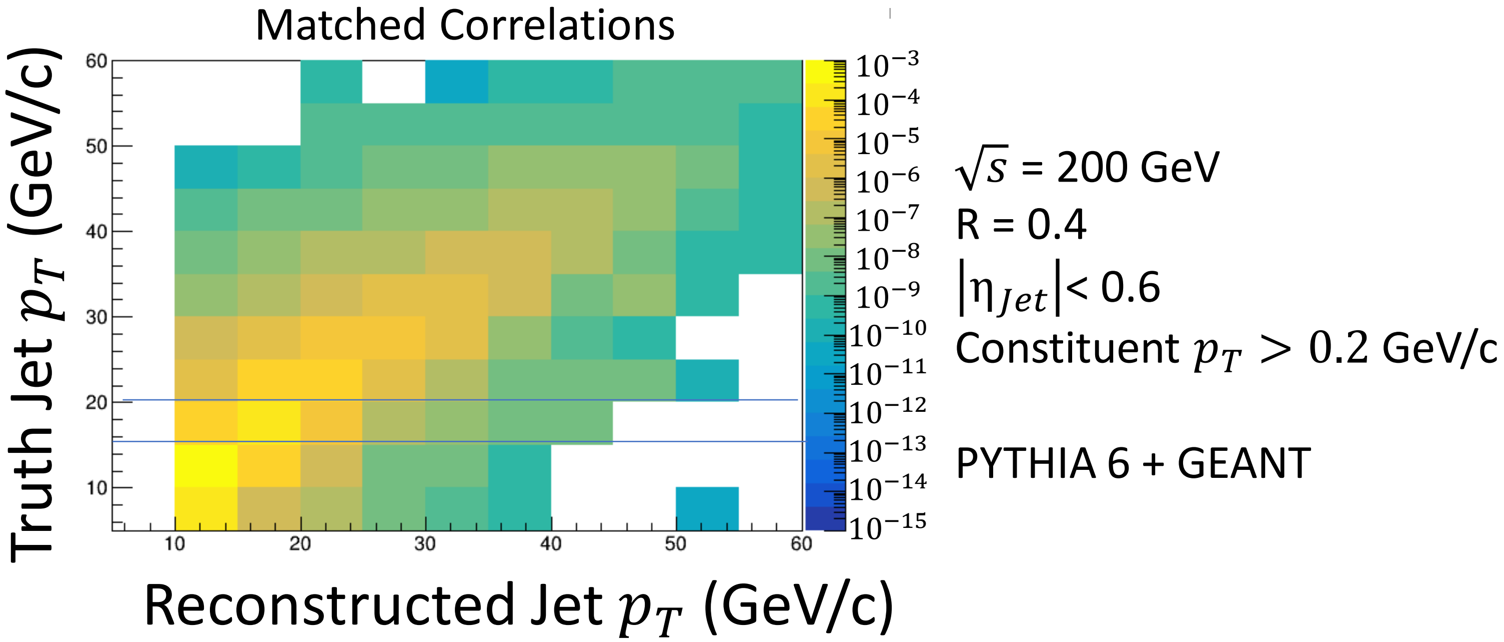
*Constant of proportionality is dependent on initiating parton flavor/mass

$$\textbf{Turnover} \propto^{*} \frac{\Lambda_{QCD}}{p_{T,Jet}}$$

- Behavior at low ΔR corresponds to a random distribution of hadrons, while behavior at high ΔR is influenced by parton shower– **Study Transition Region**

p_T^{Jet} Correction Method

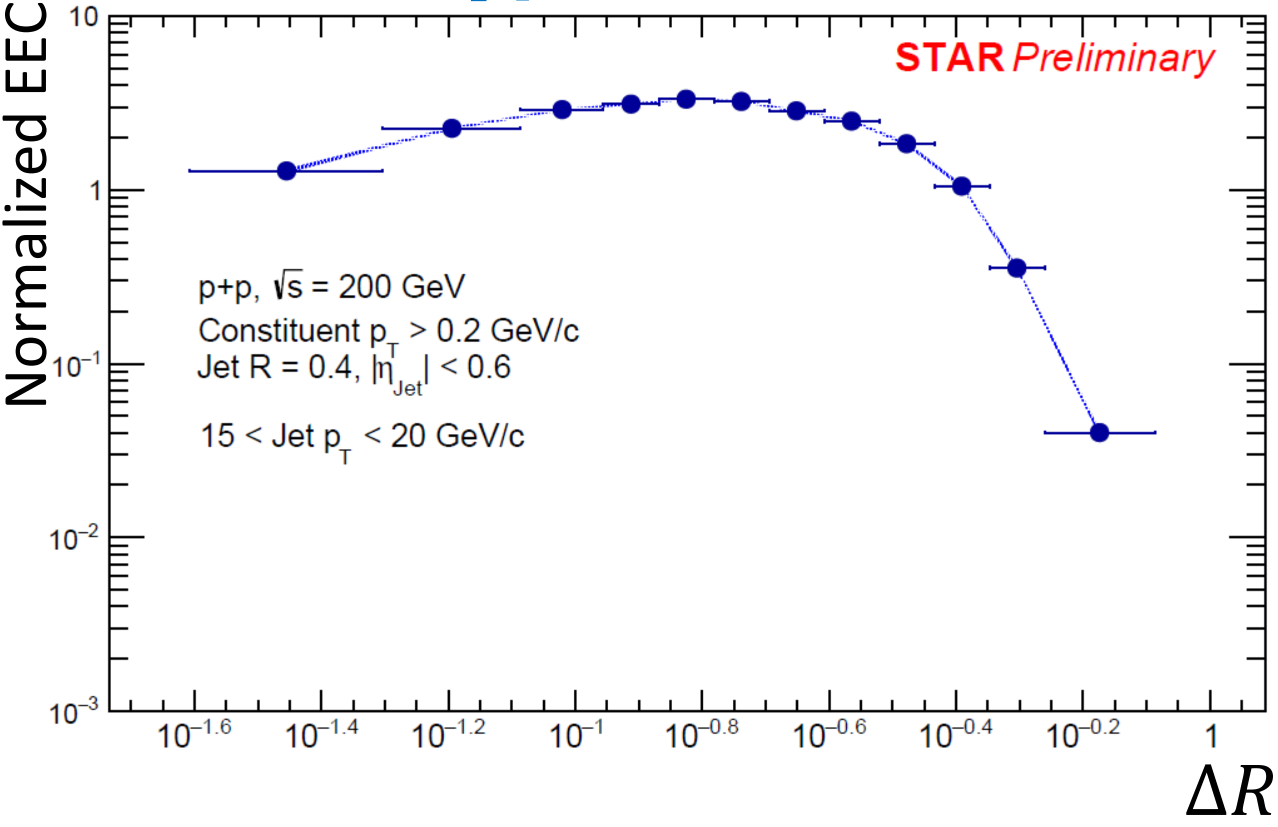
- Inform correction via use of PYTHIA6 (Truth) and PYTHIA6 + GEANT Embedded in min-bias data (Reconstructed)
- Match jets between Truth and Reconstructed samples within a ΔR of 0.4 and then match constituents inside of jets within a ΔR of 0.02 and form response matrix



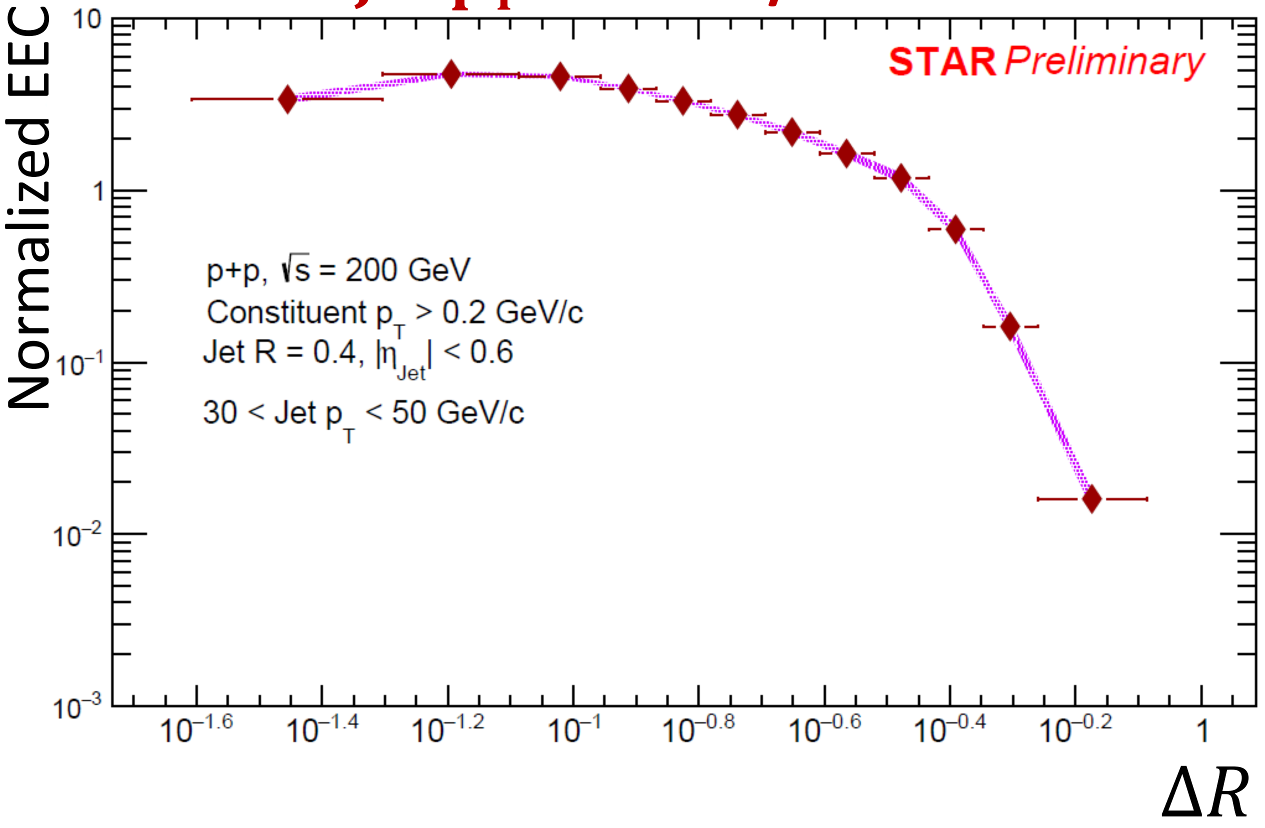
- Preliminary results use a correction procedure in which $p_{T,jet}$ is the only variable in which a response matrix is formed
  - Detailed in **arXiv:2309.05761**
  - Planning to expand to full three-dimensional unfolding

First EEC Measurement at RHIC

15 < Full Jet p_T < 20 GeV/c



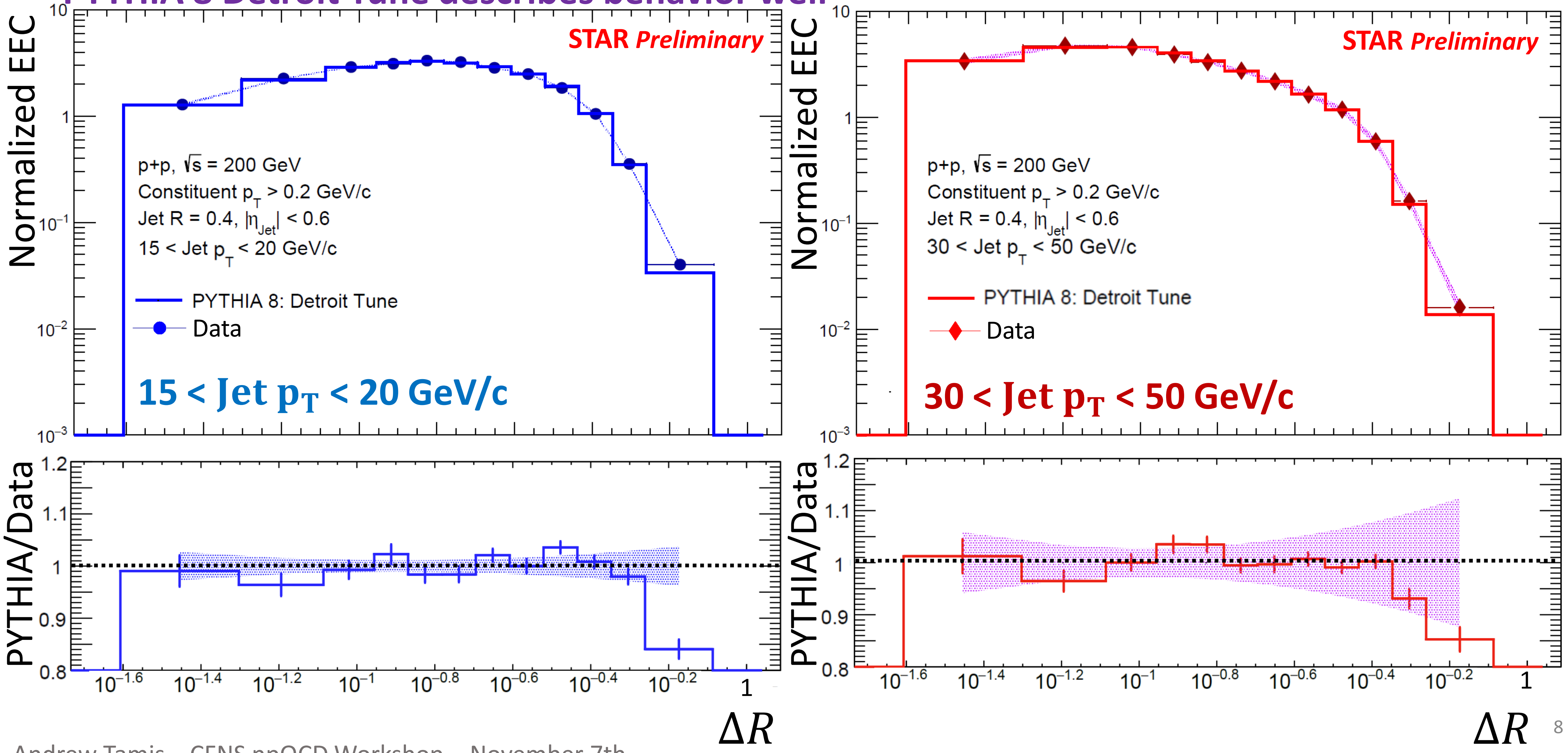
30 < Full Jet p_T < 50 GeV/c



Monte-Carlo Comparison

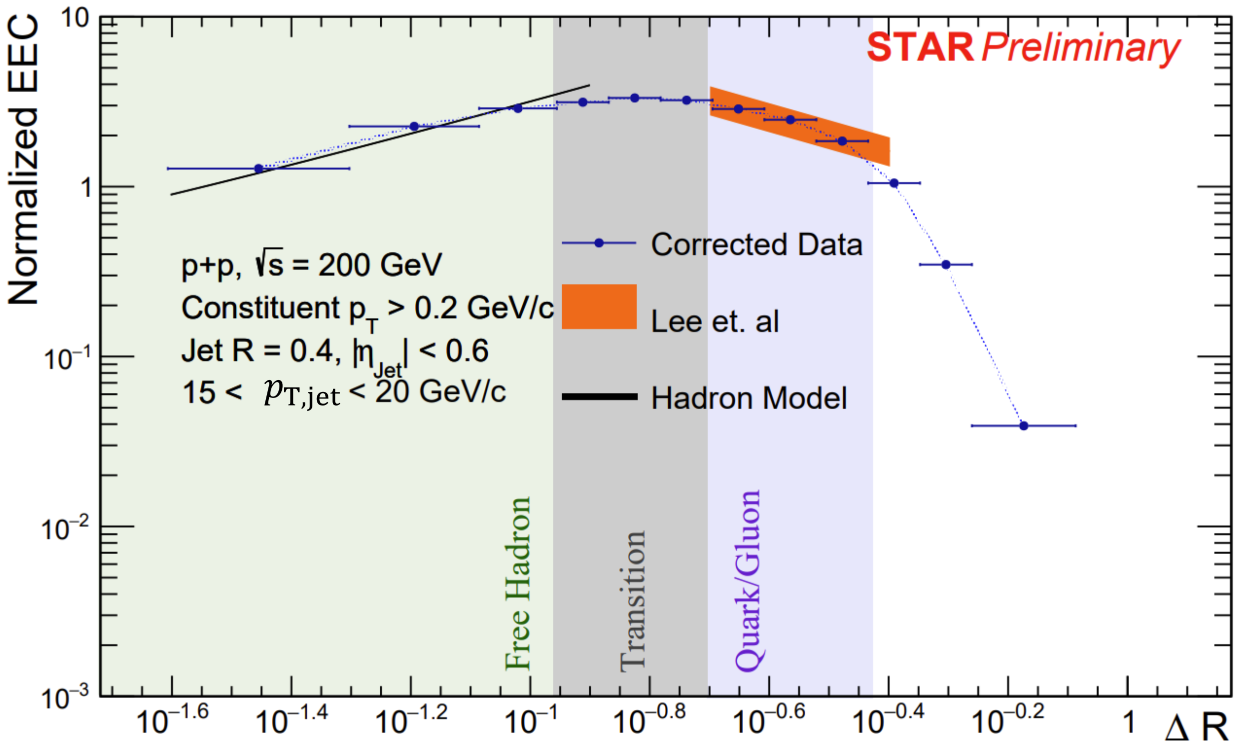
- **PYTHIA 8 Detroit Tune describes behavior well**

Aguilar et al., PRD 105, 016011



Theoretical Comparison (R = 0.4)

15 < Full Jet p_T < 20 GeV/c



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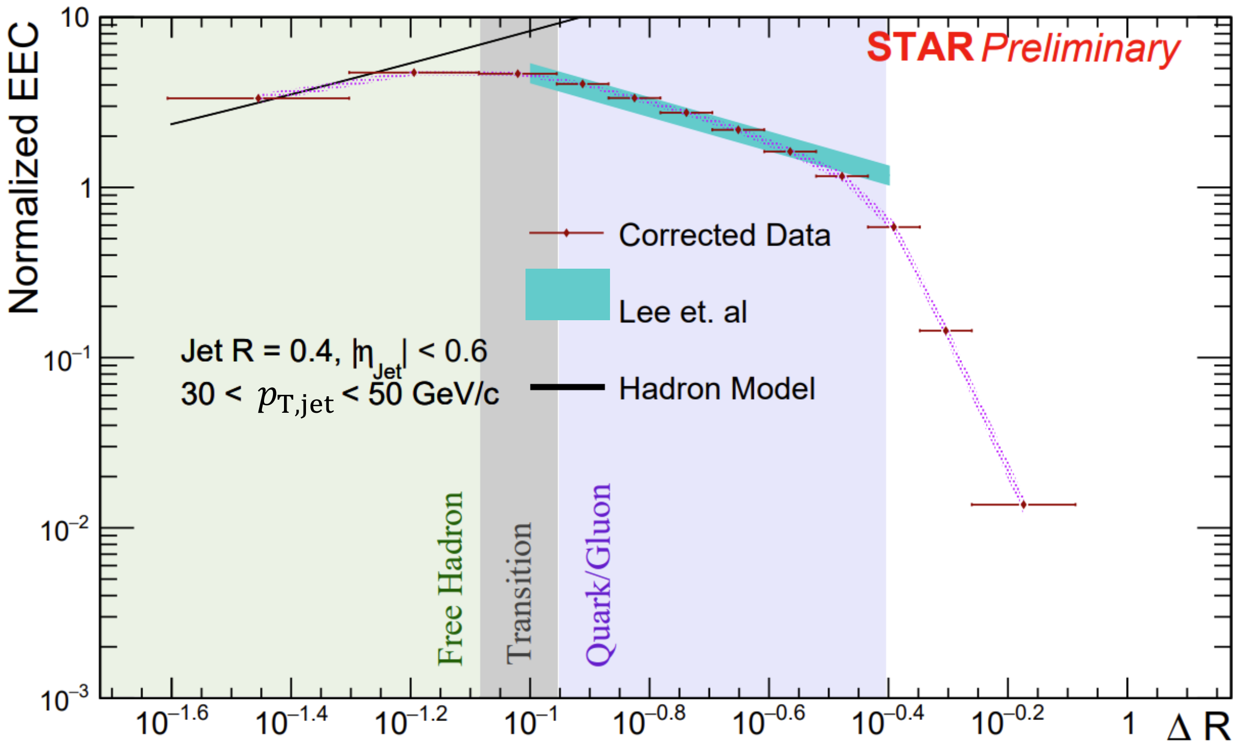
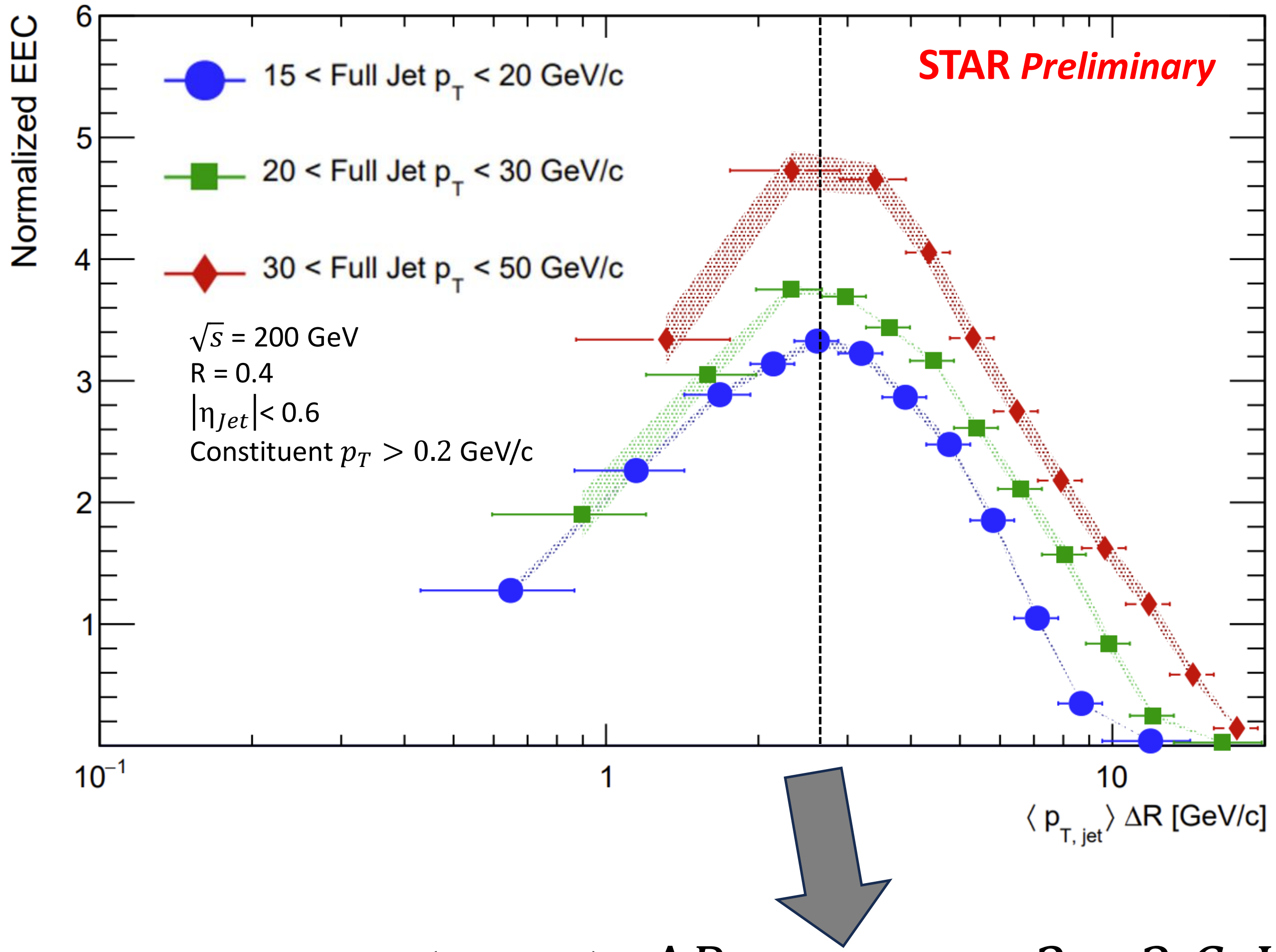


[Lee, Mecaj, Moult (2023): arXiv:2205.03414]

- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{{p_T^{Jet}}_{Low}} < \Delta R <$ Jet R)
- **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

p_T-Shifted Distributions

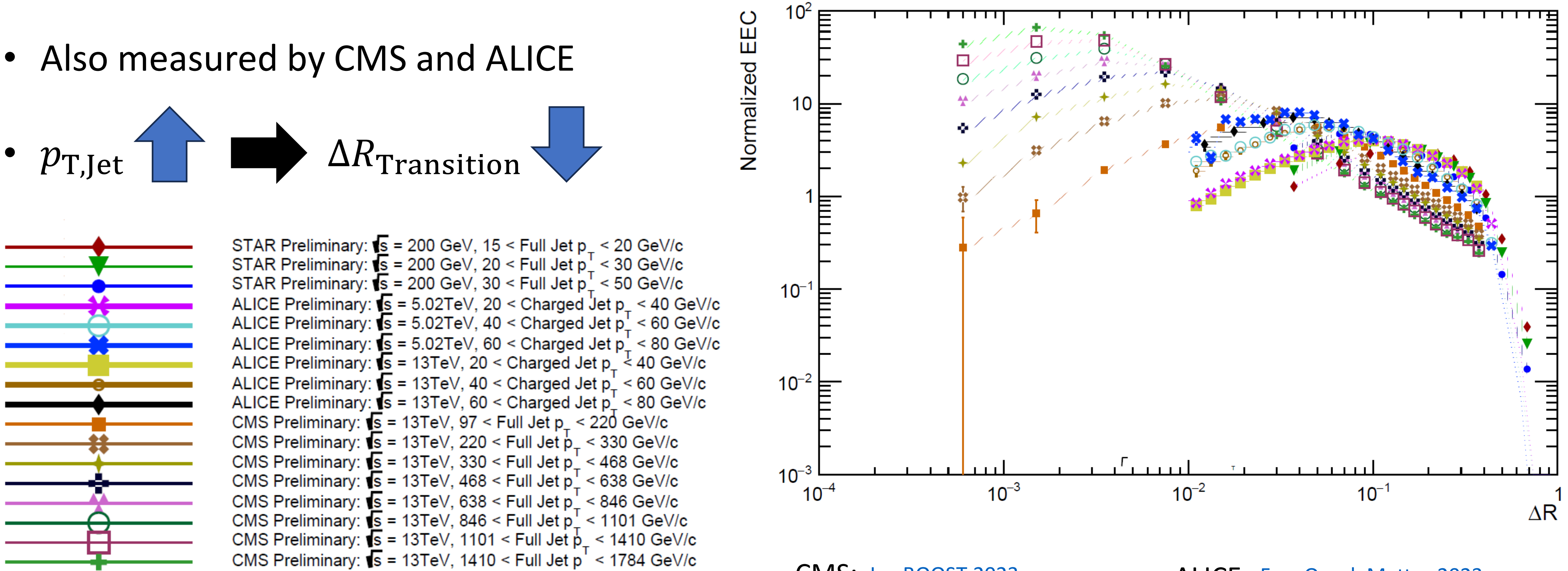
- Shift Corrected Result on x axis by average $p_{\mathrm{T,jet}}$ in a given bin
- As location of transition $\propto \frac{\Lambda_{\mathrm{QCD}}}{\mathrm{p_T}^{\mathrm{Jet}}}$, this will collapse it onto a single point
- In this case, average momentum is determined via PYTHIA and applied post-correction



$< p_{T,\mathrm{jet}} > \Delta R_{Turnover} \sim 2 - 3\ GeV$

Comparison with ALICE and CMS Results

- Also measured by CMS and ALICE
- $p_{\mathrm{T,Jet}}$ ⇧ ➡ $\Delta R_{\mathrm{Transition}}$ ⇩



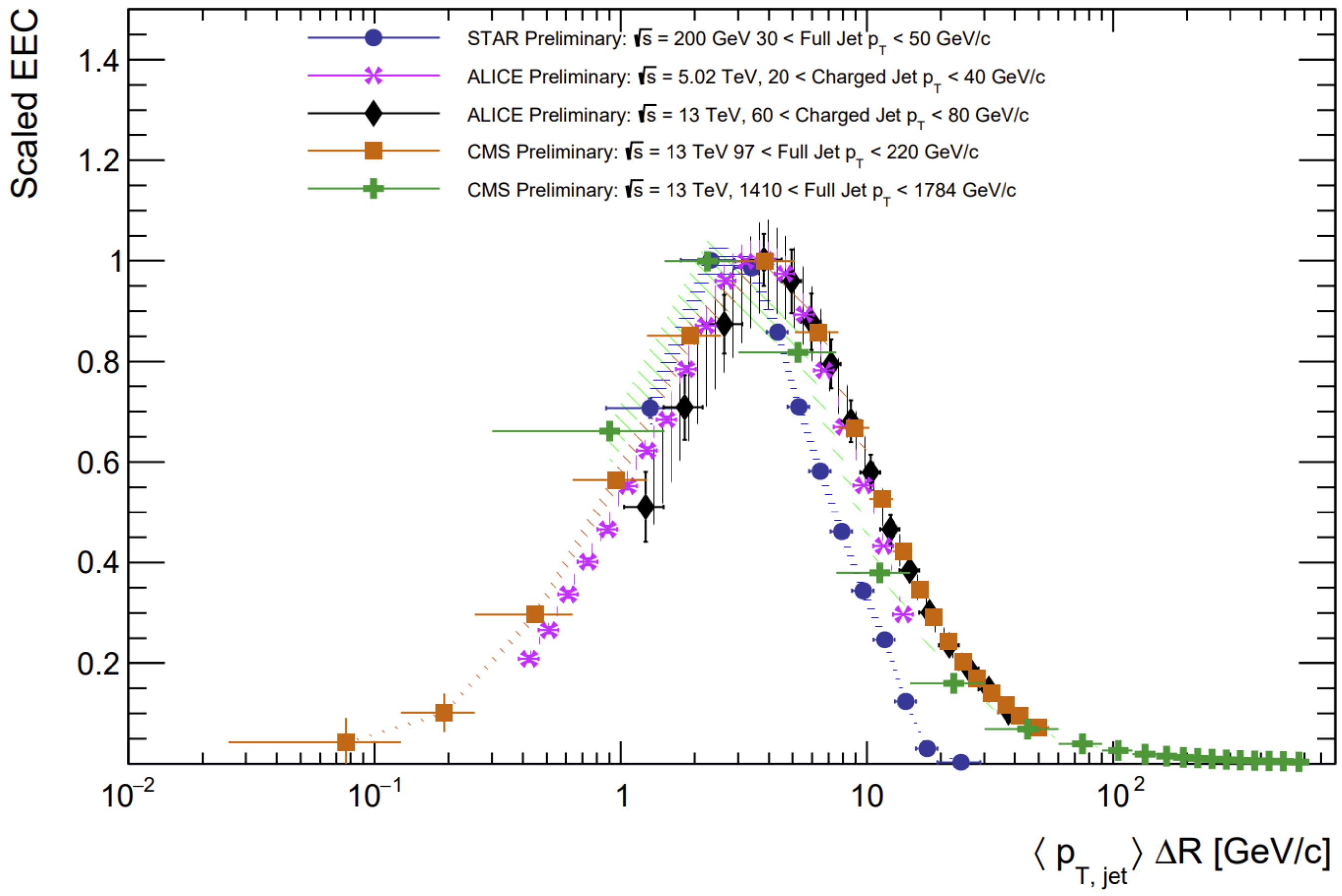
CMS: Lu, BOOST 2023

ALICE: Fan, Quark Matter 2023

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

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

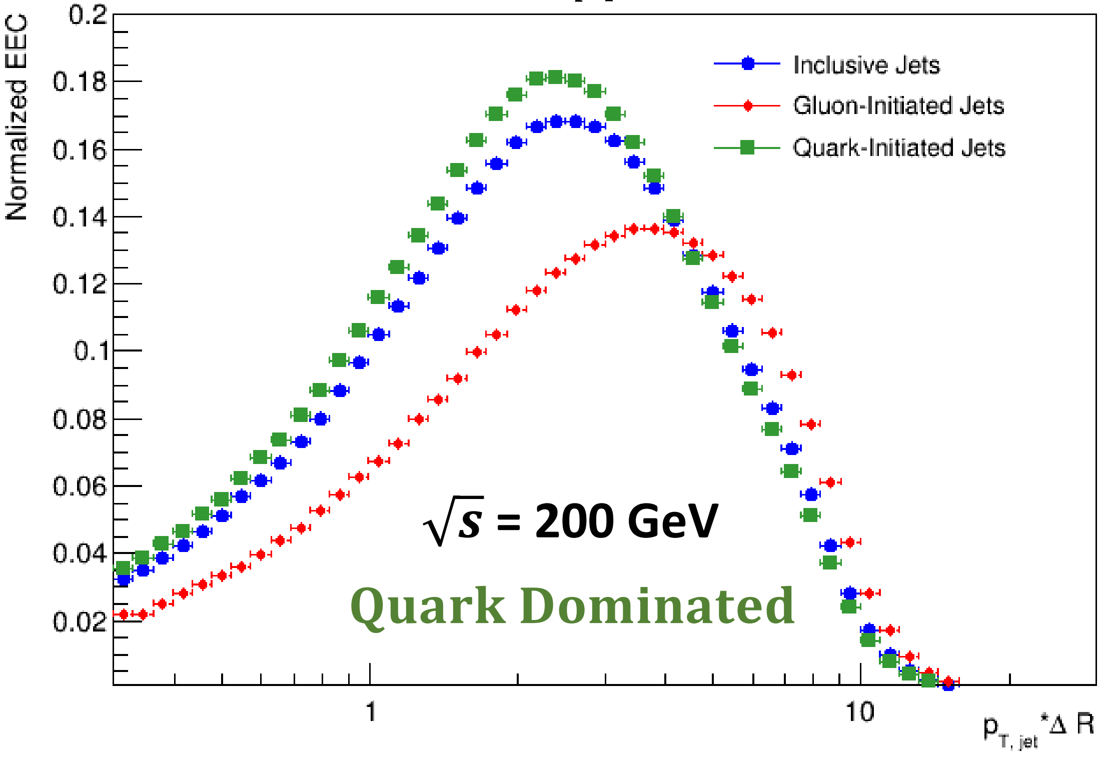


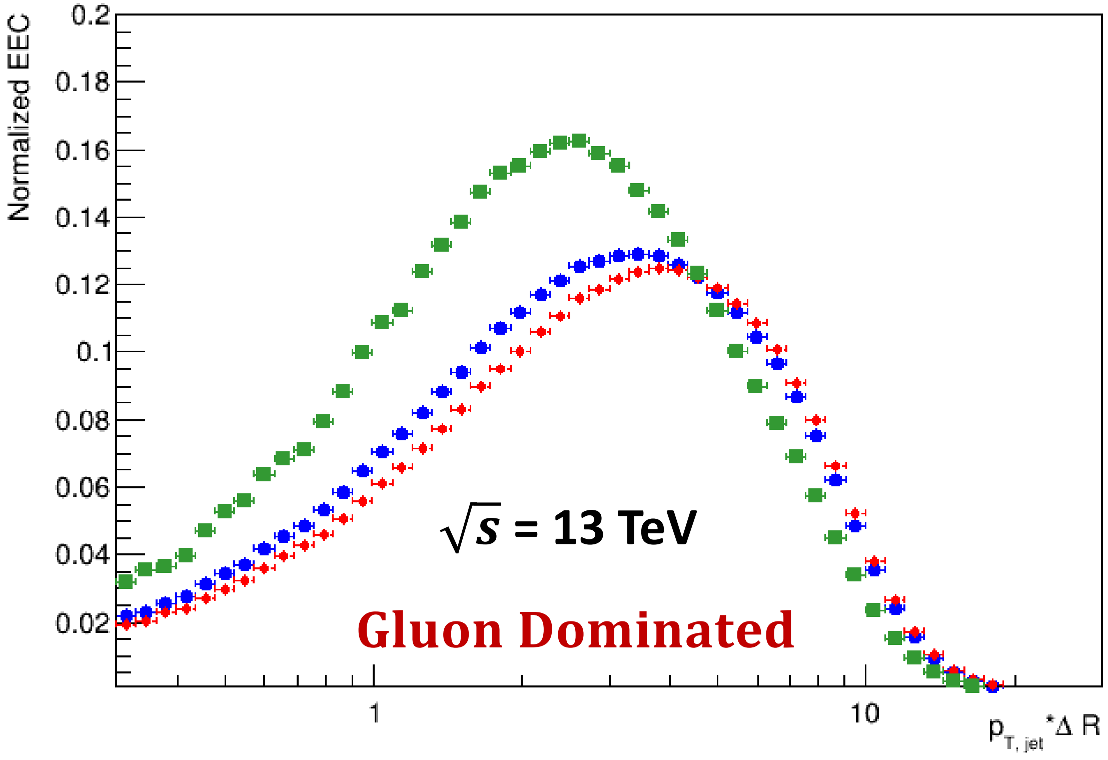
Impact of Quark/Gluon Fraction

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

R = 0.4
$|\eta_{Jet}| < 0.6$
Constituent $p_T > 0.2$ GeV/c

20 GeV/c < $p_{\mathrm{T,jet}}$ < 40 GeV/c
PYTHIA8
Multi-Parton Interactions OFF

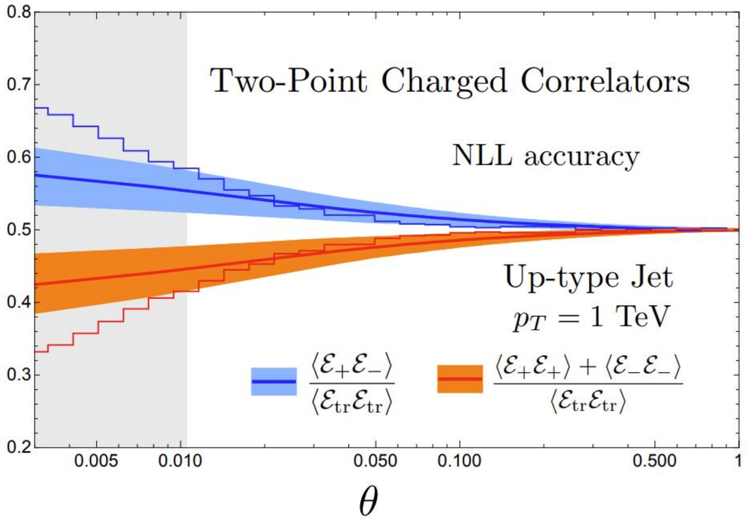




Outlook

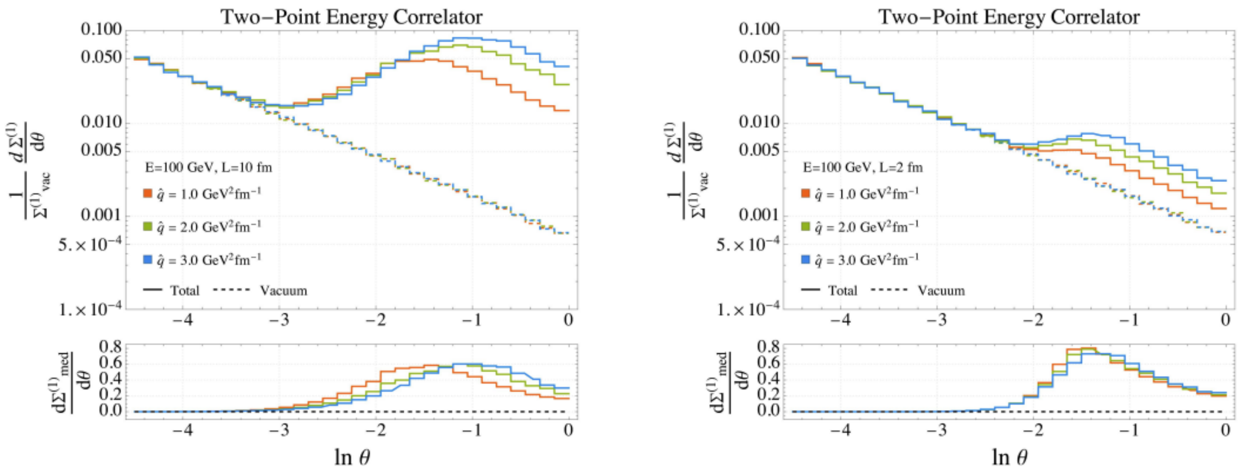
- New Unfolding method will allow for more accurate measurement of $p_{\mathrm{T,jet}}$-shifted distributions

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

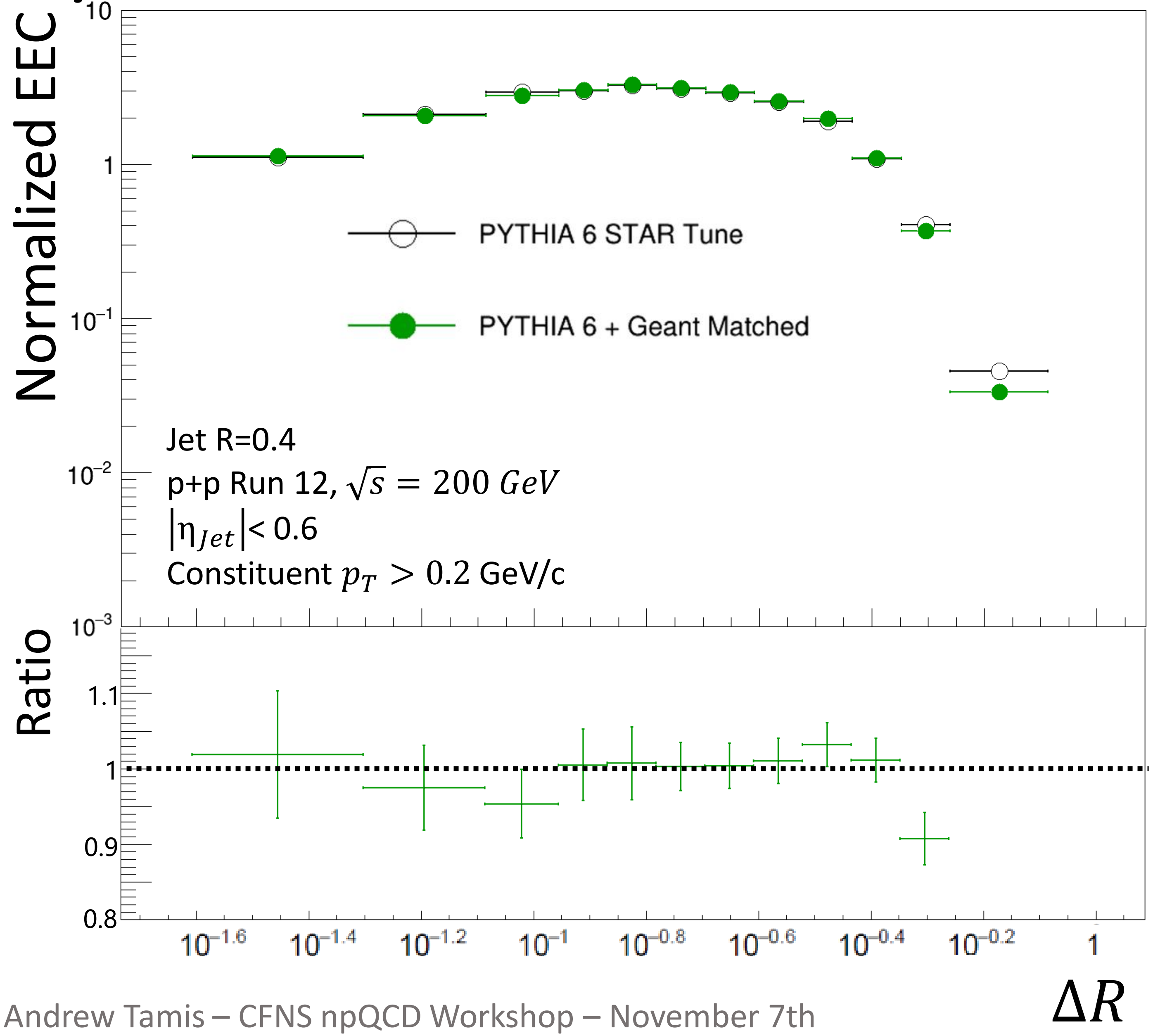


Conclusions

- 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

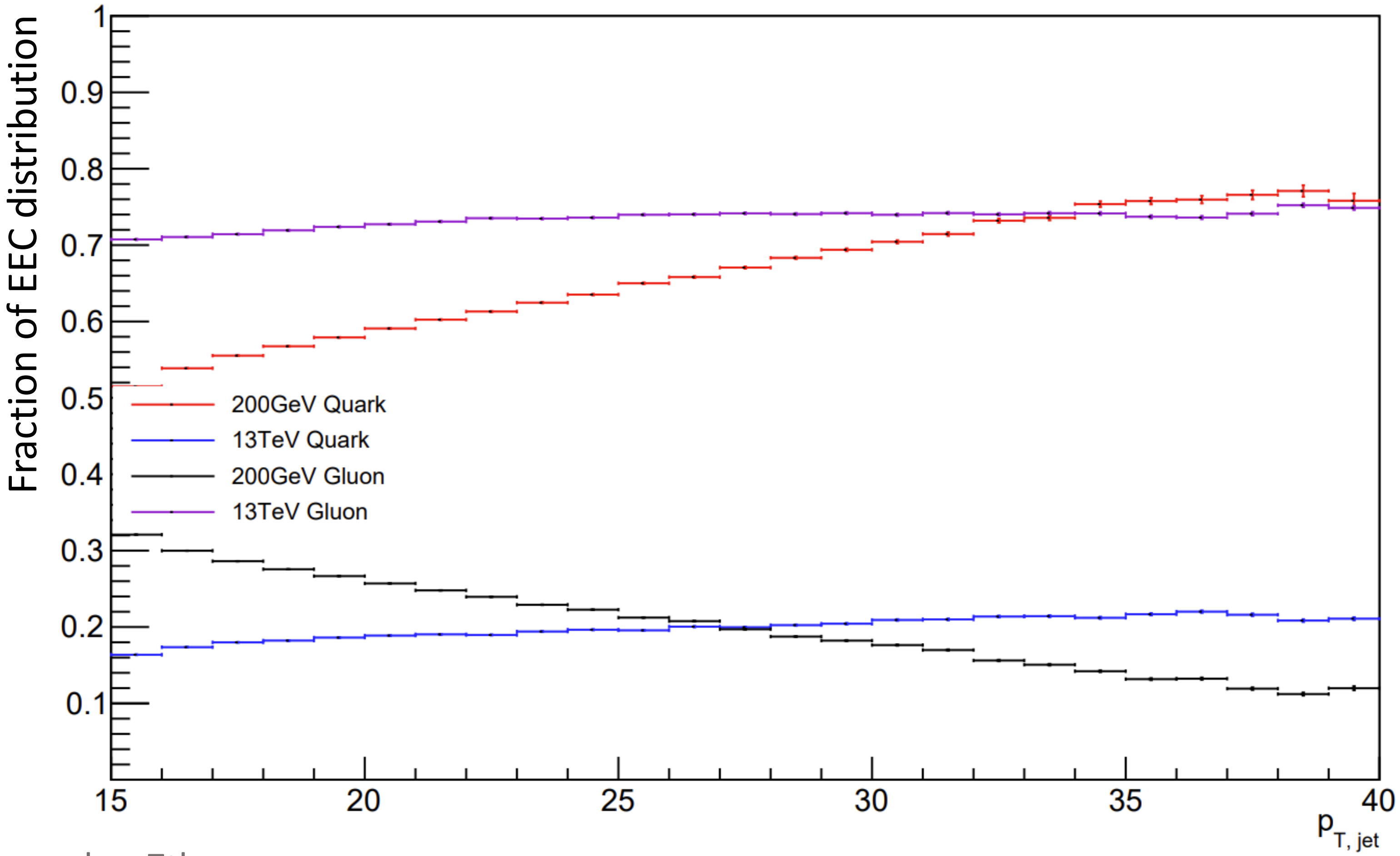


Impact of Detector on EEC outside of ${p_T}^{Jet}$

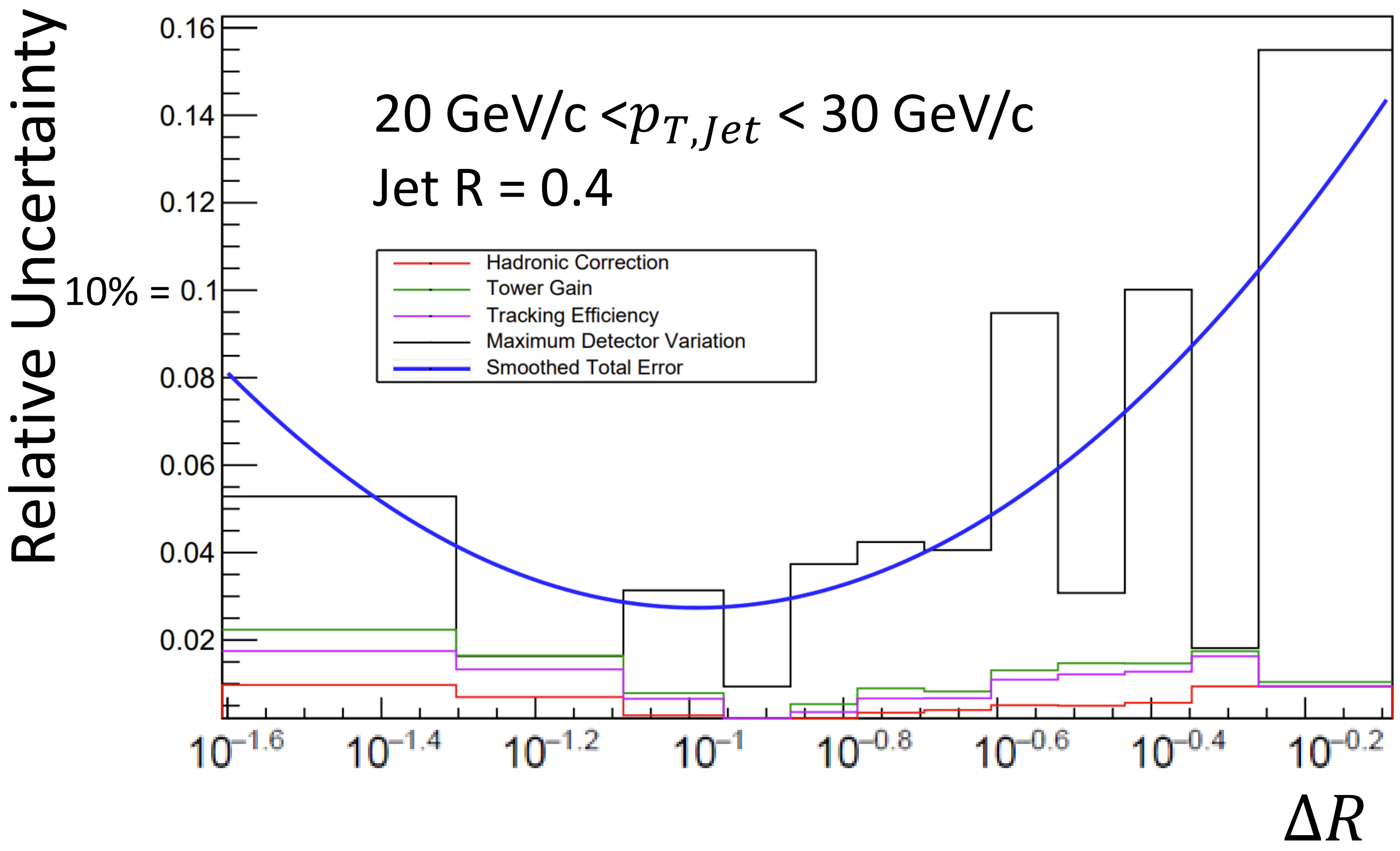
- **Treat Percentage difference between Truth and Detector level for MATCHED Jets as an uncertainty**
- **Approximates Detector effects assuming jet p_T was corrected successfully**
- **Hovers around unity in hadron, quark/gluon and Transition regions, do not need to correct in addition to ${p_T}^{Jet}$**

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



Systematic Uncertainties



- 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 ± 3.8%**

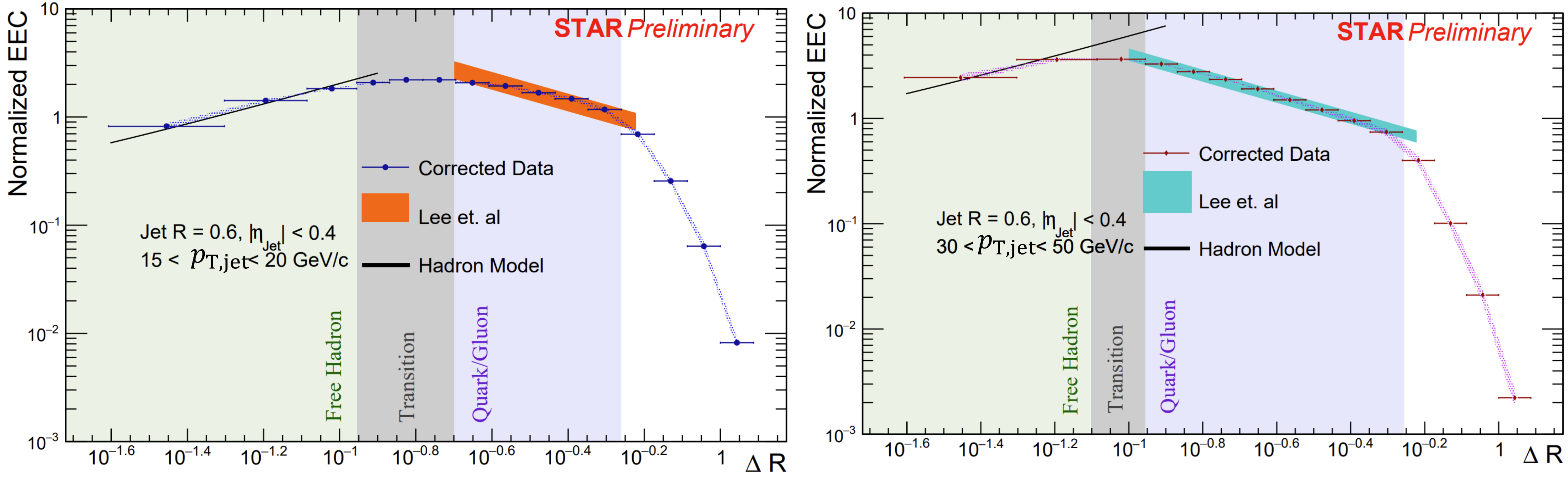
Tracking Efficiency

- 4% Uncertainty

Maximum Detector Variation

- Previous Slide

Theoretical Comparison (R = 0.6)

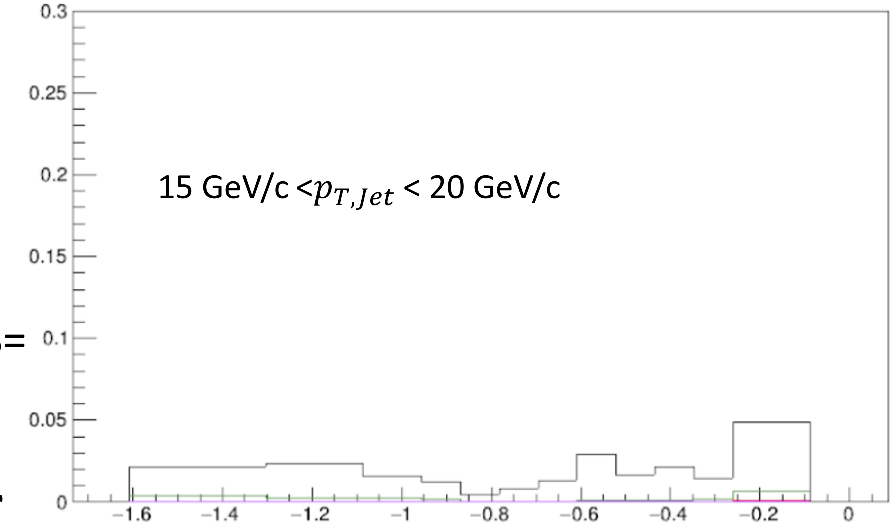


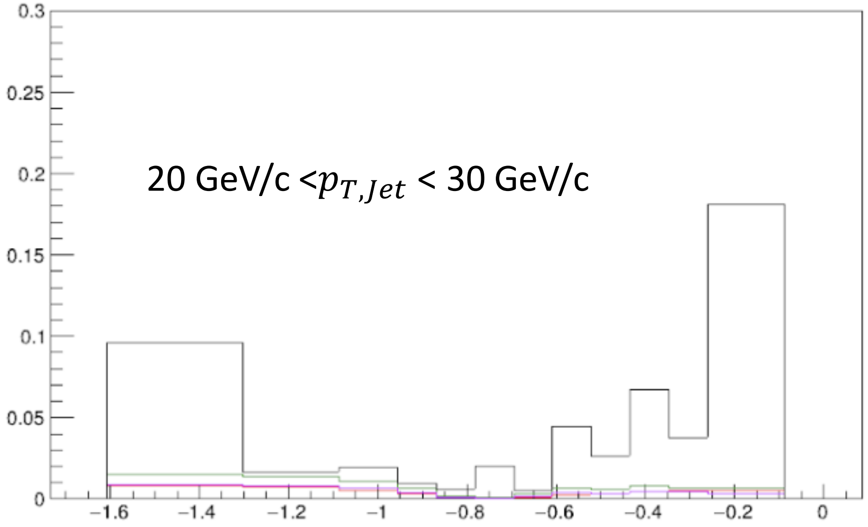
- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{p_T{}^{\text{Jet}}{}_{\text{Low}}} < \Delta R <$ Jet R) received directly from Kyle Lee, MIT.
- **Behavior agrees well with directly calculable theoretical expectations!**

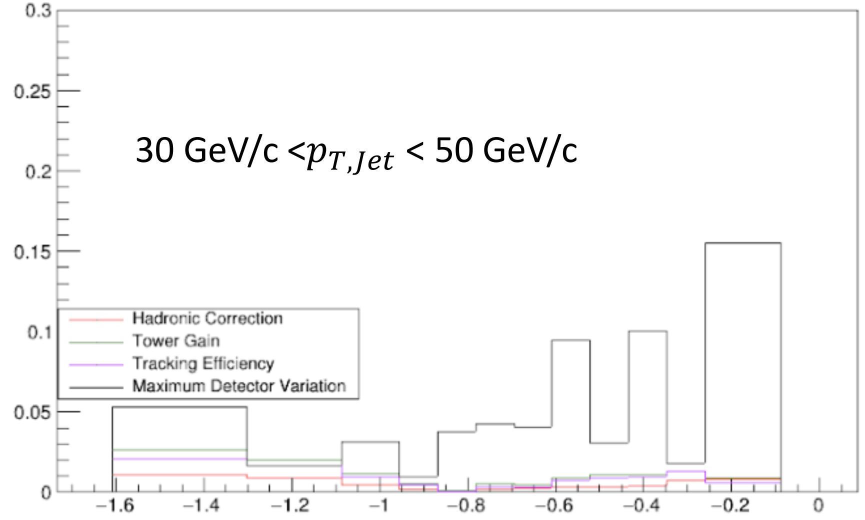
Systematic Uncertainties (R=0.4)

10%=

Relative Uncertainty





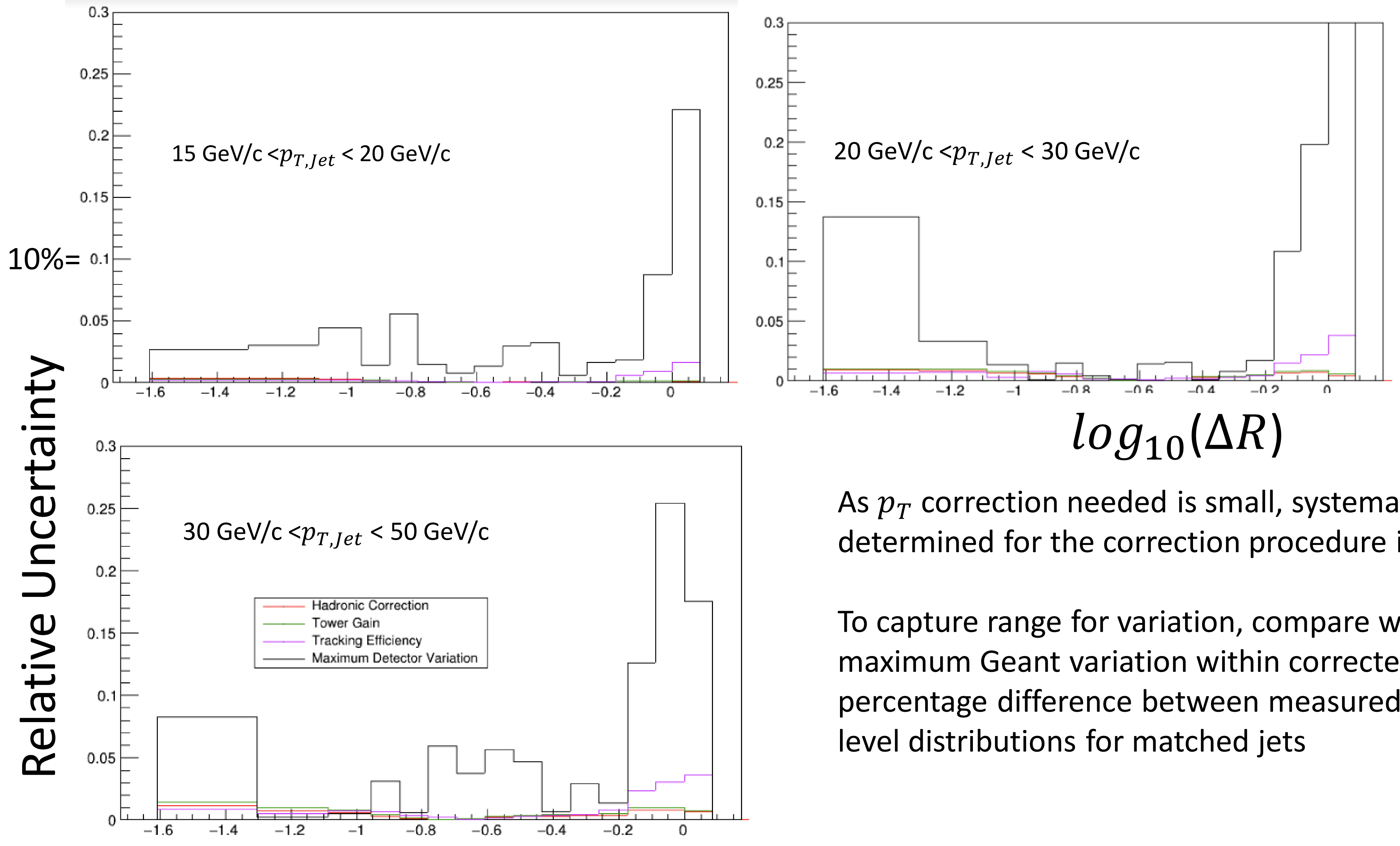


$log_{10}(\Delta R)$

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

Systematic Uncertainties (R=0.6)



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