2023 HARD PROBES Aschaffenburg

STAR

Measurement of Two-Point Energy Correlators Within Jets in $p+p$ Collisions at $\sqrt{s} = 200$ GeV

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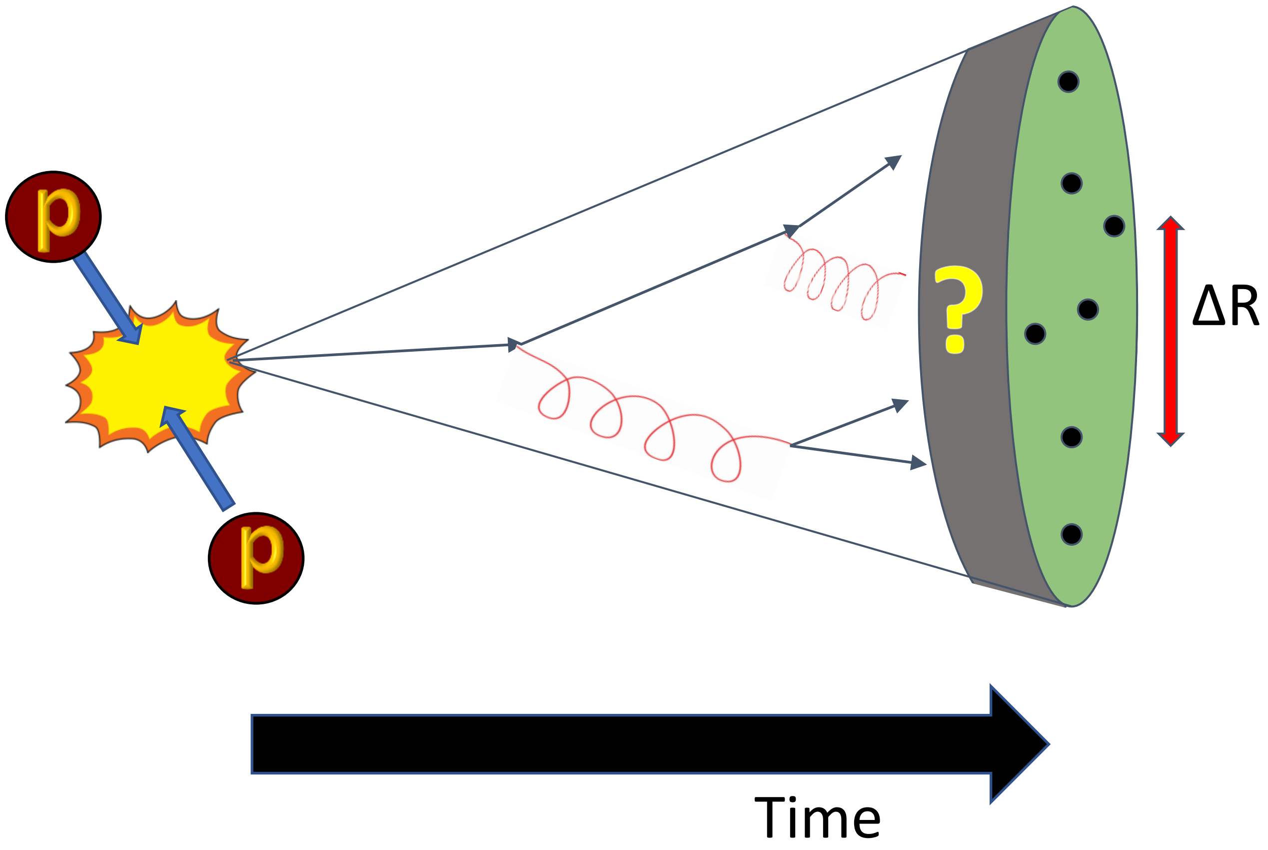
March 29th 2023

Yale Wright Laboratory

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

Jets and Hadronization

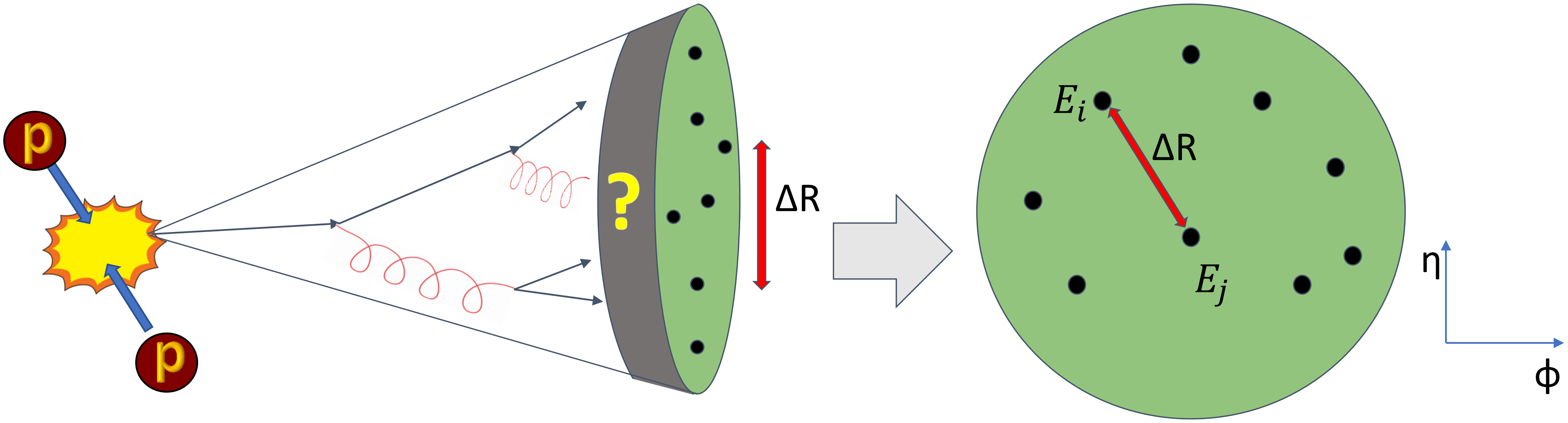


- **Jets are proxies for hard-scattered partons**
- Clustered from final state particles using a jet finding algorithm
- Interesting to follow time evolution of jet

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

Apolinário, Cordeiro, Zapp 2021 EPJC 81, Article Number 561

Energy Energy Correlators (EEC)



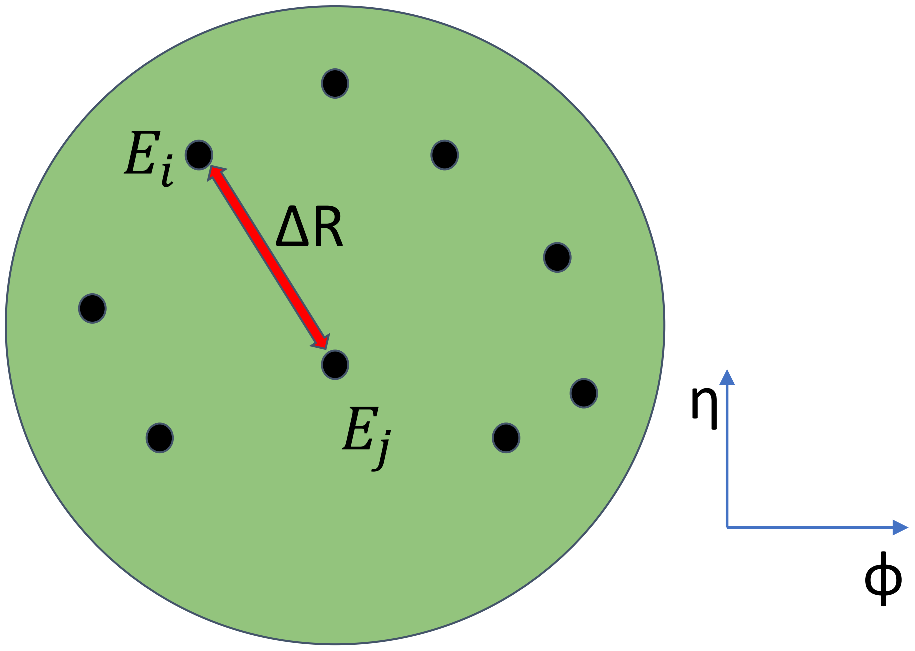
- Use all final state charged particles, and examine how energy is distributed as a function of their separation
- **Allows for study of jet evolution using final state jet constituents as they are**, no additional clustering after jet-finding

Energy Energy Correlators (EEC)

Theoretical Calculation of N-Point Correlator

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

Komiske et al. 2023, PRL 130, 051901



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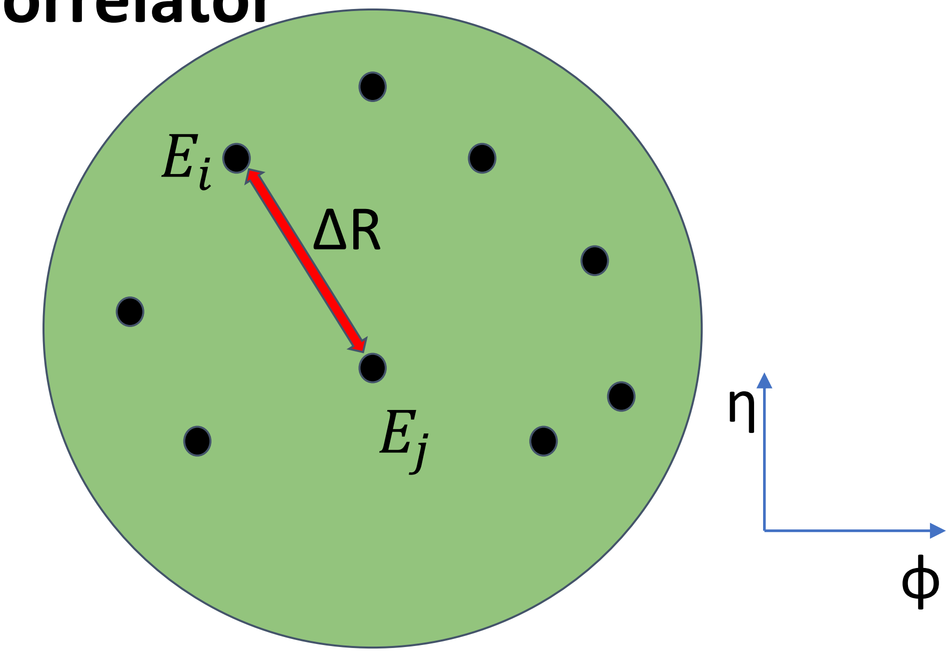
Energy Energy Correlators (EEC)

Experimental Construction of Two-Point Correlator

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



Note: Energy assumes pion mass

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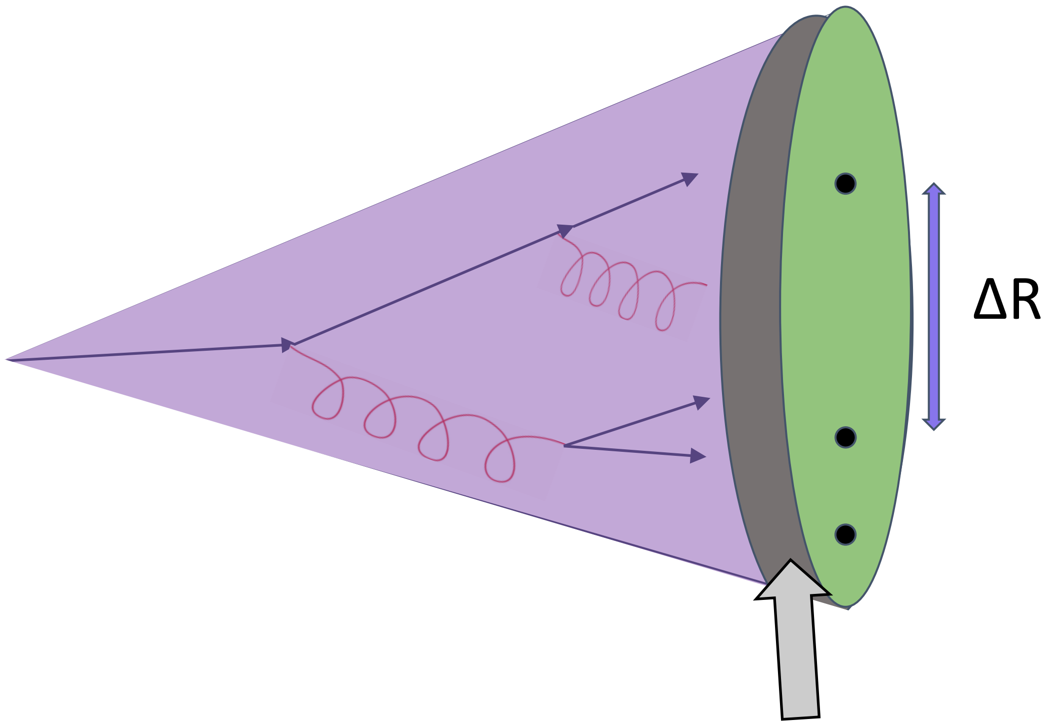
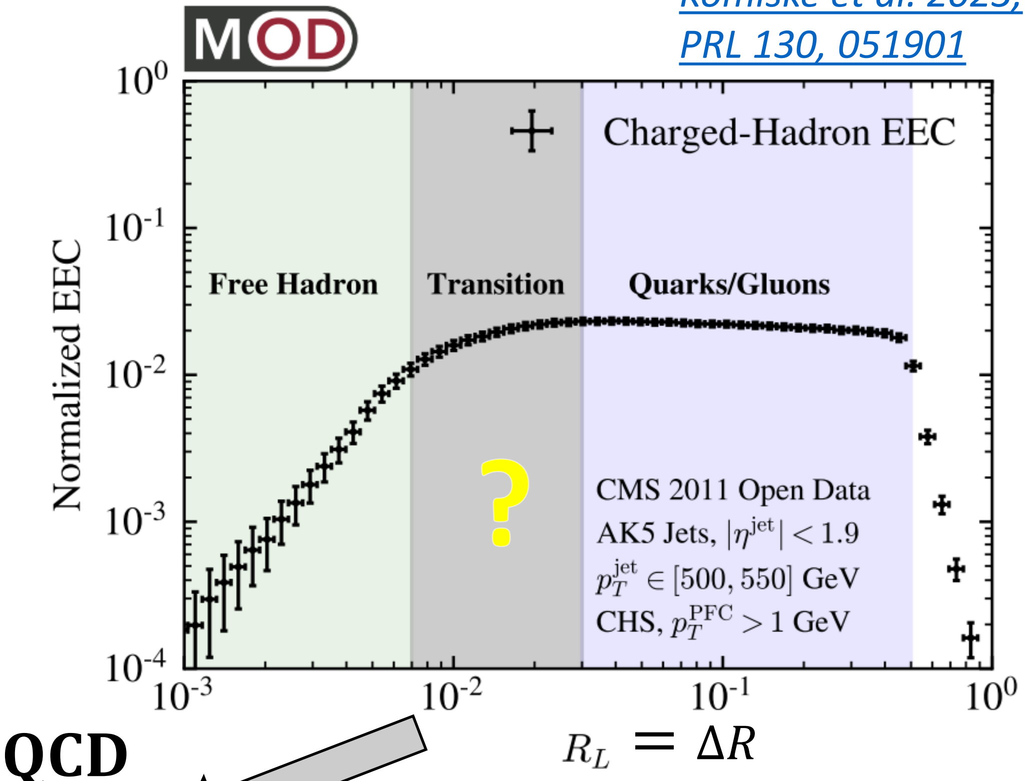
Relate This to Jet Evolution

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



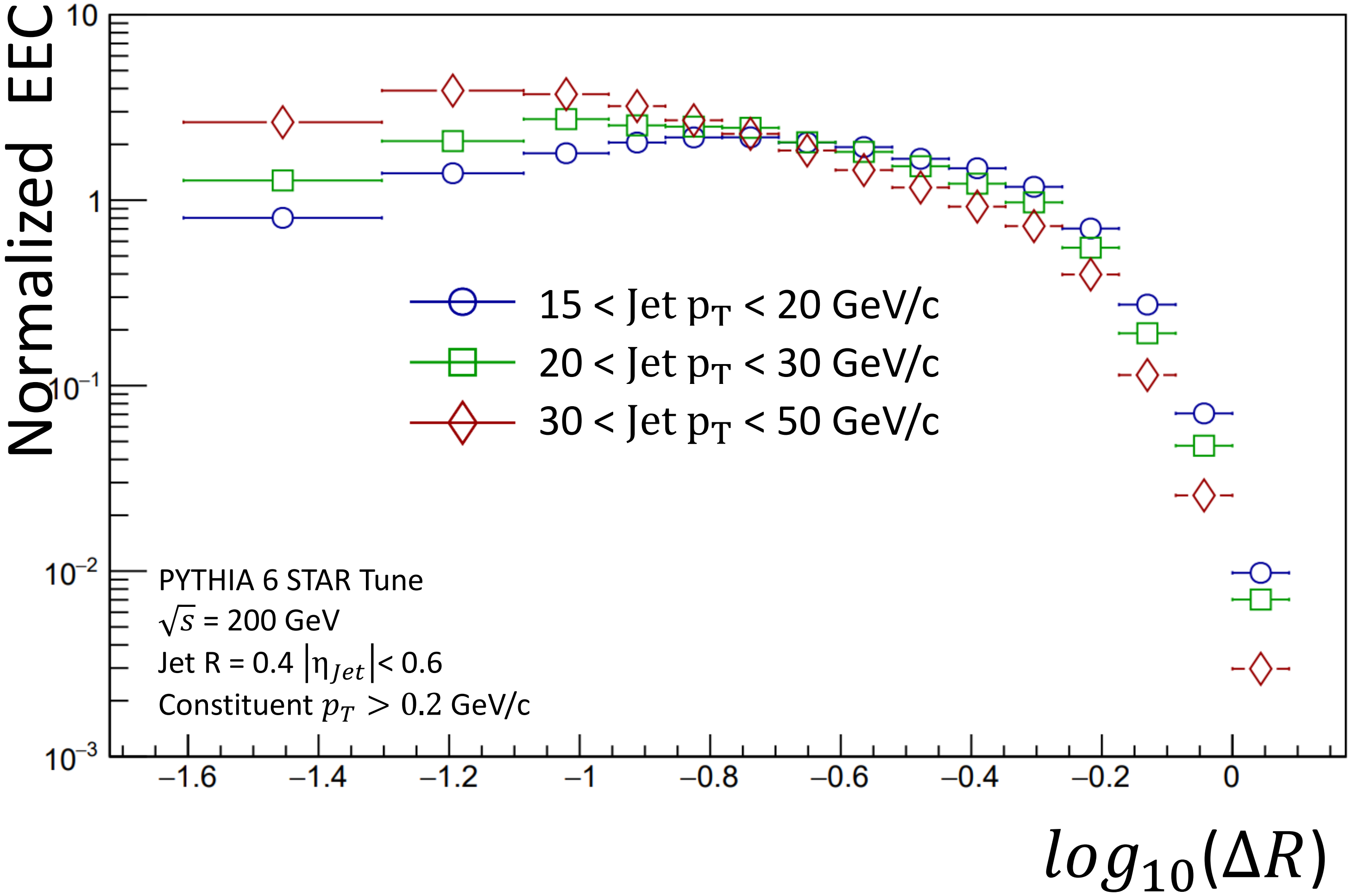
Komiske et al. 2023, PRL 130, 051901



$$\textbf{Turnover} \propto \frac{\Lambda_{\text{QCD}}}{p_T^{\text{Jet}}}$$

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

Studying the Transition Region



- Transition region corresponds to onset of hadronization

- **Transition region moves to smaller opening angle with higher Jet transverse momentum**

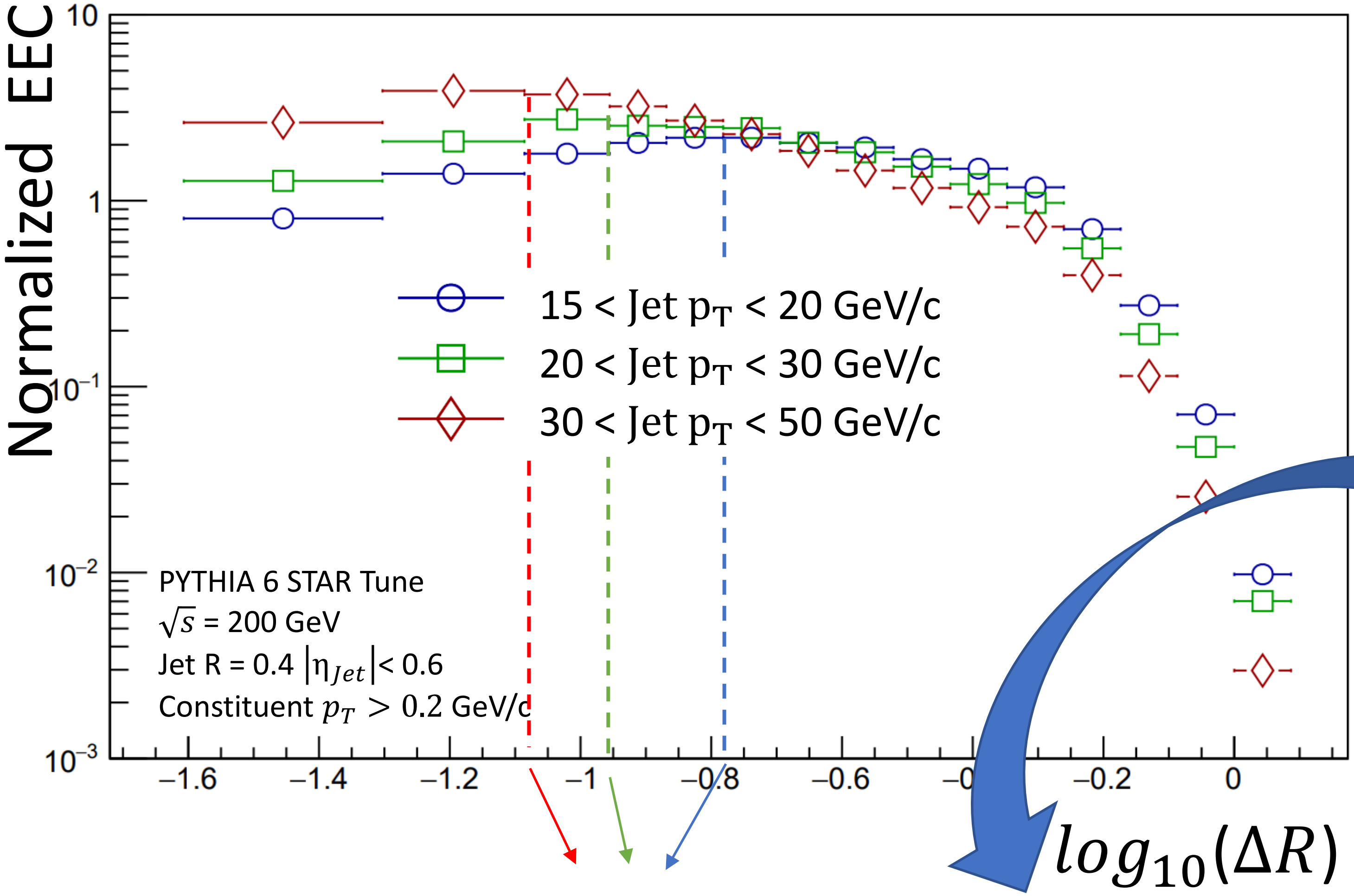
➡ Hadronization happens later in time!

$$\textbf{Turnover} \propto \frac{\Lambda_{QCD}}{p_T^{Jet}}$$

Komiske et al. 2023, PRL 130, 051901

Note: Curve normalized to integrate to unity in ΔR in order to compare different momentum ranges accurately

Studying the Transition Region



${p_T}^{jet}{}_{Low} * \Delta R_{Turnover}$ ~ 2 to 3 GeV

- Transition region corresponds to onset of hadronization
- **Transition region moves to smaller opening angle with higher jet transverse momentum**

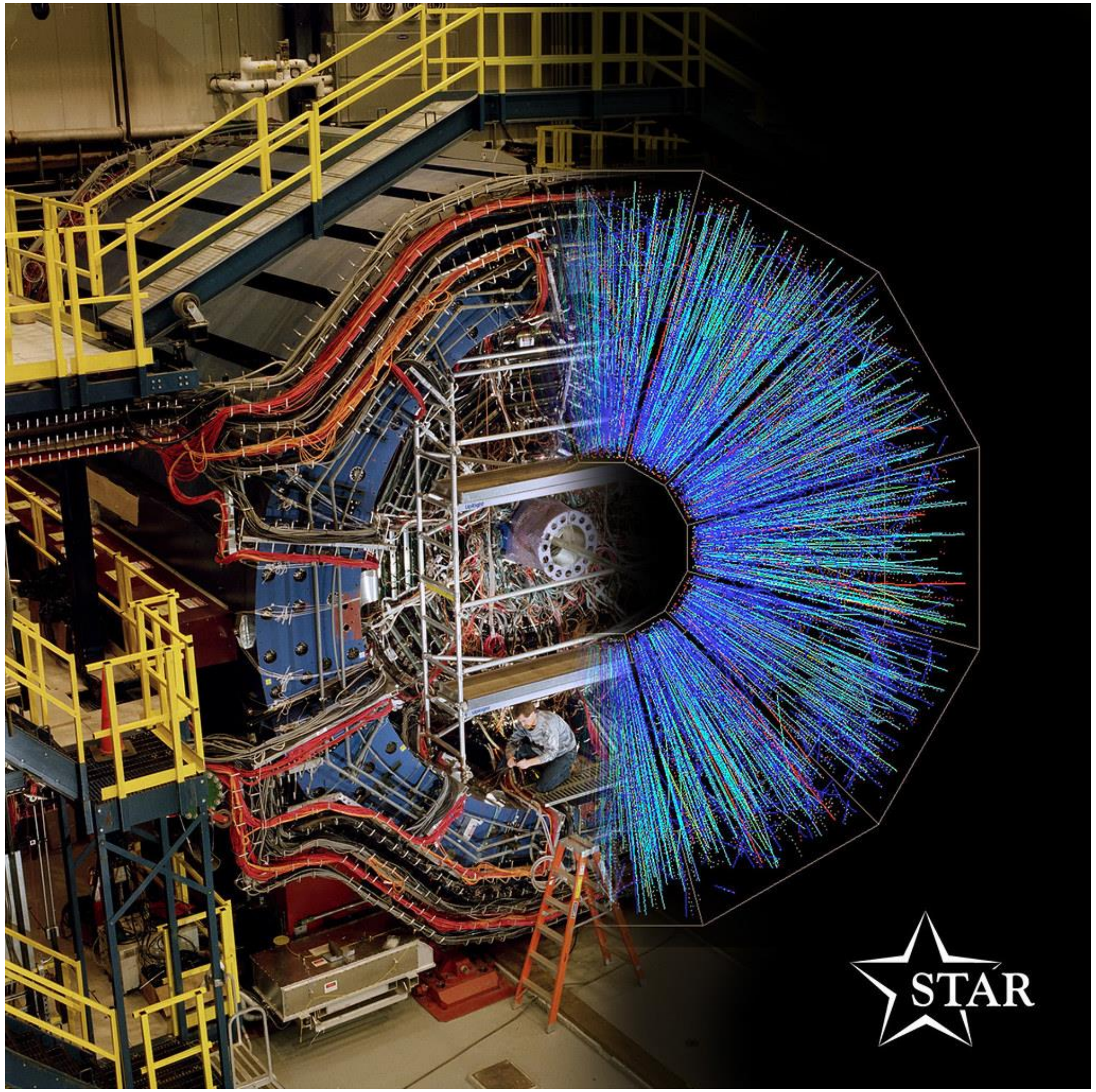
➡ Hadronization happens later in time!

$$\textbf{Turnover} \propto \frac{\Lambda_{QCD}}{{p_T}^{Jet}}$$

(Where the linear behavior breaks)

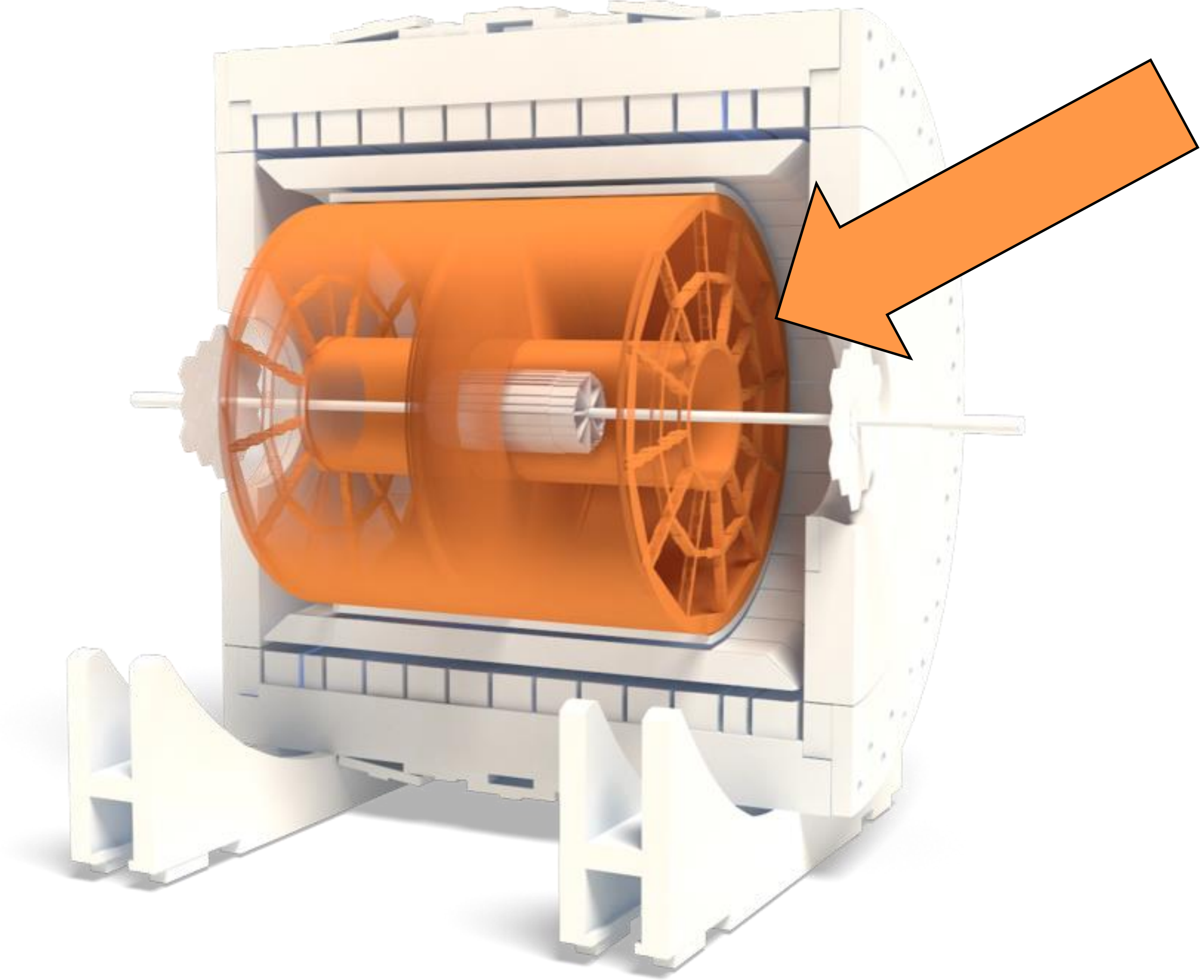
We see this behavior in PYTHIA!

STAR Detector



- STAR Time Projection Chamber (TPC) provides excellent charged track resolution
- Barrel Electromagnetic Calorimeter (BEMC) provides energy measurement for neutral components of jets, and provides jet trigger
- **Must correct for detector effects to reconstruct correct jet p_T**
- Learn what to correct by simulating detector effects with PYTHIA + Geant

STAR Detector



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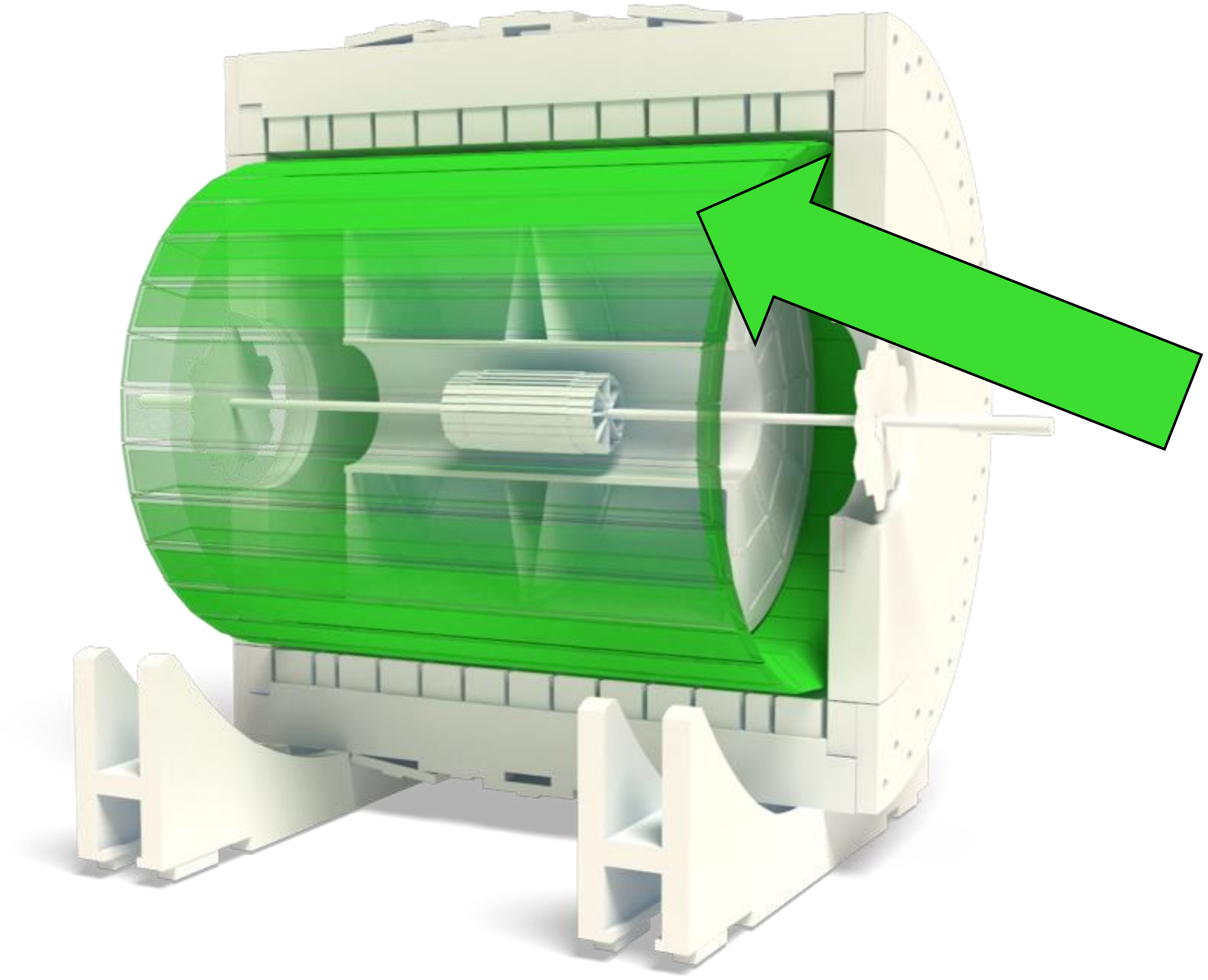

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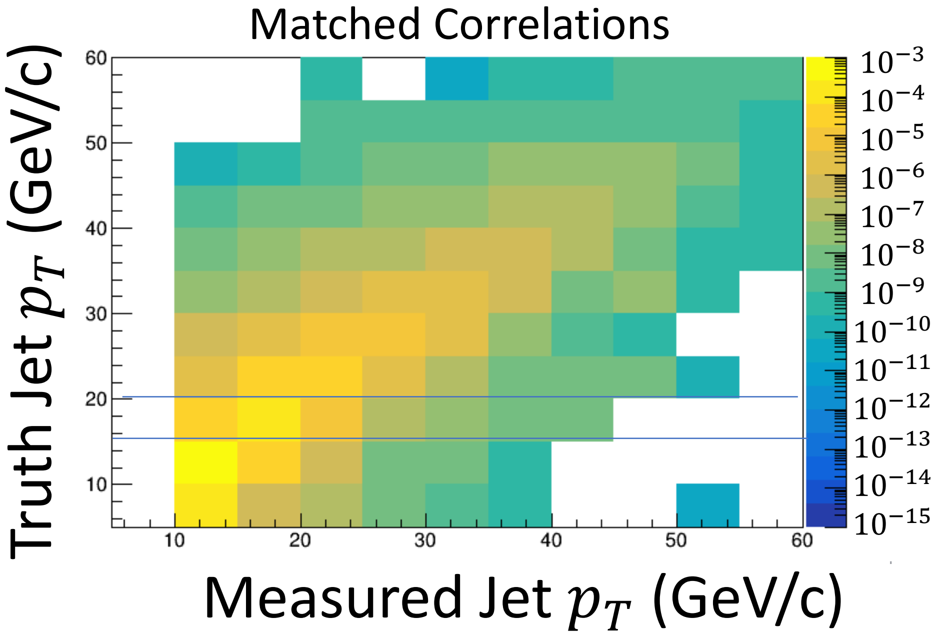
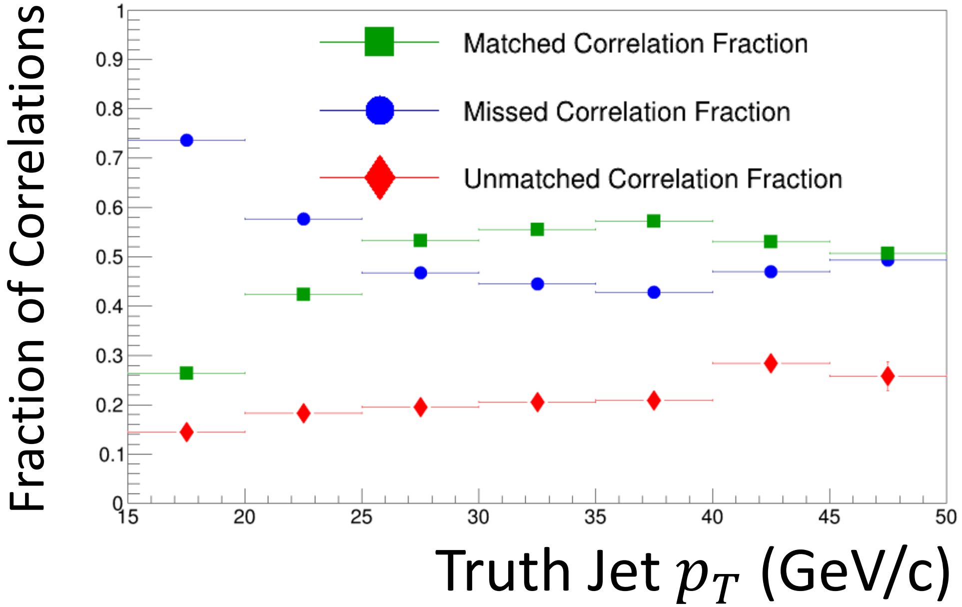
p_T^{Jet} Correction Method

Match jets between PYTHIA and PYTHIA + Geant distributions within a ΔR of 0.4 and then match constituents inside of jets within a ΔR of 0.02





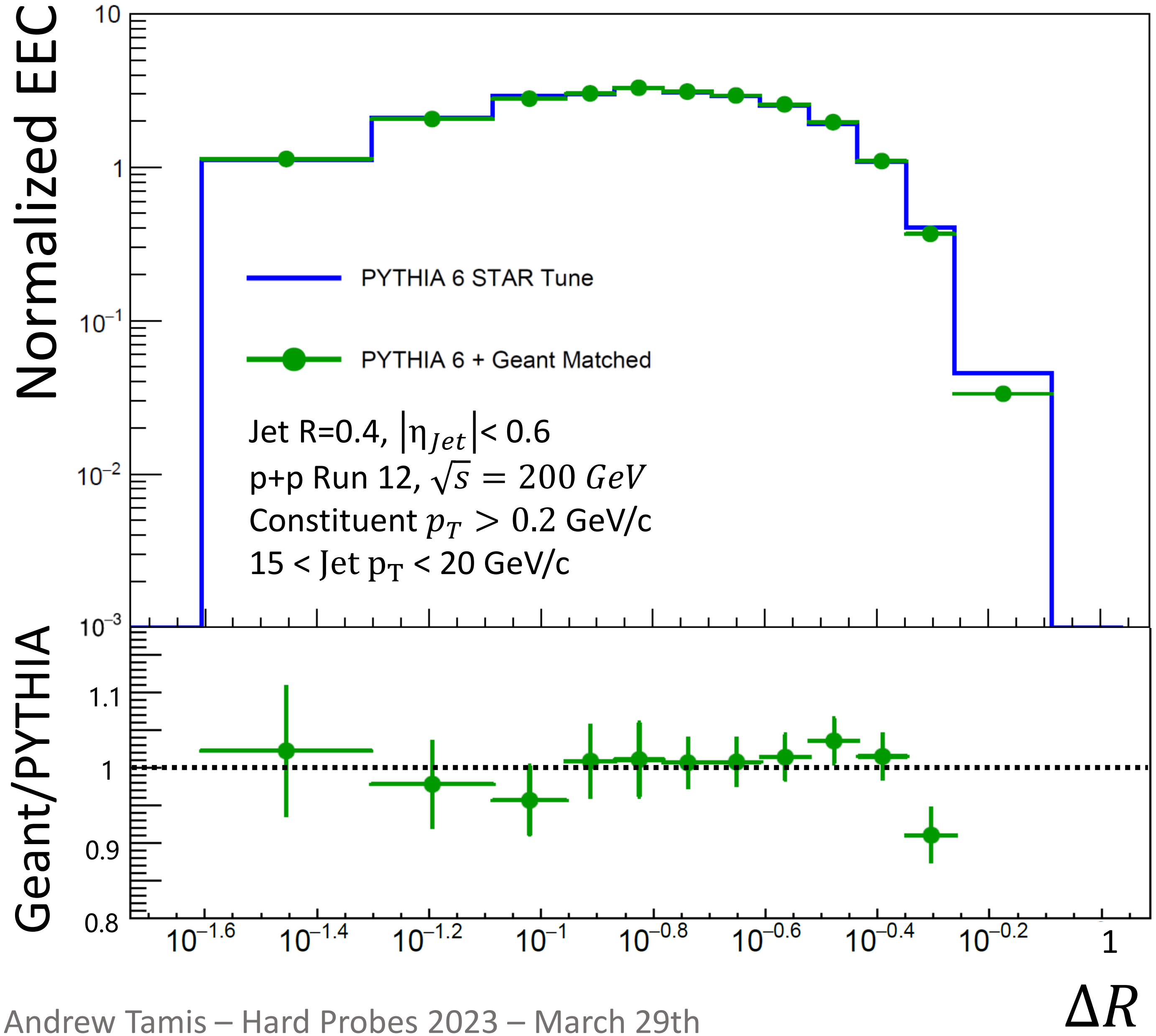
$\sqrt{s}$ = 200 GeV
R = 0.4
$|\eta_{Jet}| < 0.6$
Constituent $p_T > 0.2$ GeV/c

PYTHIA 6 + GEANT

- Fill in response matrix for jet p_T for each matched correlation
- Reconstruct the distribution for a truth jet p_T bin out of measured distributions according to the response matrix
- Add in misses from PYTHIA distribution

Method performed previously at STAR, Robotková, DIS 2022

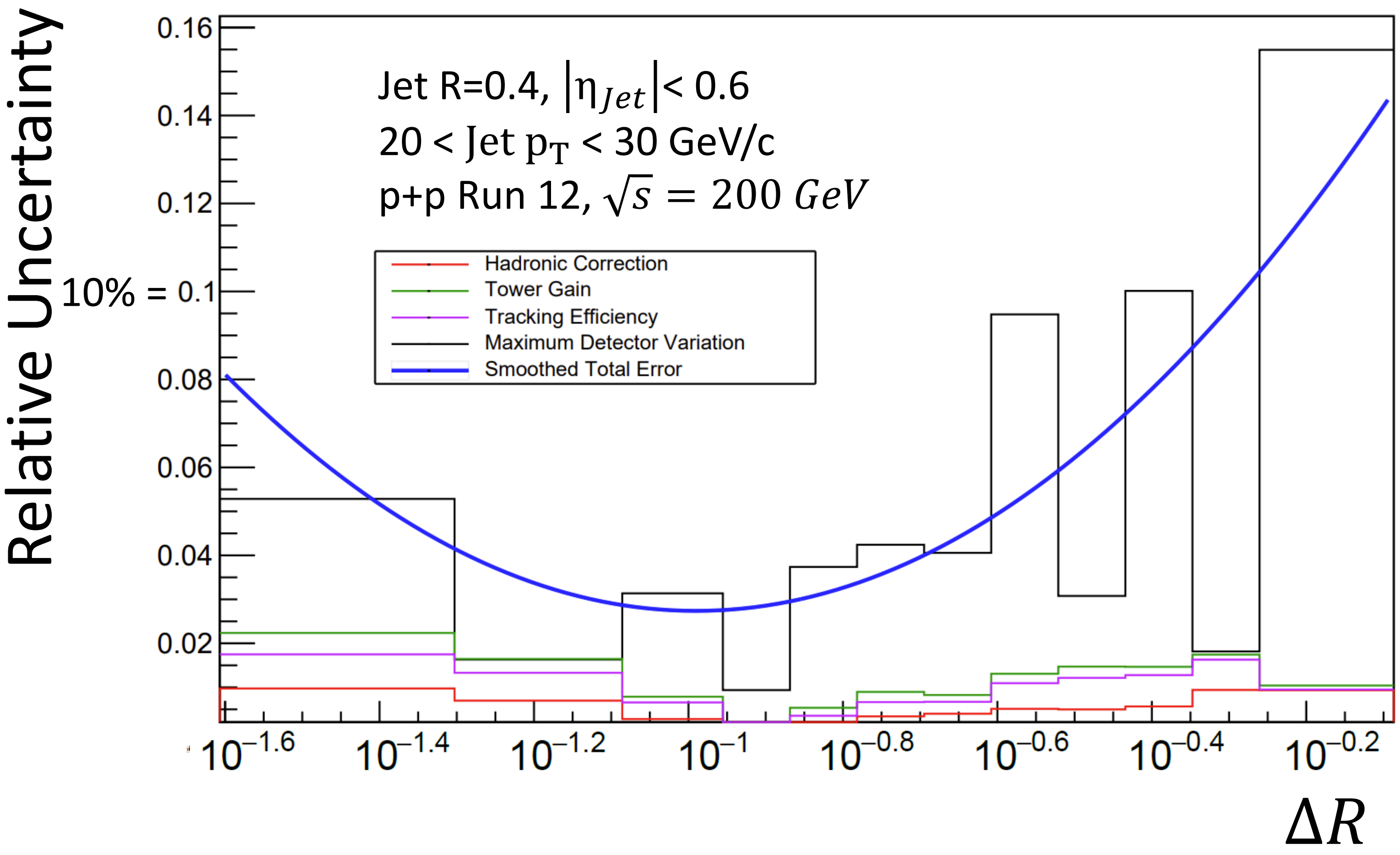
Simulating Detector Effects



Impact of detector effects on EEC other than $p_T{}^{Jet}$ correction

- Approximates detector effects after jet p_T has been corrected
- Hovers around unity in hadron, quark/gluon and transition regions, **do not apply any additional corrections**
- Treat percentage difference between truth and detector level for MATCHED jets as an uncertainty

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

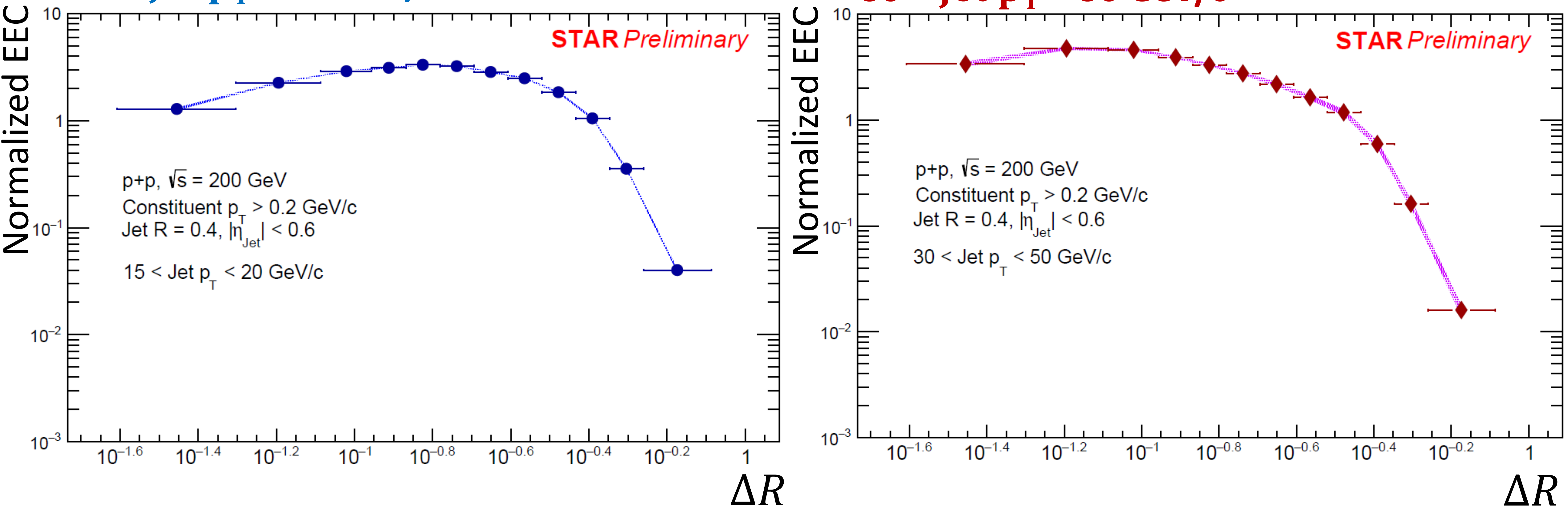
- 4% uncertainty

Maximum Detector Variation

- Previous slide

First EEC Measurement at RHIC

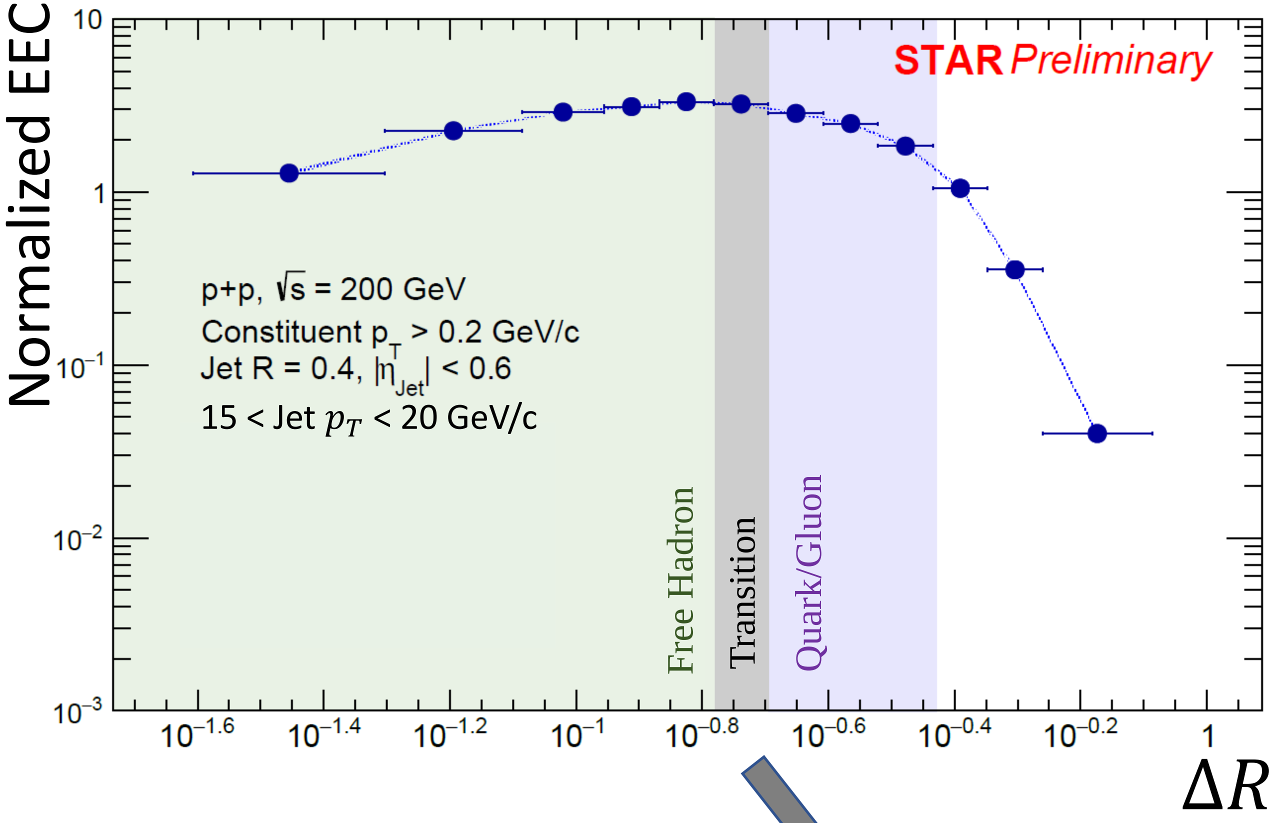
$15 < \text{Jet } p_T < 20$ GeV/c **$30 < \text{Jet } p_T < 50$ GeV/c**



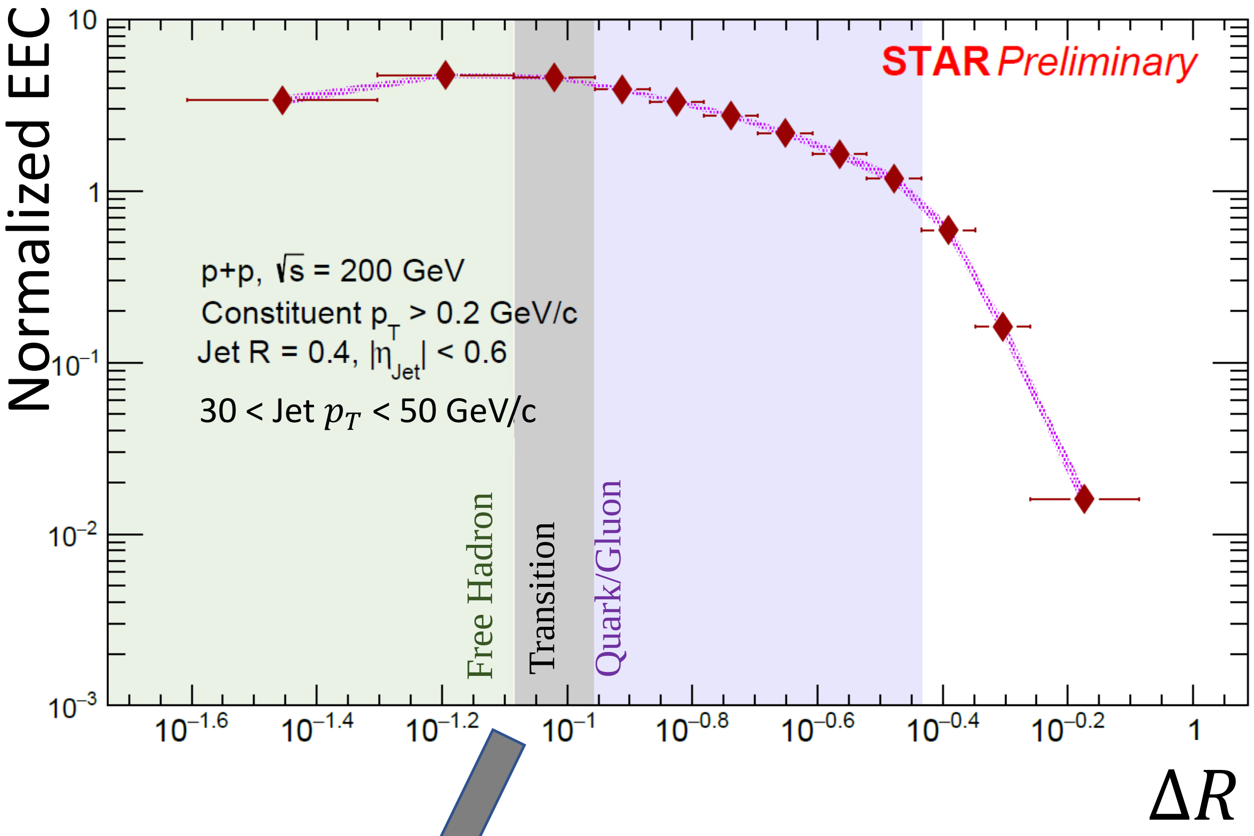
Average of the distribution moves to smaller angles with increasing p_T^{Jet}

First Corrected EEC Measurement

15 < Jet p_T < 20 GeV/c



30 < Jet p_T < 50 GeV/c

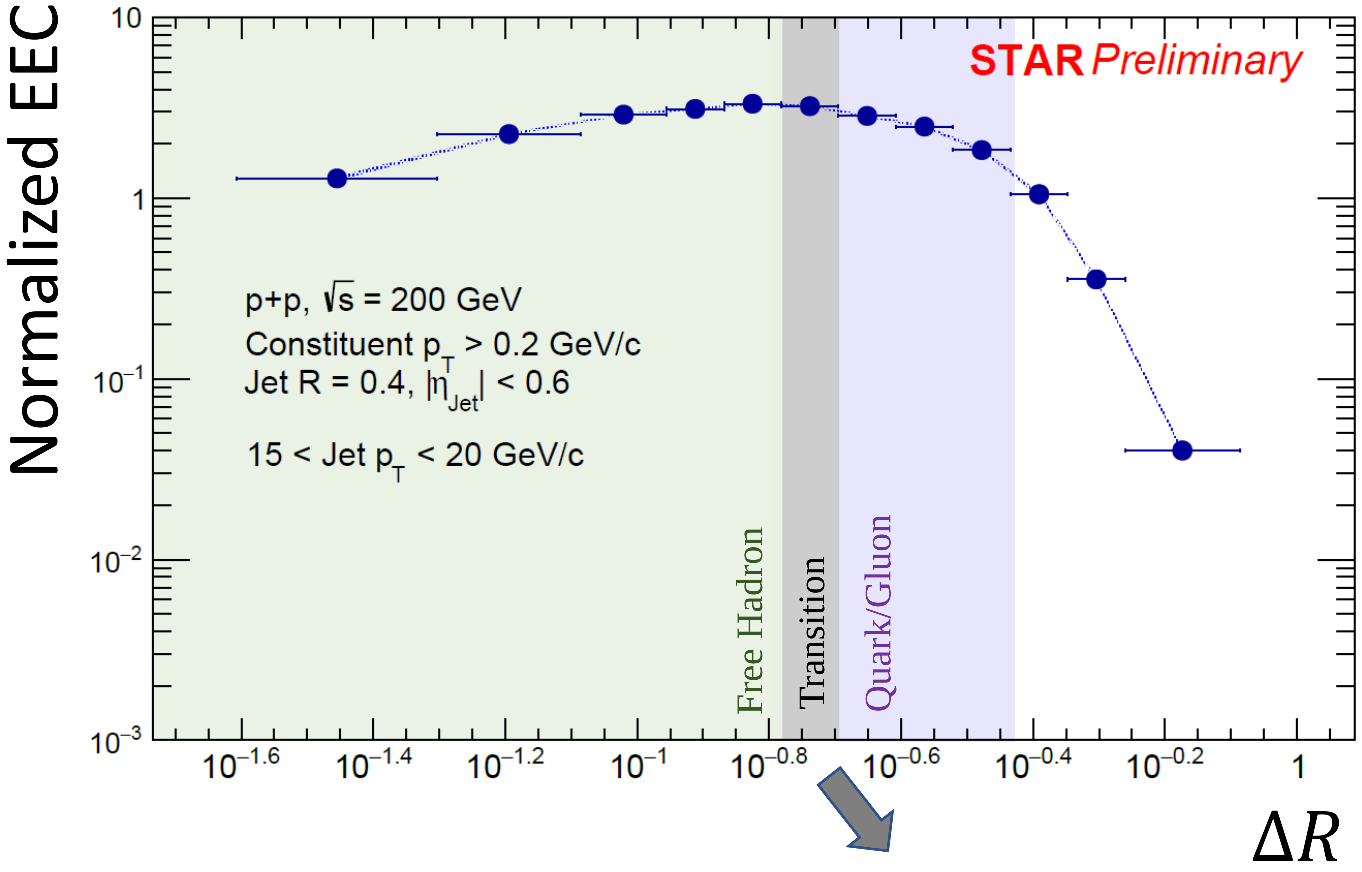


$$p_T{}^{Jet}{}_{Low} * \Delta R_{Turnover} = 10^{-0.75} * (15\text{GeV/c}) = 2.7 \sim 2.4 = 10^{-1.1} * (30\text{GeV/c})$$

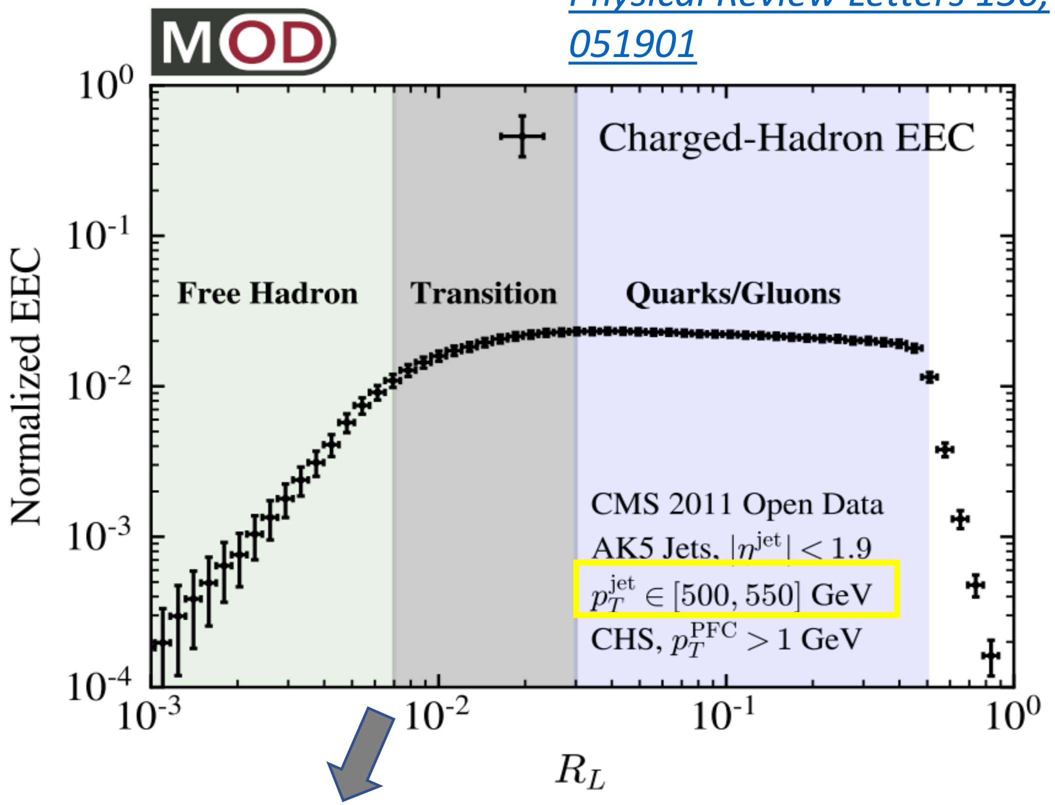
Recover expected behavior, transition region moves as $\frac{1}{p_T{}^{Jet}}$

Comparison With Result from CMS Open Data

15 < Jet p_T < 20 GeV/c



Komiske et al. 2023, Physical Review Letters 130, 051901

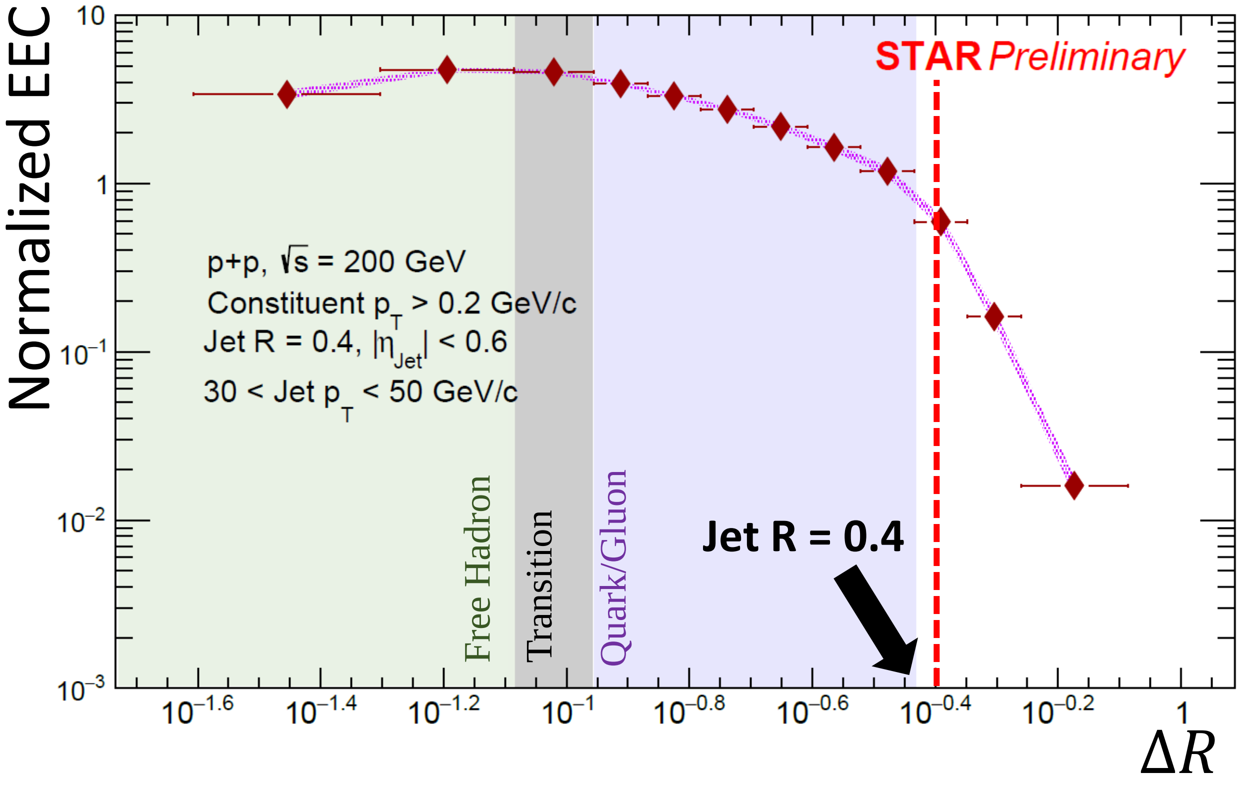


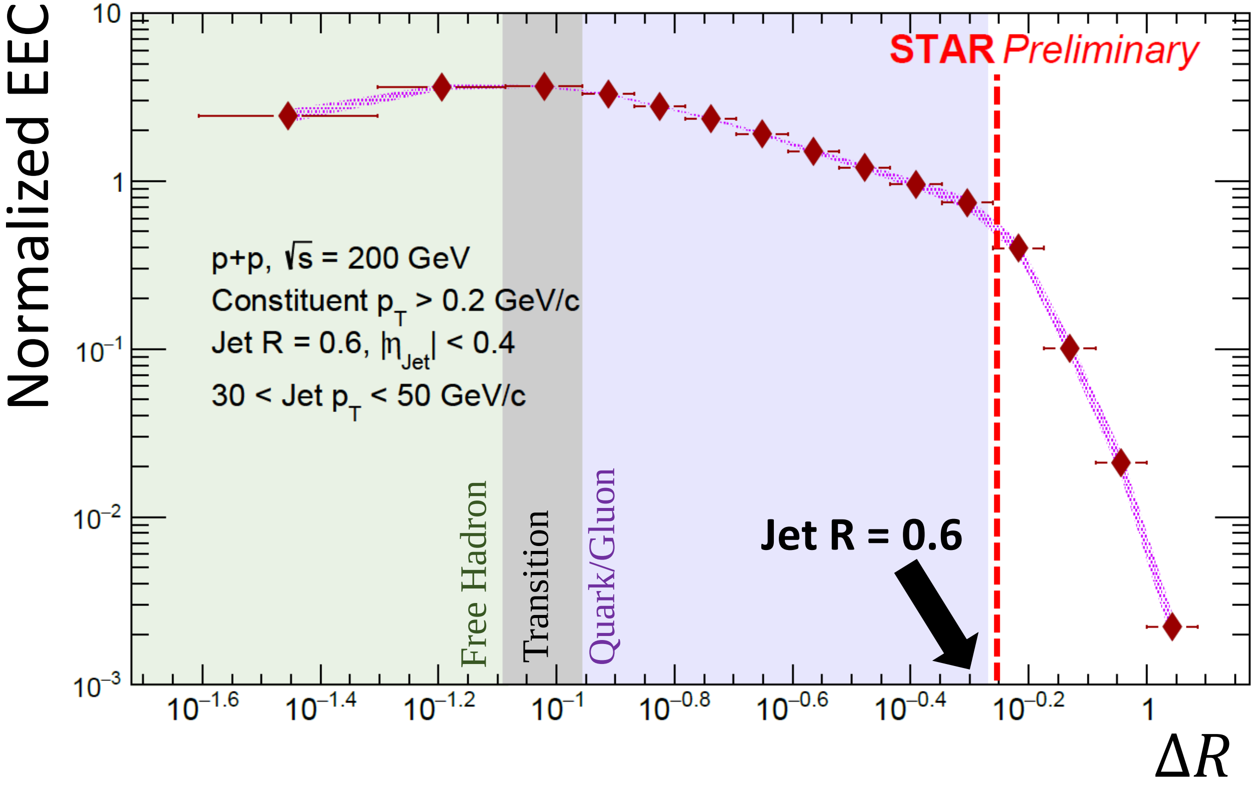
$$p_T{}^{Jet}{}_{Low} * \Delta R_{Turnover} = 10^{-0.75} * (15\text{GeV/c}) = 2.7\text{GeV} \sim 2.5\text{GeV} = 10^{-2.3} * (500\text{GeV/c})$$

Note: proportionality may depend on quark/gluon fraction

Consistent scale implies universality for varying jet p_T!

Effects of Larger Radius



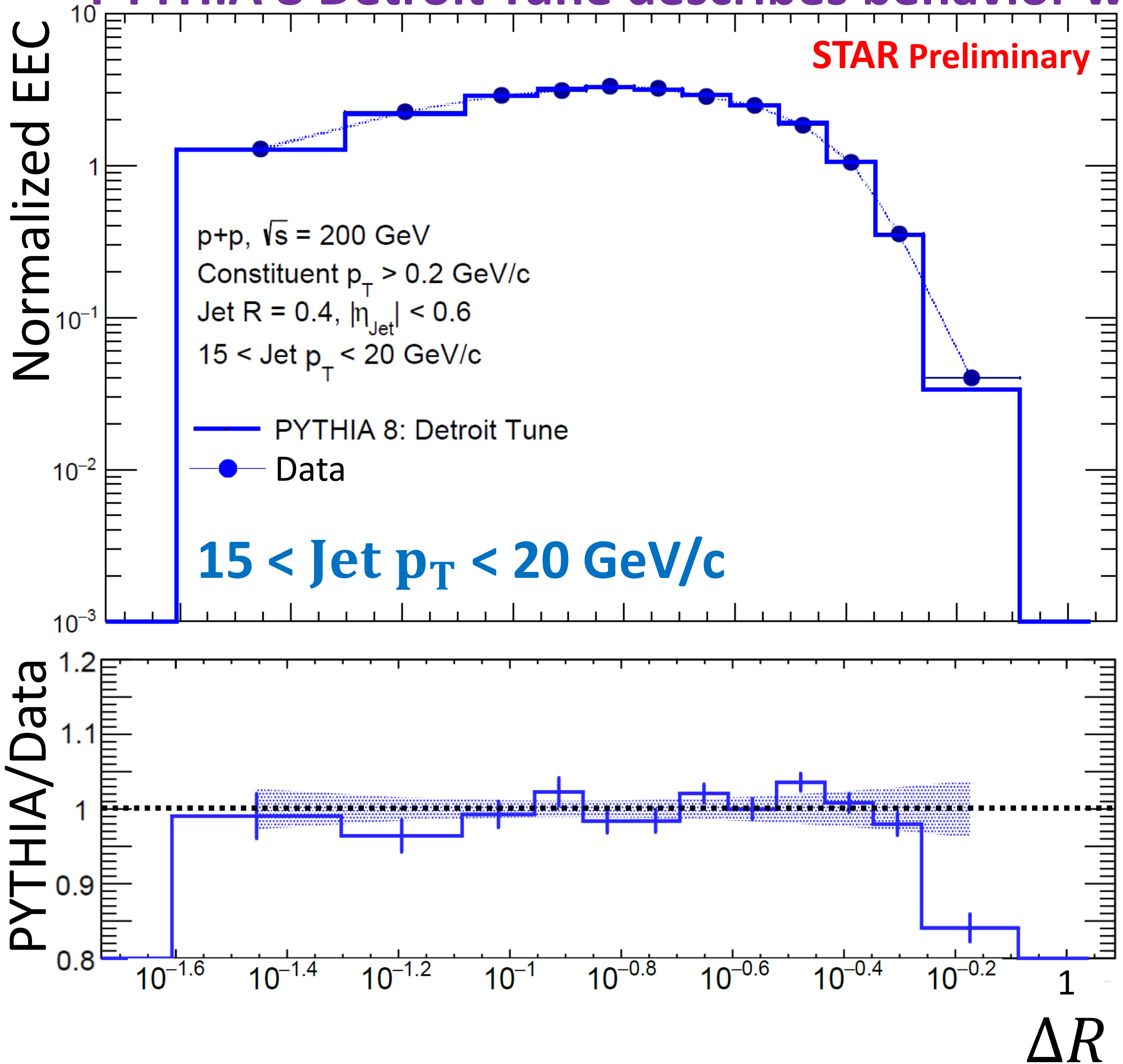


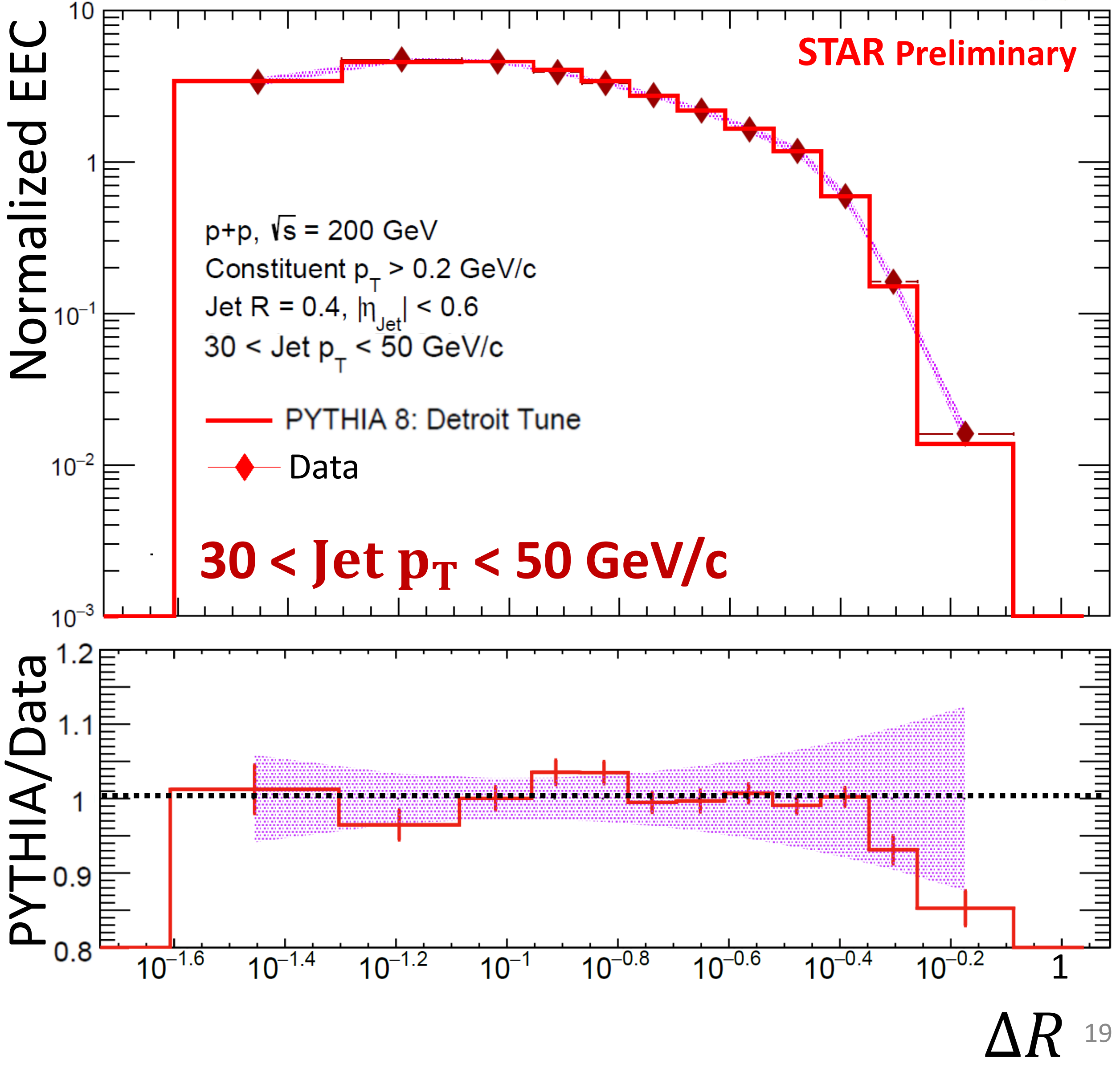
- As we move to larger jet radius, onset of transition region remains relatively constant, but quark/gluon region continues longer before geometric cutoff

- **Increasing R increases phase space for radiation – Scaling Behavior Persists**

Monte-Carlo Comparison

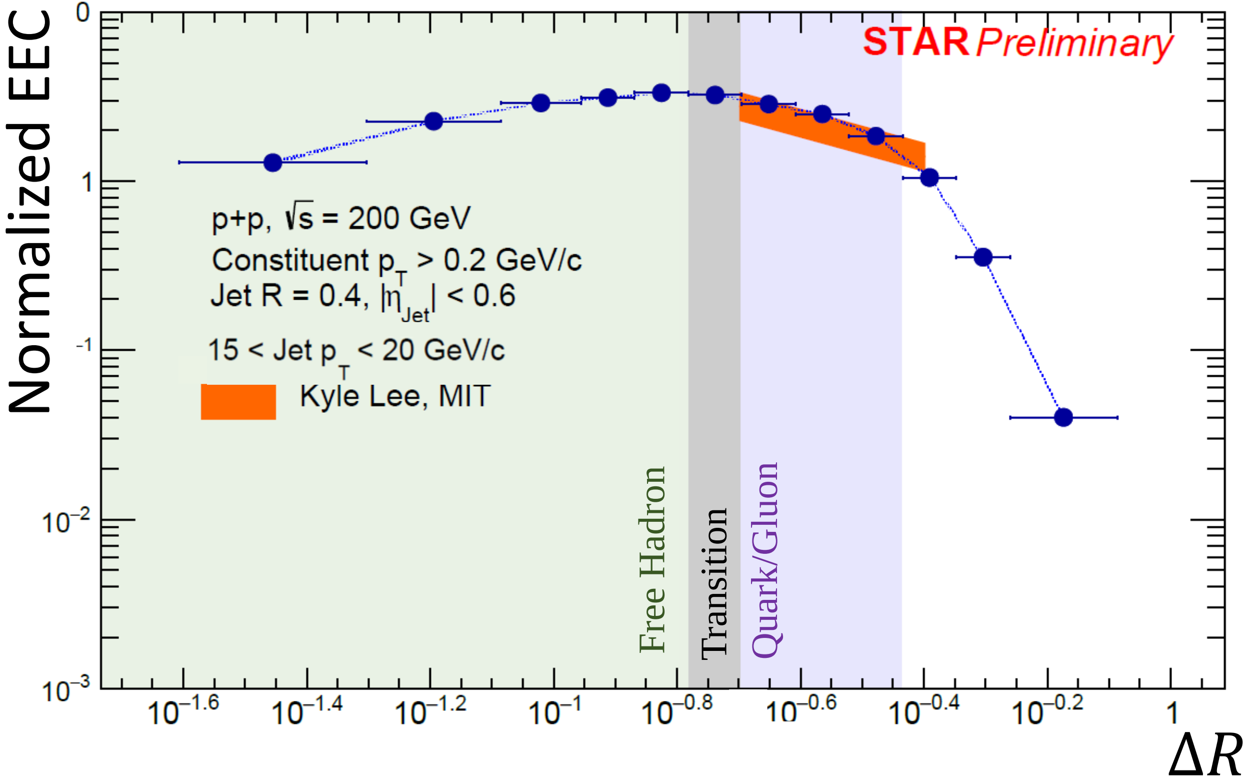
- **PYTHIA 8 Detroit Tune describes behavior well**



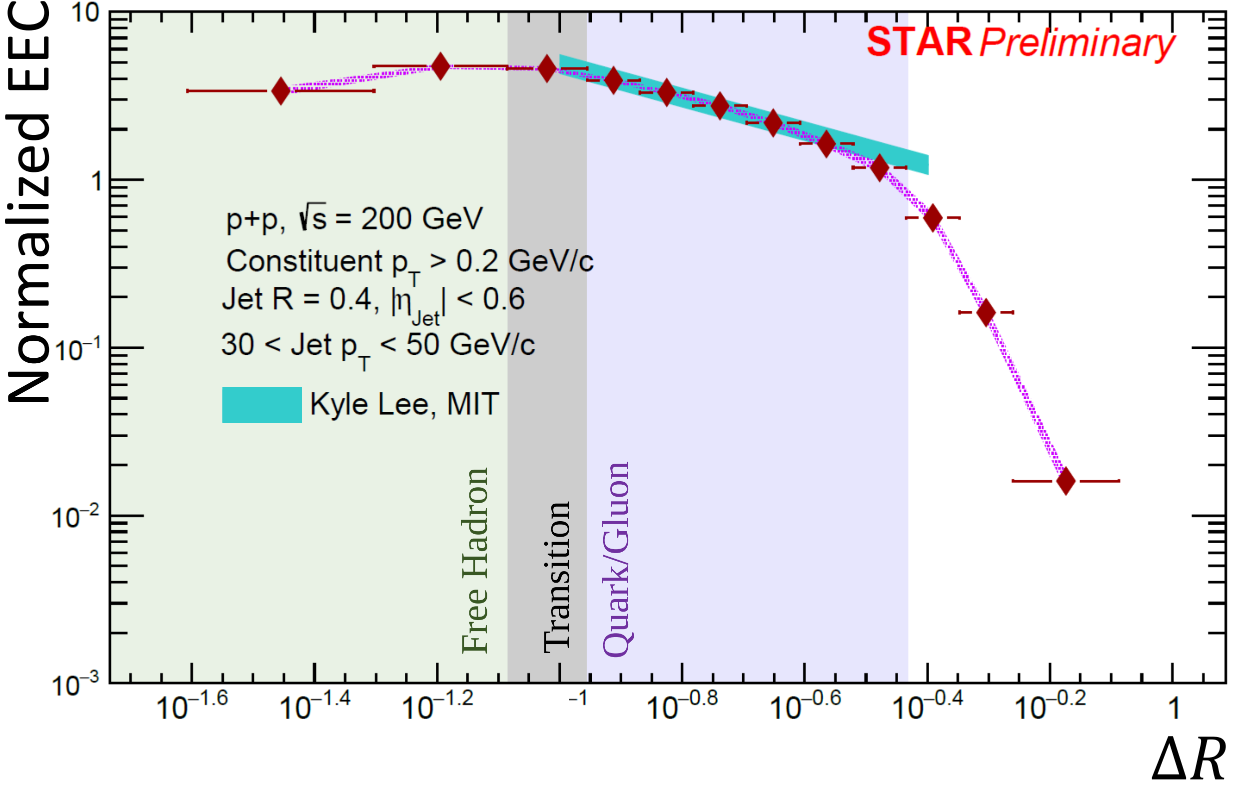


Theoretical Comparison (R = 0.4)

$15 < \text{Jet } p_T < 20$ GeV/c



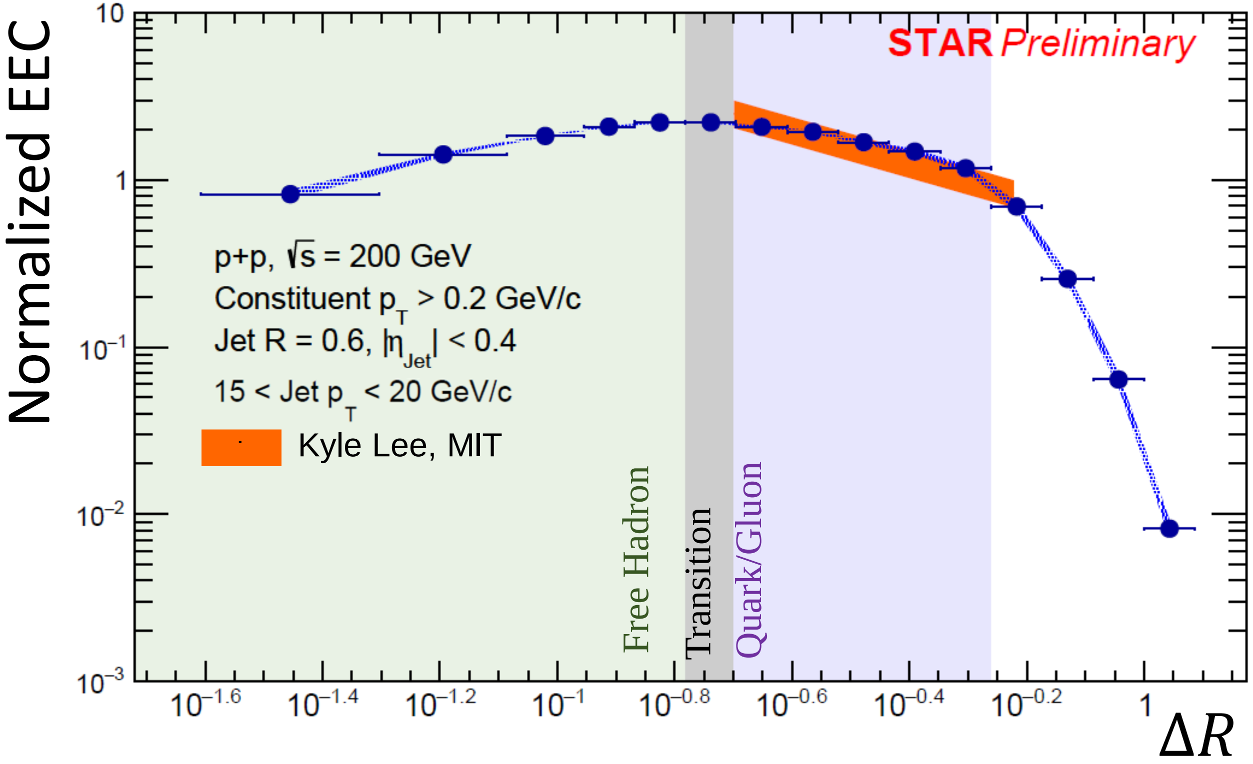
$30 < \text{Jet } p_T < 50$ GeV/c



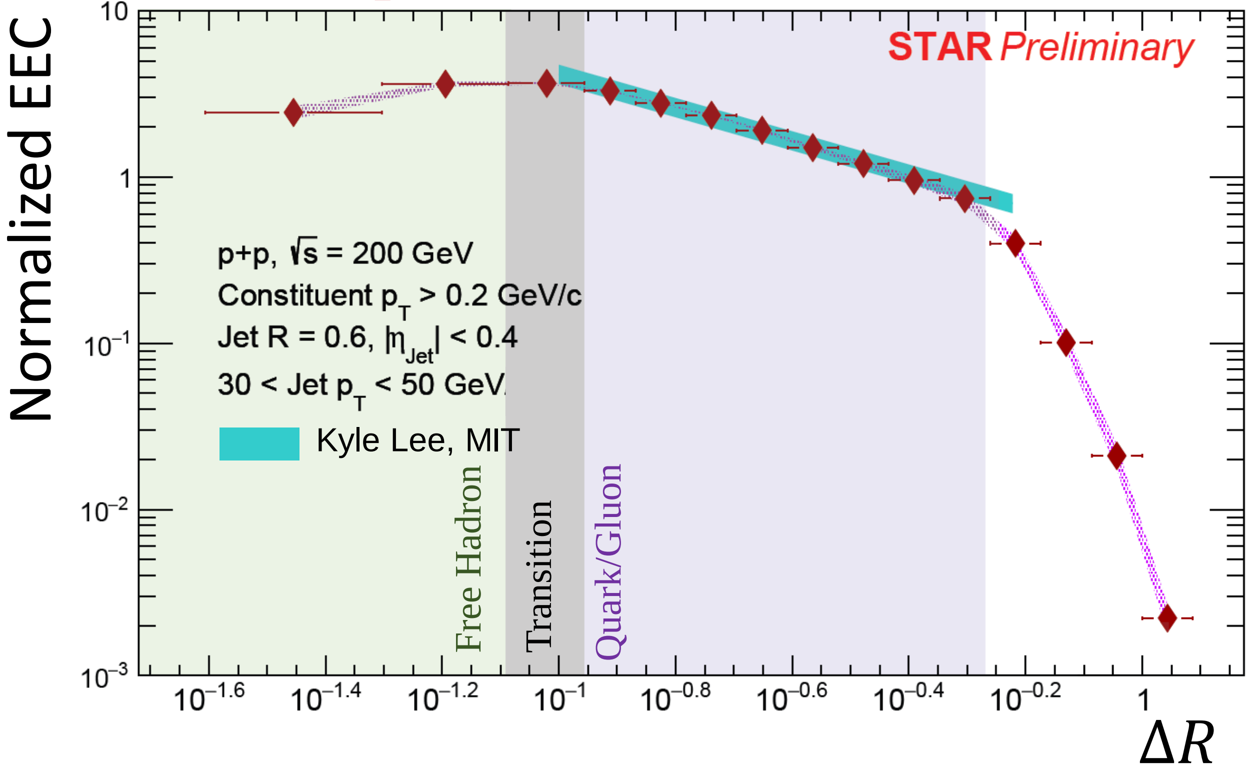
- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{{p_T}^{\text{Jet}}_{\text{Low}}} < \Delta R <$ Jet R) received directly from Kyle Lee, MIT.
- **Behavior agrees well with directly calculable theoretical expectations!**

Theoretical Comparison (R = 0.6)

15 < Jet p_T < 20 GeV/c



30 < Jet p_T < 50 GeV/c



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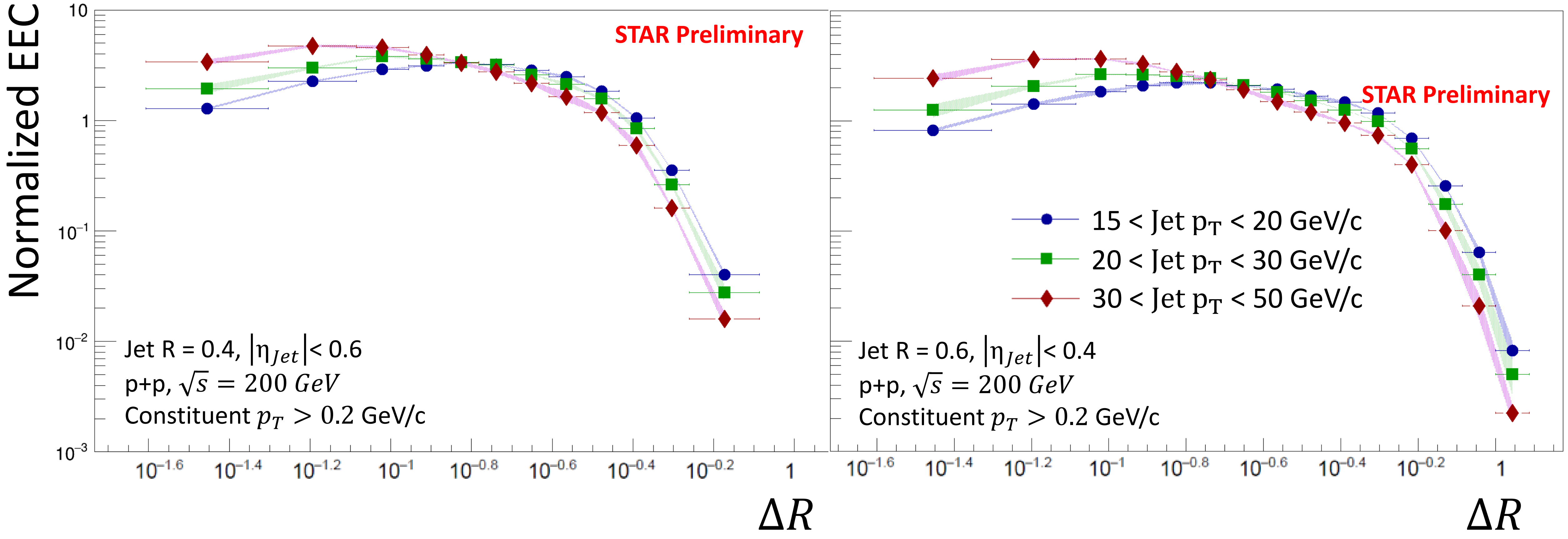
Summary



- Effect of ${p_T}^{Jet}$ selection persists in larger Jet radius
- **First measurement of EEC at STAR across various kinematic regions!**

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
- **First measurement of EEC at RHIC**
- **Future applications in heavy ions and higher order correlation functions**