Measurement of Full and Charged Two-Point EECs at STAR

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For the STAR Collaboration

Energy Correlators at the Collider Frontier
Week 1
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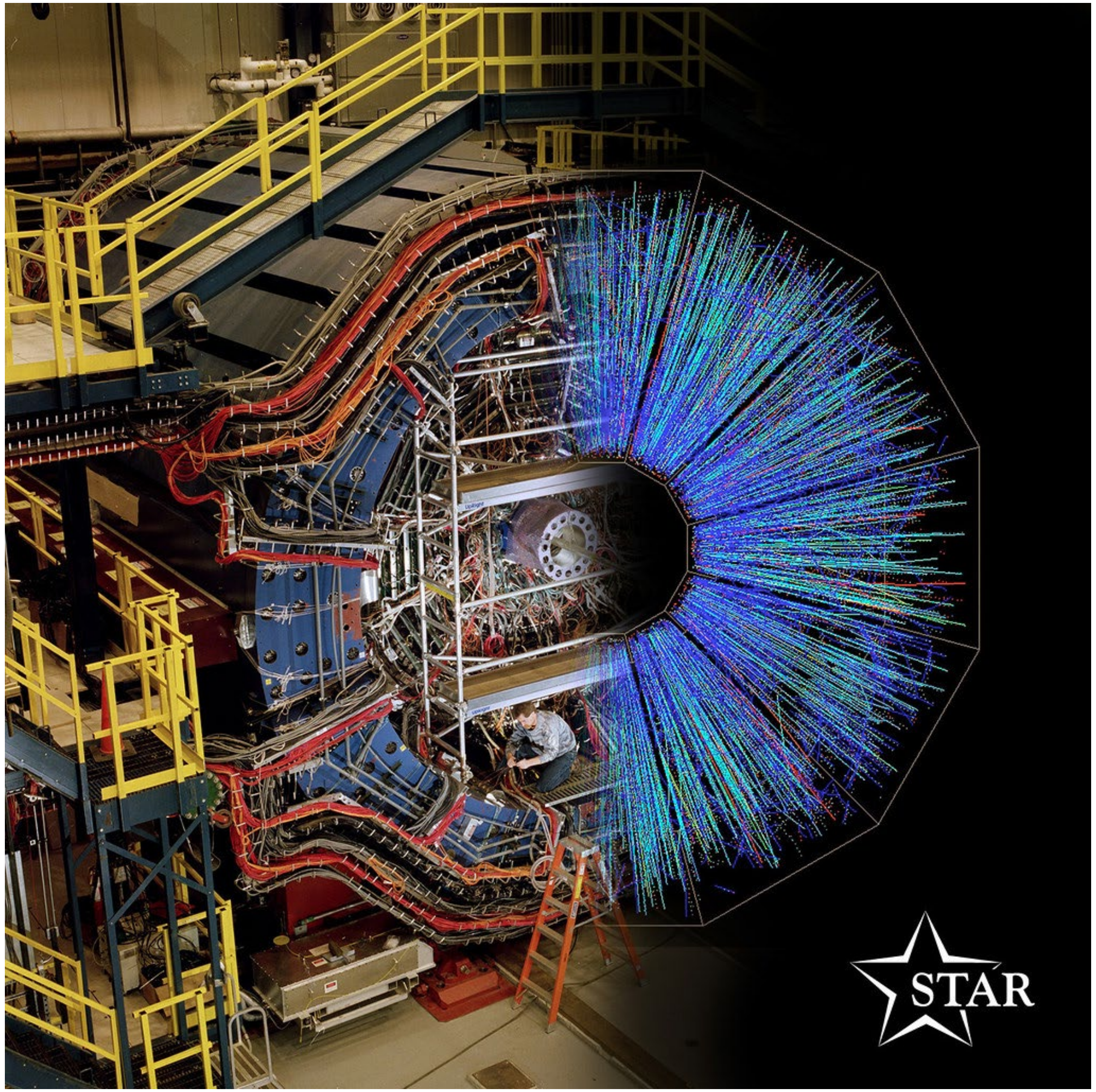
Measurement at STAR



- STAR Time Projection Chamber (TPC) provides excellent charged track resolution
- Barrel Electromagnetic Calorimeter (BEMC) allows for measurement of **full jets**
- BEMC used for trigger in order to obtain jet-rich data sample

Energy Energy Correlators (EEC)

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

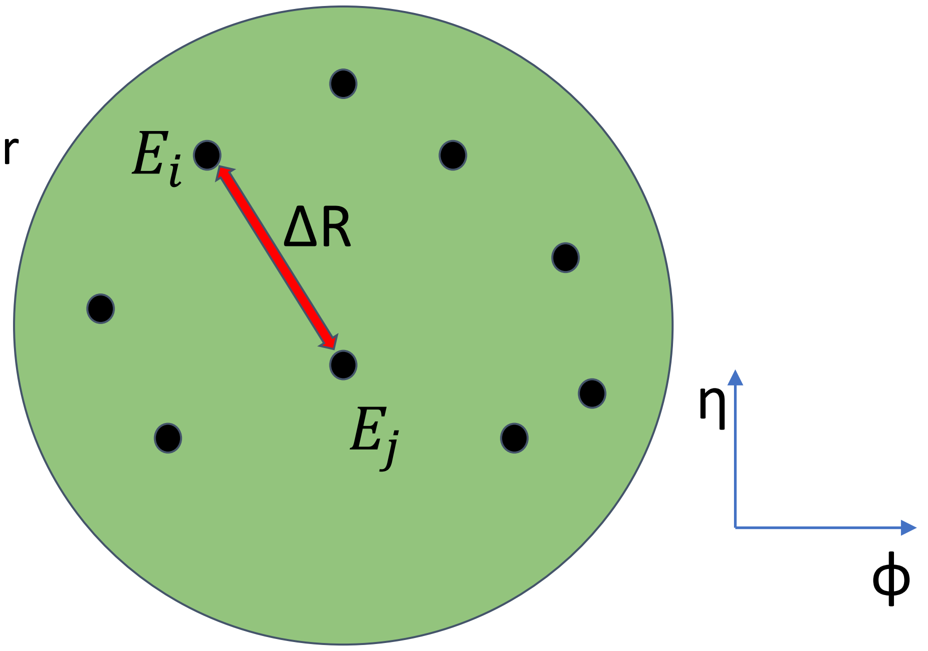
Chen et al. 2020, PRD 102, 5

Theoretical Definition of projected N-Point Correlator

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

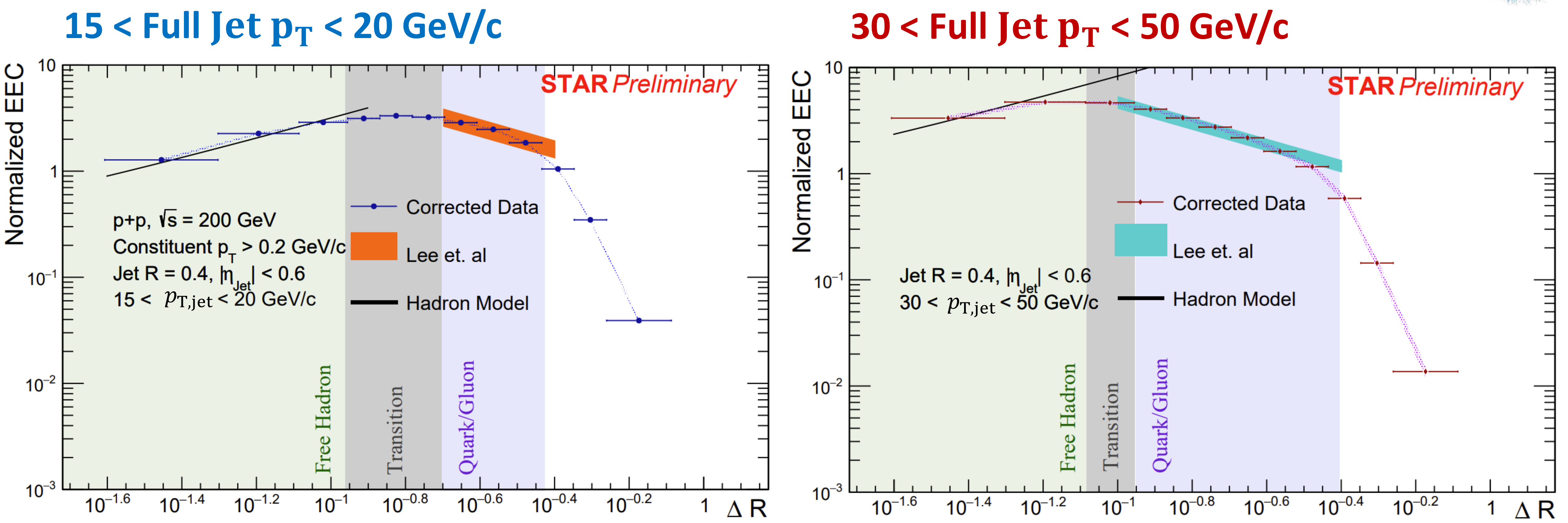
Experimental Construction of Two-Point Correlator

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

Measurement at STAR

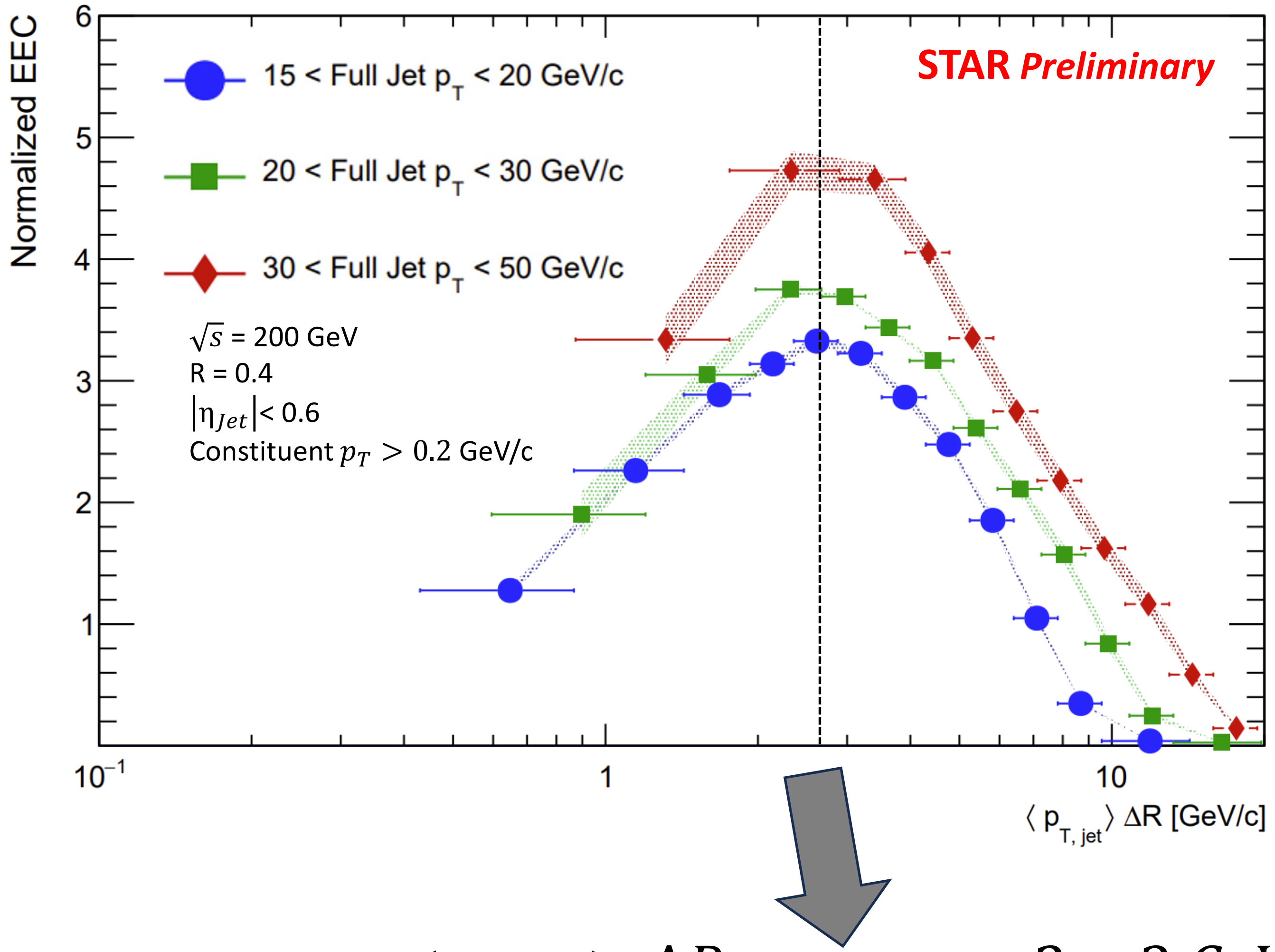


Lee, Mecaj, Moult (2023): arXiv:2205.03414

- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{{p_T^{Jet}}_{Low}} < \Delta R <$ Jet R)
- **Behavior agrees well with theoretical expectations!**
- Low angle behavior compared with toy model of hadrons, assuming uniform energy distribution

p_T-Shifted Distributions

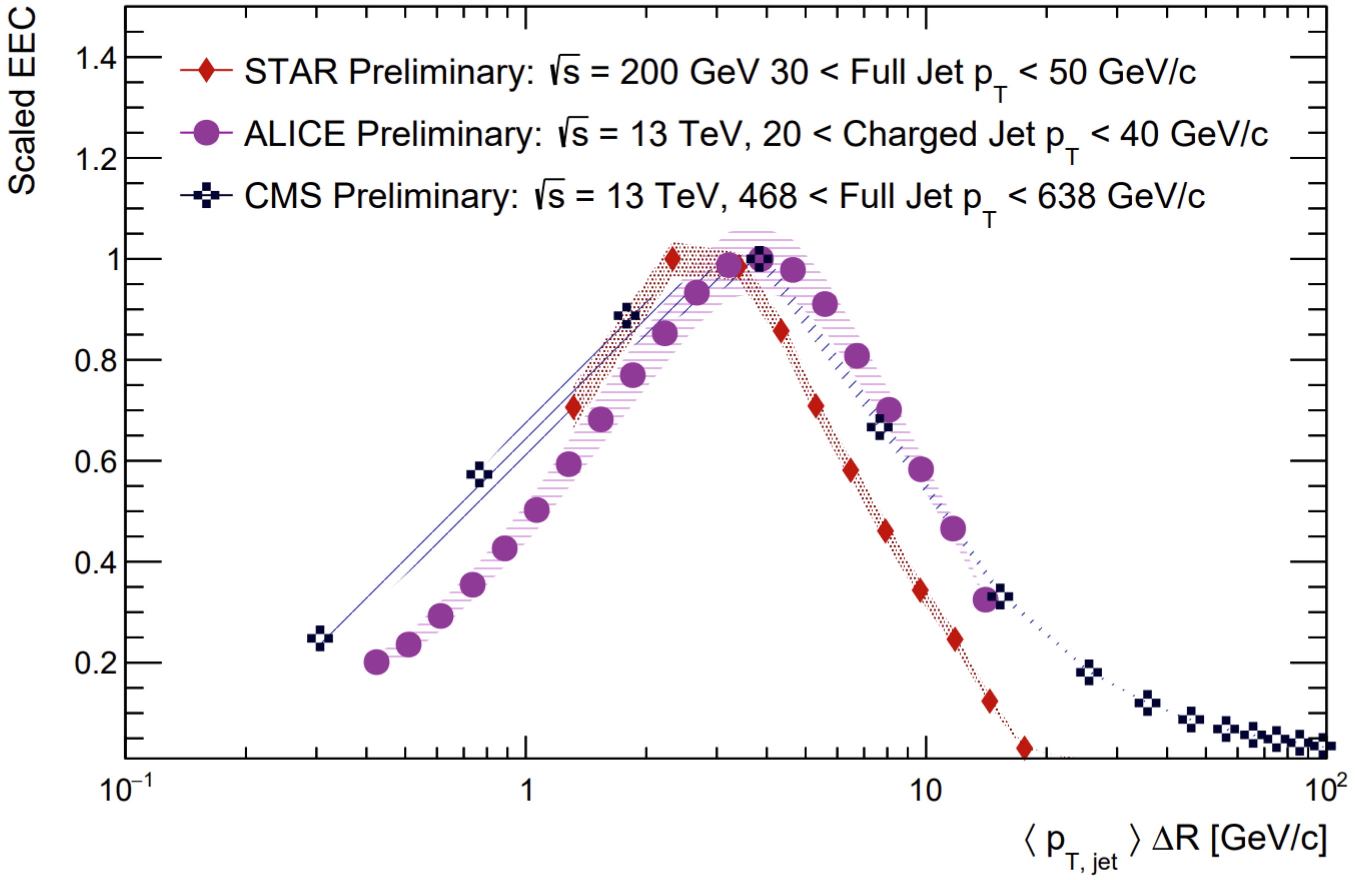
- Shift Corrected Result on x axis by average $p_{\mathrm{T,jet}}$ in a given bin
- As location of transition $\propto \frac{\Lambda_{\mathrm{QCD}}}{p_T^{\mathrm{Jet}}}$, this will collapse it onto a single point
- In this case, average momentum is determined via PYTHIA and applied post-correction



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

Comparison with ALICE and CMS Results

- STAR result is comparable 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 region shifts based on initiator

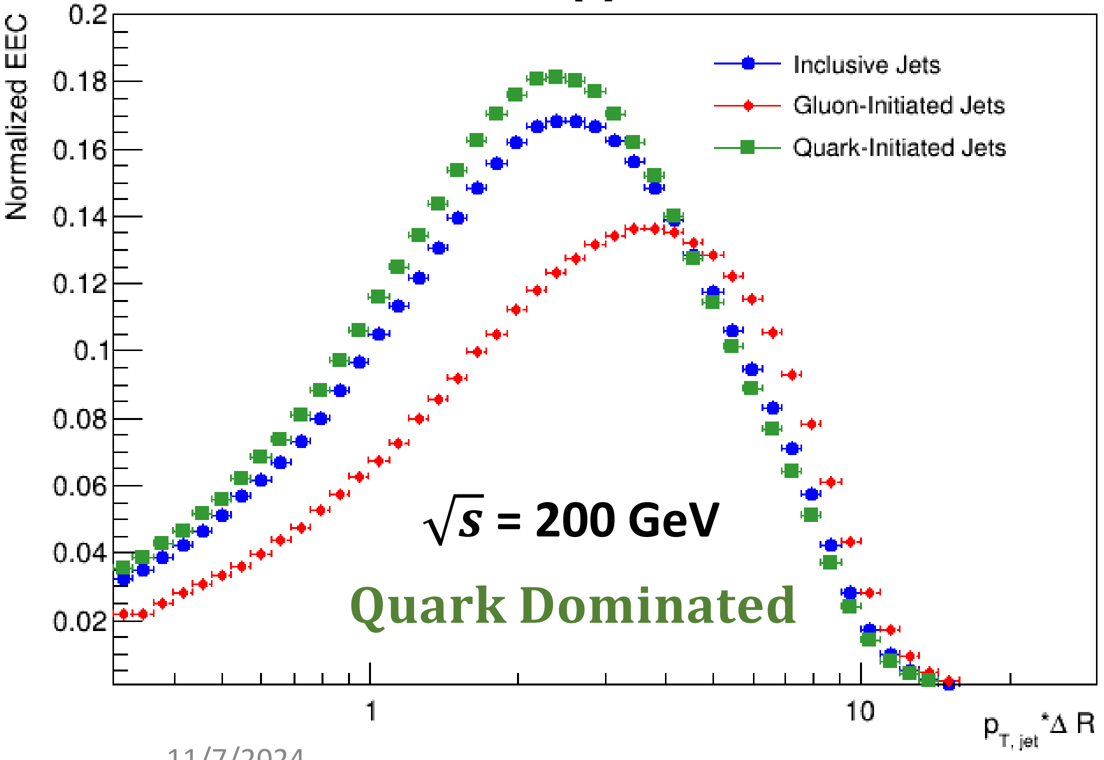


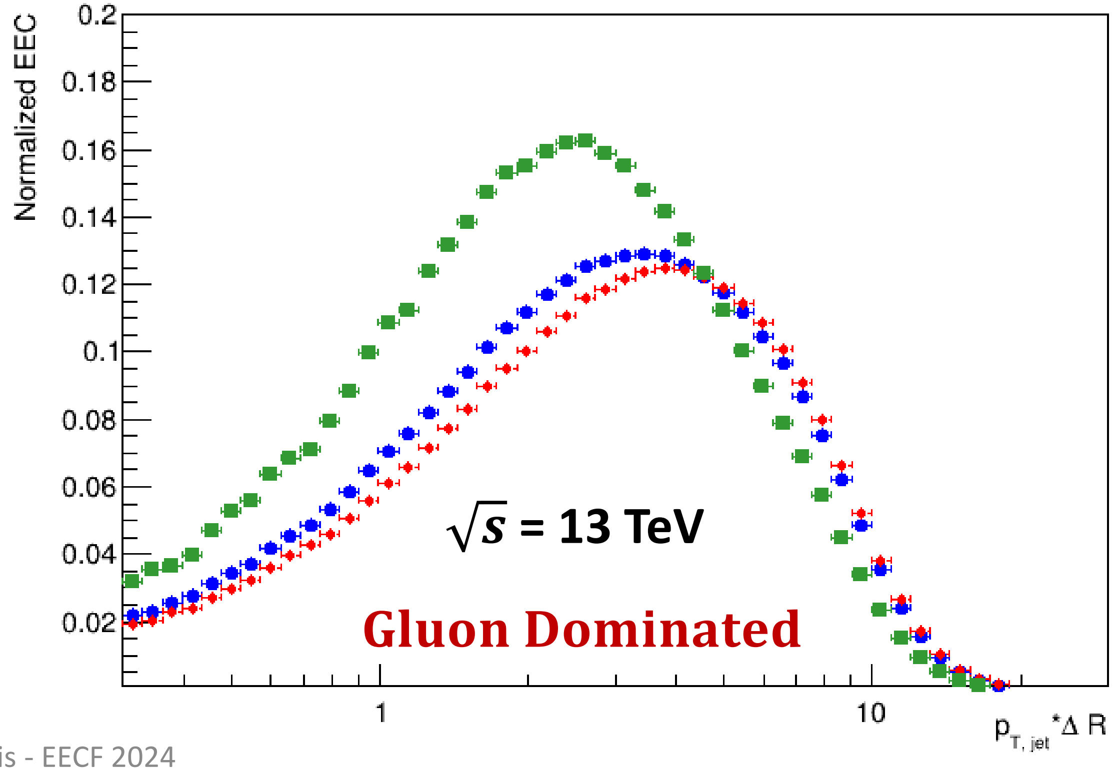
Impact of Quark/Gluon Fraction

- Observed turnover region for ALICE result occurs at larger $< p_{T,\text{jet}} > \Delta R_{Turnover}$
- This is largely due to difference in quark/gluon fraction as gluons fragment to larger angles
- ***Quark-rich environment of STAR is unique place to study EECs***

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

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





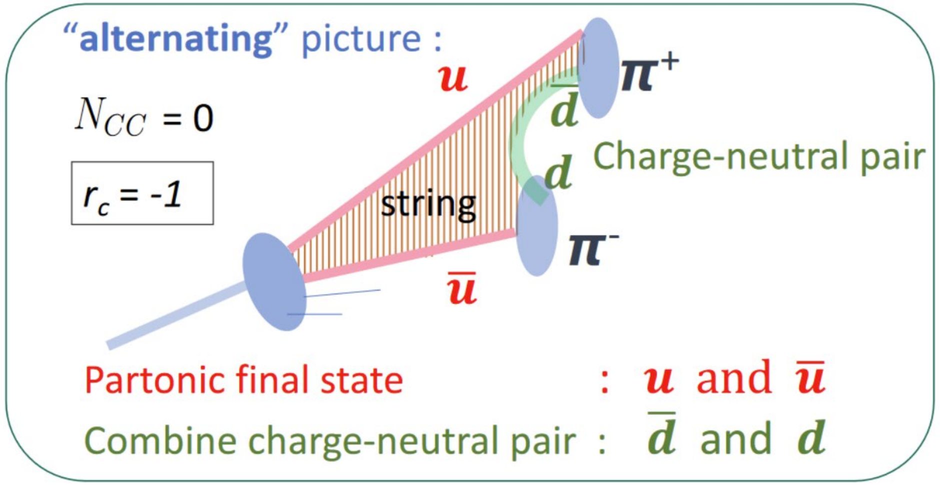
Charge-Dependent Hadronization

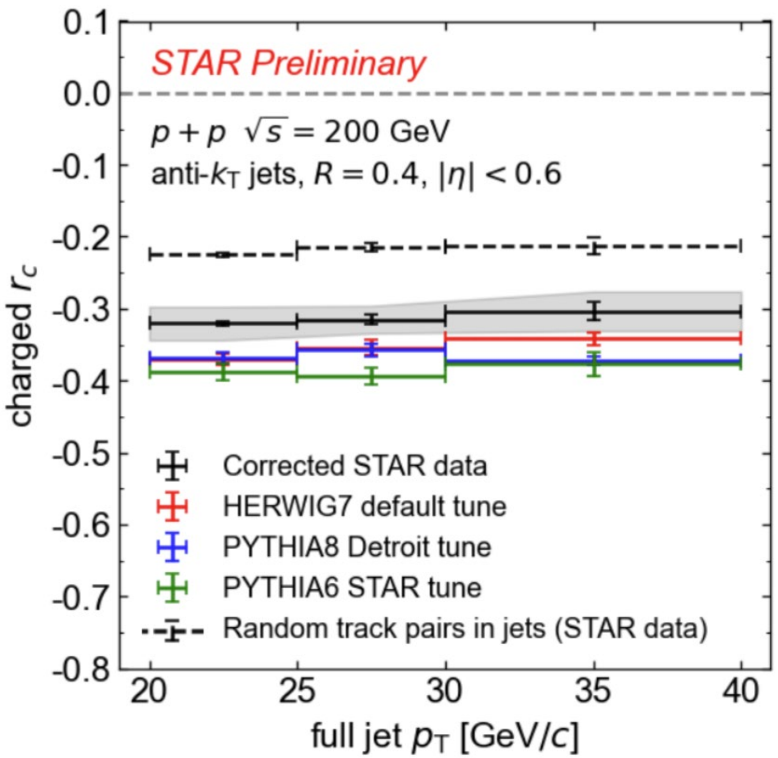
- Hadronization may introduce explicit charge dependence dependent on mechanism
- String-Like hadronization used by PYTHIA, while cluster hadronization used by HERWIG
- Studied by several charge dependent observables, such as r_c

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}$$

h_1h_2: same charge hadrons,
$h_1\bar{h}_2$: opposite charge hadrons

Figure: Mriganka Mouli Mondal

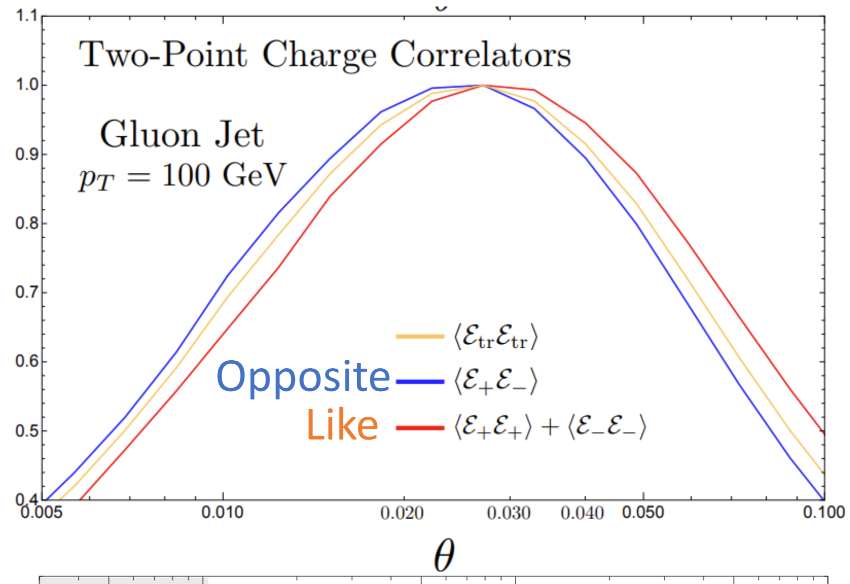


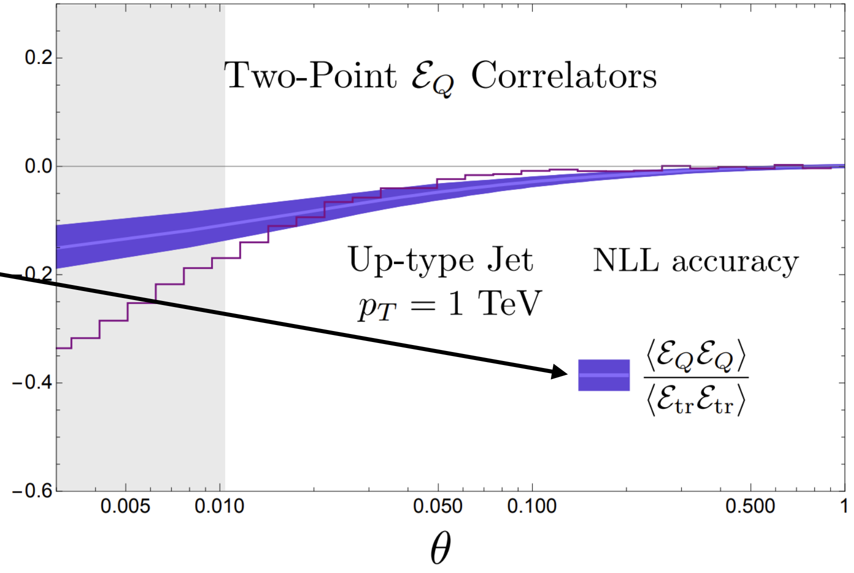


Charged EECs

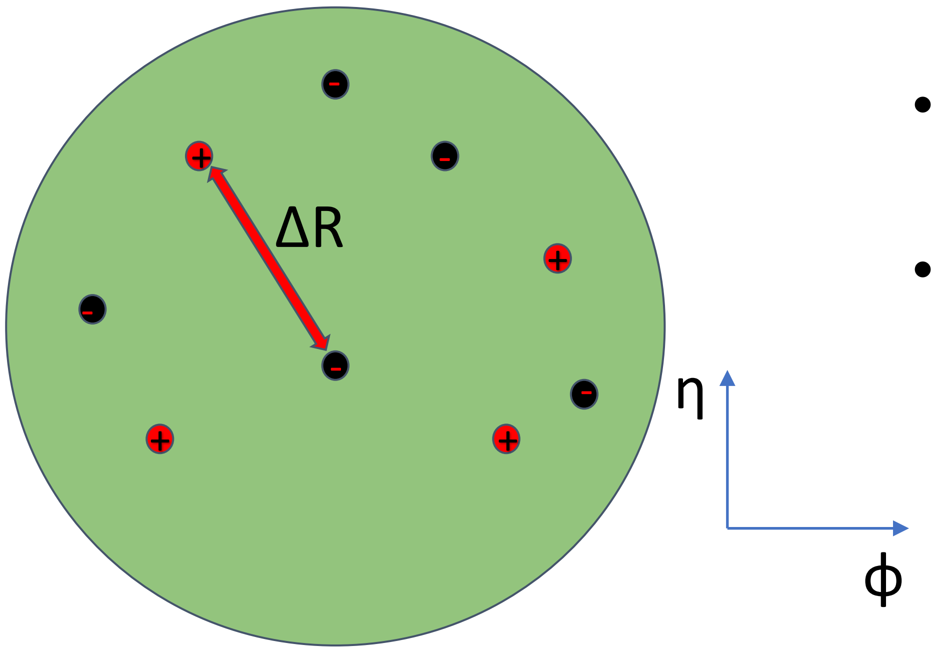
- Can further extend non-perturbative power of EEC by exploring correlation of both angle and charge distribution.
- Replace energy flow operator with some selection on charge (Like or Opposite charge correlations)
  - Or by weighting energy flow operator by charge operator
- Seen in Pythia simulations done by Lee and Moult, Transition region shifts on like- and opposite-charge selection

Lee,Moult 2023: arXiv:2308.00746





Charged EEC Experimental Measurement

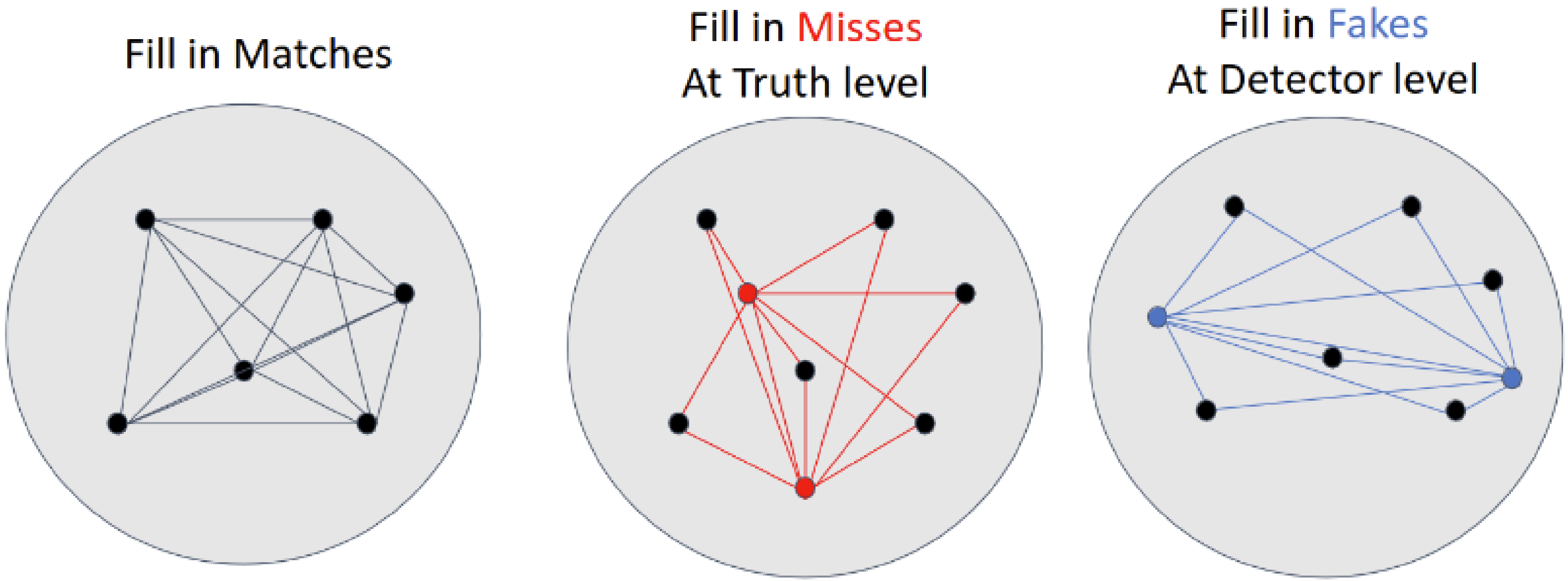


- Experimentally: Build distributions out of like-sign correlations and opposite-sign correlations
- Perform 3D Bayesian unfolding separately to each distribution
- Construct charge-weighted EEC via their difference

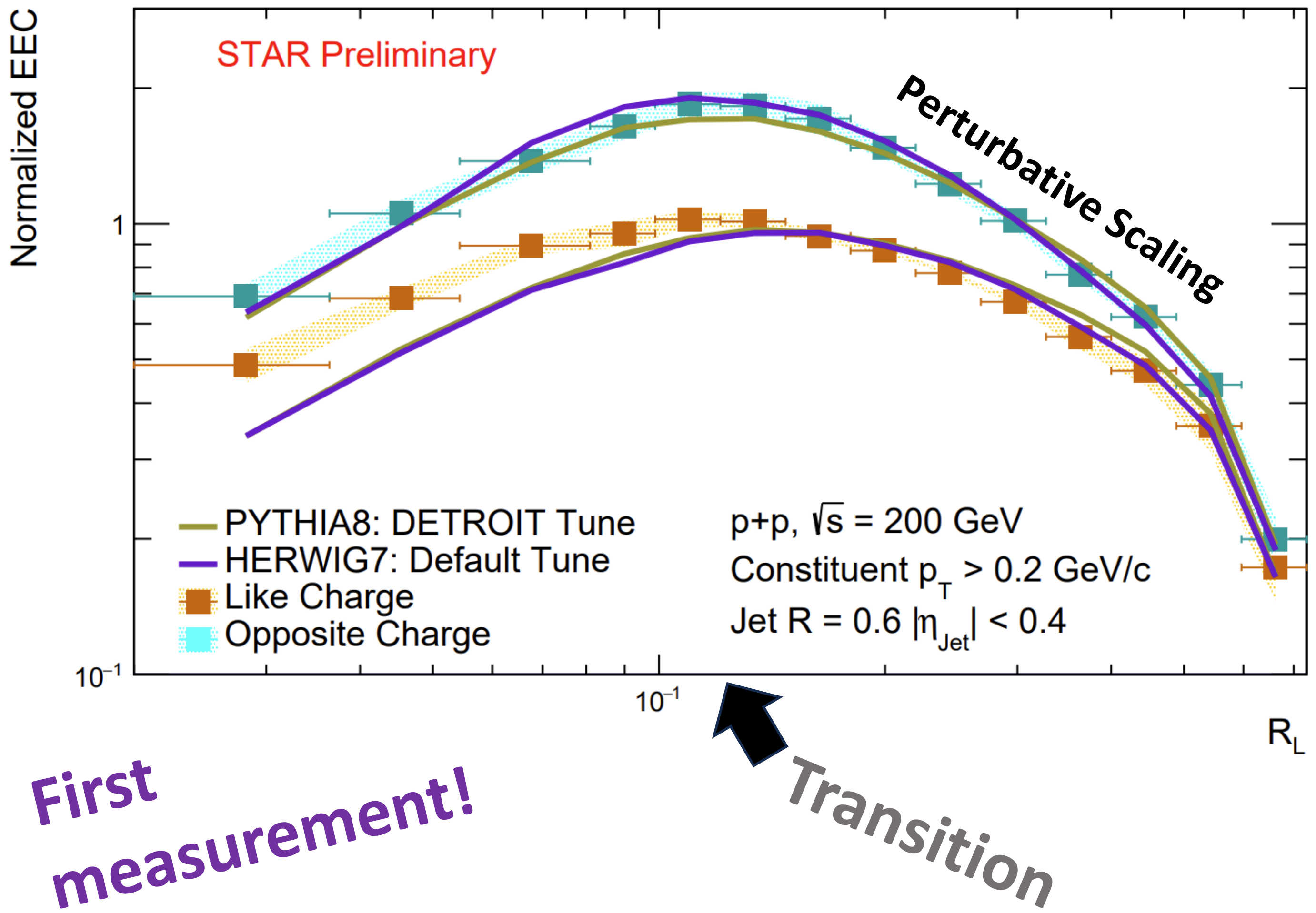
$$\text{Charged EEC} = \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iQ_iE_jQ_j}{p_{T,Jet}{}^2}\right)}{d\ (\Delta R)} = \mathrm{EEC}_{\mathrm{Like}} - \mathrm{EEC}_{\mathrm{Opposite}}$$

3D Unfolding – Method

- Unfold separately for like-charge and opposite-charge correlations
- Perform matching between particle and detector level
  - Once for Jets (Within Jet Radius) and once for constituents (Within 0.01 in eta-phi)
- Bayesian Unfolding in three variables per correlation
  - $p_{T,jet}$, R_L , $\frac{E_1 E_2}{{p_{T,jet}}^2}$



Like and Opposite charge Distributions

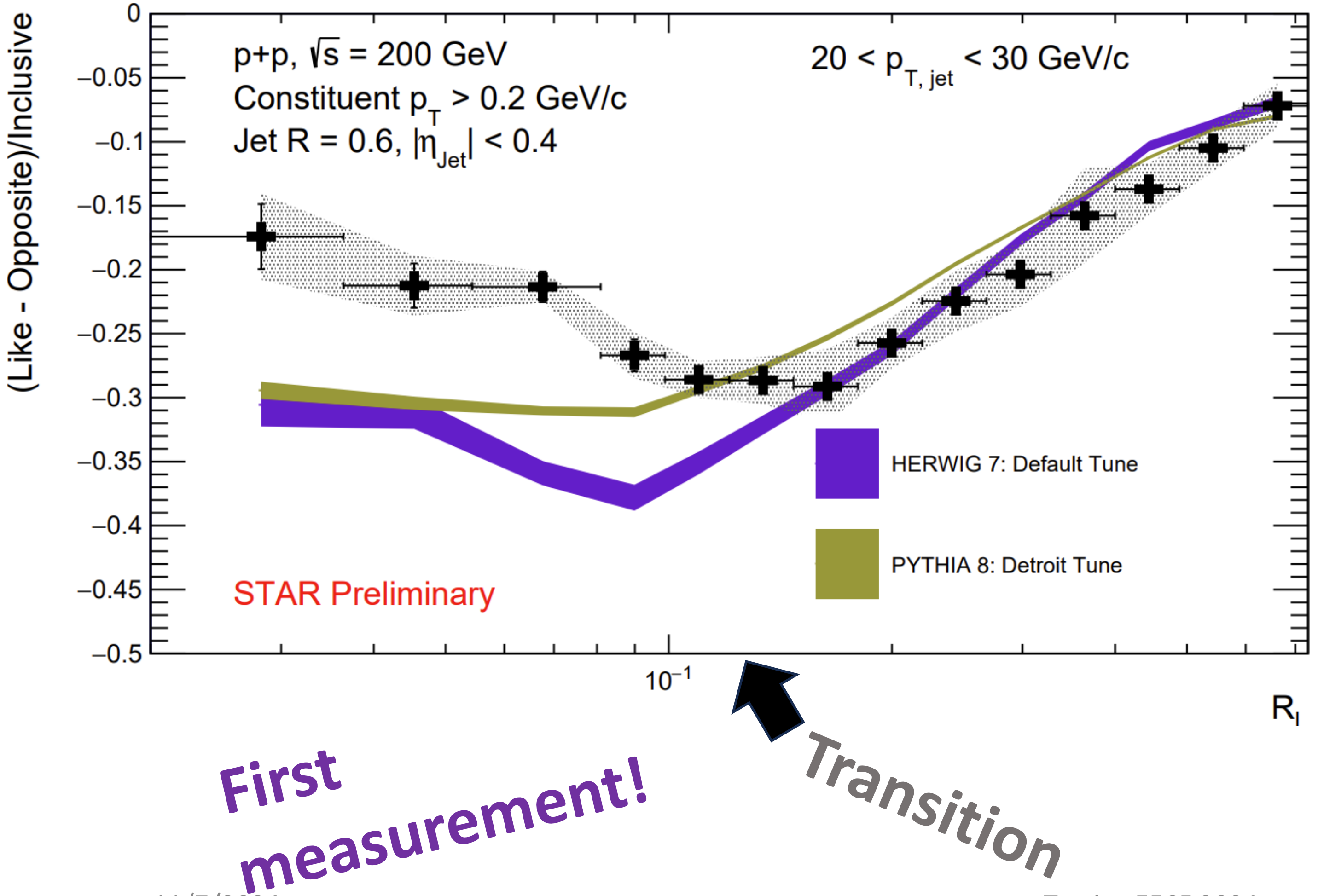


First measurement!

- Both Like and Opposite sign follow expectations in perturbative region
- Excess of like-charge correlations below transition region
- Compared with Herwig 7 ([Bellm et. al.)](#) and Pythia 8 Detroit Tune ([Aguilar et. al](#).)
- Shift in location of transition region seen in Monte-Carlo, but not resolved in data

Charge Ratio

$$\frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iQ_iE_jQ_j}{p_{T,Jet}{}^2}\right)}{d\,(\Delta R)} \Big/ \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}{}^2}\right)}{d\,(\Delta R)} \approx \frac{\langle \mathcal{E}_Q\mathcal{E}_Q\rangle}{\langle \mathcal{E}_{\mathrm{tr}}\mathcal{E}_{\mathrm{tr}}\rangle}$$



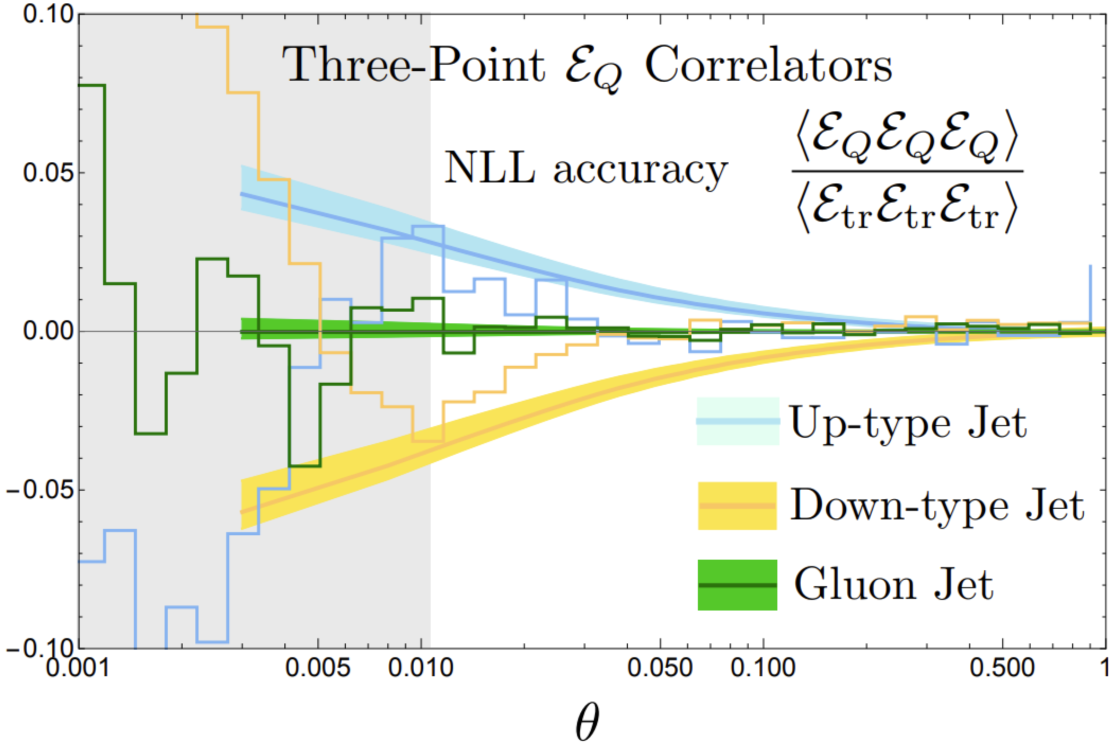
- Cluster hadronization (Herwig) and String hadronization (Pythia) both predict same qualitative behavior
- Both describe scaling of data in perturbative region, but neither describe data below transition region
- Implementation of charge dependence/conservation in hadronization mechanism may not fully capture effects

Extension to Three-Point

- Extension to Three-point charge correlators extremely interesting
  - Charge odd – separates based on initiator charge
  - Identically zero for gluon jets

- Well suited to be measured at STAR energies – high quark fraction with little antiquark cancellation

Lee,Moult 2023: arXiv:2308.00746



Conclusions

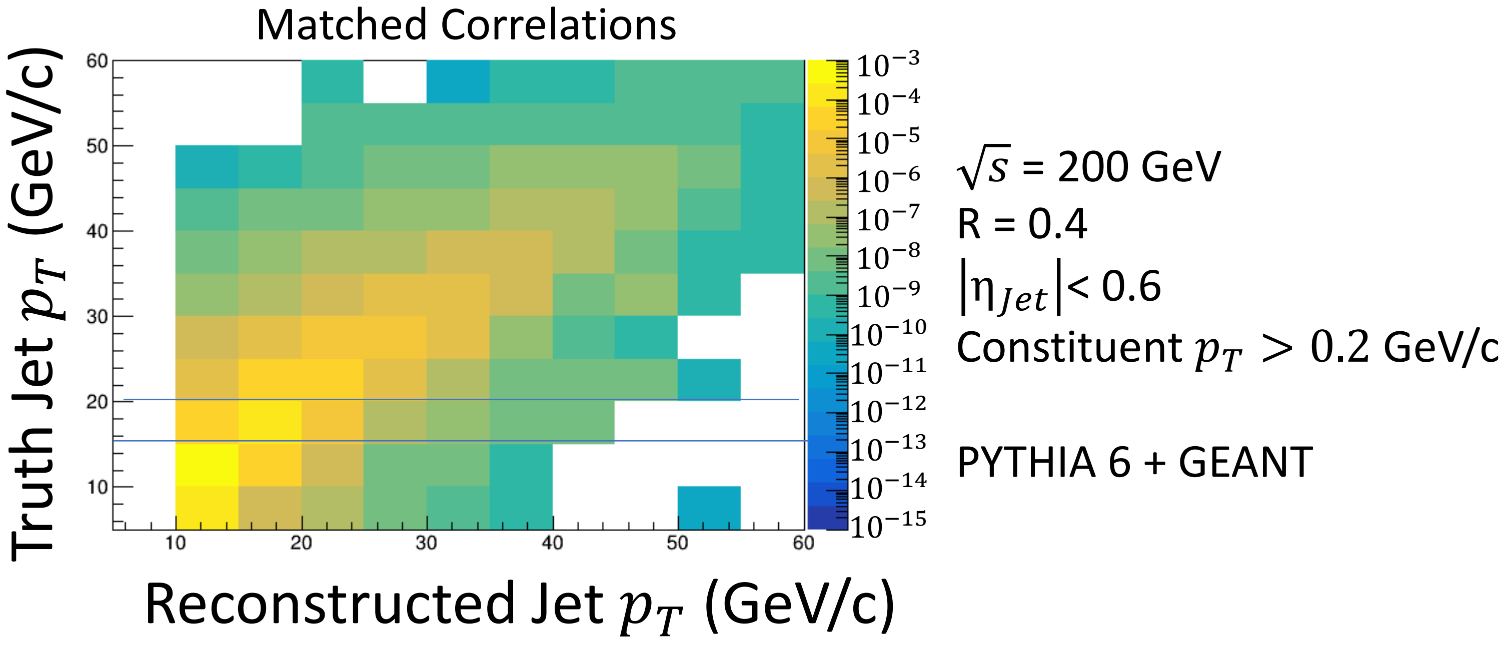
- STAR is an extremely useful environment for study of ENCs, and an excellent complement to LHC measurements
- Charged ENCs expand sensitivity of ENCs to non-perturbative effects and the hadronization mechanism
  - Observe tension with current Monte-Carlo models in charge-dependent hadronization
- First measurements of Two-Point Charged EECs shown, with three-point extension in progress

Backup

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 [Proceedings from HardProbes2023]
  - Planning to expand to full three-dimensional unfolding