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Exploiting Two- and Three-point Charge-Energy Correlators at STAR as Probes of Jet Evolution

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For the STAR Collaboration
Hard Probes 2024

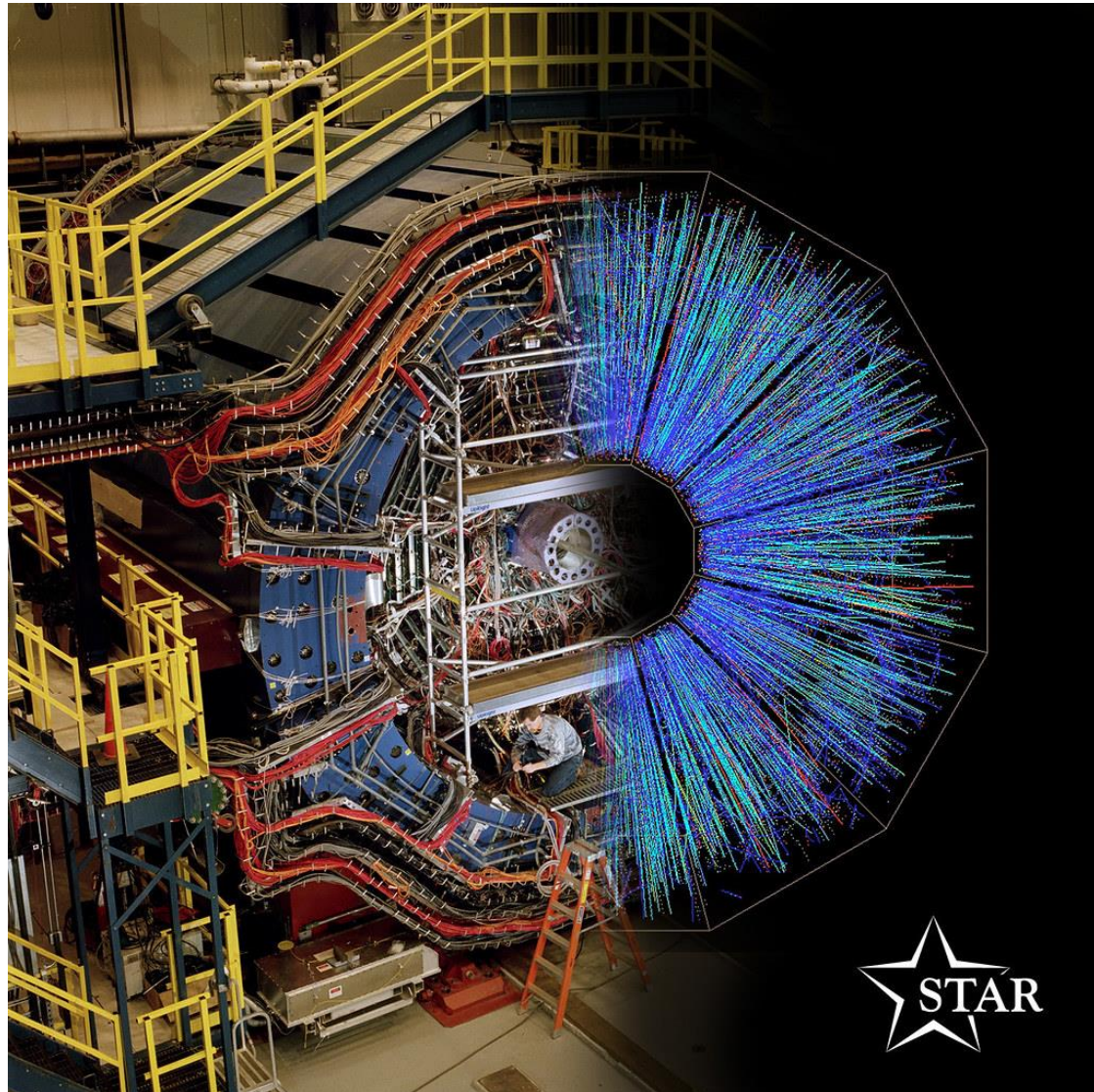
24/9/24

Yale  **Wright
Laboratory**

24/09/2024



Measurement at STAR



- STAR Time Projection Chamber (TPC) provides excellent charged track resolution for tracks with $p_T > 0.2$ GeV/c
- Barrel Electromagnetic Calorimeter (BEMC) provides neutral energy deposits
- Both have full coverage in azimuthal angle and $|\eta| < 1$
- Allows for measurement of **full jets** via anti- k_t algorithm
- BEMC used for trigger in order to obtain jet-rich data sample

Projected N-Point Energy Correlators (ENC)

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

[Chen et al. 2020, PRD 102, 5](#) · $\frac{1}{(E_{\text{jet}})^N} \langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \dots \mathcal{E}(\vec{n}_N) \rangle$



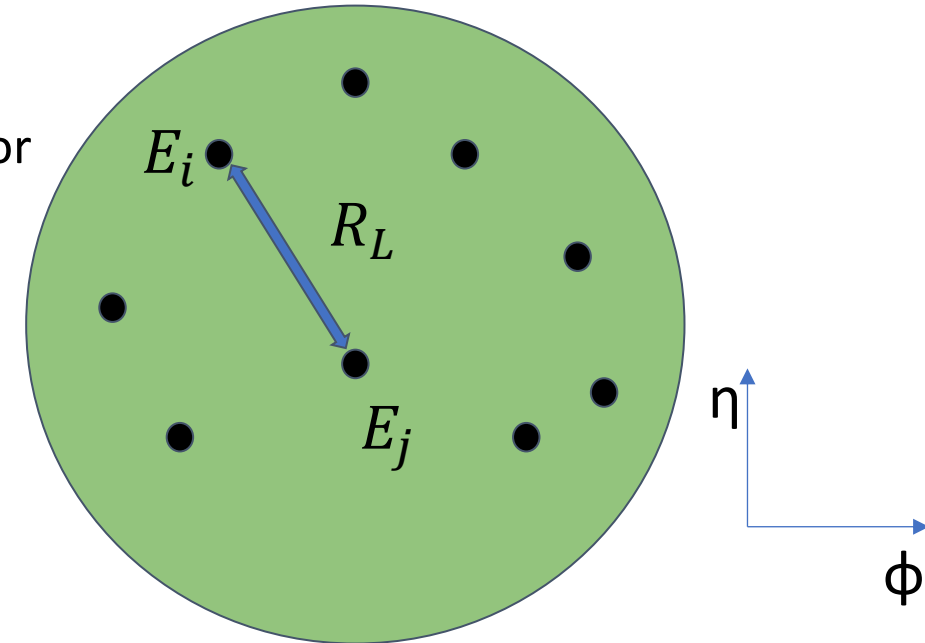
Theoretical Definition of projected N-Point Correlator

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



Experimental Construction of **Two-Point** Correlator

Two-Point



Note: Energy assumes pion mass

- **Allows for study of jet evolution using final state jet constituents as they are**, no additional clustering or grooming after jet-finding
- Ratios of ENCs (i.e. E3C/EEC) allows for isolation of perturbative effects

Projected N-Point Energy Correlators (ENC)

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

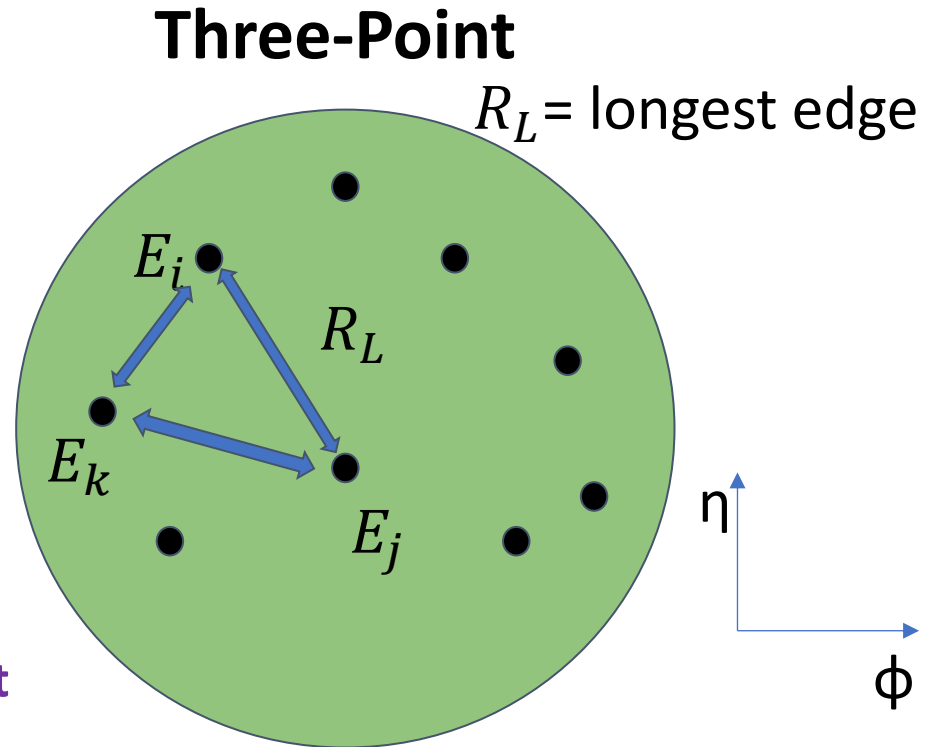
[Chen et al. 2020, PRD 102, 5](#)

$$\cdot \frac{1}{(E_{\text{jet}})^N} \langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \dots \mathcal{E}(\vec{n}_N) \rangle$$

$$\text{Normalized E3C} = \frac{1}{\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j E_k}{p_{T, \text{Jet}}^3}} \frac{d \left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j E_k}{p_{T, \text{Jet}}^3} \right)}{d(R_L)}$$



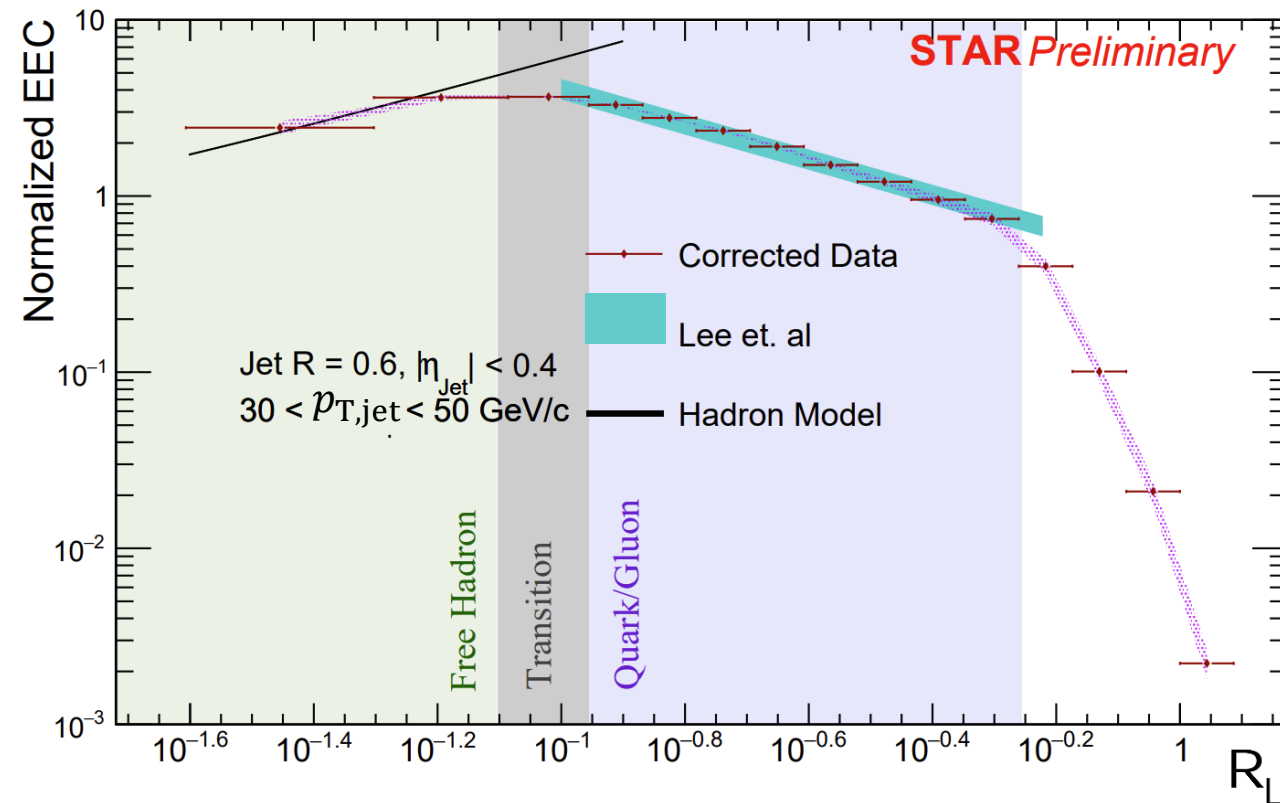
Experimental Construction of **Three-Point Correlator**



Note: Energy assumes pion mass

- **Allows for study of jet evolution using final state jet constituents as they are**, no additional clustering or grooming after jet-finding
- Ratios of ENCs (i.e. E3C/EEC) allows for isolation of perturbative effects

Two-Point Correlator at STAR (R = 0.6)



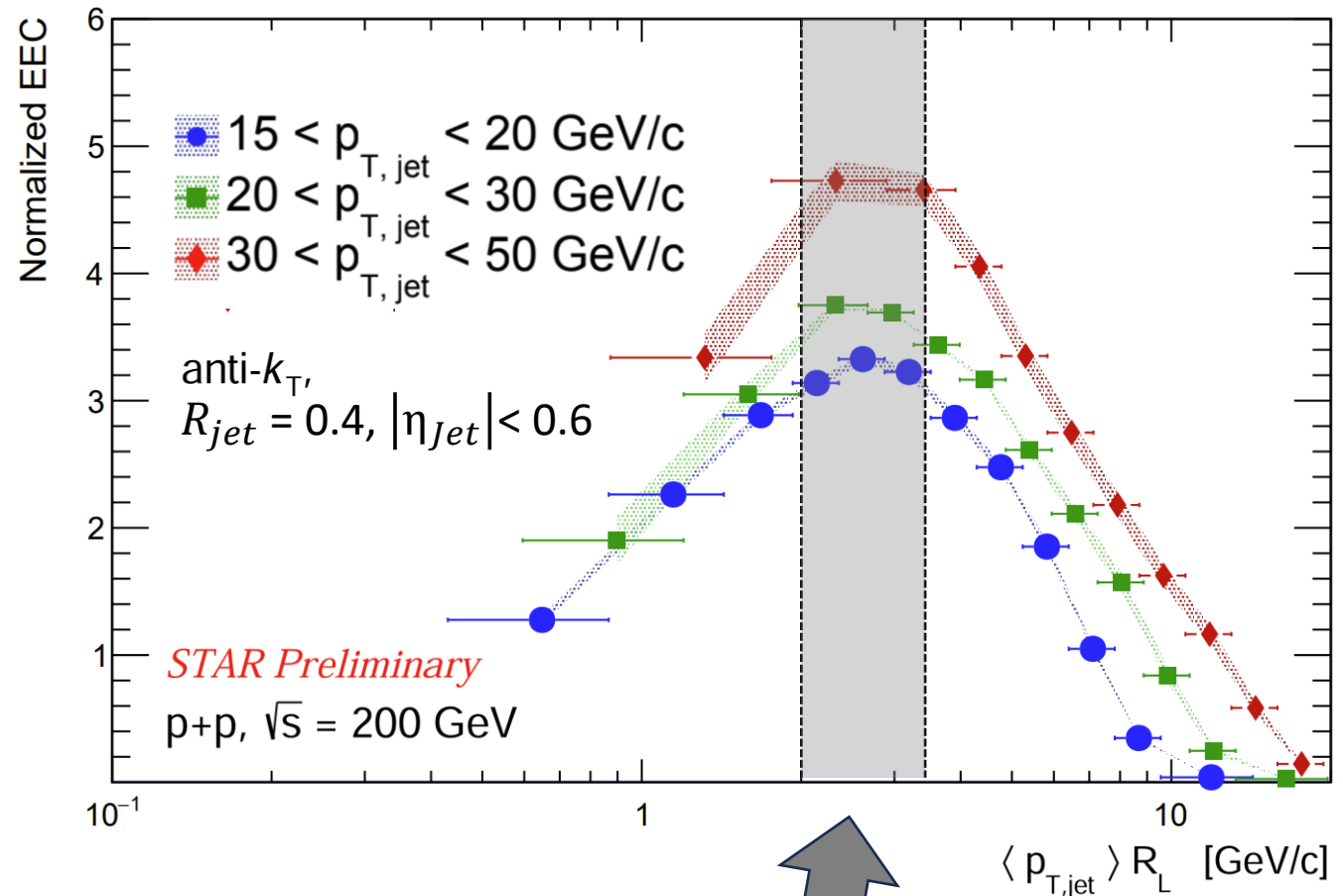
[Lee, Mecaj, Mout \(2023\): arXiv:2205.03414](https://arxiv.org/abs/2205.03414)

- Separates distribution into non-perturbative and perturbative regimes, separated by a transition region
- Theoretical comparison calculated in the Perturbative Region ($\frac{3\text{GeV}}{p_{T,\text{Jet Low}}} < R_L < R_{\text{jet}}$)
- **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 results on x axis by average $p_{T,jet}$ in a given bin
- Since location of turnover $\propto \frac{\Lambda_{QCD}}{p_{T}^{Jet}}$, scaled curves will turn over within **the same region**
- In this case, average momentum is determined via PYTHIA and applied post-correction

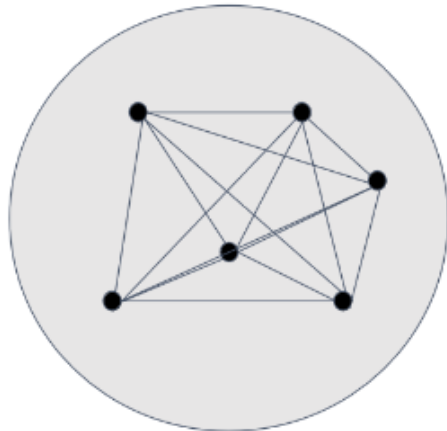


$$\langle p_{T,jet} \rangle \Delta R_{Turnover} \sim 2 - 3.5 \text{ GeV}/c$$

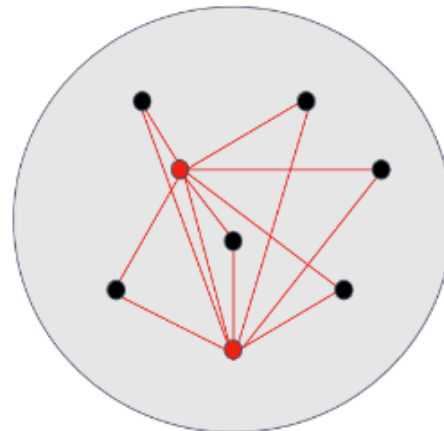
3D Unfolding – Method

- Used for all results going forward, and in upcoming paper
- Perform matching between particle and detector level
 - Match jets (within Jet Radius) and constituents (within 0.01 in η - ϕ)
- Bayesian Unfolding in three variables per correlation
 - $p_{T,jet}$, R_L , Energy Weight

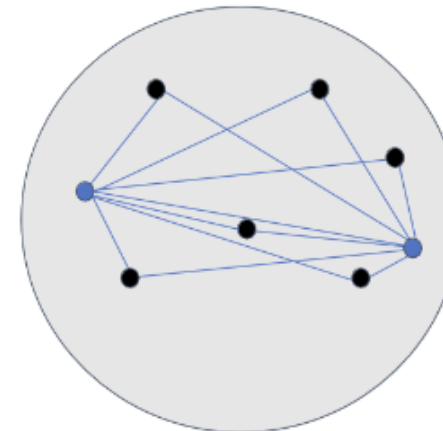
Fill in Matches



Fill in **Misses**
At Truth level

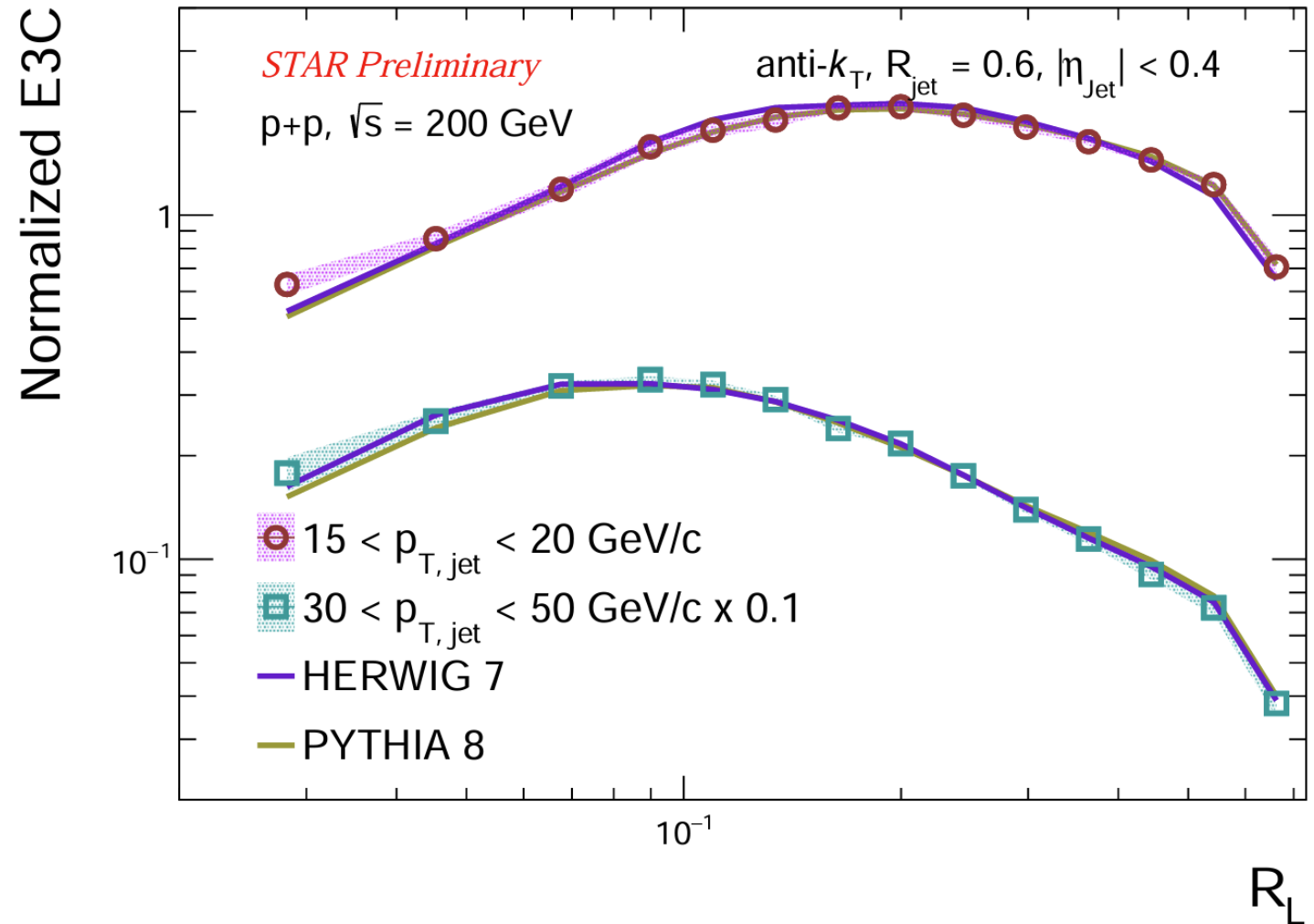


Fill in **Fakes**
At Detector level



E3C Measurement

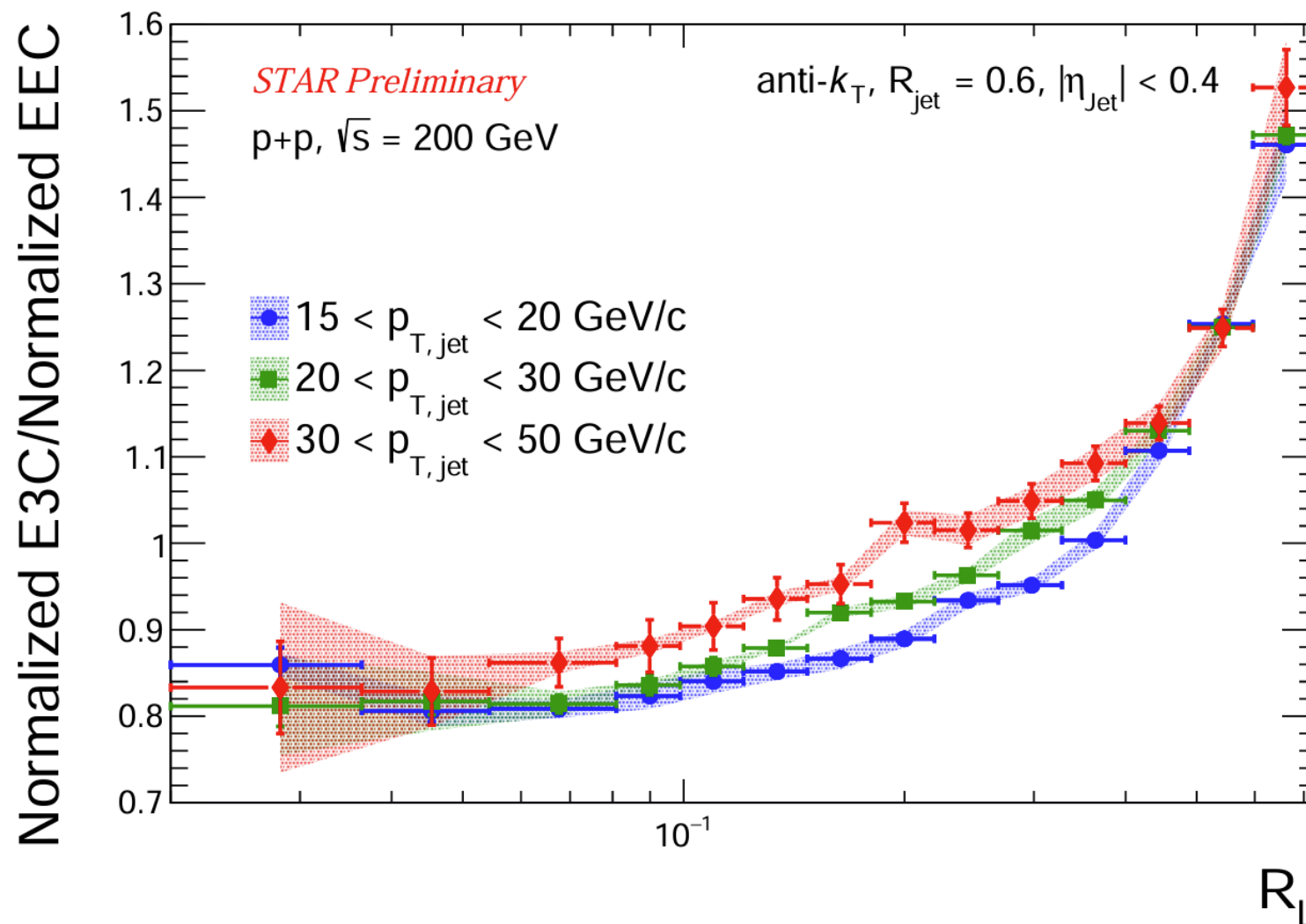
- Shows movement of transition region with jet momentum
- Quantify difference in scaling in ratio
- PYTHIA and HERWIG describe behavior well



E3C/EEC Ratio

- Ratio shows a positive slope in perturbative regime
- Change in slope with jet p_T is dependent on **running of coupling constant α_s**

[Chen et al. Phys. Rev. D 102, 054012](#)



Charge-weighted EECs

- Can further extend non-perturbative power of EEC by exploring correlation of both angle and charge distribution.
- Weight energy flow operator by particle's electric charge:
- Charge-weighted EEC =
$$\frac{d\left(\sum_{Jets} \sum_{i \neq j} \frac{E_i Q_i E_j Q_j}{p_{T,Jet}^2}\right)}{d(R_L)}$$
- Sensitive to hadronization mechanism

[Lee, Moul, arxiv:2308.00746](https://arxiv.org/abs/2308.00746)

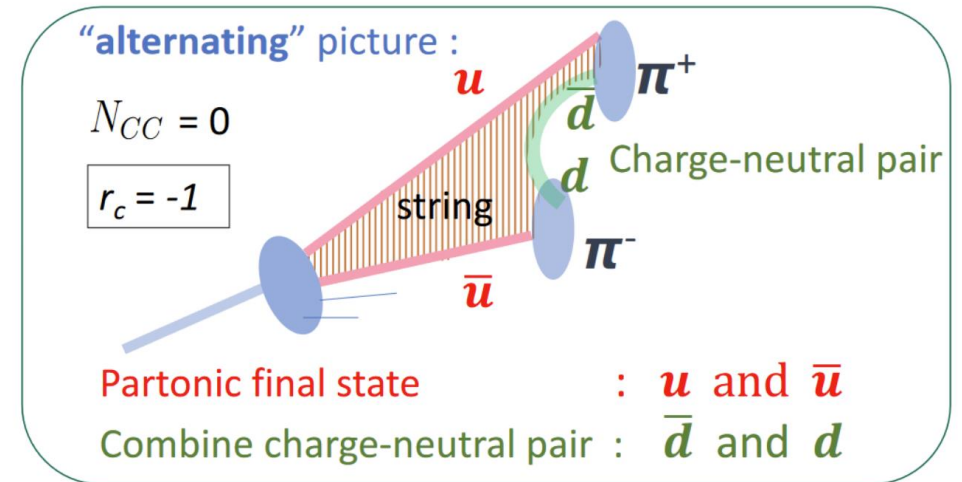
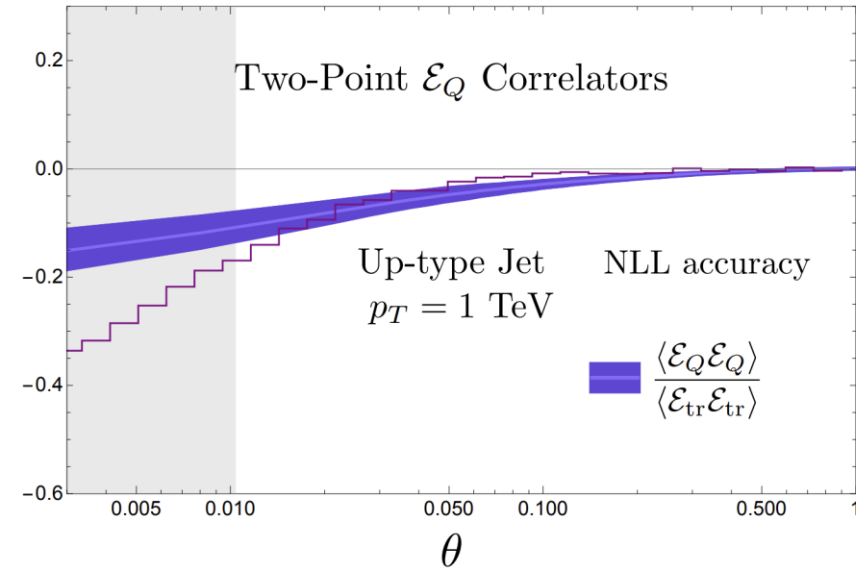


Figure: [Mriganka Mouli Mondal](#)



Charge-weighted EECs

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- Weight energy flow operator by particle's electric charge:

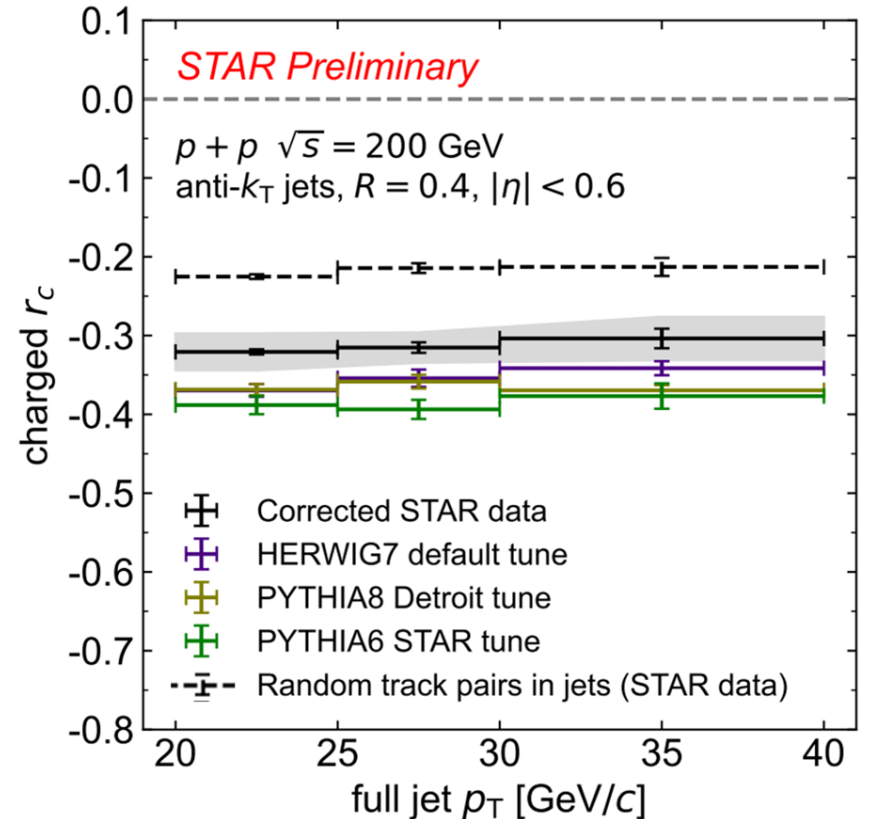
$$d \left(\sum_{Jets} \sum_{i \neq j} \frac{E_i Q_i E_j Q_j}{p_{T,Jet}^2} \right)$$

$$d(R_L)$$

- Sensitive to hadronization mechanism

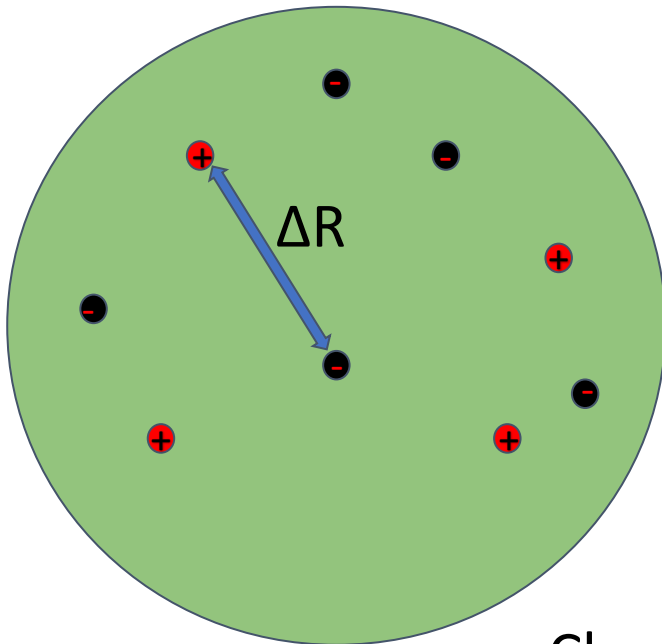
Probes similar physics to r_c measurement performed by STAR

See talk by [Youqi Song](#) on 25/9





Charge-weighted EEC 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



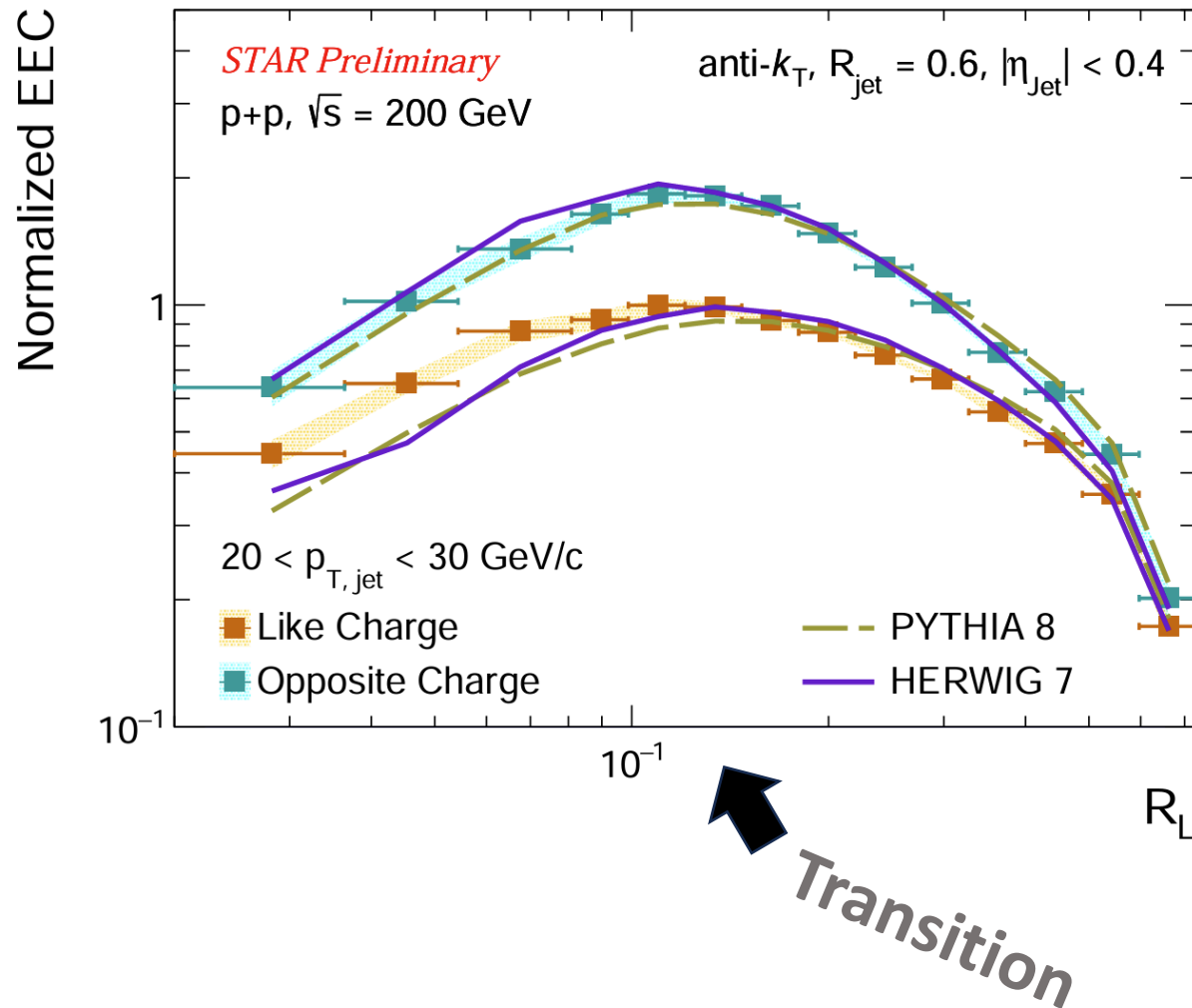
$$\text{Charge-weighted EEC} = \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i Q_i E_j Q_j}{p_{T, \text{Jet}}^2}\right)}{d(R_L)} = \text{EEC}_{\text{Like}} - \text{EEC}_{\text{Opposite}}$$





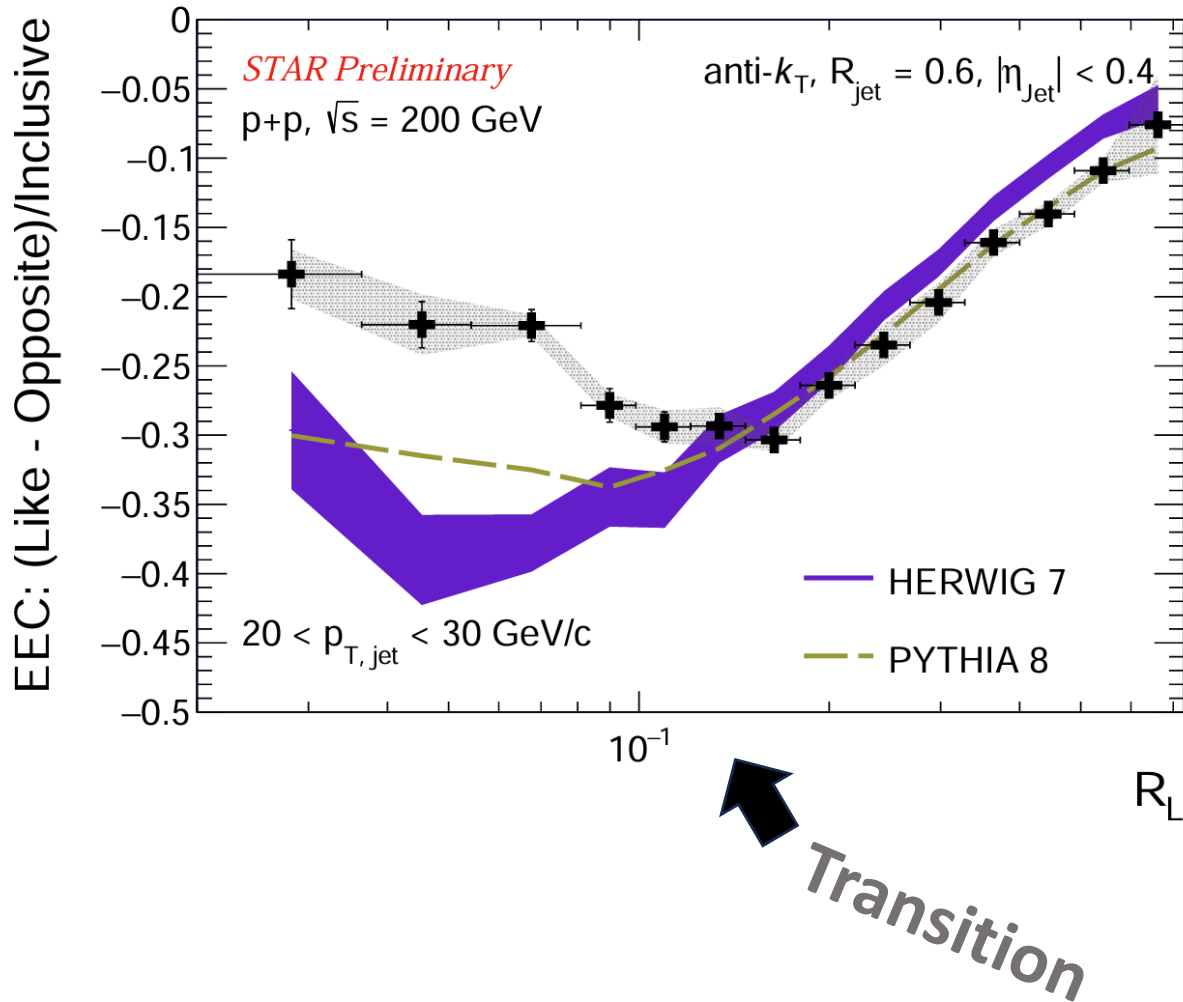


Like and Opposite charge Distributions

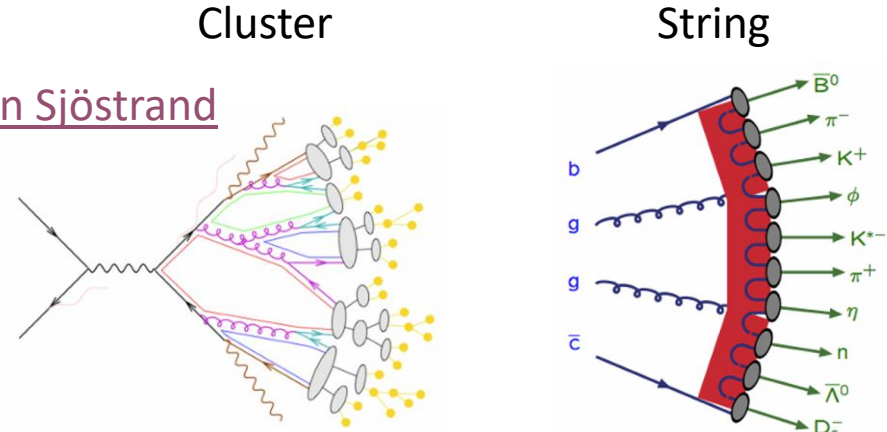


- Both Like and Opposite sign follow expectations in perturbative region
- Excess of like-charge correlations below transition region
- Shift in location of transition region seen in Monte-Carlo, but not resolved in data
- PYTHIA 8: Detroit tune and HERWIG 7: Default tune

Charge-weighted Ratio



Torbjörn Sjöstrand

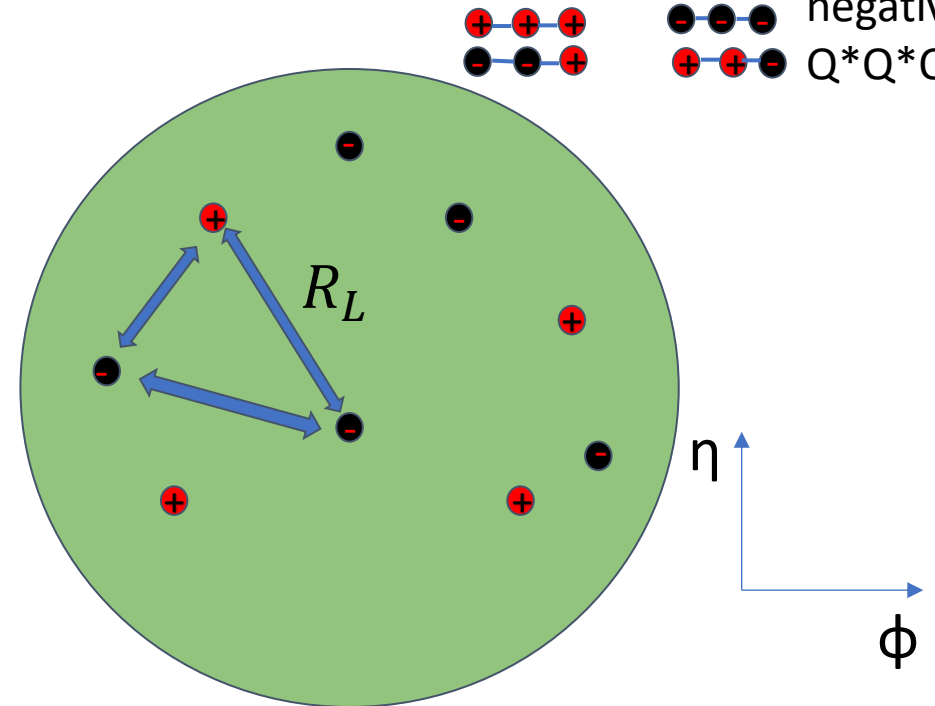
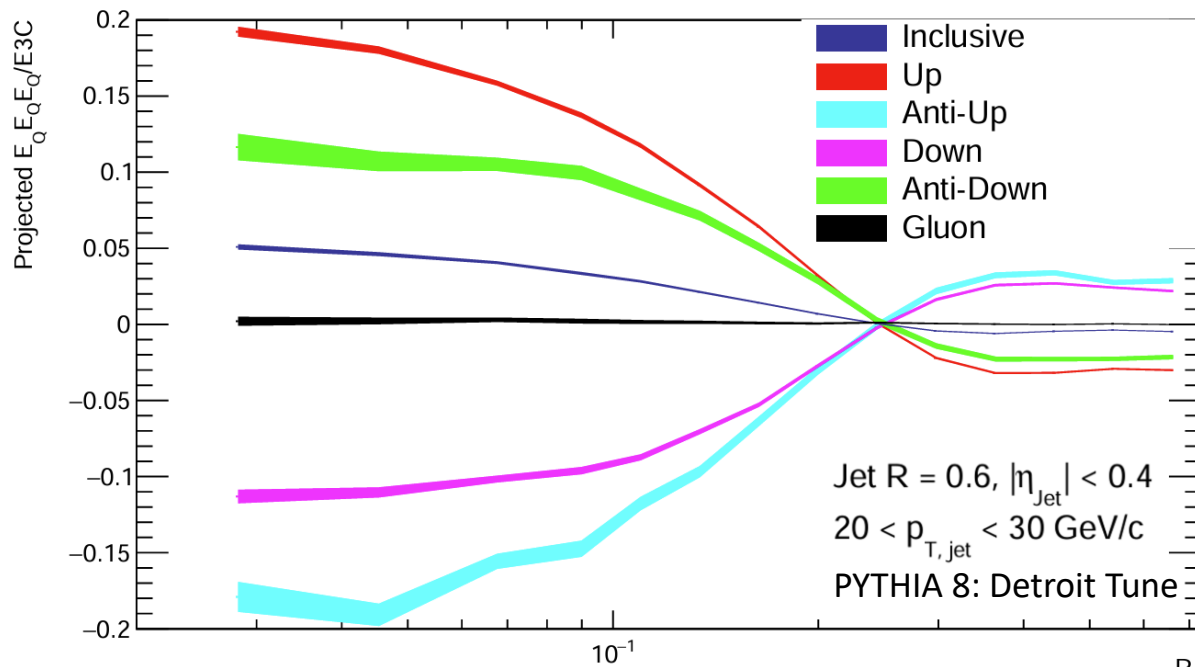


- Cluster hadronization (HERWIG) and String hadronization (PYTHIA) both predict same qualitative behavior
- Pythia describes perturbative regime better, but neither describe data below transition region
- Implementation of charge dependence/conservation in hadronization mechanism may not fully capture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

Charge-weighted E3Cs

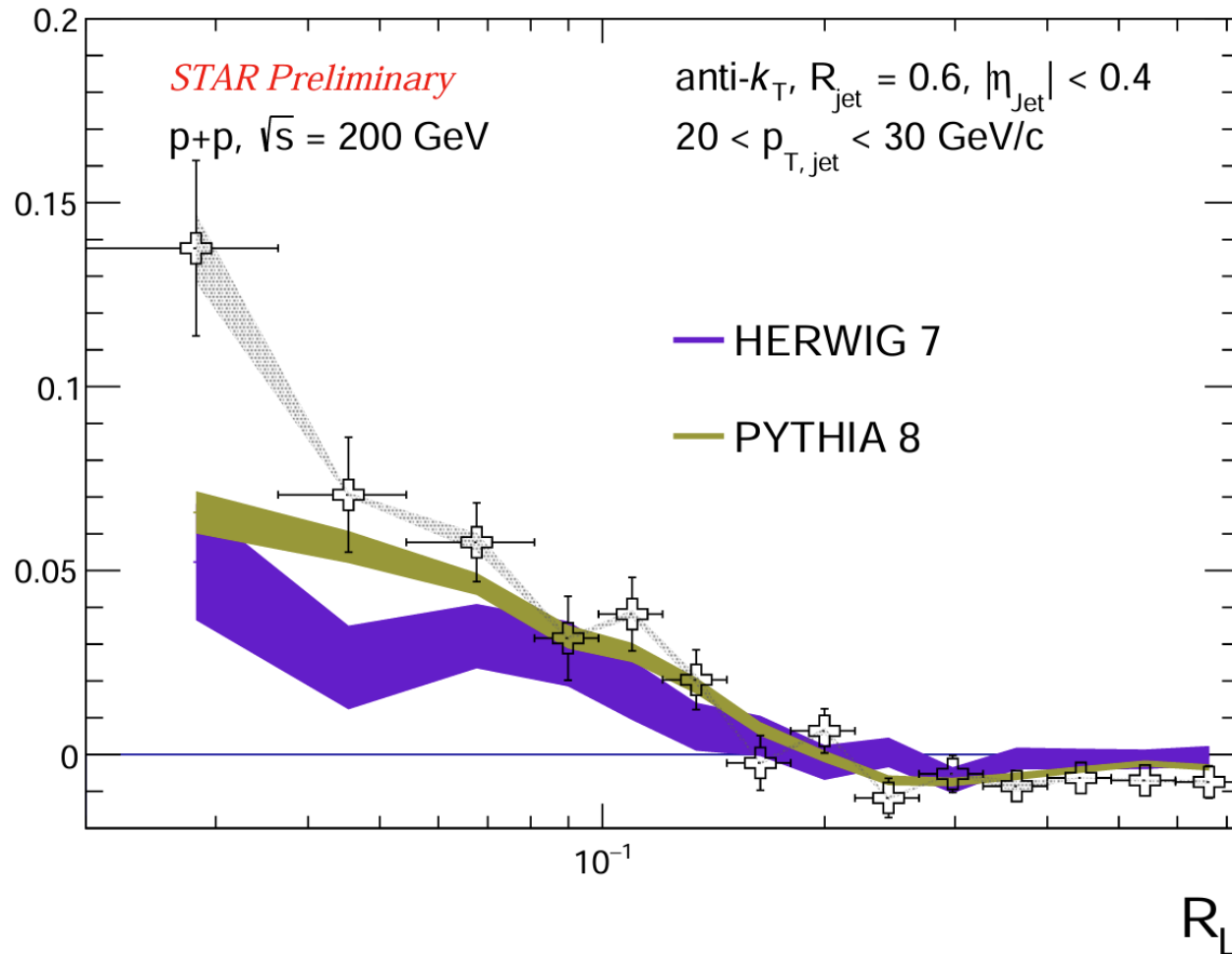
- Distribution is now charge odd - directly dependent on initiator charge
- Unique study at RHIC – Quark rich regime
 - Signal suppressed for gluons

$$\text{Charge-weighted E3C} = \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i Q_i E_j Q_j E_j Q_j}{p_{T, \text{Jet}}^3}\right)}{d(R_L)} = \text{E3C} - \text{E3C} \begin{matrix} \text{Positive} \\ \text{or} \\ \text{negative} \\ \text{Q*Q*Q} \end{matrix}$$



Charge-weighted Ratio – Three Point

Charge-weighted E3C / Inclusive E3C

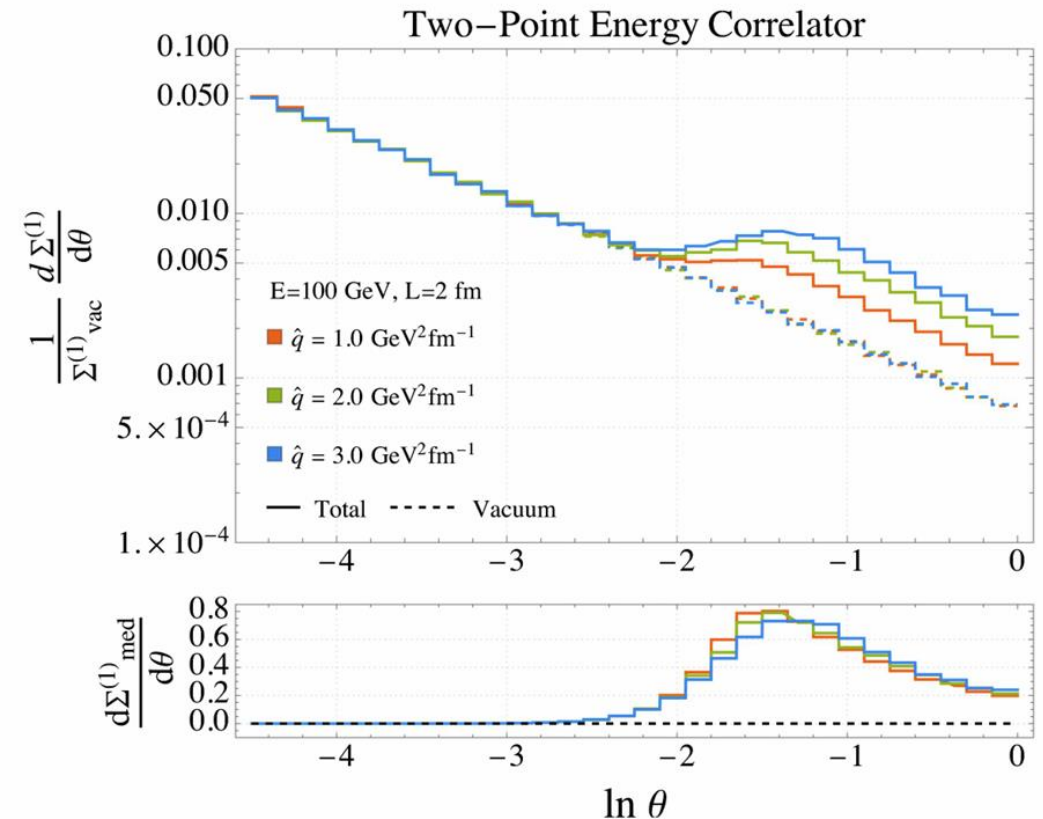


- Monte-Carlo models predict 3-point charge correlations better than 2-Point
- Suggests hadronization mechanism that has greater two-point charge dependence than three-point

Extension to Heavy-Ion

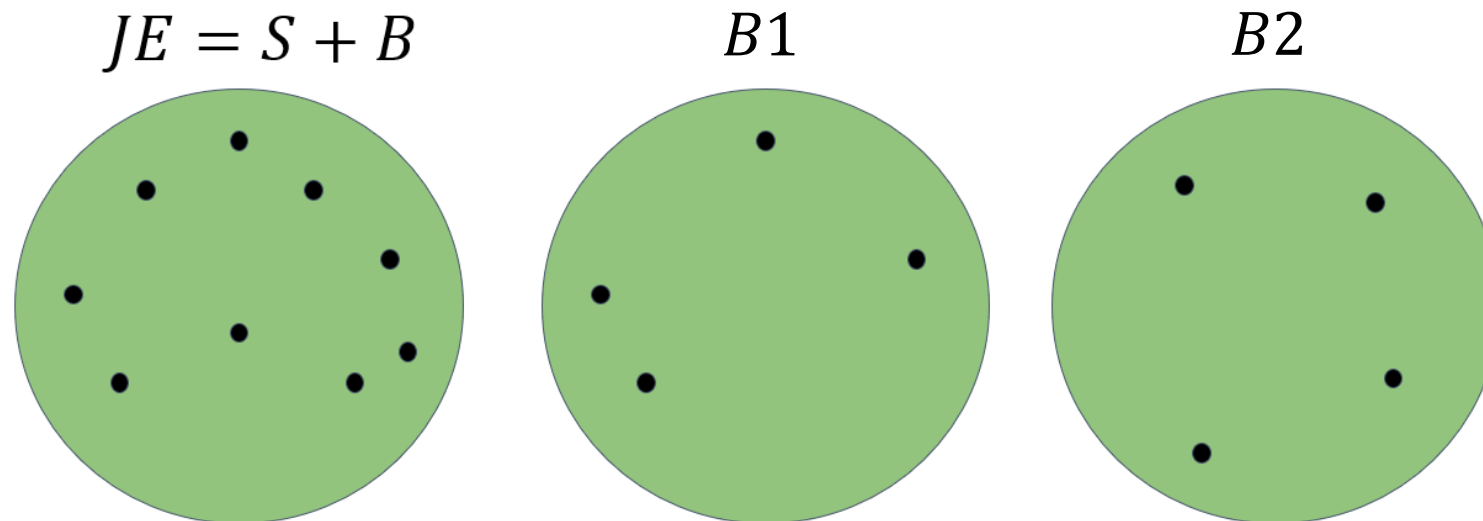
- Energy Correlators in heavy-ion systems can isolate interactions with medium to discrete angular scales
 - See [poster](#) by Ananya Rai on wake effects
- However, there is significant contribution from background-signal as well as background-background
- Background subtraction method used by CMS is able to subtract both
 - See talk by [Jussi Viinikainen](#) earlier today

[Andres et al. Phys. Rev. Lett. 130, 262301](#)



Background Simulation

- Measured Jet Event (JE) contains both signal and background
- Test viability of background subtraction method used by CMS at STAR with toy model tuned to resemble STAR isobar data
- Generate jets in PYTHIA, and generate background associated with jet event as well as two unassociated background events (Minimum-Bias)
 - Impose unique shape on background (*particles* $> 1 \frac{\text{GeV}}{c}$ have minimum distance of 0.01) to verify that self-correlations are removed



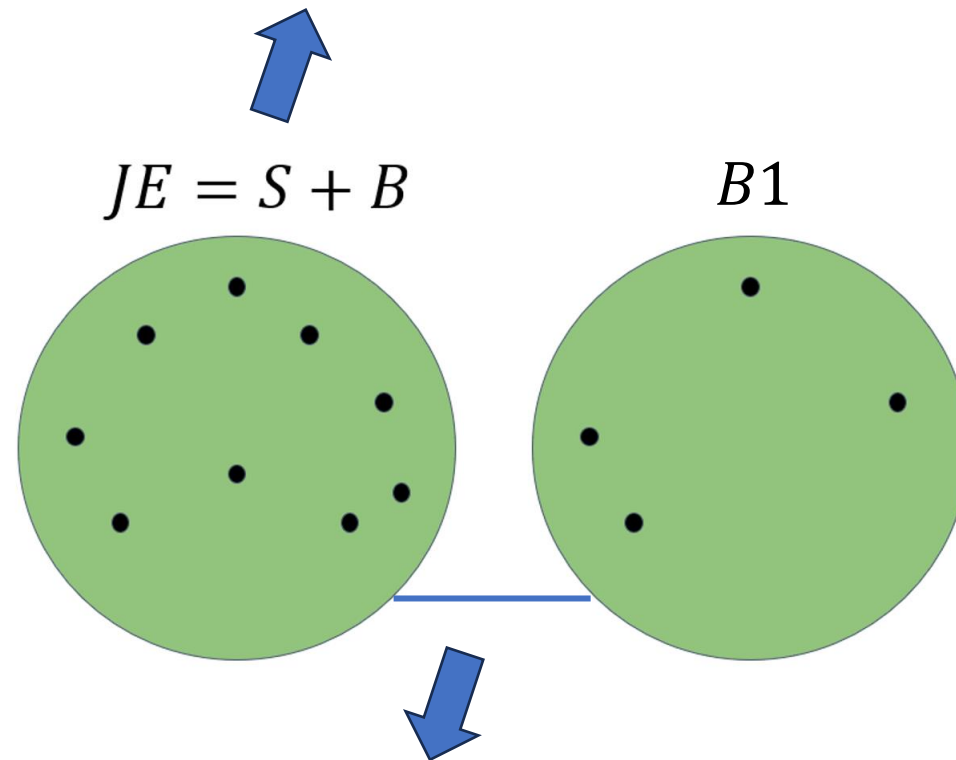
Background Subtraction

- Form correlation between jet event and mixed event to remove signal-background and background-background contributions

$$JE \times JE - 2 JE \times B1 - B1 \times B1 = S \times S - 2 B \times B1$$

- However, leaves over uncorrelated background contribution
- Require second mixed event to remove uncorrelated contribution

$$JE \times JE = S \times S + 2 S \times B + B \times B$$

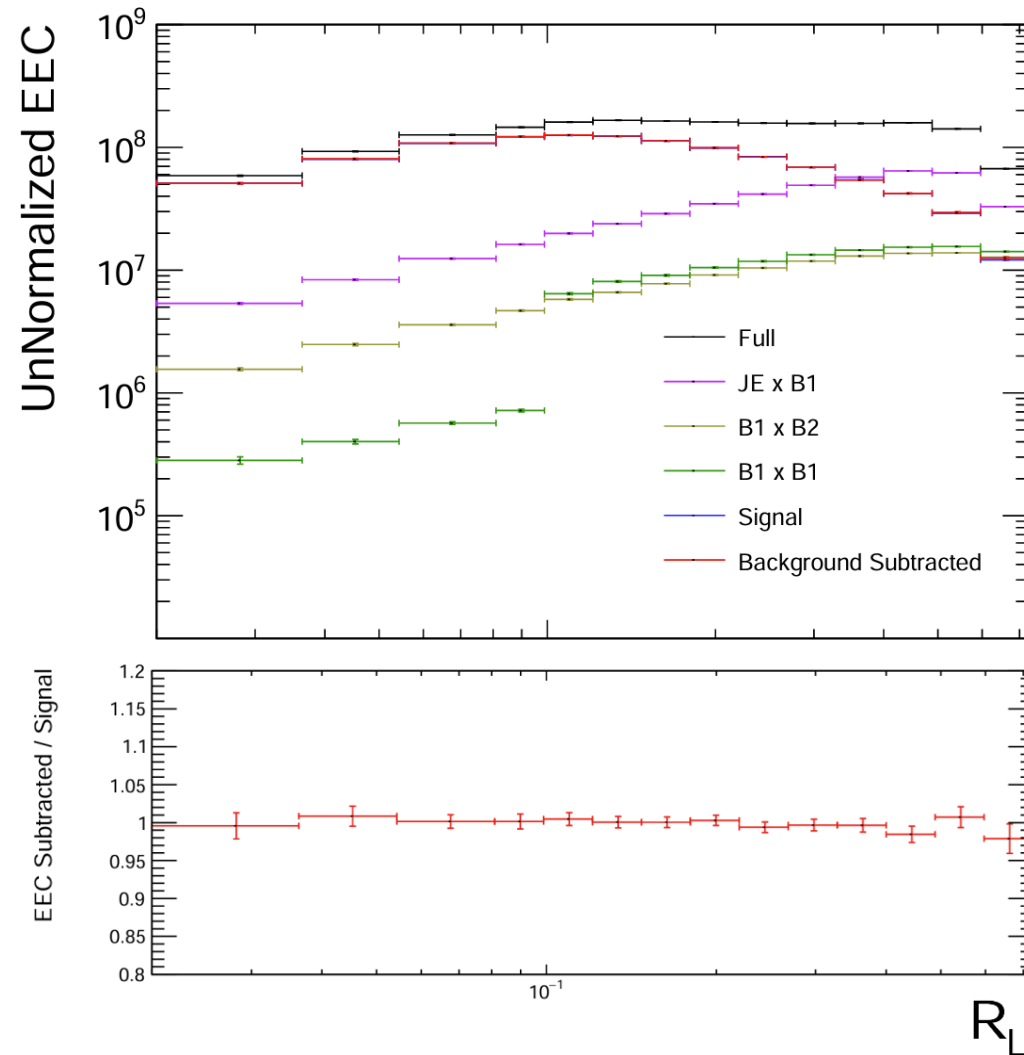


$$JE \times M1 = S \times B1 + B \times B1$$

Uncorrelated

Two-Point Background Subtraction

- $S^2_{Two-Point} = JE^2 - 2JE \times B1 - B1^2 + 2B1 \times B2$
- Signal-background correlations are by far most significant contribution
- This method successfully removed both correlated and uncorrelated background





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 **two-point** charge-dependent hadronization
- First measurements of Two and Three-Point Charged EECs shown, with heavy ion extension in progress

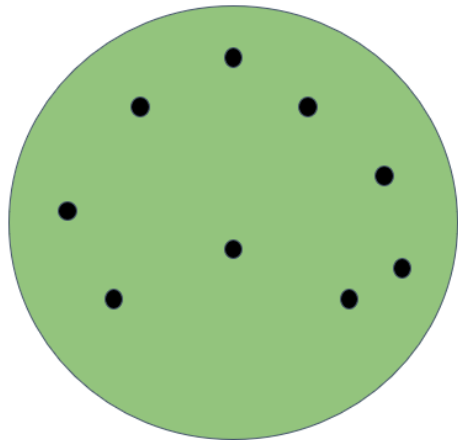


Backup

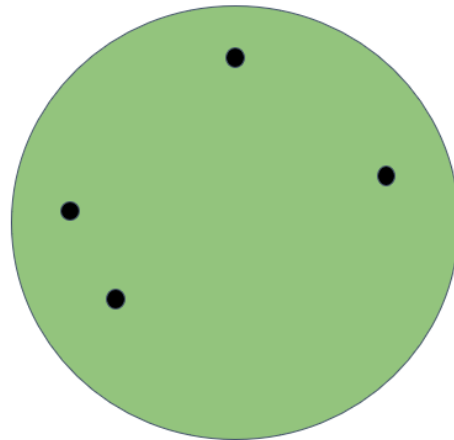
Background Simulation – Three Point

- Requires introduction of a third minimum bias event to correct for fully uncorrelated three-point correlations

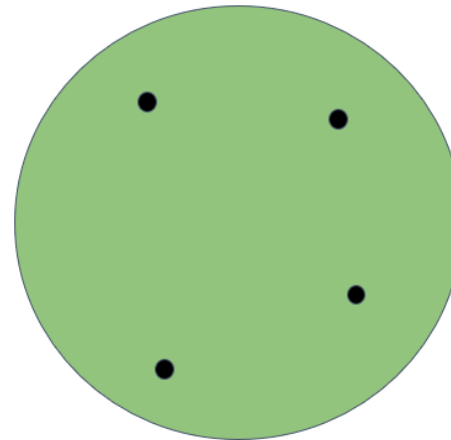
$JE = S + B$



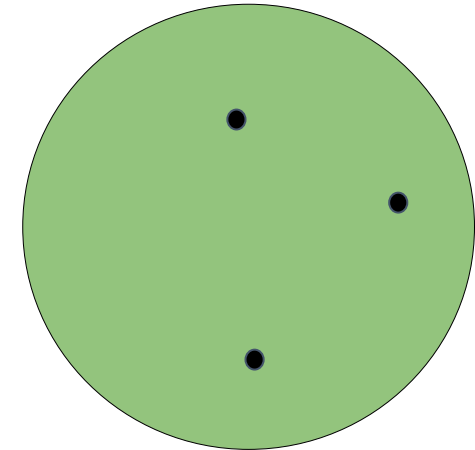
$B1$



$B2$



$B3$



Three-Point Background Subtraction

- Method can be applied very similarly to three-point
- Requires a third minimum-bias event

$$S^2_{Three-Point} = JE^3$$

$$- 3 JE^2 B1$$

$$- 3 JE B1^2$$

$$- B1^3$$

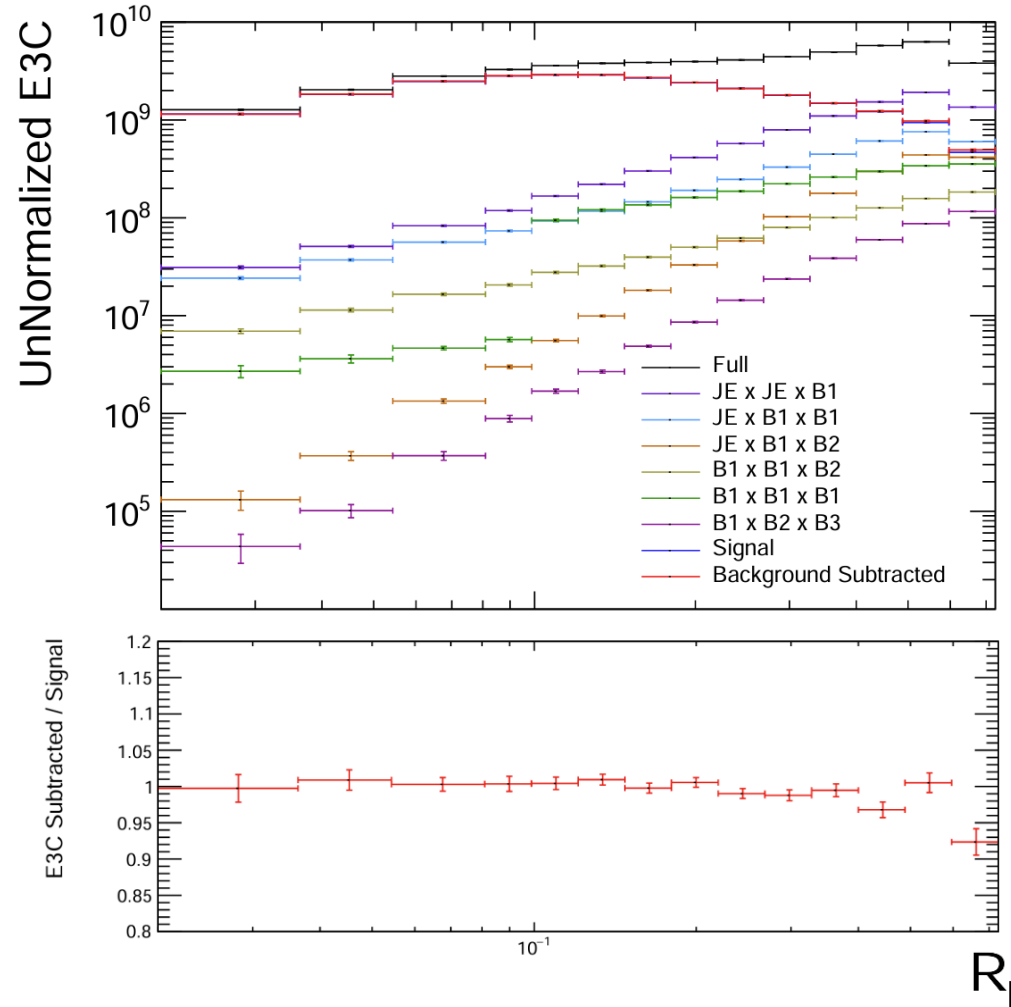
$$+ 6B1^2 B2$$

$$+ 6JE B1 B2$$

$$- 6 B1 B2 B3$$

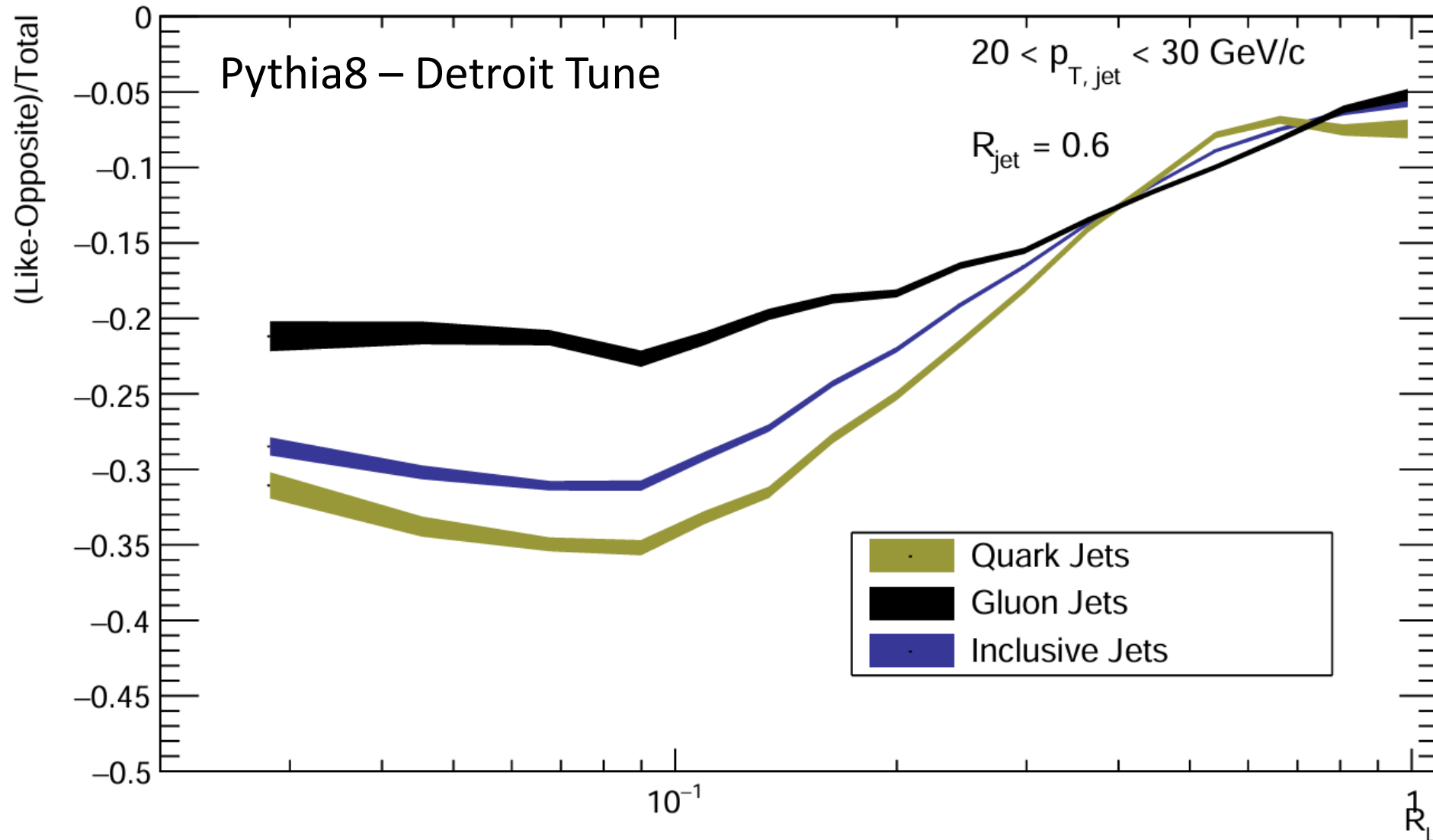


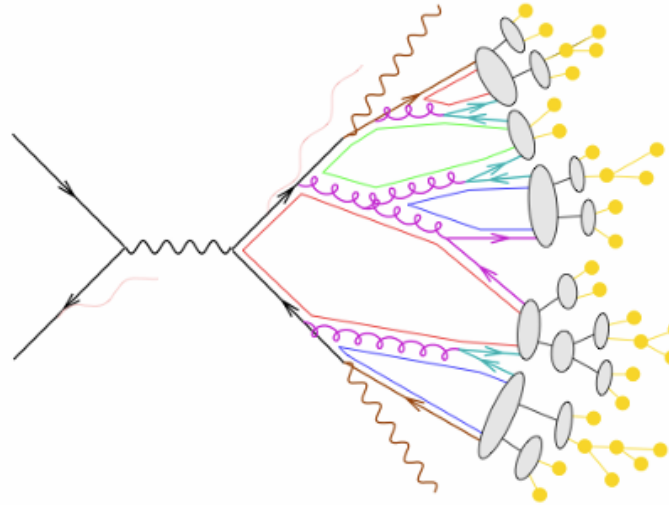
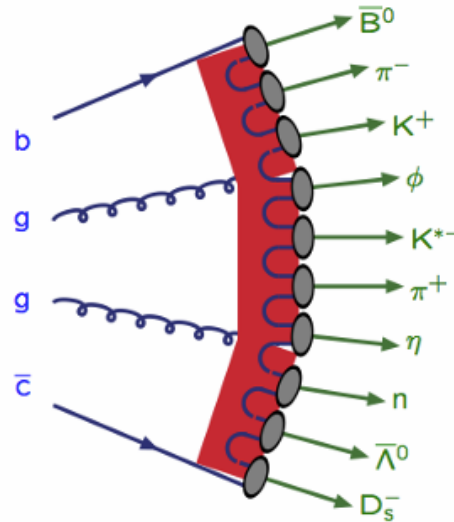
Decreasing Magnitude





Quark/Gluon Behavior of Charged Ratio



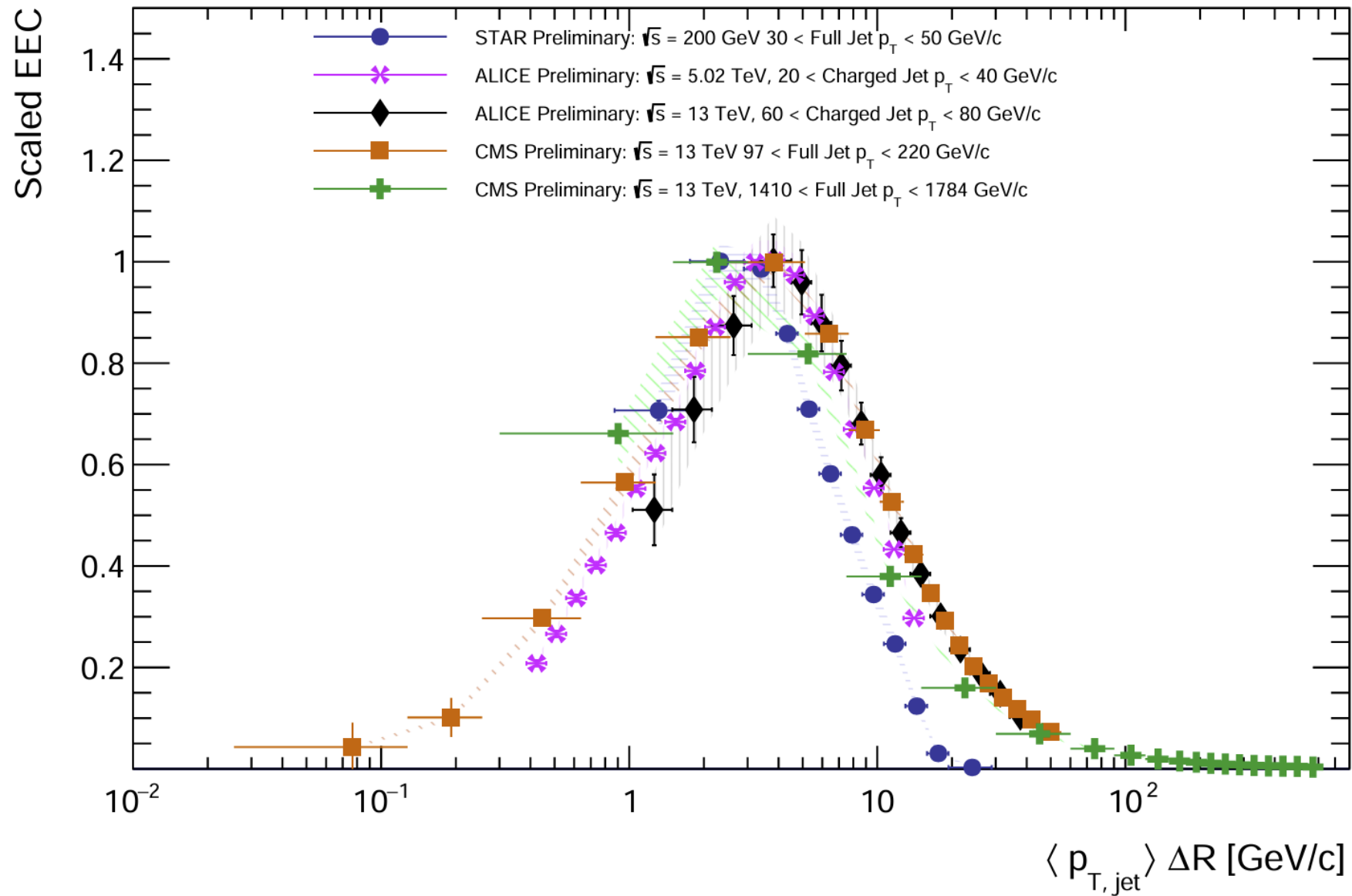


Torbjörn Sjöstrand
50 Years of Quantum Chromodynamics
UCLA

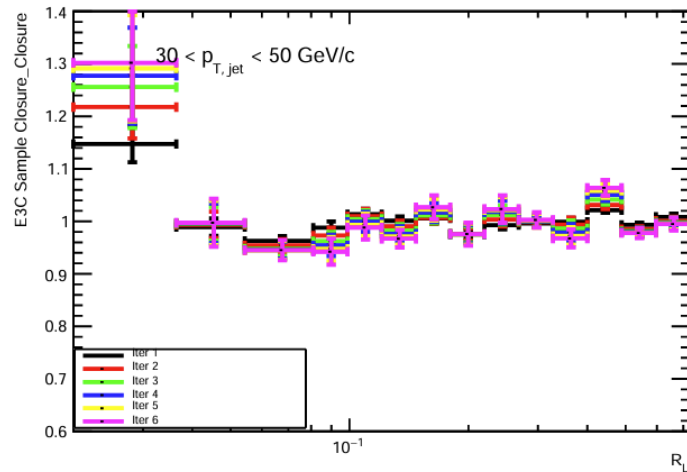
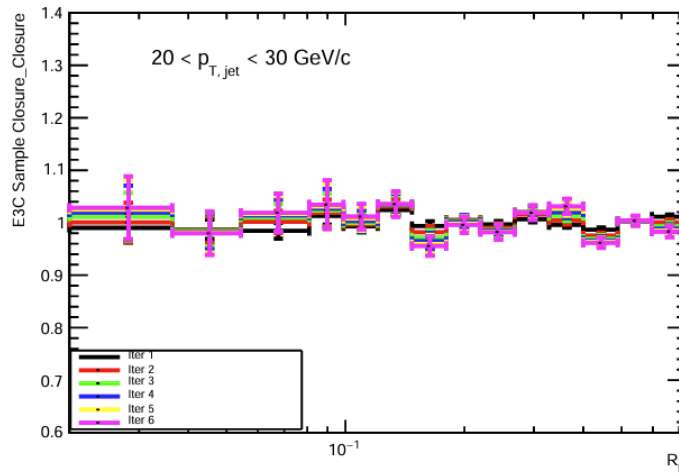
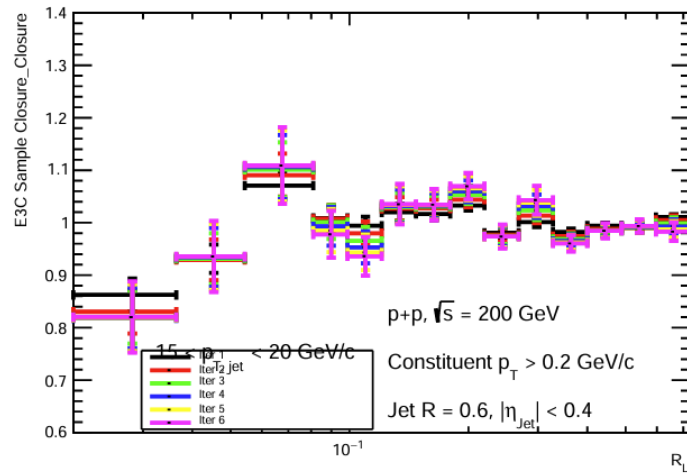
[ucla23ts.pdf \(cern.ch\)](http://ucla23ts.pdf.cern.ch)

program	PYTHIA	Herwig, SHERPA
model	string	cluster
energy–momentum picture	powerful	simple
parameters	predictive	unpredictive
flavour composition	few	many
parameters	messy	simple
	unpredictive	in-between
parameters	many	few

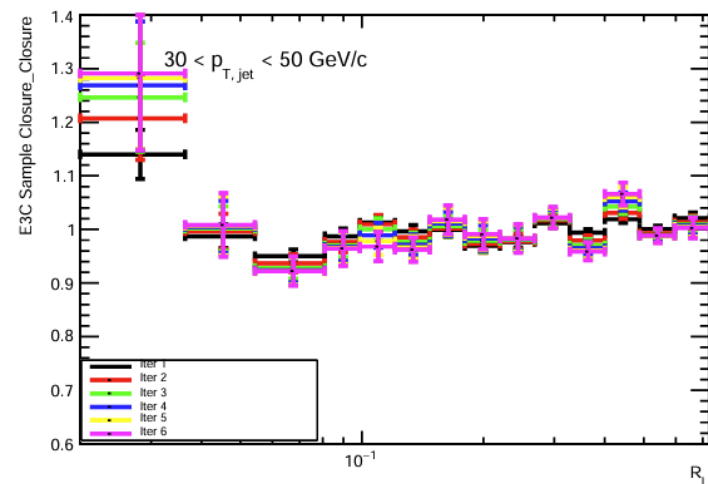
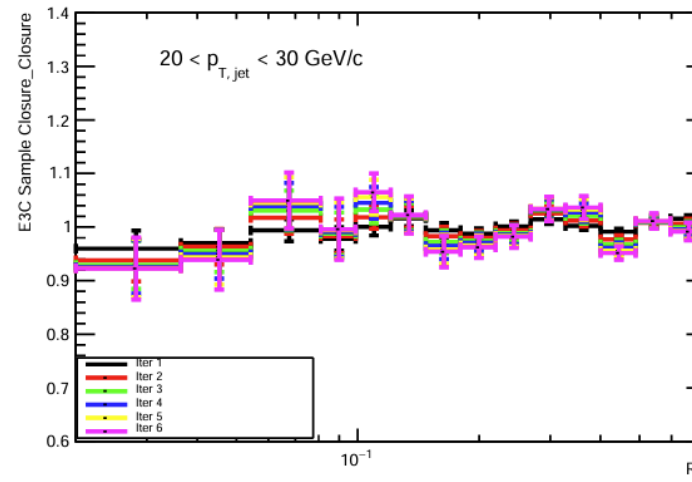
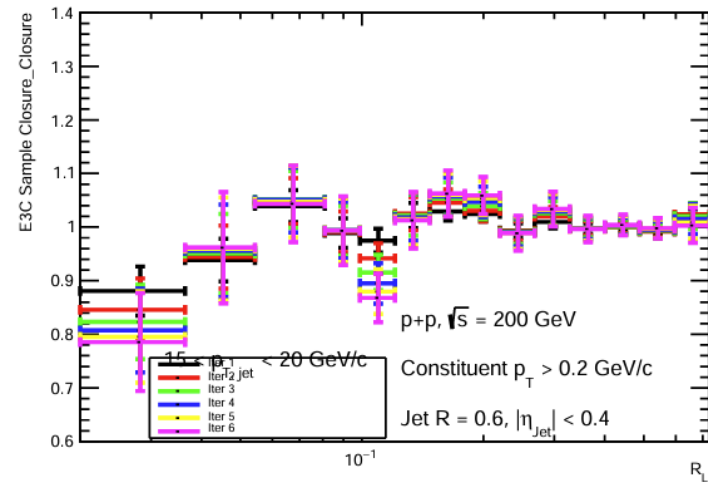
Free parameters abound in each nonperturbative description.



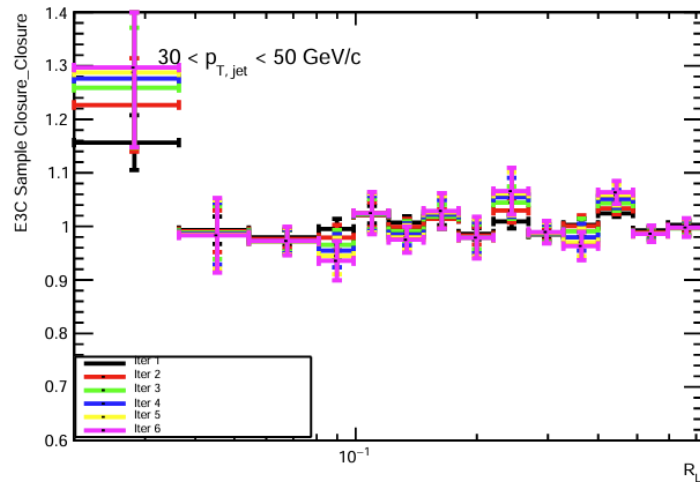
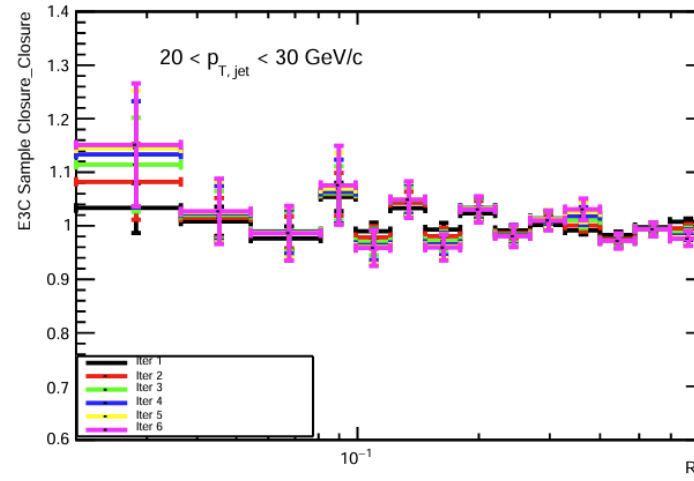
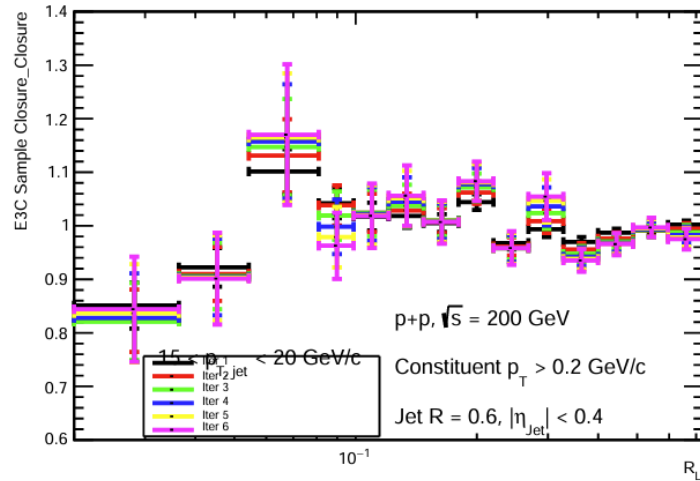
Closure – E3C



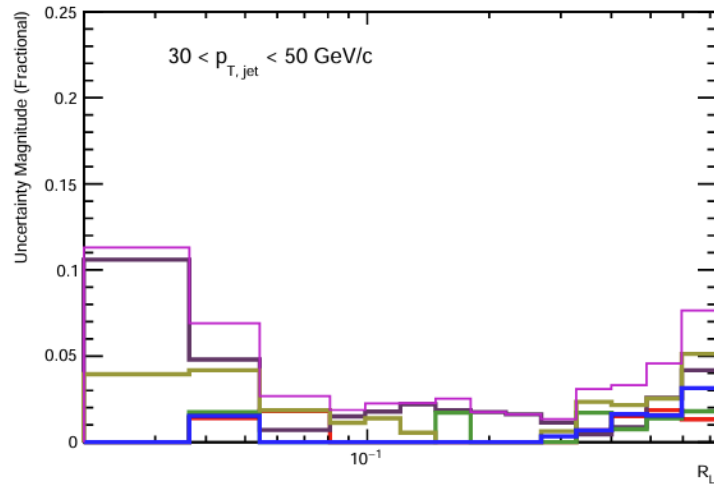
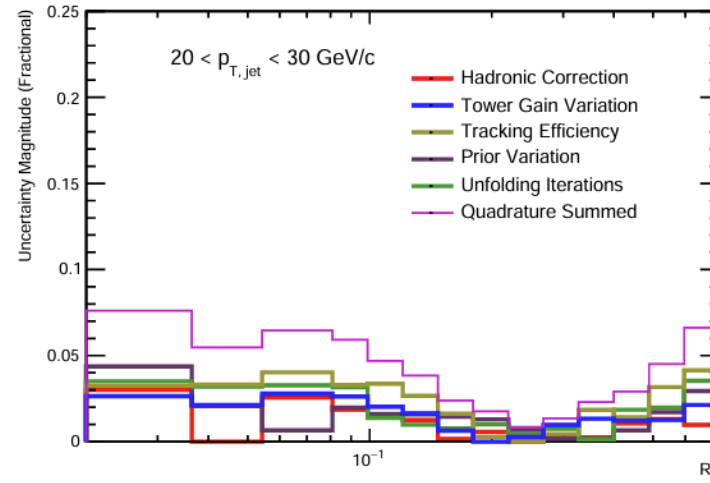
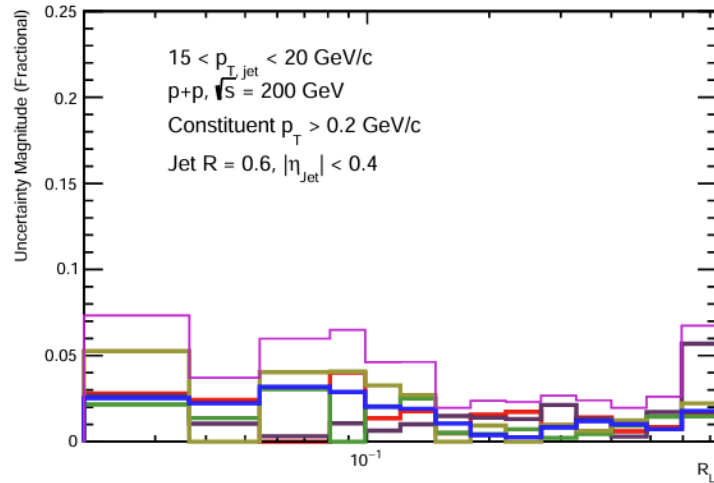
Closure – E3C Positive Charge Product



Closure – E3C Negative Charge Product



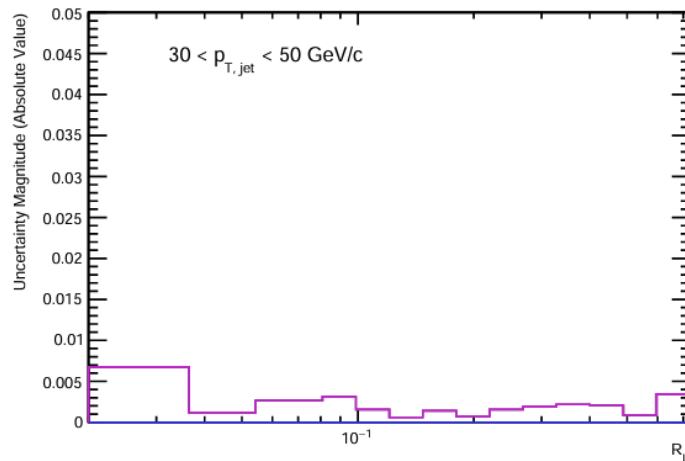
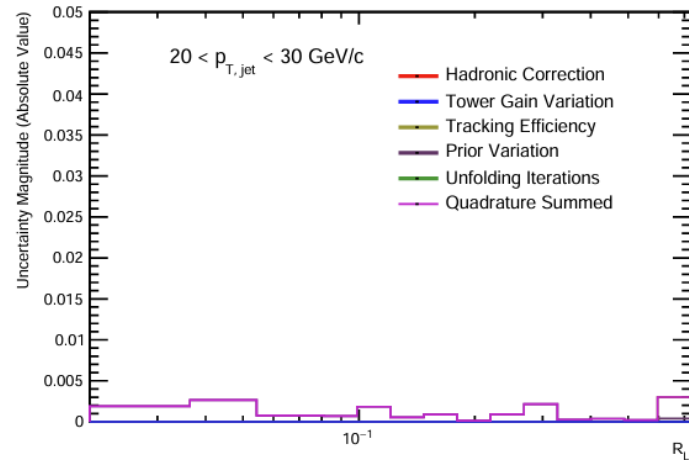
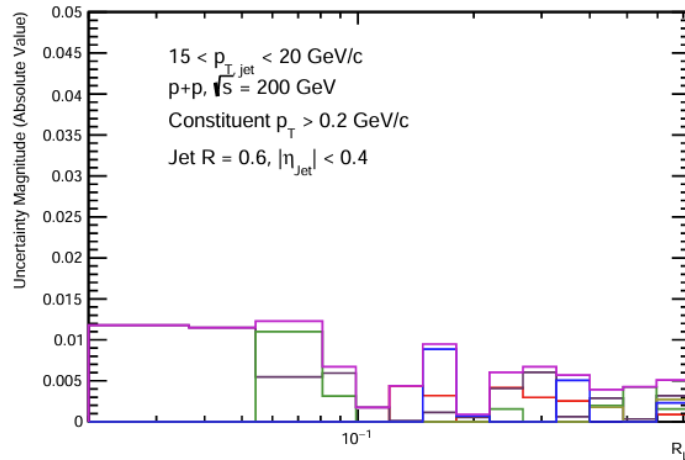
Systematics – E3C



- Hadronic Correction– Varied from nominal 100% to 50%
 - Tower Scale Variation – Varied by 3.8 %
 - Tracking Efficiency – Varied by 4 %
 - Unfolding Prior – PYTHIA embedding sample was re-weighted to resemble HERWIG at each correlation, and then used to train the response matrix.
 - Unfolding Iteration – Varied from the nominal 4 iterations to 2 (6) iterations

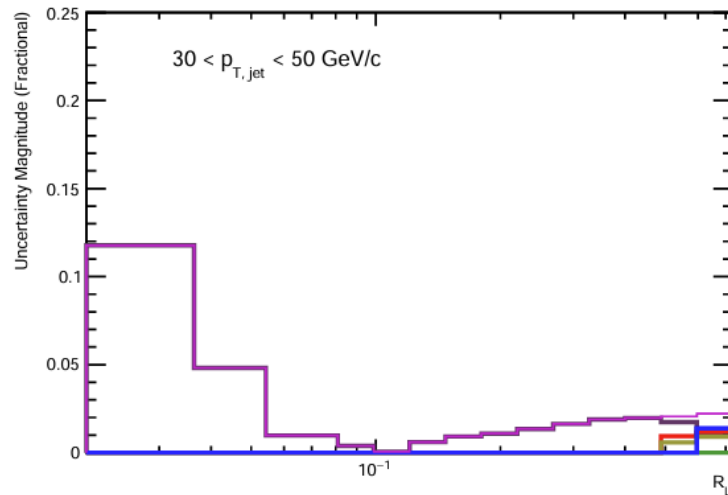
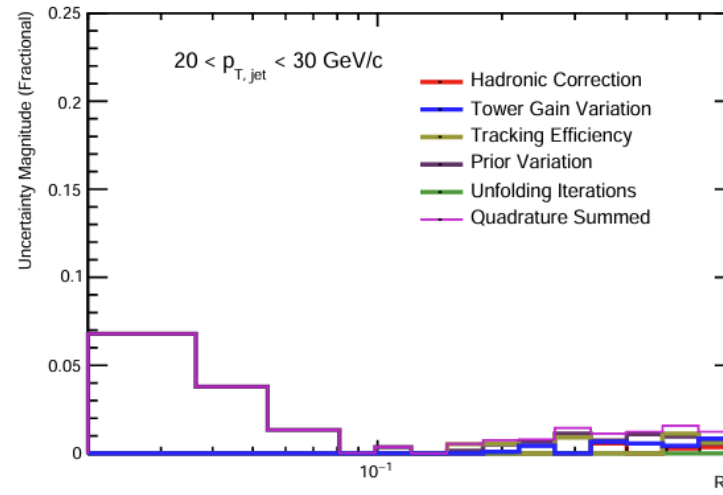
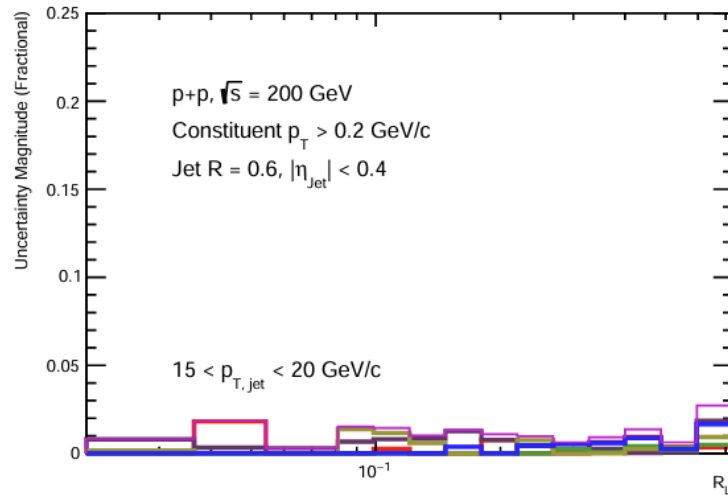


Systematics – E3C/EEC Ratio



- Presented as absolute value of error rather than fractional as distribution hovers around zero
- Many systematics are brought below Barlow test due to cancellation in ratio
 - Barlow test not performed on prior variation – treated as statistically independent sample

Closure – E3C Charge Ratio





Charged E3Cs

$$\text{Charged E3C} = \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i Q_i E_j Q_j E_k Q_k}{p_{T, \text{Jet}}^3}\right)}{d(R_L)} = \text{E3C} - \text{E3C}$$

Positive or negative Q*Q*Q



- Distribution is now charge odd -> Many two-point correlations cancel
- Equivalent $++$ and $--$ correlations cancel out
 - Distribution only affected by net charge
- $+-$ correlations exactly cancel with themselves

This would fill one $++$ correlation and one $--$ correlation, cancelling exactly

