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HP2024
NAGASAKI

STAR

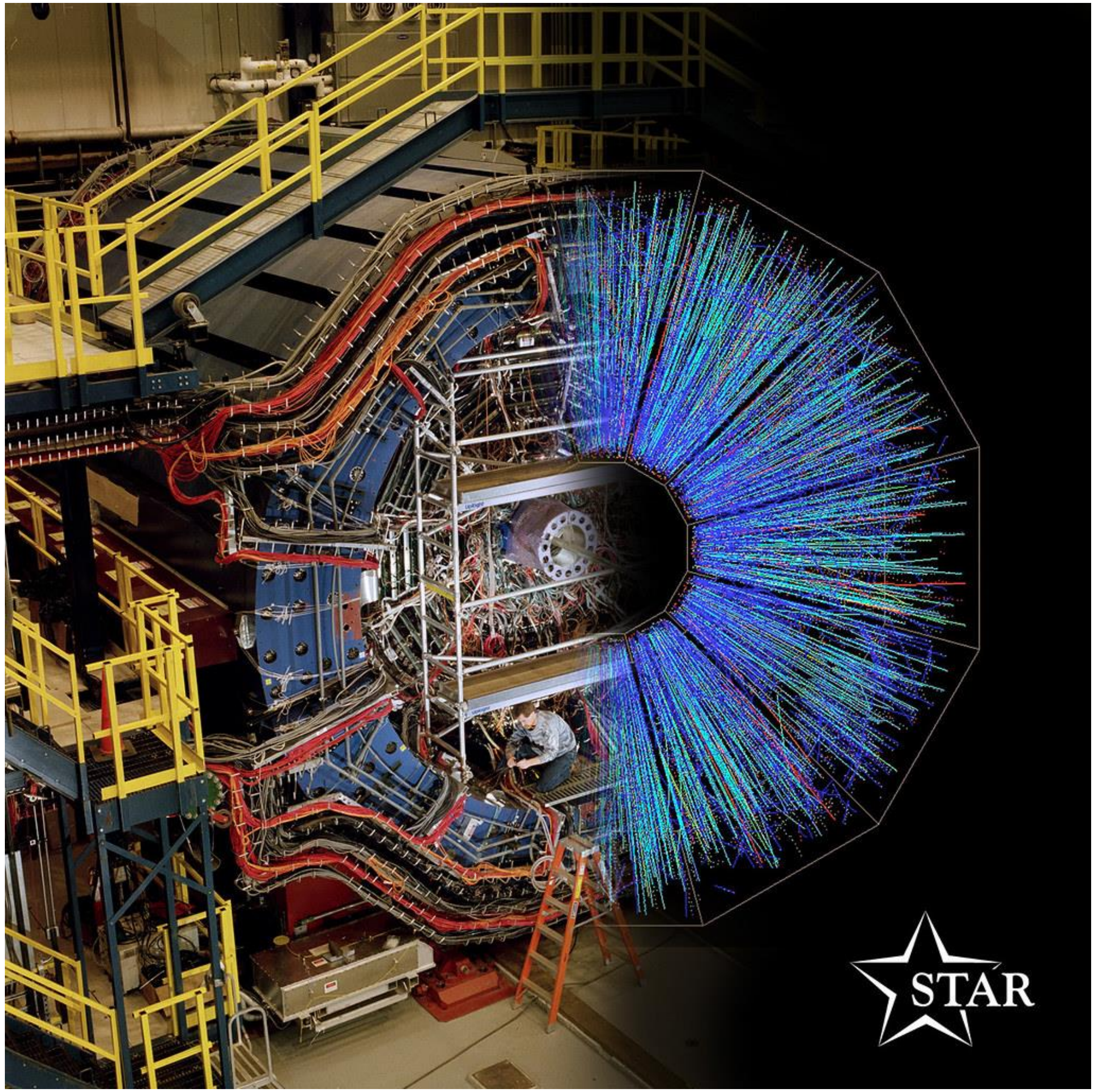
Exploiting Two- and Three-point Charge-Energy Correlators at STAR as Probes of Jet Evolution

Andrew Tamis (Yale University)
For the STAR Collaboration
Hard Probes 2024

24/9/24

Yale Wright Laboratory

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 |η|< 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)

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

Chen et al. 2020, PRD 102, 5

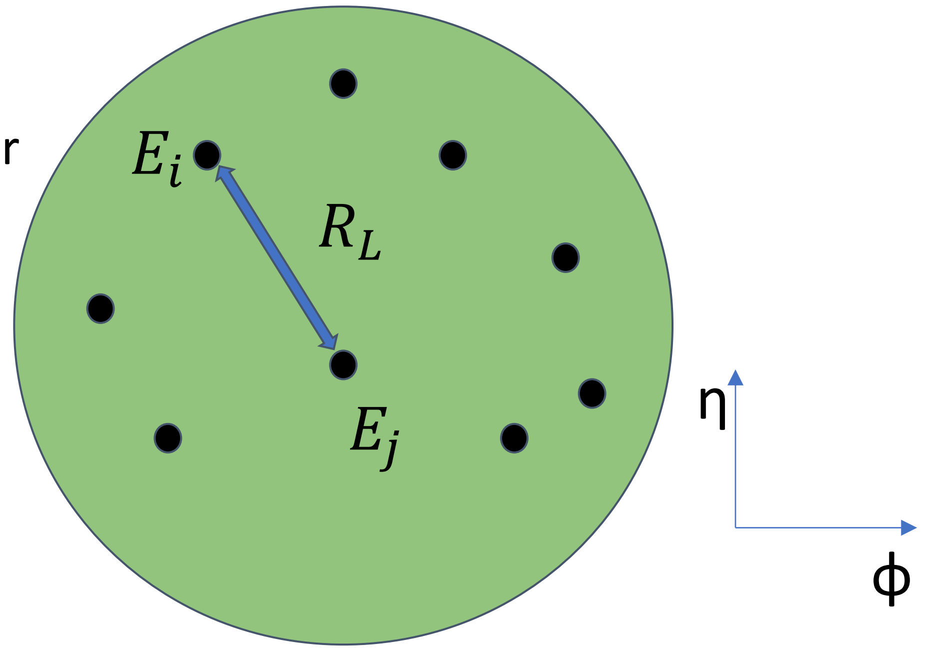
Theoretical Definition of projected N-Point Correlator

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

Experimental Construction of Two-Point Correlator

Note: Energy assumes pion mass

Two-Point



- **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)

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Chen et al. 2020, PRD 102, 5

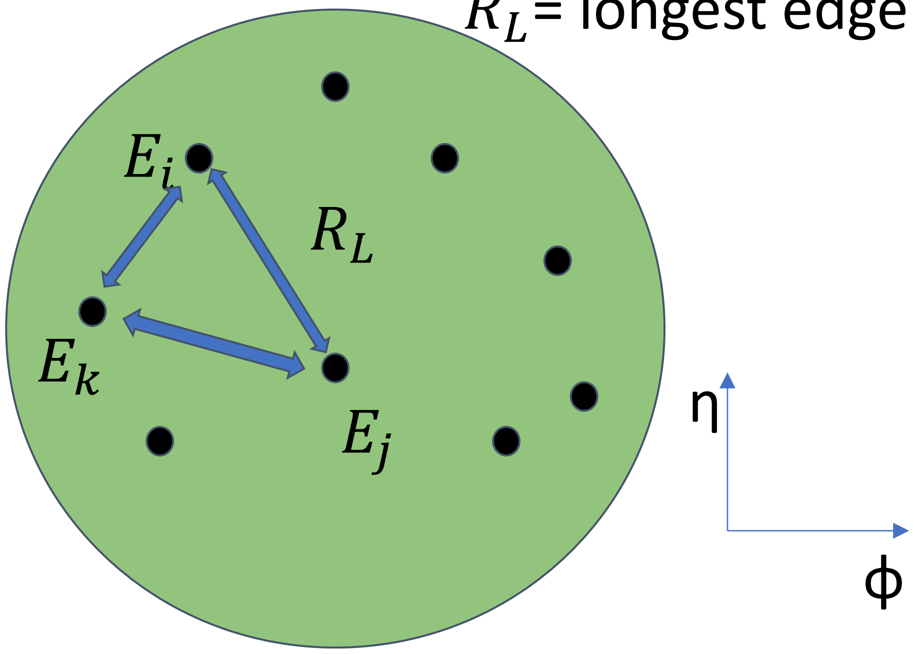
Normalized E3C = $\frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_jE_k}{{p_{T,Jet}}^3}}\frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_jE_k}{{p_{T,Jet}}^3}\right)}{d\,(R_L)}$

Note: Energy assumes pion mass

Experimental Construction of Three-Point Correlator

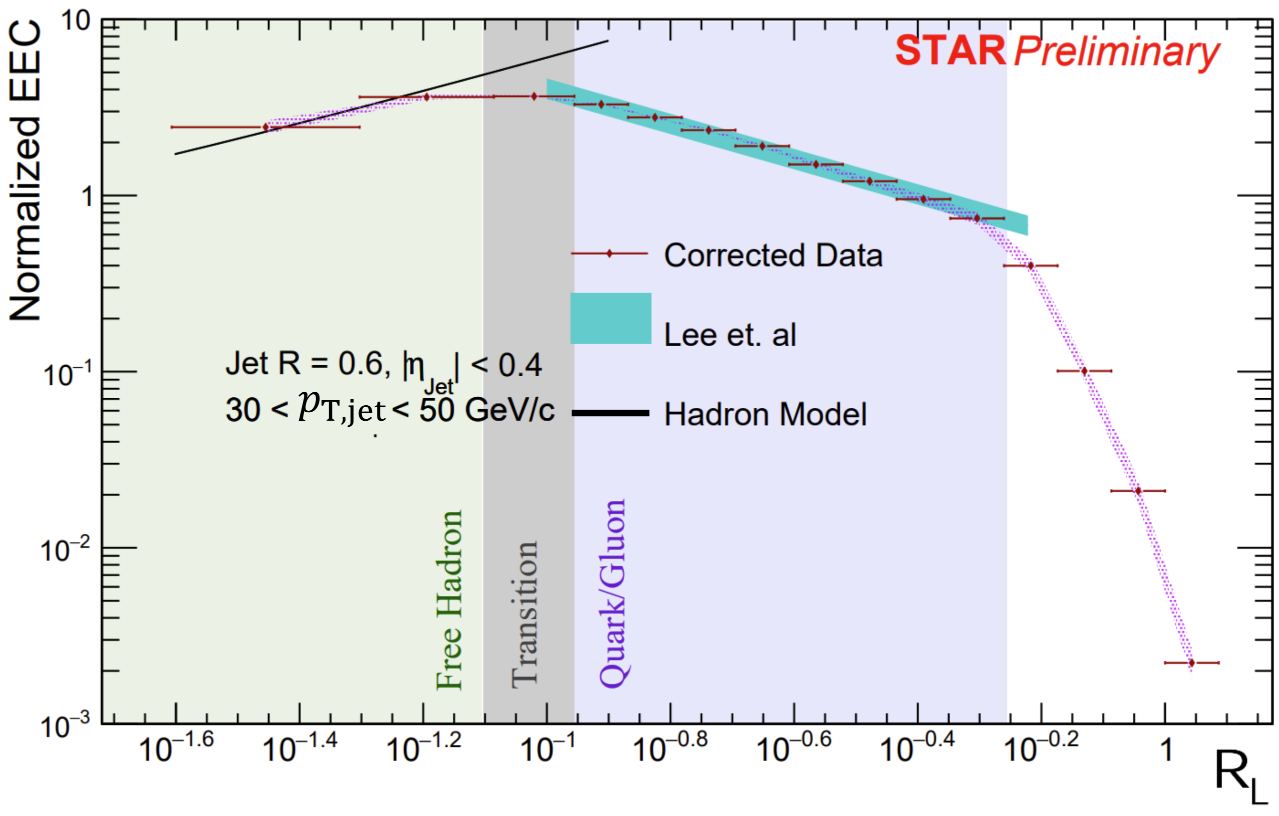
Three-Point

R_L = longest edge



- **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)

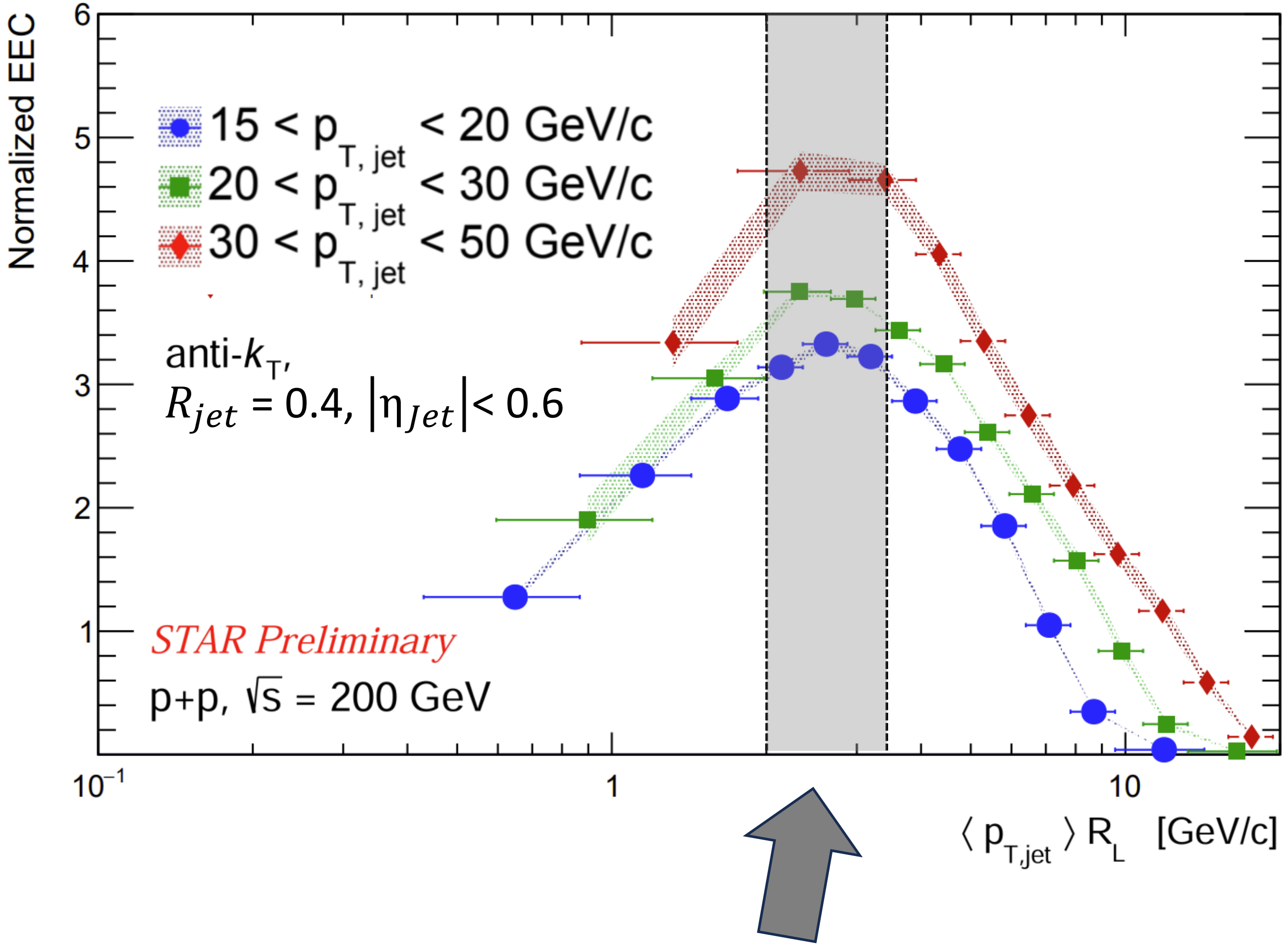


Lee, Mecaj, Moult (2023): arXiv:2205.03414

- Separates distribution into non-perturbative and perturbative regimes, separated by a transition region
- Theoretical comparison calculated in the Perturbative Region ($\frac{3\mathrm{GeV}}{\mathrm{p_T}^{\mathrm{Jet}}{}_{\mathrm{Low}}} < R_L < R_{jet}$)
- **Behavior agrees well with theoretical expectations!**
- Low angle behavior compared with toy model of hadrons, assuming uniform energy distribution

p_T-Shifted Distributions

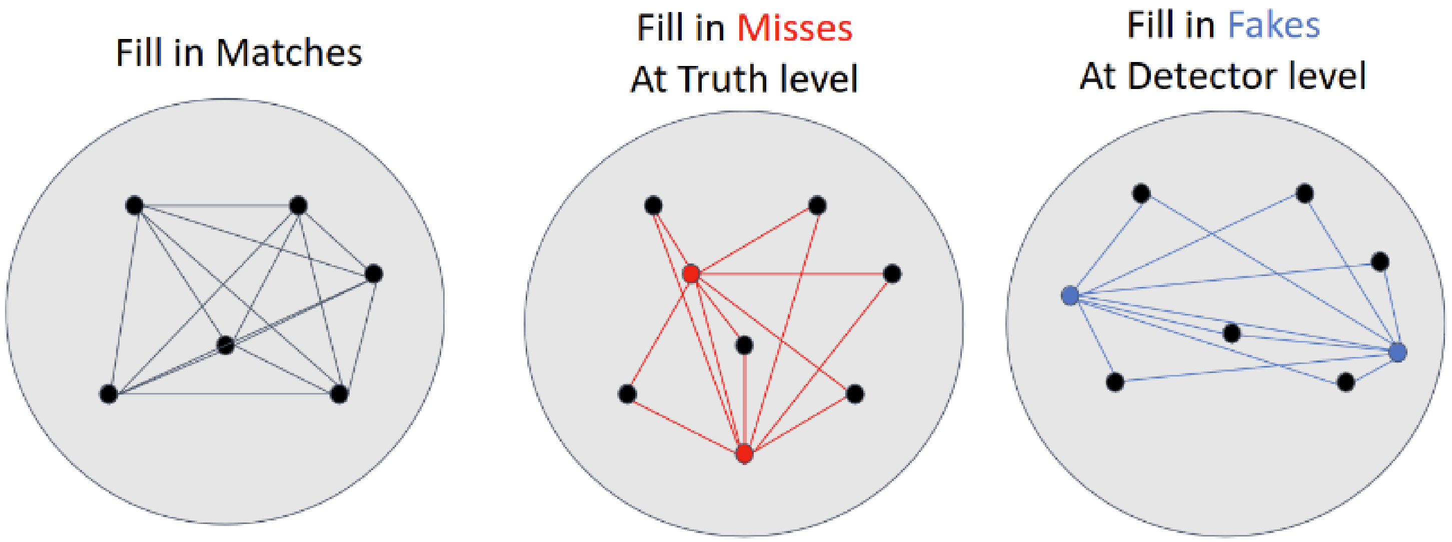
- Shift corrected results on x axis by average $p_{\mathrm{T,jet}}$ in a given bin
- Since location of turnover $\propto \frac{\Lambda_{\mathrm{QCD}}}{p_T^{\mathrm{Jet}}}$, scaled curves will turn over within **the same region**
- In this case, average momentum is determined via PYTHIA and applied post-correction



$$< p_{T,\mathrm{jet}} > \Delta R_{Turnover} \sim 2 - 3.5\ GeV/c$$

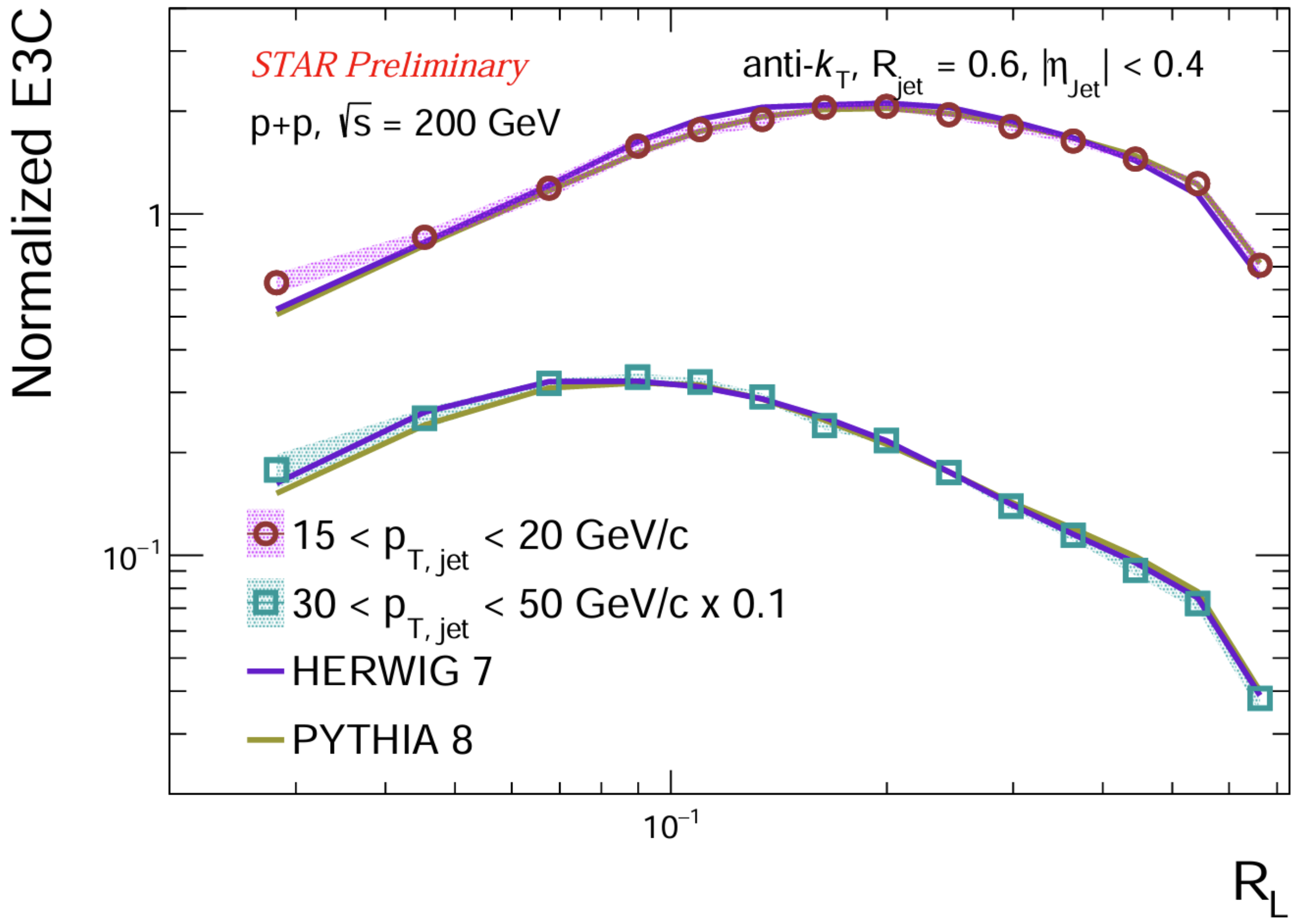
3D Unfolding – Method

- 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 <u>per correlation</u>
  - $p_{T,jet}$, R_L , Energy Weight



E3C Measurement

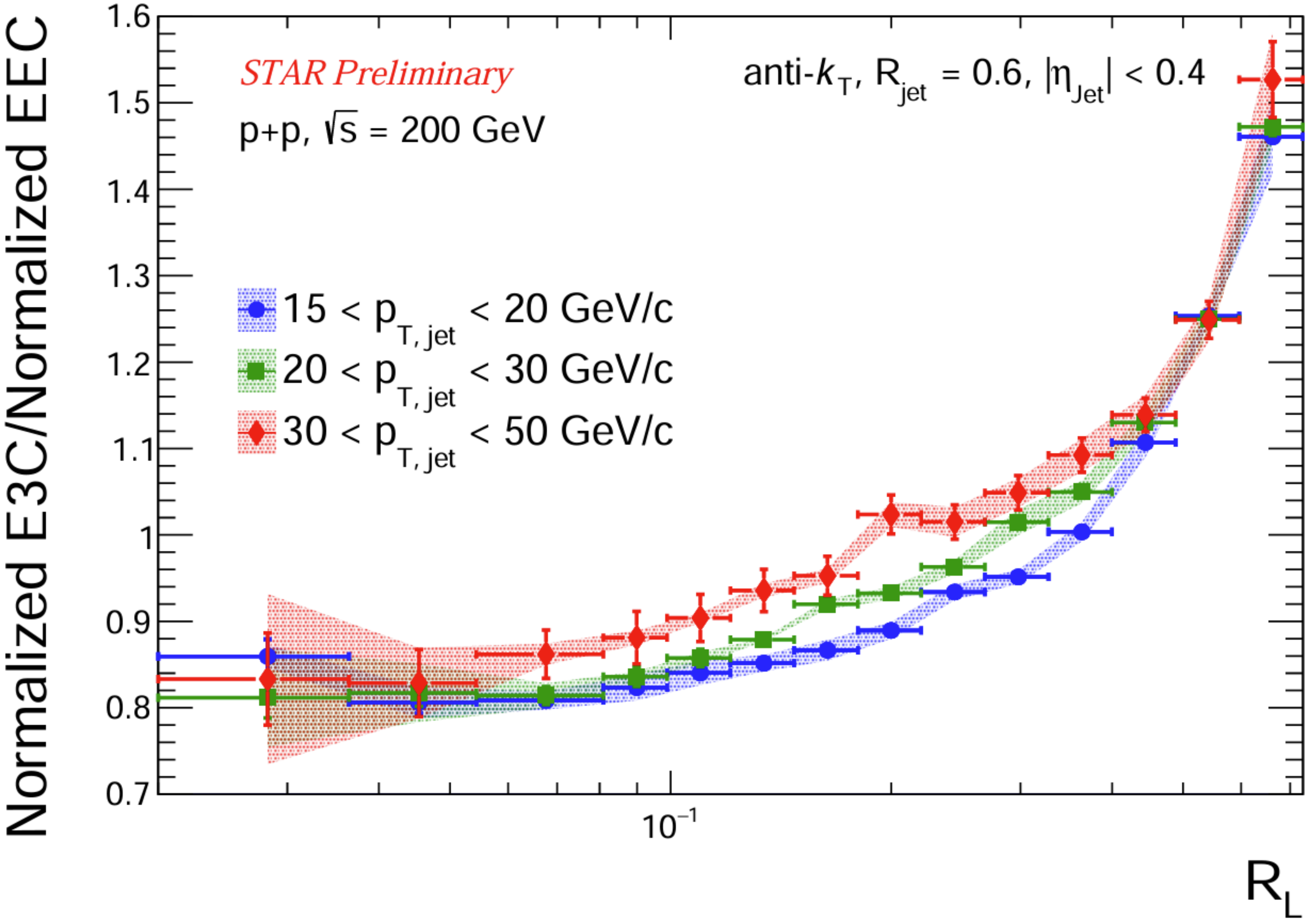
- Shows movement of transition region with jet momentum
- Quantify difference in scaling in ratio
- PYTHIA and HERWIG describe behavior well



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**

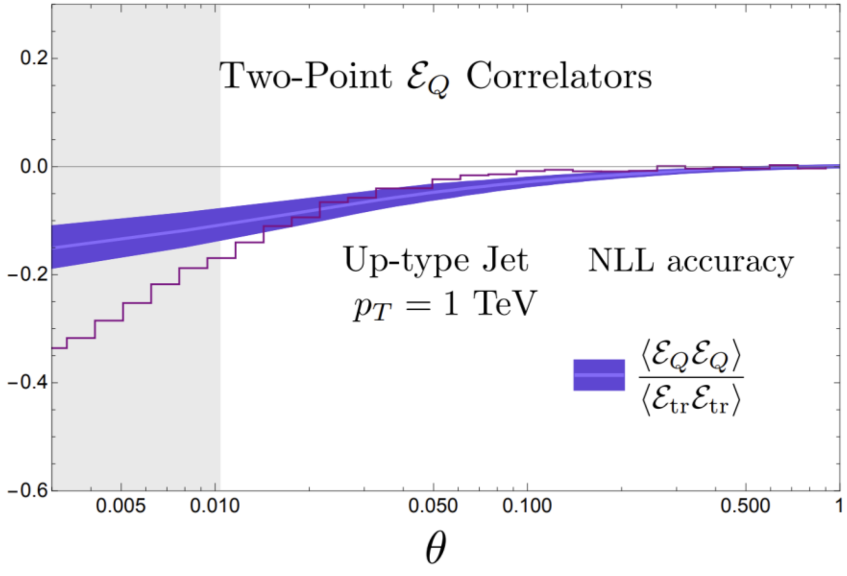
[Chen et al. Phys. ReV. D 102, 054012]



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 = $\dfrac{d\left(\sum_{Jets}\sum_{i\neq j}\dfrac{E_i Q_i E_j Q_j}{{p_{T,Jet}}^2}\right)}{d\,(R_L)}$
- Sensitive to hadronization mechanism

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



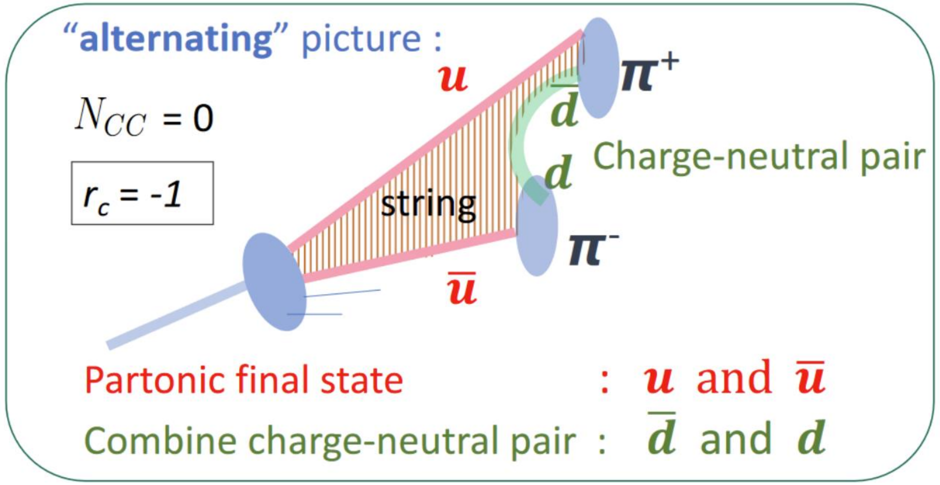


Figure: Mriganka Mouli Mondal

Charge-weighted EECs

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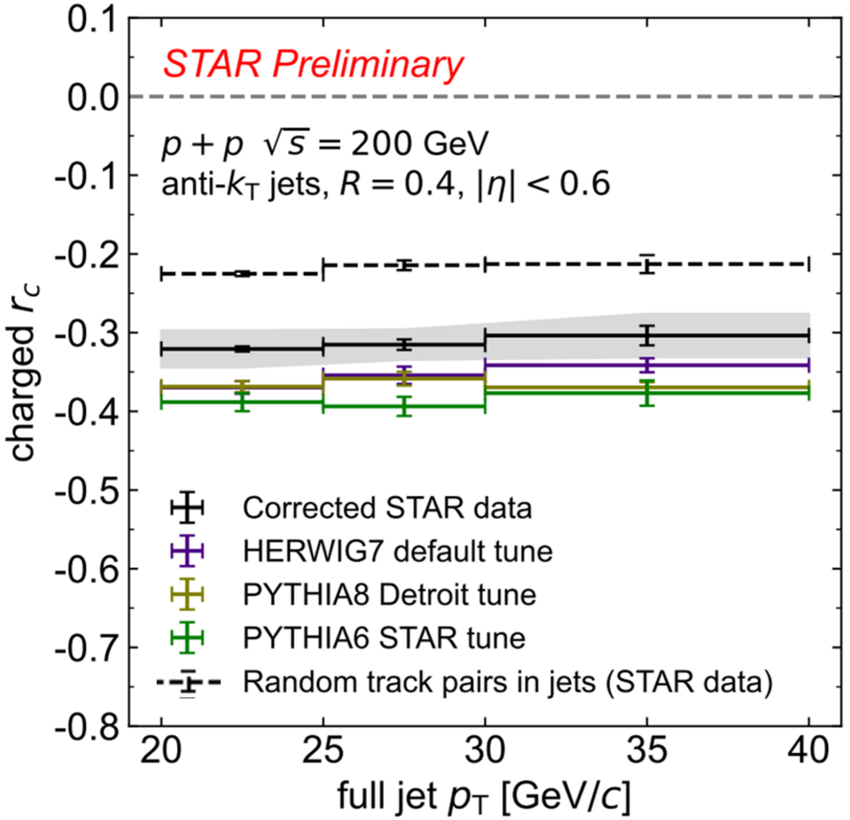
- Weight energy flow operator by particle's electric charge:

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

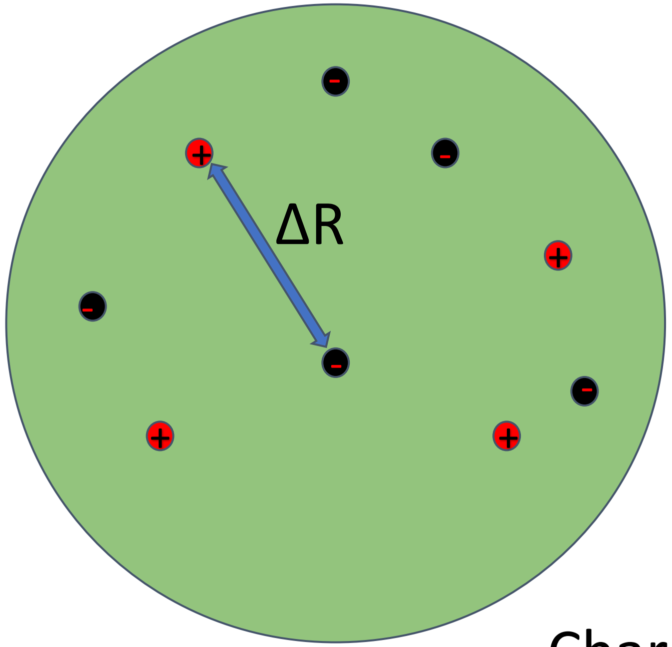
- Sensitive to hadronization mechanism

Probes similar physics to r_c measurement performed by STAR

See talk by Youqi Song on 25/9



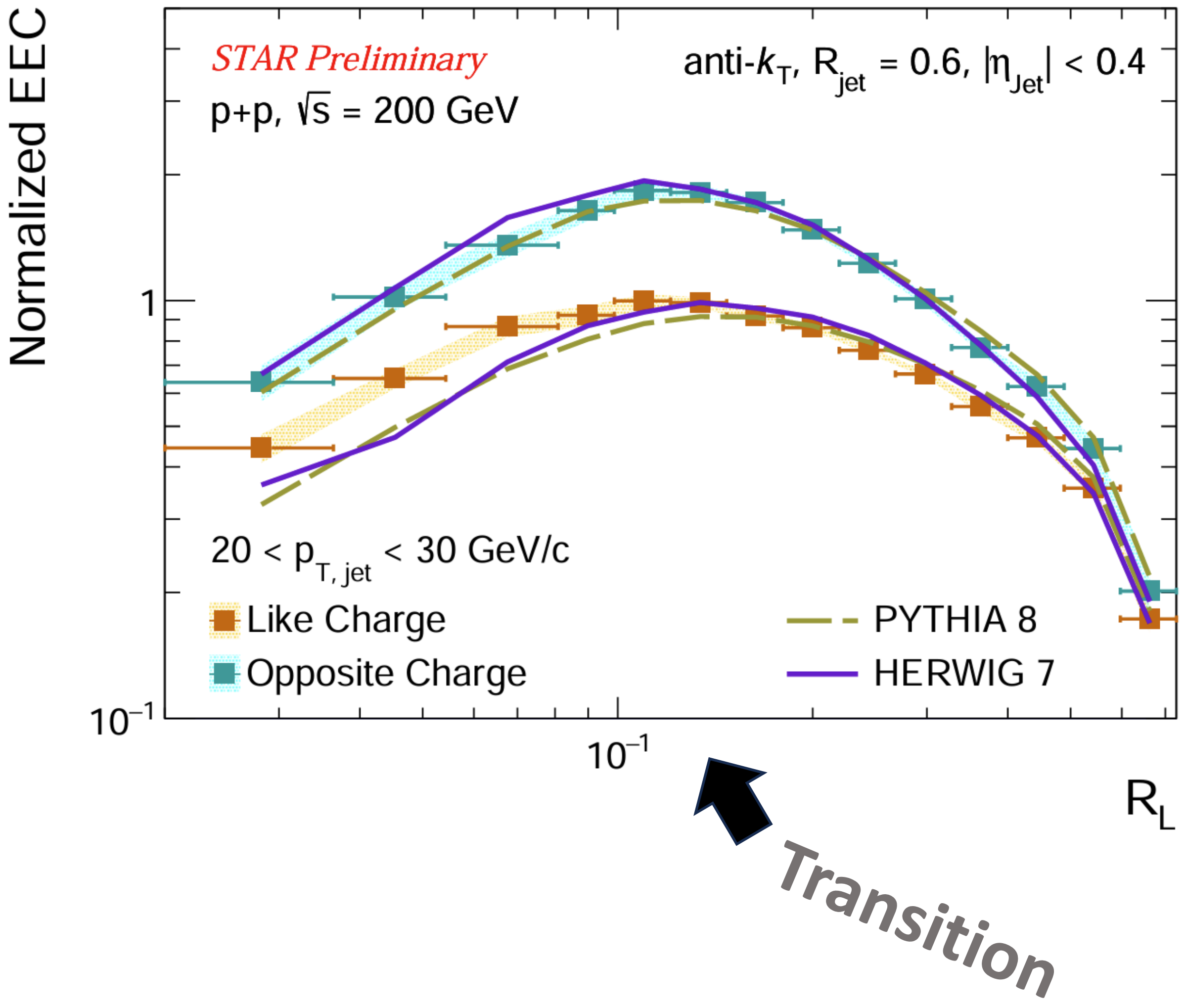
Charge-weighted EEC Measurement



- 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

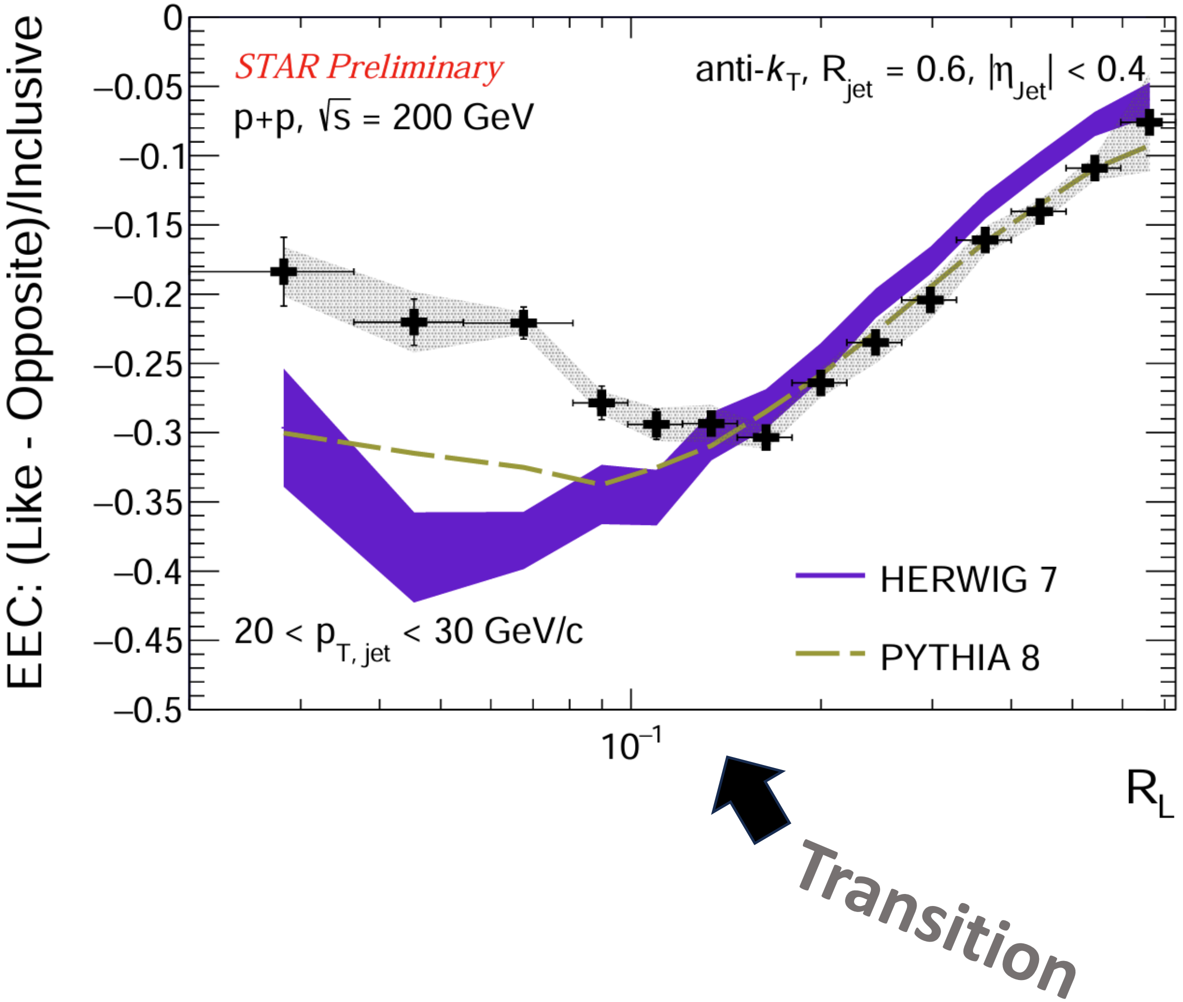
$$\text{Charge-weighted EEC} = \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i Q_i E_j Q_j}{{p_{T,Jet}}^2}\right)}{d\,(R_L)} = \mathrm{EEC}_{\mathrm{Like}} - \mathrm{EEC}_{\mathrm{Opposite}}$$

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

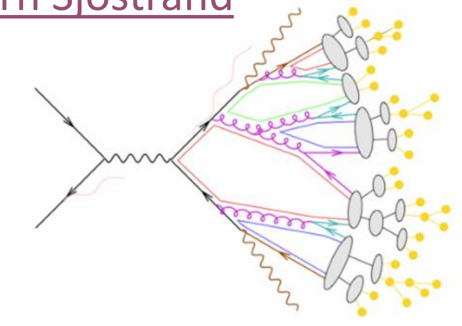
Charge-weighted Ratio

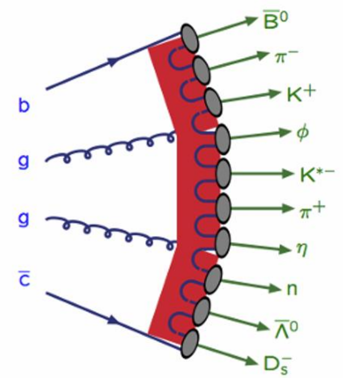


Cluster

String

[Torbjörn Sjöstrand]





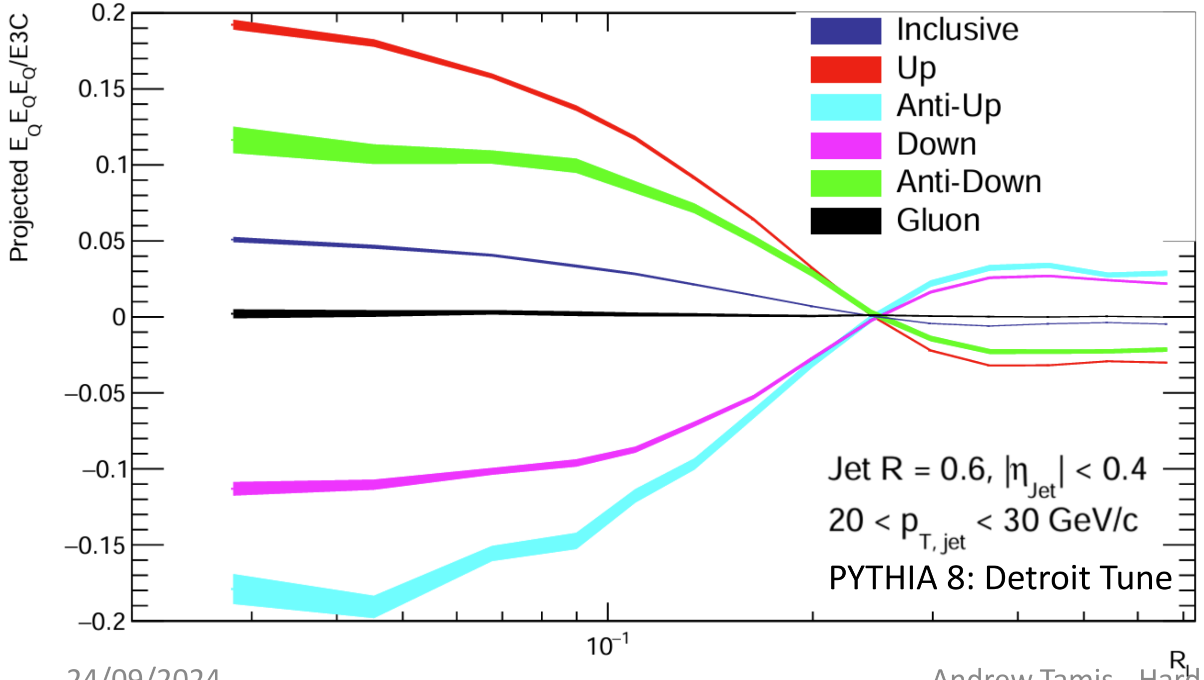
- Cluster hadronization (HERWIG) and String hadronization (PYTHIA) both predict same qualitative behavior
- Pythia describes perturbative regime better, but neither describe data below transition region
- Implementation of charge dependence/conservation in hadronization mechanism may not fully capture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

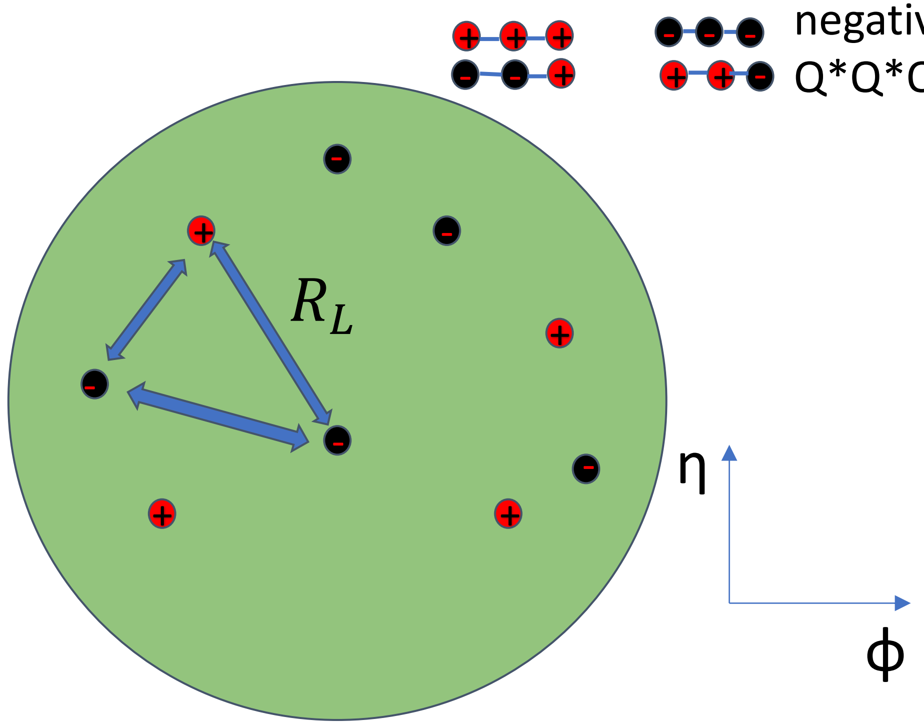
Charge-weighted E3Cs

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

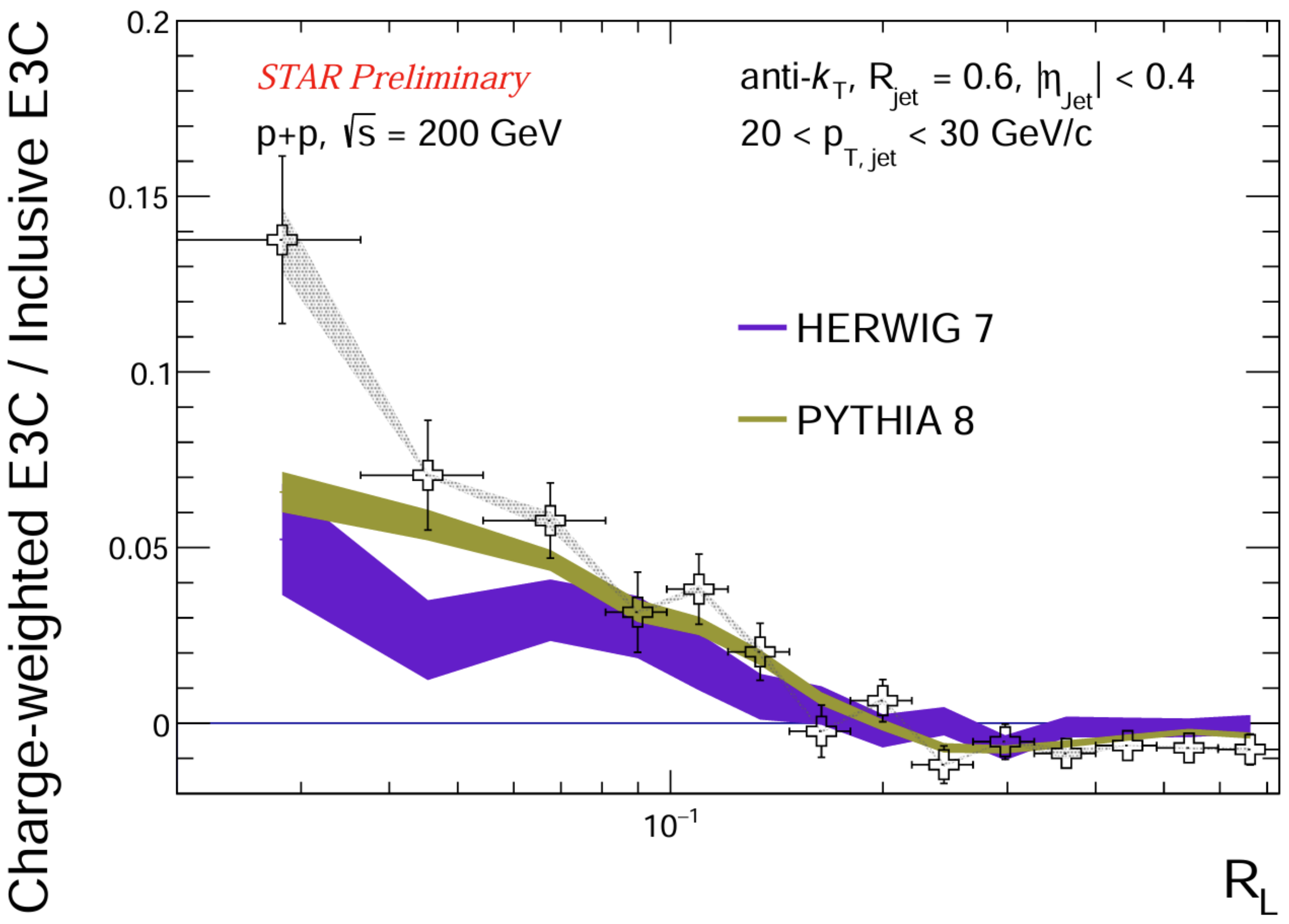
$$\text{Charge-weighted E3C} = \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iQ_iE_jQ_jE_jQ_j}{p_{T,Jet}{}^3}\right)}{d\,(R_L)} = \text{E3C} - \text{E3C}$$

Positive or negative Q*Q*Q





Charge-weighted Ratio – Three Point

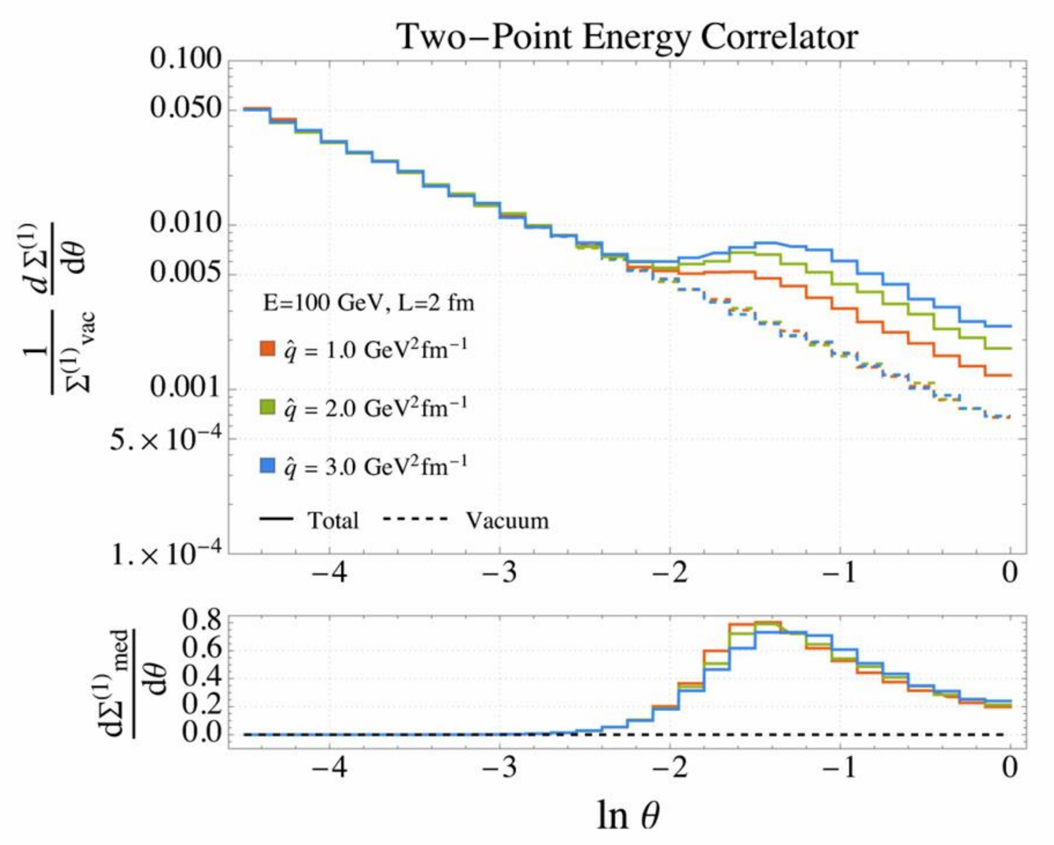


- Monte-Carlo models predict 3-point charge correlations better than 2-Point
- Suggests hadronization mechanism that has greater two-point charge dependence than three-point

Extension to Heavy-Ion

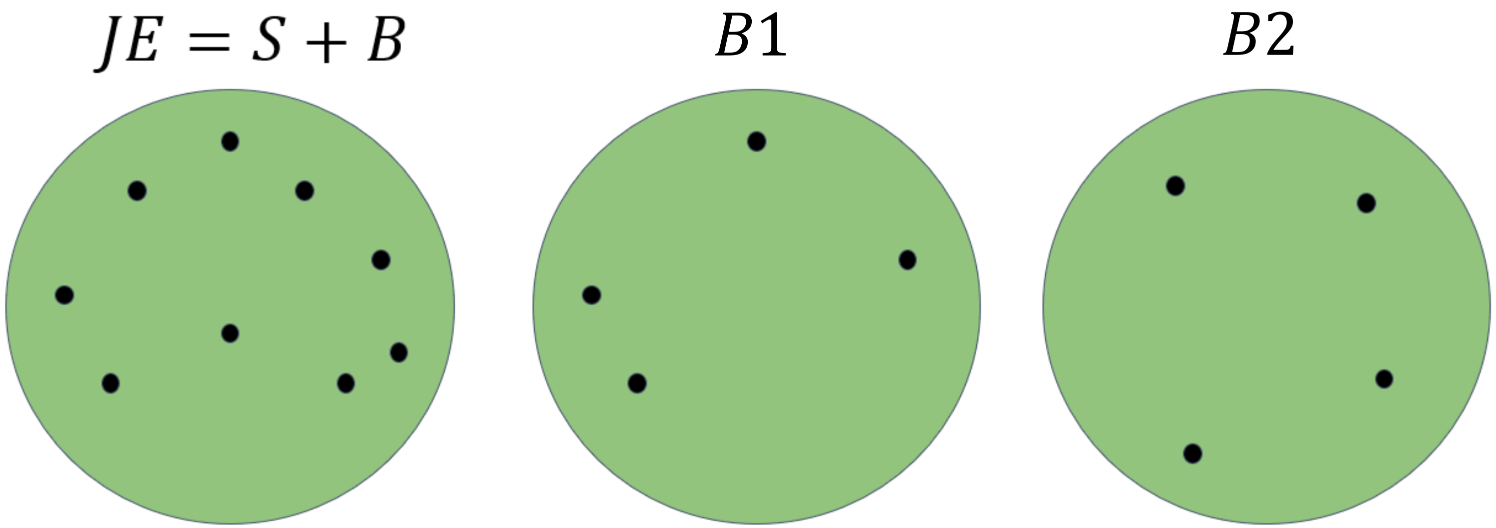
Andres et al. Phys. Rev. Lett. 130, 262301

- 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



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 ($particles > 1\frac{GeV}{c}\, have\ minimum\ distance\ of\ 0.01$) to verify that self-correlations are removed



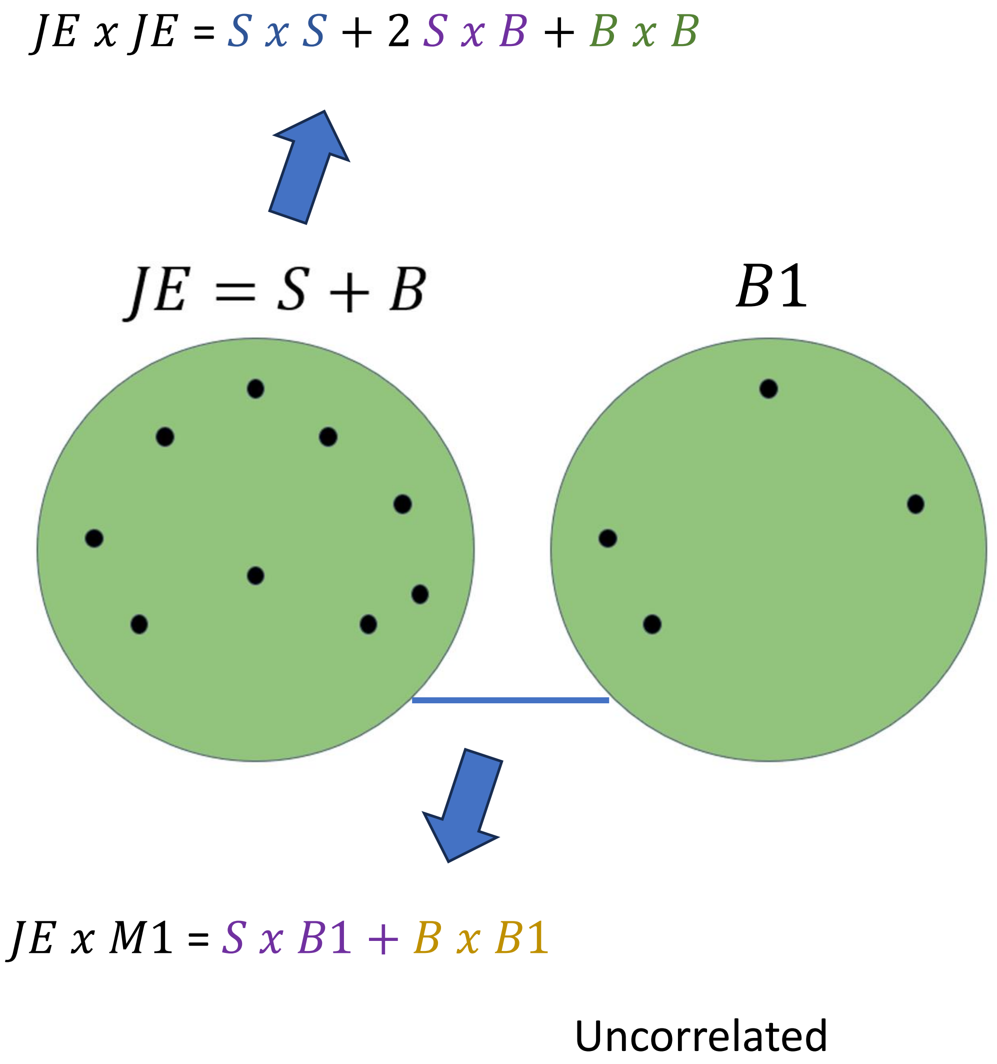
Background Subtraction

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

$$JE \ x \ JE - 2 \ JE \ x \ B1 \ - B1 \ x \ B1$$

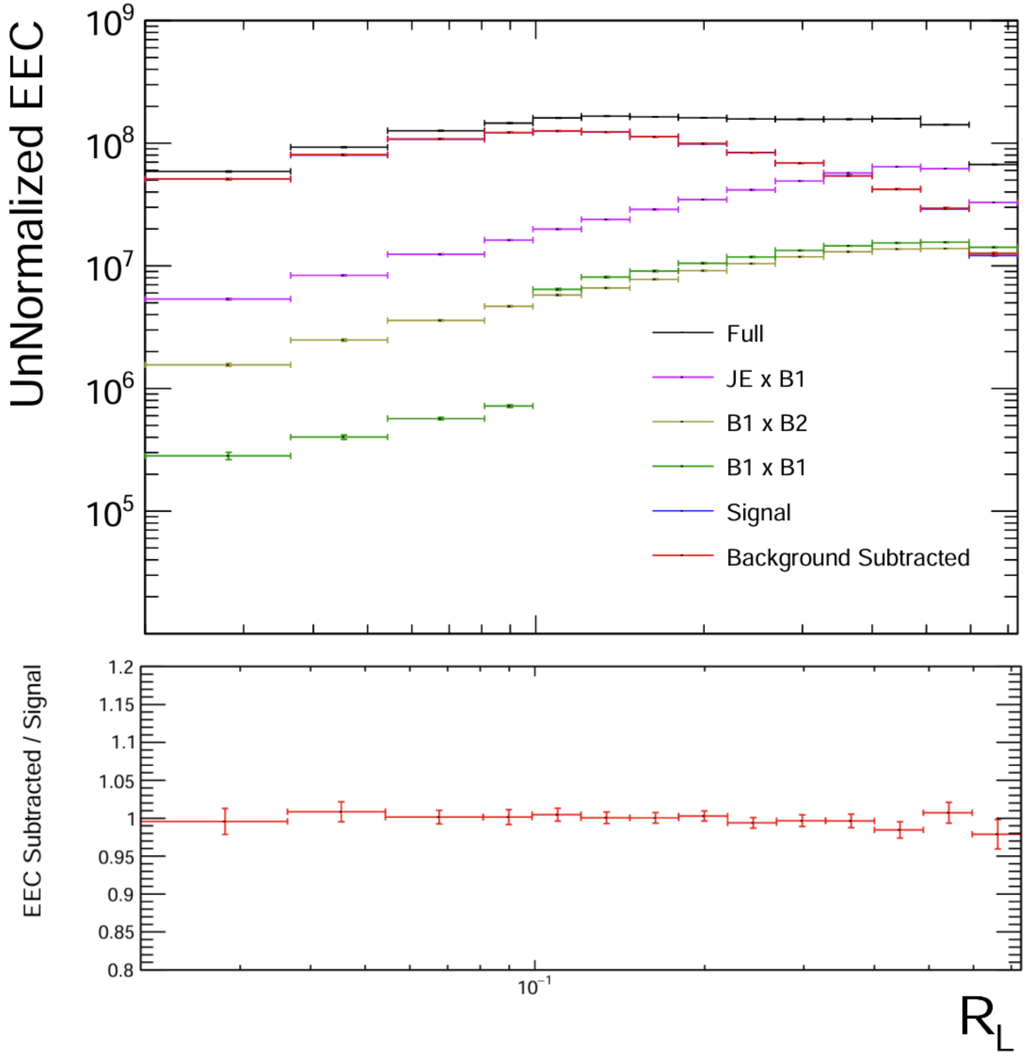
$$= \boldsymbol{SxS} \ - 2 \ B \ x \ B1$$

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



Two-Point Background Subtraction

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



Conclusions

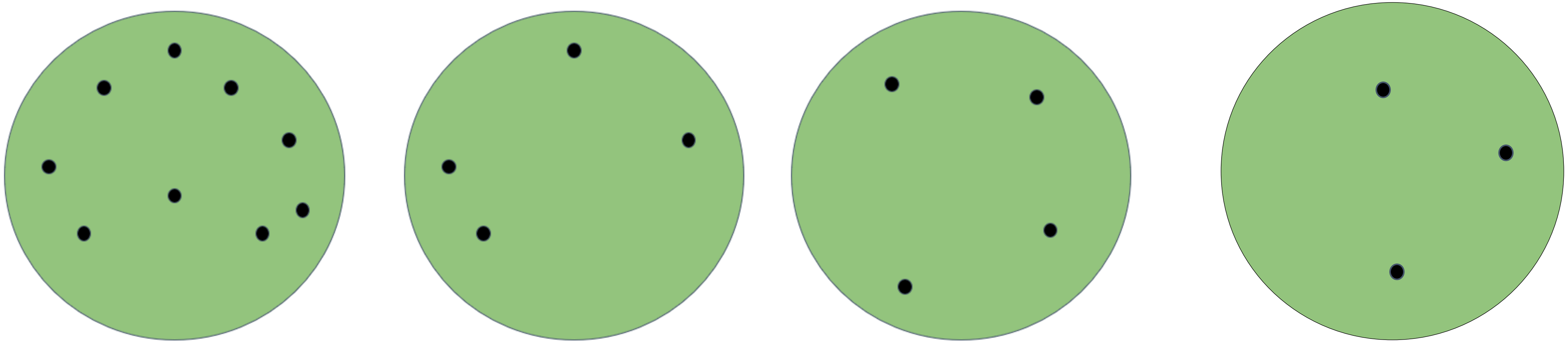
- STAR is an extremely useful environment for study of ENCs, and an excellent complement to LHC measurements
- Charged ENCs expand sensitivity of ENCs to non-perturbative effects and the hadronization mechanism
  - Observe tension with current Monte-Carlo models in **two-point** charge-dependent hadronization
- 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

$JE = S + B$ $B1$ $B2$ $B3$

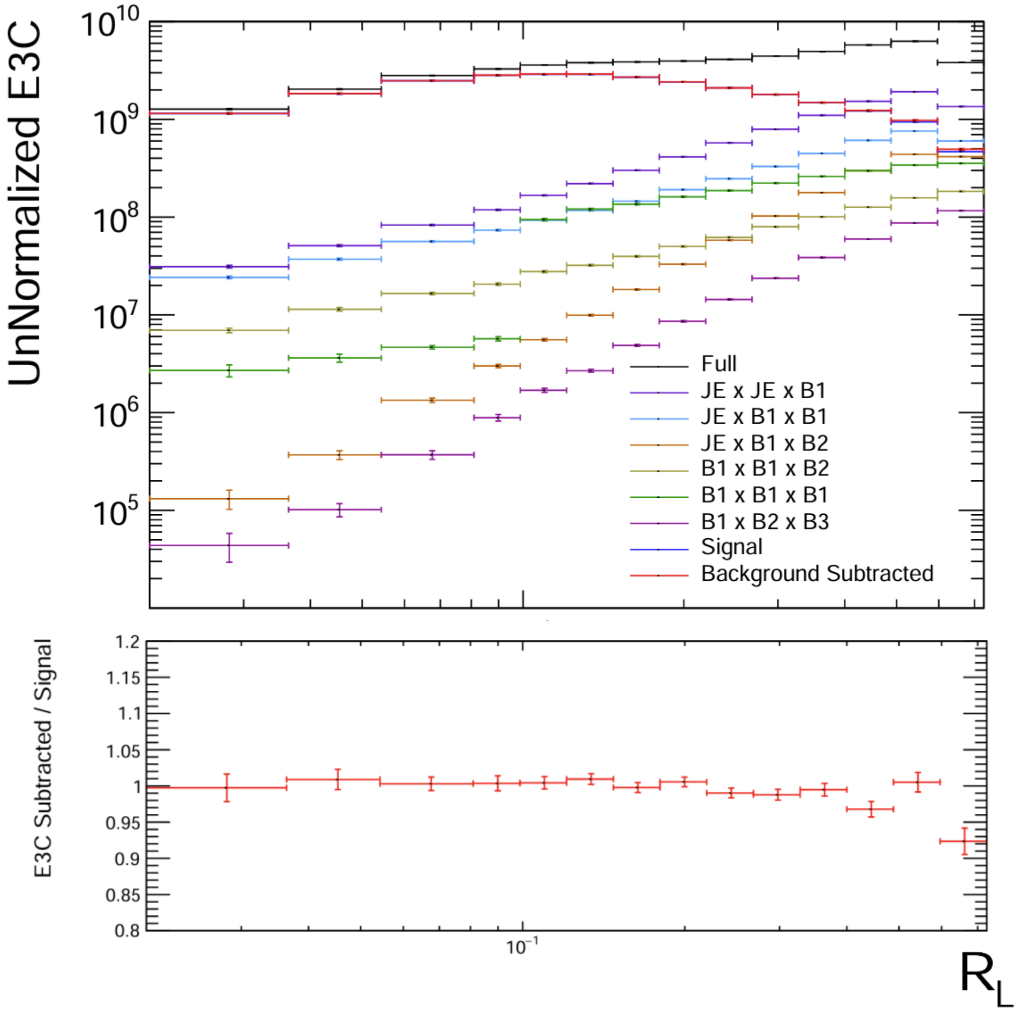


Three-Point Background Subtraction

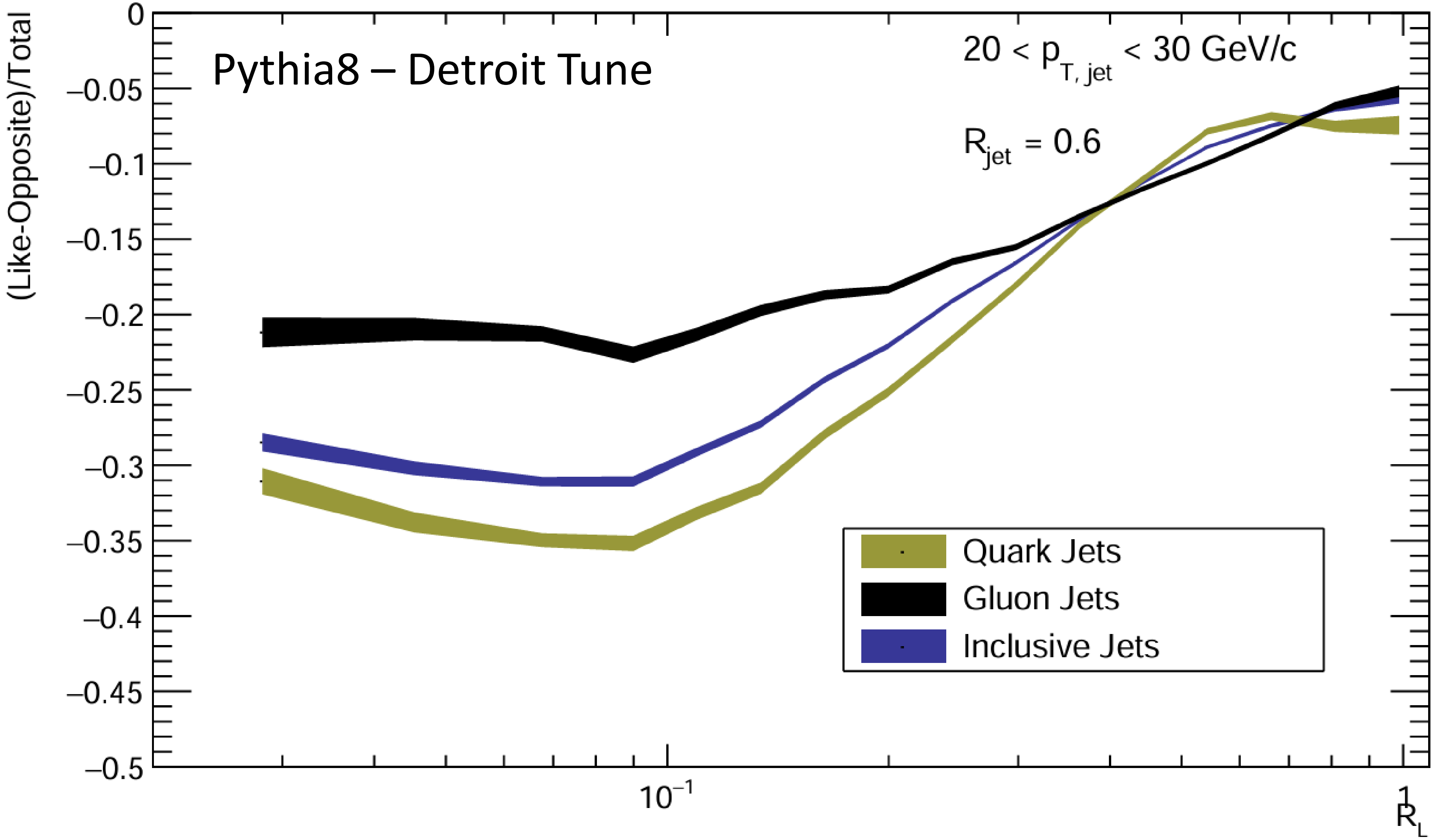
- Method can be applied very similarly to three-point
- Requires a third minimum-bias event
- $S^2{}_{Three-Point} = JE^3$

- $3\, JE^2\, B1$
- $3\, JE\, B1^2$
- $-B1^3$
- $+6B1^2B2$
- $+6JE\ B1\ B2$
- $-6\ B1\ B2\ B3$

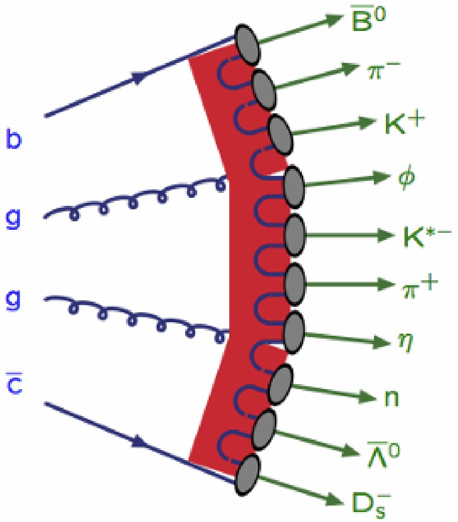
Decreasing Magnitude

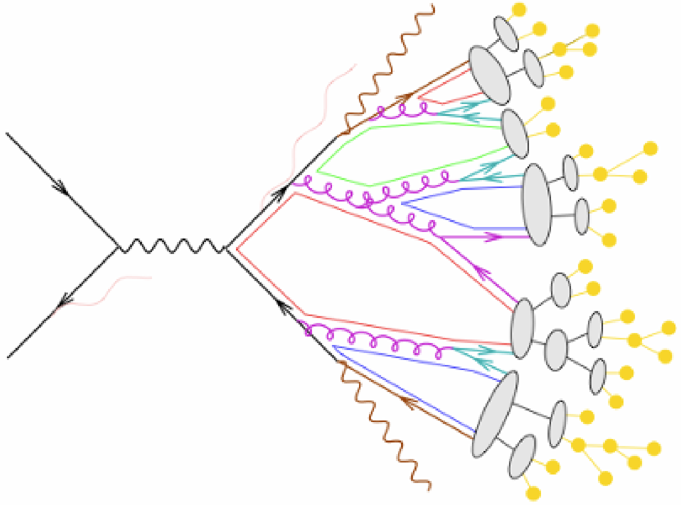


Quark/Gluon Behavior of Charged Ratio



String vs. Cluster



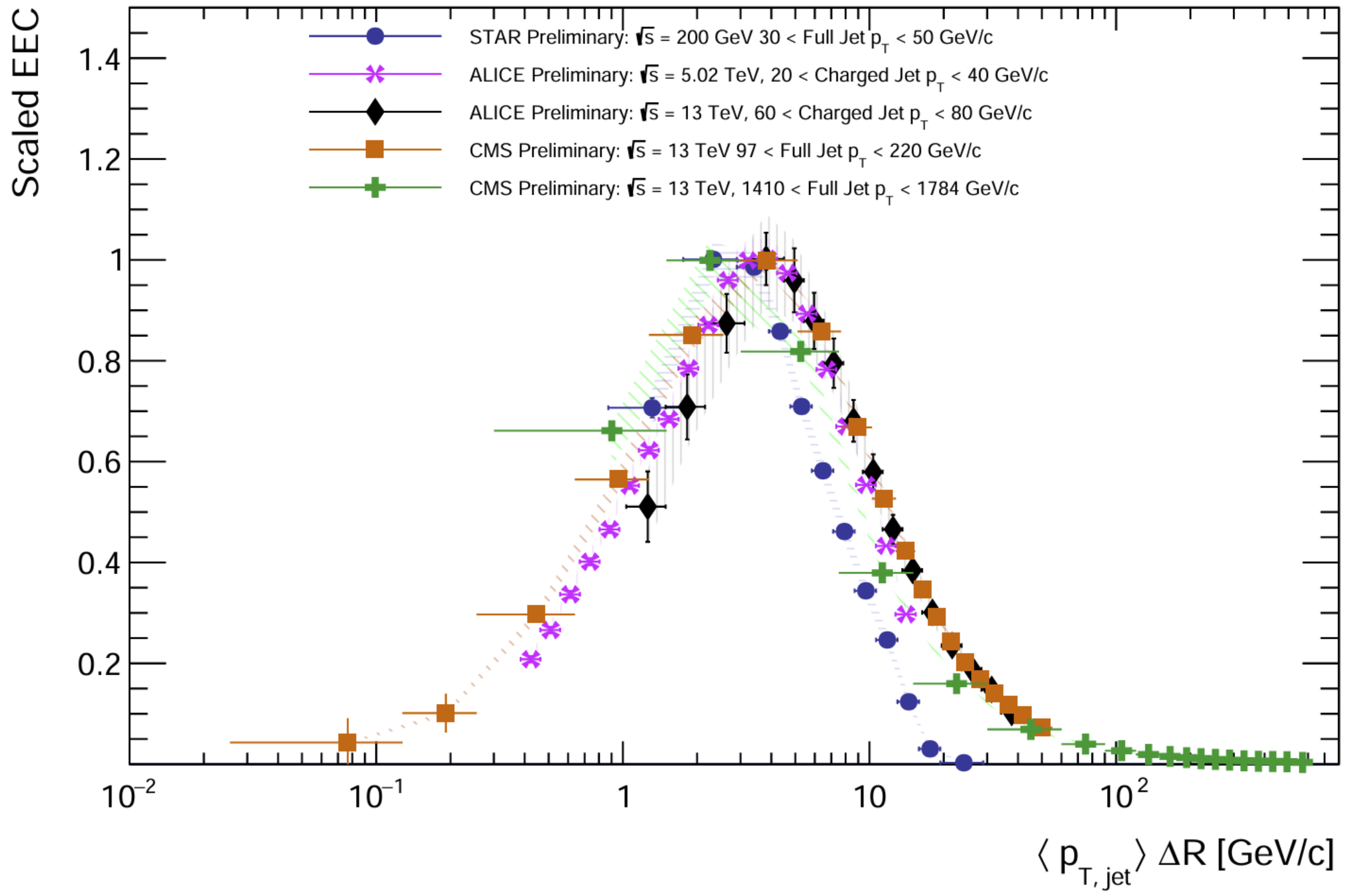


Torbjörn Sjöstrand
50 Years of Quantum Chromodynamics
UCLA

[ucla23ts.pdf (cern.ch)](ucla23ts.pdf)

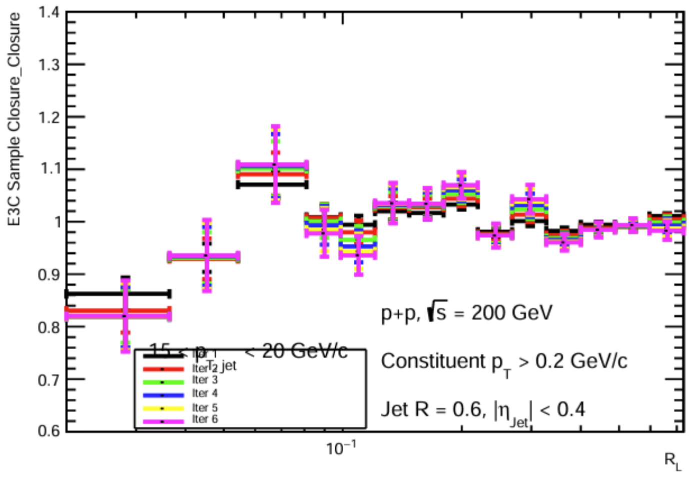
program	PYTHIA	Herwig, SHERPA
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Free parameters abound in each nonperturbative description.

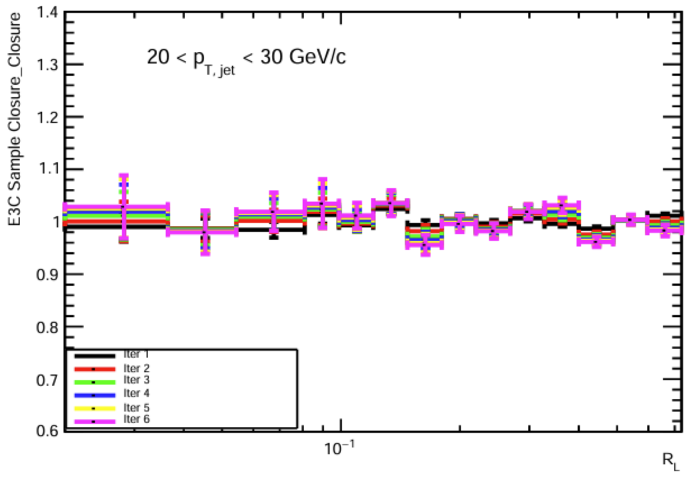


Scaled EEC
STAR Preliminary: √s = 200 GeV 30 < Full Jet p_T < 50 GeV/c
ALICE Preliminary: √s = 5.02 TeV, 20 < Charged Jet p_T < 40 GeV/c
ALICE Preliminary: √s = 13 TeV, 60 < Charged Jet p_T < 80 GeV/c
CMS Preliminary: √s = 13 TeV 97 < Full Jet p_T < 220 GeV/c
CMS Preliminary: √s = 13 TeV, 1410 < Full Jet p_T < 1784 GeV/c
1.4
1.2
1
0.8
0.6
0.4
0.2
10^-2
10^-1
1
10
10^2
⟨p_T, jet⟩ ΔR [GeV/c]
STAR

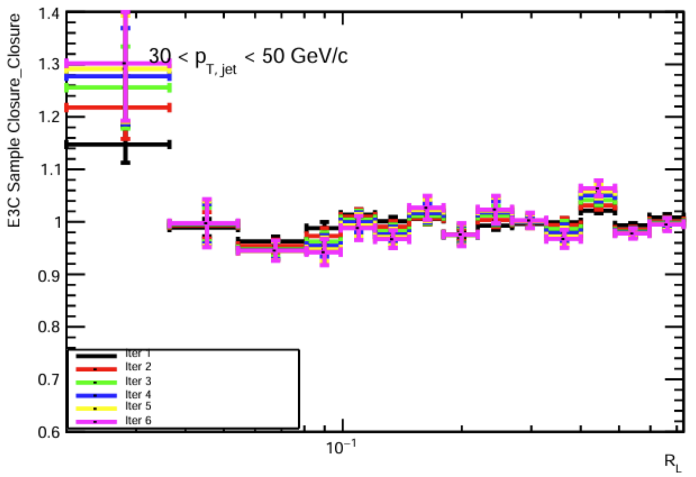
Closure – E3C



E3C Sample Closure_Closure
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^{-1}
R_L
p+p, $\sqrt{s}$ = 200 GeV
15 < $p_{T,\,jet}$ < 20 GeV/c
Constituent p_T > 0.2 GeV/c
Jet R = 0.6, $|\eta_{Jet}|$ < 0.4
Iter 1
Iter 2
Iter 3
Iter 4
Iter 5
Iter 6

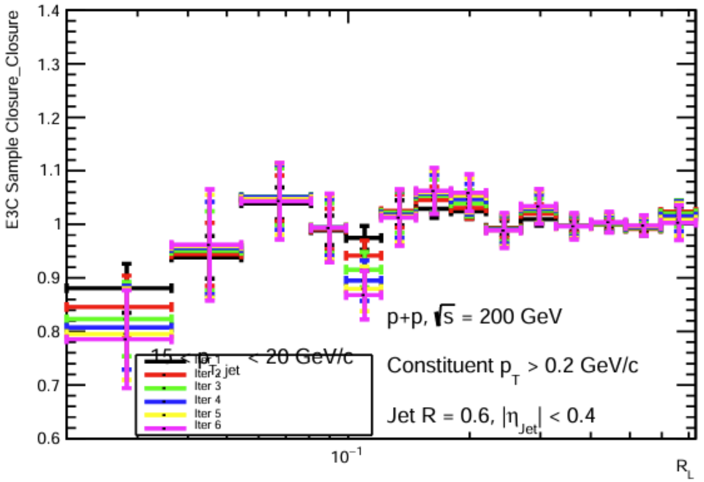


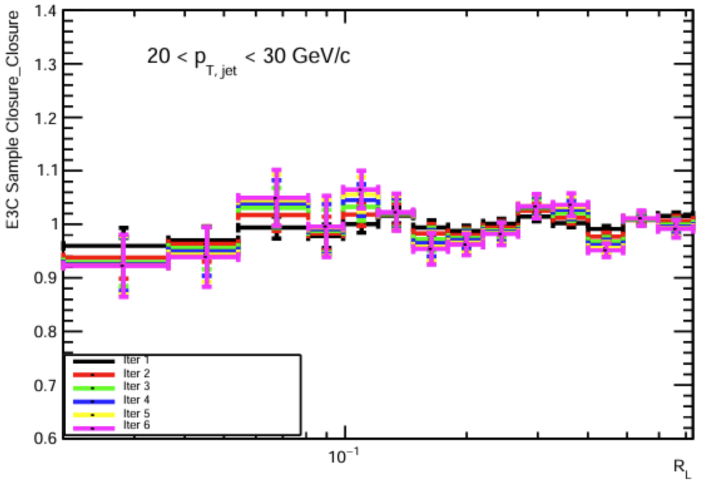
E3C Sample Closure_Closure
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^{-1}
R_L
20 < $p_{T,\,jet}$ < 30 GeV/c
Iter 1
Iter 2
Iter 3
Iter 4
Iter 5
Iter 6

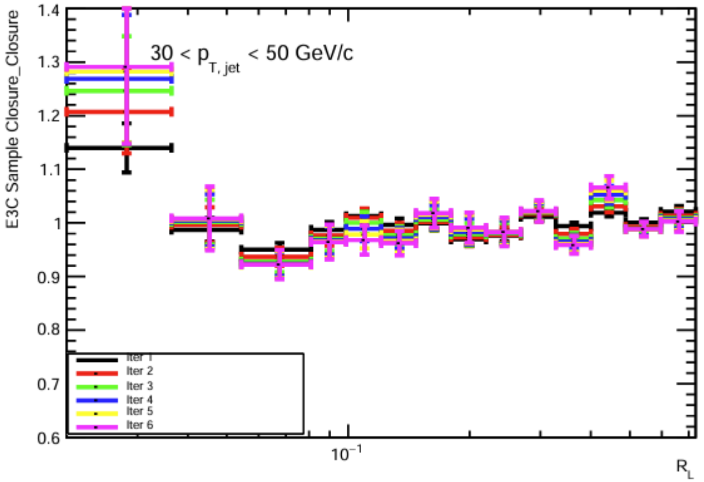


E3C Sample Closure_Closure
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^{-1}
R_L
30 < $p_{T,\,jet}$ < 50 GeV/c
Iter 1
Iter 2
Iter 3
Iter 4
Iter 5
Iter 6

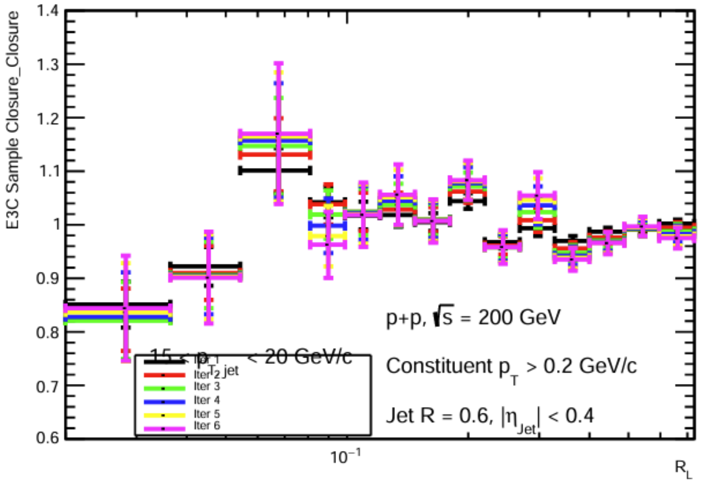
Closure – E3C Positive Charge Product

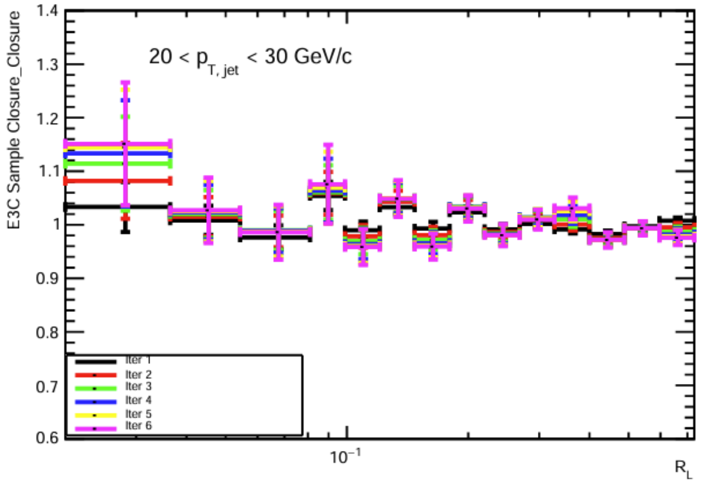


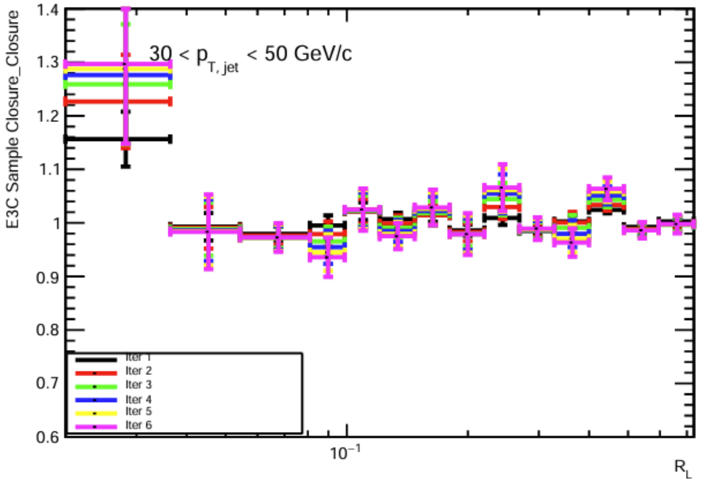




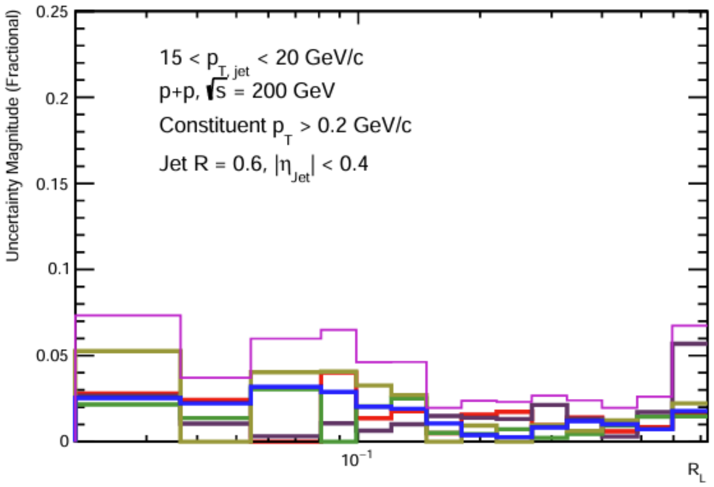
Closure – E3C Negative Charge Product

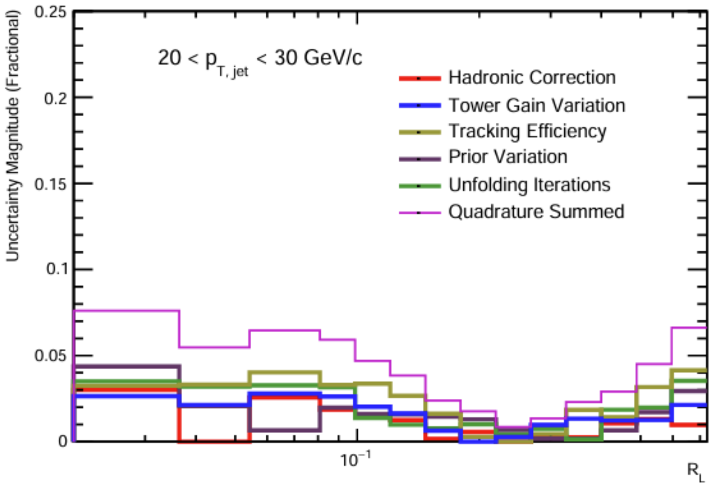


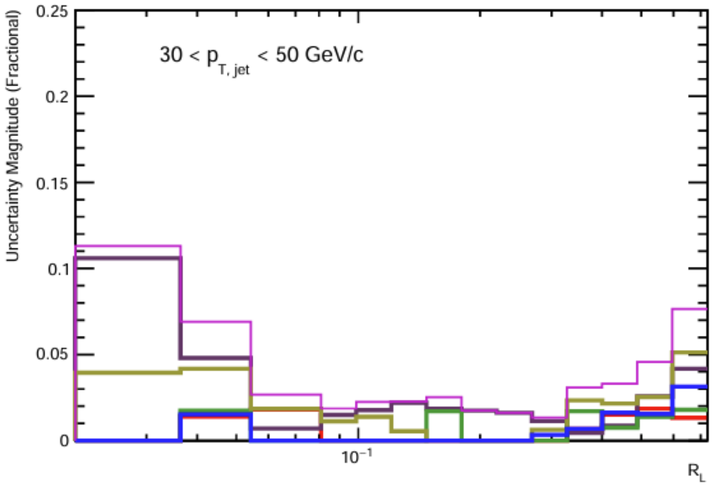




Systematics – E3C

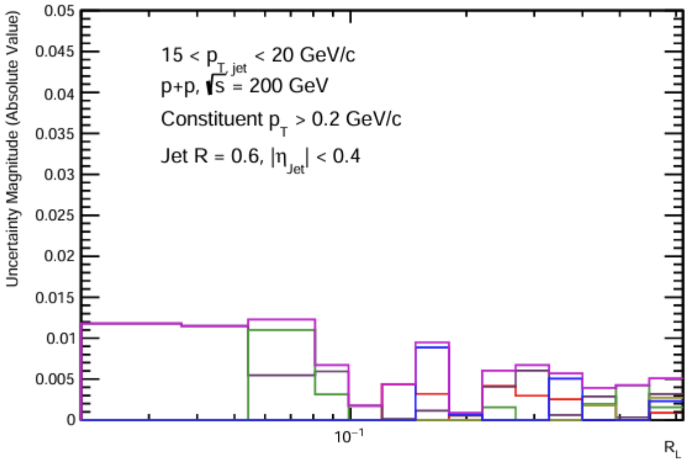


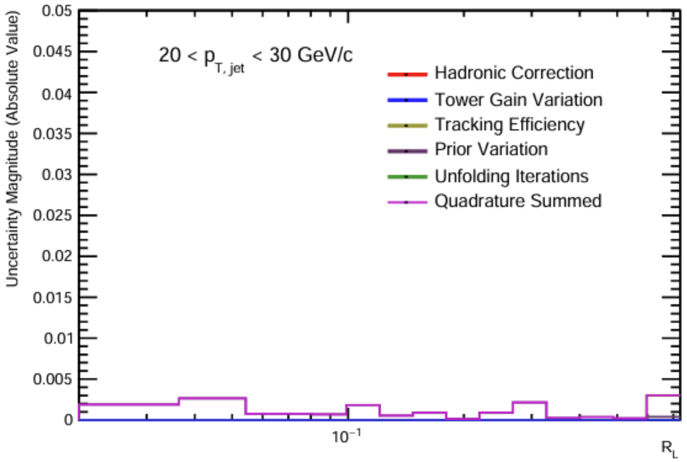


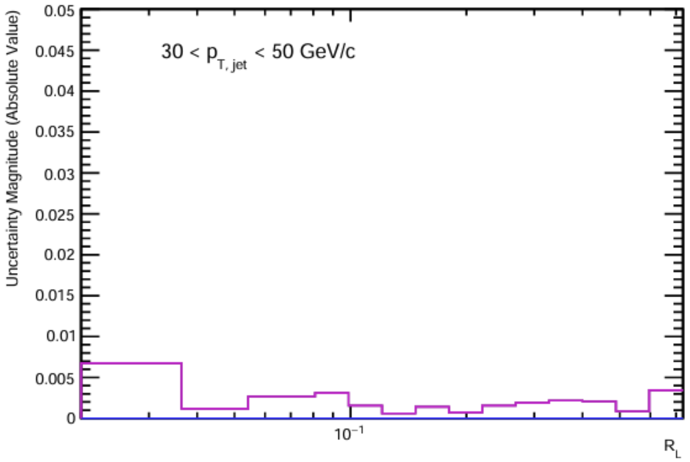


- Hadronic Correction– Varied from nominal 100% to 50%
  - Tower Scale Variation – Varied by 3.8 %
  - Tracking Efficiency – Varied by 4 %
  - Unfolding Prior – PYTHIA embedding sample was re-weighted to resemble HERWIG at each correlation, and then used to train the response matrix.
  - Unfolding Iteration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

Systematics – E3C/EEC Ratio

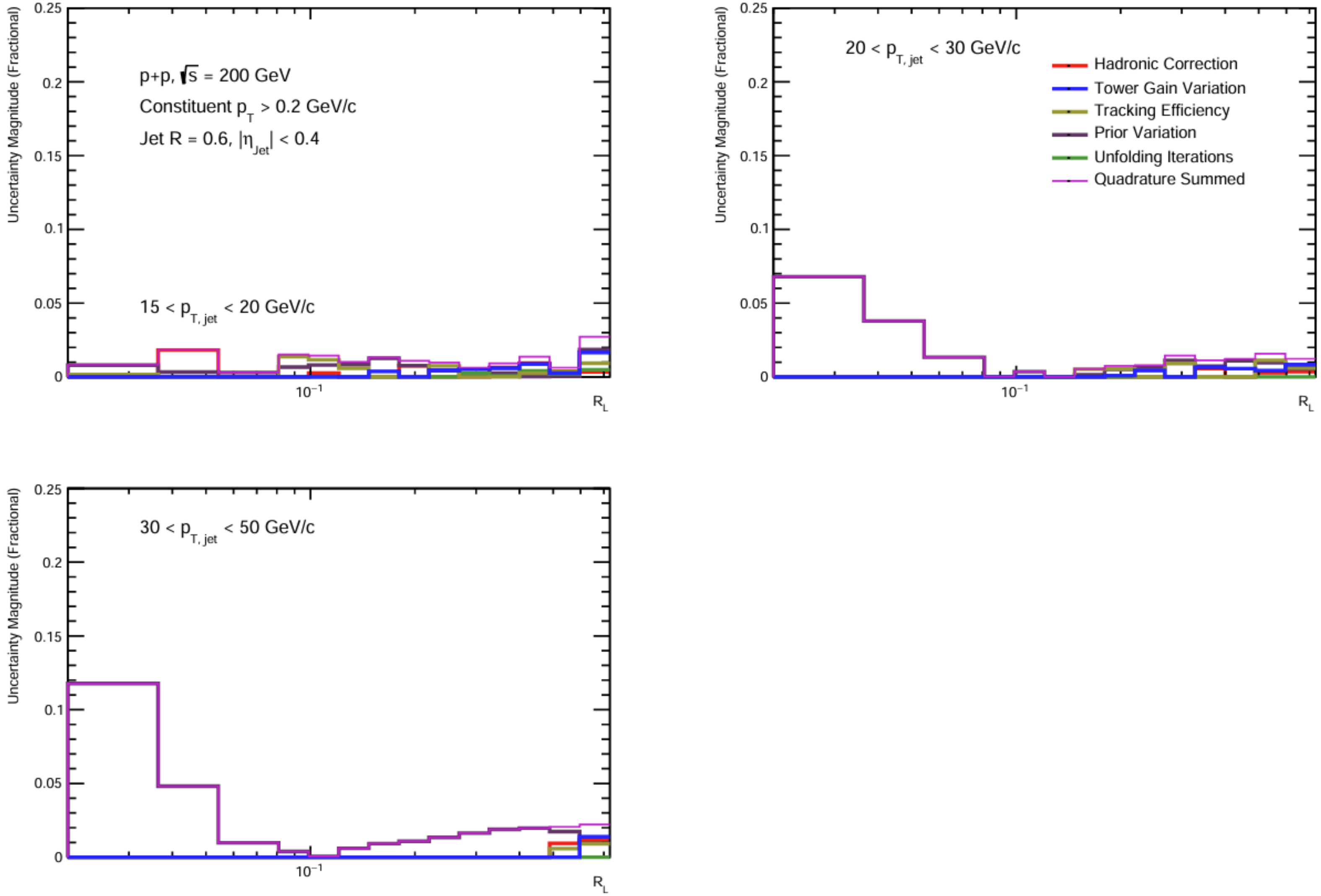






- Presented as absolute value of error rather than fractional as distribution hovers around zero
- Many systematics are brought below Barlow test due to cancellation in ratio
  - Barlow test not performed on prior variation – treated as statistically independent sample

Closure – E3C Charge Ratio



Charged E3Cs

$$\text{Charged E3C} = \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iQ_iE_jQ_jE_jQ_j}{{p_{T,Jet}}^3}\right)}{d\,(R_L)} = \text{E3C} - \text{E3C}$$

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