Supported in part by

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STAR

Imaging the QGP in Ru+Ru and Zr+Zr Collisions using Energy Correlators at STAR

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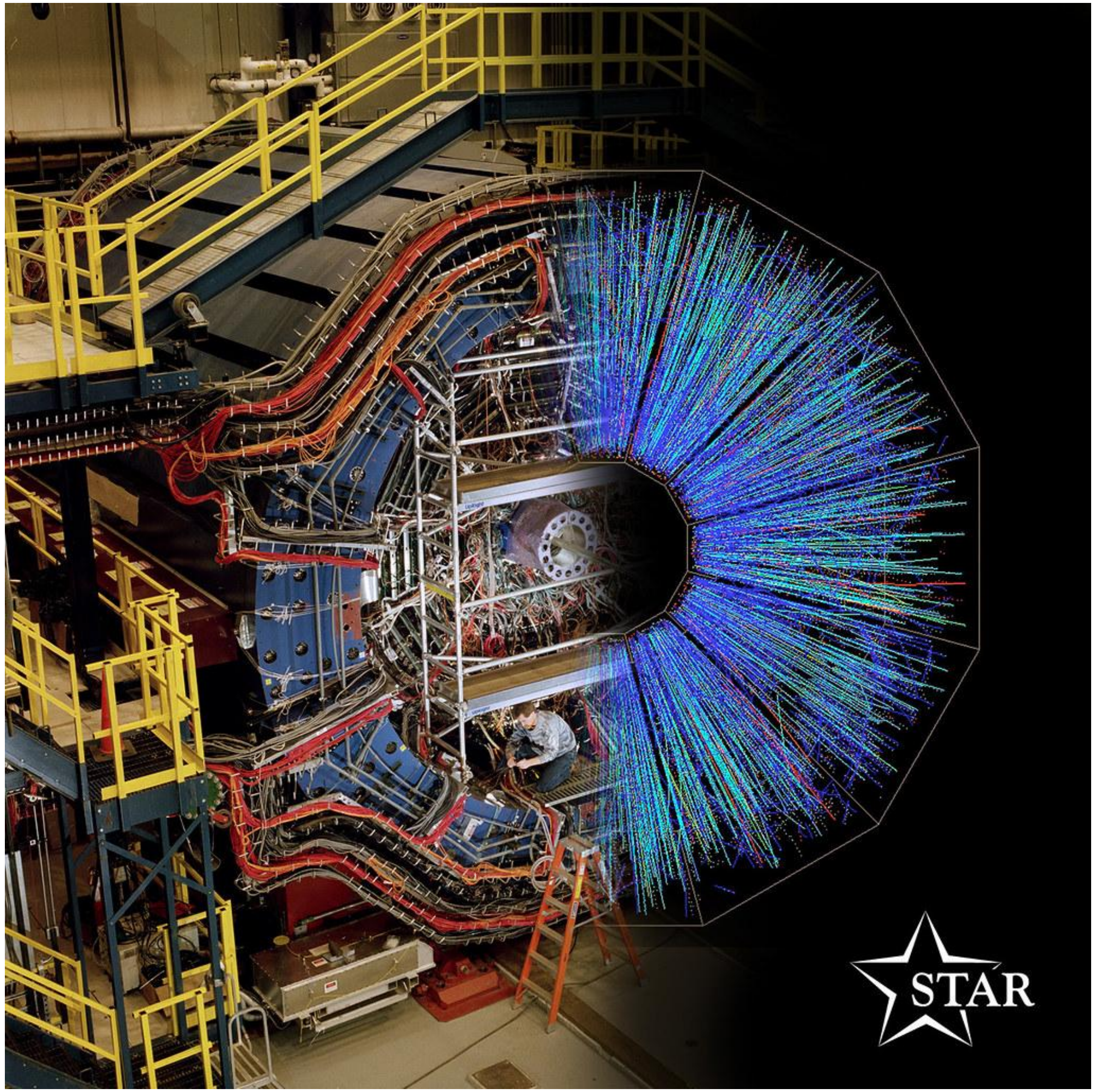
For the STAR Collaboration

Yale Wright Laboratory

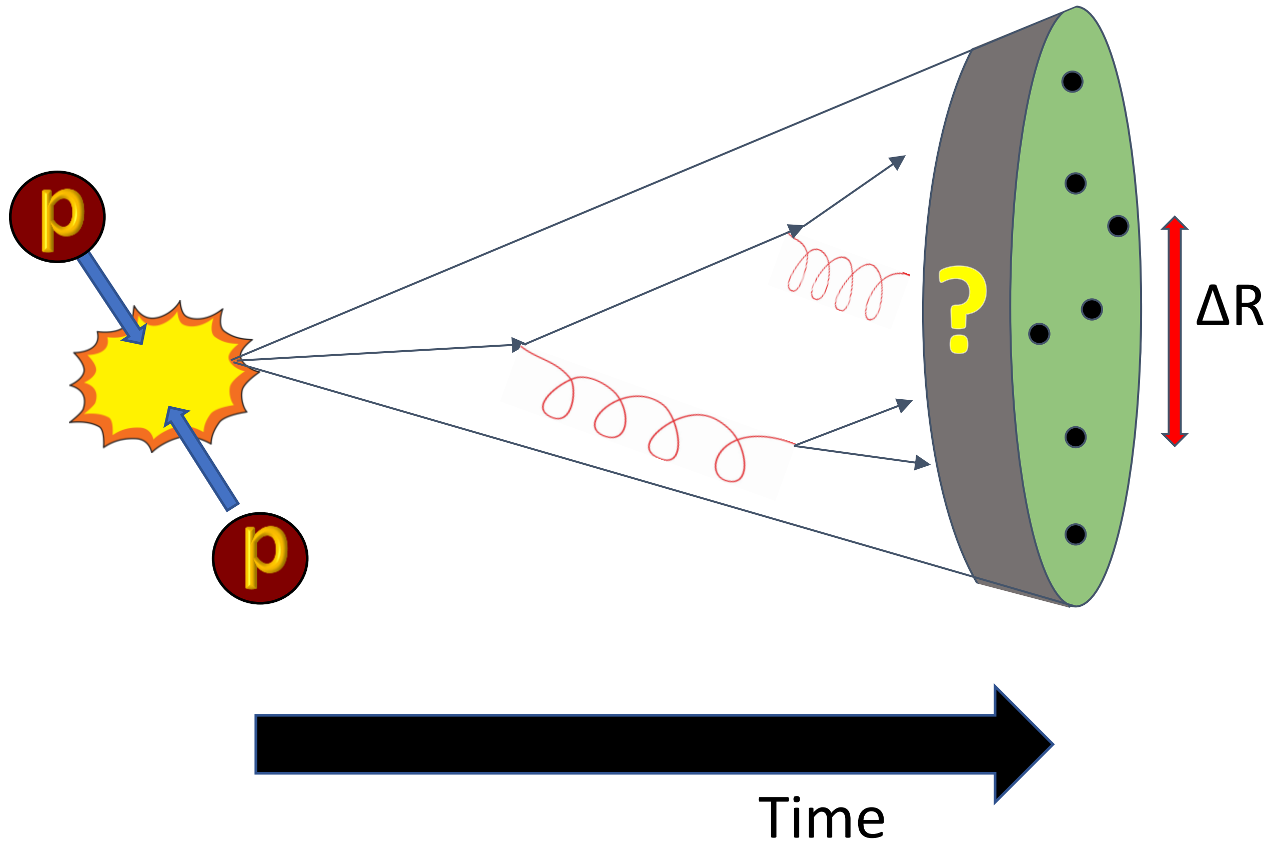
HOT QUARKS 2025
HEFEI, CHINA

Measurement At STAR



- STAR Time Projection Chamber (TPC) provides excellent charged track spatial 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 $|\eta| < 1$
- BEMC used for trigger in order to obtain jet-rich data sample

Jets and Hadronization

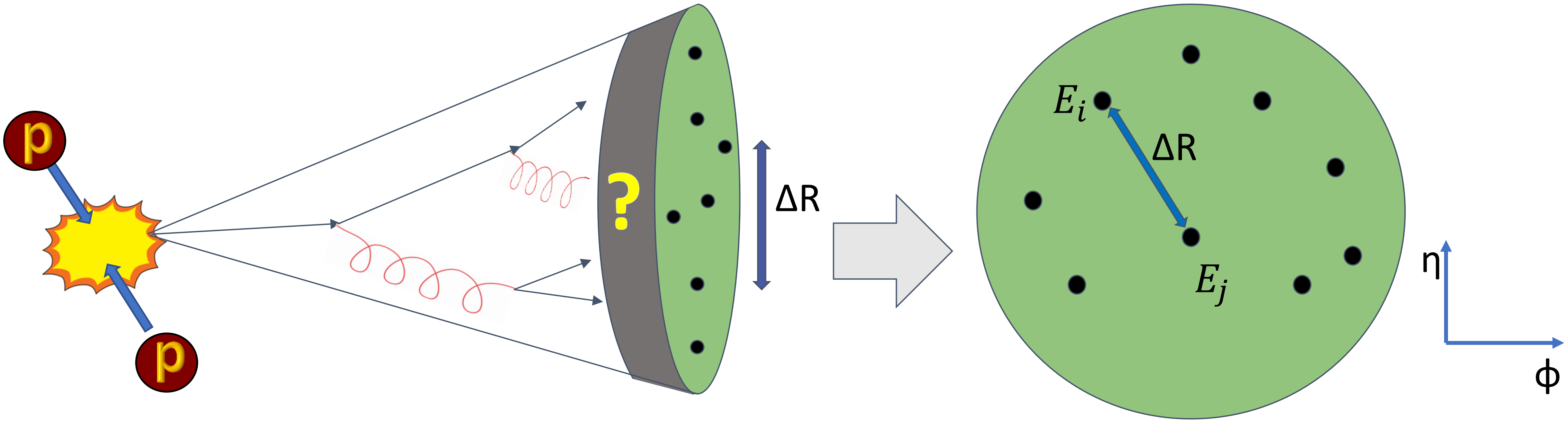


- **Jets are proxies for hard-scattered partons**
- Clustered from final state particles using a jet finding algorithm
- Testing energy evolution of parton shower in time.

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

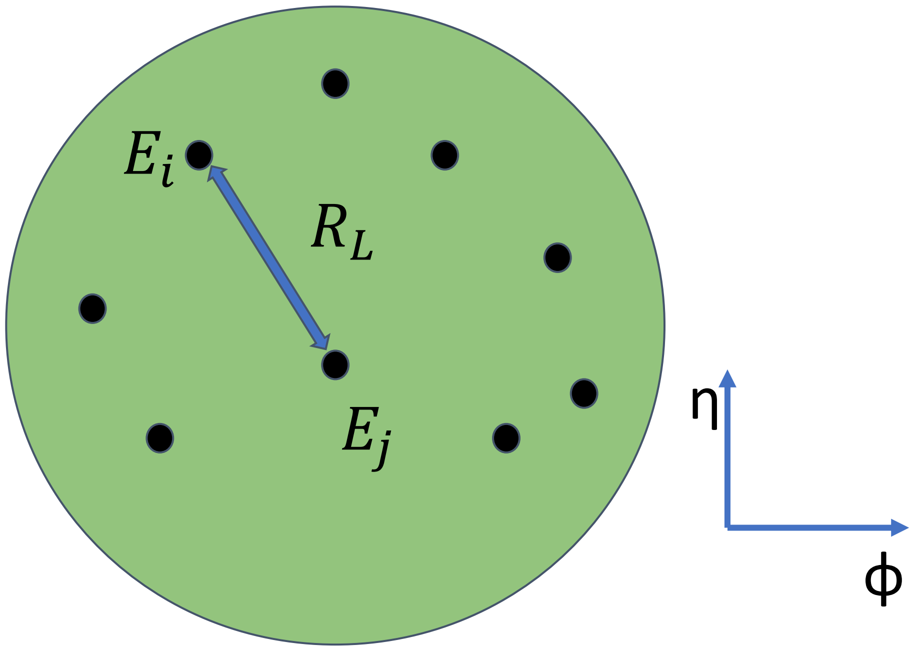
Projected N-Point Energy Correlators (ENC)

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

Note: Energy assumes pion mass

Experimental Construction of Two-Point Correlator

Two-Point

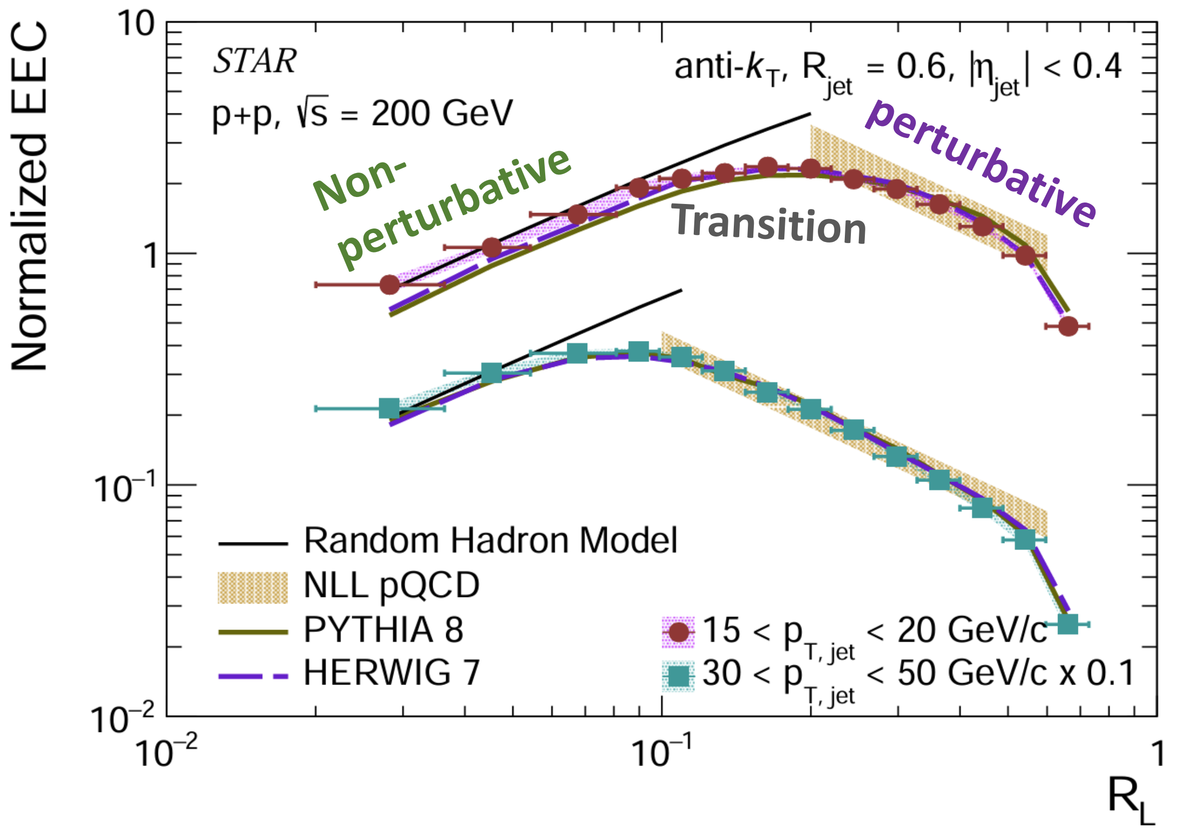


- **Allows for study of jet evolution using final state jet constituents as they are**, no additional clustering or grooming after jet-finding
- Ratios of ENCs (i.e. E3C/EEC) allows for isolation of perturbative effects

p+p Measurement

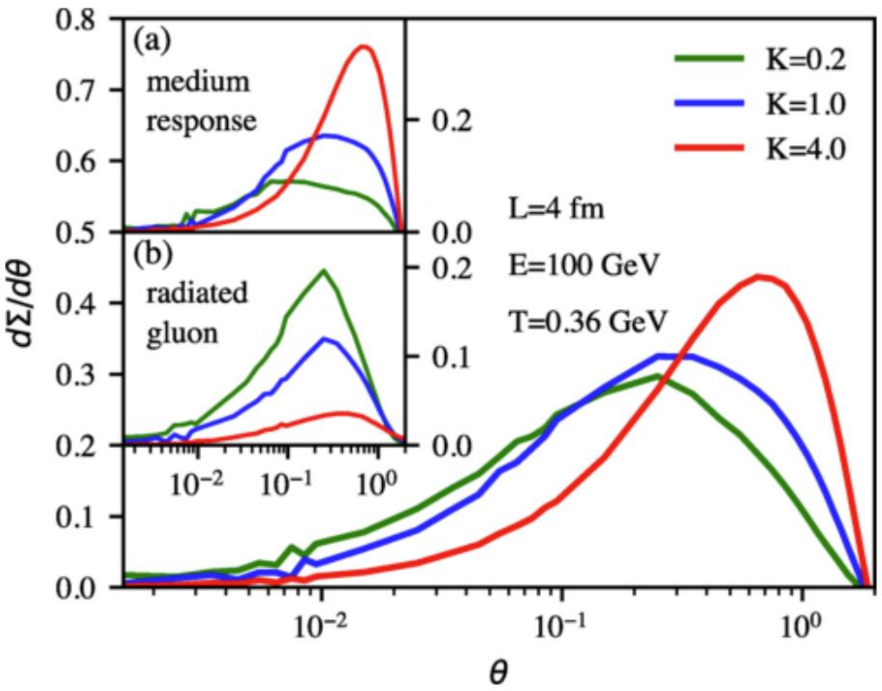
- Separates distribution into non-perturbative and perturbative regimes, separated by a transition region
- **Behavior agrees well with theoretical expectations in perturbative regime!**
- EECs are well understood in vacuum

[ArXiv: 2502.15925](https://arxiv.org/abs/2502.15925)

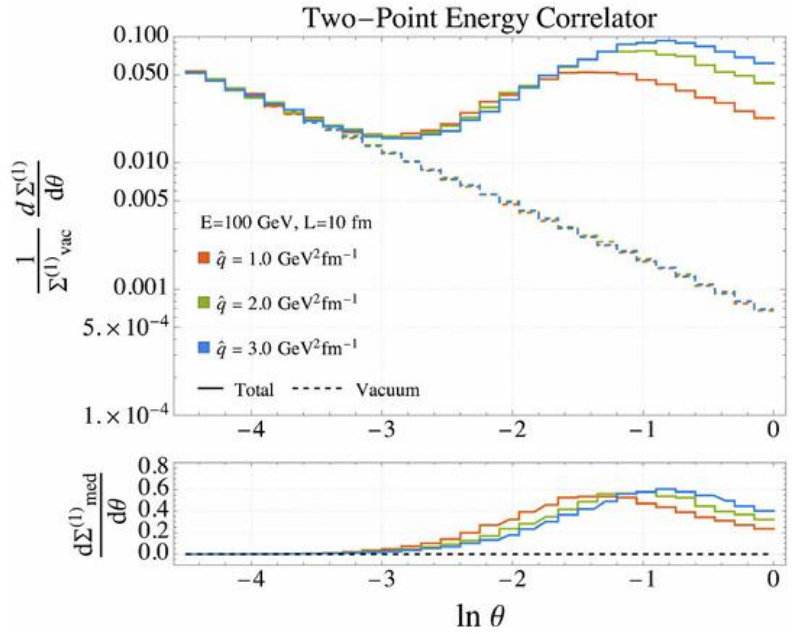


EECs in Heavy Ion

- Energy Correlators can help discriminate both **when** and **how** jets are modified in medium
- Measured by CMS and ALICE
- Probes (Disentangles?) many effects
- Decorrelation Angle
- Jet Wake
- Narrowing



PRL. **132**, 011901 (2024) Yang et al.

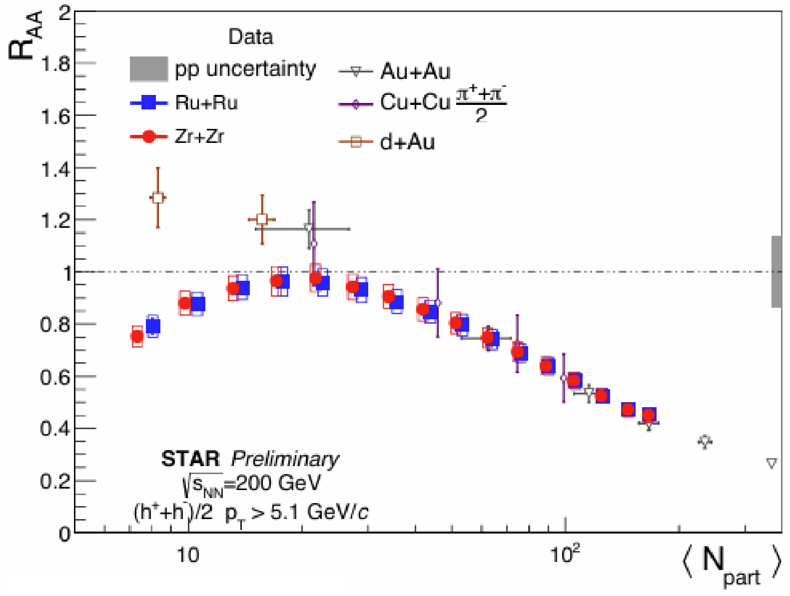


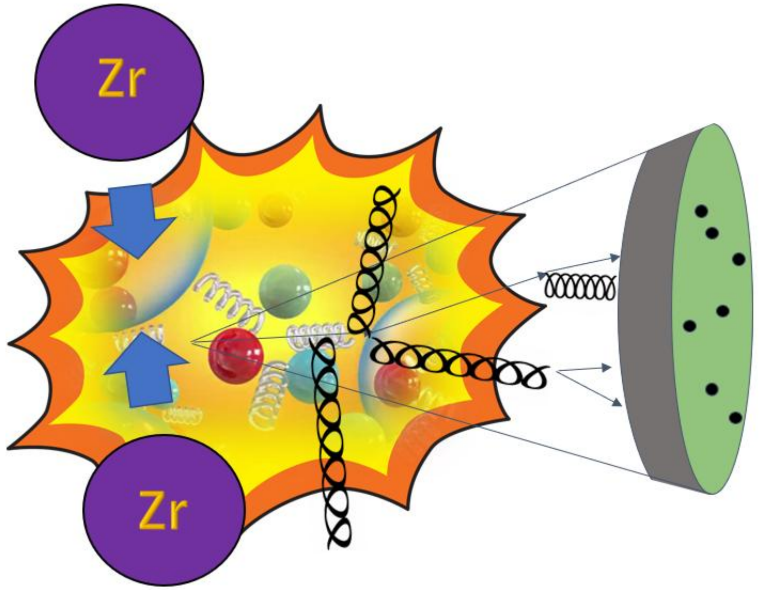
PRL. **130**, 262301 (2023) Andres et al.

Dataset

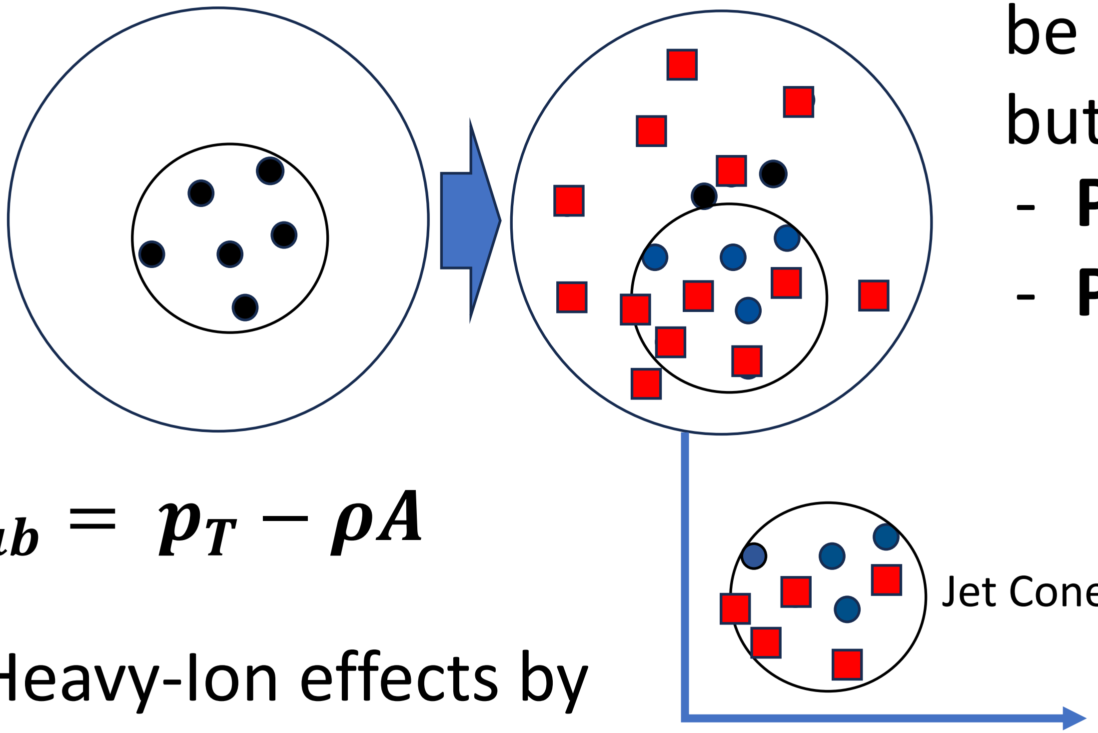
- Ru+Ru/Zr+Zr
  - Collected by STAR in 2018 at $\sqrt{s}$ = 200 GeV
  - Medum-sized system (A=96)
  - Central collisions have been shown to see significant jet suppression
  - Select jet-rich events with high-tower trigger (deposit > 3.4 GeV/c)
  - Find jets with R = 0.4 using the anti-k_T algorithm

- Pseudo-Embedding
  - PYTHIA8: Detroit Tune events with $\hat{p}_{\mathrm{T}}$ > 5 GeV/c
  - Embedded in minimum-bias Ru+Ru data
  - Require each jet to have neutral particle > 3.4 GeV/c





Finding Jets in A+A Data

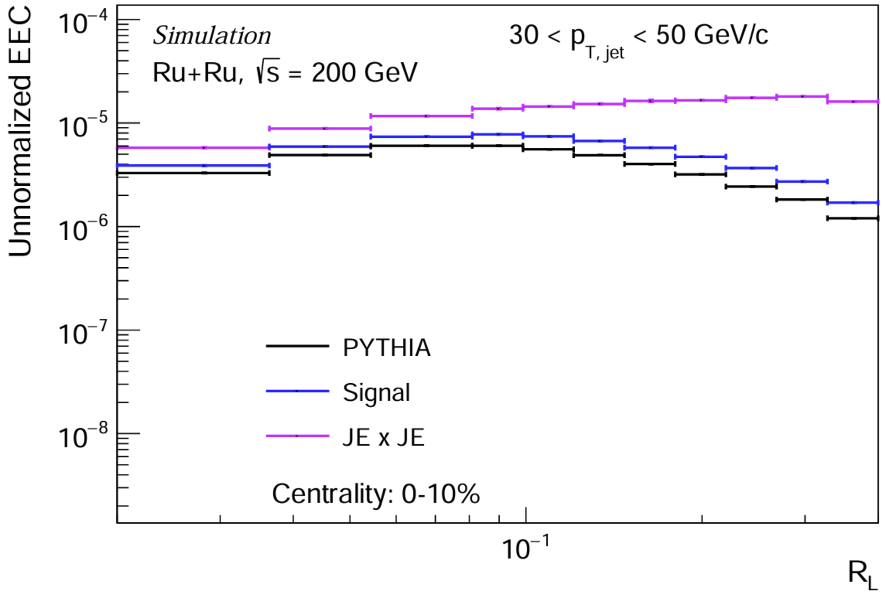


Problem 1: Background pedestal needs to be subtracted

but subtracted signal ≠ PYTHIA

- **Problem 2:** Momentum is smeared
- **Problem 3:** Jet axis is shifted

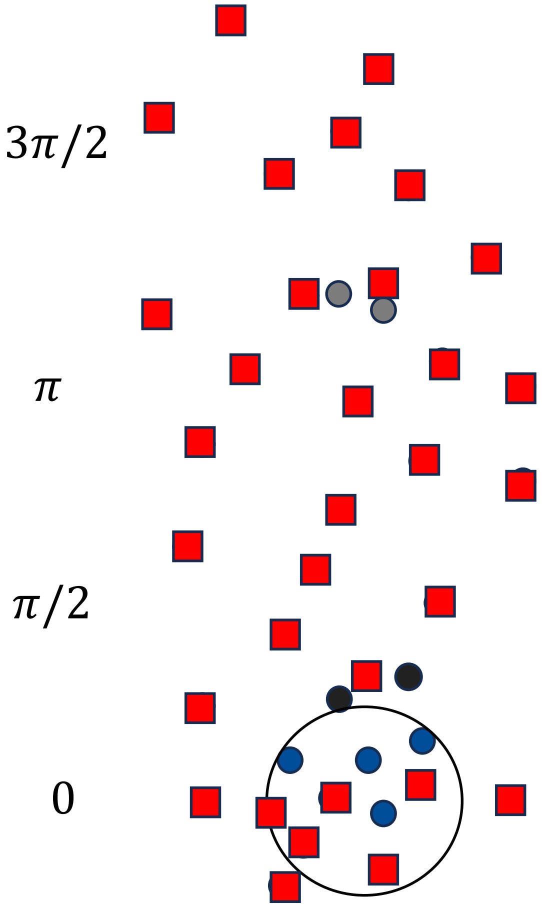
$$p_{T,sub} = p_T - \rho A$$



Study Heavy-Ion effects by embedding PYTHIA particles into minimum-bias Ru+Ru data

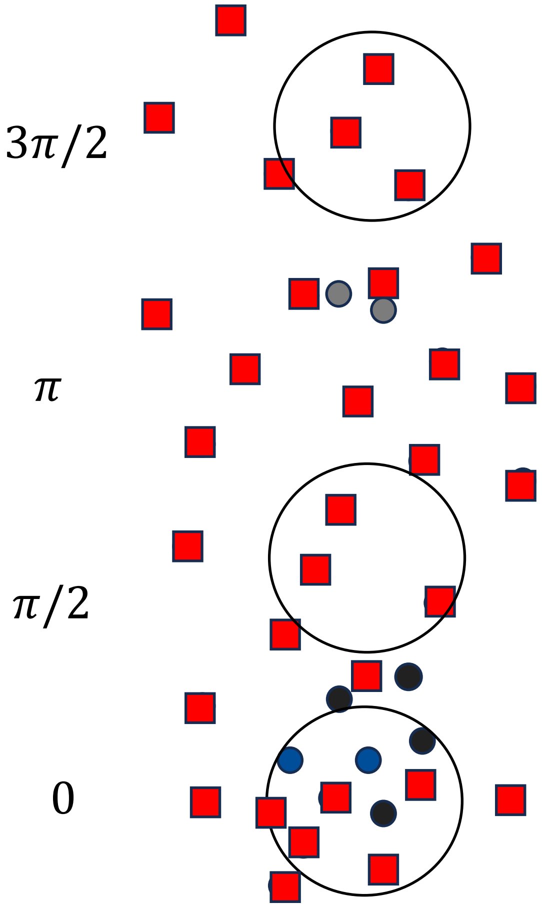
- Toy Model

Subtraction Method



Identify jet as it would be found in data

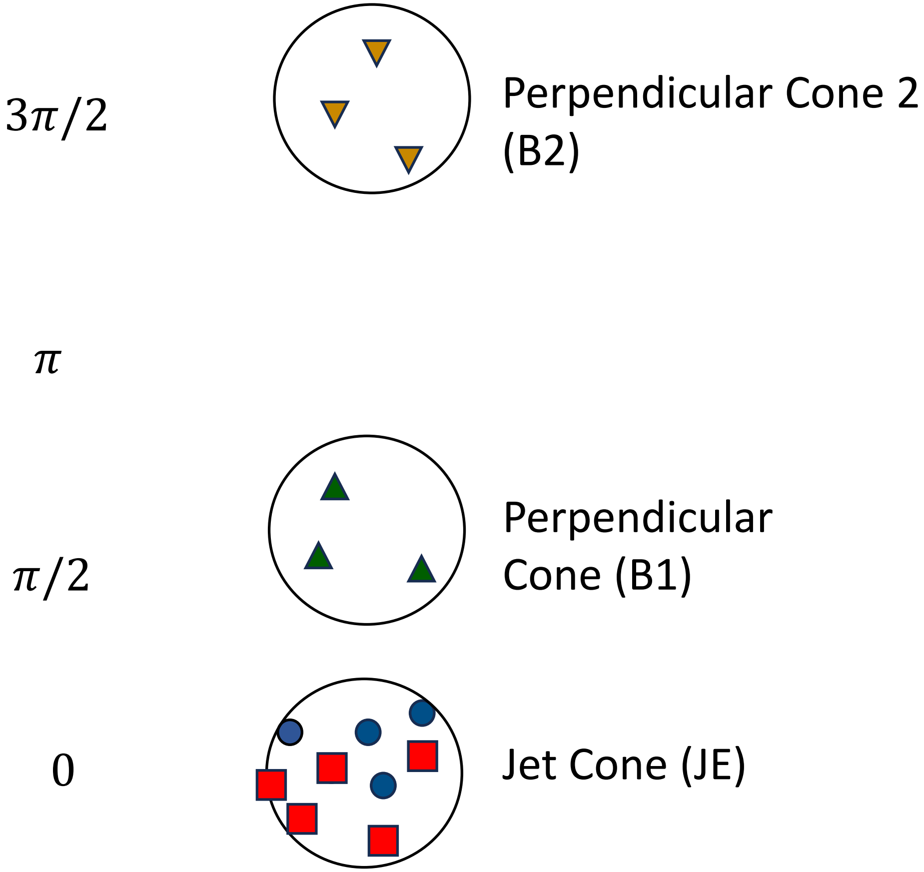
Subtraction Method



Identify jet as it would be found in data

Grab two perpendicular cones to inform background in event

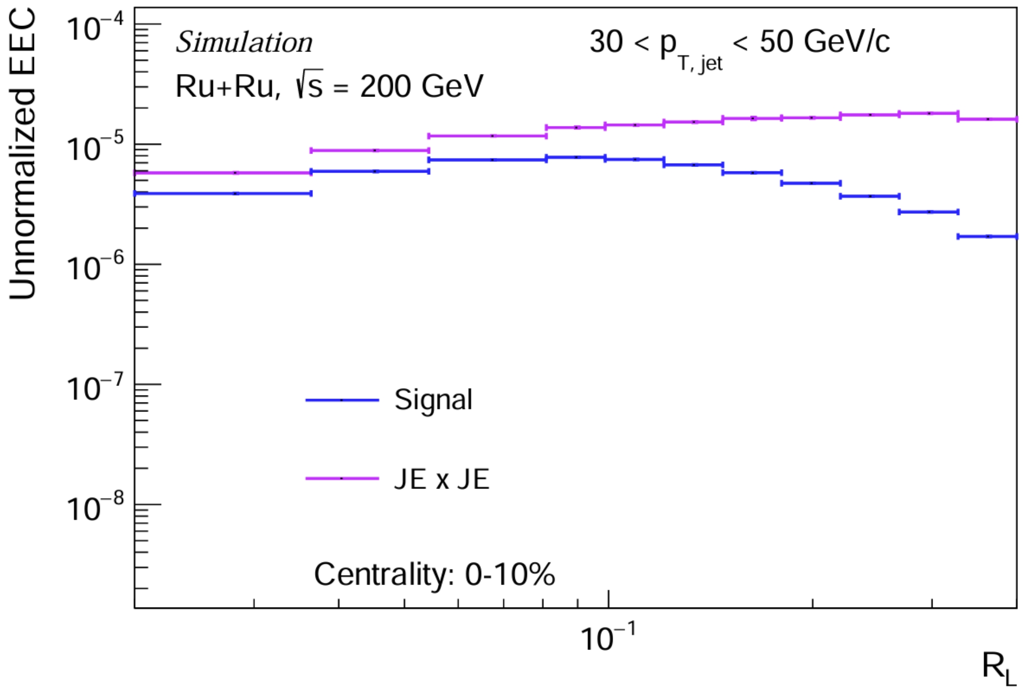
Subtraction Method

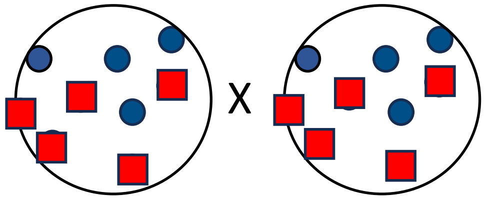


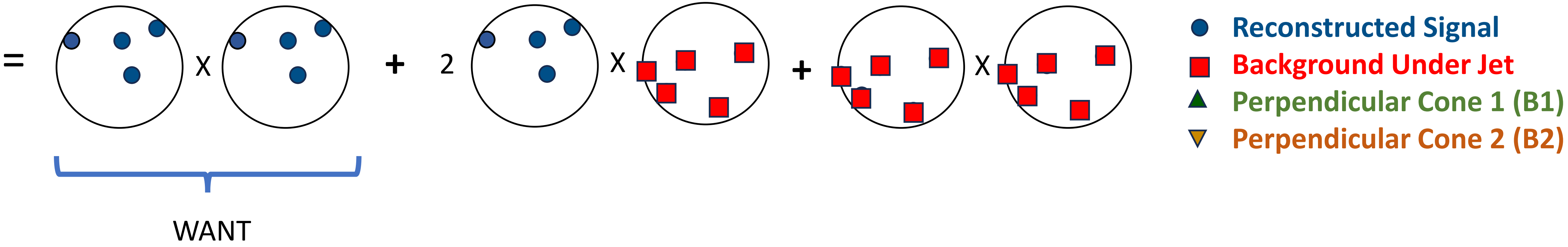
Information that is available to us in data

- **Reconstructed Signal**
- **Background Under Jet**
- **Perpendicular Cone 1 (B1)**
- **Perpendicular Cone 2 (B2)**

Subtraction Method





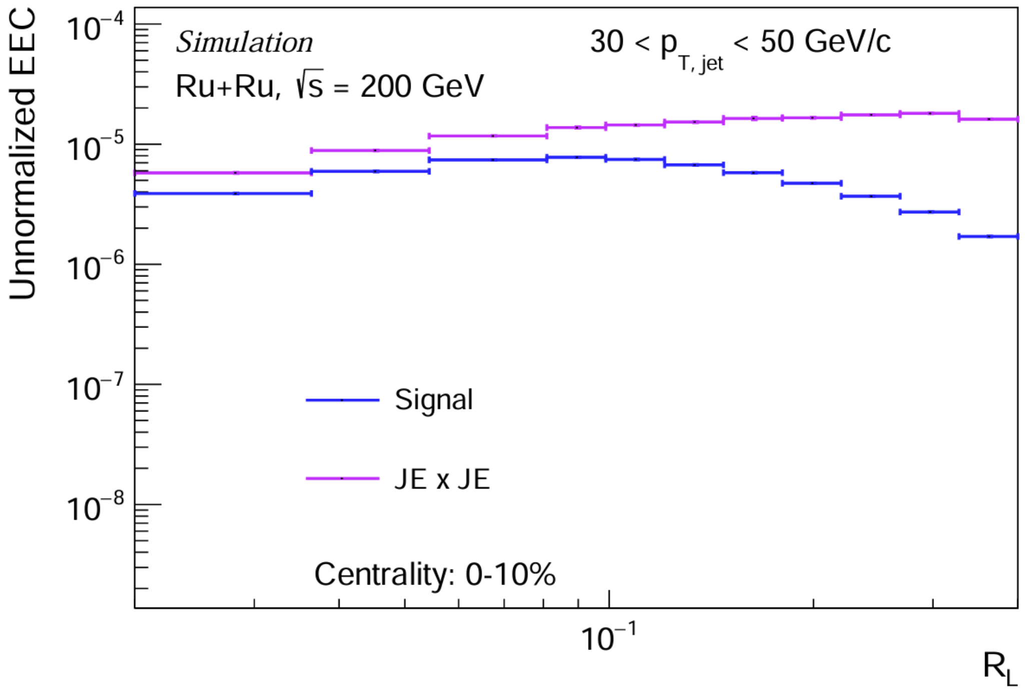


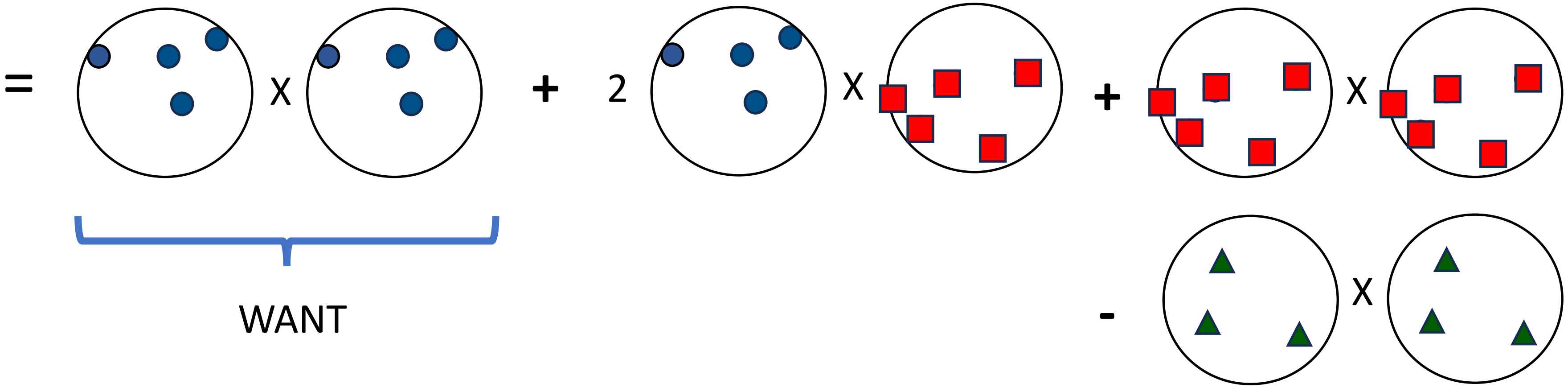
Start taking correlations in jet cone, as we would find it in data

- Can deconstruct into several components

Subtraction Method

- Cancel out pure background contribution using perpendicular cone



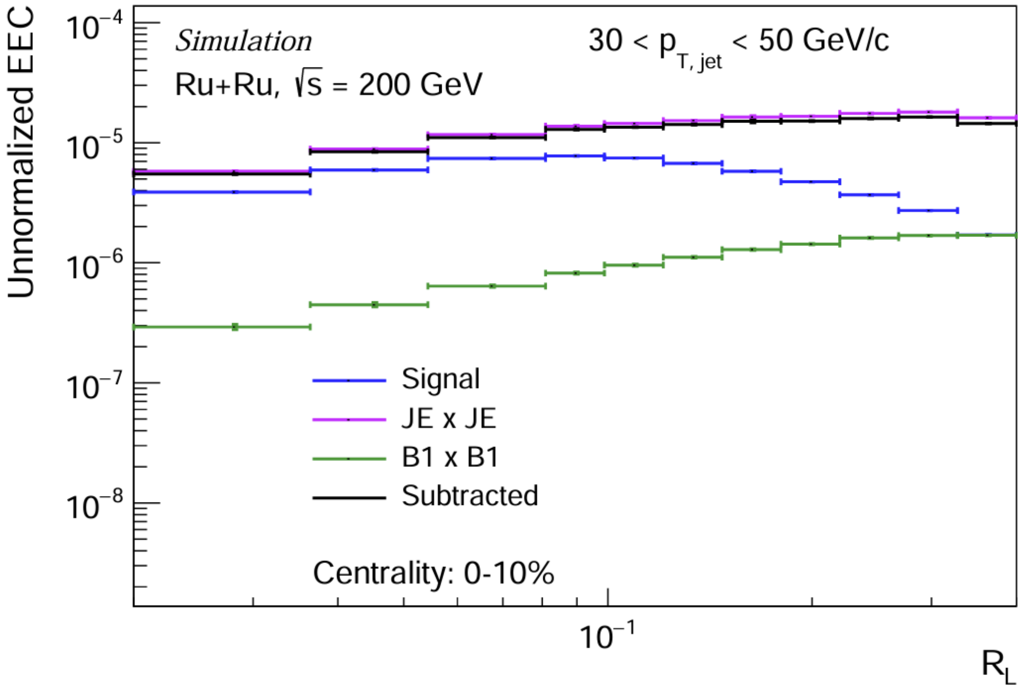


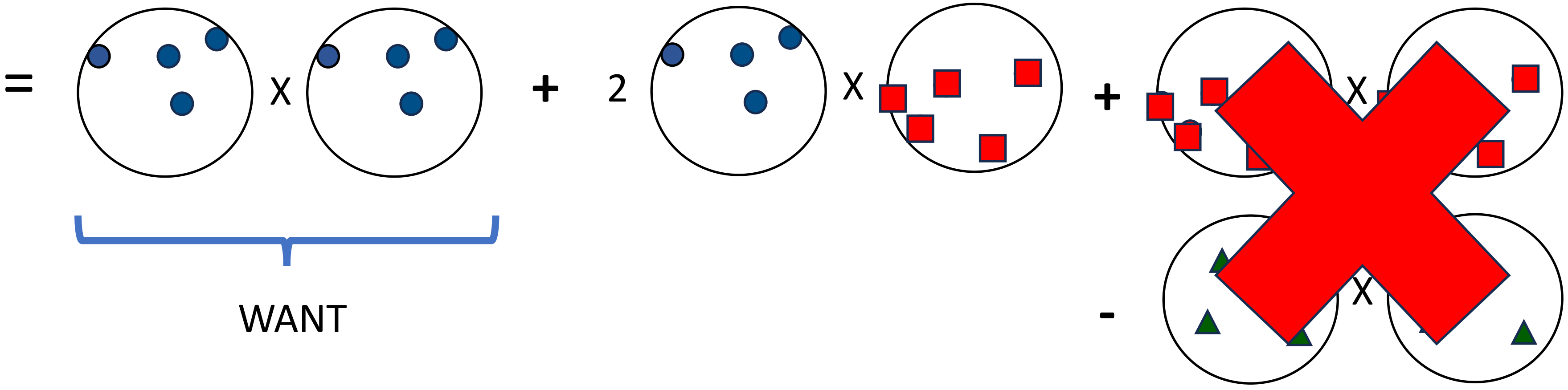
- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Background Under jet is larger than our perpendicular cone
- **Problem 1A**

Subtraction Method

- Cancel out pure background contribution using perpendicular cone



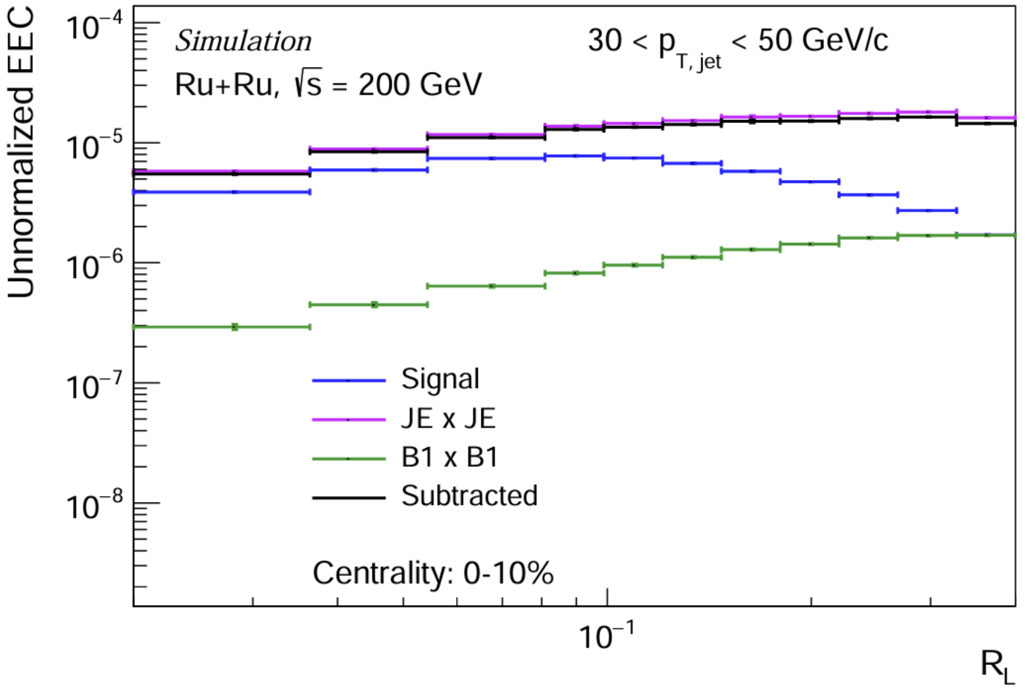


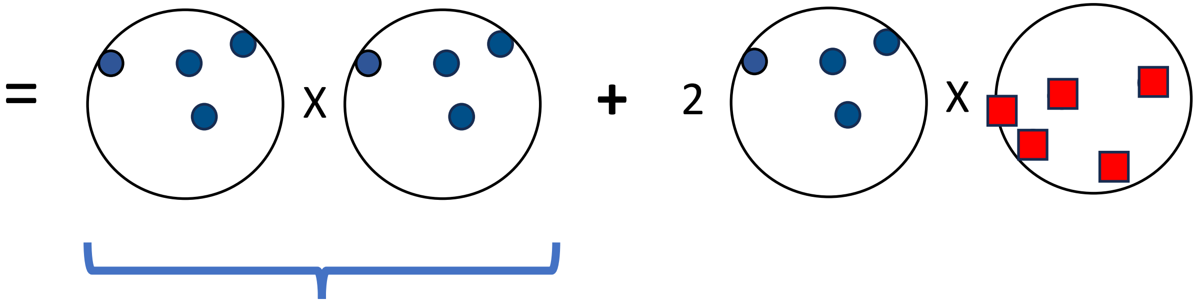
- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Assume (for now) ▲ ~ ■

Subtraction Method

- Cancel out pure background contribution using perpendicular cone

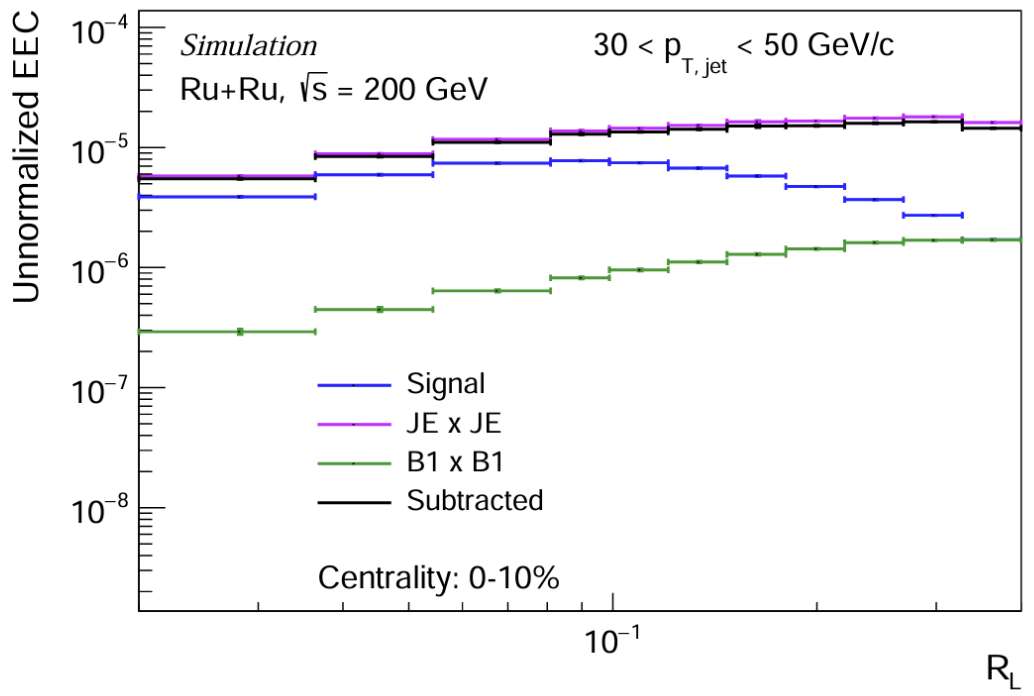


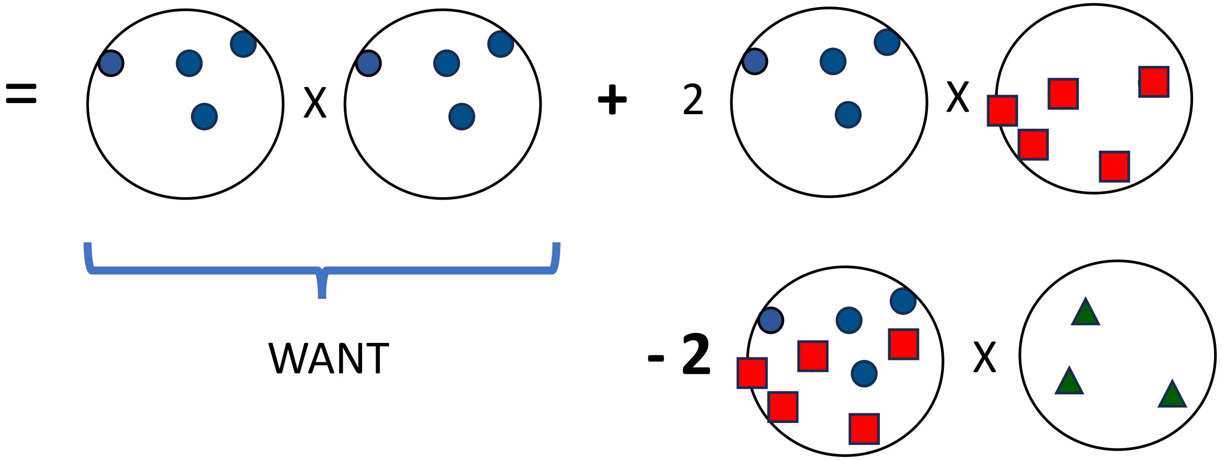


Reconstructed Signal
Background Under Jet
Perpendicular Cone 1 (B1)
Perpendicular Cone 2 (B2)

Subtraction Method

Subtract Signal-Background correlations using jet and perpendicular cone

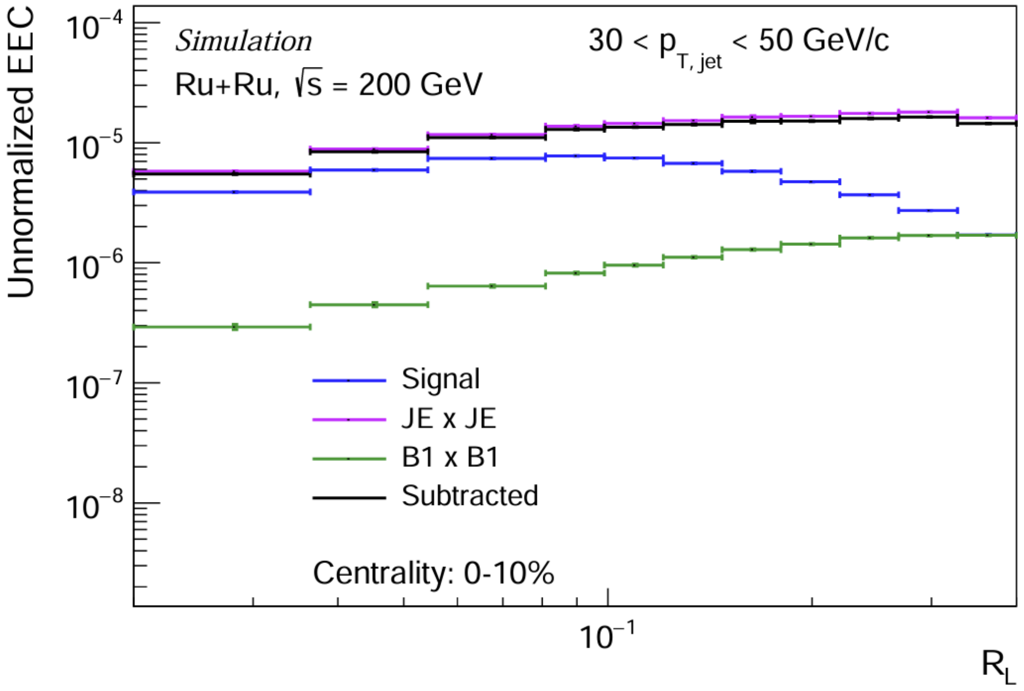


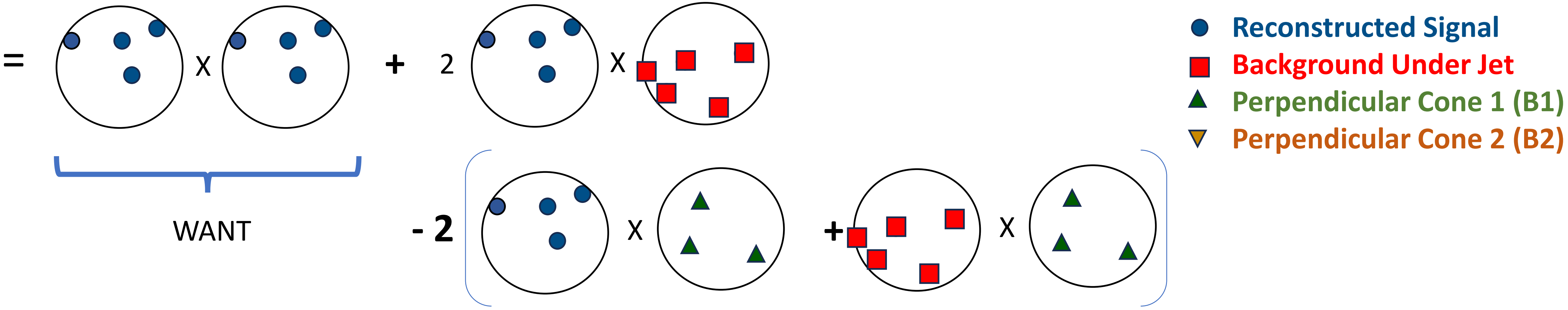


- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Subtraction Method

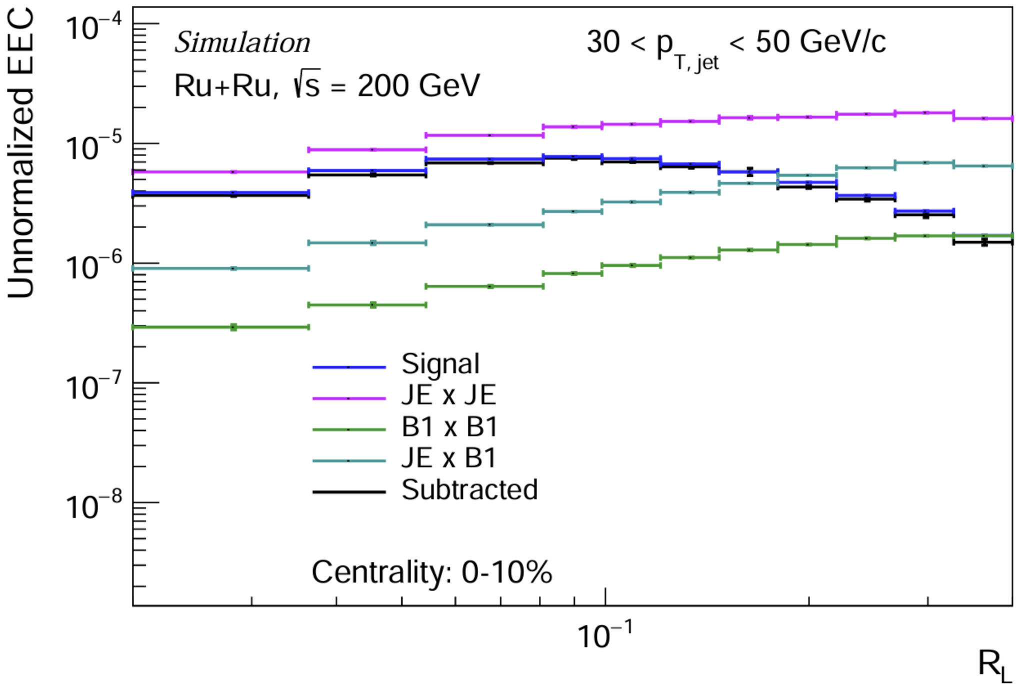
Subtract Signal-Background correlations using jet and perpendicular cone

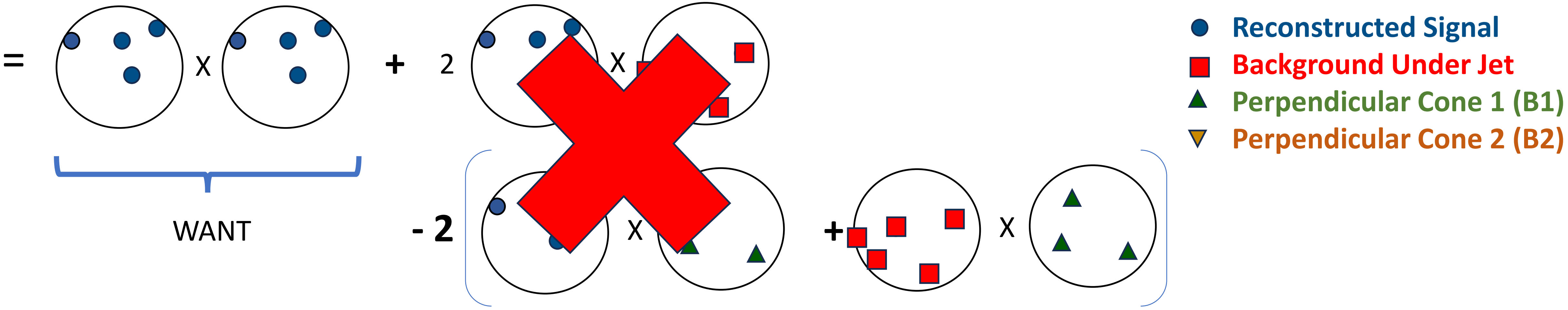




Subtraction Method

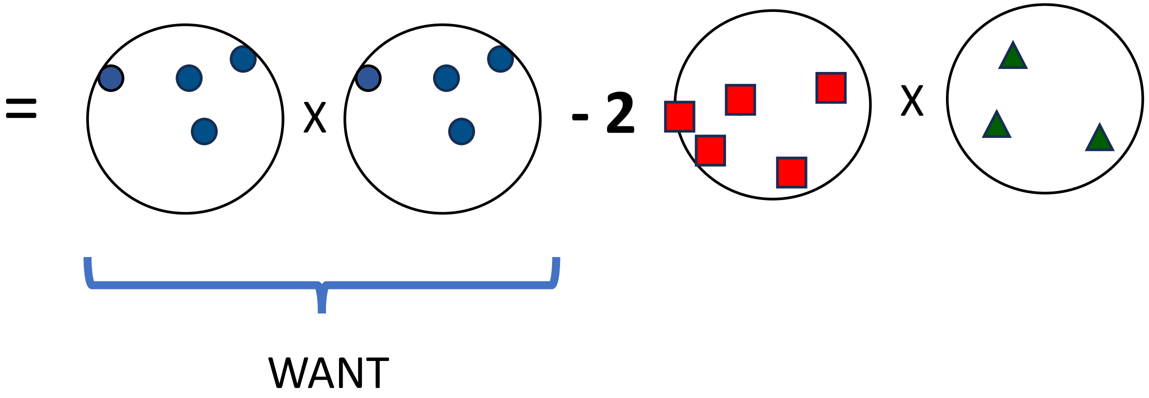
Subtract Signal-Background correlations using jet and perpendicular cone

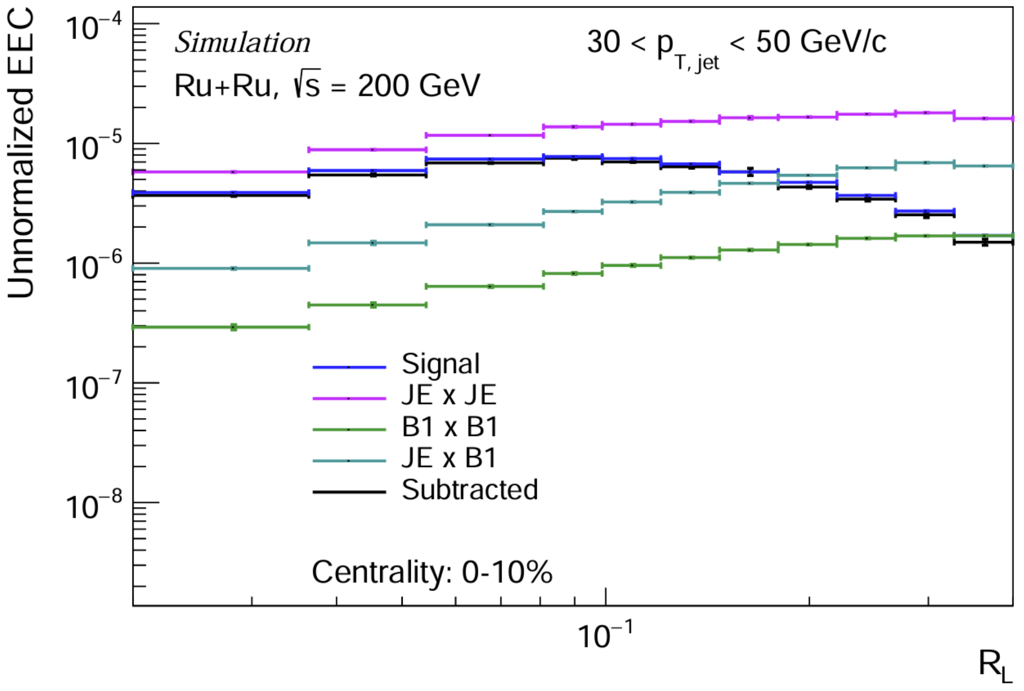




Subtraction Method

Now we have over-subtracted an uncorrelated background-background term

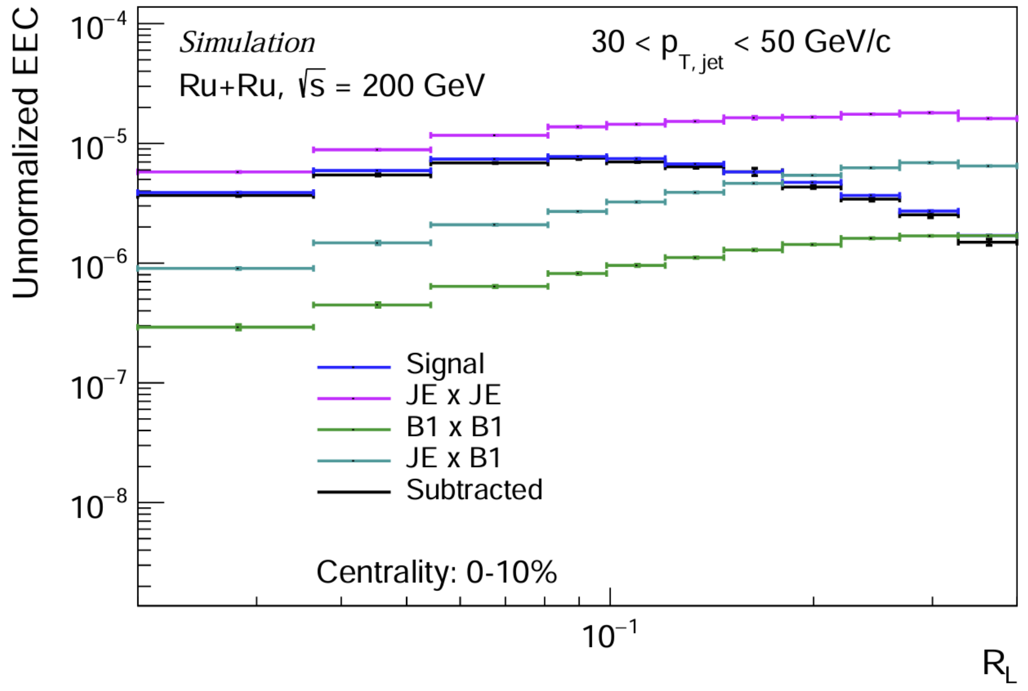


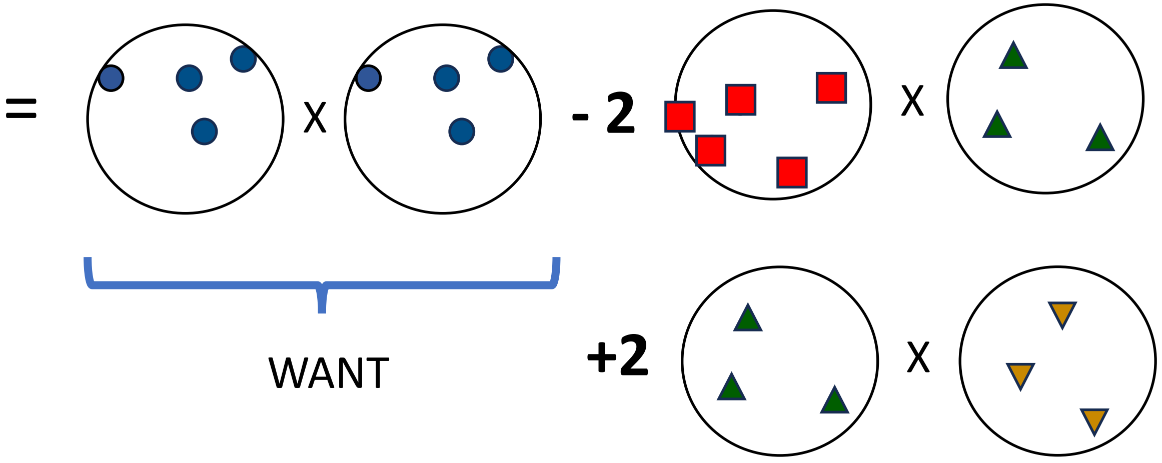


- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Subtraction Method

Remove it using two uncorrelated perpendicular cones





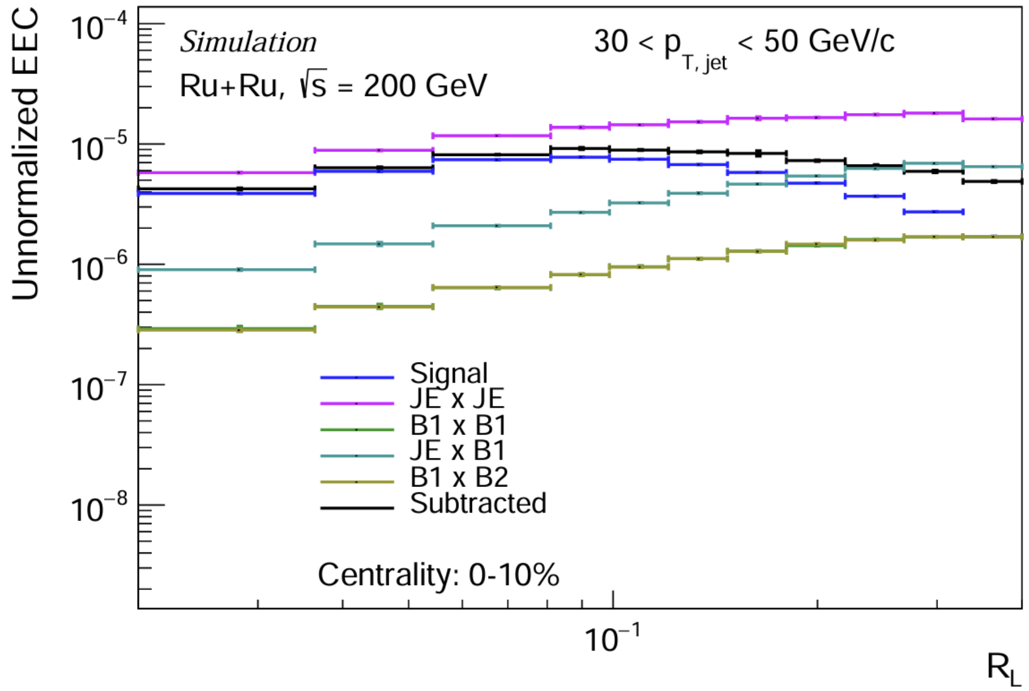
Reconstructed Signal

Background Under Jet

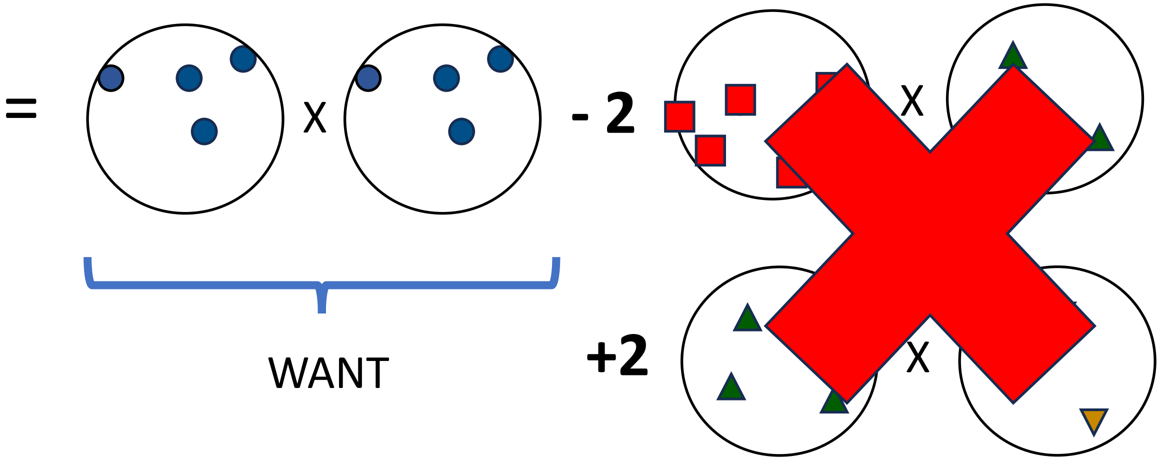
Perpendicular Cone 1 (B1)

Perpendicular Cone 2 (B2)

Subtraction Method



Remove it using two uncorrelated perpendicular cones

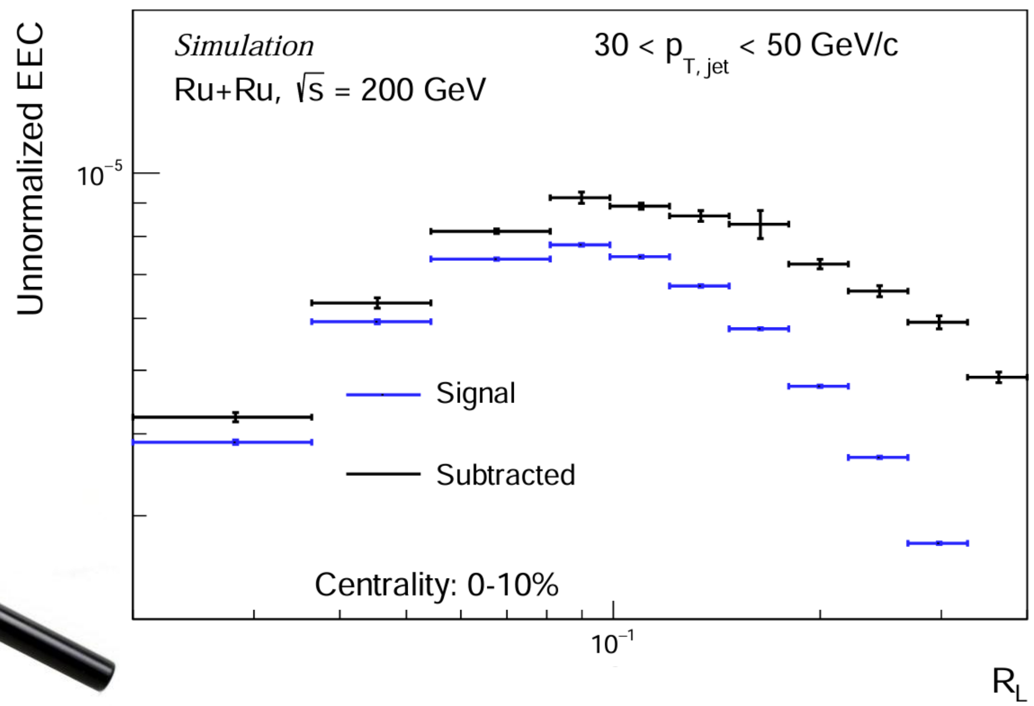


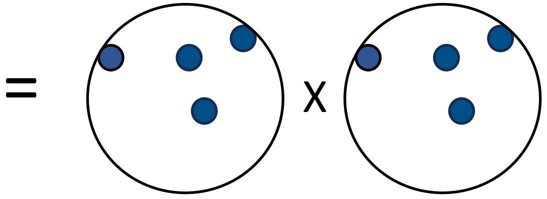
- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Cancels uncorrelated background

Subtraction Method

But it doesn't look right…

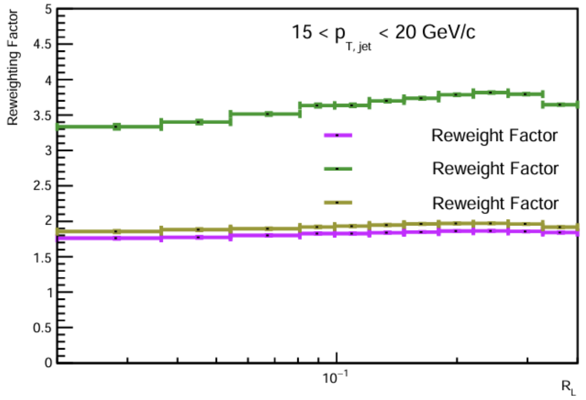


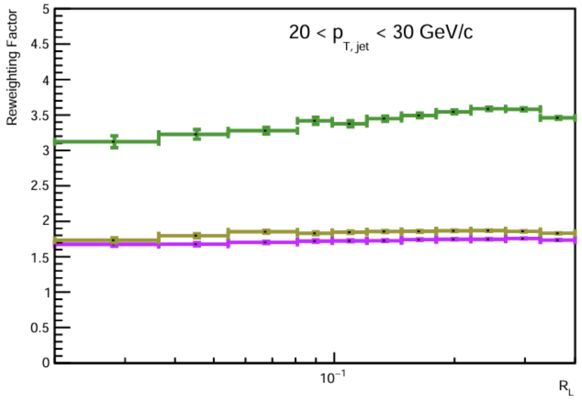


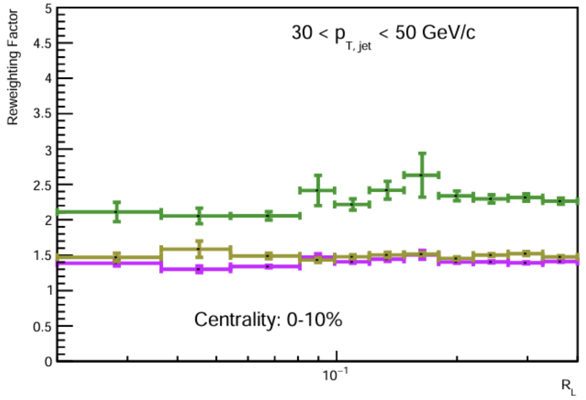
- Reconstructed Signal
- Background Under Jet
- Perpendicular Cone 1 (B1)
- Perpendicular Cone 2 (B2)

Problem 1A - Background Under Jets Correction

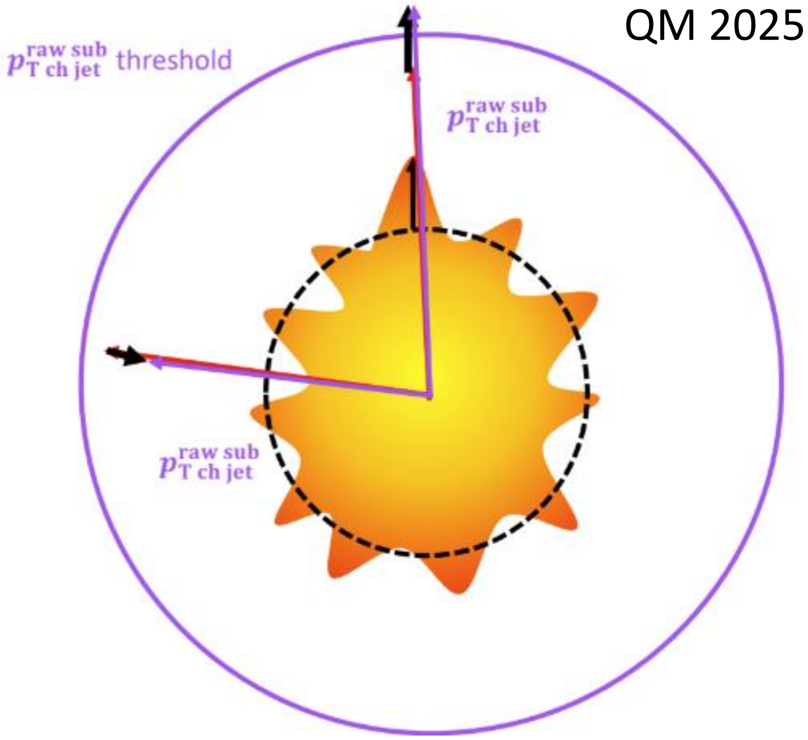
- Jets have a preference for sitting on upward fluctuations, which needs to be corrected for.
- Take ratio of background found under jets in embedding over random cones
- Reweight EACH of: JE x B1, B1 x B2, and B1 x B1 individually, and use for subtraction







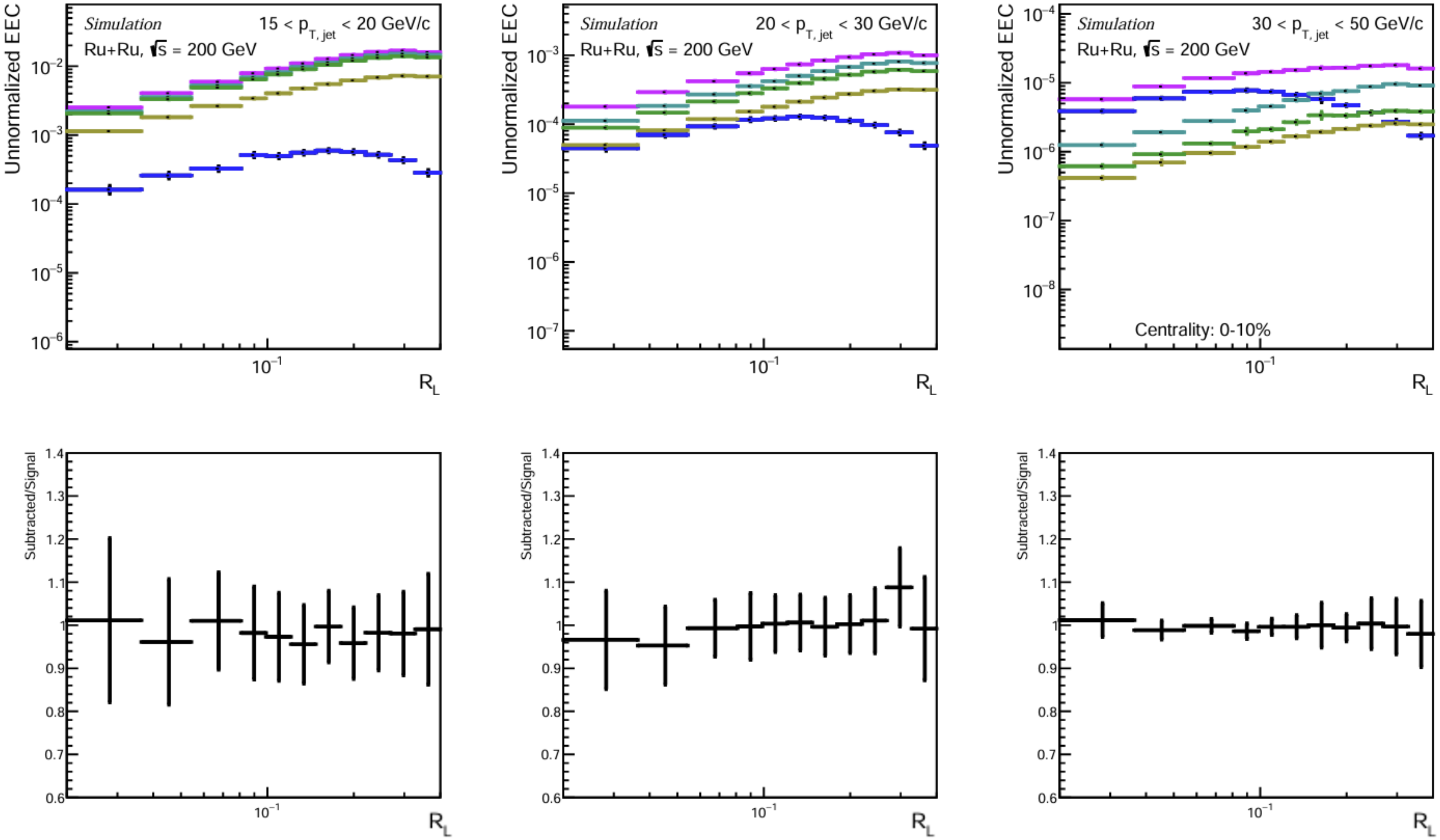
Sierra Cantway, QM 2025



Final Background Subtraction

- After Reweighting via split sample, closes well!

- Problem 1



Signal

JE x JE

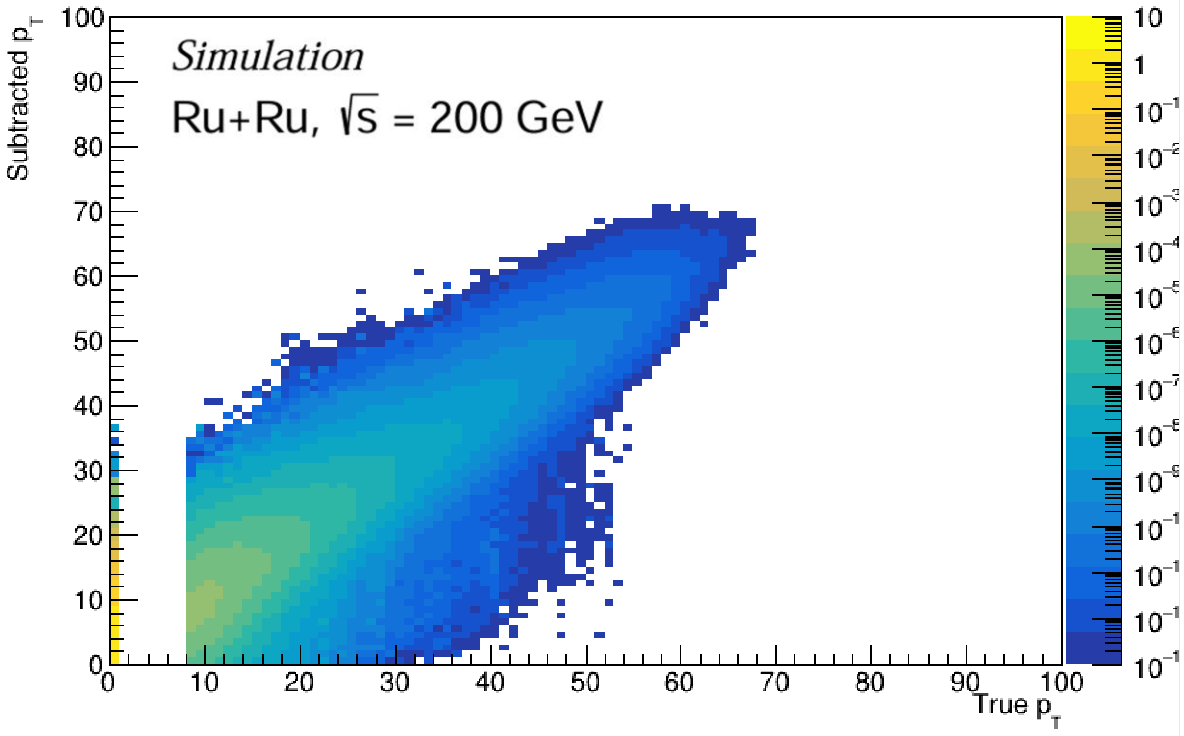
B1 x B1 (Reweighted)

JE x B1 (Reweighted

B1 x B2 (Reweighted)

Subtracted

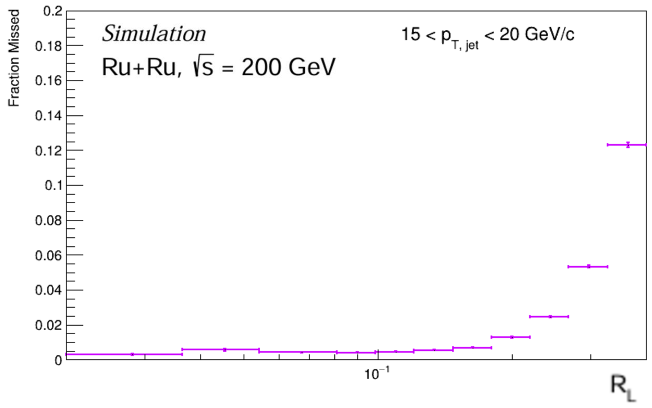
Problem 2 - p_T Correction

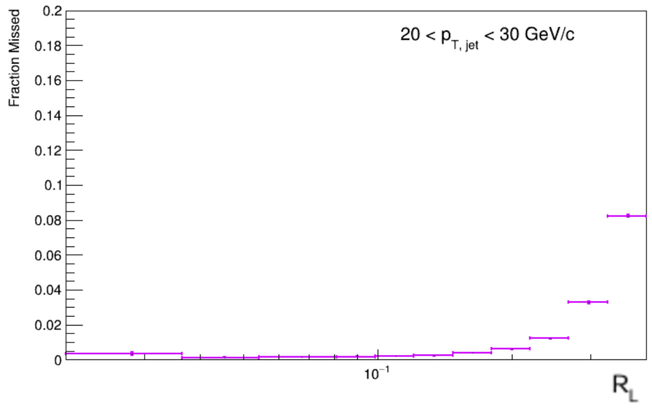


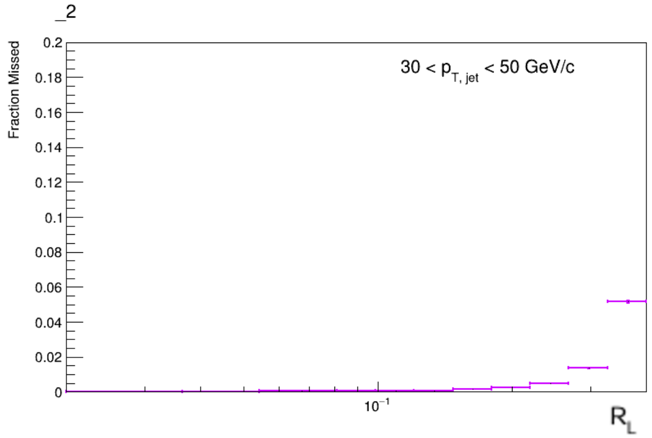
- Area subtraction is an average, some jets will be over-subtracted, some under-subtracted
- Create a response matrix informed by pseudo-embedding to map from subtracted momentum to true momentum
- Problem 2 ✓

Problem 3 -Correction for Jet Axis Drift

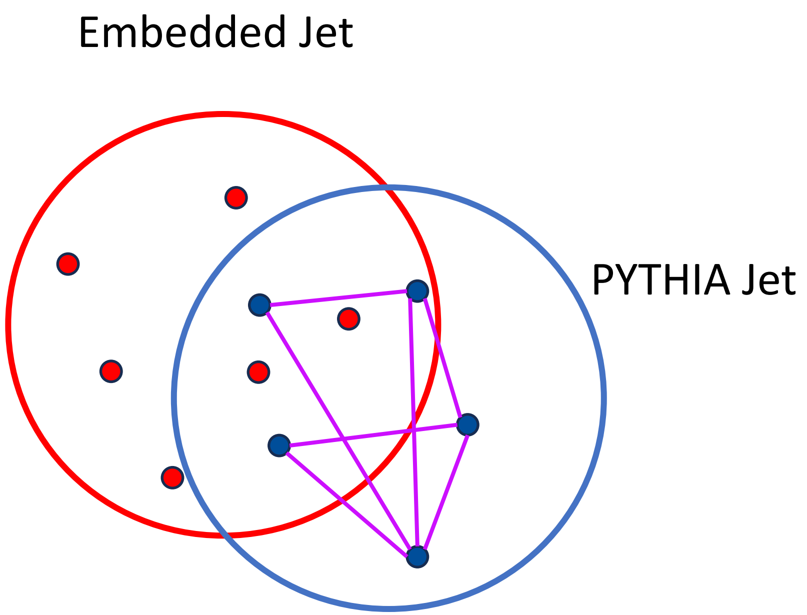
- Fill in Correlations missed due to axis drift in response matrix
- Problem 3 ✓



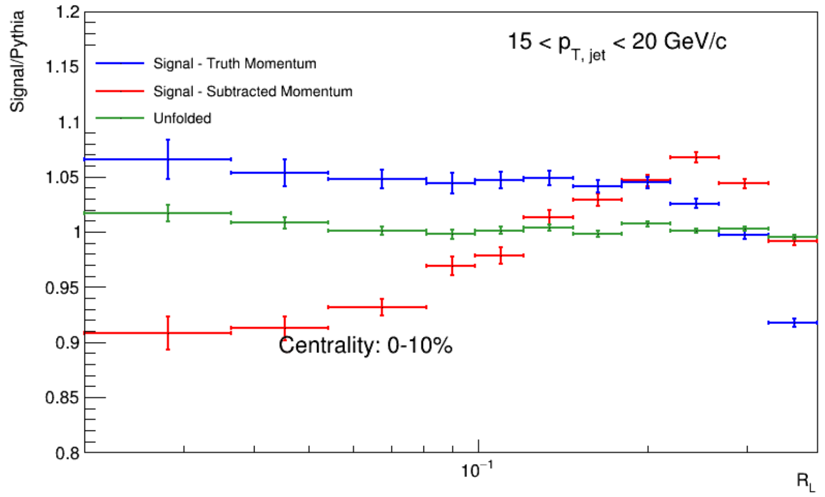


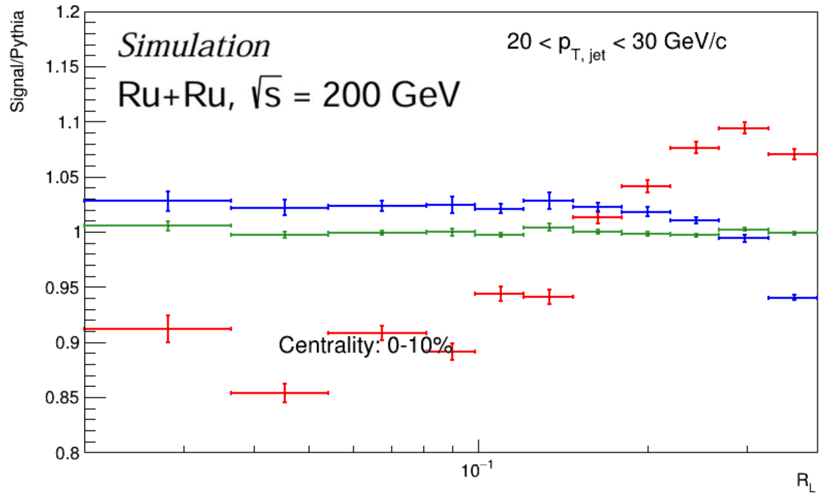


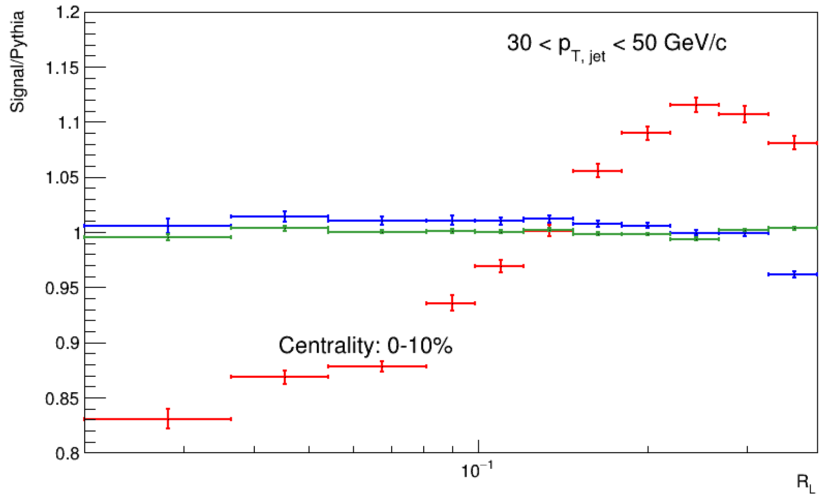
Fraction of EEC missed as a function of R_L



Momentum Unfolding Performance





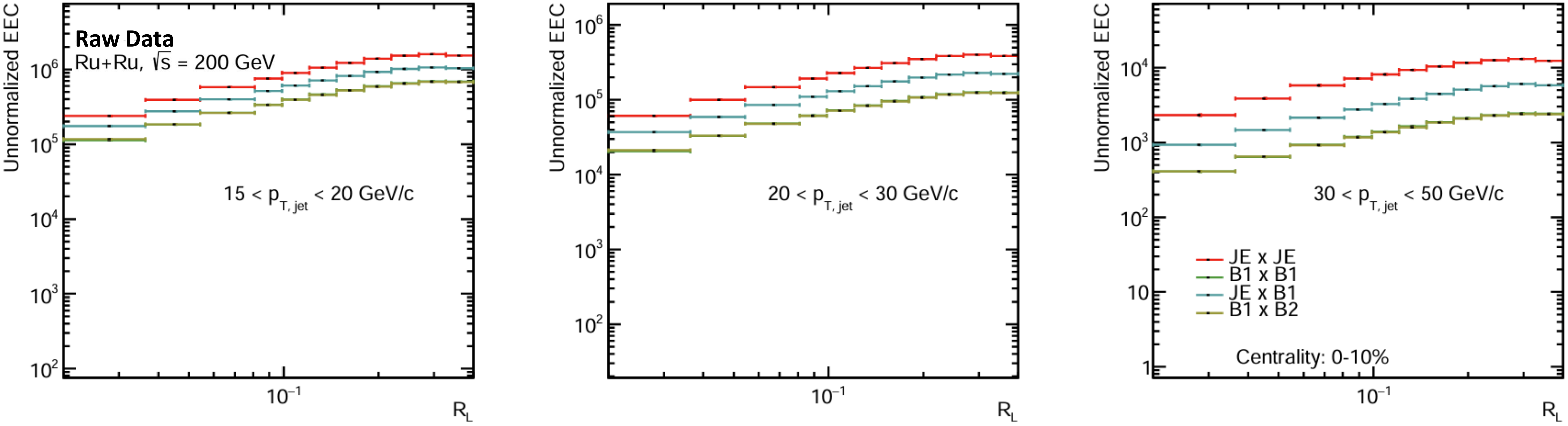


Ratio over particle-level PYTHIA:

- Problem 1 Solved: **reconstructed signal**
- Problem 2 Solved: **correct jet momentum**
- Problem 3 Solved: **Missed Correlations taken into account with unfolding**

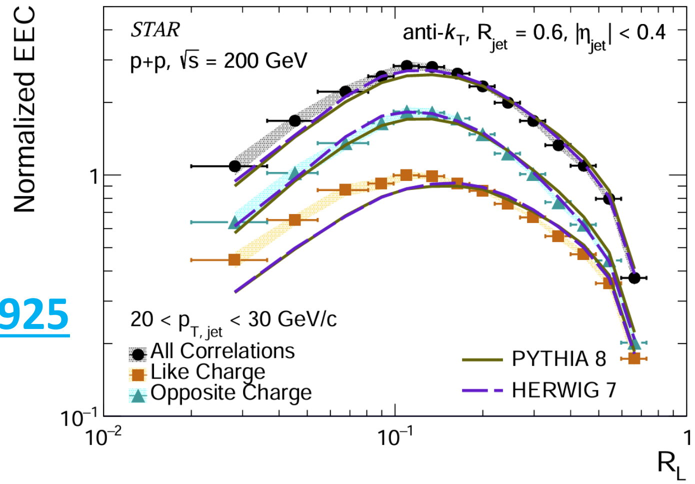
Un-subtracted Data

- Now, we want to apply this to data
- Have replicated general trend seen in data in our simulations
- Work in progress to perform correction

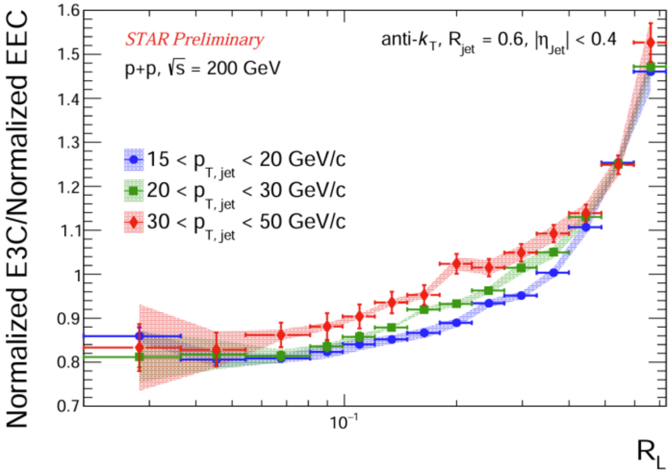


Summary

- Measurement of EEC in heavy-ion environment at STAR in progress
- Correction method is well-defined and applicable to the energy range we are looking at
- Work in progress to model background correctly
- Many more interesting measurements in p+p to extend to heavy-ion!



[ArXiv: 2502.15925]

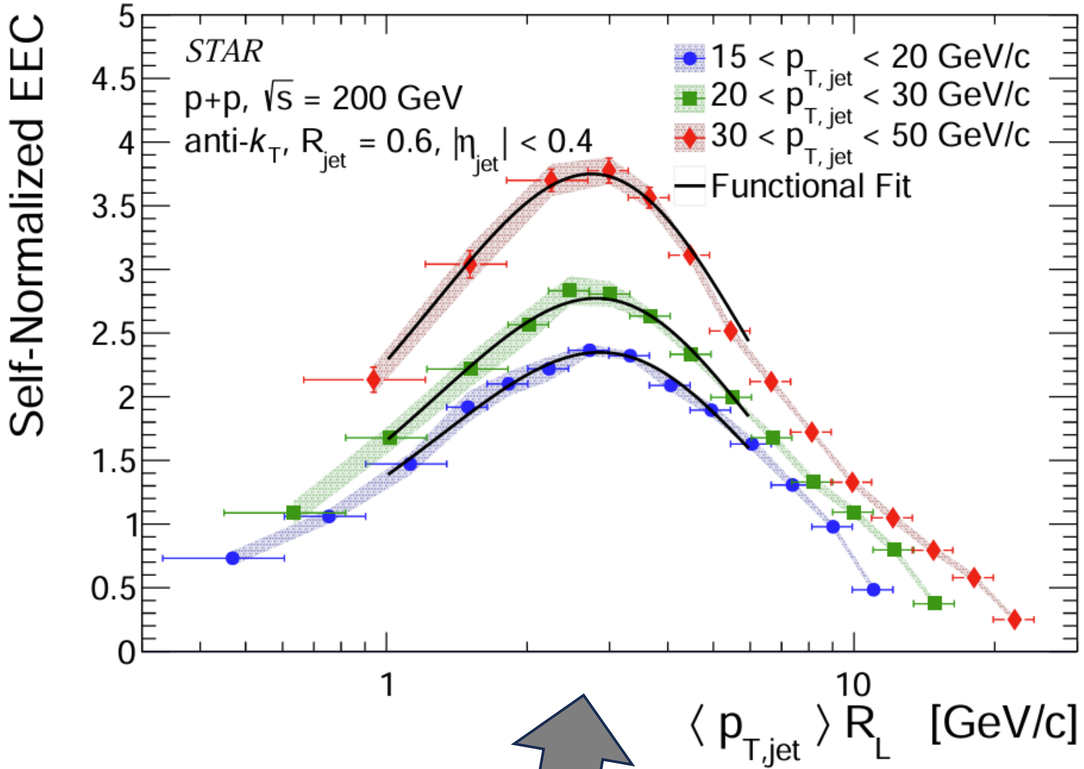


Backup

p_{T}-shifted EECs

- Shift corrected results on x axis by average $p_{\mathrm{T,jet}}$ in a given bin
- Since location of turnover $\propto \frac{\mathbf{1}}{\mathbf{p_T}^{\mathbf{Jet}}}$, scaled curves will turn over within **the same region**
- In this case, average momentum is determined via PYTHIA and applied post-correction

[ArXiv: 2502.15925](https://arxiv.org/abs/2502.15925)



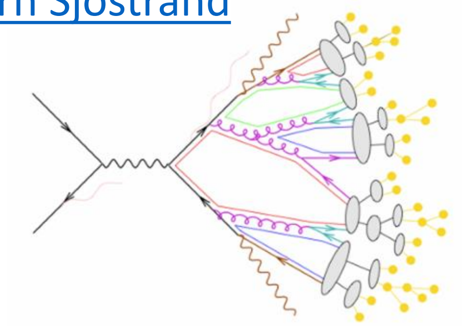
$$< p_{T,\mathrm{jet}} > \Delta R_{Turnover} \sim 2 - 3.5\ GeV/c$$

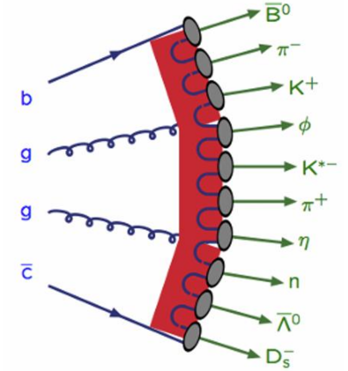
Charged EECs

Cluster (HERWIG)

String (PYTHIA)

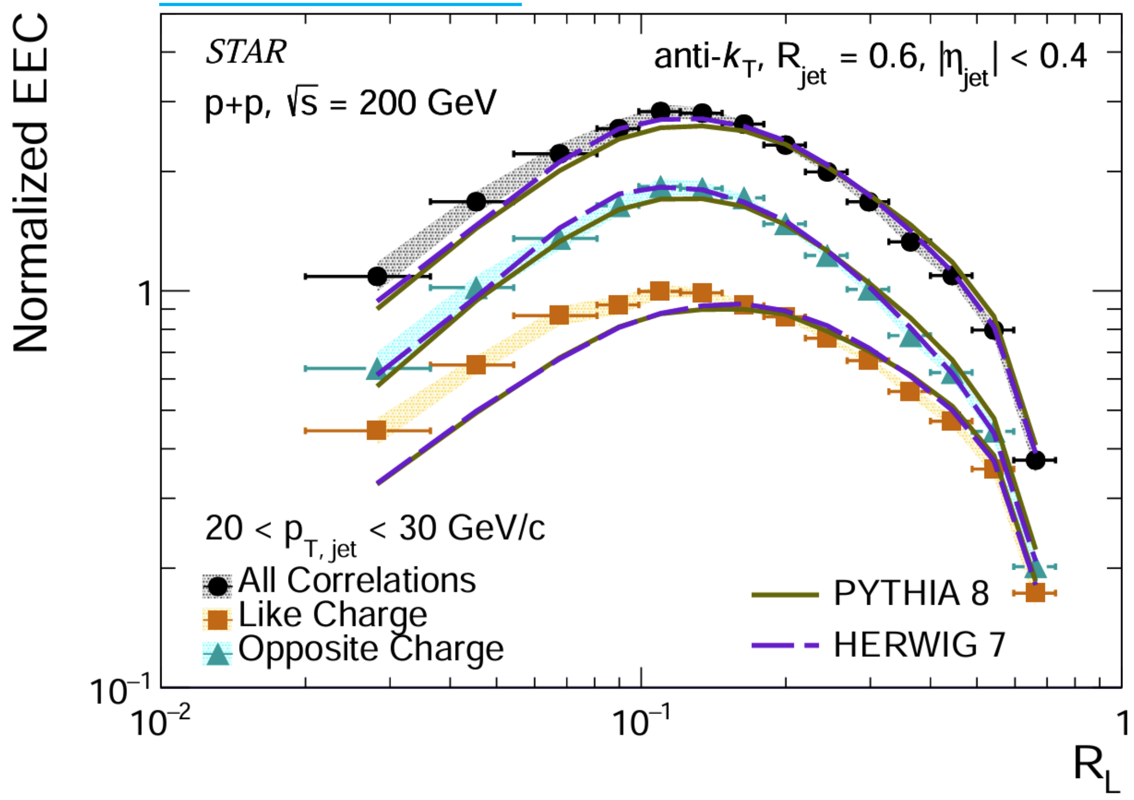
[Torbjörn Sjöstrand]





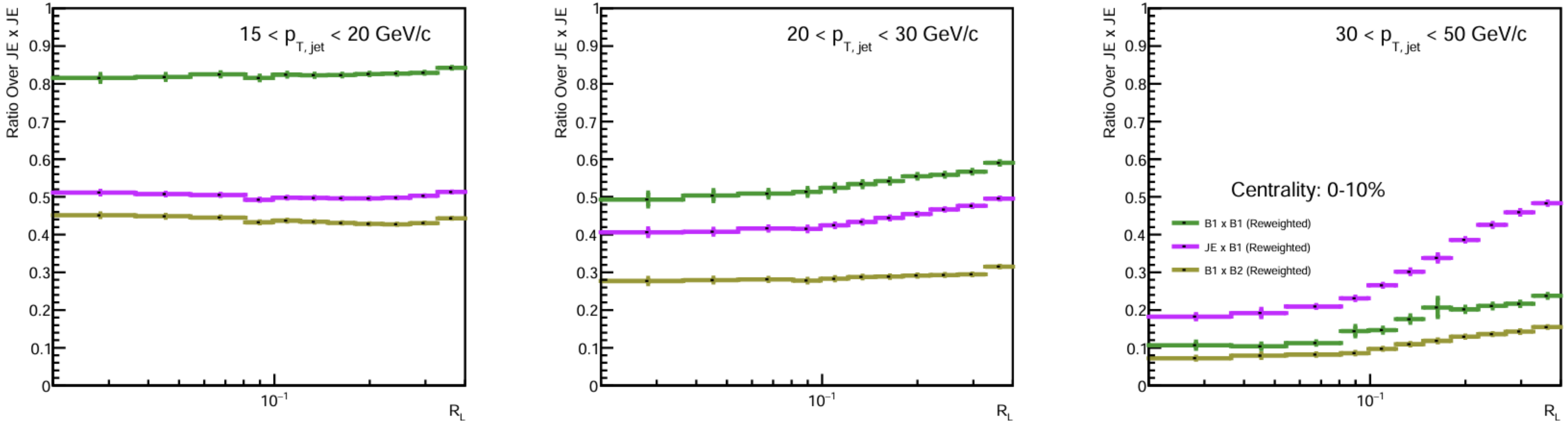
- Separating correlations into opposite- and like-charge distributions **increases sensitivity to hadronization mechanism**
- Models underestimate like-charge correlations left of transition region
- Shift in location of transition region seen in Monte-Carlo, but not resolved in data

[ArXiv: 2502.15925]



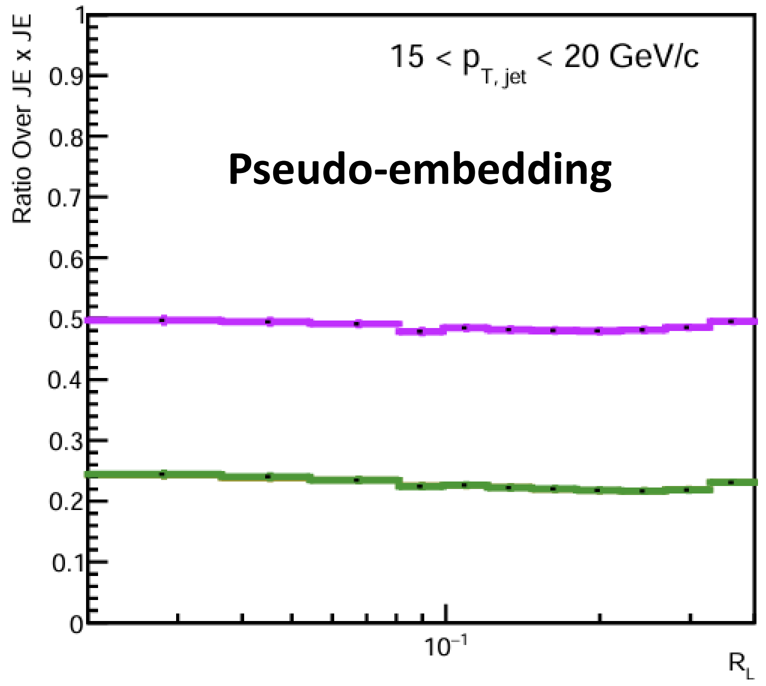
Relative Contributions of Background

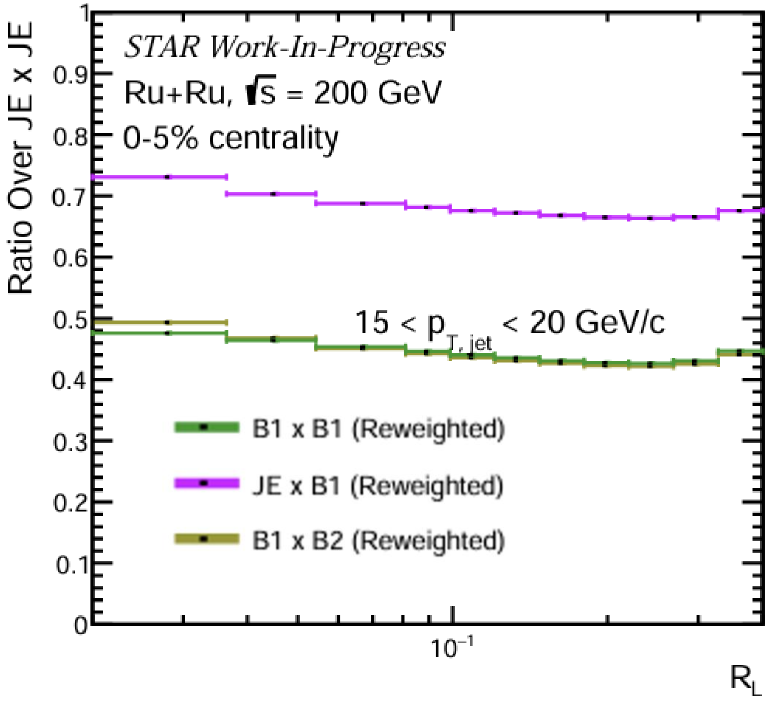
- Can see relative contribution from each type of background in pseudo-embedding
- Combinatoral background becomes less significant at higher jet momenta as B1 x B1 moves closer to B1 x B2



Compare With Data

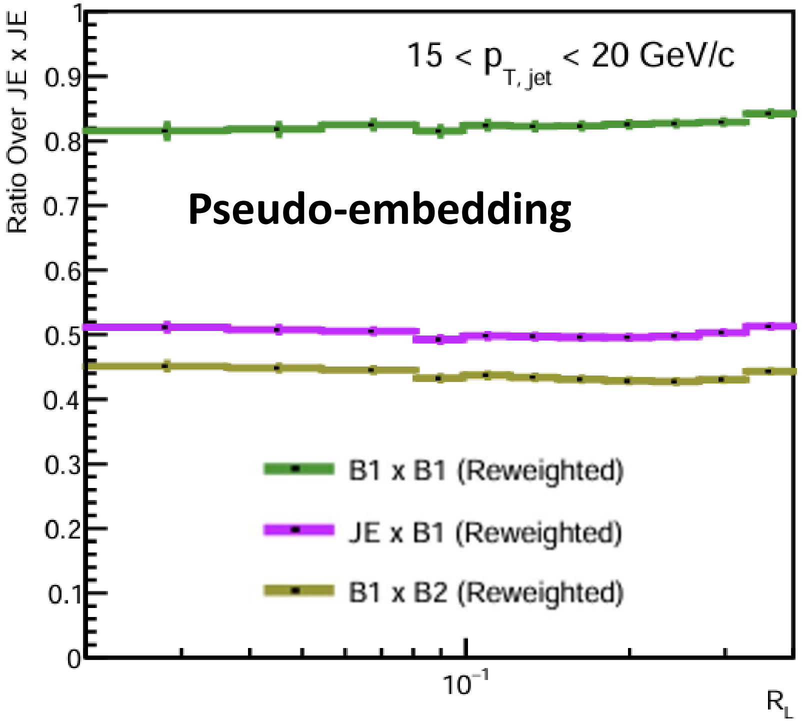
- **Before reweighting**, model underpredicts background contribution
- Due to model assuming that each event contains a hard scattering





Compare With Data

- **After reweighting** data, background is over subtracted
- Amount of combinatorial jets in data is underestimated by model, and their energy is over-predicted, leading to large reweighting
- Most likely due to residual hard scatterings in minimum-bias data used



Note change in axis