Multipoint Energy Correlators in Heavy Ion Collisions at RHIC Energies from Simulation

HotJets: Advancing the Understanding of High Temperature QCD with Jets

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January 8th, 2025

VANDERBILT UNIVERSITY

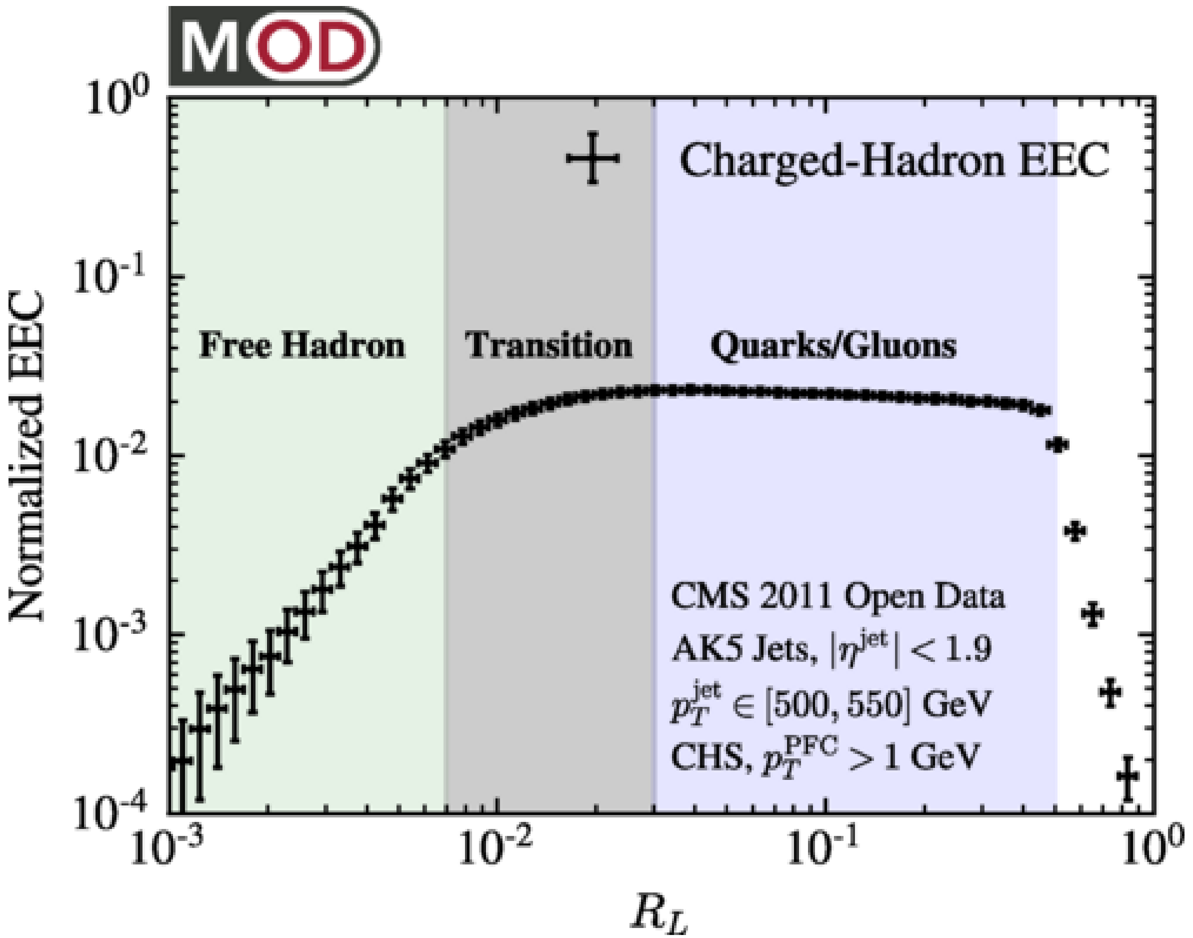
U.S. DEPARTMENT OF ENERGY
Office of Science

We would like to thank DOE Office of Science grant number DE-SC0024660 for support

Outline

- Energy Correlators
- Background Subtraction
- Biases in Background Subtraction
- Revision to Background Subtraction

Energy-Energy Correlators



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P. Komiske et al. Phys. Rev. Lett. **130**, 051901

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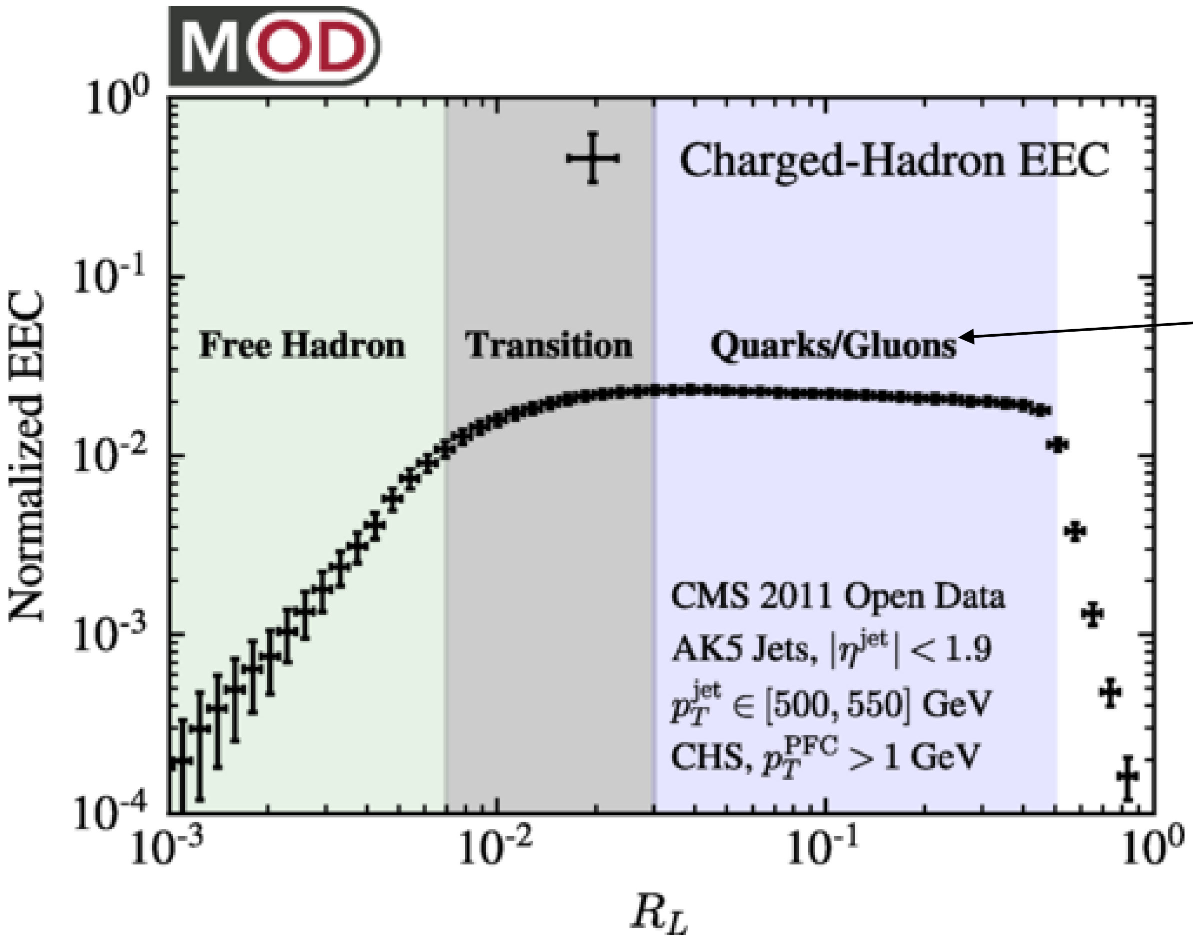

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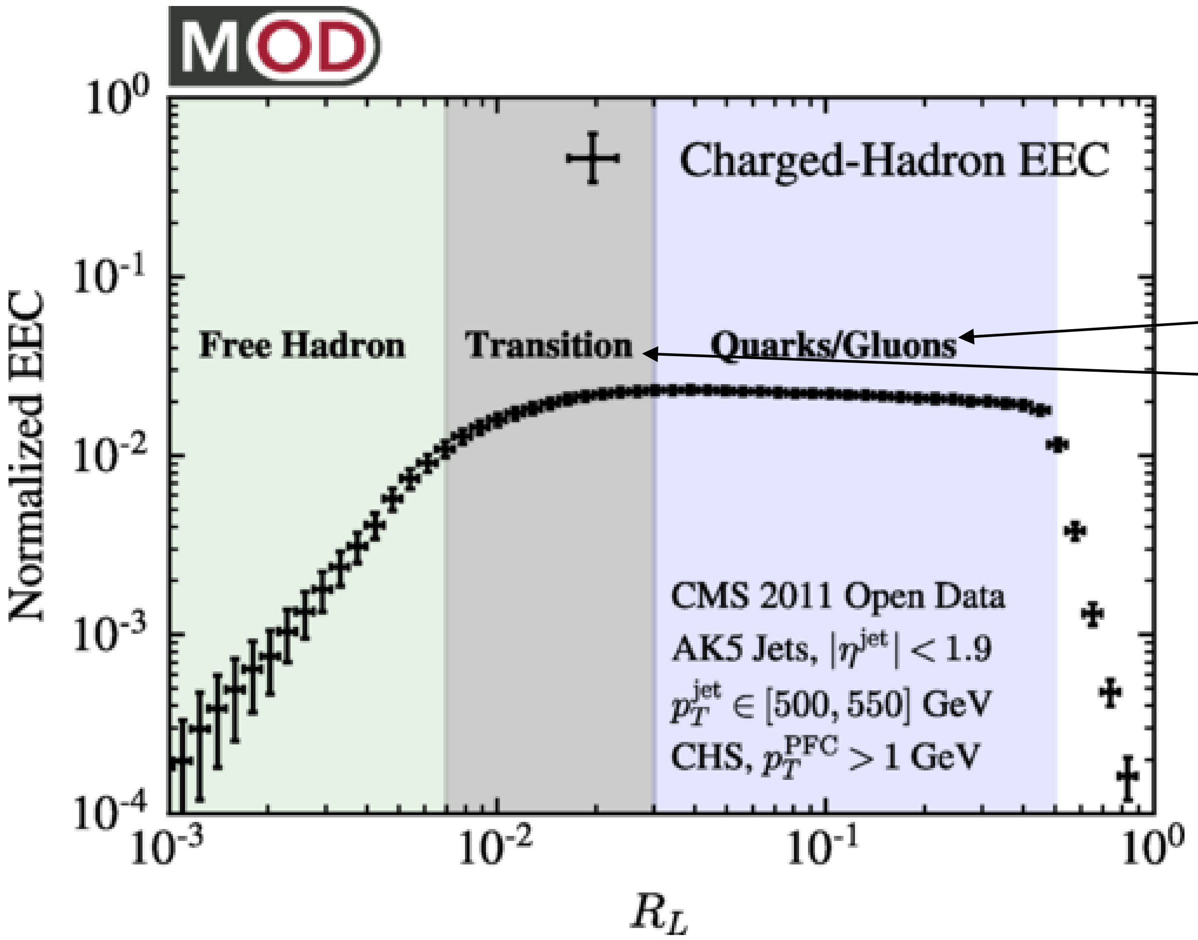

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- Transition $\sim\Lambda_{QCD}/p_{T,jet}$

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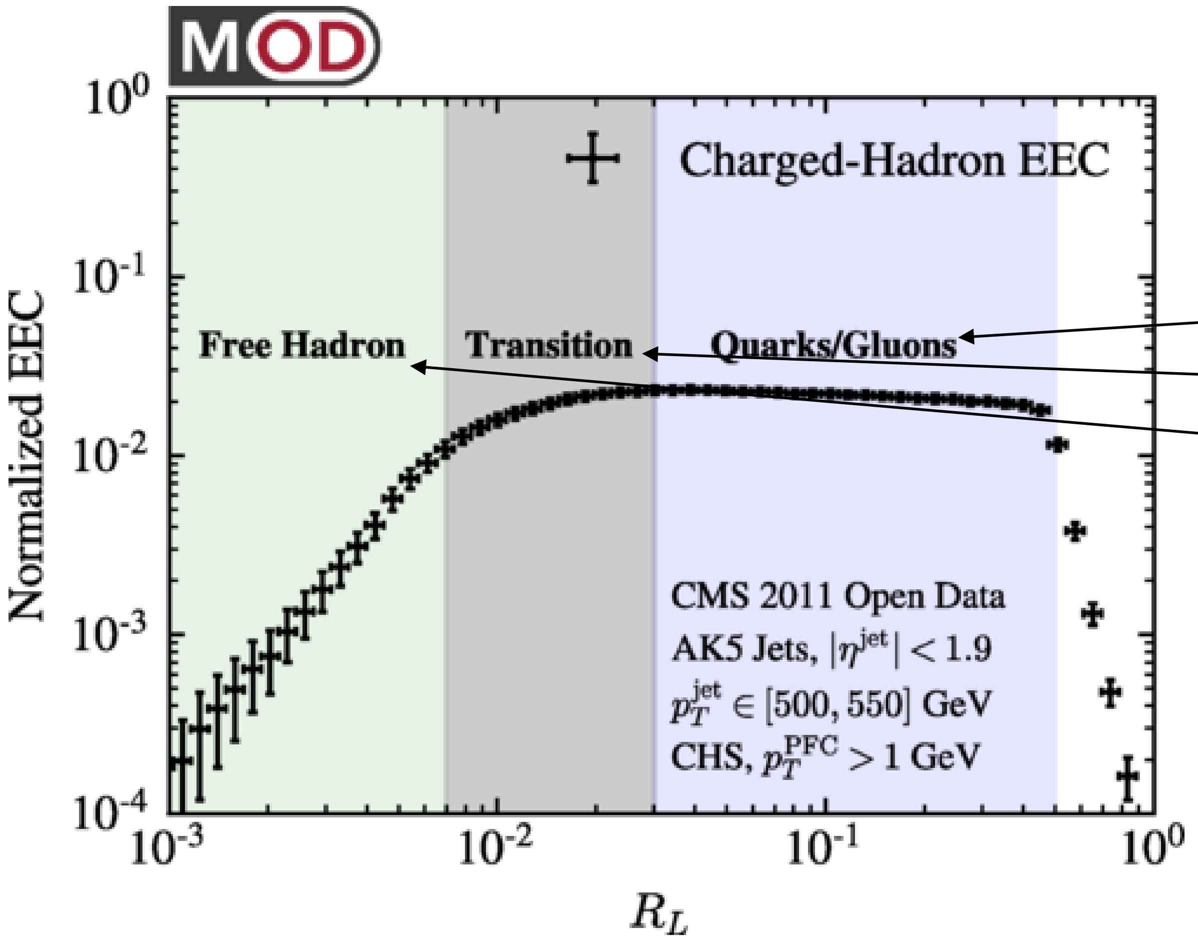
Energy-Energy Correlators



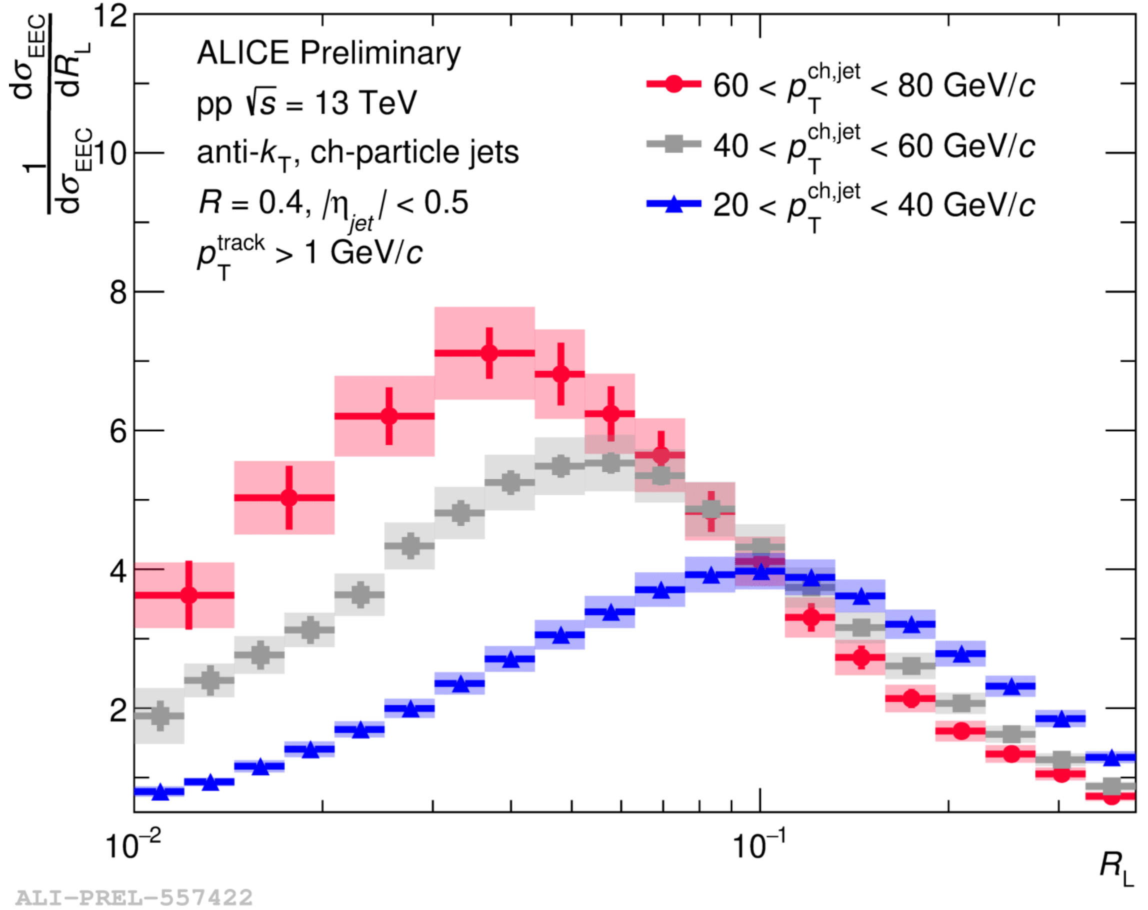
EECs have been proposed to study jet structure as they provide a way to easily separate different scales:

- Perturbative
- Transition $\sim\Lambda_{QCD}/p_{T,jet}$
- Non-perturbative

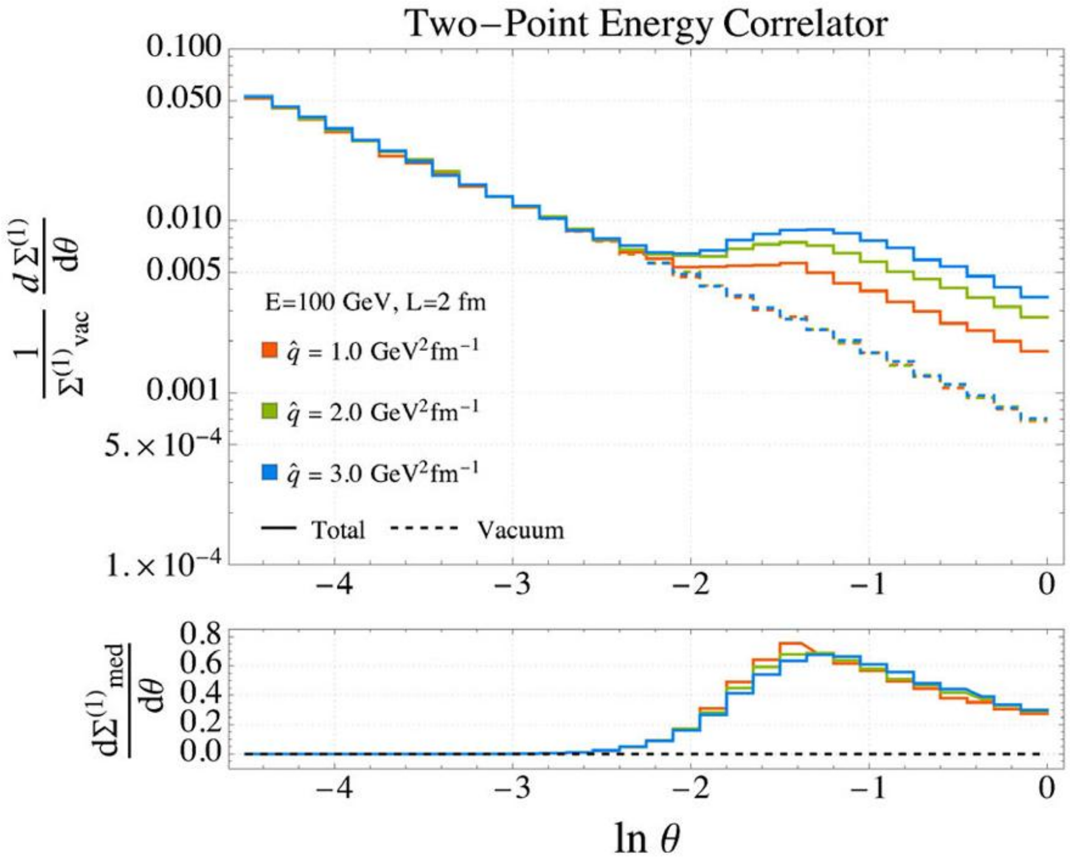
P. Komiske et al. Phys. Rev. Lett. **130**, 051901

Energy-Energy Correlators

Peak shift at different jet p_T indicative of changing virtuality



Energy-Energy Correlators in Heavy Ion Collisions



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

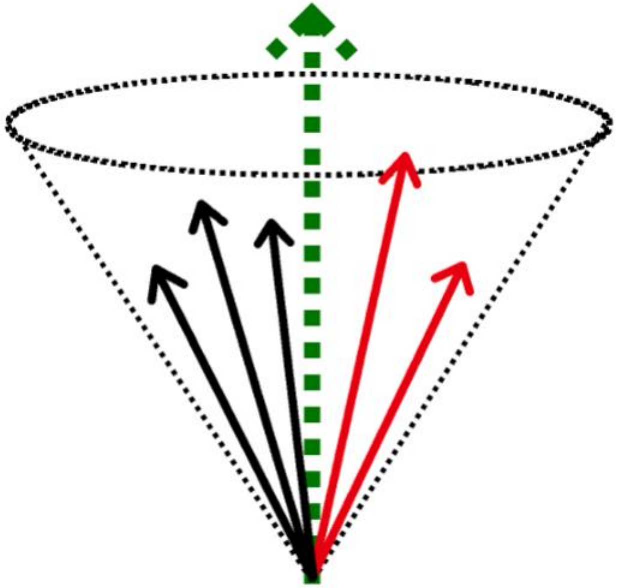
Medium modification of EEC expected to provide enhancement at large Δr (equivalent to R_L or θ)

Experimental Definition of Energy-Energy Correlators

$$\frac{d\Sigma}{d\theta} = \int d\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$$

$$EEC(\Delta r) = C_{norm} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{pairs \in [\Delta r_a, \Delta r_b]} \frac{p_{T,i} p_{T,j}}{p_{T,jet}^2}$$

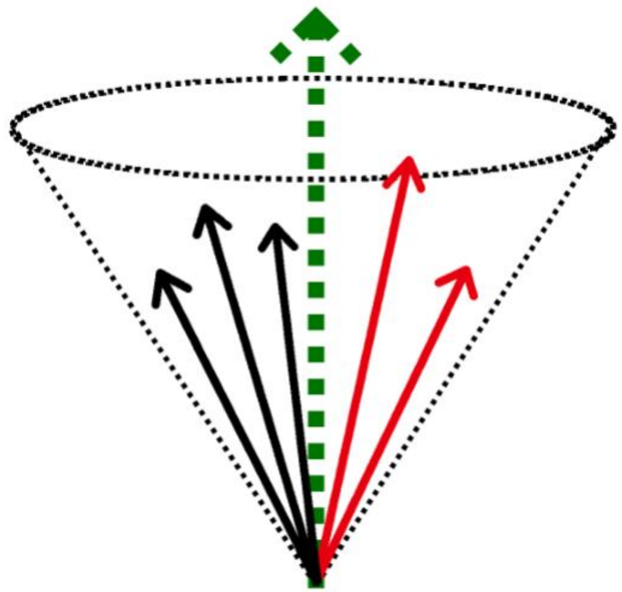
- C_{norm} = Normalization factor
- $p_{T,i}$ $p_{T,j}$ = Particle transverse momentum
- $p_{T,jet}$ = Jet transverse momentum
- $\Delta r = \sqrt{(\Delta\eta_{a,b})^2 + (\Delta\phi_{a,b})^2}$ = Angular distance between particles



Experimental Definition of Energy-Energy Correlators in Practice

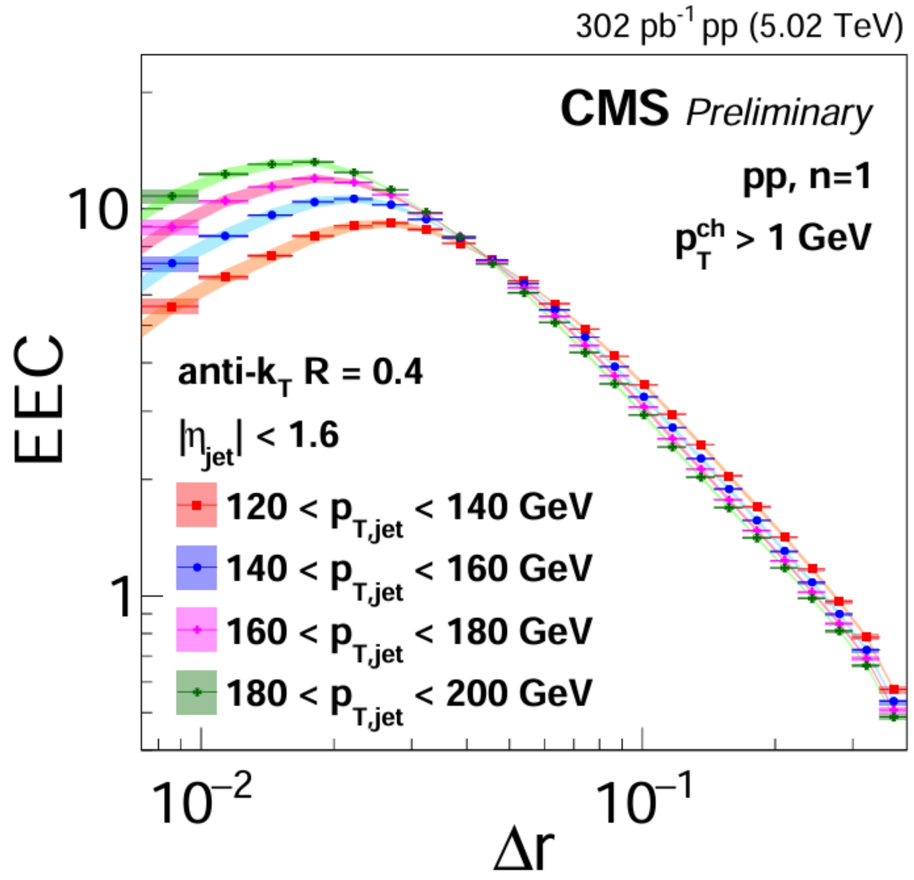
$$EEC(\Delta r) = C_{norm} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{pairs \in [\Delta r_a, \Delta r_b]} \frac{p_{T,i} p_{T,j}}{p_{T,jet}^2}$$

$$EEC(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{pairs \in [\Delta r_a, \Delta r_b]} p_{T,i} p_{T,j}$$



- Normalize with weighted number of pairs
  - Integral over analyzed area is one
- Bin width normalization: $\delta r = \Delta r_b - \Delta r_a$
- Do not add jet p_T to the pair weight
  - Improves resolution, no need for unfolding
- Select pairs within R=0.4 from winner-take-all jet axis

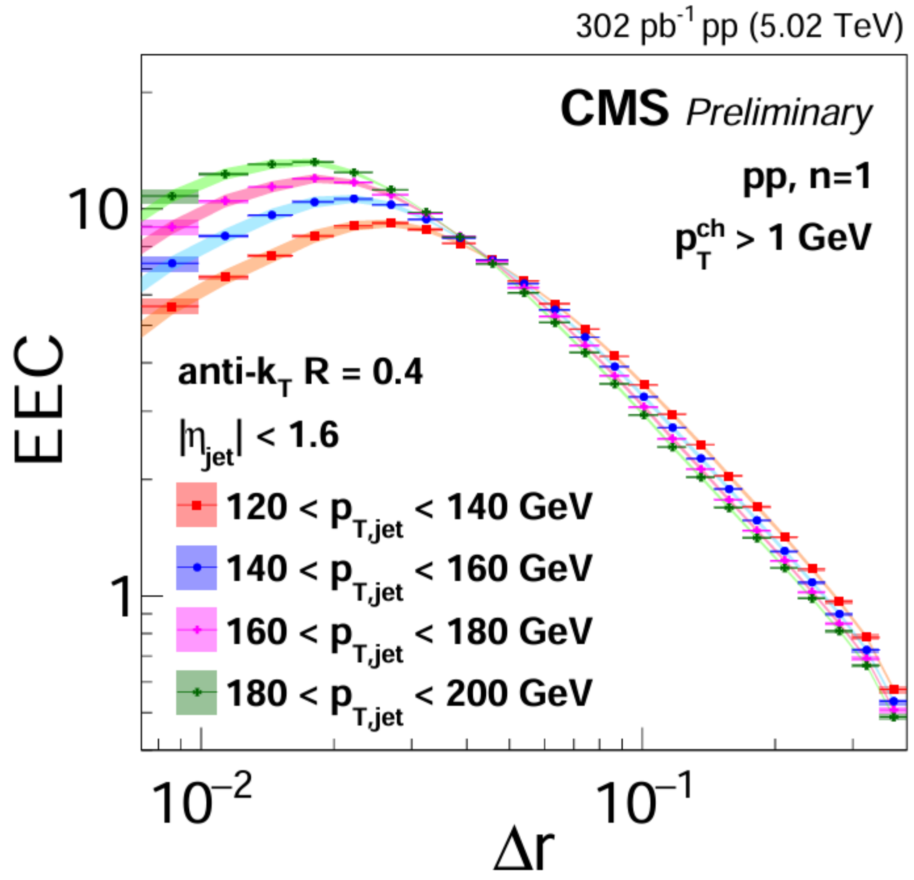
Recent EEC Results

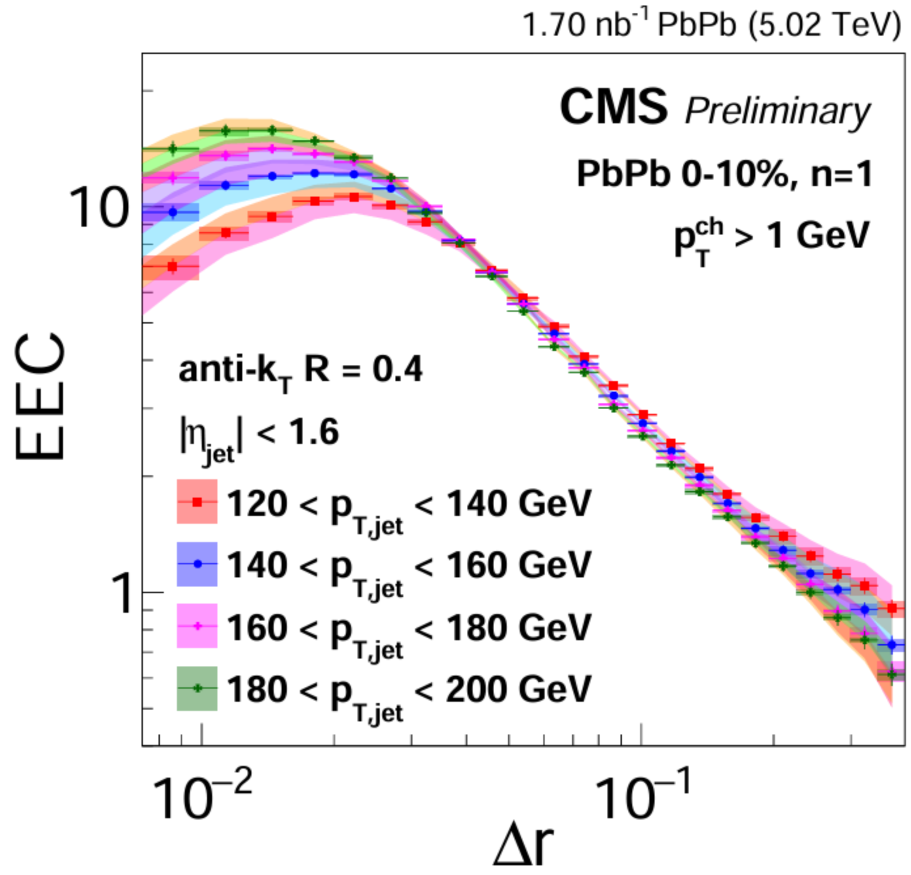


CMS-PAS-HIN-23-004

Recent EEC Results

CMS-PAS-HIN-23-004





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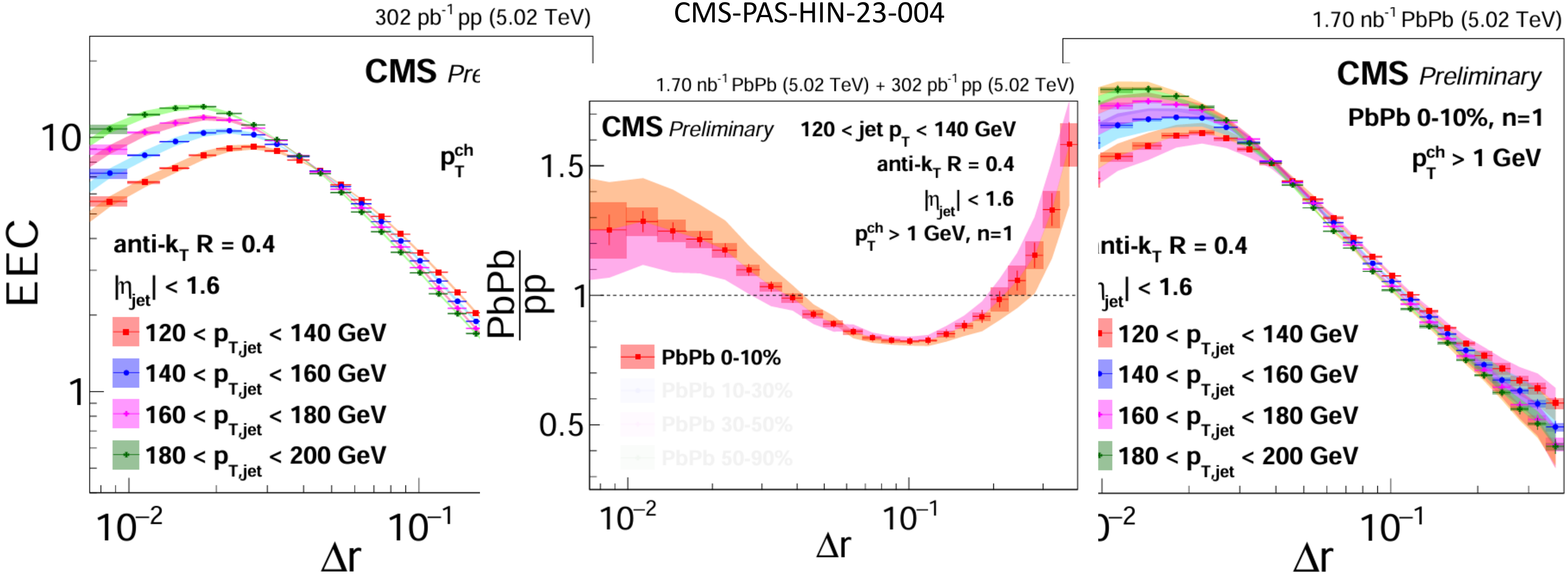
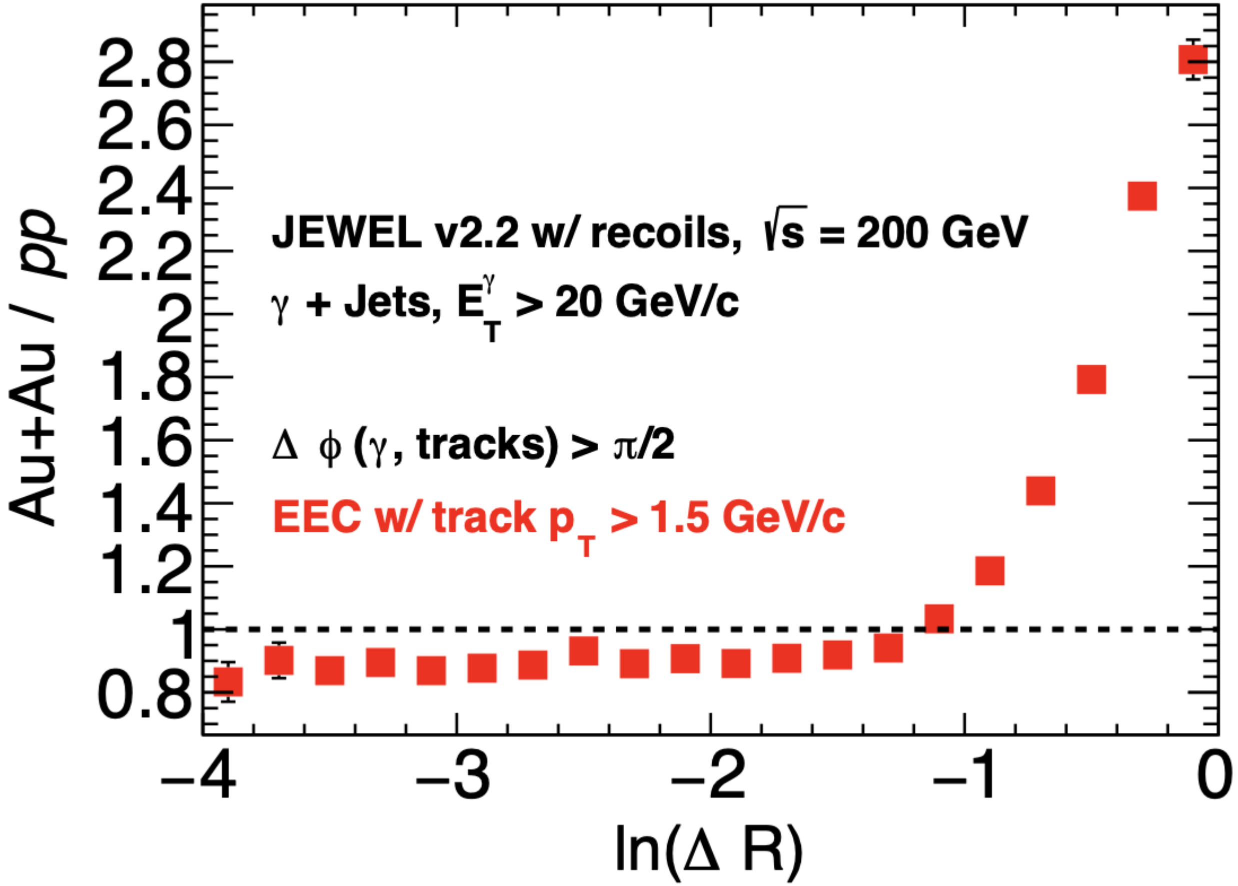


EEC Predictions at RHC

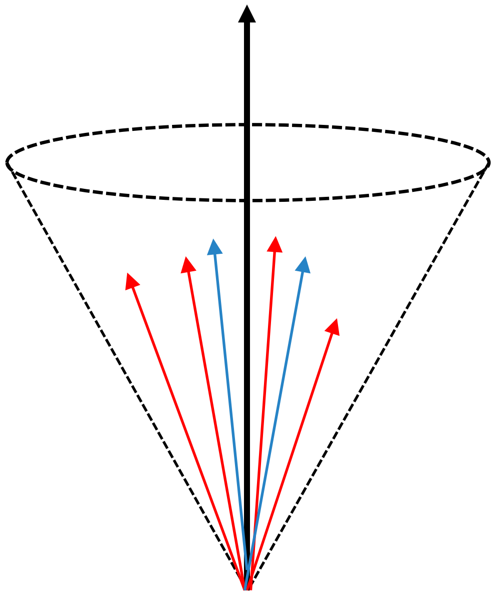


Larger enhancement at large Δr than at LHC!

Larger signal comes with larger background

- Need to validate background subtraction method for RHIC energy jets

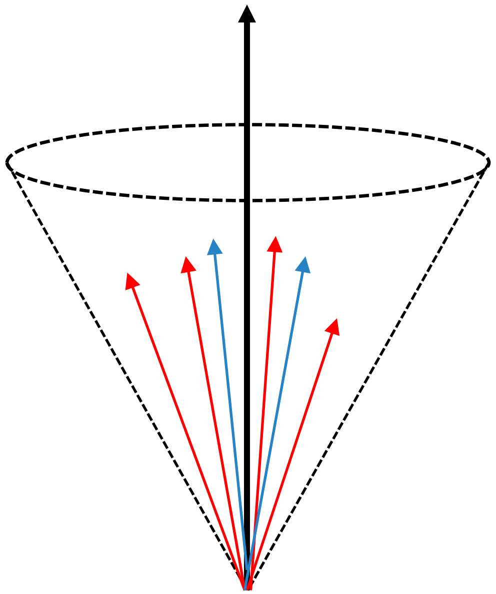
EEC Background in AA



Possible particle combinations:

- Signal + Signal (SS)
- Signal + Background (SB)
- Background + Background (BB)

EEC Background in AA



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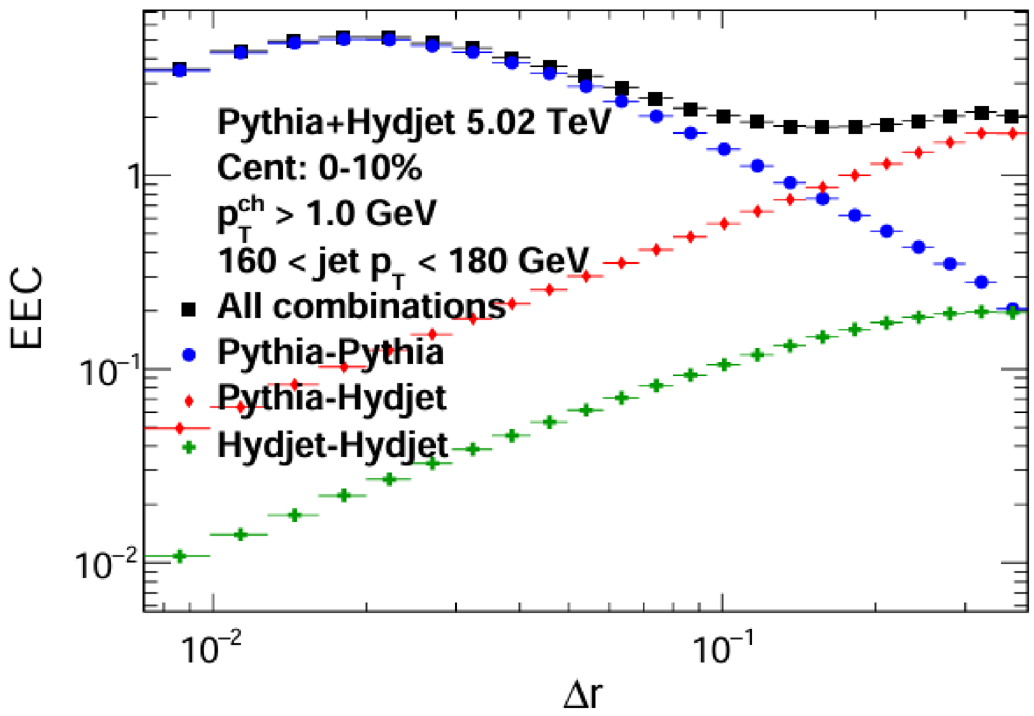
$p_T^{ch} > 1$ GeV



Mixed Event Background Subtraction

Three cones used in this method:

- Signal cone: around the studied jet
- Mixed cone 1: same location as signal cone in minimum bias mixed event
- Mixed cone 2: same location as signal cone in another mixed event

If two particles from signal cone: SS + SB + BB

If one particle from signal cone and other from mixed cone 1: SM1 + BM1

- SM1 properly models SB
- BM1 incorrectly models BB (background from different events) and needs to be removed
  - M1M2 models the incorrect background since the pairs are from different events

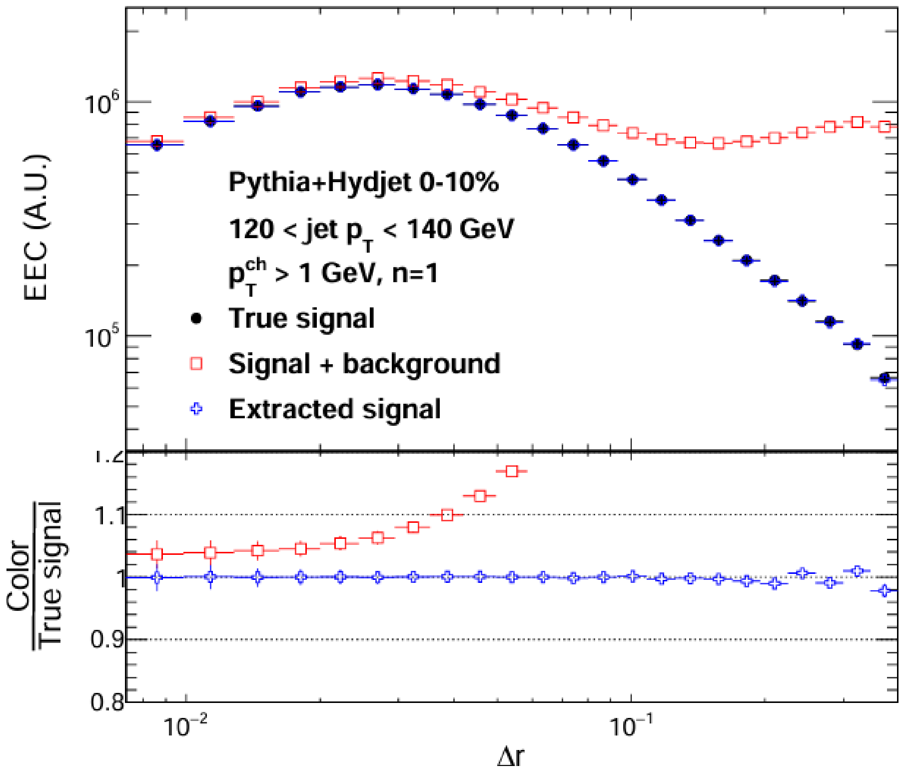
If two particles from Mixed cone 1: M1M1

- M1M1 models BB since the pairs are from the same event

Extract background: BG = (SM1 – M1M2) + M1M1

Mixed Event Background Subtraction in Practice

$\mathrm{C} = 0 - 10\%$



Closure on the sub-percent level

Mixed Event Subtraction of EECs at RHIC

Jet signal from PYTHIA8

Thermal background (T=0.3 GeV) uniform in η and ϕ

1500 thermal particles per jet event → central AuAu @ RHIC or mid-central PbPb @ LHC

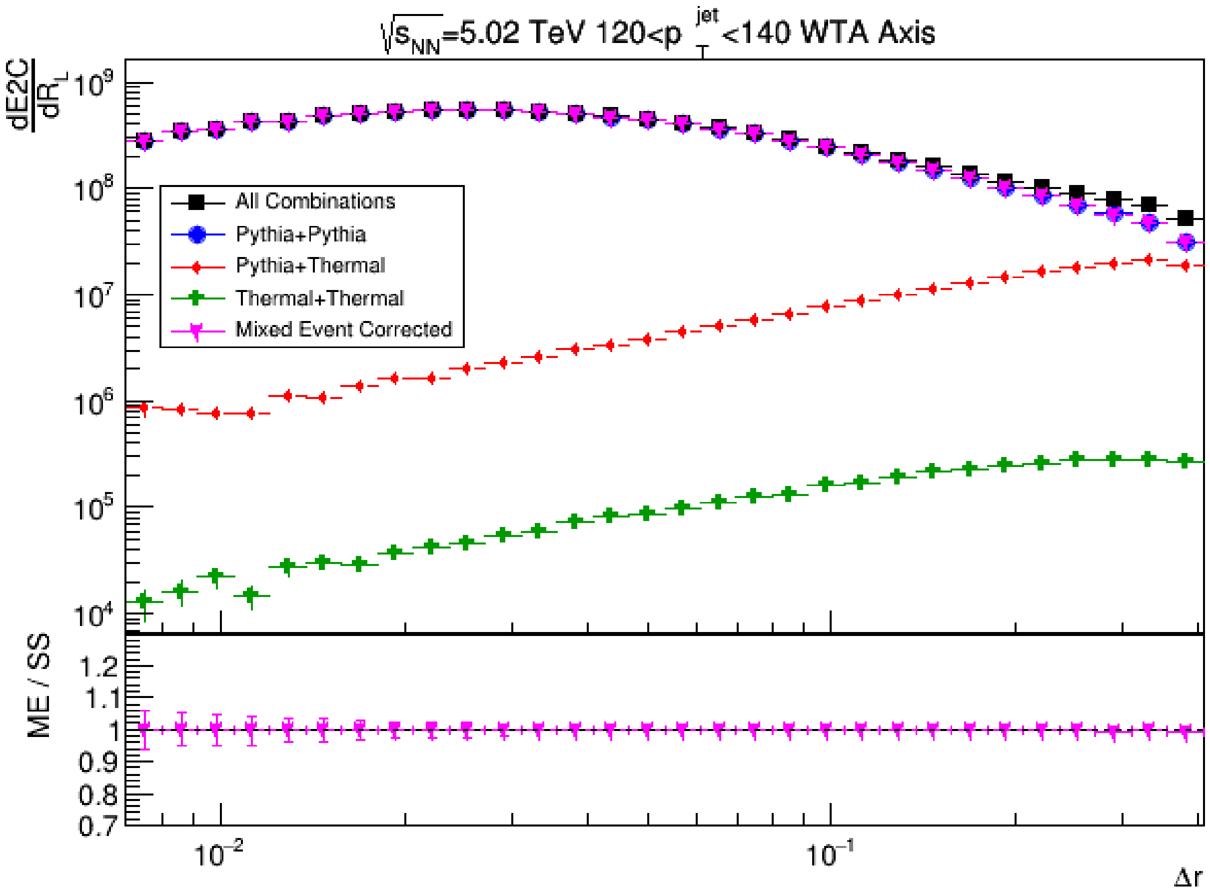
$p_T^{ch} > 0.3$ GeV

$|\eta^{ch}| < 1.1$

Jet R=0.4

$|\eta^{jet}| < 0.7$

Confirmation of Closure

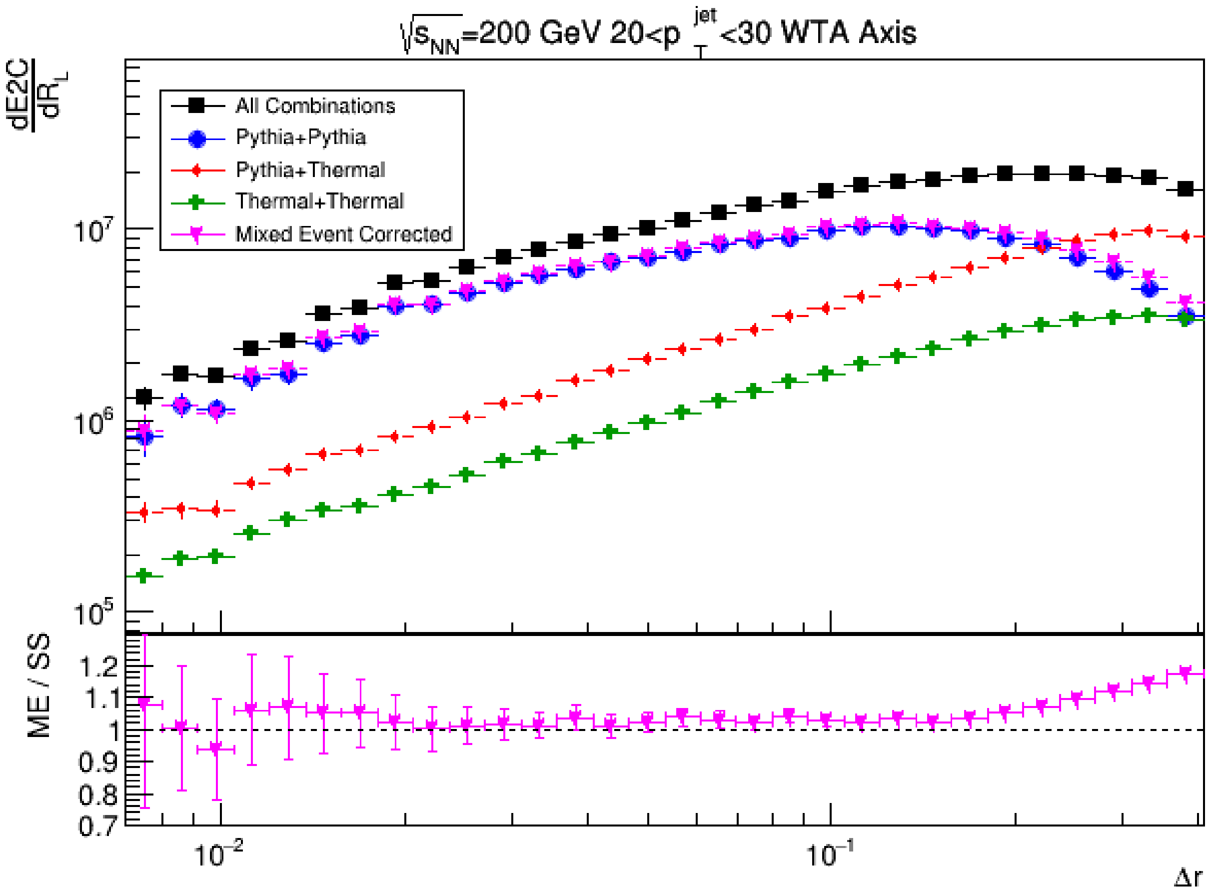


New implementation need to confirm same degree of closure

Also uses thermal background instead of Hydjet

Very similar result, sub-percent closure

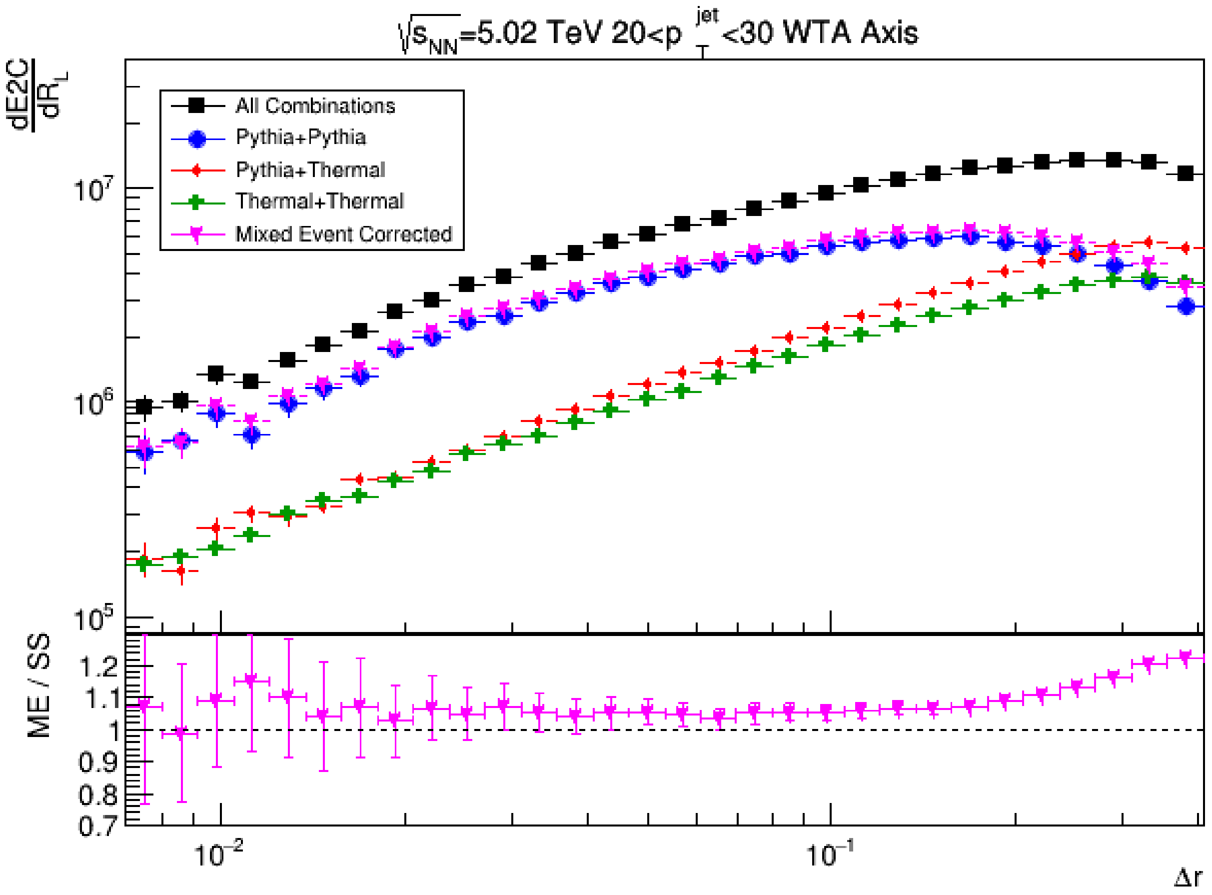
Mixed Event Subtraction at RHIC Energy



Mixed event subtraction severely underestimates background

Is this a problem with RHIC energies?

Mixed Event Subtraction at LHC Energy with Low p_T Jets

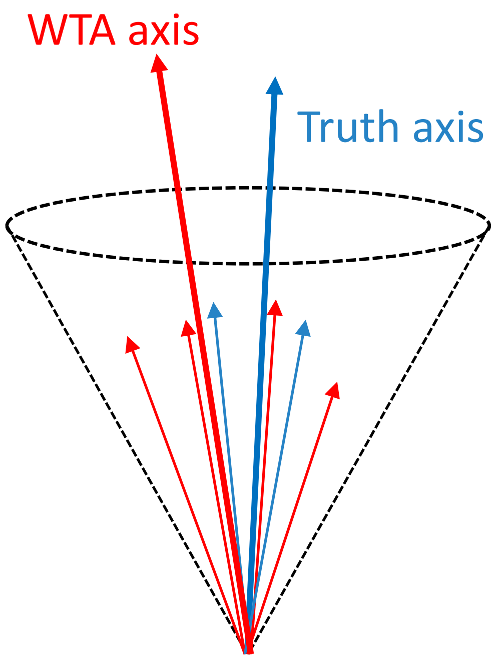


Mixed event subtraction still severely underestimates background

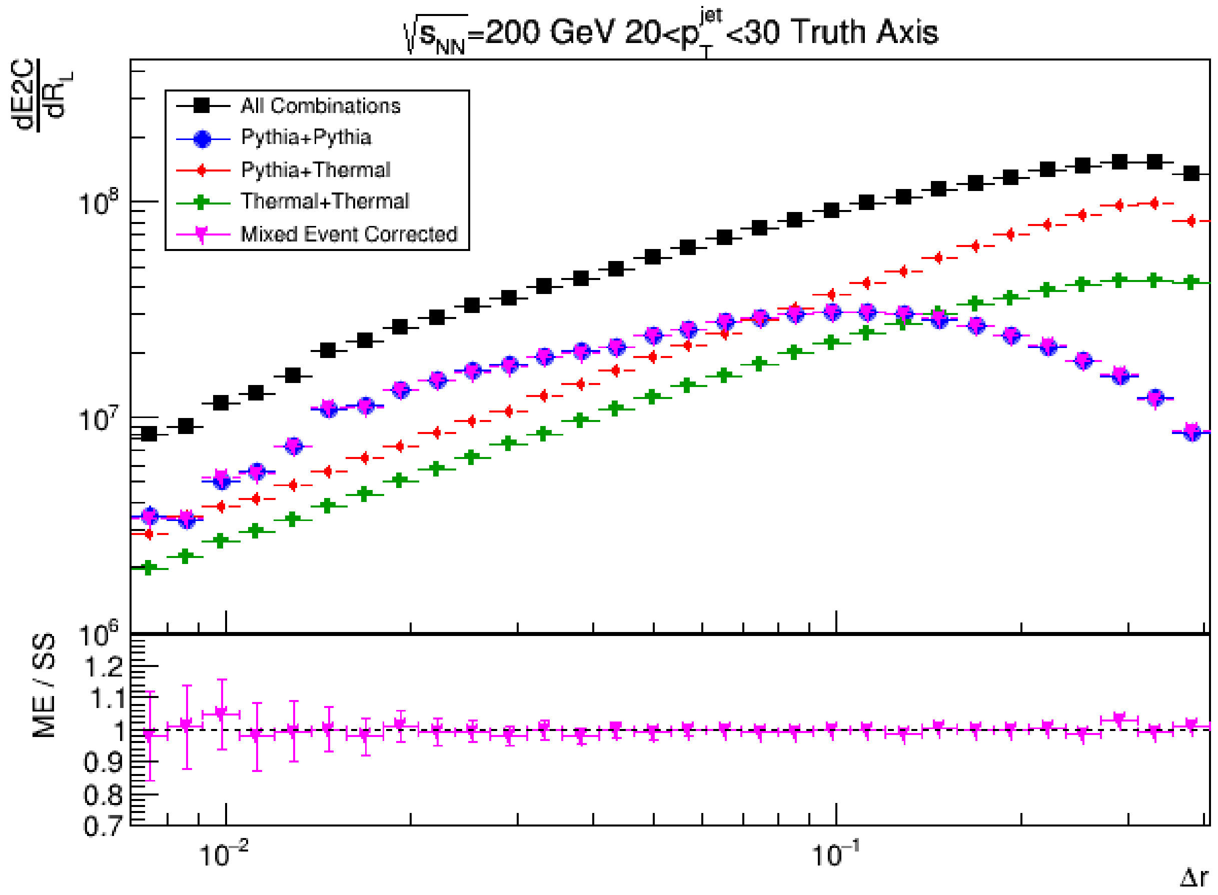
Subtraction method breaks down at low jet p_T, not just at RHIC but LHC too

What Biases are in the Mixed Event Method?

- Use all particles within R-0.4 of winner-take-all jet axis
  - WTA, E-scheme, and truth axis will all be close for high p_T jets
  - Low p_T jets are broader and fragment differently, so WTA axis is not necessarily close to truth axis
    - ➢ Main reason that WTA fails!
- Developed at high jet p_T so underlying event is assumed to be small compared to jet
  - Not true at low jet p_T
  - Jet reconstruction at low p_T is sensitive to UE fluctuations

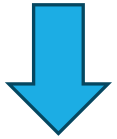


Does the Truth Axis Save Us?



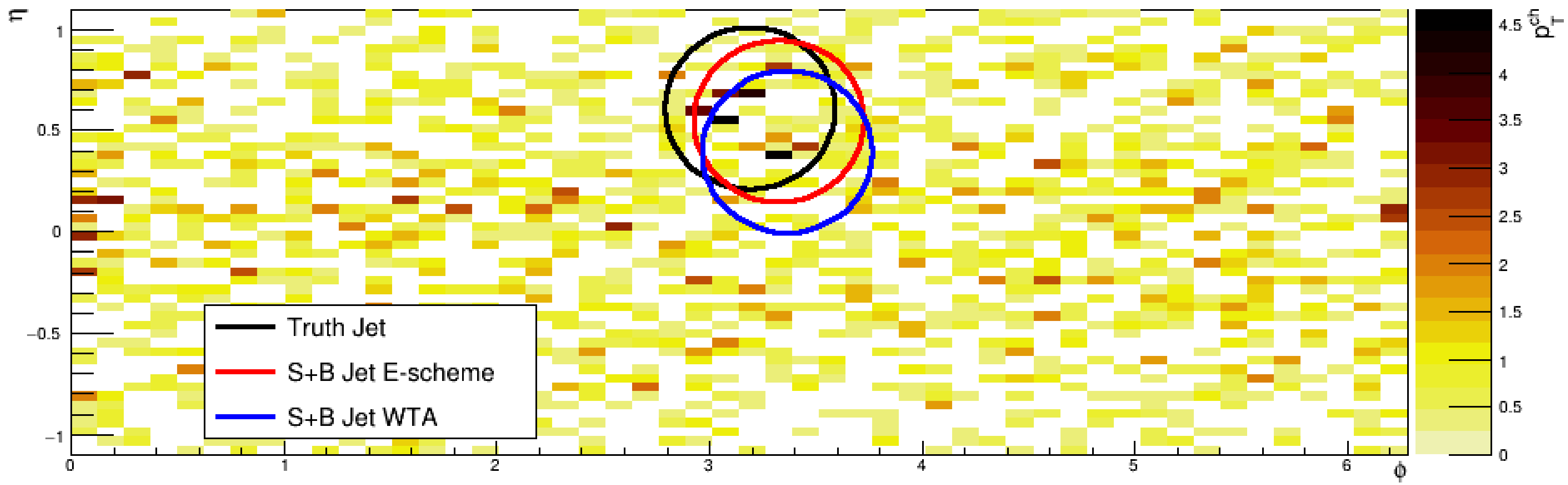
Yes it does!

Without UE to shift axis, mixed event method can correctly model background



Mixed event method is sensitive to jet axis and fluctuations

Jet Axis Comparison

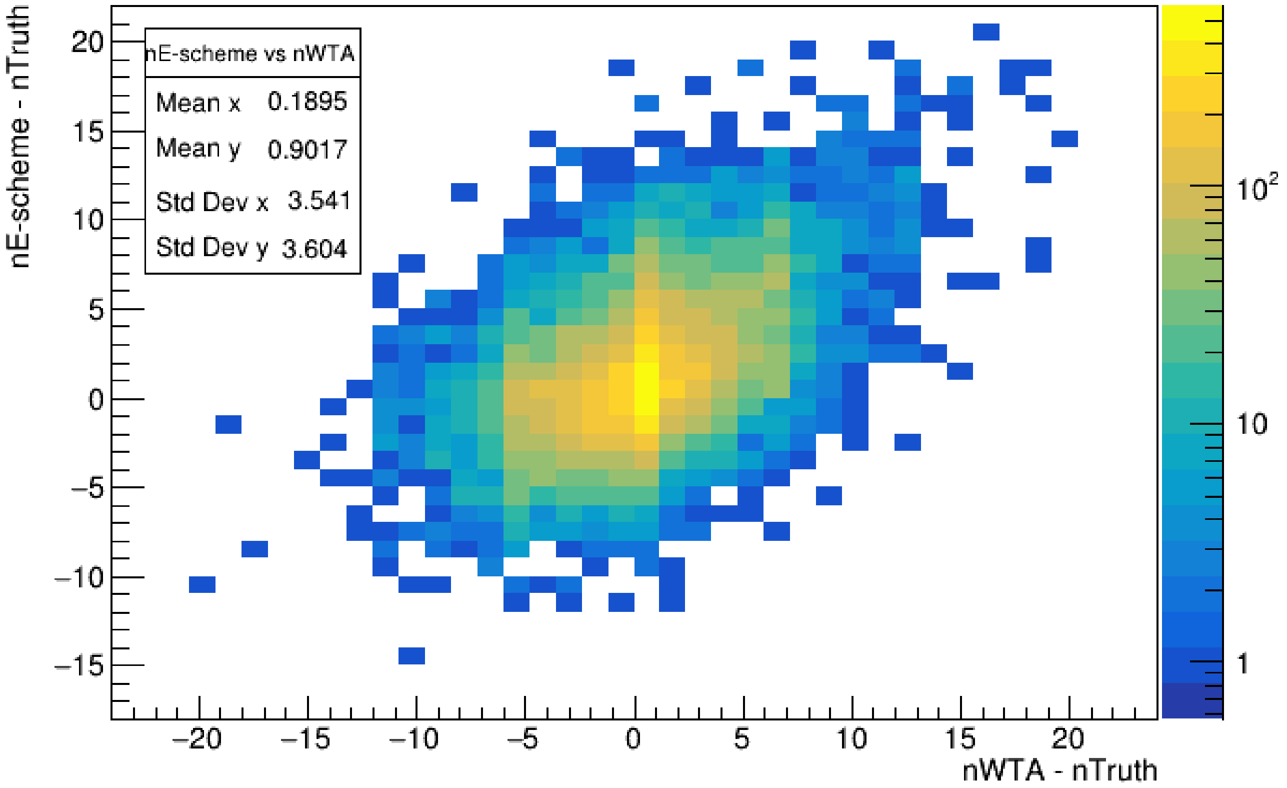


Truth axis (from PYTHIA signal only) points in slightly different direction from E-scheme and WTA axis

Number of particles in each cone is different due to fluctuations in UE, causing jet axis to point toward higher UE density:

- Truth cone: 55 constituents
- E-scheme cone: 66 constituents
- WTA cone: 62 constituents

Number of Constituents in Cones



Each cone has a different number of constituents compared to the truth cone

Both E-scheme (vertical axis) and WTA (horizontal axis) have more particles in cone on average than truth

- ➢Jet axis shifted toward high UE fluctuations or away from low ones

How to Reduce Bias in Jet Axis from UE Fluctuations?

Impossible to model event-by-event fluctuations correctly

Need method to get jet axis from data that is insensitive to UE

Like finding a needle (and where it’s pointing) in a haystack

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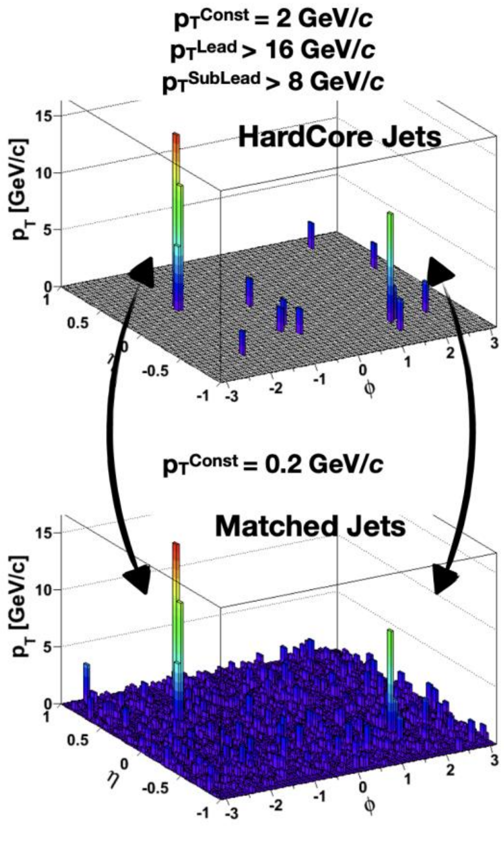
Like finding a needle (and where it's pointing) in a haystack

- ➢ Find axis with Hard Core jet

Hard core jets have been used before at RHIC to remove sensitivity to UE

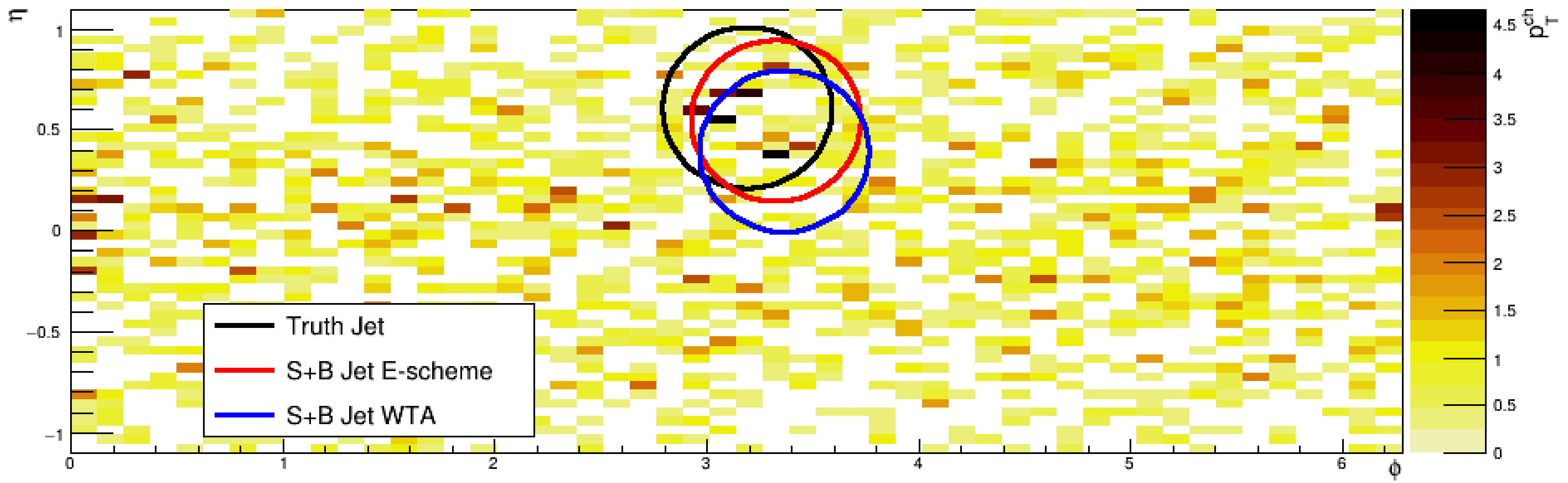
Hard core jets do introduce bias due to different fragmentation and p_T

- Working to find method to reduce bias, but has not converged yet



STAR

Does the Hard Core Jet Axis Work?



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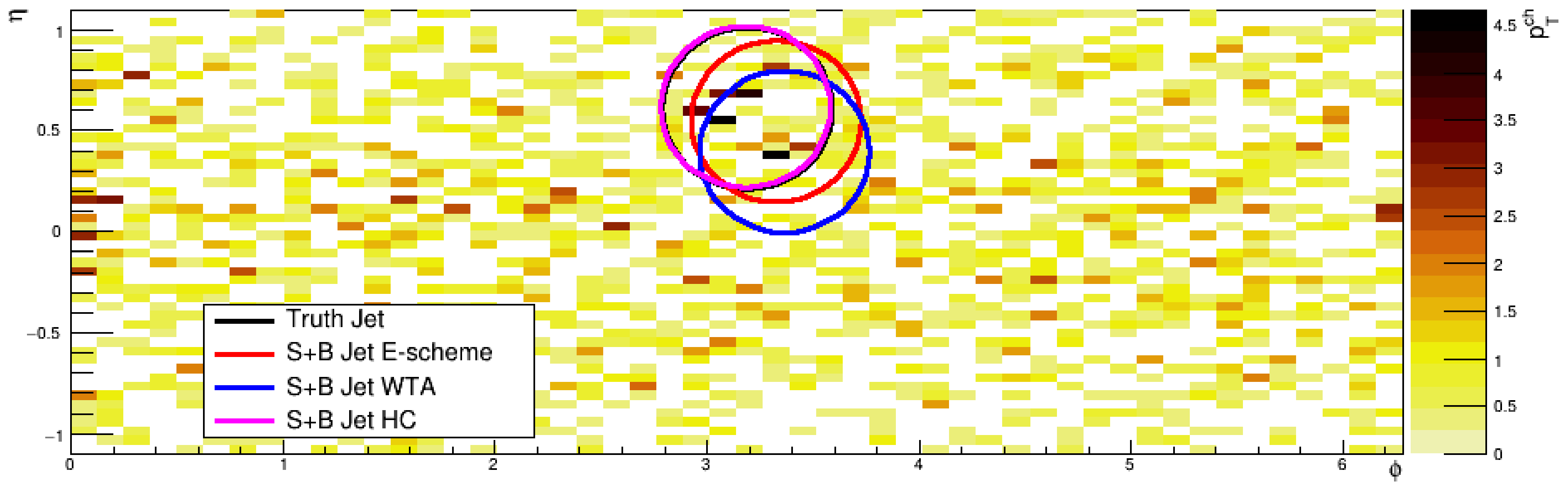

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Number of particles in each cone is different due to fluctuations in UE, causing jet axis to point toward higher UE density:

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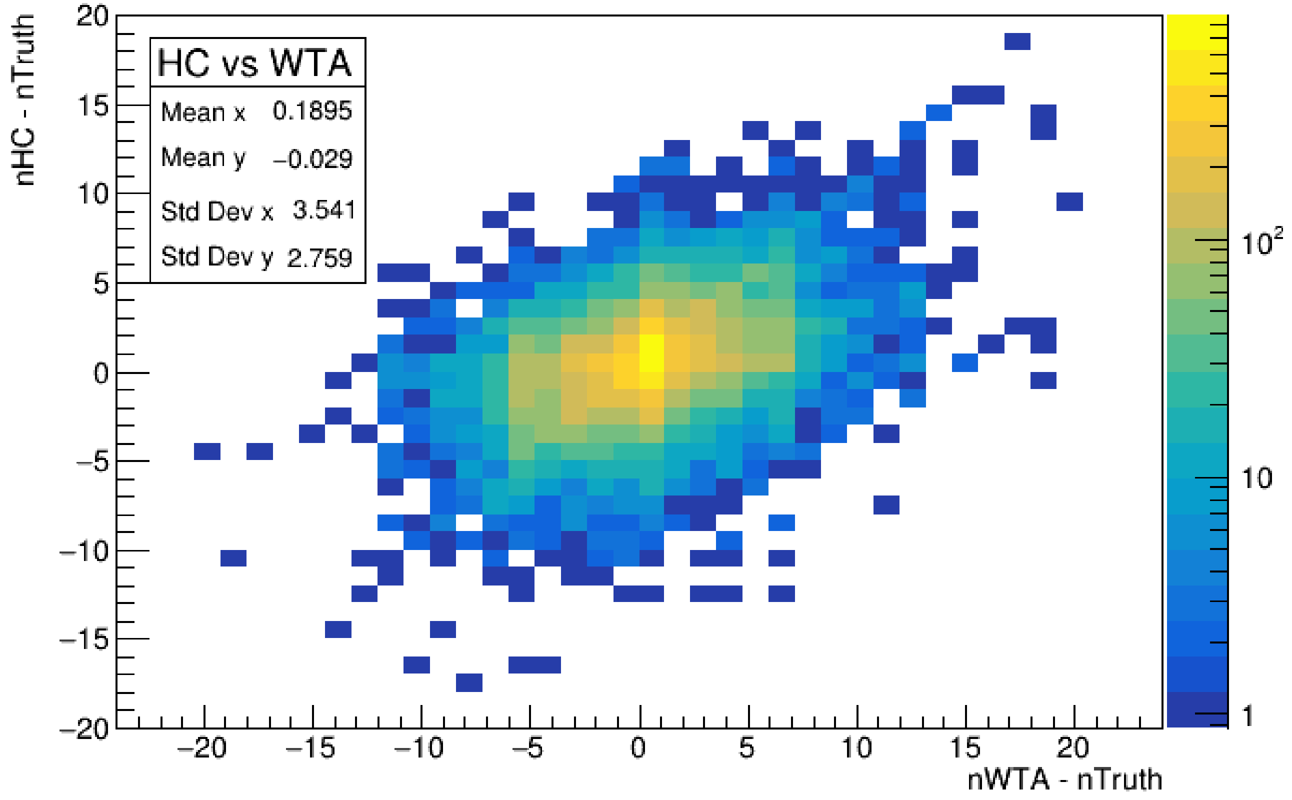
- Hard Core cone: 56 constituents

Number of Constituents in Cones

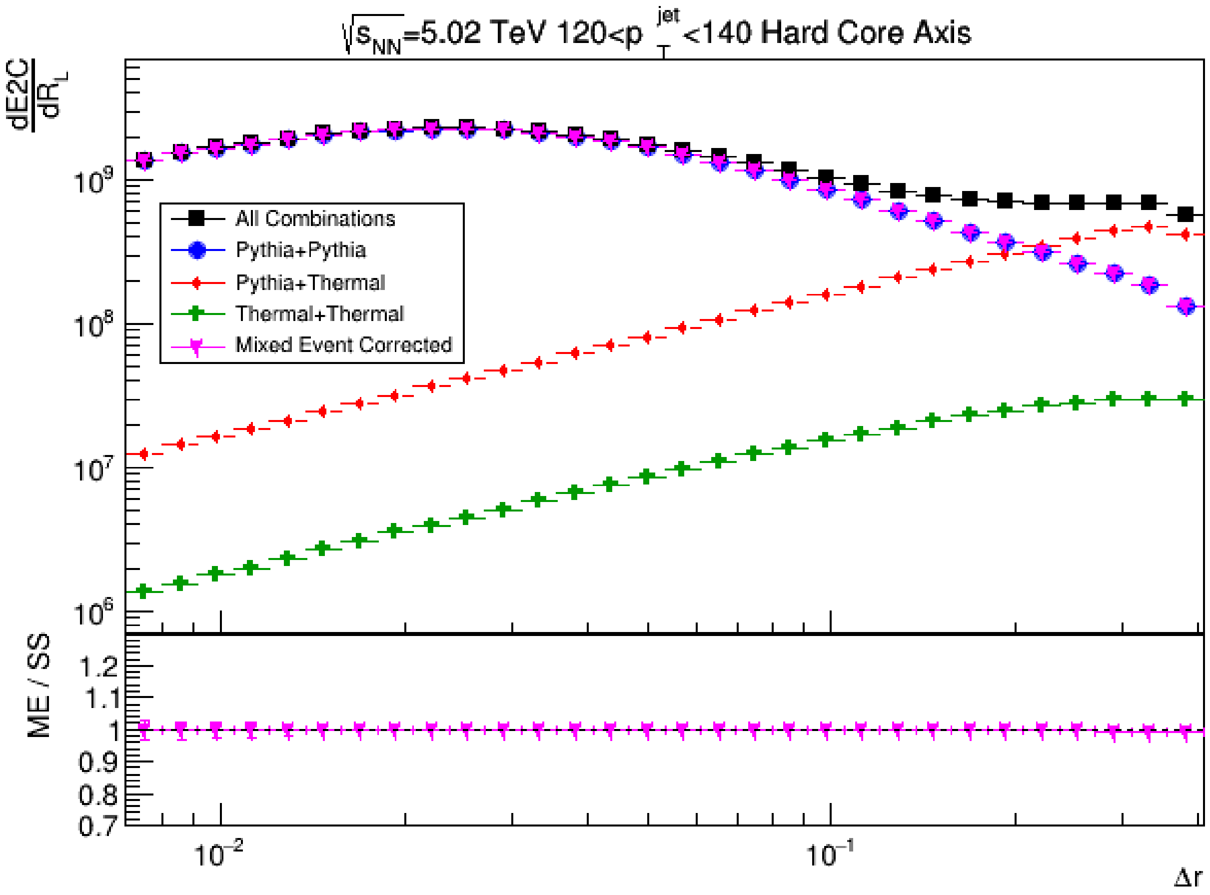


Each cone has a different number of constituents compared to the truth cone

Now Hard Core (vertical axis) has approximately the same number of particles in cone compared to truth axis while WTA (horizontal axis) has more particles in cone than truth

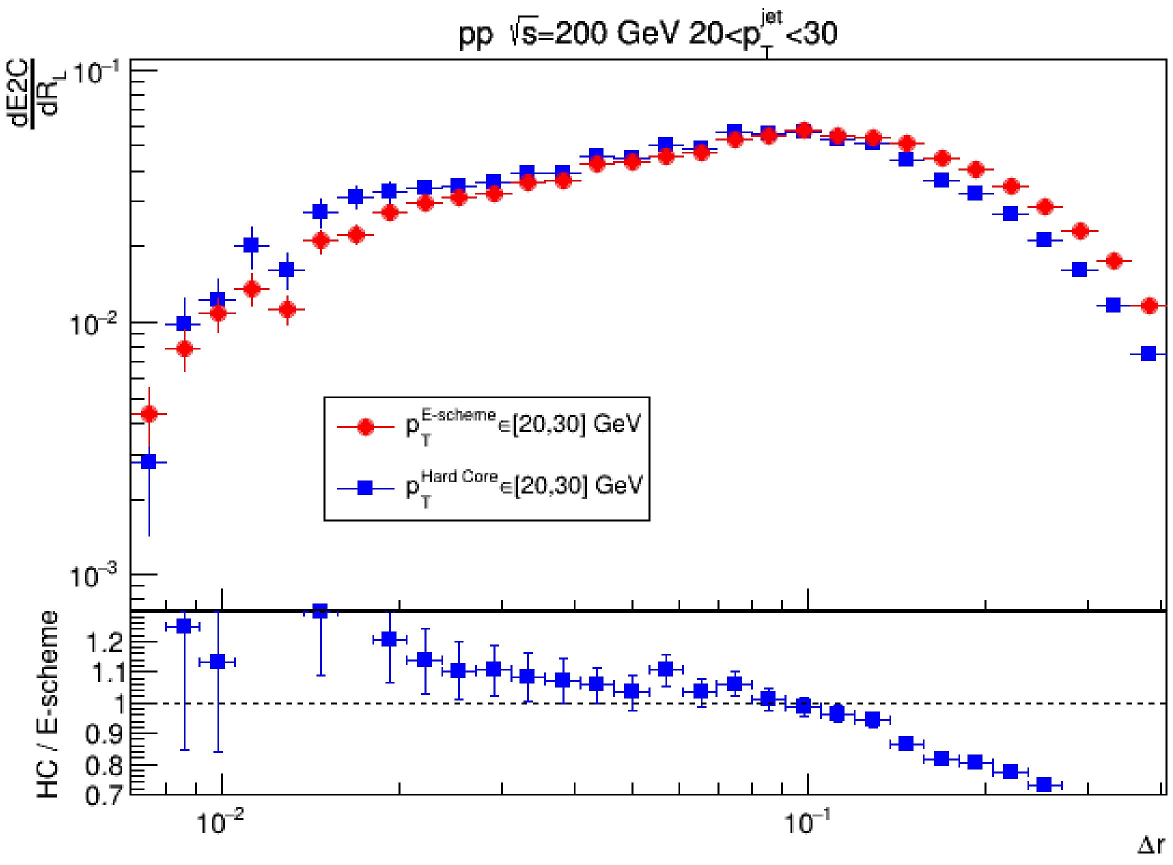
- ➢ Hard core axis not as sensitive to UE fluctuations!

Hard Core Works for High p_T Jets



WTA worked well at high jet p_T and Hard Core works just as well

Does the Hard Core Axis Bias the EEC?



In PYTHIA only, calculate EEC with E-scheme and Hard Core axis

For each method, select jets with 20<p_T<30 GeV

Hard core jets higher virtuality

- ➢ Inherent shift to lower Δr

Different shape indicates different fragmentation

How to do Mixed Event Subtraction with the Hard Core Axis

1. Find anti-kt jets using E-scheme for all particles with p_T>2 GeV (3 GeV cut used for LHC energies motivated by PbPb/pp fragmentation function)

2. For each jet in p_T bin, find all particles within jet radius (R=0.4 used here) of the jet axis with p_T>0.3 GeV (or whatever detector limitation you have), these will be our constituents

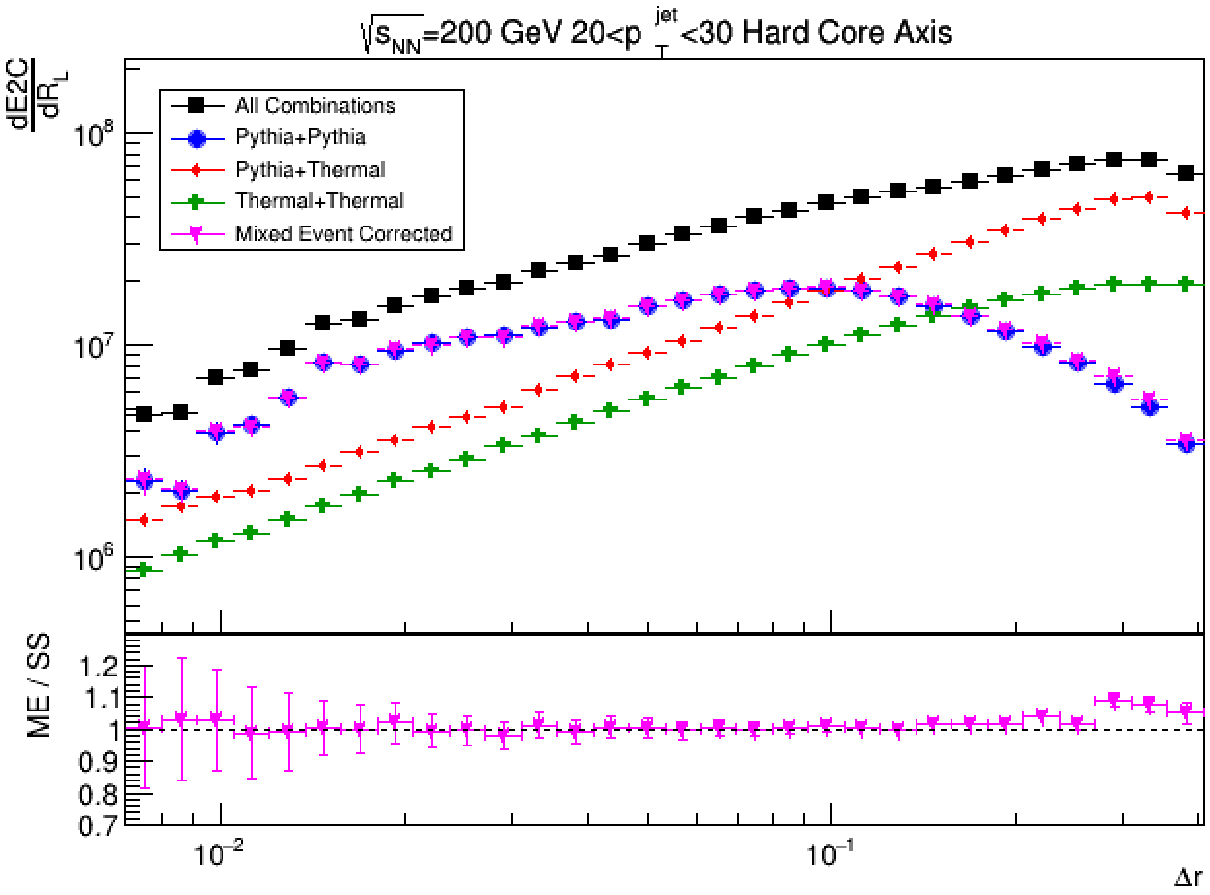
3. Make all pairs of constituents and calculate total EEC = SS + SB + BB

4. Take two different minimum bias events (M1 and M2) with similar global properties and find all particles within jet radius (R=0.4 used here) of the jet axis with whatever detector p_T cut used

5. Make all combinations of SM1, M1M1, and M1M2

6. Correct the total EEC as SS = total EEC – (SM1 + M1M2 – M1M1)

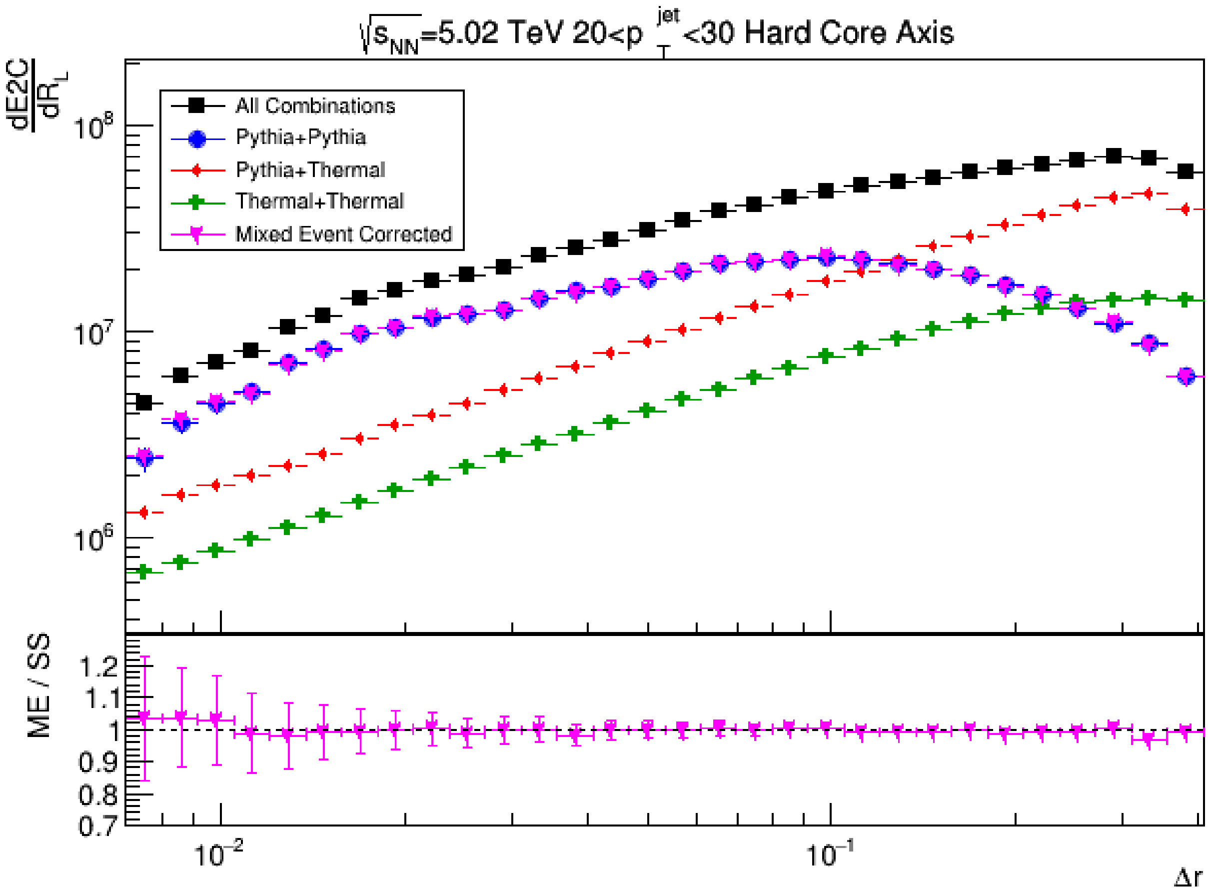
Hard Core Works for Low p_T Jets @ RHIC



Closure within 5%

- Large background will always be difficult to subtract

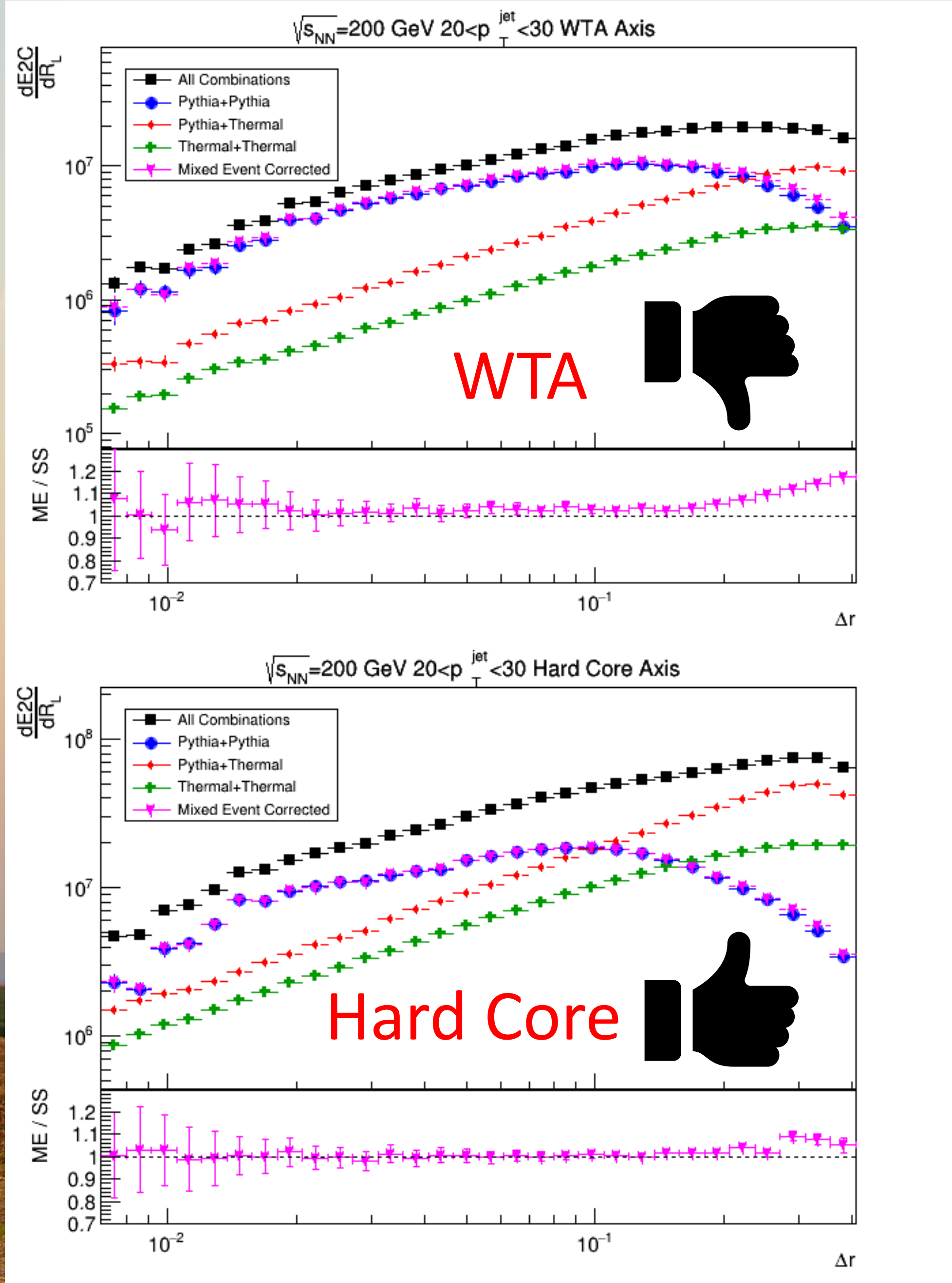
Hard Core Works for Low p_T Jets @ LHC



Closure within 5%

- Large background will always be difficult to subtract, but not as bad as RHIC
  - Difference likely due to more high p_T particles in jet @ LHC energy

Summary



Current method of mixed event subtraction for EEC fails at low jet p_T due to jet axis bias toward UE fluctuations

New method uses hard core jets to reduce sensitivity of jet axis to UE

- Mixed event subtraction works well at all jet p_Ts
- Additional bias due to use of hard core jets, but subtraction works
- Investigating possible methods to reduce bias by matching hard core jet to E-scheme and using matched p_T for binning

We have figured out how to find the needle in the haystack