How to measure energy-energy correlators from heavy ion collisions

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Probing QCD at High Energy and Density with Jets

INT WORKSHOP INT-21R-2B

Contents

Contents

Physics motivation

- A two-point energy correlator can be defined as

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

where $\epsilon(\vec{n}_i)$ measures the asymptotic energy flux in the direction $\vec{n}_i$, θ is the angle between $\vec{n}_1$ and $\vec{n}_2$, and Q is the hard scale

- Energy-energy correlators are predicted to be sensitive to several phenomena in heavy-ion collisions:
  - Color coherence: arXiv:2209.11236, arXiv:2303.03413
  - Jet wake: arXiv:2310.01500
  - Dead cone: arXiv:2307.15110
 - Anisotropic jet shapes: arXiv:2308.01294
  - . . .

Experimental definition of energy-energy correlator

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

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

- C_{norm} = Normalization factor
- $p_{\mathrm{T},i}\, p_{\mathrm{T},j}$ = Particle transverse momentum
- $p_{\mathrm{T,jet}}$ = Jet transverse momentum
- $\Delta r_{i,j} = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ = Angular distance between particles

# Energy-energy correlators in pp collisions by STAR
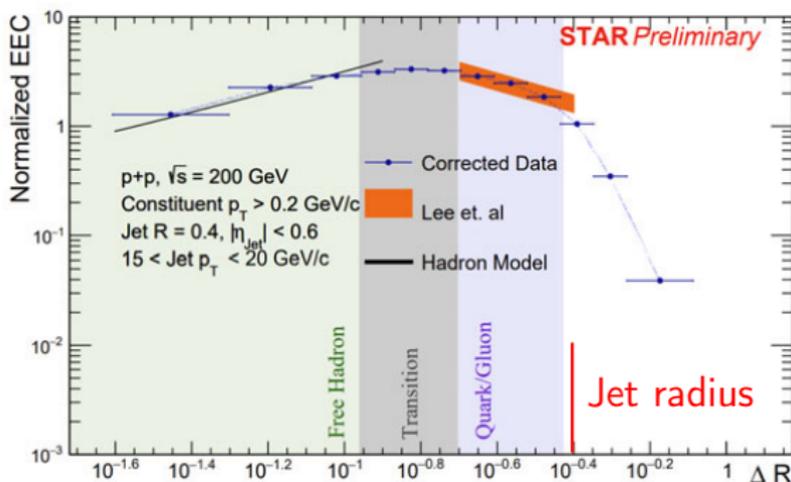
- Different regions of correlator explained in arXiv:2201.07800
- Free hadron region: scaling from uniformly distributed hadrons
- Transition region: break of scaling corresponding to confinement
- Quark/gluon region: perturbative interactions between quarks/gluons

Energy-energy correlators in pp collisions by ALICE

ALI-PREL-557422
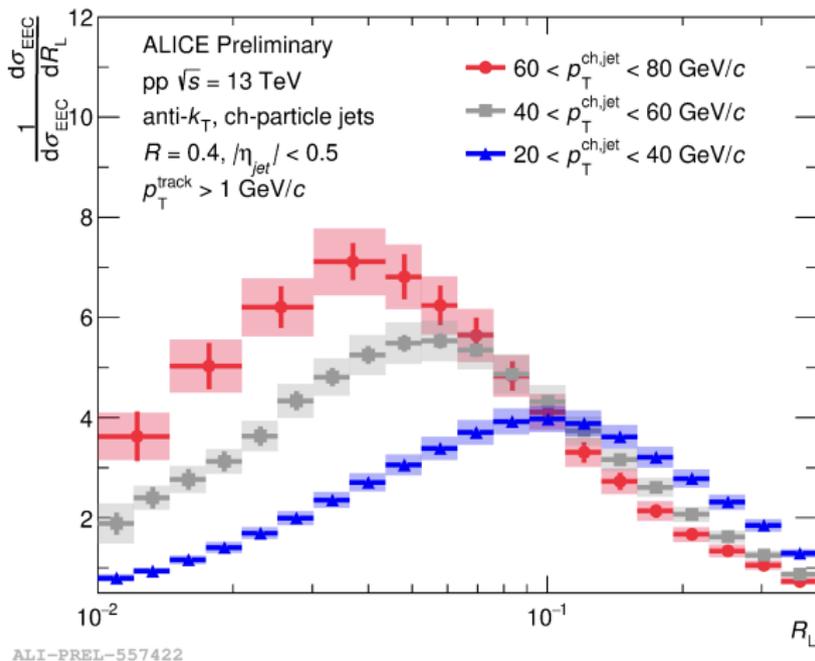
- Higher p_T jets peak at smaller opening angles between particles
  - Higher initial virtuality, more energy to radiate to reach Λ_{QCD}
  - Angular ordering $\Rightarrow$ hadronization starts at later time!

Energy-energy correlators in pp collisions by CMS

CMS *Preliminary* CMS-PAS-SMP-22-015 36.3 fb^{-1} (13 TeV)

$\frac{1}{N_{jet}} \frac{d\sigma^{[2]}}{dx_L}$

Ratio to PYTHIA8 CP5

$97 < p_T^j < 220$ GeV $468 < p_T^j < 638$ GeV $846 < p_T^j < 1101$ GeV $1410 < p_T^j < 1784$ GeV

x_L

Data   PYTHIA8 CP5(simple shower)   PYTHIA8 Vincia   PYTHIA8 Dire   HERWIG7 CH3(angular-ordered)   HERWIG7 Dipole   SHERPA2
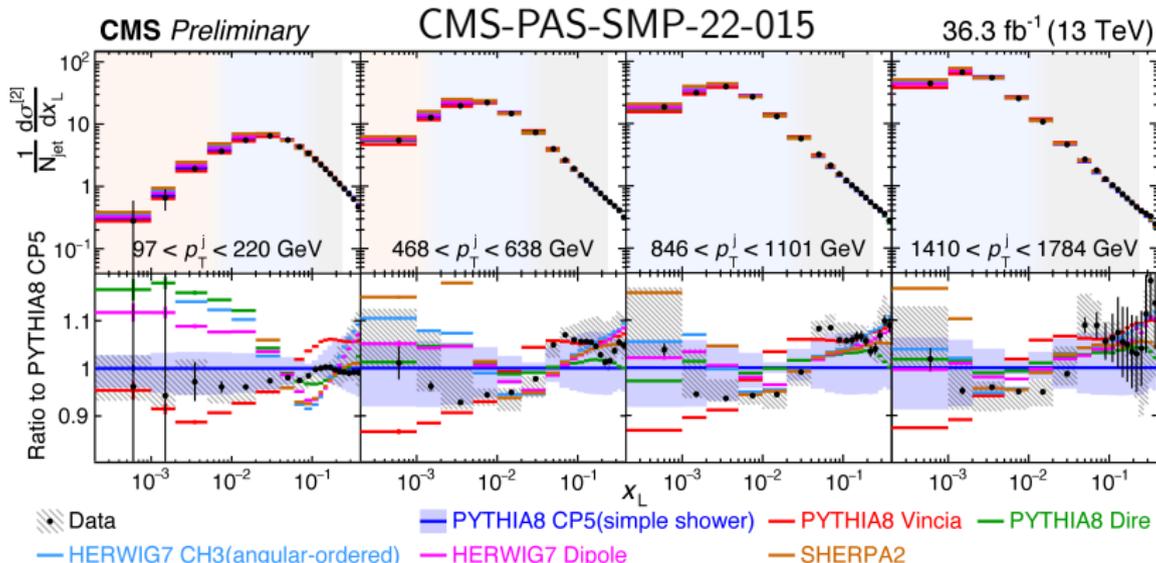
- Shift of peak in EEC continues until very high jet p_T
- Different event generators give different predictions
- No event generator can describe data over the whole jet p_T range

Contents

Simulations used in this study

- Pythia8 (CP5)
  - Study energy-energy correlators in vacuum
- Pythia+Hydjet
  - Hard jet events generated by Pythia8 (CP5) are embedded into soft underlying event generated by Hydjet (Drum5F)
  - Select the 0-10% most central events based on UE energy density
  - Jet energy loss is not simulated
  - Jet reconstruction is done only using Pythia8 particles
    - $\Rightarrow$ Particle from Pythia = signal
    - $\Rightarrow$ Particle from Hydjet = background

Signal	Pythia+Pythia	Signal+Signal
Background	Pythia+Hydjet	Signal+Fake
	Hydjet+Hydjet	Fake+Fake

Energy-energy correlator definition for this analysis

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

$$\text{EEC}(\Delta r) = \frac{1}{N_{\text{pairs}}} \sum_{\text{jets} \in [p_{\text{T},1}, p_{\text{T},2}]} \sum_{\text{pairs}} p_{\text{T},i}\, p_{\text{T},j} \, \Delta r_{i,j}$$

- Normalize with weighted number of pairs
  - $\Rightarrow$ Integral over analyzed area is one
- Do not add jet p_{T} to the pair weight
  - Improves resolution, no need for unfolding
- Selects pairs within $R = 0.4$ from winner-take-all jet axis

Energy-energy correlators as a function of jet p_T

Pythia+Hydjet 5.02 TeV
Cent: 0-10%
$3.0 <$ track p_T
■ $120 <$ jet $p_T < 140$
● $140 <$ jet $p_T < 160$
♦ $160 <$ jet $p_T < 180$
✚ $180 <$ jet $p_T < 200$
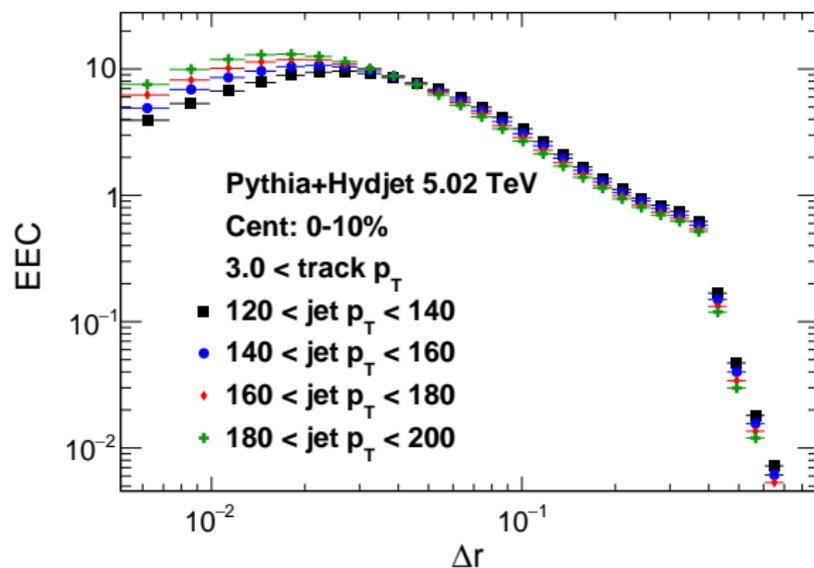
- The shape of the correlators are similar to pp data
  - Regions for free hadrons, transition, and free quarks/gluons visible
  - $0.4 < \Delta r$: Acceptance drop outside of jet radius
 - Higher p_T jets peak at lower values of Δr

Energy-energy correlators as a function of track p_T
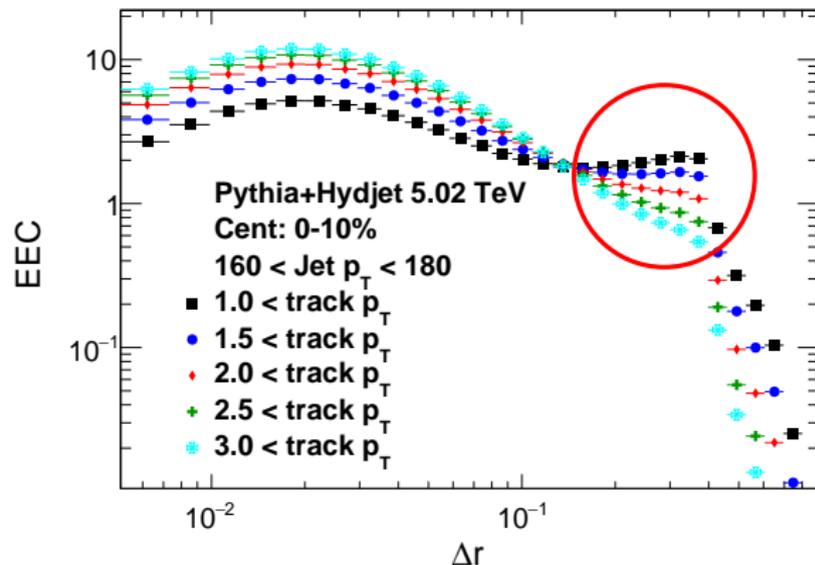
- For lower track p_T cuts, enhancement close to jet radius
- This is caused by background contributions
- Is high track p_T cut enough to suppress background?

Expected background from Pythia+Hydjet simulation

1 GeV < track p_T
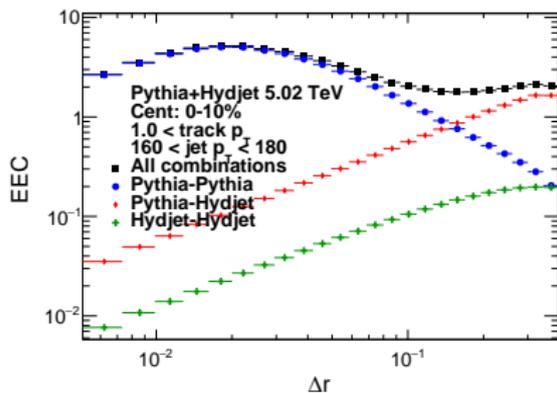
3 GeV < track p_T
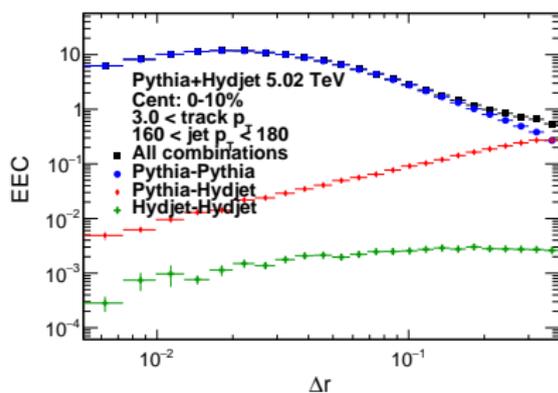
- Significant background contribution with 1 GeV cut
- Even with 3 GeV cut, significant background around $0.2 \lesssim \Delta r \lesssim 0.4$
- Background subtraction needed in PbPb

Background estimation: reflected η cone

- Reflect jet η coordinate, require at least twice the cone radius distance from original axis to avoid overlapping cones
  - if $|\eta_{\text{jet}}| > R \Rightarrow \eta_{\text{reflected}} = -\eta_{\text{jet}}$
  - if $-R \le \eta_{\text{jet}} < 0 \Rightarrow \eta_{\text{reflected}} = \eta_{\text{jet}} + 2R$
  - if $0 \le \eta_{\text{jet}} \le R \Rightarrow \eta_{\text{reflected}} = \eta_{\text{jet}} - 2R$
- The background estimation is constructed by pairing all particles from the signal cone with all particles in the reflected cone
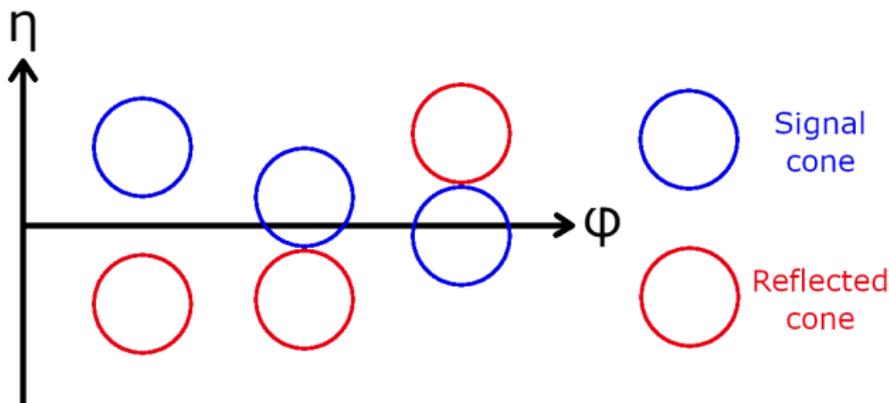
Normalization of reflected η cone background

- Even when one reflected cone per event is used to estimate background, this still needs to be normalized
  - Assume 10 background particles in signal cone and 10 in reflected cone
  - True background: $9 + 8 + \cdots + 2 + 1 = 45$ pairings
  - Reflected cone estimate: $10 + 9 + \cdots + 2 + 1 = 55$ pairings
  - There might be a random jet in the reflected cone
- $\Rightarrow$ Estimate the effect on total normalization from MC by taking ratio of background pairs in signal cone and all pairs in reflected cone

Fake+fake background within reflected η cone
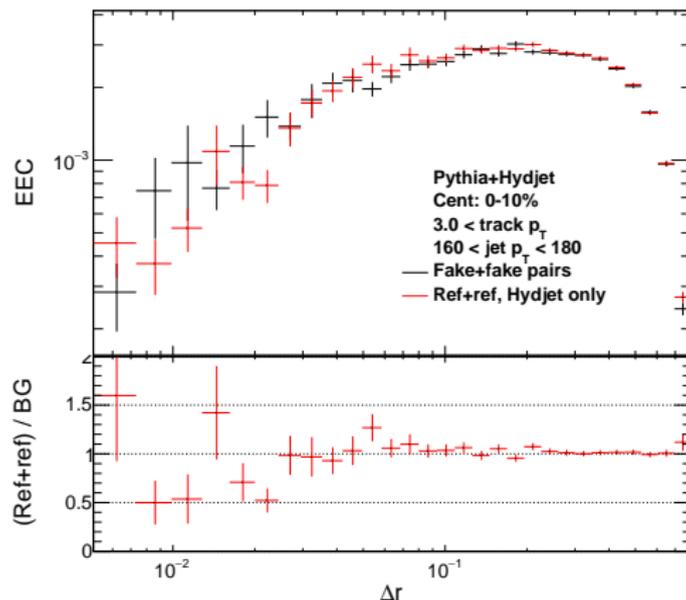
- Pairing reflected cone particles reproduces fake+fake contribution within signal cone

Signal+fake background estimation with reflected η cone
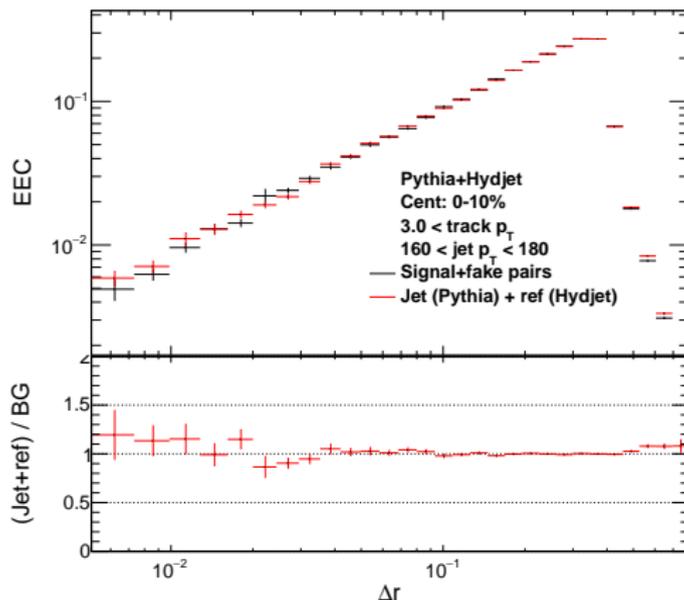
- Pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution

Fake+fake background estimation with reflected η cone
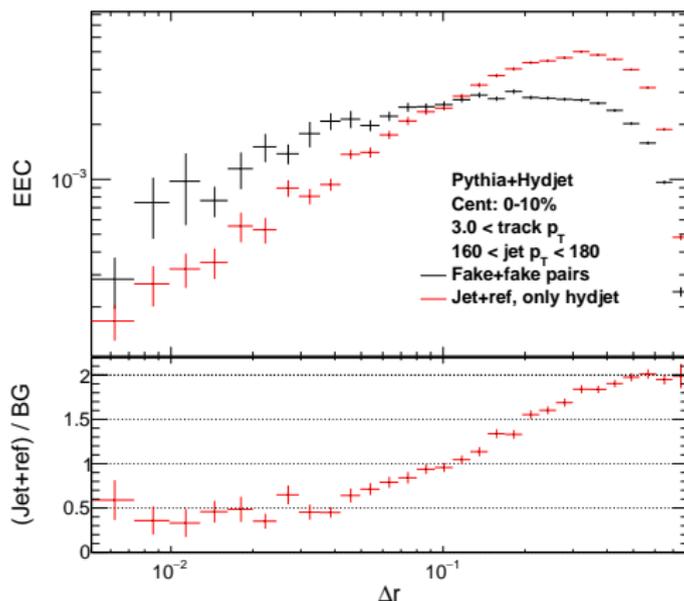
- Pairing background particles from jet cone with reflected cone does not reproduce fake+fake contribution. Missing local correlations

Overall performance of reflected η cone
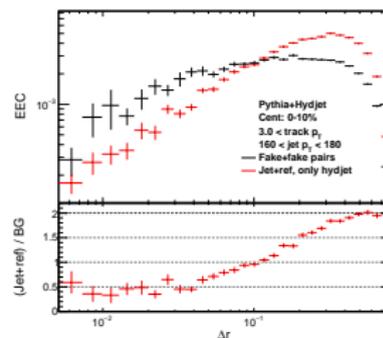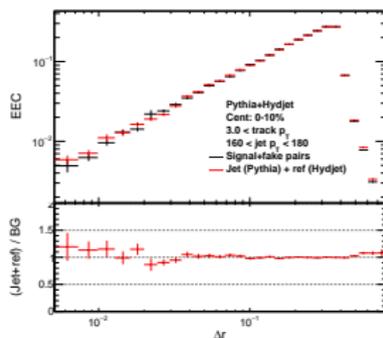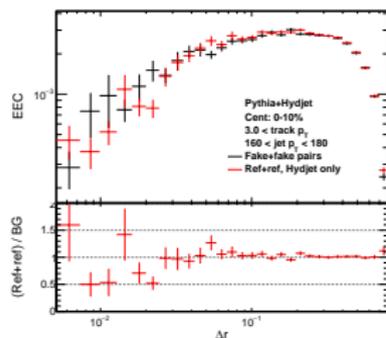
- Left: pairing reflected cone particles reproduces fake+fake contribution within signal cone
- Middle: pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution
- Right: pairing background particles from jet cone with reflected cone does not reproduce fake+fake contribution. Missing local correlations.
- ⇒ Restrict analysis to region where fake+fake contribution is small

Determine region of validity for reflected η cone
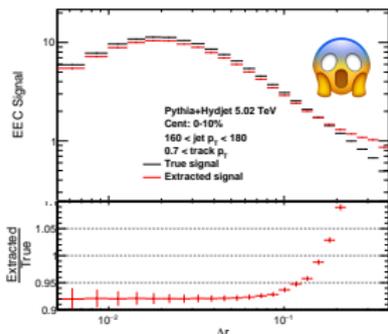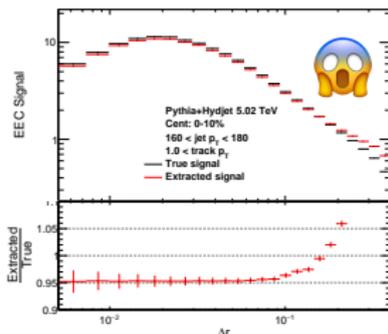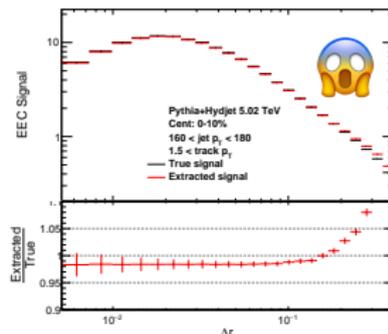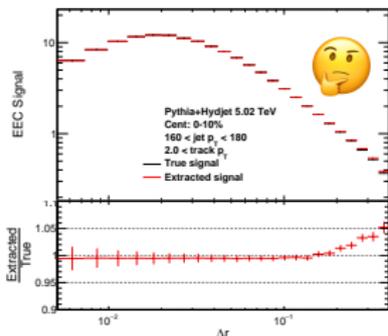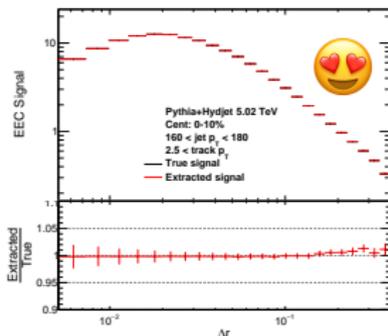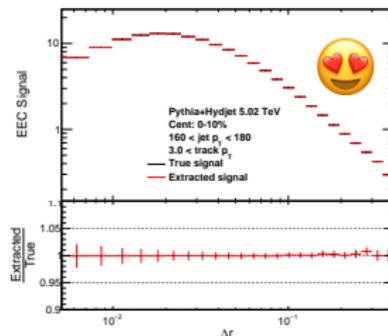
- Better than 5% closure at $p_T > 2\,\text{GeV}$ and 1% at $p_T > 2.5\,\text{GeV}$

Contents

Unfolding the measurement, how is this done in pp?

- Example from CMS-PAS-SMP-22-015
- Three-dimensional unfolding with variables:
  - Jet p_T
  - Energy weight $\frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2}$
 - Pair opening angle Δr
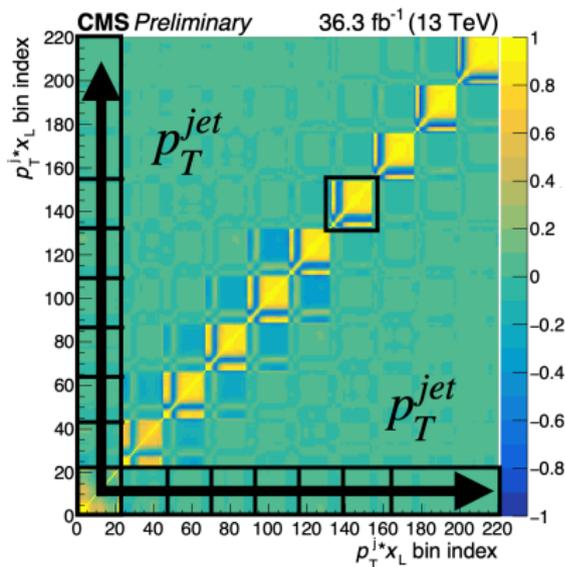
- Multidimensional unfolding in heavy ion collisions is difficult
  - Worse jet resolution compared to pp
  - Use of vacuum reference questionable
- Is there a way to simplify the unfolding procedure?

Does my observable need unfolding: jet p_T

- Jet p_T has significant resolution effects
- Gaussian smearing with $\sigma = 0.16$ applied for jet p_T to estimate resolution effects
- Resolution combined with steeply falling spectrum $\Rightarrow$ correlator shifts to right
- Conclusion: jet p_T needs unfolding
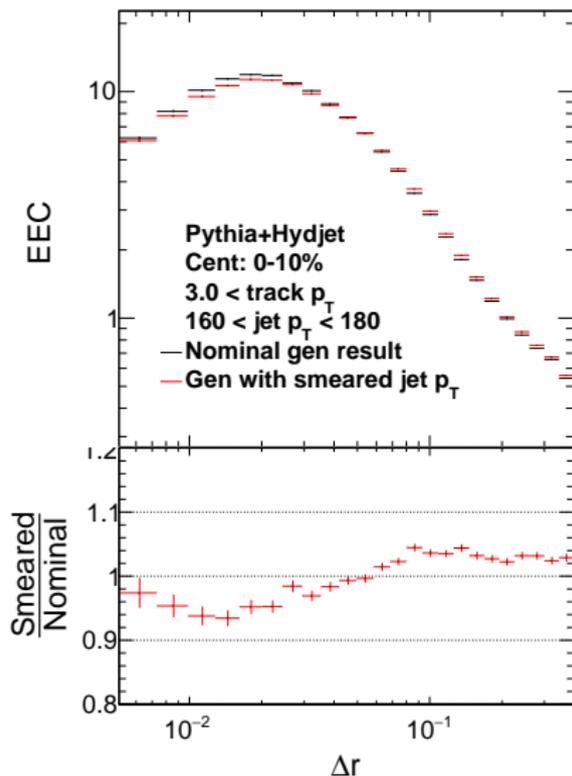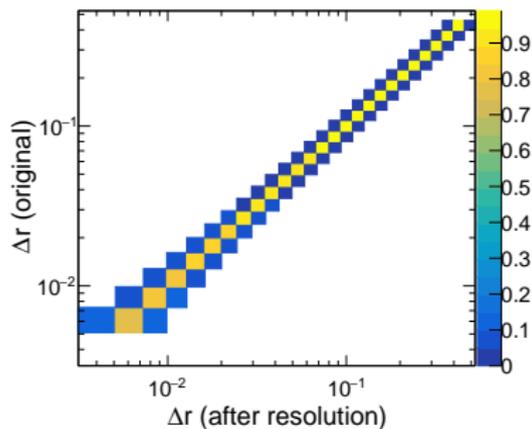
Pythia+Hydjet
Cent: 0-10%
$3.0 < $ track p_T
$160 < $ jet $p_T < 180$
— Nominal gen result
— Gen with smeared jet p_T

- Resolution model: certain probability Δr moves to neighboring bin

- Particle pair Δr resolution effects only important at very small Δr
- Conclusion: when very small angles are avoided, no unfolding needed
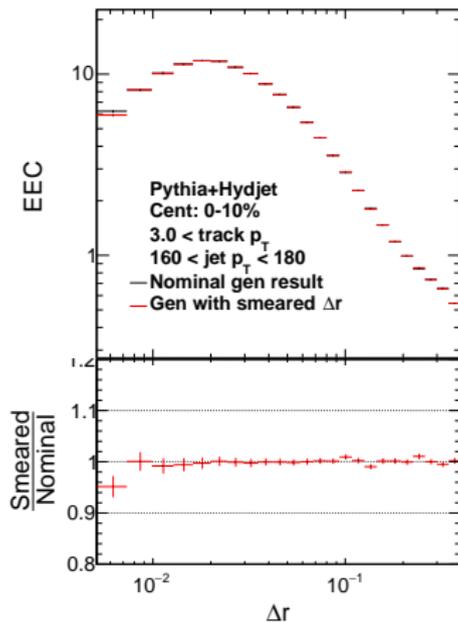
Does my observable need unfolding: Δr
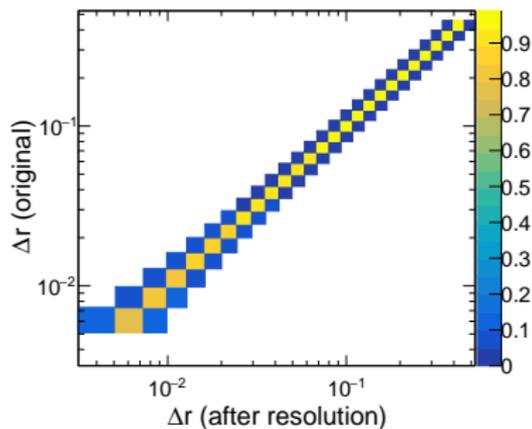
- Resolution model: certain probability Δr moves to neighboring bin

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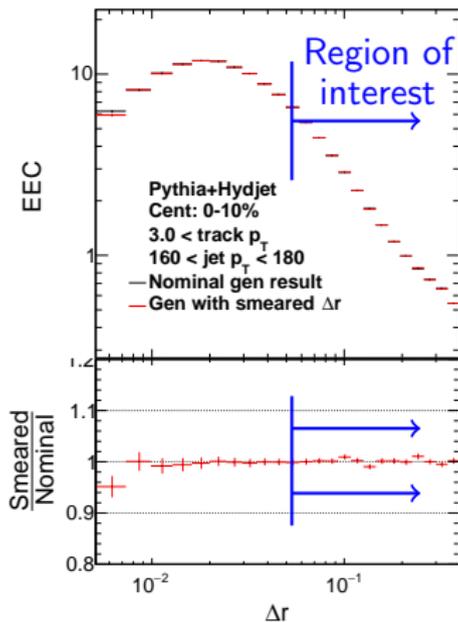
Does my observable need unfolding: $p_{T,1}\, p_{T,2}$ weight

- Particle p_T resolution generally good
- Gaussian smearing with $\sigma = 0.024$ applied for $p_{T,1}\, p_{T,2}$ to estimate resolution effects
- Conclusion: no unfolding needed

Pythia+Hydjet
Cent: 0-10%
3.0 < track p_T
160 < jet p_T < 180
— Nominal gen result
— Gen with smeared $p_{T,1} p_{T,2}$
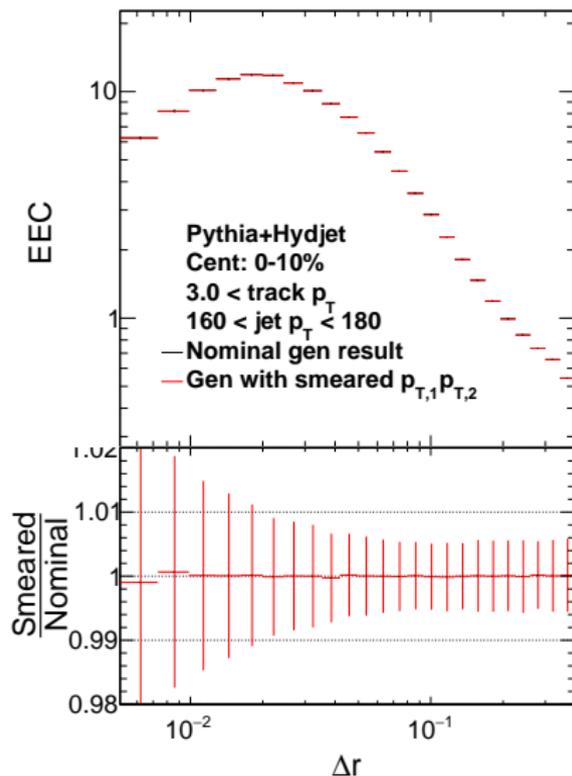
Unfolding jet p_T as binning variable

- Unfolding with RooUnfold
  - Since unfolding deals with distributions, need to combine jet p_T bins and Δr axis
  - Create response matrix from matched reconstructed and generator level jets
  - Use generator level particles for both $\Rightarrow \Delta r$ axis is diagonal


Response for 0-10%, 3.0 < track p_T
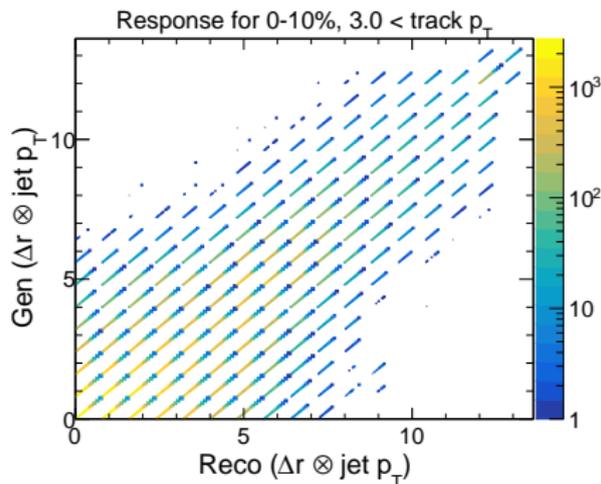
- This construction allows unfolding jet p_T bins without touching the other variables for which resolution effects are small

Contents

# Simple energy loss model: p_T spectrum shift in Pythia8
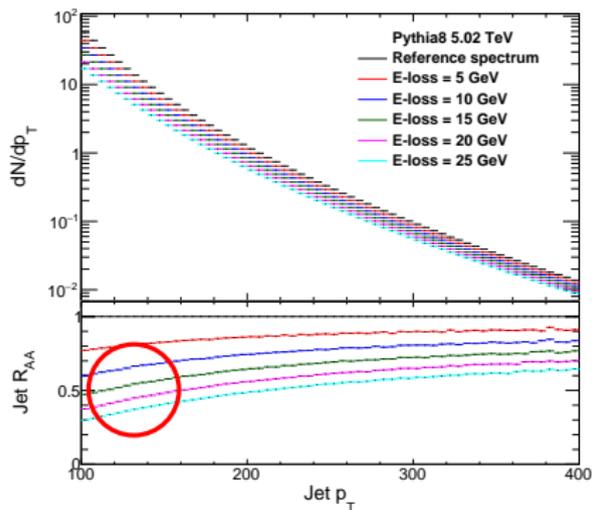
ATLAS: PRL 114 (2015) 072302
CMS: PRC 96 (2017) 015202
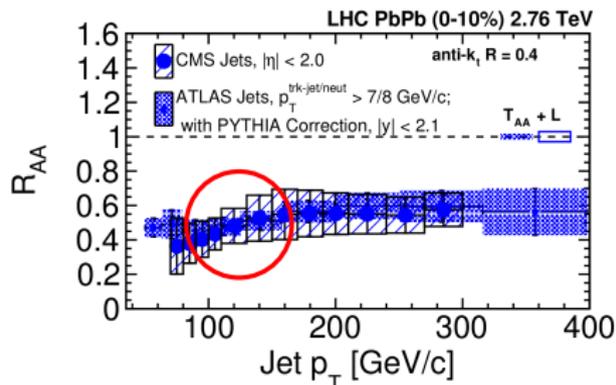
- Estimating energy loss effects in data
  - Shift the jet p_T spectrum in Pythia8
  - Find a shift that produces measured jet R_{AA} around $p_T = 120$ GeV
  - Compare energy-energy correlators in shifted and reference p_T bins

Estimate effect of energy loss to energy-energy correlator
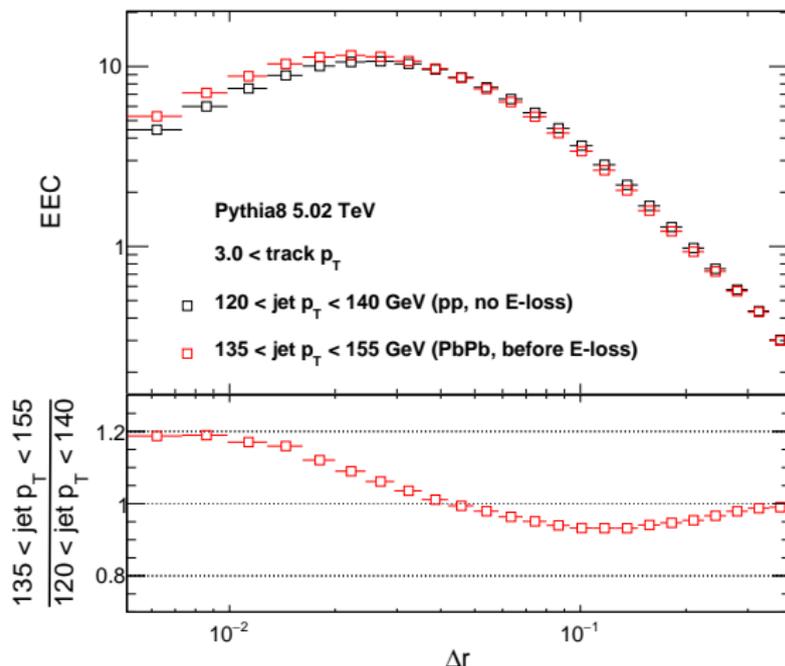
- Comparing distribution with higher initial jet p_T to a lower one leads to narrowing of energy-energy correlator

Summary

- Energy-energy correlators have been measured in pp collisions
- Main issues in heavy ion measurement with respect to pp
  - Large background, cannot get rid of with p_T cut
  - Worse object resolution, more challenging unfolding
- Methods exist to mitigate these effects
  - Reflected η cone background estimate + p_T cut
  - Clever weight definition and binning choices reduce dimensions to unfold
- Bottom line: there is a way to measure energy-energy correlators in heavy ion collisions! Stay tuned for results!
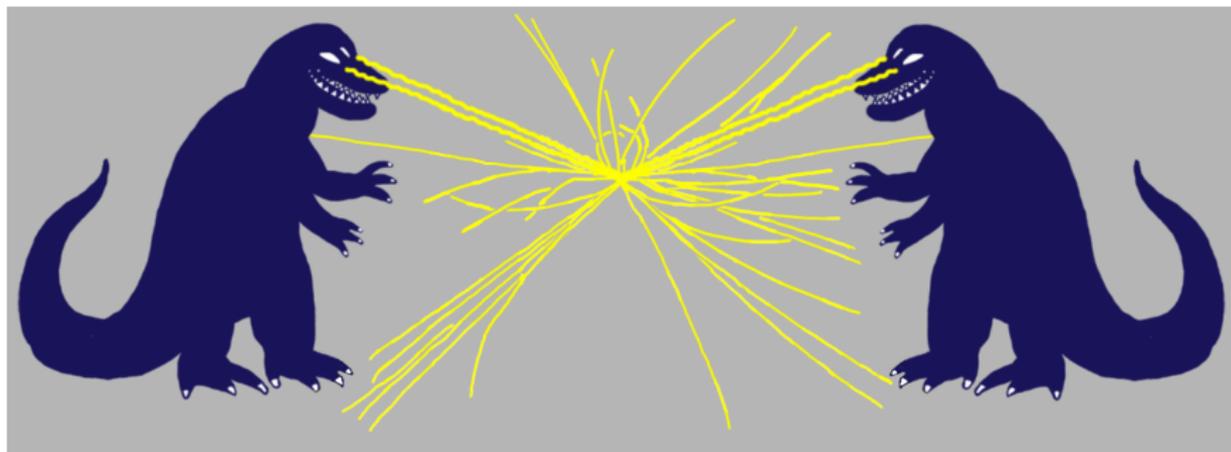
Image credit: BOOST 2022 conference logo

Particle density with respect to jet axis in Pythia8

- E-Scheme axis has a dip in particle density around jet radius
- In correlation measurements, good to avoid sharp structures like this

Pythia8
$160 <$ jet $p_T < 180$
$3.0 <$ track p_T
WTA
E-Scheme
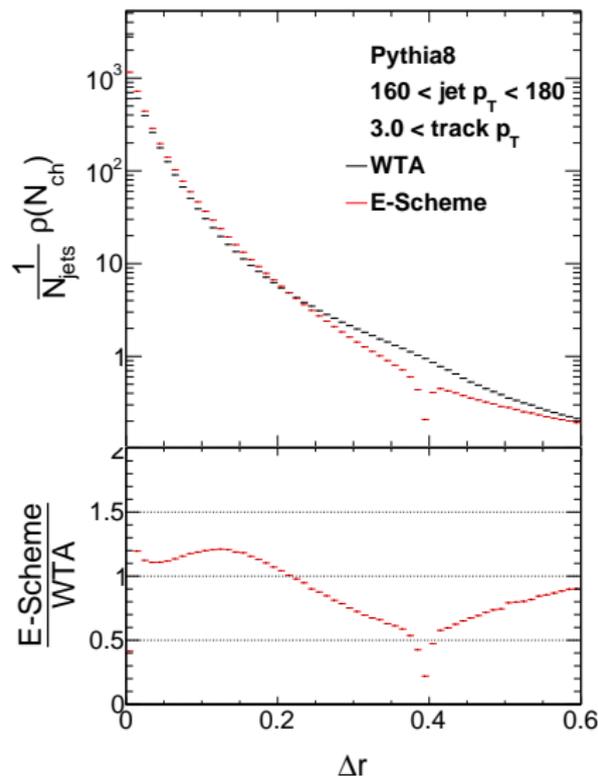
Energy-energy correlator axis comparison in Pythia8

- Most of the pairs are the same
- For e-scheme axis, strong enhancement with respect to WTA around the jet radius

Pythia8
$3.0 < $ track p_T
$160 < $ jet $p_T < 180$
— WTA
— E-Scheme