

Experimental determination of energy-energy correlators in heavy ion collisions

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Physics motivation

- A two-point energy correlator can be defined as

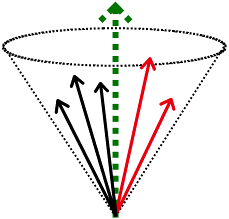
$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\theta} = \int \mathrm{d}\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$$

  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: PRL 130 (2023) 262301, JHEP 09 (2023) 088
  - Jet wake: PRL 132 (2024) 011901
  - Dead cone: arXiv:2307.15110
  - Anisotropic jet shapes: arXiv:2308.01294
  - ...

Experimental definition of energy-energy correlator

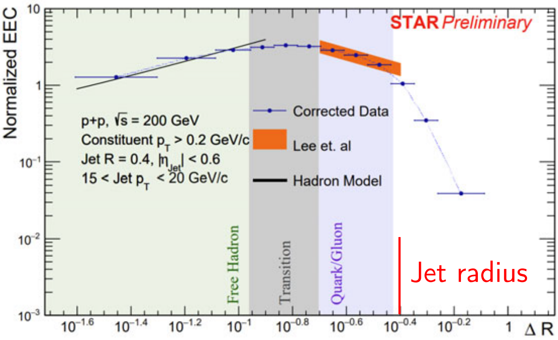
$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\theta} = \int \mathrm{d}\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$$

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



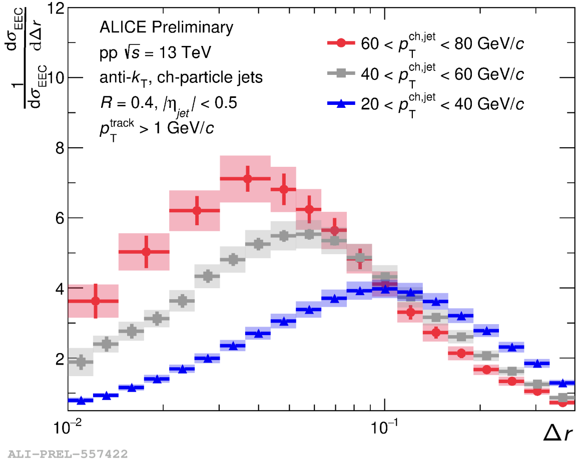
- C_{norm} = Normalization factor
- $p_{\mathrm{T},i}\, p_{\mathrm{T},j}$ = Particle transverse momentum
- $p_{\mathrm{T,jet}}$ = Jet transverse momentum
- $\Delta r_{i,j} = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ = Angular distance between particles

Energy-energy correlators in pp collisions by STAR



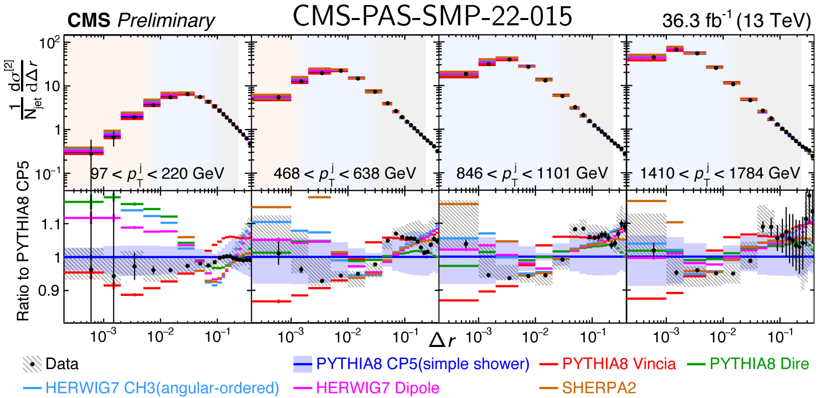
- Different regions of correlator explained in PRL 130 (2023) 051901
- Quark/gluon region: perturbative interactions between quarks/gluons
- Transition region: break of scaling corresponding to confinement
- Free hadron region: scaling from uniformly distributed hadrons

Energy-energy correlators in pp collisions by ALICE



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

Energy-energy correlators in pp collisions by CMS



- 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

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Simulations used in this study

- Only generator level information is used
- 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

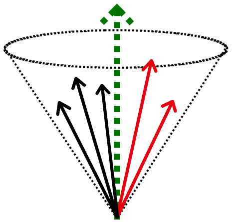
    ⇒ Particle from Pythia = signal

    ⇒ 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

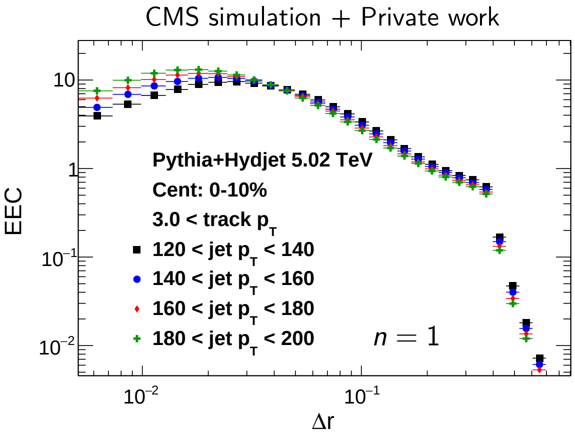
$$\mathrm{EEC}(\Delta r) = C_{\mathrm{norm}} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\mathrm{pairs}} \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^2} \Delta r_{i,j}$$



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

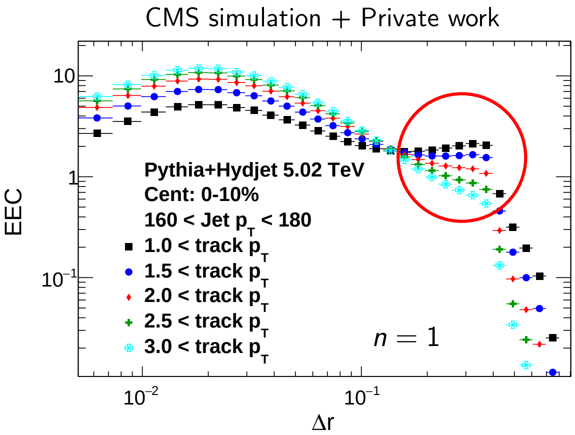
- Normalize with weighted number of pairs
  - ⇒ Integral over analyzed area is one
- Do not add jet p_{T} to the pair weight
  - Improves resolution, no need for unfolding
- Sensitivity to soft particles can be decreased by setting $n = 2$
- Selects pairs within $R = 0.4$ from winner-take-all jet axis

Energy-energy correlators as a function of jet p_{T}



- 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

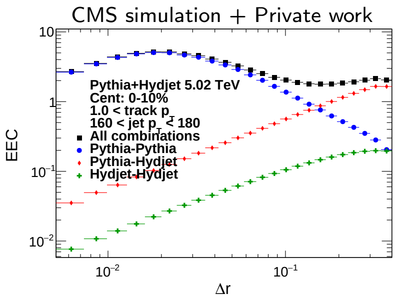
Energy-energy correlators as a function of track p_{T}



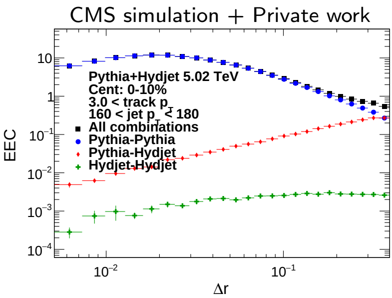
- For lower track p_{T} cuts, enhancement close to jet radius
- This is caused by background contributions
- Is high track p_{T} cut enough to suppress background?

Expected background from Pythia+Hydjet, $n = 1$

$1\,\text{GeV} < \text{track } p_{\mathrm{T}}, \quad n = 1$



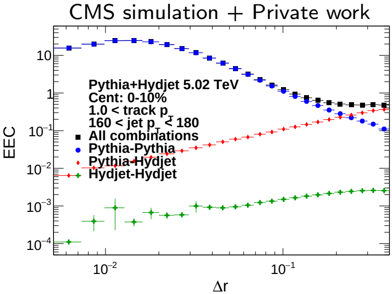
$3\,\text{GeV} < \text{track } p_{\mathrm{T}}, \quad n = 1$



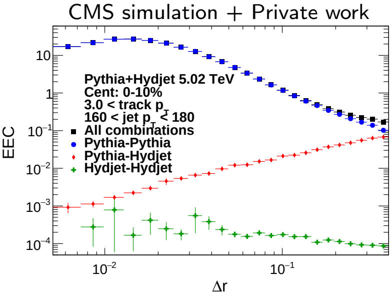
- Significant background contribution with 1 GeV cut
- Even with 3 GeV cut, significant background around $0.2 \lesssim \Delta r \lesssim 0.4$
- Can this be helped with increasing the weight exponent n?

Expected background from Pythia+Hydjet, $n = 2$

$1\,\mathrm{GeV} < \text{track } p_{\mathrm{T}}, \quad n = 2$



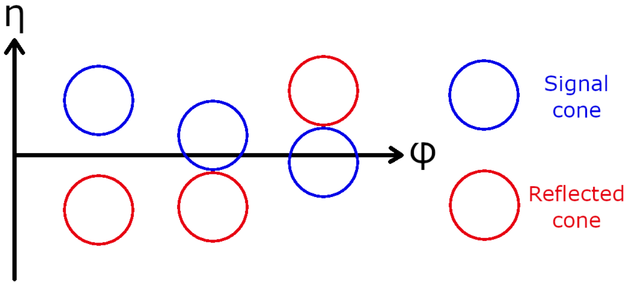
$3\,\mathrm{GeV} < \text{track } p_{\mathrm{T}}, \quad n = 2$



- Fake+fake background significantly reduced with respect to $n = 1$
- Signal+fake background is still significant
- 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 $-R \leq \eta_{\text{jet}} < 0 \Rightarrow \eta_{\text{reflected}} = \eta_{\text{jet}} + 2R$
  - if $0 \leq \eta_{\text{jet}} \leq R \Rightarrow \eta_{\text{reflected}} = \eta_{\text{jet}} - 2R$
- The background estimation is constructed by pairing all particles from the signal cone with all particles in the reflected cone

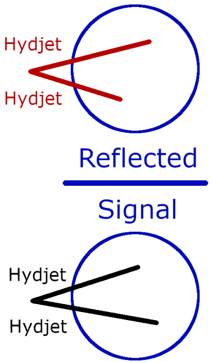


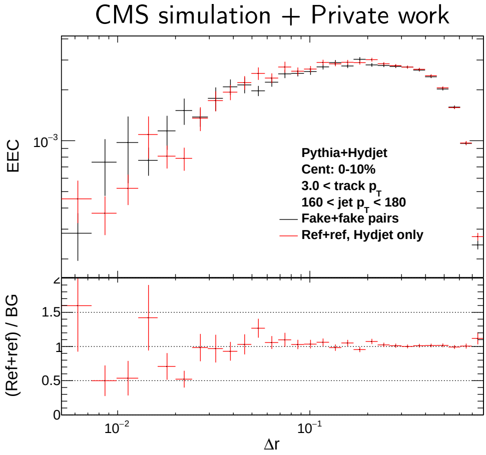
Normalization of reflected η cone background

- 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: $10 + 10 + \cdots + 10 + 10 = 100$ 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

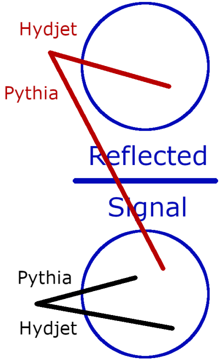
Fake+fake background within reflected η cone

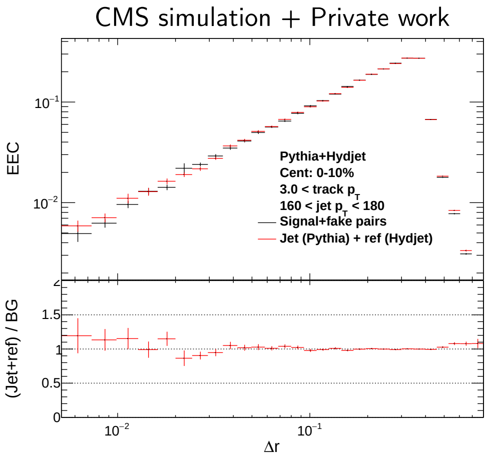




- Pairing reflected cone particles reproduces fake+fake contribution within signal cone

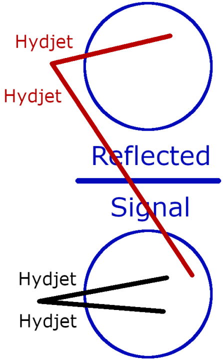
Signal+fake background estimation with reflected η cone

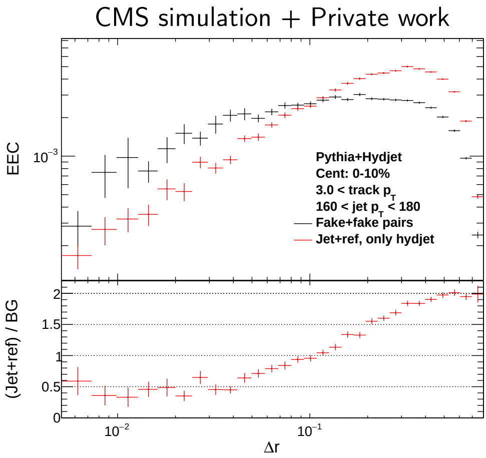




- Pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution

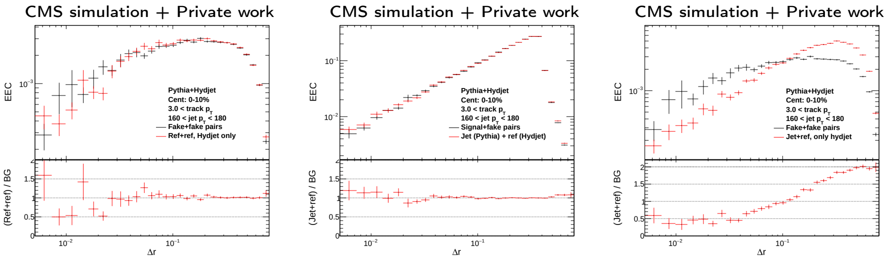
Fake+fake background estimation with reflected η cone





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

Overall performance of reflected η cone

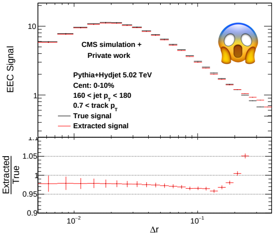


- Left: pairing reflected cone particles reproduces fake+fake contribution within signal cone
- Middle: pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution
- Right: pairing background particles from jet cone with reflected cone does not reproduce fake+fake contribution. Missing local correlations.

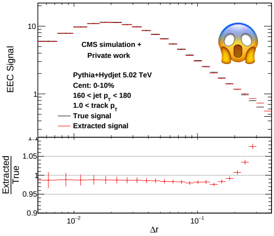
$\Rightarrow$ Restrict analysis to region where fake+fake contribution is small

Determine region of validity for reflected η cone, $n = 1$

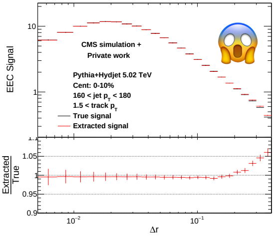
track $p_T > 0.7$ GeV



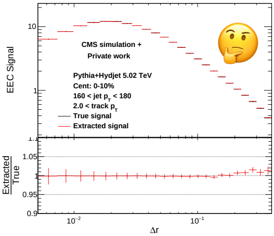
track $p_T > 1$ GeV



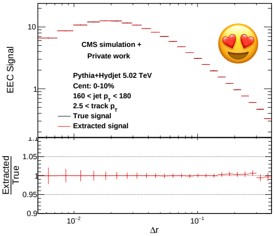
track $p_T > 1.5$ GeV



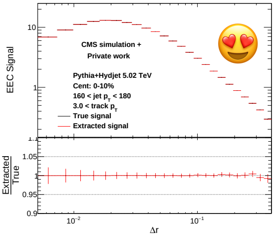
track $p_T > 2$ GeV



track $p_T > 2.5$ GeV



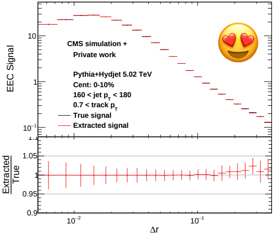
track $p_T > 3$ GeV



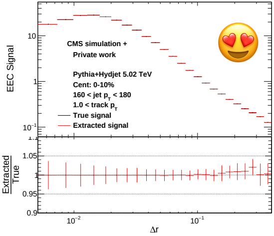
- Better than 2% closure at $p_T > 2$ GeV and 1% at $p_T > 2.5$ GeV

Determine region of validity for reflected η cone, $n = 2$

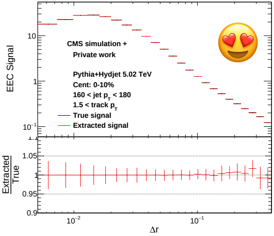
track $p_T > 0.7$ GeV



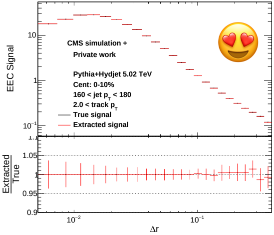
track $p_T > 1$ GeV



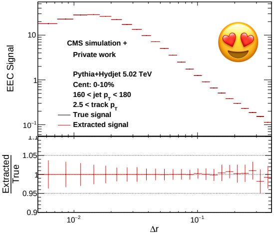
track $p_T > 1.5$ GeV



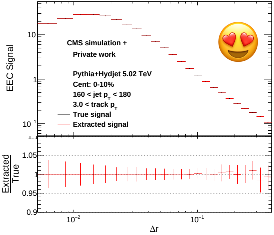
track $p_T > 2$ GeV



track $p_T > 2.5$ GeV



track $p_T > 3$ GeV

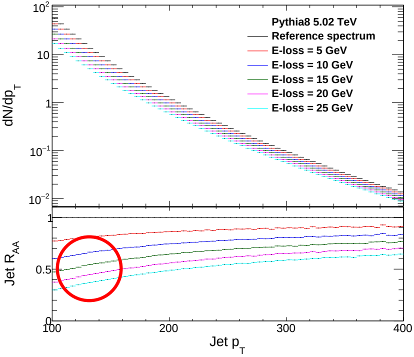


- With $n = 2$, very good closure in the whole studied track p_T range!

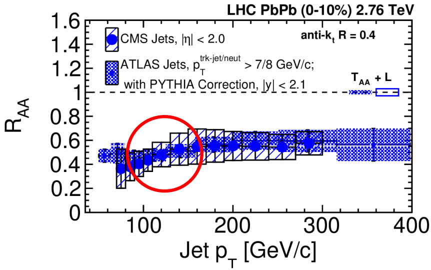
Contents

Simple energy loss model: p_{T} spectrum shift in Pythia8

CMS simulation + Private work

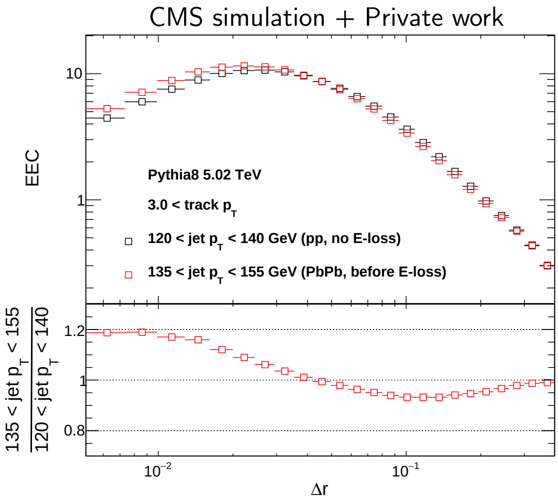


ATLAS: PRL 114 (2015) 072302
CMS: PRC 96 (2017) 015202



- Estimating energy loss effects in data
  - Shift the jet p_{T} spectrum in Pythia8
  - Find a shift that produces measured jet R_{AA} around $p_{\mathrm{T}} = 120\,\mathrm{GeV}$
  - Compare energy-energy correlators in shifted and reference p_{T} bins

Estimate effect of energy loss to energy-energy correlator



- Simple energy loss leads to narrowing of energy-energy correlator
- Possible substructure modifications will be on top of this shape!

Summary

- Energy-energy correlators have been measured in pp collisions
- In PbPb collisions, large underlying event makes measurement difficult
- Effects of background can be mitigated
  - Reflected η cone background estimate
  - Apply higher track p_{T} cut
  - Use higher exponent for energy weight
- Possible substructure modifications will be on top of a narrowing from energy loss
- Bottom line: there is a way to measure energy-energy correlators in heavy ion collisions! Stay tuned for results!

This work is supported by the grant DE-FG05-92ER40712 from the US Department of Energy

Back-up

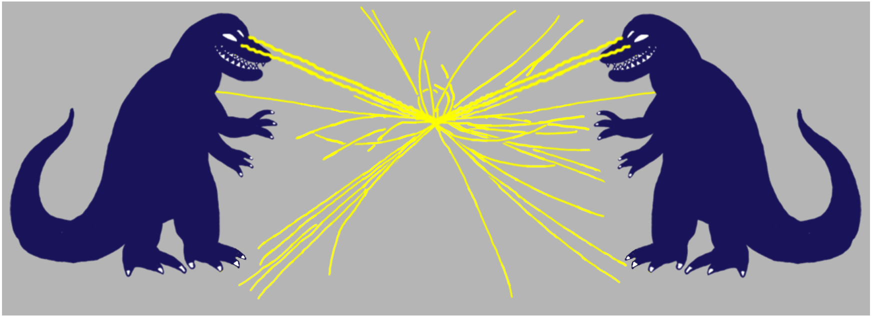
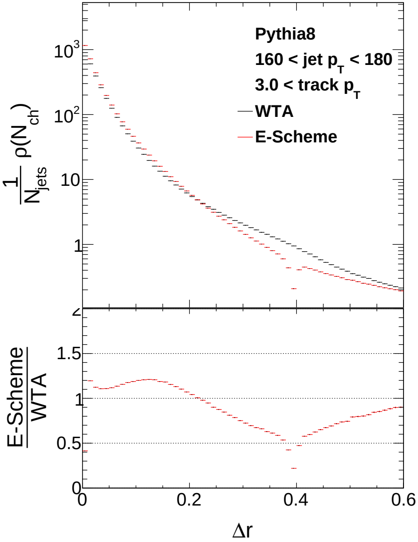


Image credit: BOOST 2022 conference logo

Particle density with respect to jet axis in Pythia8

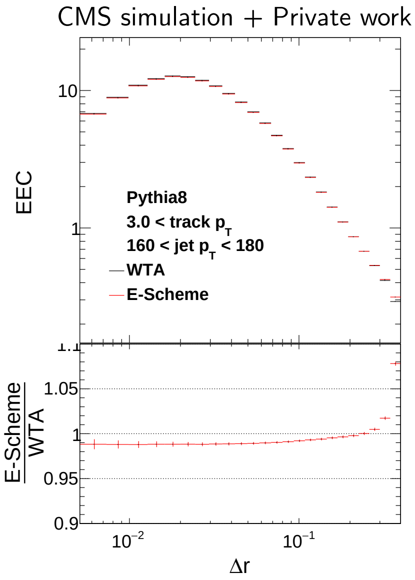
- E-Scheme axis has a dip in particle density around jet radius
- In correlation measurements, good to avoid sharp structures like this

CMS simulation + Private work



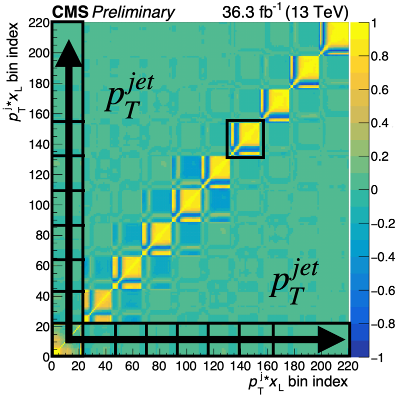
Energy-energy correlator axis comparison in Pythia8

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



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 $\frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$
  - Pair opening angle Δr

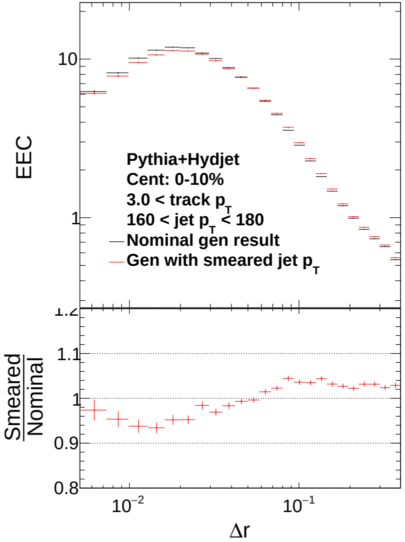


- Multidimensional unfolding in heavy ion collisions is difficult
  - Worse jet resolution compared to pp
  - Use of vacuum reference questionable
- Is there a way to simplify the unfolding procedure?

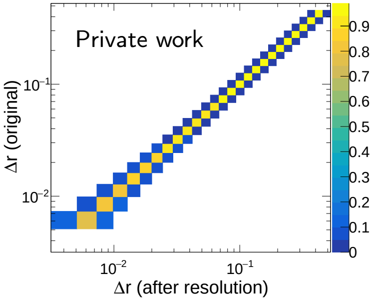
Does my observable need unfolding: jet p_T

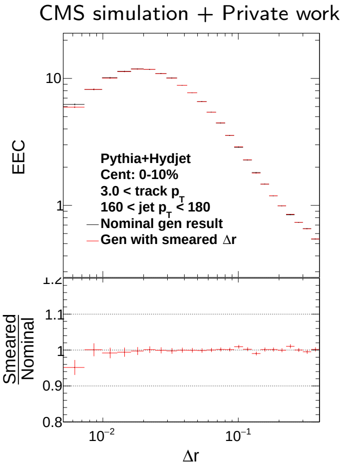
- Jet p_T has significant resolution effects
- Gaussian smearing with $\sigma = 0.16$ applied for jet p_T to estimate resolution effects
- Resolution combined with steeply falling spectrum $\Rightarrow$ correlator shifts to right
- Conclusion: jet p_T needs unfolding

CMS simulation + Private work



Does my observable need unfolding: Δr

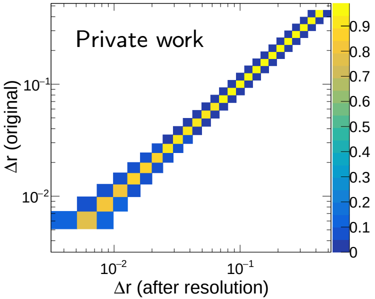


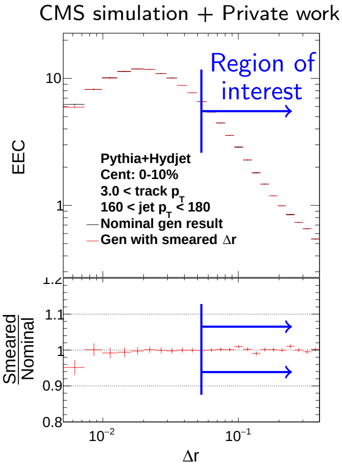


- Resolution model: certain probability Δr moves to neighboring bin

- 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

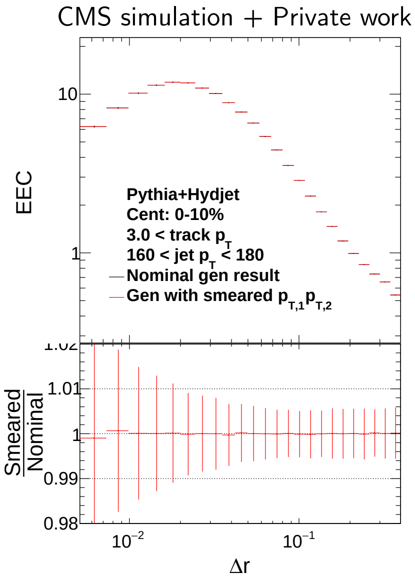




- Resolution model: certain probability Δr moves to neighboring bin
- Particle pair Δr resolution effects only important at very small Δr
- Conclusion: when very small angles are avoided, no unfolding needed

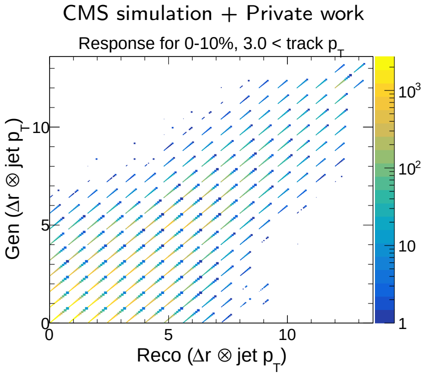
Does my observable need unfolding: $p_{T,1}\,p_{T,2}$ weight

- 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



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 $\Rightarrow$ Δr axis is diagonal



- This construction allows unfolding jet p_{T} bins without touching the other variables for which resolution effects are small