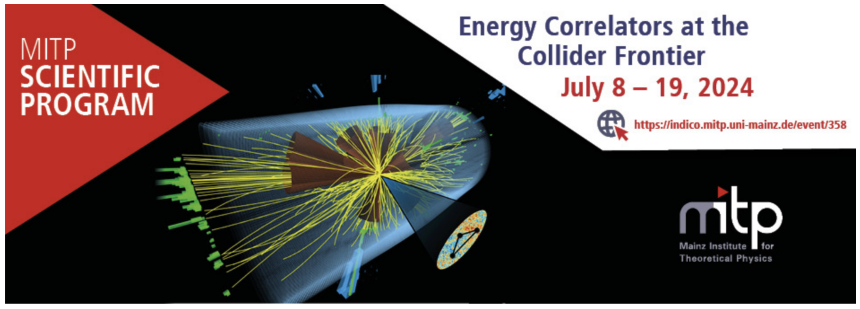

Energy-energy correlators from PbPb and pp collisions at 5.02 TeV with CMS

Jussi Viinikainen

https://jusaviin.github.io

Vanderbilt University

for the CMS Collaboration

Energy Correlators at the Collider Frontier

Contents

Image credit: Jennifer James (Vanderbilt)

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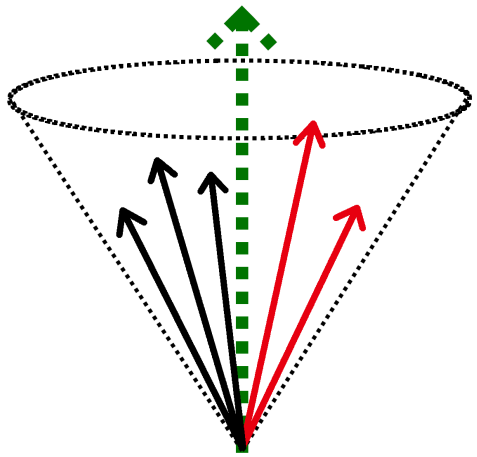
Image credit: Jennifer James (Vanderbilt)

Experimental definition of energy-energy correlator

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

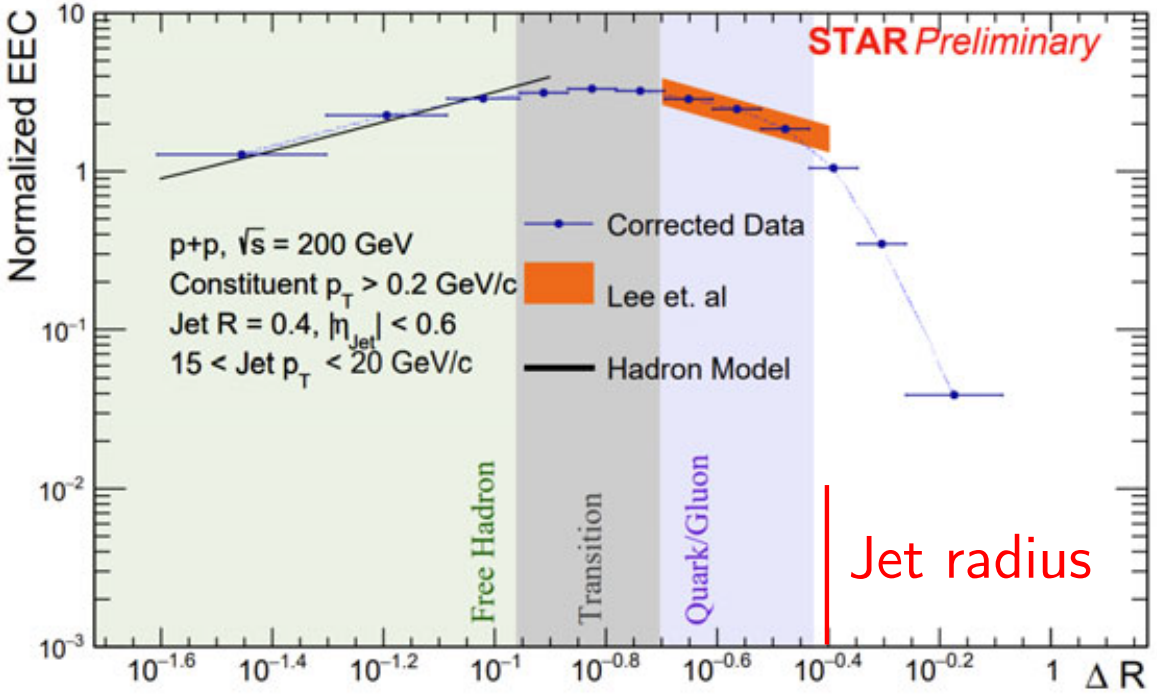


$$\mathrm{EEC}(\Delta r) = C_{\mathrm{norm}} \sum_{\mathrm{jets}\in[p_{\mathrm{T},1},p_{\mathrm{T},2}]} \sum_{\mathrm{pairs}\in[\Delta r_a,\Delta r_b]} \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

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

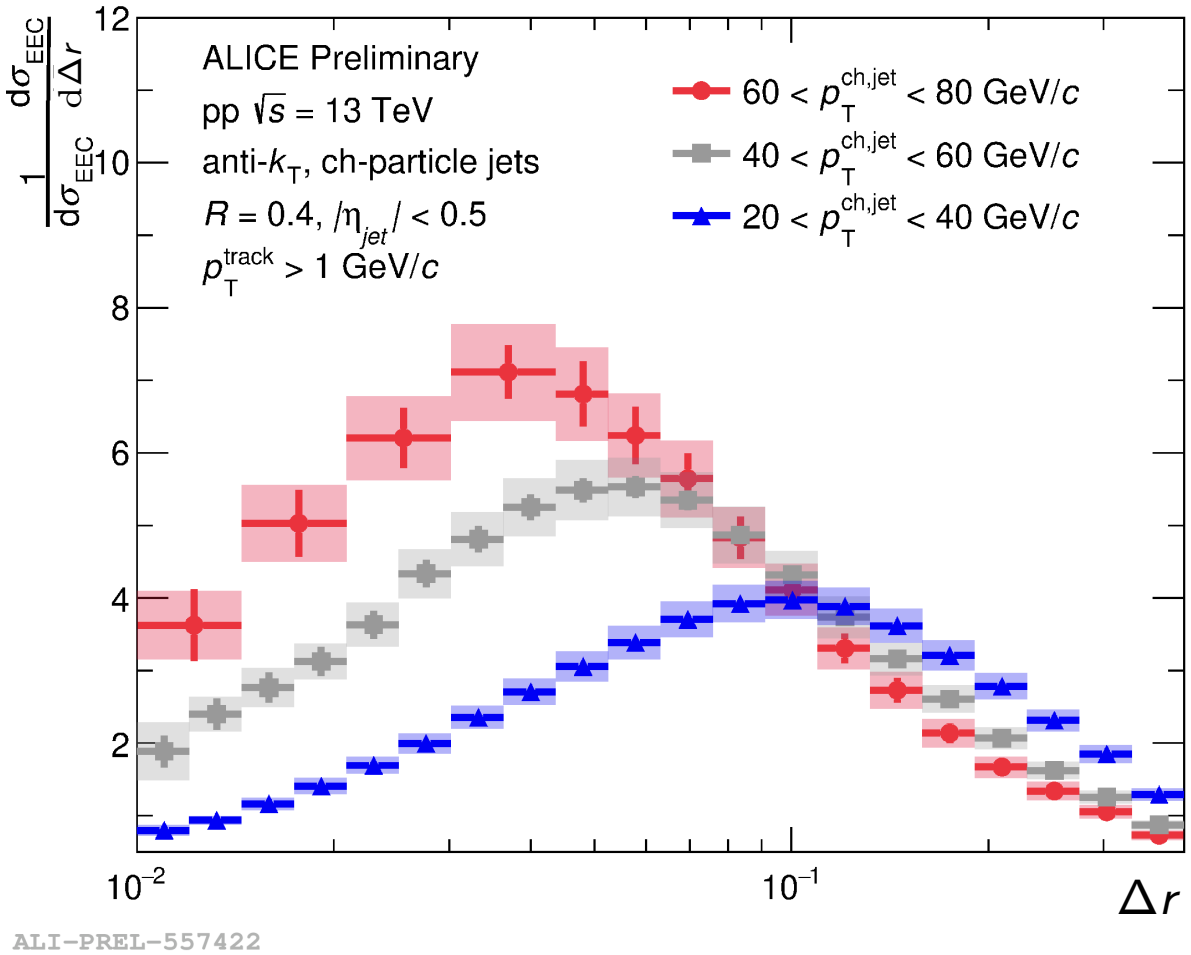
Energy-energy correlators in pp collisions by STAR

PoS HardProbes2023 (2024) 175



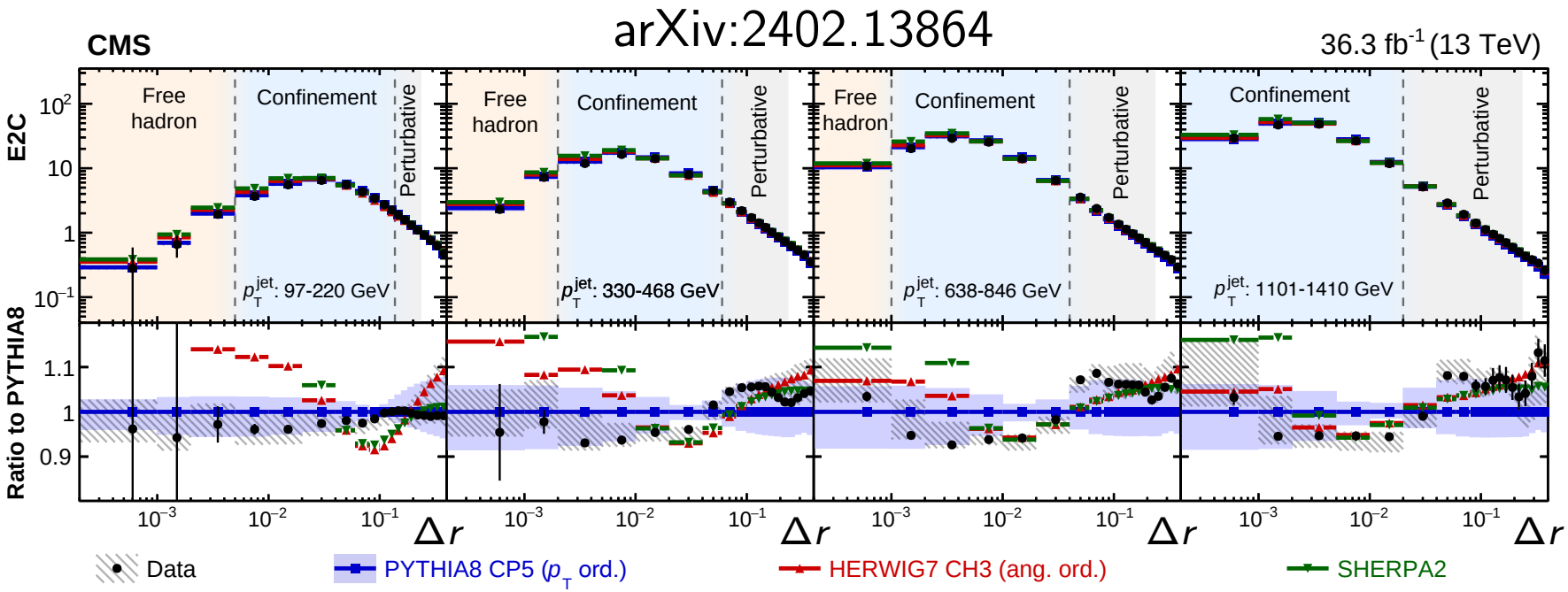
- Different regions are explained in PRL 130 (2023) 5, 051901
- Free hadron region: scaling from uniformly distributed hadrons
- Transition region: break of scaling corresponding to confinement
- Quark/gluon region: perturbative interactions between quarks/gluons

Energy-energy correlators in pp collisions by ALICE



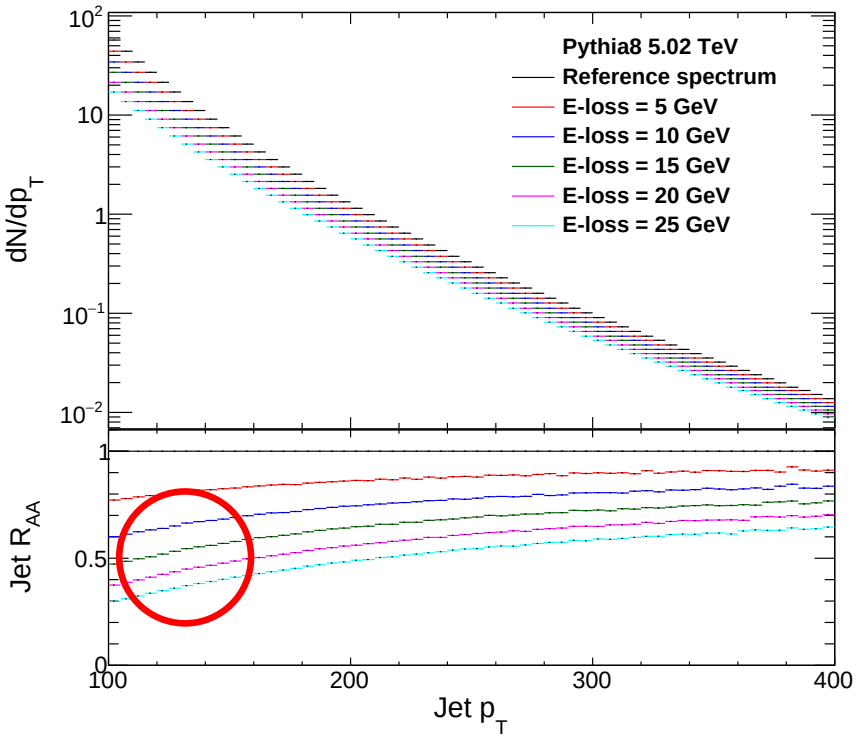
- Higher p_{T} jets peak at smaller opening angles between particles
  - Higher initial virtuality, more energy to radiate to reach Λ_{QCD}
  - Angular ordering $\Rightarrow$ hadronization starts at later time!

Energy-energy correlators in pp collisions by CMS

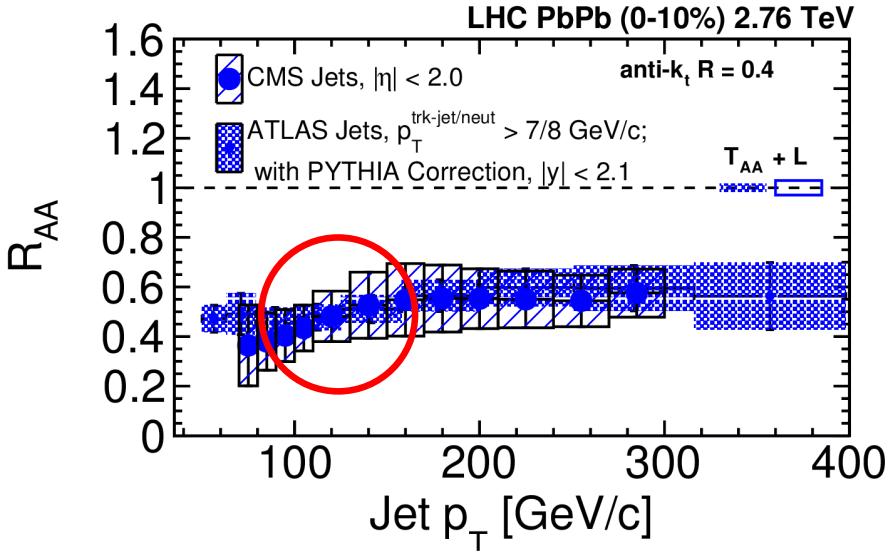


- Shift of peak in EEC continues until very high jet p_{T}
- Different event generators give different predictions
- No event generator can describe data over the whole jet p_{T} range

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

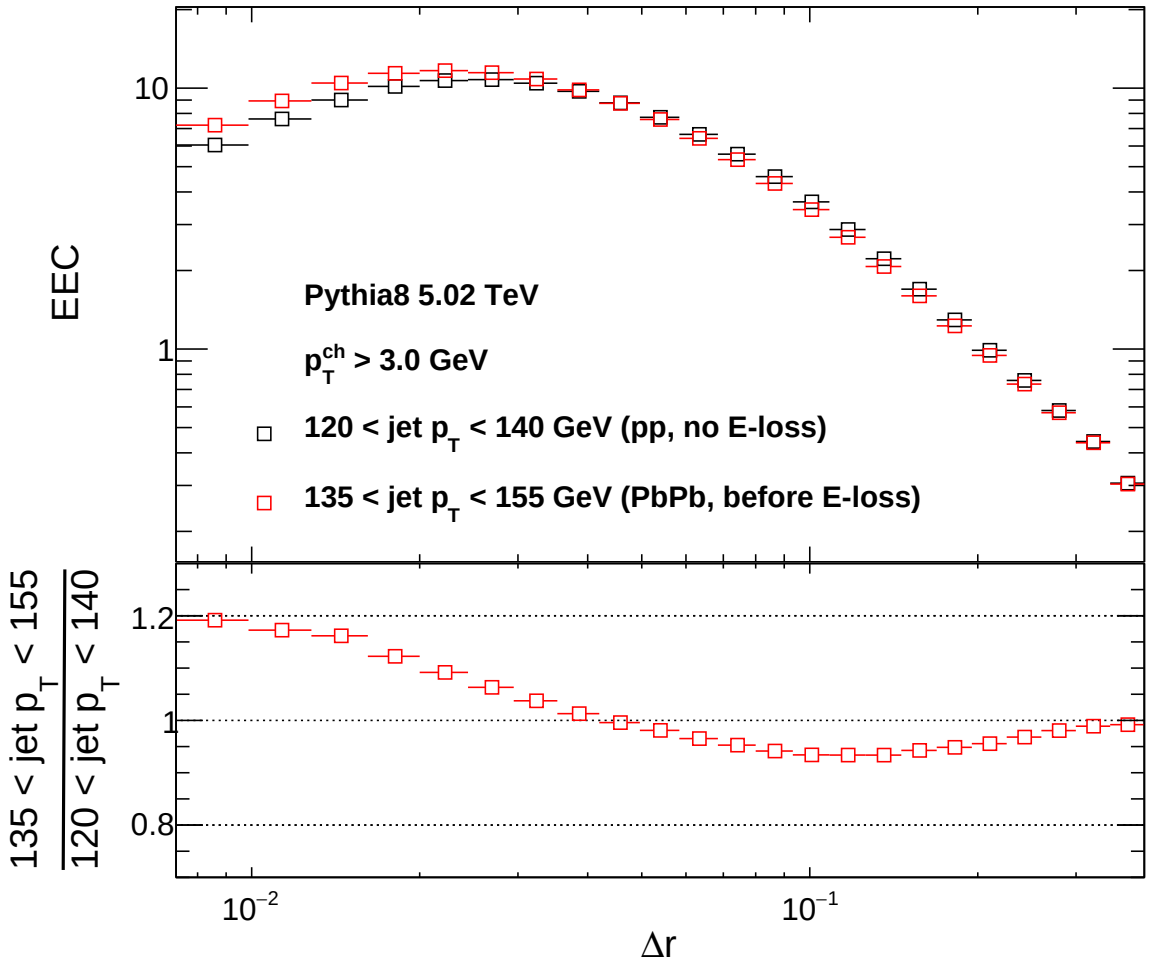


ATLAS: PRL 114 (2015) 072302
CMS: PRC 96 (2017) 015202



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

Medium effects: jet p_{T} spectrum shift

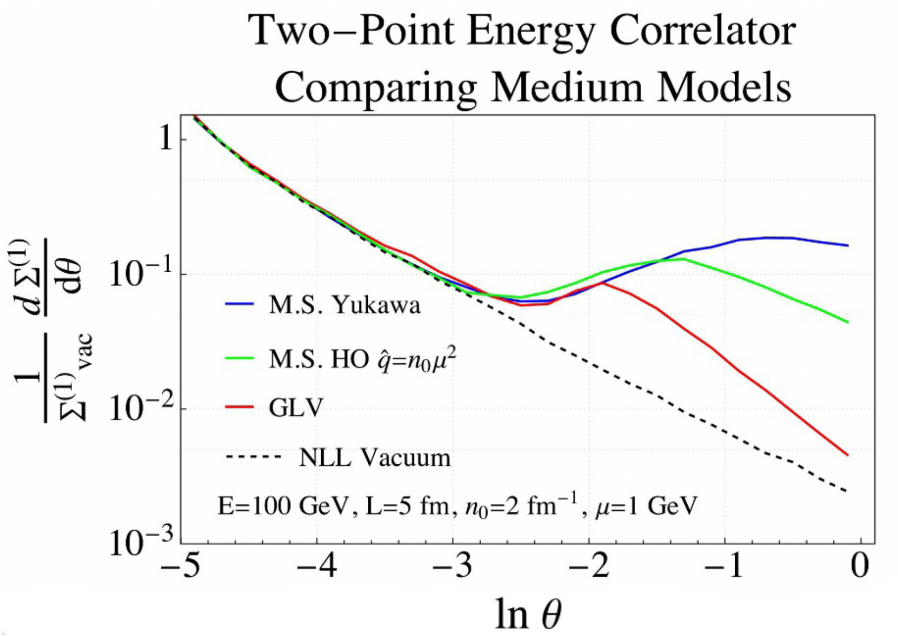


- Comparing distribution with higher initial jet p_{T} to a lower one leads to narrowing of energy-energy correlator

Color coherence effects to the correlator shape

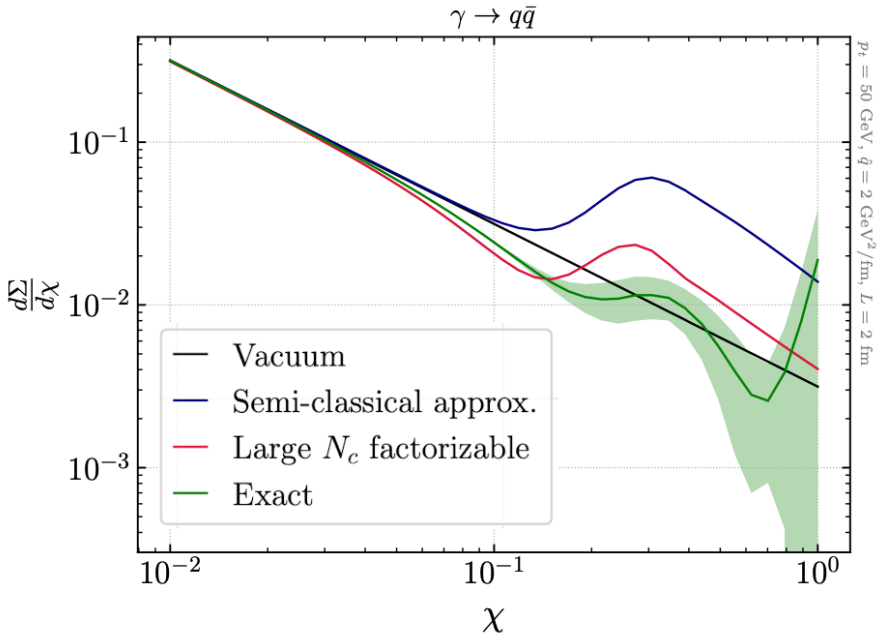
Andrés, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult

JHEP 09 (2023) 088



Barata, Caucal, Soto-Ontoso, Szafron

arXiv:2312.12527

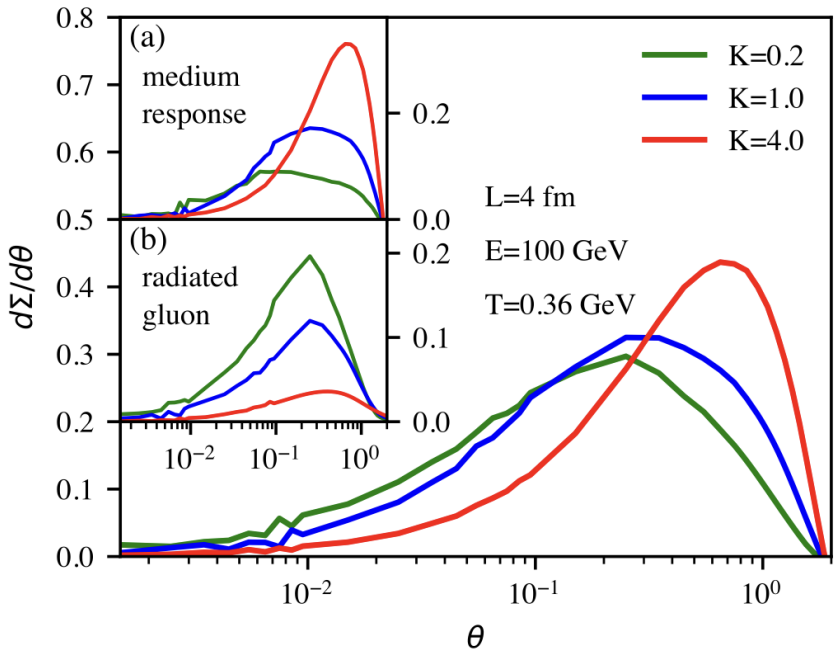


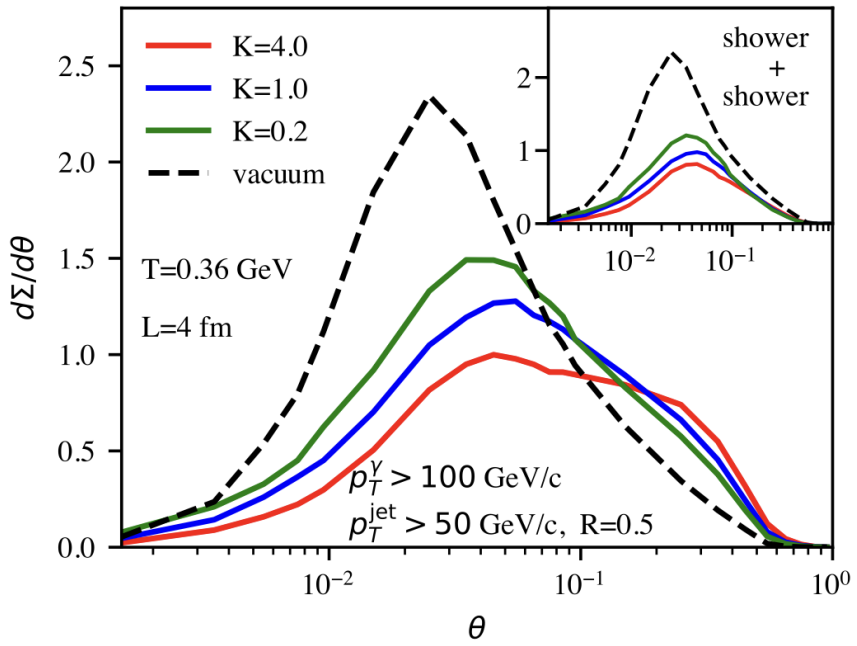
- Color coherence effects expected to change the shape at large angles

Jet wake effects to the correlator shape

Yang, He, Moult, Wang

PRL 132 (2024) 1, 011901





- Also jet wake effects expected to modify the shape at large angles

Contents

Image credit: Jennifer James (Vanderbilt)

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

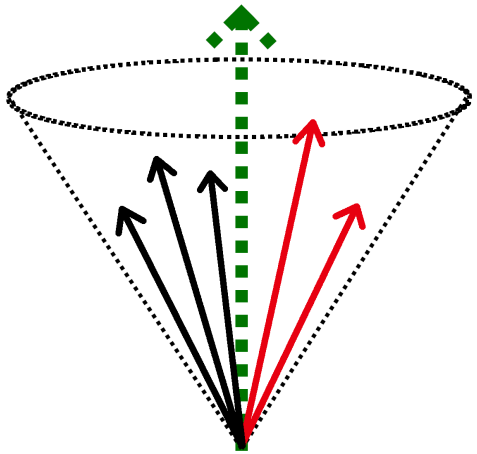
Signal	Pythia+Pythia	Signal+Signal
Background	Pythia+Hydjet	Signal+Fake
	Hydjet+Hydjet	Fake+Fake

Energy-energy correlator definition for this analysis

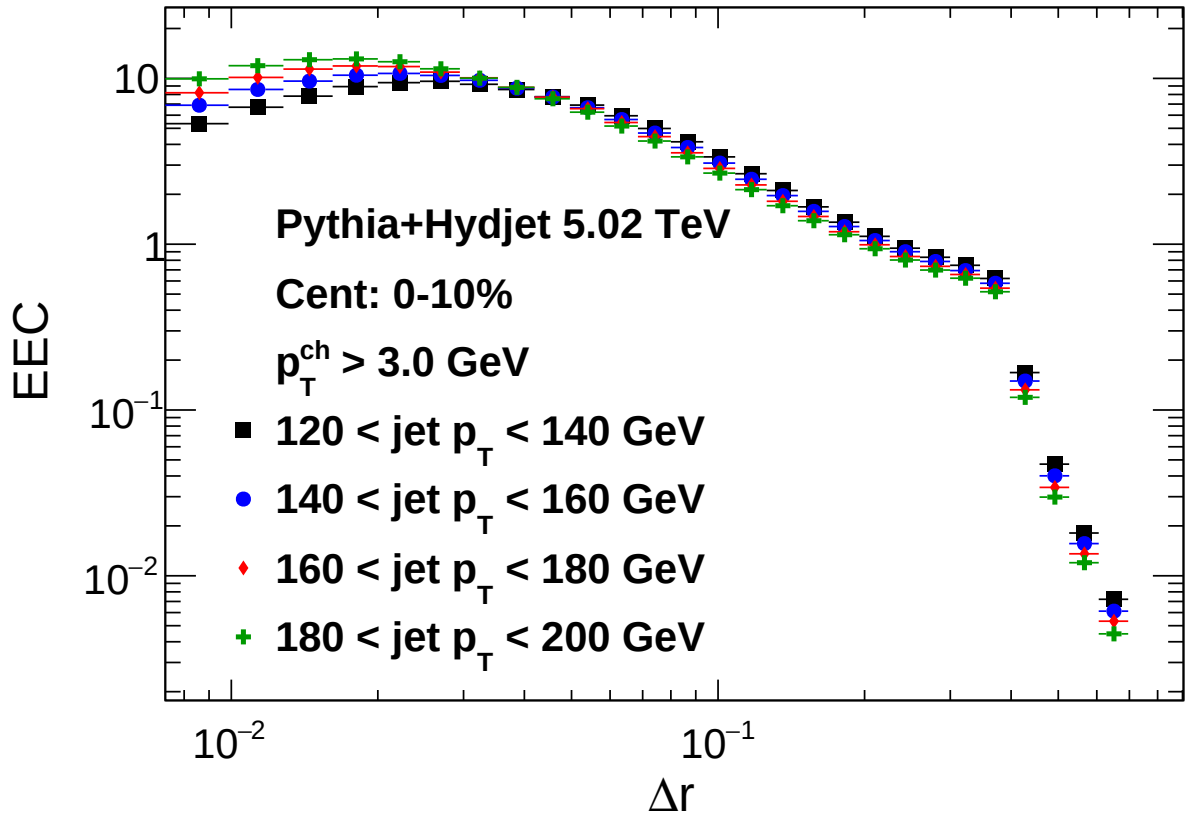
$$\mathrm{EEC}(\Delta r) = C_{\mathrm{norm}} \sum_{\mathrm{jets}\in[p_{\mathrm{T},1},p_{\mathrm{T},2}]} \sum_{\mathrm{pairs}\in[\Delta r_a,\Delta r_b]} \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

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

- Normalize with weighted number of pairs
  - $\Rightarrow$ 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
- Exponent n controls sensitivity to soft particles
- Selects pairs within $R = 0.4$ from winner-take-all jet axis

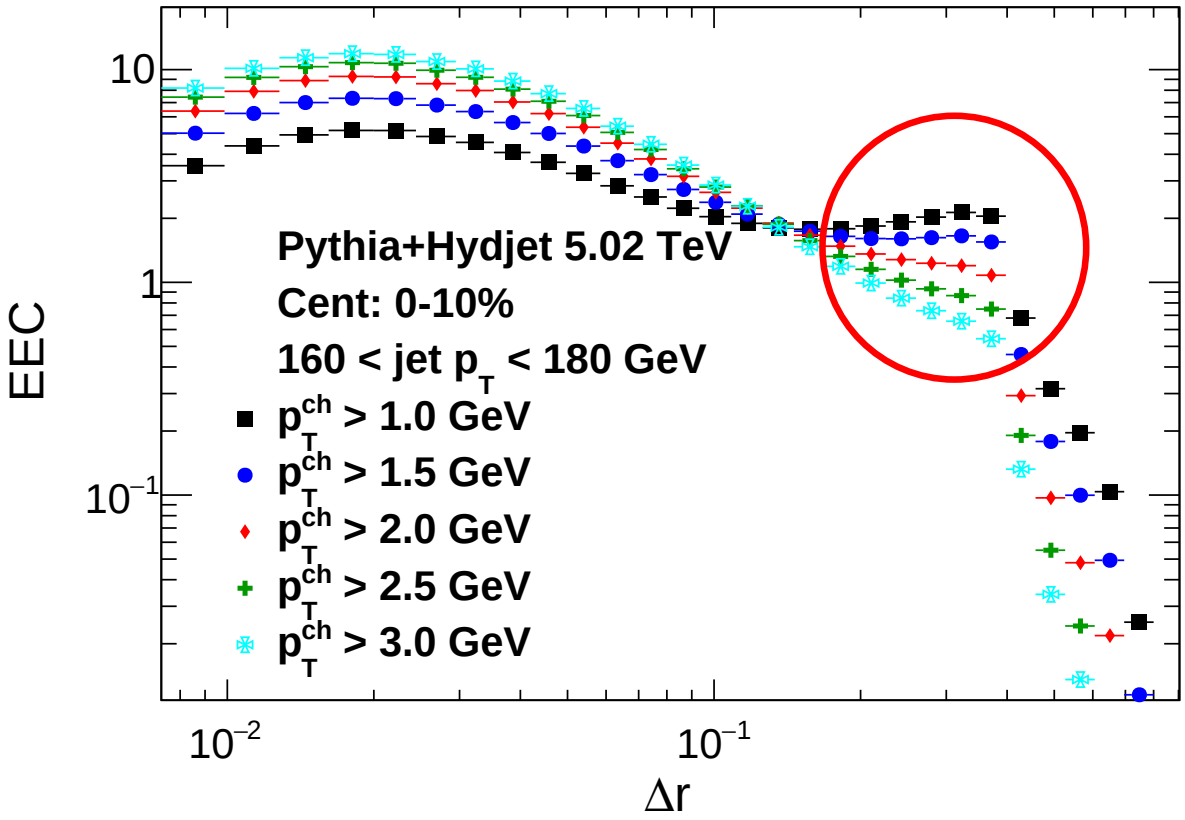


Energy-energy correlators as a function of jet p_{T}



- 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

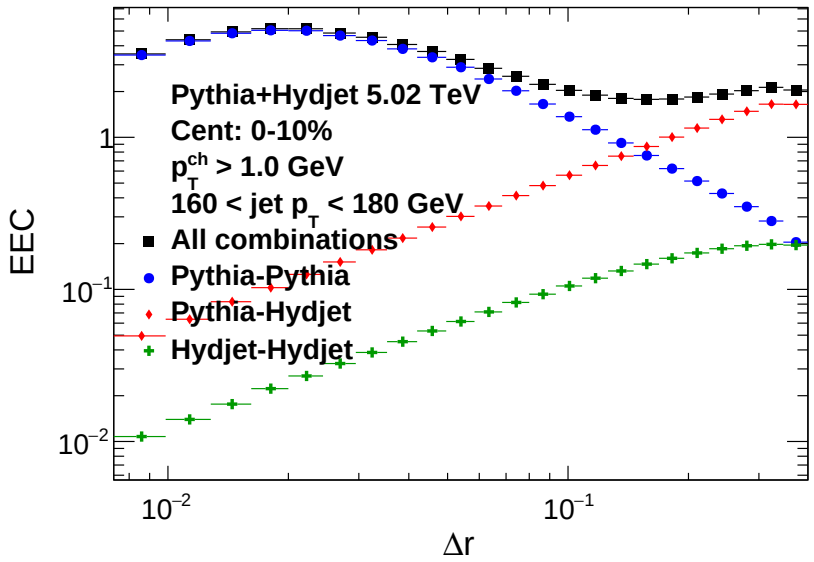
Energy-energy correlators as a function of particle p_{T}



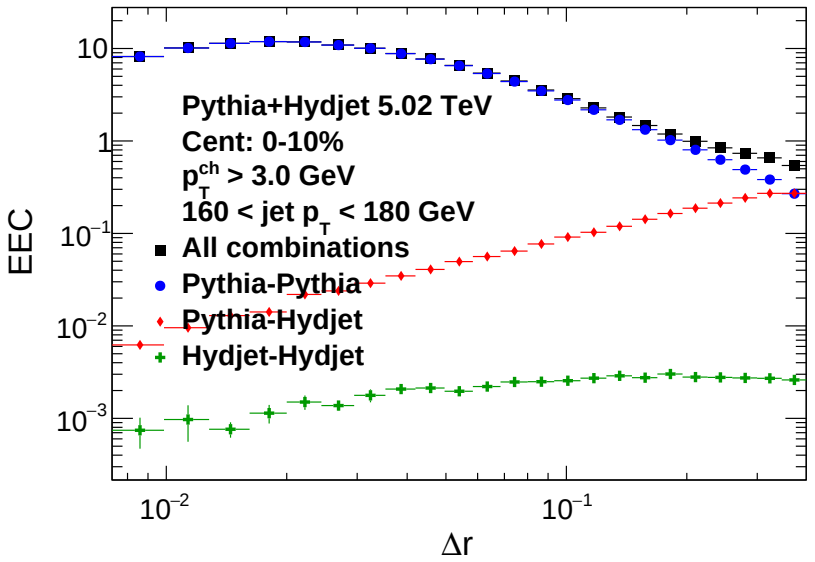
- For lower particle p_{T} cuts, enhancement close to jet radius
- This is caused by background contributions
- Is high particle p_{T} cut enough to suppress background?

Expected background from Pythia+Hydjet simulation

$p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$



$p_{\mathrm{T}}^{\mathrm{ch}} > 3\,\mathrm{GeV}$



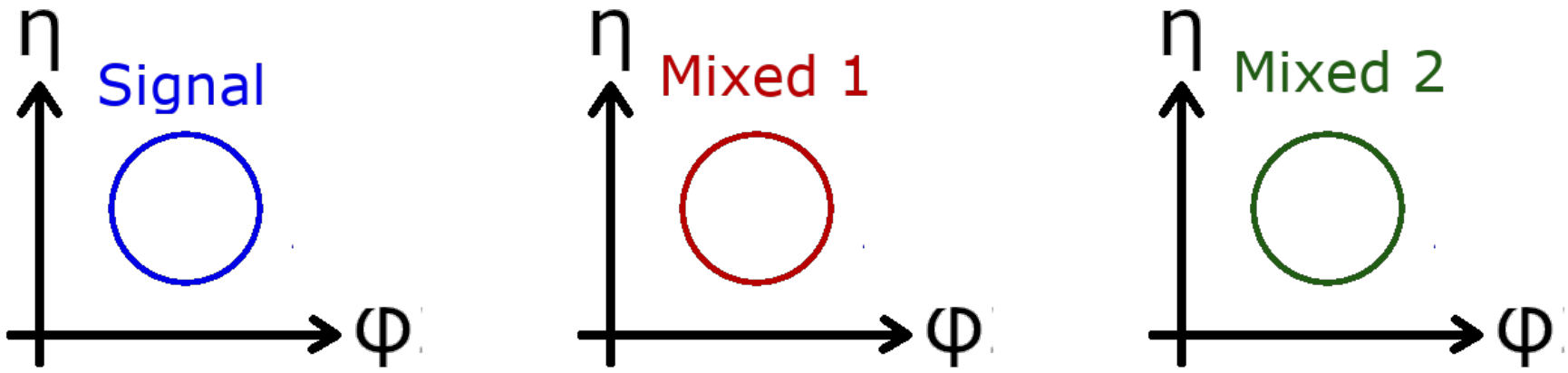
The good 

The bad 

The ugly 

- Significant background contribution with $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$ cut
- Even with 3 GeV cut, significant background around $0.2 \lesssim \Delta r \lesssim 0.4$
- Background subtraction needed in PbPb

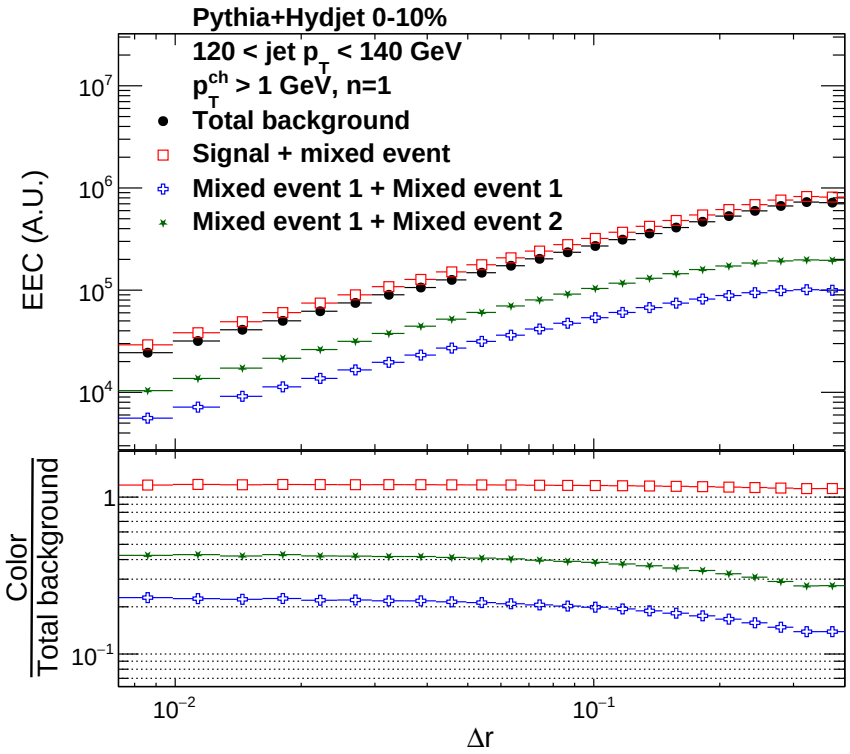
Mixed event background subtraction method



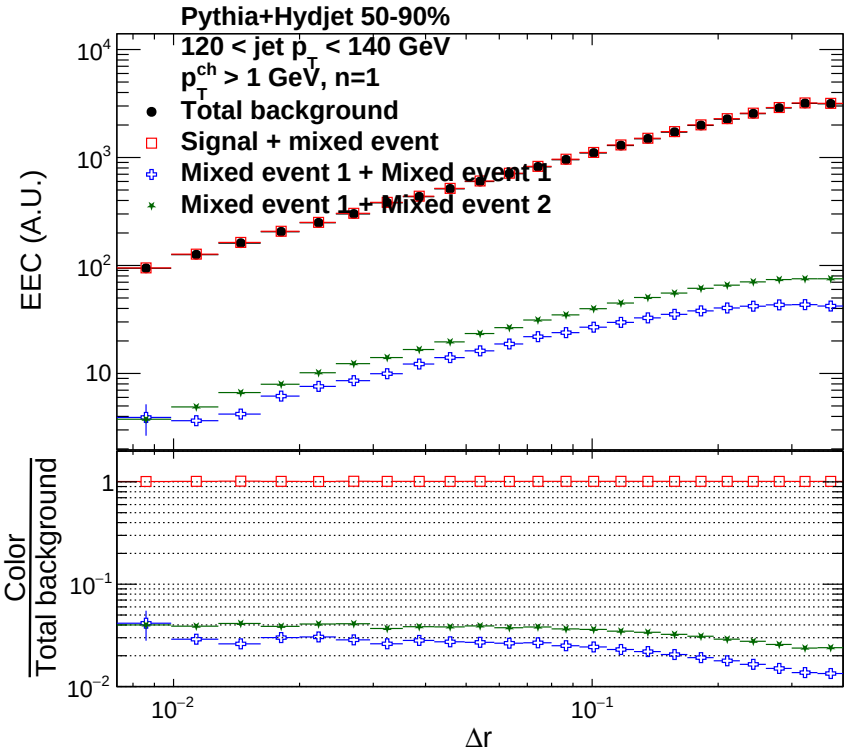
- Three cones are used in this method
  1. Signal cone: this is around the studied jet
  2. Mixed cone 1: same location as jet cone in minimum bias mixed event
  3. Mixed cone 2: same location as jet cone in another mixed event
- Three different pairings are made from the cones
  1. $\mathrm{S} + \mathrm{M1}$: signal+fake together with mismodeled fake+fake
  2. $\mathrm{M1} + \mathrm{M1}$: properly modeled fake+fake
  3. $\mathrm{M1} + \mathrm{M2}$: mismodeled fake+fake
- Extract background: $\mathrm{BG} = (\mathrm{S} + \mathrm{M1}) + (\mathrm{M1} + \mathrm{M1}) - (\mathrm{M1} + \mathrm{M2})$

Mixed cone decomposition in Pythia+Hydjet

$C = 0 - 10\%$



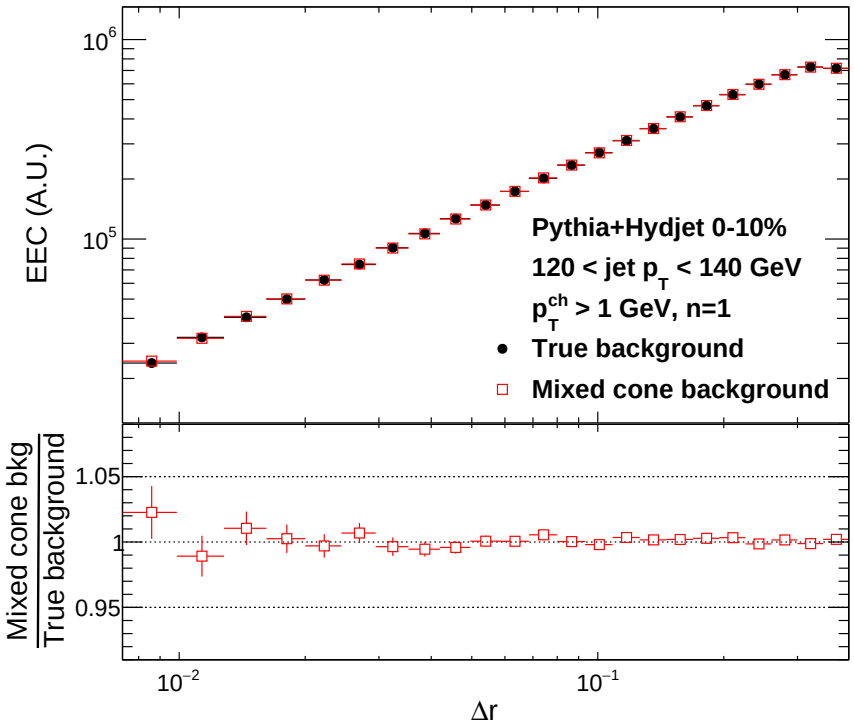
$C = 50 - 90\%$



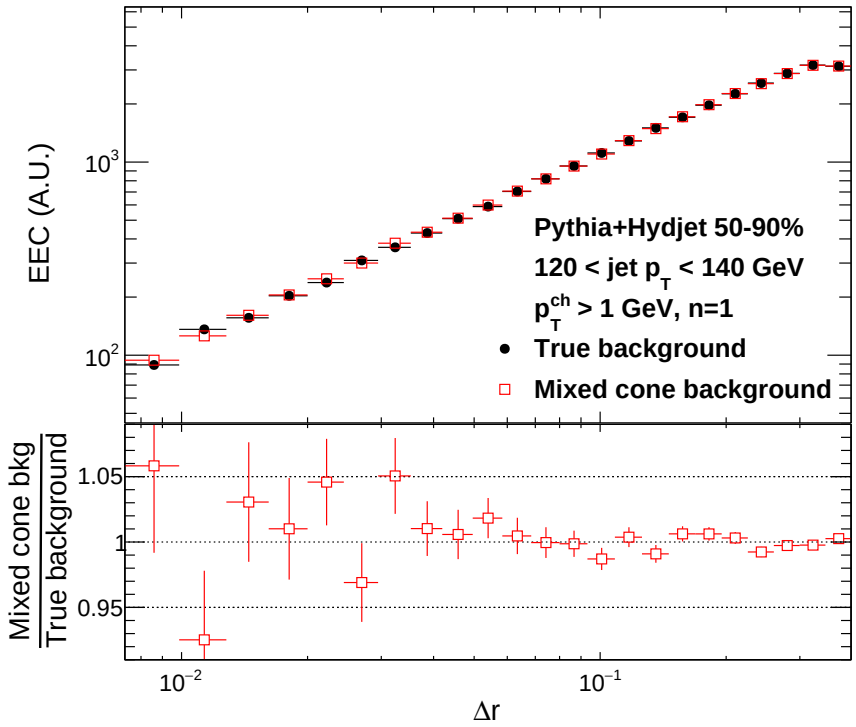
- $(\mathrm{M1} + \mathrm{M1}) - (\mathrm{M1} + \mathrm{M2})$ correction significant in central collisions
- Less so in a region where signal+fake contribution dominates

Mixed cone bkg vs. true bkg in Pythia+Hydjet

$C = 0 - 10\%$



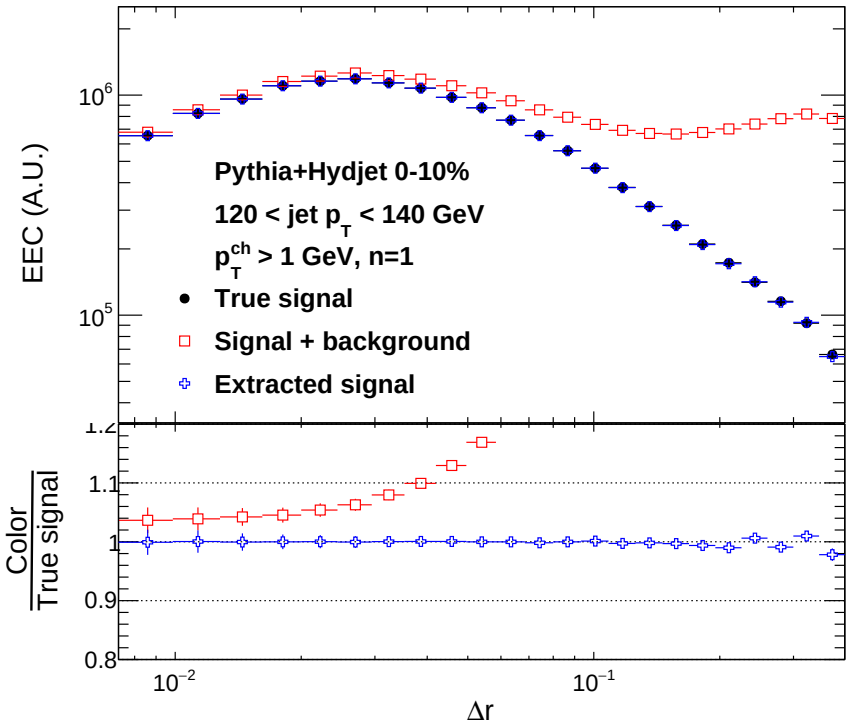
$C = 50 - 90\%$



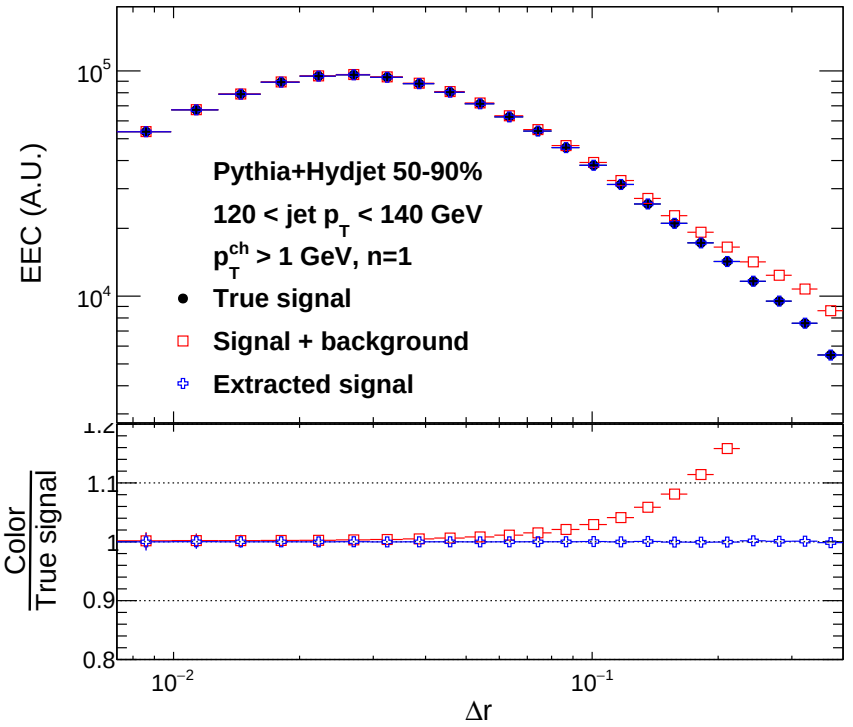
- Mixed cone gives accurate background estimate even for $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$!
- Mixed cone estimate is self-normalized, no additional scaling needed

Signal extraction in Pythia+Hydjet

$C = 0 - 10\%$

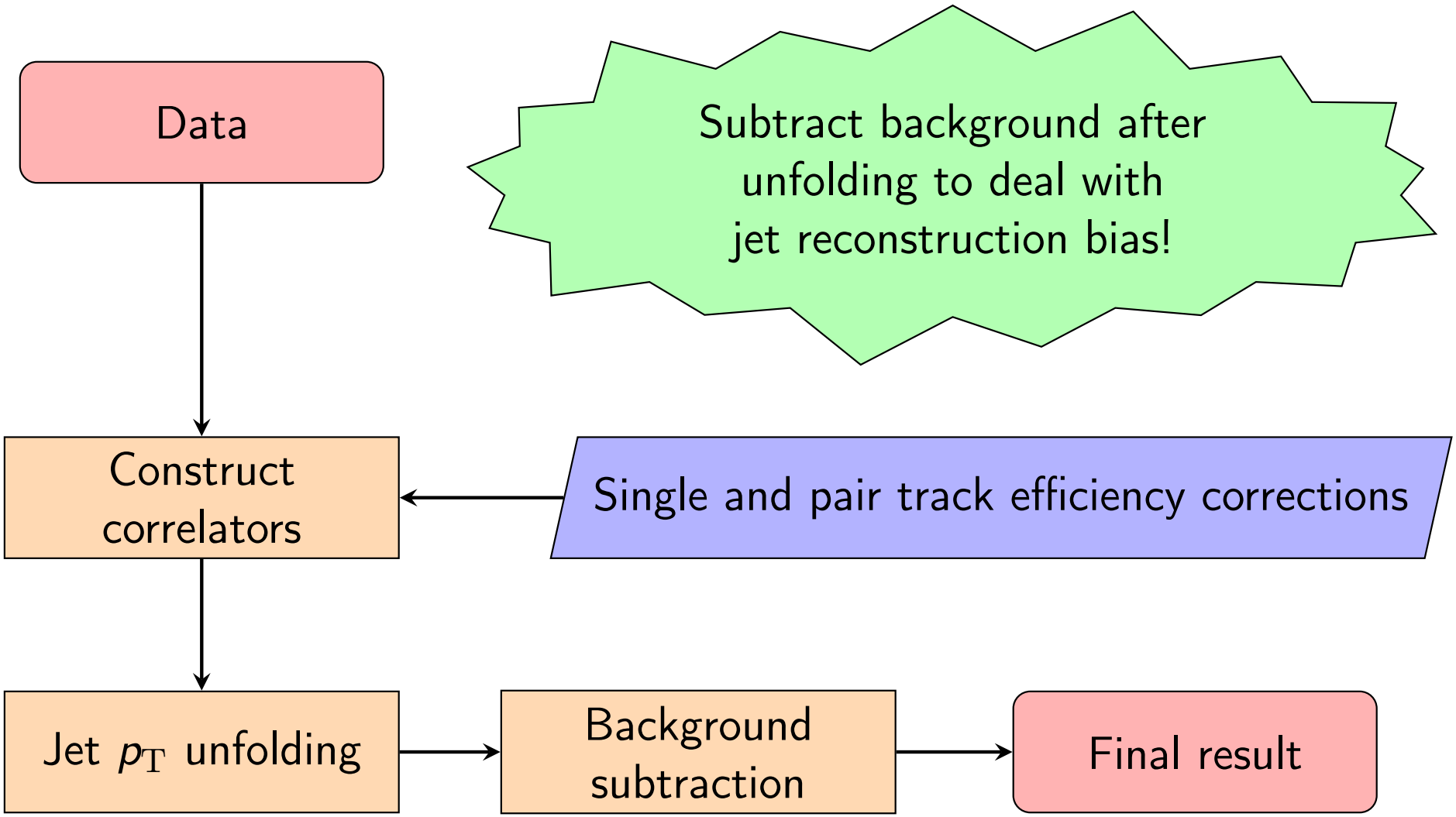


$C = 50 - 90\%$

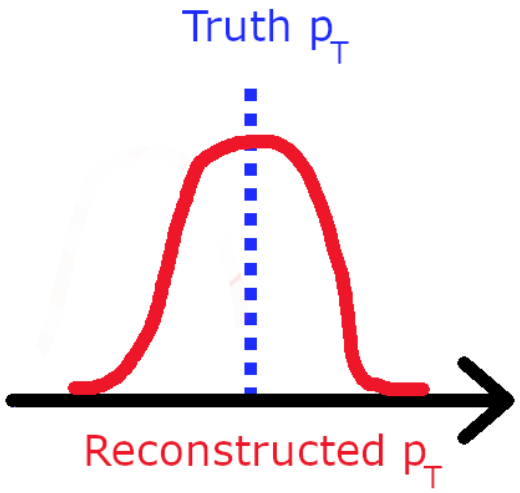


- Even with high background, signal can be very accurately extracted!

Analysis flow

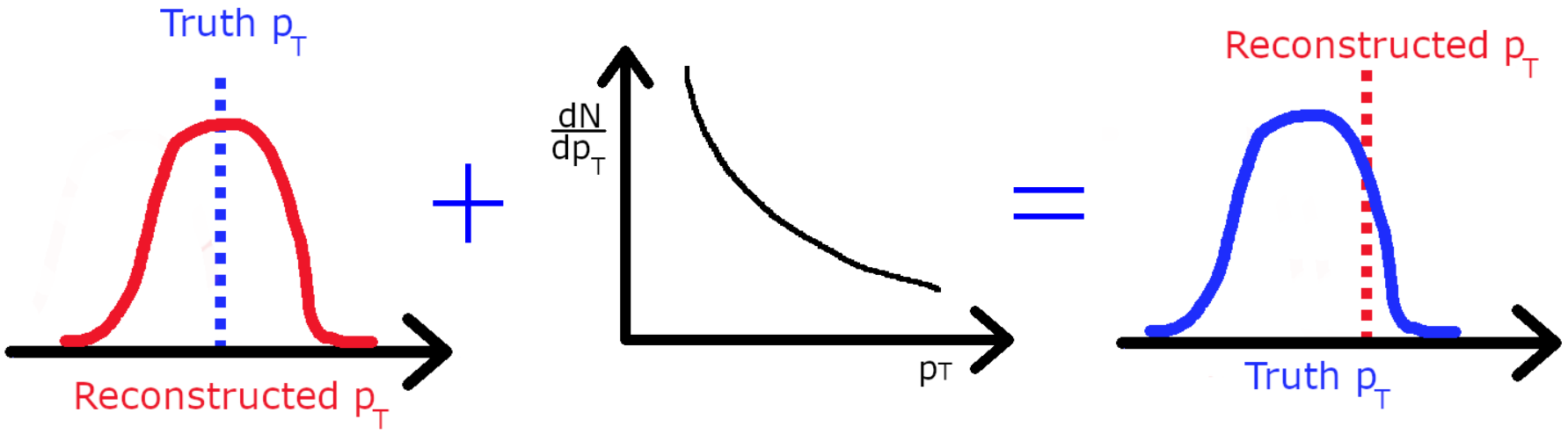


Jet resolution effects and unfolding



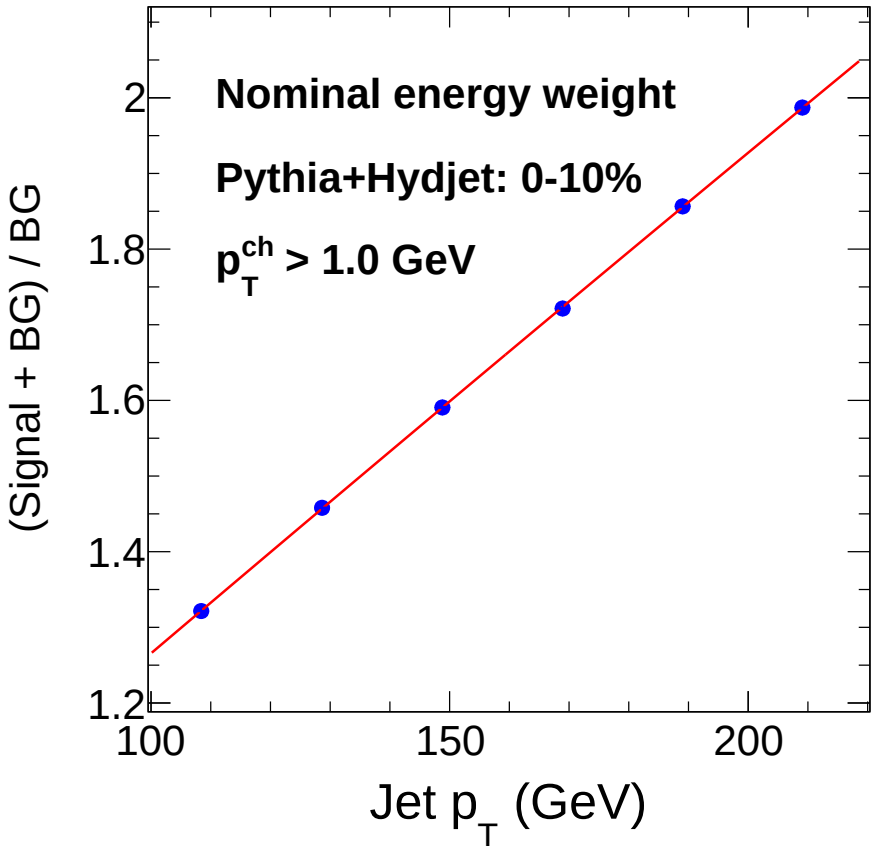
- Jet energy corrections are derived such that for each truth p_{T}, the most likely reconstructed p_{T} matches

Jet resolution effects and unfolding



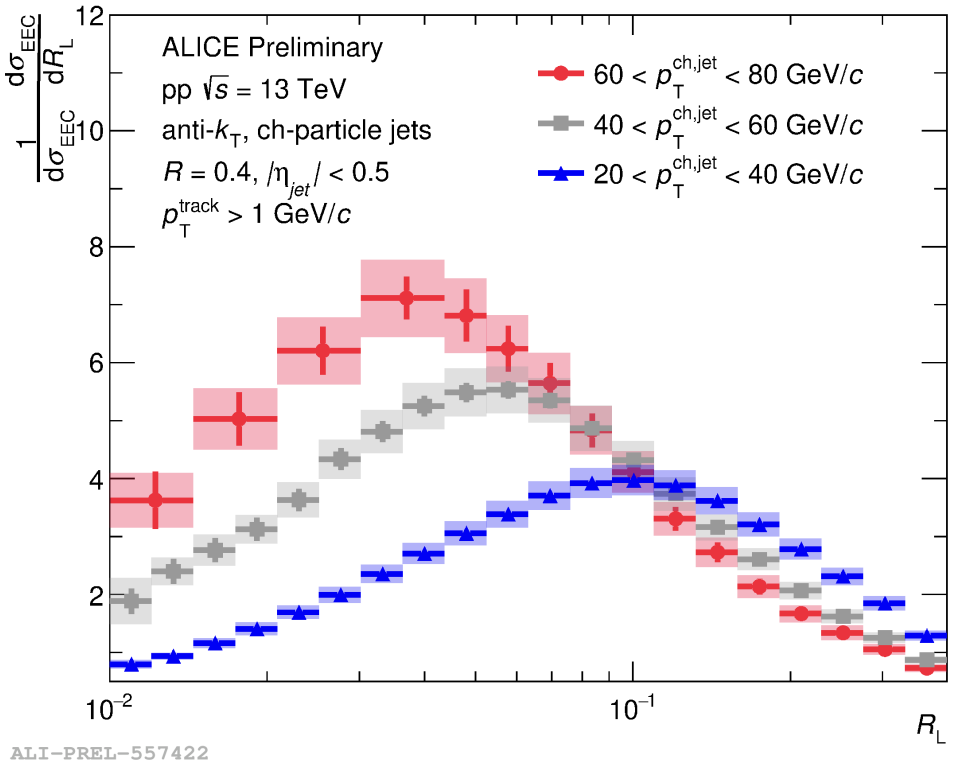
- Jet energy corrections are derived such that for each truth p_{T}, the most likely reconstructed p_{T} matches
- Steeply falling spectrum $\rightarrow$ for given reconstructed p_{T}, the most likely truth p_{T} is shifted down
- Unfolding corrects for this by effectively increasing the mean p_{T} in each measured bin

Signal-to-background ratio in Pythia+Hydjet



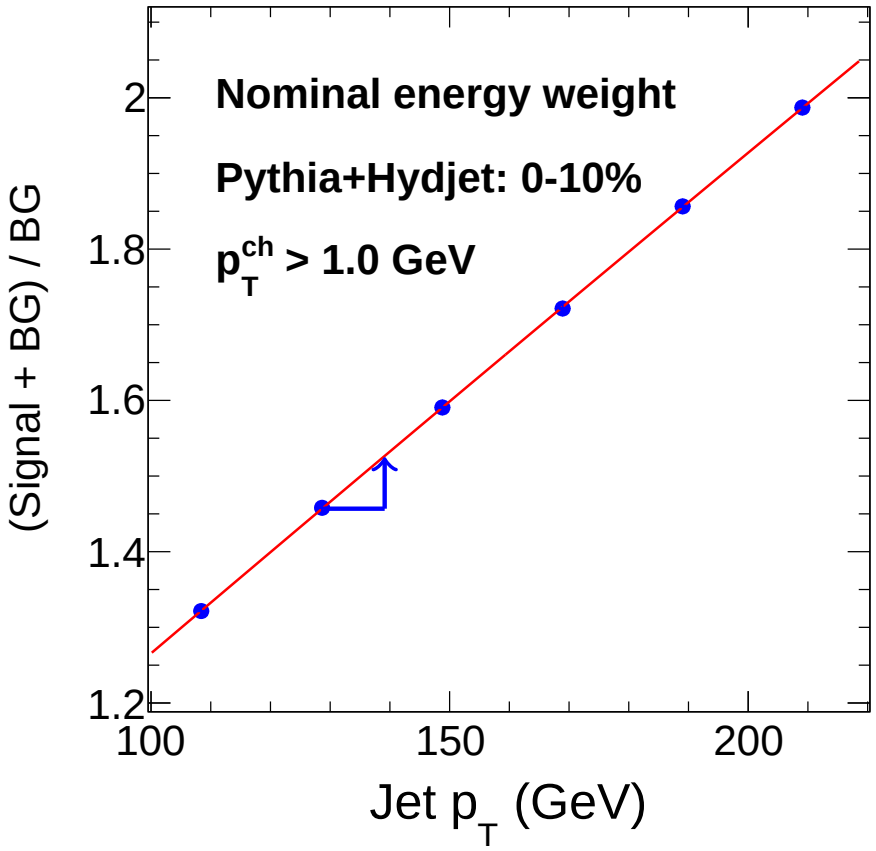
- Signal-to-background ratio depends on jet p_{T}
- Background needs to be scaled to take into account the mean jet p_{T} shift from unfolding
- This can be done in fully data driven way

The shift in peak position during unfolding



- Position of the peak depends on jet p_{T}
- We fit the peak before and after unfolding to determine the turning point
- Peak position after unfolding can be related back to mean jet p_{T}

Scaling factor for background



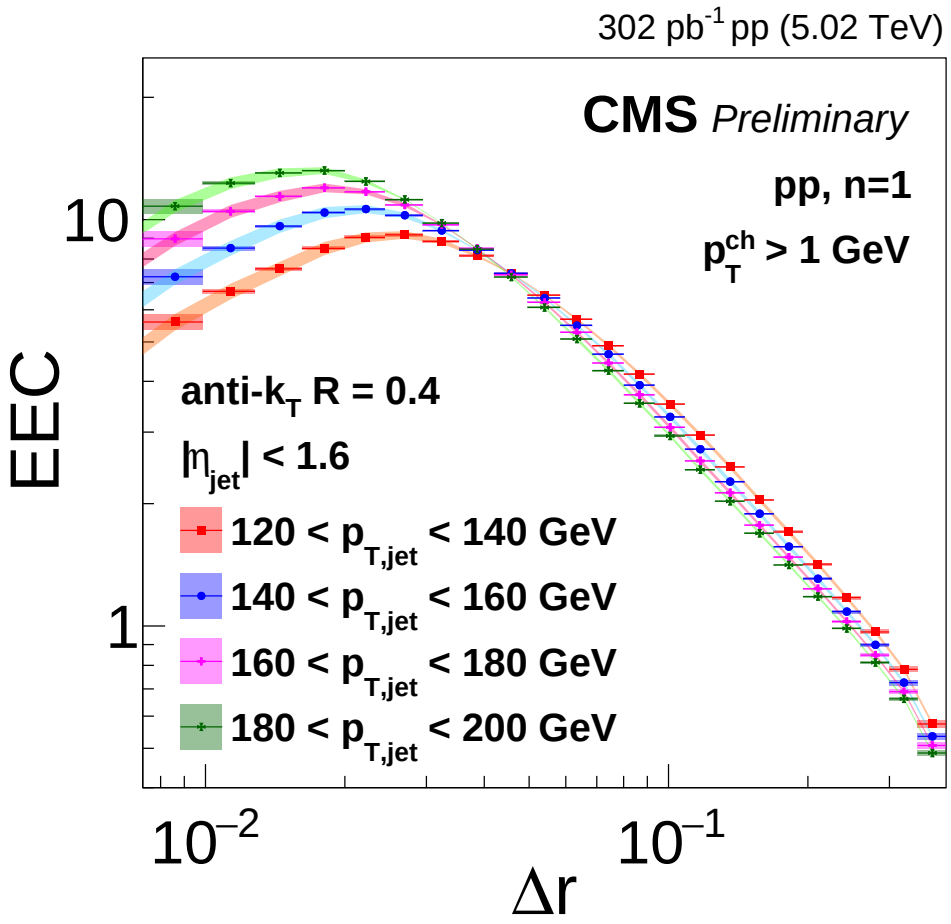
- Knowing the mean jet p_{T} after unfolding, we can determine the signal-to-background ratio
- We scale the background estimate to match this ratio
- In simulation, the extracted signal matches well with truth only if this method is applied

Contents

Image credit: Jennifer James (Vanderbilt)

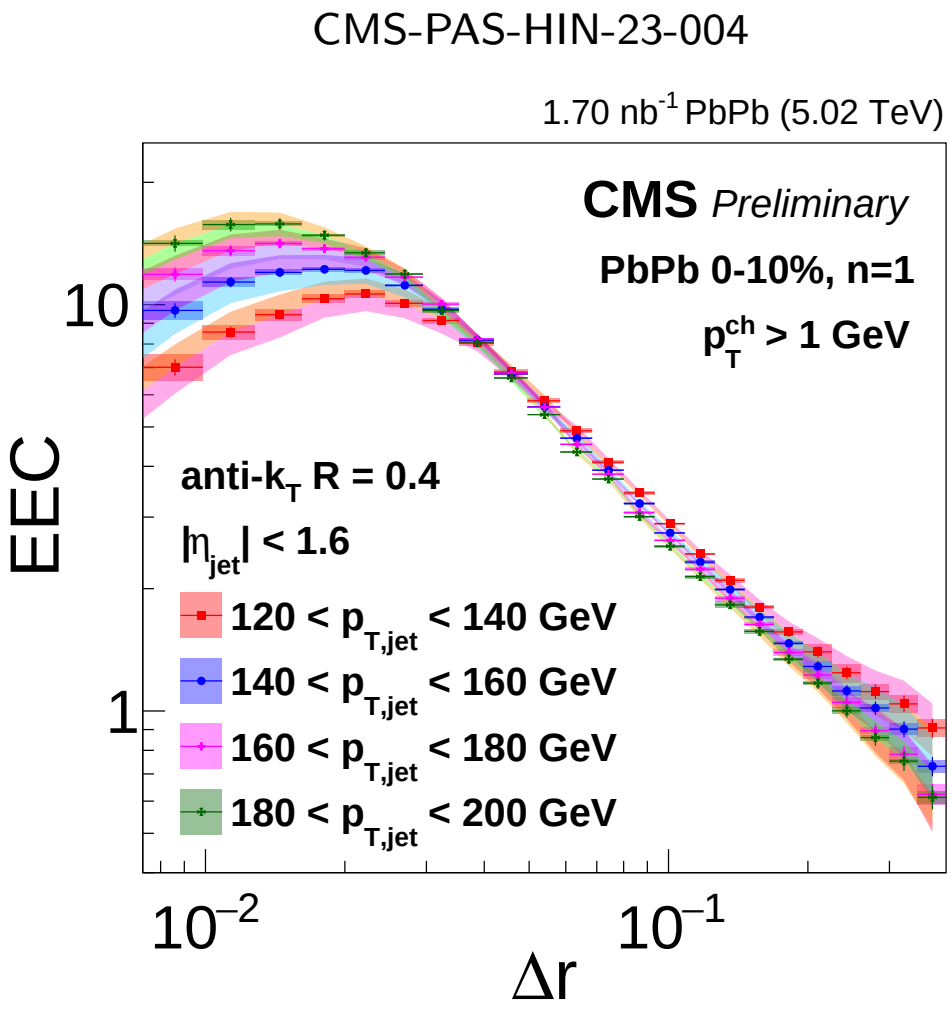
Energy-energy correlator distributions, pp

CMS-PAS-HIN-23-004



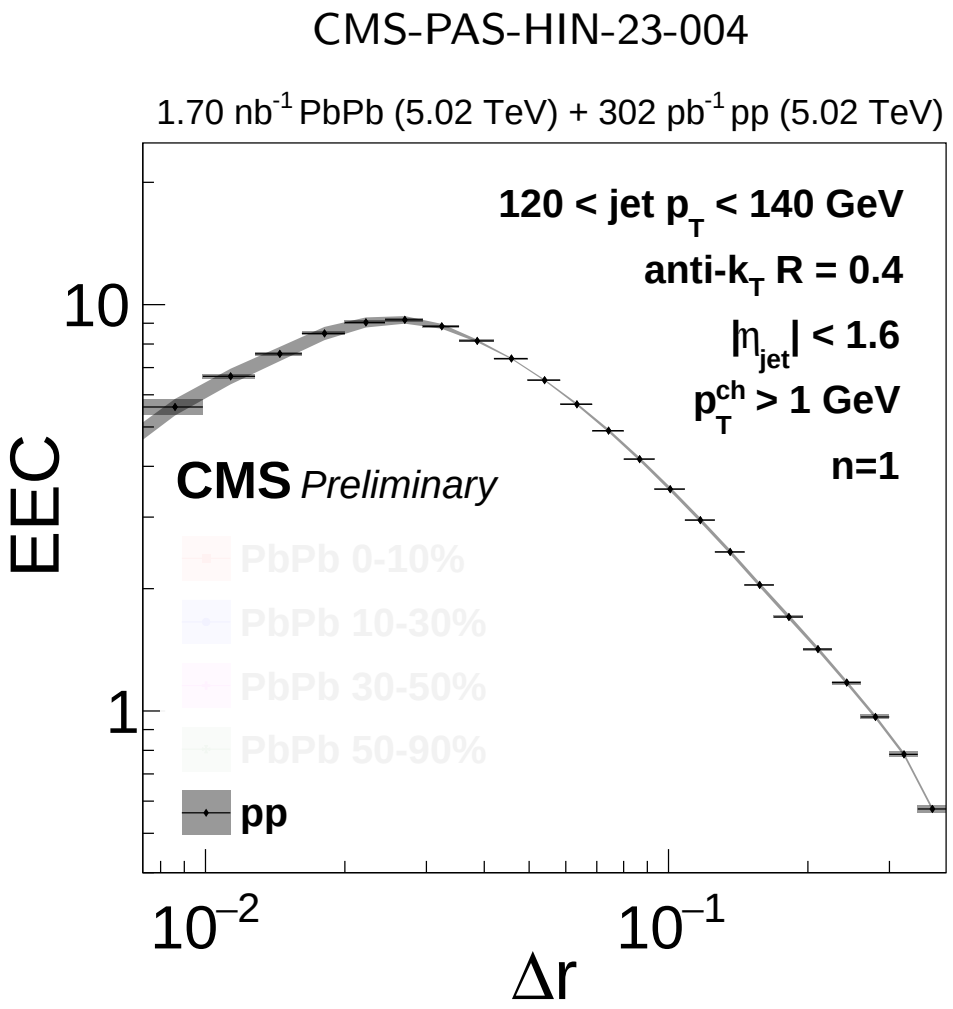
- pp results have consistent features with previous measurements
- Low $\Delta r \rightarrow$ free hadrons
- Moderate $\Delta r \rightarrow$ transition
- High $\Delta r \rightarrow$ free quark/gluon
- Peak depends on jet p_{T}

Energy-energy correlator distributions, PbPb 0-10%



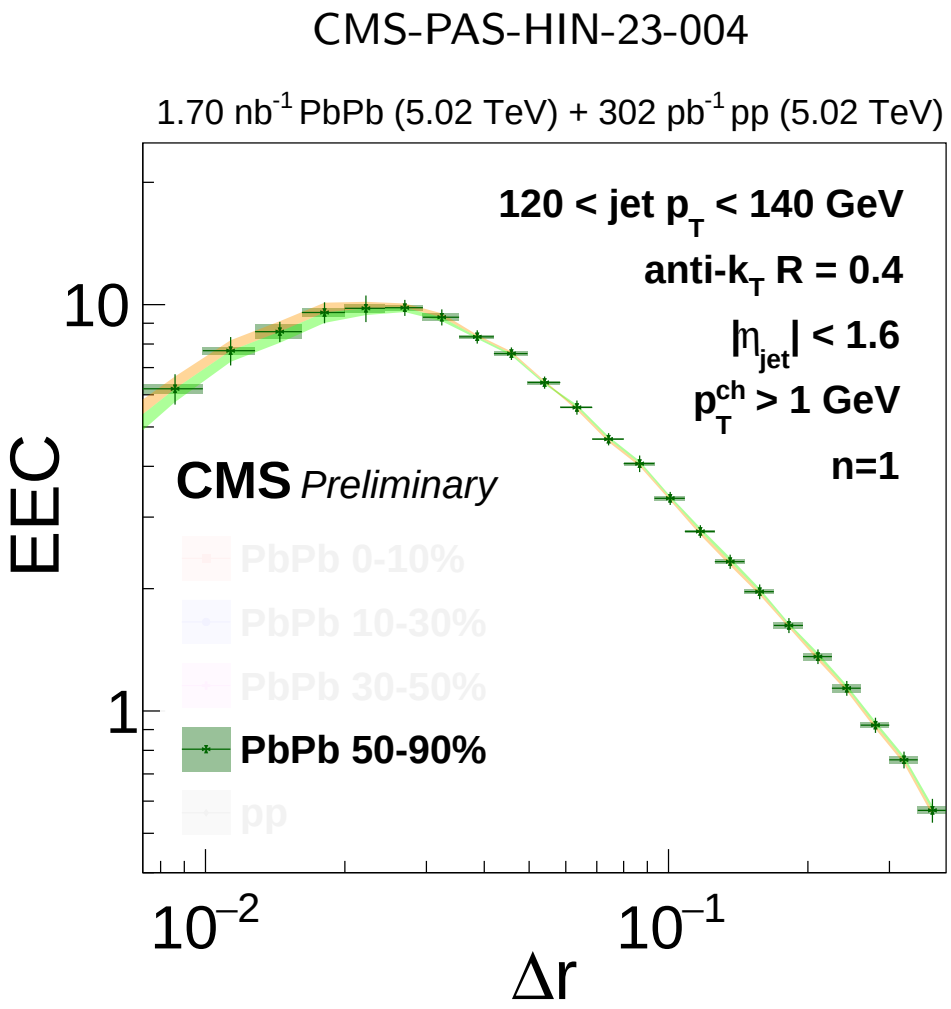
- PbPb distributions have the same features as in pp!
- Regions for free hadrons, transition and free quarks/gluons clearly visible
- Peak depends on jet p_{T}

Medium modifications in energy-energy correlators



- The jet peak moves towards smaller Δr when going to more central collisions
- Effect from energy loss $\rightarrow$ more central jets have higher initial virtuality

Medium modifications in energy-energy correlators



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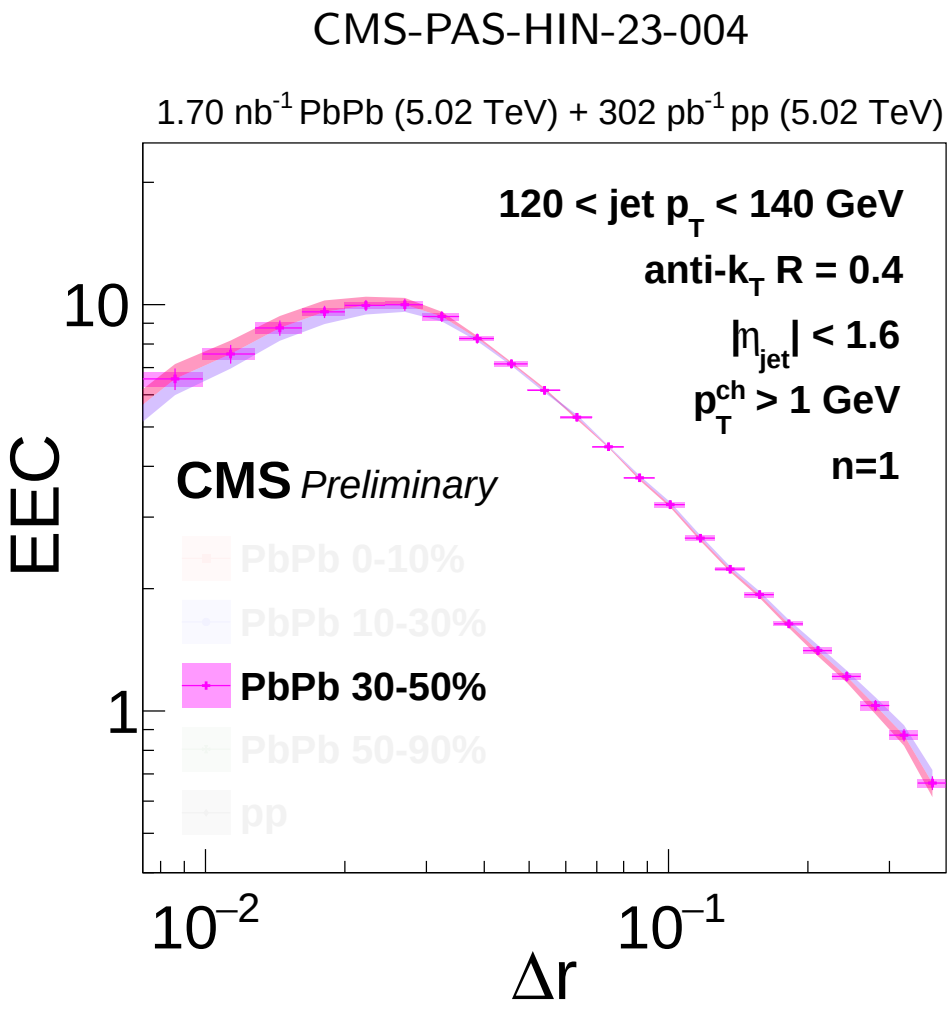

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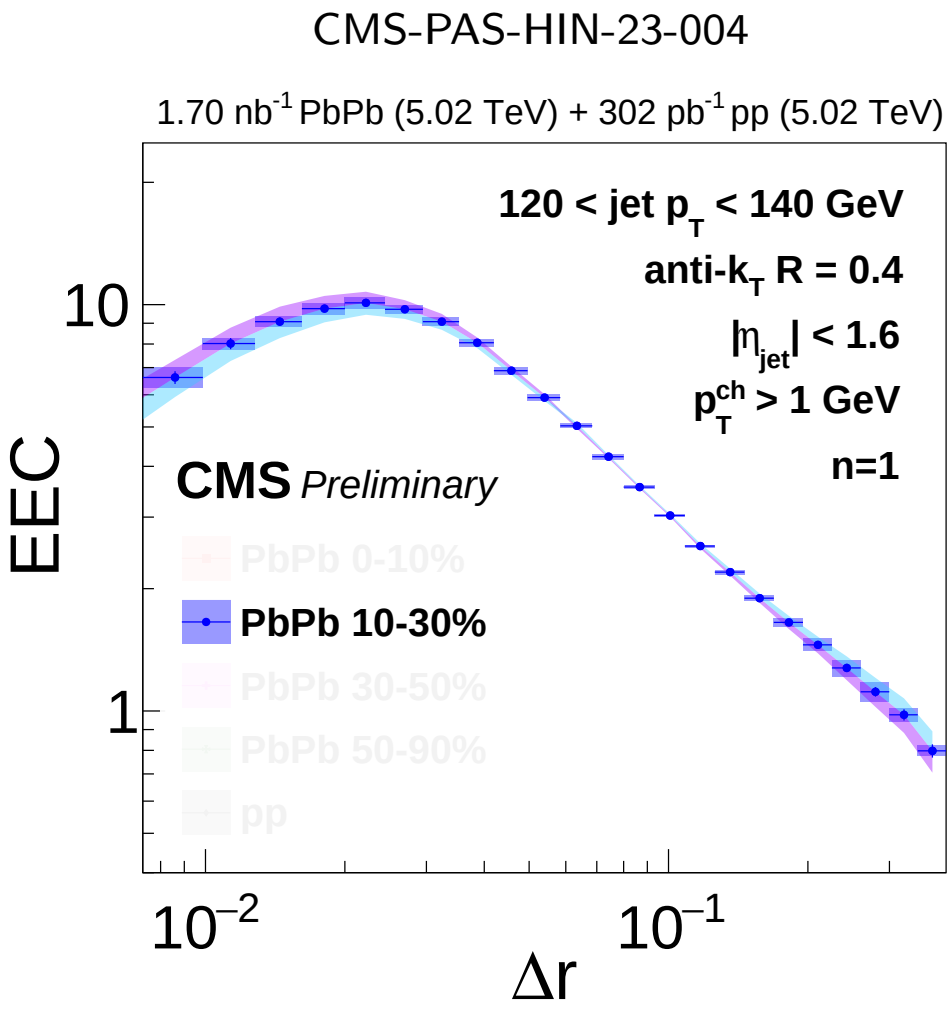

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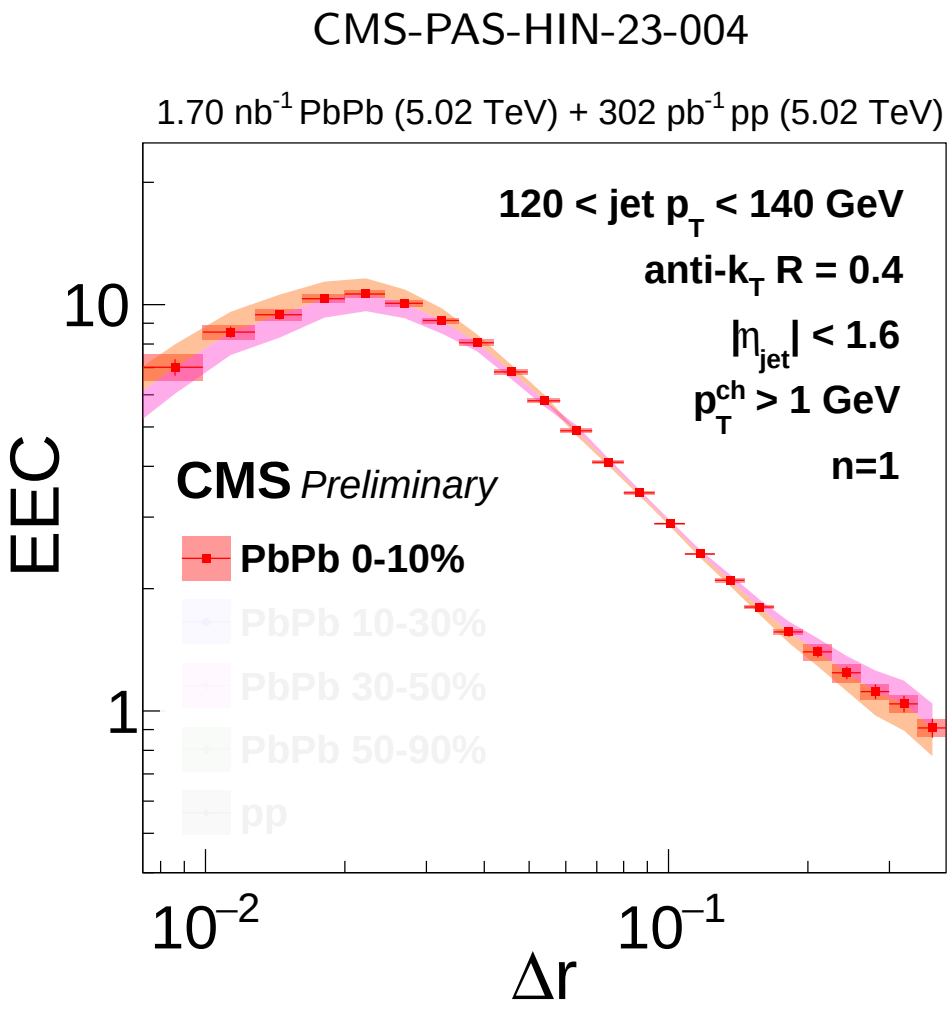

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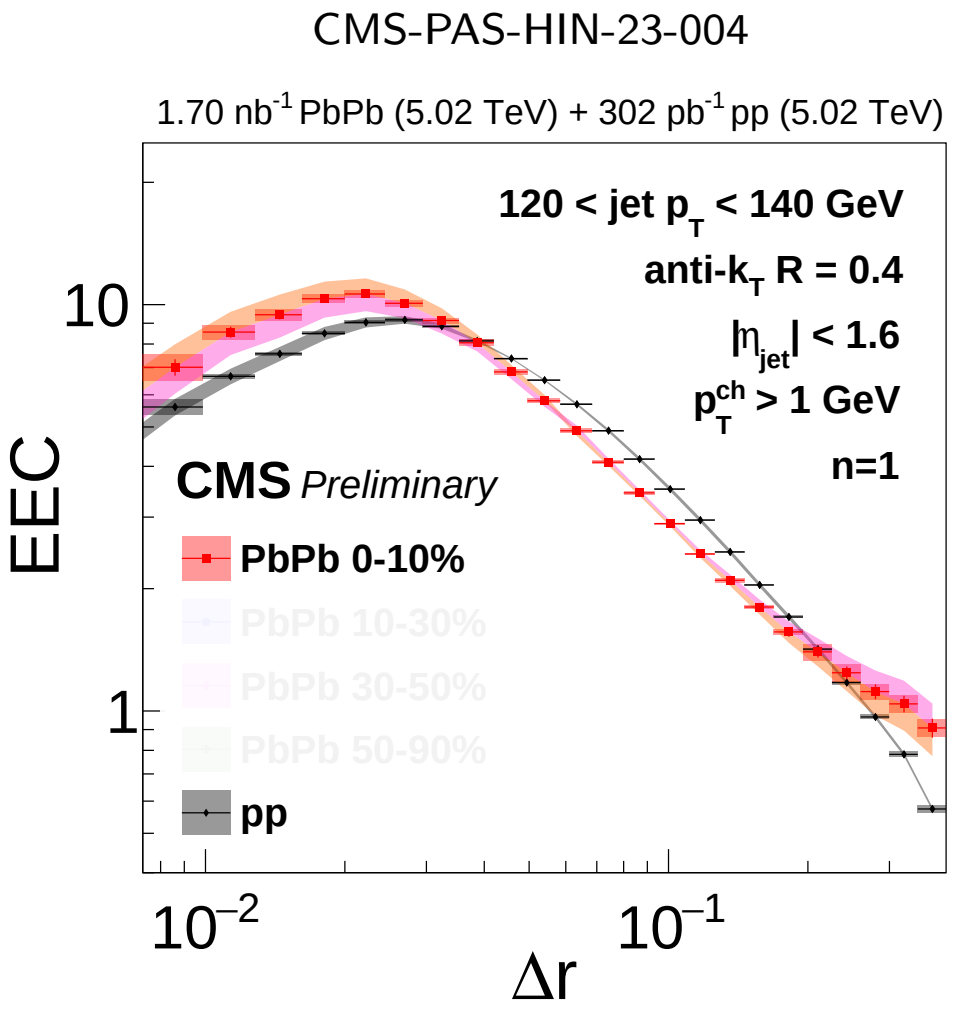
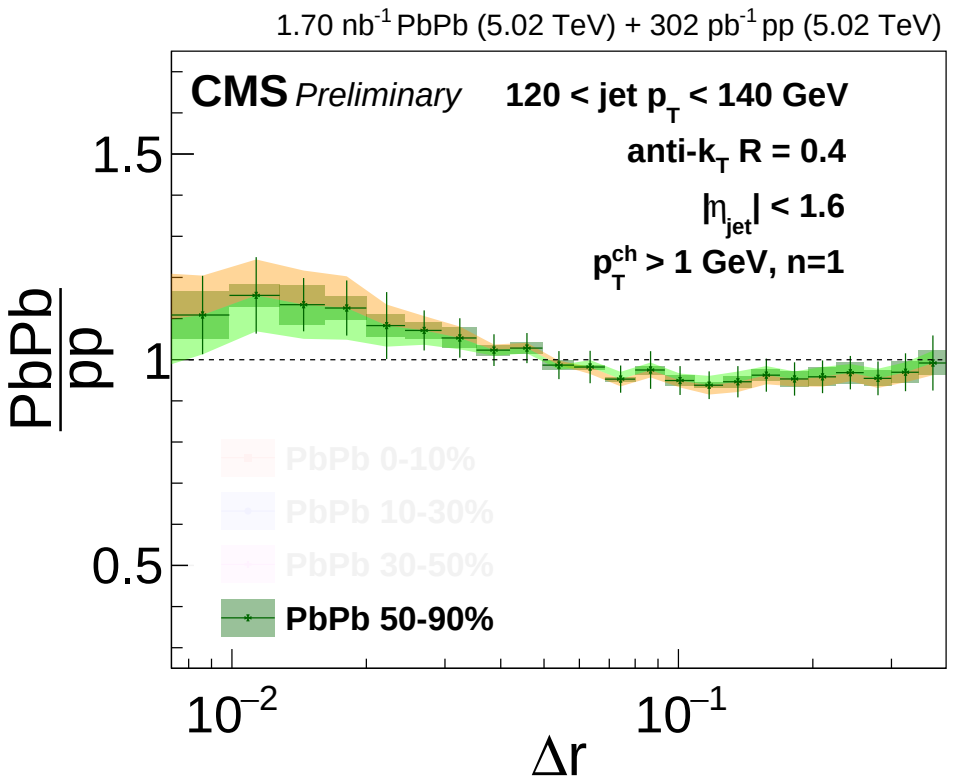
Medium modifications in energy-energy correlators



- The jet peak moves towards smaller Δr when going to more central collisions
- Effect from energy loss $\rightarrow$ more central jets have higher initial virtuality
- Also the shape of the distribution at large Δr is modified!

PbPb to pp ratio, centrality evolution

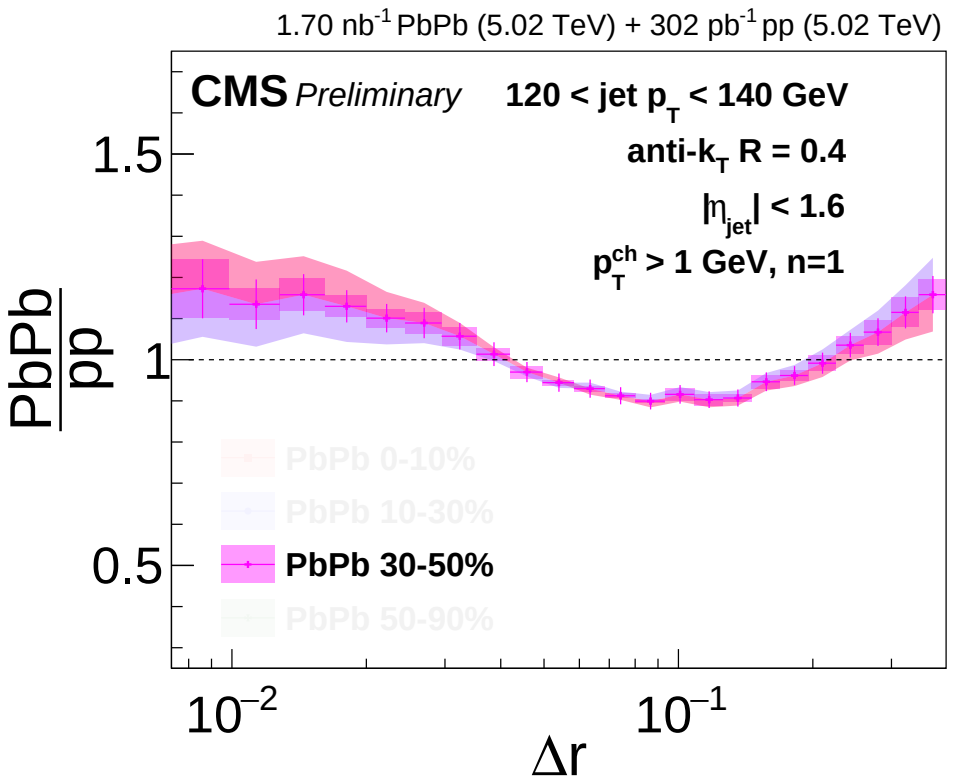
CMS-PAS-HIN-23-004



- Peripheral distribution shows only small modifications

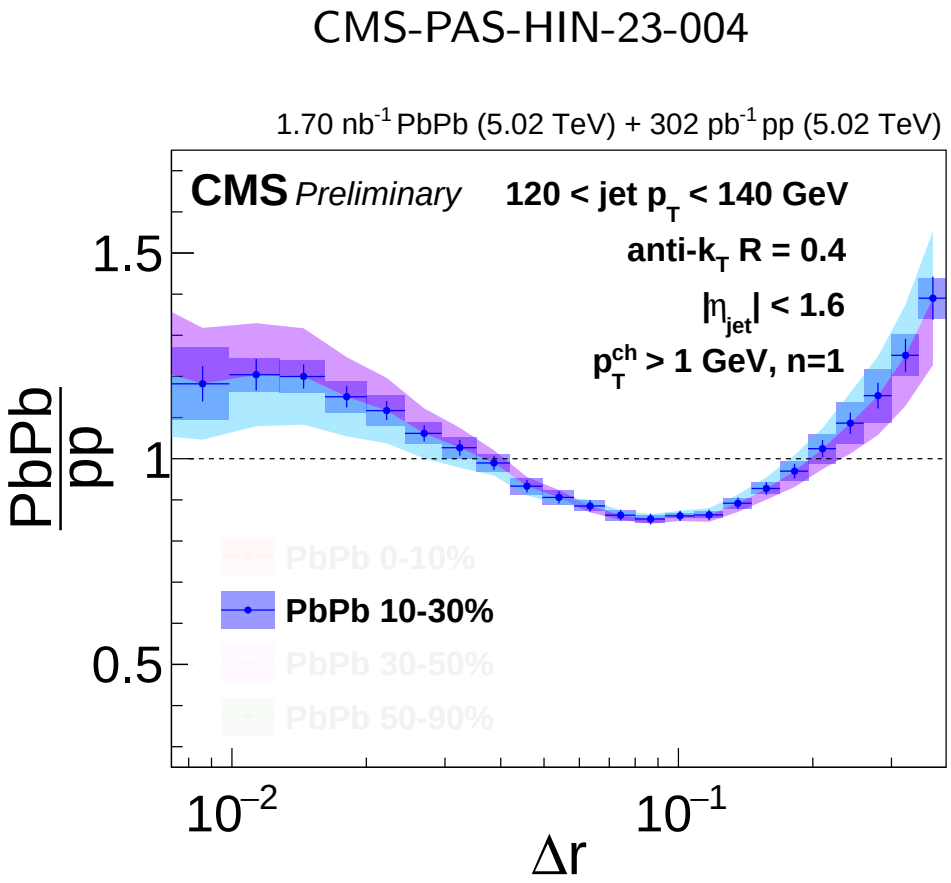
PbPb to pp ratio, centrality evolution

CMS-PAS-HIN-23-004



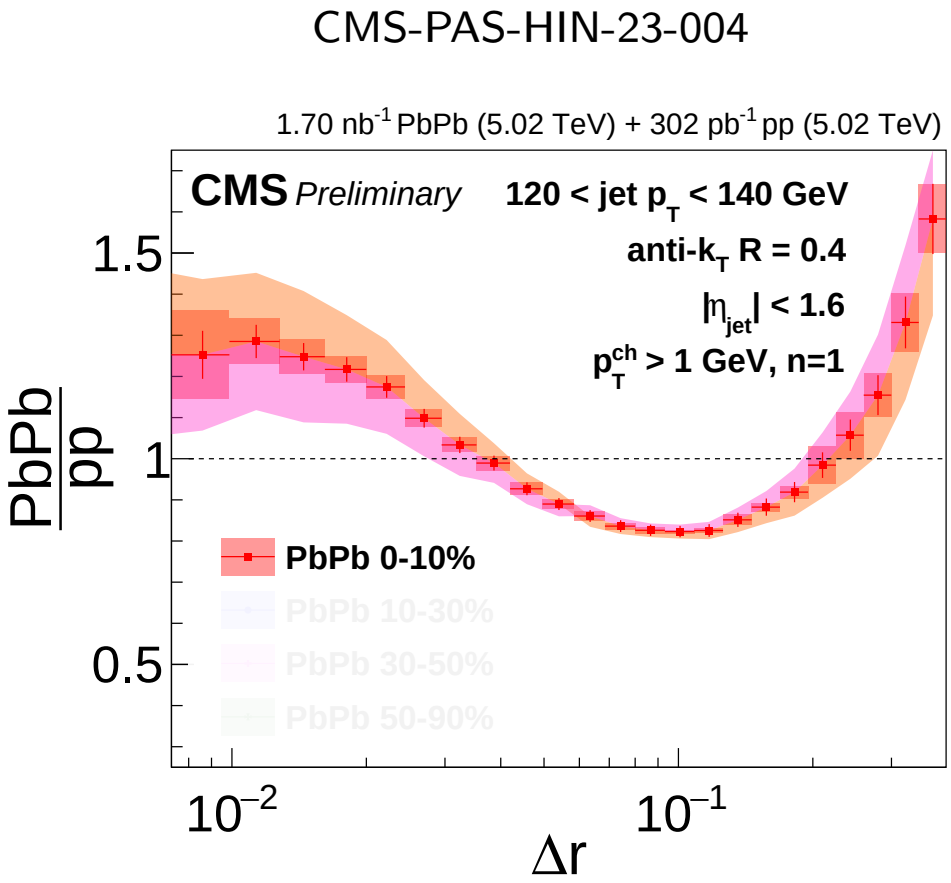
- Peripheral distribution shows only small modifications
- Enhancement at low Δr due to energy loss

PbPb to pp ratio, centrality evolution



- Peripheral distribution shows only small modifications
- Enhancement at low Δr due to energy loss
- Change in trend around $\Delta r \sim 0.1$ to enhancement at large Δr

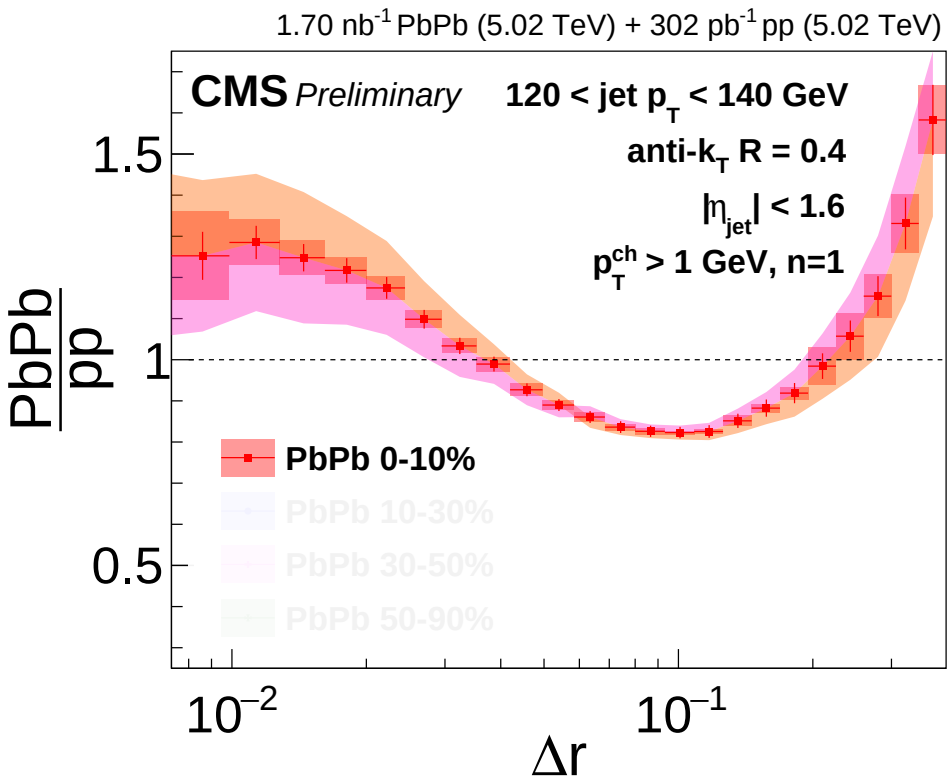
PbPb to pp ratio, centrality evolution

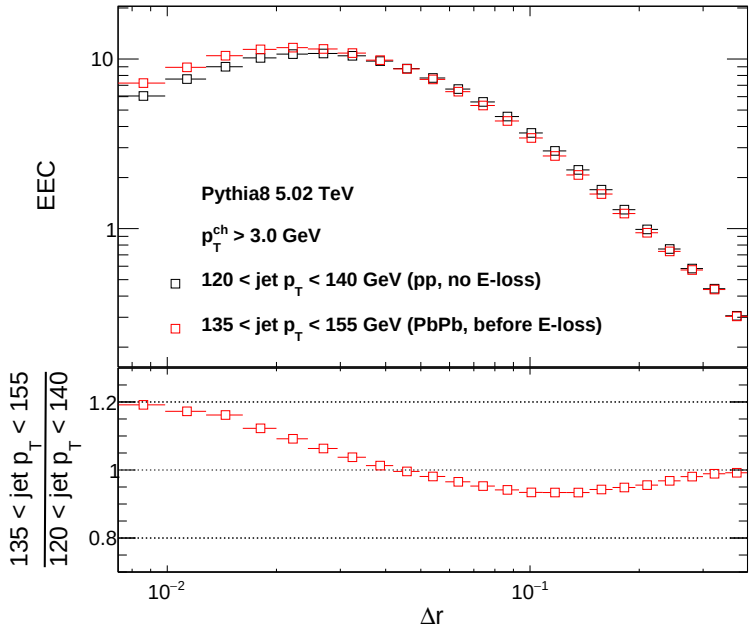


- Peripheral distribution shows only small modifications
- Enhancement at low Δr due to energy loss
- Change in trend around $\Delta r \sim 0.1$ to enhancement at large Δr
- Flat trend at few lowest Δr bins $\rightarrow$ universal scaling for free hadrons

PbPb to pp ratio, centrality evolution

CMS-PAS-HIN-23-004

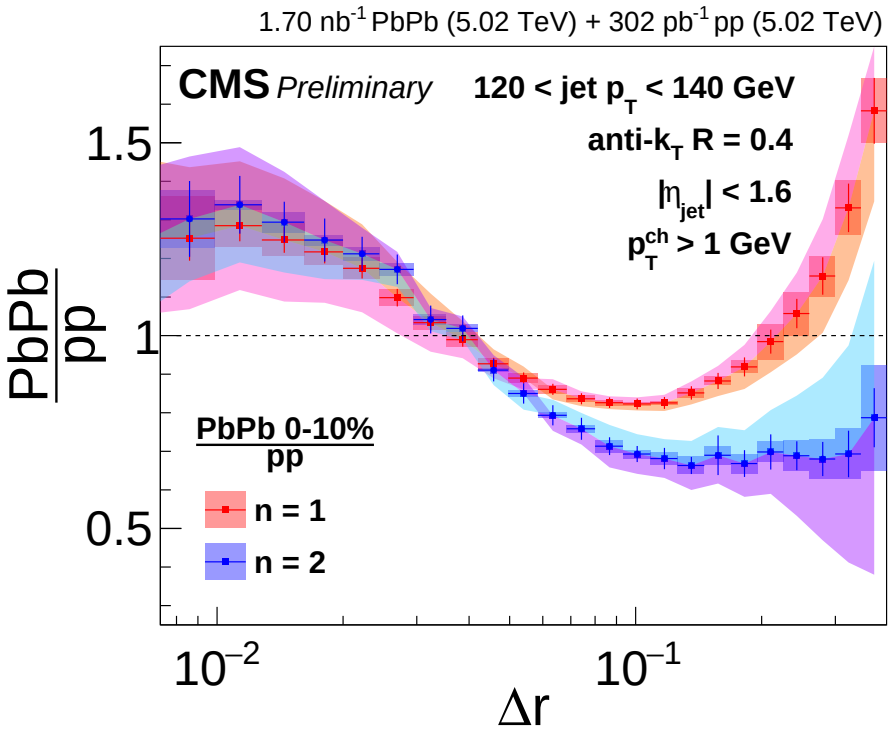




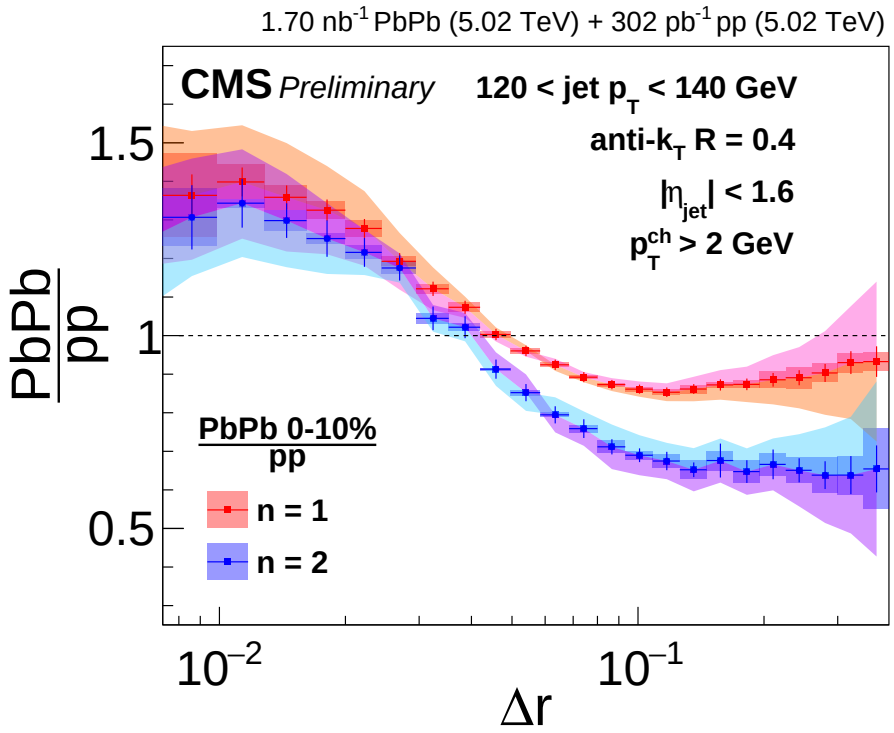
PbPb to pp ratio and kinematic cuts

CMS-PAS-HIN-23-004

$p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$



$p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$



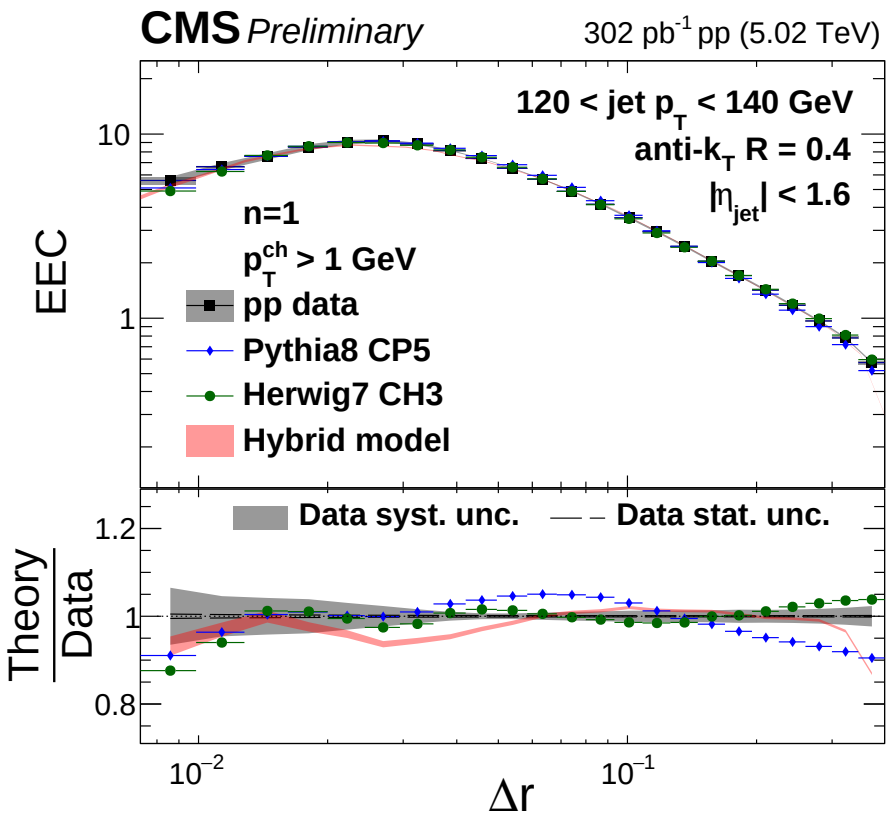
- Sensitivity to low p_{T} particles essential for large Δr enhancement!

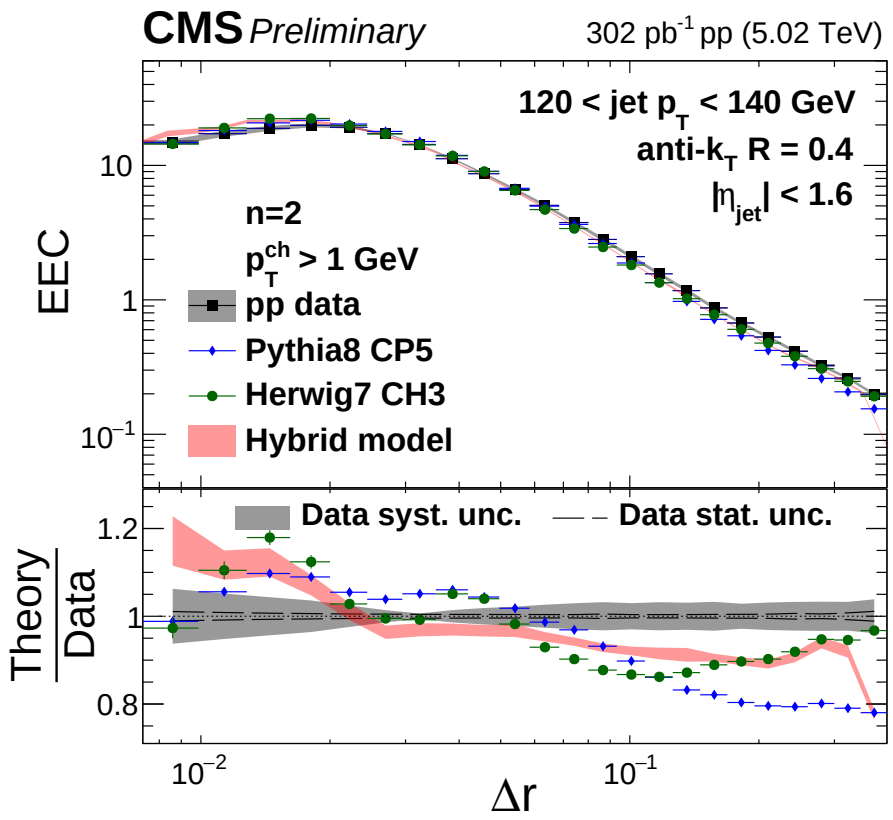
Contents

Image credit: Jennifer James (Vanderbilt)

Model comparisons with pp distribution

$n = 1$ CMS-PAS-HIN-23-004 $n = 2$

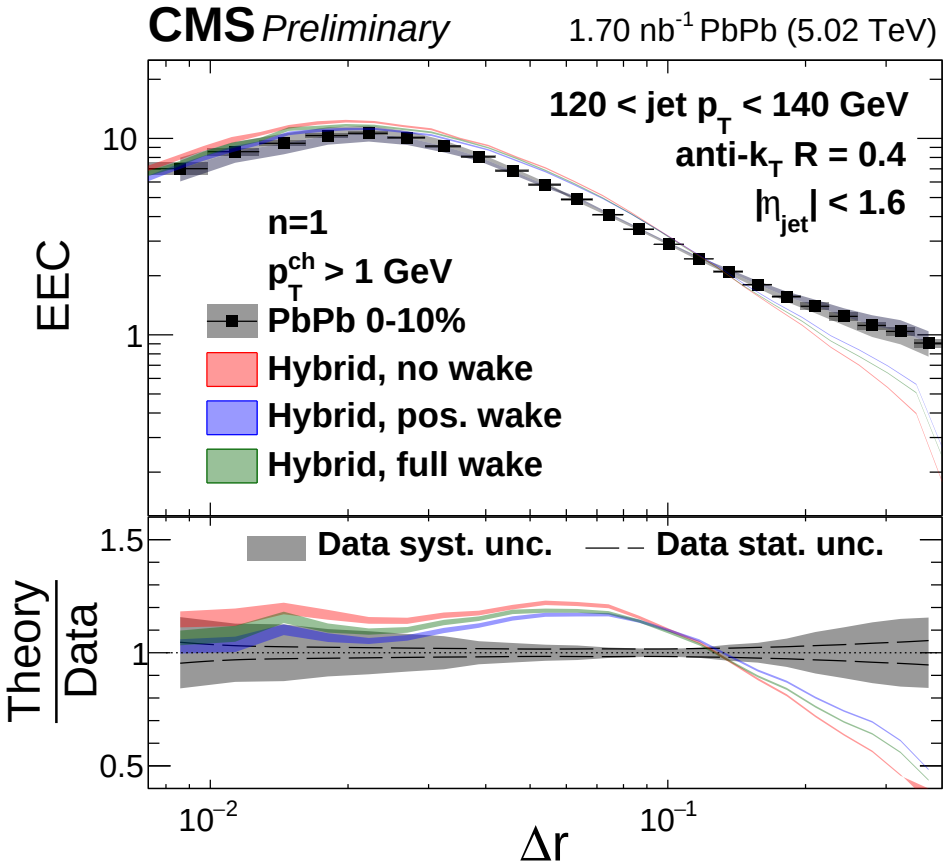




- Models agree with pp data within $\sim 5\%$ for $n = 1$
- Models predict too narrow shape for $n = 2$
- Hybrid vacuum = Pythia8 with MPI off

Hybrid model comparison for PbPb 0-10%

CMS-PAS-HIN-23-004



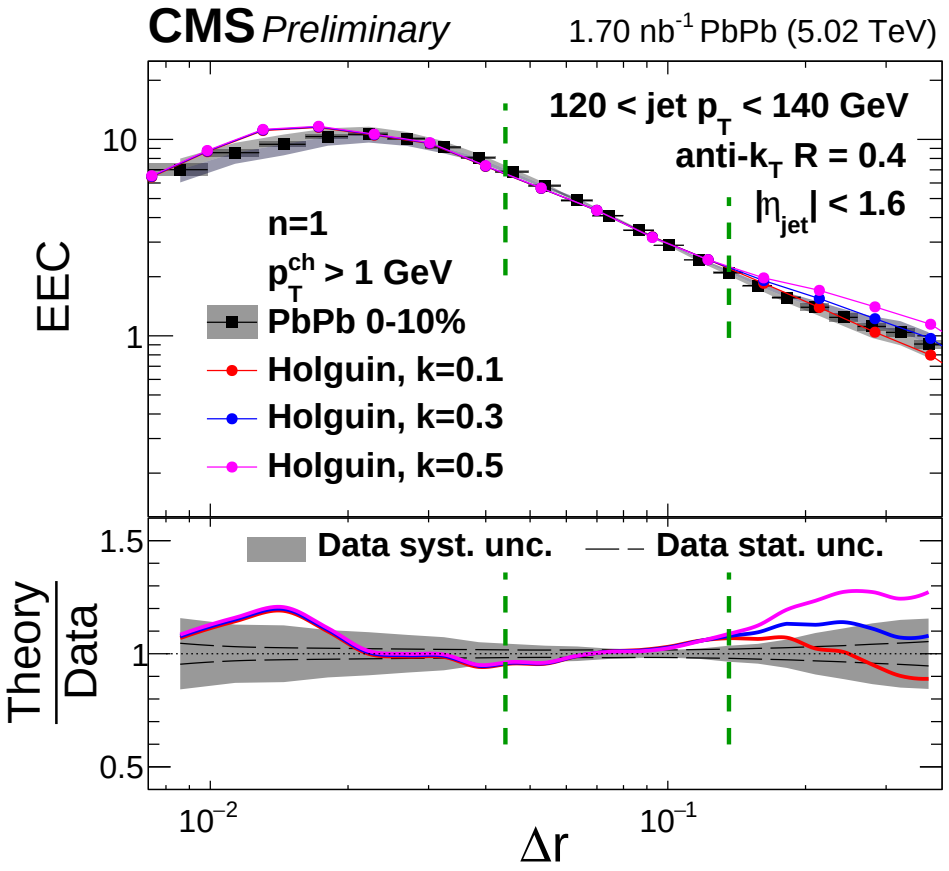
Pablos, Kudinoor, Rajagopal

- Hybrid model[1] with all three wake configurations underpredicts the data at large Δr
- Including wake brings prediction closer to data

[1] JHEP 09 (2015) 175, JHEP 03 (2017) 135, PRC 99 (2019) 5, 051901

Perturbative calculation comparison for PbPb 0-10%

CMS-PAS-HIN-23-004

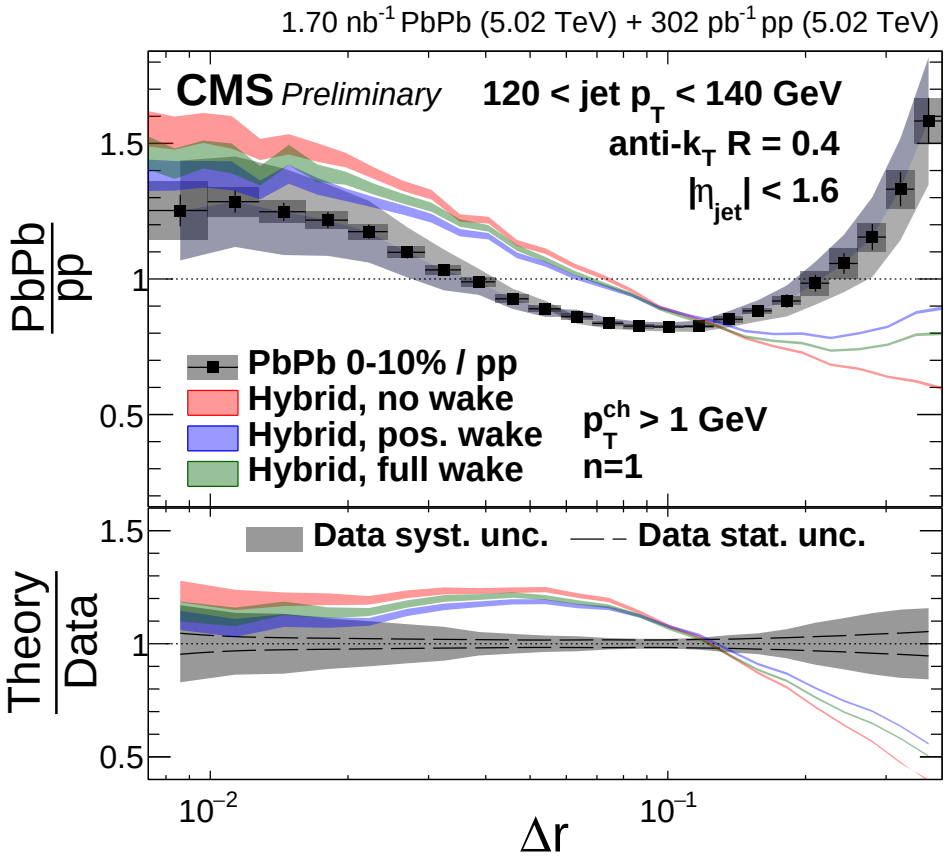


Holguin, Andrés, Dominguez, Marquet, Moult

- Calculation with color coherence from Holguin + collaborators is normalized to data in region $0.042 < \Delta r < 0.126$
- k is constant of proportionality between hydro temperature and $\hat{q}$ of eikonalized scatters against the medium
- Shape at large Δr close to data for $0.1 \lesssim k \lesssim 0.3$

Hybrid model comparison for PbPb/pp ratio

CMS-PAS-HIN-23-004



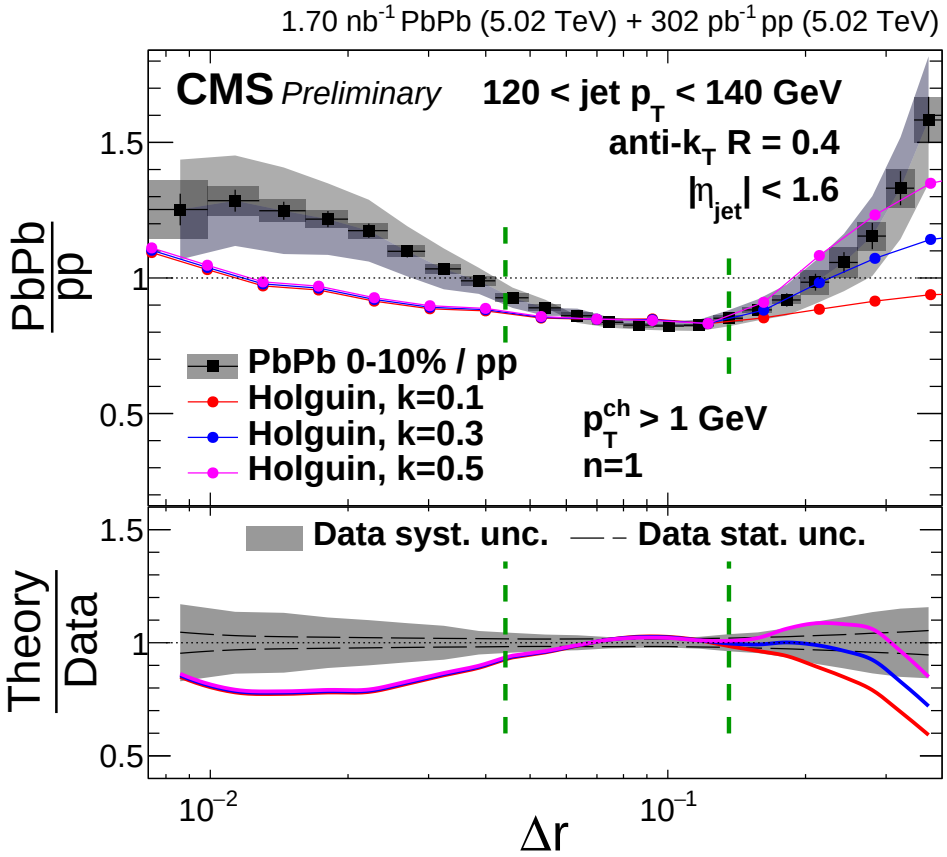
Pablos, Kudinoor, Rajagopal

- Hybrid model[1] does not predict enough enhancement at large Δr
- Only configurations with wake give same qualitative behavior
- Turn-on angle for wake is larger than in data

[1] JHEP 09 (2015) 175, JHEP 03 (2017) 135, PRC 99 (2019) 5, 051901

Perturbative calculation comparison for PbPb/pp ratio

CMS-PAS-HIN-23-004

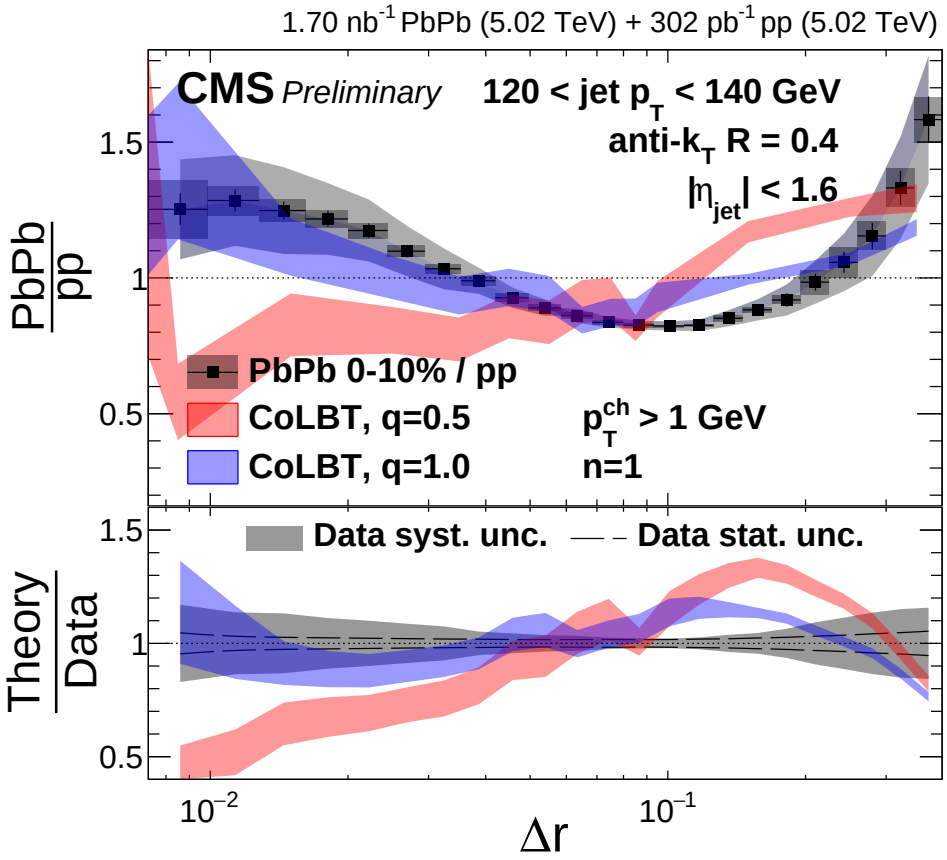


Holguin, Andrés, Dominguez, Marquet, Moult

- Calculation again normalized to data in region $0.042 < \Delta r < 0.126$
- Underprediction at large Δr
- Turn-on angle is similar in calculation and data
- Best description of data with $0.3 \lesssim k \lesssim 0.5$

CoLBT model comparison for PbPb/pp ratio

CMS-PAS-HIN-23-004



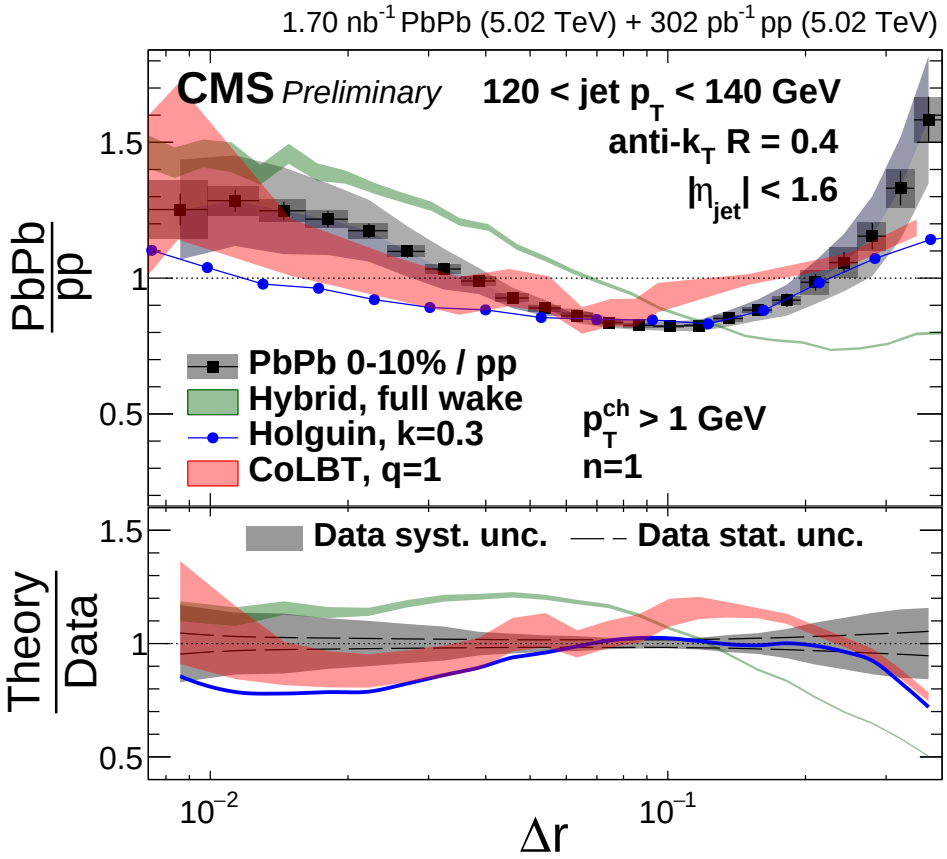
Yang, He, Wang

- q-parameter in CoLBT[2] model describes the minimum virtuality for vacuum splittings
- $q = 0.5$ does not describe the data well
- $q = 1$ is better, but earlier turn-on and less enhancement than in data

[2] PLB 777 (2018) 86, PLB 810 (2020) 135783, PRL 128 (2022) 2, 022302

Different model comparisons for PbPb/pp ratio

CMS-PAS-HIN-23-004

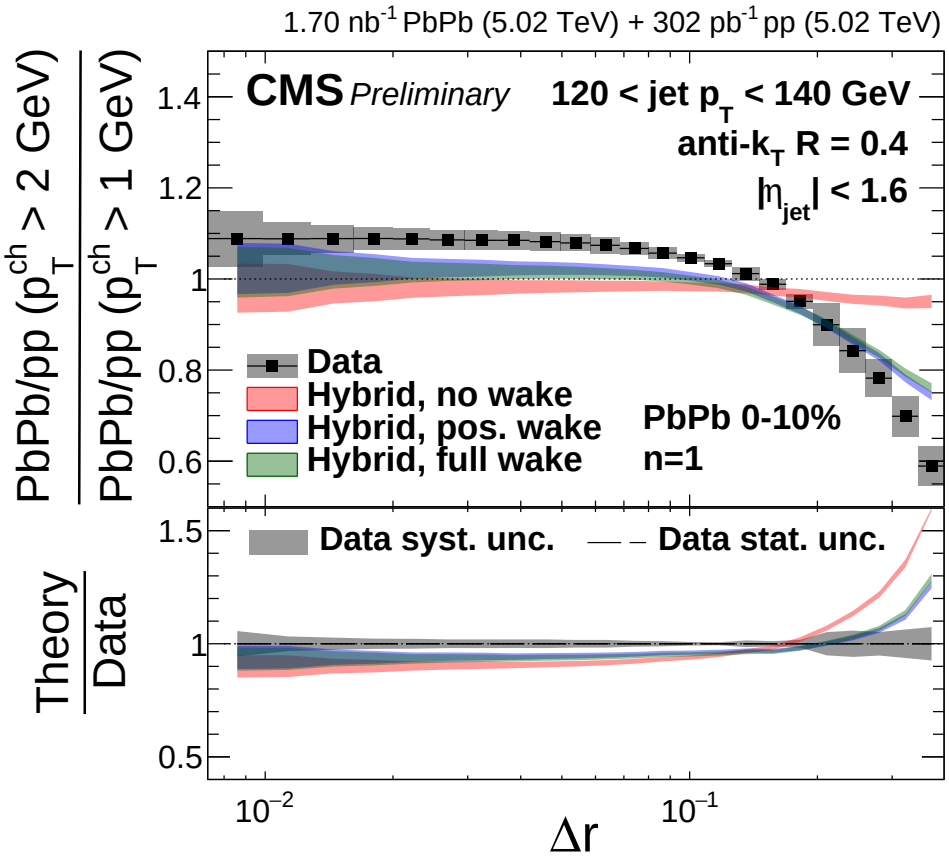


Pablos, Kudinoor, Rajagopal
Holguin, Andrés, Dominguez, Marquet, Moult
Yang, He, Wang

- Similar qualitative features between all models and data
  - Small Δr narrowing turns to large Δr enhancement
- Differences on turn-on point and magnitude of large Δr enhancement highlight different physics effects modeled

Hybrid model comparison for double ratio

CMS-PAS-HIN-23-004



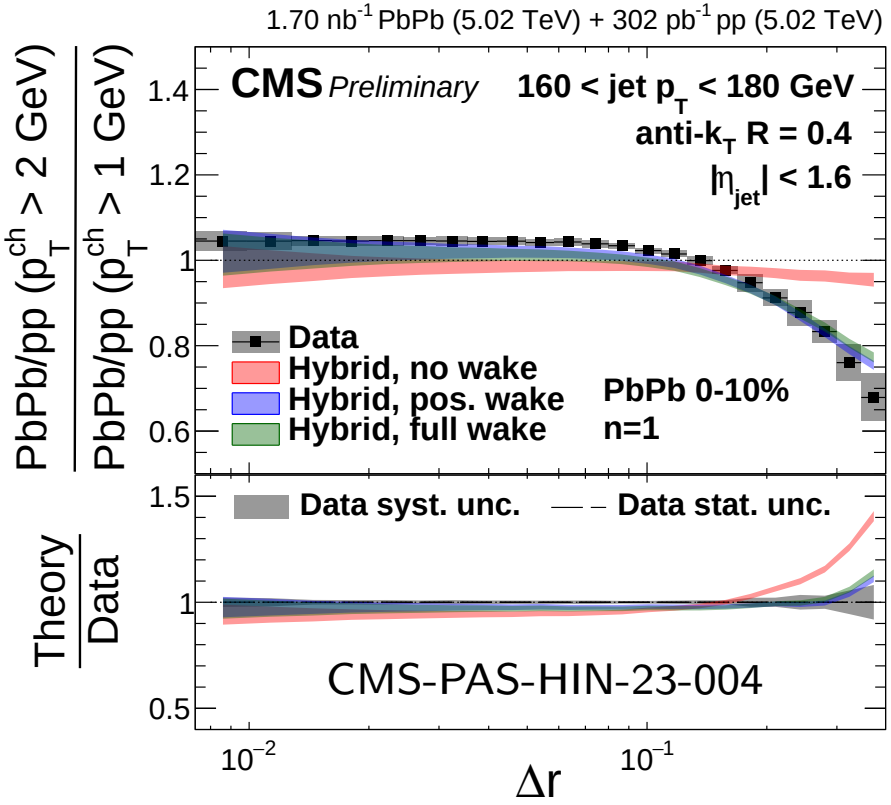
Pablos, Kudinoor, Rajagopal

- Isolate the effects of soft-hard correlations with double ratio
- Hybrid model[1] underpredicts the effect
- Again, same qualitative features only with wake

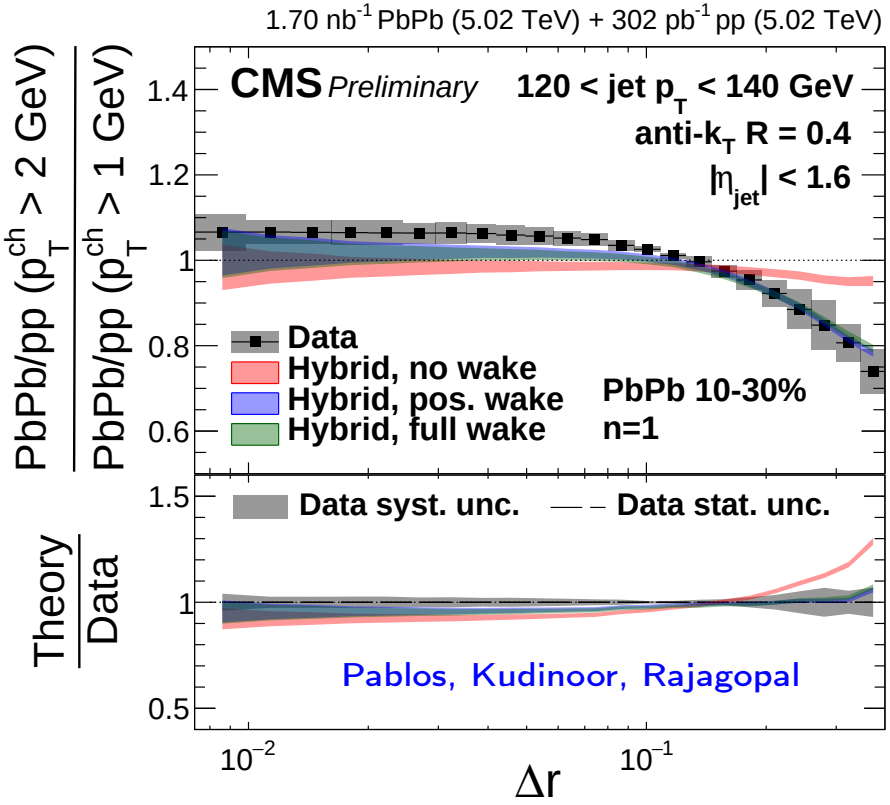
[1] JHEP 09 (2015) 175, JHEP 03 (2017) 135, PRC 99 (2019) 5, 051901

Hybrid model comparison for double ratio, other bins

$160 < p_{\mathrm{T,jet}} < 180$ GeV



$C = 10 - 30\%$

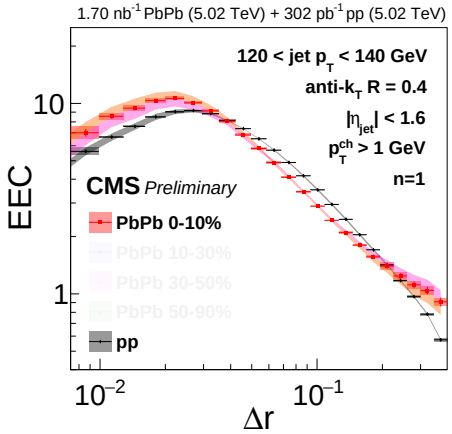


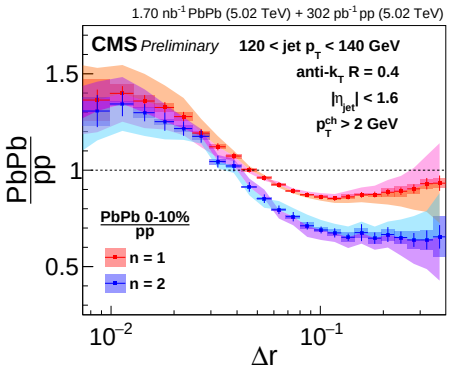
- Hybrid model[1] predicts the double ratio accurately for higher jet p_{T} selection and more peripheral bins

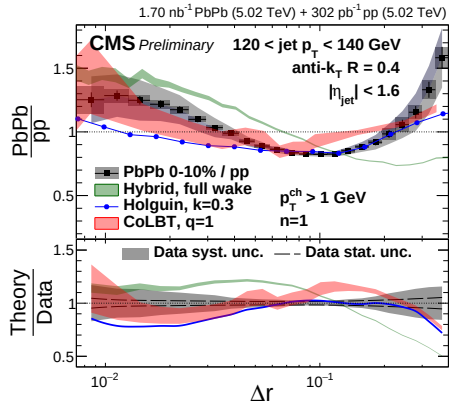
[1] JHEP 09 (2015) 175, JHEP 03 (2017) 135, PRC 99 (2019) 5, 051901

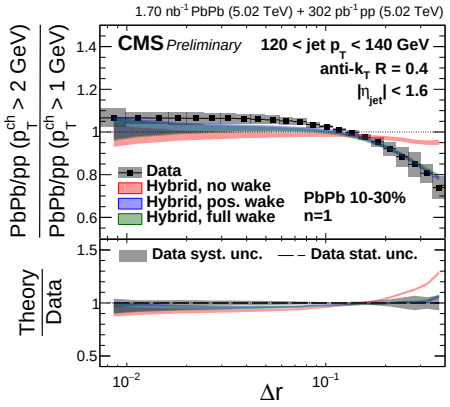
Summary

- Free hadron, transition, and free quark/gluon regions visible in PbPb
- Energy loss leads to narrowing of the shape
- Interesting modifications are seen at large Δr region
  - Important to include low p_{T} particles
- Wake needed in Hybrid model to describe data qualitatively
  - Also good quantitative description for double ratio
- Calculation by Holguin+co and CoLBT show same qualitative features as data with different turn-on points









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

Back-up

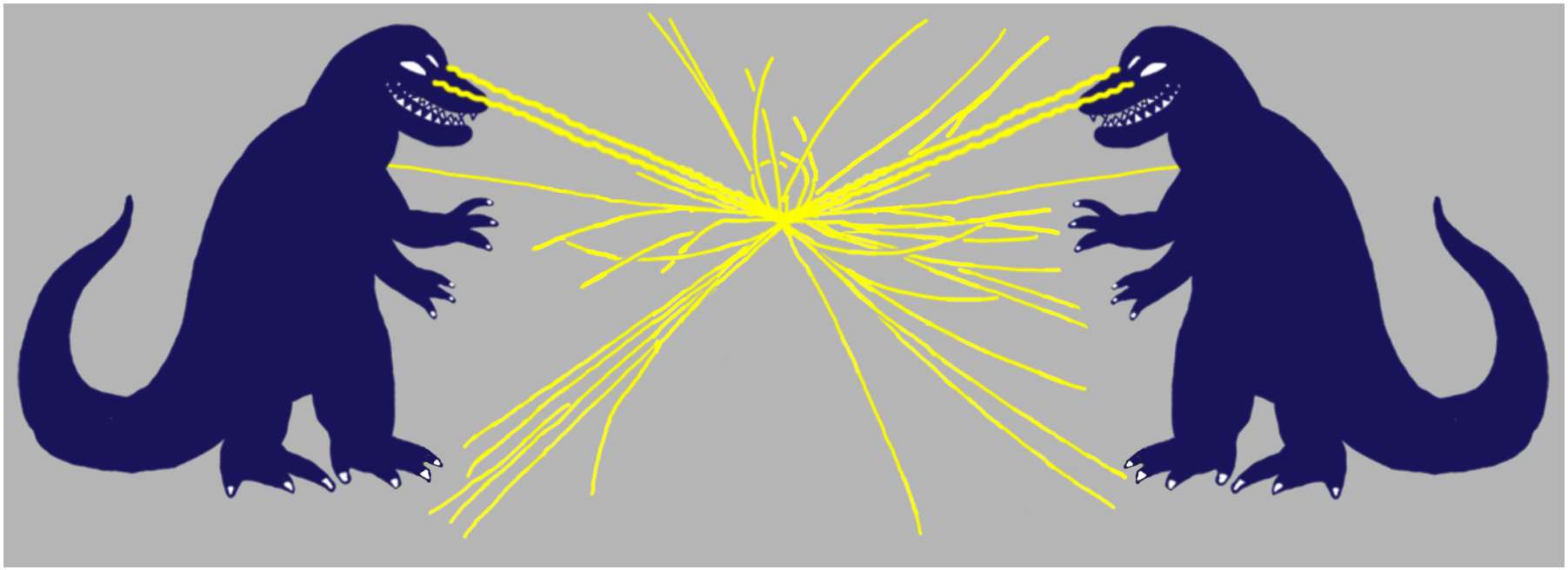


Image credit: BOOST 2022 conference logo

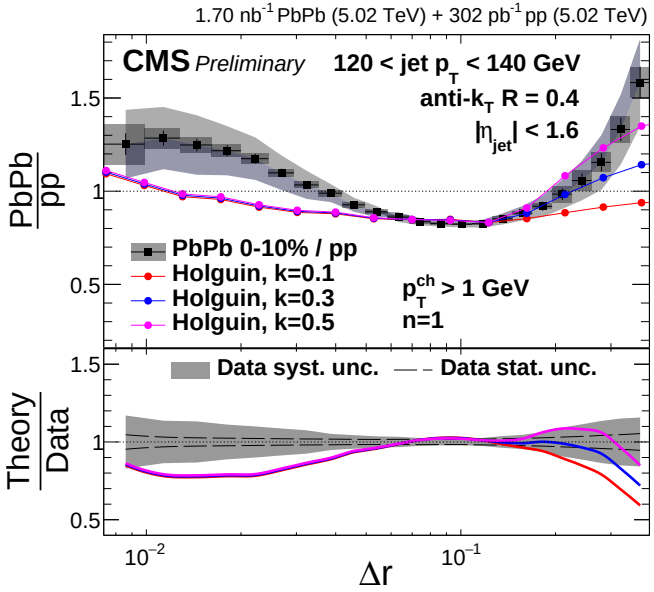
Disclaimer about the model comparisons in back-up

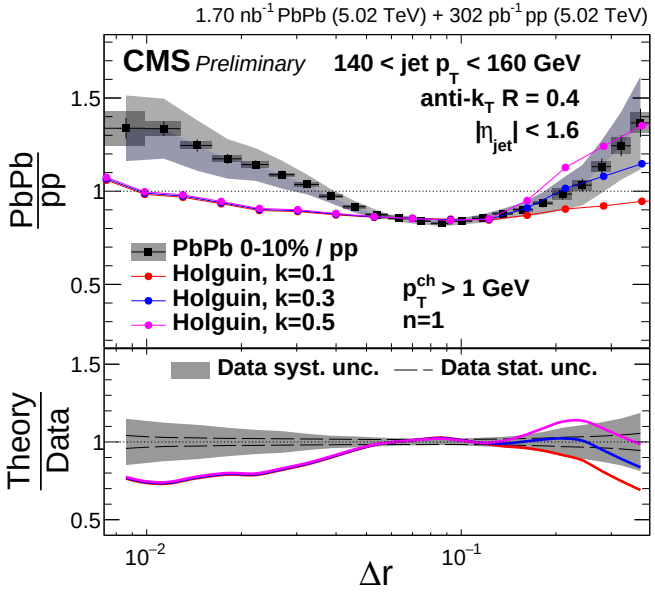
- All the data is from CMS-PAS-HIN-23-004, this is not repeated in every slide
- Title of the slide specifies the model, centrality selection, $p_{\mathrm{T}}^{\mathrm{ch}}$ cut, and the exponent n
- The illustration below shows how different jet p_{T} bins are positioned in each slide

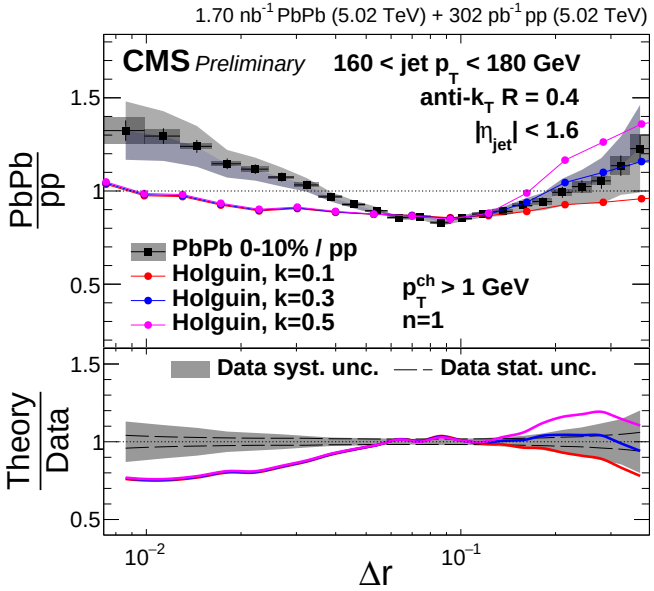
$120 < p_{\mathrm{T,jet}} < 140\,\mathrm{GeV}$ $140 < p_{\mathrm{T,jet}} < 160\,\mathrm{GeV}$

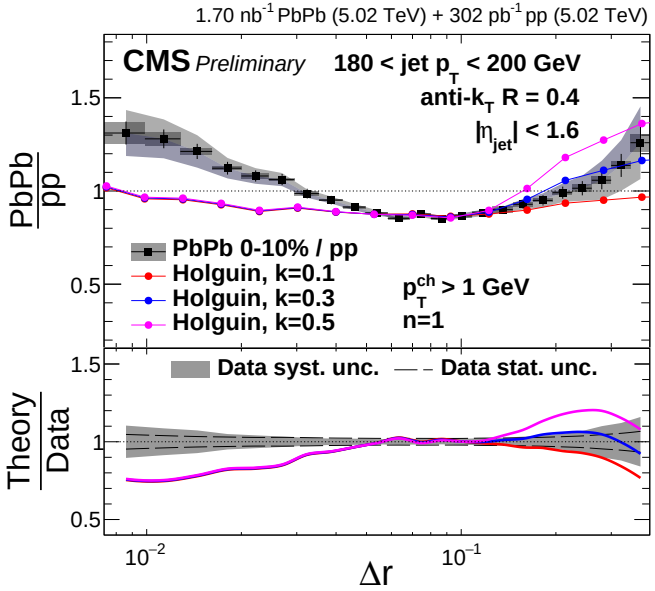
$160 < p_{\mathrm{T,jet}} < 180\,\mathrm{GeV}$ $180 < p_{\mathrm{T,jet}} < 200\,\mathrm{GeV}$

PbPb to pp ratio, Holguin, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

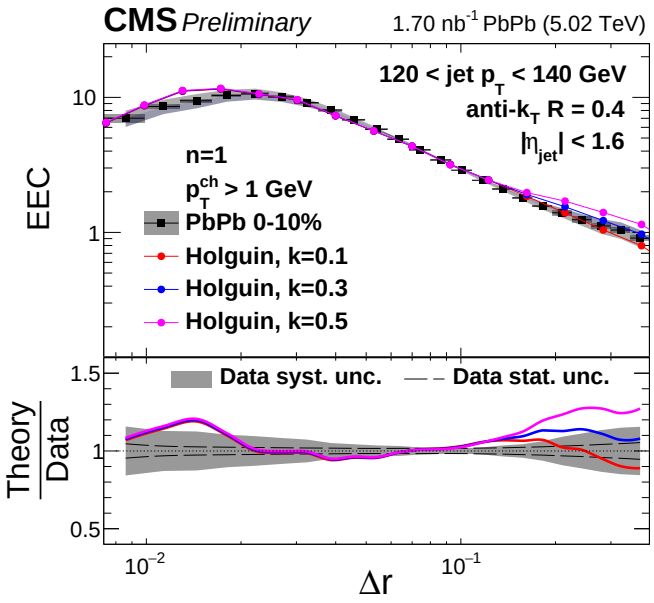


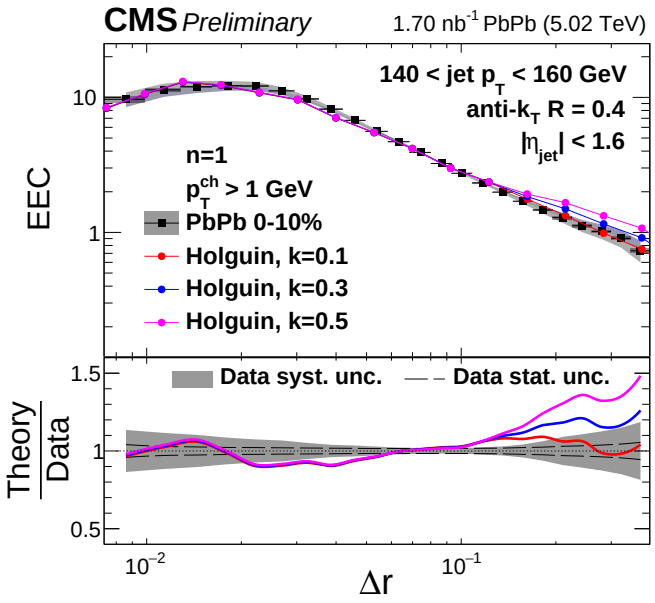


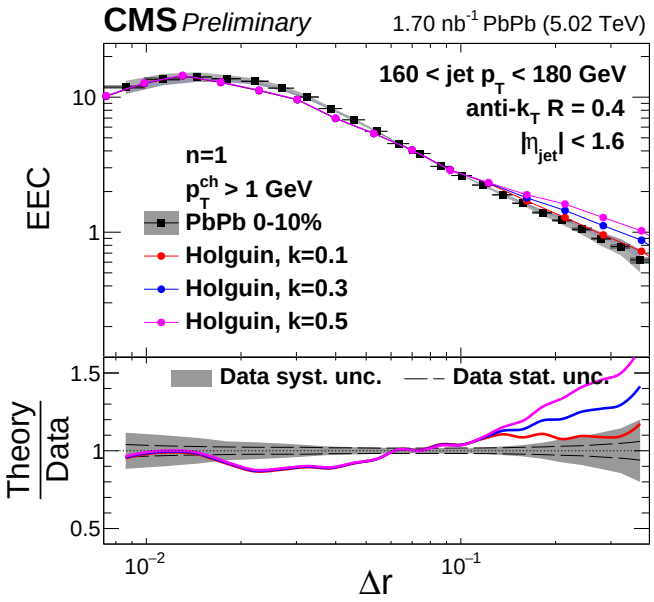


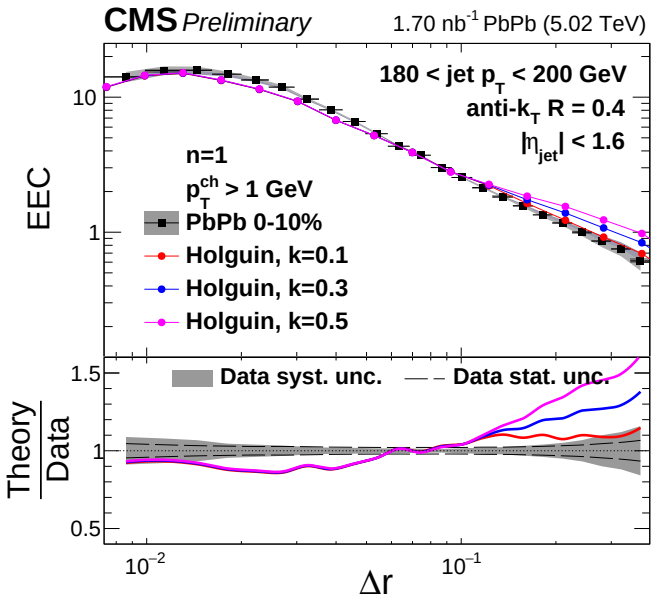


PbPb distribution, Holguin, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

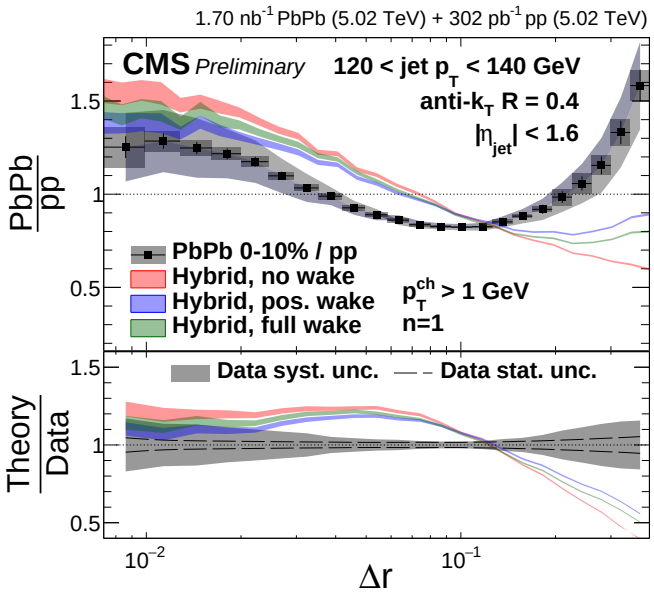


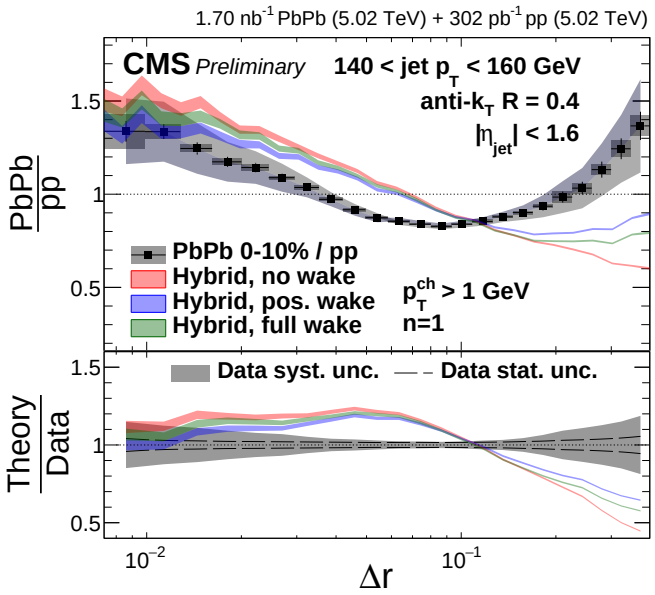


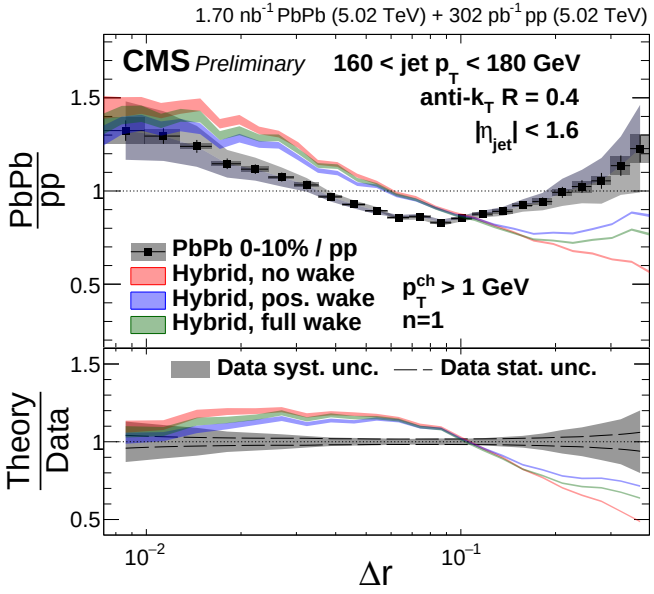


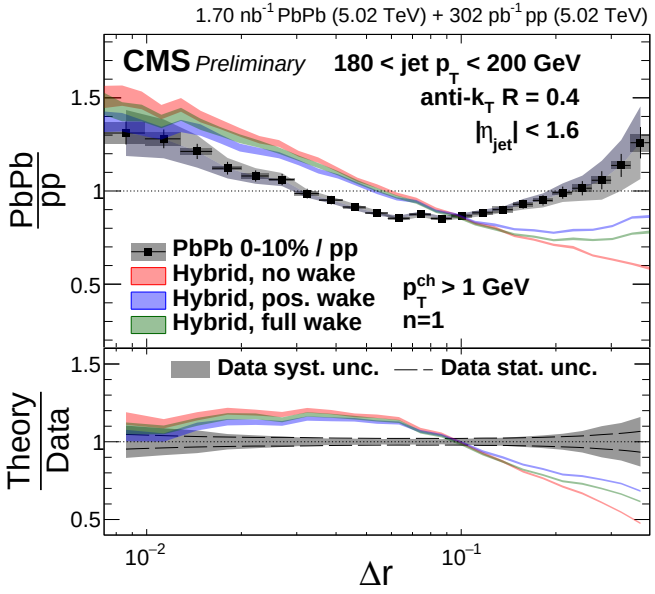


PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

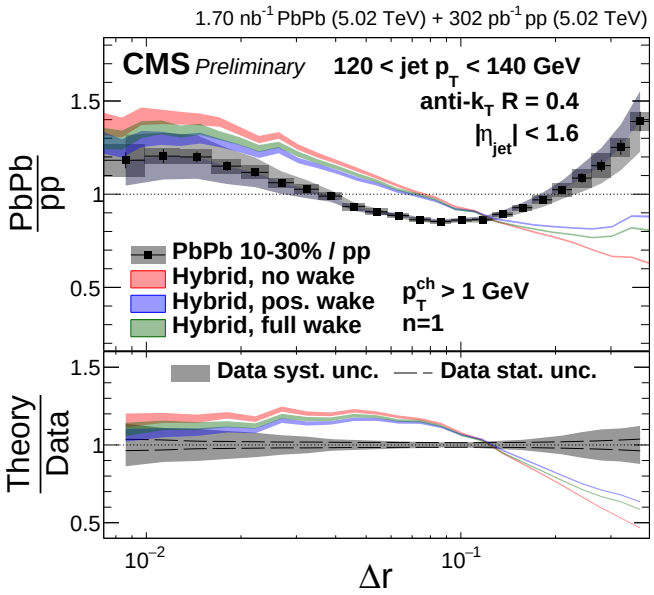


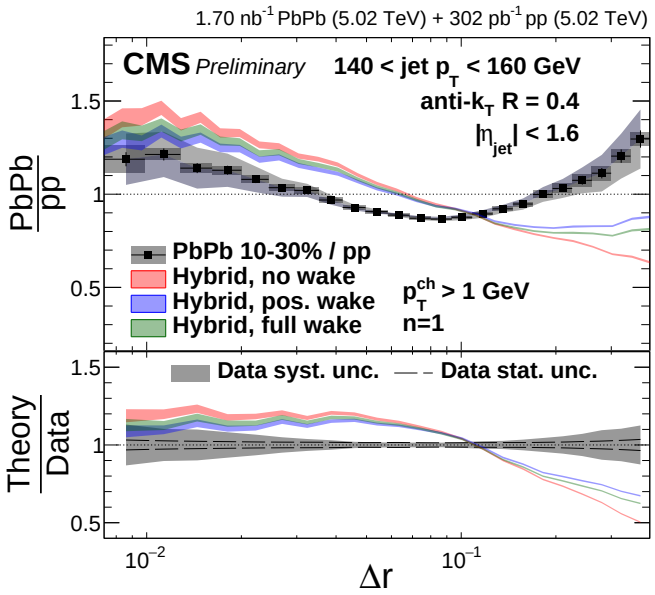


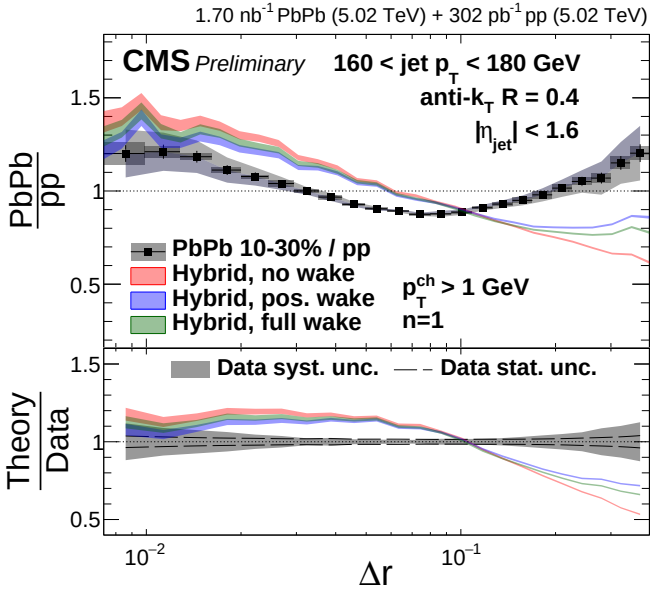


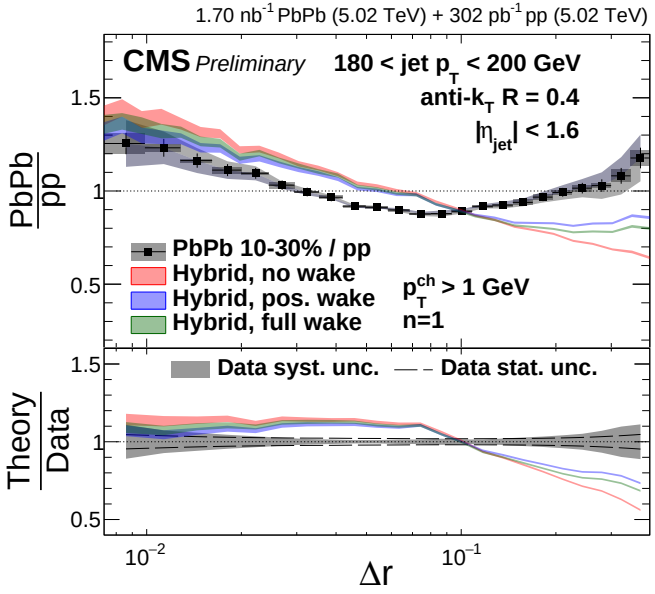


PbPb to pp ratio, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

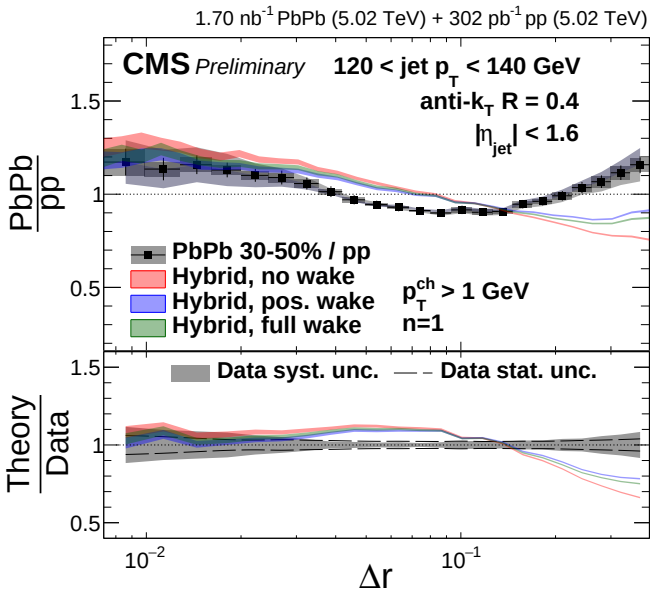


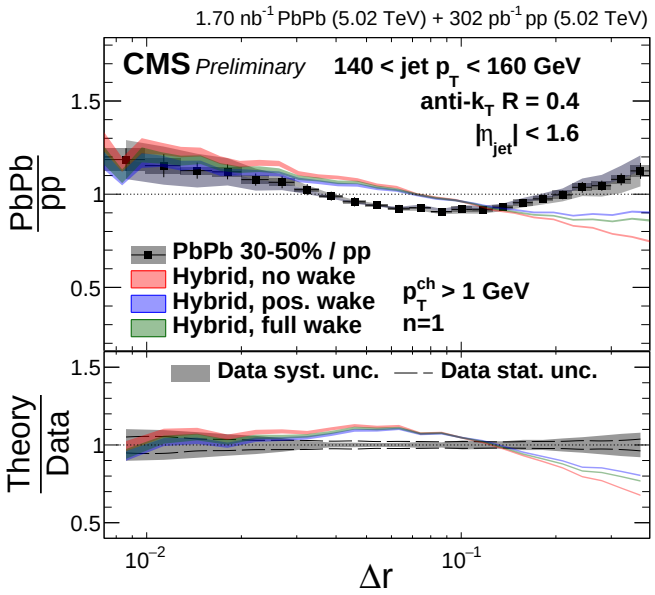


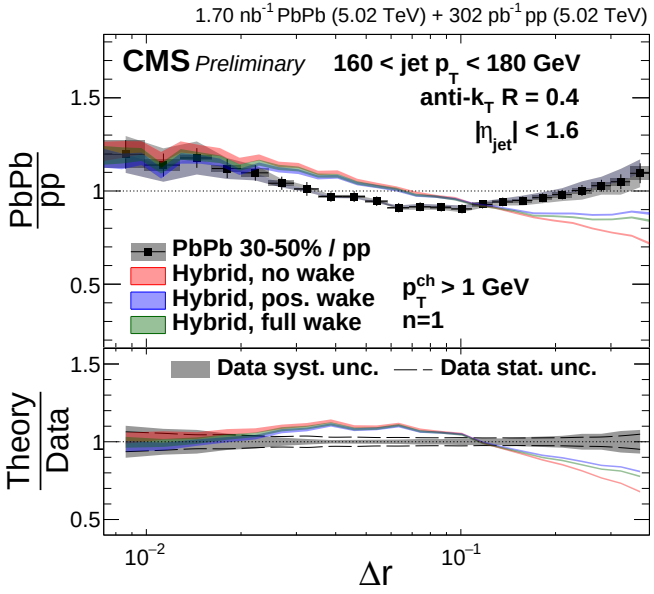


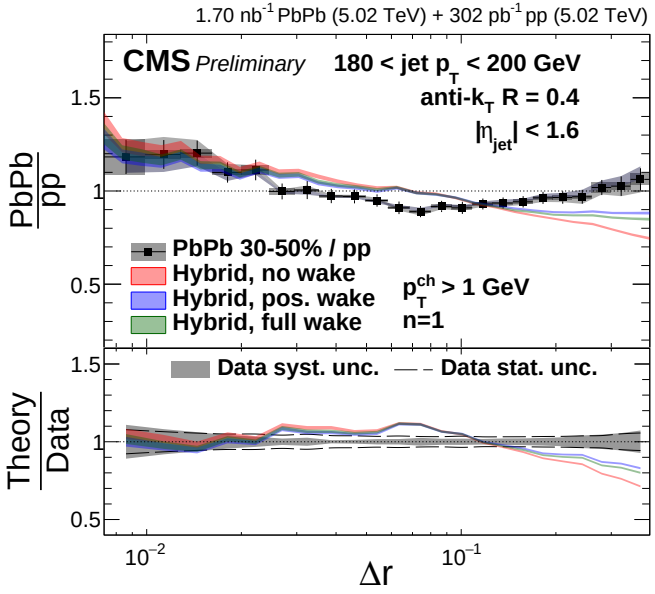


PbPb to pp ratio, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

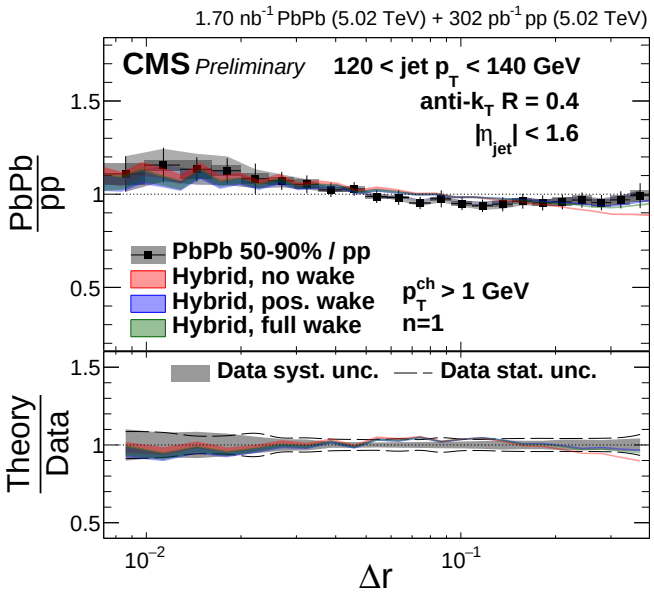


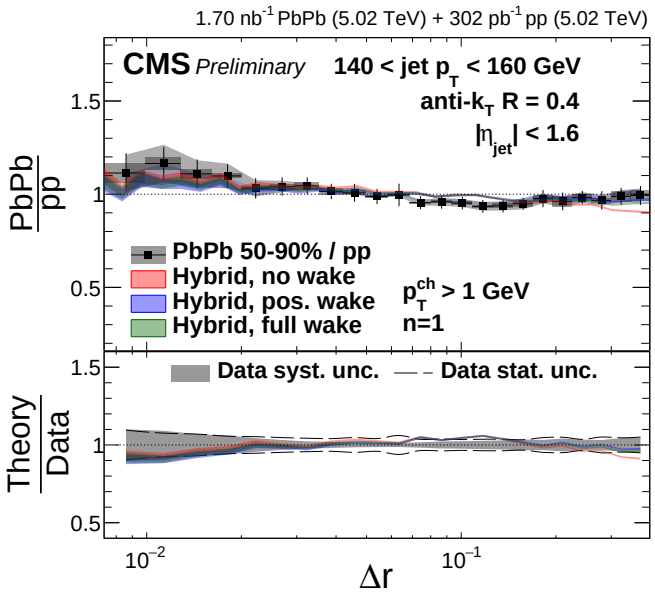


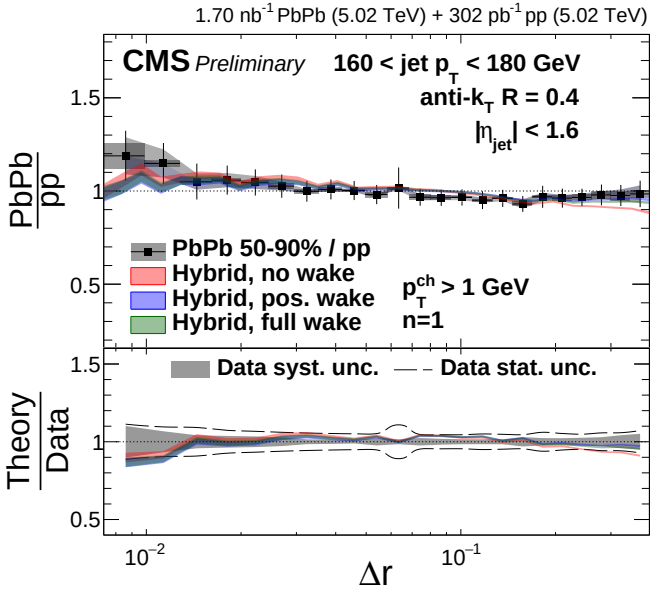


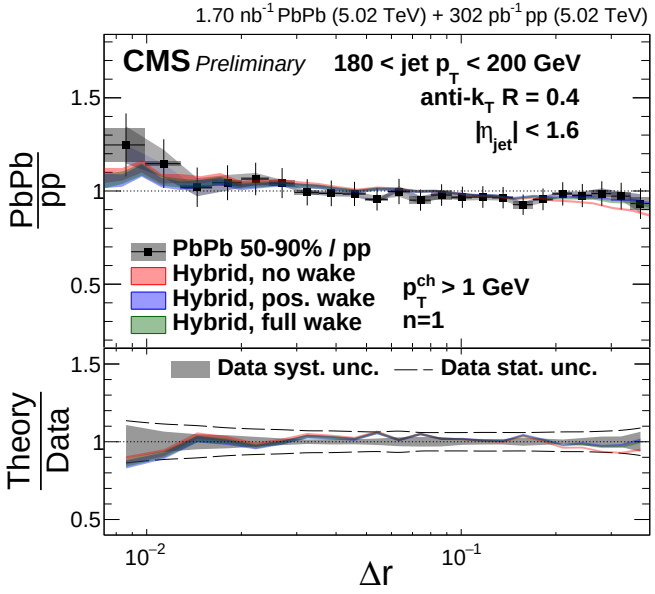


PbPb to pp ratio, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

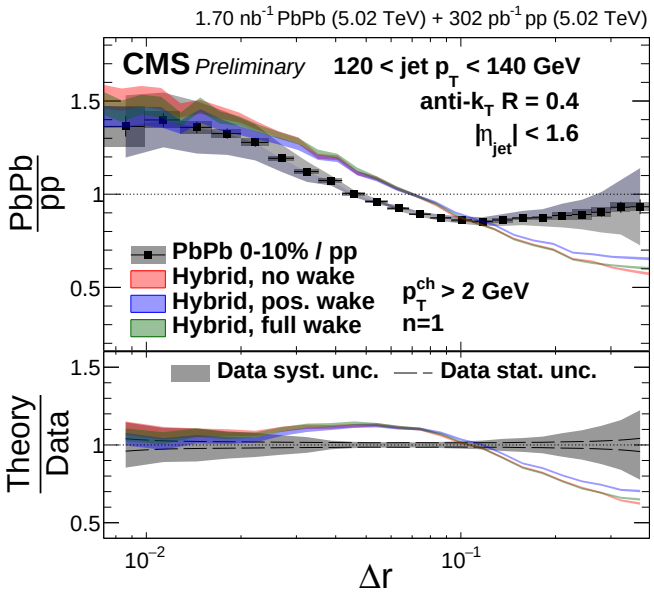


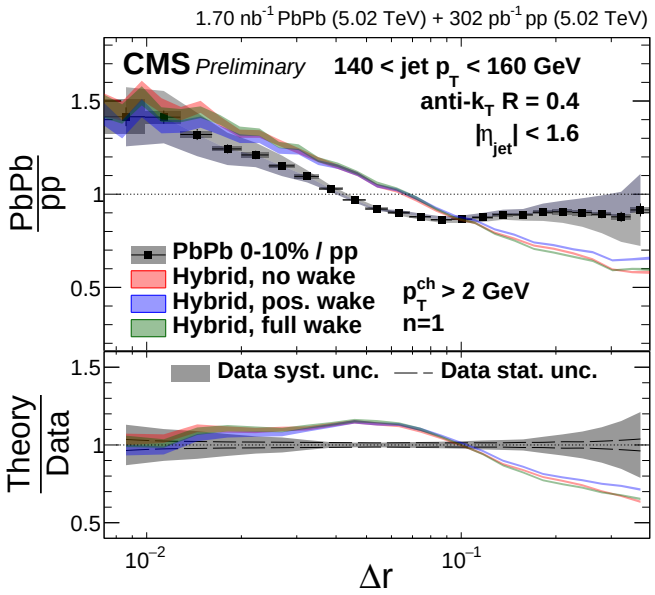


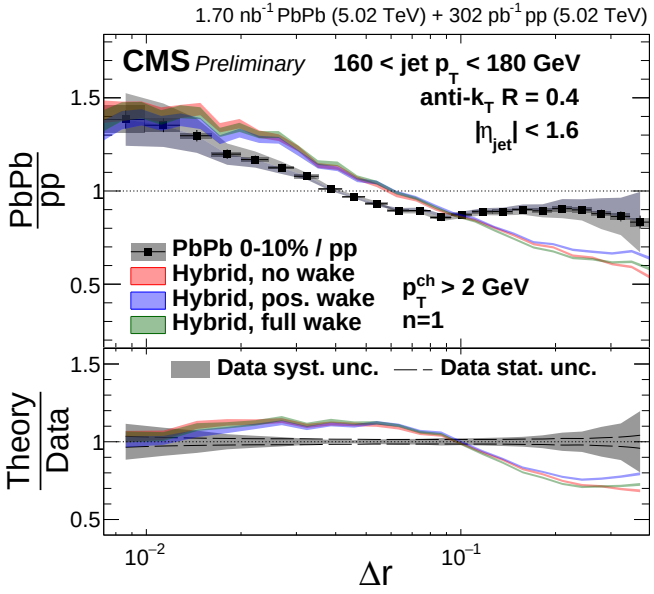


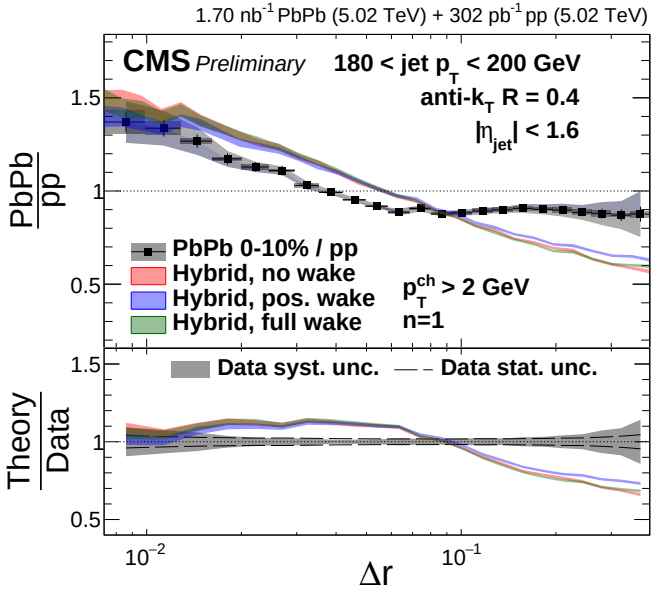


PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

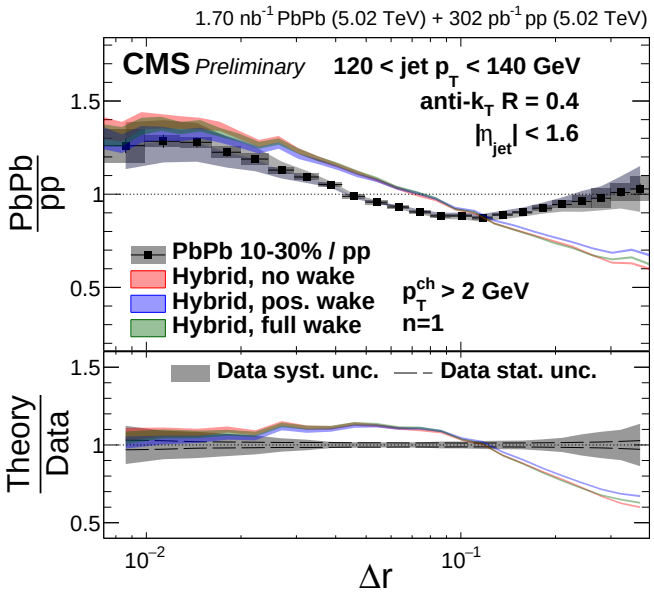


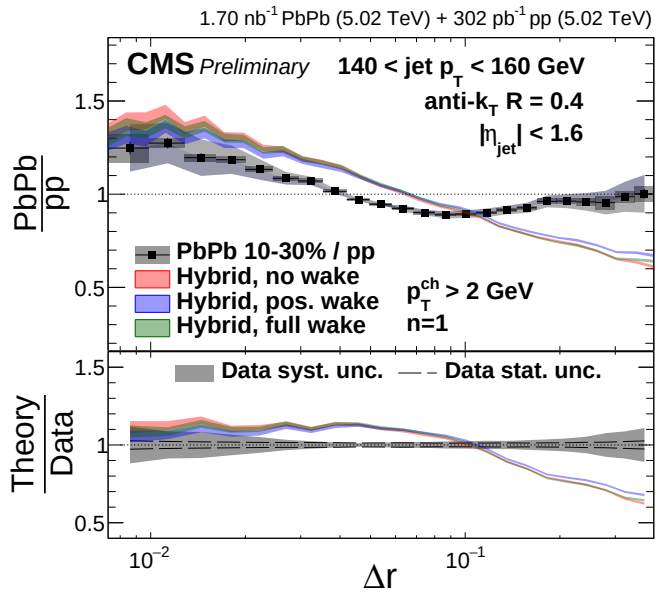


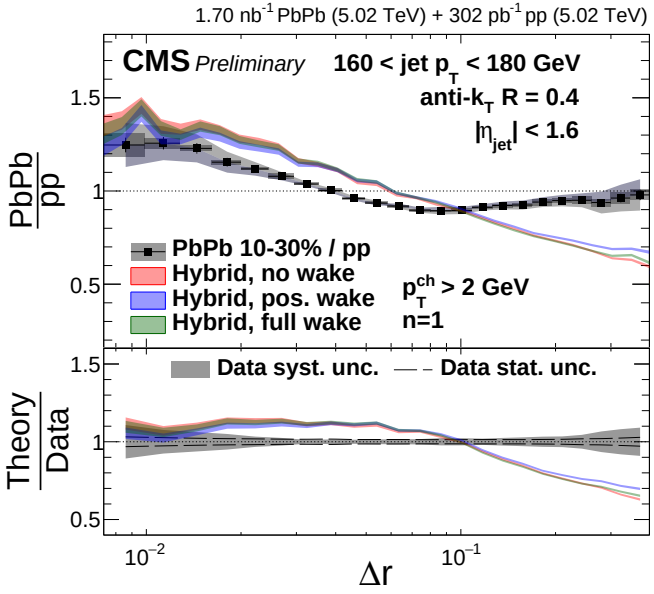


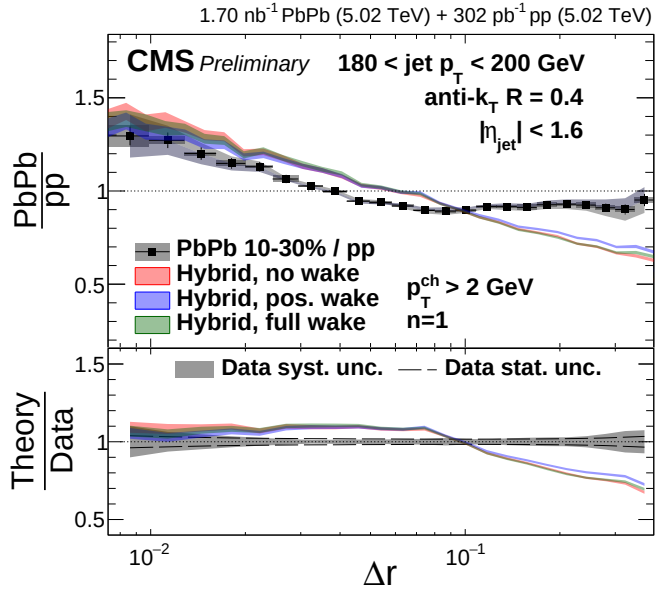


PbPb to pp ratio, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

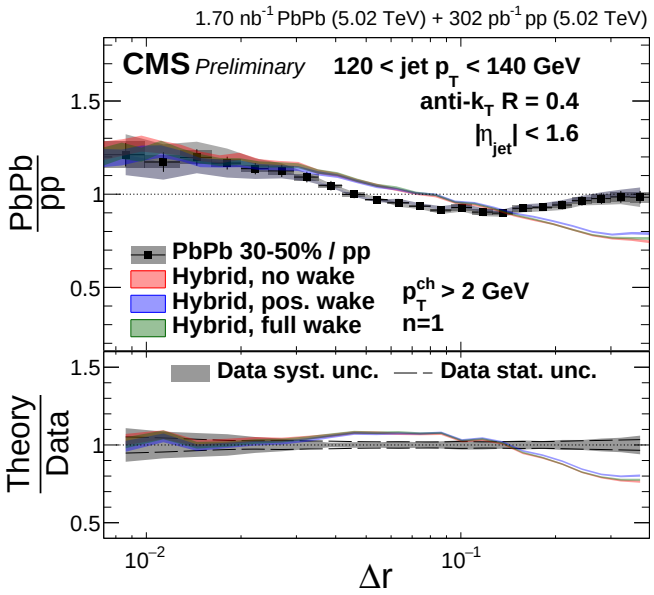


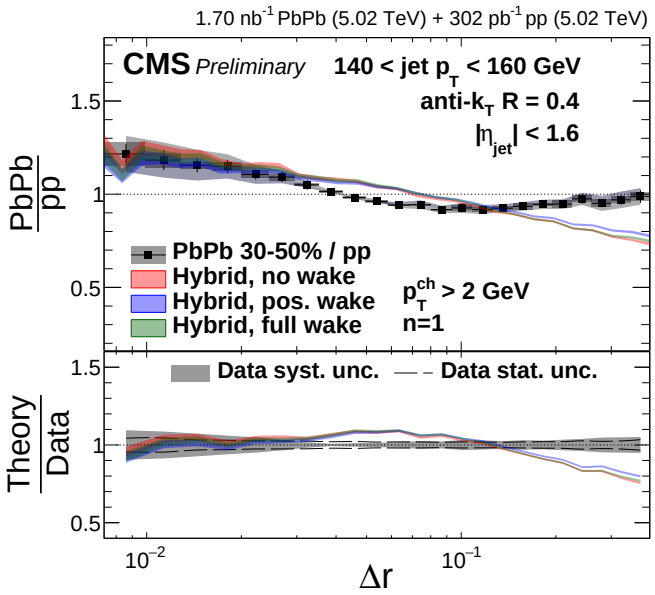


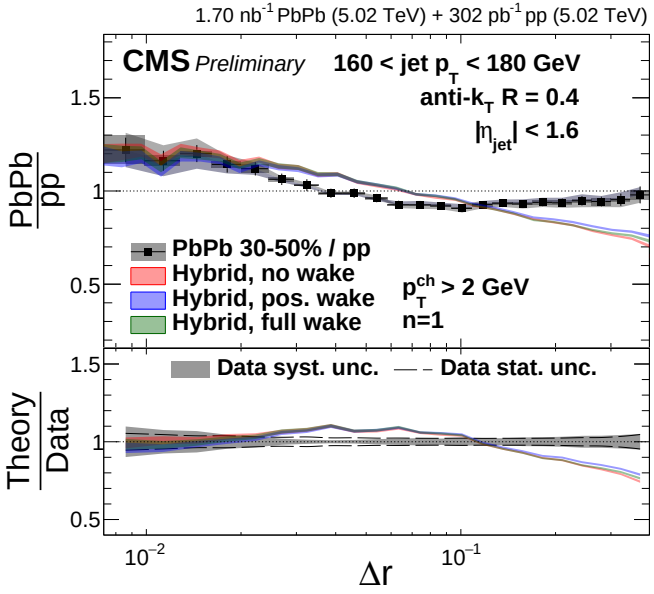


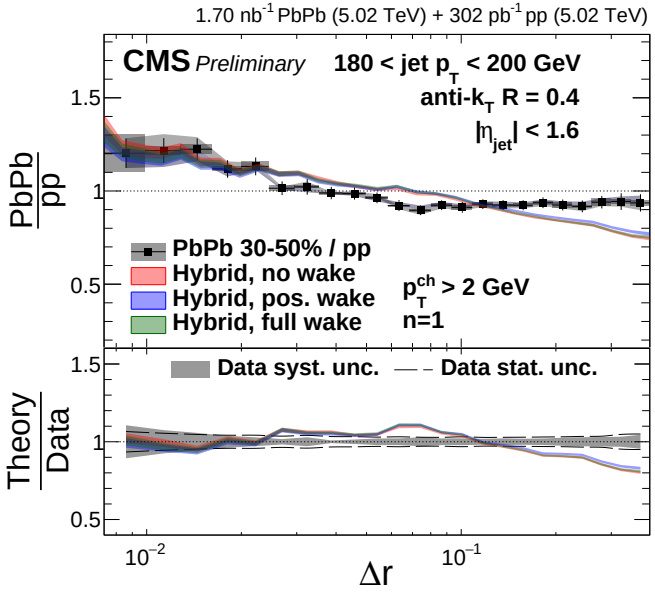


PbPb to pp ratio, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

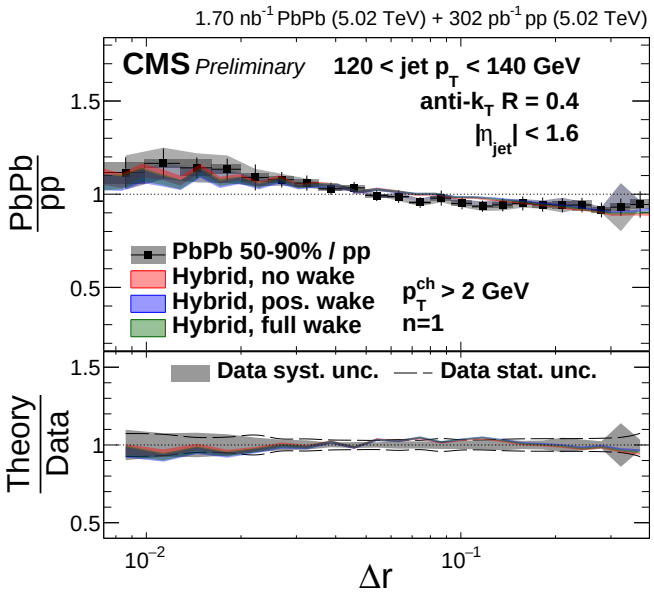


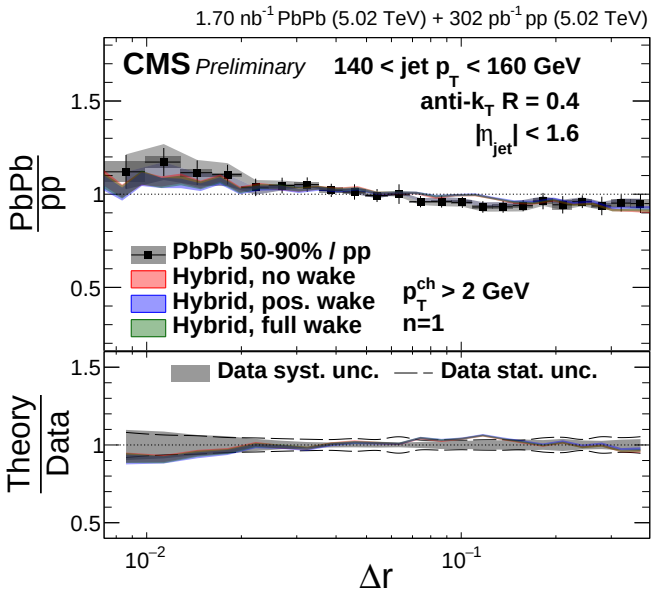


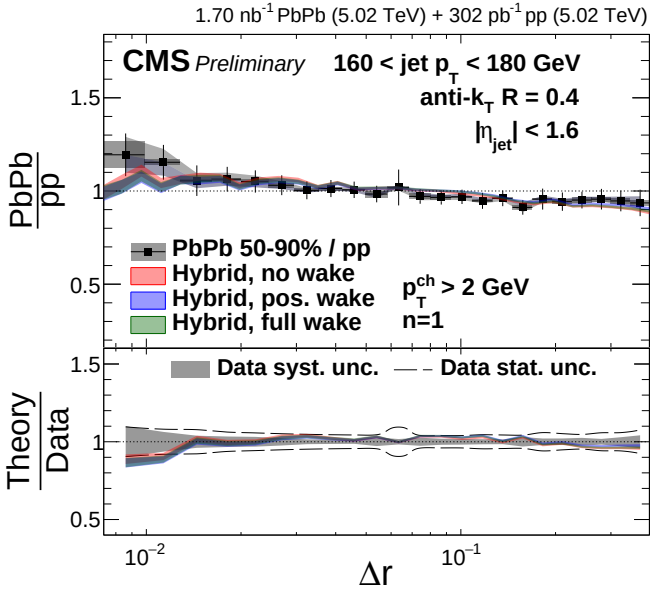


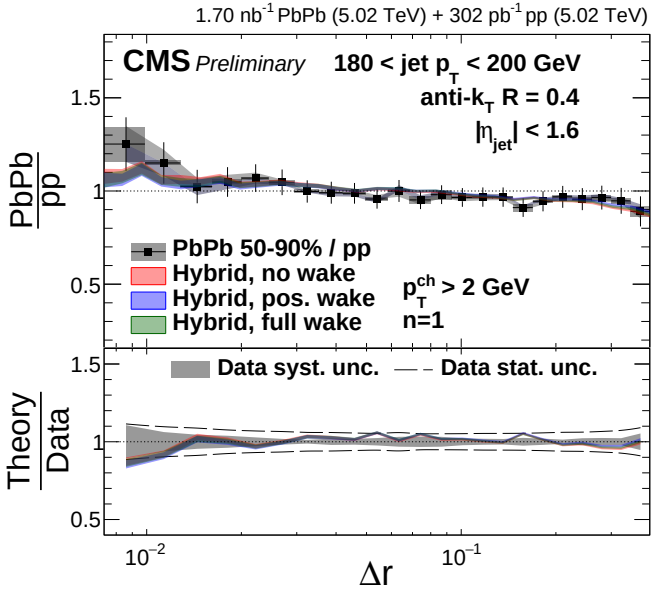


PbPb to pp ratio, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

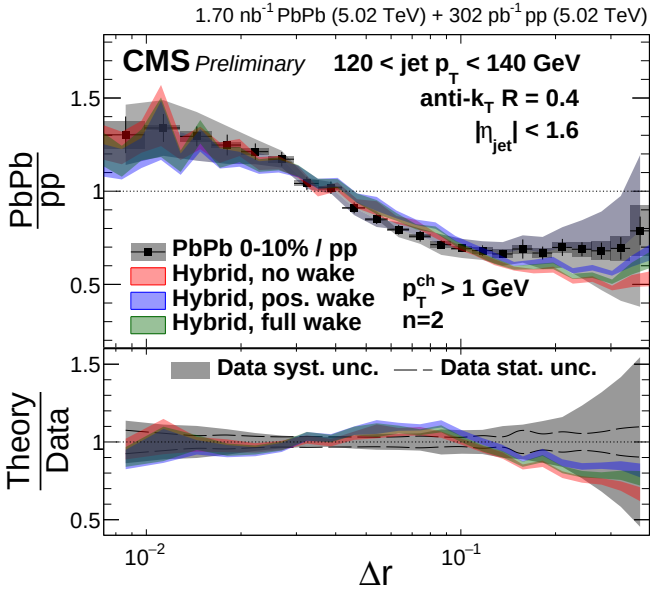


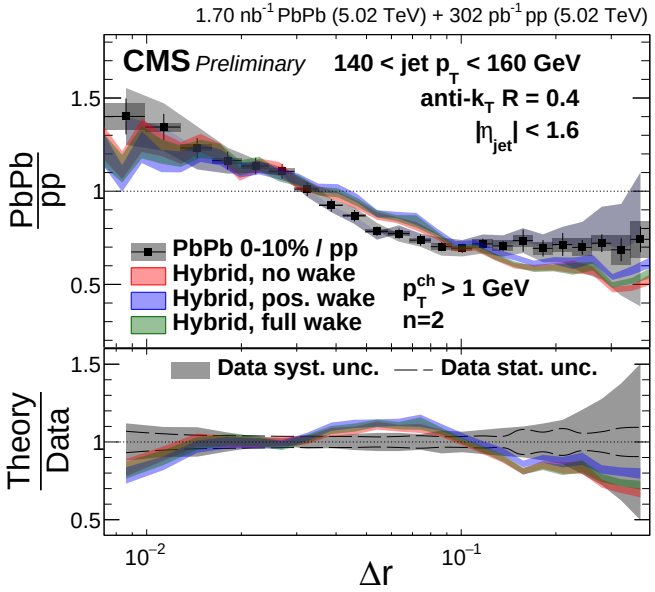


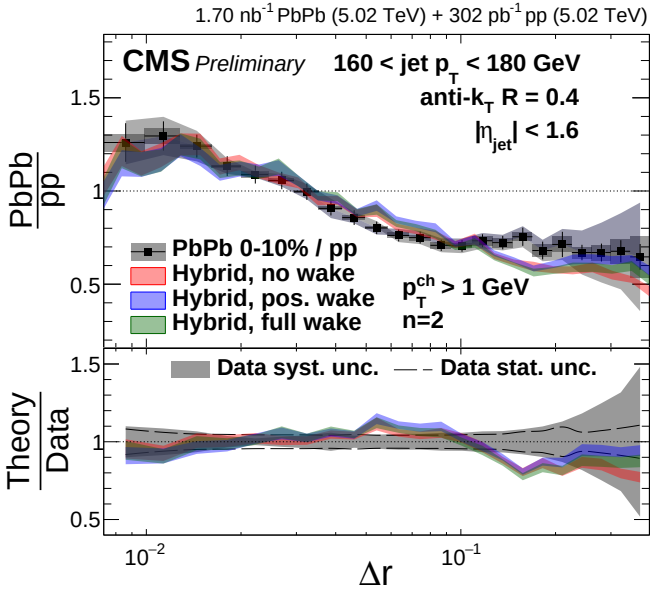


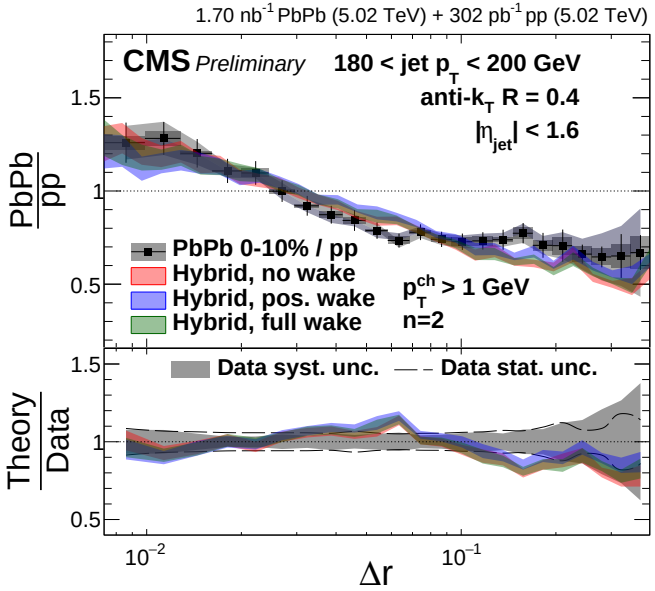


PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

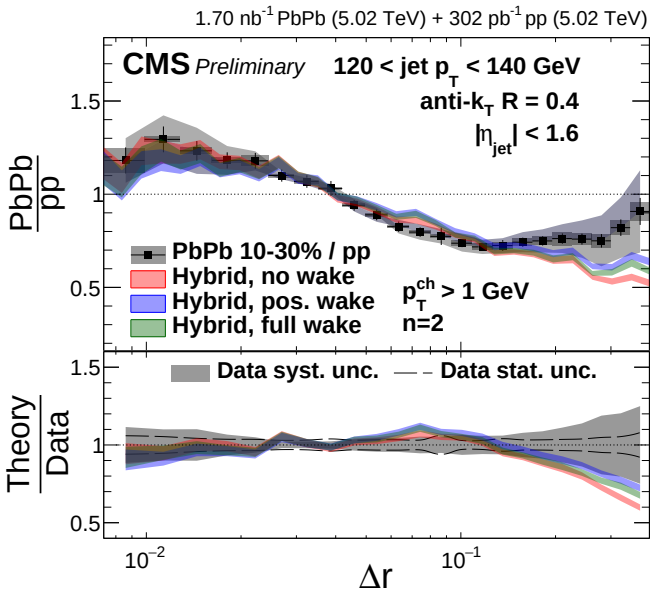


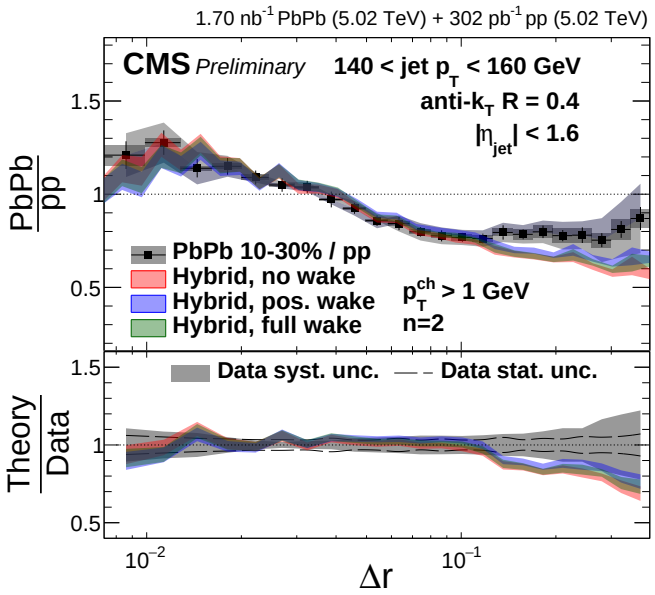


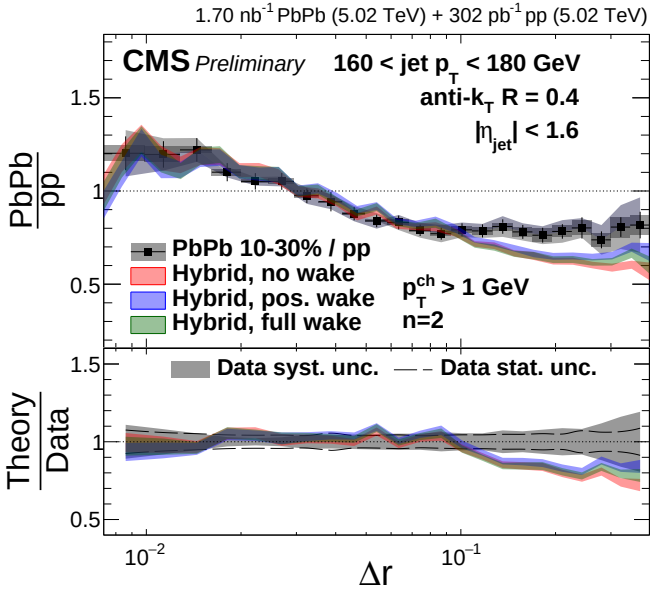


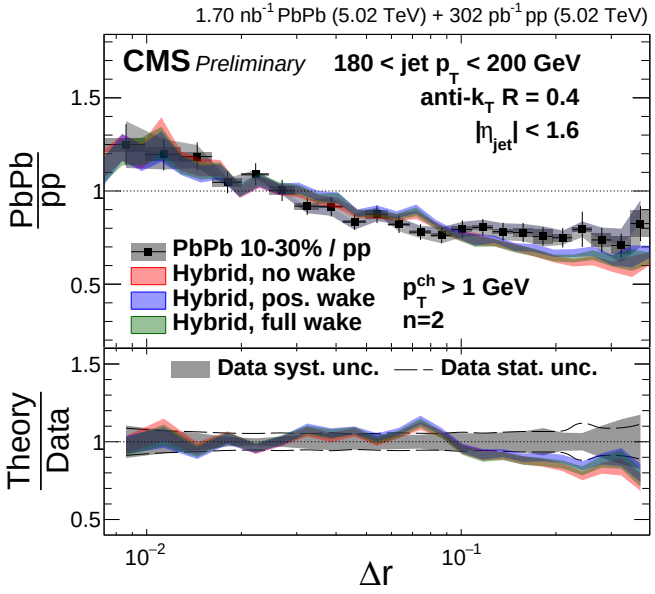


PbPb to pp ratio, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

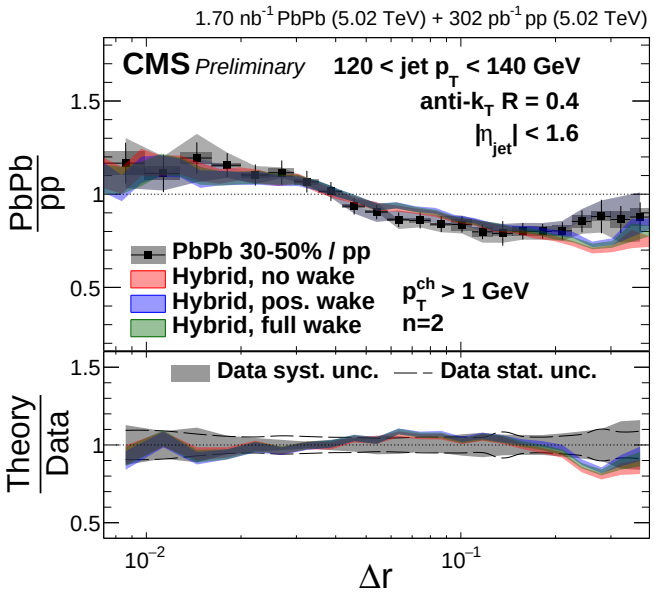


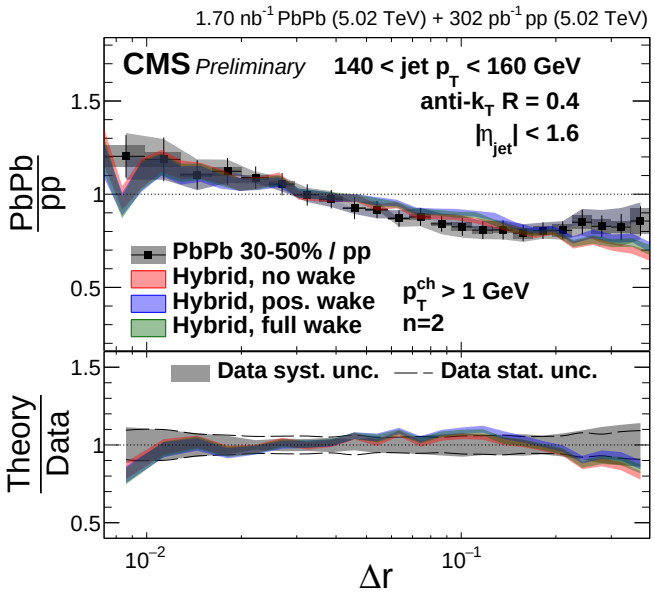


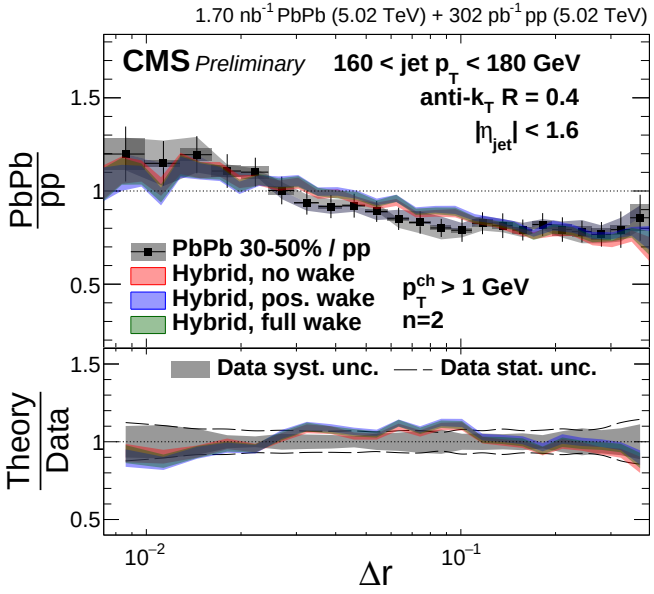


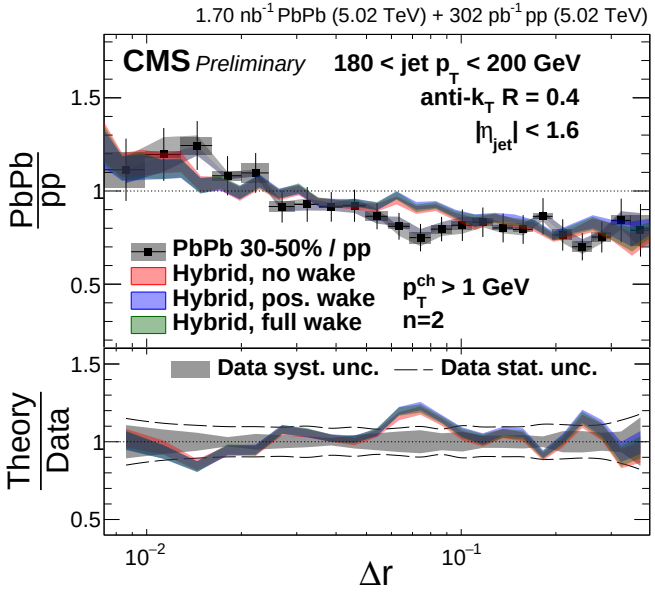


PbPb to pp ratio, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

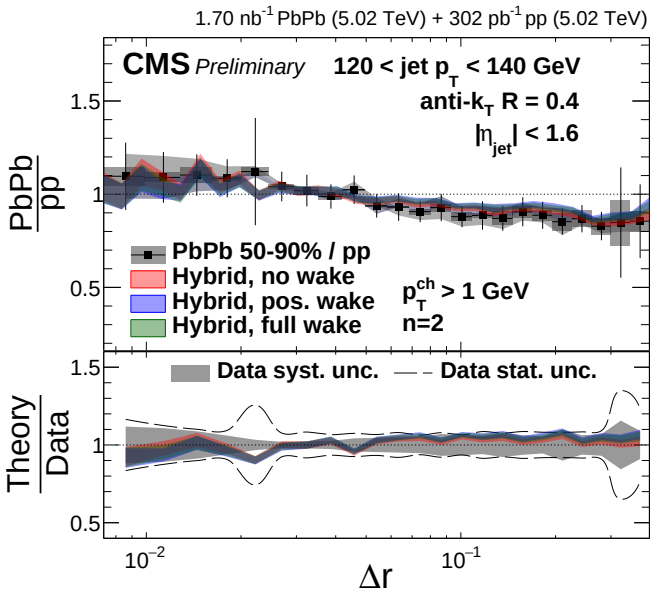


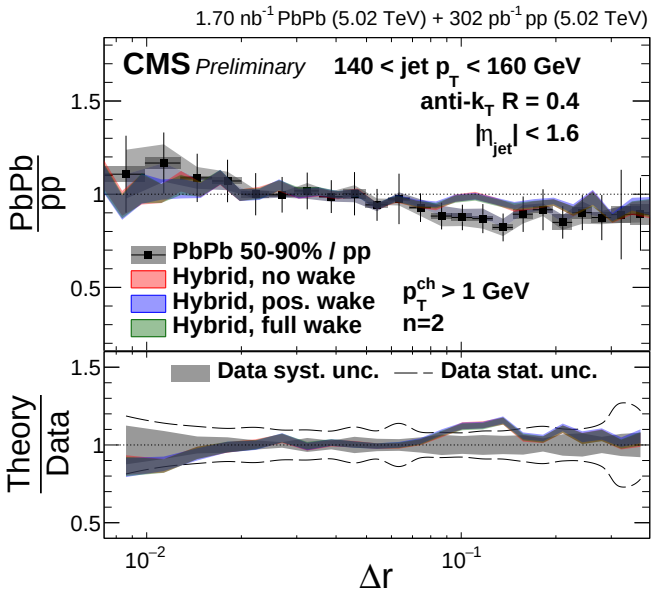


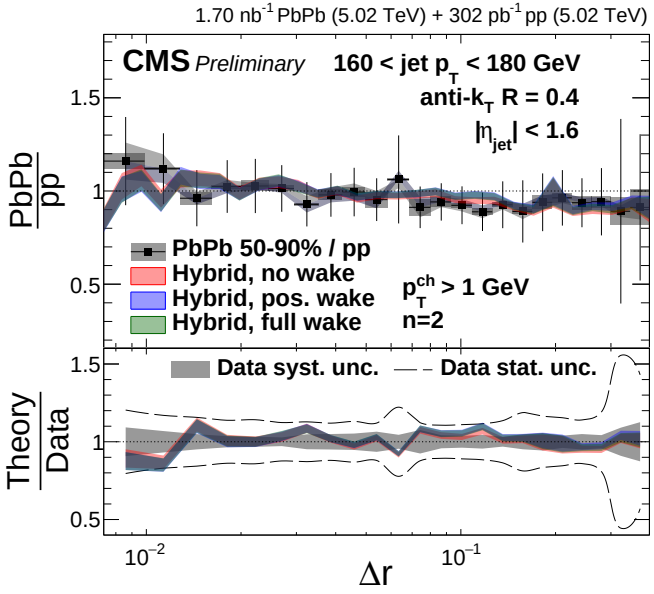


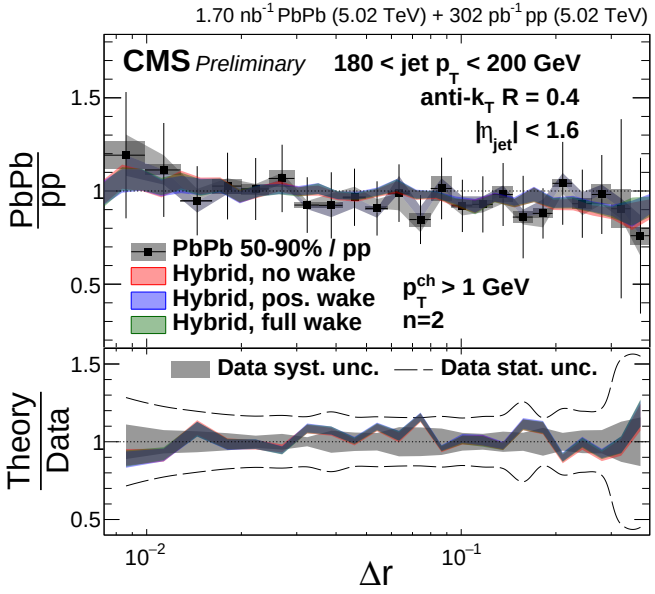


PbPb to pp ratio, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

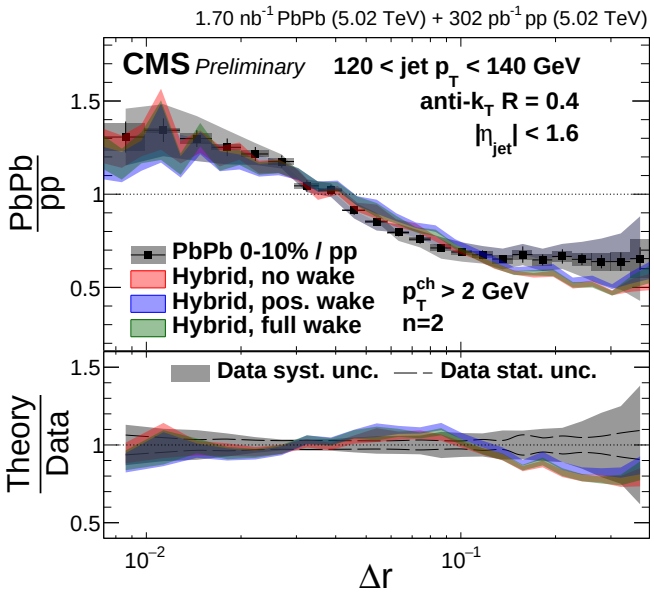


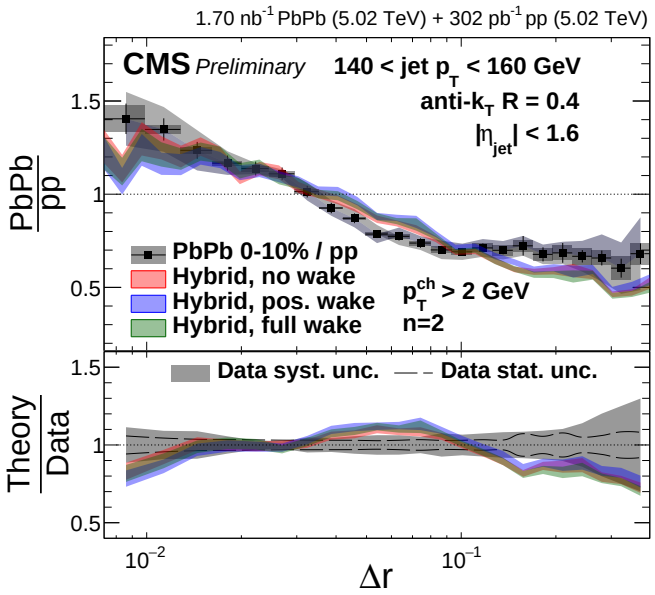


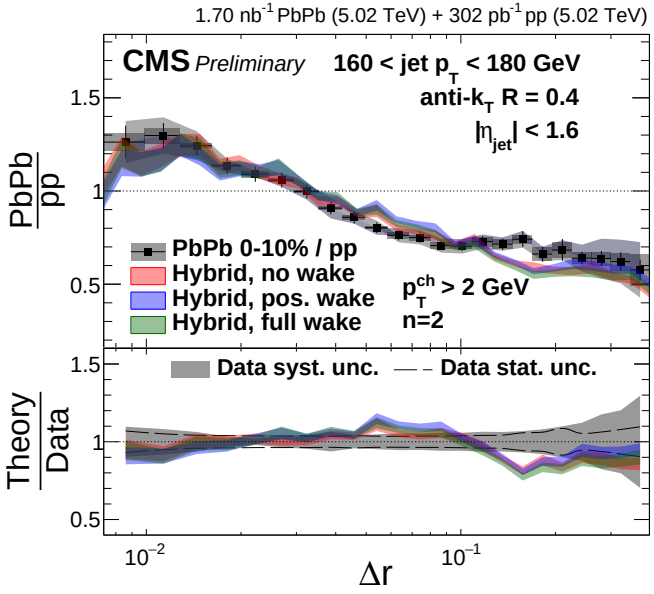


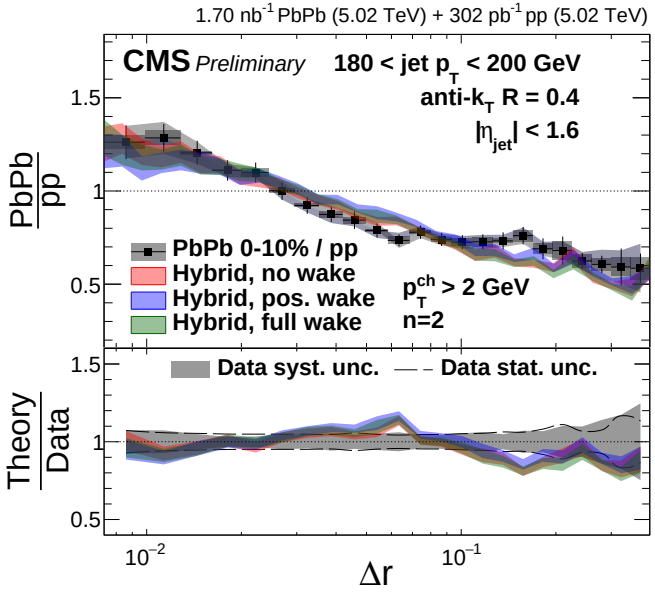


PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

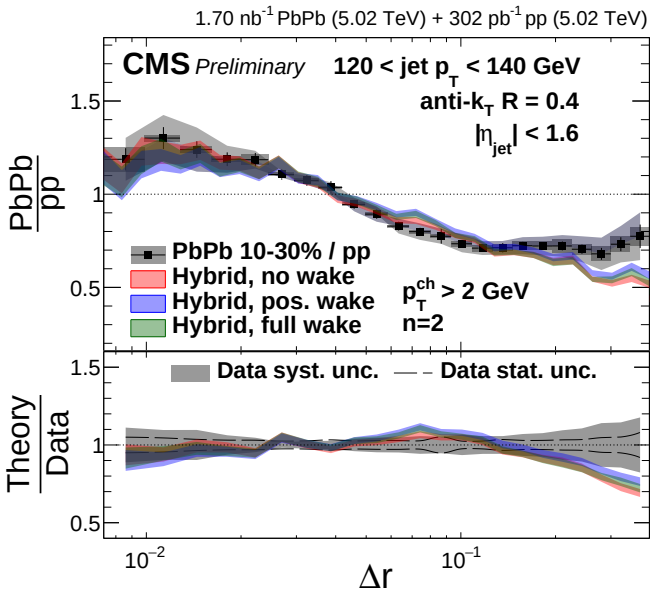


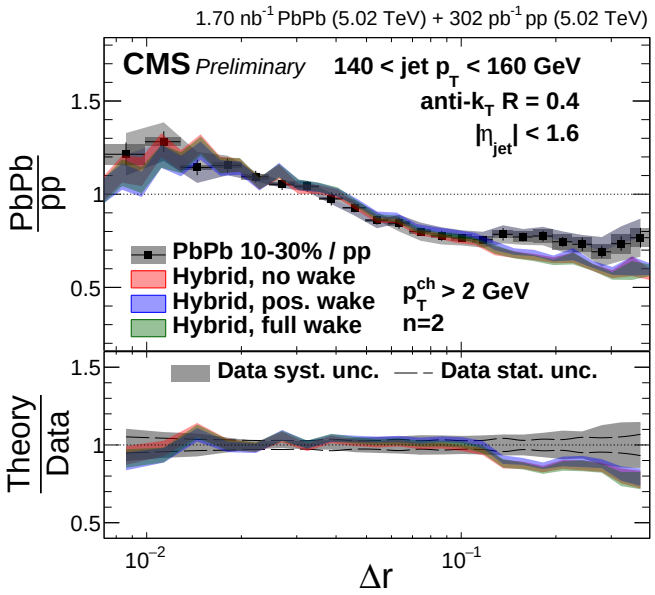


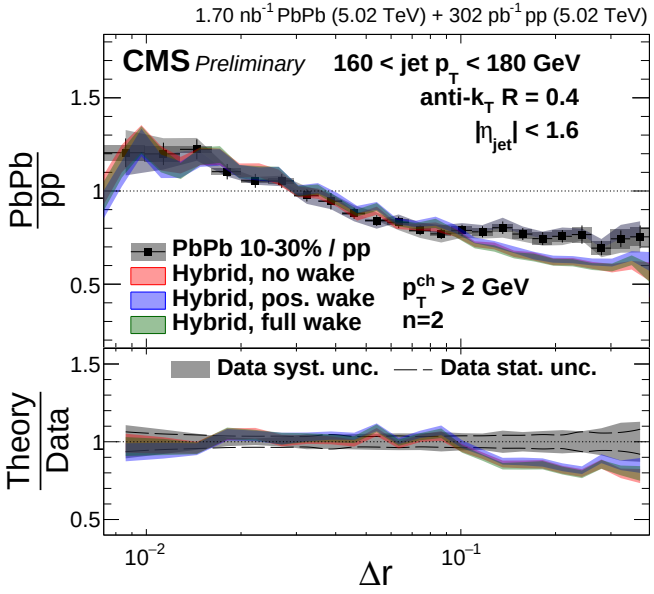


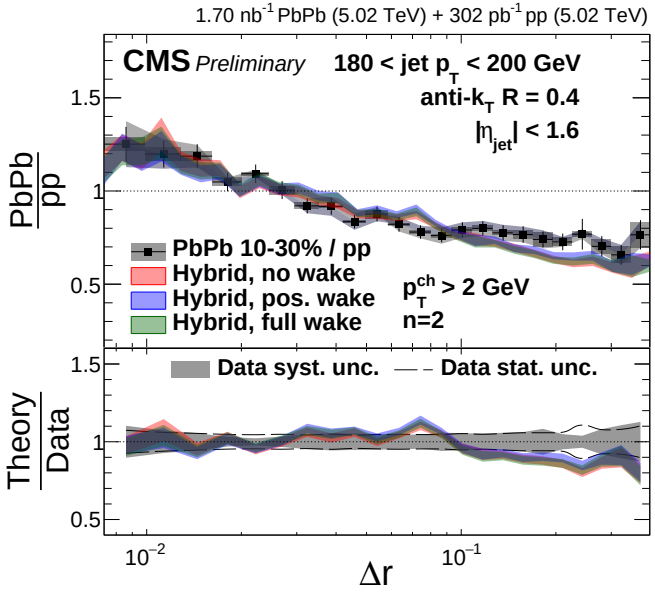


PbPb to pp ratio, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

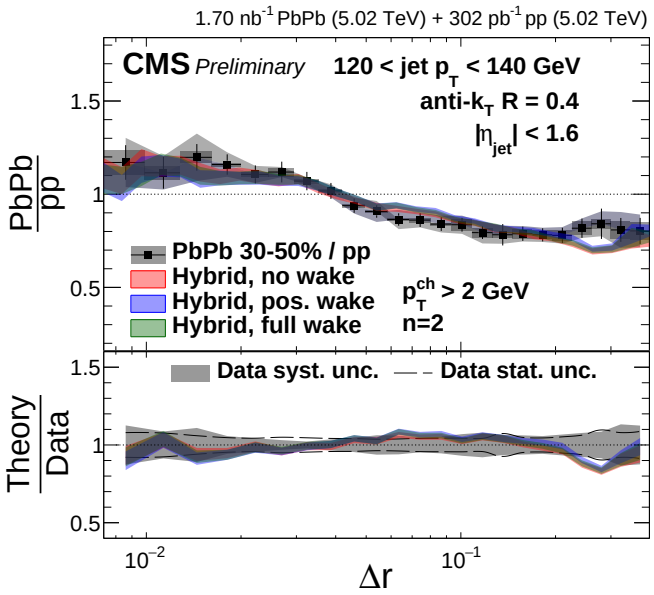


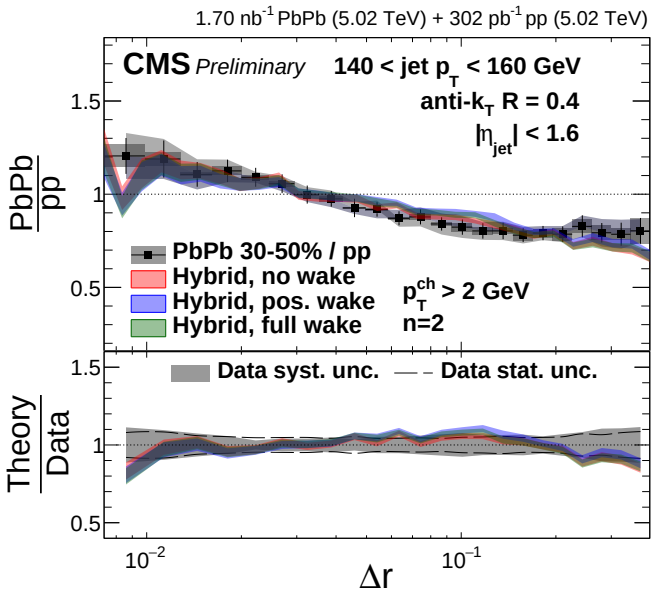


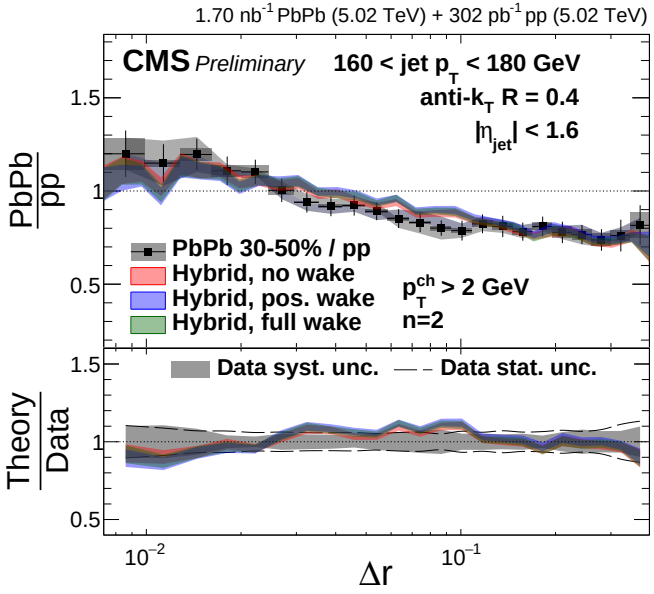


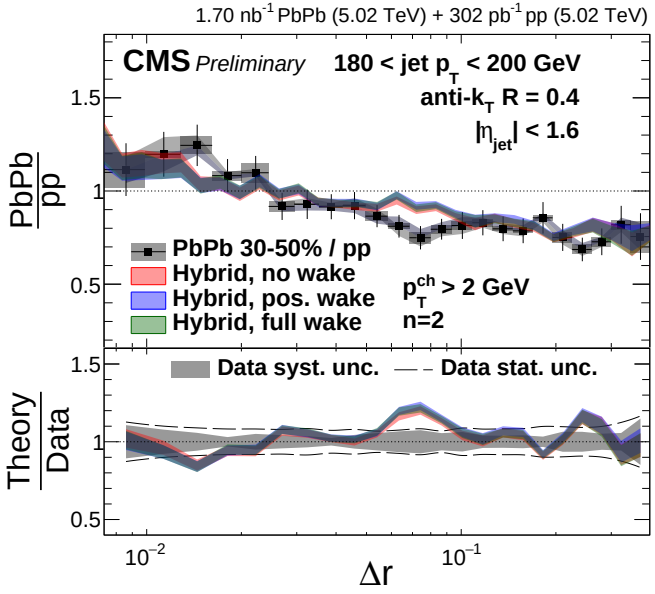


PbPb to pp ratio, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

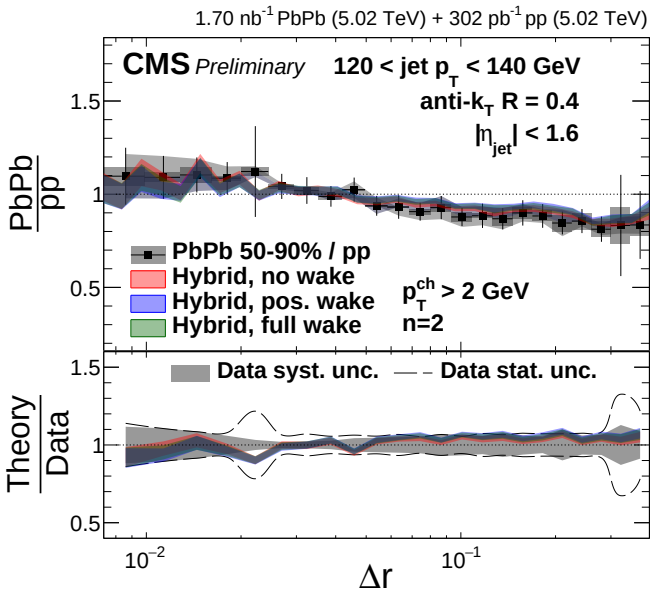


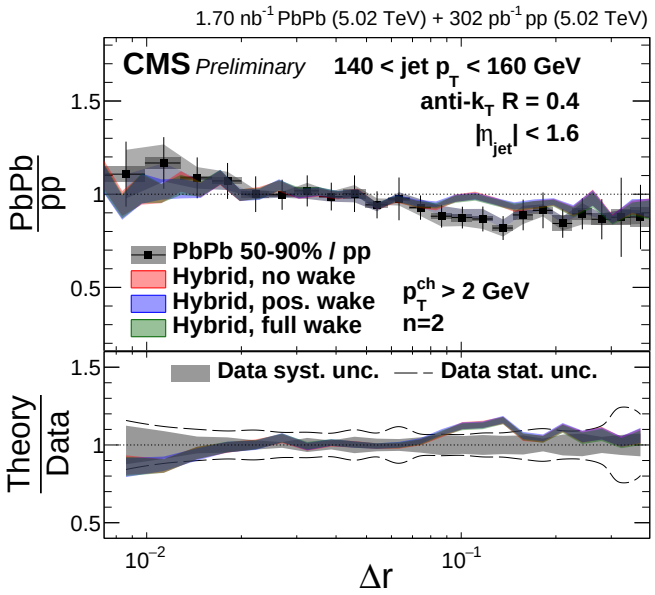


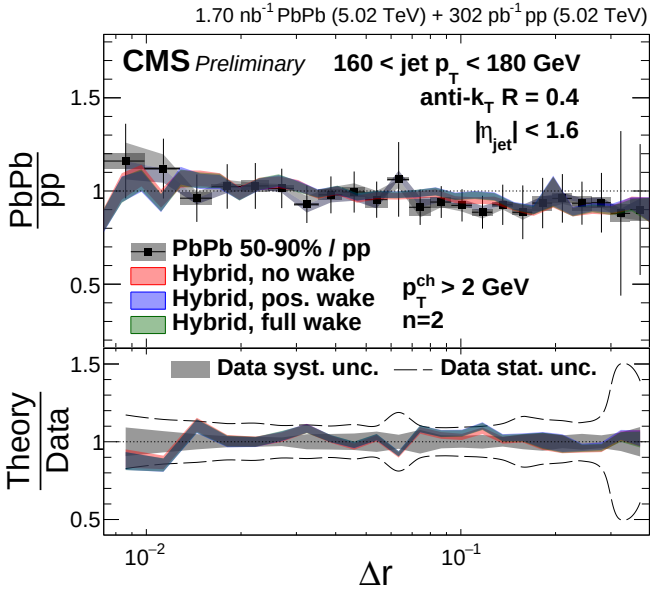


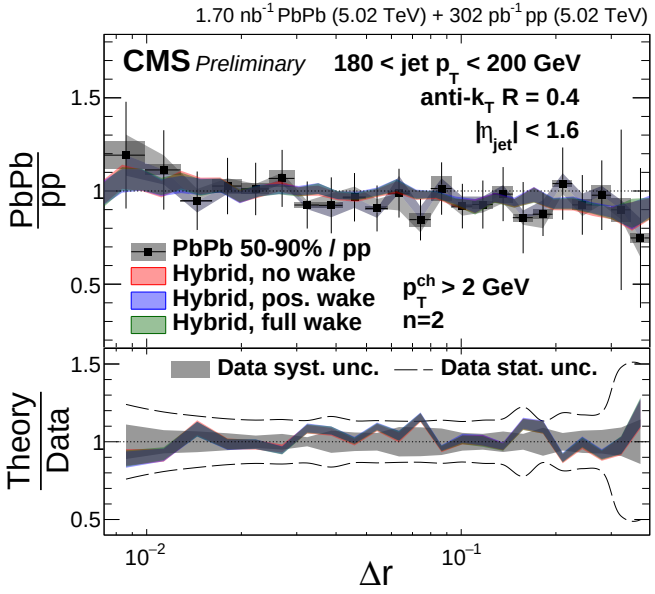


PbPb to pp ratio, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

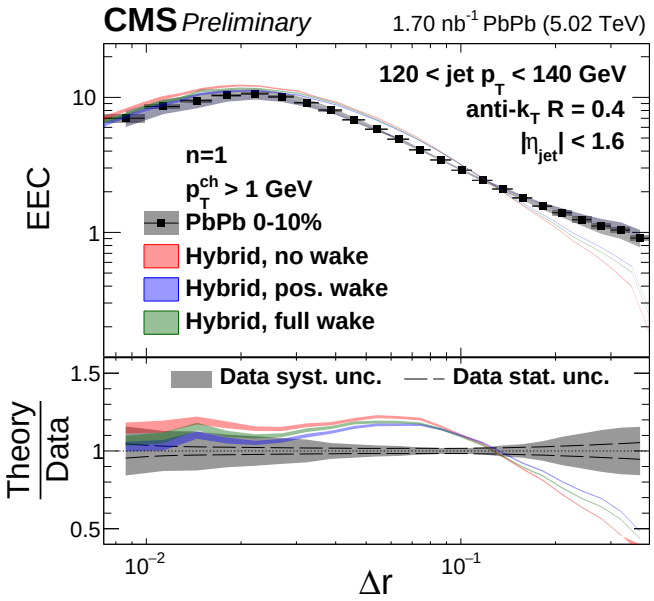


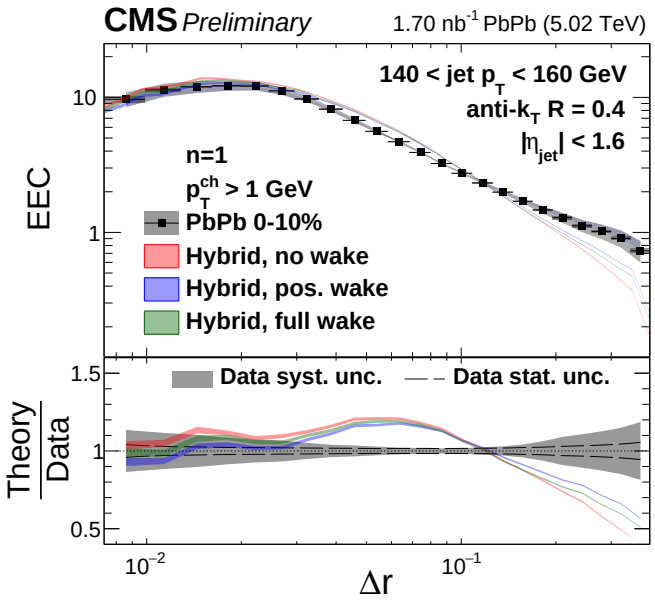


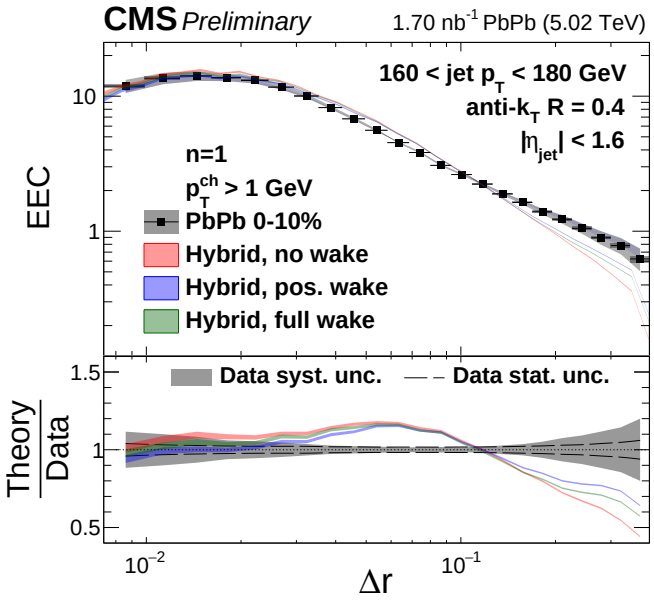


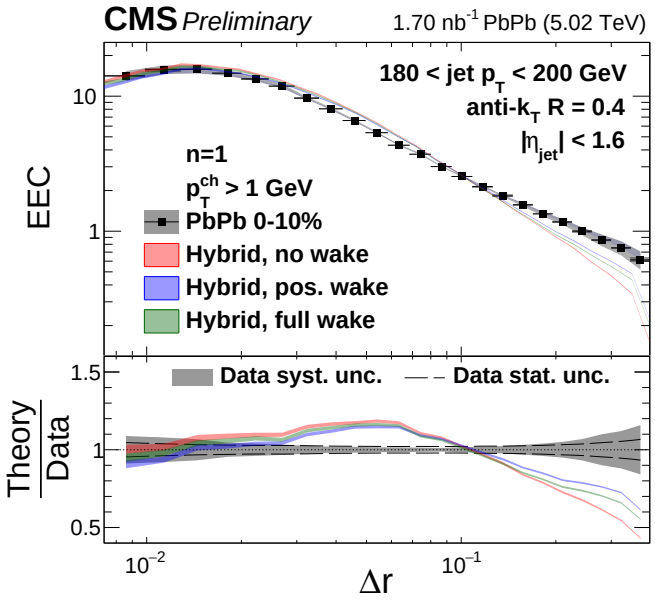


PbPb distribution, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

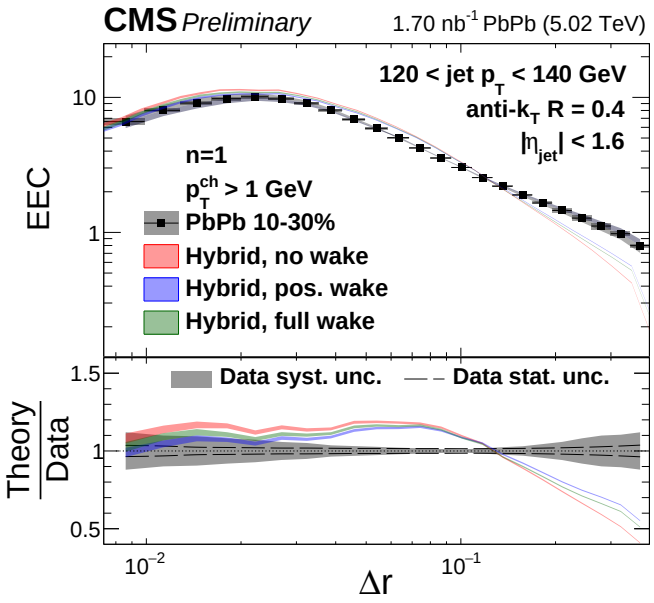


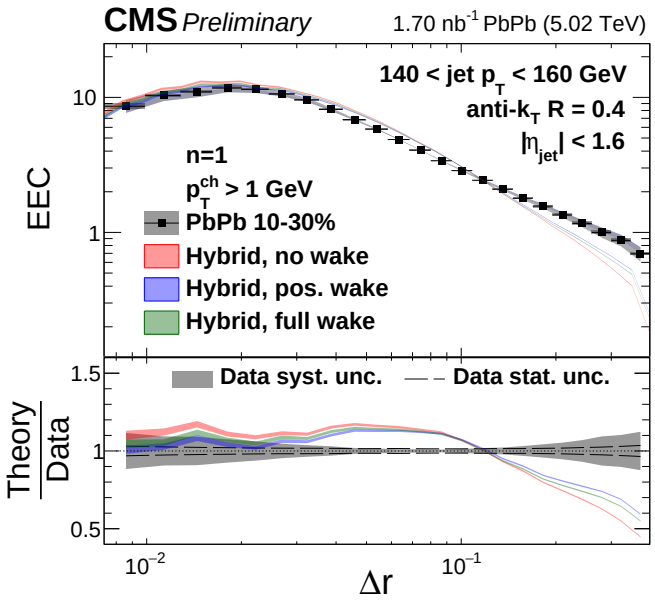


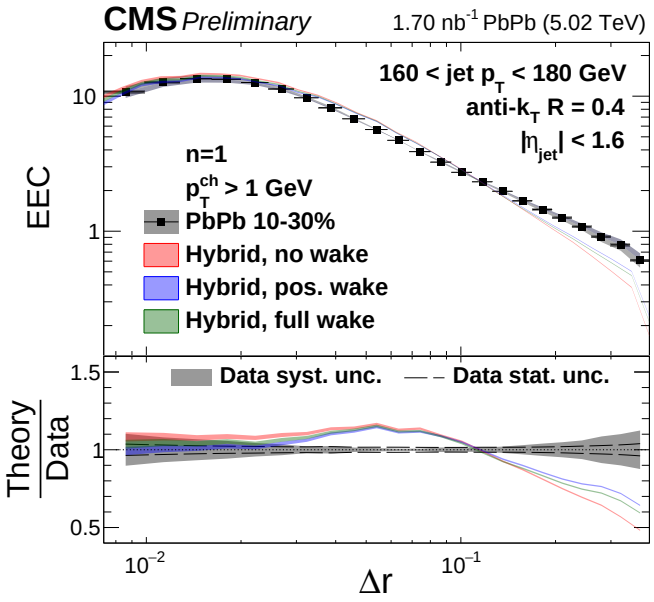


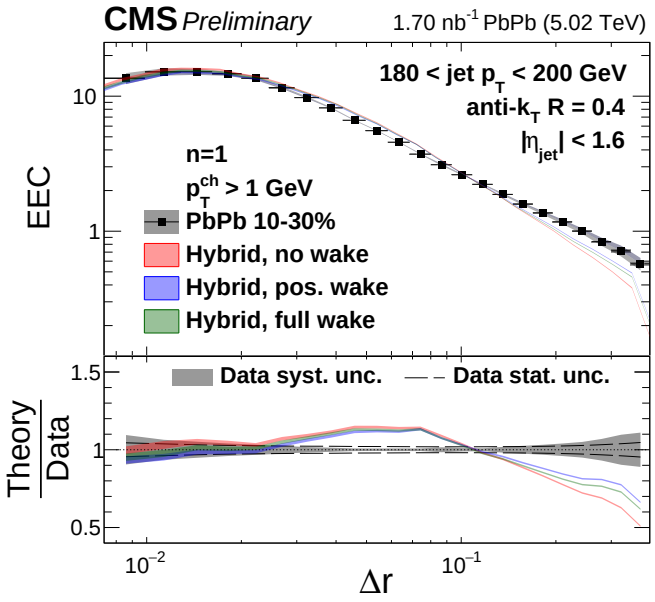


PbPb distribution, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

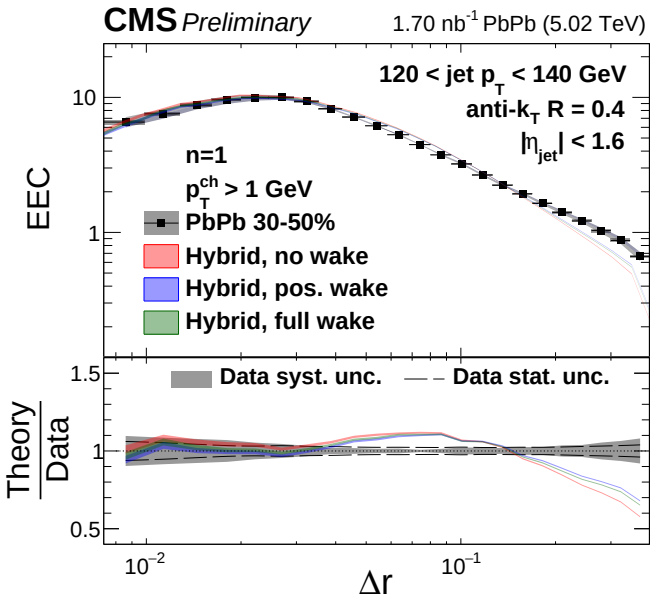


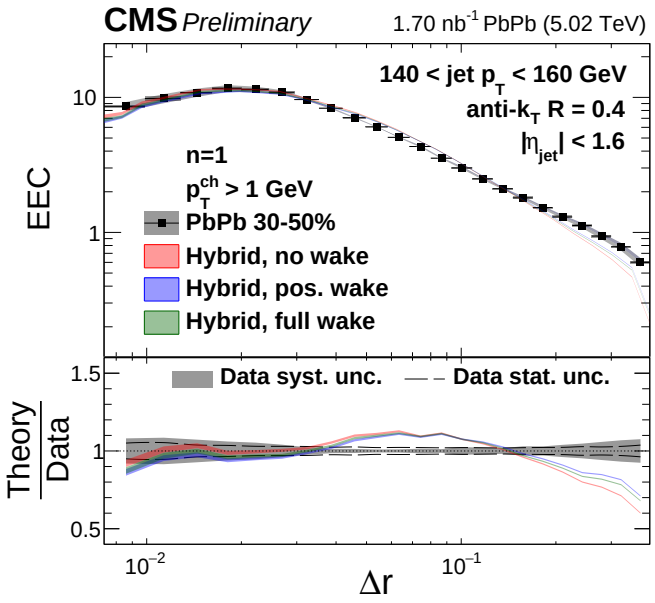


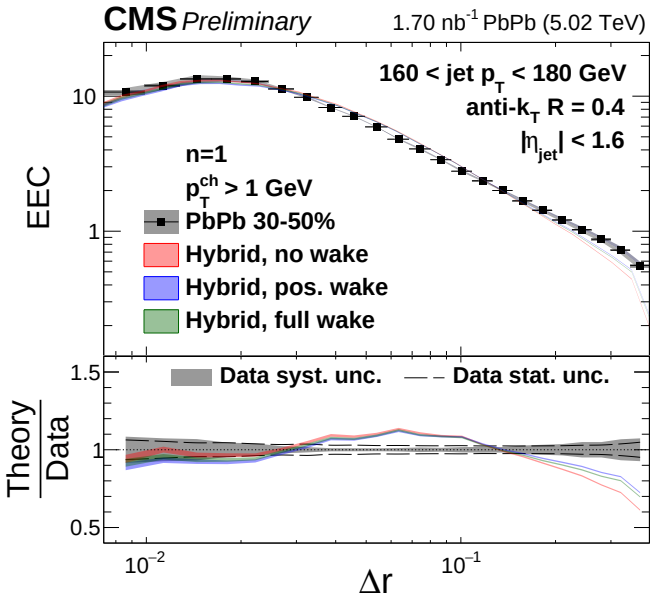


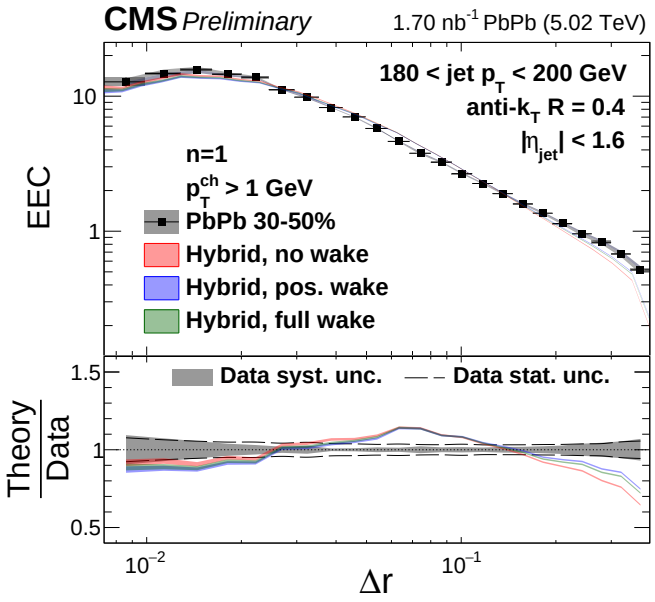


PbPb distribution, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

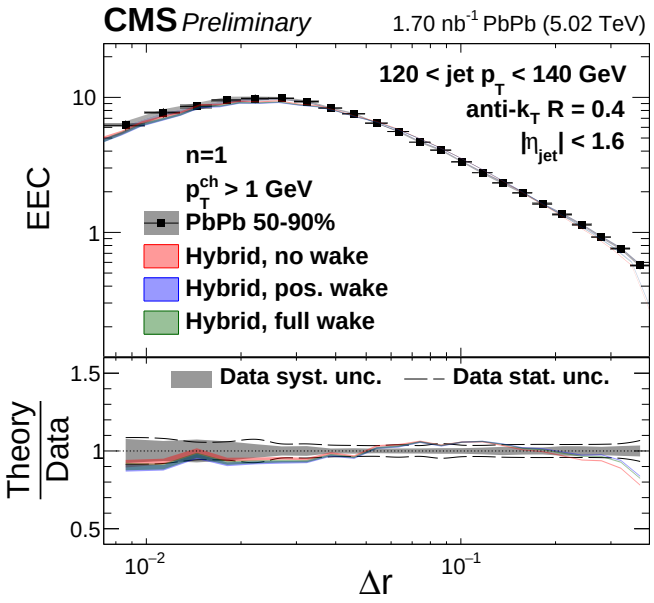


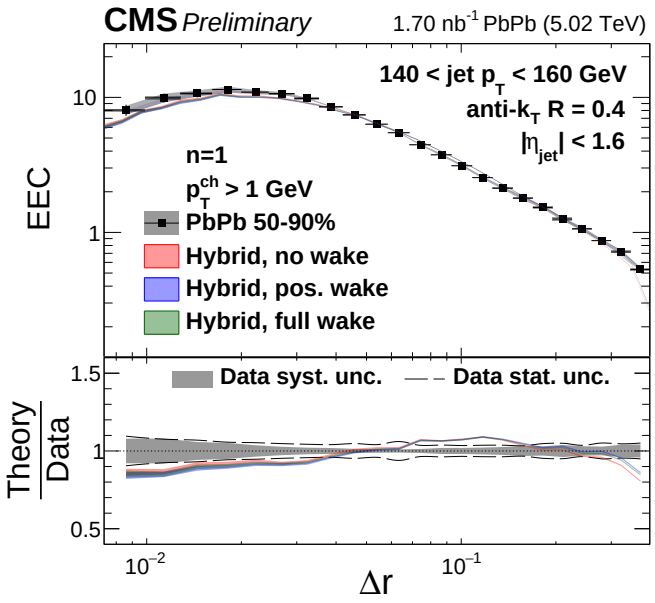


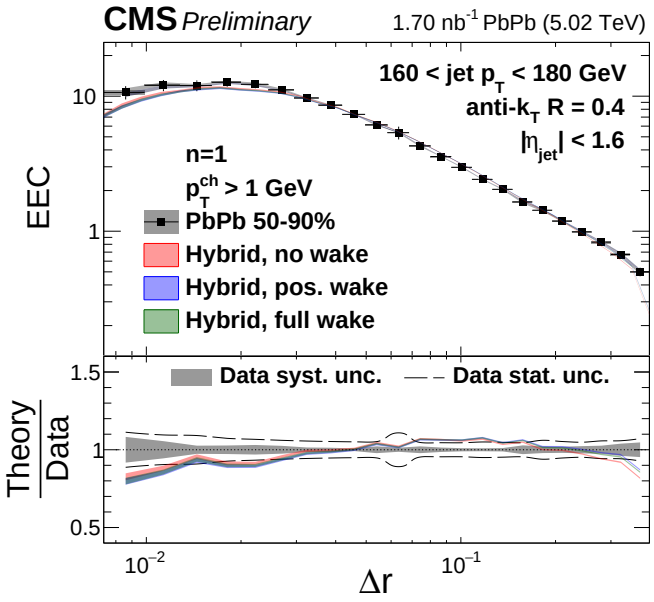


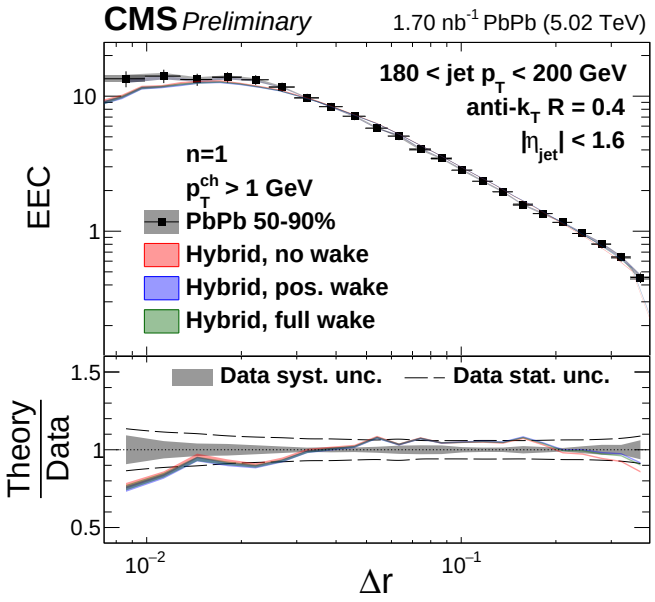


PbPb distribution, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

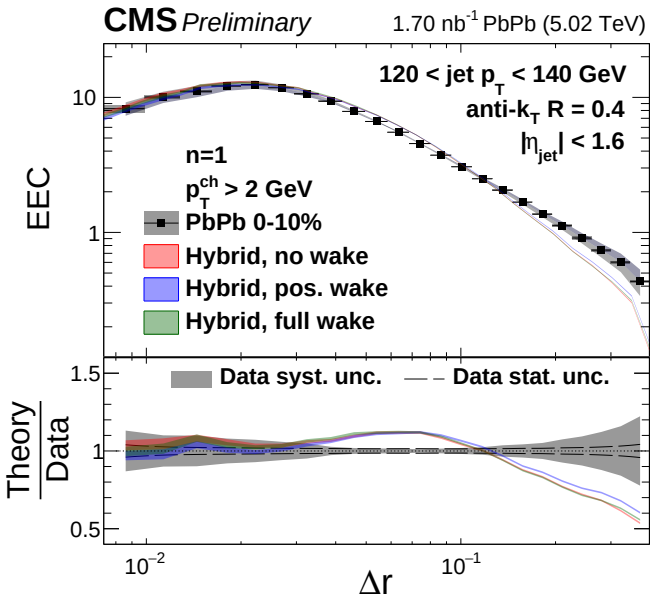


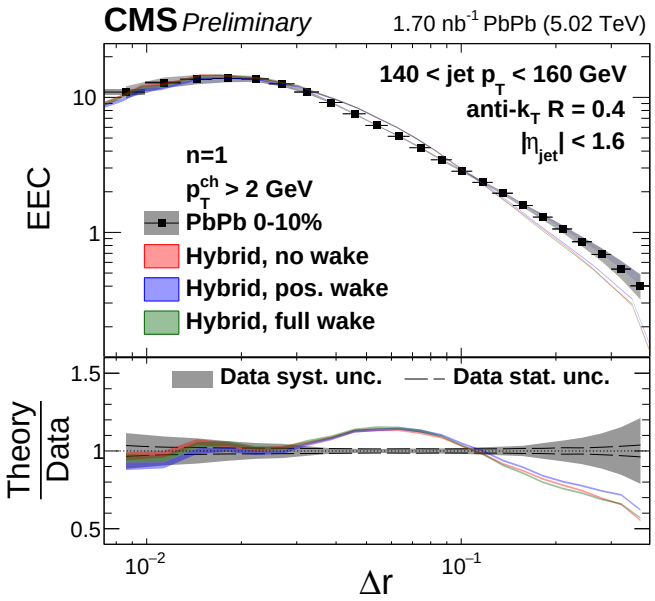


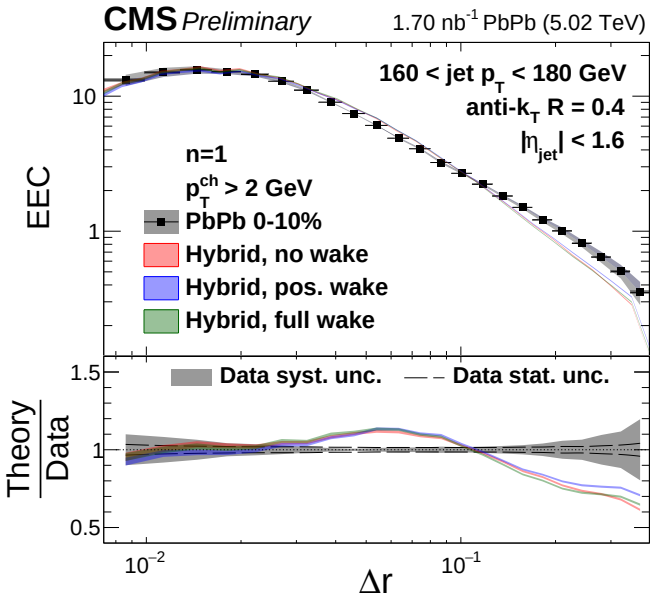


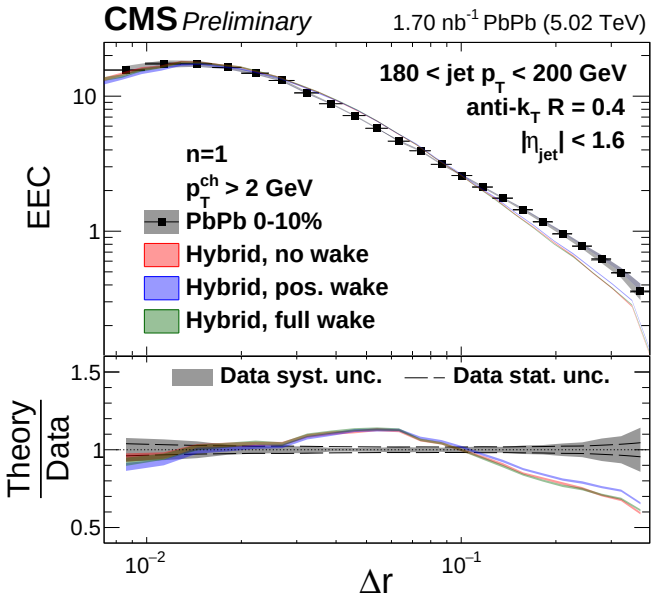


PbPb distribution, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

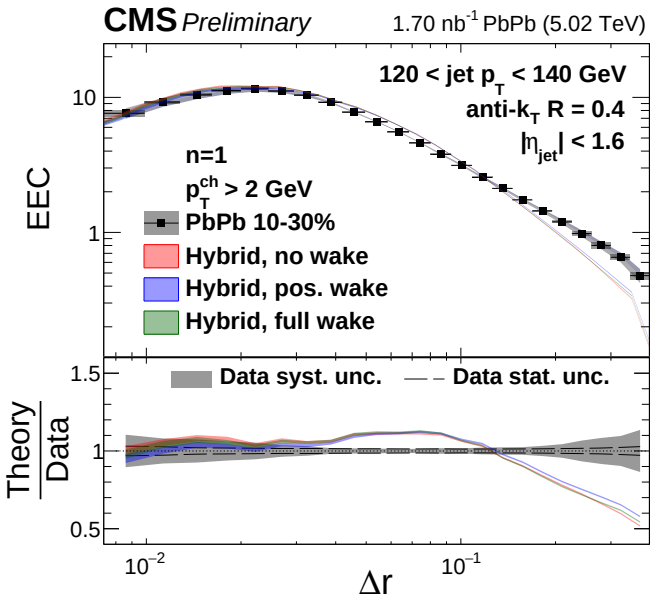


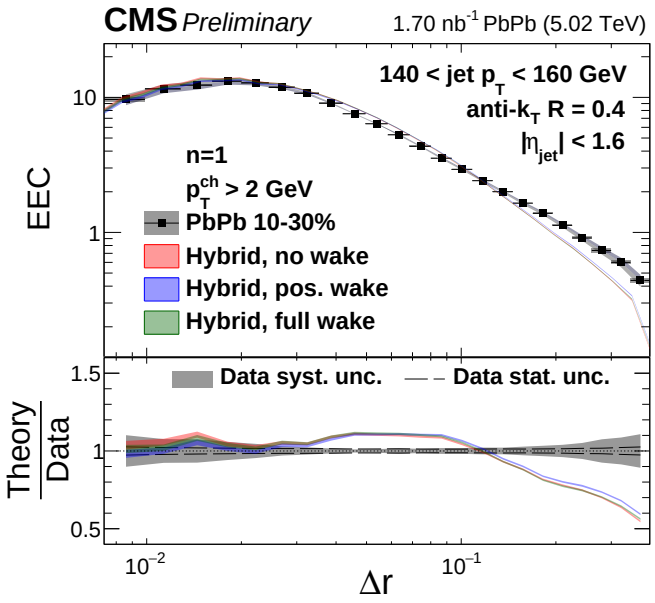


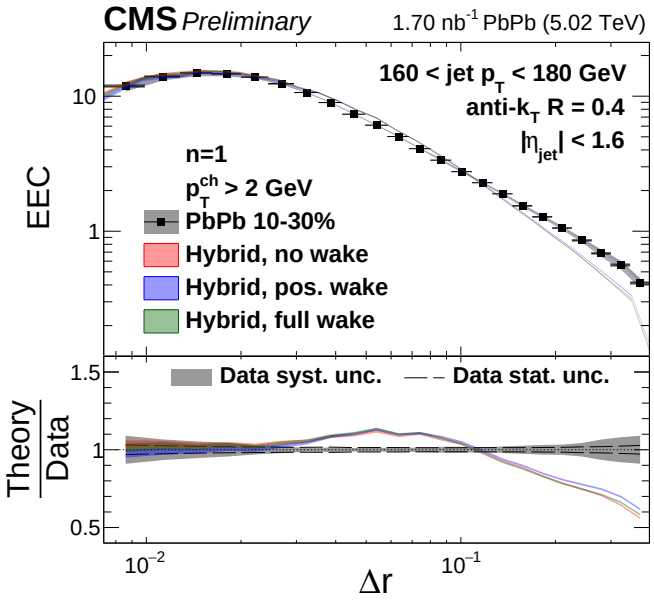


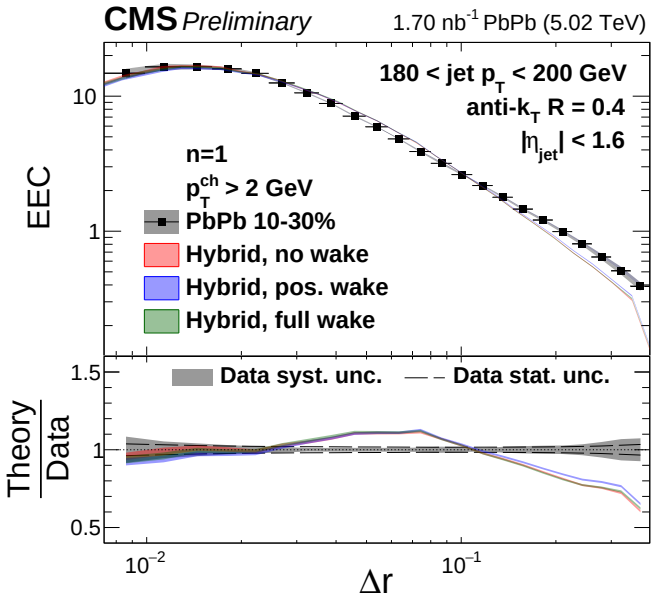


PbPb distribution, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

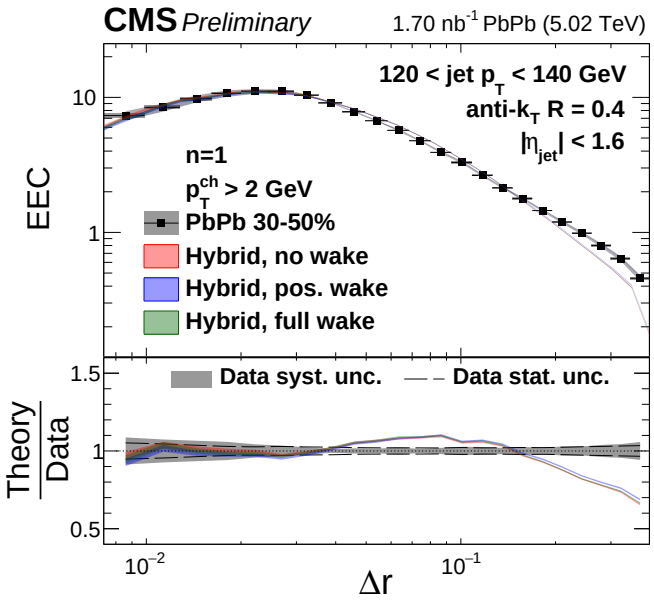


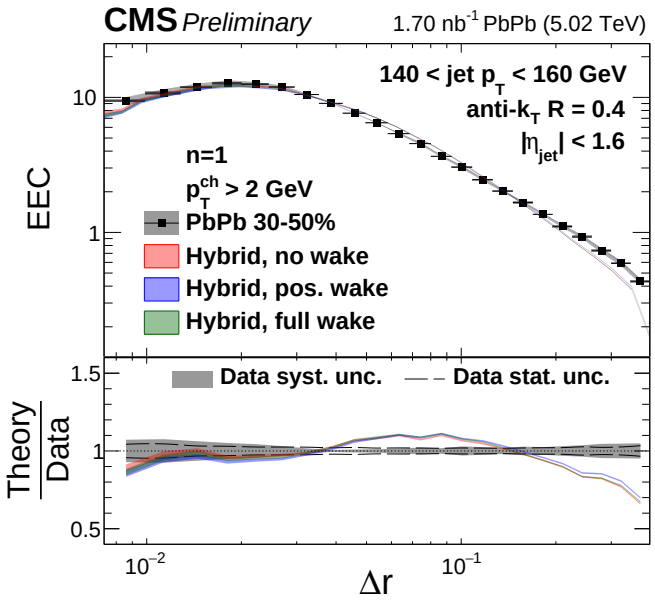


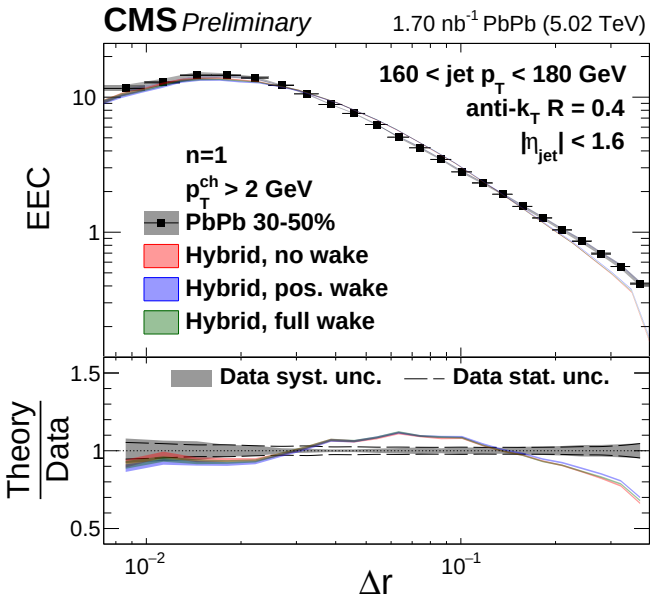


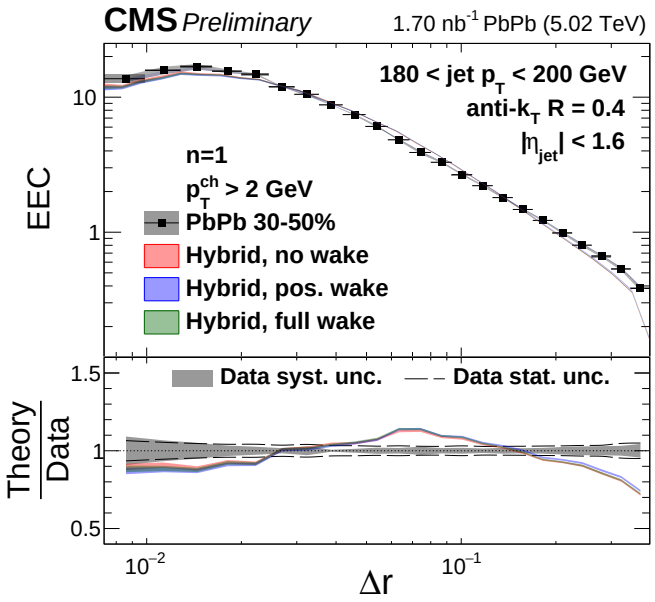


PbPb distribution, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

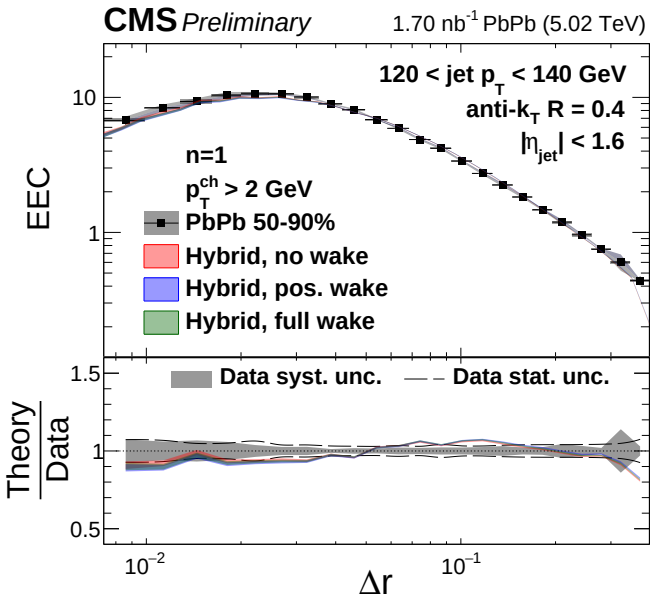


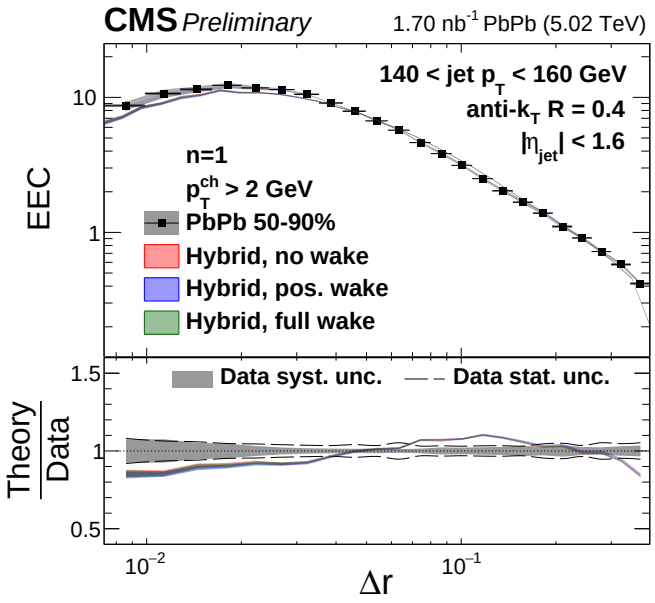


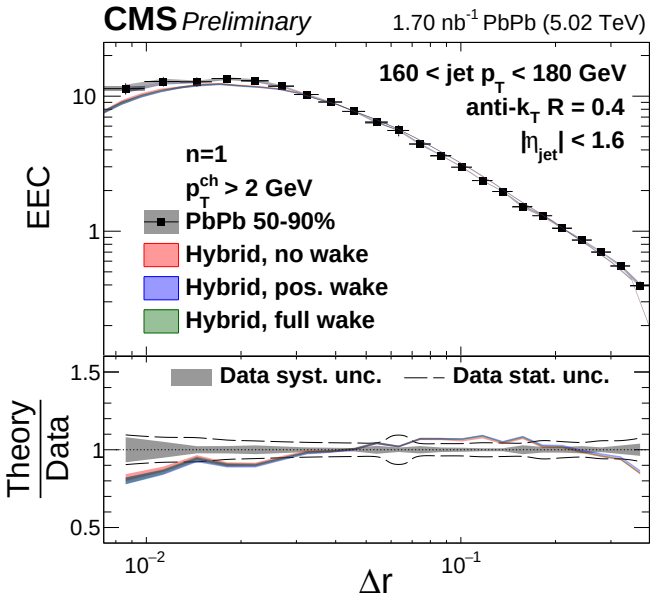


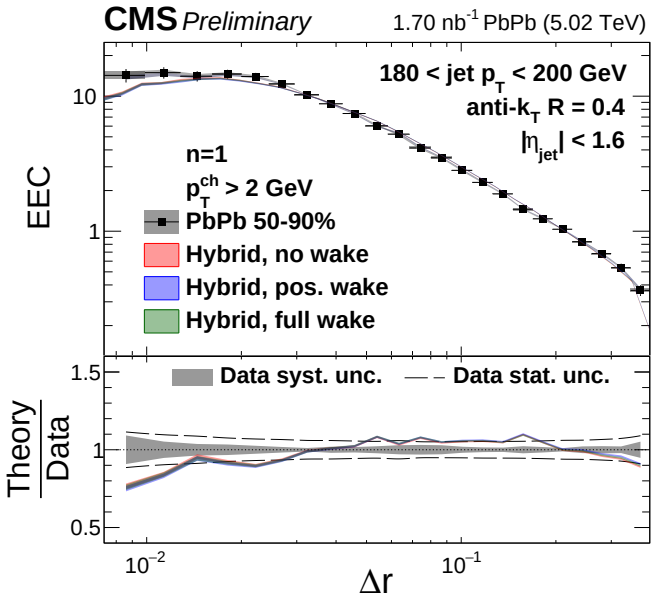


PbPb distribution, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

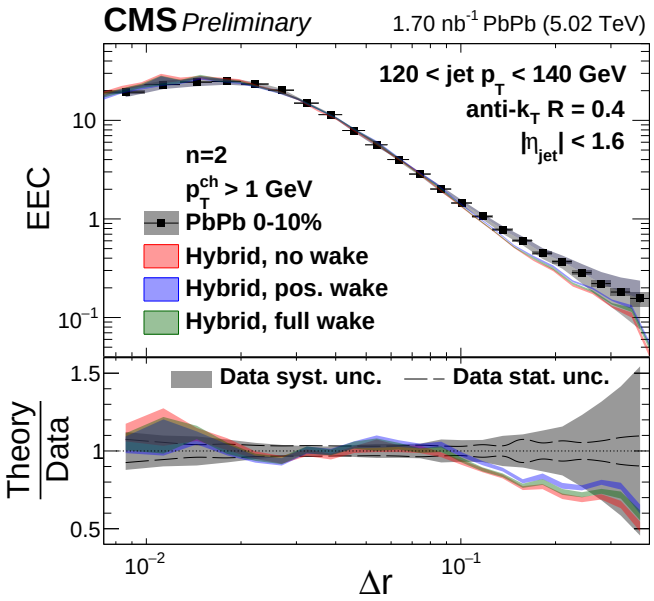


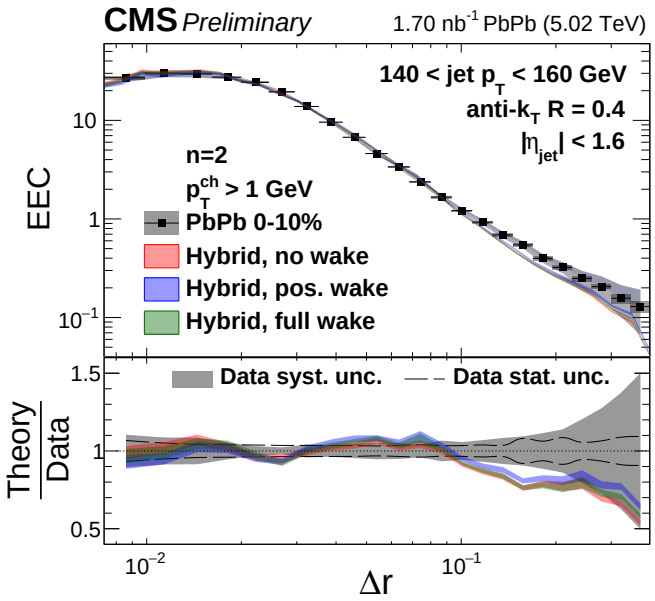


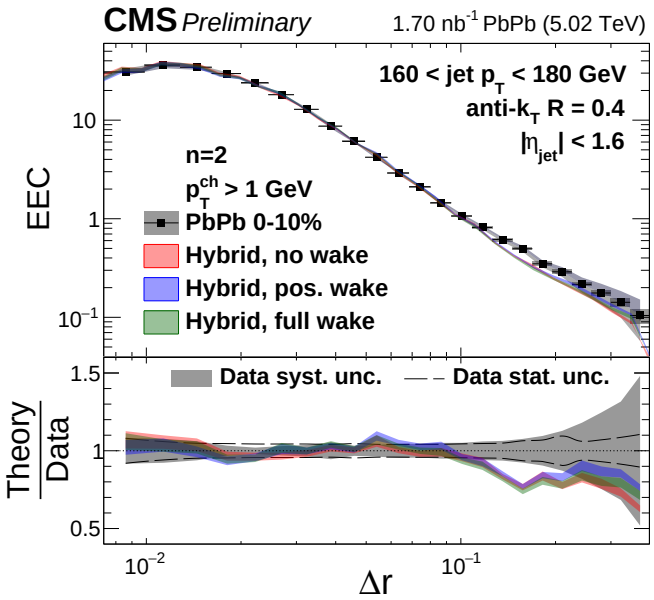


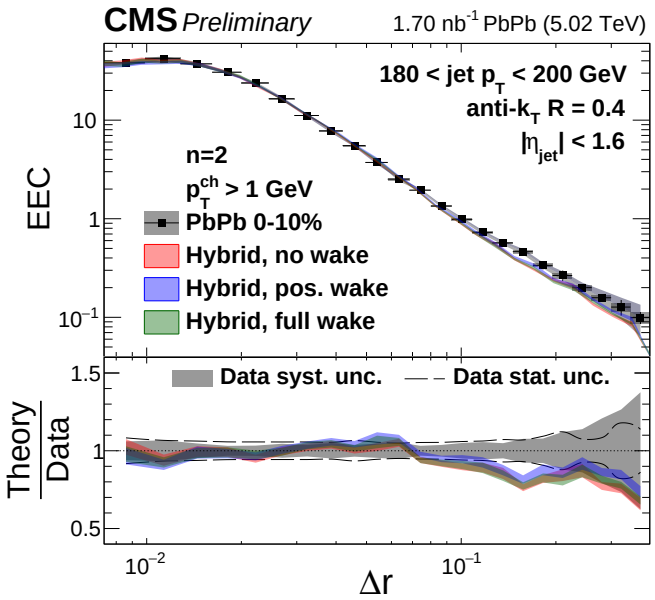


PbPb distribution, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

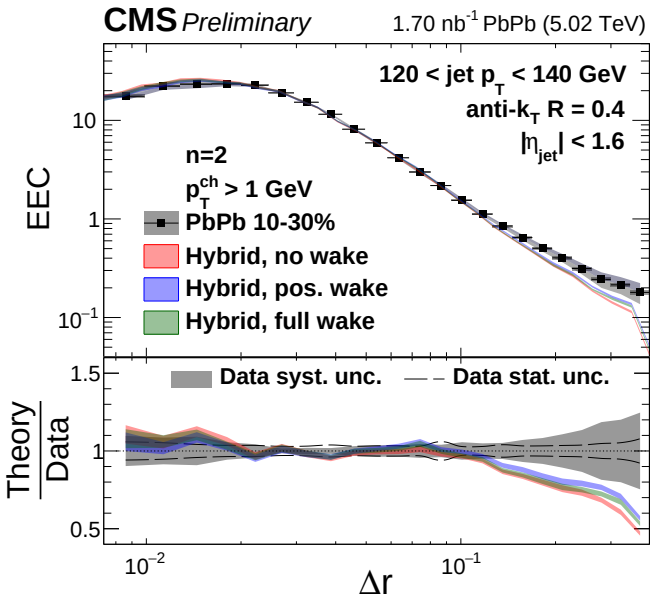


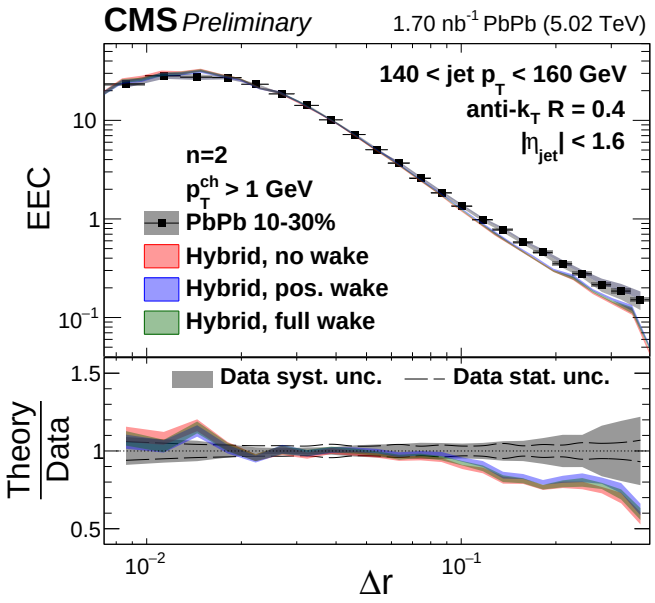


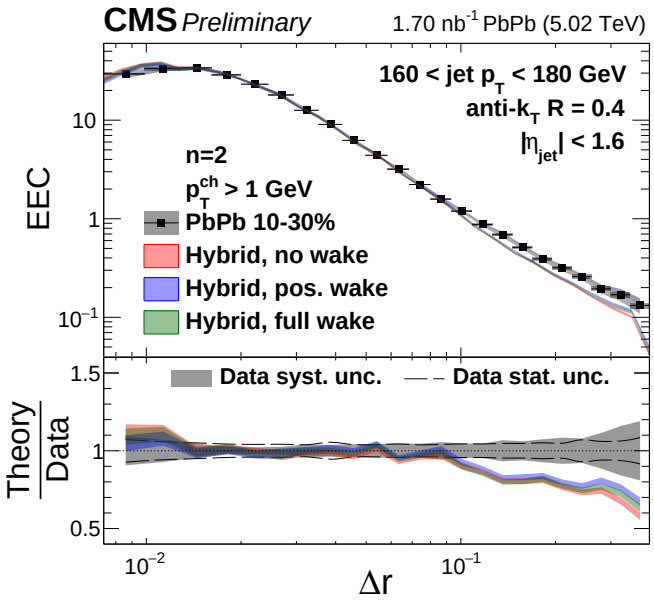


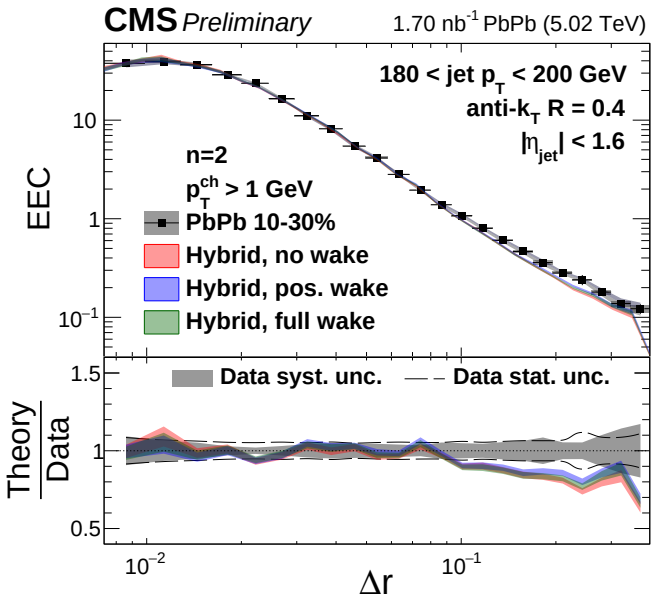


PbPb distribution, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

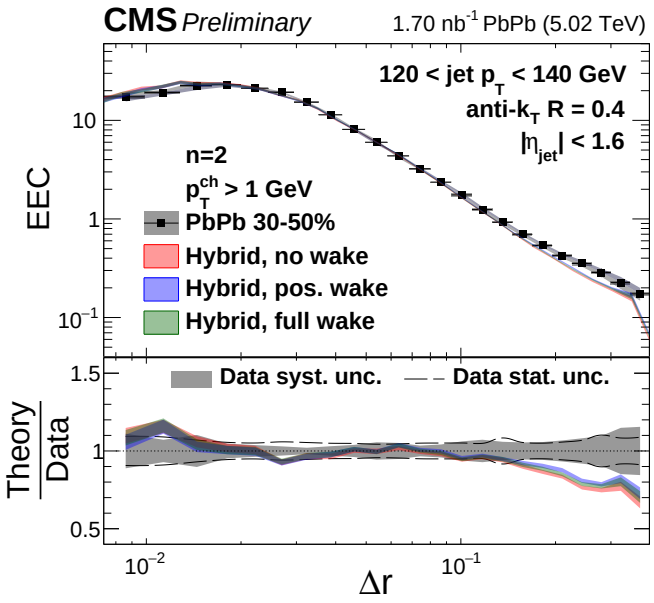


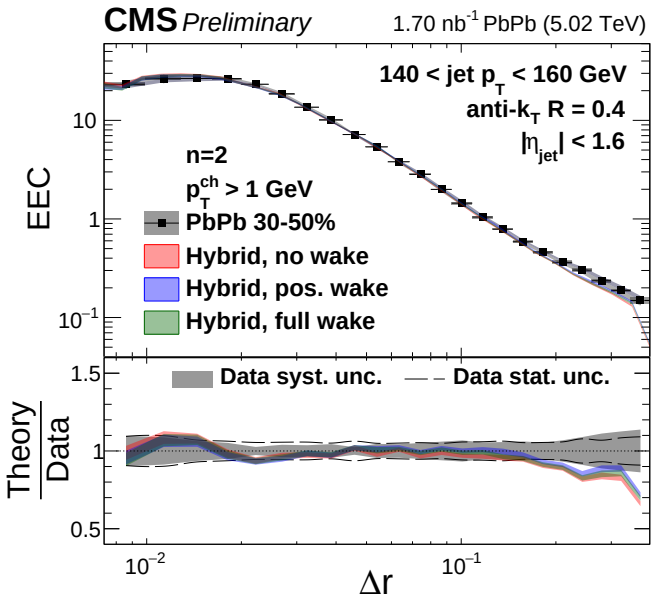


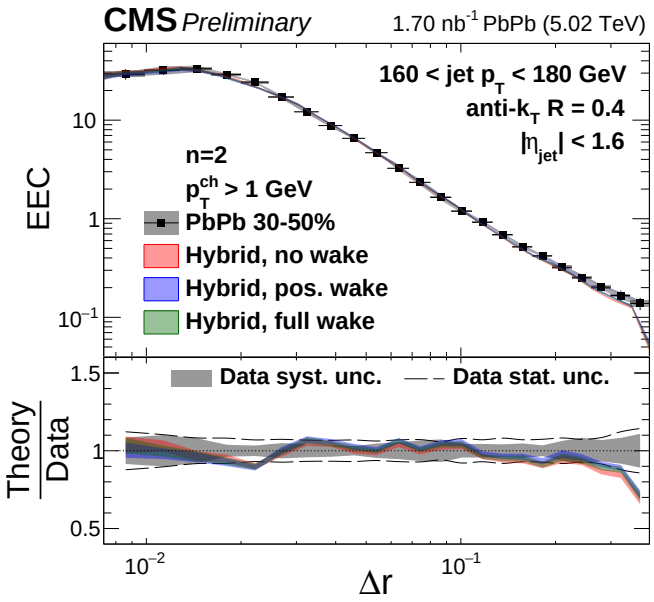


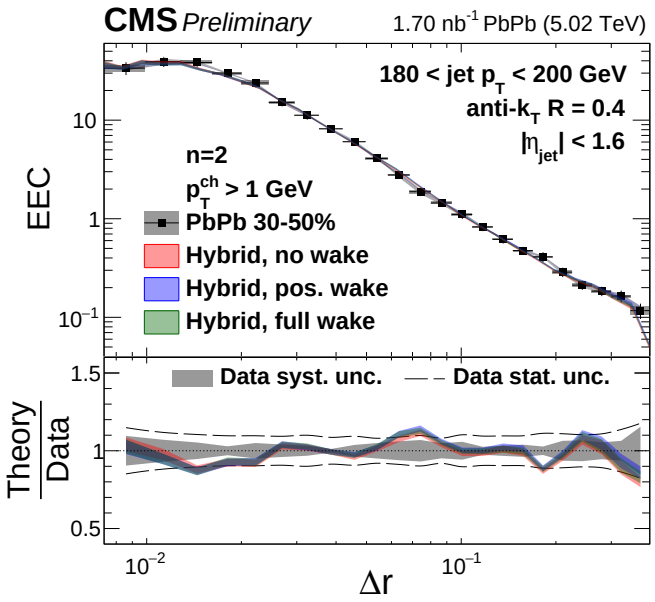


PbPb distribution, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

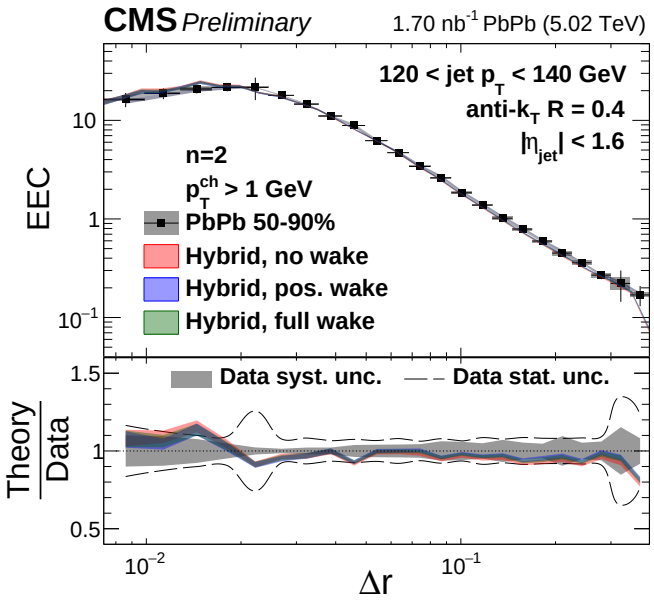


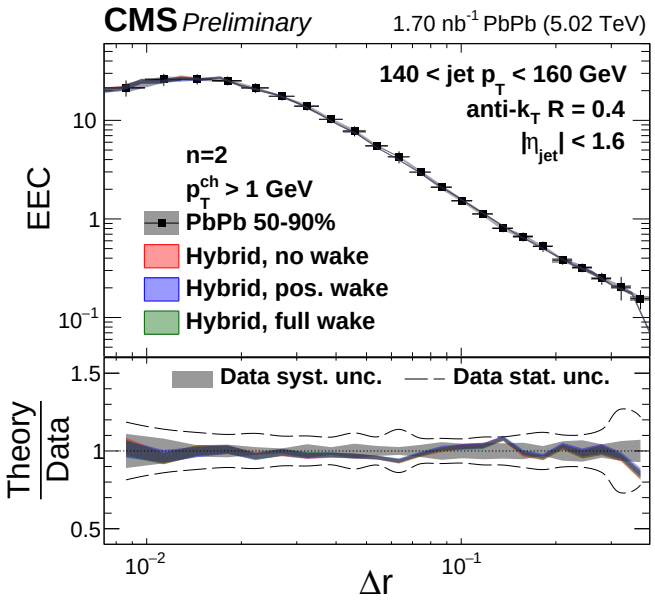


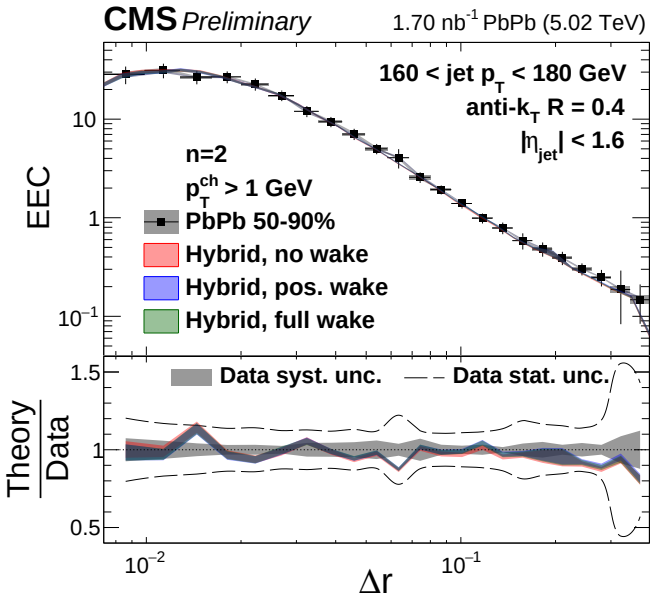


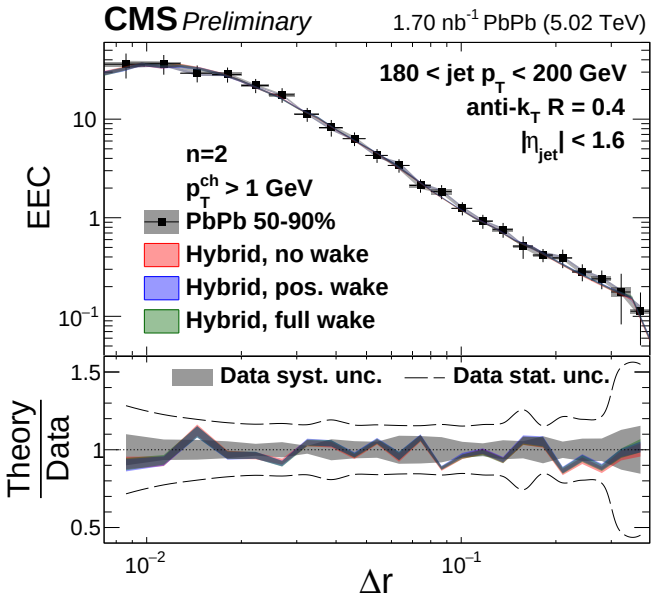


PbPb distribution, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

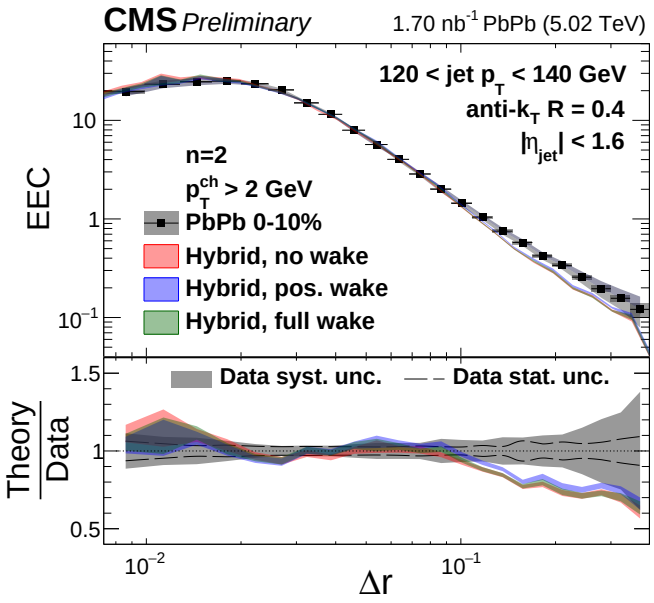


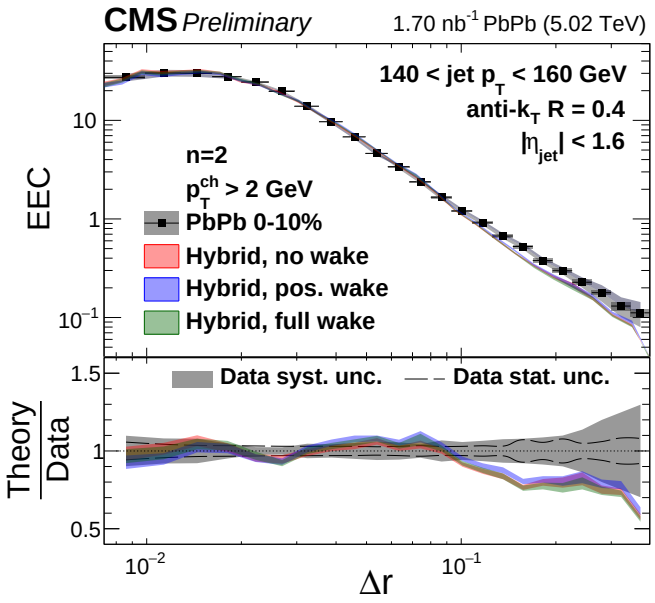


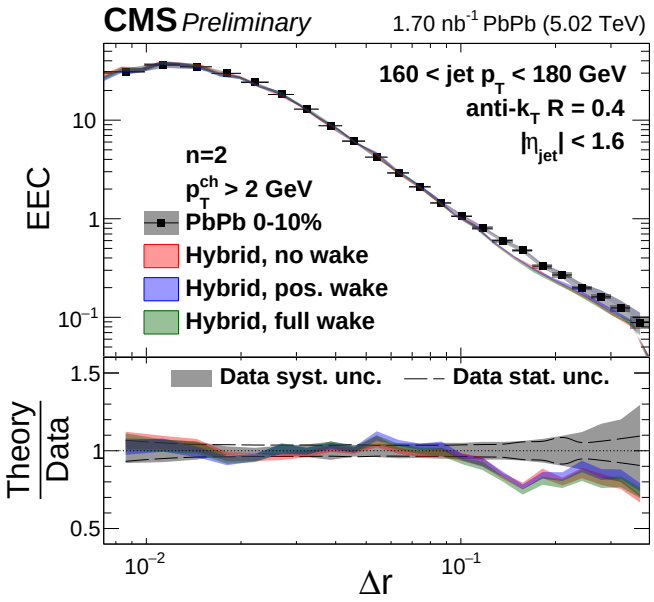


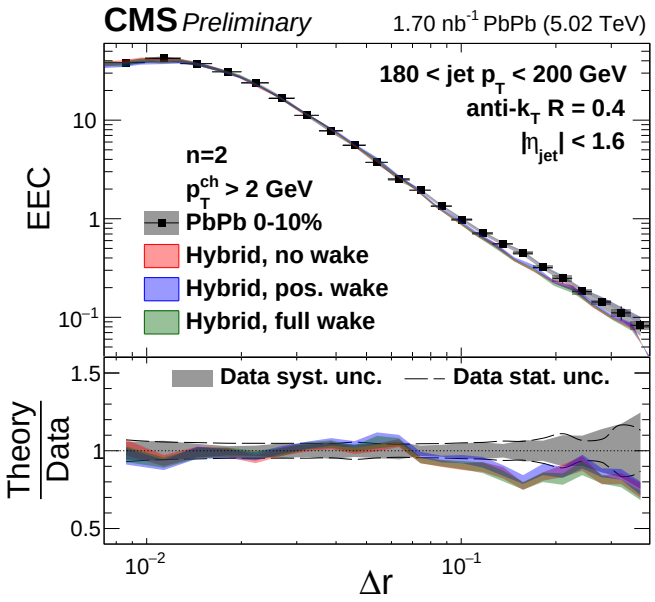


PbPb distribution, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

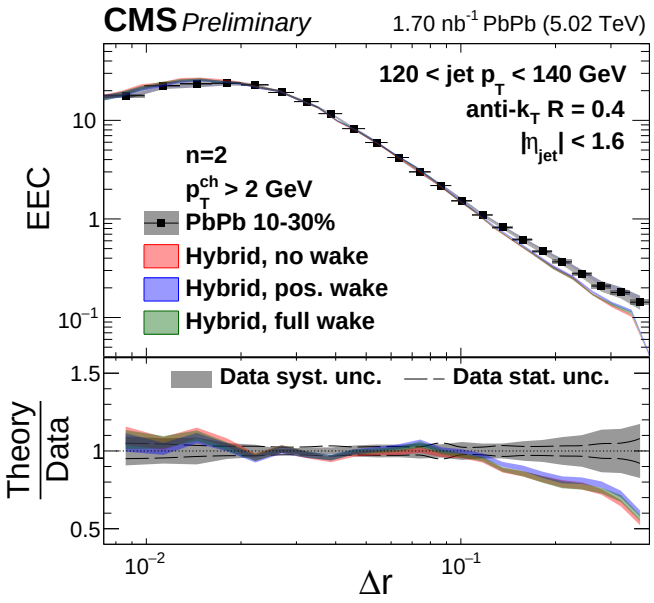


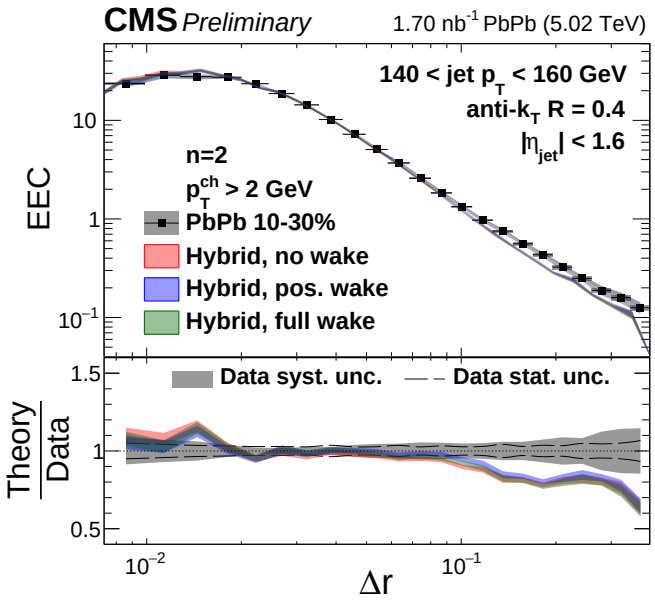


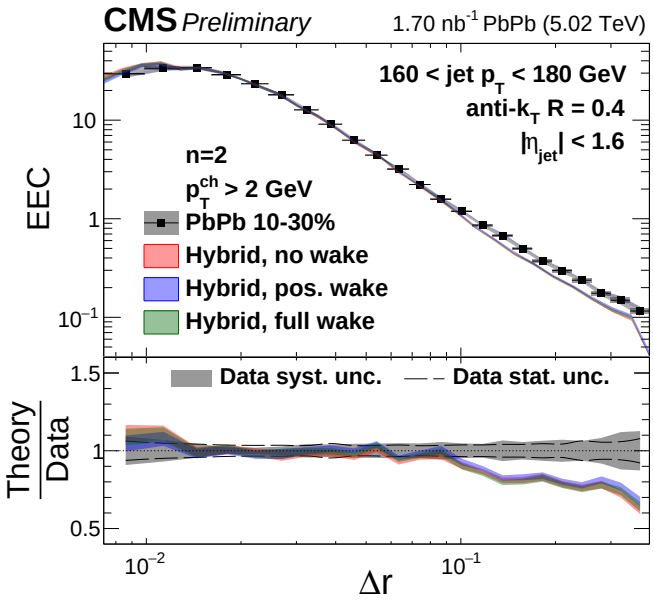


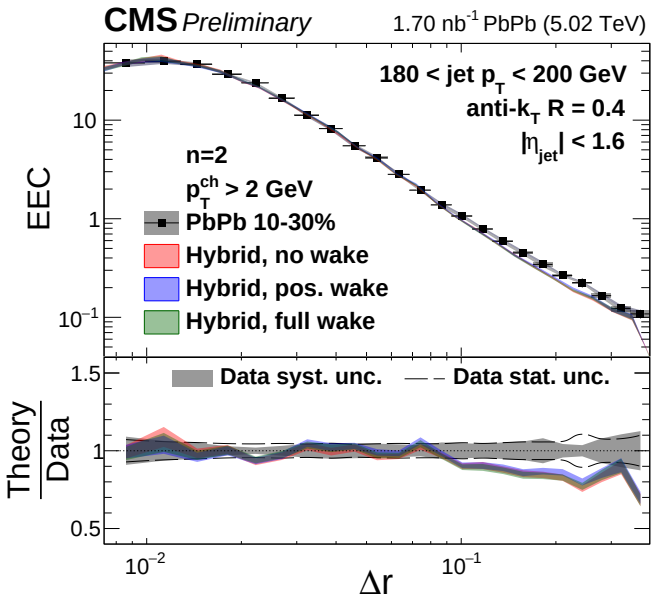


PbPb distribution, Hybrid, 10-30%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

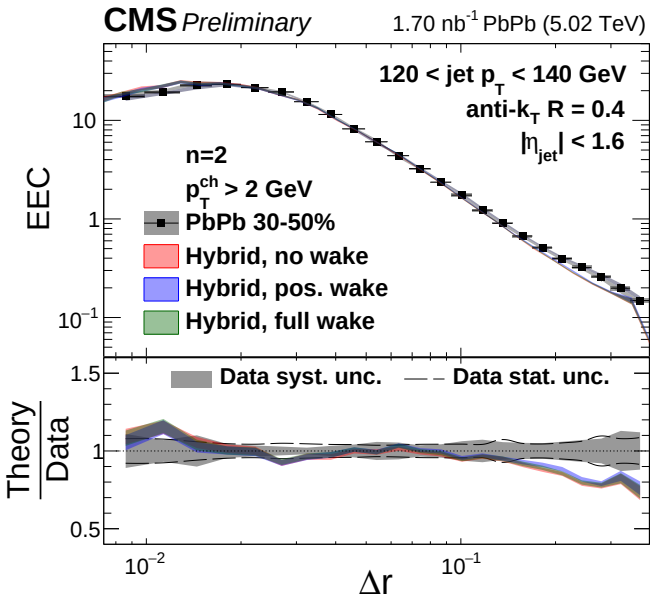


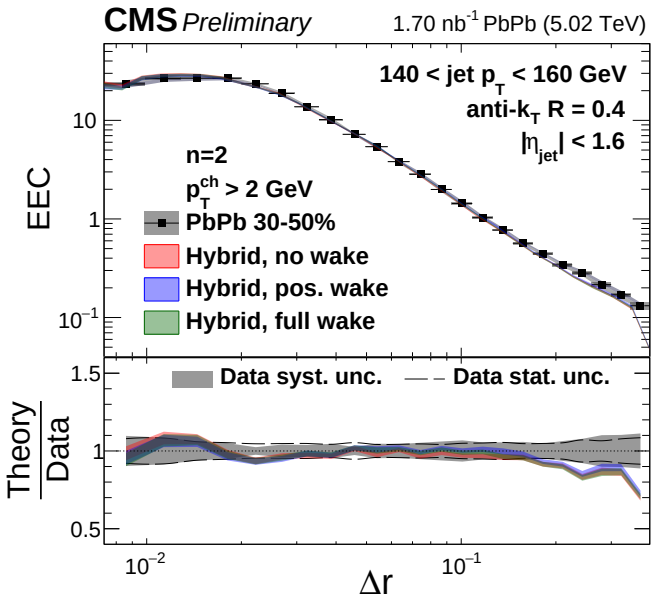


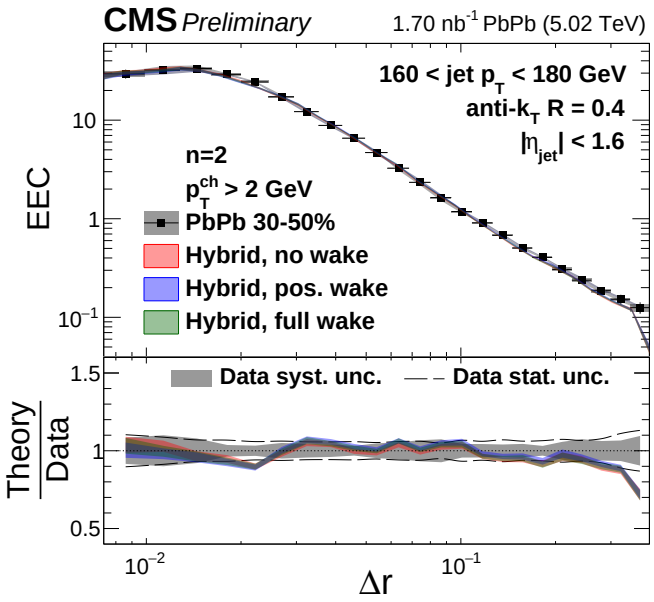


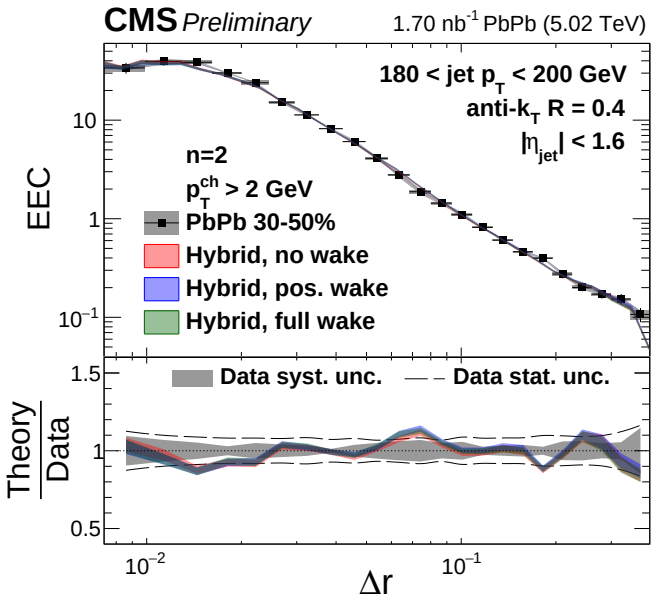


PbPb distribution, Hybrid, 30-50%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

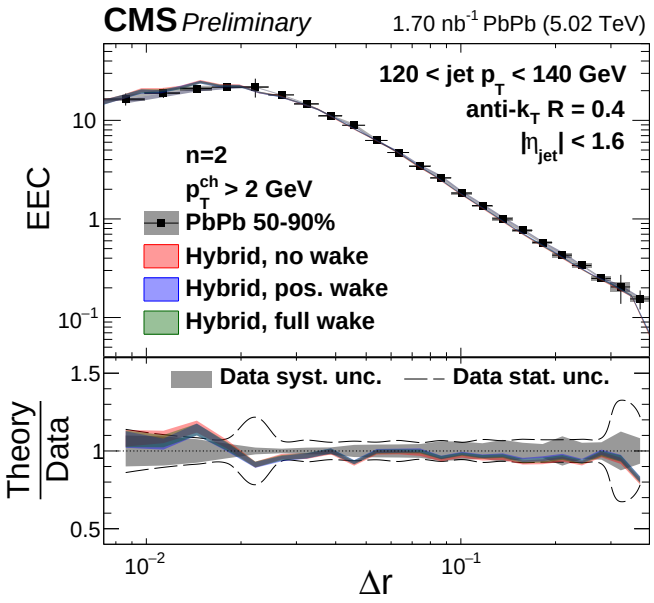


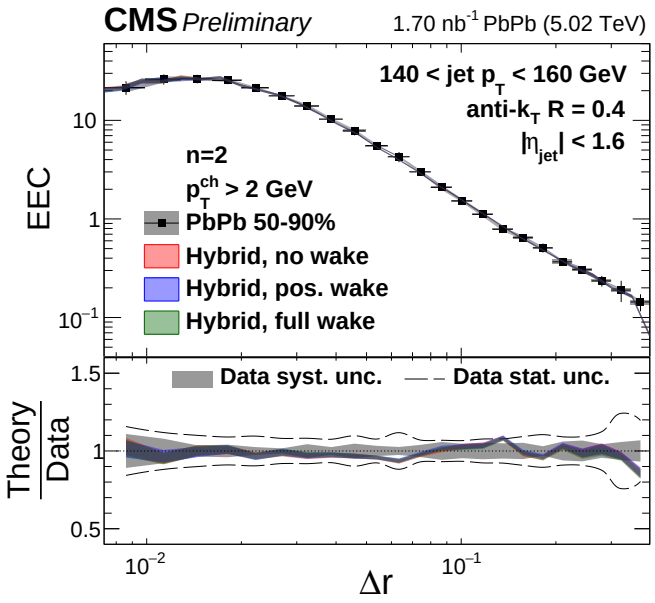


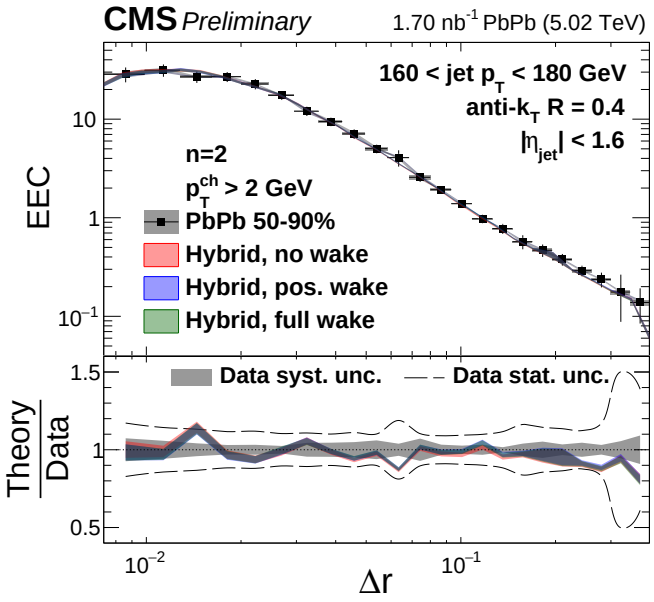


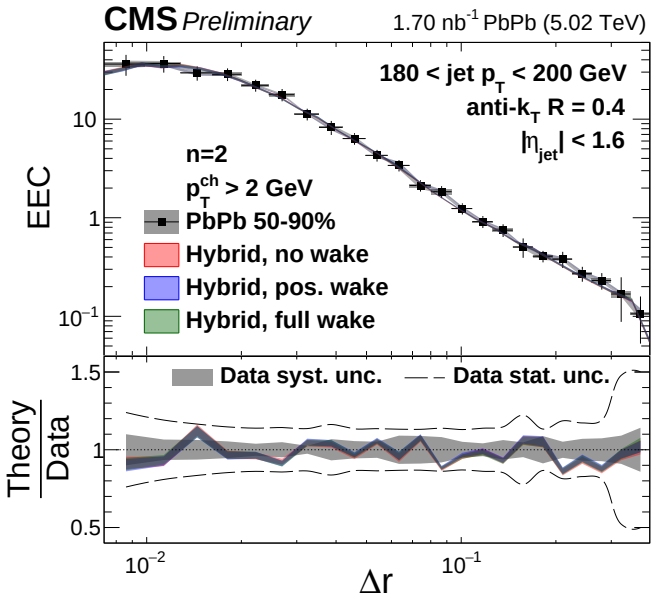


PbPb distribution, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$

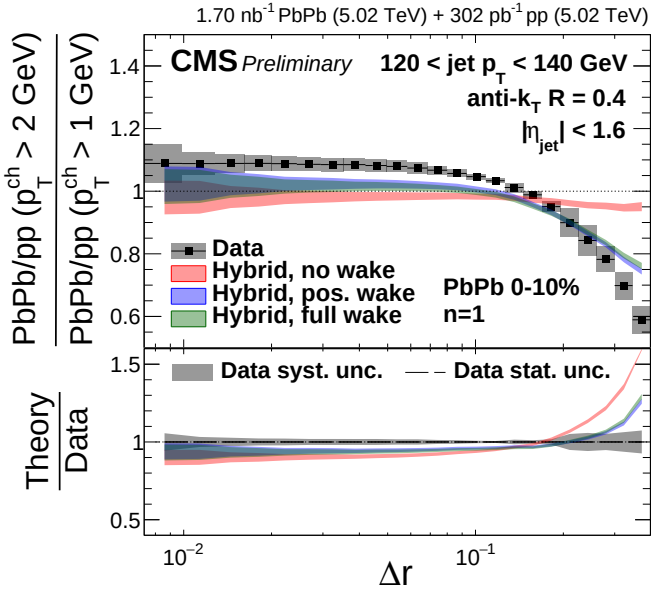


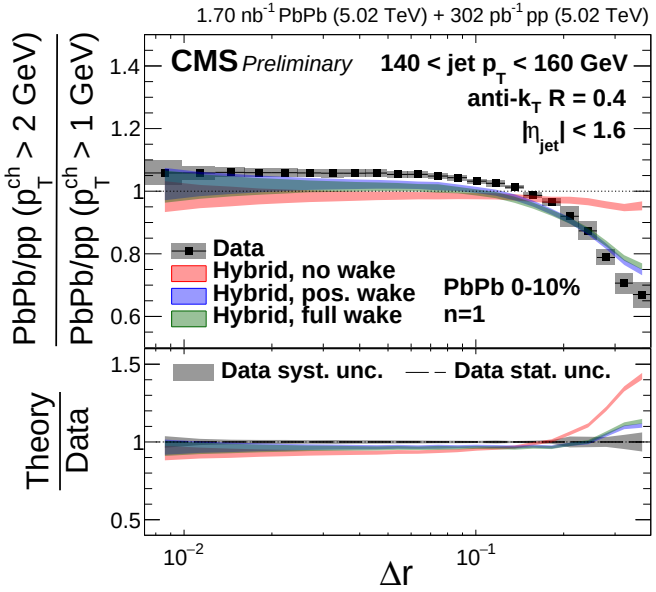


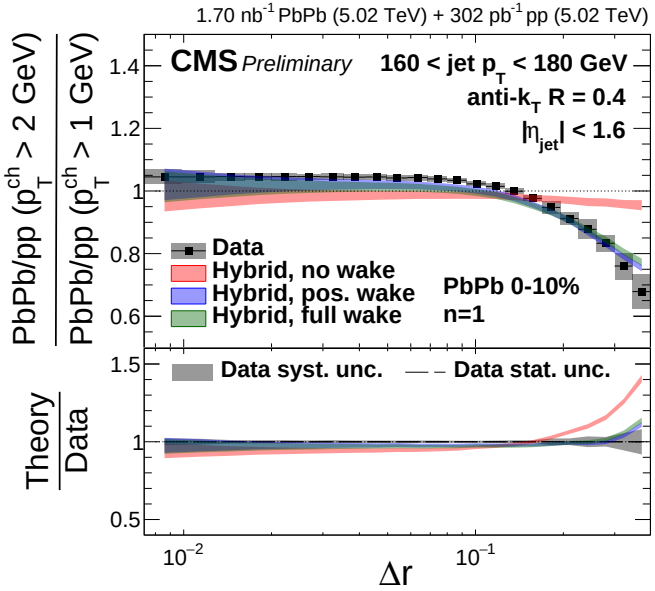


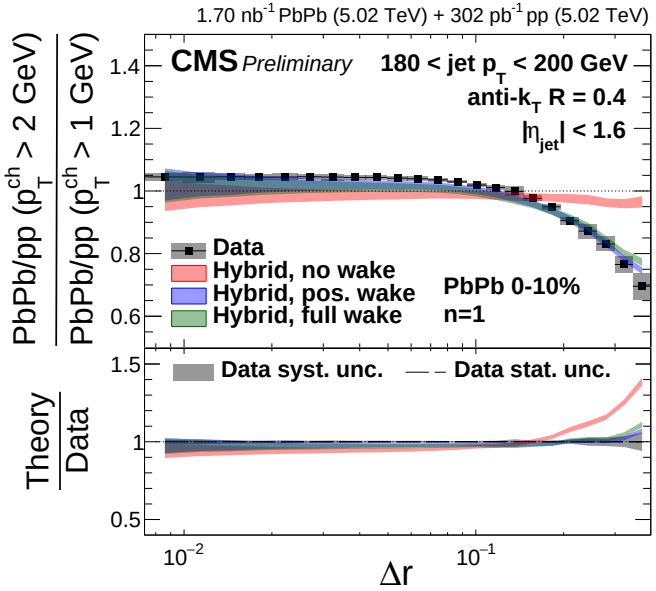


PbPb to pp double ratio, Hybrid, 0-10%, $n = 1$

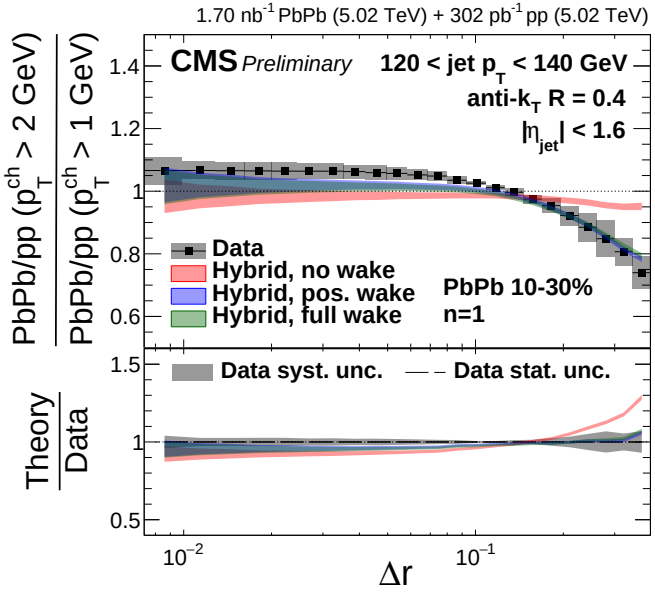


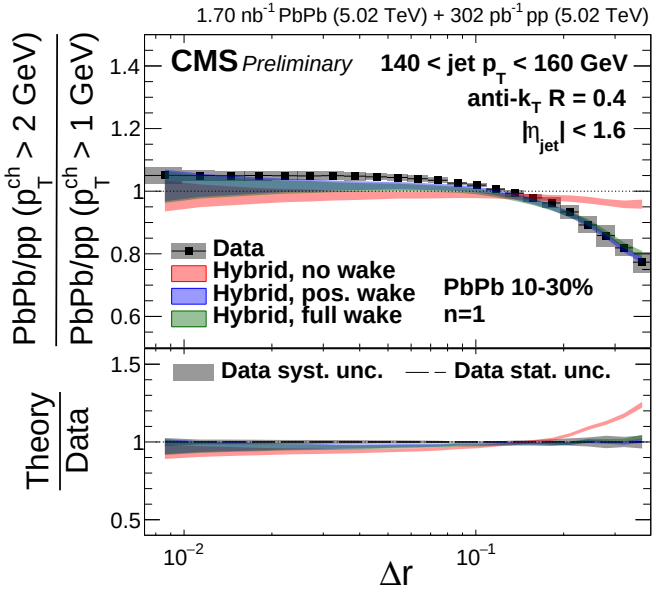


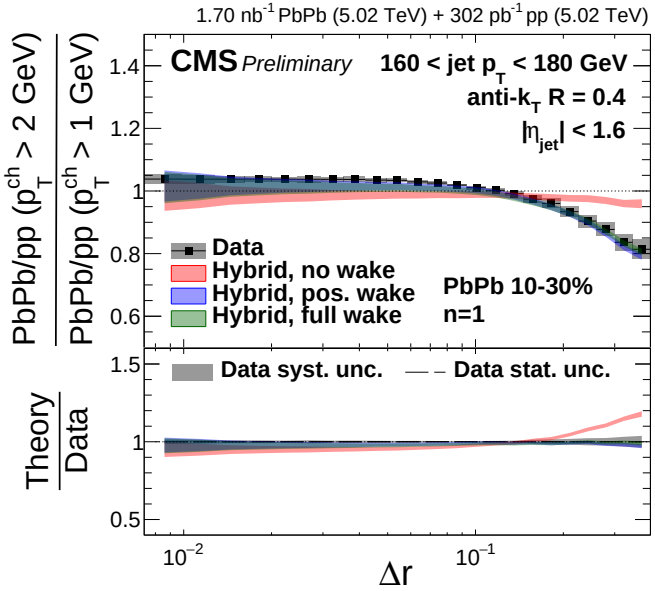


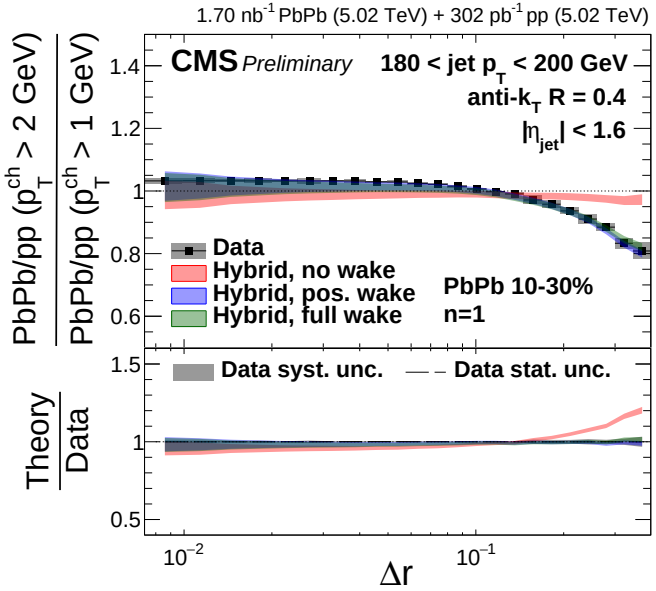


PbPb to pp double ratio, Hybrid, 10-30%, $n = 1$

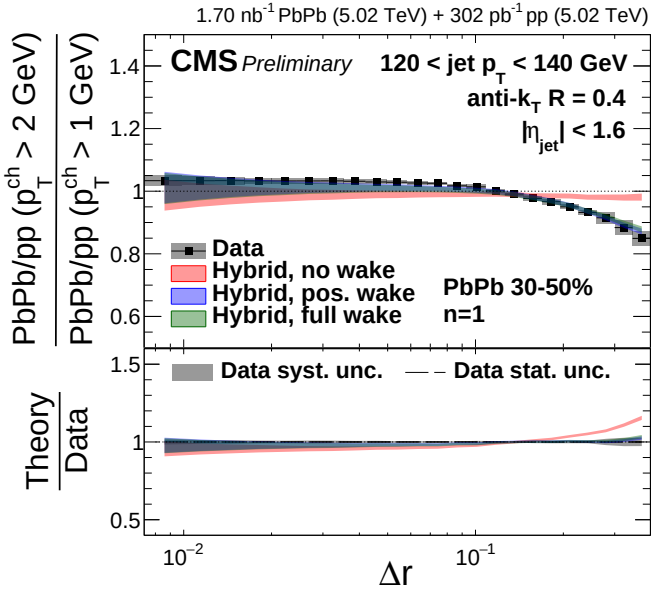


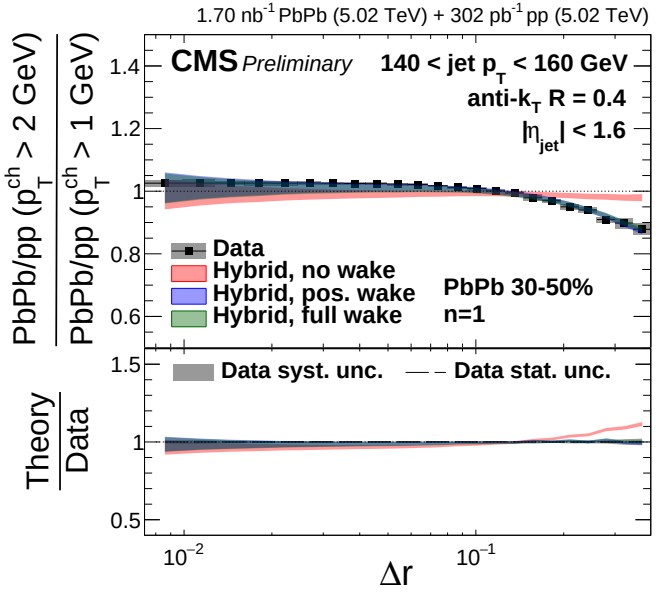


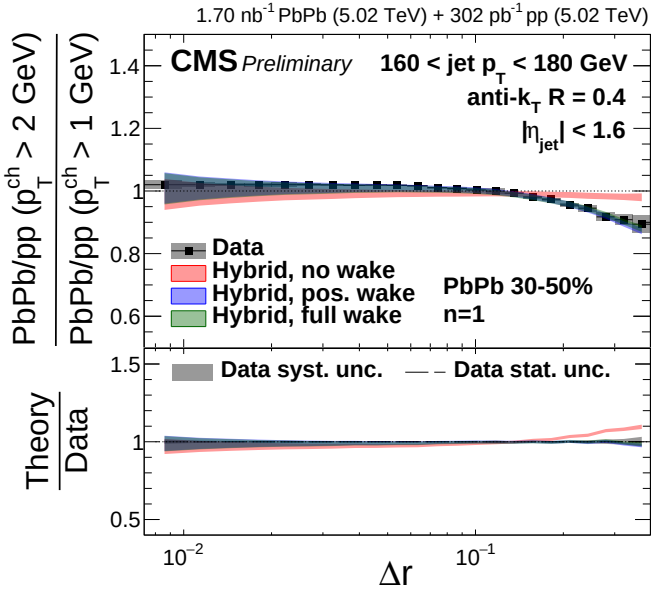


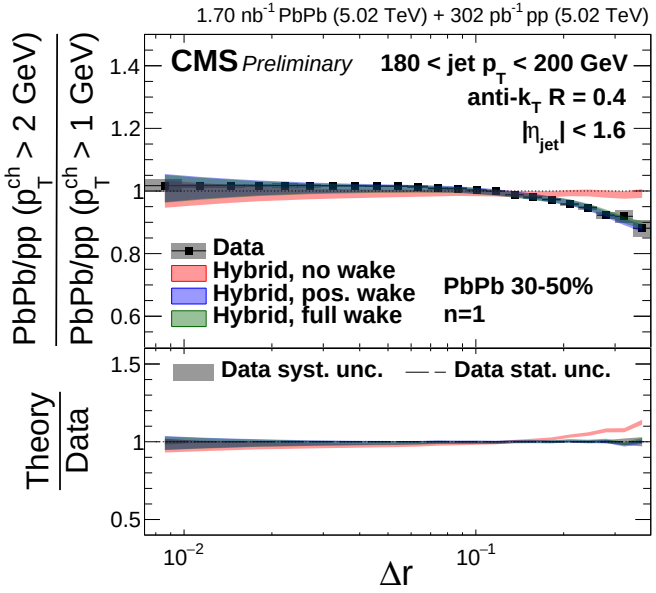


PbPb to pp double ratio, Hybrid, 30-50%, $n = 1$

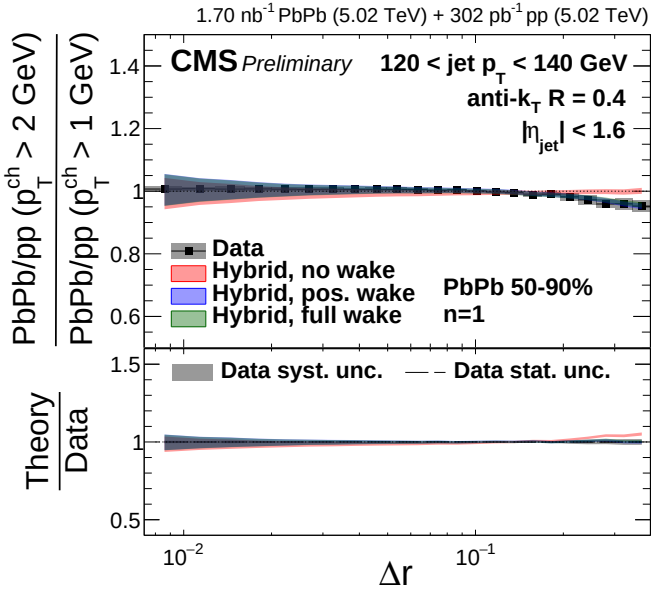


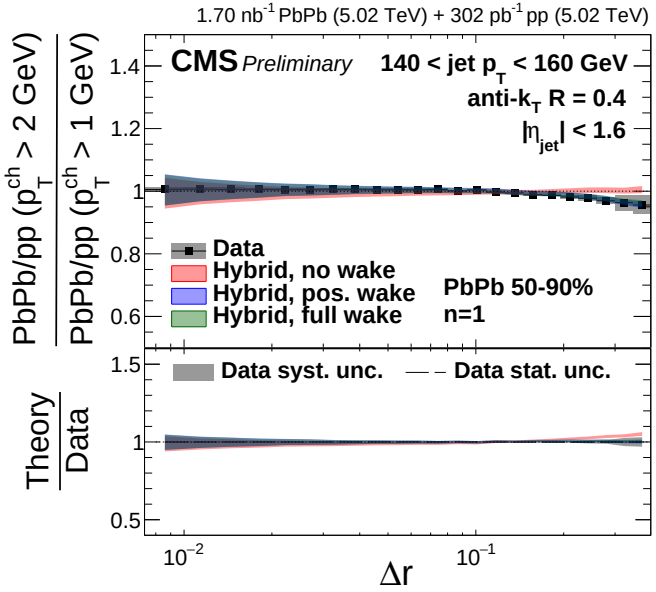


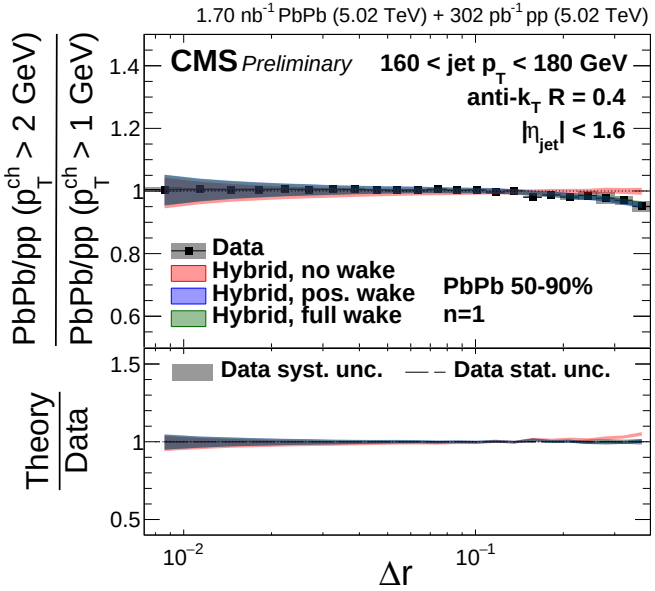


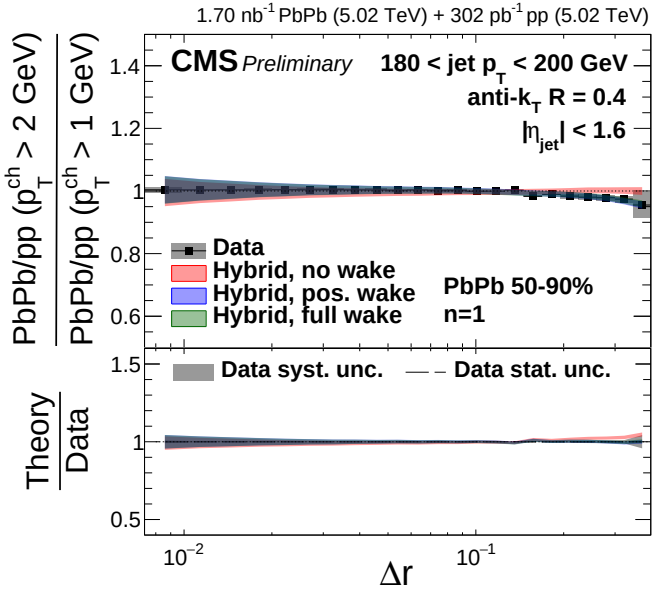


PbPb to pp double ratio, Hybrid, 50-90%, $n = 1$

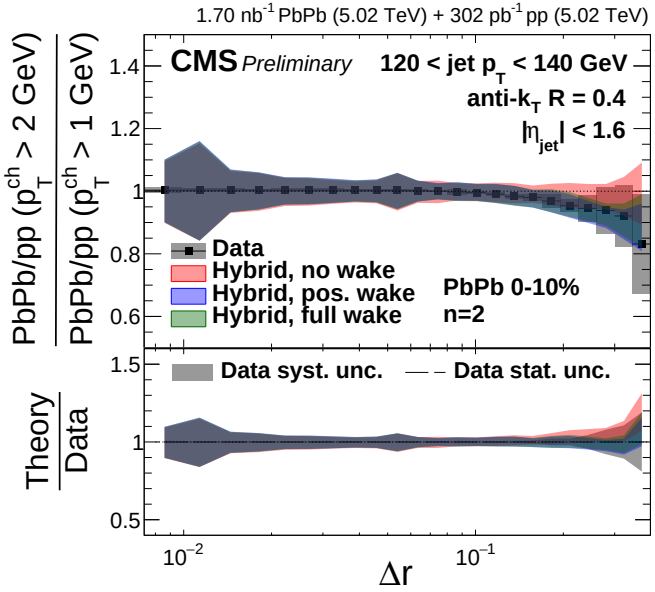


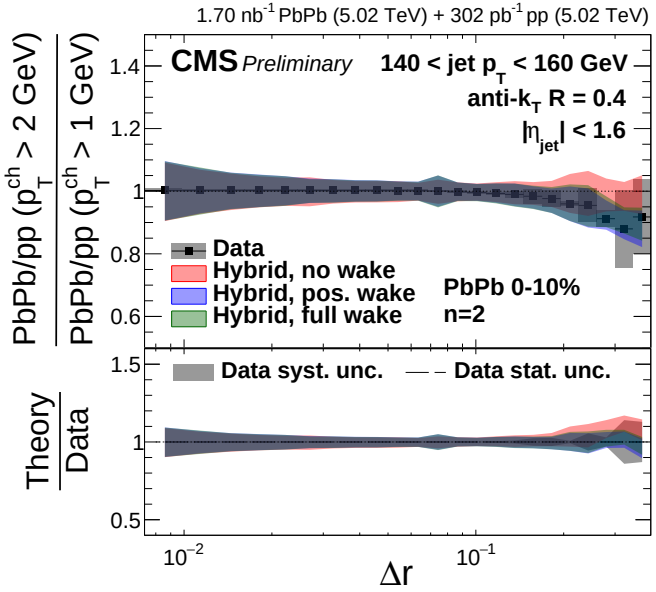


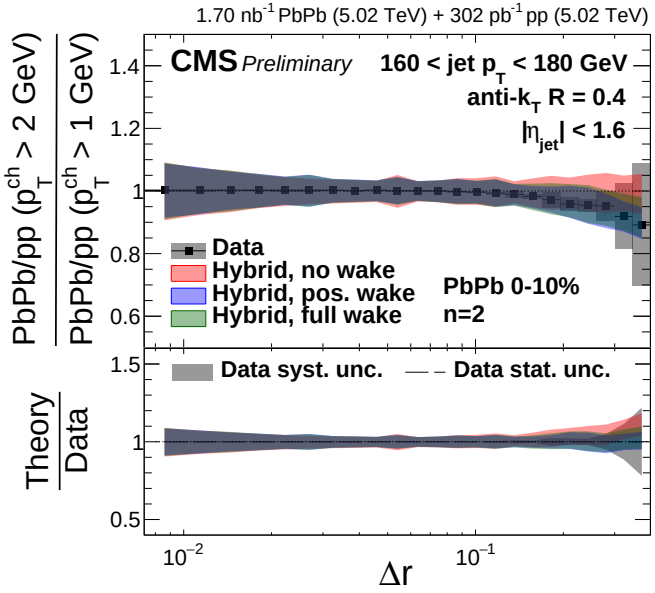


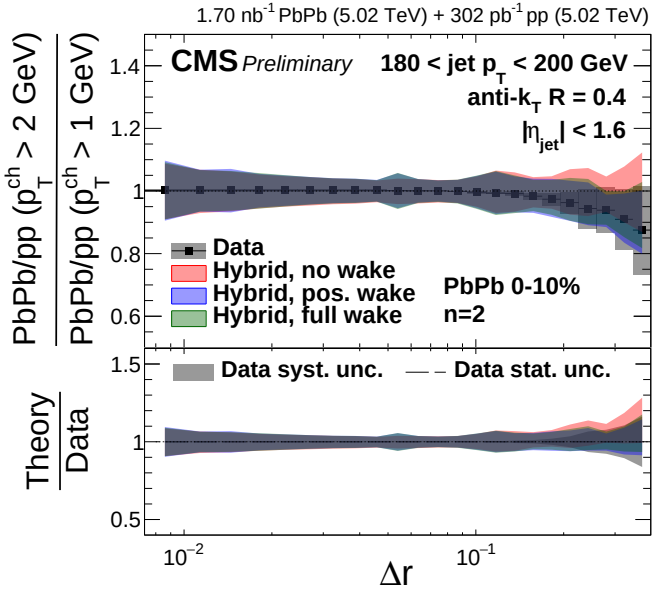


PbPb to pp double ratio, Hybrid, 0-10%, $n = 2$

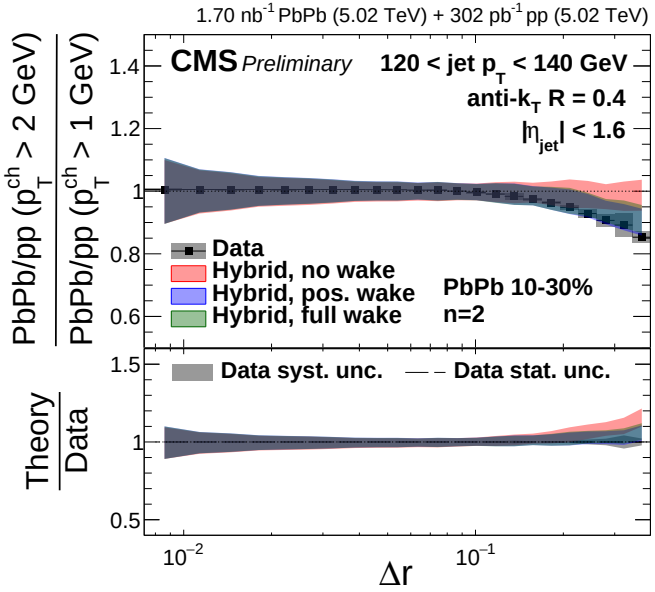


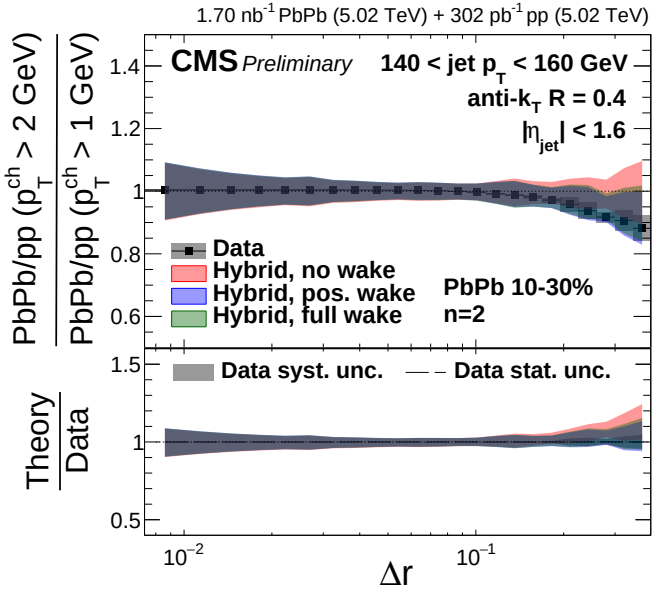


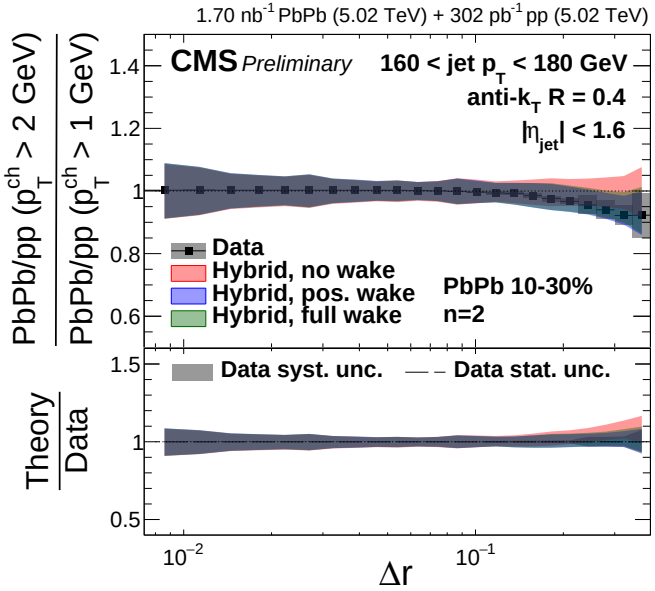


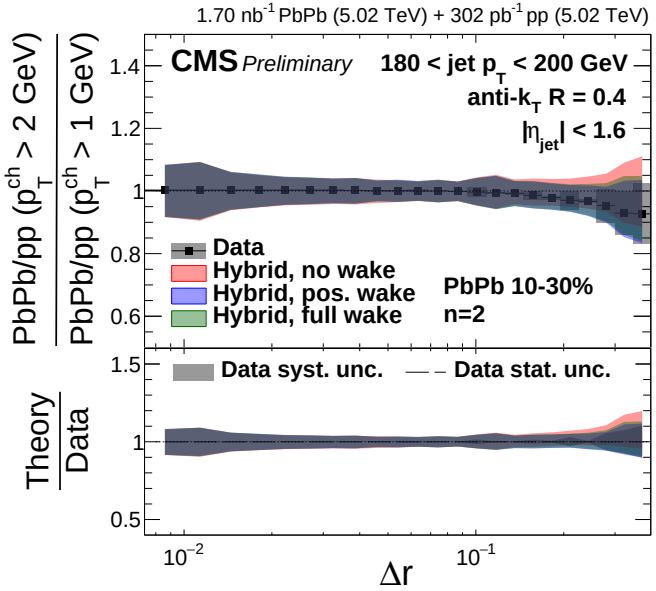


PbPb to pp double ratio, Hybrid, 10-30%, $n = 2$

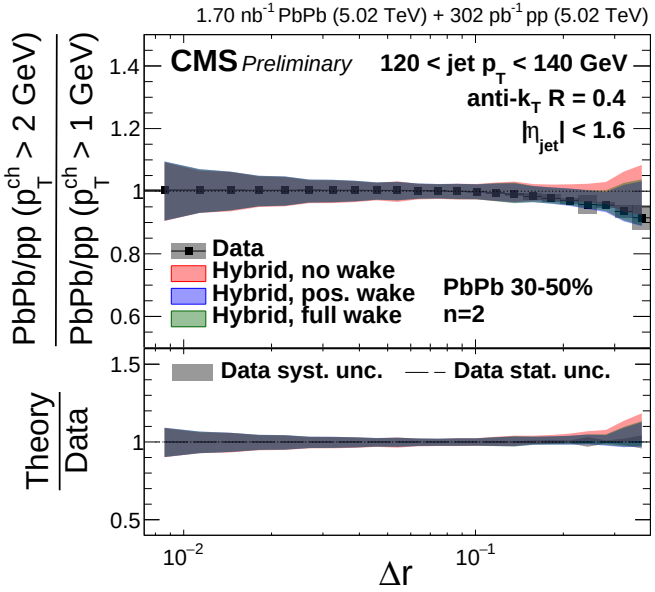


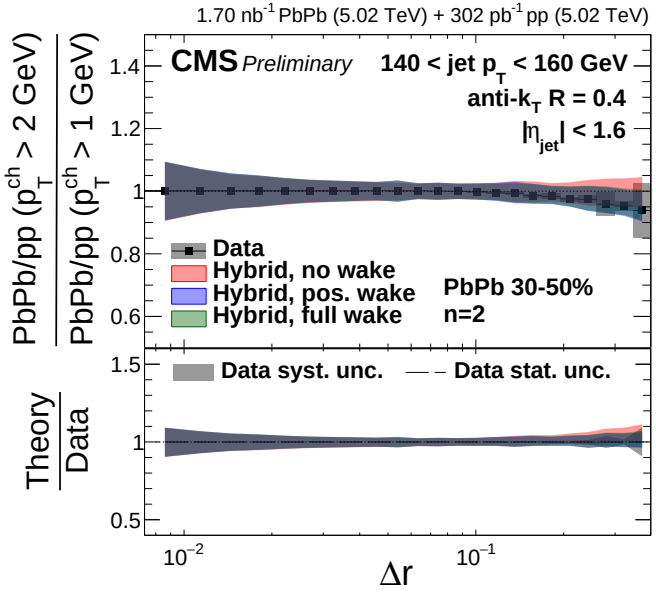


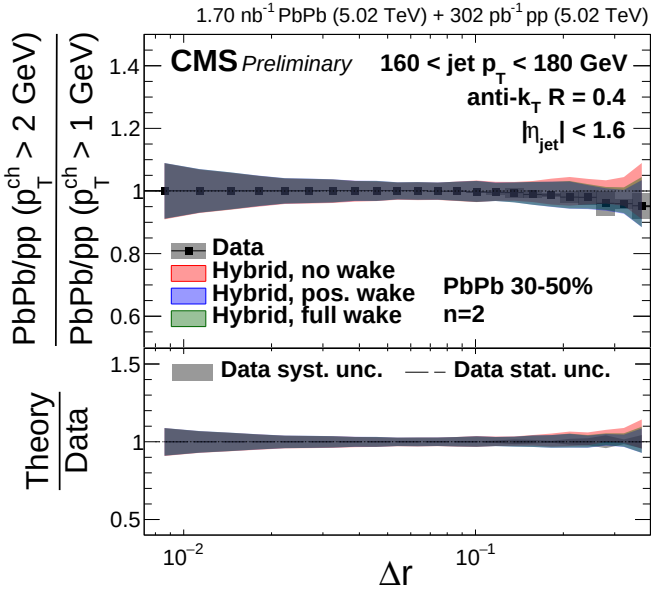


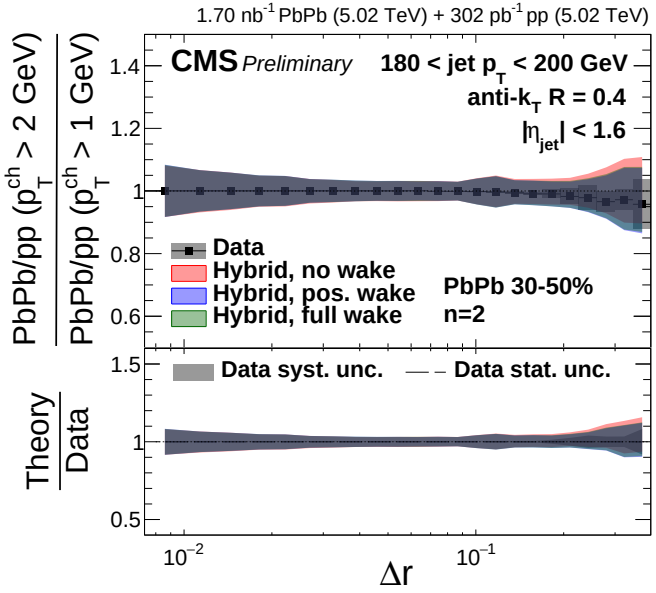


PbPb to pp double ratio, Hybrid, 30-50%, $n = 2$

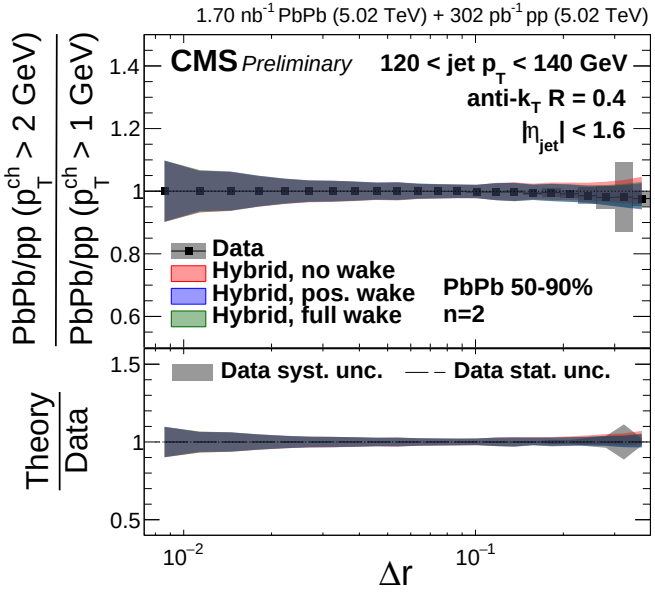


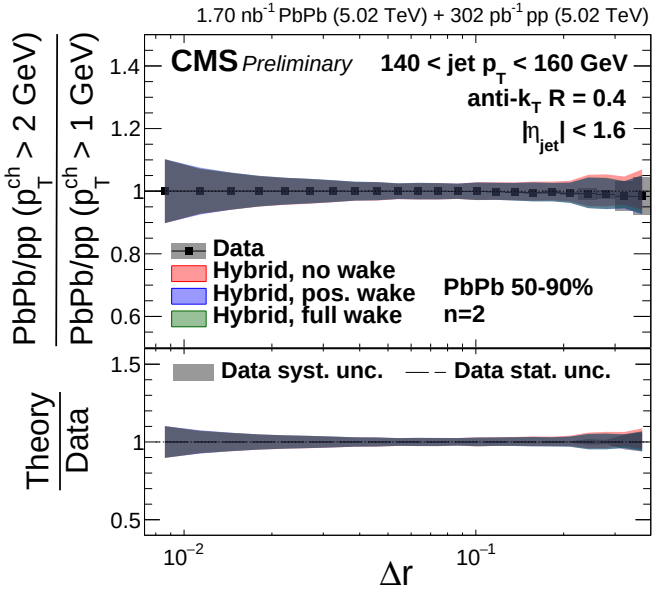


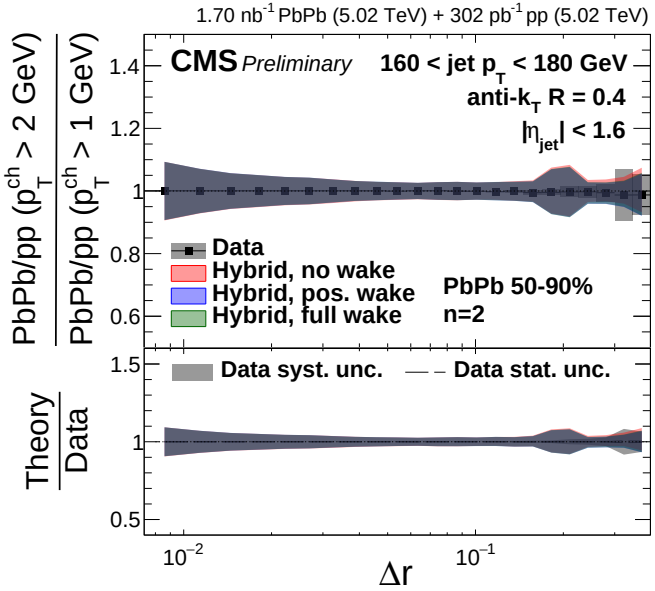


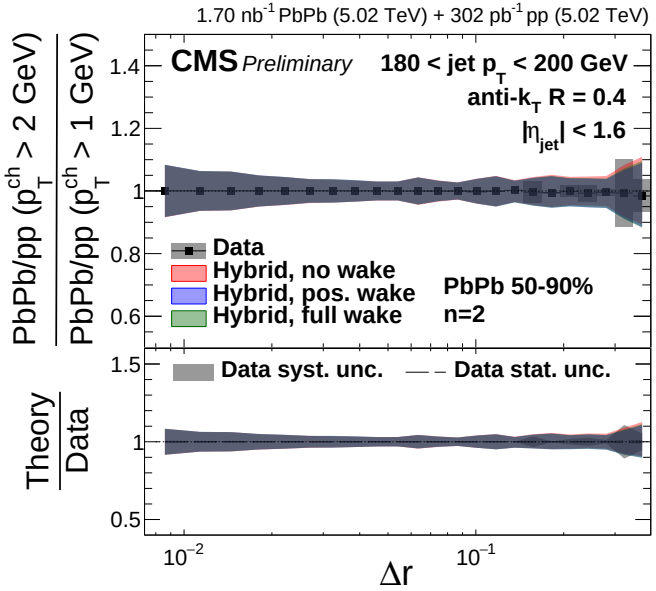


PbPb to pp double ratio, Hybrid, 50-90%, $n = 2$

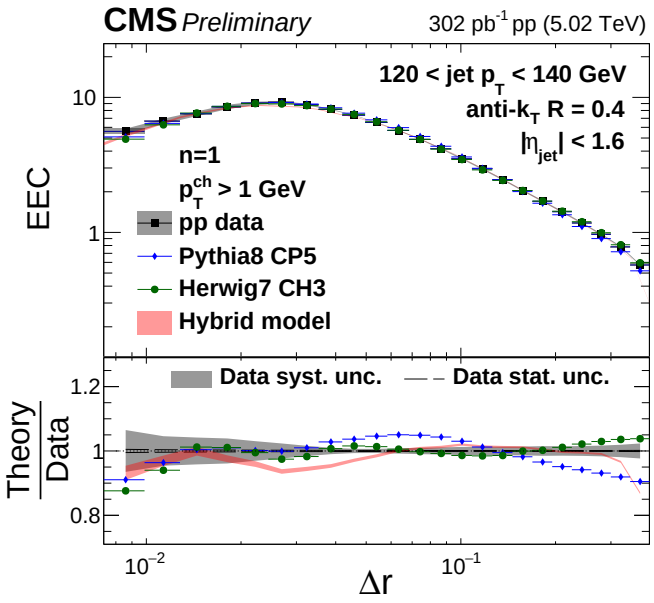


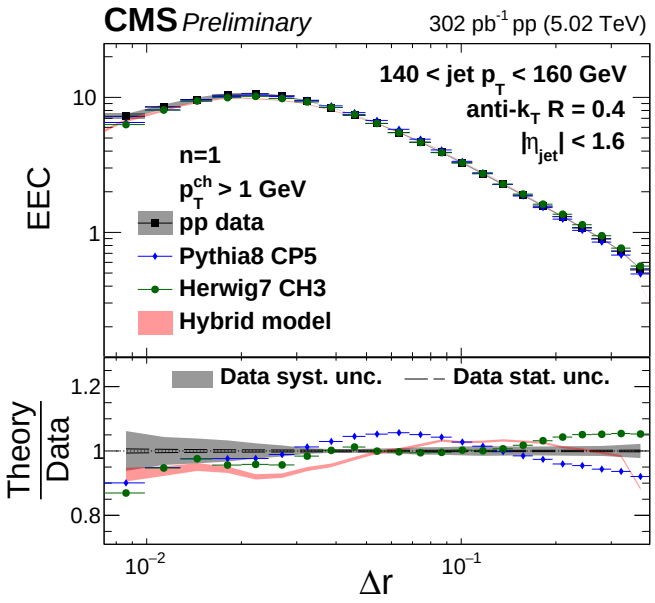


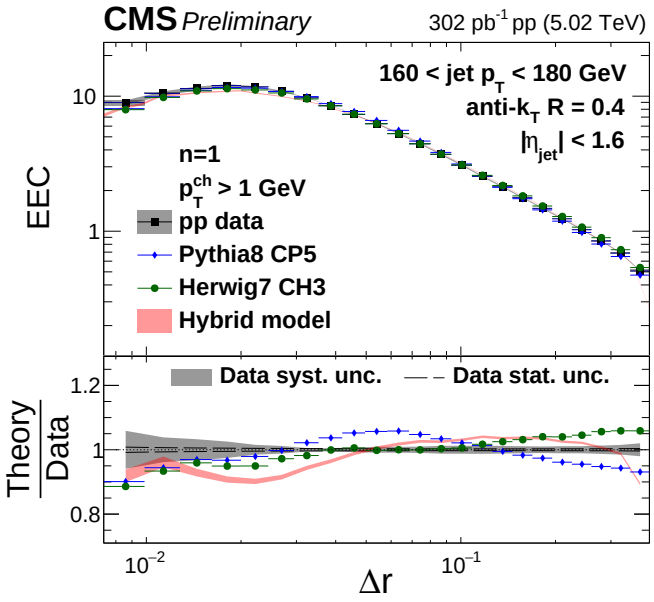


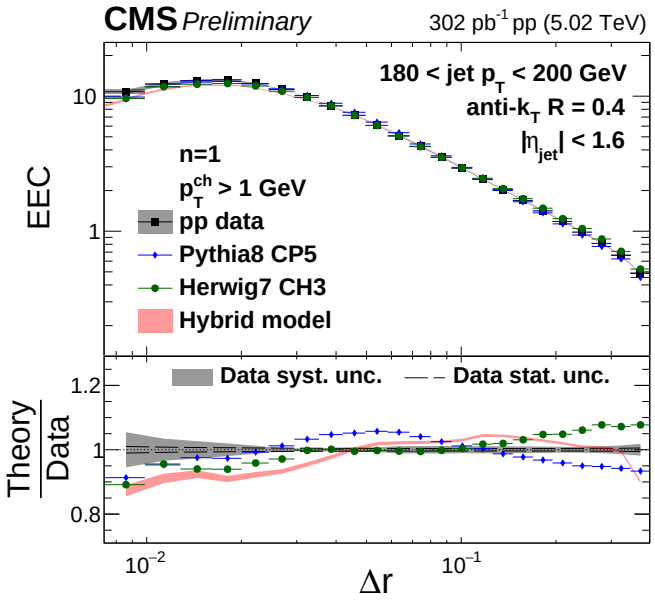


pp distribution, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 1$

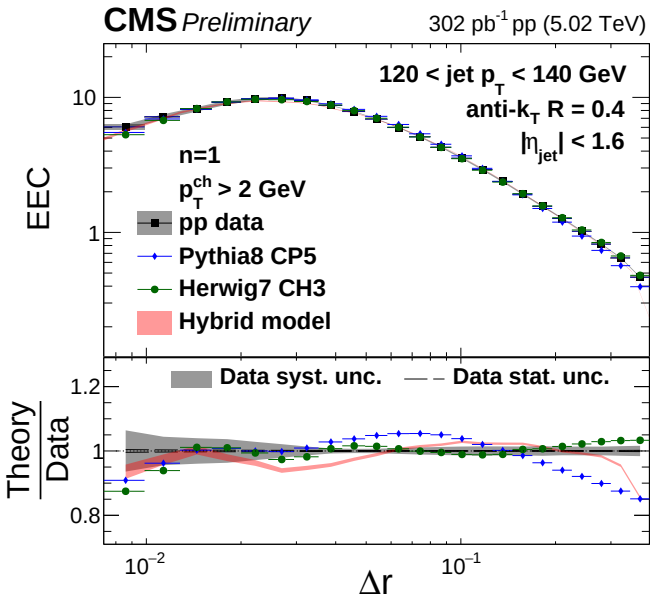


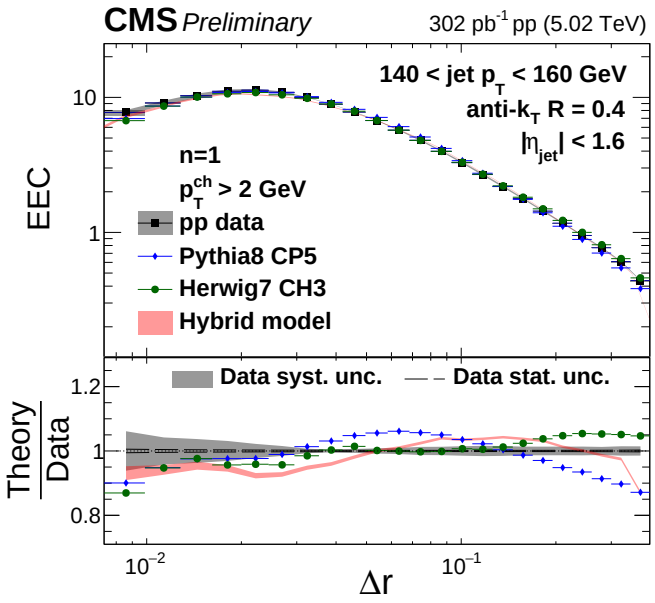


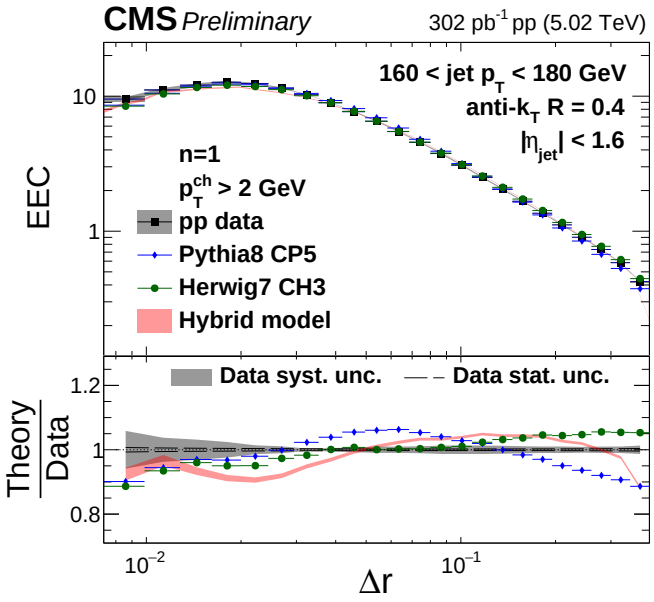


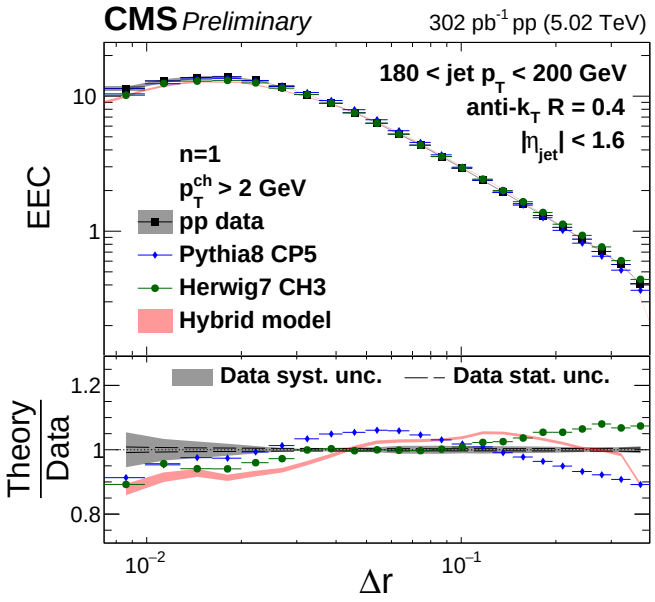


pp distribution, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 1$

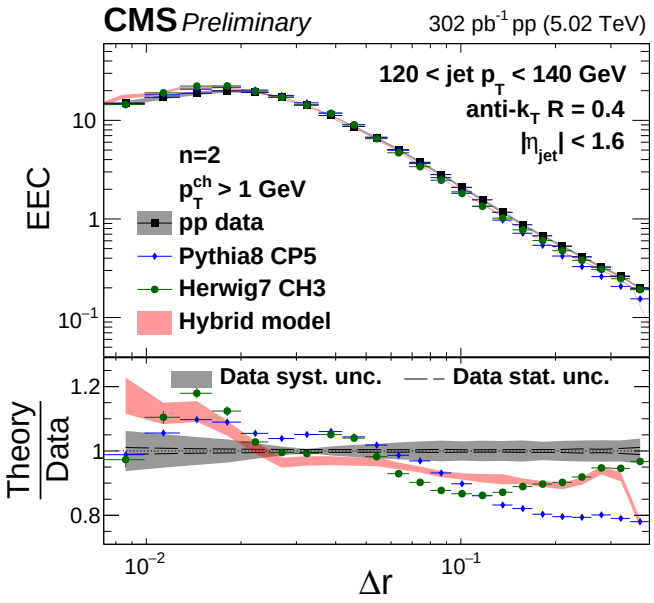


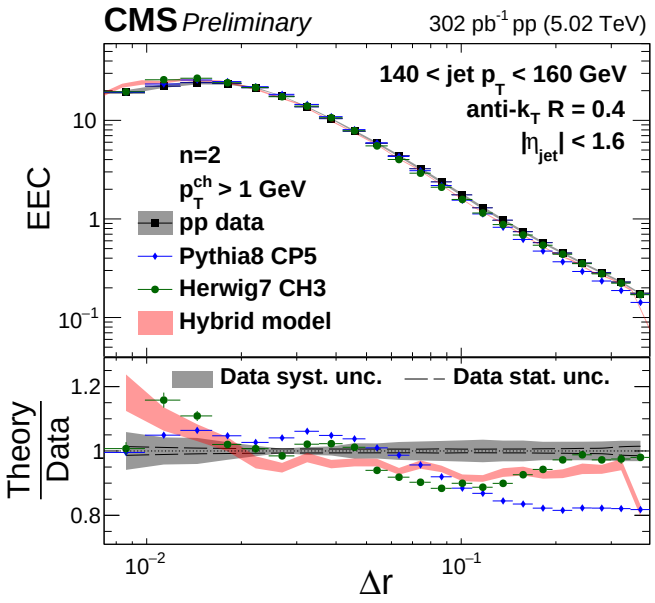


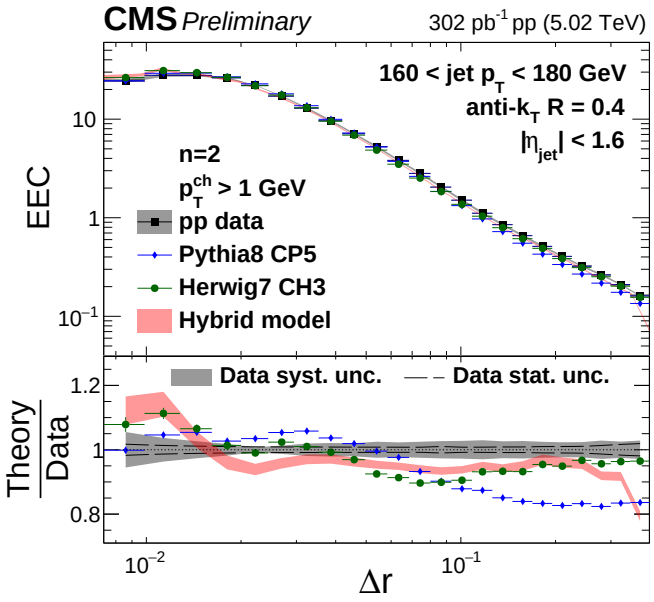


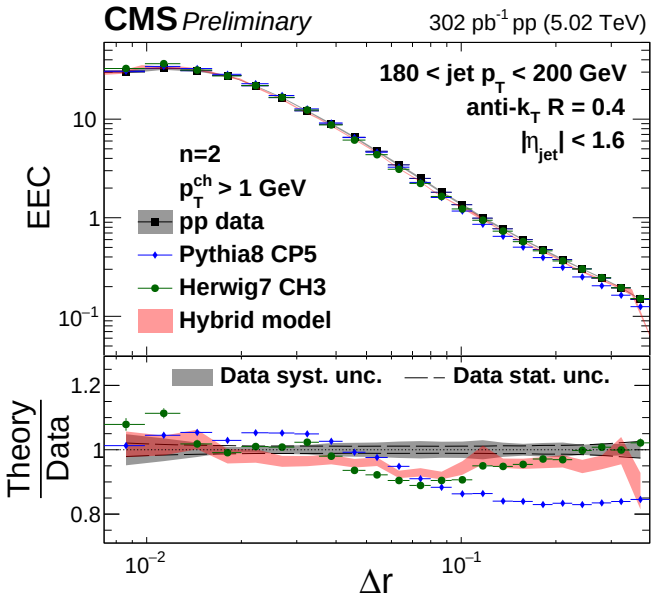


pp distribution, $p_{\mathrm{T}}^{\mathrm{ch}} > 1\,\mathrm{GeV}$, $n = 2$

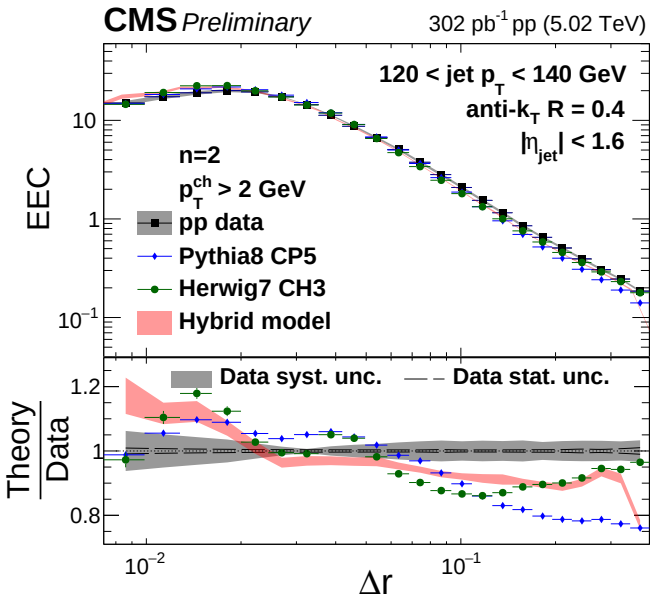


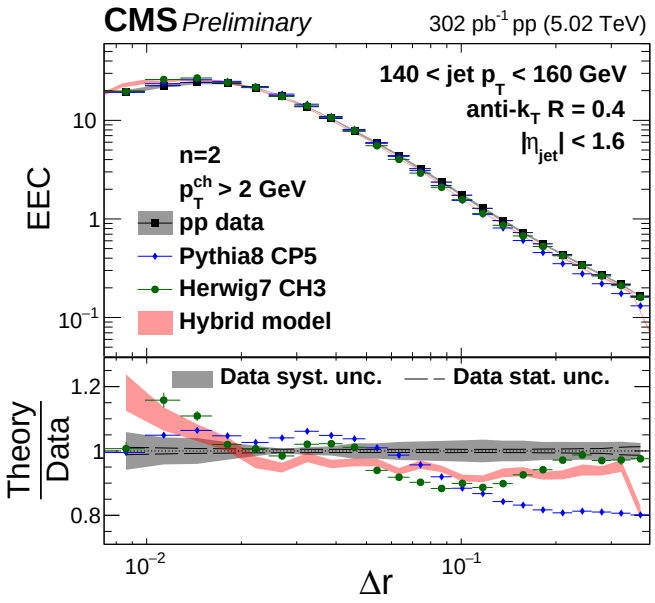


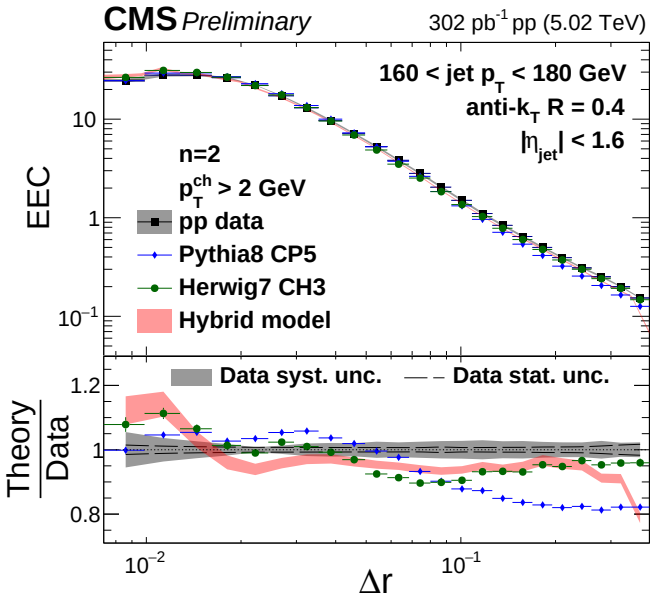


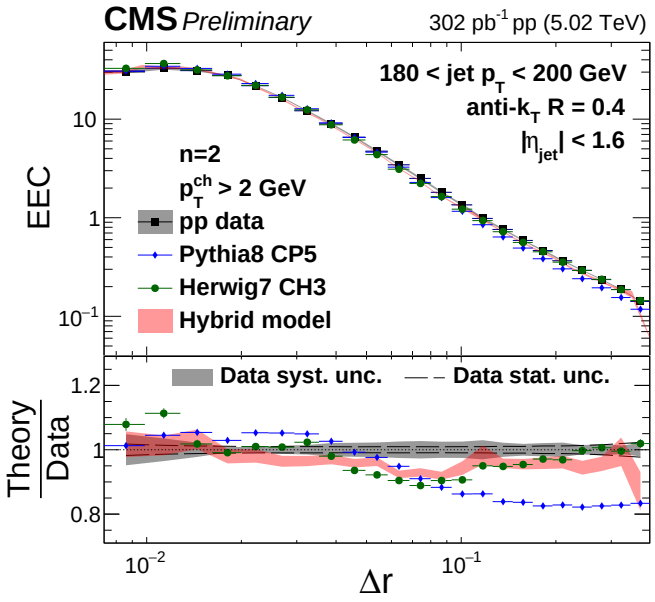


pp distribution, $p_{\mathrm{T}}^{\mathrm{ch}} > 2\,\mathrm{GeV}$, $n = 2$









Sources of systematic uncertainty

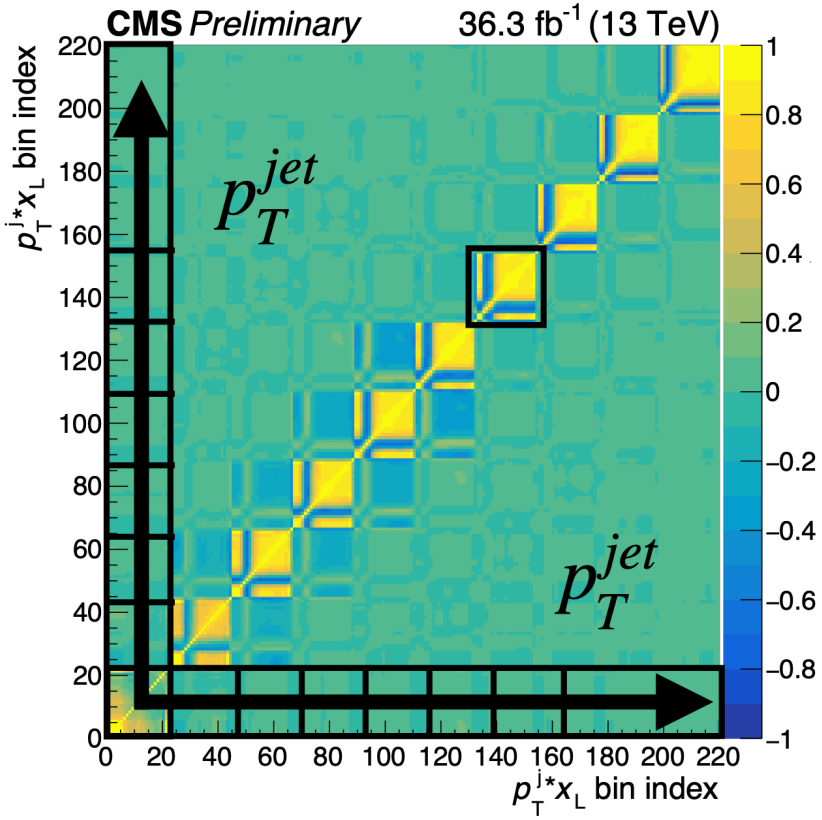
Color coding for size of uncertainty

- Small, medium, large

- Jet energy scale
- Jet energy resolution
- Jet p_{T} prior for unfolding
- Number of iterations for unfolding
- Track selection
- Track pair efficiency
- Background subtraction
- Signal-to-background ratio scaling

Unfolding the measurement, how is this done in pp?

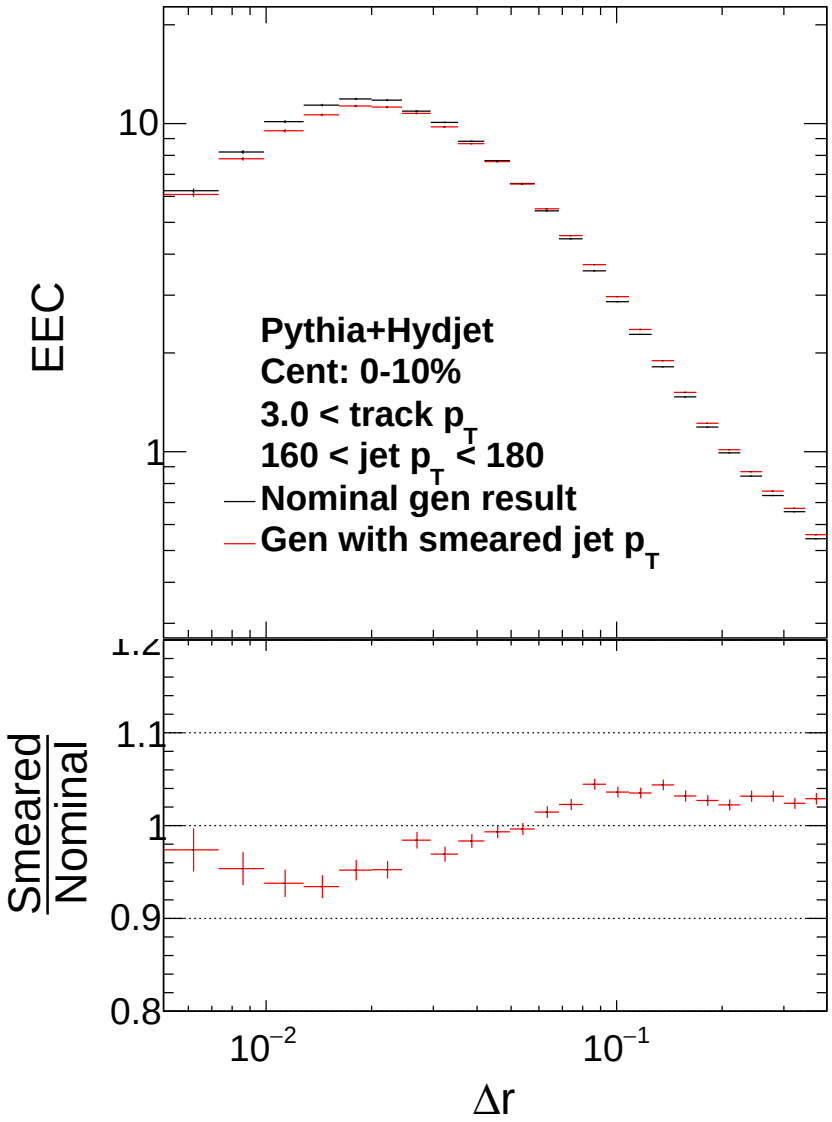
- Example from CMS-PAS-SMP-22-015
- Three-dimensional unfolding with variables:
  - Jet p_{T}
  - Energy weight $\frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$
  - Pair opening angle Δr



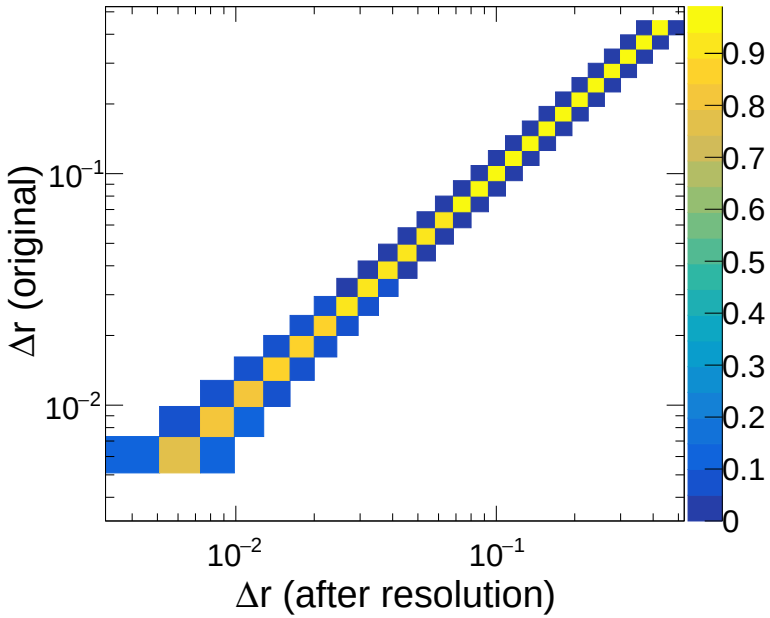
- Multidimensional unfolding in heavy ion collisions is difficult
  - Worse jet resolution compared to pp
  - Use of vacuum reference questionable
- Is there a way to simplify the unfolding procedure?

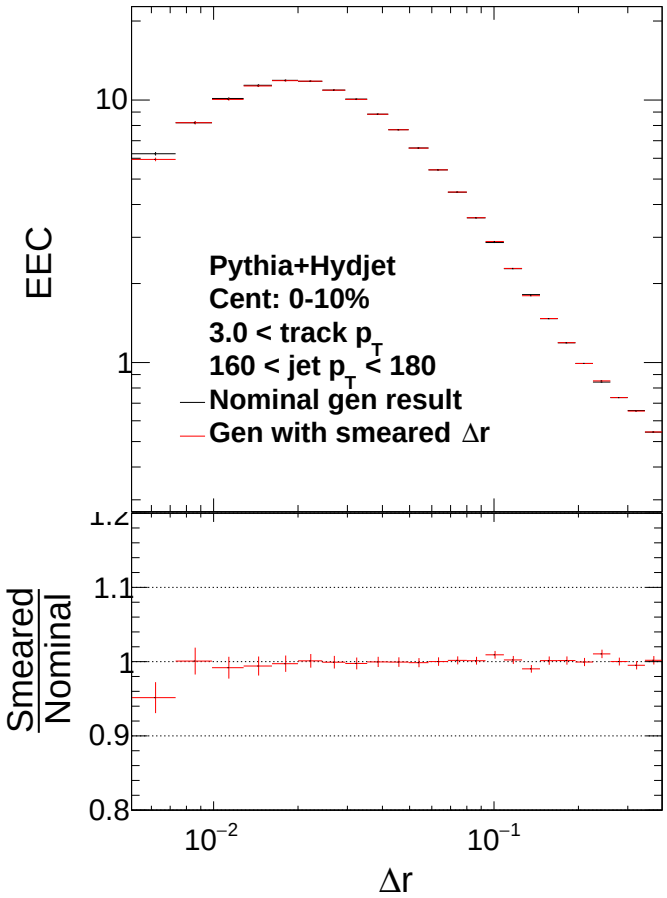
Does my observable need unfolding: jet p_{T}

- 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



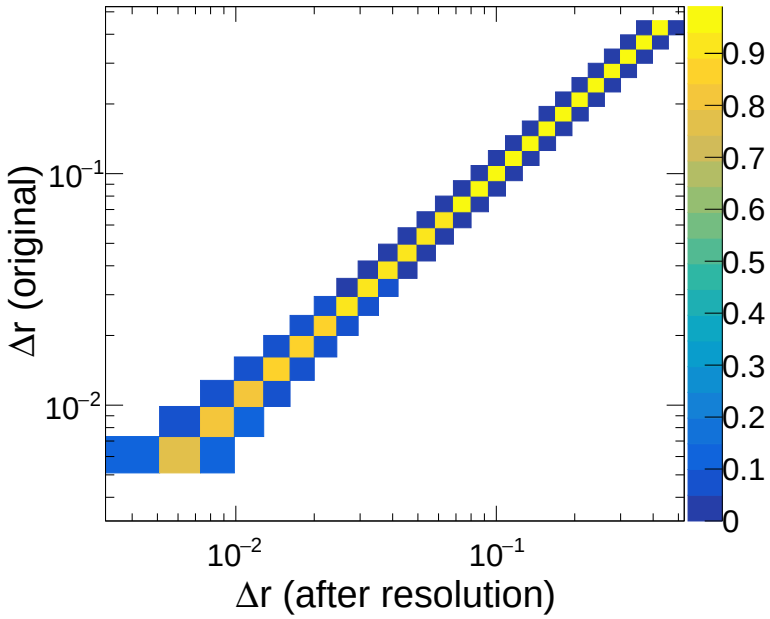
Does my observable need unfolding: Δr

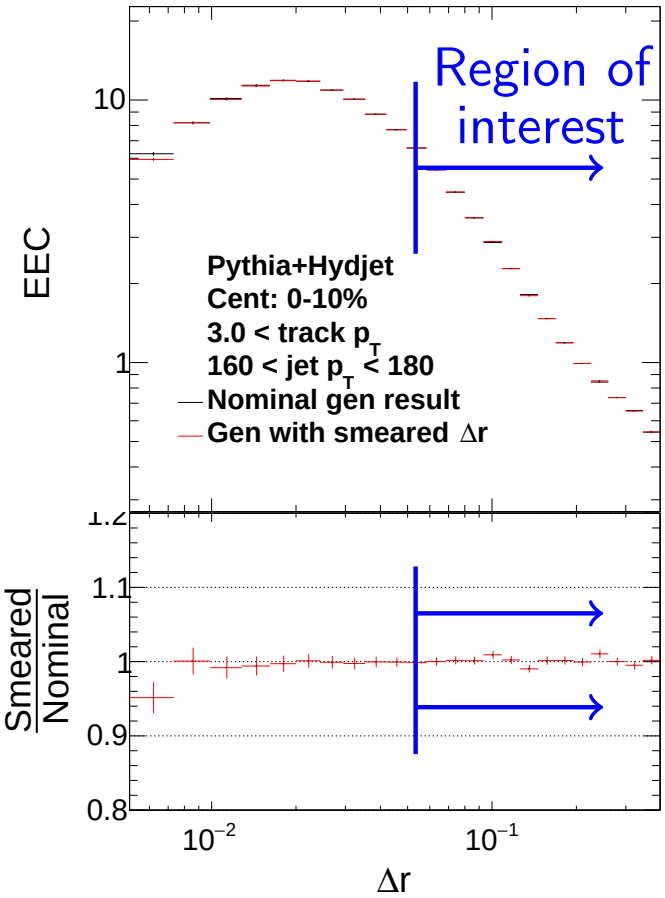




- Resolution model: certain probability Δr moves to neighboring bin
- Particle pair Δr resolution effects only important at very small Δr
- Conclusion: when very small angles are avoided, no unfolding needed

Does my observable need unfolding: Δr

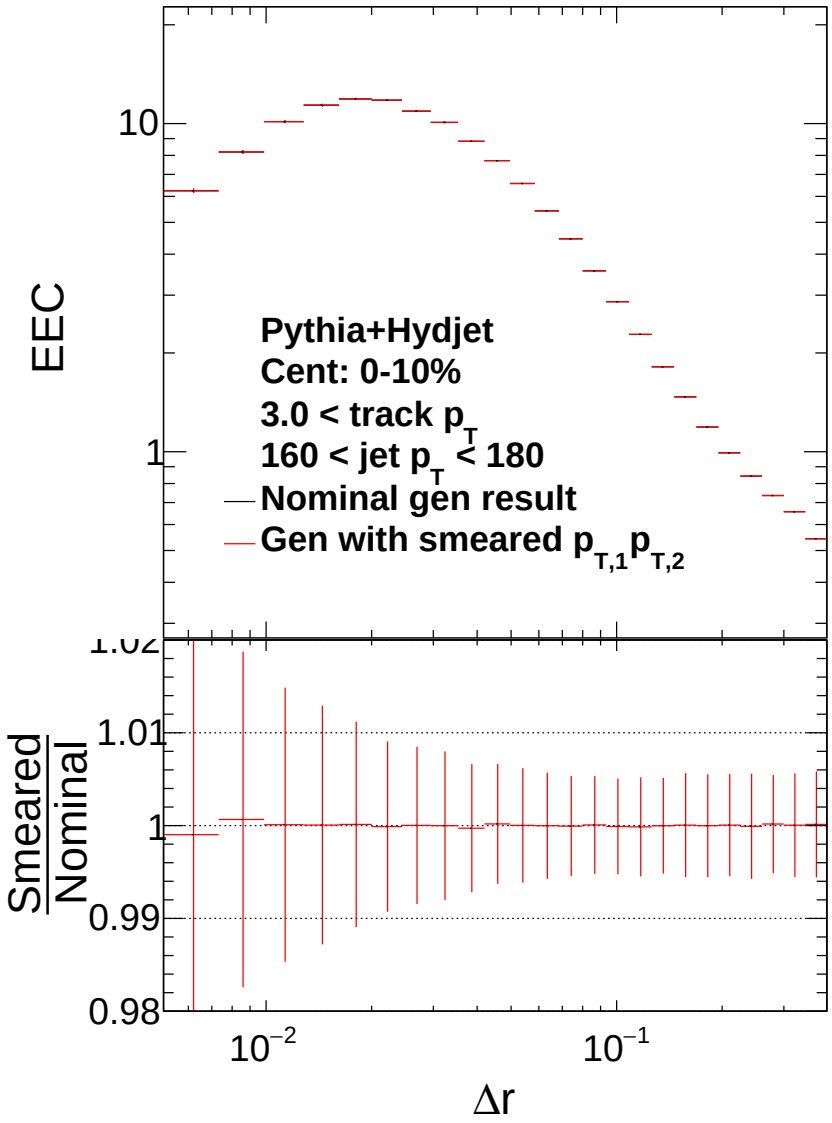




- Resolution model: certain probability Δr moves to neighboring bin
- Particle pair Δr resolution effects only important at very small Δr
- Conclusion: when very small angles are avoided, no unfolding needed

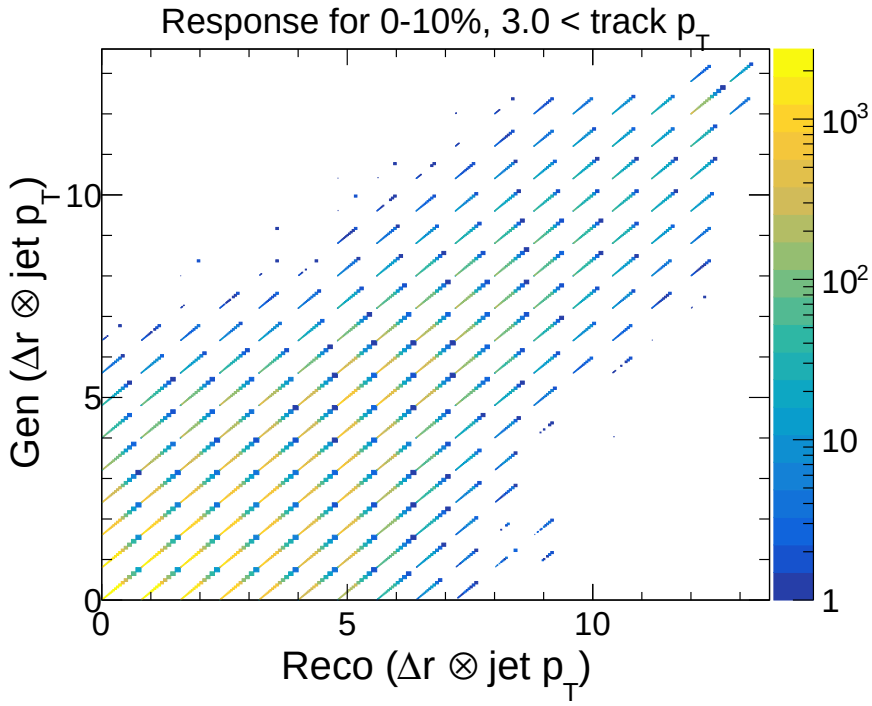
Does my observable need unfolding: $p_{\mathrm{T},1}\, p_{\mathrm{T},2}$ weight

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



Unfolding jet p_{T} as binning variable

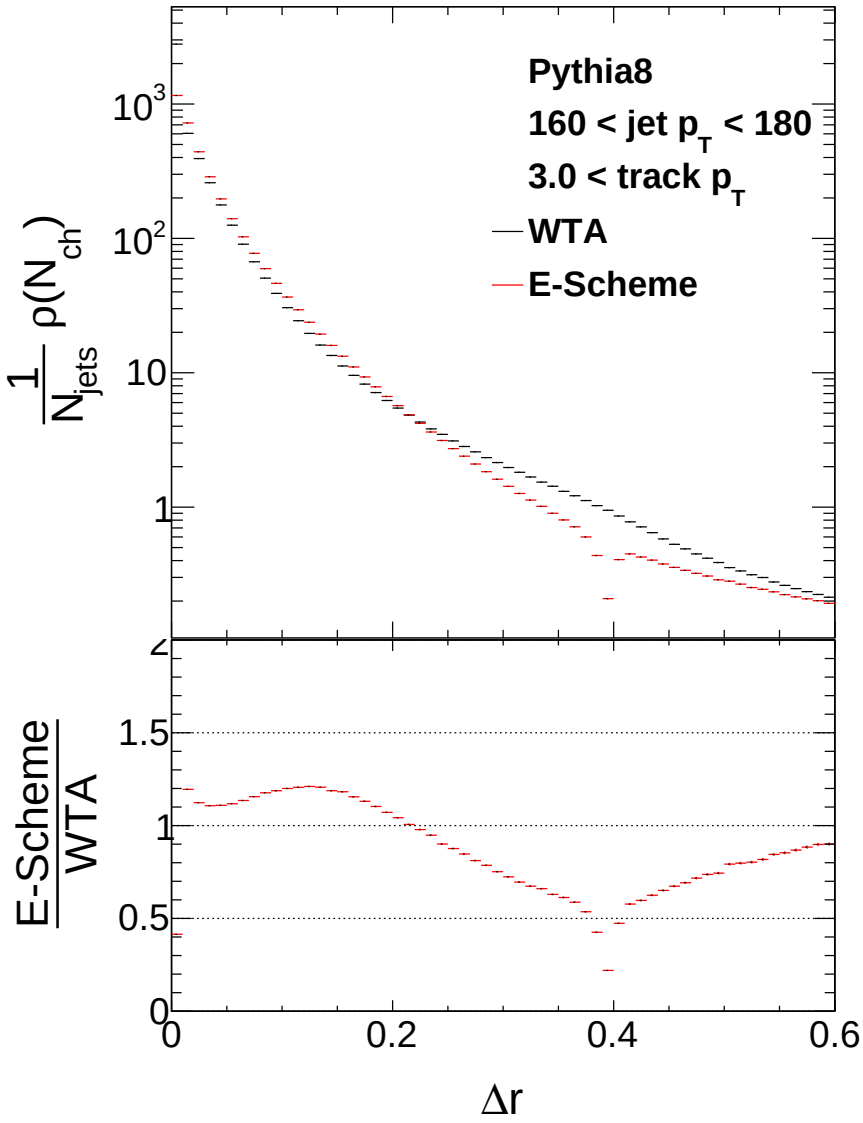
- Unfolding with RooUnfold
  - Since unfolding deals with distributions, need to combine jet p_{T} bins and Δr axis
  - Create response matrix from matched reconstructed and generator level jets
  - Use generator level particles for both $\Rightarrow$ Δr axis is diagonal



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

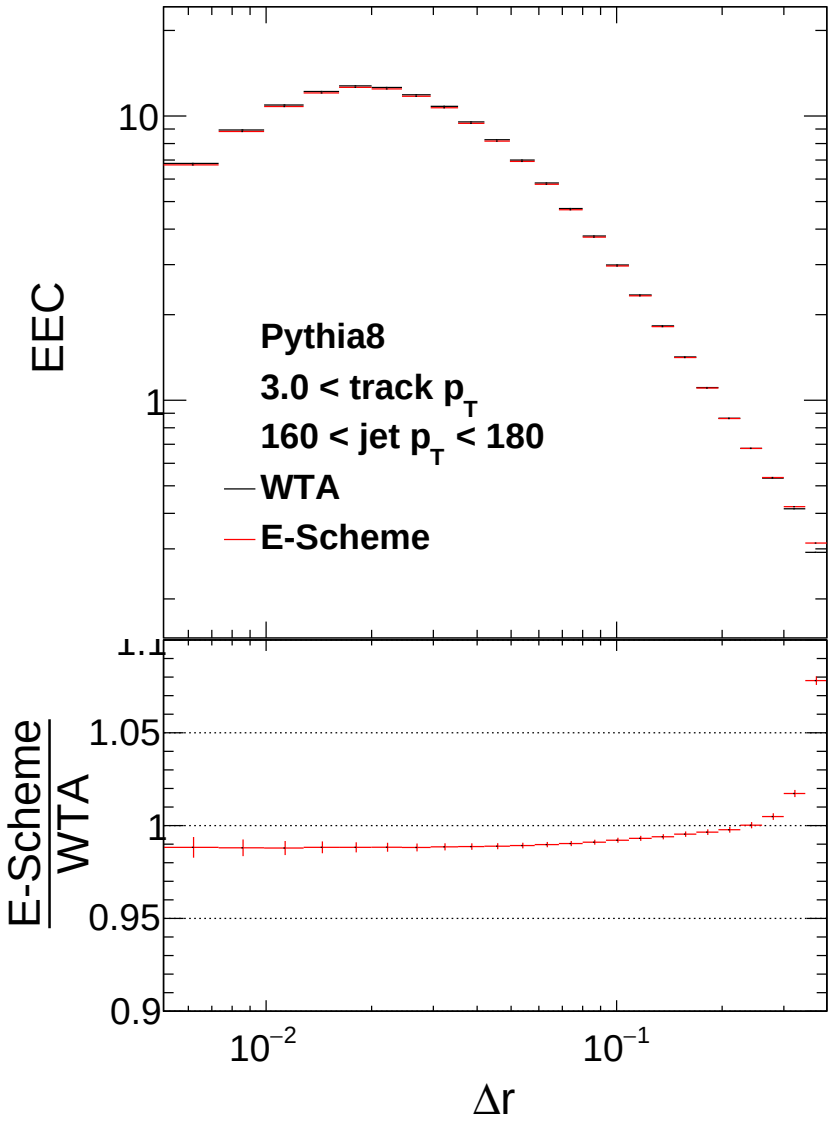
Particle density with respect to jet axis in Pythia8

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



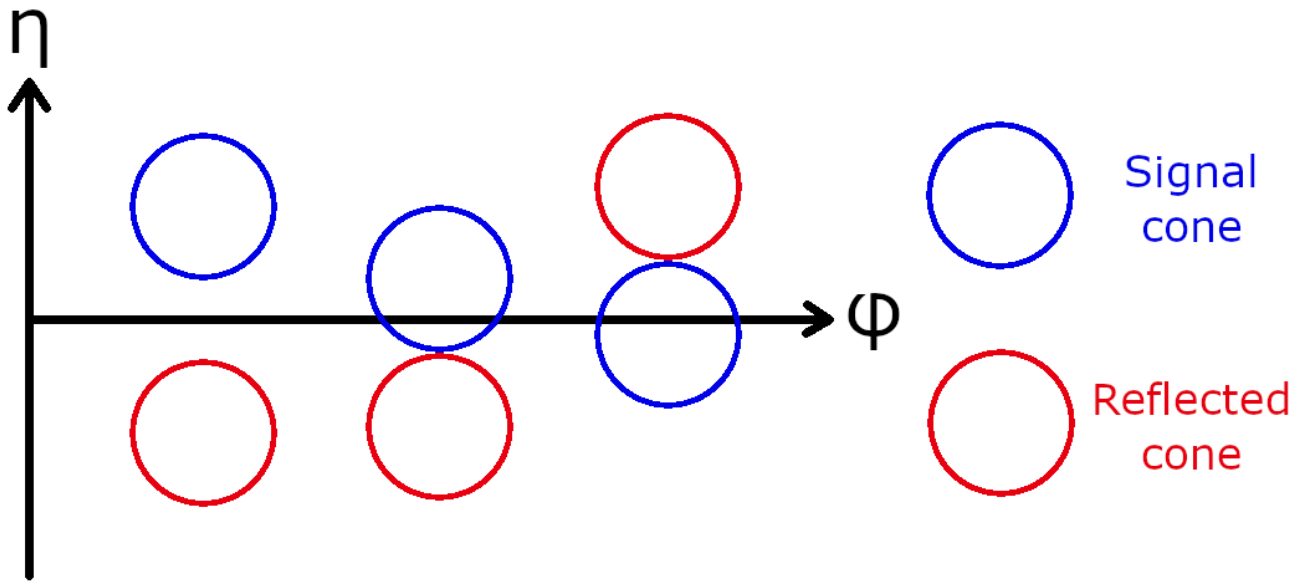
Energy-energy correlator axis comparison in Pythia8

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



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

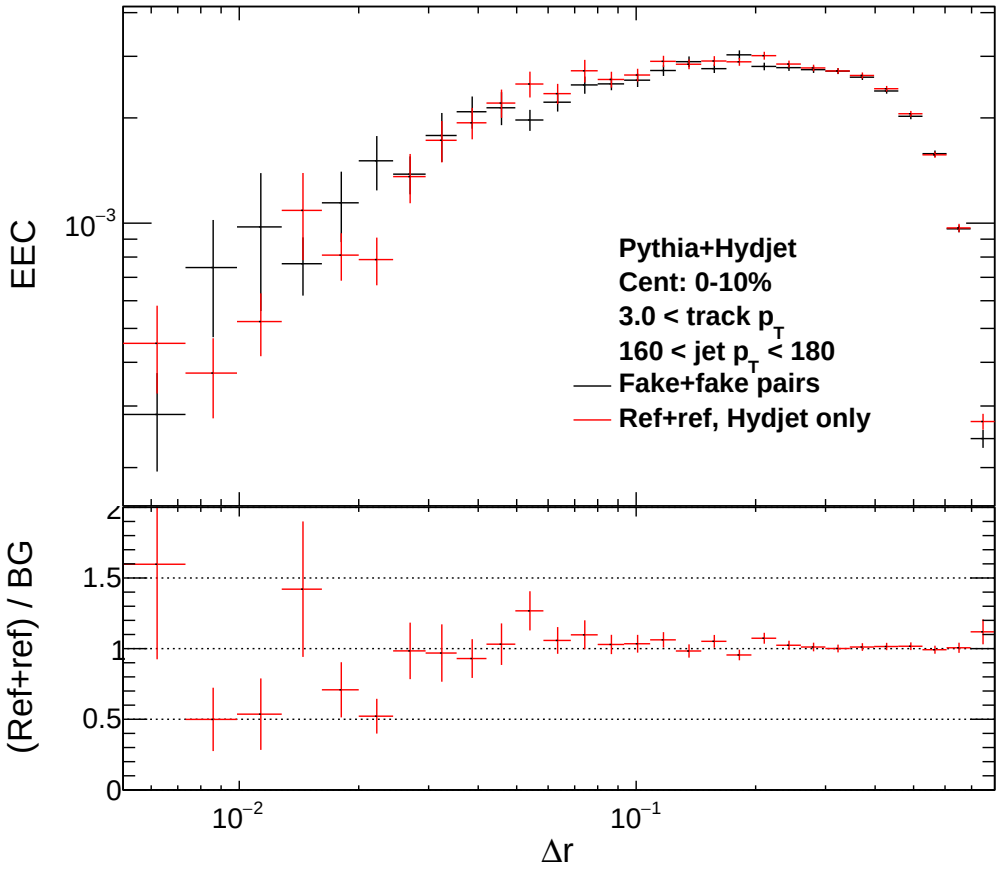


Normalization of reflected η cone background

- 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: $10 + 9 + \cdots + 2 + 1 = 55$ pairings
  - There might be a random jet in the reflected cone

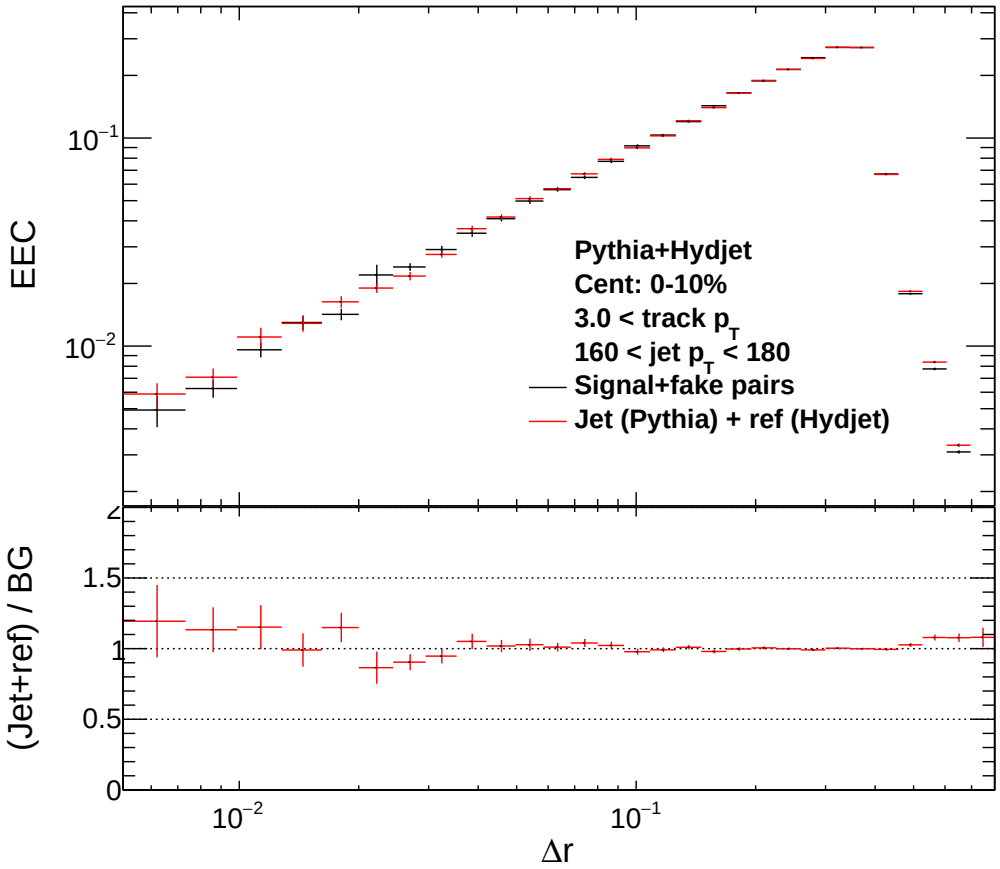
$\Rightarrow$ Estimate the effect on total normalization from MC by taking ratio of background pairs in signal cone and all pairs in reflected cone

Fake+fake background within reflected η cone



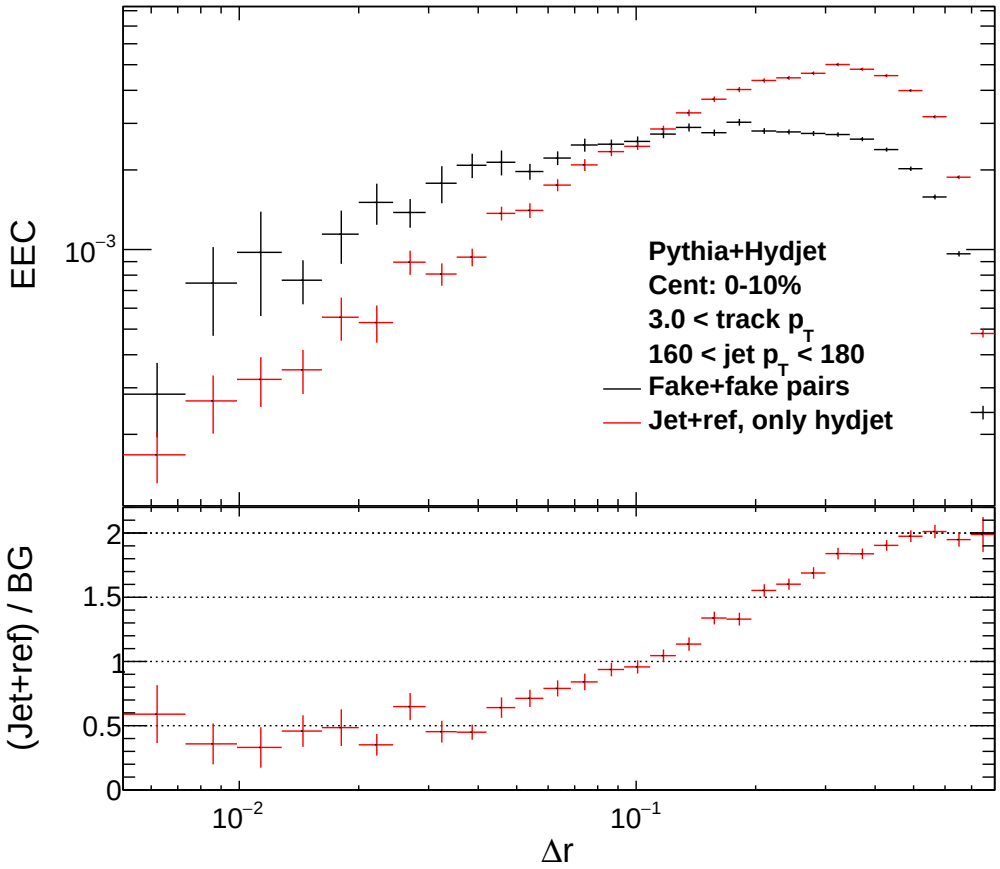
- Pairing reflected cone particles reproduces fake+fake contribution within signal cone

Signal+fake background estimation with reflected η cone



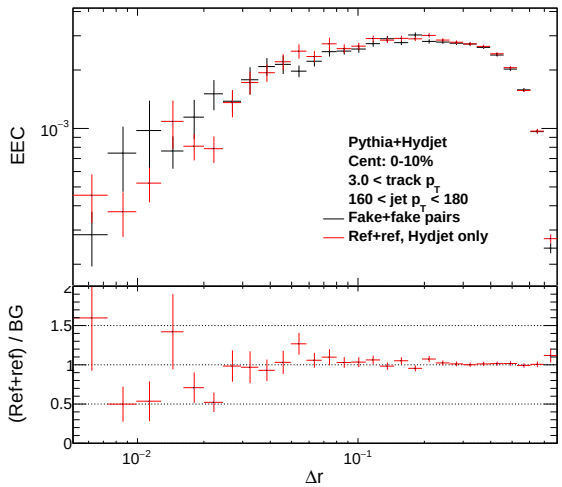
- Pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution

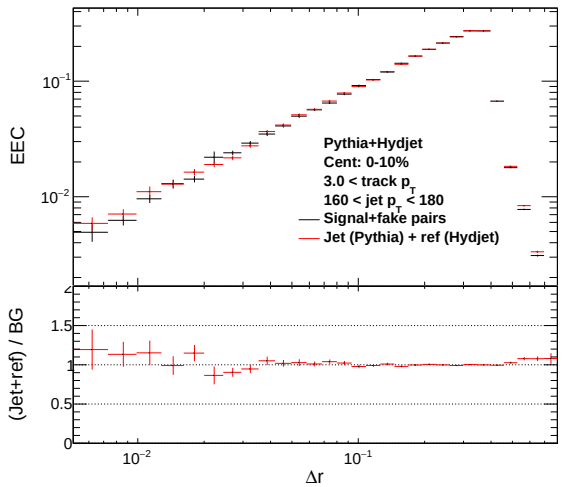
Fake+fake background estimation with reflected η cone

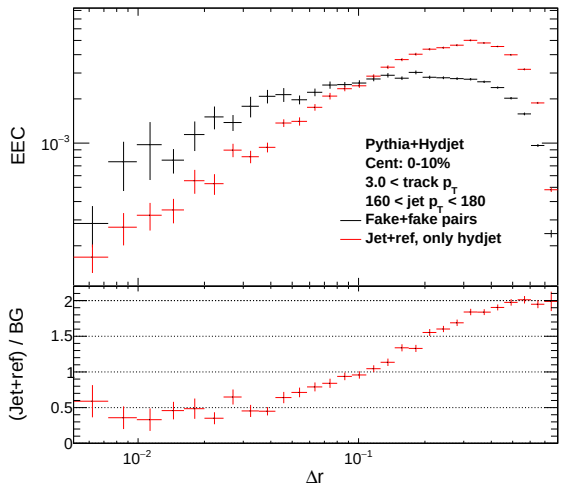


- Pairing background particles from jet cone with reflected cone does not reproduce fake+fake contribution. Missing local correlations

Overall performance of reflected η cone





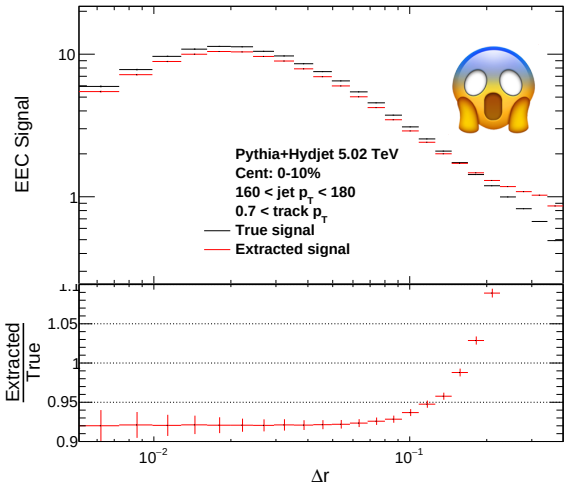


- Left: pairing reflected cone particles reproduces fake+fake contribution within signal cone
- Middle: pairing signal particles from jet cone with reflected cone particles reproduces signal+fake contribution
- Right: pairing background particles from jet cone with reflected cone does not reproduce fake+fake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

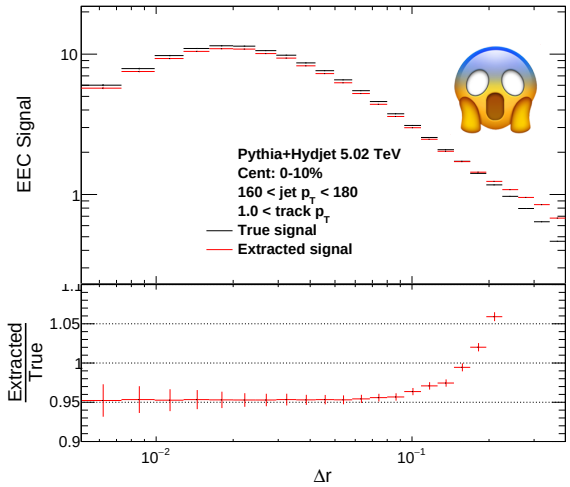
$\Rightarrow$ Restrict analysis to region where fake+fake contribution is small

Determine region of validity for reflected η cone

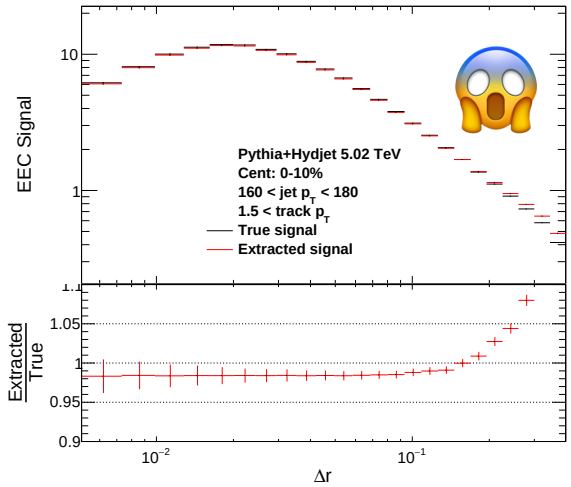
track $p_{\mathrm{T}} > 0.7$ GeV



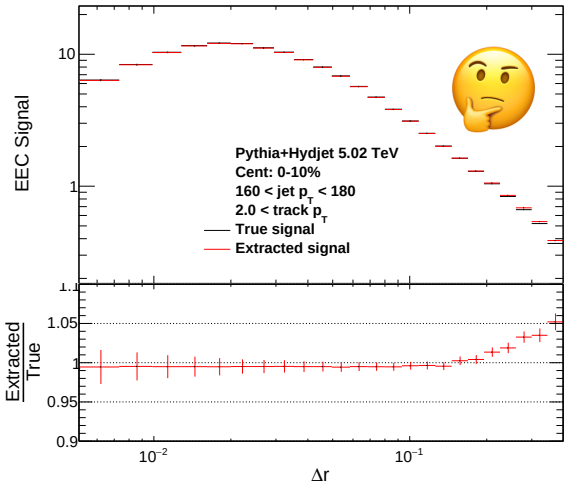
track $p_{\mathrm{T}} > 1$ GeV



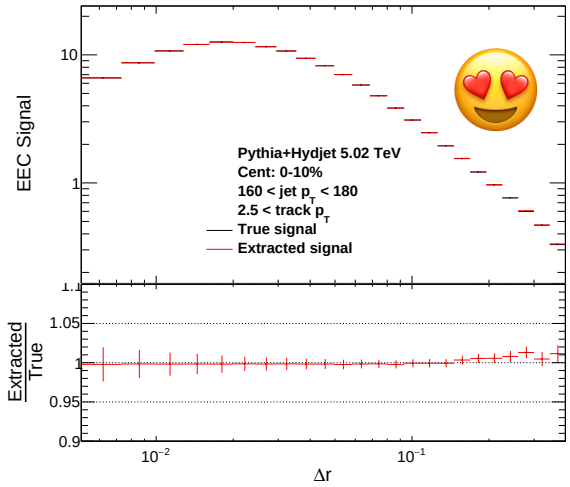
track $p_{\mathrm{T}} > 1.5$ GeV



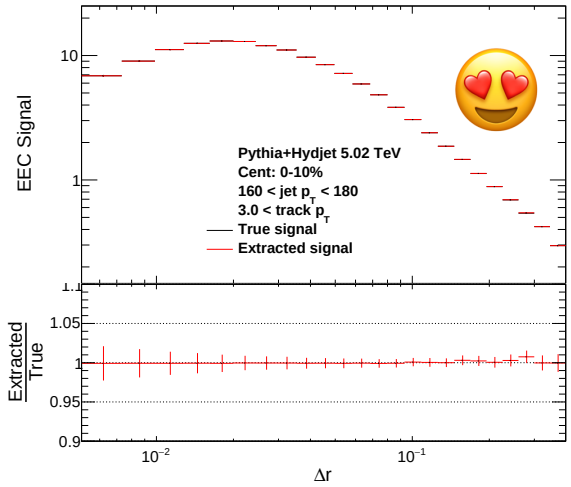
track $p_{\mathrm{T}} > 2$ GeV



track $p_{\mathrm{T}} > 2.5$ GeV



track $p_{\mathrm{T}} > 3$ GeV



- Better than 5% closure at $p_{\mathrm{T}} > 2$ GeV and 1% at $p_{\mathrm{T}} > 2.5$ GeV