# Study of energy-energy correlator of jets in PbPb collisions at CMS

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for the CMS Collaboration

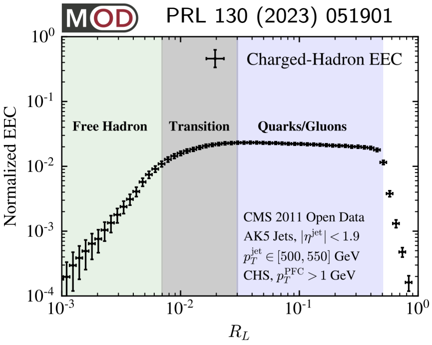
Hard Probes 2024

# Energy-energy correlator definition

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

- $\epsilon(\vec{n})$ = Energy flow to direction $\vec{n}$
- $Q^2$ = Hard scale of the process
- $\delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$ = Require angle $\theta$ between direction vectors

Komiske, Moult, Thaler, Zhu




- Reasons to love energy correlators:
  - Scaling: Different time scales of jet evolution imprinted in different angular scales
  - Simplicity: No jet declustering needed, can be constructed using tracks
  - Control: Well understood pp baseline, medium modifications perturbatively calculable

# Color coherence

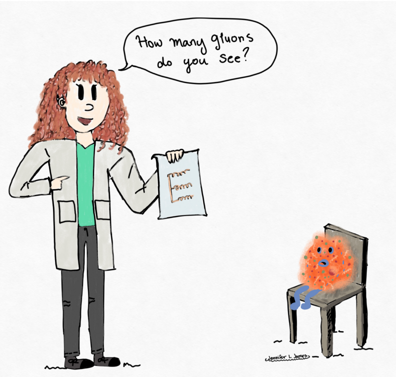
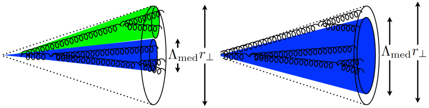



Image credit: Jennifer James (Vanderbilt)

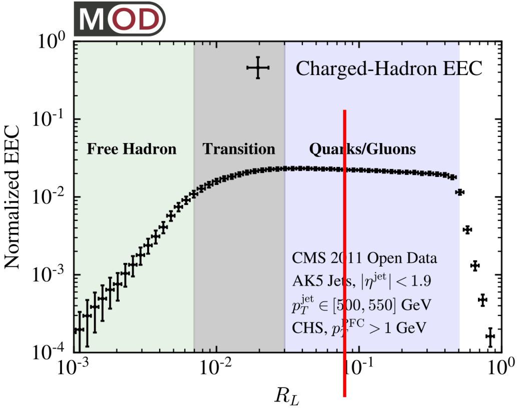
Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk

PLB 725 (2013) 357-360

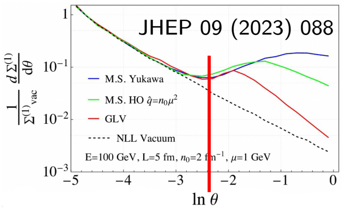



- Large angle emission: medium resolves emitted gluon as separate object
- Small angle emission: emitted gluon and emitter resolved as single object
- Critical angle: minimum separation where medium resolves separate objects

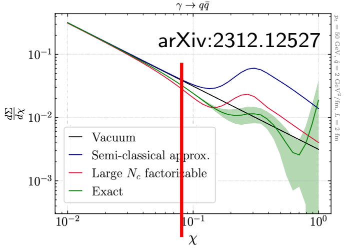
# Color coherence effects to the correlator shape




Andrés, Dominguez, Holguin, Marquet, Moult




Barata, Caucal, Soto-Ontoso, Szafron

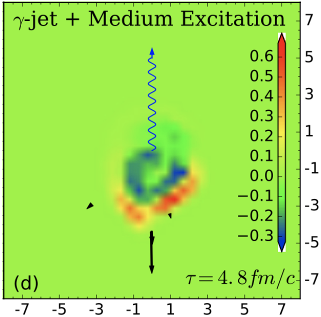



- Color coherence effects expected to change the shape at $\theta \gtrsim 0.08$

## Jet wake

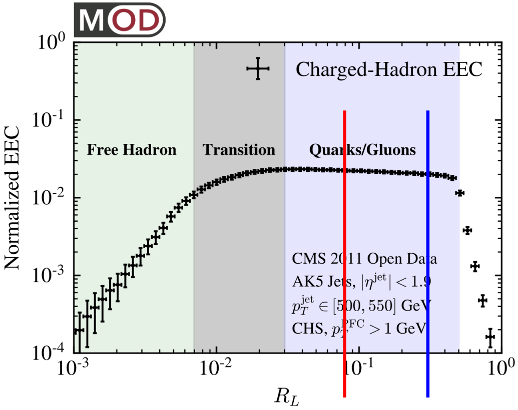
Image stolen from: Yen-Jie Lee (MIT)

Chen, Cao, Luo, Pang, Wang
PLB 777 (2018) 86



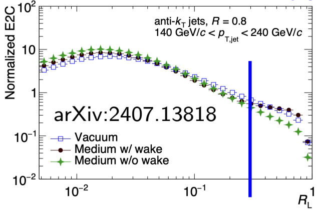

- Energetic parton pulls medium with it, leaving depletion behind

# Jet wake effects to the correlator shape

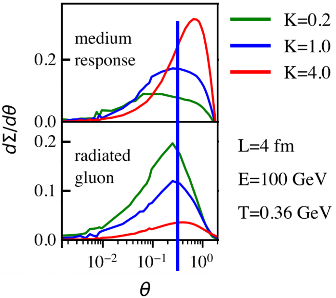



- Jet wake effects expected to change the shape at $\theta \gtrsim 0.3$

Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal




Yang, He, Moult, Wang



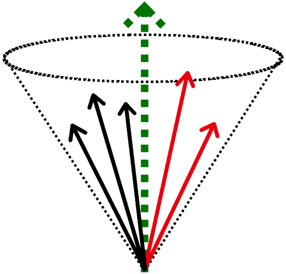

PRL 132 (2024) 1, 011901

# Energy-energy correlator definition for this analysis

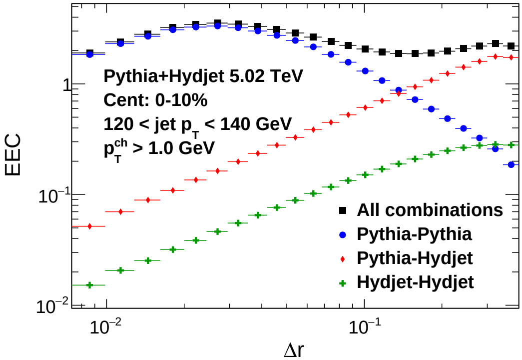
$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\theta} = \int \mathrm{d}\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$$

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

- Normalize with weighted number of pairs $W_{\mathrm{pairs}}$
- Bin width normalization: $\delta r = \Delta r_b - \Delta r_a$
- Hard scale appears only in jet $p_{\mathrm{T}}$ binning
  - Improves resolution, no need for unfolding
- Exponent values $n = 1$ and $n = 2$ used in this analysis
- Selects pairs within $R = 0.4$ from winner-take-all jet axis



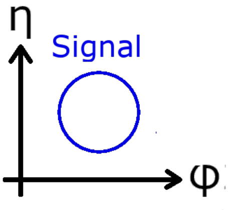
# Expected background in PbPb collisions

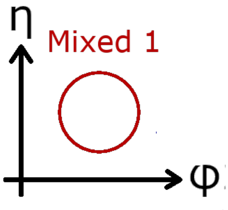


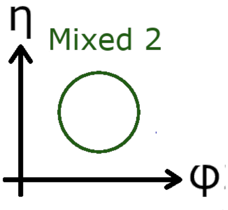

- Different pairings in the simulation
  - All pairs
  - Signal+signal pairs
  - Signal+background pairs
  - Background+background pairs
- Background contributions dominant at large $\Delta r$
- Background subtraction needed

The good  The bad  The ugly 

# Mixed event background subtraction method

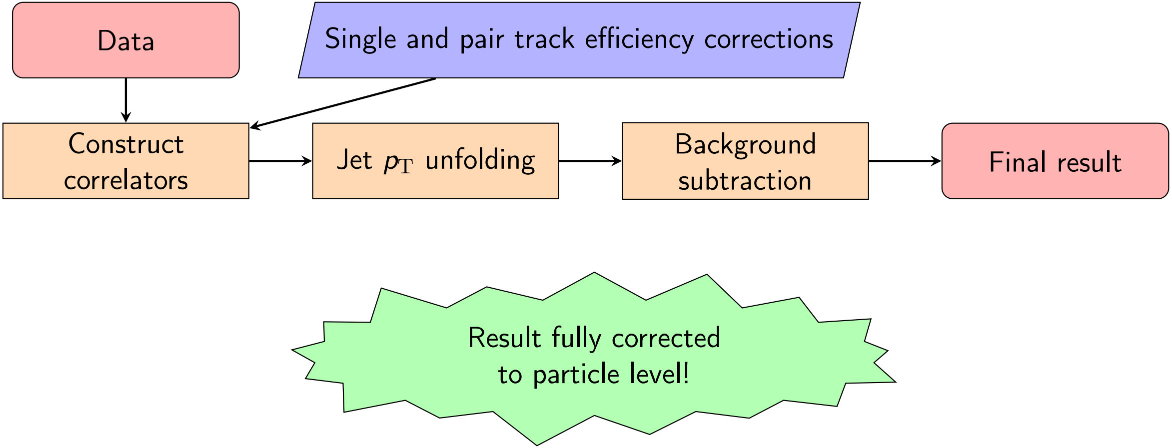


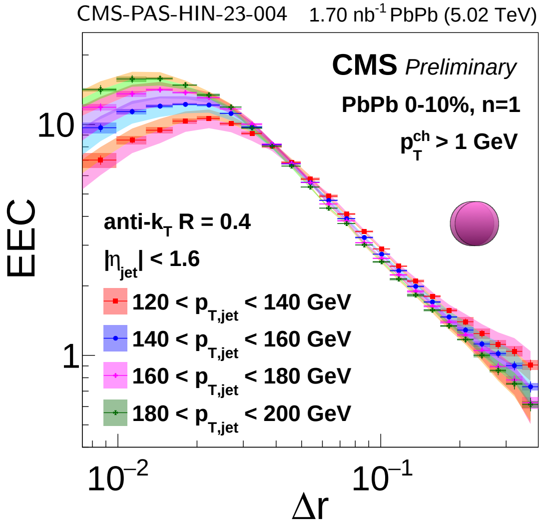




- Three cones are used in this method
  1. Signal cone: this is around the studied jet
  2. Mixed cone 1: same location as jet cone in minimum bias event
  3. Mixed cone 2: same location as jet cone in another minimum bias event
- Three different pairings are made from the cones
  1. $\mathrm{S} + \mathrm{M1}$: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

# Jet $p_T$ unfolding and tracking corrections

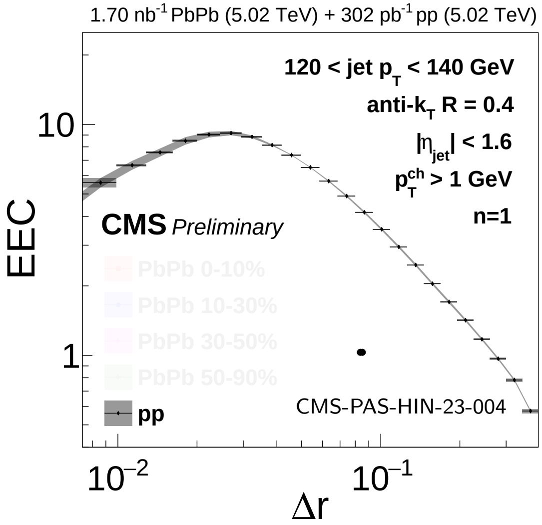


# Final results: energy-energy correlator distributions, PbPb 0-10%




- PbPb distributions have the same features as previously seen in pp!
  - CMS: PRL 133 (2024) 071903
  - STAR: PoS HP2023 (2024) 175
  - ALICE: ALI-PREL-540213
- Low $\Delta r \rightarrow$ free hadrons
- Moderate $\Delta r \rightarrow$ transition
- High $\Delta r \rightarrow$ free quark/gluon
- Peak depends on jet $p_{\mathrm{T}}$

# Medium modifications in energy-energy correlators




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

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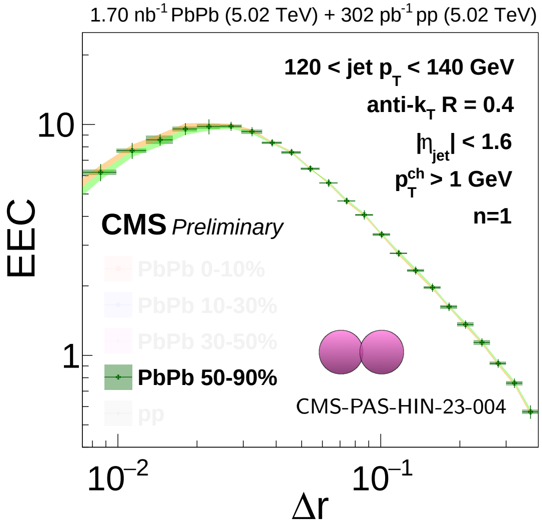


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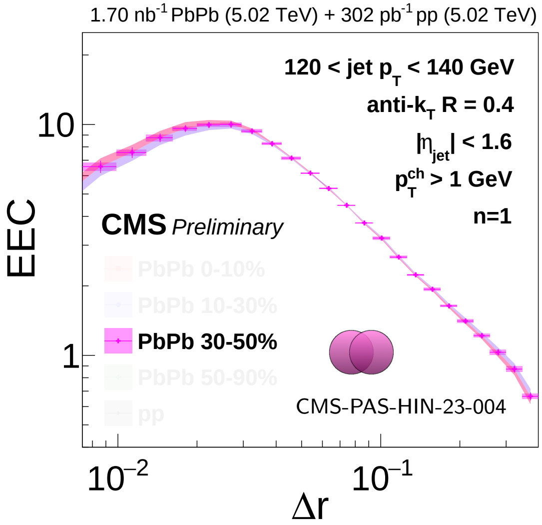


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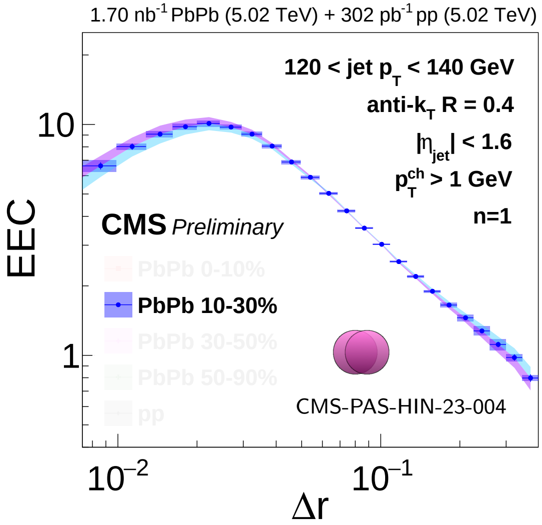


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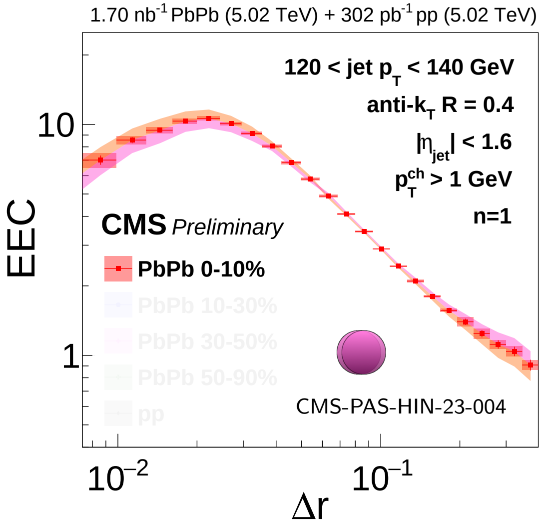


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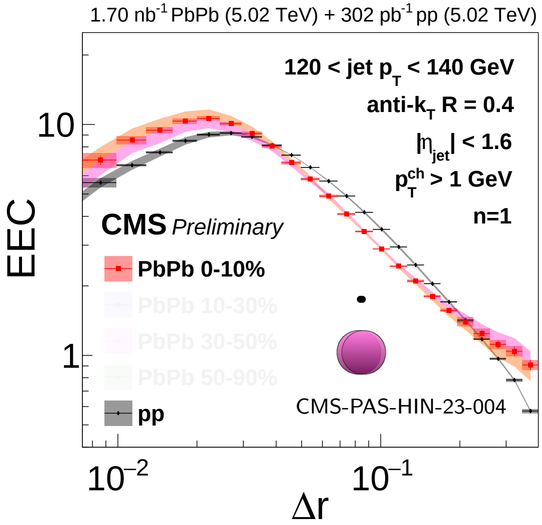
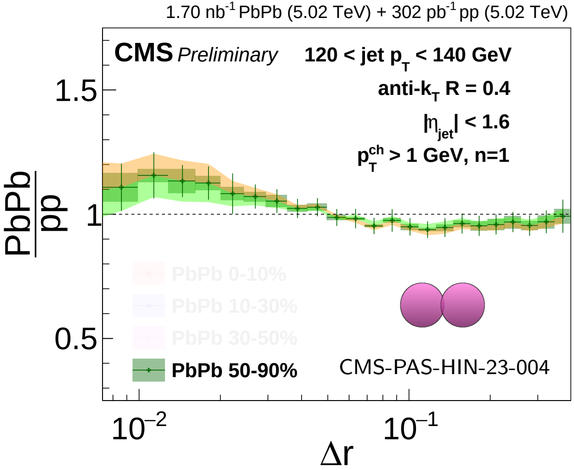



- The jet peak moves towards smaller $\Delta r$ when going to more central collisions
- Effect from energy loss $\rightarrow$ more central jets have higher initial virtuality
- Also the shape of the distribution at large $\Delta r$ is modified!

# PbPb to pp ratio, centrality evolution




- Peripheral distribution shows only small modifications

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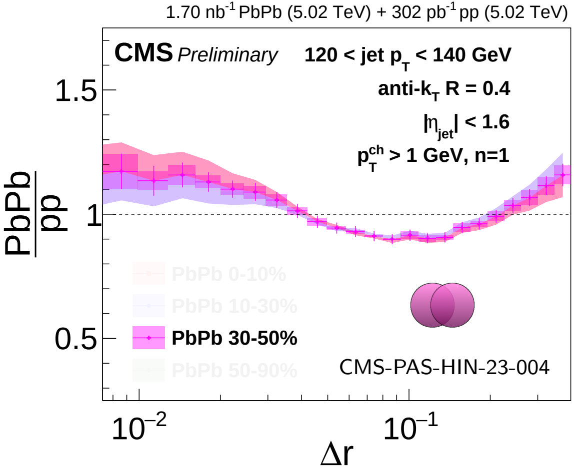


- Peripheral distribution shows only small modifications
- Enhancement at low $\Delta r$ due to energy loss

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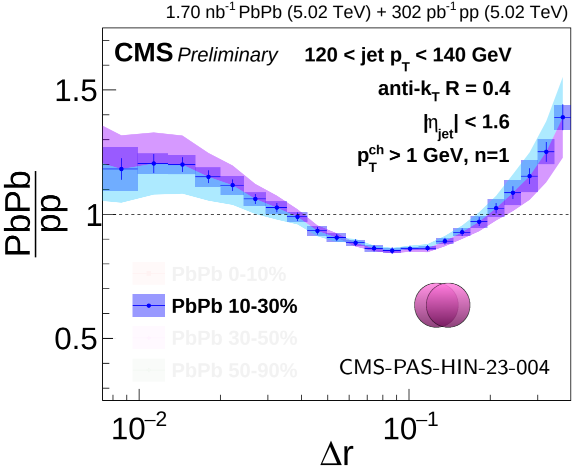


- Peripheral distribution shows only small modifications
- Enhancement at low $\Delta r$ due to energy loss
- Change in trend around $\Delta r \sim 0.1$ to enhancement at large $\Delta r$

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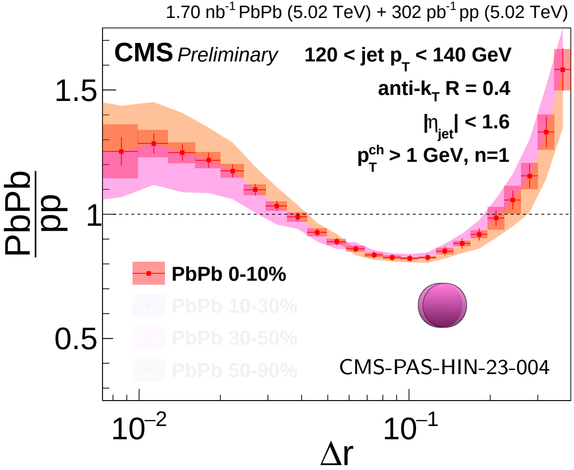
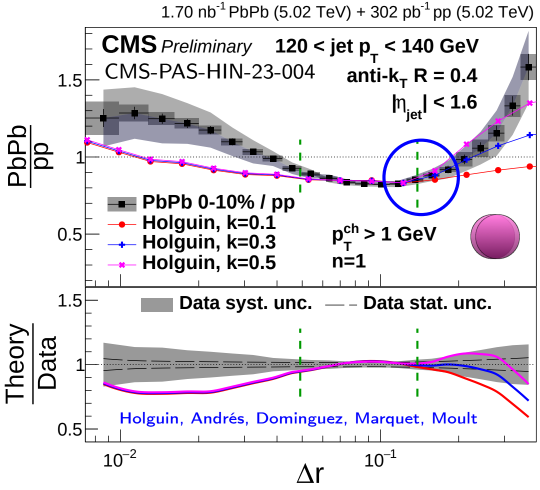



- Peripheral distribution shows only small modifications
- Enhancement at low $\Delta r$ due to energy loss
- Change in trend around $\Delta r \sim 0.1$ to enhancement at large $\Delta r$
- Flat trend at few lowest $\Delta r$ bins → universal scaling for free hadrons

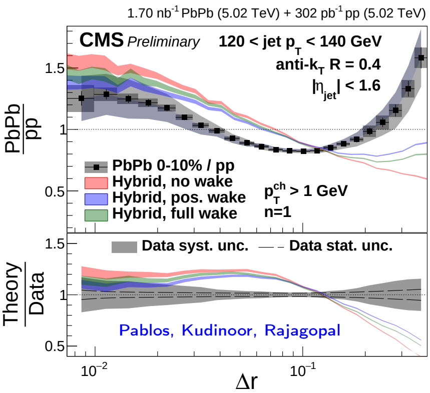
# Perturbative calculation with color coherence effects



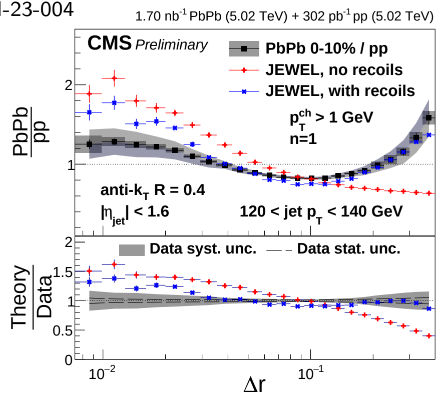

- Perturbative calculation by Holguin&co[1] includes color coherence
- Two free parameters: $k$ and normalization
- Calculation normalized to data in region $0.042 < \Delta r < 0.126$
- Turn-on angle is similar in calculation and data

[1] arXiv:2407.07936

# Jet wake in the Hybrid model and JEWEL




CMS-PAS-HIN-23-004

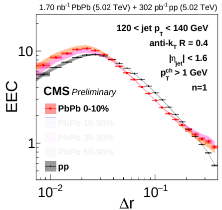


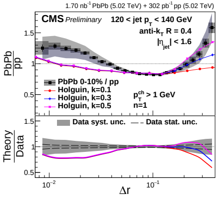

- Both Hybrid model[2] and JEWEL[3] only predict large $\Delta r$ enhancement with wake included
- Models show different magnitudes of enhancement and turn-on angles

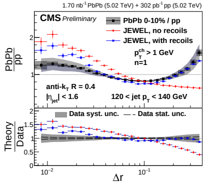
[2] JHEP 09 (2015) 175, JHEP 03 (2017) 135 [3] EPJC 60 (2009) 617, JHEP 1707 (2017) 141

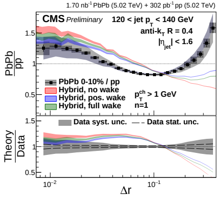
# Summary

- EEC measured for the first time ever in heavy ion collisions!
- Free hadron, transition, and free quark/gluon regions visible in PbPb EECs
- Energy loss moves the peak in PbPb to smaller $\Delta r$
- Interesting modifications are seen at large $\Delta r$ region
- Models with jet wake and color coherence show qualitatively similar behavior as data




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

# Back-up

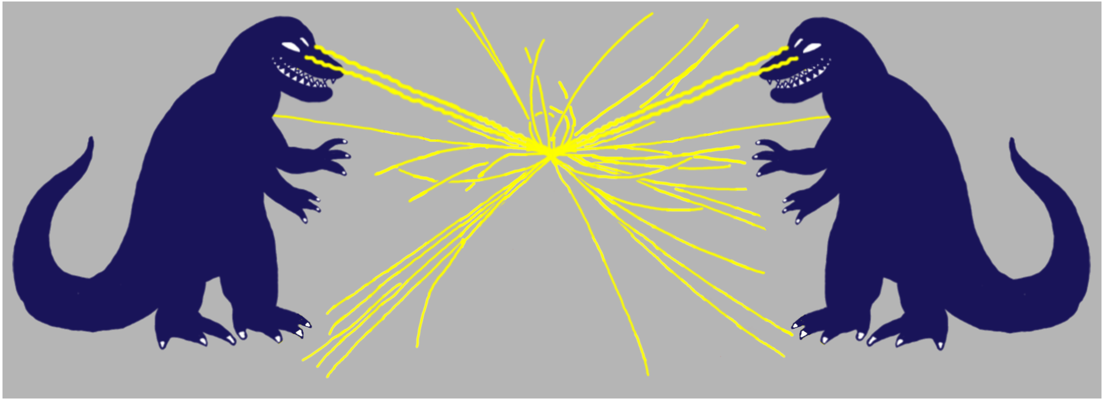
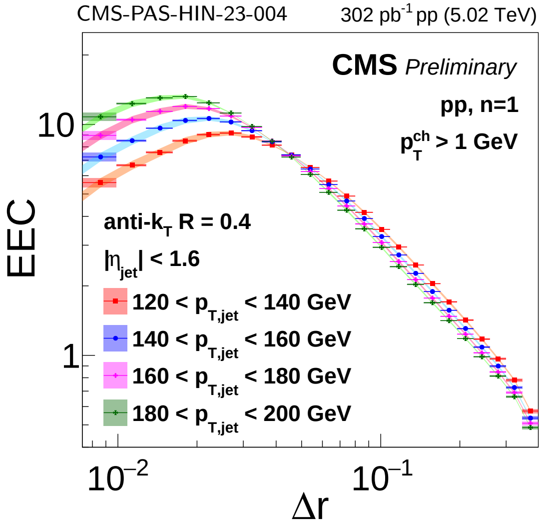


Image credit: BOOST 2022 conference logo

# Energy-energy correlator distributions, pp

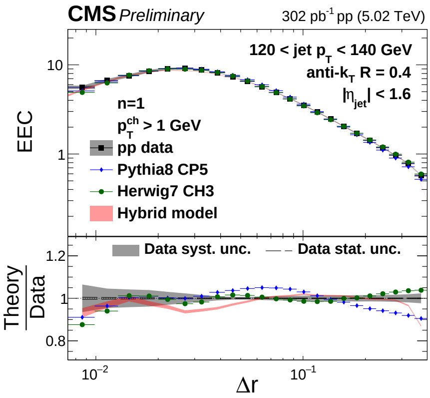


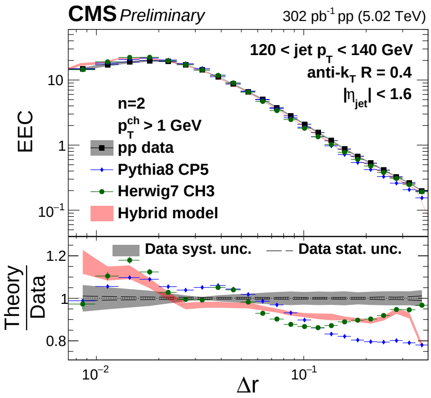

- pp results have consistent features with previous measurements
  - CMS: PRL 133 (2024) 071903
  - STAR: PoS HP2023 (2024) 175
  - ALICE: ALI-PREL-540213
- Low $\Delta r \rightarrow$ free hadrons
- Moderate $\Delta r \rightarrow$ transition
- High $\Delta r \rightarrow$ free quark/gluon
- Peak depends on jet $p_{\mathrm{T}}$

# Model comparisons with pp distribution

CMS-PAS-HIN-23-004

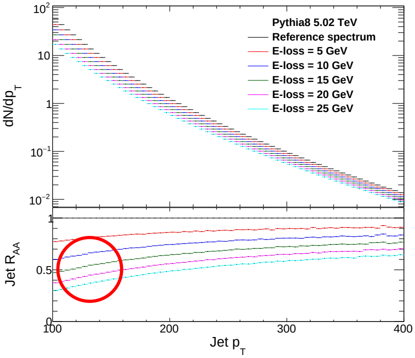
$n = 1$ | $n = 2$



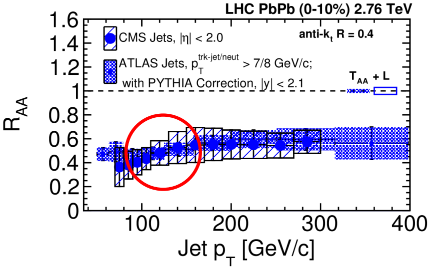




- Hybrid vacuum = Pythia8 with MPI off
- Models agree with pp data within $\sim 5\%$ for $n = 1$, but too narrow shape for $n = 2$

# Simple energy loss model: $p_{\mathrm{T}}$ spectrum shift in Pythia8

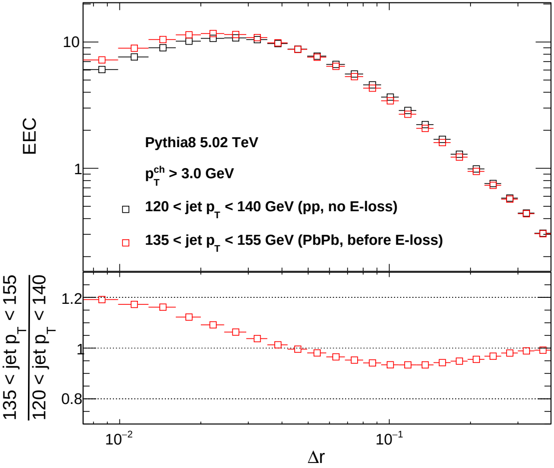



ATLAS: PRL 114 (2015) 072302
CMS: PRC 96 (2017) 015202




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

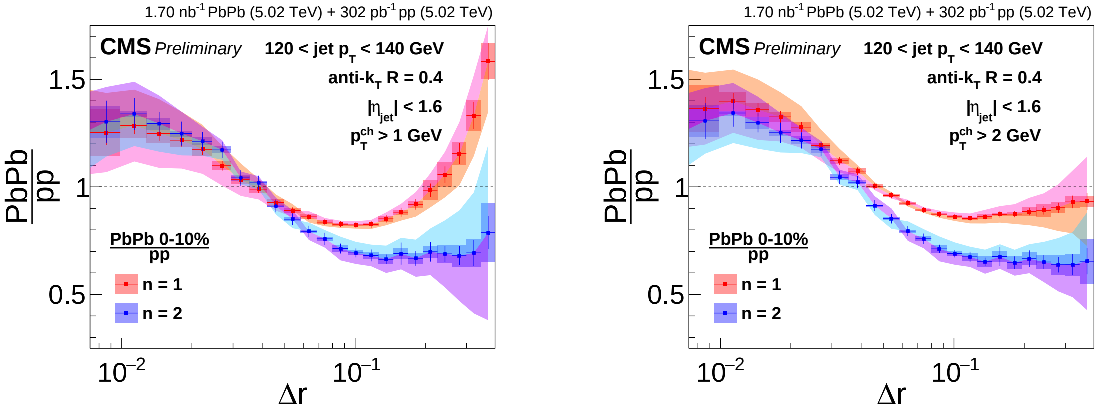
# Medium effects: jet $p_{\mathrm{T}}$ spectrum shift




- Enhancement seen at low $\Delta r$ due to shift of the peak position
- If energy loss is just spectrum shift, it does not produce enhancement at large $\Delta r$

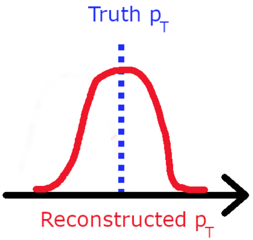
# PbPb to pp ratio and kinematic cuts

$p_T^{ch} > 1$ GeV CMS-PAS-HIN-23-004 $p_T^{ch} > 2$ GeV



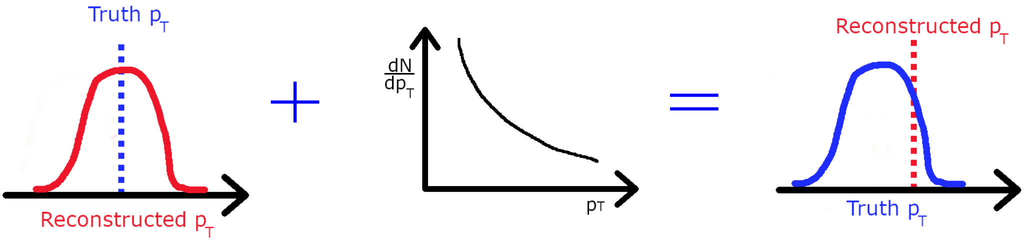

- Sensitivity to low $p_T$ particles essential for large $\Delta r$ enhancement!

# Jet resolution effects and unfolding



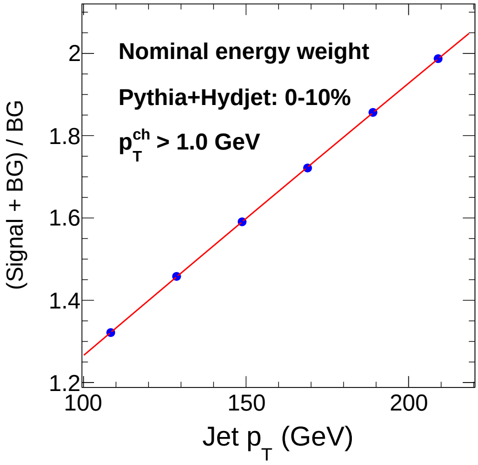

- Jet energy corrections are derived such that for each truth $p_{\mathrm{T}}$, the most likely reconstructed $p_{\mathrm{T}}$ matches

# Jet resolution effects and unfolding



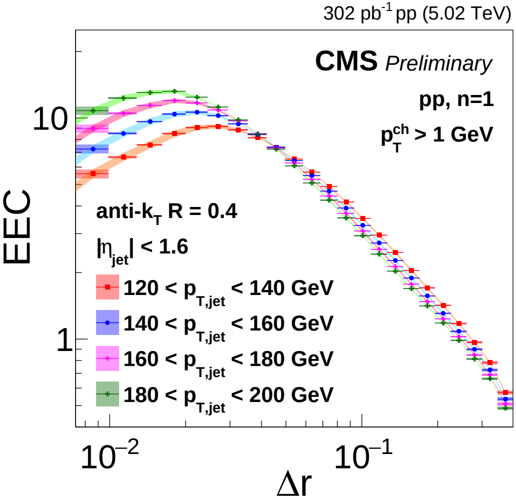

- Jet energy corrections are derived such that for each truth $p_\mathrm{T}$, the most likely reconstructed $p_\mathrm{T}$ matches
- Steeply falling spectrum $\rightarrow$ for given reconstructed $p_\mathrm{T}$, the most likely truth $p_\mathrm{T}$ is shifted down
- Unfolding corrects for this by effectively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

# Signal-to-background ratio in Pythia+Hydjet



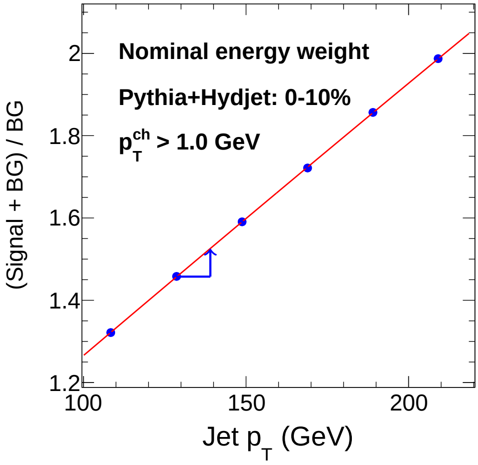

- Signal-to-background ratio depends on jet $p_{\mathrm{T}}$
- Background needs to be scaled to take into account the mean jet $p_{\mathrm{T}}$ shift from unfolding
- This can be done in fully data driven way

# The shift in peak position during unfolding




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

# 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

# Sources of systematic uncertainty

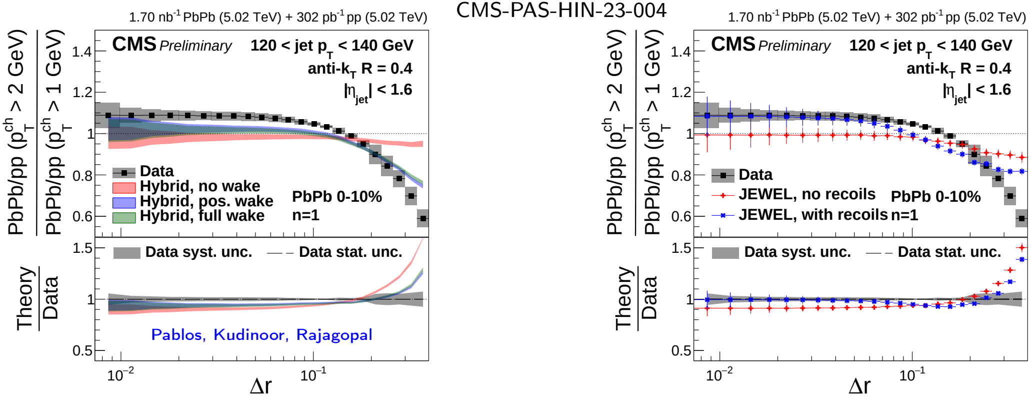
## Color coding for size of uncertainty

- Small, medium, large

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

# Hybrid model and JEWEL comparison for double ratio

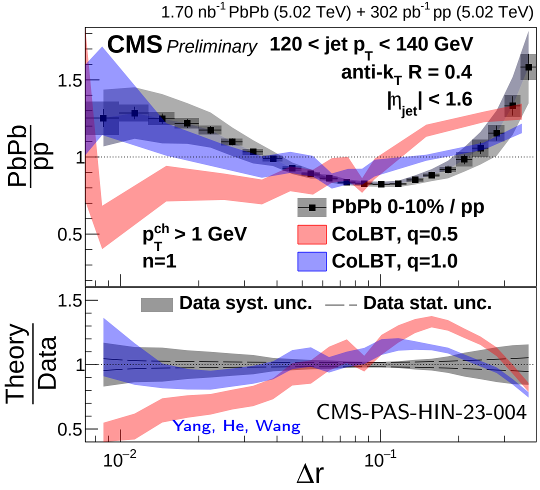
CMS-PAS-HIN-23-004




- Isolate the effects of soft-hard correlations with double ratio
- Interestingly, the Hybrid model is better in describing the double ratio at large $\Delta r$

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

# CoLBT model comparison for PbPb/pp ratio

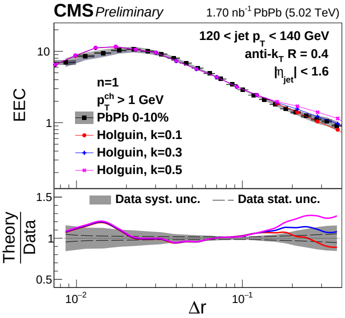



- q-parameter in CoLBT[1] model describes the minimum virtuality for vacuum splittings
- $q = 0.5$ doesn't describe the data well
- $q = 1$ is better, but earlier turn-on and less enhancement than in data
- Enhancement at large $\Delta r$ in CoLBT mainly coming from medium response
- There is also gluon radiation component

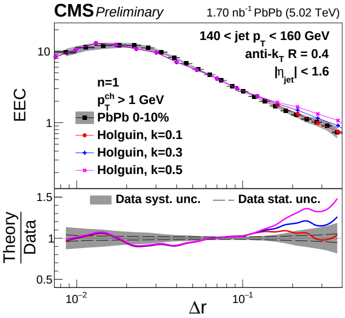
[1] PLB 777 (2018) 86, PLB 810 (2020) 135783, PRL 128 (2022) 2, 022302

# PbPb distribution, Holguin, 0-10%, $p_T^{ch} > 1$ GeV, $n = 1$

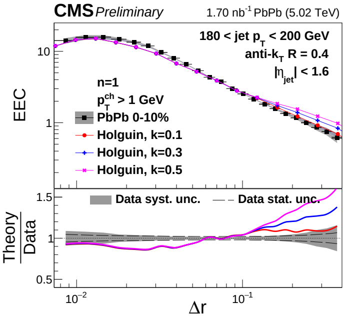
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Calculation by Holguin, Andrés, Dominguez, Marquet, Moult (arXiv:2407.07936)

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

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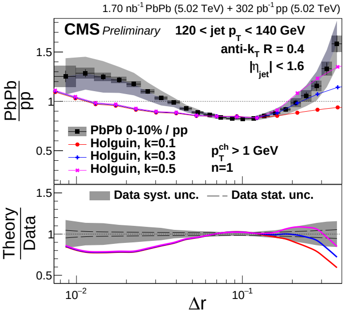
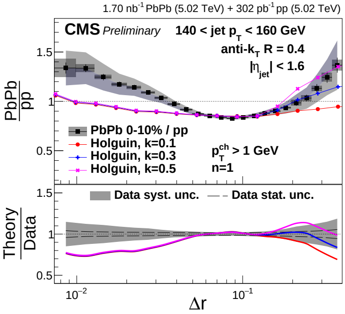
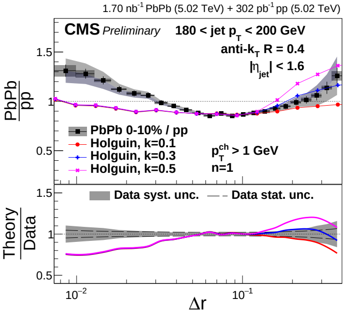



$140 < p_{\mathrm{T}}^{\mathrm{jet}} < 160$ GeV




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

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# PbPb distribution, Hybrid, 0-10%, $p_T^{ch} > 1$ GeV, $n = 1$

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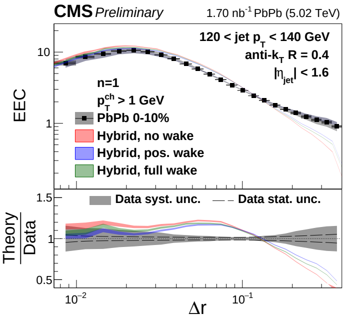
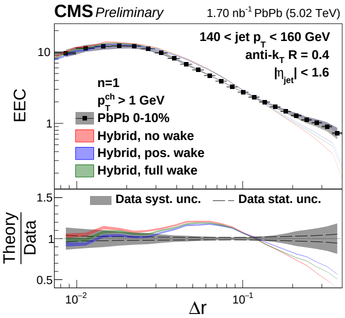
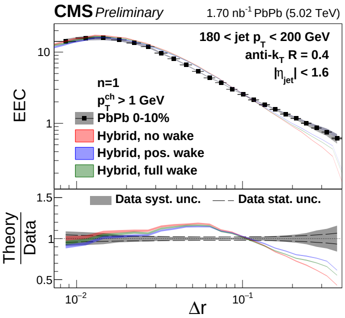



$140 < p_T^{jet} < 160$ GeV



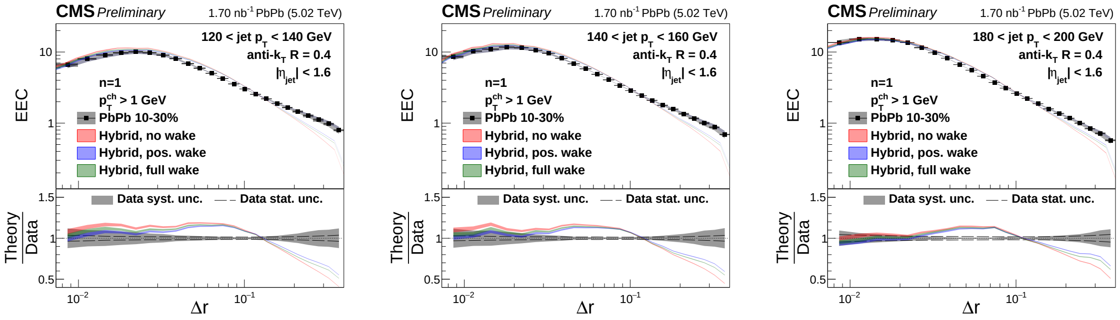

$180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV  $140 < p_{\mathrm{T}}^{\mathrm{jet}} < 160$ GeV  $180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV

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# PbPb distribution, Hybrid, 30-50%, $p_T^{ch} > 1$ GeV, $n = 1$

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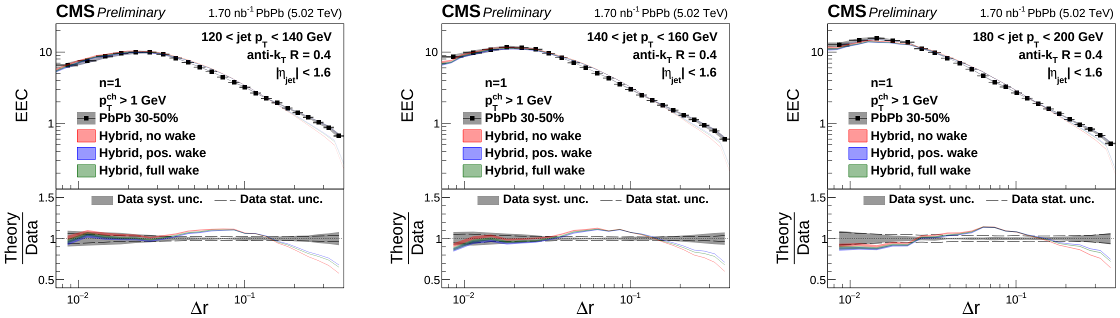


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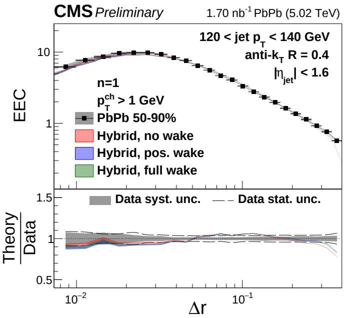
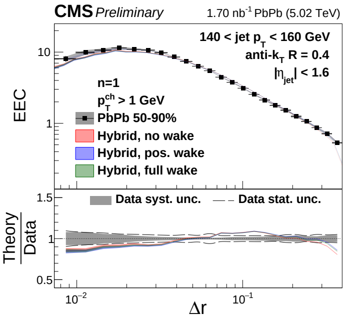
# PbPb distribution, Hybrid, 50-90%, $p_T^{ch} > 1$ GeV, $n = 1$

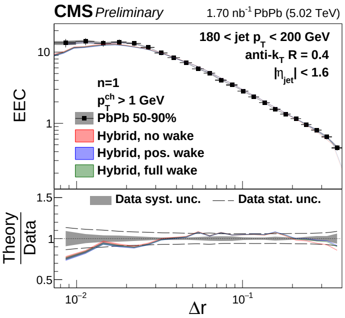
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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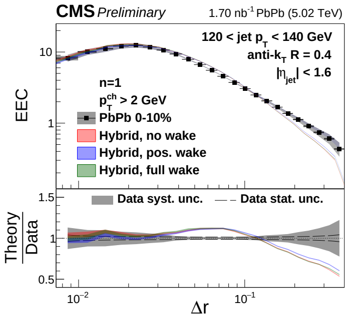
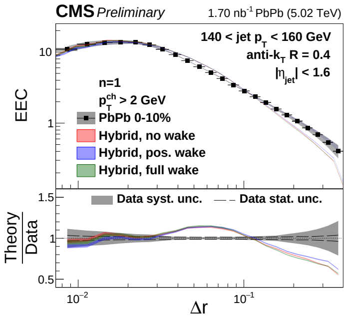
# PbPb distribution, Hybrid, 0-10%, $p_T^{ch} > 2$ GeV, $n = 1$

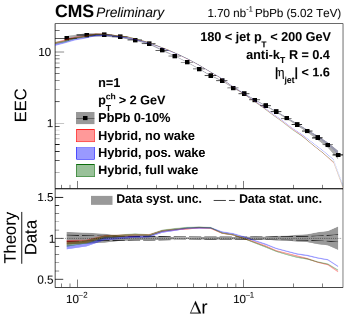
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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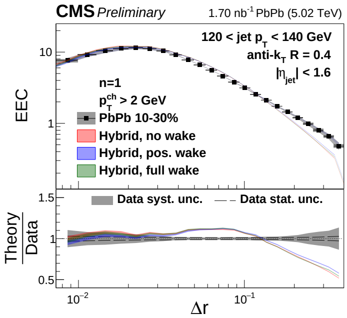
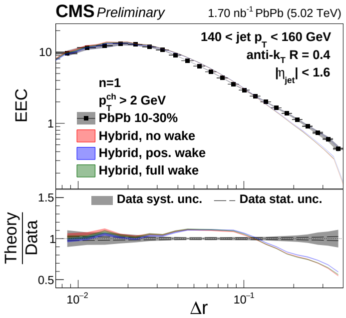
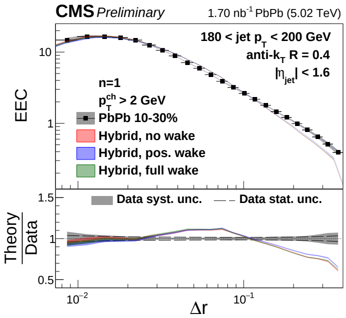



$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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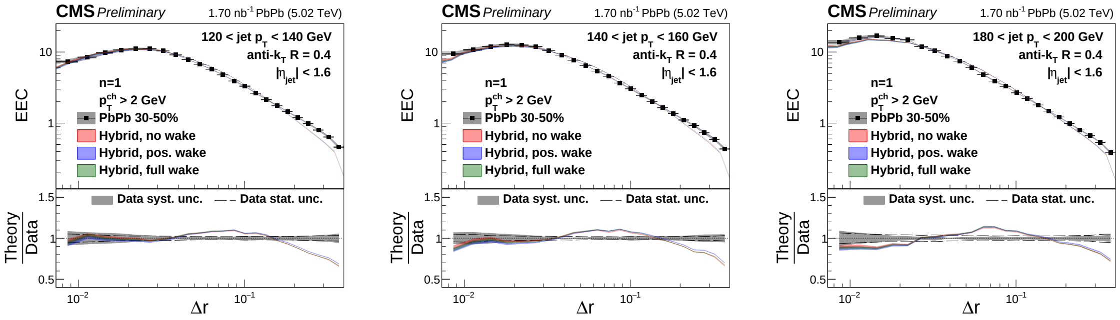
$120 < p_T^{jet} < 140$ GeV | $140 < p_T^{jet} < 160$ GeV | $180 < p_T^{jet} < 200$ GeV

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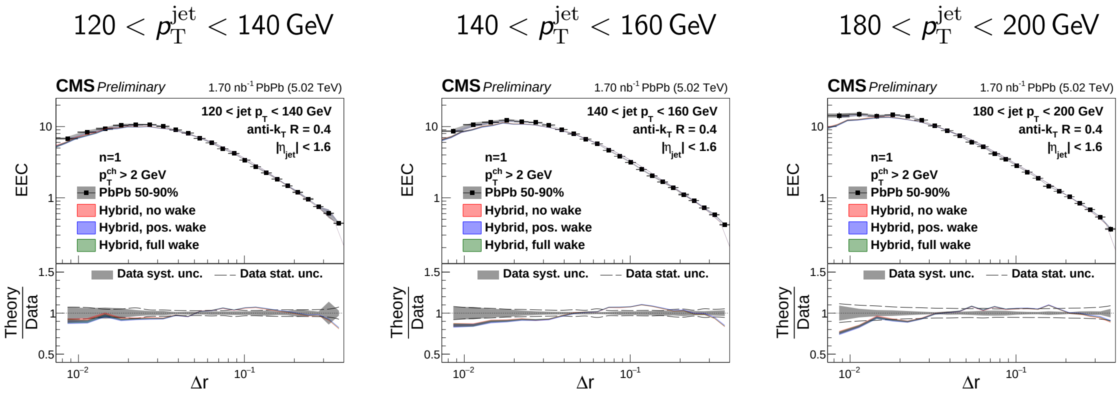


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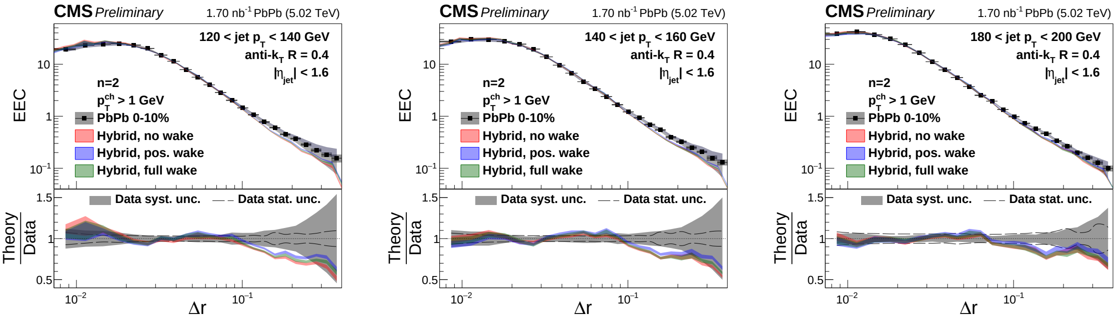
$120 < p_T^{jet} < 140$ GeV | $140 < p_T^{jet} < 160$ GeV | $180 < p_T^{jet} < 200$ GeV

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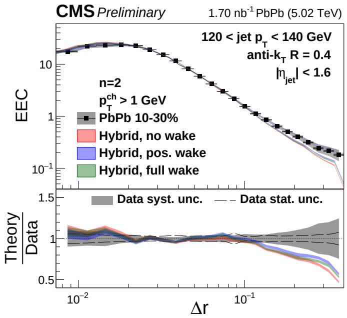


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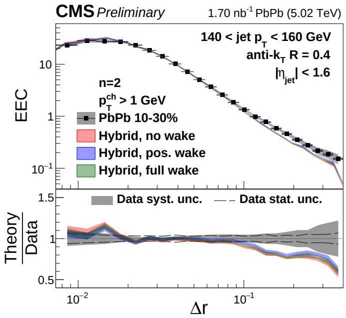


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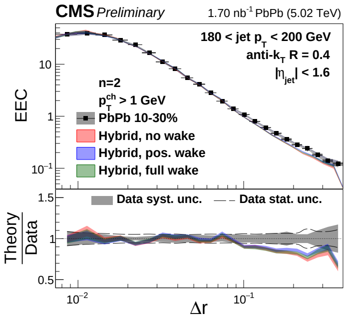


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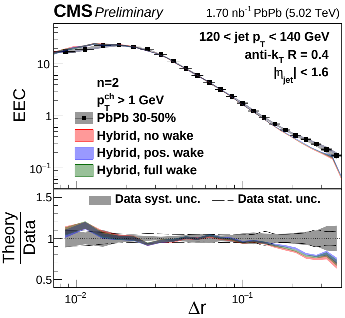


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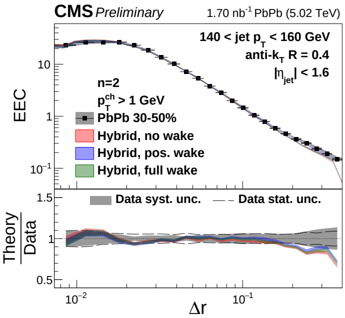


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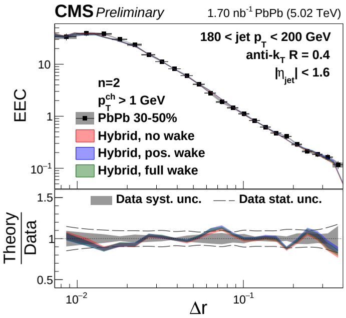


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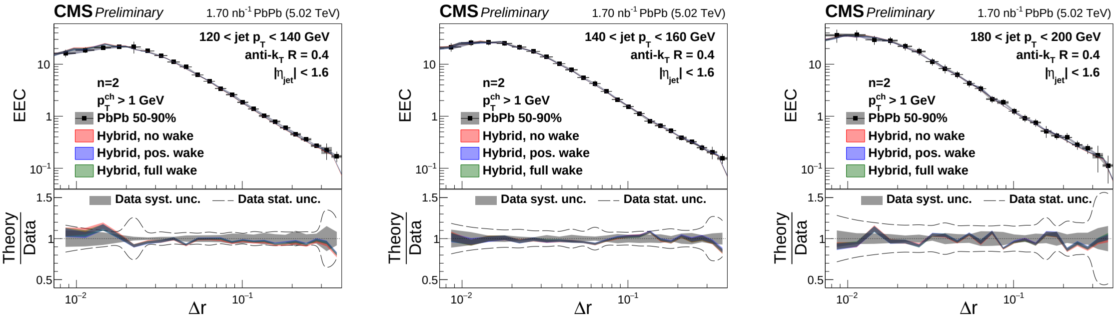


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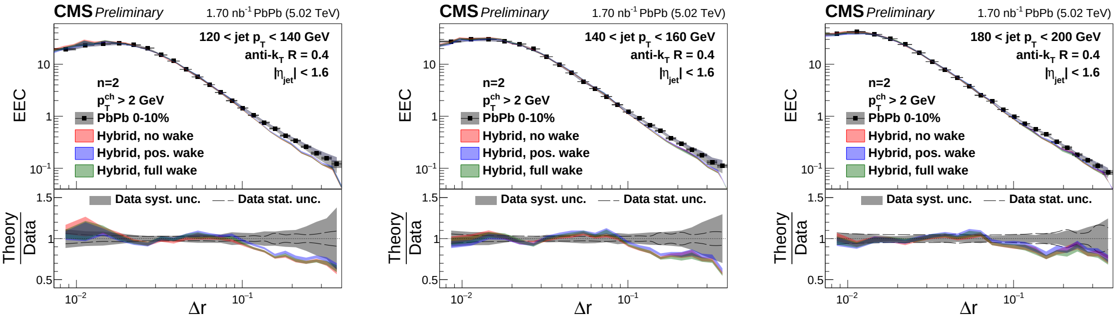


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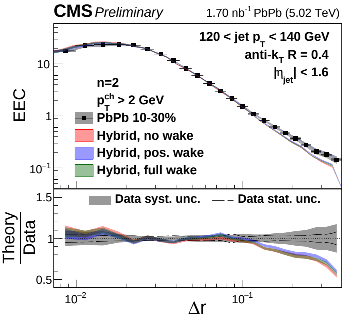
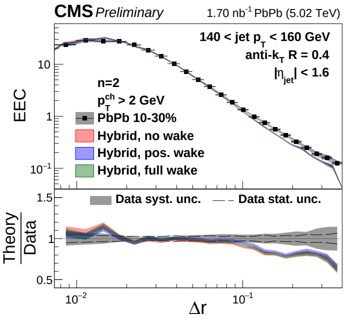
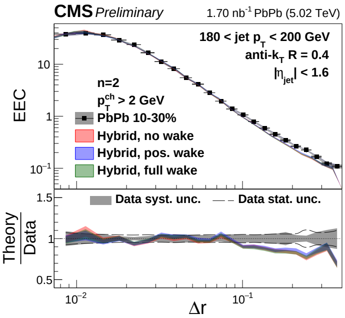



$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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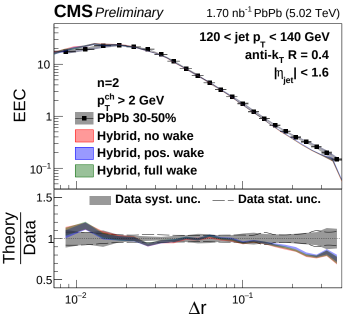


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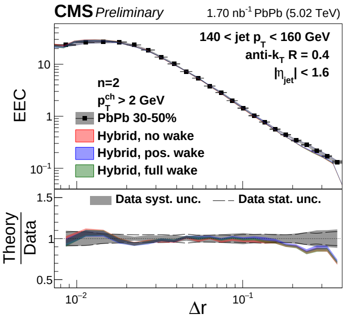
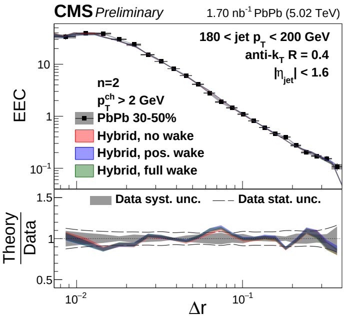



$180 < p_T^{jet} < 200$ GeV

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# PbPb distribution, Hybrid, 50-90%, $p_T^{ch} > 2$ GeV, $n = 2$

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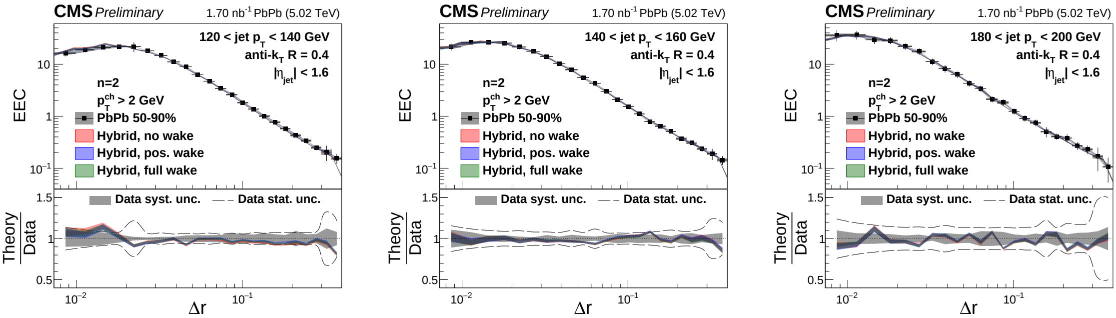


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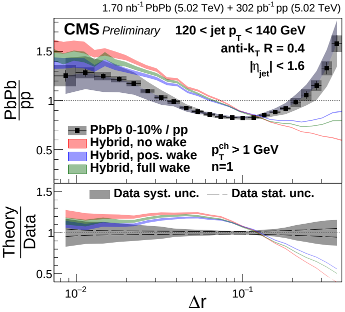
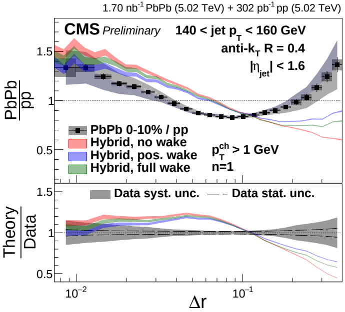
# PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1$ GeV, $n = 1$

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




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

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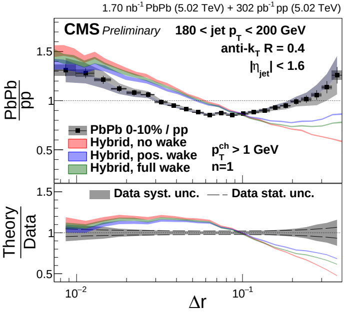


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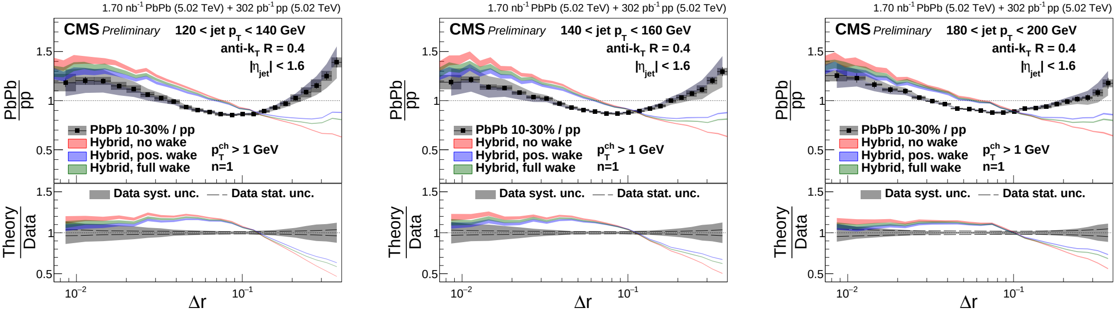
# PbPb to pp ratio, Hybrid, 10-30%, $p_T^{ch} > 1$ GeV, $n = 1$

$120 < p_T^{jet} < 140$ GeV — $140 < p_T^{jet} < 160$ GeV — $180 < p_T^{jet} < 200$ GeV

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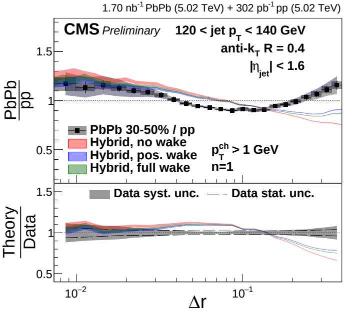
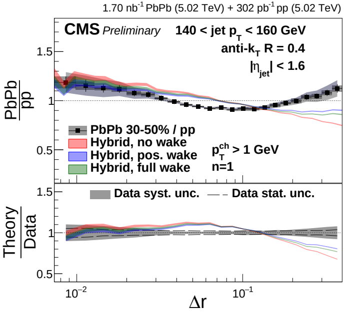
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 30-50%, $p_T^{ch} > 1$ GeV, $n = 1$

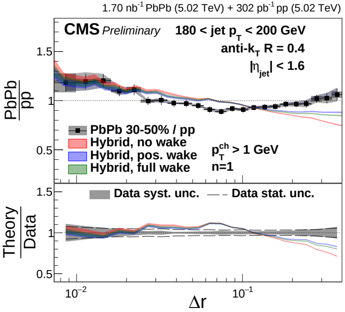
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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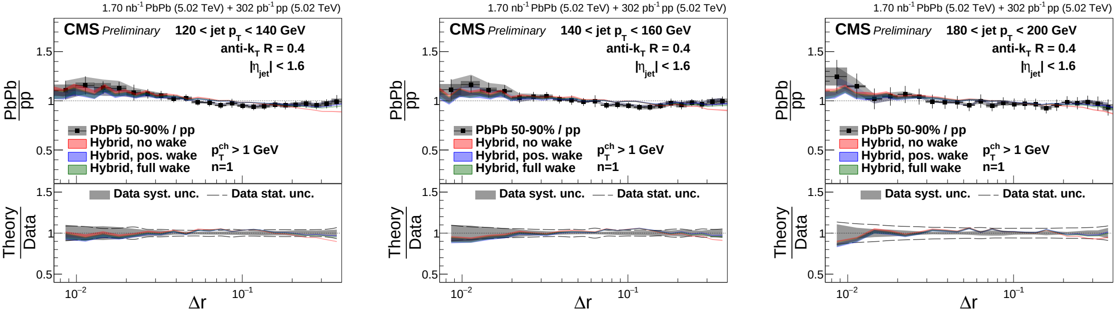
# PbPb to pp ratio, Hybrid, 50-90%, $p_{\mathrm{T}}^{\mathrm{ch}} > 1$ GeV, $n = 1$

$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV | $140 < p_{\mathrm{T}}^{\mathrm{jet}} < 160$ GeV | $180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
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# PbPb to pp ratio, Hybrid, 0-10%, $p_{\mathrm{T}}^{\mathrm{ch}} > 2$ GeV, $n = 1$

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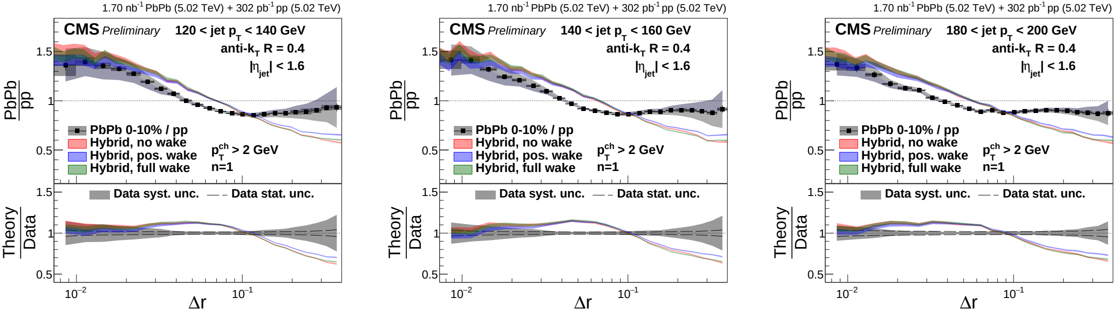


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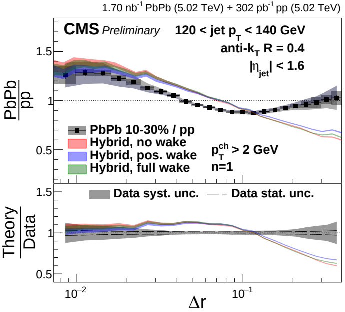


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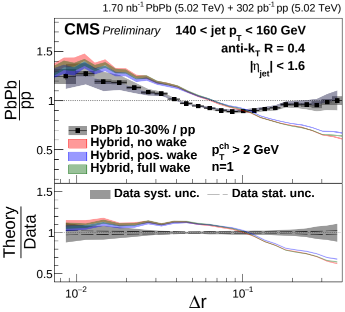
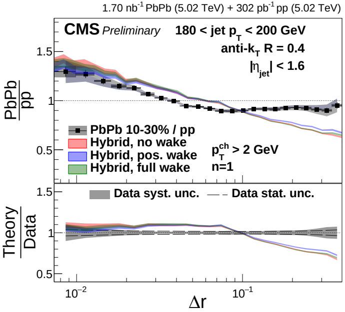


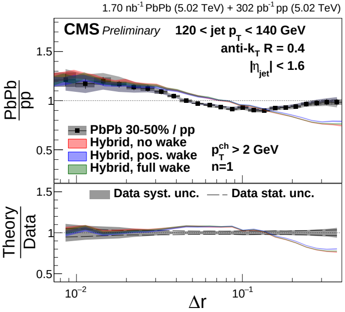

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV



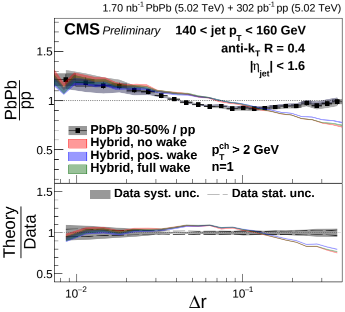

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

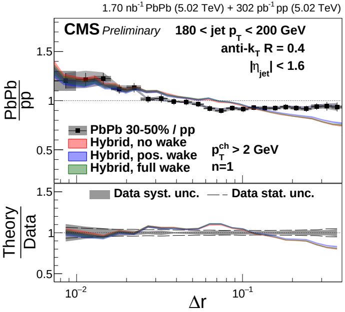
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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



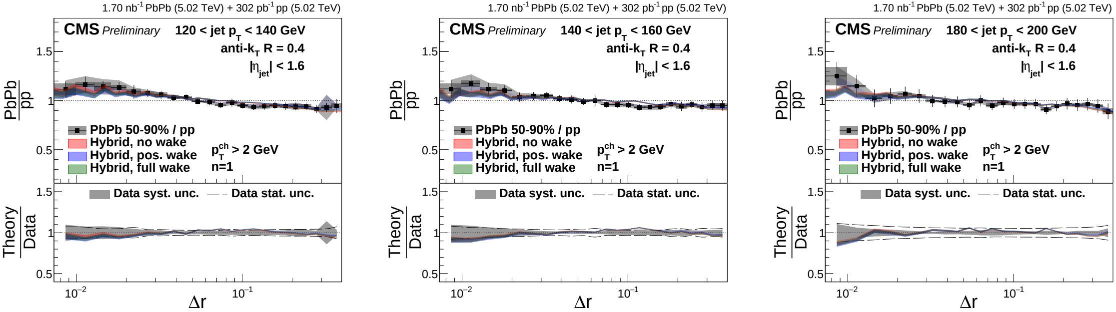

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 50-90%, $p_T^{ch} > 2$ GeV, $n = 1$

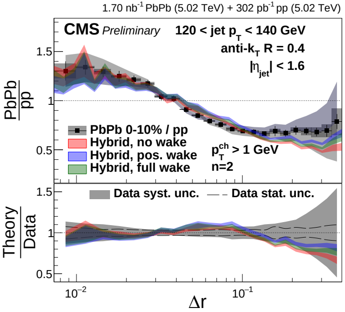
$120 < p_T^{jet} < 140$ GeV | $140 < p_T^{jet} < 160$ GeV | $180 < p_T^{jet} < 200$ GeV



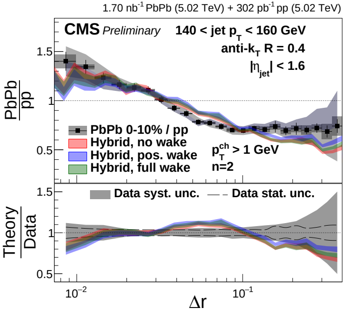

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

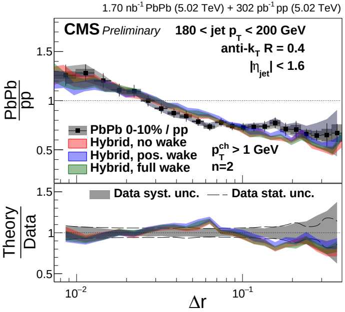
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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

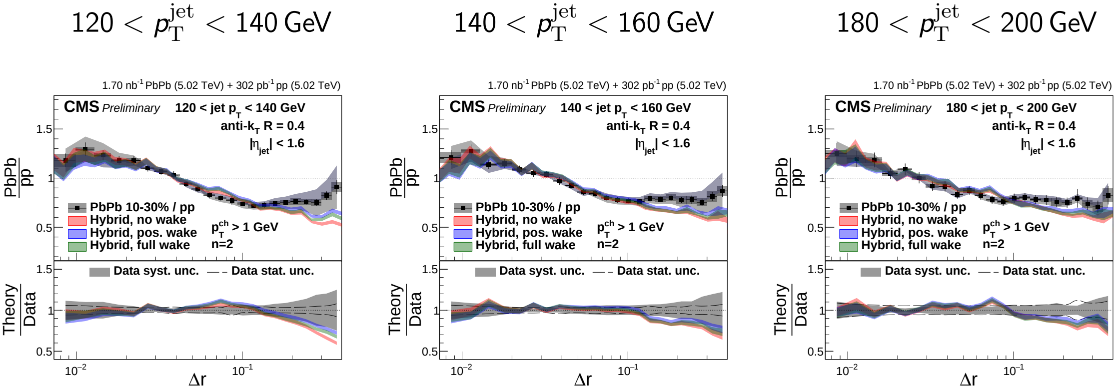



$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

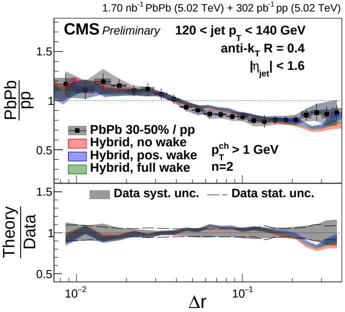
# PbPb to pp ratio, Hybrid, 10-30%, $p_T^{ch} > 1$ GeV, $n = 2$



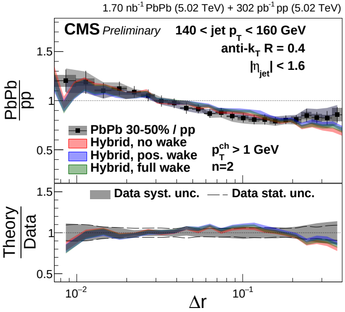

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 30-50%, $p_T^{ch} > 1$ GeV, $n = 2$

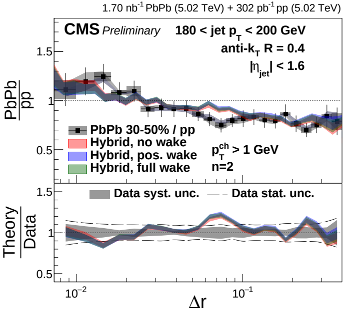
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



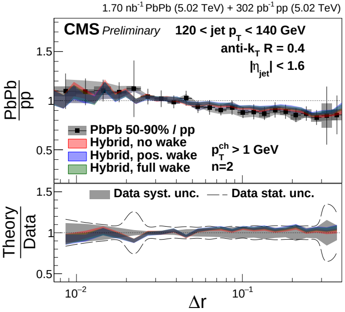

$180 < p_T^{jet} < 200$ GeV



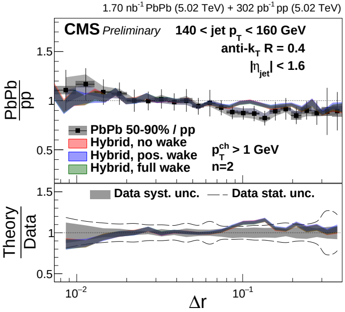

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 50-90%, $p_T^{ch} > 1$ GeV, $n = 2$

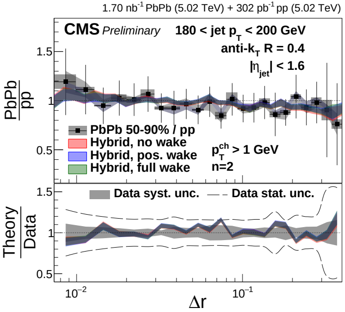
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



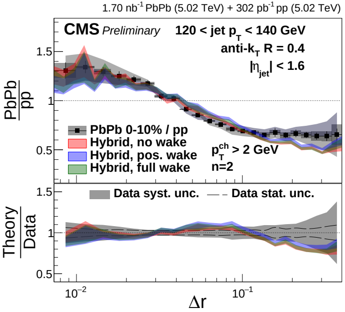

$180 < p_T^{jet} < 200$ GeV



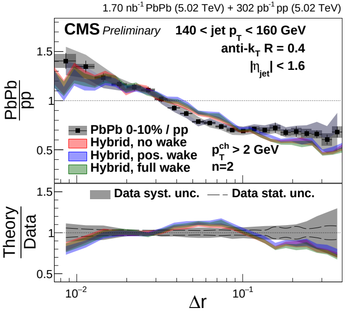

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

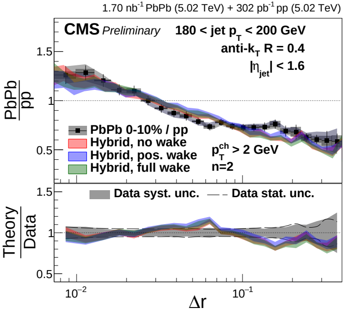
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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



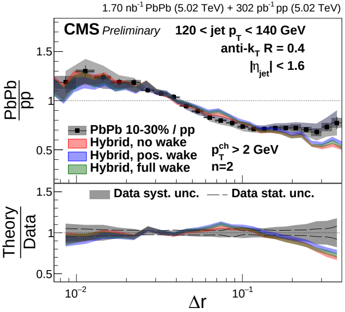

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV

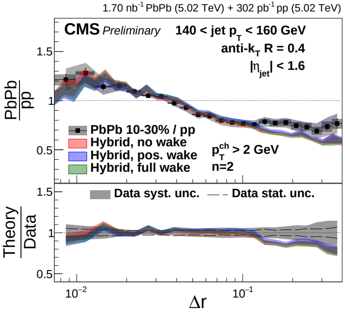


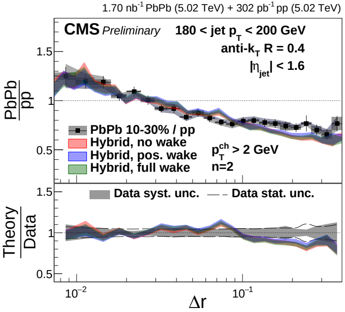

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 10-30%, $p_T^{ch} > 2$ GeV, $n = 2$

$120 < p_T^{jet} < 140$ GeV | $140 < p_T^{jet} < 160$ GeV | $180 < p_T^{jet} < 200$ GeV



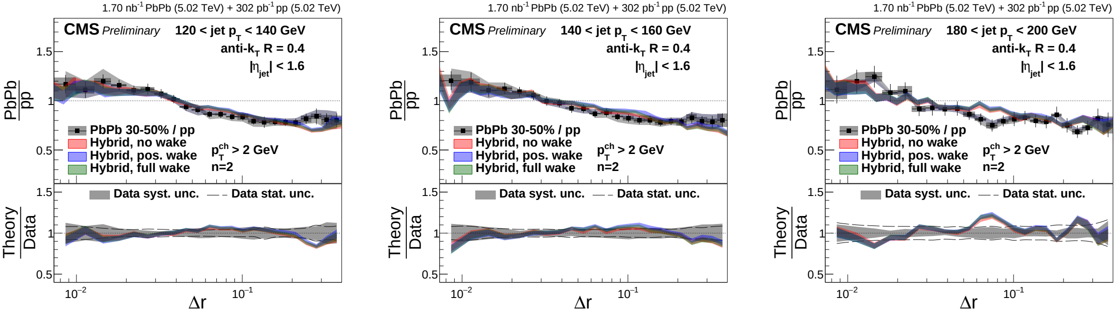




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 30-50%, $p_T^{ch} > 2$ GeV, $n = 2$

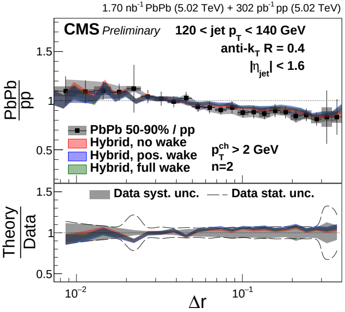
$120 < p_T^{jet} < 140$ GeV    $140 < p_T^{jet} < 160$ GeV    $180 < p_T^{jet} < 200$ GeV



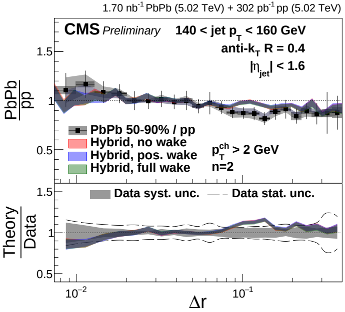

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

# PbPb to pp ratio, Hybrid, 50-90%, $p_T^{ch} > 2$ GeV, $n = 2$

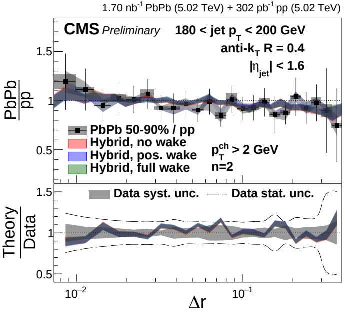
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



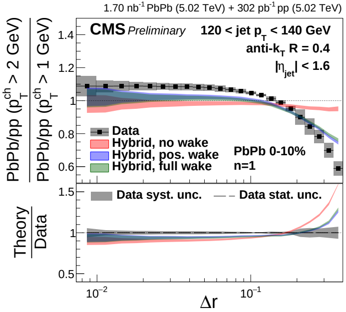

$180 < p_T^{jet} < 200$ GeV



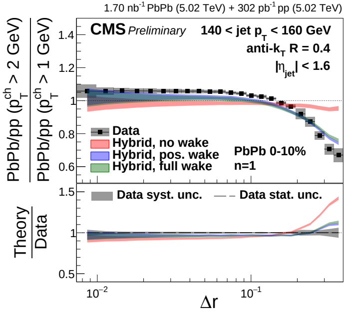

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

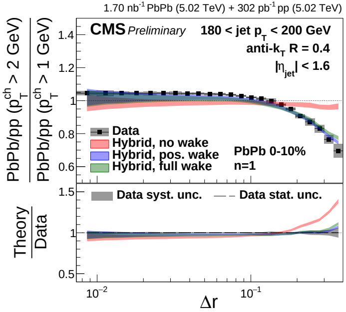
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



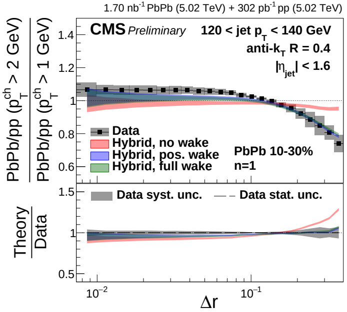

$180 < p_T^{jet} < 200$ GeV



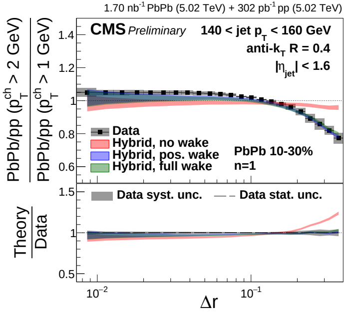

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

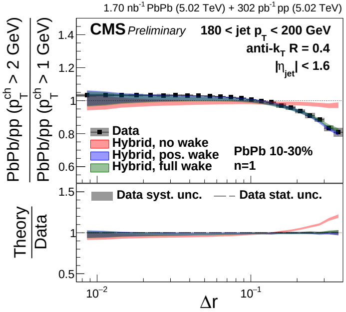
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



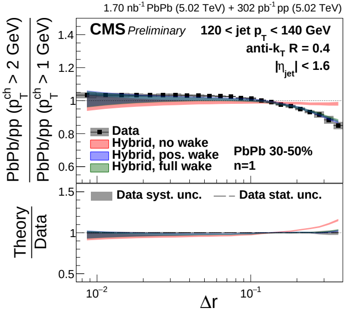

$180 < p_T^{jet} < 200$ GeV



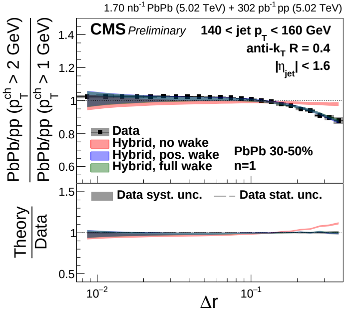

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

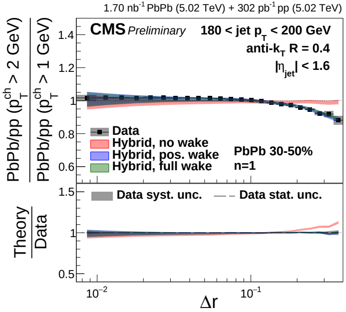
$120 < p_T^{\text{jet}} < 140$ GeV




$140 < p_T^{\text{jet}} < 160$ GeV



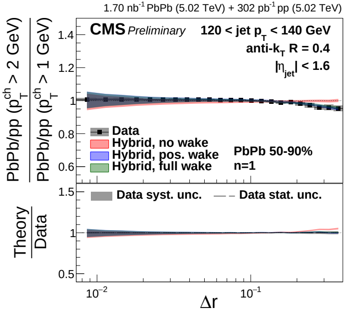

$180 < p_T^{\text{jet}} < 200$ GeV



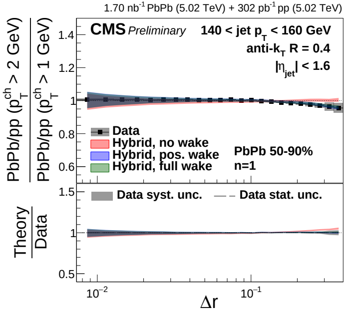

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

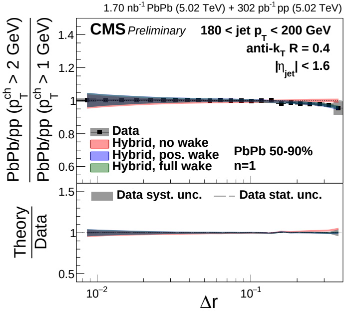
$120 < p_T^{\text{jet}} < 140$ GeV




$140 < p_T^{\text{jet}} < 160$ GeV



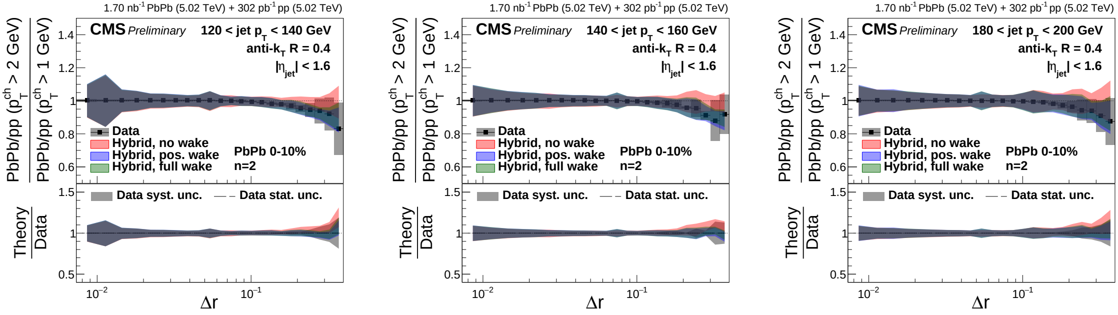

$180 < p_T^{\text{jet}} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

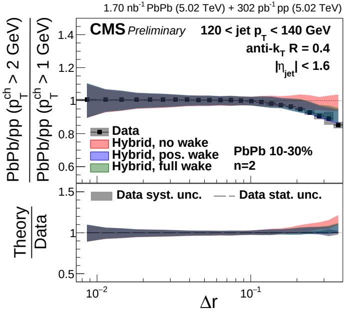
$120 < p_T^{\mathrm{jet}} < 140$ GeV $\quad$ $140 < p_T^{\mathrm{jet}} < 160$ GeV $\quad$ $180 < p_T^{\mathrm{jet}} < 200$ GeV



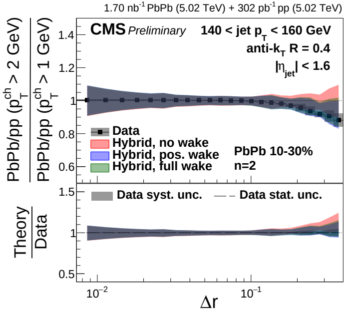

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

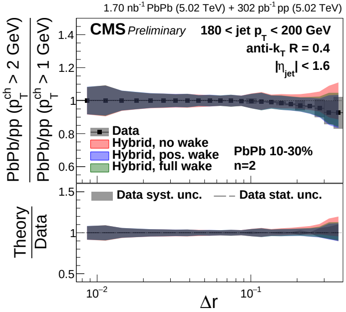
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



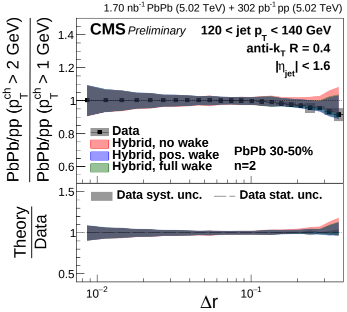

$180 < p_T^{jet} < 200$ GeV



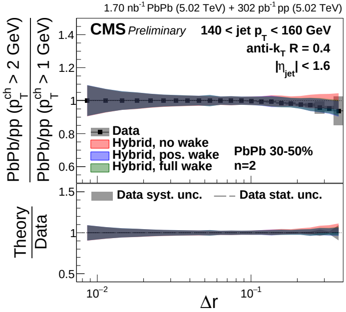

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

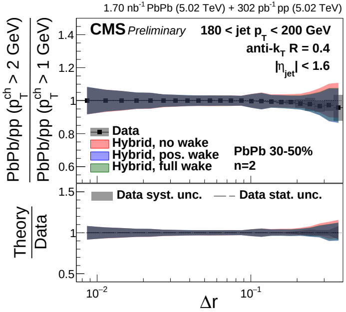
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV



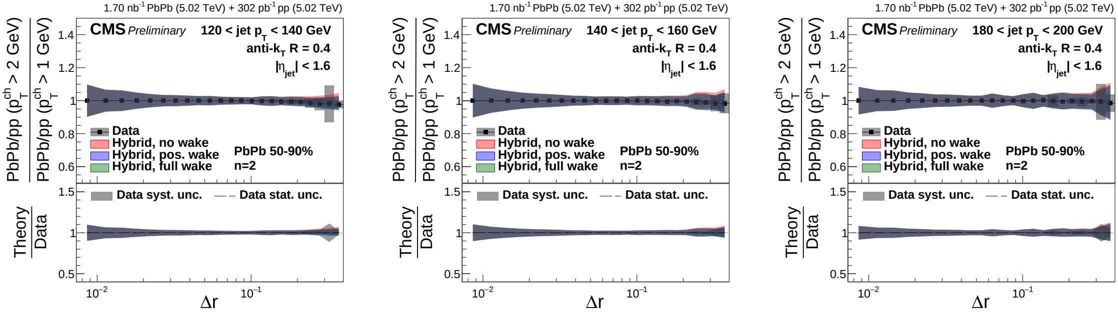

$180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

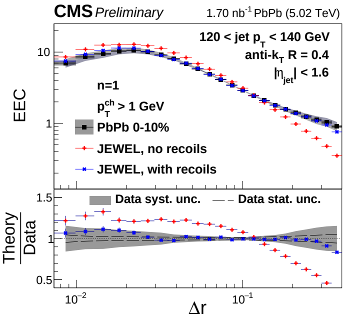
$120 < p_T^{jet} < 140$ GeV　　$140 < p_T^{jet} < 160$ GeV　　$180 < p_T^{jet} < 200$ GeV



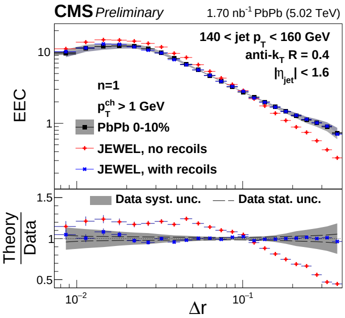

- Data from CMS-PAS-HIN-23-004
- Hybrid model prediction provided by Pablos, Kudinoor, Rajagopal

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

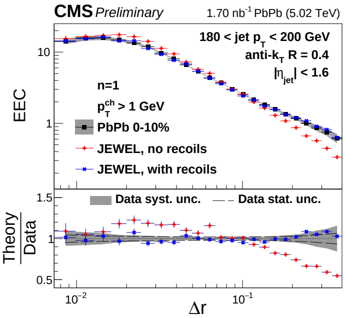
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140\,\mathrm{GeV}$




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



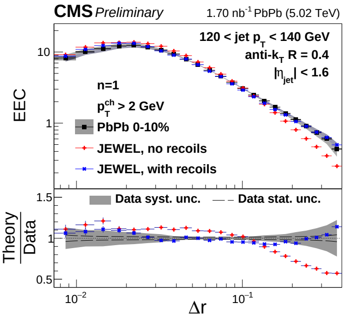

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200\,\mathrm{GeV}$



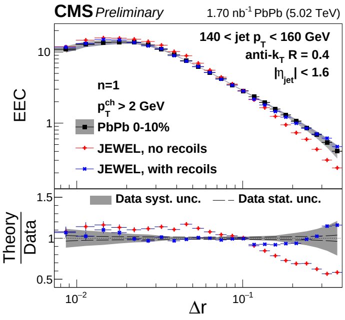

- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

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

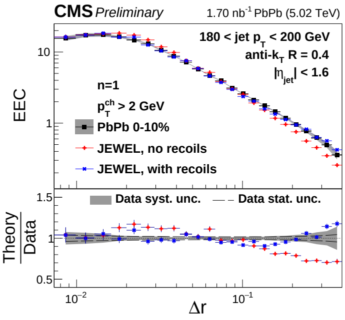
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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



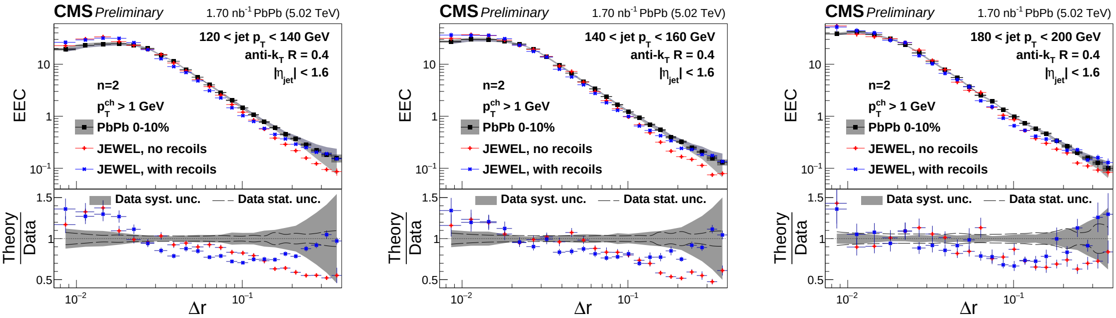

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

# PbPb distribution, JEWEL, 0-10%, $p_T^{ch} > 1$ GeV, $n = 2$

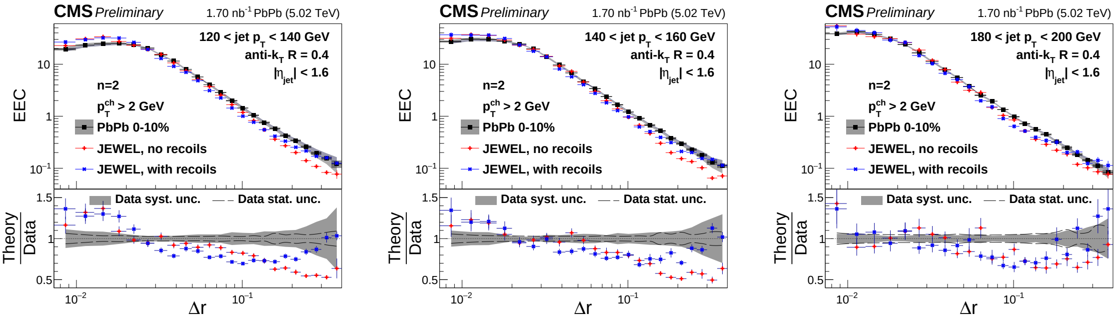
$120 < p_T^{jet} < 140$ GeV　　$140 < p_T^{jet} < 160$ GeV　　$180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

# PbPb distribution, JEWEL, 0-10%, $p_T^{ch} > 2$ GeV, $n = 2$

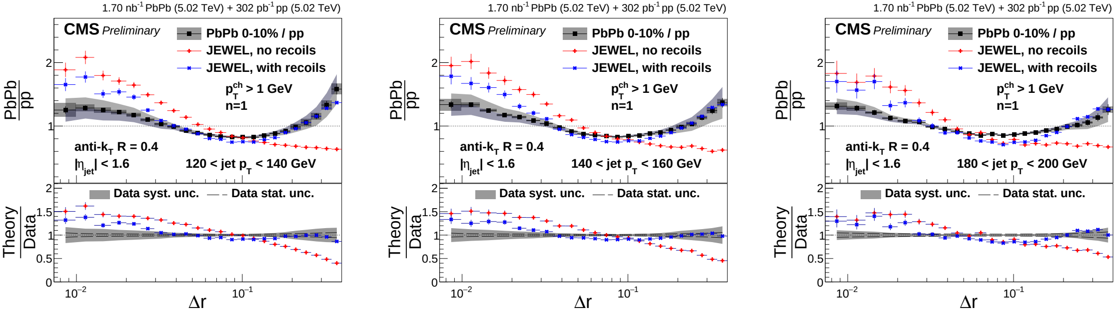
$120 < p_T^{jet} < 140$ GeV | $140 < p_T^{jet} < 160$ GeV | $180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

# PbPb to pp ratio, JEWEL, 0-10%, $p_T^{ch} > 1$ GeV, $n = 1$

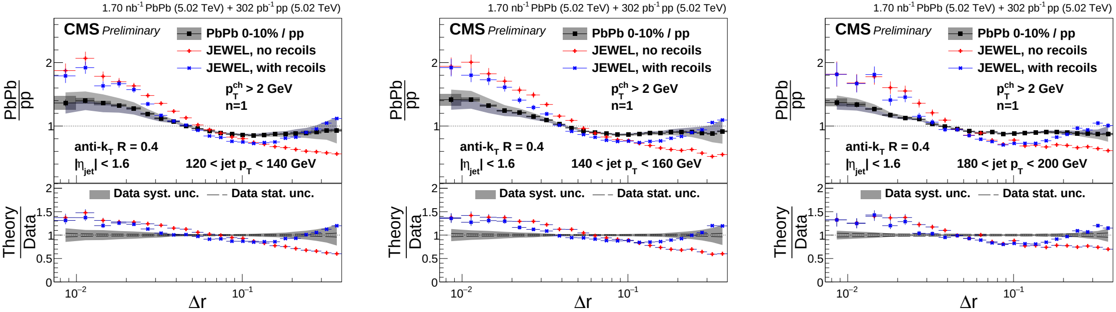
$120 < p_T^{jet} < 140$ GeV — $140 < p_T^{jet} < 160$ GeV — $180 < p_T^{jet} < 200$ GeV




- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

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

$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV $\quad$ $140 < p_{\mathrm{T}}^{\mathrm{jet}} < 160$ GeV $\quad$ $180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV

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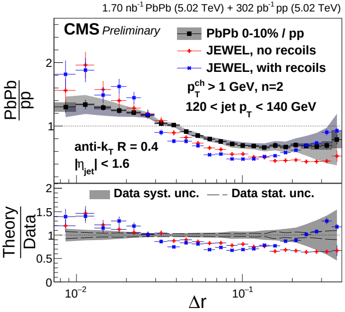
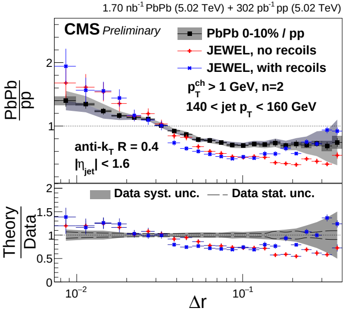
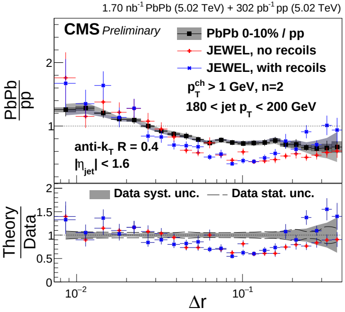



$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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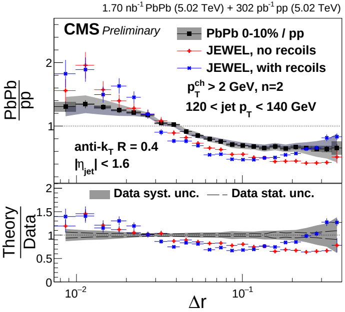
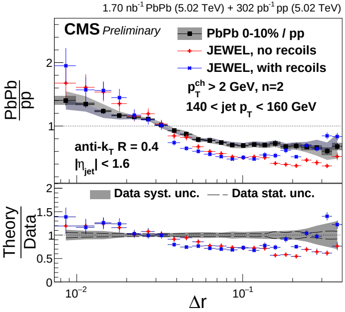
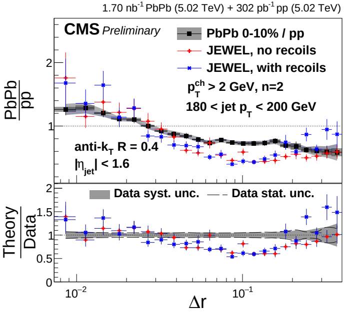



$140 < p_{\mathrm{T}}^{\mathrm{jet}} < 160$ GeV



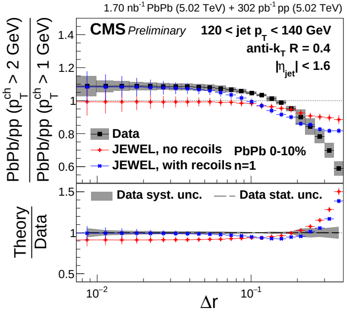

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV



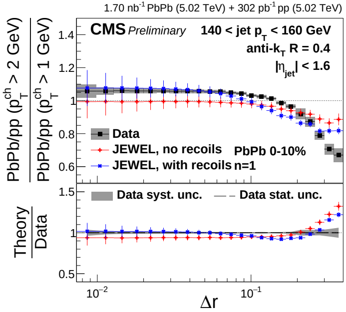

- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

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

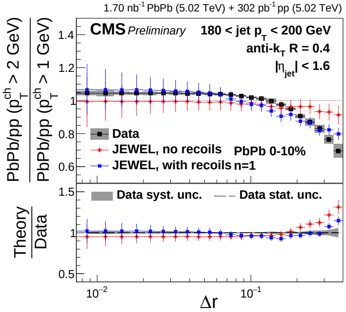
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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



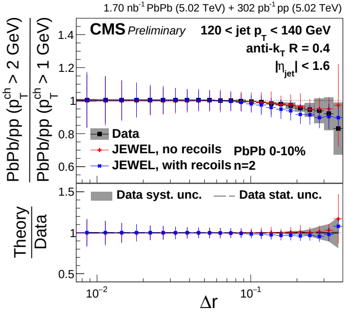

$180 < p_{\mathrm{T}}^{\mathrm{jet}} < 200$ GeV



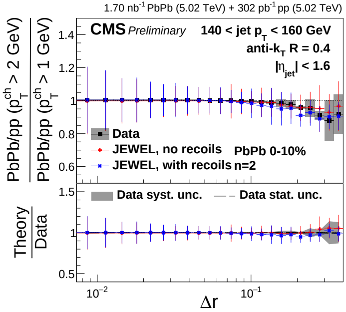

- Data from CMS-PAS-HIN-23-004
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

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

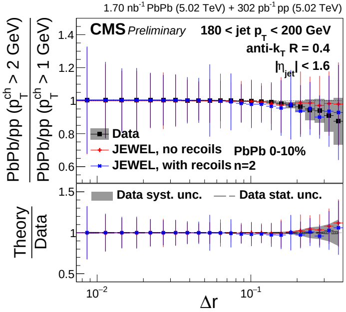
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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




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




- Data from CMS-PAS-HIN-23-004
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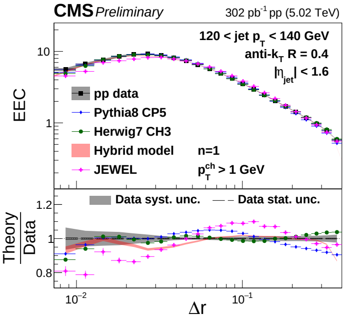
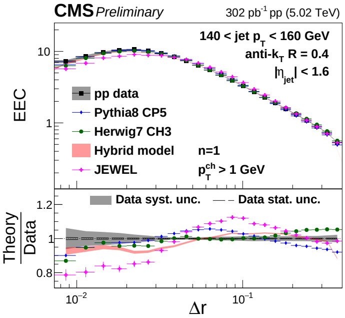
# pp distribution, $p_{\mathrm{T}}^{\mathrm{ch}} > 1$ GeV, $n = 1$

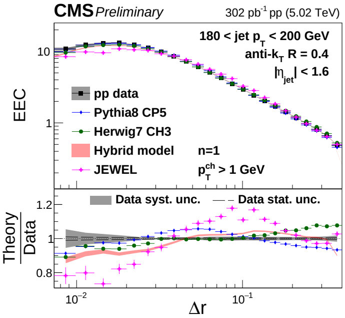
$120 < p_{\mathrm{T}}^{\mathrm{jet}} < 140$ GeV




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




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



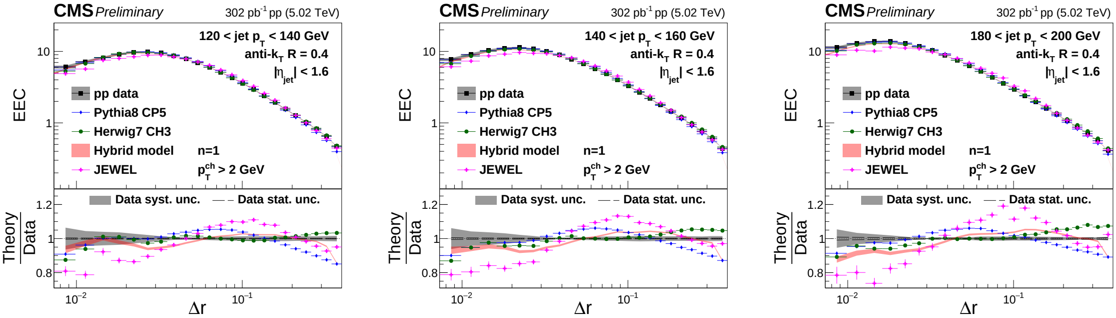

- Data from CMS-PAS-HIN-23-004
- Hybrid model vacuum a specific Pythia8 tune, provided by Pablos, Kudinoor, Rajagopal
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

# pp distribution, $p_T^{ch} > 2$ GeV, $n = 1$

$120 < p_T^{jet} < 140$ GeV

$140 < p_T^{jet} < 160$ GeV

$180 < p_T^{jet} < 200$ GeV

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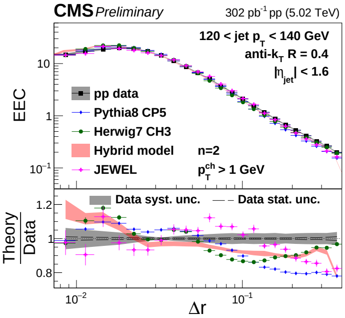
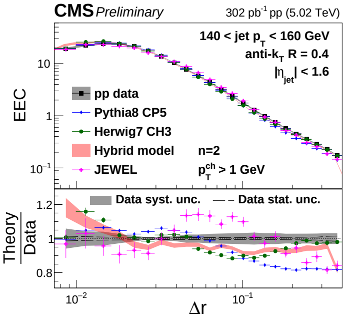
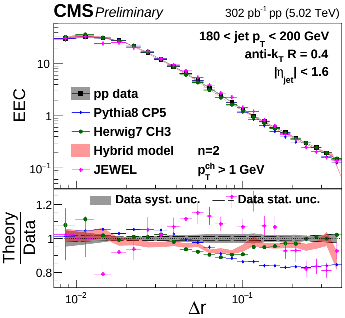
$120 < p_T^{jet} < 140$ GeV




$140 < p_T^{jet} < 160$ GeV




$180 < p_T^{jet} < 200$ GeV

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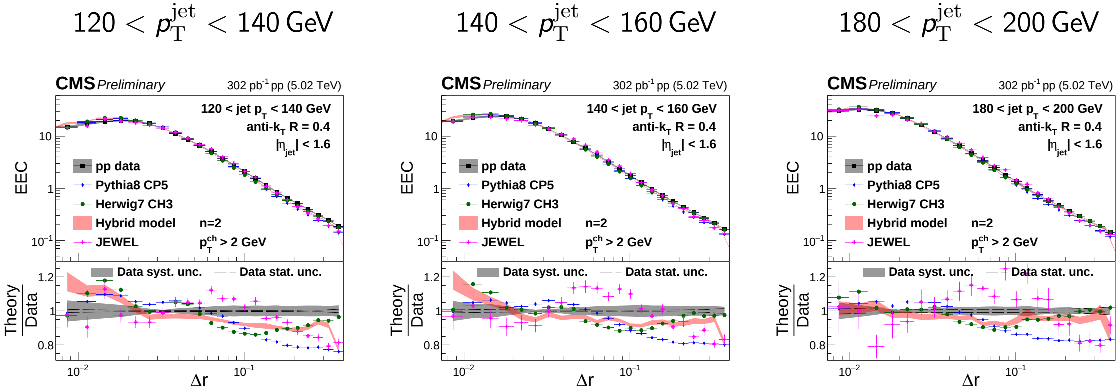
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

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

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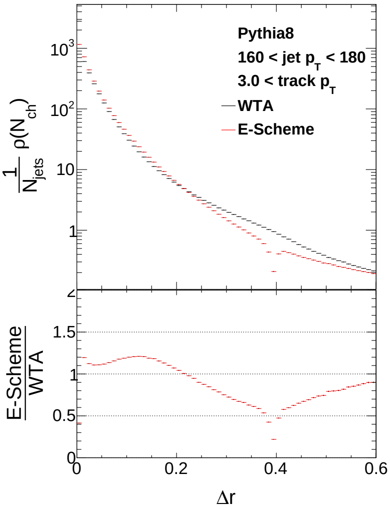
- Hybrid model vacuum a specific Pythia8 tune, provided by Pablos, Kudinoor, Rajagopal
- JEWEL 2.4.0 simulation done by Sheng, Kunnawalkam Elayavalli

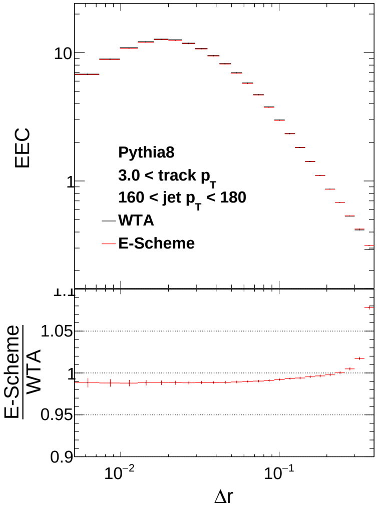
# Particle density with respect to jet axis in Pythia8

- 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 for systematics: reflected $\eta$ cone

- Reflect jet $\eta$ 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