Measurement of the photon-tagged jet axis decorrelation in pp and PbPb collisions at 5.02 TeV with CMS

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Massachusetts Institute of Technology
for the CMS collaboration

Boost 2024

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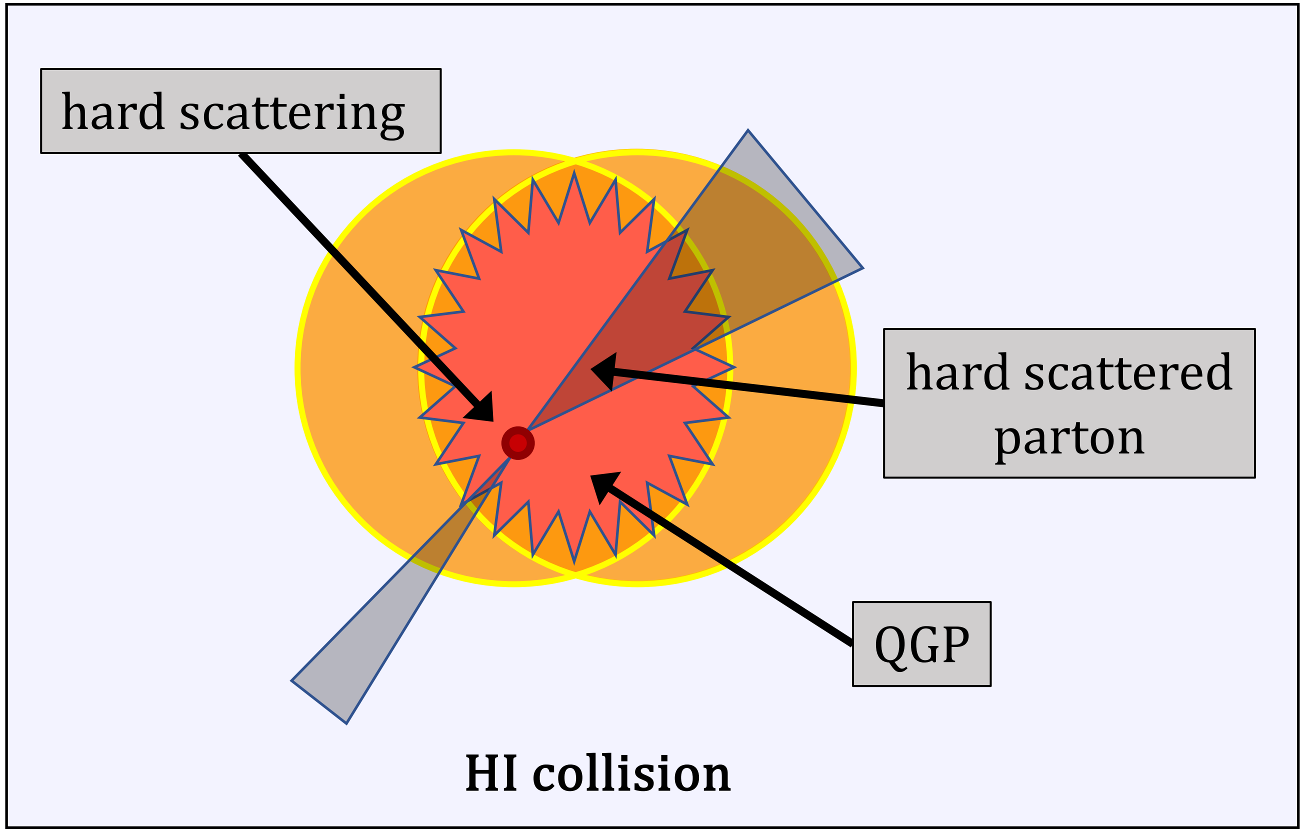
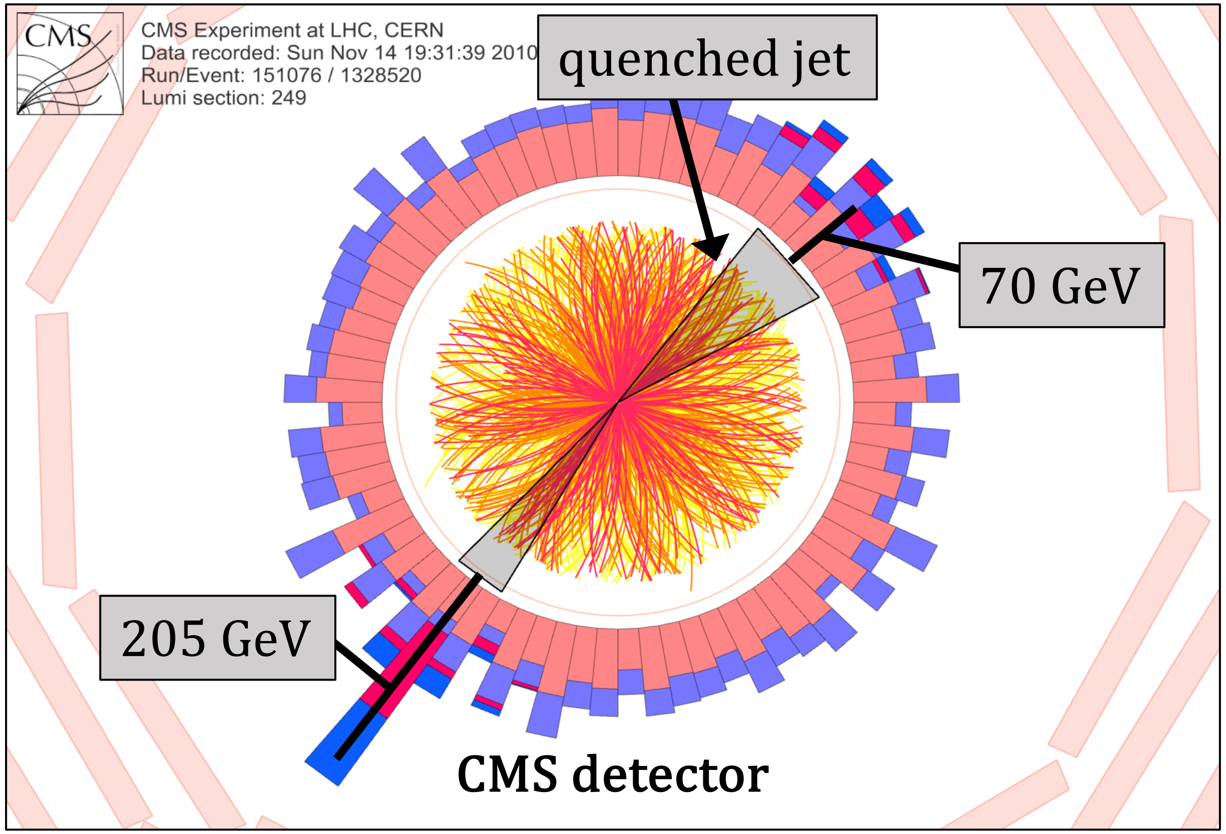
MITHIG group's work was supported by US DOE-NP

Jet quenching in heavy ion collisions



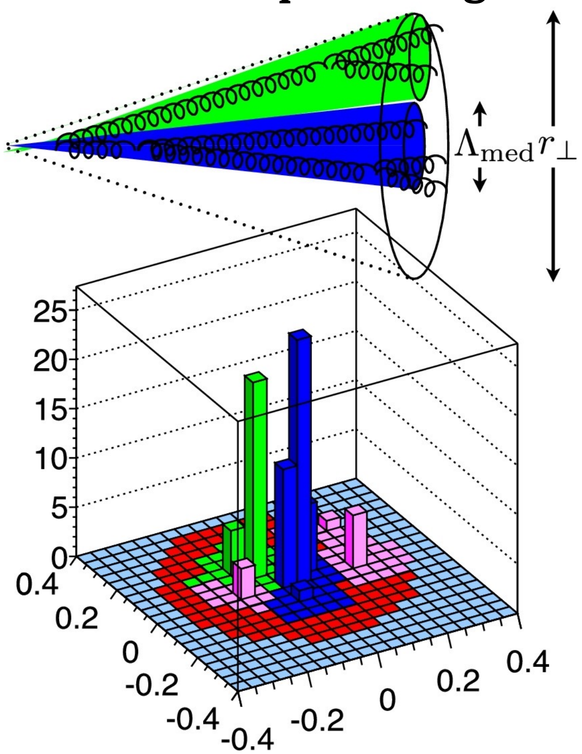


- QGP is formed when heavy ions collide
- Hard scattered partons interact with QGP and lose energy → **jet quenching**
- Studies of jet quenching can probe medium properties, such as transverse momentum broadening
- In dijet events there is a selection bias from jet p_T requirements, since both jets lose energy

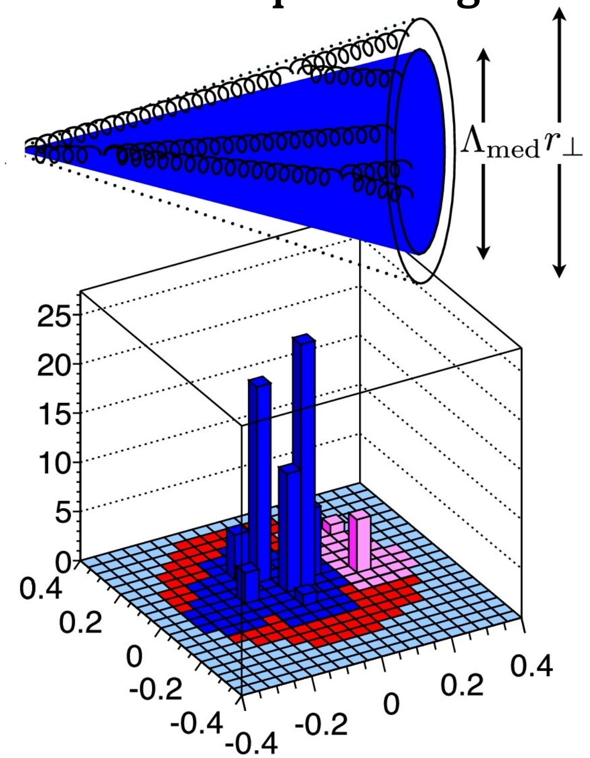
Medium resolution length and color coherence

- Depending on medium resolution length, resolve as single charge or multiple charges → **color coherence**
- Emergent property of the QGP due to quantum interference

Resolved as two charges
→ more quenching

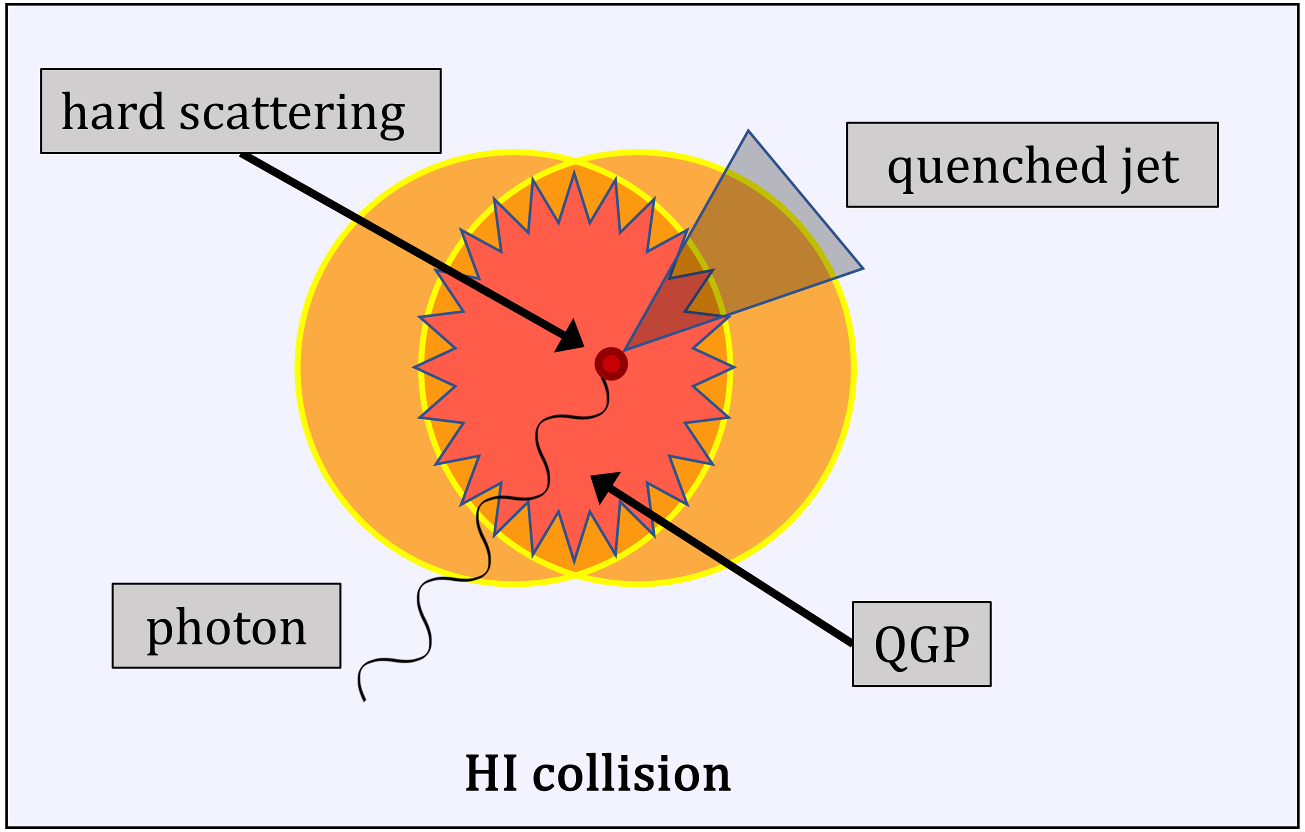


Resolved as a single charge
→ less quenching



Diagrams from
J. Casalderrey-Solana,
Y. Mehtar-Tani,
C. A. Salgado,
K. Tywoniuk,
arXiv:1210.7765

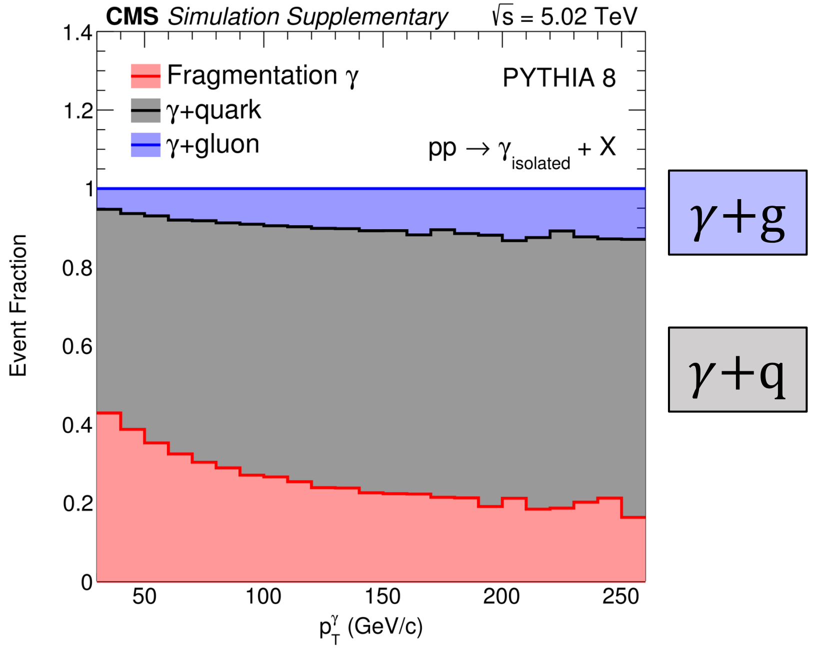
Using photon-tagged jets

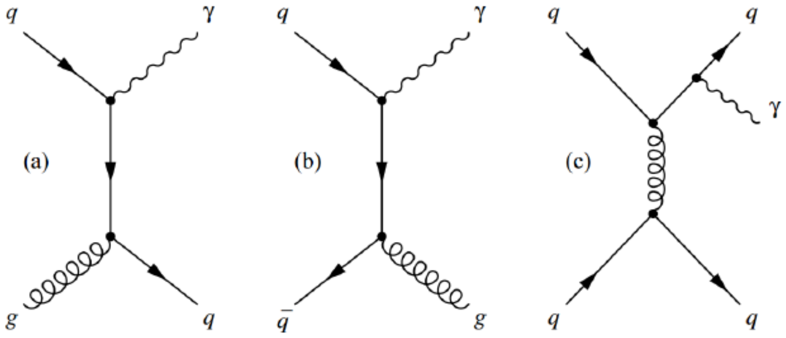


- Photon does not interact strongly with QGP

  => tags initial recoil parton p_T
- No selection bias from photon tag
- Good handle on q/g fraction of recoil parton

Composition of events with isolated photons

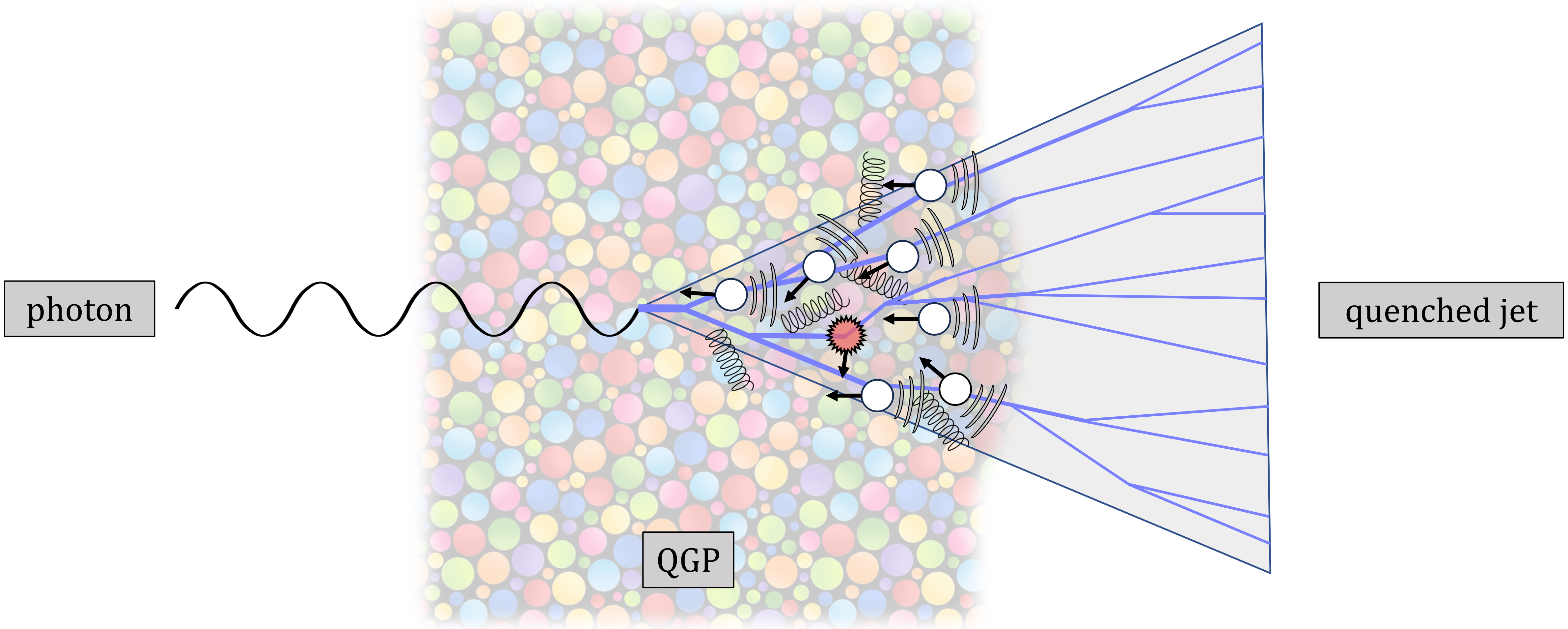




CMS: PRL 122 (2019) 152001

Jet energy loss

- Jet quenching involves modification of the jet radiation pattern
- Jet substructure observables map 4-momenta of jet constituents to physically meaningful observables



Based on figure from Yen-Jie Lee

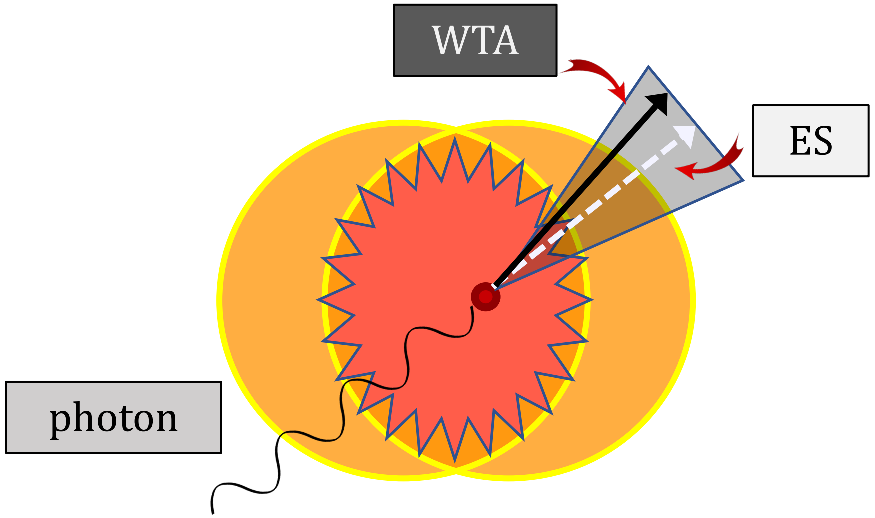
Jet axis differences

Studying the jet axis decorrelation, which is the angular difference between the WTA and E-Scheme jet axes

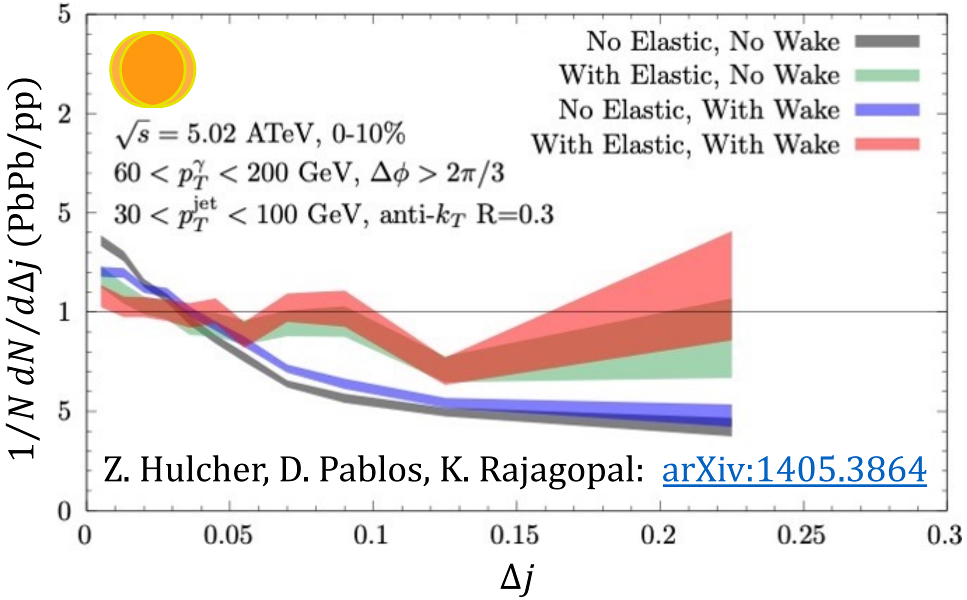
WTA axis = direction of leading energy flow in jet **E-Scheme axis** = direction of average energy flow in jet

$$\Delta j = \sqrt{(\eta^{E-Scheme} - \eta^{WTA})^2 + (\phi^{E-Scheme} - \phi^{WTA})^2}$$

Photon-jet schematic



Hybrid model prediction



Potentially sensitive to elastic scattering effects in the QGP

Photon tags hard scattering energy and constrains the quark/gluon fraction of recoiling jets

Previous measurement in inclusive jets

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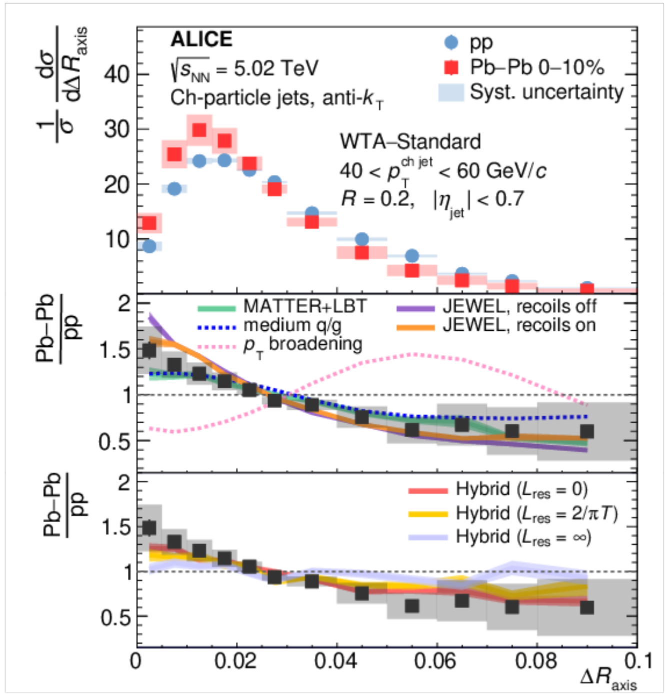
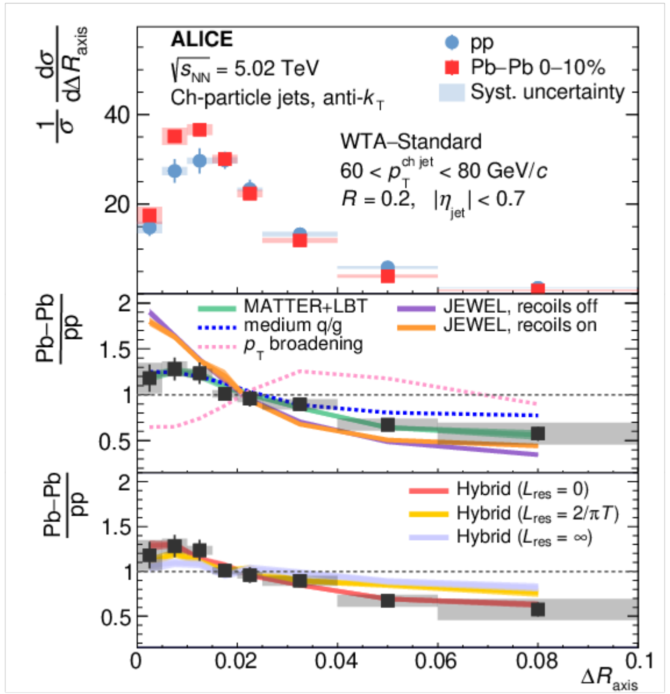




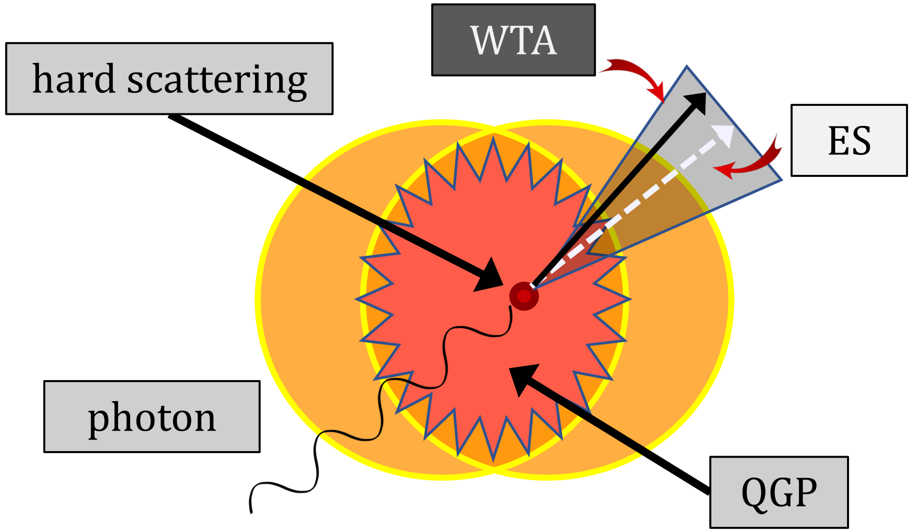
ALICE: arXiv:2303.13347

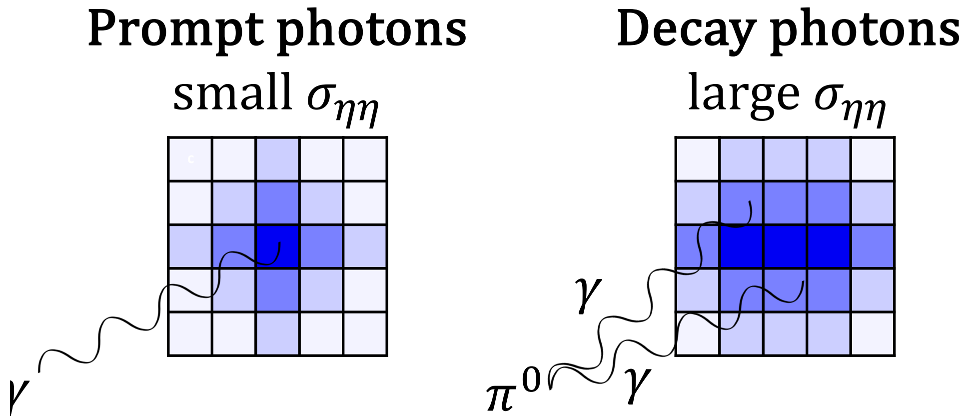
Inclusive jet measurements of Δj show signs of narrowing in PbPb compared to pp collisions

In other jet measurements such as R_g, narrowing in inclusive jets found to likely be due to selection bias

Measurement setup

- Selections
  - Isolated photons: $60 < p_T^{\gamma} < 200$ GeV and $|\eta^{\gamma}| < 1.44$
  - Associated anti-k$_T$ jets: $R = 0.3$, $|\Delta\phi^{j\gamma}| > \frac{2\pi}{3}$, $|\eta^{jet}| < 1.6$
    - $30 < p_T^{jet} < 200$ GeV before unfolding
    - $30 < p_T^{jet} < 60$ GeV and $60 < p_T^{jet} < 100$ GeV after unfolding





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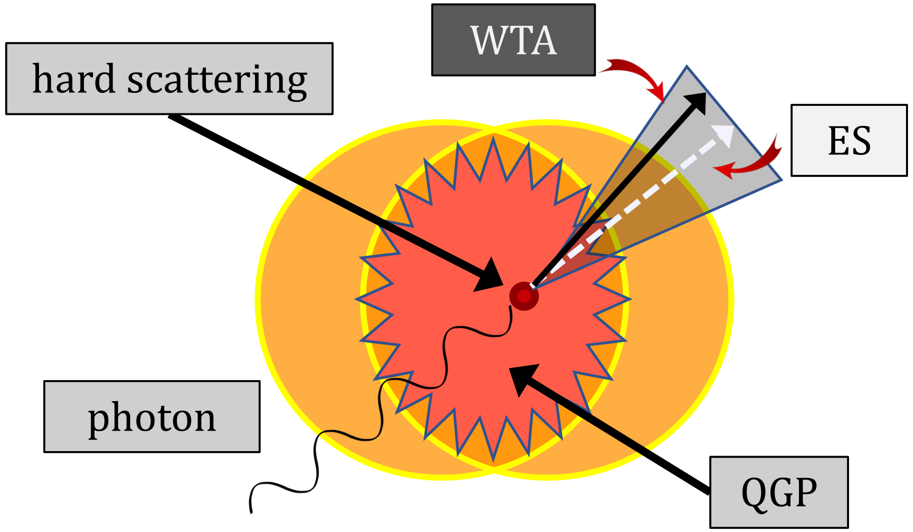
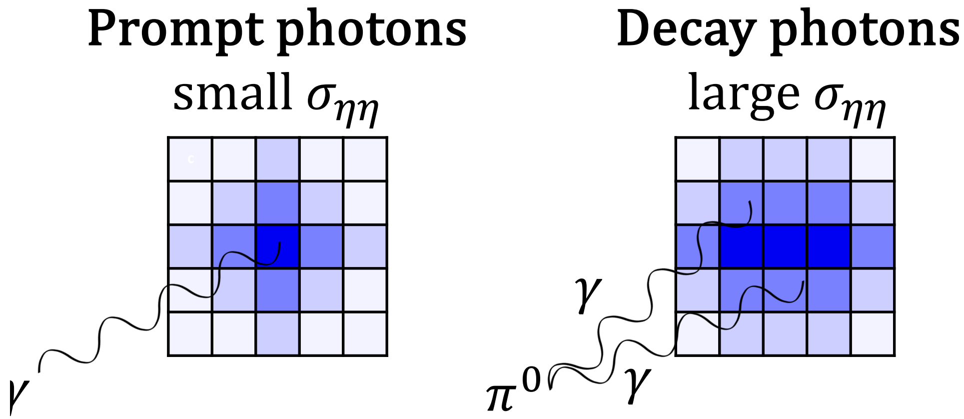
- Observable
  - $\Delta j = \sqrt{(\eta^{E-Scheme} - \eta^{WTA})^2 + (\phi^{E-Scheme} - \phi^{WTA})^2}$





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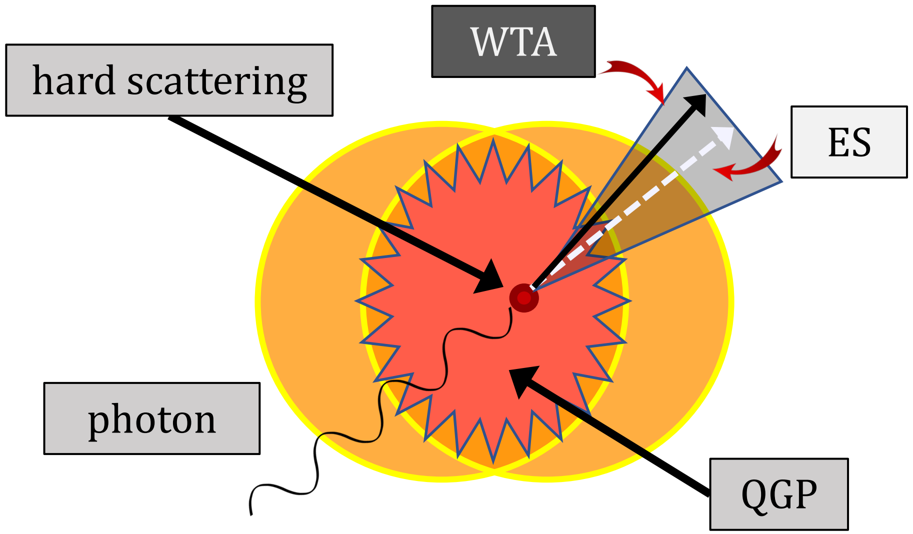
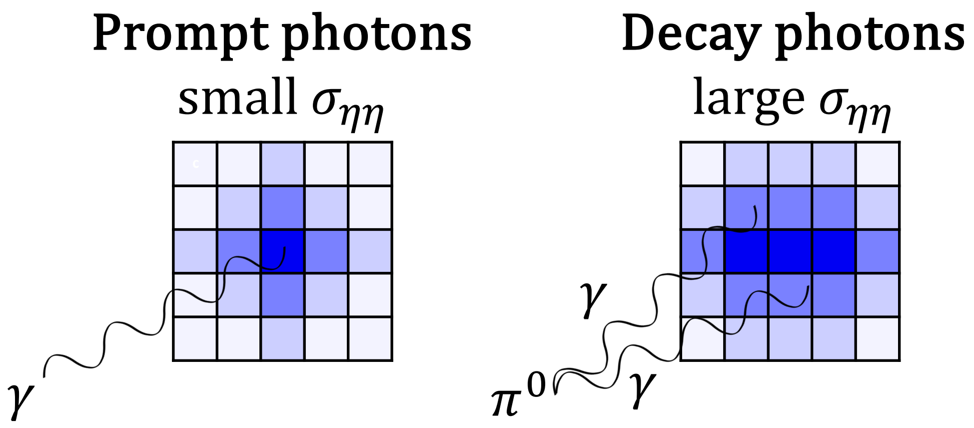
- Observable
  - $\Delta j = \sqrt{(\eta^{E-Scheme} - \eta^{WTA})^2 + (\phi^{E-Scheme} - \phi^{WTA})^2}$
- Analysis method
  - Subtract background jets using mixed-event background subtraction
  - Subtract background photons using purity subtraction, where purity is found from template fit of shower shape
  - Correct detector resolution effects, acceptance, and efficiency with D'Agostini unfolding





Analysis procedure

Data

- signal photons
- decay photons
- signal jets
- UE jets

Analysis procedure

Data

signal photons

decay photons

signal jets

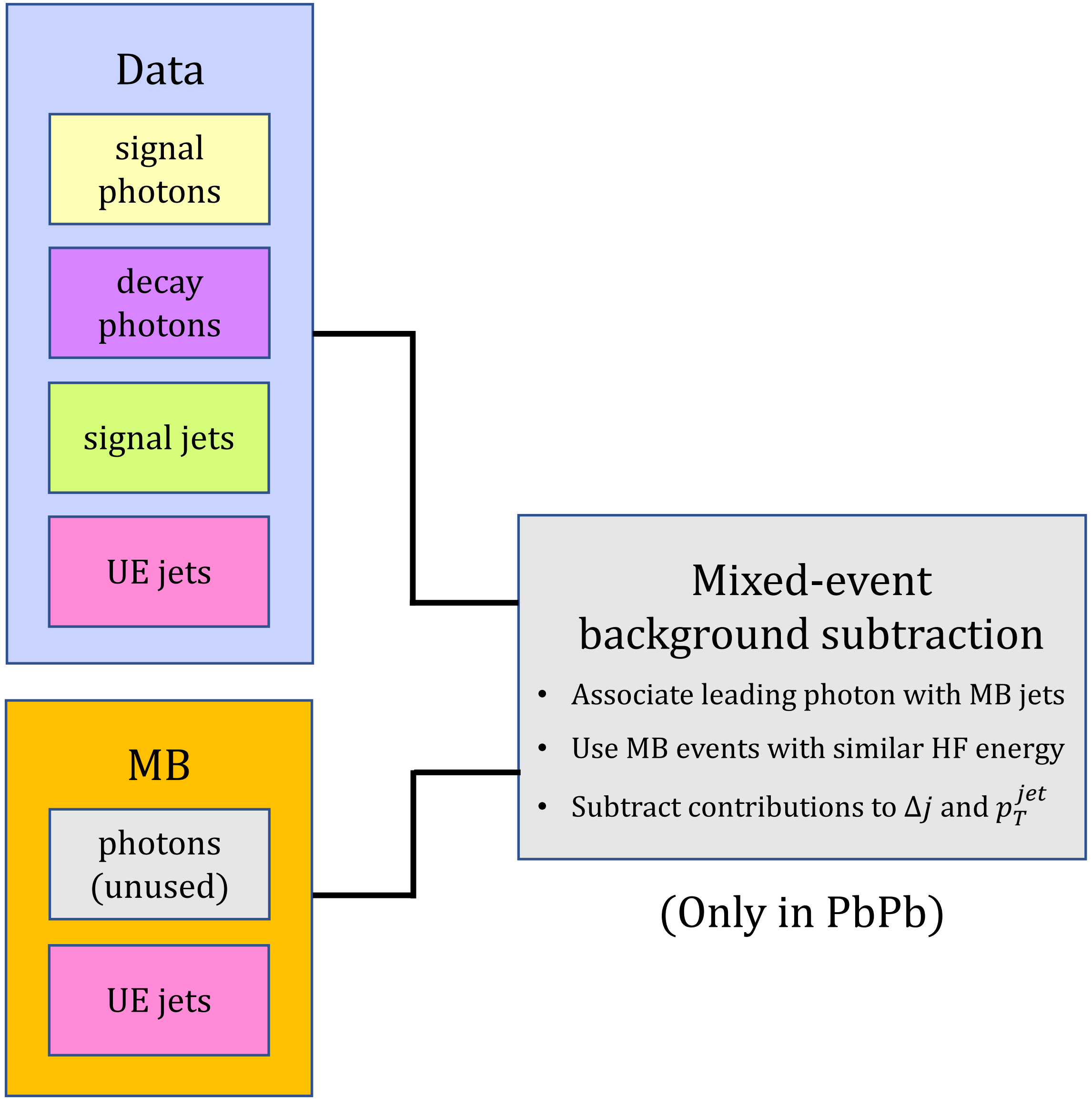
UE jets

MB

photons (unused)

UE jets

Analysis procedure



(Only in PbPb)

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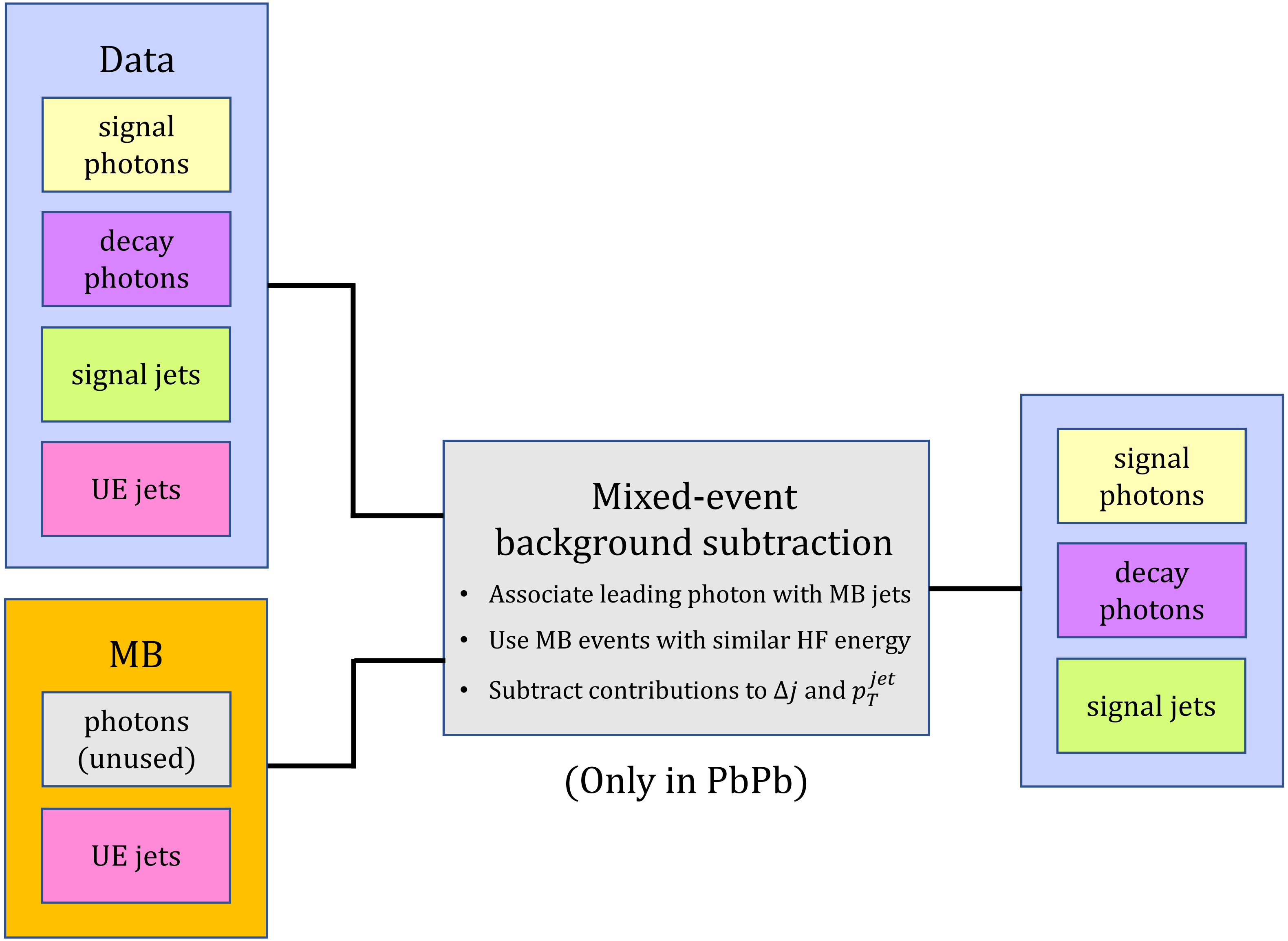

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Mixed-event background subtraction
- Associate leading photon with MB jets
- Use MB events with similar HF energy
- Subtract contributions to Δj and p_T^{jet}

(Only in PbPb)

- signal photons
- decay photons
- signal jets

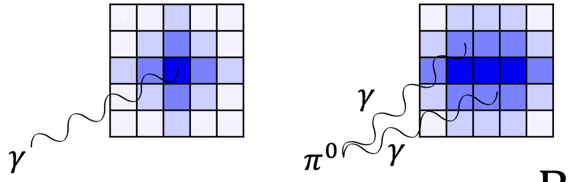
Purity subtraction

$$\Delta j_{signal} = \frac{1}{p} \cdot \Delta j_{raw} + \frac{1-p}{p} \cdot \Delta j_{decay}$$

signal photons = isolated photons, $\sigma_{\eta\eta} < 0.01$
decay photons = any $\sigma_{\eta\eta}$
- $\sigma_{\eta\eta} > 0.01$ is almost 100% decay photons
- $\sigma_{\eta\eta} > 0.01$ used for decay photon δj distribution

raw photons = $\sigma_{\eta\eta} < 0.01$

Prompt photons small $\sigma_{\eta\eta}$ | **Decay photons** large $\sigma_{\eta\eta}$



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(Only in PbPb)

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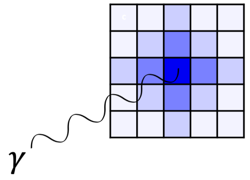

Decay photons
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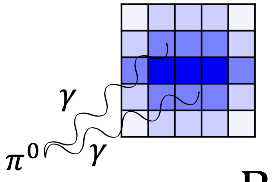
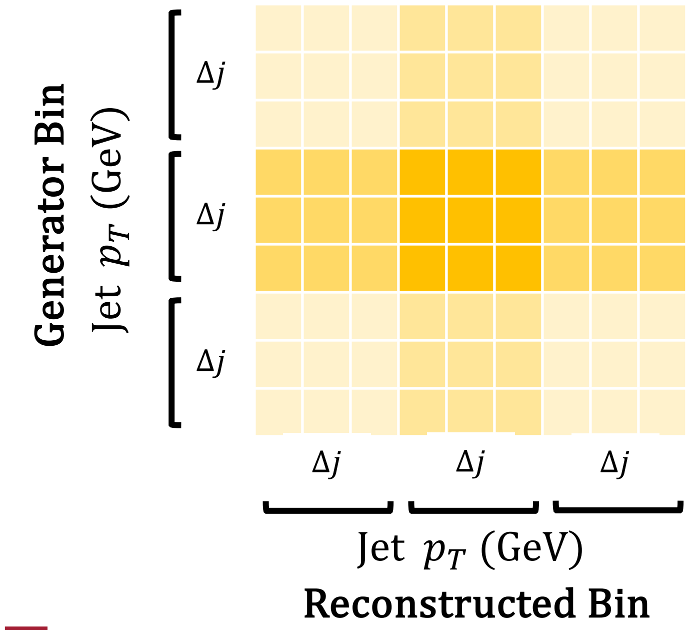
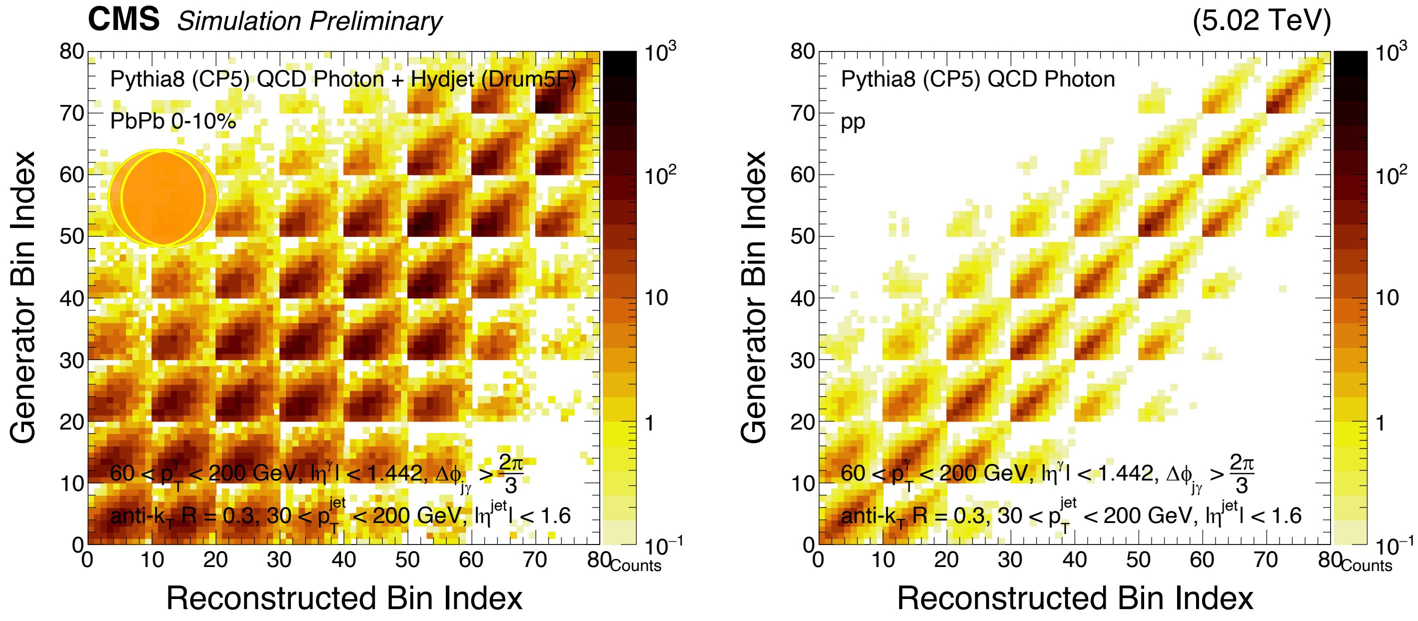


Unfolding

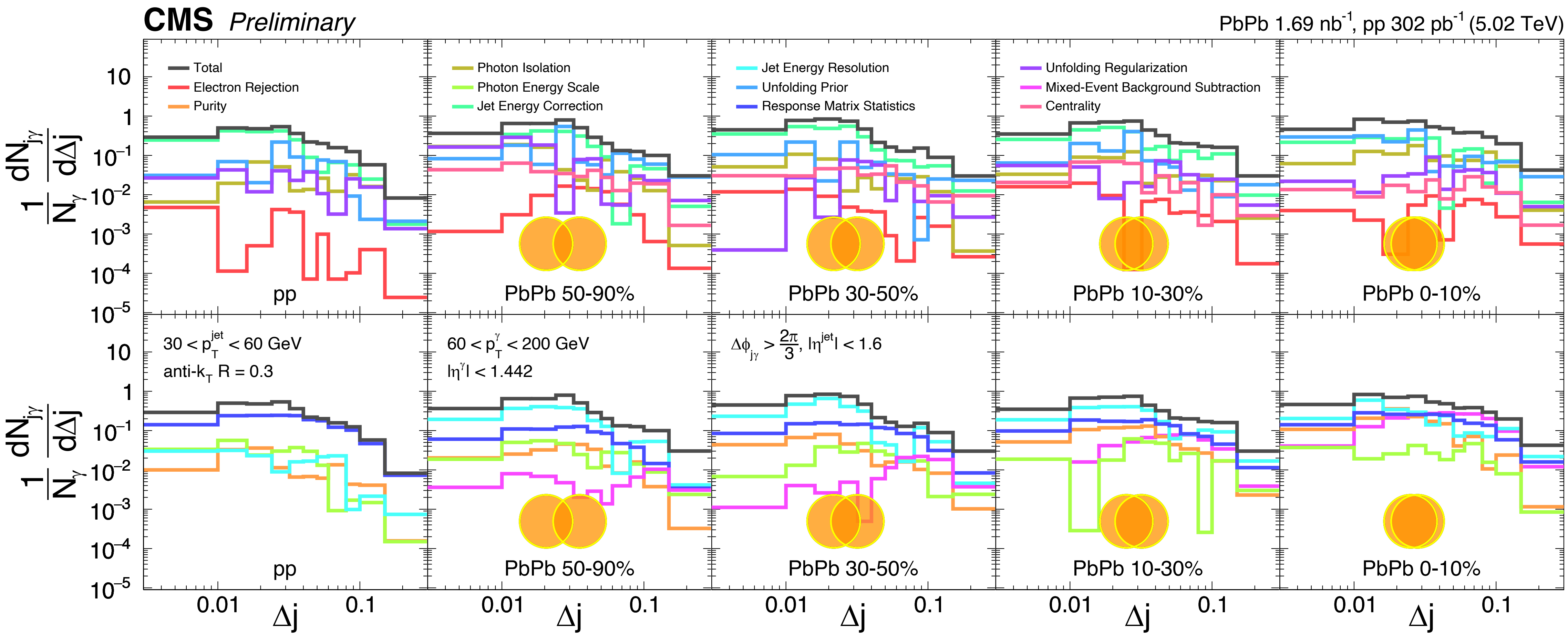
- Unfold two-dimensionally in p_T^{jet} and Δj
- Unfold with the D'Agostini iteration with early stopping method
  - Starts with a prior and successively updates the solution based on Bayes' Theorem
  - Regularization parameter is the number of iterations
  - Choose regularization strength by minimizing the mean squared error using Asimov datasets
- Apply purity and efficiency corrections to account for generator and reconstruction level jets not matched within acceptance





Systematic uncertainties: $30 < p_T^{jet} < 60$ GeV

CMS: PAS-HIN-21-019



- Dominant systematics are the jet energy correction and jet energy resolution uncertainties
- Subdominant systematics are the mixed-event background subtraction, response matrix statistics, and unfolding prior

Systematic uncertainties: $60 < p_T^{jet} < 100$ GeV

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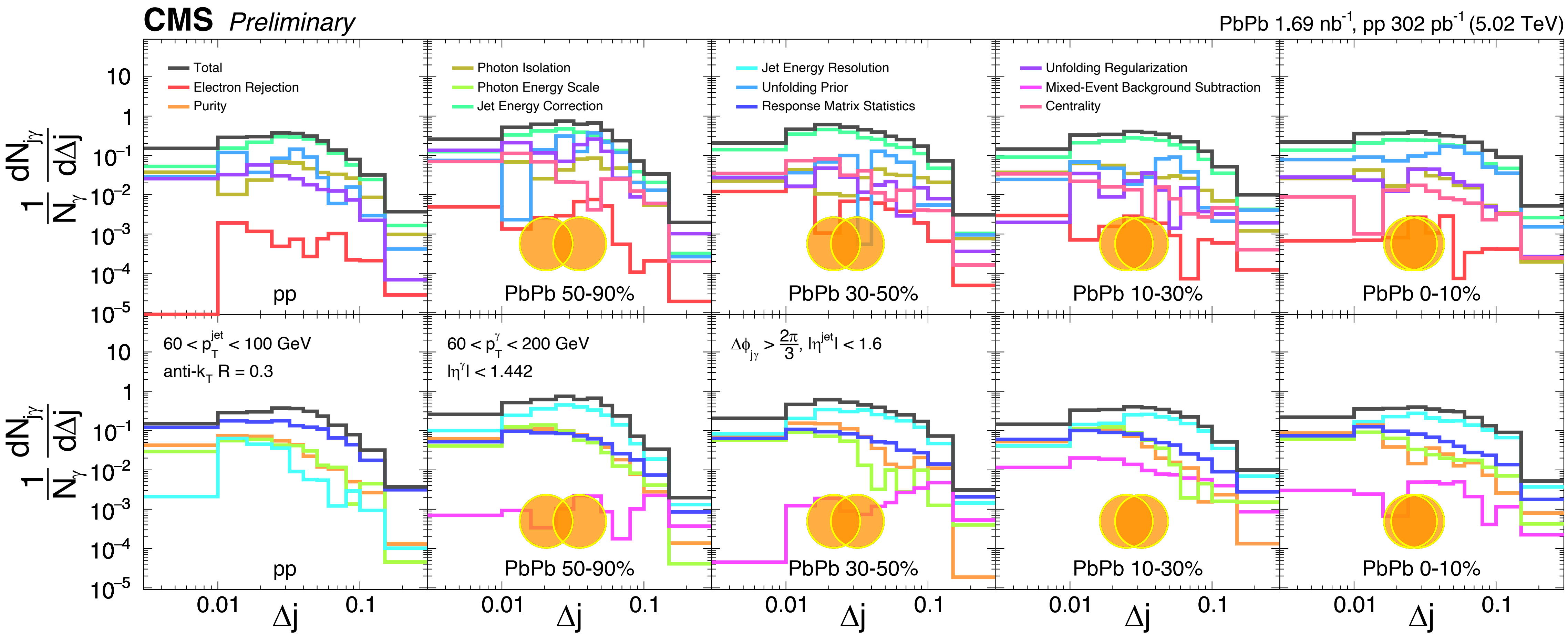

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Δj spectra normalized per photon

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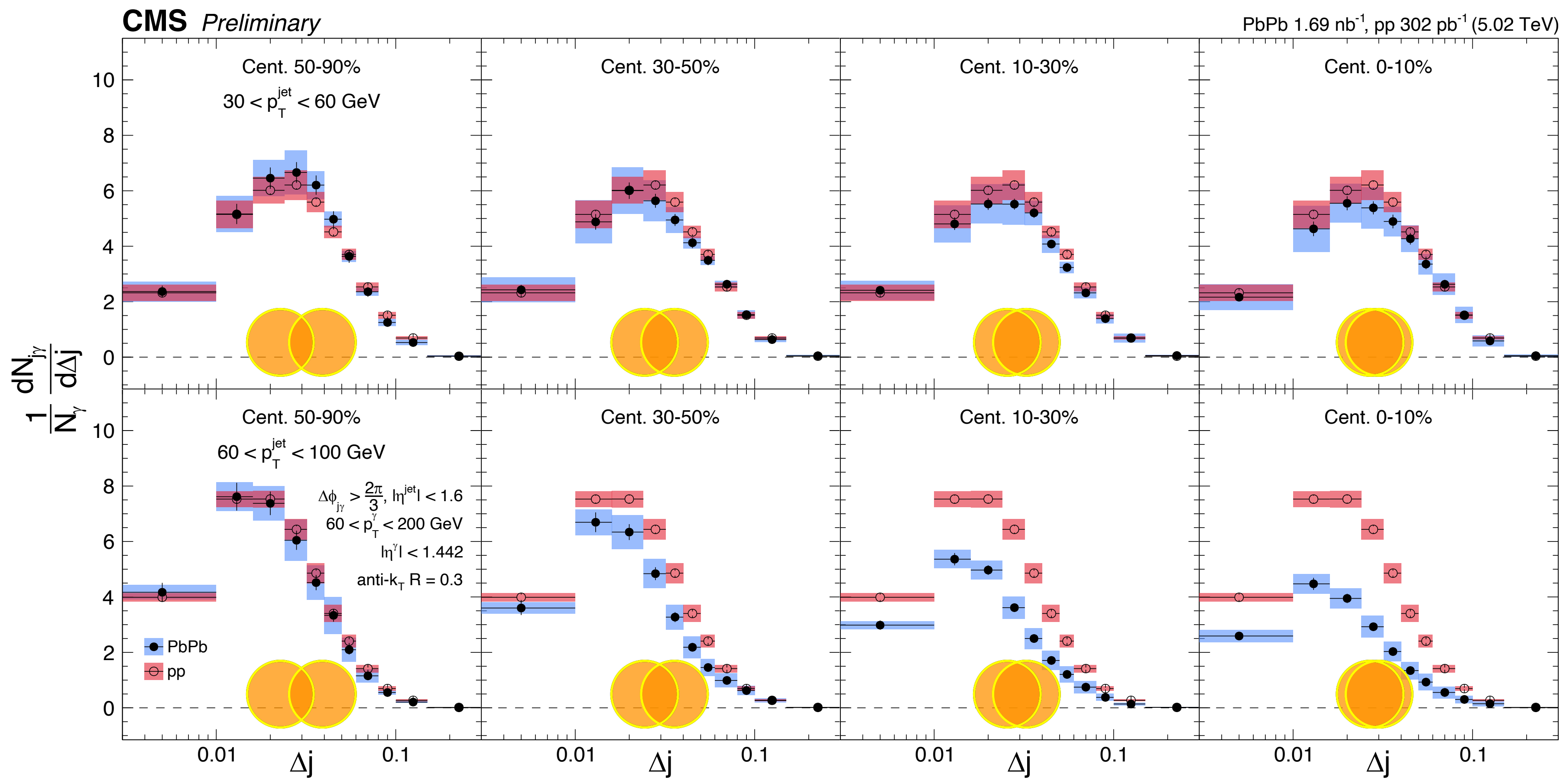

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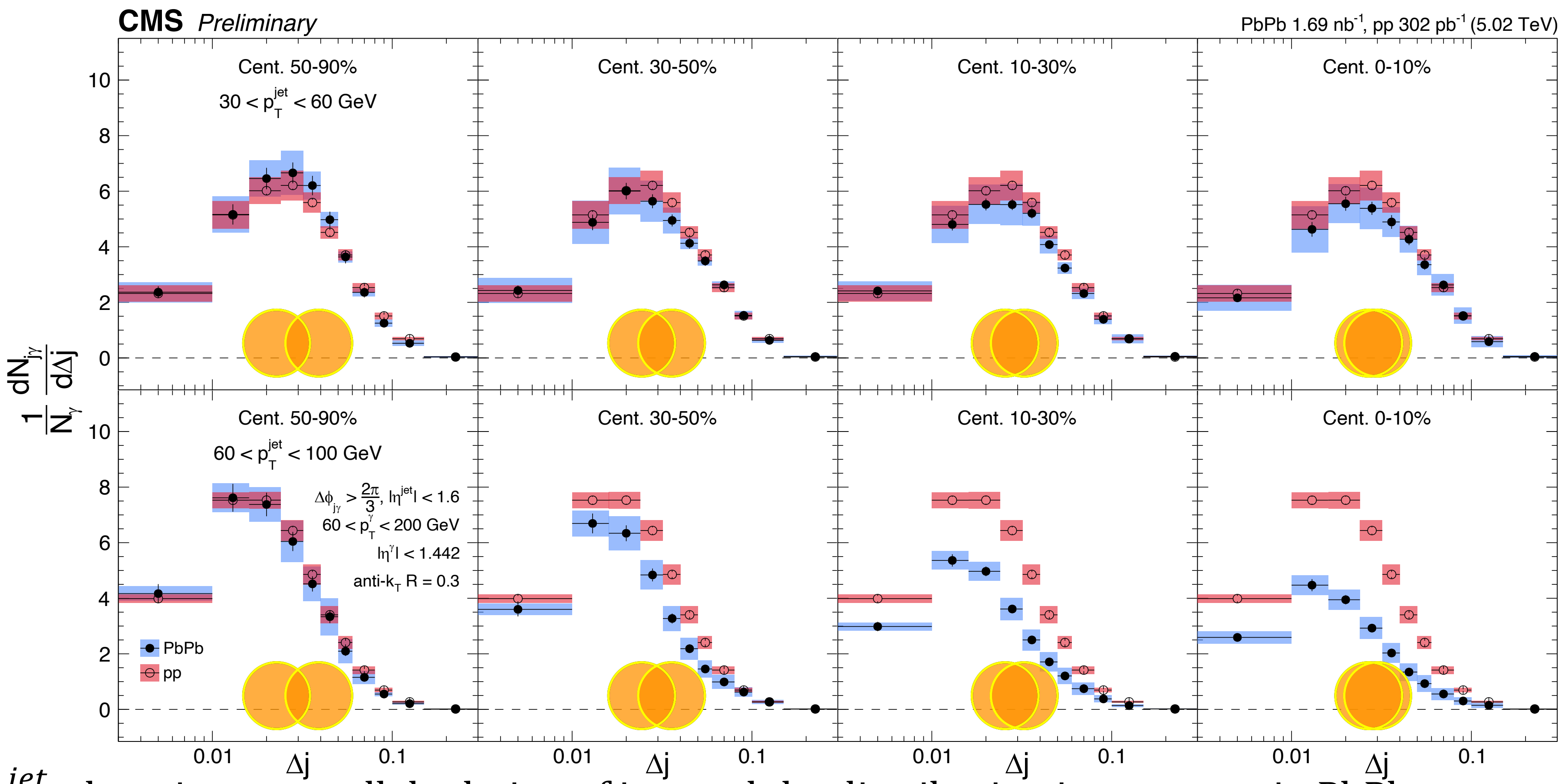

- At high p_T^{jet}: there is an overall depletion of jets and the distribution is narrower in PbPb compared to pp

Δj spectra normalized per photon

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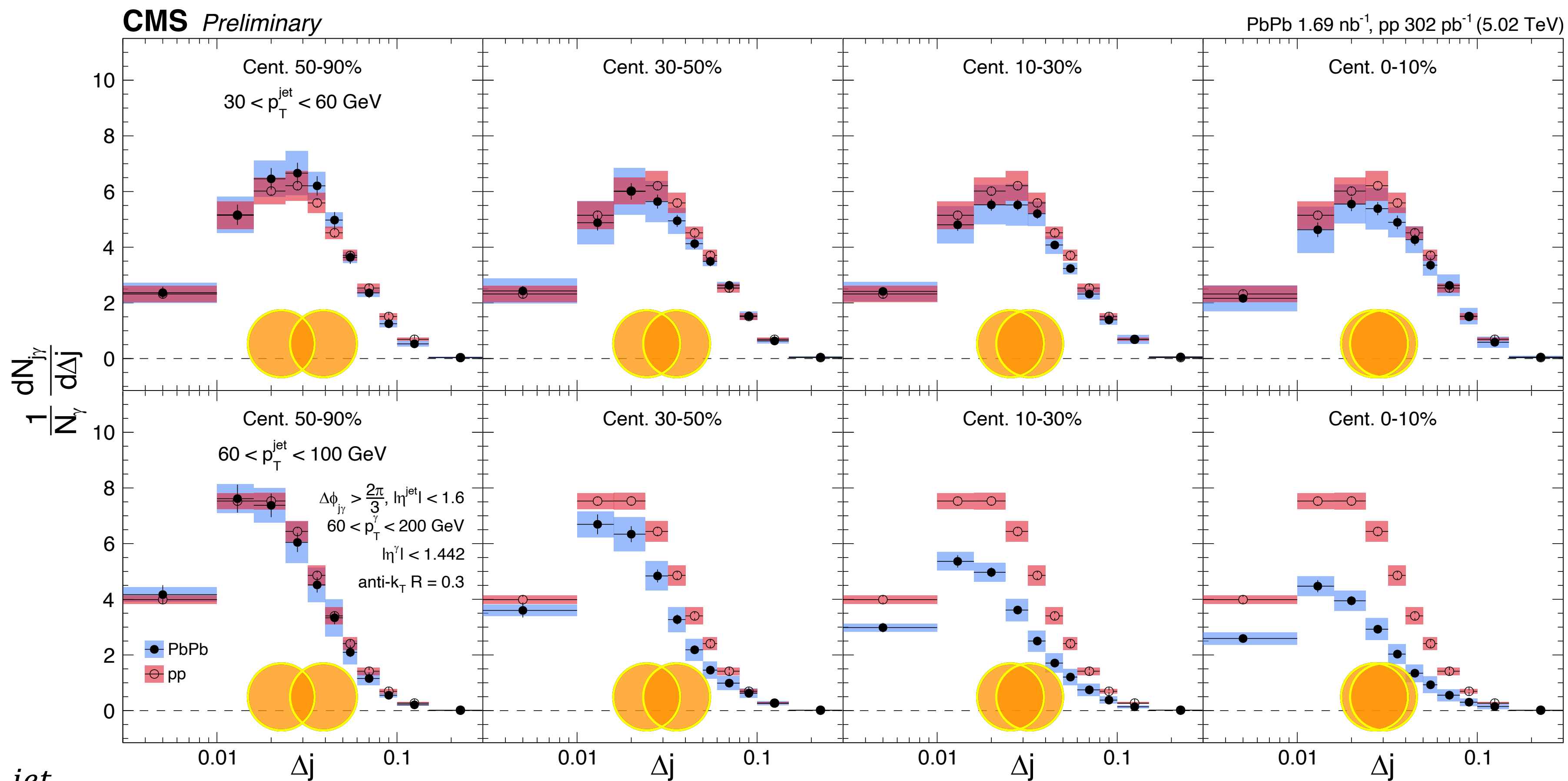

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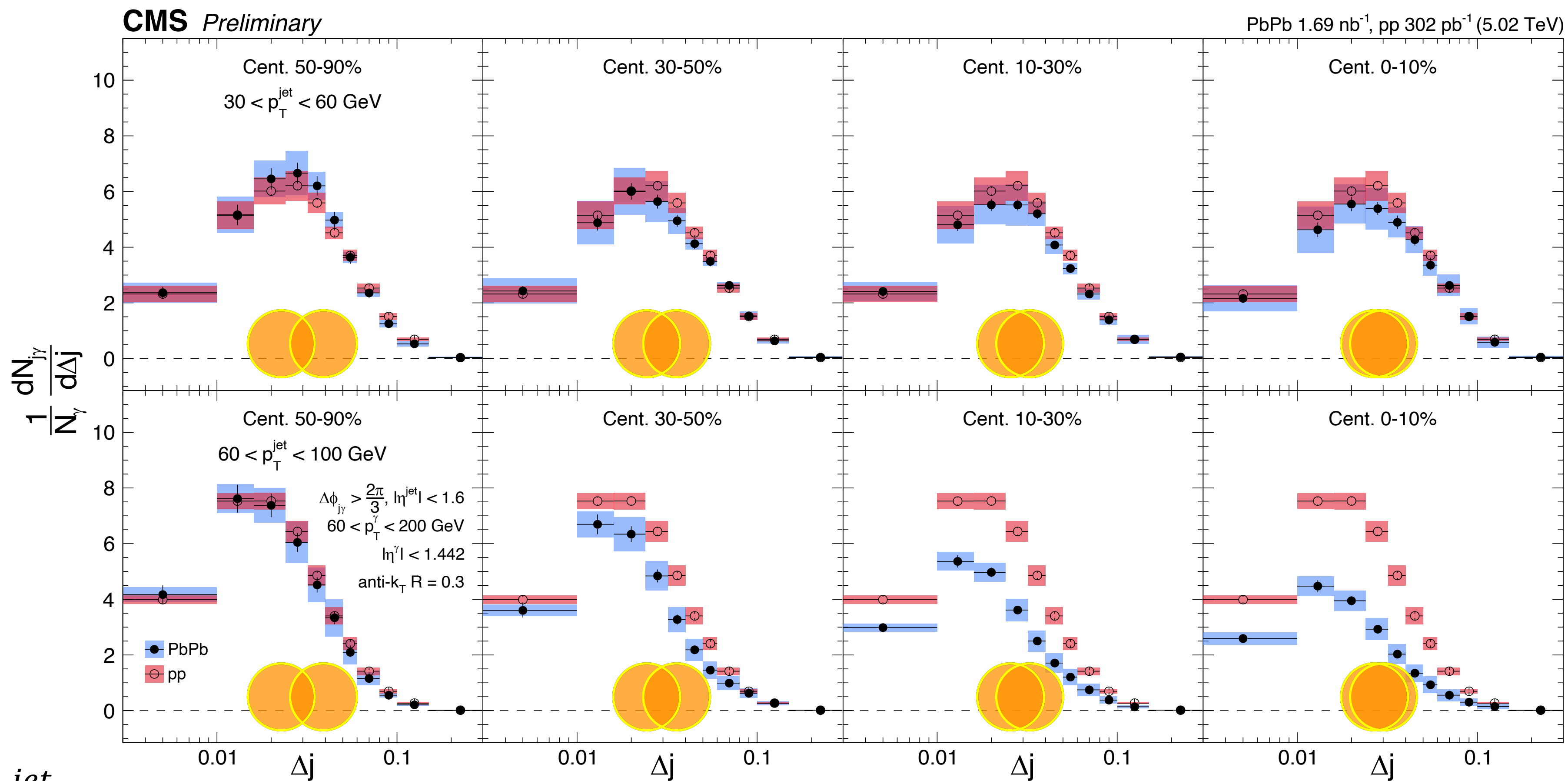

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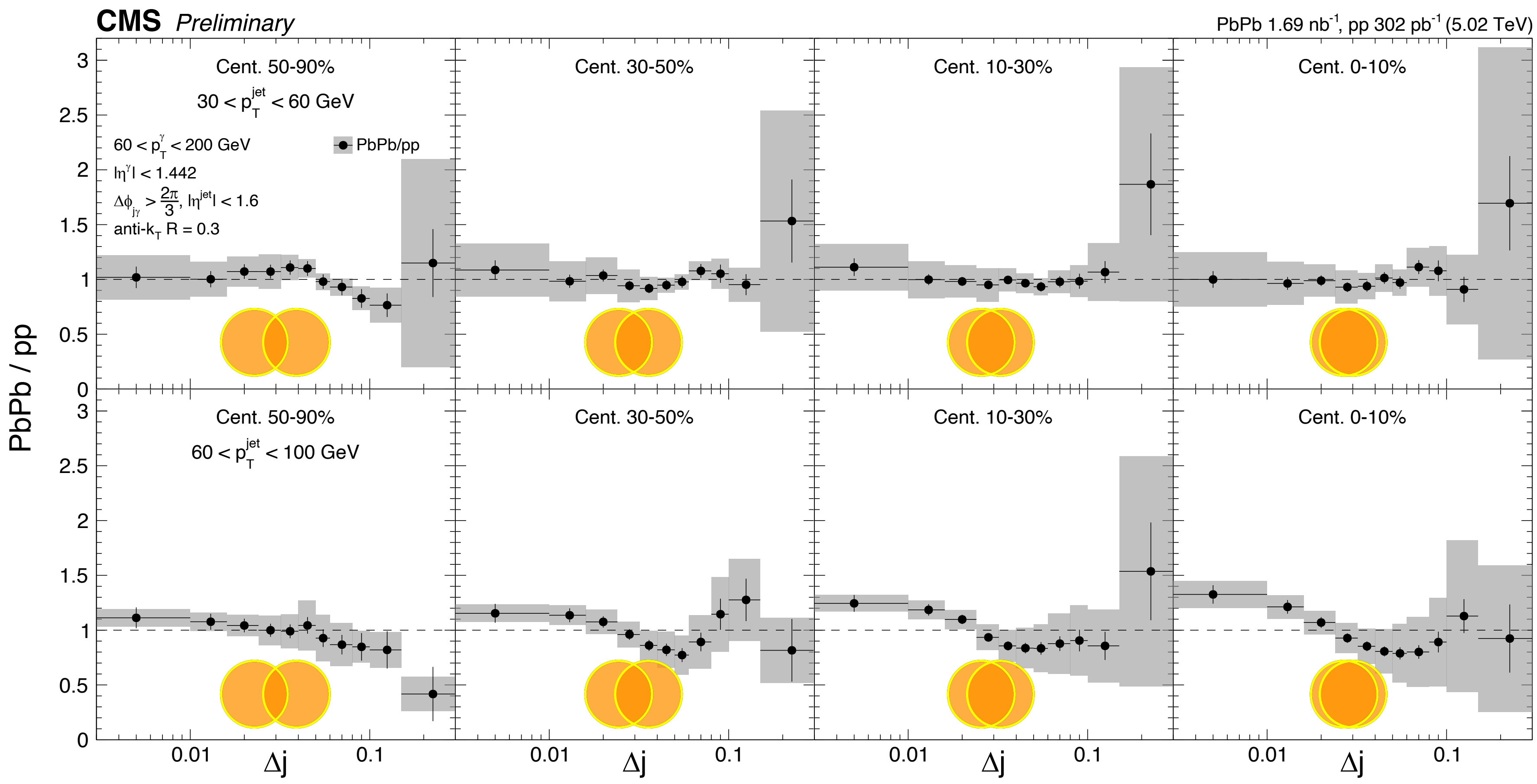
- At low p_T^{jet}: the PbPb and pp spectra are consistent within uncertainties, possibly due to competing effects and the relatively flat p_T^{jet} spectrum, which arises from the photon tag requirement
- Per photon jet yields are consistent with past measurements of photon-jet I_{AA} [CMS: PLB 785 (2018) 14]

Δj shape ratios

CMS: PAS-HIN-21-019



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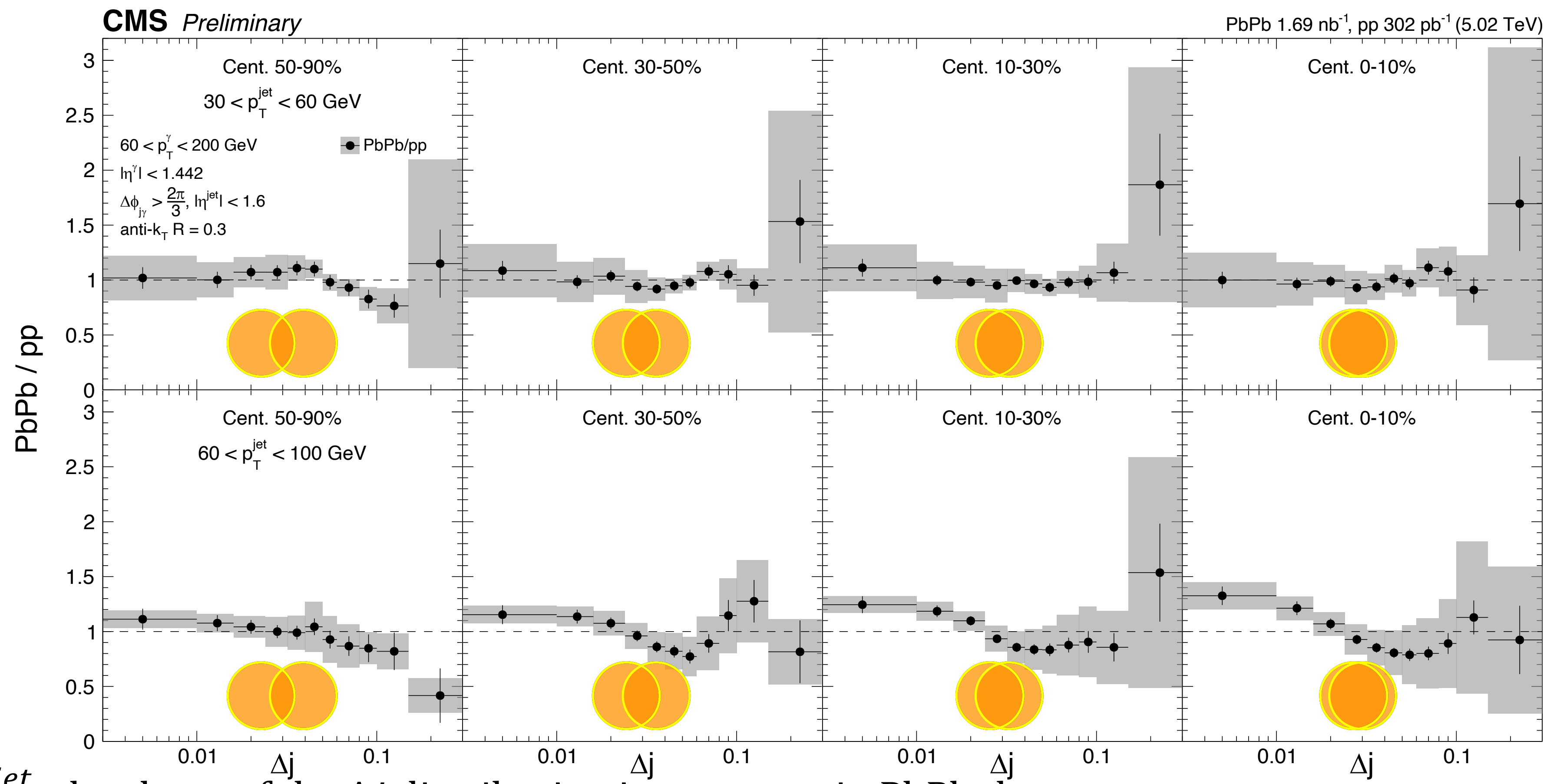

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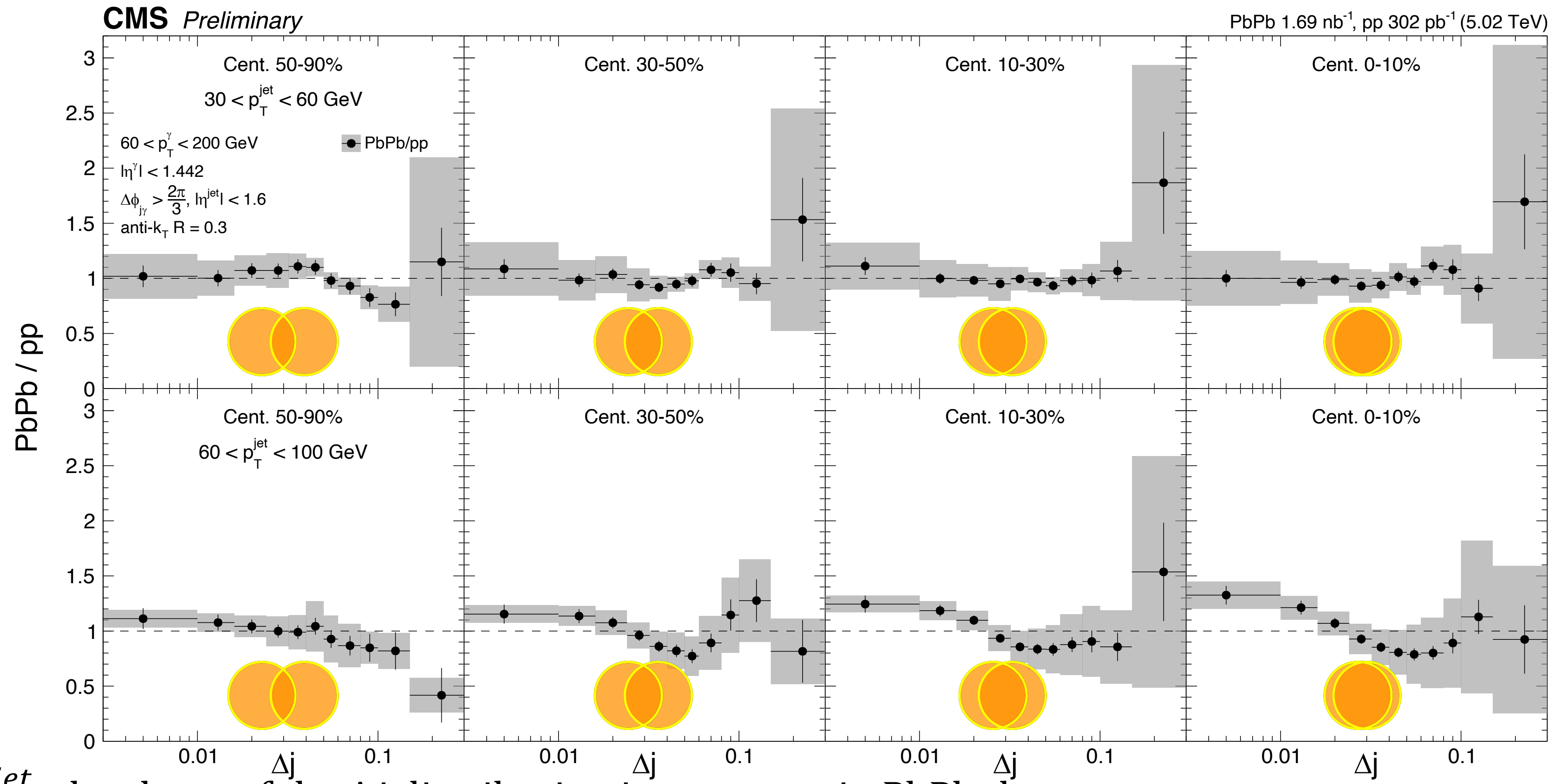

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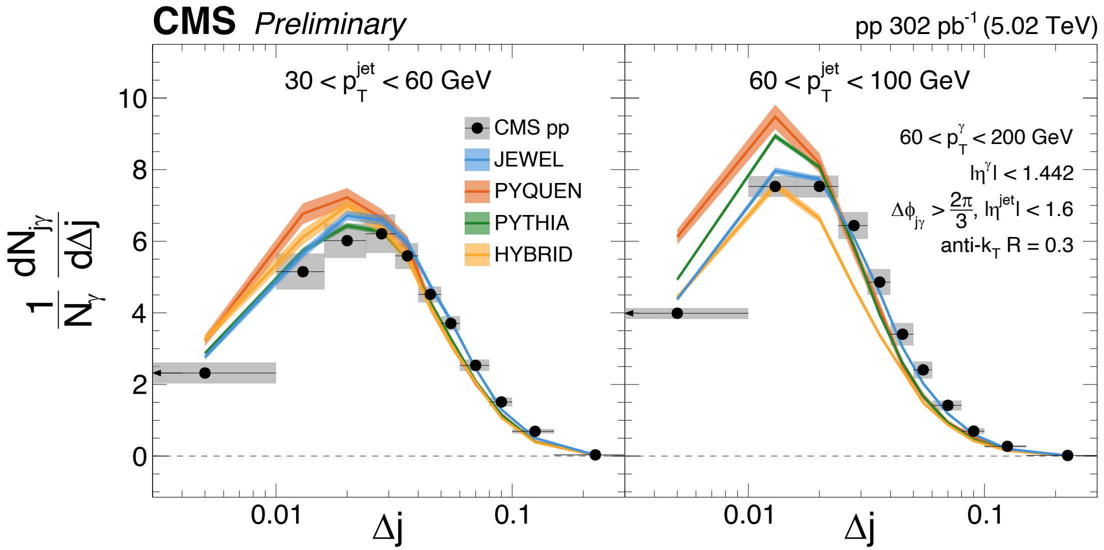
Δj spectra theory comparison: pp collisions

CMS: [PAS-HIN-21-019]

- **Jewel**: based on Pythia 6.4
- **Pyquen**: based on Pythia 6.4
- **Pythia**: Pythia 8.230 with the CP5 tune
- **Hybrid**: based on Pythia 8.3 with the Monash tune



Δj spectra theory comparison: pp collisions

CMS: PAS-HIN-21-019

- PP data agrees best with Jewel prediction, especially at high p_T^{jet}
- Hybrid prediction undershoots the data at large Δj
- Pyquen predicts much narrower distribution than data

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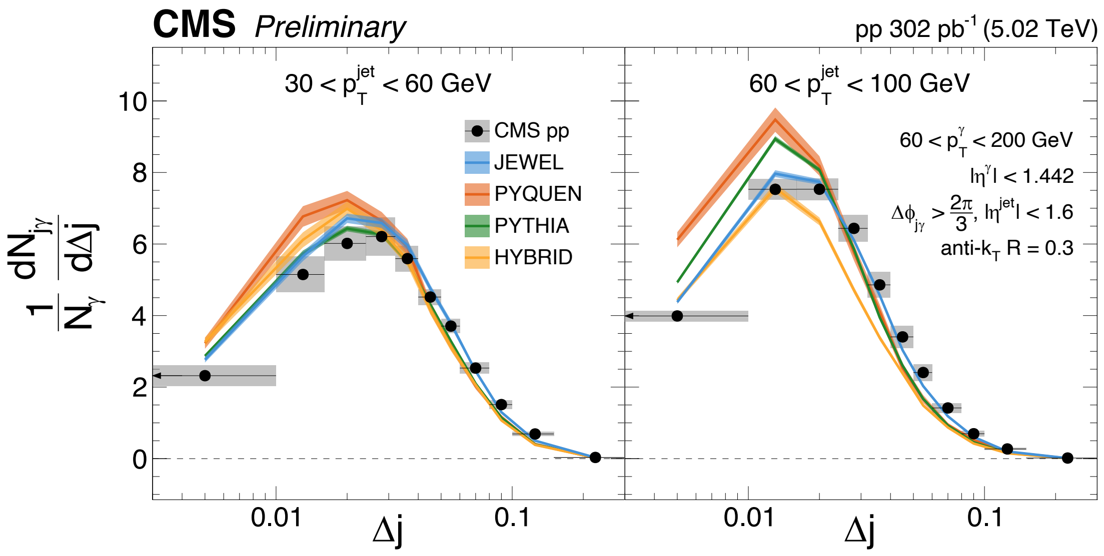
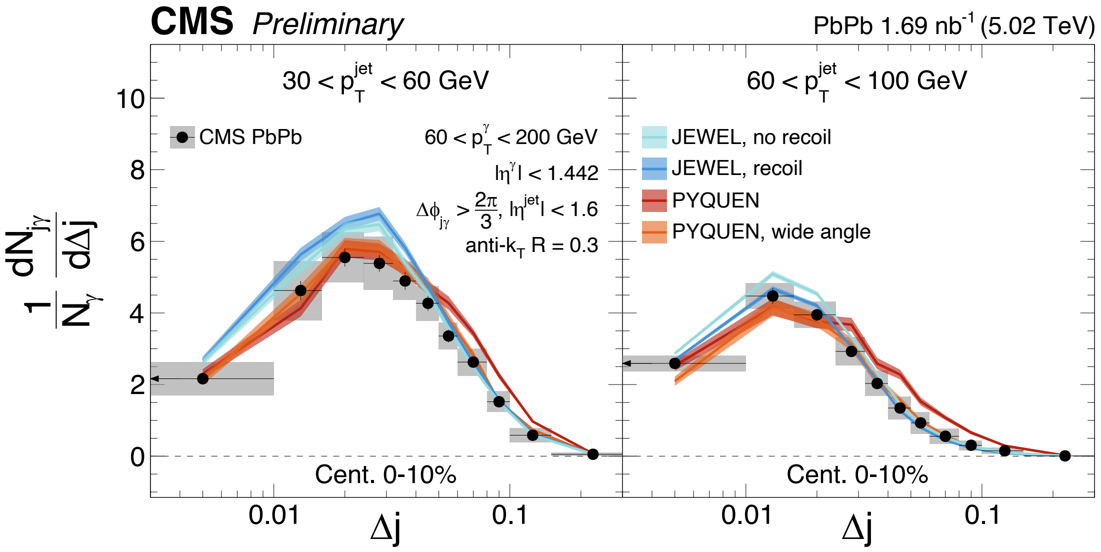


Δj spectra theory comparison: PbPb collisions

- PbPb data agrees best with Jewel prediction at high p_T^{jet}
- Pyquen with wide angle radiation describes data well

- **Jewel, recoil**: medium recoil particles included and subtracted
- Jewel, no recoil: medium recoil particles ignored
- **Pyquen**: baseline model of jet quenching
- **Pyquen, wide angle**: additional wide angle gluon radiation

CMS: PAS-HIN-21-019



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- Hybrid, no elastic, no wake: baseline model of jet quenching
- **Hybrid, no elastic, wake**: conservation of energy
- **Hybrid, elastic, no wake**: scattering from medium particles
- **Hybrid, elastic, wake**: conservation of energy + scattering

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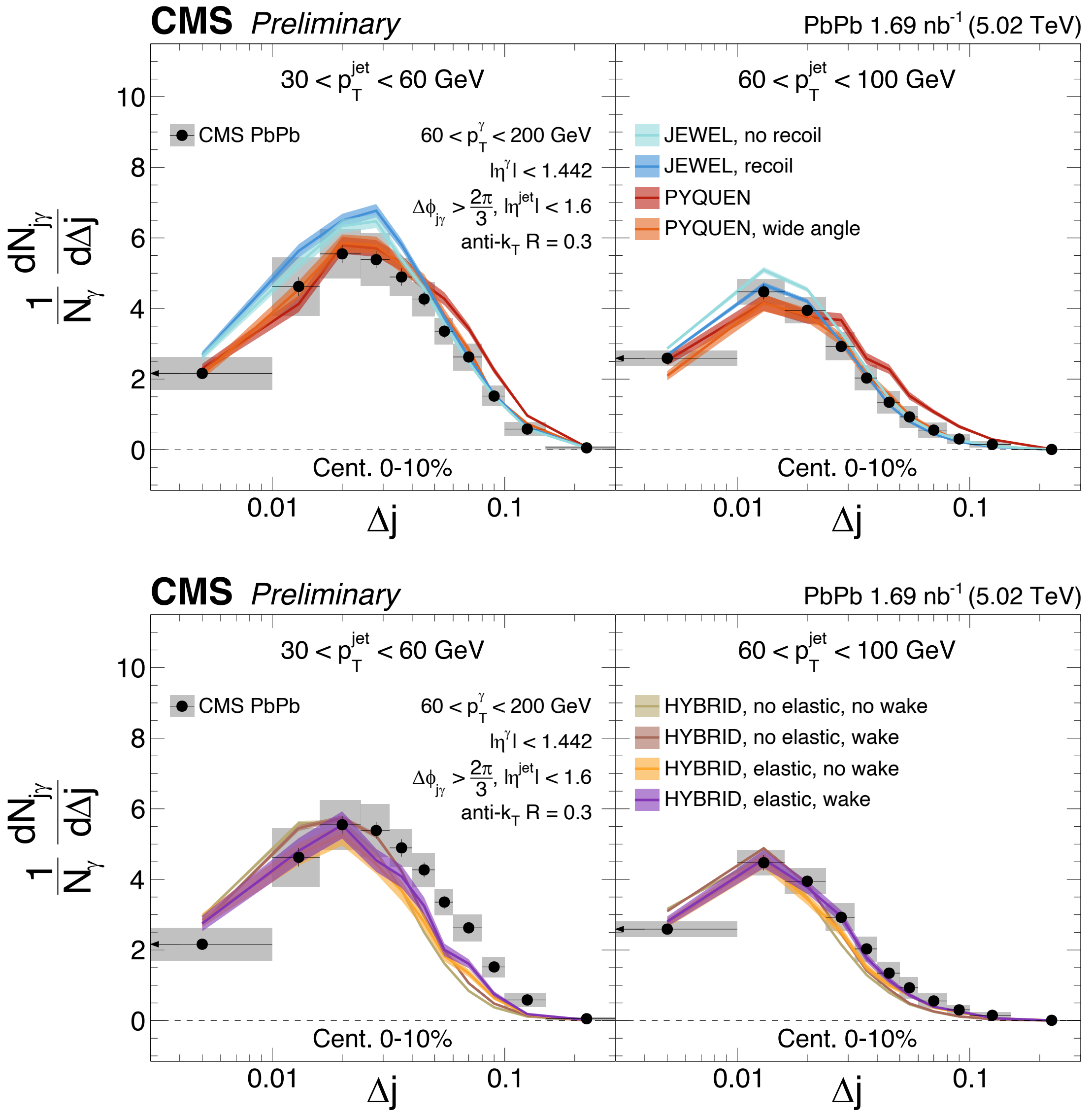

Δj shape ratio theory comparison

CMS: PAS-HIN-21-019

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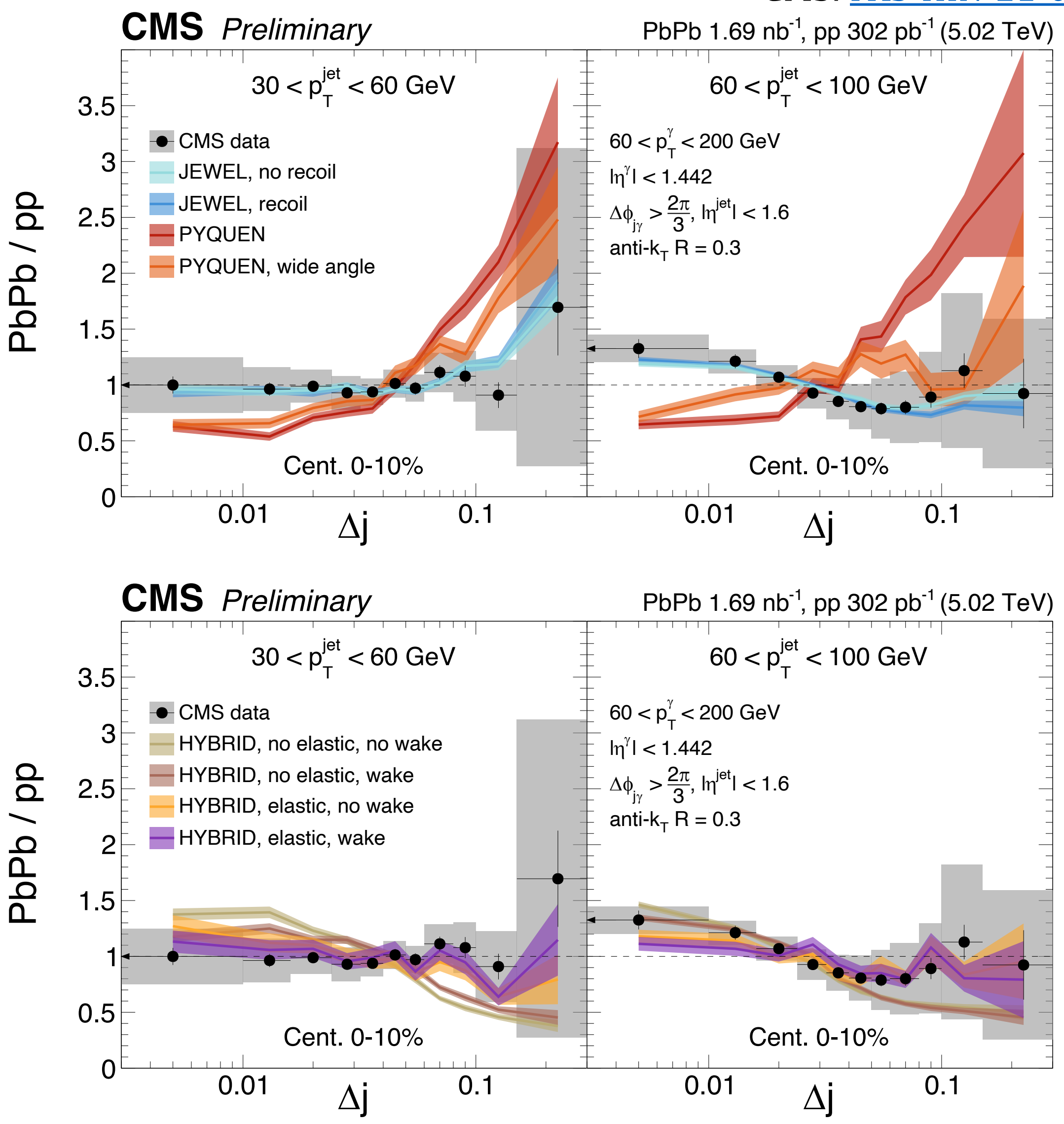

Δj shape ratio theory comparison

- Data agrees well with Jewel and with Hybrid with elastic scattering effects
- Pyquen overpredicts broadening effects
- Shapes are relatively insensitive to wake affects, which appear to mostly affect the overall jet yield

- **Jewel, recoil**: medium recoil particles included and subtracted
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- **Pyquen**: baseline model of jet quenching
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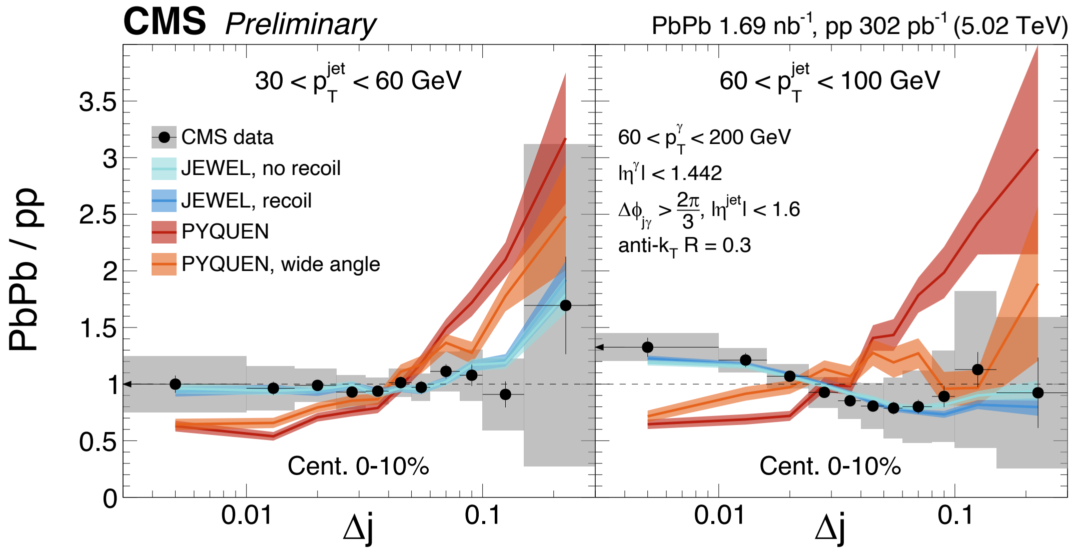
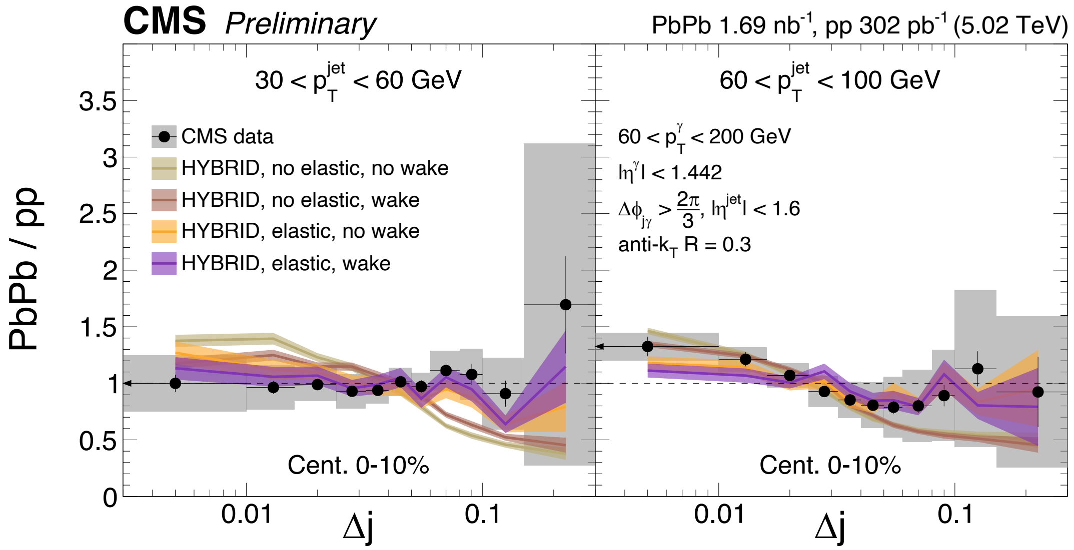
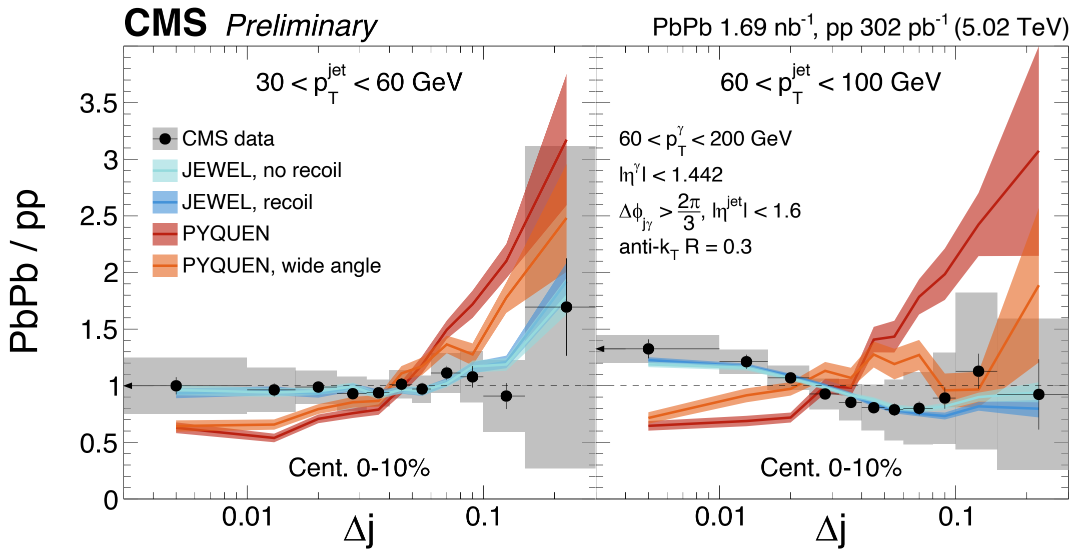


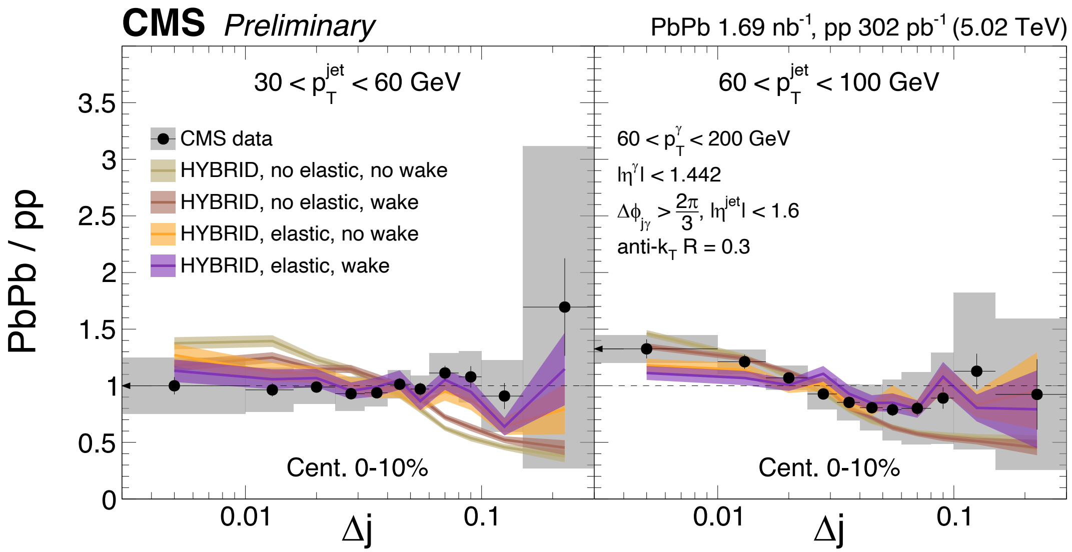


Summary

CMS: [PAS-HIN-21-019]

- Measured jet axis decorrelation in photon-tagged jet events in PbPb and pp
  - Jets with 30-60 GeV are compatible in PbPb and pp collisions
  - Jets with 60-100 GeV are narrower in PbPb compared to pp collisions
- Observable is insensitive to medium wake effects
- Selection bias in higher jet p_T may cause the observed narrowing
- At lower jet p_T, Hybrid predictions indicate that elastic scattering effects are important to describe data

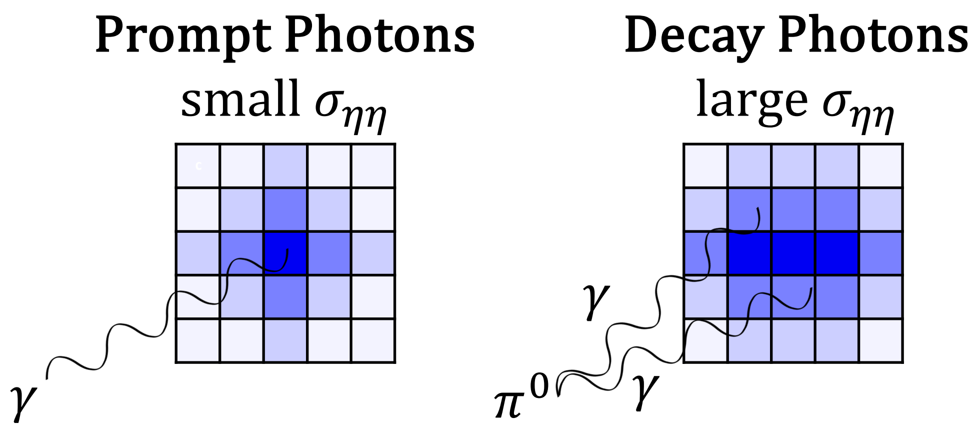


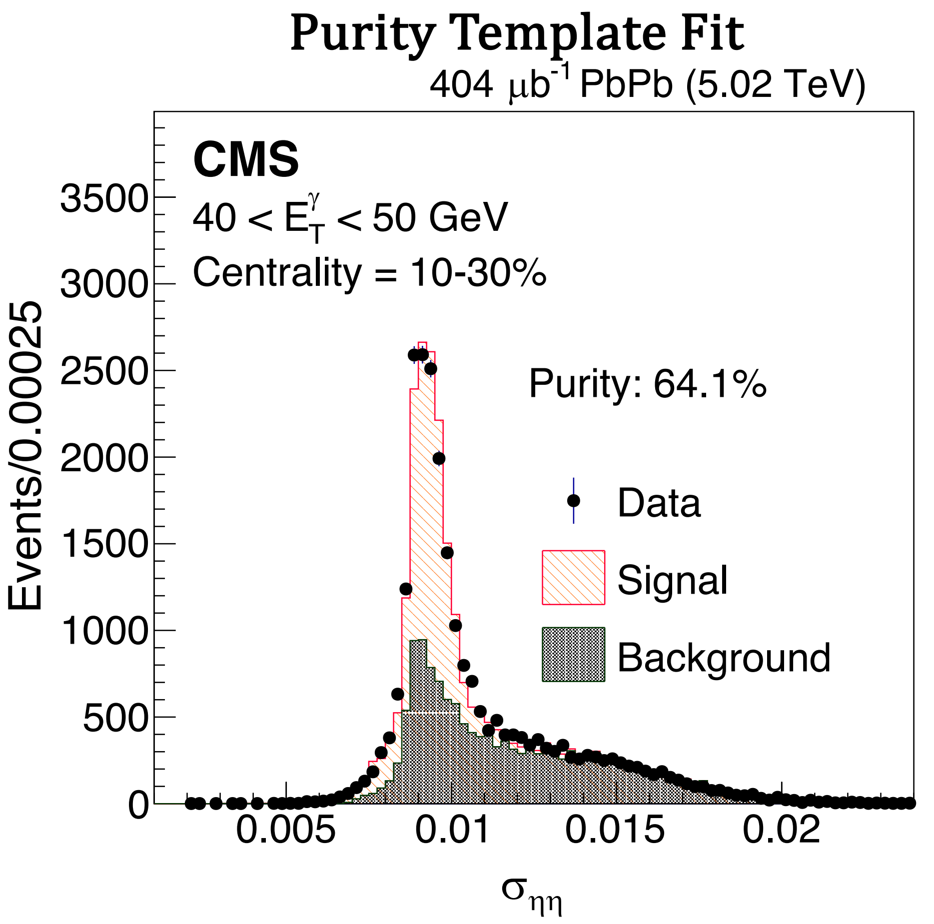


Backup

Purity subtraction

- After isolation requirements and electron rejection, dominant background is from neutral meson decay
- Use modified second moment of ECal distribution
- Most decay photons have larger values of $\sigma_{\eta\eta}$
- Estimate purity with a template fit method and subtract





$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i} \qquad w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}\right)$$

Purity fit example from previous analysis:
CMS: JHEP 2020, 116 (2020)

Systematic uncertainties

- **Electron contamination**: Accounts for electrons remaining in the sample after electron rejection
  Evaluated by turning off electron rejection throughout analysis and scaling difference in Δj by electron rejection inefficiency
- **Photon purity**: Accounts for uncertainty in the background template shape for purity fitting
  Evaluated by varying the isolation cuts used to obtain the background template, running analysis with alternate purity values, and taking the largest variation in the final result
  - Nominal: 10 GeV $<$ sumIso $<$ 20 GeV sideband used for background template
  - Loose: 15 GeV $<$ sumIso $<$ 25 GeV sideband used for background template
  - Tight: 5 GeV $<$ sumIso $<$ 15 GeV sideband used for background template
- **Photon isolation definition**: Accounts for difference between reconstruction-level and generator-level isolation
  Evaluated by running MC with generator-level photon isolation through the analysis, comparing to MC with reconstruction-level photon isolation, and scaling the difference to data
- **Photon energy scale**: Accounts for uncertainty in the photon energy scale
  Evaluated by finding the ratio in the Z boson mass peak between data and MC and applying the scale difference to photons in data

★ **Jet energy correction**: Accounts for uncertainty in the overall jet energy scale
Evaluated by increasing and decreasing the jet energy scale by its uncertainty when making response matrices, and taking the largest variation in the final result
  - PbPb: Autumn18_HI_V8_DATA_Uncertainty_AK3PF.txt
  - PP: Spring18_ppRef5TeV_V6_DATA_Uncertainty_AK3PF.txt

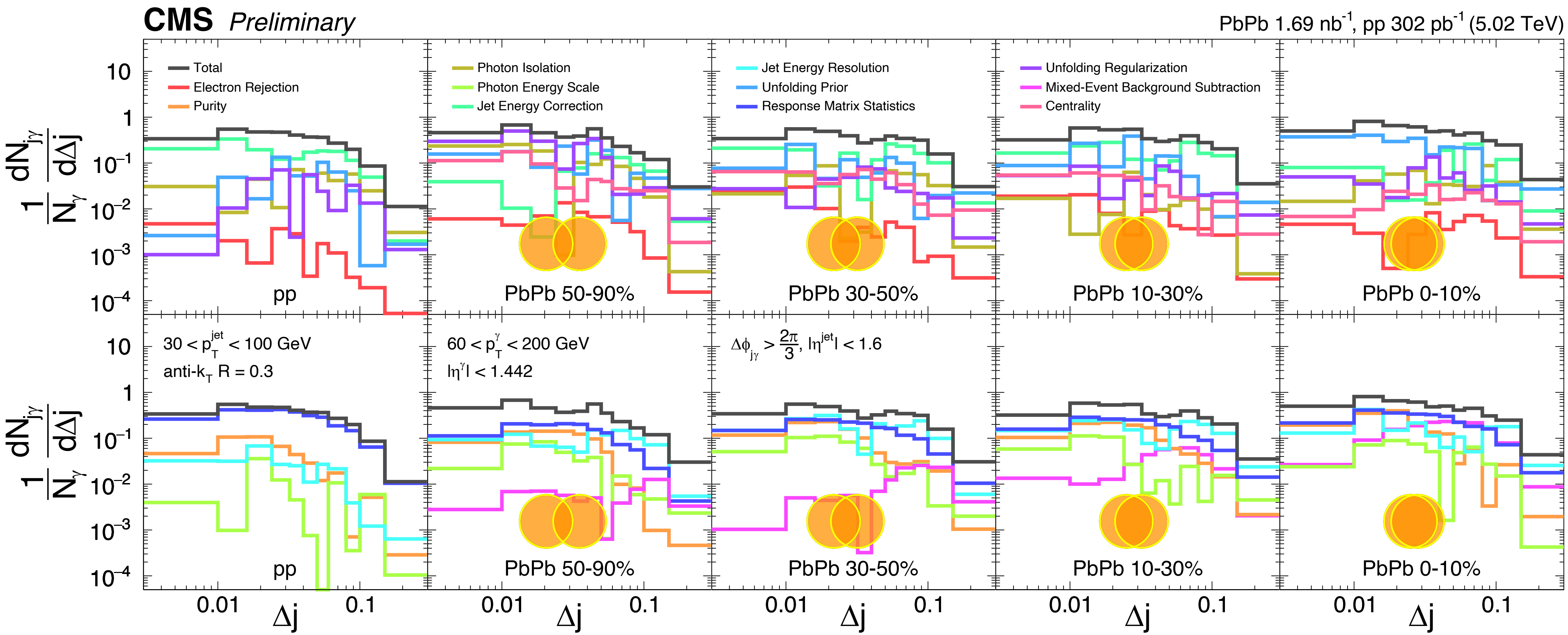
★ **Jet energy resolution**: Accounts for uncertainty the data/MC JER difference
Evaluated by smearing response matrices by an additional amount according to the scale factor uncertainty

Systematic uncertainties

- ★ Unfolding prior: Accounts for prior bias effects
  Evaluated by reweighting the response matrix truth with Jewel PbPb 0-10% for all centrality classes and collision systems
  - BayesUnfold takes prior from response matrix truth
- ★ Response matrix statistics: Accounts for uncertainty in the unfolded result due to limited response matrix statistics
  Evaluated by throwing 100 toys from the response matrix using each bin's uncertainty, unfolding data with each response matrix, and calculating the standard deviation in the sample of unfolded results
- Unfolding regularization: Accounts for uncertainty in regularization determination
  Evaluated by finding the maximal variation in the unfolded results with regularization strength chosen based on other Asmiov datasets MSE
  - Nominal: use Jewel PbPb 0-10% to determine regularization of minimum MSE
  - Alternate: use Jewel PP, Pyquen PbPb 0-10%, or Pyquen PP to determine regularization of minimum MSE
- ★ Mixed-event background subtraction: accounts for effects of potential over-subtraction
  Evaluated by running MC that bypasses the mixed-event background subtraction with truth-jet matching through the analysis and scaling the difference in the final result to data
- Centrality: Accounts for uncertainty in centrality determination from HF energy sum
  Evaluated by varying the centrality bounds up and down according to the provided centrality tables (link)

Systematic uncertainties: $30 < p_T^{jet} < 100$ GeV

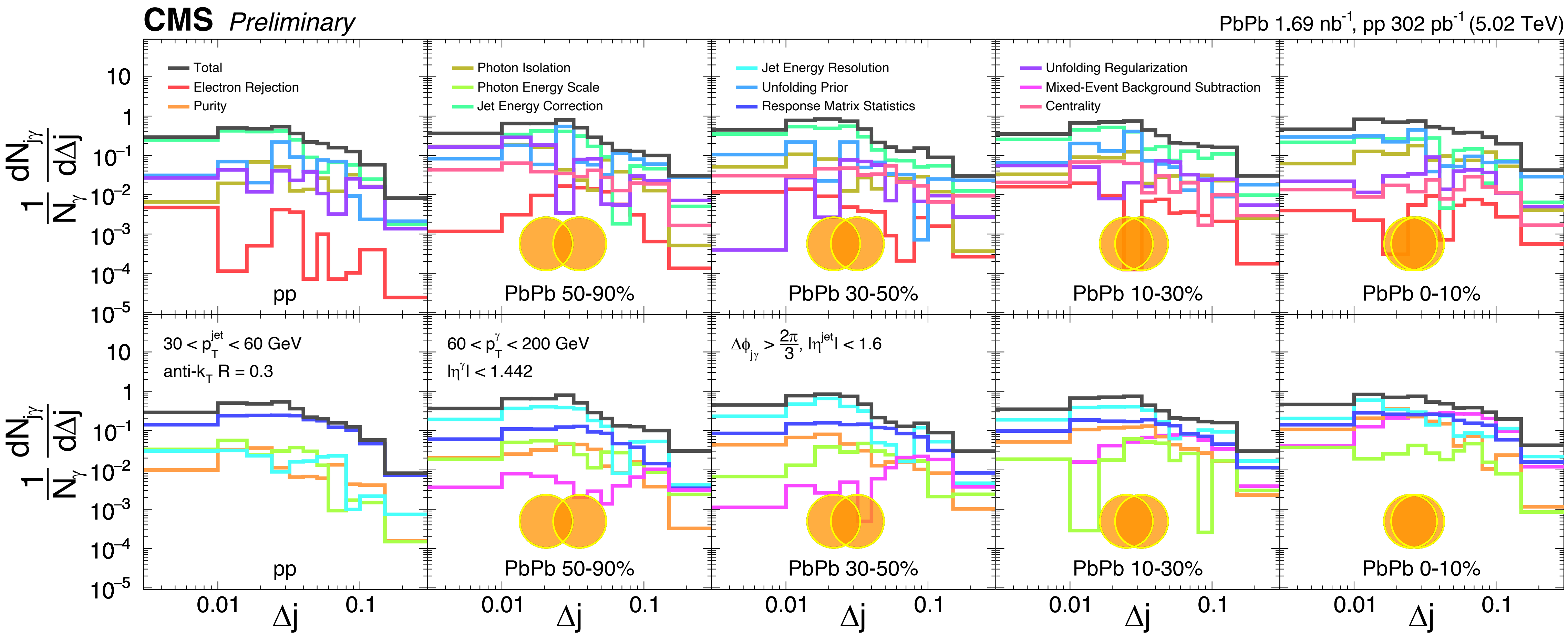
CMS: PAS-HIN-21-019



- Dominant systematics are the jet energy correction and jet energy resolution uncertainties
- Subdominant systematics are the mixed-event background subtraction, response matrix statistics, and unfolding prior

Systematic uncertainties: $30 < p_T^{jet} < 60$ GeV

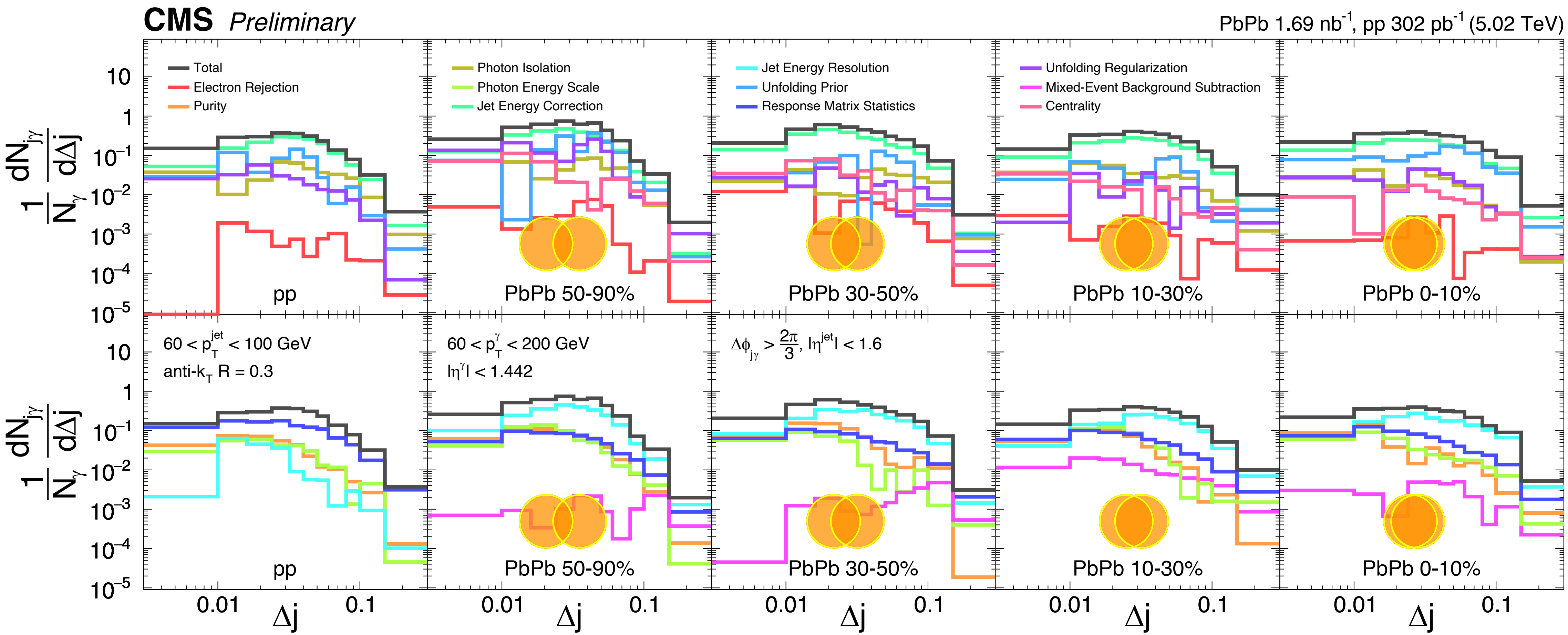
CMS: PAS-HIN-21-019



- Dominant systematics are the jet energy correction and jet energy resolution uncertainties
- Subdominant systematics are the mixed-event background subtraction, response matrix statistics, and unfolding prior

Systematic uncertainties: $60 < p_T^{jet} < 100$ GeV

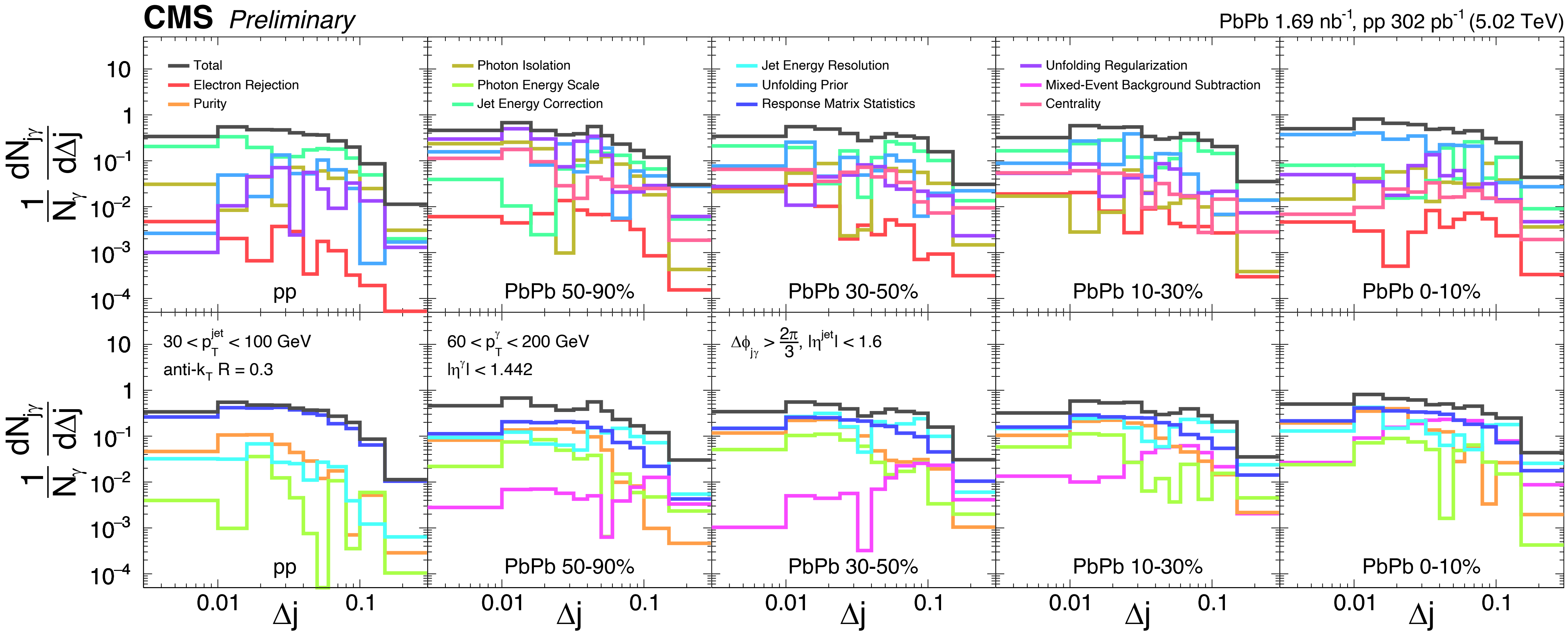
CMS: PAS-HIN-21-019



- Dominant systematics are the jet energy correction and jet energy resolution uncertainties
- Subdominant systematics are the response matrix statistics and unfolding prior

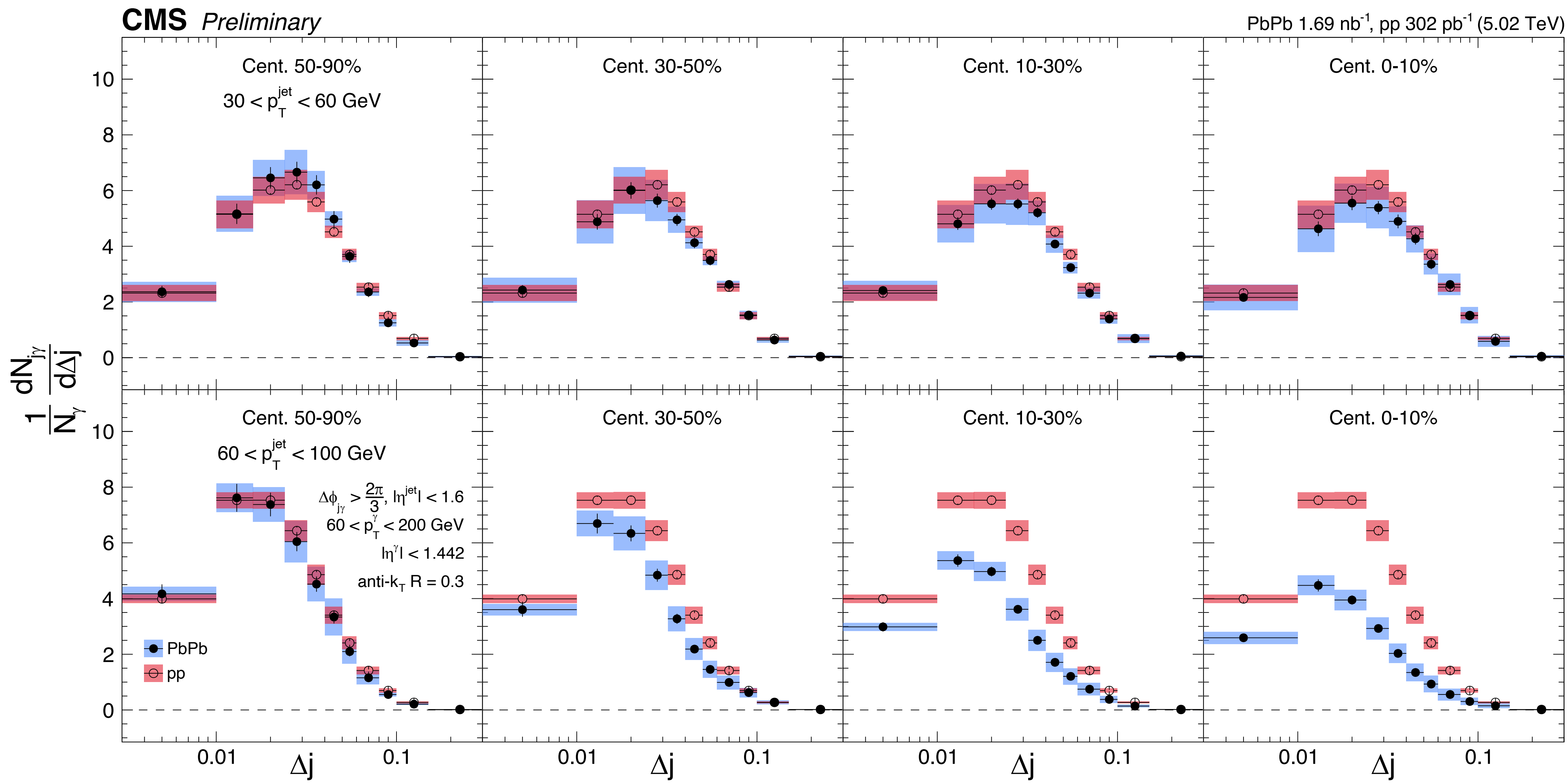
Systematic uncertainties: $30 < p_T^{jet} < 100$ GeV

$30 < p_T^{jet} < 100$ GeV

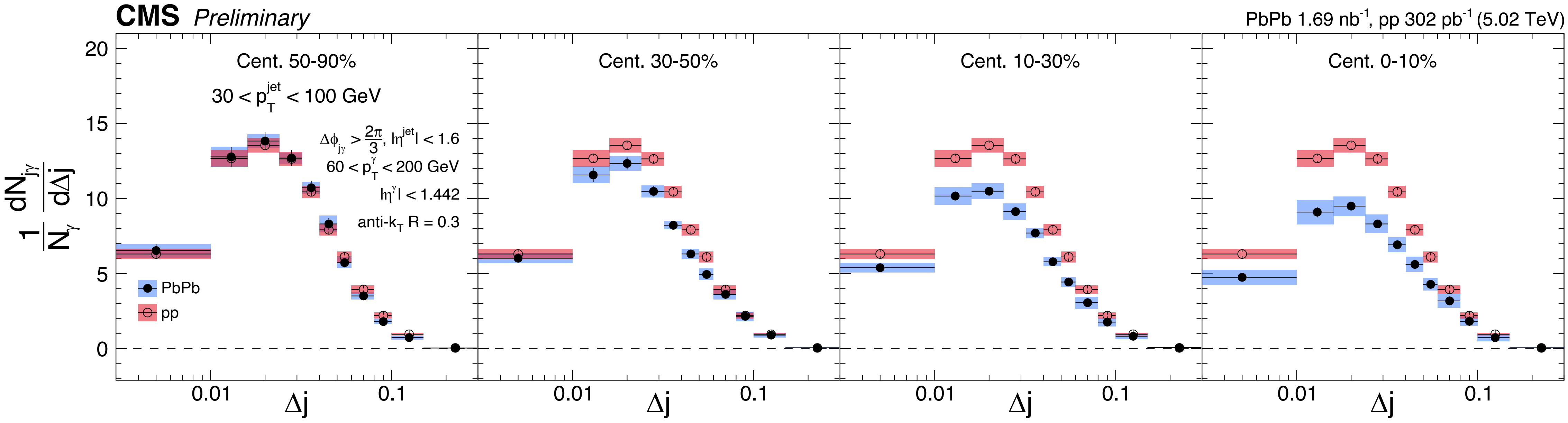


CMS: PAS-HIN-21-019

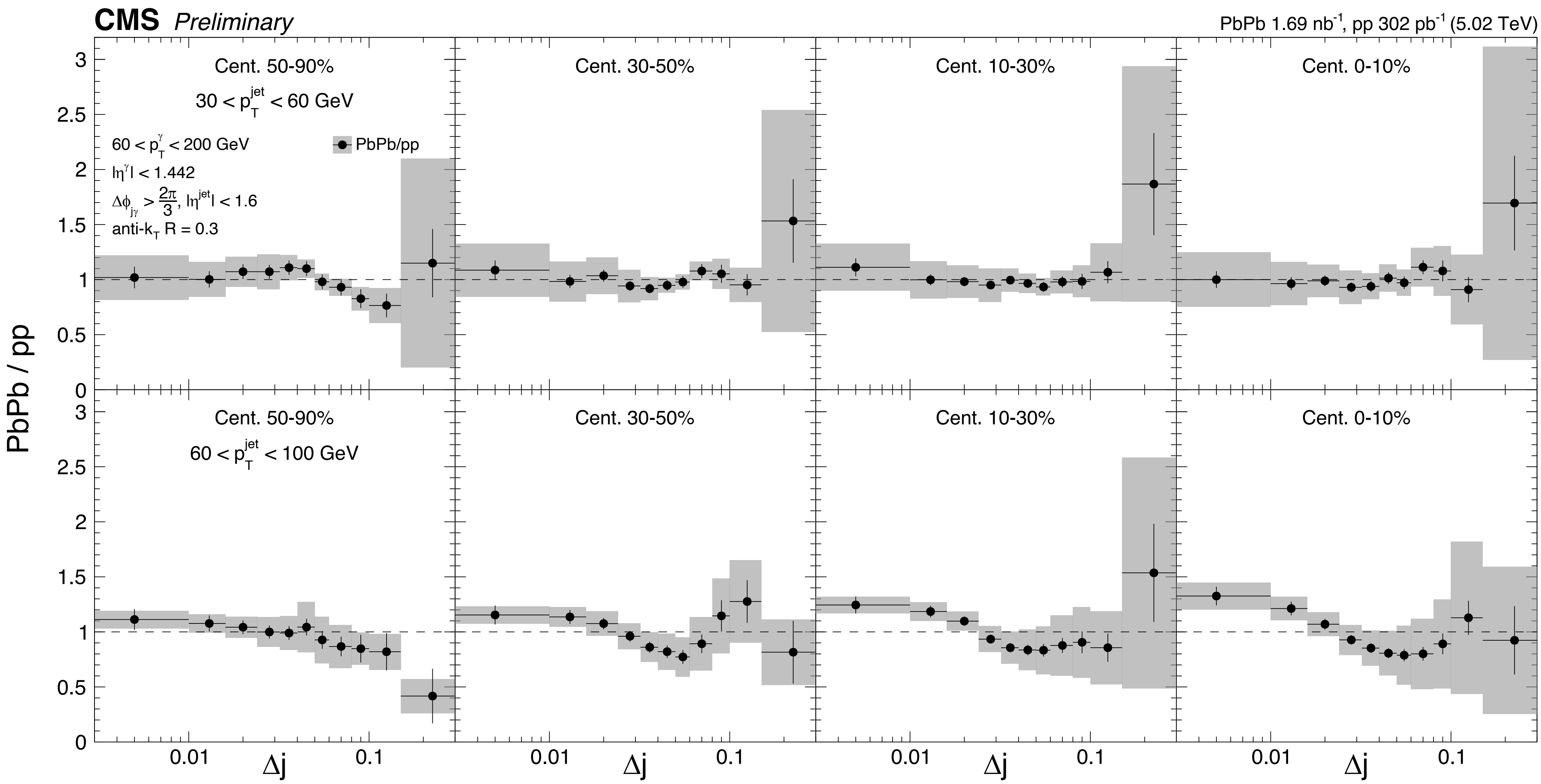
Δj spectra normalized per photon



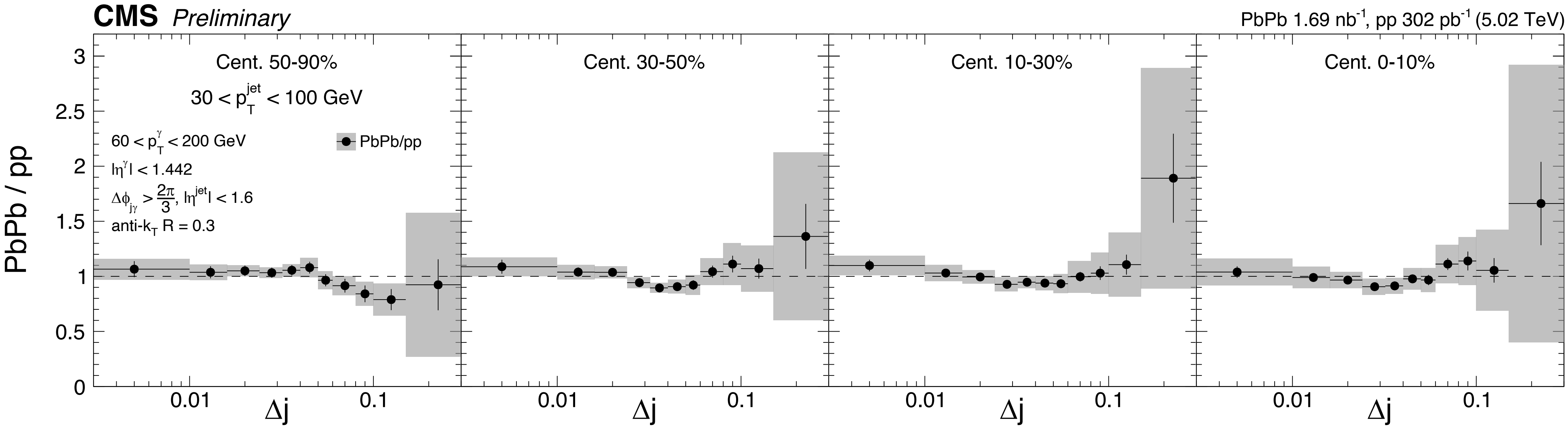
Δj spectra normalized per photon



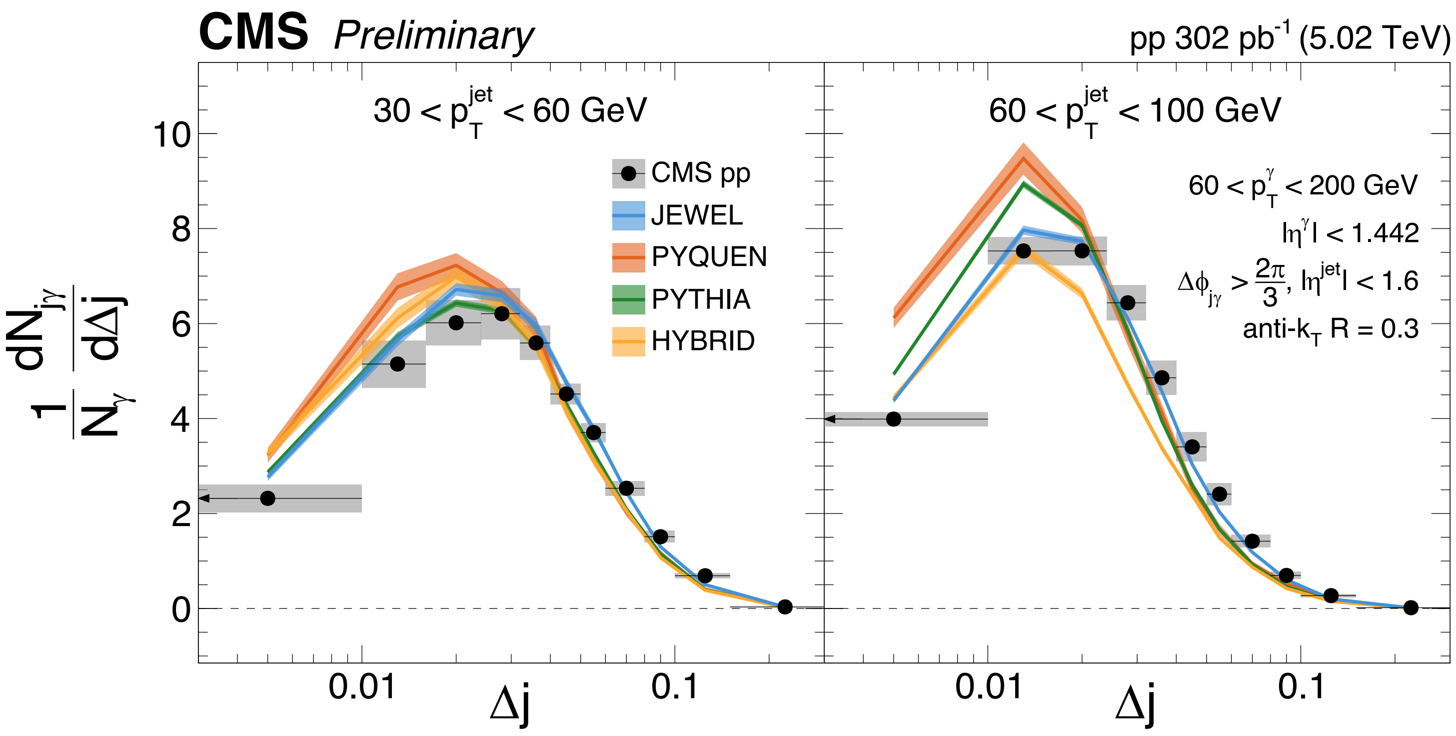
Δj shape ratios

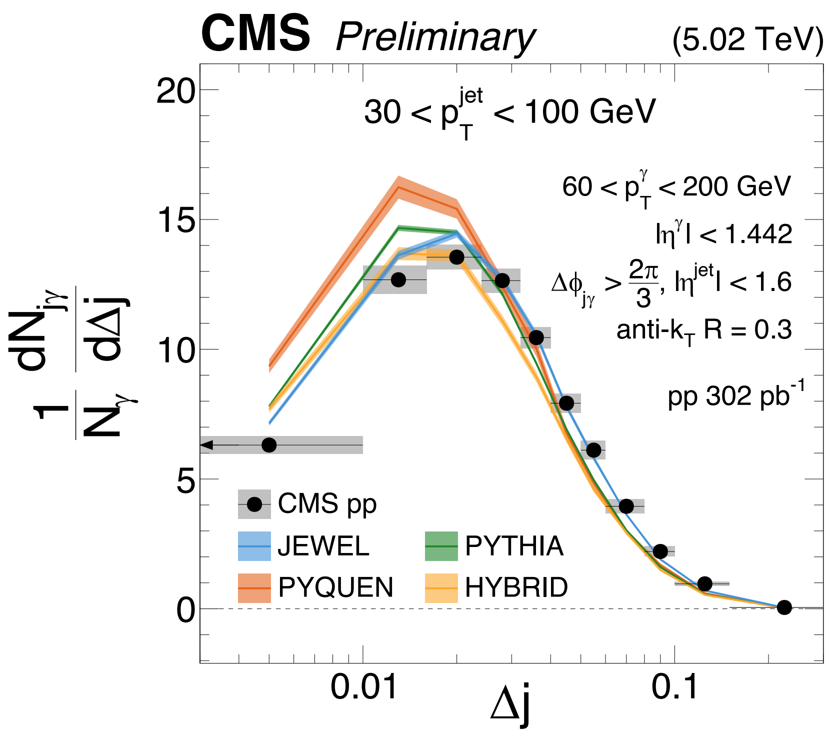


Δj shape ratios

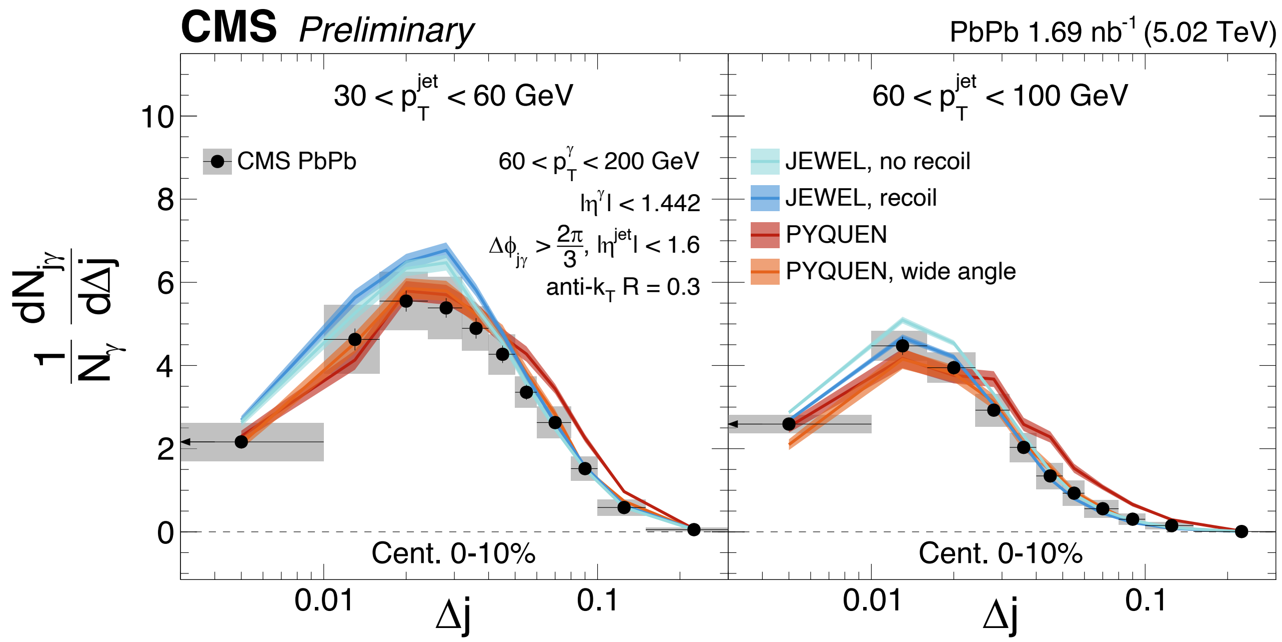


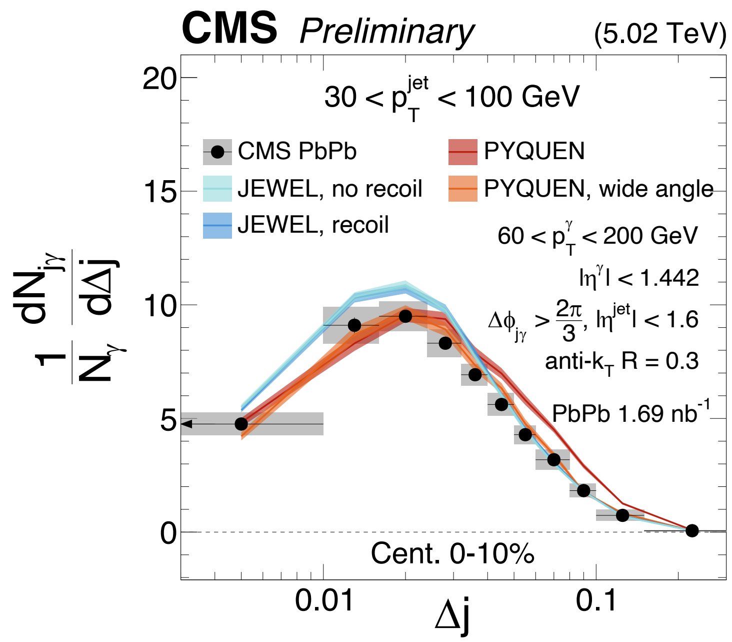
Δj spectra theory comparison: pp collisions

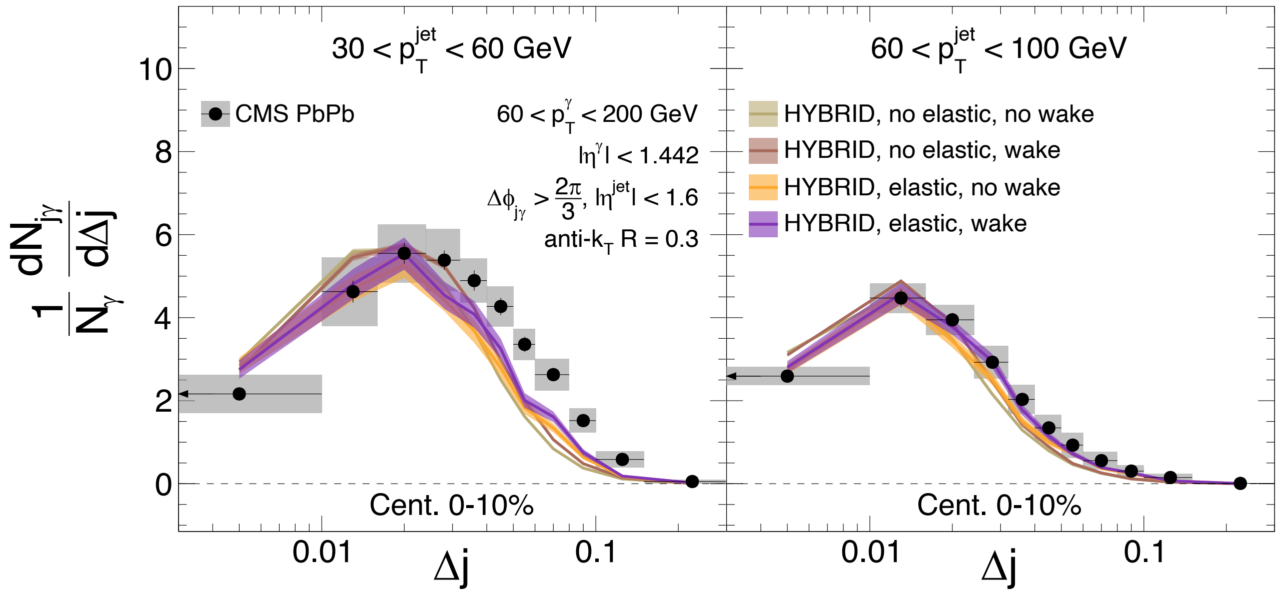


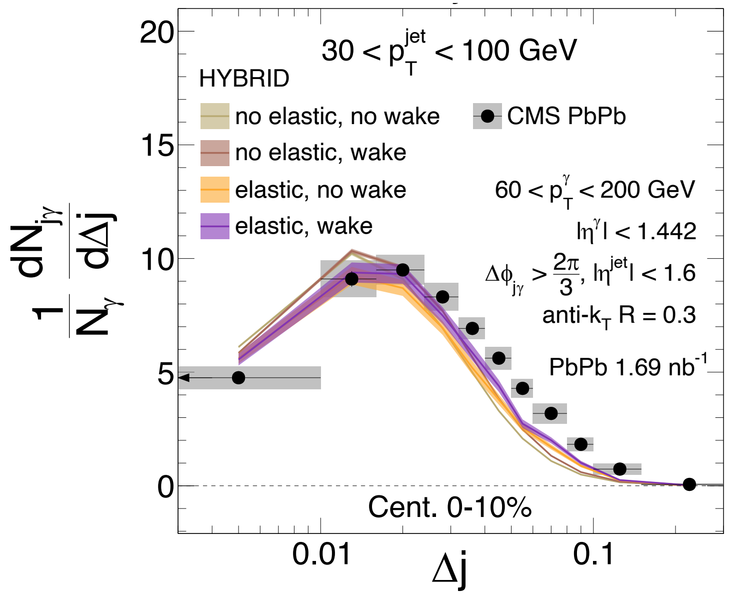


Δj spectra theory comparison: PbPb collisions

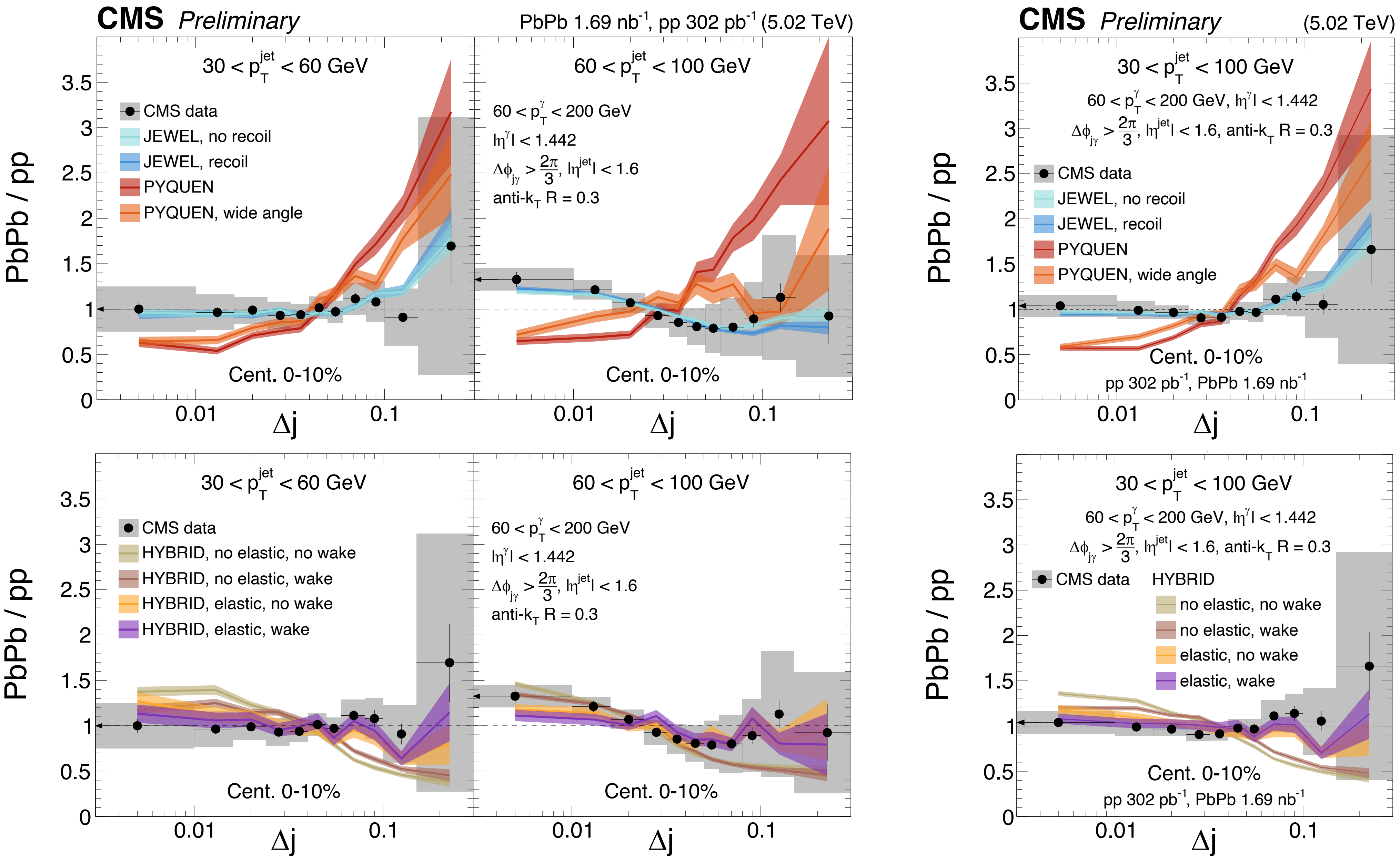




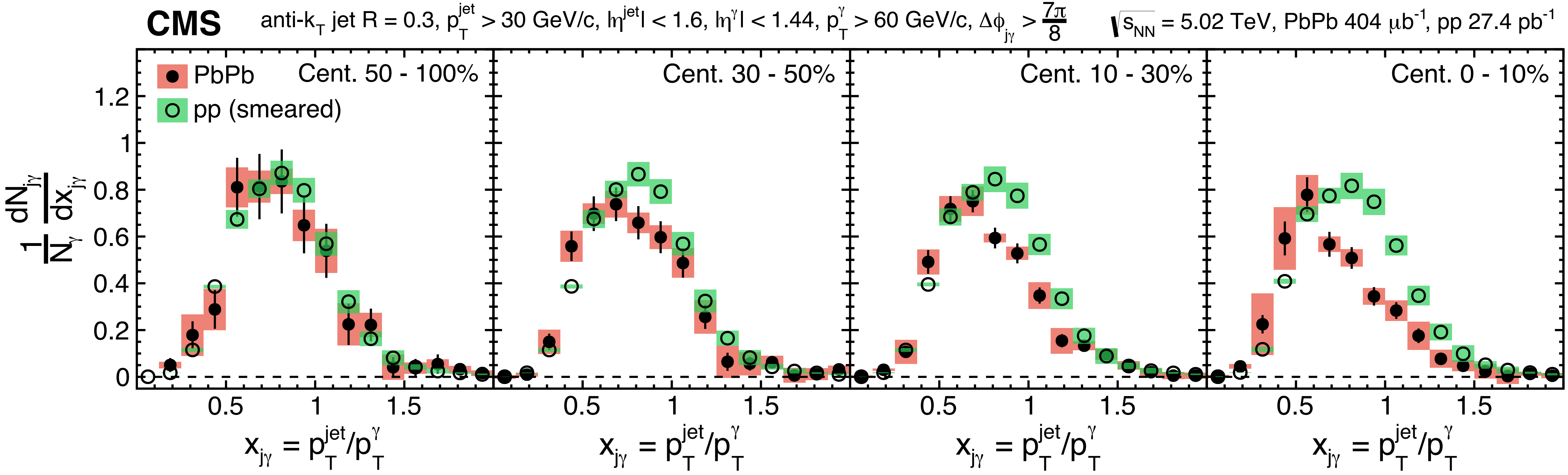




Δj shape ratio theory comparison



$x_{j\gamma}$ measurement



I_{AA} measurement