

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



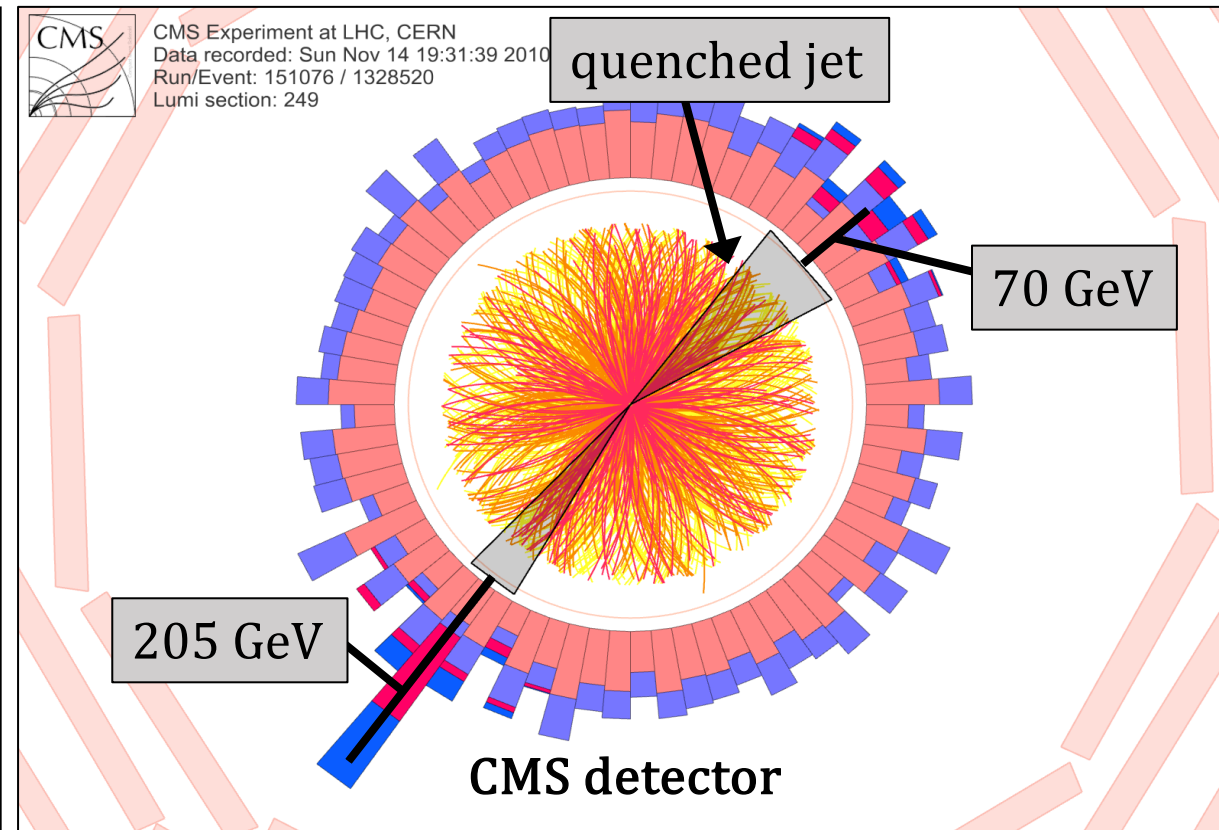
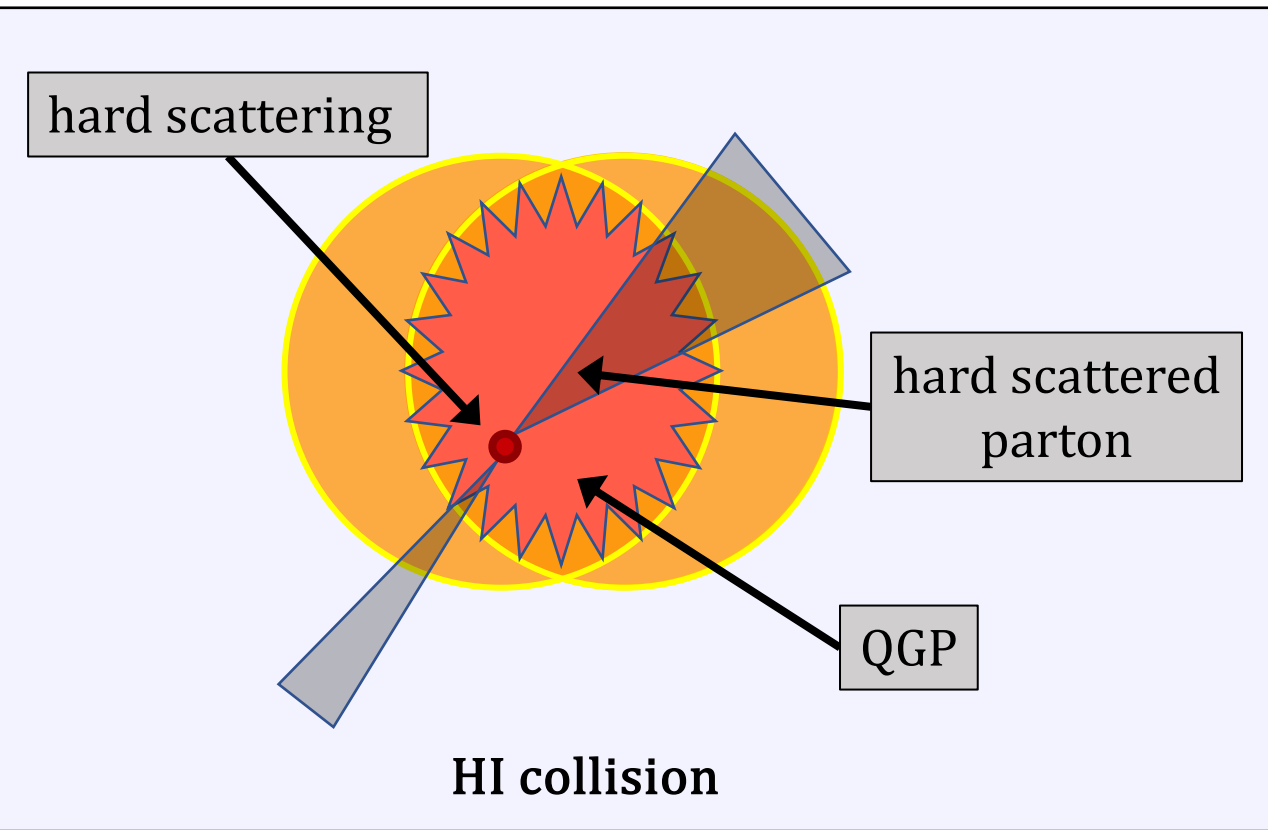
Molly Park
Massachusetts Institute of Technology
for the CMS collaboration

Hard Probes 2024
September 23, 2024



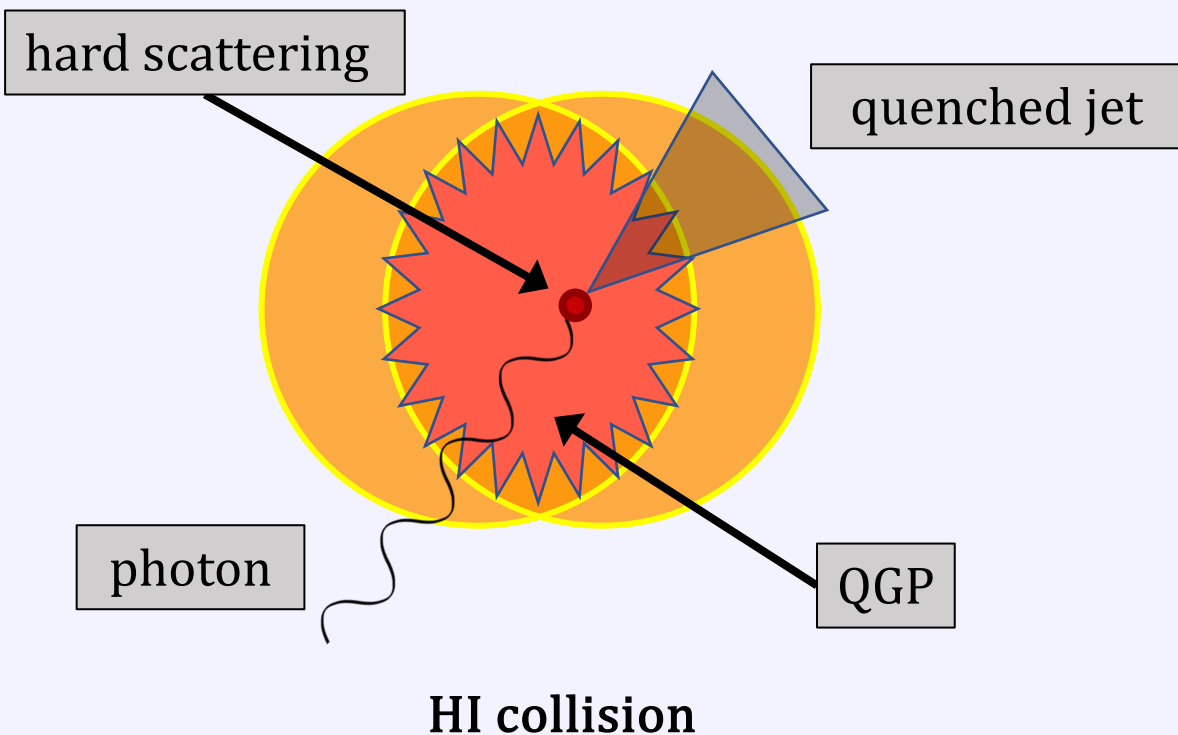
MITHIG group's work was supported
by US DOE-NP

Jet quenching in heavy ion collisions



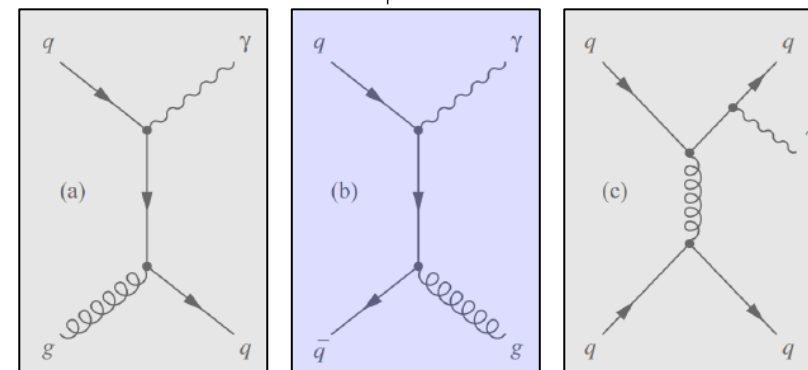
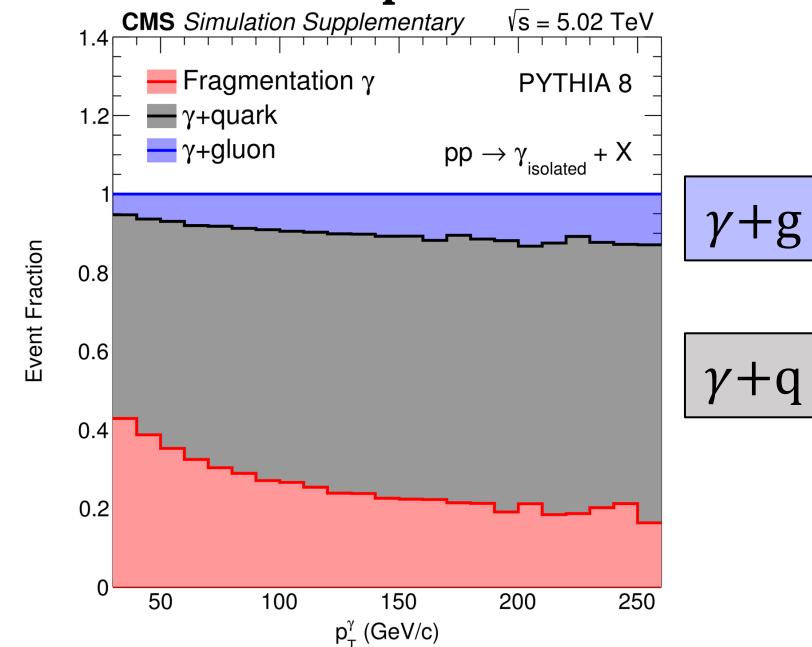
- QGP is formed when heavy ions collide
- Hard scattered partons interact with QGP and lose energy → **jet quenching**
- Studies of jet quenching can probe medium properties, such as transverse momentum broadening
- In dijet events there is a **selection bias** from jet p_T requirements, since both jets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

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

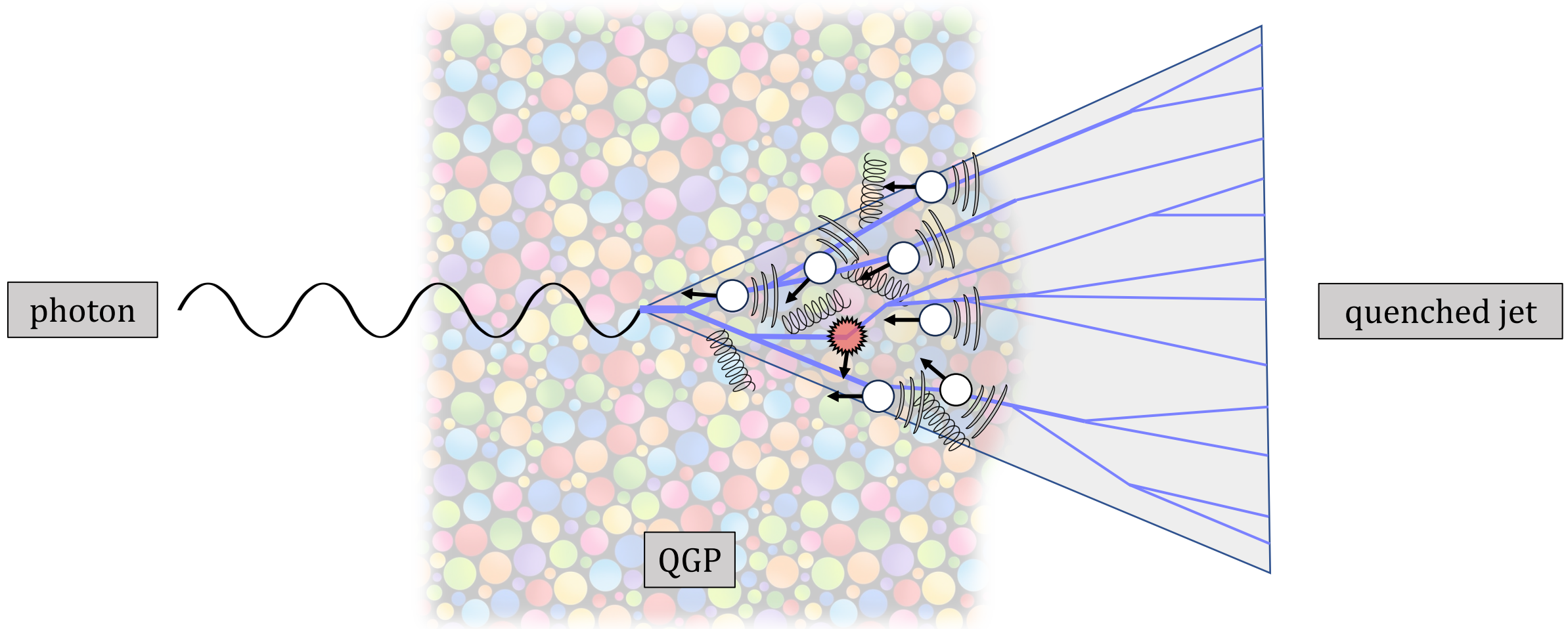
Composition of events with isolated photons



CMS: [PRL 122 \(2019\) 152001](#)

Jet energy loss and substructure observables

- 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

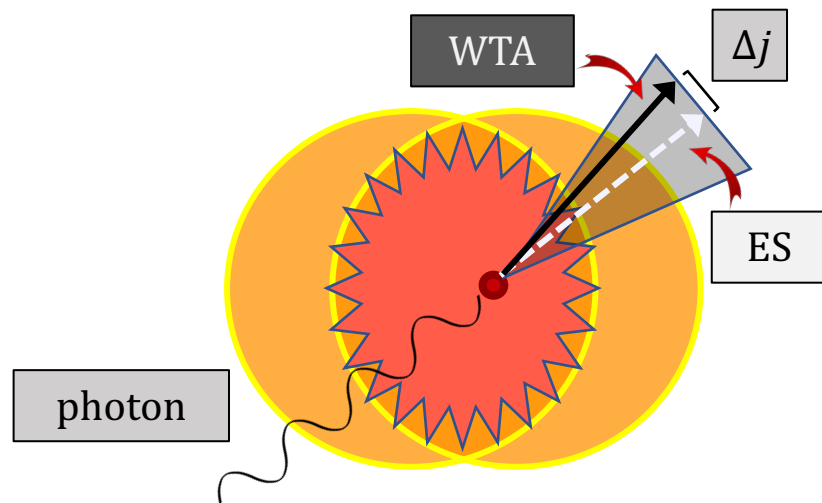
Jet axis difference

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

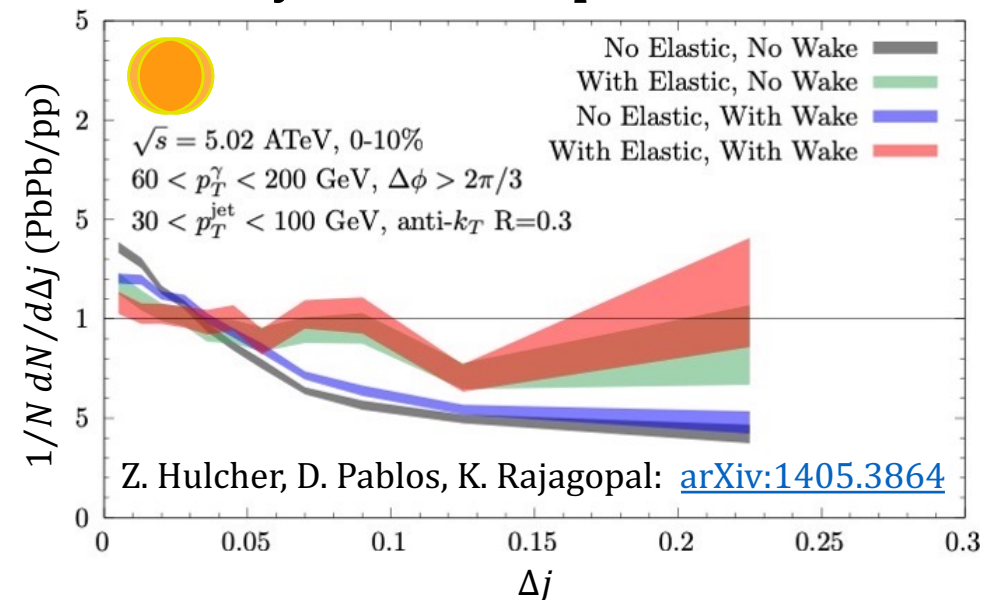
WTA axis = direction of leading energy flow in jet **E-Scheme axis** = direction of average energy flow in jet

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

Photon-jet schematic



Hybrid model prediction



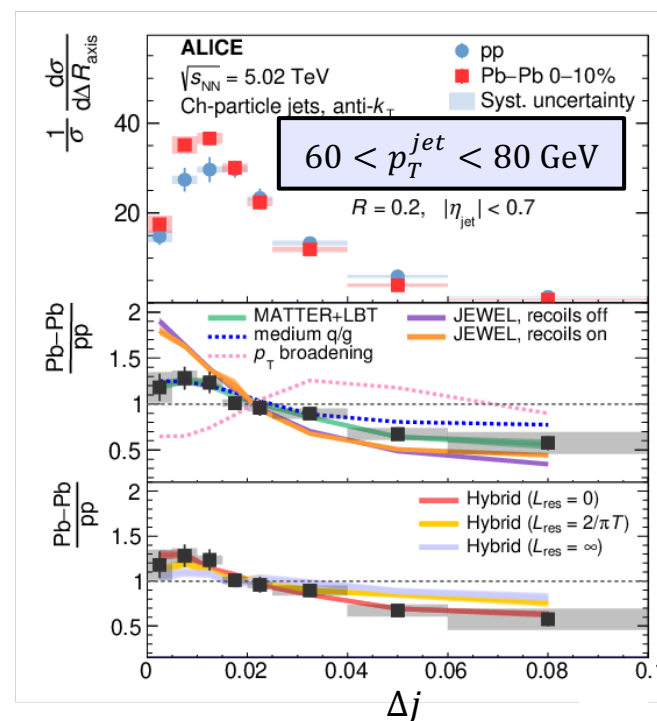
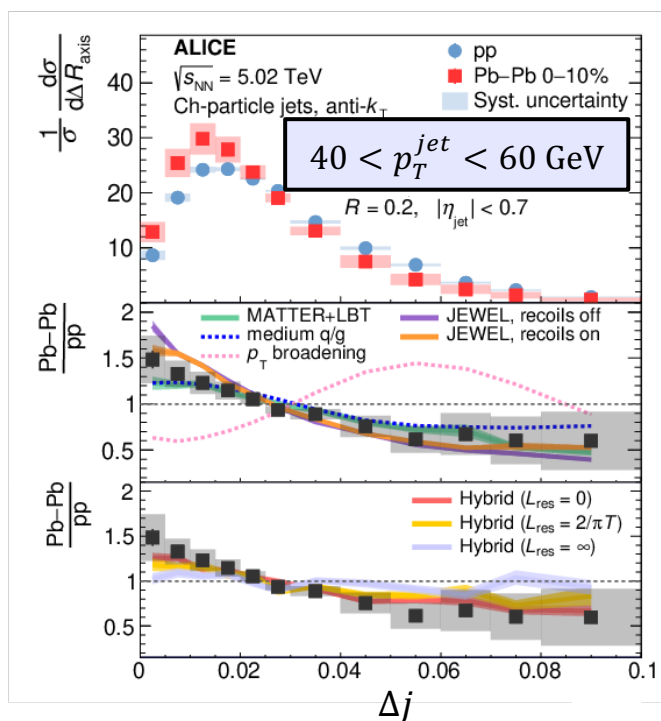
Potentially sensitive to **elastic scattering** effects in the QGP

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

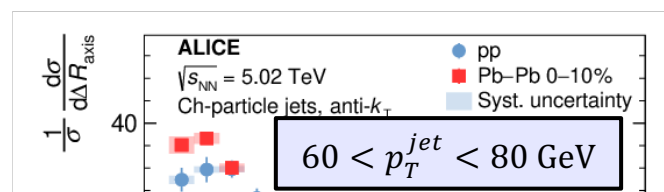
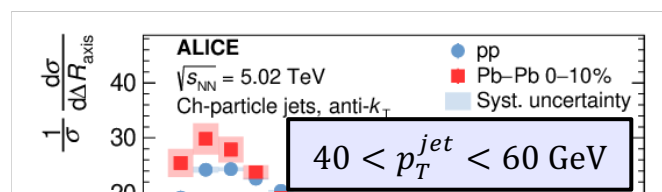
Inclusive jet measurements of Δj show signs of narrowing in PbPb compared to pp collisions
 In other jet measurements such as R_g , narrowing in inclusive jets likely due to **selection bias**

Previous measurement in inclusive jets

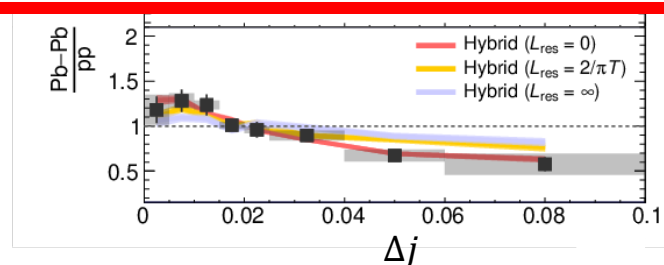
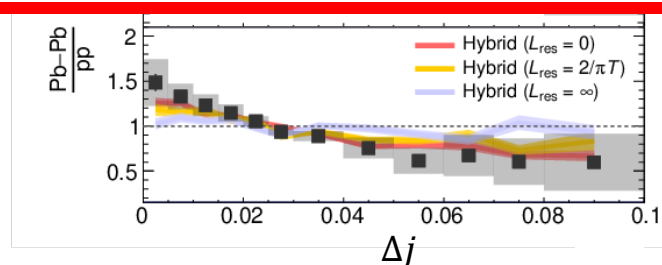
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See Raghunath's talk next for the new CMS inclusive jet Δj measurement at high jet p_T

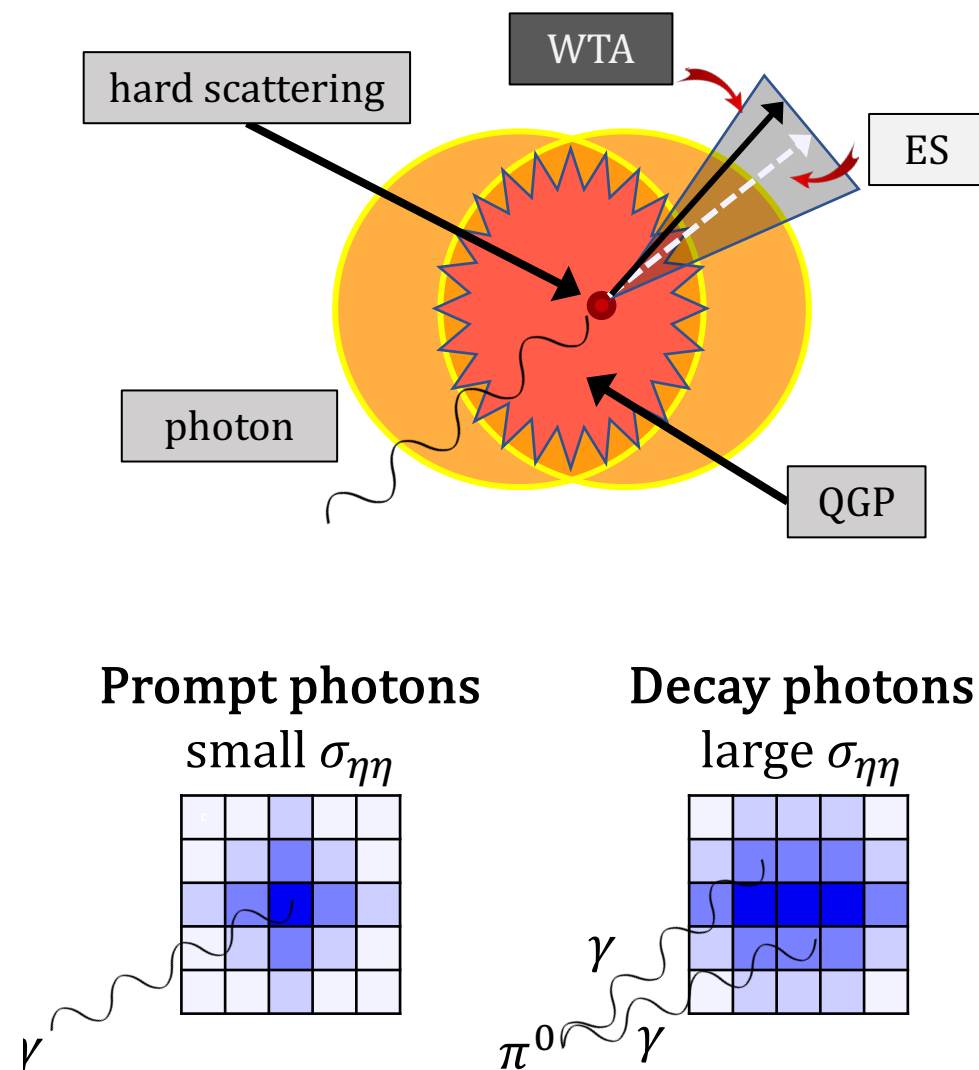


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Measurement setup

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



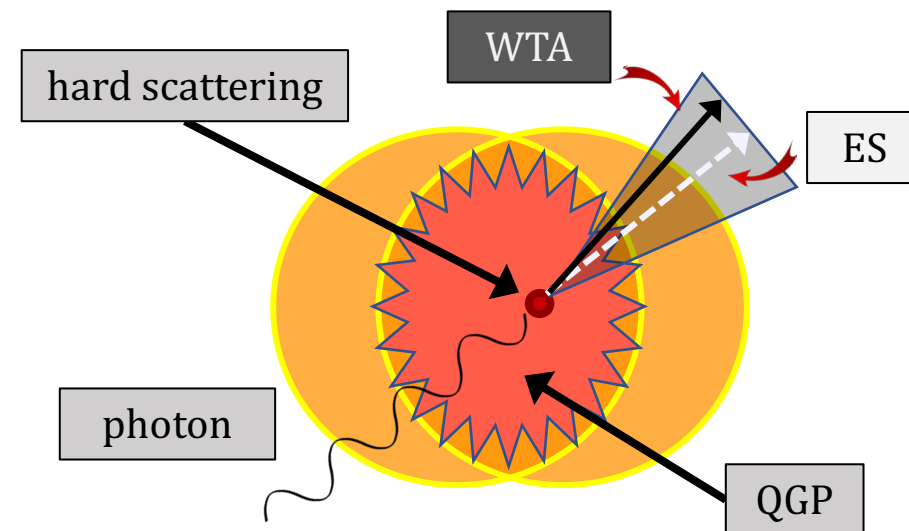
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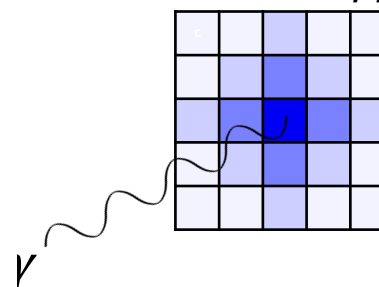
- Observable

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



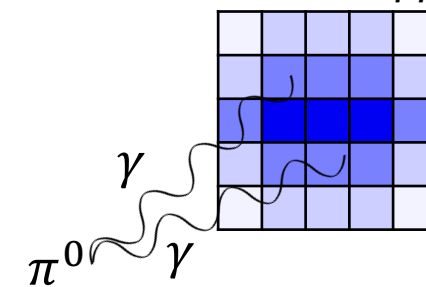
Prompt photons

small $\sigma_{\eta\eta}$



Decay photons

large $\sigma_{\eta\eta}$



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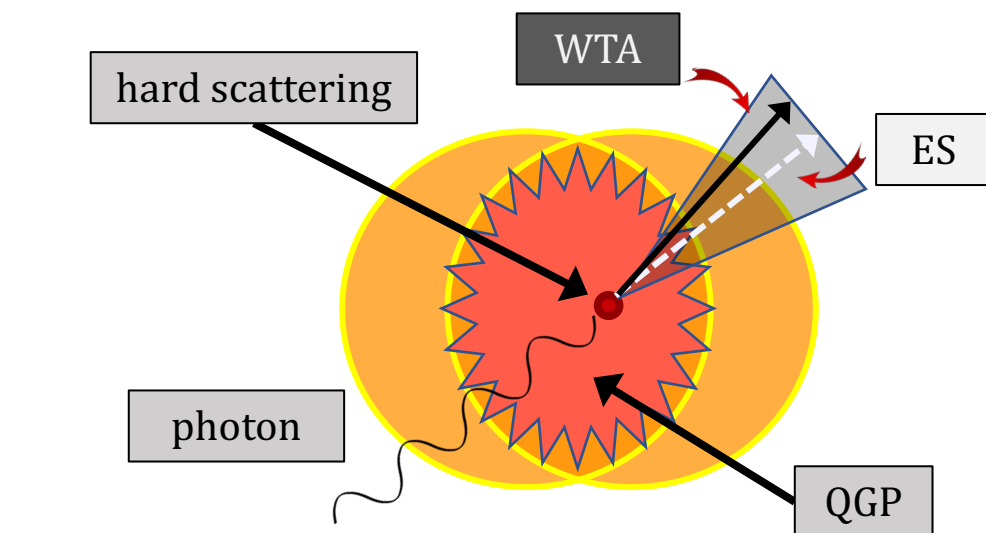
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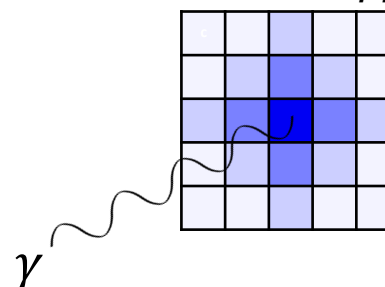
- Analysis method

- 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



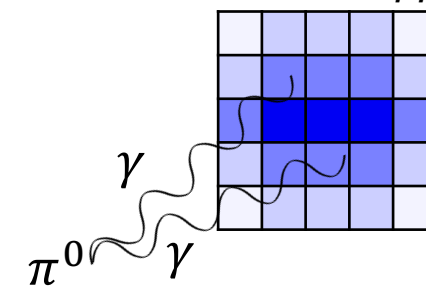
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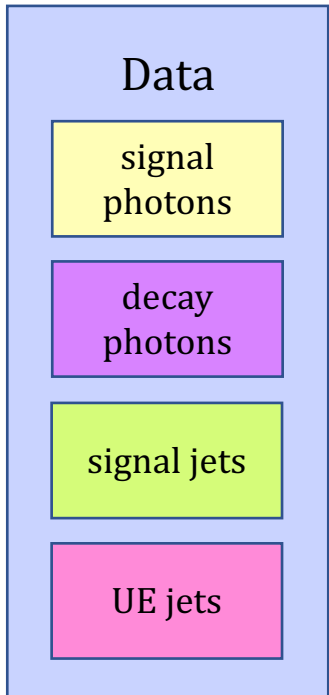


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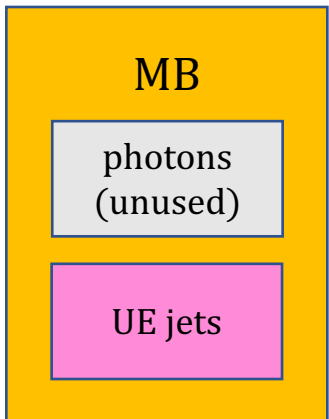
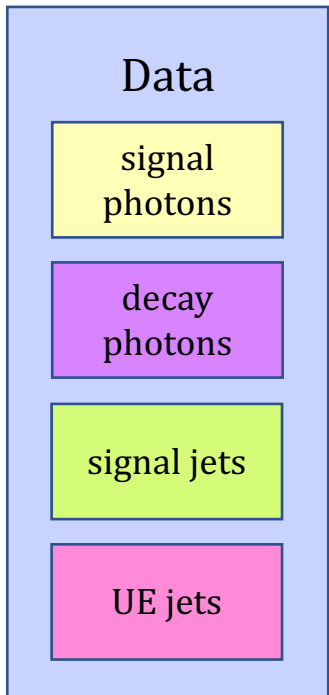
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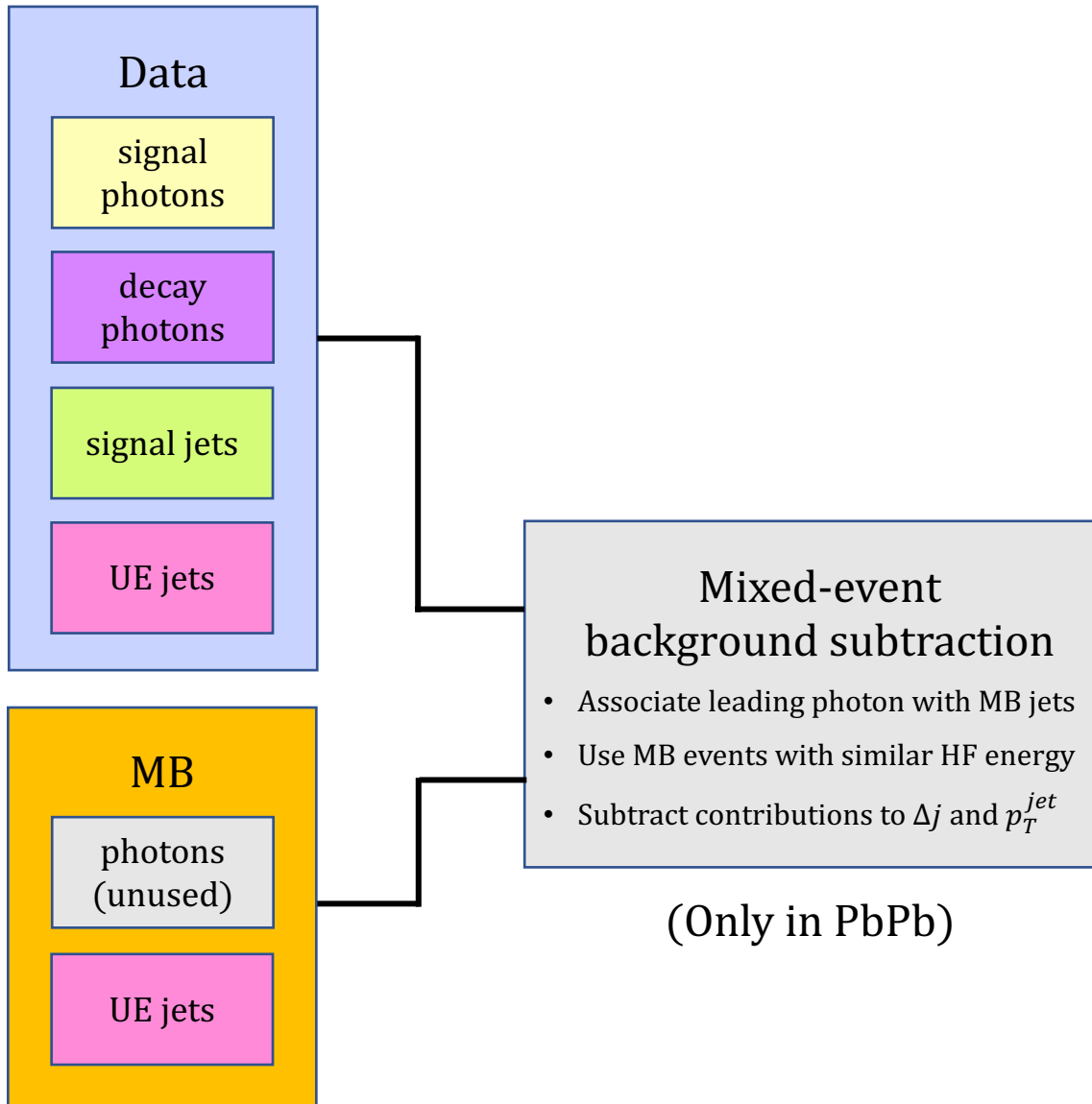
Analysis procedure



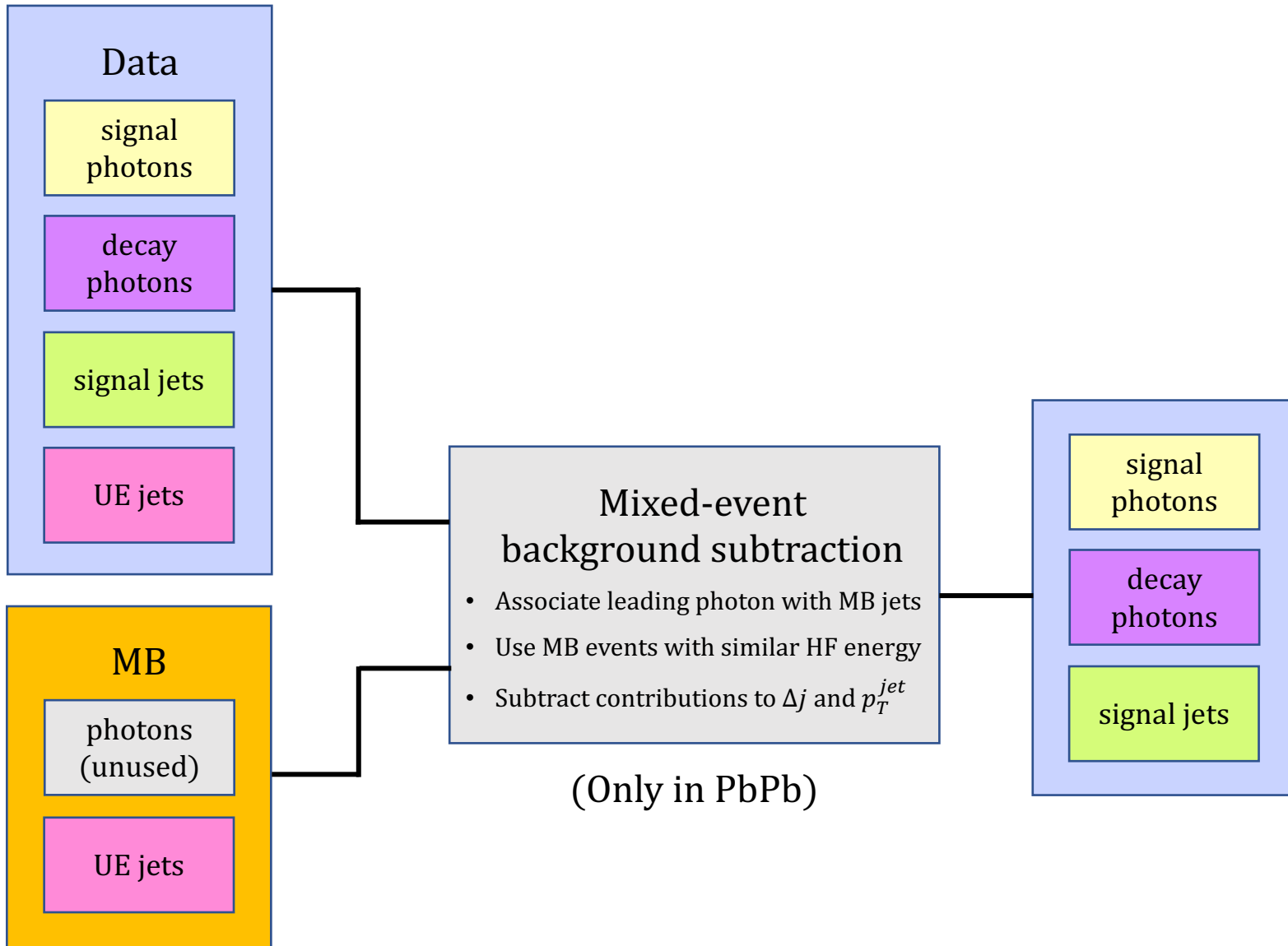
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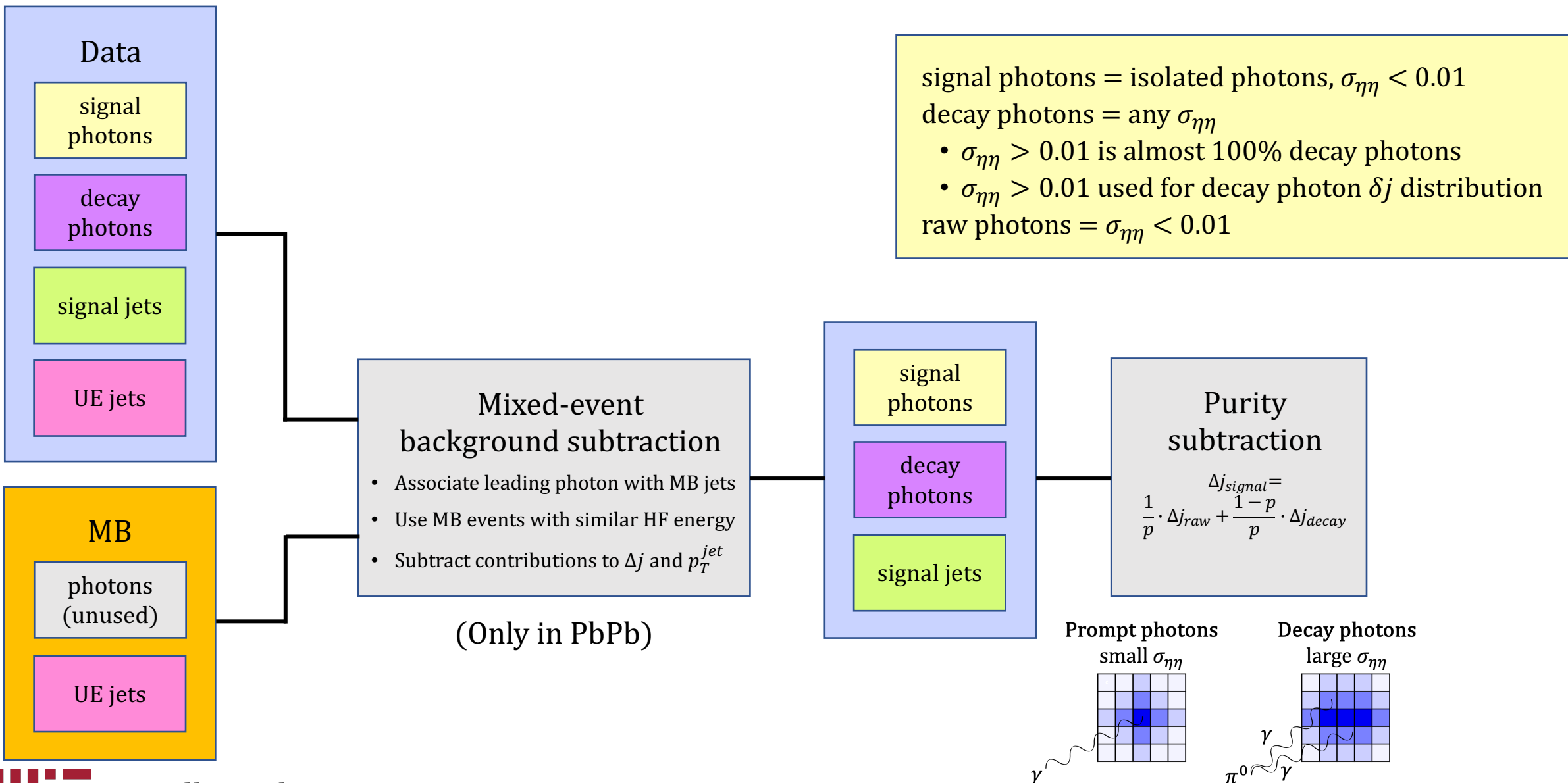
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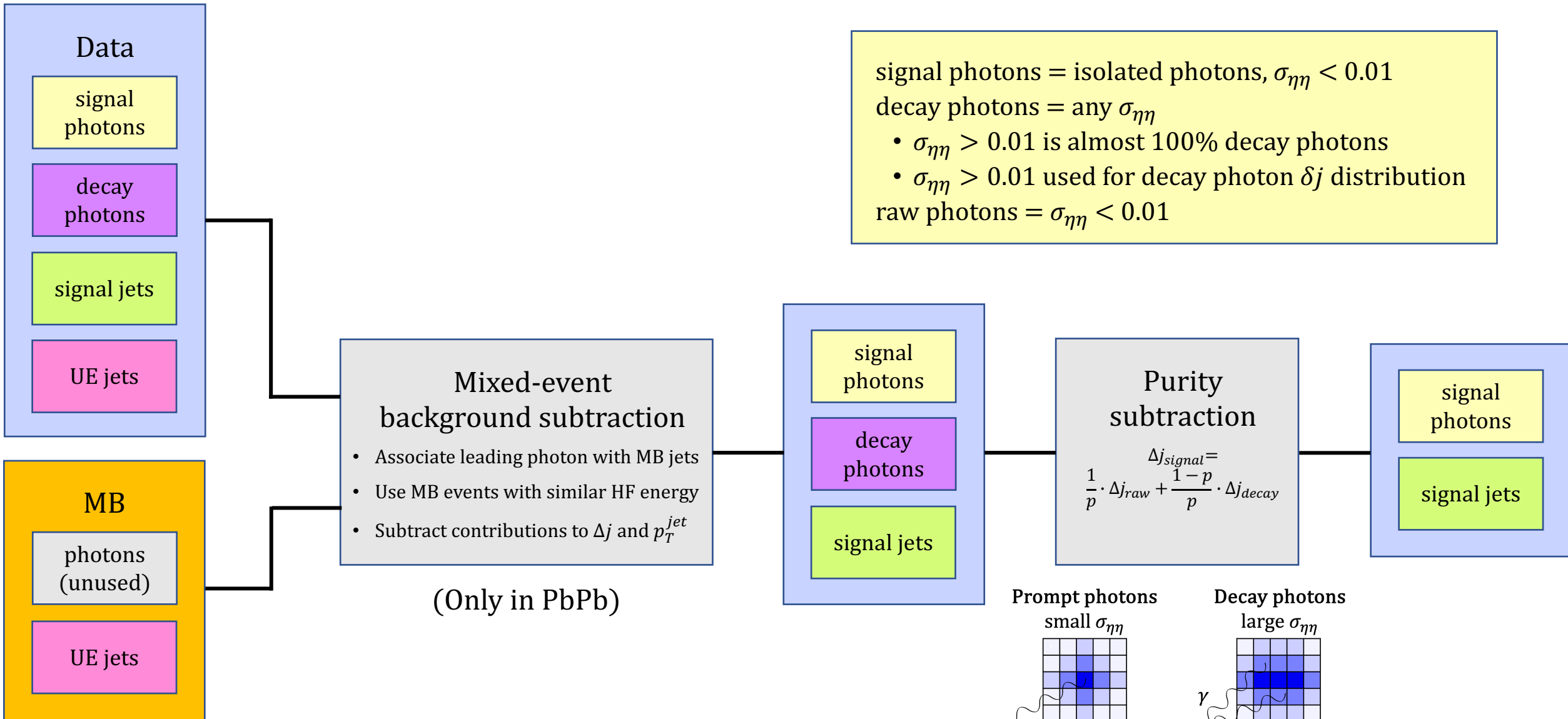
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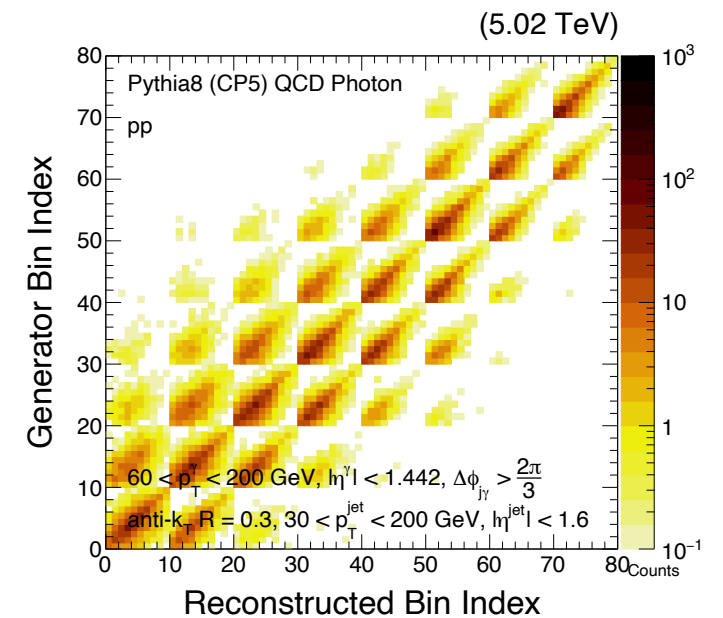
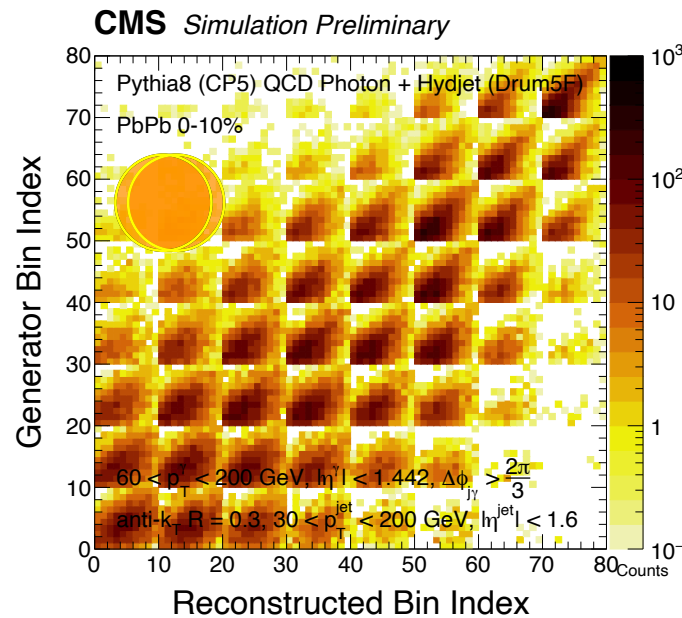
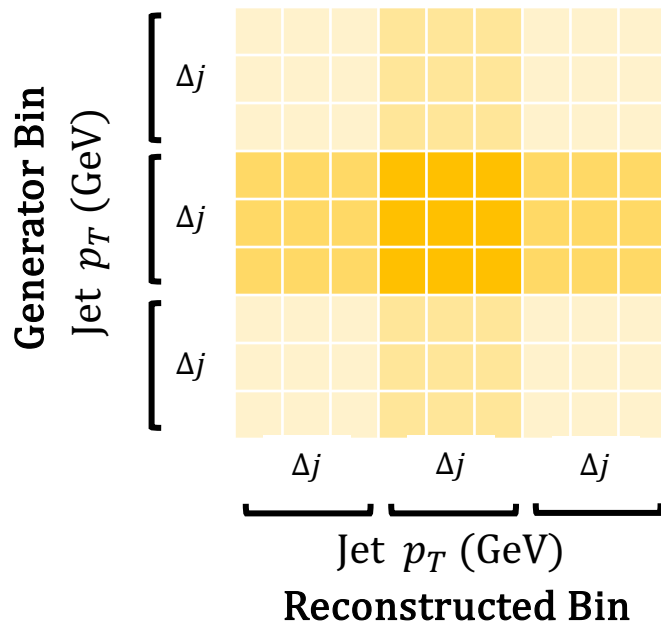


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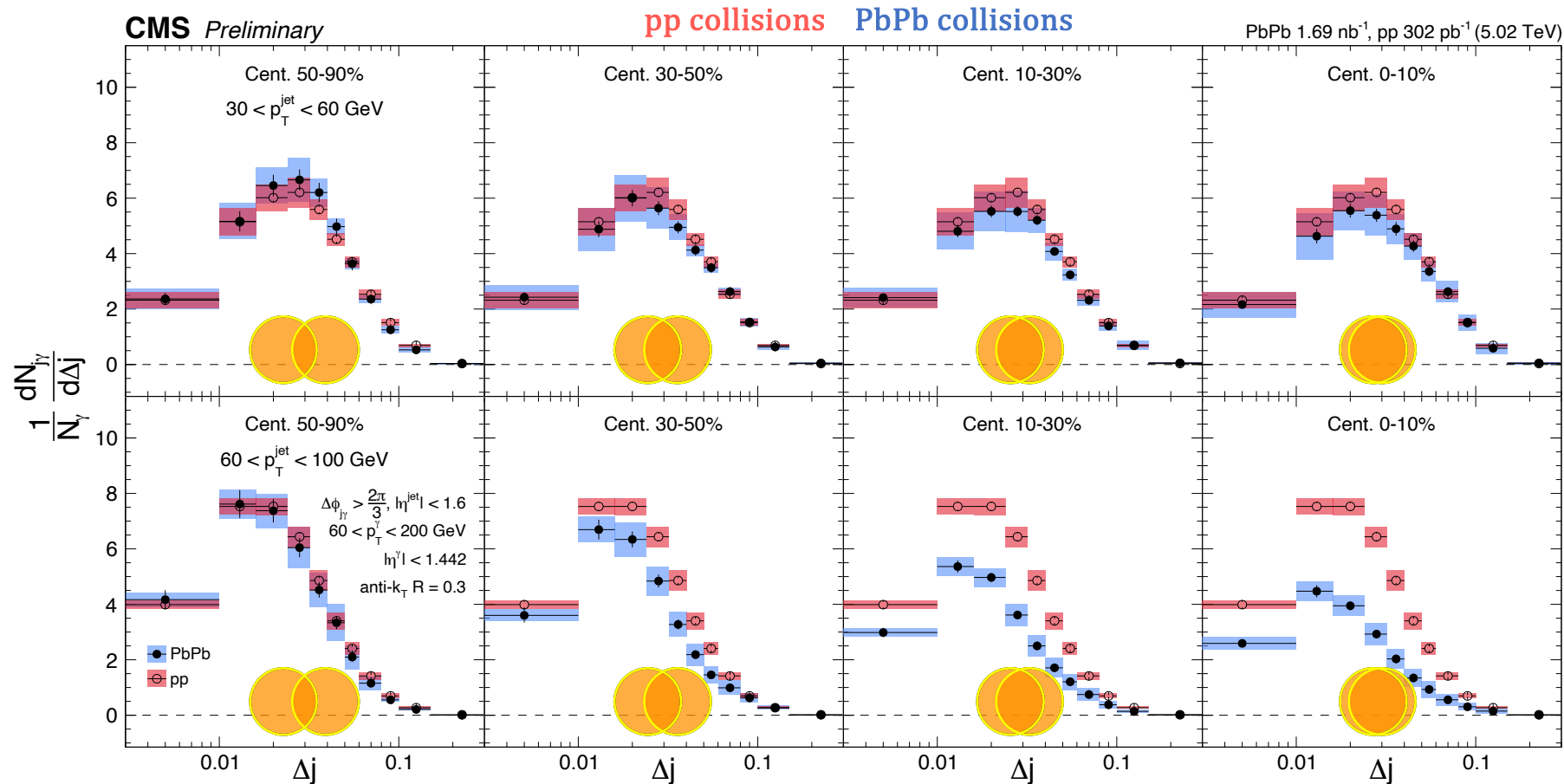


Unfolding

- 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



Result: Δj spectra normalized per photon

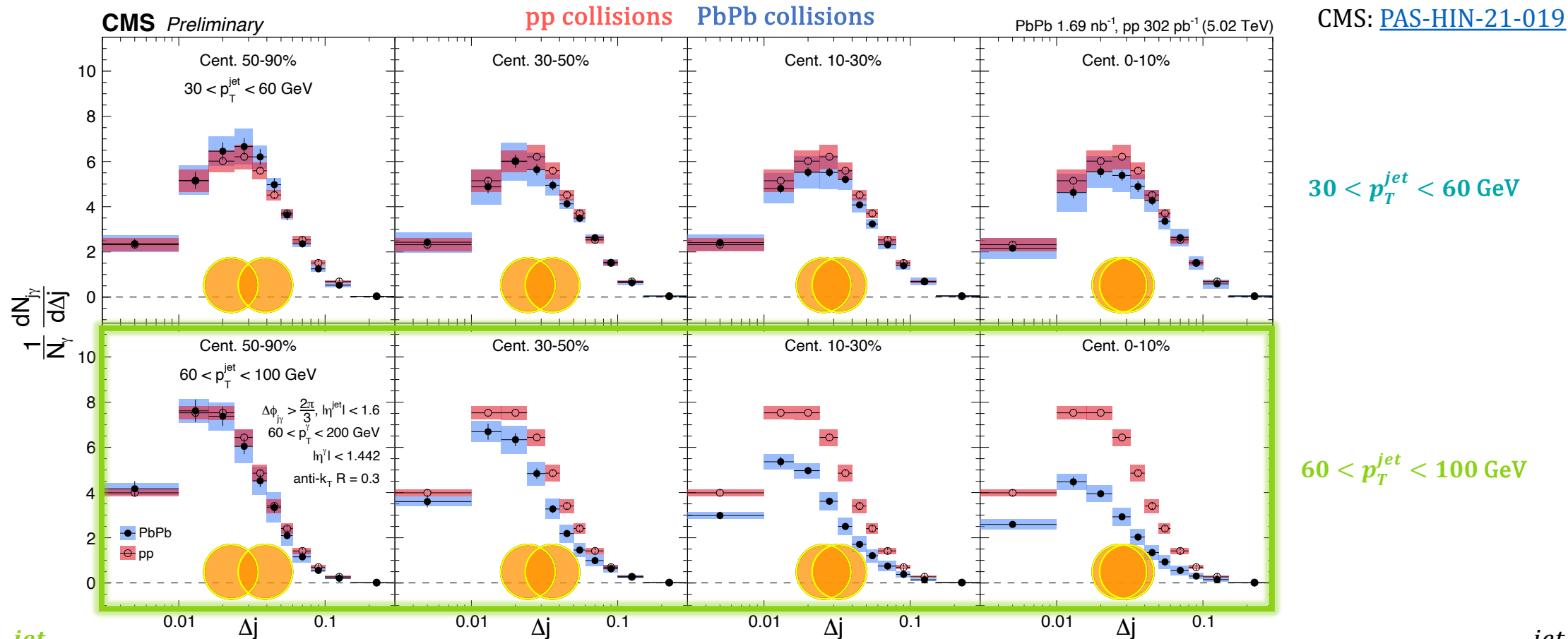


CMS: [PAS-HIN-21-019](#)

$30 < p_T^{\text{jet}} < 60$ GeV

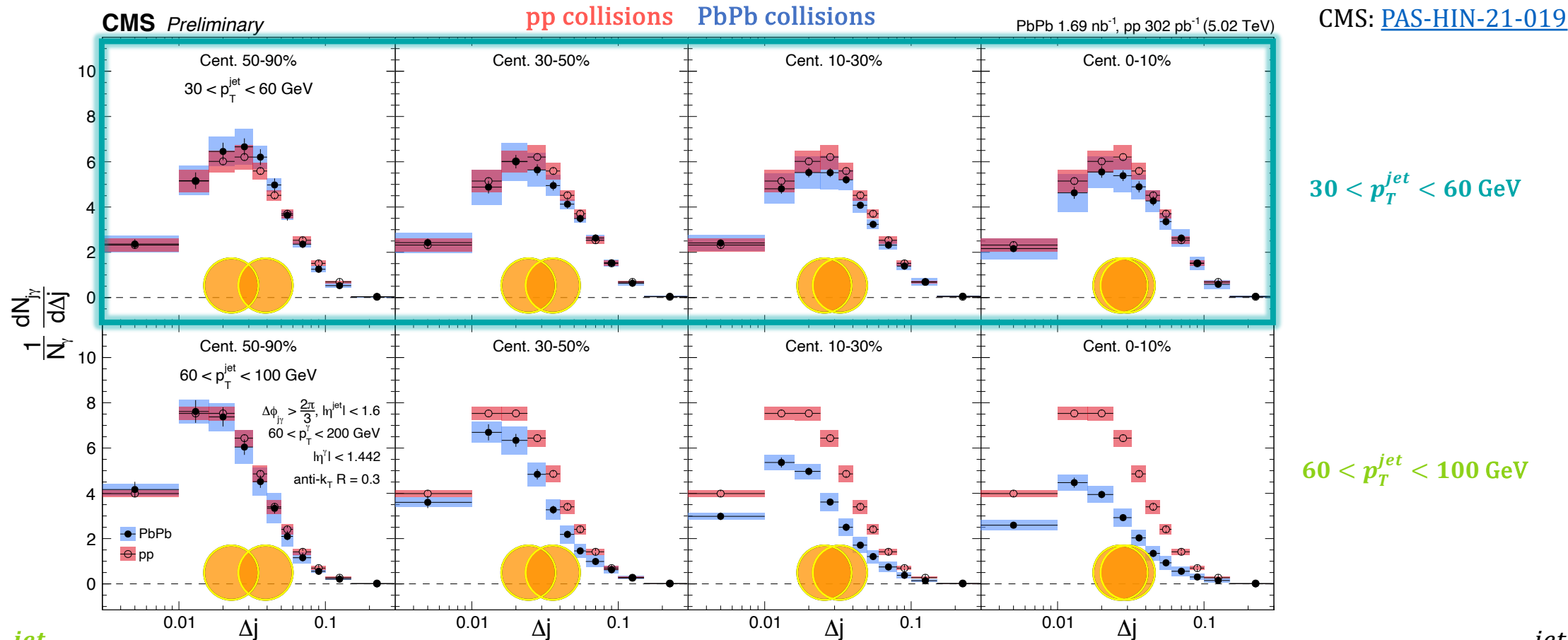
$60 < p_T^{\text{jet}} < 100$ GeV

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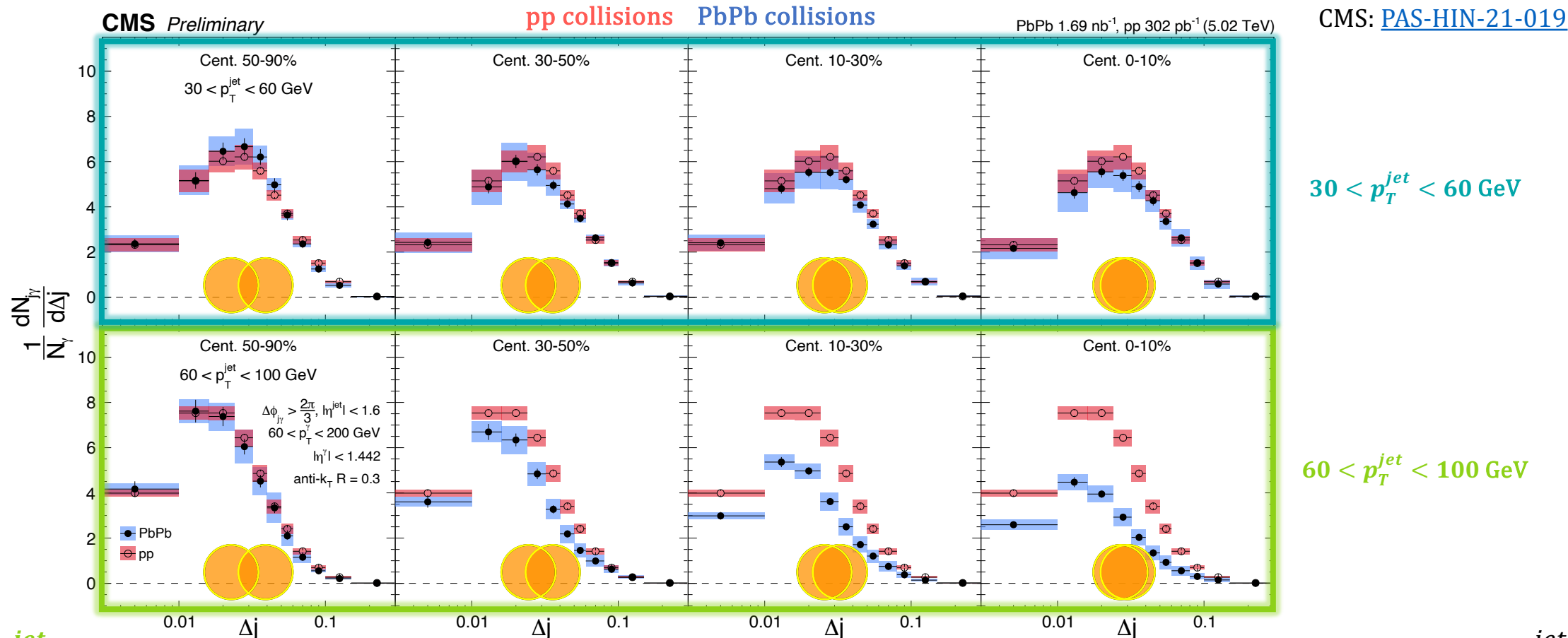
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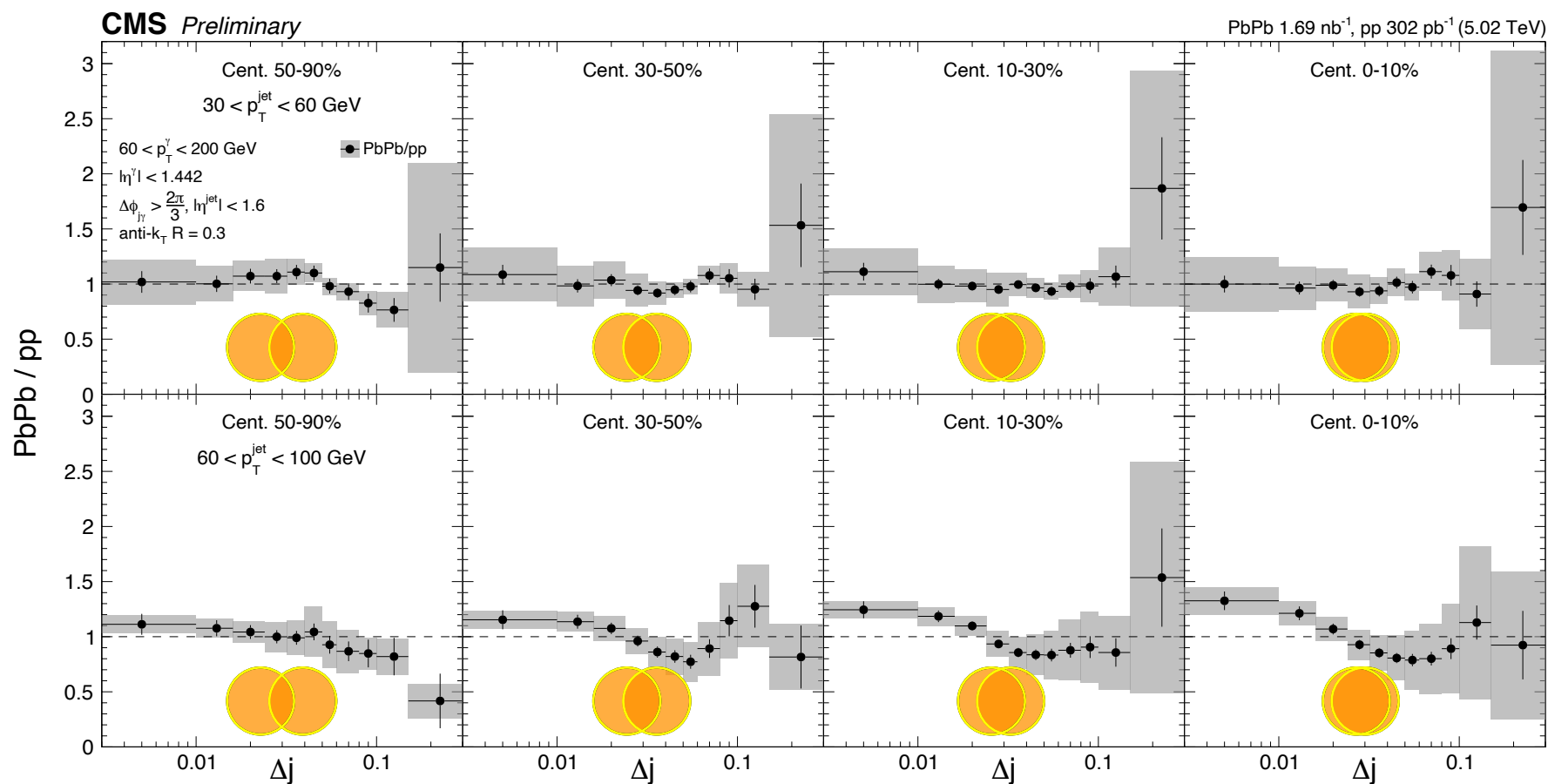
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- Per-photon jet yields are consistent with past measurements of photon-jet I_{AA} [CMS: [PLB 785 \(2018\) 14](#)]

Result: Δj shape ratios

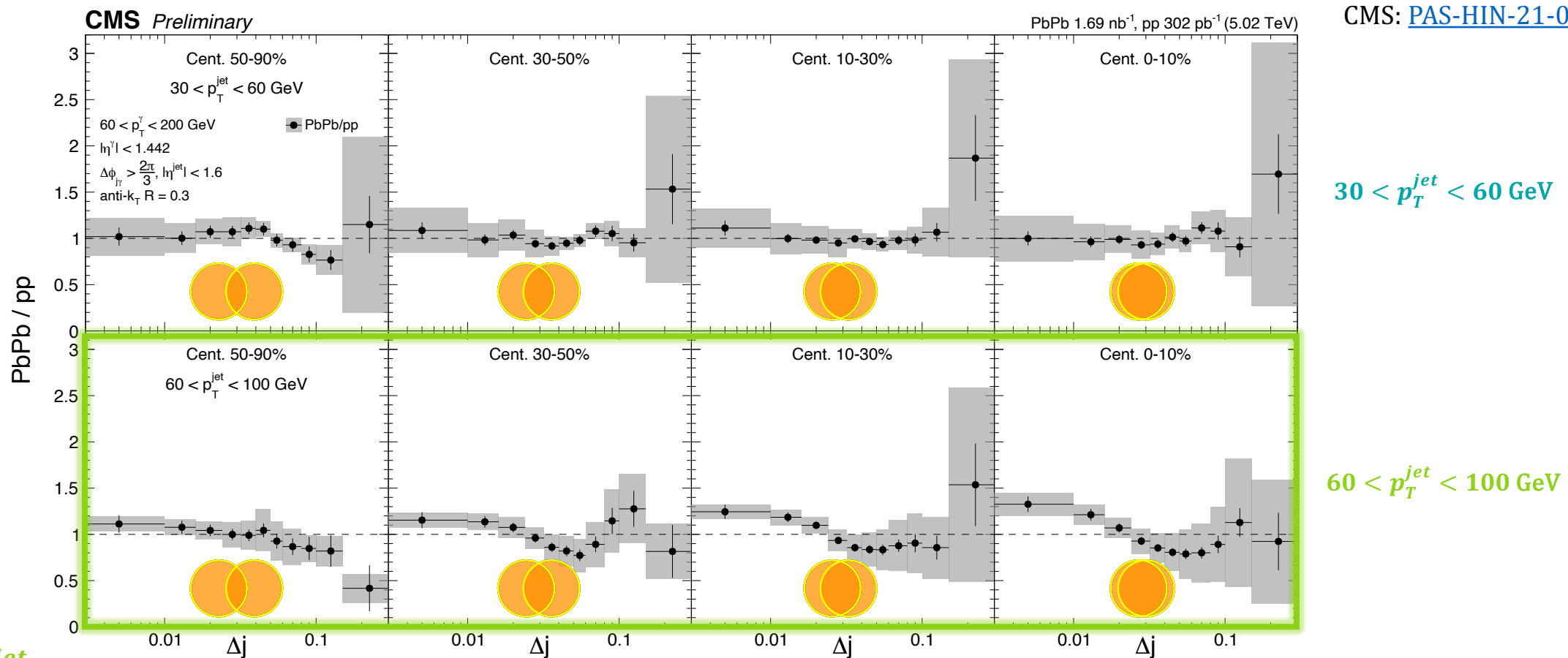


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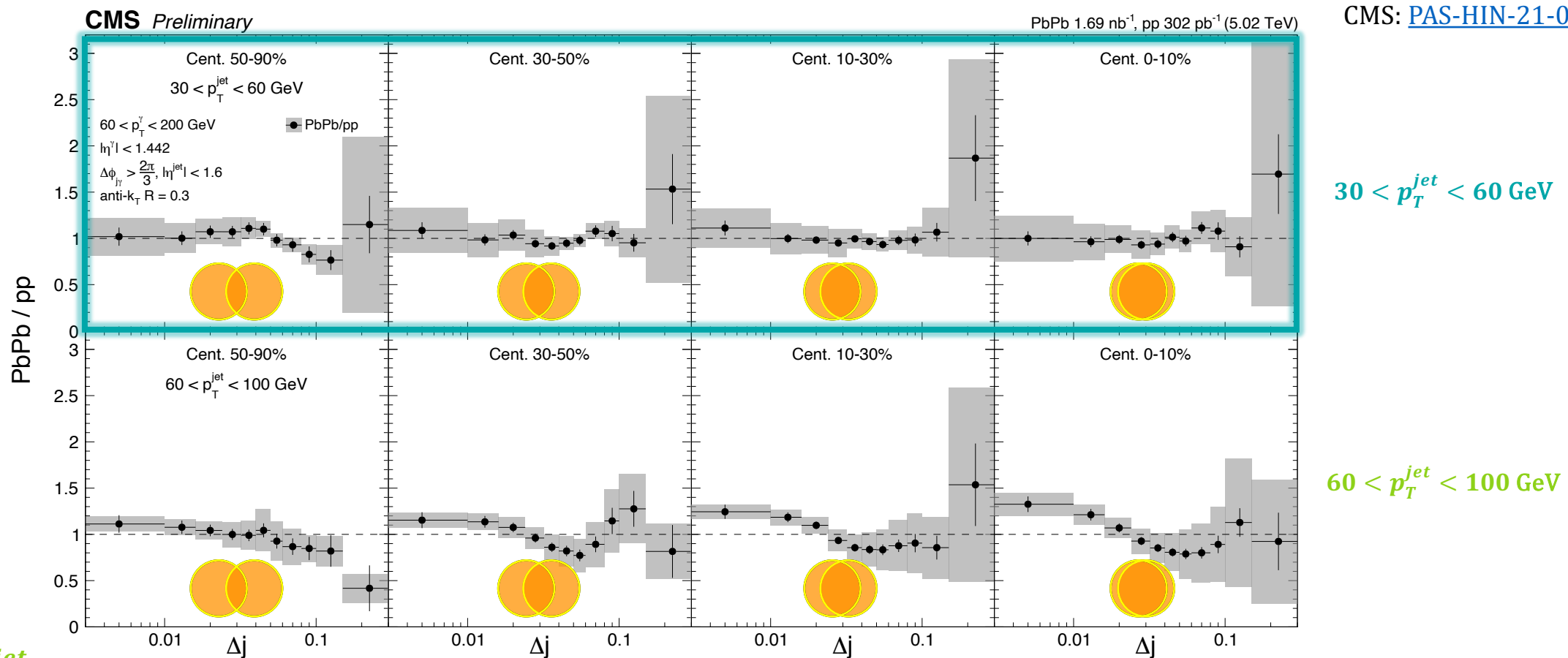
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Result: Δj shape ratios



- At **high p_T^{jet}** : the shape of the Δj distribution is narrower in PbPb than pp
 - This p_T^{jet} interval is designed to have more jet selection bias
 - The trends in the ratios are consistent with the ALICE inclusive jet measurement

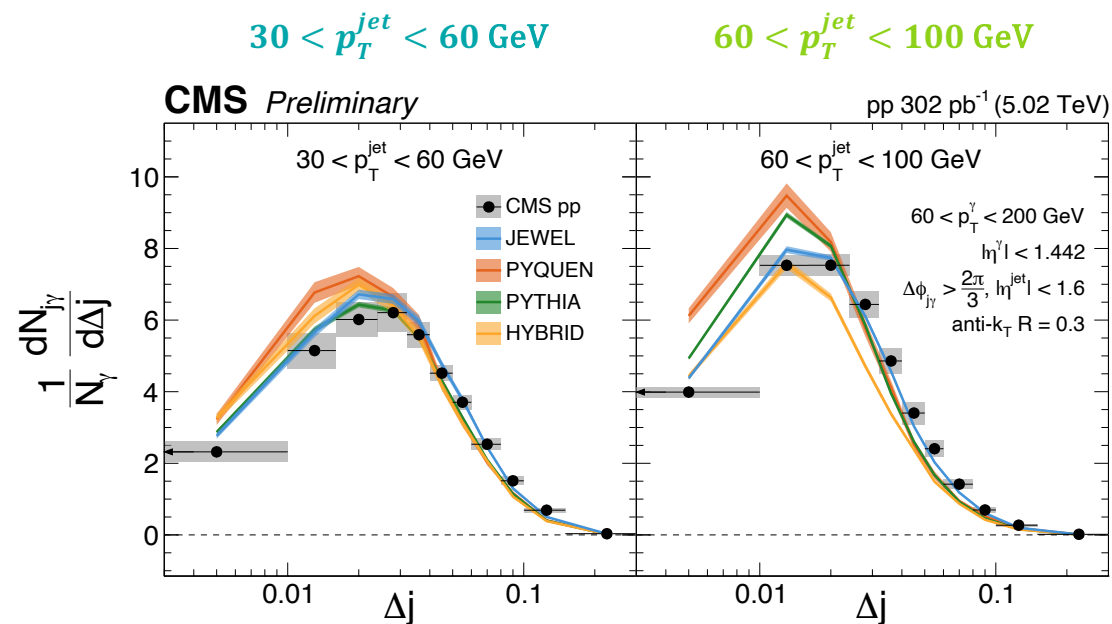
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Result: pp Δj spectra theory comparison

CMS: [PAS-HIN-21-019](#)



Jewel: based on Pythia 6.4

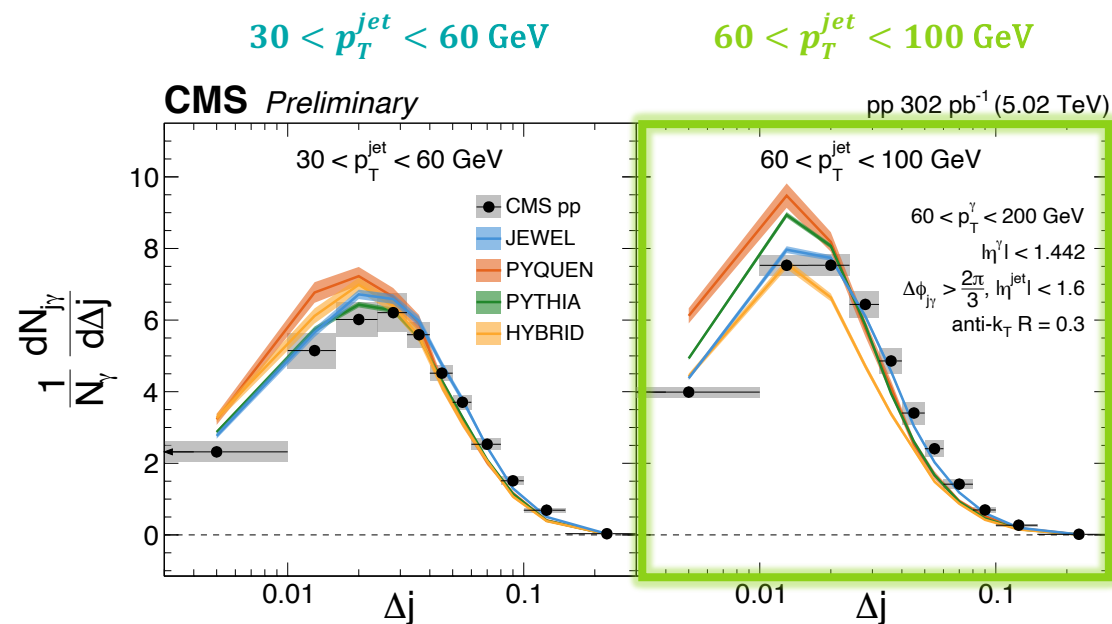
Pyquen: based on Pythia 6.4

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CMS: [PAS-HIN-21-019](#)



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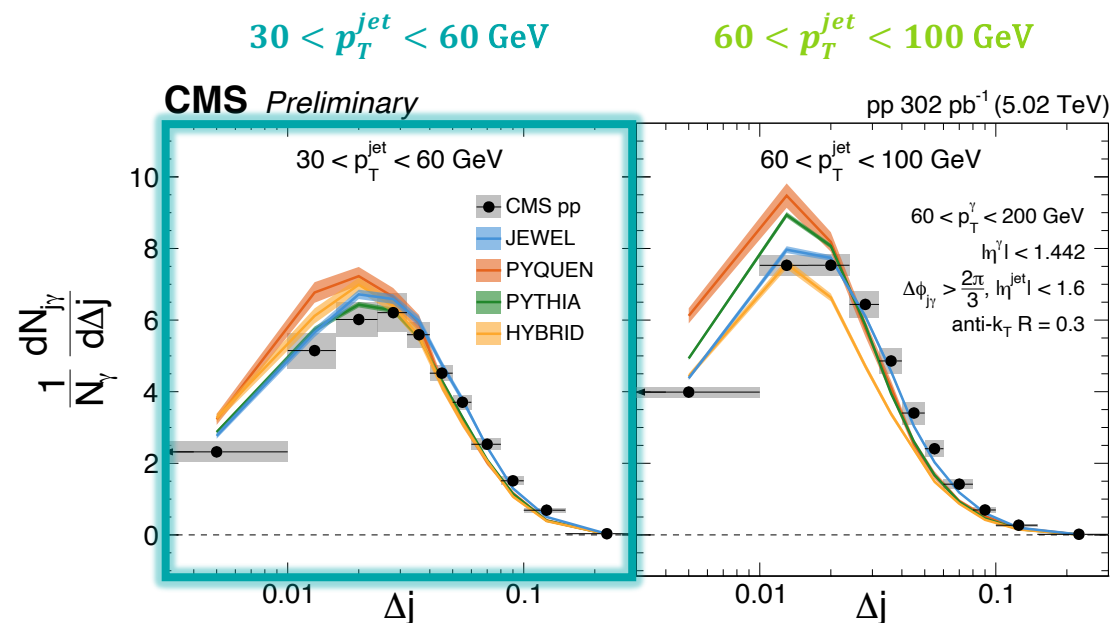
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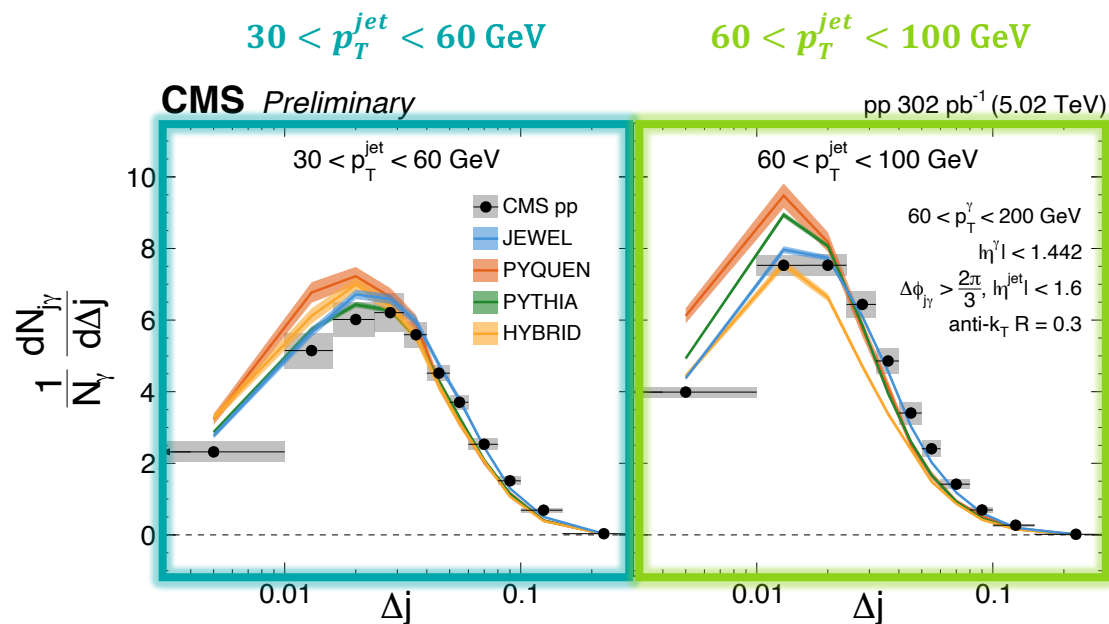
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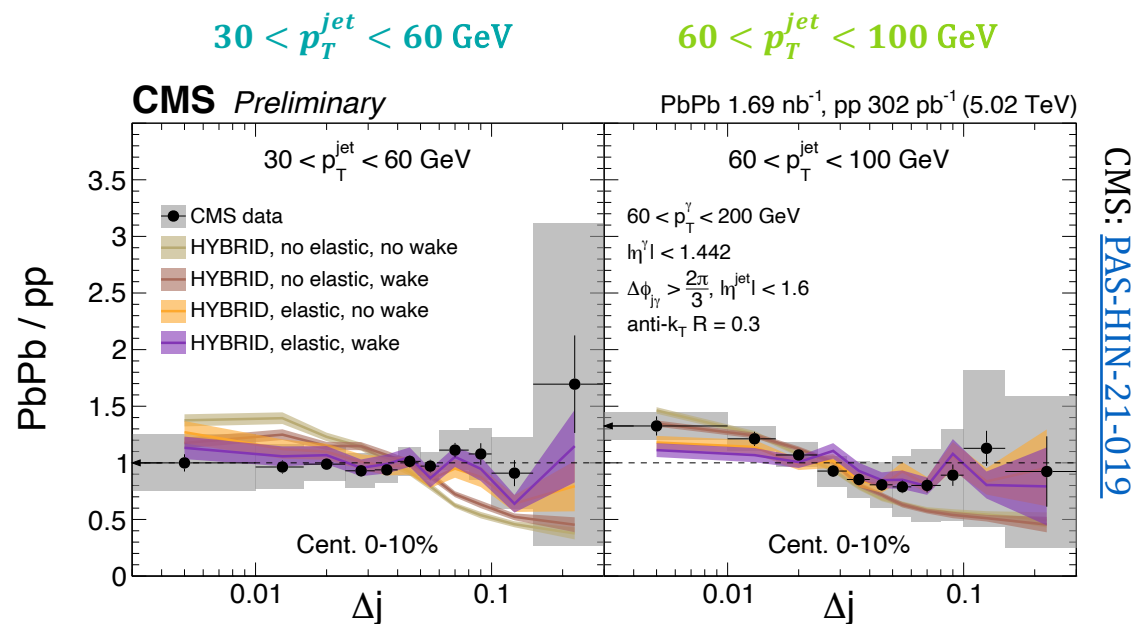
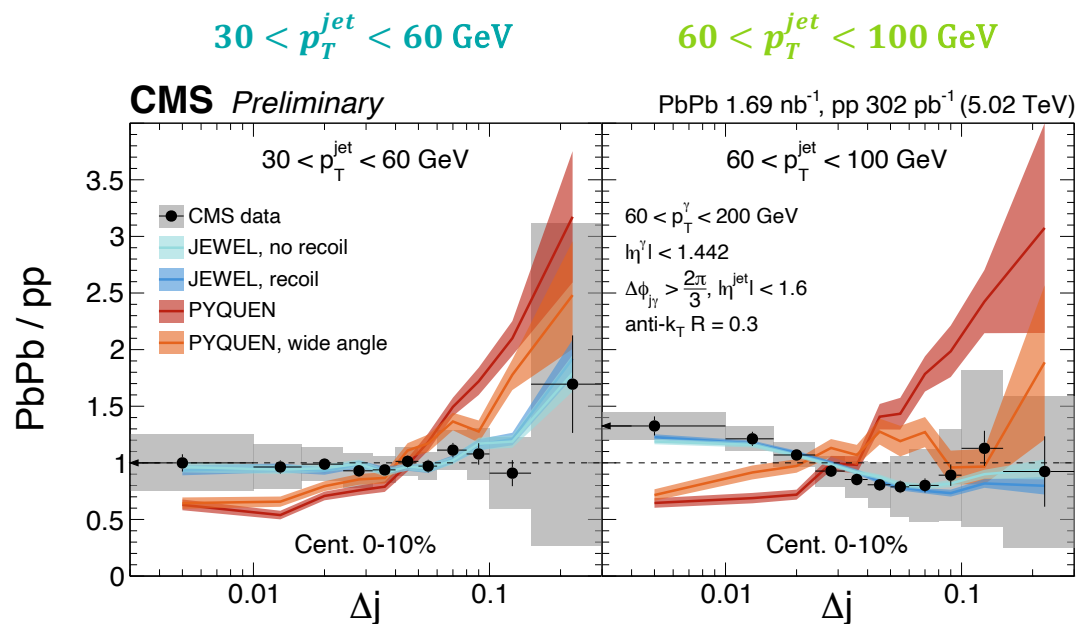
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Jewel, recoil: medium recoil particles included and subtracted

Jewel, no recoil: medium recoil particles ignored

Pyquen: baseline model of jet quenching

Pyquen, wide angle: additional wide angle gluon radiation

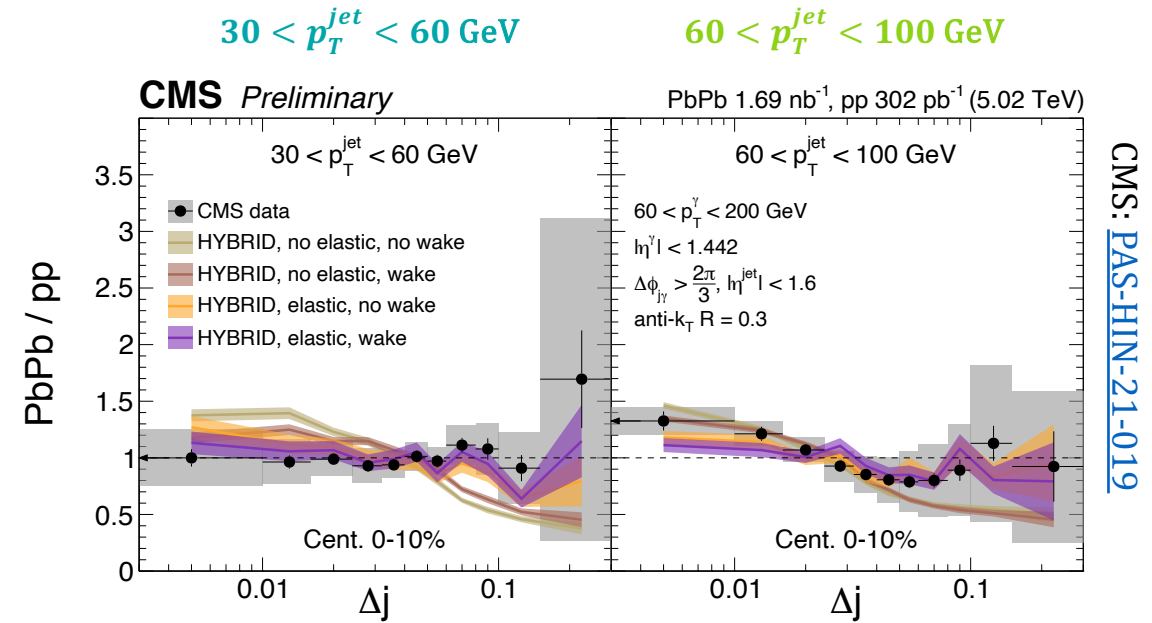
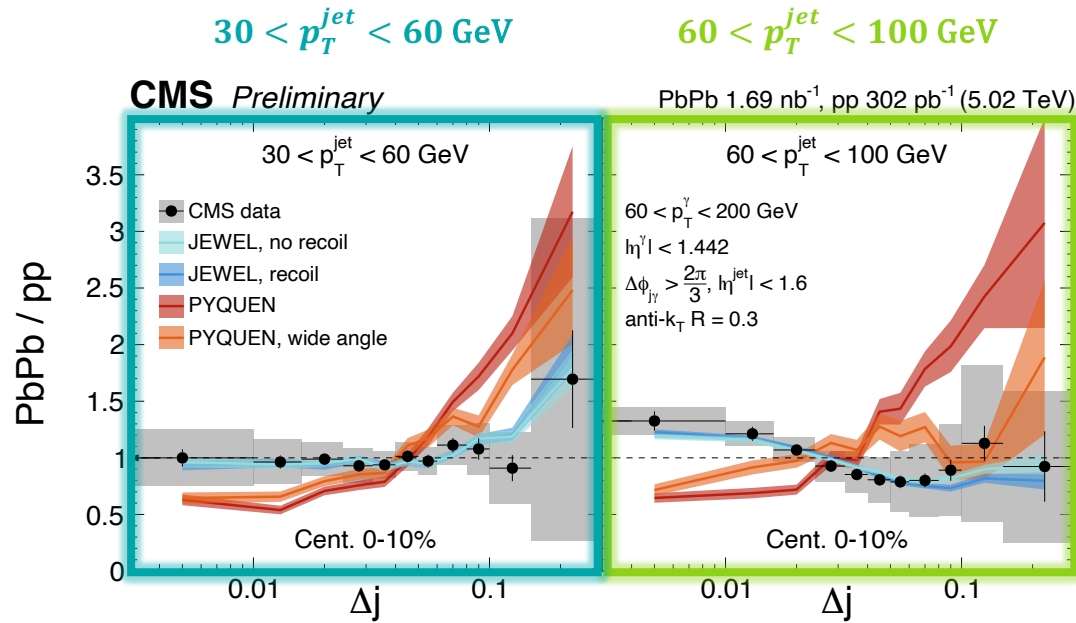
Hybrid, no elastic, no wake: strongly-coupled model of jet quenching

Hybrid, no elastic, wake: conservation of energy imposed

Hybrid, elastic, no wake: scattering from medium particles

Hybrid, elastic, wake: conservation of energy + scattering within medium

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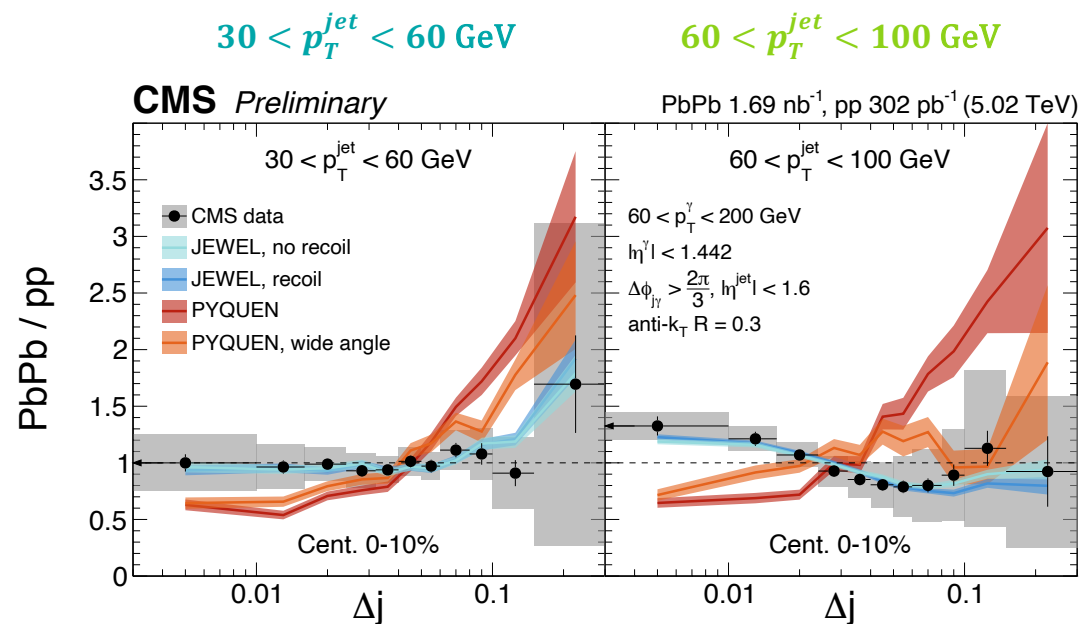
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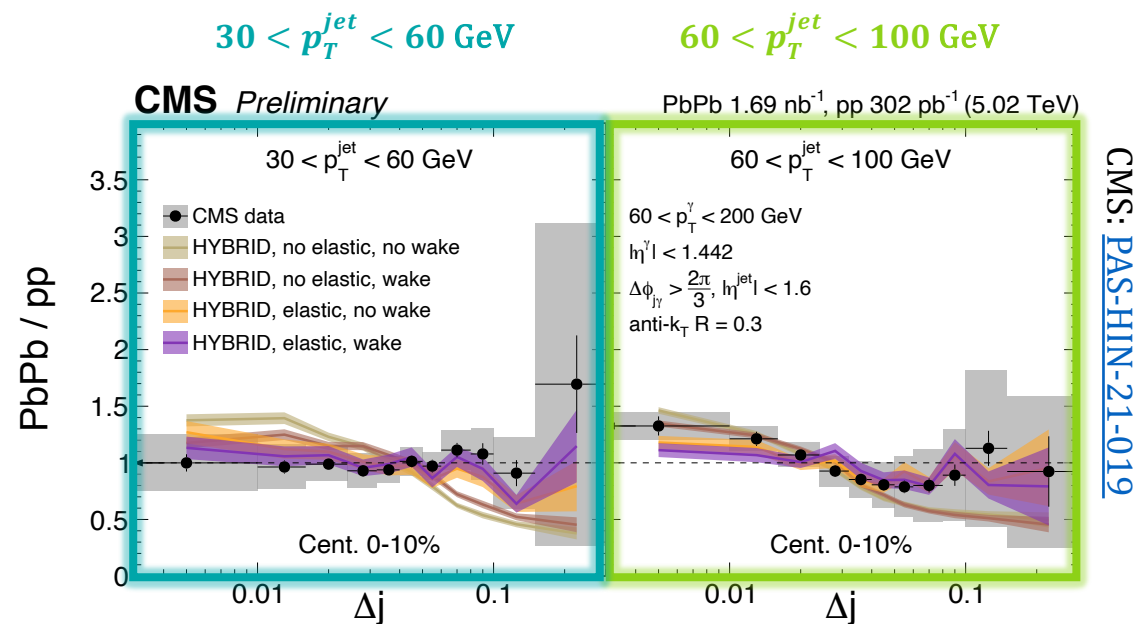


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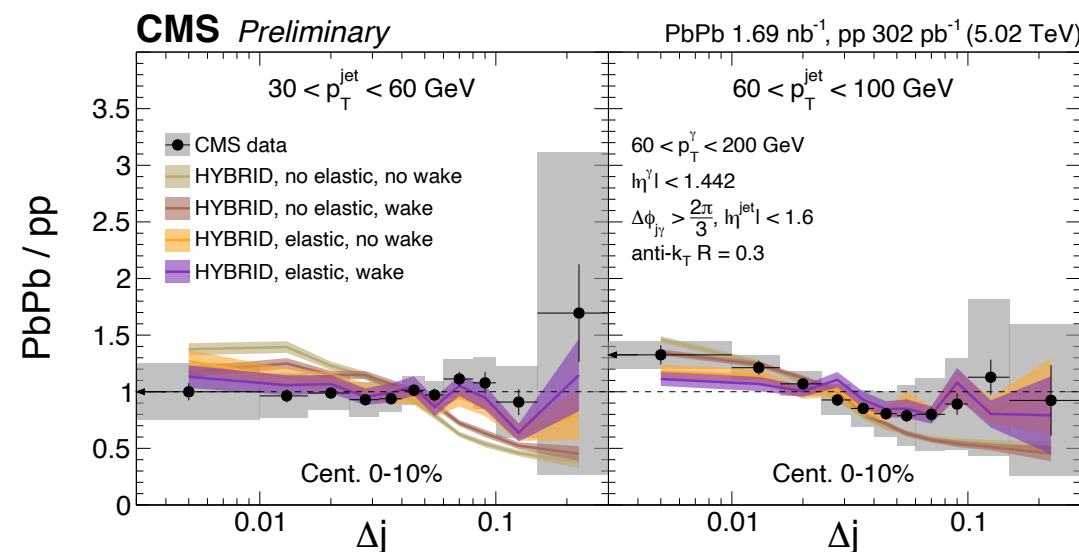
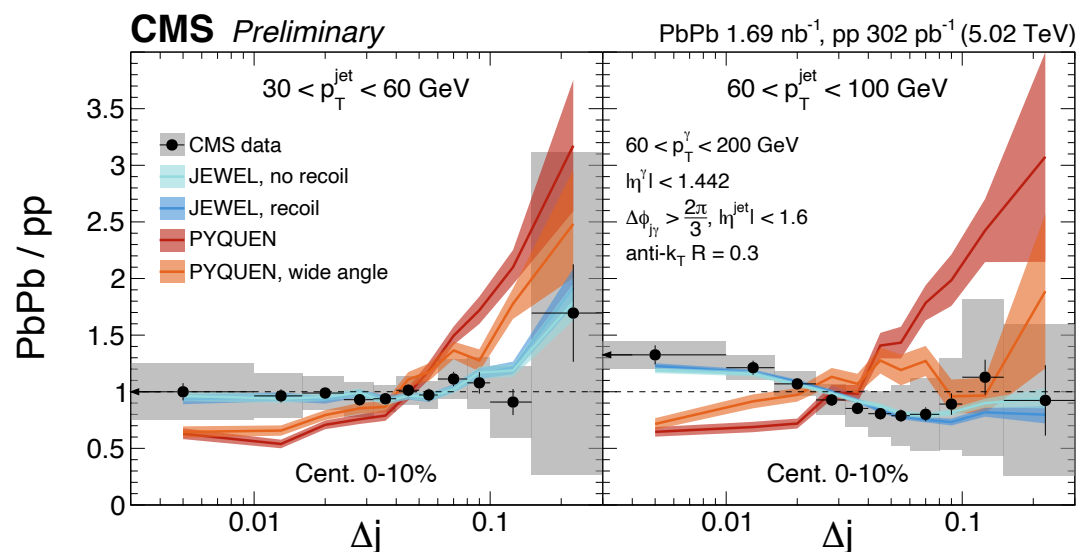
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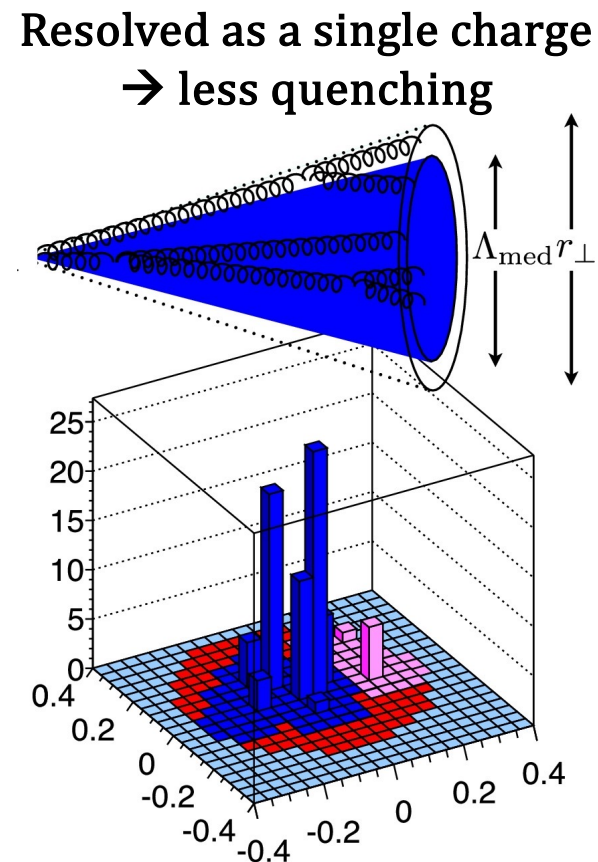
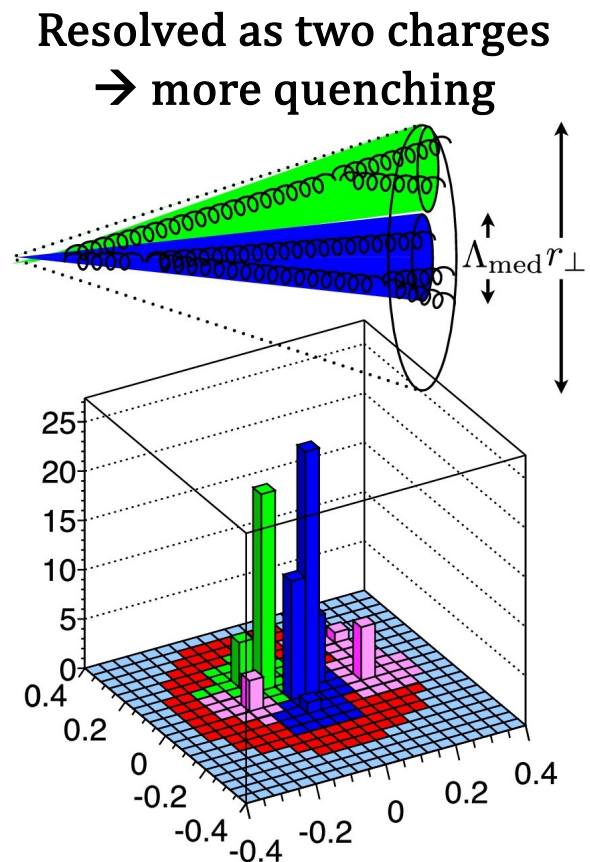
- Measured jet axis decorrelation in photon-tagged jet events in PbPb and pp collisions
 - Jets with 30-60 GeV are compatible in PbPb and pp collisions
 - Jets with 60-100 GeV are narrower in PbPb compared to pp collisions
- Observable is insensitive to medium wake effects
- Selection bias in higher 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

Color coherence

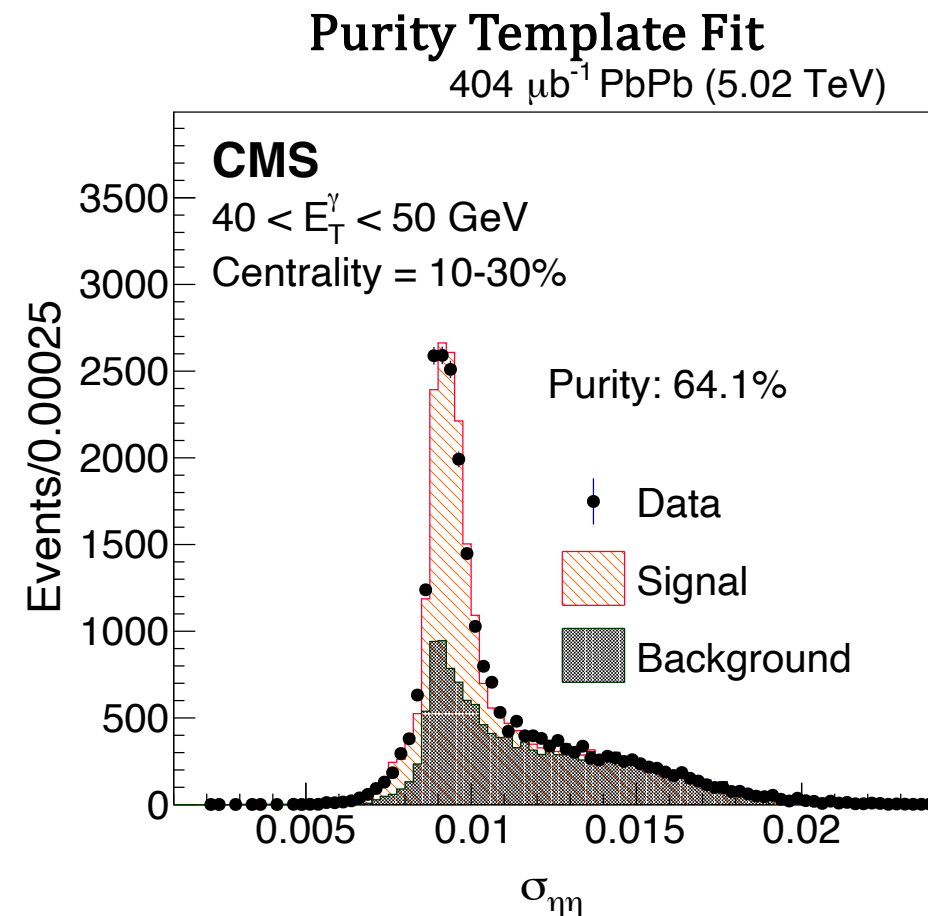
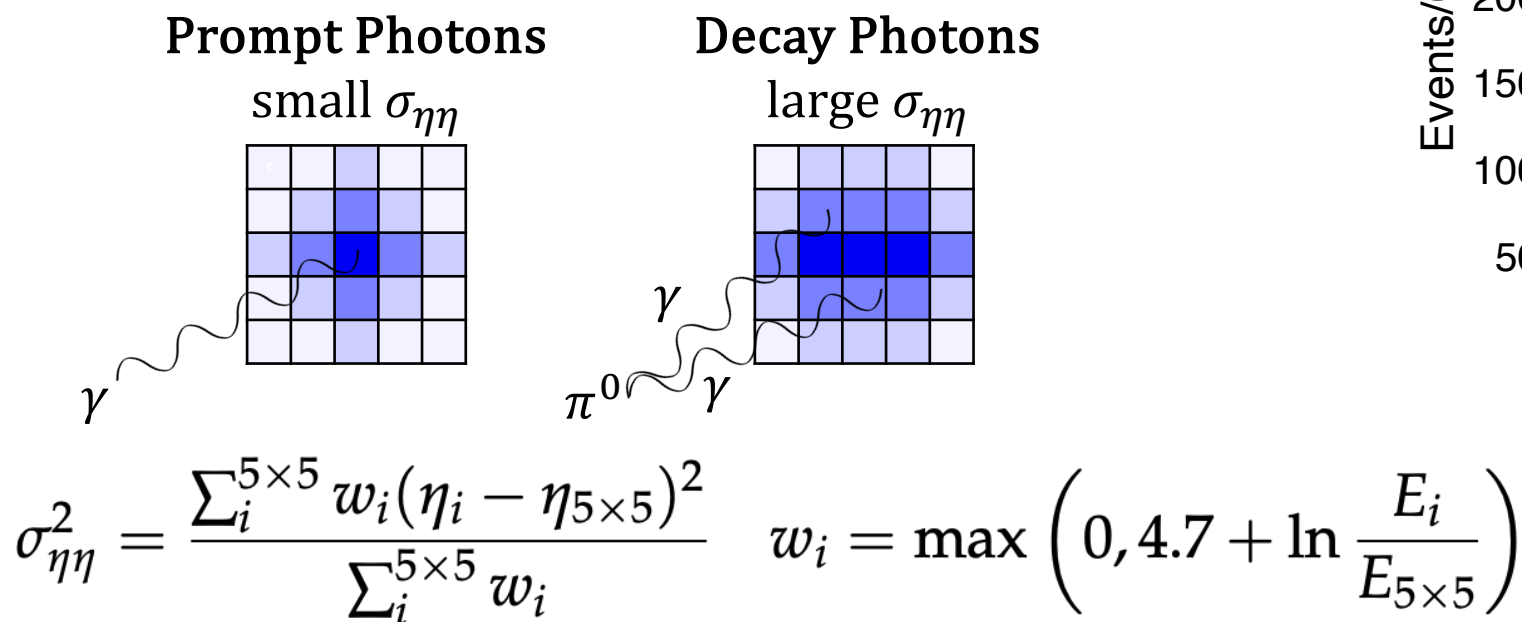
- Depending on medium resolution length, resolve as single charge or multiple charges → color coherence
- Emergent property of the QGP due to quantum interference



Diagrams from
J. Casalderrey-Solana,
Y. Mehtar-Tani,
C. A. Salgado,
K. Tywoniuk,
[arXiv:1210.7765](https://arxiv.org/abs/1210.7765)

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



Purity fit example from previous analysis:
CMS: [JHEP 2020, 116 \(2020\)](#)

Systematic uncertainties

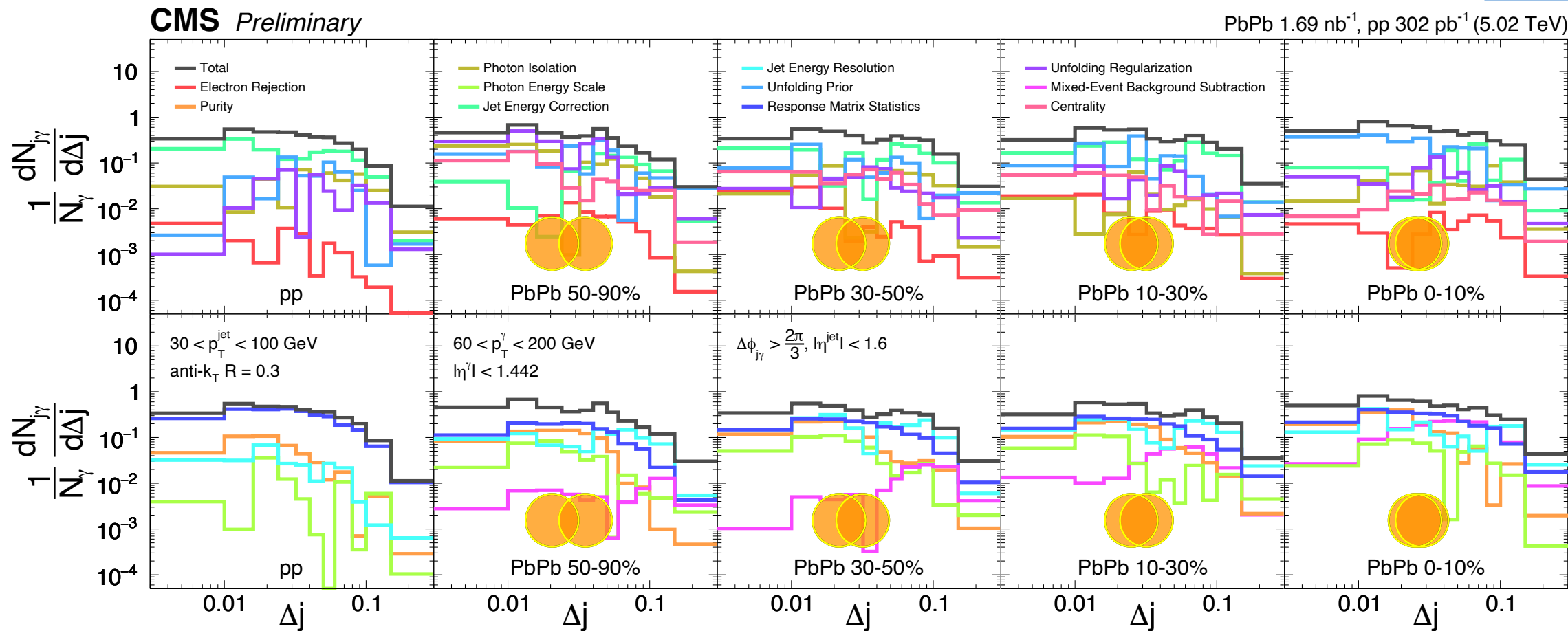
- **Electron contamination:** Accounts for electrons remaining in the sample after electron rejection
Evaluated by turning off electron rejection throughout analysis and scaling difference in Δj by electron rejection inefficiency
- **Photon purity:** Accounts for uncertainty in the background template 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: $10 \text{ GeV} < \text{sumIso} < 20 \text{ GeV}$ sideband used for background template
 - Loose: $15 \text{ GeV} < \text{sumIso} < 25 \text{ GeV}$ sideband used for background template
 - Tight: $5 \text{ GeV} < \text{sumIso} < 15 \text{ GeV}$ 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 Asmiouv 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

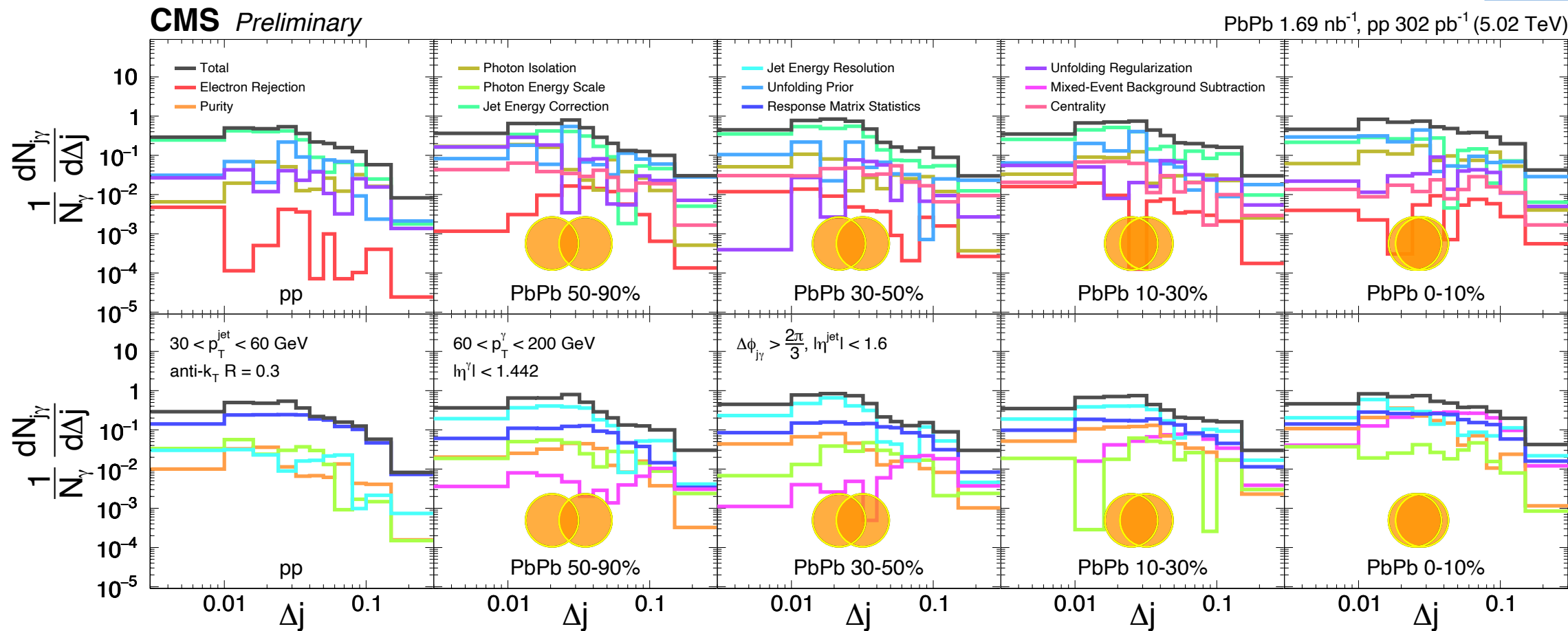
CMS: [PAS-HIN-21-019](#)



- 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

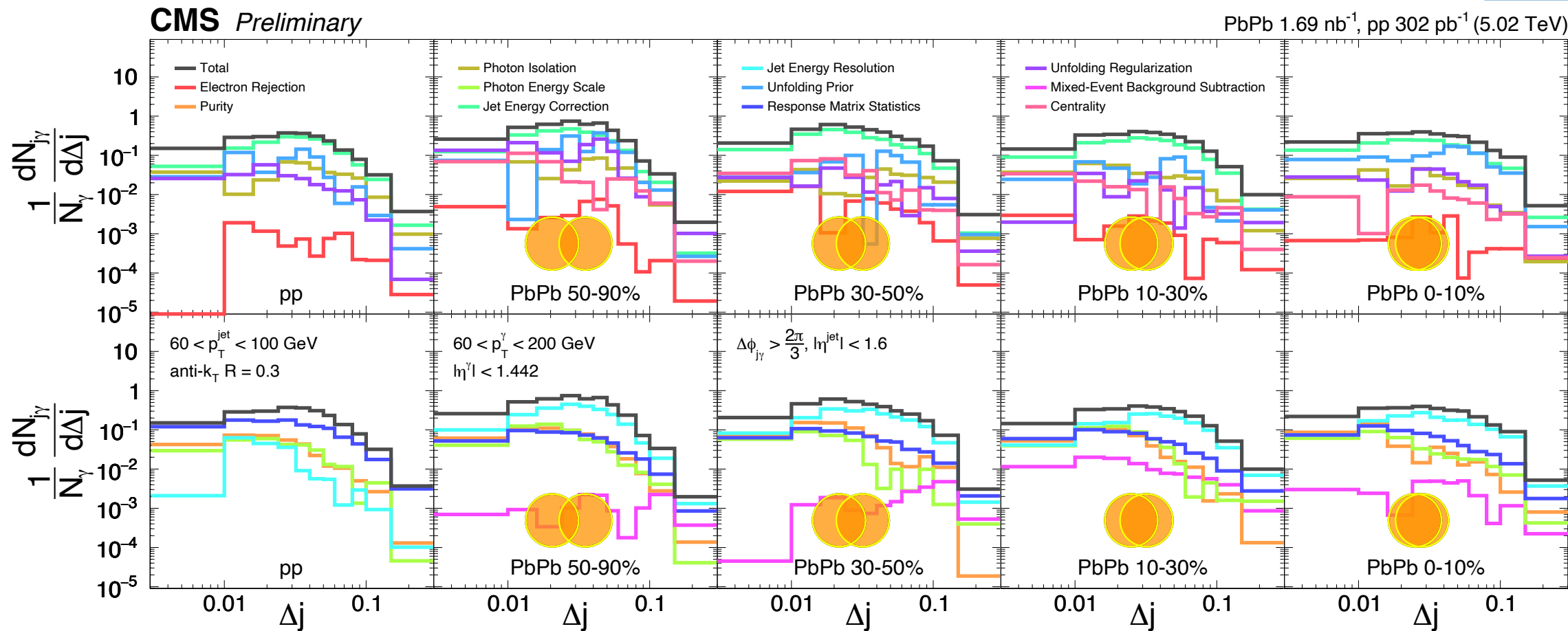
CMS: [PAS-HIN-21-019](#)



- 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

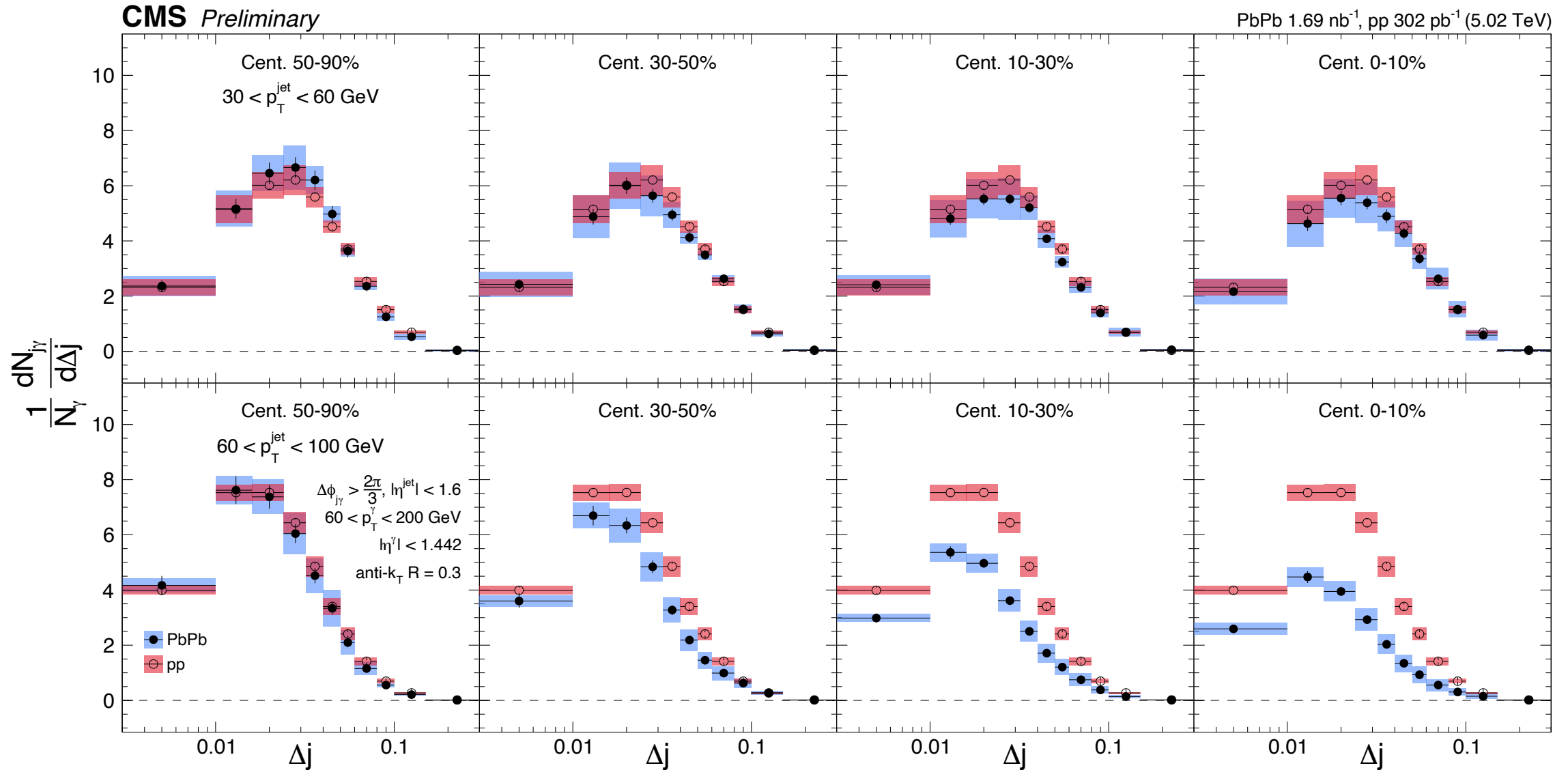
Systematic uncertainties: $60 < p_T^{jet} < 100$ GeV

CMS: [PAS-HIN-21-019](#)

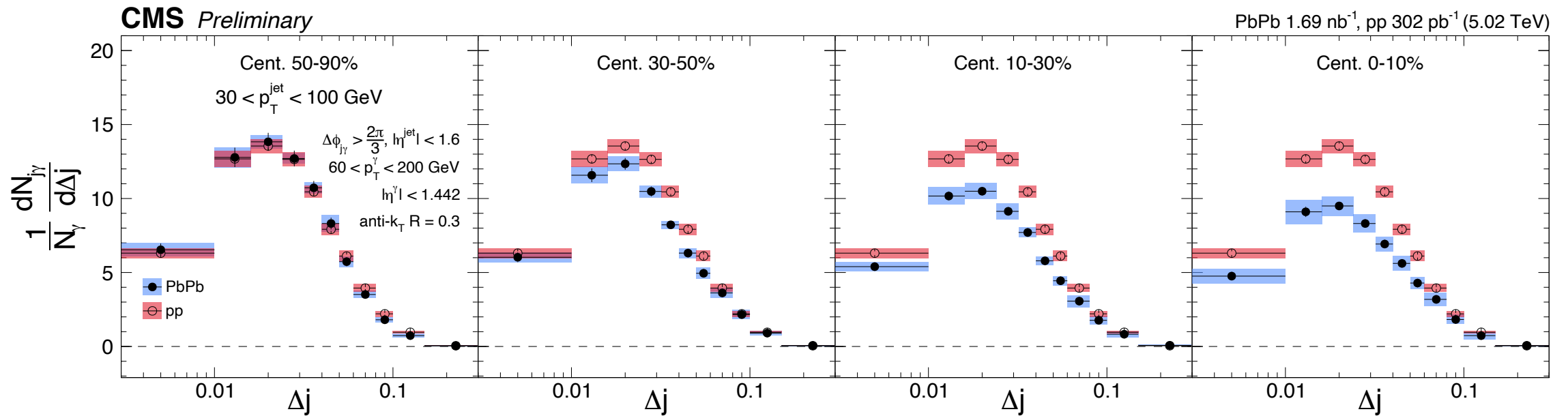


- Dominant systematics are the jet energy correction and jet energy resolution uncertainties
- Subdominant systematics are the response matrix statistics and unfolding prior

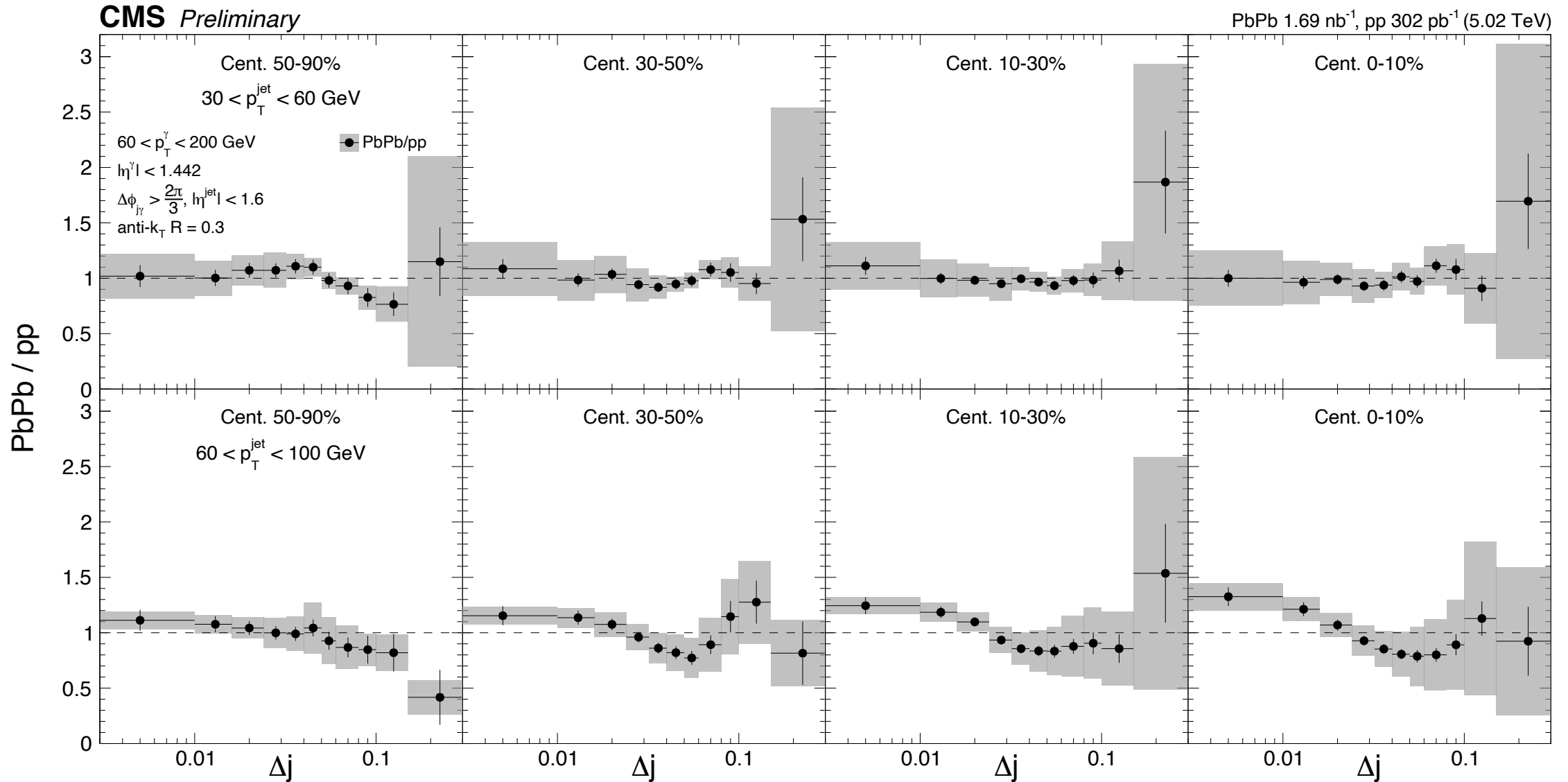
Δj spectra normalized per photon



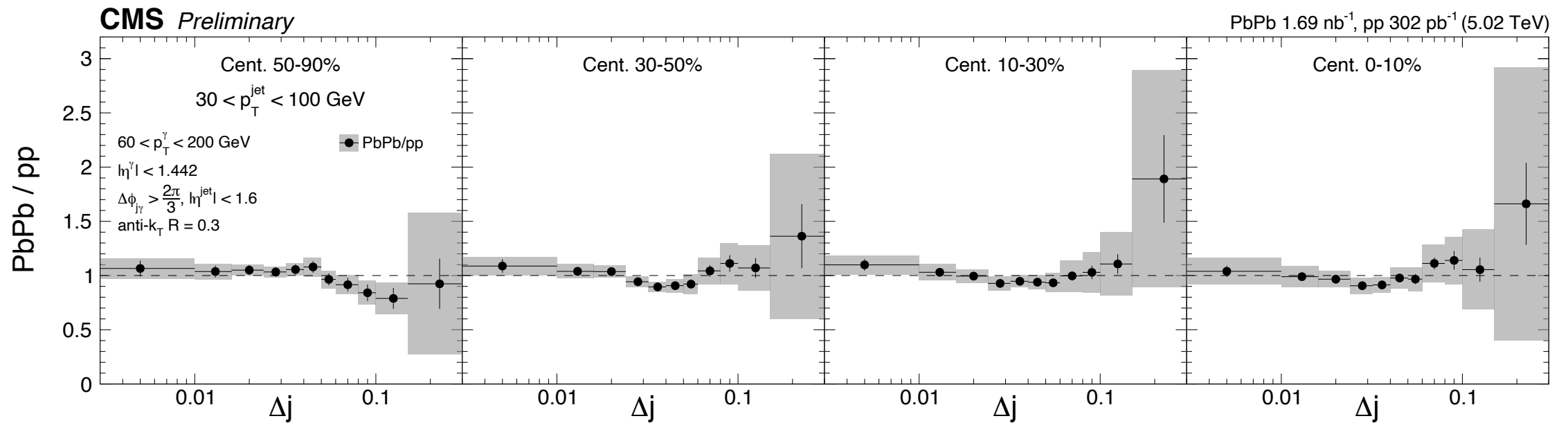
Δj spectra normalized per photon



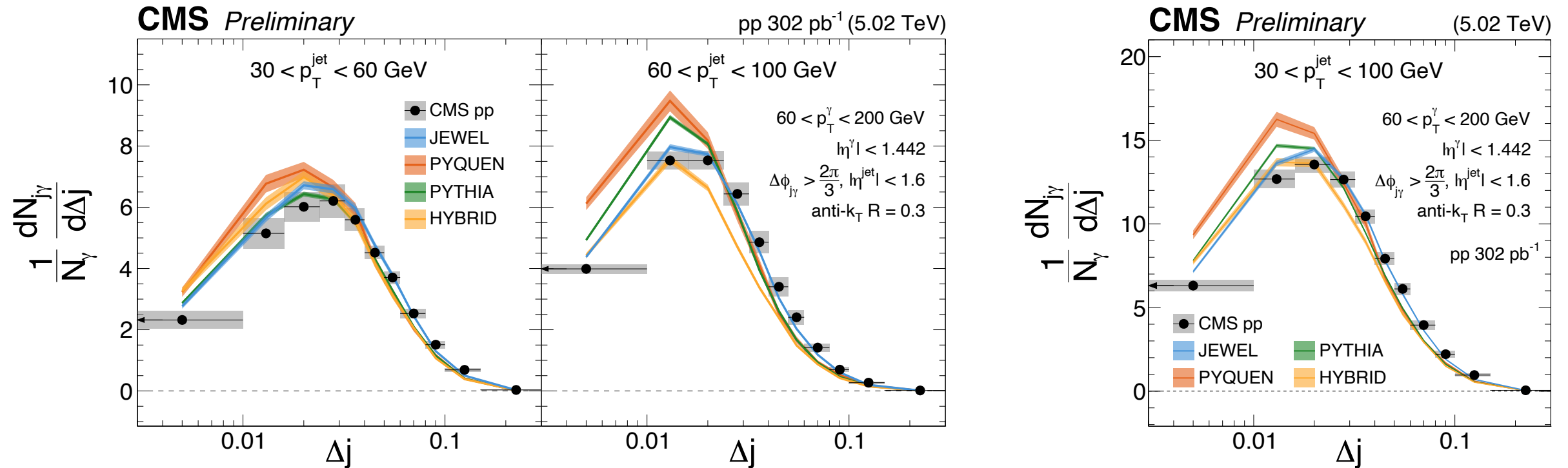
Δj shape ratios



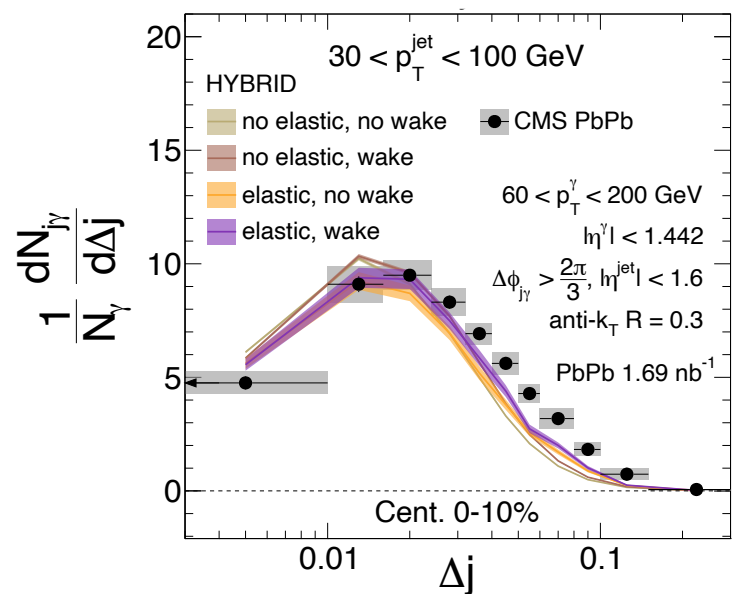
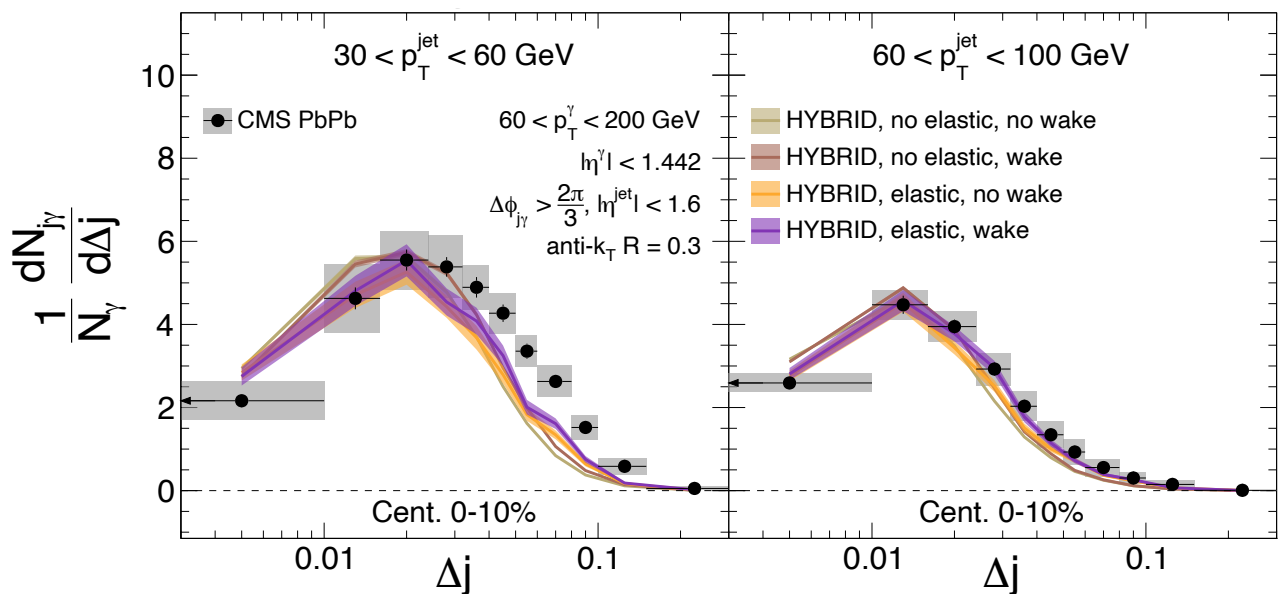
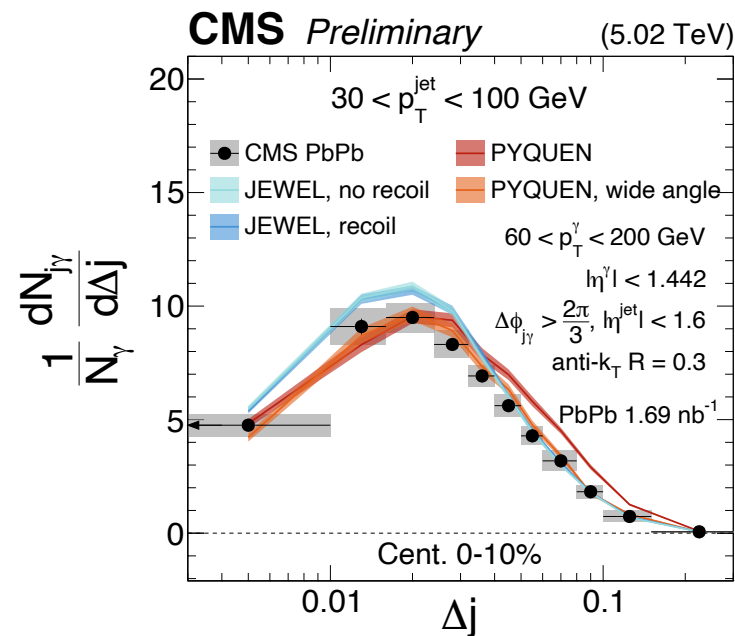
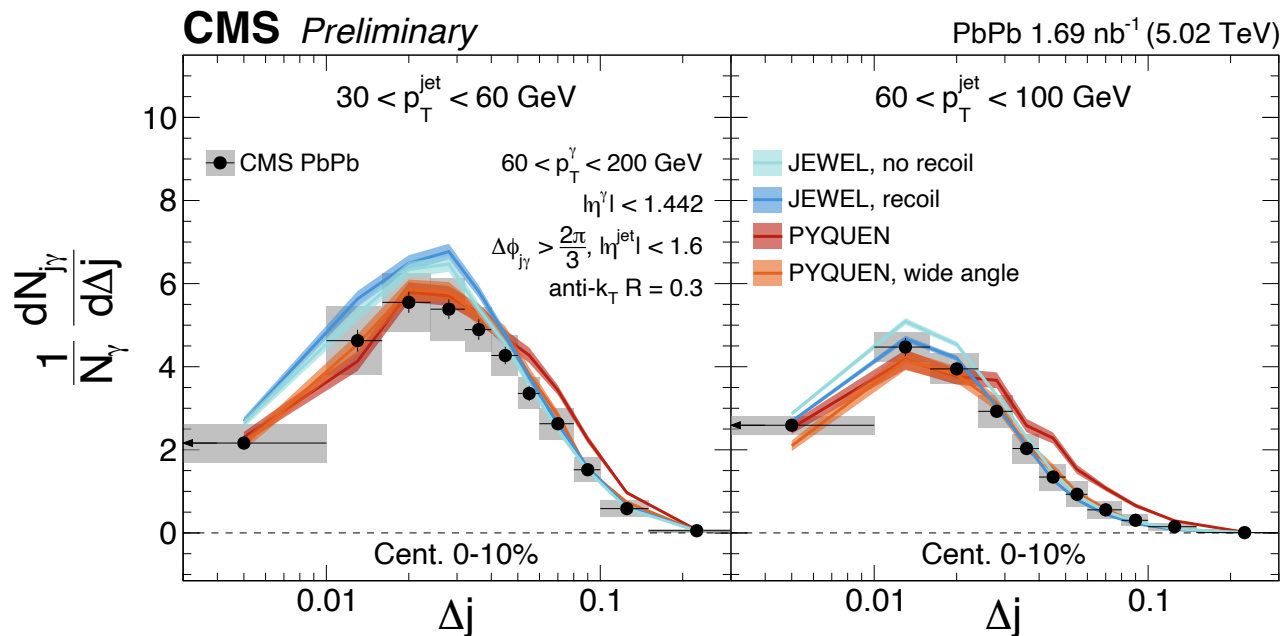
Δj shape ratios



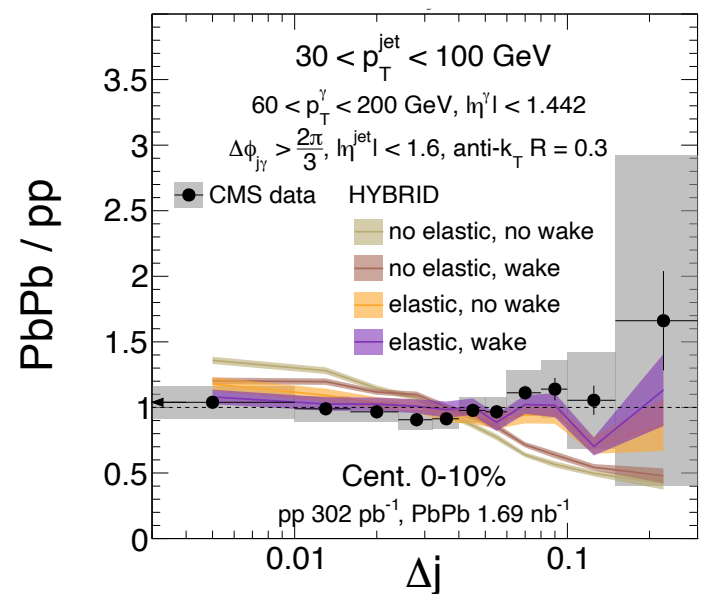
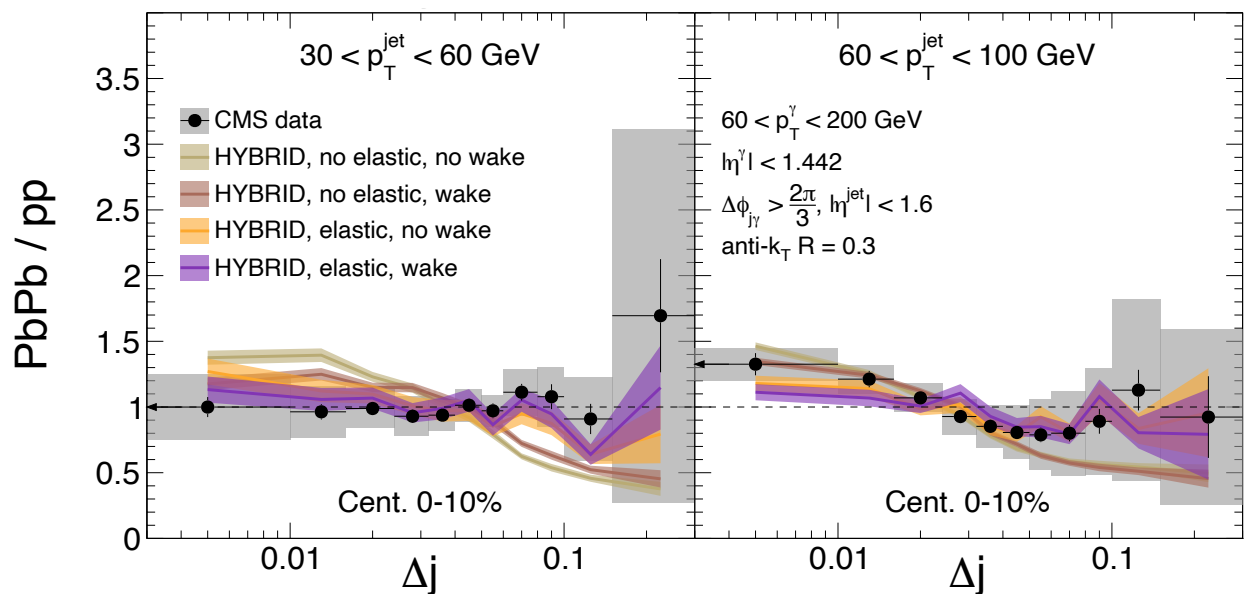
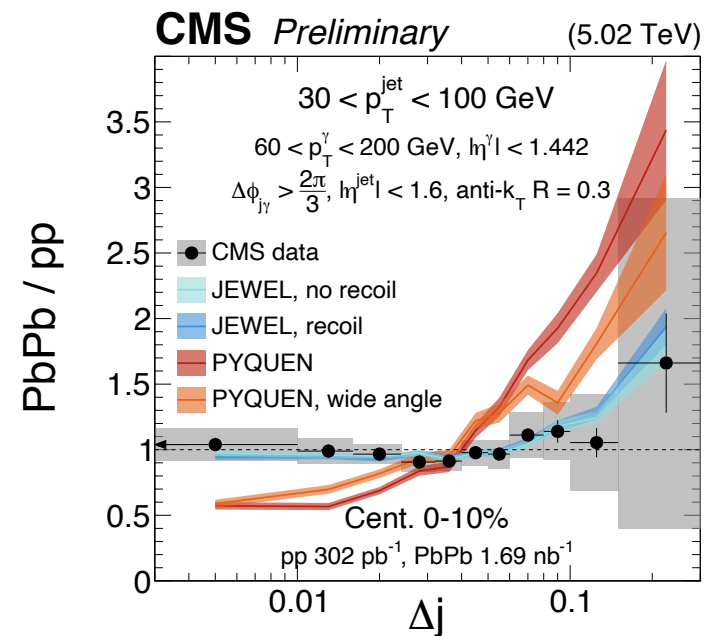
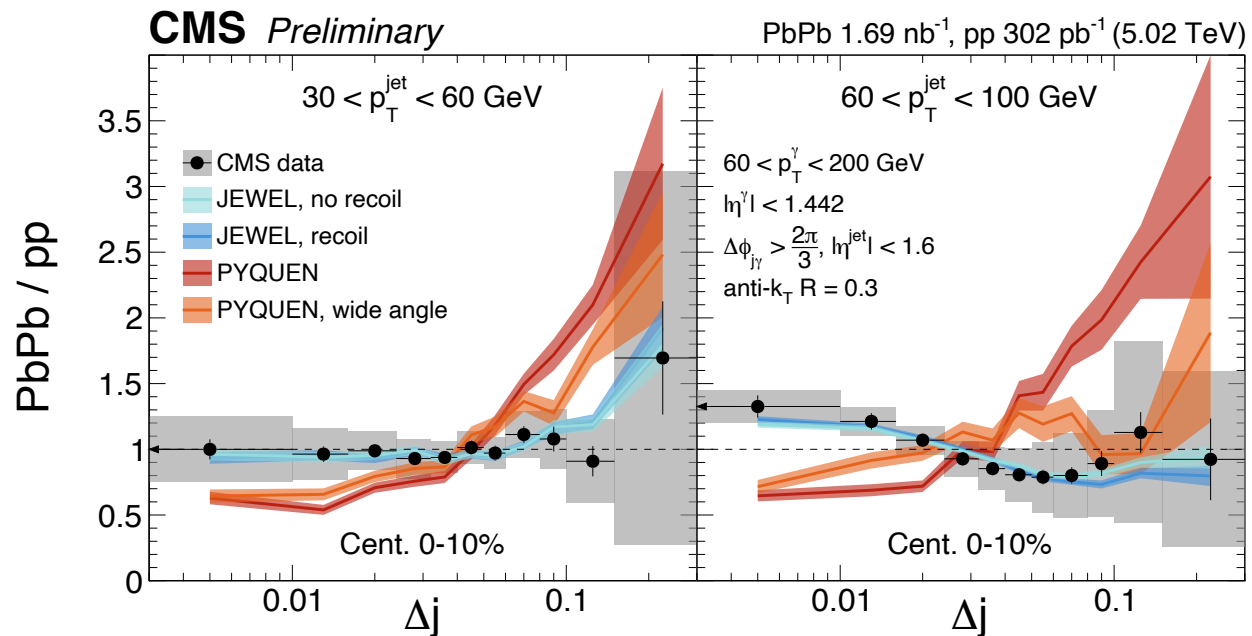
Δj spectra theory comparison: pp collisions



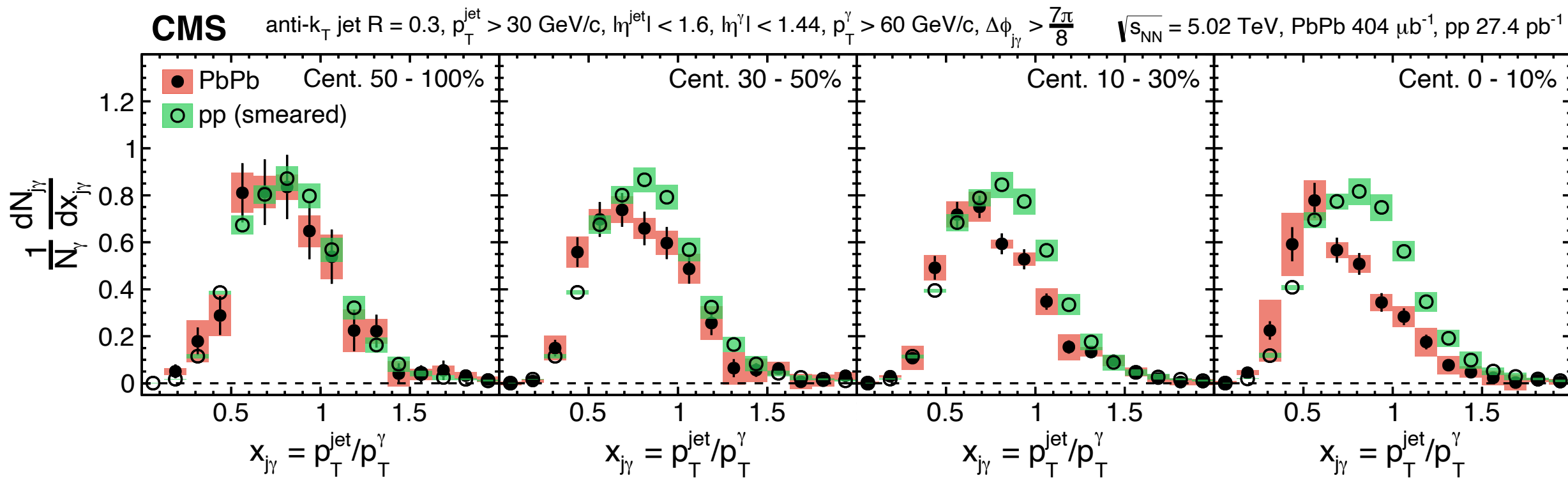
Δj spectra theory comparison: PbPb collisions



Δj shape ratio theory comparison



$x_{j\gamma}$ measurement



I_{AA}^{jet} measurement

