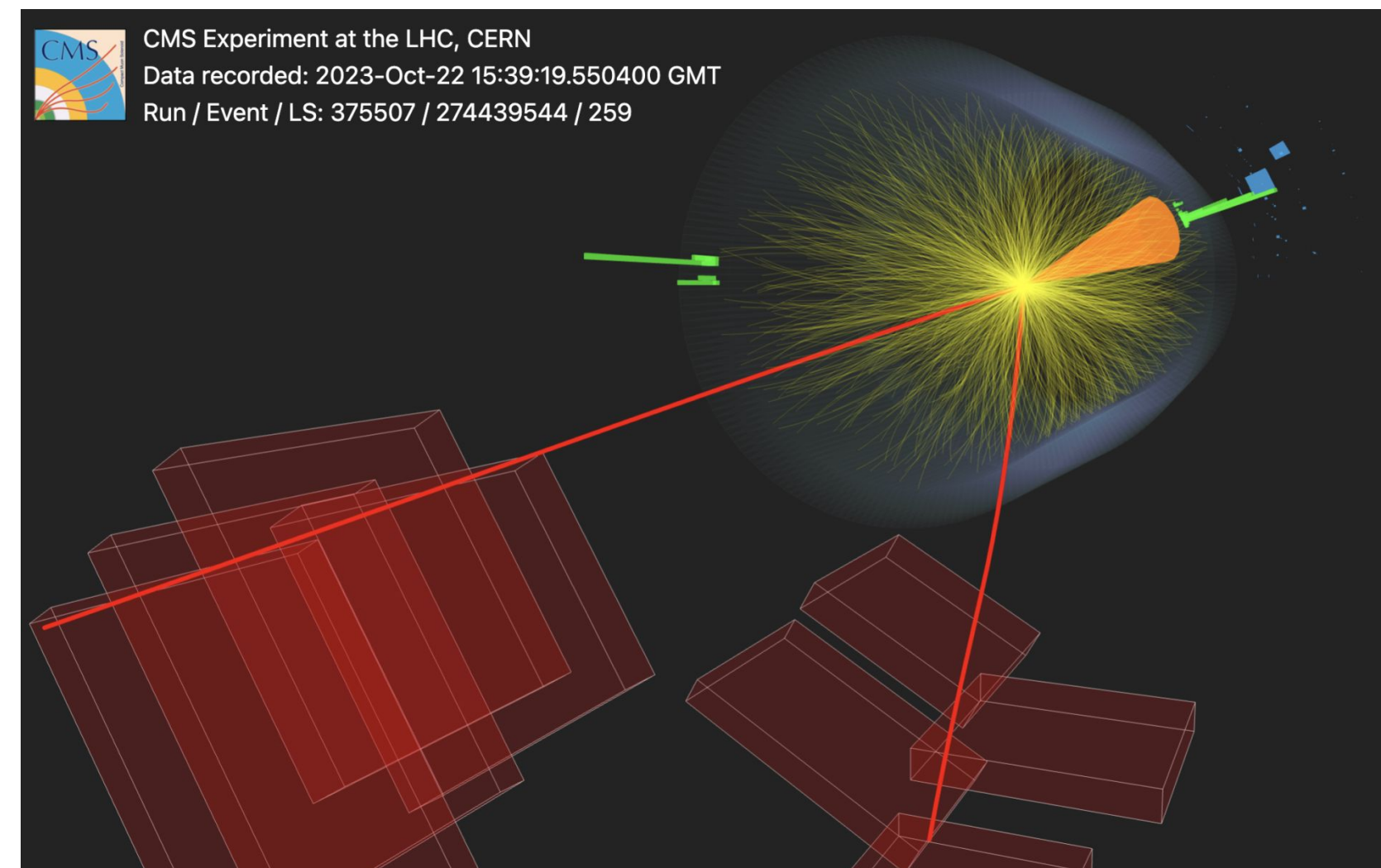




Measurement of the jet quenching effect with Z +jet events in PbPb and pp collisions at 5.36 TeV with Run 3 data

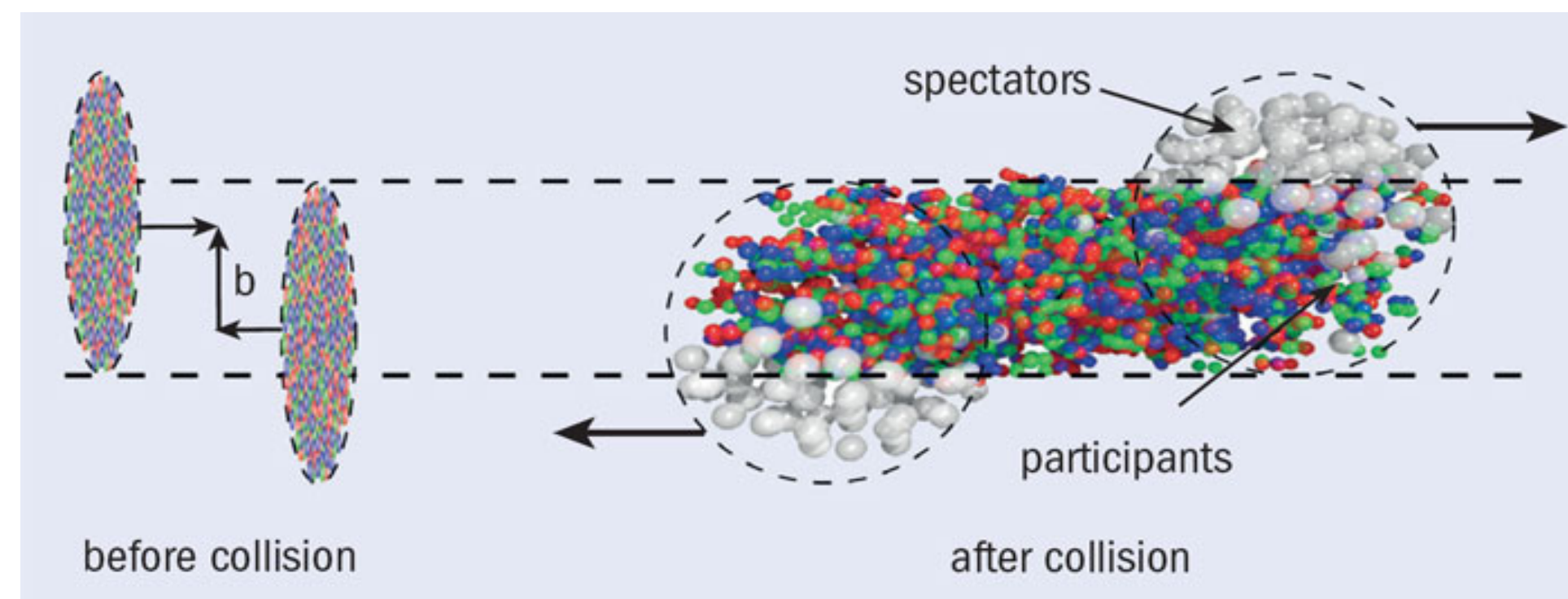
Raffaele Delli Gatti for the CMS Collaboration



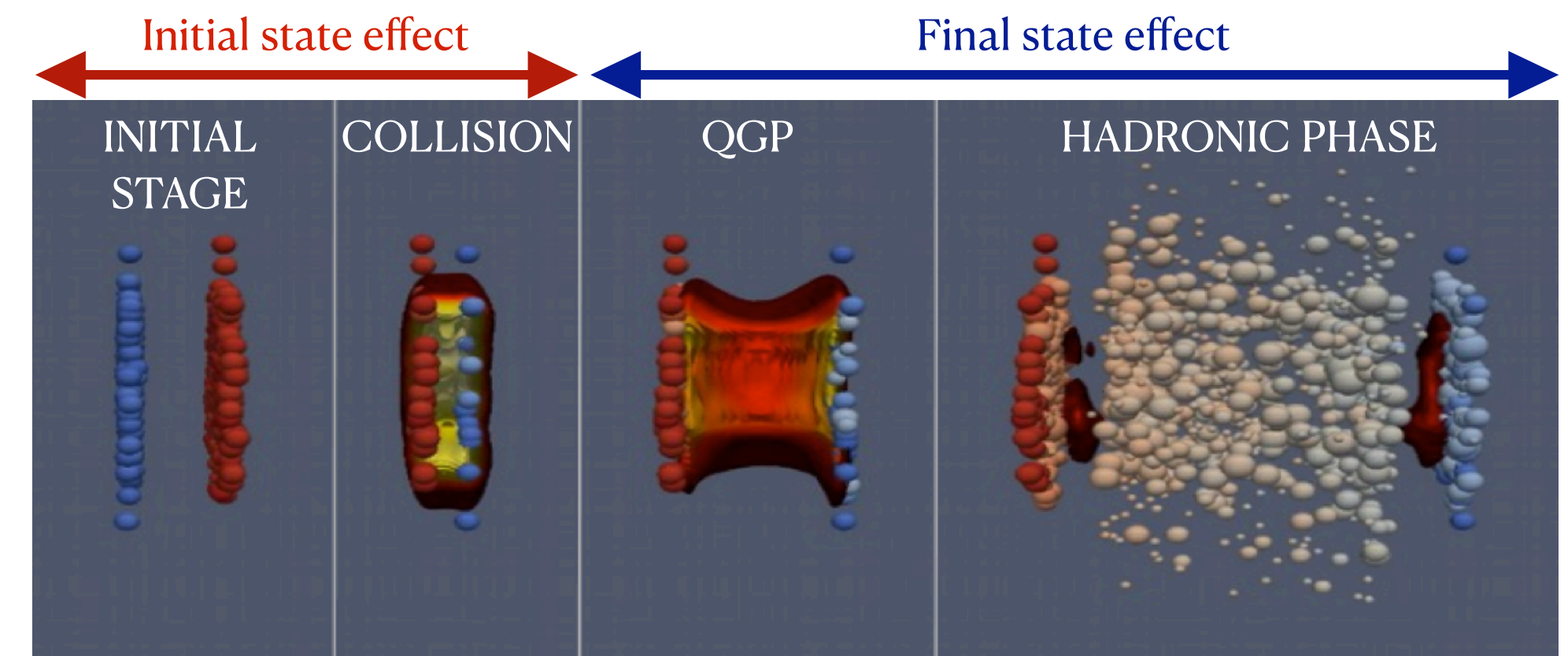
Introduction

PbPb collisions produce droplets of quark-gluon plasma (**QGP**) - a hot, strongly interacting, near-perfect liquid with **colour** degrees of freedom

- Jets can provide a multi-scale probe of the QGP
- As they propagate through the QGP, jets get modified, or “**quenched**”
- Allow measurement of QGP transport properties (e.g. $\hat{q}$, T) and probe microscopic medium dynamics (e.g., color coherence, quasiparticle interactions)



[CERN COURIER](#)



H. Petersen and J. Bernhard, MADAI collaboration

Physics Motivation

GOAL: Characterize jet energy loss through QGP using $Z(\rightarrow \mu\mu) + jet$ events with **Run 3** data, **first unfolded measurement** with the CMS experiment

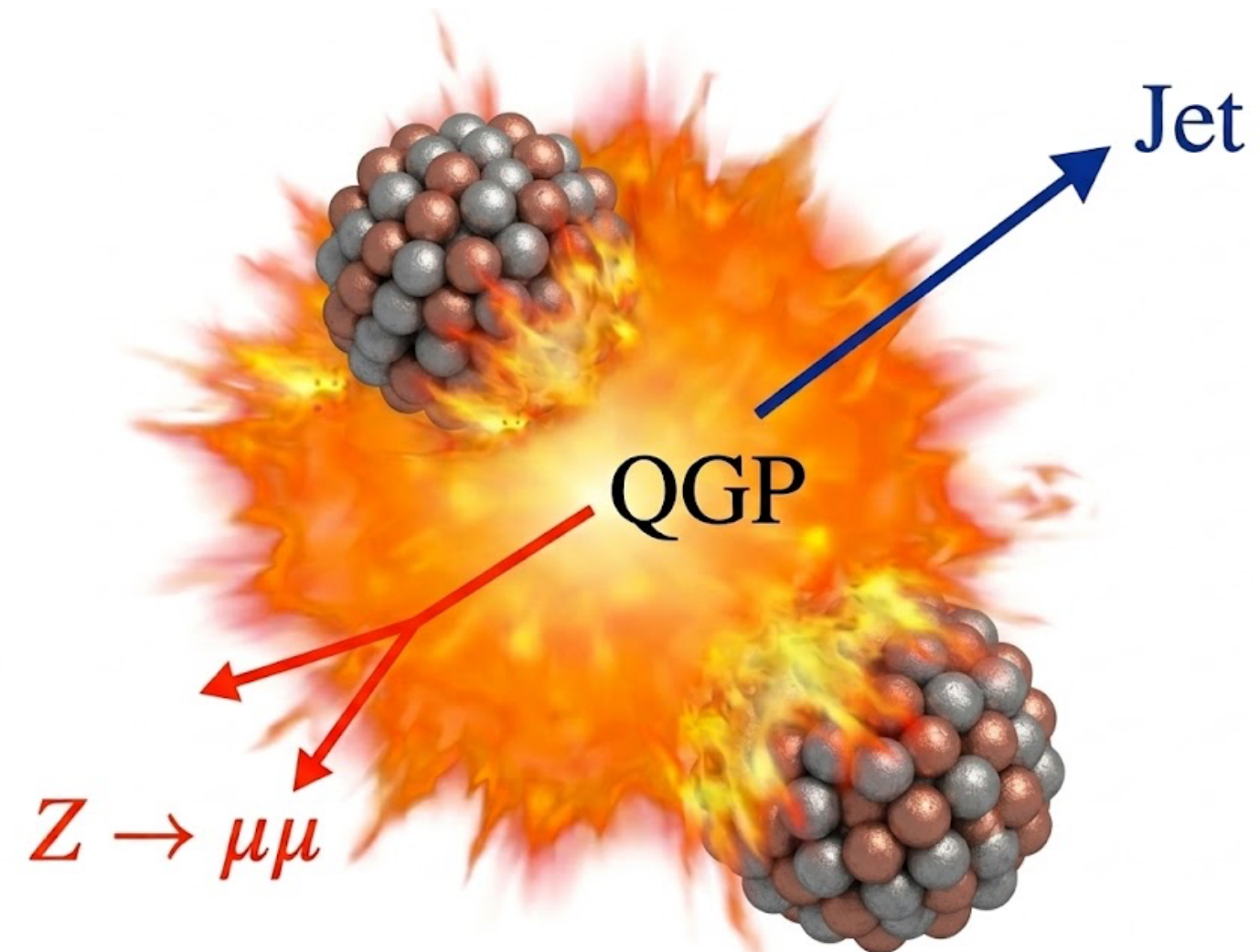
- Unfold momentum imbalance: $x_{Zj} = p_T^{jet} / p_T^Z$
- Compare PbPb with pp reference and theory prediction

The Target

- High-energy quark and gluons are modified by the medium

The Probe

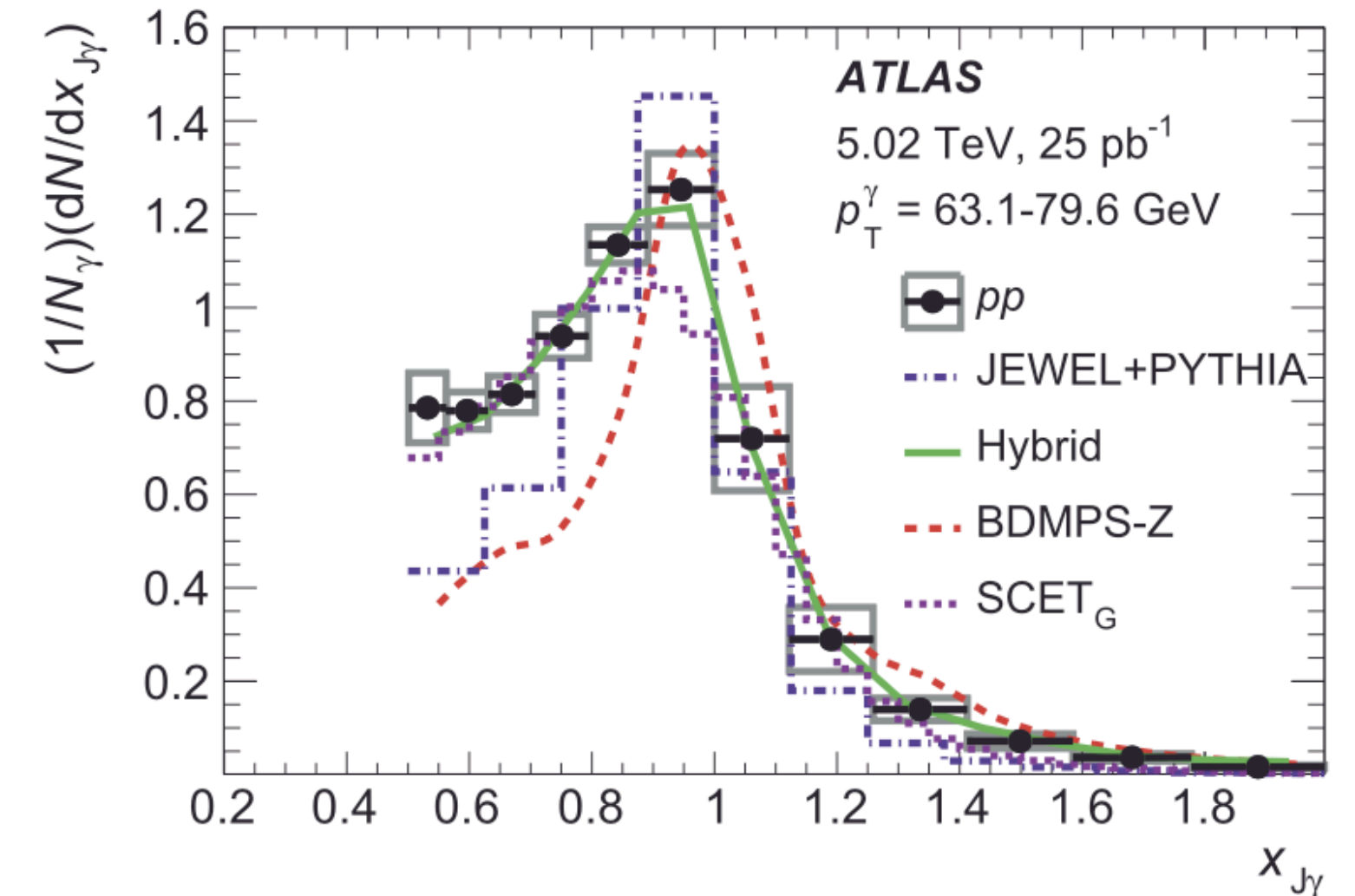
- Z bosons decay before the emergence of the QGP phase
- Leptonic decay products do not interact strongly with the medium
- Low bkg contamination



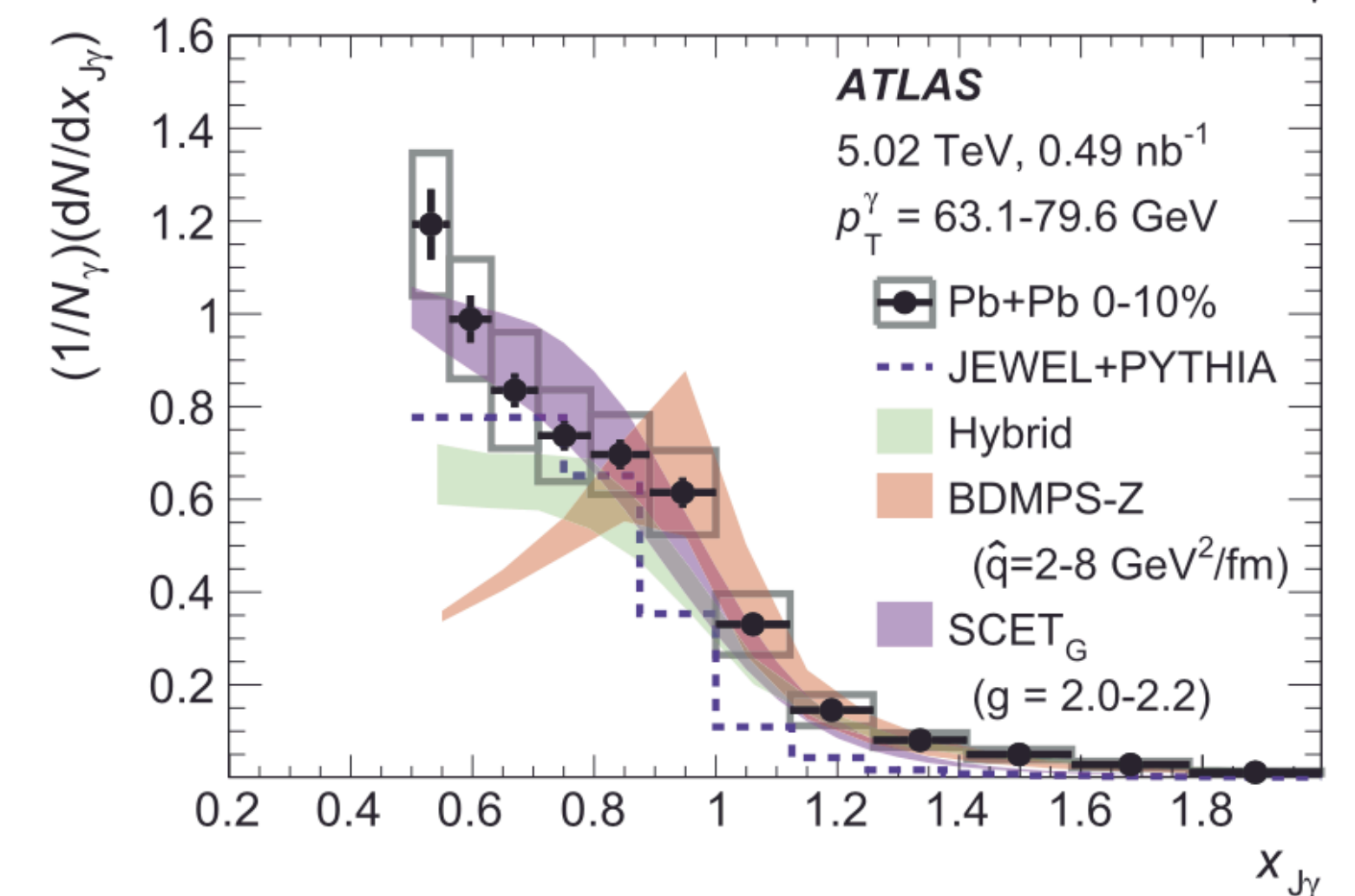
Unfolded result from ATLAS using photon+jet

Phys.Lett.B 789 (2019) 167-190

- In pp collisions, the $x_{J\gamma}$ distributions exhibit a sharp peak
- In the most central PbPb collisions, at lower photon energies, the distributions are so strongly modified that the peak disappears, and the yield simply decreases monotonically across the measured $x_{J\gamma}$ range
- Conclusion: while several theoretical models can capture general features of the data (such as the absence of a peak at low p_T^γ), none of the models fully describe all the details, such as the increase in jet yield at low $x_{J\gamma}$ values



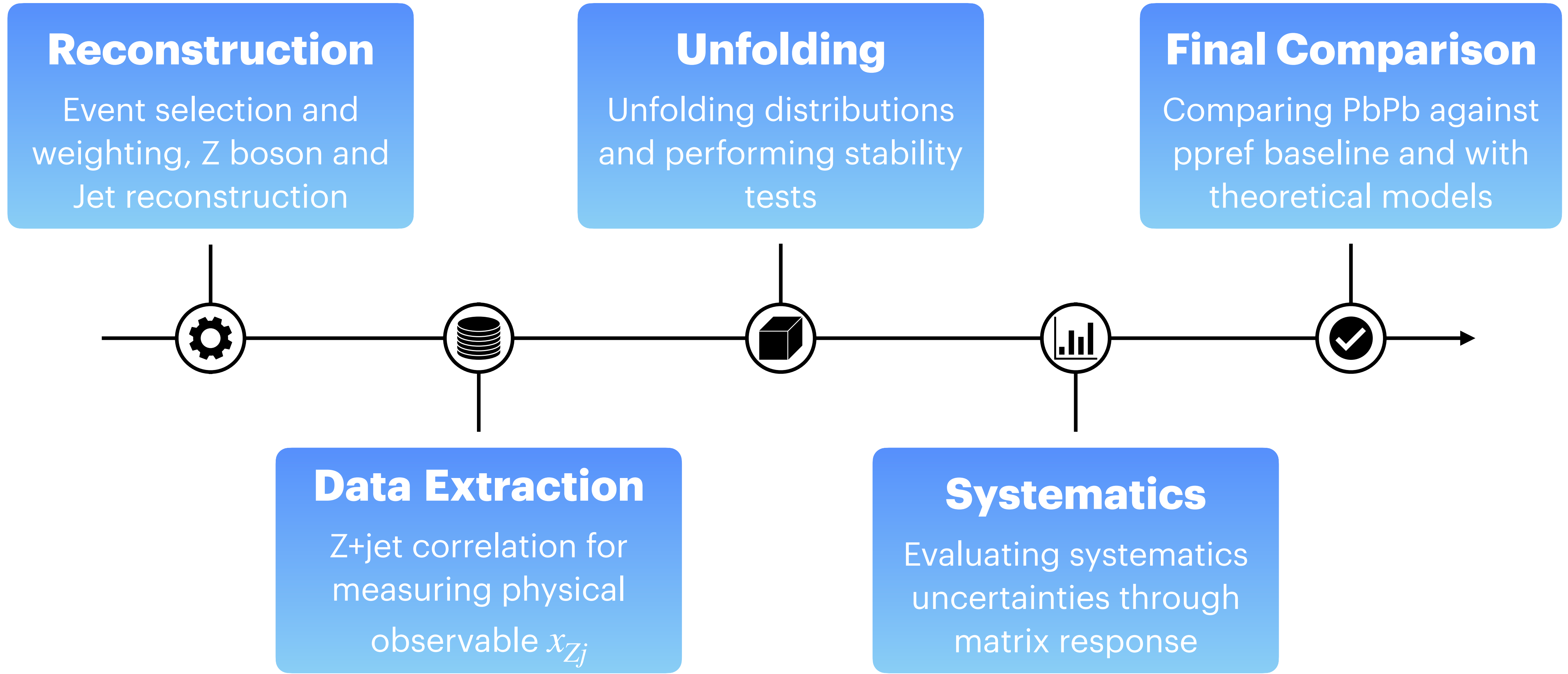
pp



Pb

Analysis steps

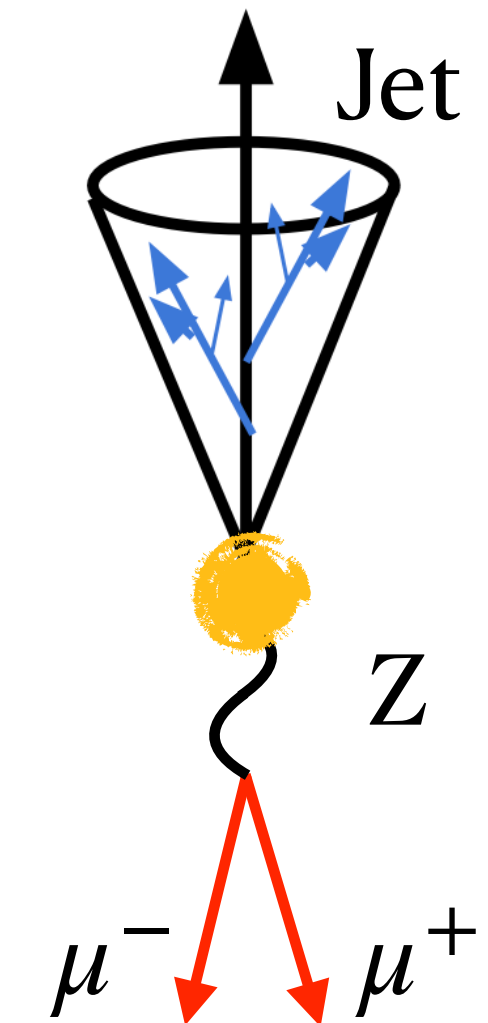
PAS-CMS-HIN-25-017



Kinematic phase space

- 1.64 nb^{-1} PbPb and 479 pb^{-1} pp datasets at 5.36 TeV (Run 3)
- Centrality 0 – 30 % for more jet quenching signal, $|v_z| < 15 \text{ cm}$
- Jets with $\Delta R < 0.2$ from a muon rejected

Selection	
Z boson	Recoiling jet
$p_T^\mu > 20 \text{ GeV}$	$p_T^{jet} > 30 \text{ GeV}$
$ \eta^\mu < 2.4$	$ \eta^{jet} < 2.1$
Highest p_T muons	Leading jet
$60 \text{ GeV} < m_{\mu\mu} < 120 \text{ GeV}, p_T^Z > 40 \text{ GeV}$	at least 1 AK2 jet
$\Delta\phi_{Zj} > 7\pi/8$	



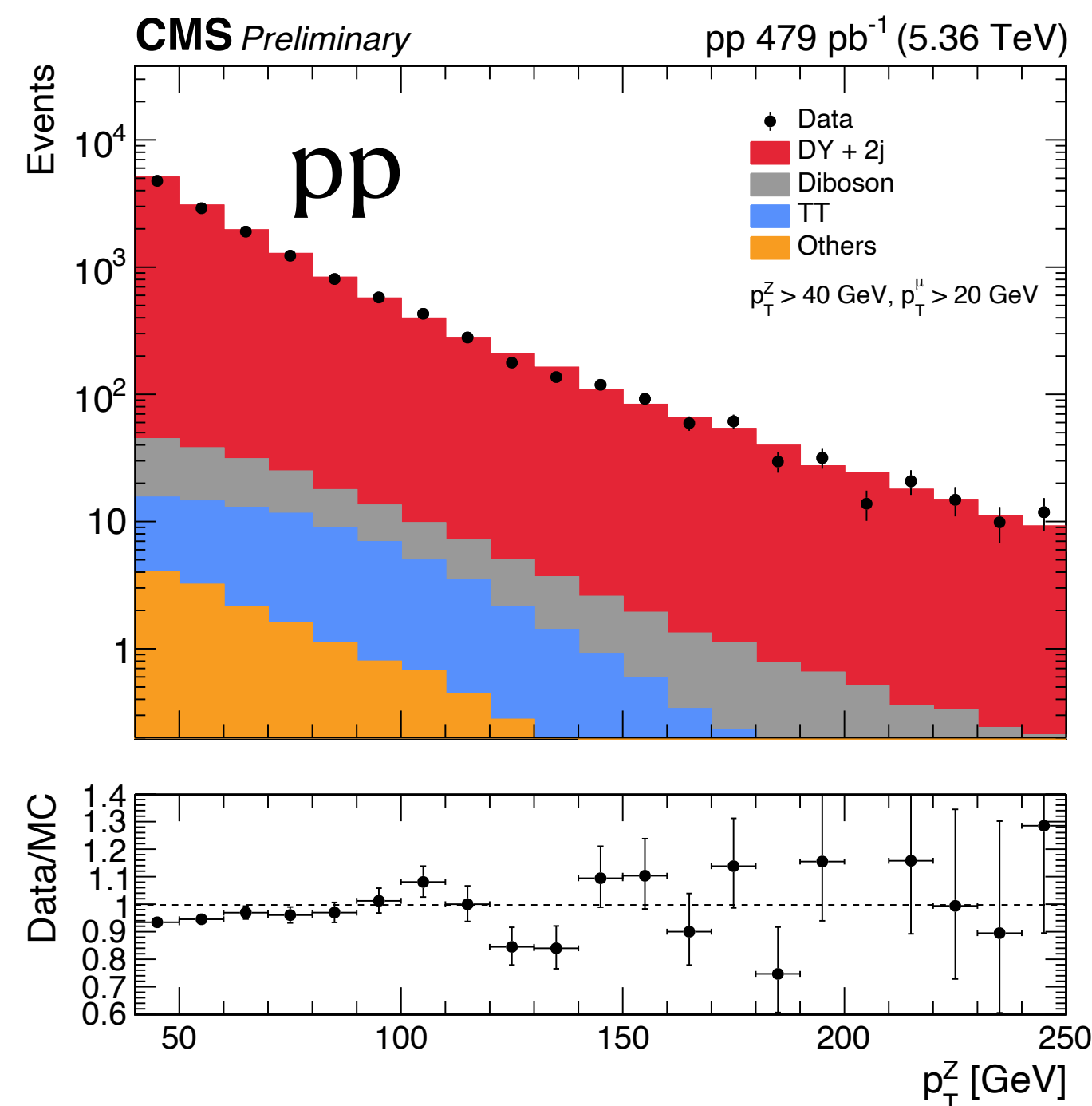
- Selection $\Delta\phi_{Zj}$ window chosen to enhance the back-to-back topology, isolating genuine hard-scattered jets and suppressing UE bkg

Detector-level distributions

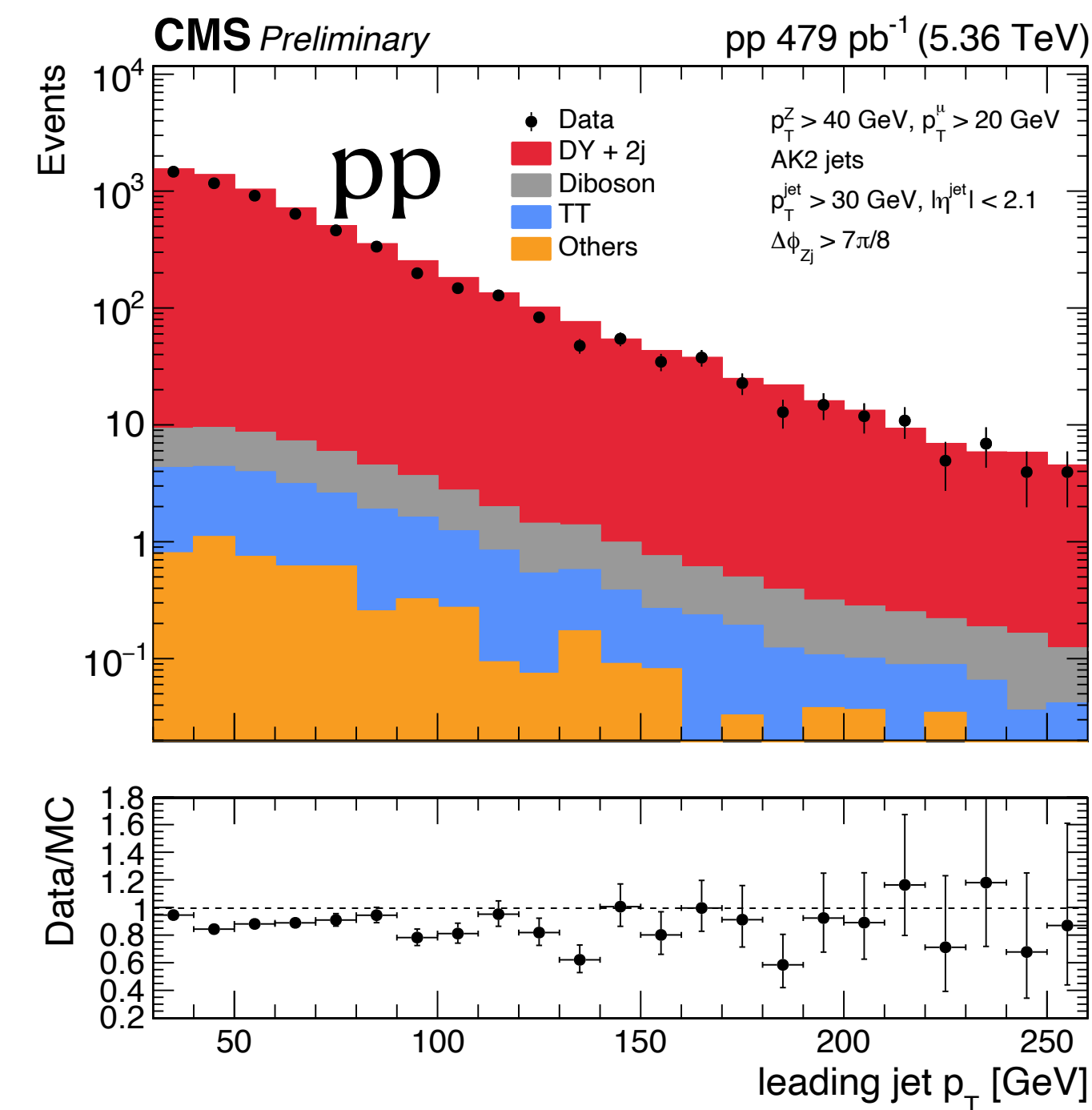
- Z and jet p_T for data compared to MC stacked histograms for signal and bkg
- MC distributions normalised using lumi, σ_{gen}^{pp} , σ_{gen}^{NN} (scaled by $A^2 = 208^2$) and final MC event weights

Step	Cuts	2024 pp	2023 PbPb (0 – 30%)
Z boson reconstruction	$60 < m_{\mu\mu} < 120$ GeV opposite charge $p_T^Z > 40$ GeV	13787	1547
Jet selection	$p_T > 30$ GeV, $\eta < 2.1$ $\Delta R_{\mu,j} > 0.2$	7743	737
Back-to-back cut	$\Delta\phi_{ZJ} > 7\pi/8$	5856	417

Z kinematic



Leading jet

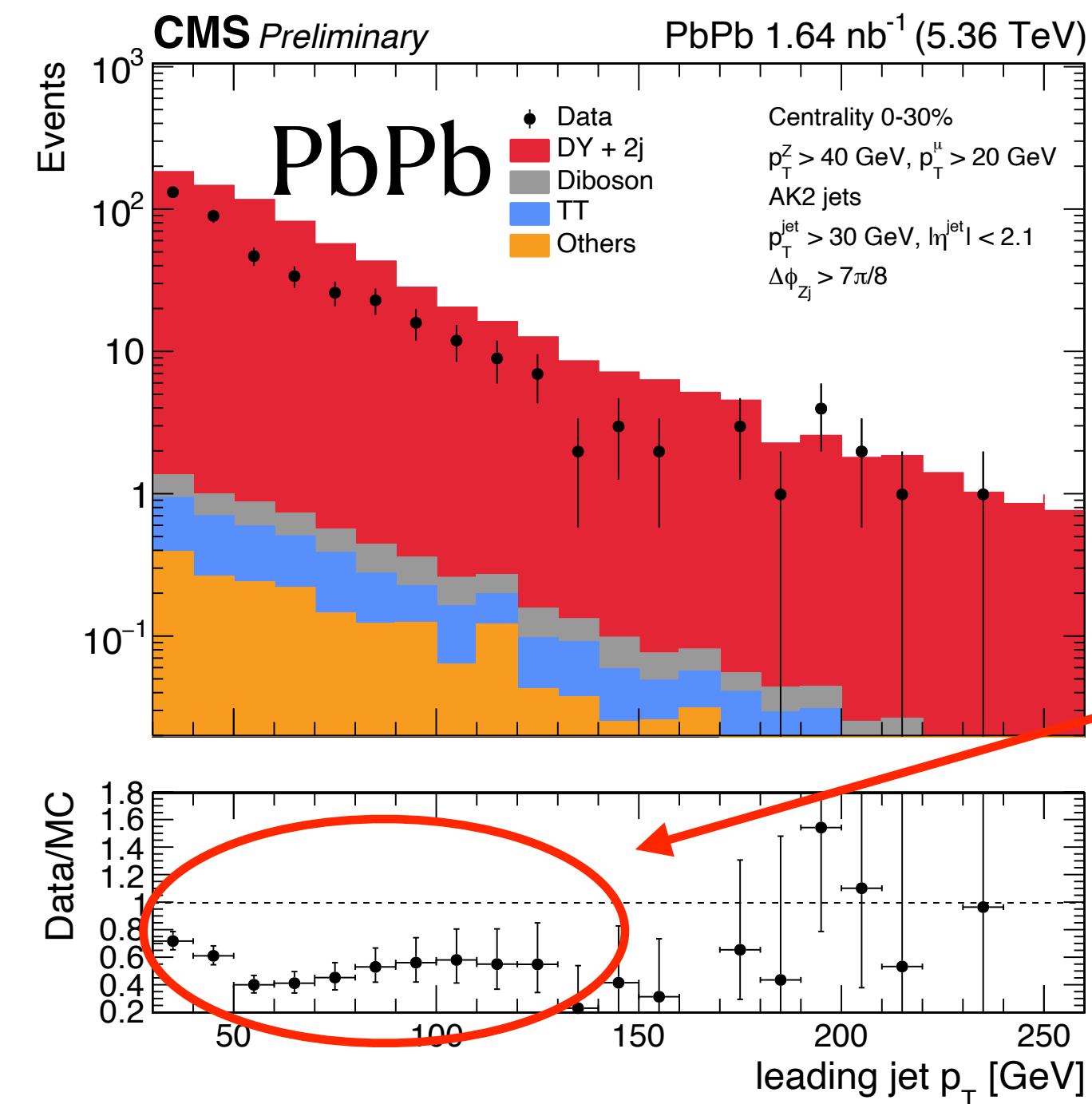
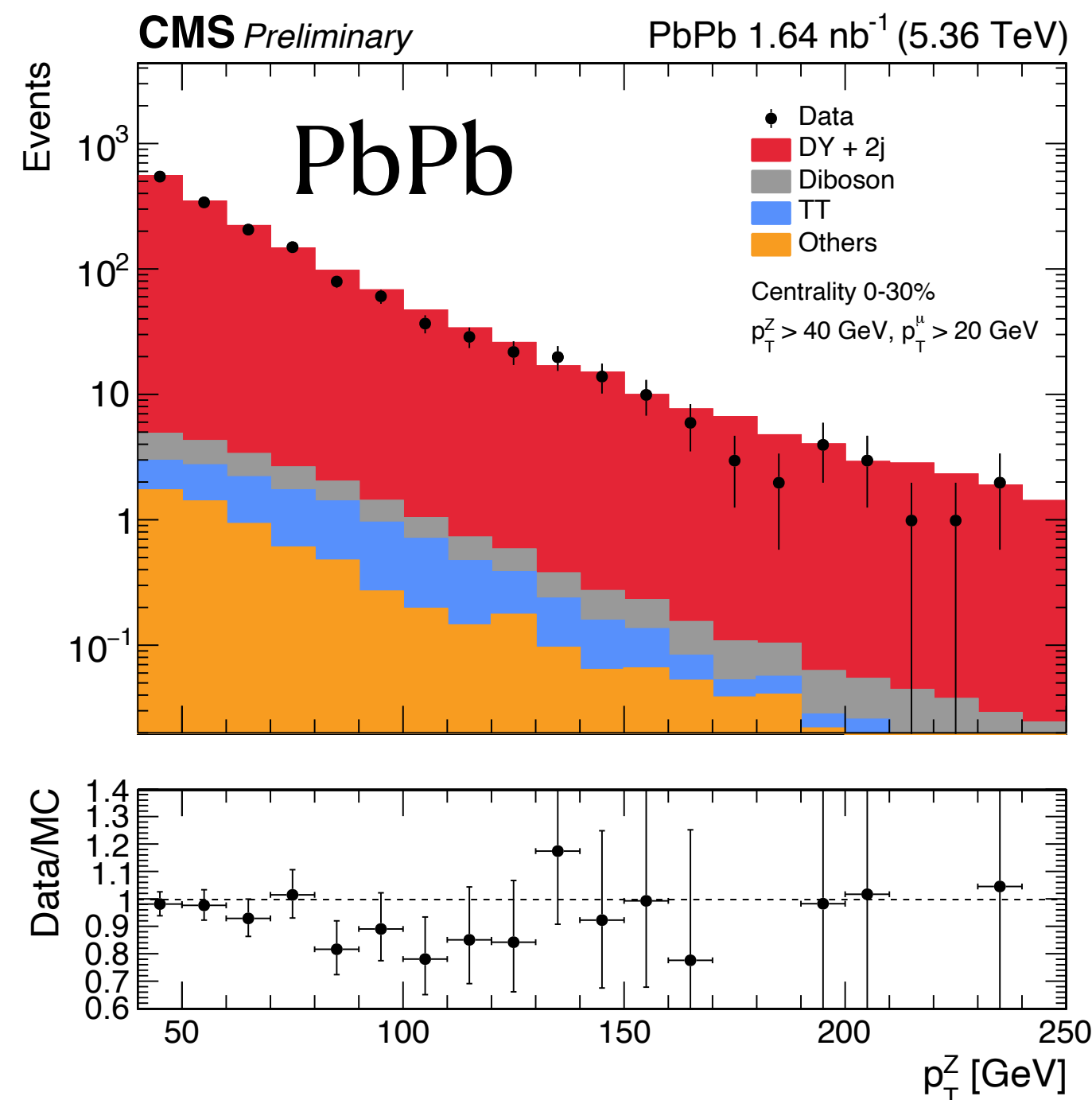


Detector-level distributions

- Z and jet p_T for data compared to MC stacked histograms for signal and bkg
- MC distributions normalised using lumi, σ_{gen}^{pp} , σ_{gen}^{NN} (scaled by $A^2 = 208^2$) and final MC event weights

Step	Cuts	2024 pp	2023 PbPb (0 – 30%)
Z boson reconstruction	$60 < m_{\mu\mu} < 120$ GeV opposite charge $p_T^Z > 40$ GeV	13787	1547
Jet selection	$p_T > 30$ GeV, $\eta < 2.1$ $\Delta R_{\mu,j} > 0.2$	7743	737
Back-to-back cut	$\Delta\phi_{ZJ} > 7\pi/8$	5856	417

Z kinematic



Leading jet

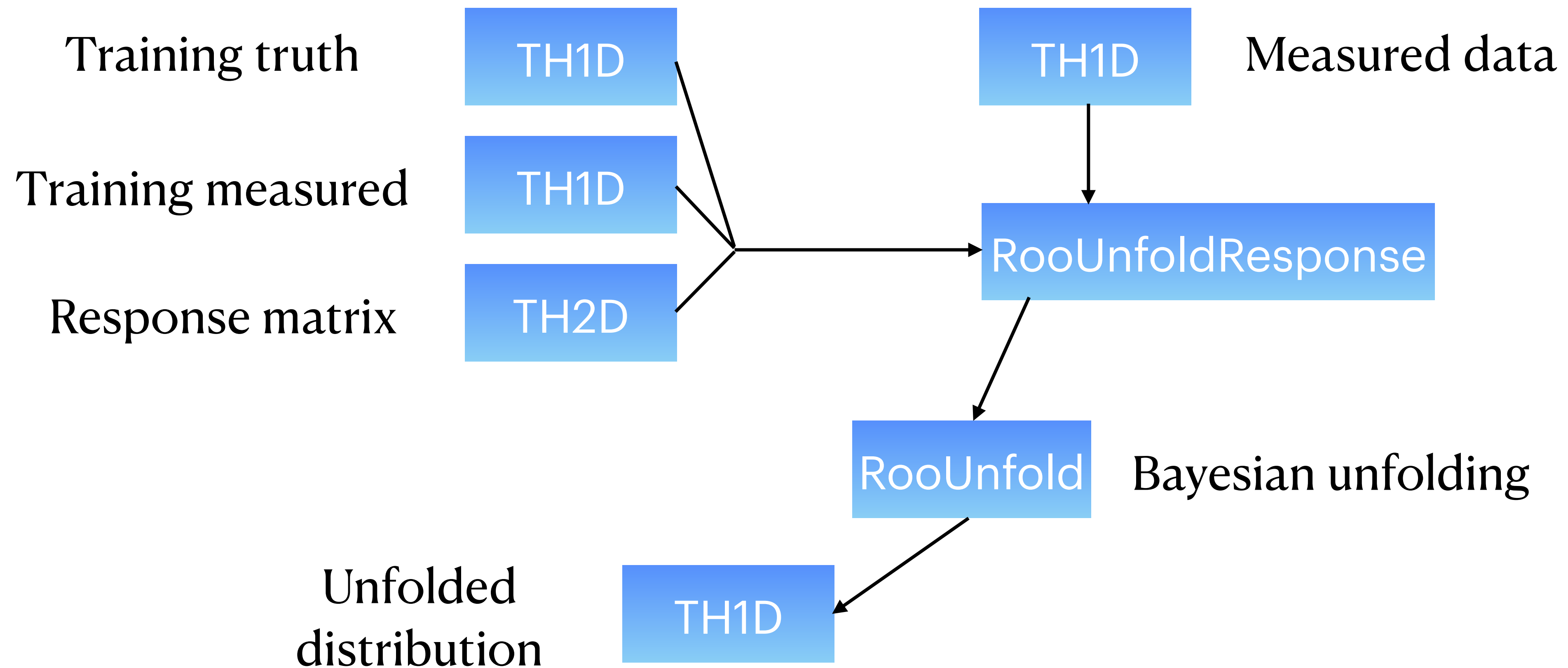
- The difference between data and MC is due to both fakes and quenching

Two-Step Jet Background Subtraction in PbPb

1. Constituent Subtraction (CS): Fixes Jet Energy
 - **How:** Subtracts average background from individual particles *before* clustering.
 - **Why:** Recovers the true energy of genuine jets.
2. Mixed Event Subtraction: Fixes Jet Population
 - **How:** Uses Minimum Bias events to model uncorrelated background jets.
 - **Why:** Statistically removes "fake" jets caused by random background fluctuations.

Unfolding

- To study the $x_{Zj} = p_T^j/p_T^Z$ distribution at the **generator level**, we need to **correct** the **reco-level** for CMS-specific **detector effects**

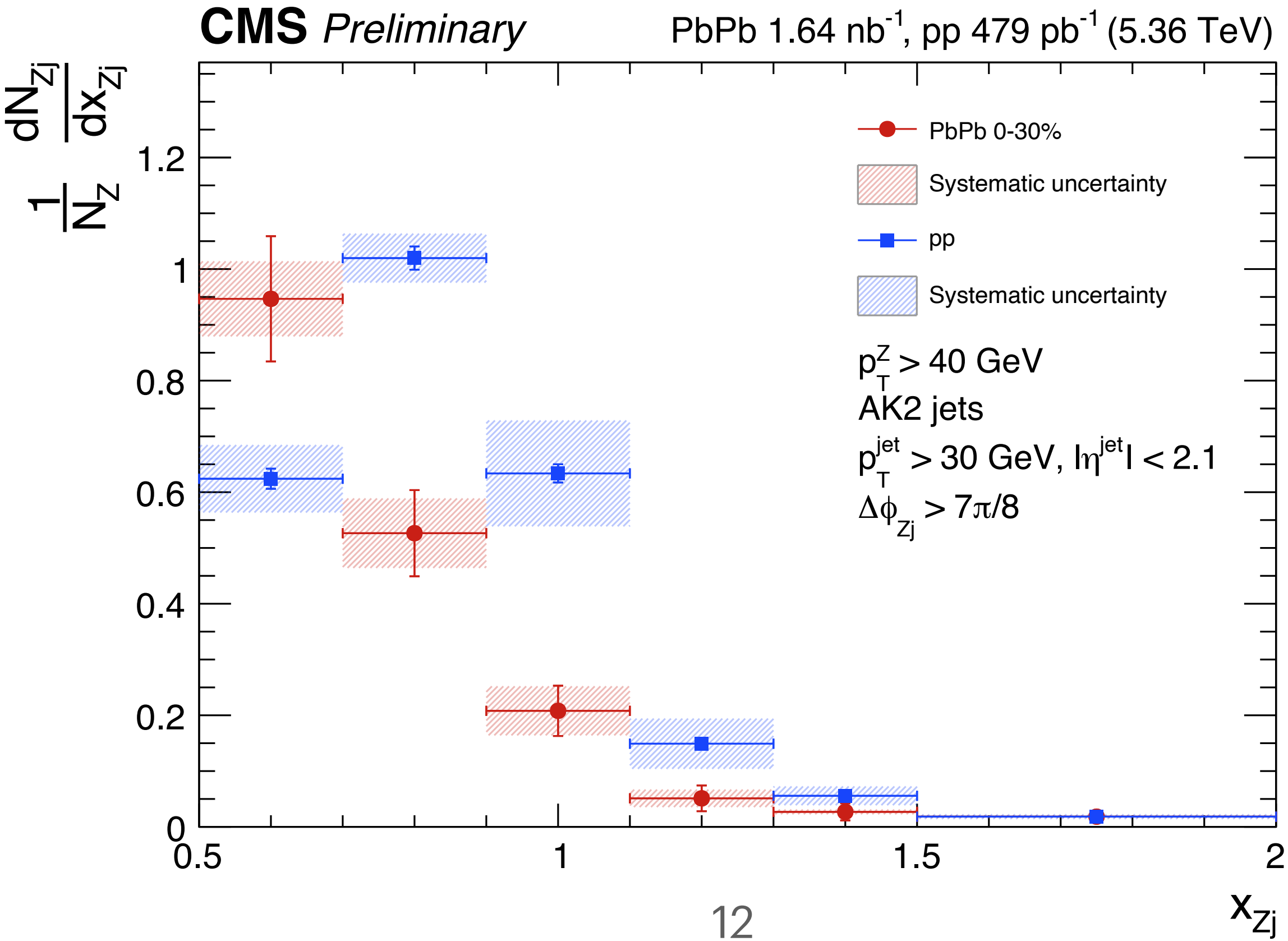


Systematic uncertainties

- The following systematic uncertainties are considered (propagated in unfolding procedure through variations in response matrix):
 - Jet energy calibration (up and down variations)
 - Muon efficiency corrections (trigger, Identification and isolation)
 - **UE Background subtraction** (Fake Removal) and UE Jet Swapping (eclipsing)
 - Physics bkg (subtraction of other events from data, unc. on normalisation using lumi)
 - **Centrality (HF transverse energy sum boundaries for each centrality interval varied up and down)**
 - MC prior (alternative MC sample JEWEL+PYTHIA6 for PbPb, DYto2Mu POWHEG for ppref)
 - MC stat. (run toys and apply random fluctuation to response matrix, efficiency and purity)
 - Regularisation bias (we fix optimal iteration to nominal case)
- When up/down variations are available, symmetrising by looking at the mean deviation from the nominal result: $\sigma_{syst} = [X_{up} - X_{nom} | + | X_{down} - X_{nom} |]/2$
- When just one alternative is available, computing as $\sigma_{syst} = | X_{other} - X_{nom} |$
- Systematic unc. assumed to be **uncorrelated** and are therefore added in **quadrature**: $\sigma_{total} = \sqrt{\sum_i \sigma_{syst,i}^2}$

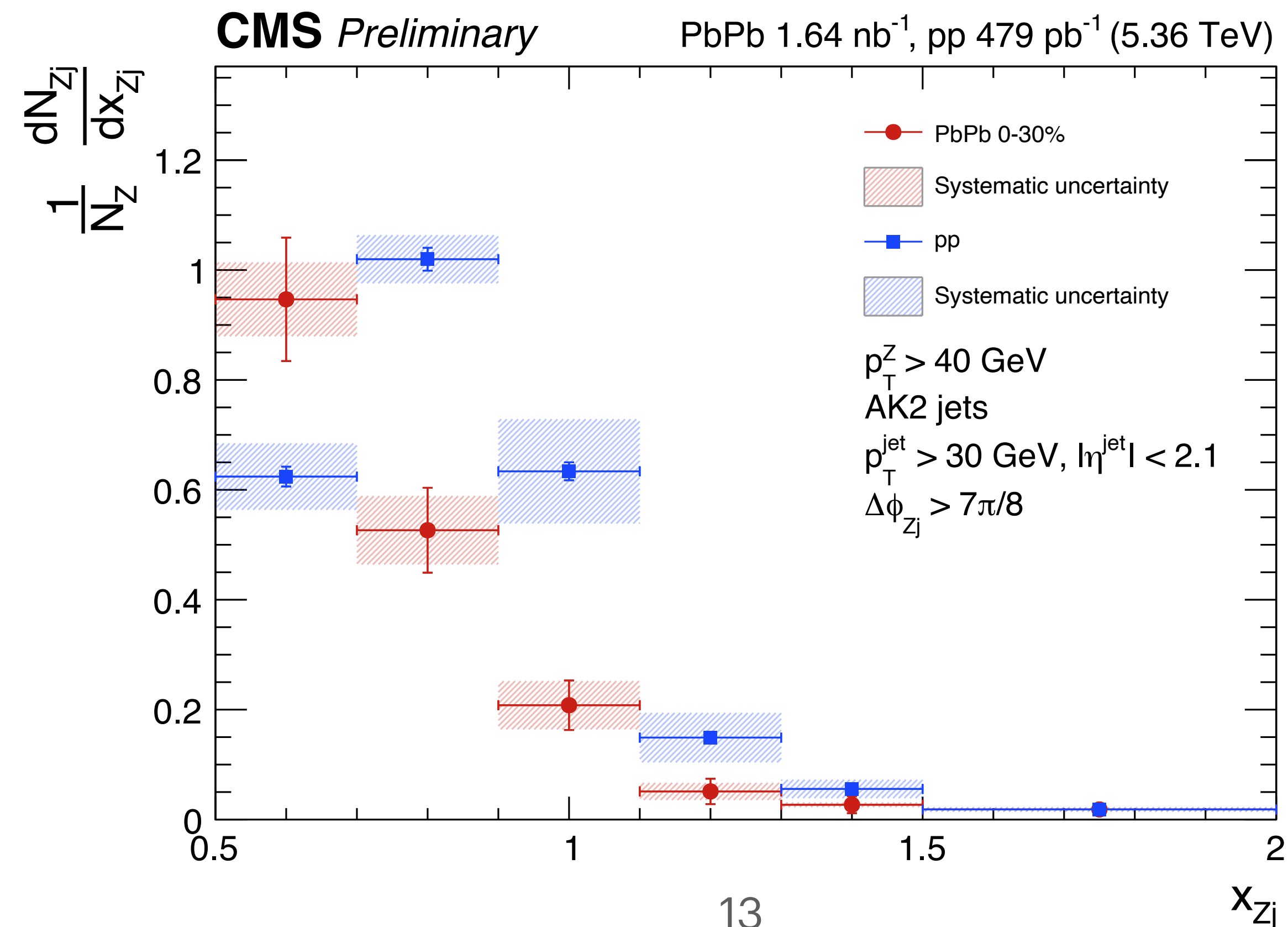
Comparison between PbPb and pp

Systematic source	PbPb uncertainty (%)	pp uncertainty (%)	Systematic source	PbPb uncertainty (%)	pp uncertainty (%)
Jet Energy Scale (JEC)	2.6–27.8	1.3–28.7	Regularization bias	0.6–2.3	0.1–2.0
Jet Energy Resolution (JER)	0.3–10.0	0.0–10.9	Prior distribution	0.9–8.6	0.2–7.3
UE background subtraction	0.0–5.7	–	Centrality determination	< 1	–
Jet swapping (Eclipsing)	< 1	< 1	MC statistical uncertainty	2.3–9.0	0.6–3.0
Physics backgrounds	< 1	< 1			
Muon scale factors (SF_μ)	1.1	1.1–1.3	Total systematic uncertainty	7.1–31.4	4.3–30.4



Comparison between PbPb and pp

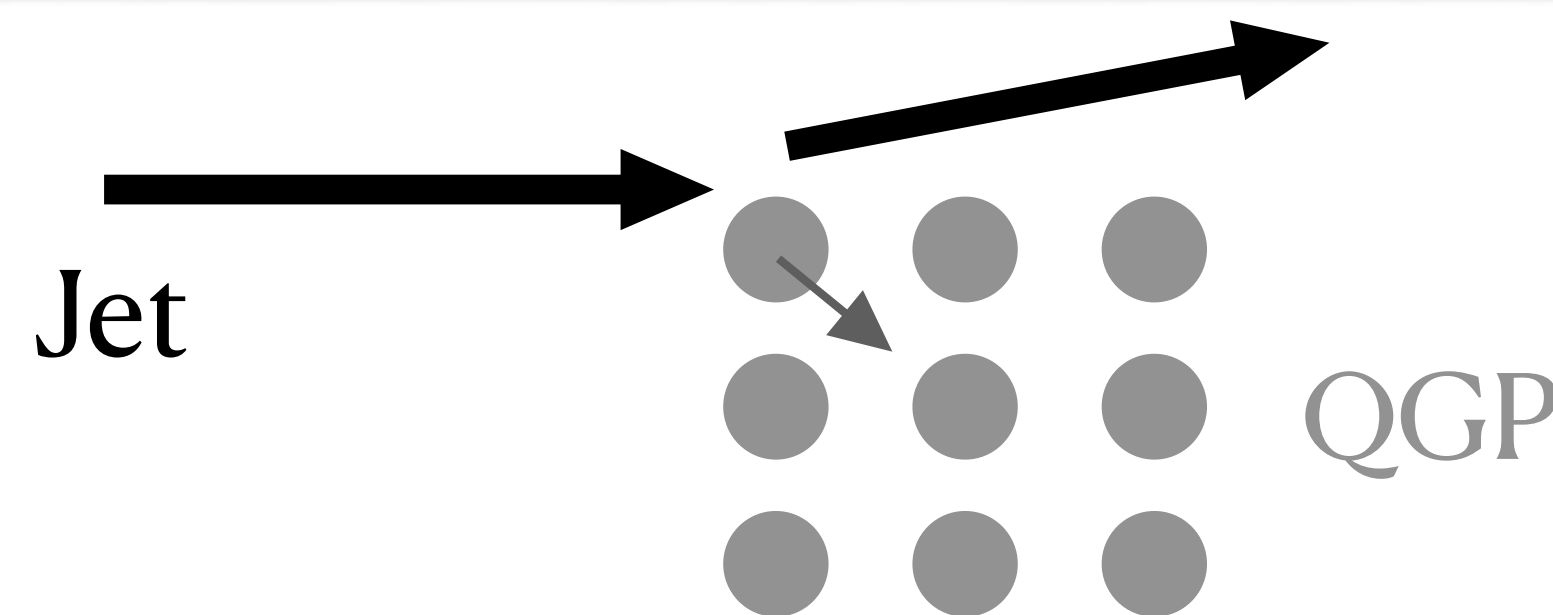
- In PbPb collisions, the Z boson decays before the emergence of the QGP phase, while the recoiling parton loses energy via jet quenching
- Jet energy loss is expected to manifest itself both as
 - A shift in the x_{Zj} distribution (**shape modification**)
 - An overall decrease in the number of Z-jet pairs as jets fall below p_T^j threshold (**overall normalisation suppression**)



Theory predictions with the Hybrid model

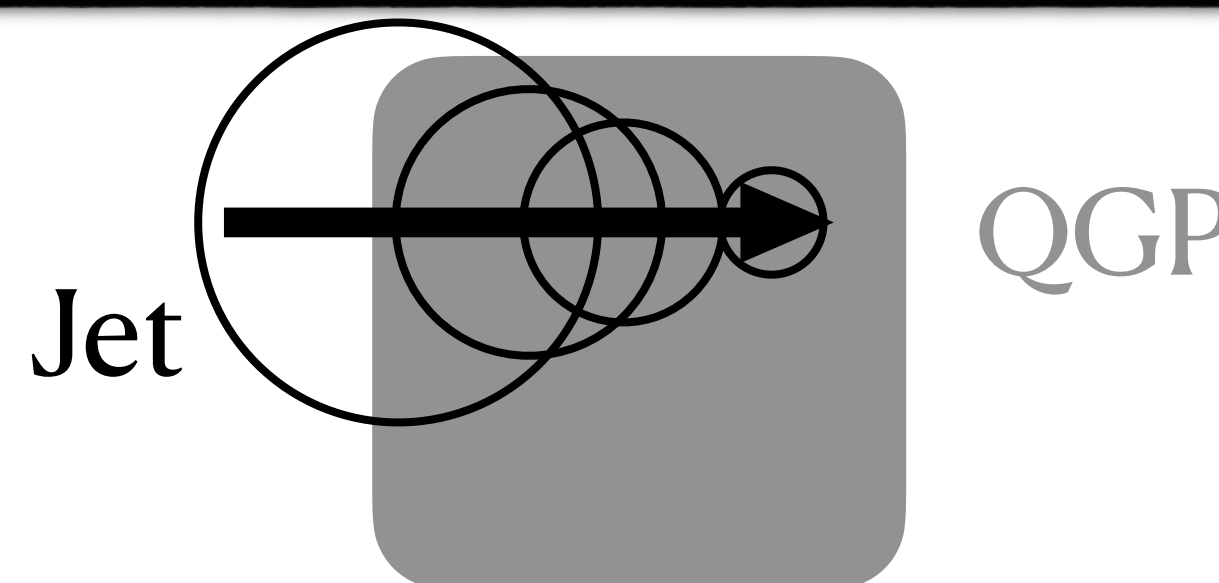
- **Molière (elastic) scattering**

- **Weakly-coupled** scenario: Large angle deflections when probed with high-momentum transfer (perturbative), asymptotic freedom mandates the presence of quark- and gluon-like quasiparticles



- **Wake effect**

- **Medium response:** At length-scales of order T^{-1} , QGP behaves as a strongly coupled liquid (to low-energy or large distances, cannot resolve the particles), non-perturbative back-reaction of the medium

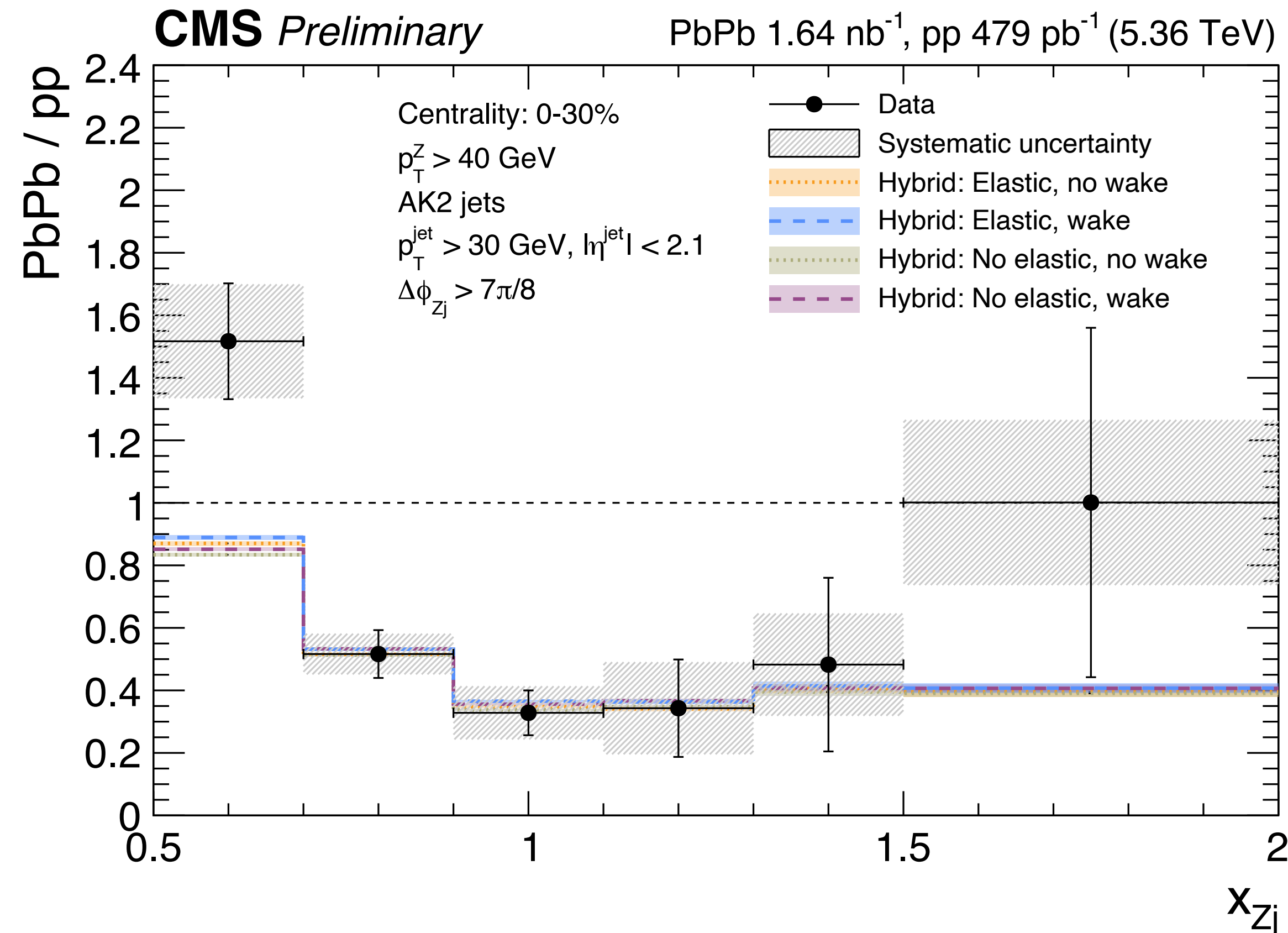


Hybrid model
([MIT-CTP/6018](#)) of
weak and strong
coupling approx
to describe
medium-induced
jet modifications

Comparison to theory predictions

- **Final PbPb/pp ratio comparisons**

- The Hybrid models capture the suppression of highly balanced jets ($0.7 < x_{Zj} < 1.5$)
- Tension in the lowest bin ($0.5 < x_{Zj} < 0.7$), fail to describe the migration of jets toward low x_{Zj}



Conclusions

- **Final result**

- This work presents the first unfolded measurement of the momentum imbalance x_{Zj} in $Z (\rightarrow \mu\mu) + \text{jets}$ events at 5.36 TeV
- We observe a strong suppression of the Z+jet yield in the balanced region alongside a shift of high-momentum jets toward lower x_{Zj} values in PbPb collisions relative to the pp reference

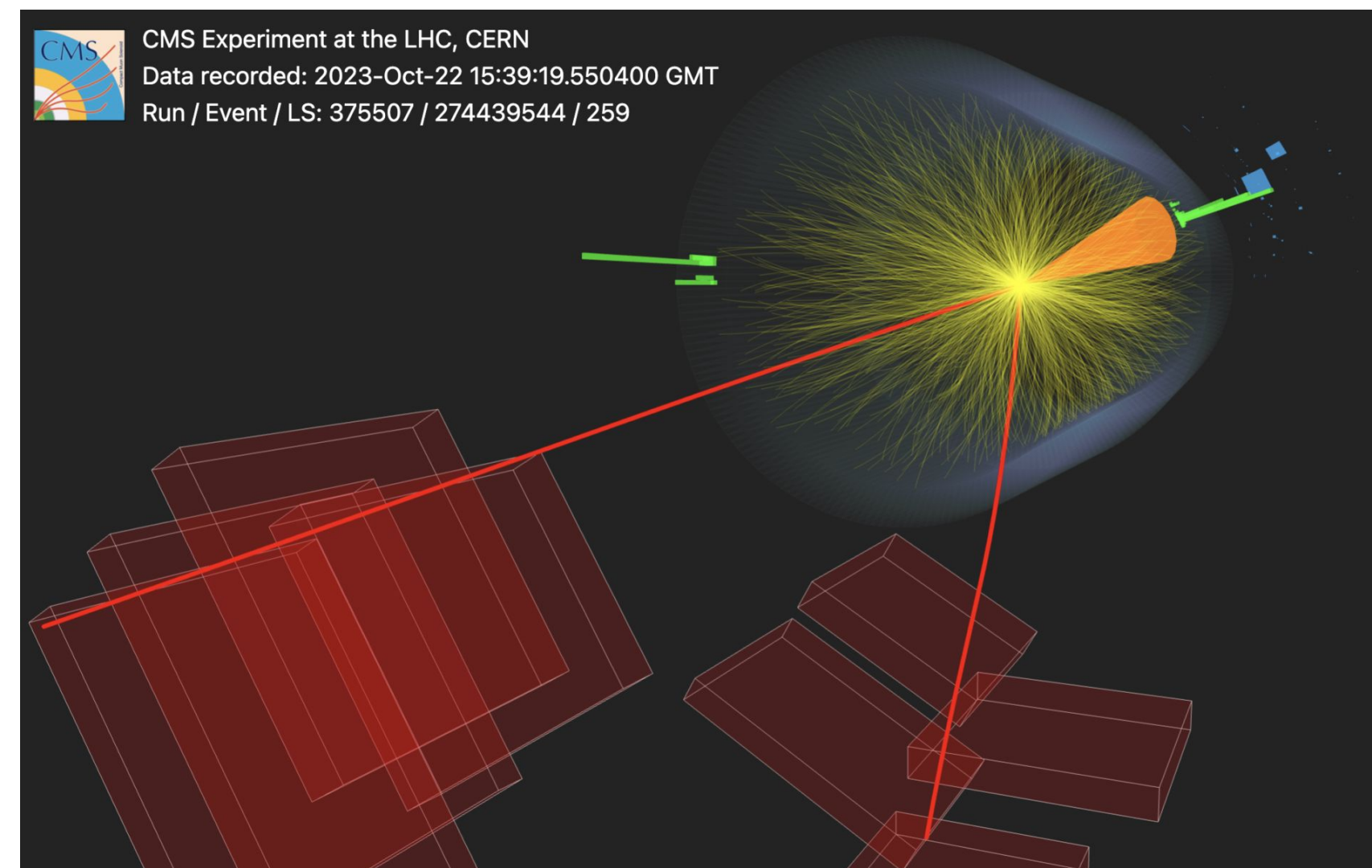
- **Physical Insights**

- Theoretical predictions from the Hybrid strong/weak coupling model successfully reproduce the suppression of balanced jets but fail to describe the migration of jets toward low momenta
- By utilizing small-radius jets ($R = 0.2$), we effectively suppressed the underlying event background, but this renders the inclusive observable insensitive to microscopic dynamics like Molière scattering and the medium wake.

Conclusions

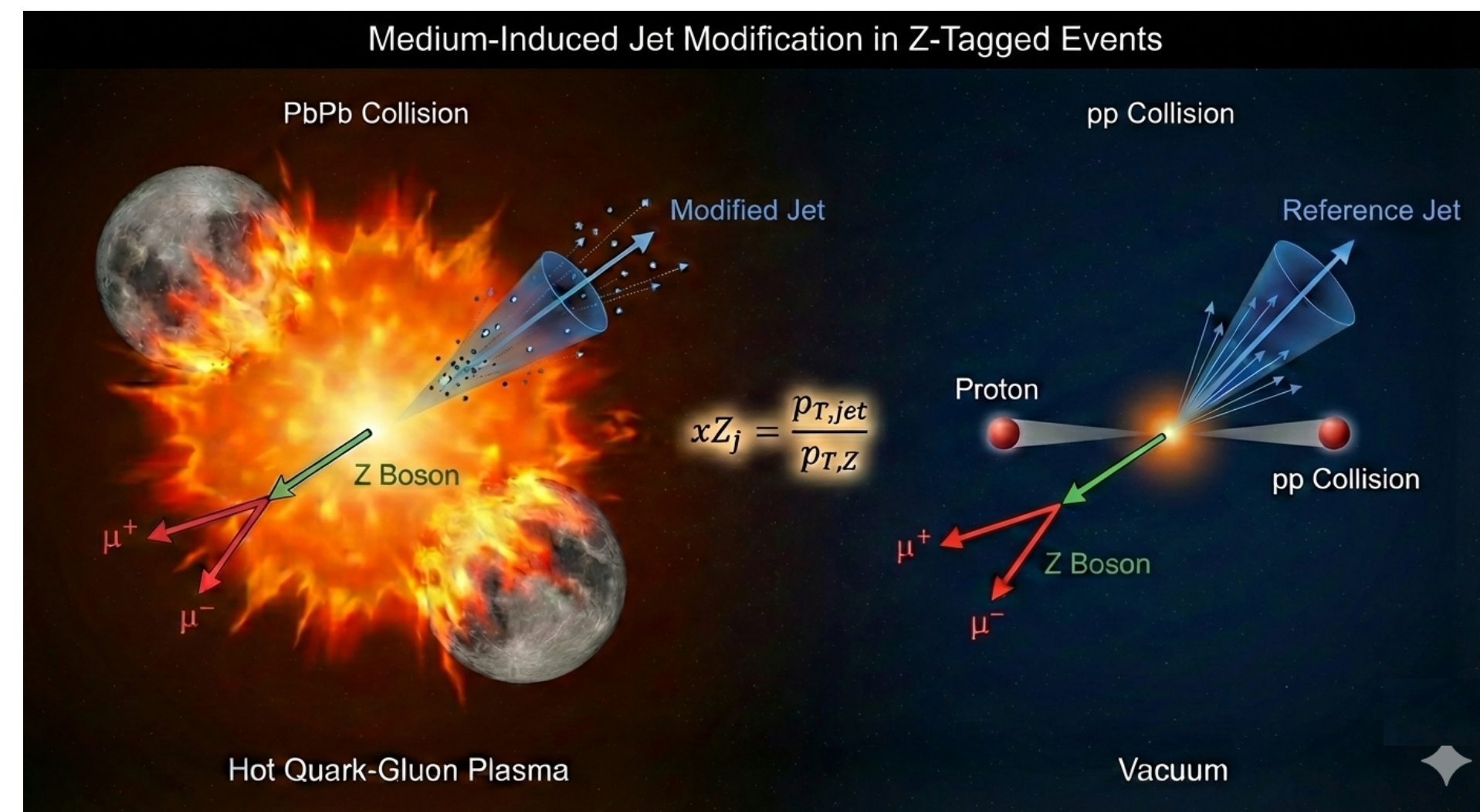
- **Next Steps & Perspectives**

- Subsequent analyses must explore larger jet radii (such as $R = 0.3$ and $R = 0.4$) to recapture out-of-cone radiation and measure the medium response
- Integrating jet substructure observables will be critical for disentangling macroscopic energy loss from microscopic quasiparticle interactions within the Quark-Gluon Plasma
- Full LHC Run-3 data will provide the precision and dataset sizes (almost $\times 5$) required to deeply probe these dynamics





Thank you

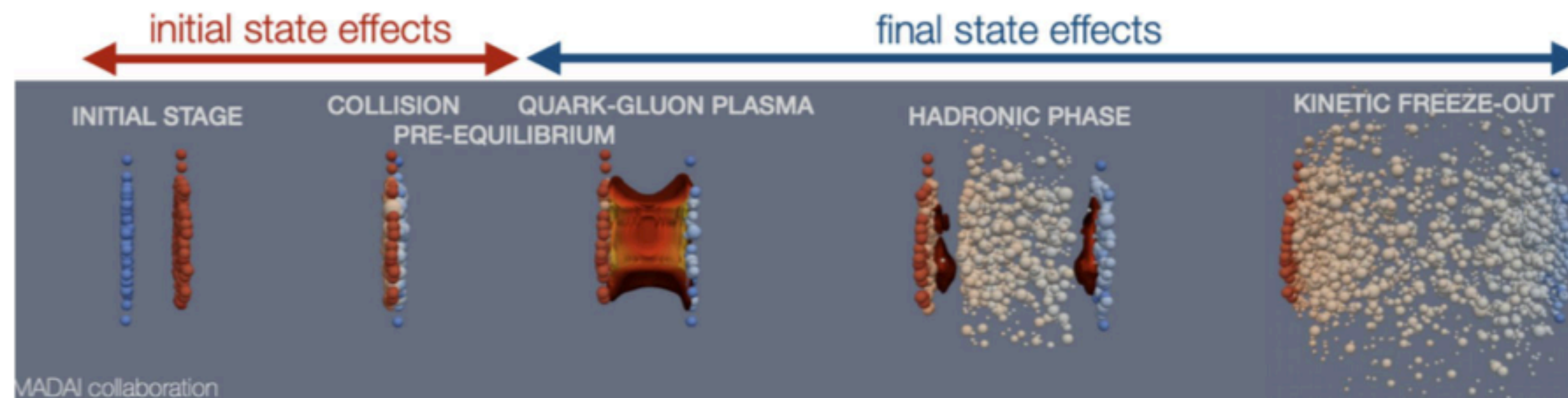




Backup

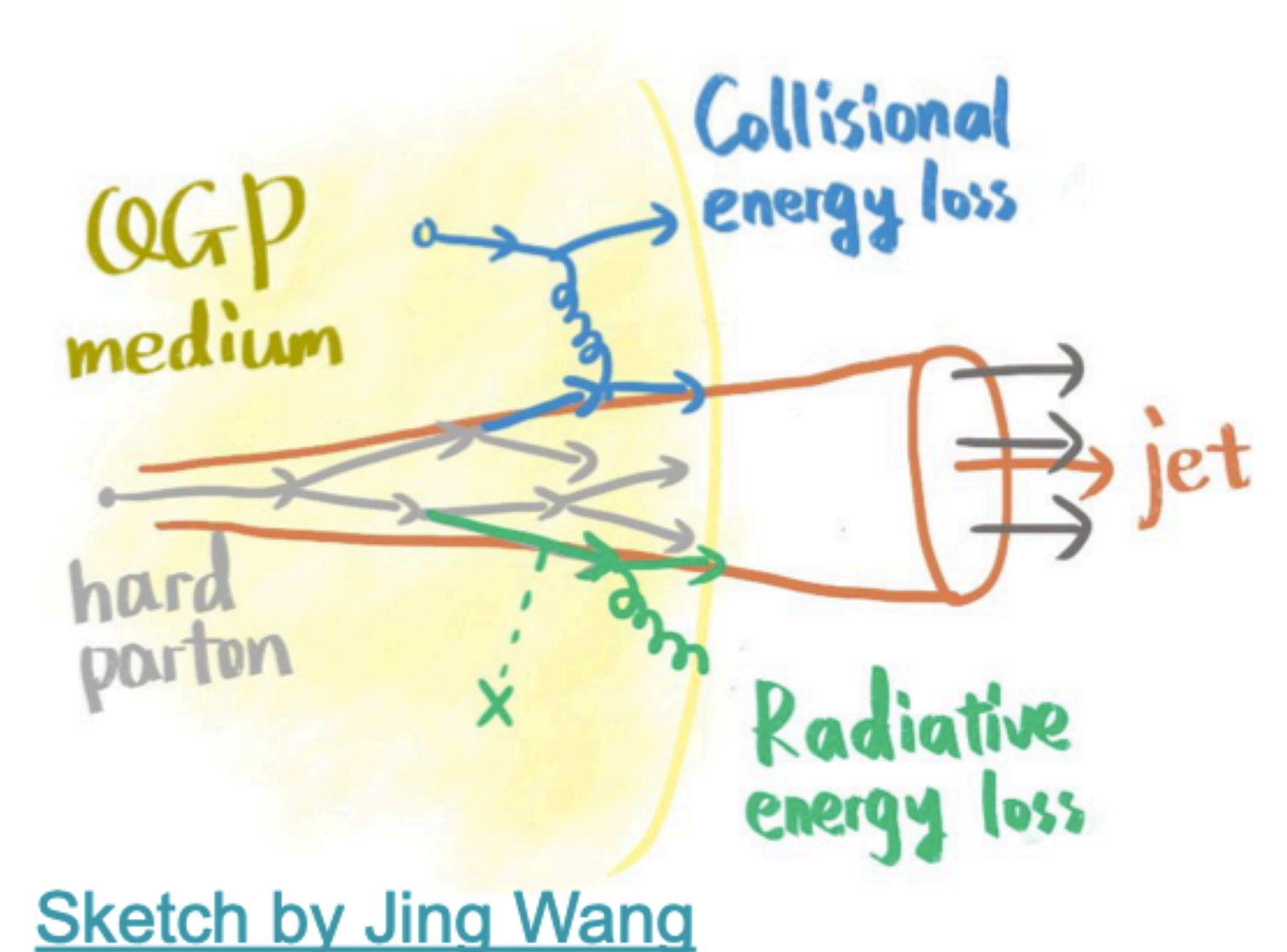
Introduction and Physics Motivation

- PbPb collisions produce droplets of quark-gluon plasma (QGP) - a hot, strongly interacting, near-perfect liquid with **colour** degrees of freedom
 - shape of QGP droplet dependent on centrality of collision, also affects how it expands
 - jets, as perturbative objects, can provide a multi-scale probe of the QGP
 - as they propagate through the QGP, jets get modified, or “quenched”



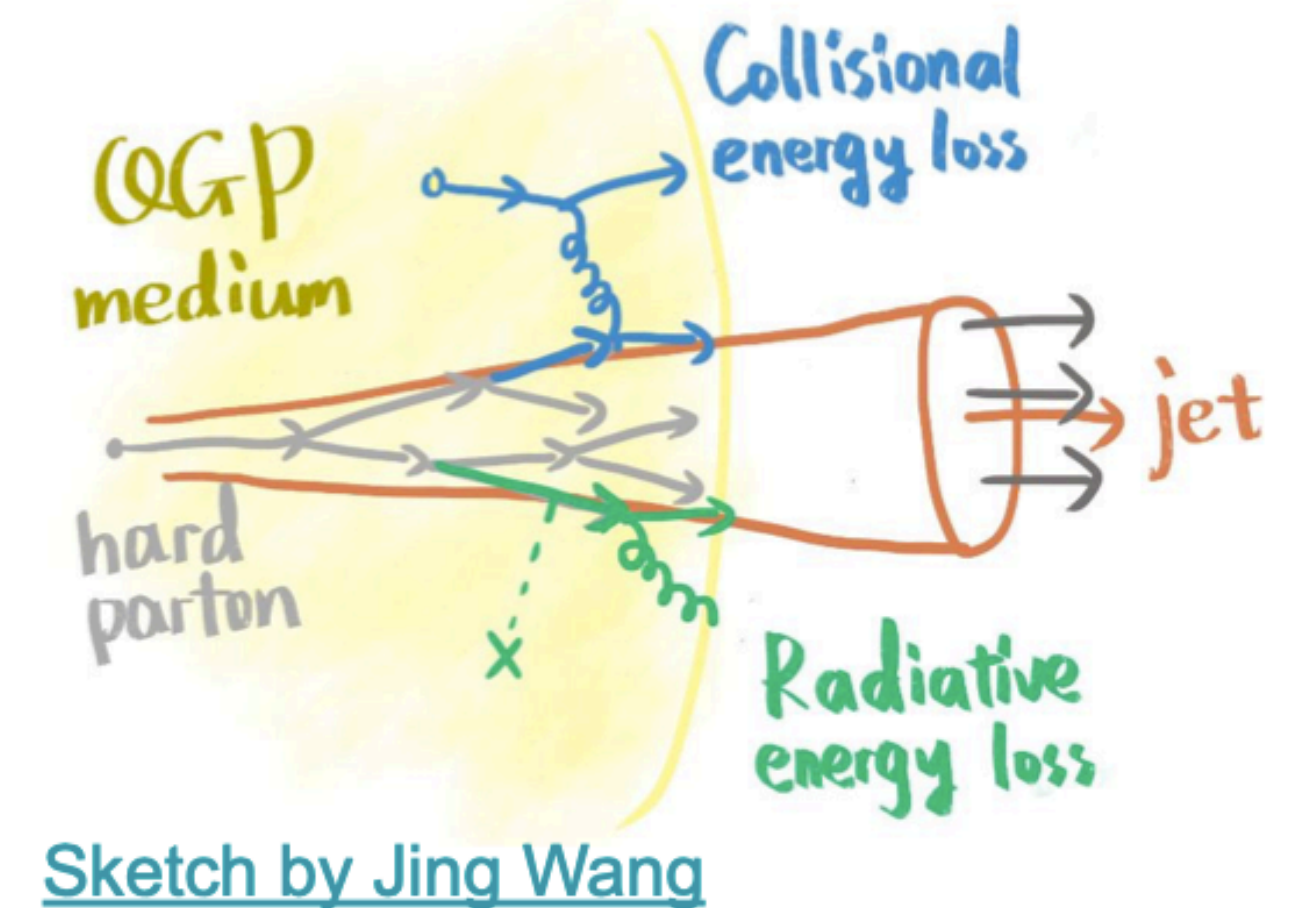
Introduction and Physics Motivation

- Jet modification in medium. Descriptions of the interaction between jets and the medium include:
 - modification of individual parton radiation
 - interplay between different emissions within the medium
 - subsequent induced medium response
- Study of jet production and jet substructure to constrain the mechanisms of jet quenching



Probing the QGP at various scales

- QGP signatures mapped at various spatial and energy scales by using **hard** (high-energy) **probes**
- When the ions collide:
 - most of the interactions are soft (little p_T transfer); gluons at lower energy scales strongly interact with each other and quickly **thermalise**, forming the QGP
 - a small fraction of the incident partons suffer **hard** perturbative interactions, producing (at the earliest times of the collision) high- p_T parton pairs and electroweak bosons
- While electroweak bosons serve as a reference for the initial hard scattering, the recoiling partons lose energy crossing the colored medium via medium-induced gluon radiation and elastic scattering before fragmenting into final-state jets
- Jet modification in medium. Descriptions of the interaction between jets and the medium include:
 - modification of individual parton radiation
 - interplay between different emissions within the medium
 - subsequent induced medium response
- Jets contain info about the produced medium, study of jet production to constrain the mechanisms of **jet quenching**



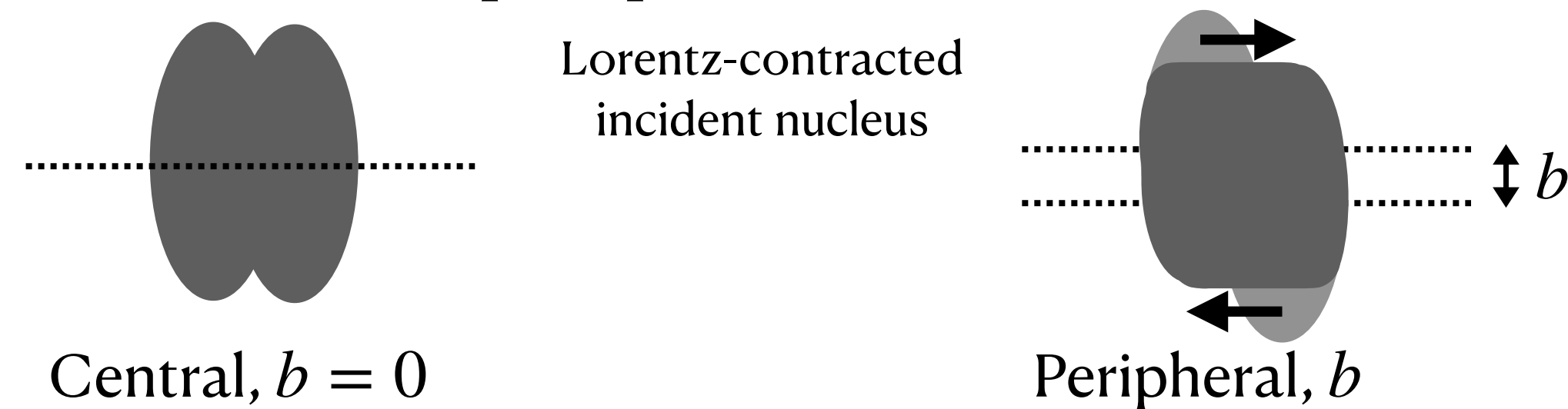
Theory predictions

- **Theory simulations with hybrid model** ([MIT-CTP/6018](#))
 - The Hybrid Model describes the production, evolution, and modification of parton showers as they propagate through the droplets of QGP formed in light- and heavy-ion collisions
 - Describe QGP as a strongly coupled liquid containing microscopic quasiparticles, combining a standard perturbative parton shower (the "weak" part, handling how quarks and gluons split) with a strongly-coupled quark-gluon plasma (the "strong" part)
 - Energy Loss Mechanism:
 - Continuous energy loss via a holographic dE/dx formula (macroscopic **strongly coupled liquid**)
 - supplemented by discrete high-momentum Molière scatterings (microscopic **Quasiparticles**)
 - **Medium Response:** energy deposited into the liquid generates a macroscopic hydrodynamic wake, producing soft hadrons
 - We processed the Hybrid files for:
 - **Vacuum reference**
 - Four cases for the **quenched scenario**: Elastic, no wake - Elastic, wake - No elastic, no wake - No elastic, wake

Glauber Model

Centrality

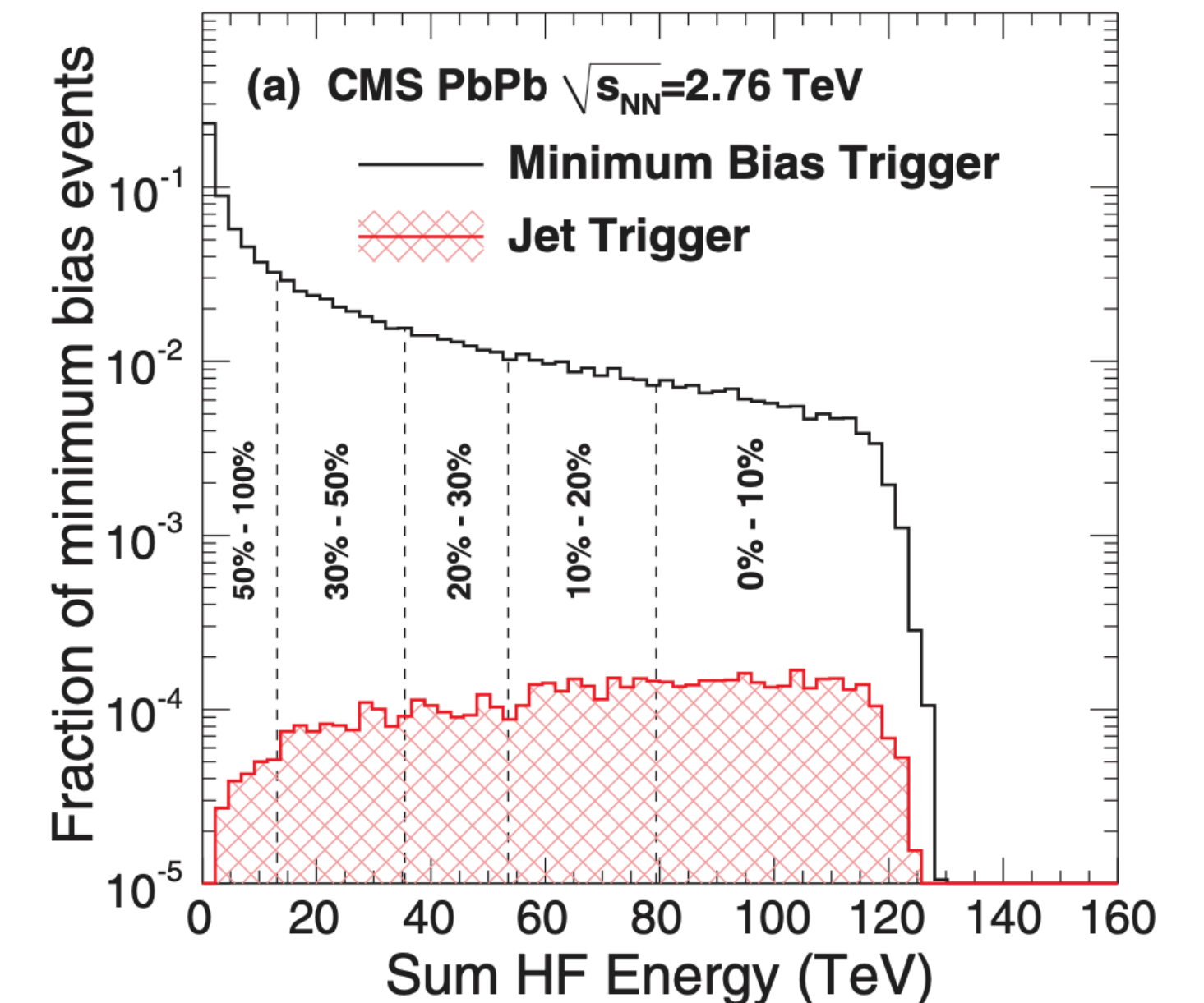
- Heavy ions are extended objects, collisions can be **central** or **peripheral**



- Centrality** is a key parameter of QCD matter, related to the initial overlap region of the colliding nuclei

$$\text{Centrality} \sim \frac{\pi b^2}{\pi(2R_A^2)}, R_A = \text{nuclear radius}$$

- Experimental observables that can be related to centrality are needed
- Multiplicity** of the **particles** produced in collision in a given rapidity range
- Energy** carried by the **spectators** close to the beam direction and deposited in the **hadron forward** (HF) ($3 < |\eta| < 5.2$)
- Experimentally, centrality is expressed as a **percentage of the total nuclear interaction cross-section**
- The measured distribution can be divided into classes that correspond to **percentile** intervals of the hadronic cross-section



[PR C 84, 024906 \(2011\)](#)

Glauber Model

Centrality

Centrality	b mean (fm)	b RMS (fm)	N_{part} mean	N_{part} RMS	N_{coll} mean	N_{coll} RMS
0%–10%	3.4 ± 0.1	1.2	355 ± 3	33	1484 ± 120	241
10%–20%	6.0 ± 0.2	0.8	261 ± 4	30	927 ± 82	183
20%–30%	7.8 ± 0.2	0.6	187 ± 5	23	562 ± 53	124
30%–50%	9.9 ± 0.3	0.8	108 ± 5	27	251 ± 28	101
50%–100%	13.6 ± 0.4	1.6	22 ± 2	19	30 ± 5	35

[PR C 84, 024906 \(2011\)](#)

- Simulations can be used to correlate centrality, as quantified using the fraction of the total interaction cross section, with the impact parameter b and to average values and variances of N_{part} and N_{coll} , using a calculation based on a **Glauber model**
- The mean and spread (RMS) values of the impact parameter N_{part} and N_{coll} for five bins, and their systematic uncertainties, were extracted and are listed in the table
- The RMS values for the centrality parameters are due to their correlation with the percentage cross section and the width of the chosen centrality bins

Glauber Model

Centrality

- The **Glauber Model** uses few assumptions to describe heavy-ion collisions and couple the collision geometry to the detector signals:

1. the two colliding nuclei are described by a realistic distribution of nucleons inside the nucleus measured in electron-scattering experiments (the **Woods-Saxon distribution**)

$$\rho_r = \rho_0 \frac{1}{1 + e^{\frac{r - R_A}{a}}}$$

Diagram illustrating the Woods-Saxon distribution formula:

- Normalisation** points to ρ_0 .
- Nuclear radius** points to R_A .
- Surface thickness** points to a .

2. the nucleons are assumed to follow **straight trajectories**
 3. two nucleons from different nuclei are assumed to collide if their distance is less than the distance corresponding to the inelastic nucleon–nucleon cross-section
 4. the same cross-section σ_{NN} is used for all successive collisions
- The model, which is implemented in a Monte Carlo calculation, takes random samples from a geometrical distribution of the impact parameter and for each collision determines N_{part} and N_{coll}
 - Fitting the measured distribution with the distribution simulated using the Glauber model creates a connection between an experimental observable and the geometrical model

Glauber Model

Centrality

- The **Glauber model** can be combined with a simple model for particle production to simulate a multiplicity distribution that is then compared with the experimental one
- The particle production is simulated in two steps:
 1. Employing a simple parameterization, the number of participants and the number of collisions can be used to determine the **number of “ancestors”**, i.e. independently emitting sources of particles

$$N_{ancestors} = f \times N_{part} + (a - f)N_{coll}$$



2. Each ancestor emits particles according to a **negative binomial distribution** (chosen because it describes particle multiplicity in nucleon–nucleon collisions)

$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{(\mu/k)^n}{[\mu/(k+1)]^{n+k}}$$

μ =average multiplicity per ancestor
 k =width of the distribution

ATLAS photon+jet

- Comparisons with ATLAS photon+jet ([10.1016/j.physletb.2018.12.023](https://arxiv.org/abs/10.1016/j.physletb.2018.12.023))
 - ATLAS saw same behaviour for low bins of x_J in hybrid simulations

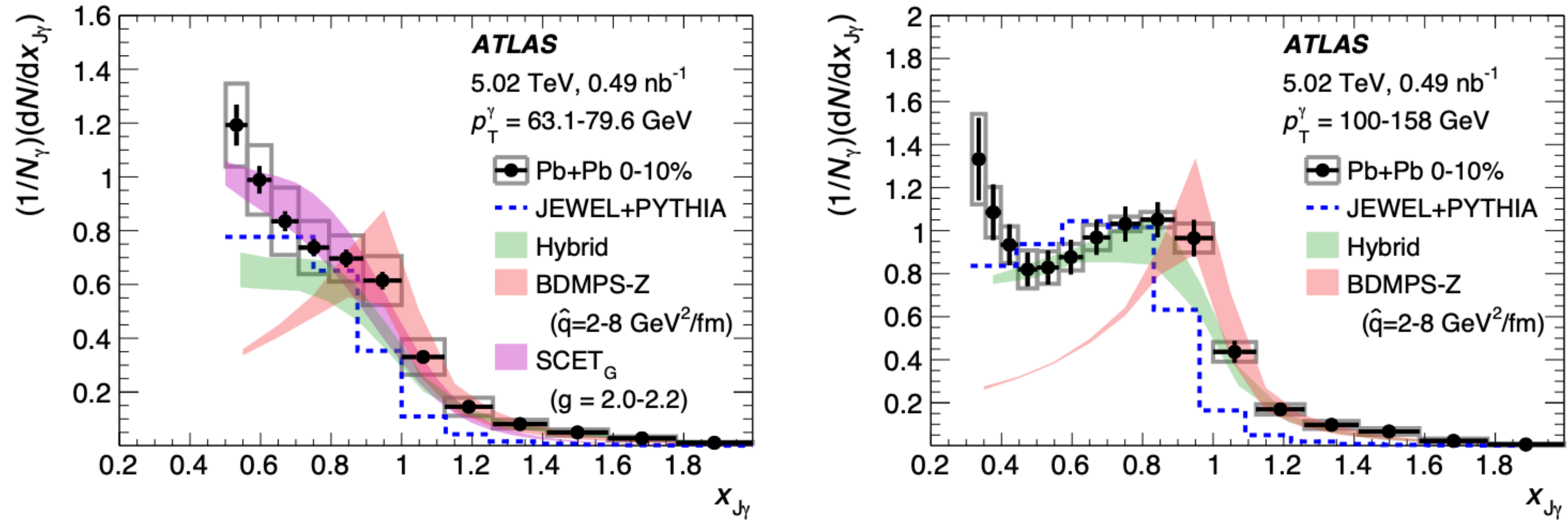
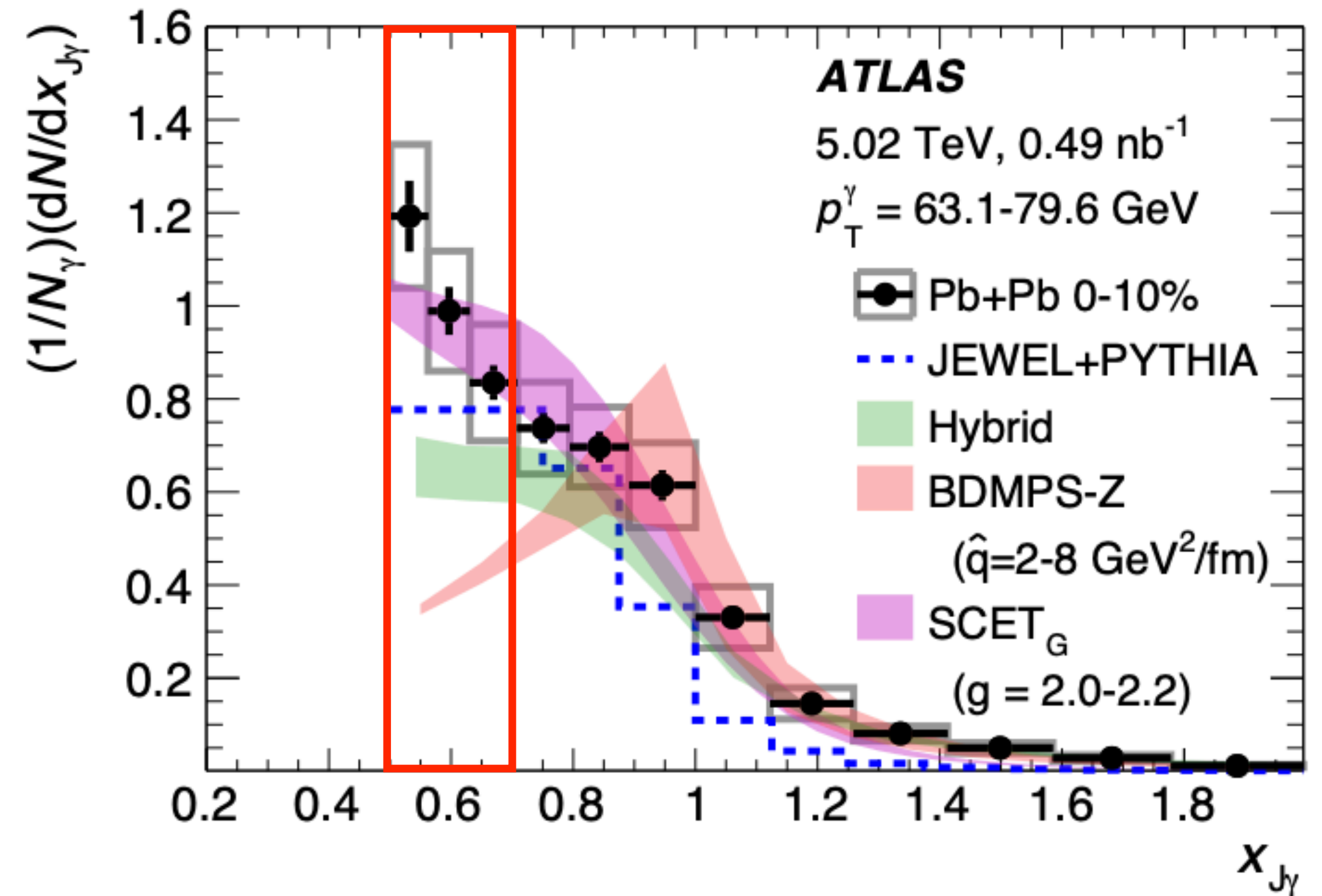
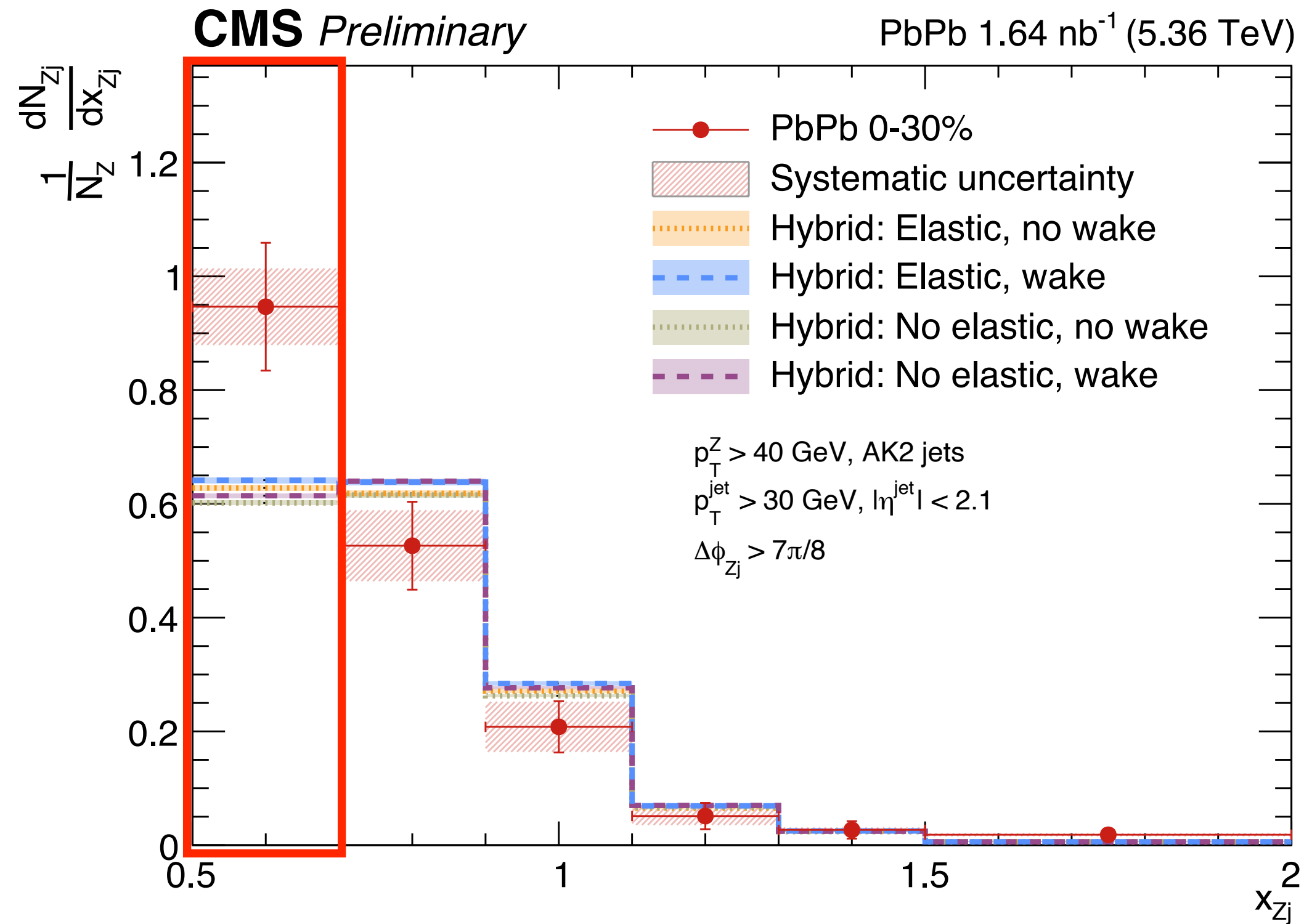


Figure 10: Photon-jet p_T -balance distributions $(1/N_\gamma)(dN/dx_{J\gamma})$ in 0–10% Pb+Pb collisions for (left) $p_T^\gamma = 63.1$ –79.6 GeV and (right) $p_T^\gamma = 100$ –158 GeV. The unfolded results are compared with the theoretical calculations shown as dashed coloured lines denoting central values or coloured bands which correspond to a range of theoretical parameters (see text). Total systematic uncertainties are shown as boxes, while statistical uncertainties are shown as vertical bars.

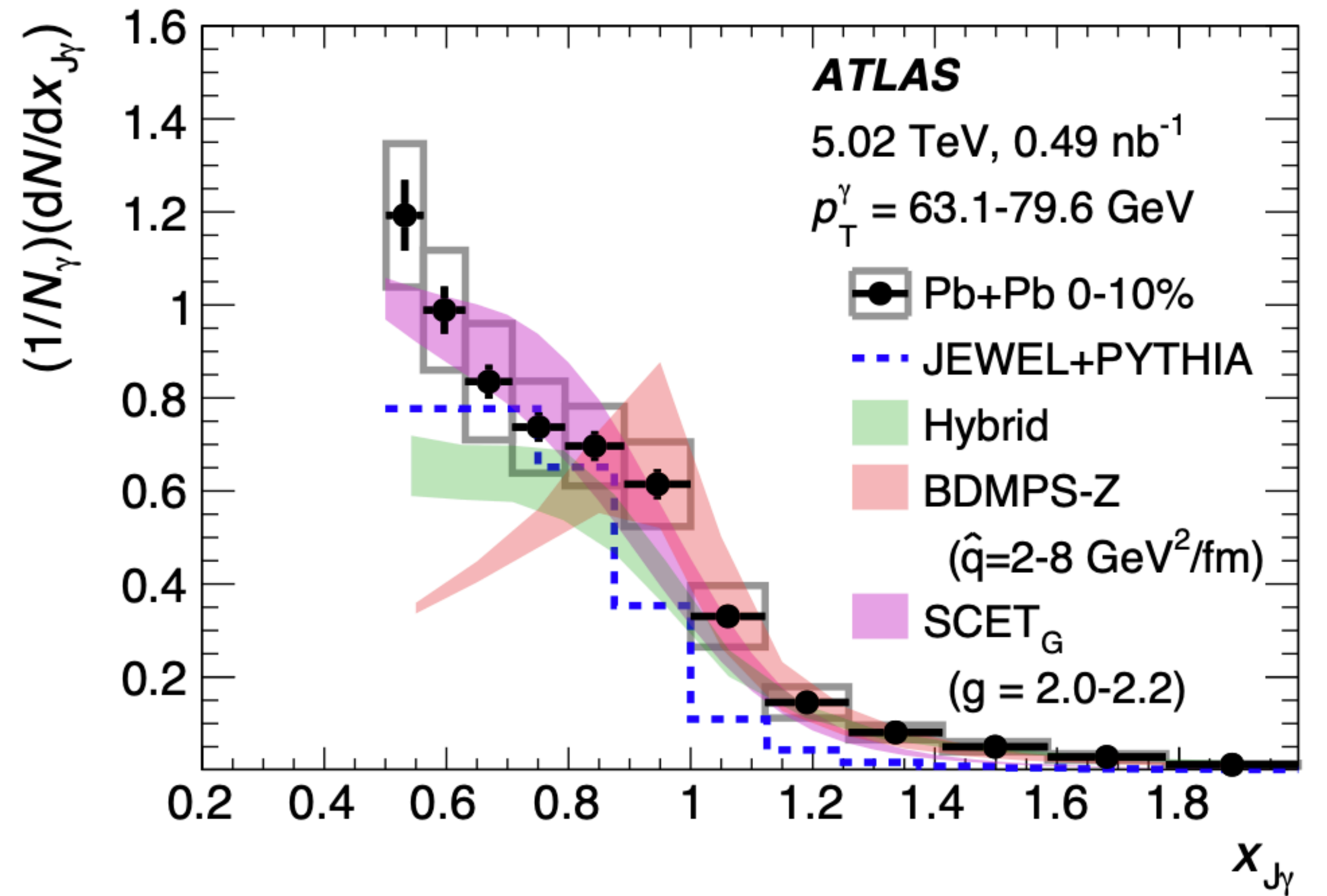
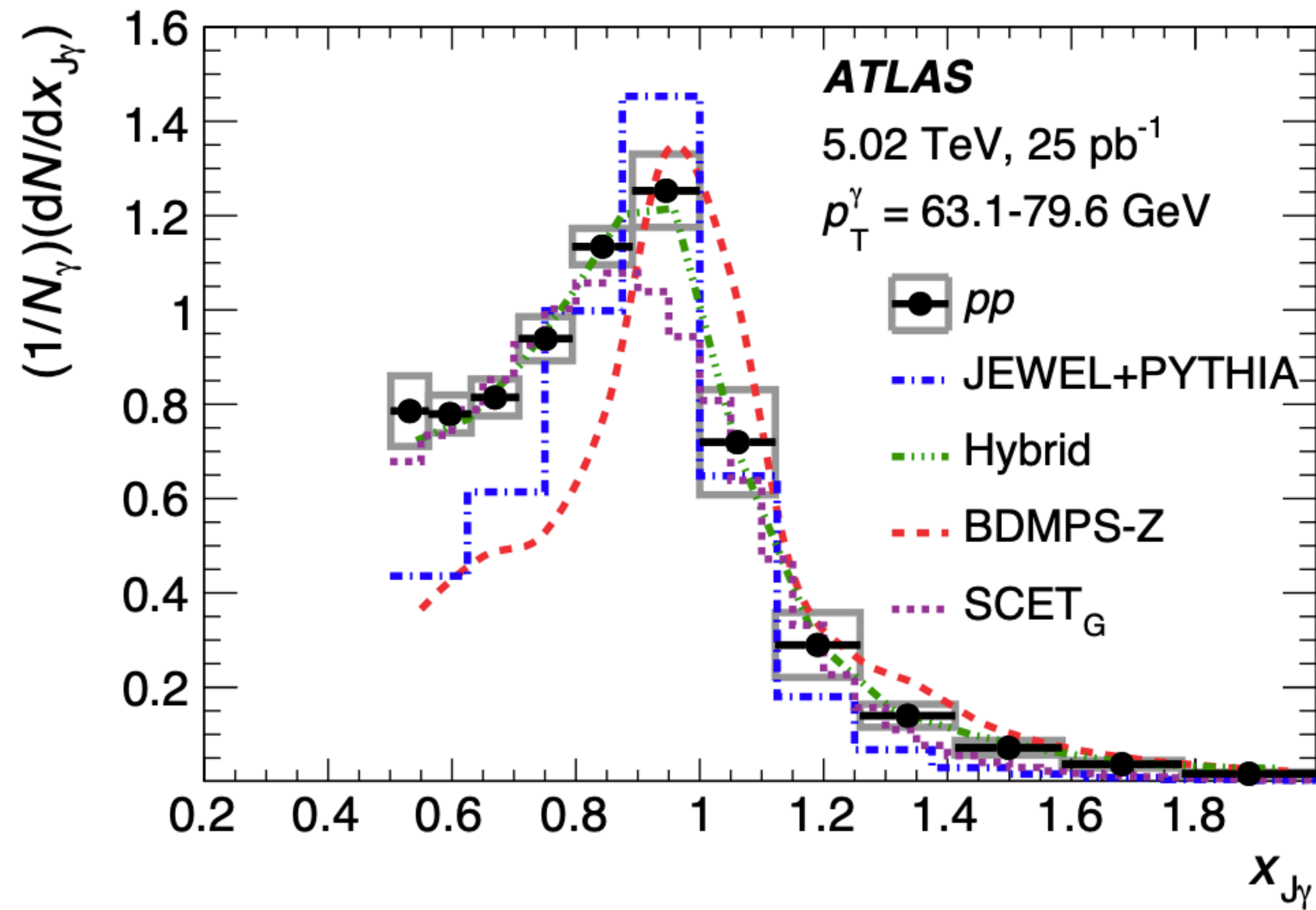
ATLAS photon+jet

- Comparisons with ATLAS photon+jet
 - ATLAS saw same behaviour for low bins of x_J in hybrid simulations



ATLAS photon+jet

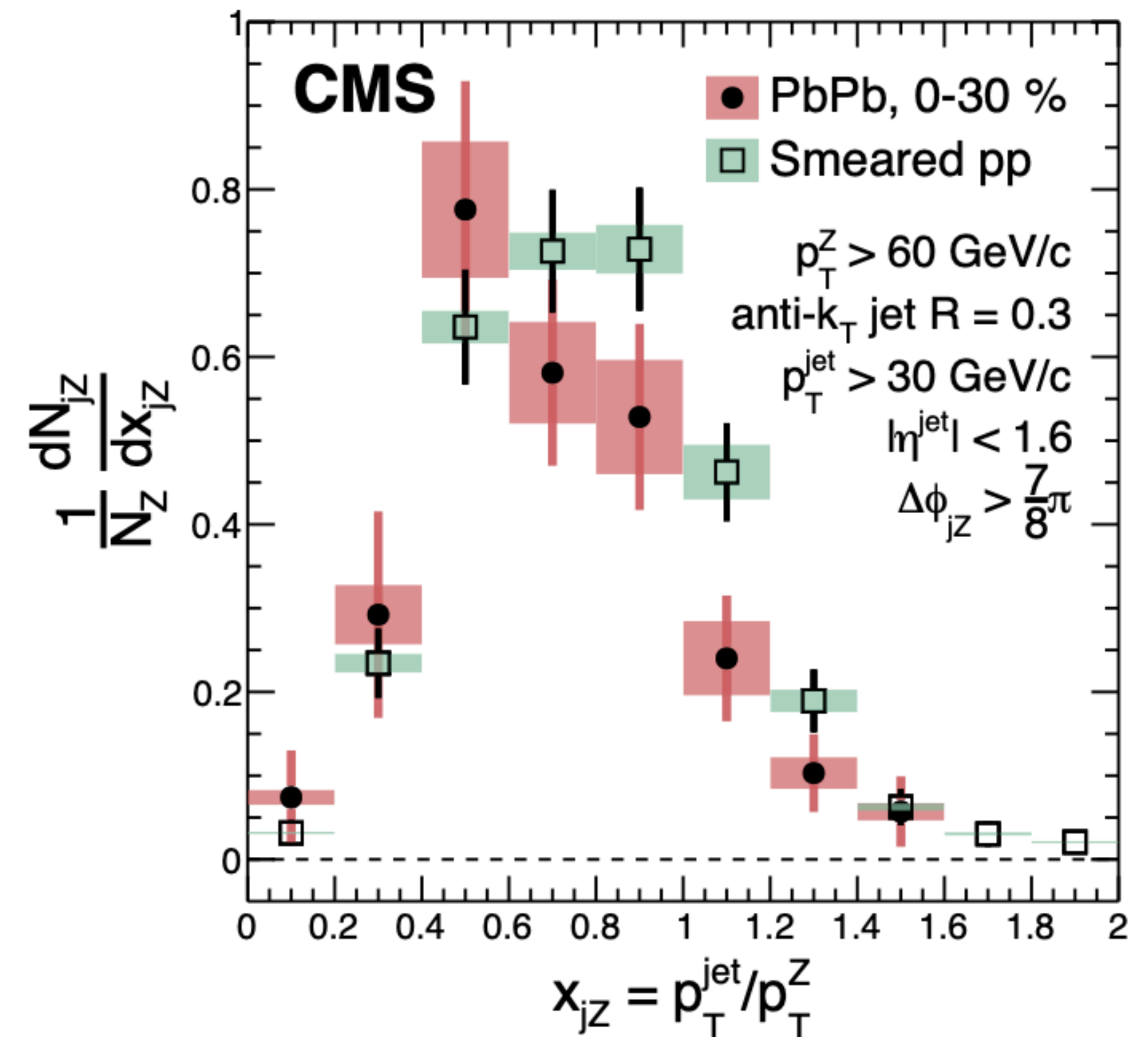
- Comparisons with ATLAS photon+jet
 - ATLAS saw same behaviour for low bins of x_J



Previous result from CMS

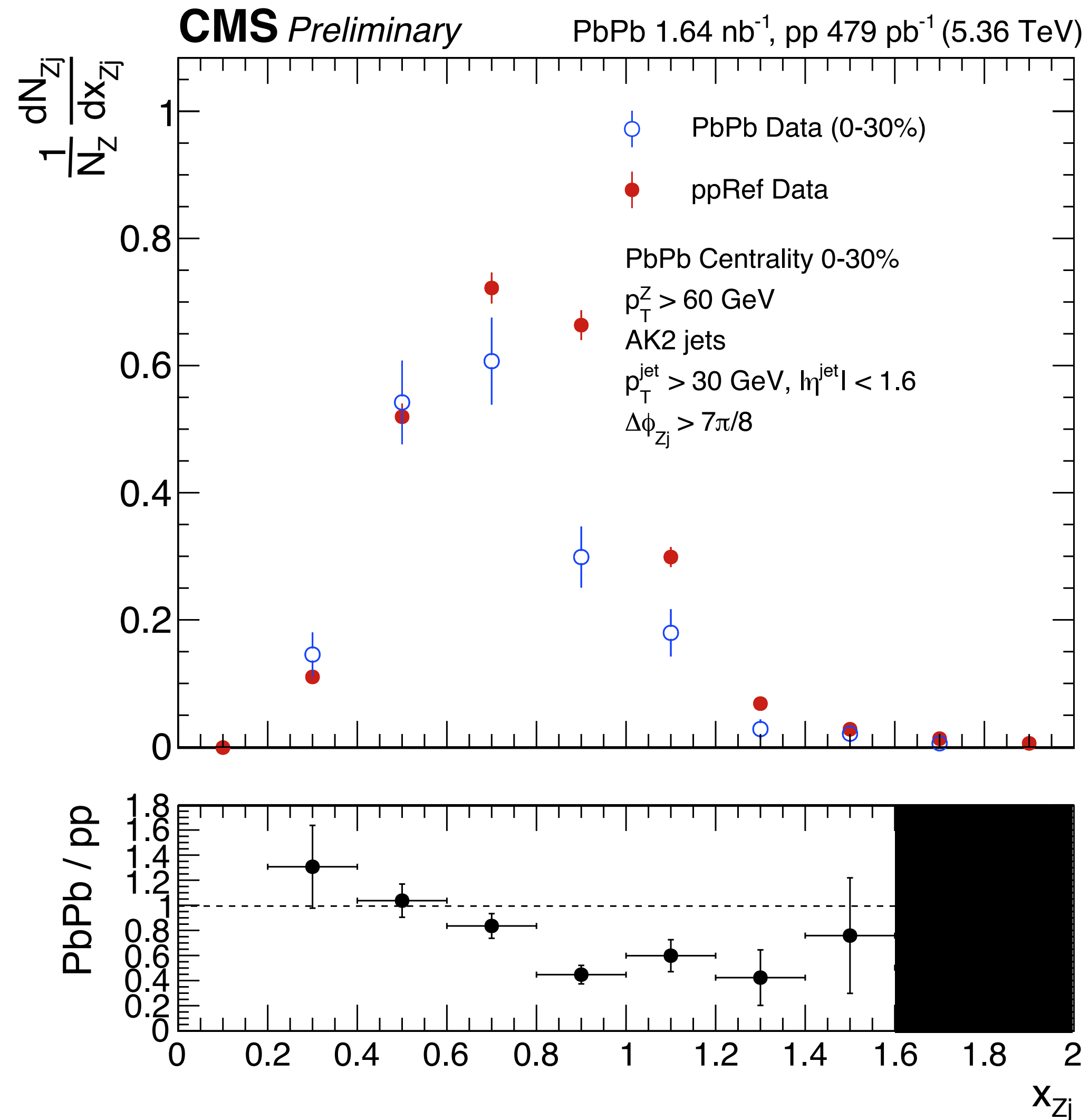
Phys.Rev.Lett. 119 (2017) 8, 082301

- Z+jet correlations at 5.02 TeV via the $\mu^+\mu^-$ and e^+e^- decay channels
- 2015 PbPb and pp datasets with limited statistics
- No unfolding, pp calculations smeared to reflect the detector resolution affecting the pp data (by relative jet energy resolution estimated from PYTHIA+HYDJET)
- Conclusion: the x_{Zj} distributions indicate that the PbPb values tend to be lower than those measured in pp collisions

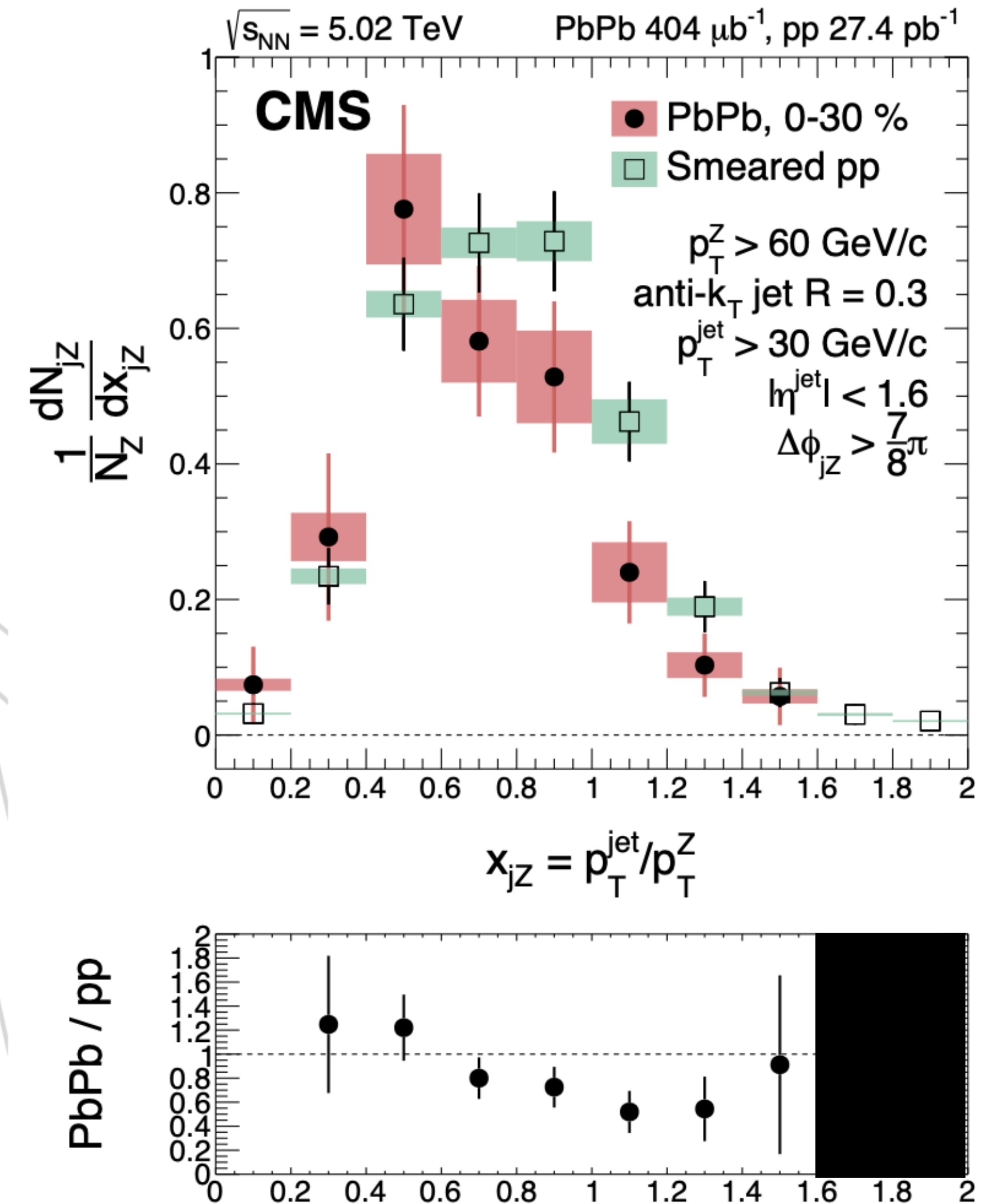


Previous result from CMS

HIN-25-017



HIN-15-013



Physics Motivation

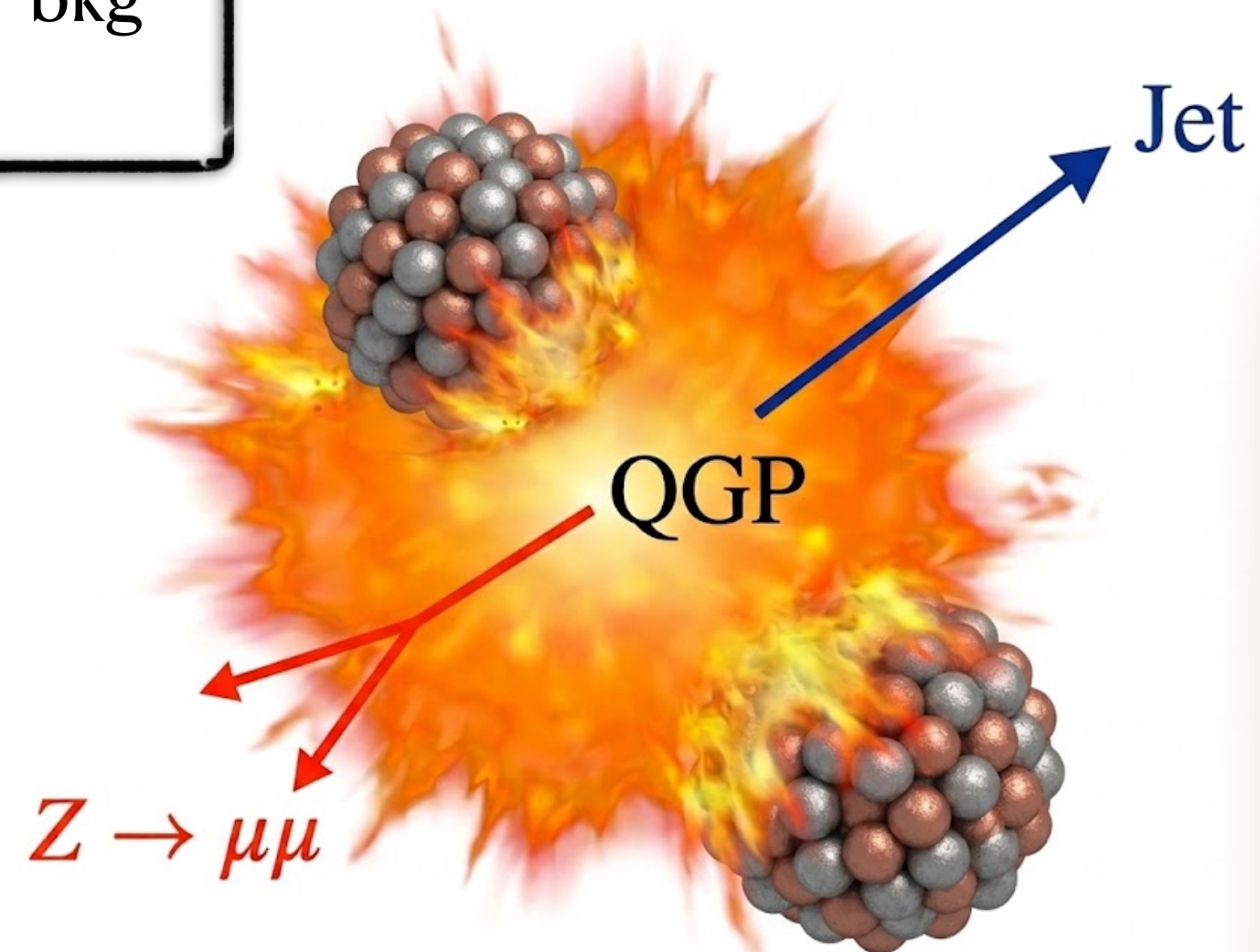
GOAL: Characterize jet energy loss through QGP using $Z(\rightarrow \mu\mu) + jet$ events with **Run 3** data, **first unfolded measurement** with the CMS experiment

The Trade-off

- Dijet vs $Z+jet$ vs $\gamma+jet$
 - Dijet large cross section but study only relative energy loss
 - $\gamma+jet$ suffer large bkg (jet fragmentation and neutral meson decay)
 - $Z+jet$ cross section lower, but less bkg contamination

The Probe

- Z bosons decay before the emergence of the QGP phase
- Leptonic decay products do not interact strongly with the medium
- Low bkg contamination



The Target

- High-energy quark and gluons are modified by the medium
- Allows measurement of QGP transport properties (e.g. $\hat{q}$, T) and probe microscopic medium dynamics (e.g., color coherence, quasiparticle interactions)

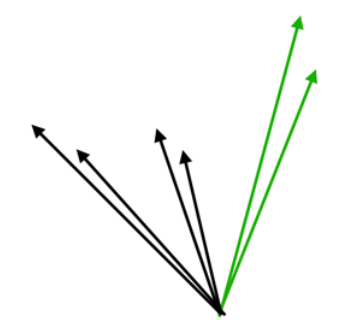
Methodology

- Unfold momentum imbalance:
$$x_{Zj} = p_T^{jet} / p_T^Z$$
- Compare PbPb with pp reference and theory prediction

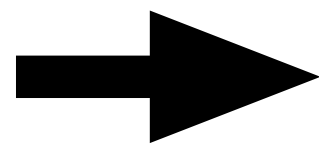
Why small radius jets

- Jets are clustered from the list of PF candidates using the anti- k_T algorithm
- The four-momentum of jets is the vector sum of all particles momenta in the jet

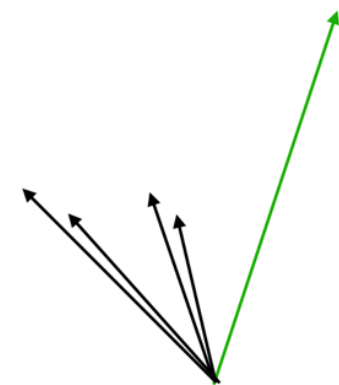
Iterating over two



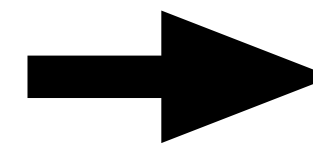
Start hard (big)



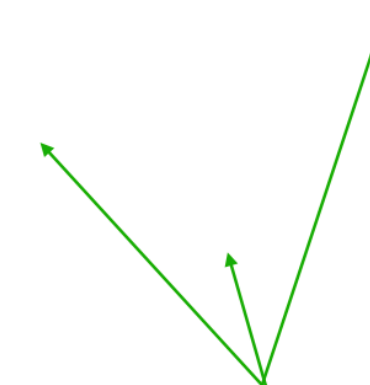
Now merge into a particle



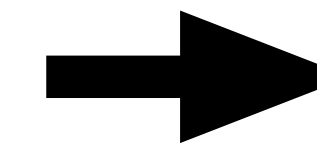
Merge into a particle



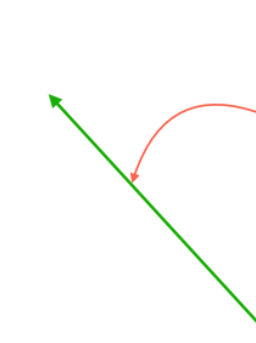
Merge next set



And next

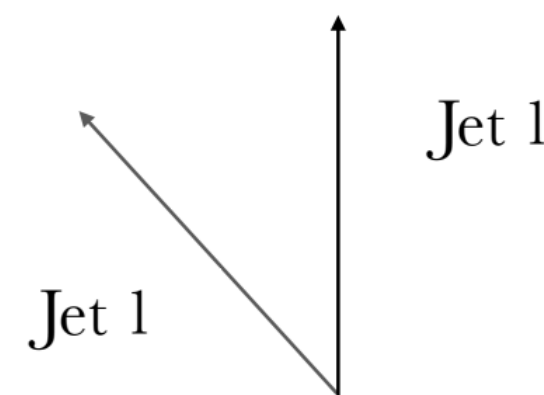
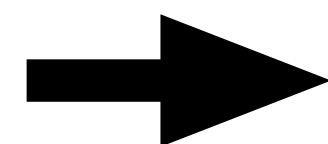


Merge next set



If distance > X
(X=0.4,0.8 - stop)

Done



Done

[CMS DAS JET 2023](#)

- Iteratively find two particles in the event that are closest in some distance measure

$$d_{ij} = \min(k_{Ti}^{2a}, k_{Tj}^{2a}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\sqrt{(\Delta y_{i,j})^2 + (\Delta \phi_{i,j})^2}$$

$a = 1$: k_T algorithm, $a = 0$: Cambridge-Aachen algorithm,
 $a = -1$: anti- k_T algorithm

- Distance parameter $R = 0.2$ (instead of 0.4) to mitigate UE spurious contributions in PbPb (which scales as R^2)
- Small- R jets can help to isolate purely energy loss effects from other effects that contribute to the modifications of the jet shower in medium such as the correlated background or medium response

akCs2 PF Jet for PbPb

- In CMS Heavy Ion analyses, the actual subtraction of the background ρ from the jet's energy is done much earlier in the pipeline (during the jet clustering phase, using algorithms like Constituent Subtraction)
- **The Constituent Subtraction (Cs):** Instead of subtracting background from the final jet, it subtracts the background from the individual particles (constituents) and then the anti-kt algorithm is run only on survived particles
- Constituent Subtraction fixes the energy of real jets, but **Mixed Event** (MinBias) **Background Subtraction** applied later fixes the population of fake jets.
 - CS removes the average background
 - Mixed events background subtraction remove the random statistical fluctuations (Data-driven technique applied for PbPb collisions only, Fake jets are not correlated to the Z boson, therefore their distribution is statistically identical to jets found in MB events, used to estimate the contribution of bkg jets)

Datasets and MC samples

- **Data** collected by the CMS experiment from two distinct collision systems: lead-lead and proton-proton
- Extensive **MC** simulations are required to unfold detector effects, estimate backgrounds, and correct for kinematic acceptance and selection efficiency
- **Parton shower** and **hadronization** handled by interfacing the hard scattering generators with PYTHIA 8
- The combinatorial background of UE particles and energy fluctuations in the PbPb is simulated by **embedding** the hard scatter into minimum bias events produced by HYDJET
- **Detector Simulation** by GEANT 4

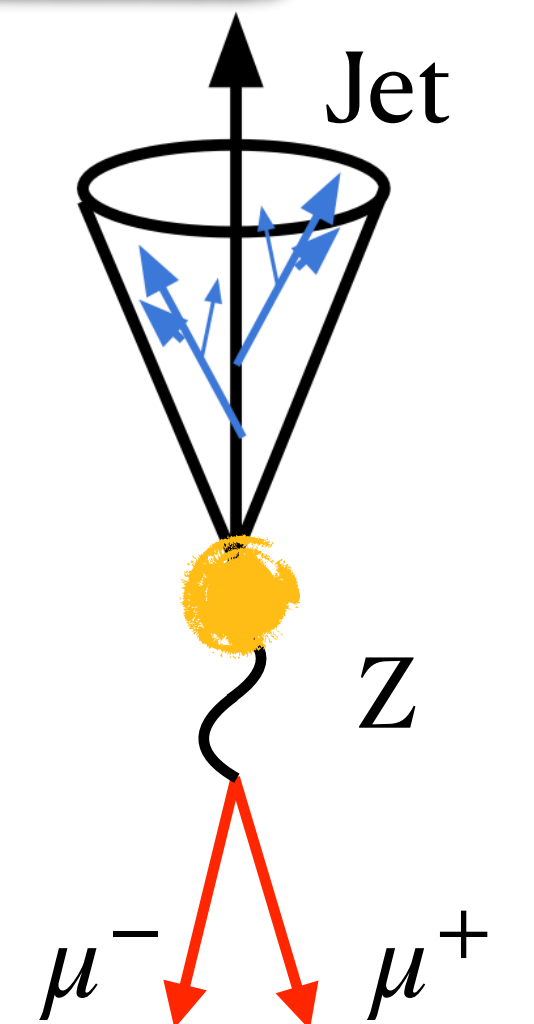
Collision	Year	Lumi	$\sqrt{s}$ (TeV)
PbPb	2023	1.64 nb-1	5.36
pp	2024	479 pb-1	5.36

	Process	Generator	$\sigma_{gen}^{NN}[pb]$	$\sigma_{gen}^{pp}[pb]$
Signal	DYto2L-2jets	MadGraph5	2328	2040
Diboson	ZZto4L	POWHEG	0.50	0.40
	ZZto2L2Q		2.24	1.88
	ZZto2L2Nu		0.29	0.27
	WZto2L2Q		2.19	1.94
	WZto3LNu		1.52	1.33
	WWto2L2Nu		3.07	2.85
TT	TT	POWHEG	66.2	69.3
Others	singleT	POWHEG	3.06	14.9
	singleTbar		3.07	14.6
	DYto2Tau		657	559.5
	WminusToMuminusNu		2730	2957
	WplusToMuplusNu		4090	2719
MinBias	MinBias_Drum5F	HYDJET		
Alternative	DYto2Mu	POWHEG	559.5	657

Kinematic phase space

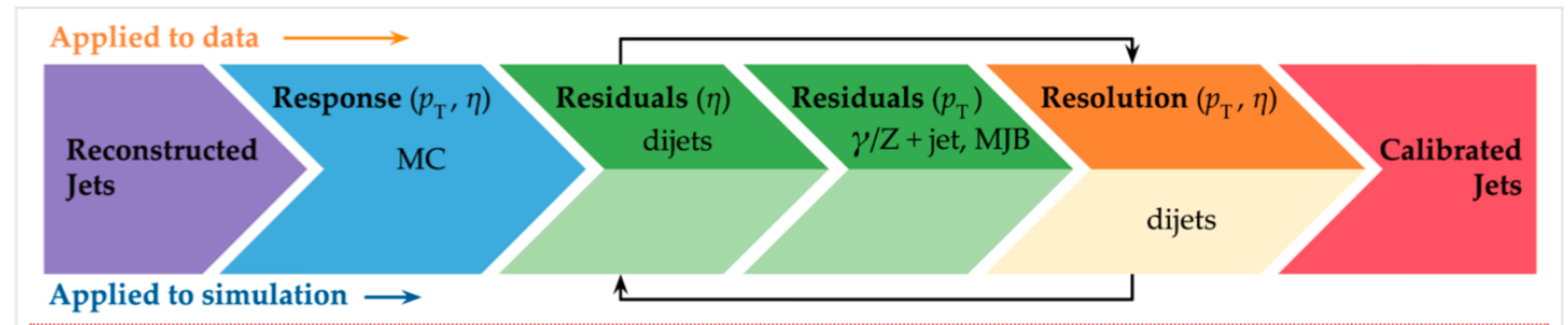
- 2023 PbPb and 2024 pp datasets at 5.36 TeV (Run 3)
- Centrality 0 – 30 % for more jet quenching signal, $|v_z| < 15$ cm
- Single Muon triggers for both PbPb and pp
- Particle Flow and Global muons, with tight Identification, isolation ($\epsilon \sim 95$ %)
- Jets with $\Delta R < 0.2$ from a muon rejected
- Jet Veto Map for handling the Barrel Pixel failure

Selection	
Z boson	Recoiling jet
$p_T^\mu > 20 \text{ GeV}$	$p_T^{jet} > 30 \text{ GeV}$
$ \eta^\mu < 2.4$	$ \eta^{jet} < 2.1$
Highest p_T muons	Leading jet
$60 \text{ GeV} < m_{\mu\mu} < 120 \text{ GeV}, p_T^Z > 40 \text{ GeV}$	at least 1 AK2 jet
$\Delta\phi_{Zj} > 7\pi/8$	



Jet Energy Calibration

- The calibration process of the jet four-momentum follows a fixed-order schematic process:
 - **L1 Pileup** (only for pp collisions), to remove extra energy in the calorimeters coming from additional interactions in nearby bunch crossings (determined by MC simulation using QCD dijet sample)
 - **L2 Relative** (or MC Truth), derived from MC by mapping reconstructed p_T to the generator level based on MC to align the detector response across η
 - **L2 Residual** (Data only), η -dependent corrections derived by comparing dijet momentum balance (asymmetry) between the simulation and real data with a tag and probe method
 - **L3 Residual**, absolute p_T -dependent corrections derived from γ/Z +jets events
 - **Jet Energy Resolution** (JER) smearing (MC only), needed because the jet energy in physical data is less resolved than in the simulation, computed using response distribution $R = p_T^{reco}/p_T^{gen}$ in bins of jet $(p_T^{gen}, |\eta|)$



Average transverse energy density ρ

- In a PbPb collision, thousands of particles are produced that do not belong to the high-energy “jets” (UE). The variable ρ represents the density of this background energy—specifically, the amount of transverse momentum (p_T) per unit area in the detector.
- Physics generators like HYDJET use phenomenological models to simulate this background. However, the exact particle multiplicity, energy flow, and momentum distribution of the UE depend heavily on the complex dynamics of the QGP. Because the simulation is an approximation, the ρ generated in MC will differ from the ρ observed in LHC data
- To measure the energy of a jet, you have to subtract the background energy that accidentally fell into the jet's area ($p_{T_jet} = p_{T_raw} - \rho \cdot A_{jet}$). If the simulation models ρ poorly, the jet energies in your simulation won't match the jet energies in your data

rho computation

- To compute ρ , the detector's geometry is divided into a 2D grid cells based on η and ϕ (or patches of area A), alternatively, a clustering algorithm (like the kT algorithm) is run to group background particles into small, artificial "background jets" with a known area.
- **Calculate Energy per Unit Area** For every single cell (or background jet) i in the event, the algorithm sums up the transverse momentum (p_T) of all the particles inside it, and divides by the area of that cell (A_i):

$$\text{Density}_i = p_{T_i}/A_i$$

- **Take the Median** Instead of taking the average (mean) of all the cells, the algorithm takes the **median**:

$$\rho = \text{median}(p_{T_i}/A_i)$$

- In proton-proton collisions, ρ is usually a single number for the whole event. But in PbPb collisions, the background energy is highly dependent on η (it is much denser in the center of the detector than at the forward edges). Therefore, CMS usually computes ρ as a function of η

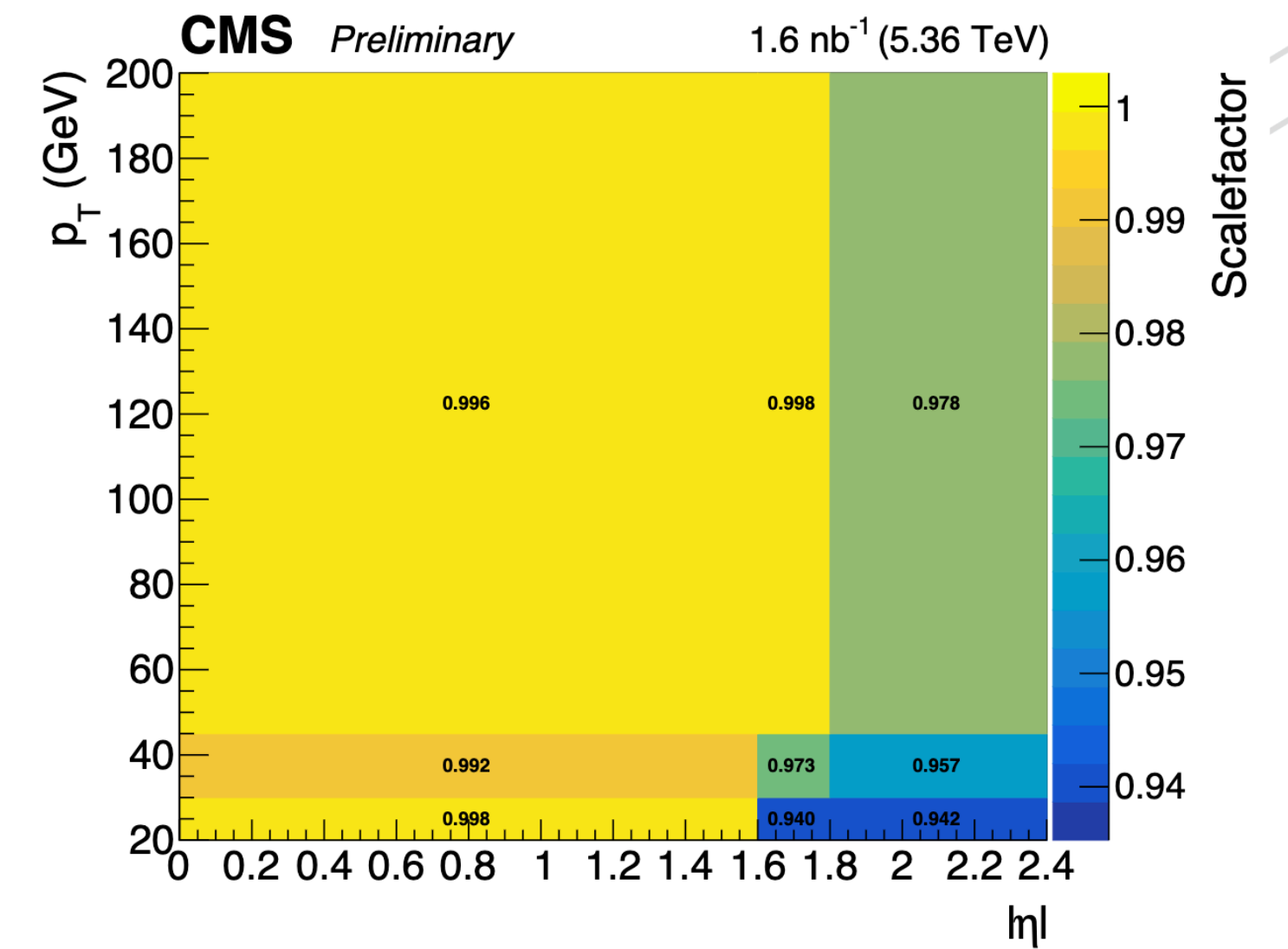
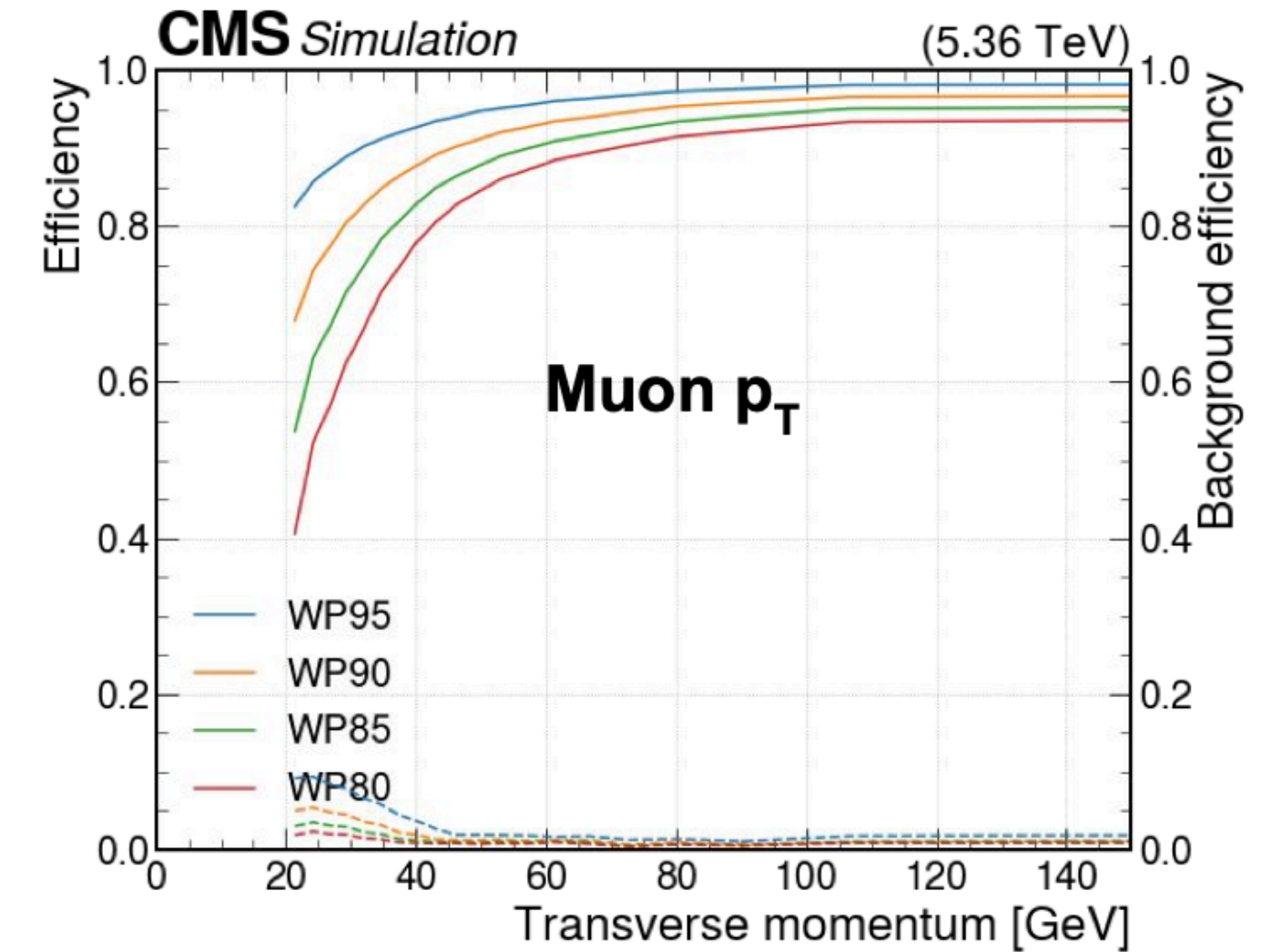
akCs2PFJetAnalyzer for PbPb

- In CMS Heavy Ion analyses, the actual subtraction of the background ρ from the jet's energy is done much earlier in the pipeline (during the jet clustering phase, using algorithms like Constituent Subtraction)
- The raw_pt in HIForest tree has *already* had the local background removed.
- **The Old Way (Area-Based Subtraction):** run the anti-kT algorithm on the whole event, find a jet, measure its physical area (A), and then subtract the background energy afterward:
 $pT_{jet} = pT_{raw} - (\rho \cdot A)$, but while this fixed the total energy, it left all the fake background particles *inside* the jet
- **The Constituent Subtraction (Cs):** Instead of subtracting background from the final jet, it subtracts the background from the individual particles (constituents) and then the anti-kt algorithm is run only on survived particles
- Constituent Subtraction fixes the energy of real jets, but Mixed Event (MinBias) Subtraction applied later fixes the population of fake jets. CS removes the average background. Mixed events remove the random statistical fluctuations

Muon isolation

PbPb collisions

- High- p_T ($p_T^\mu > 20$ GeV) muon isolation requirement to suppress bkg
- Lepton isolation in heavy ion collisions is challenging since UE activity scales with centrality
- Instead of cut-based method, we use BDT developed by [HIN-24-021](#), to:
 - achieve a robust isolation independently of the PbPb collision centrality
 - maximize the efficiency for isolated muons from W or Z/ γ^* decays
 - minimize the contamination of non-isolated muons from QCD jets
- The WP95 is used and scale factors are applied for residual differences



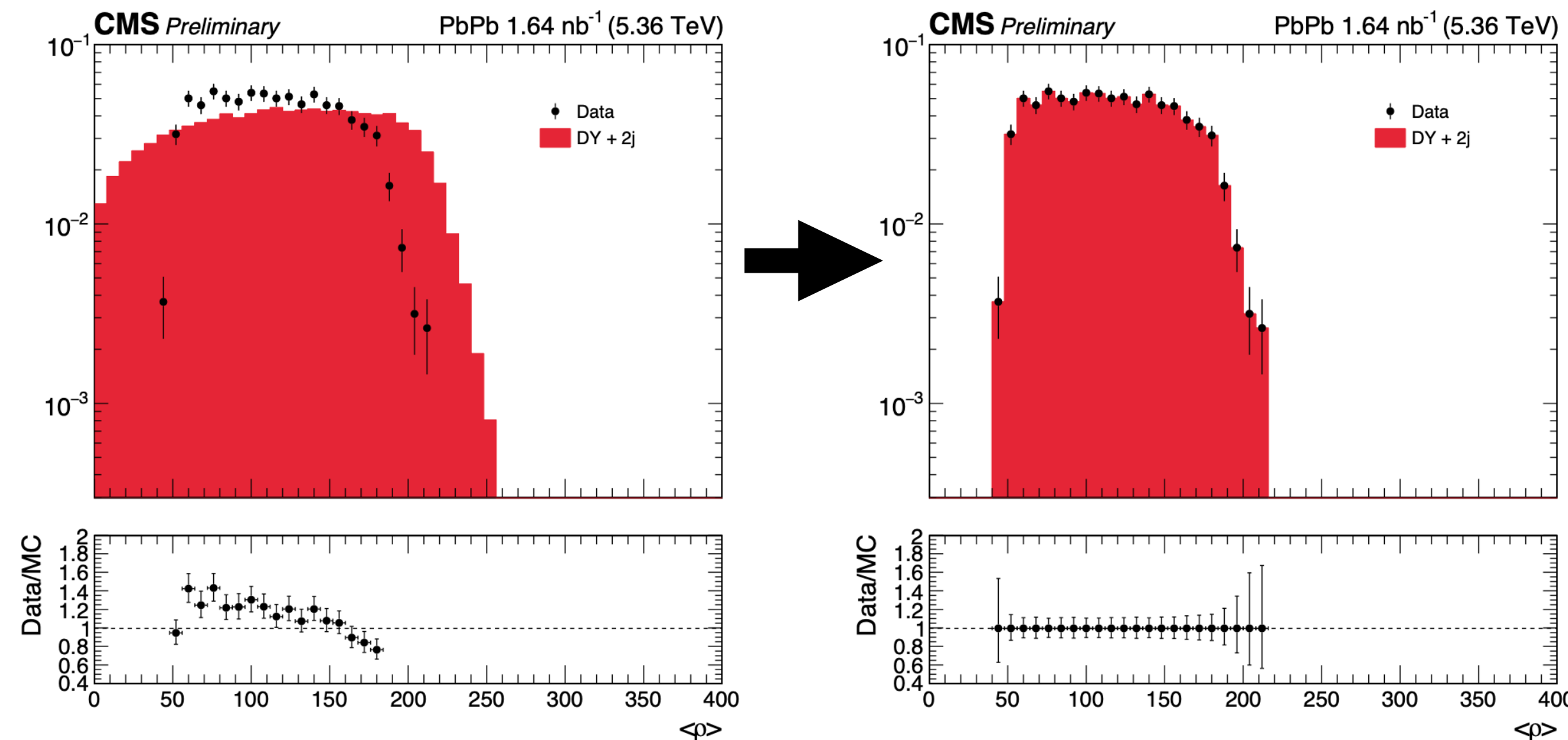
pp collisions

- A standard relative PF isolation is applied, requiring ($\epsilon \sim 95\%$)

$$I_{\text{rel}}^{\text{PF}} = \frac{\sum p_T^{\text{ch}} + \max\left(0, \sum E_T^{\text{neu}} + \sum E_T^\gamma - 0.5 \times \sum p_T^{\text{PU}}\right)}{p_T^\mu} < 0.15$$

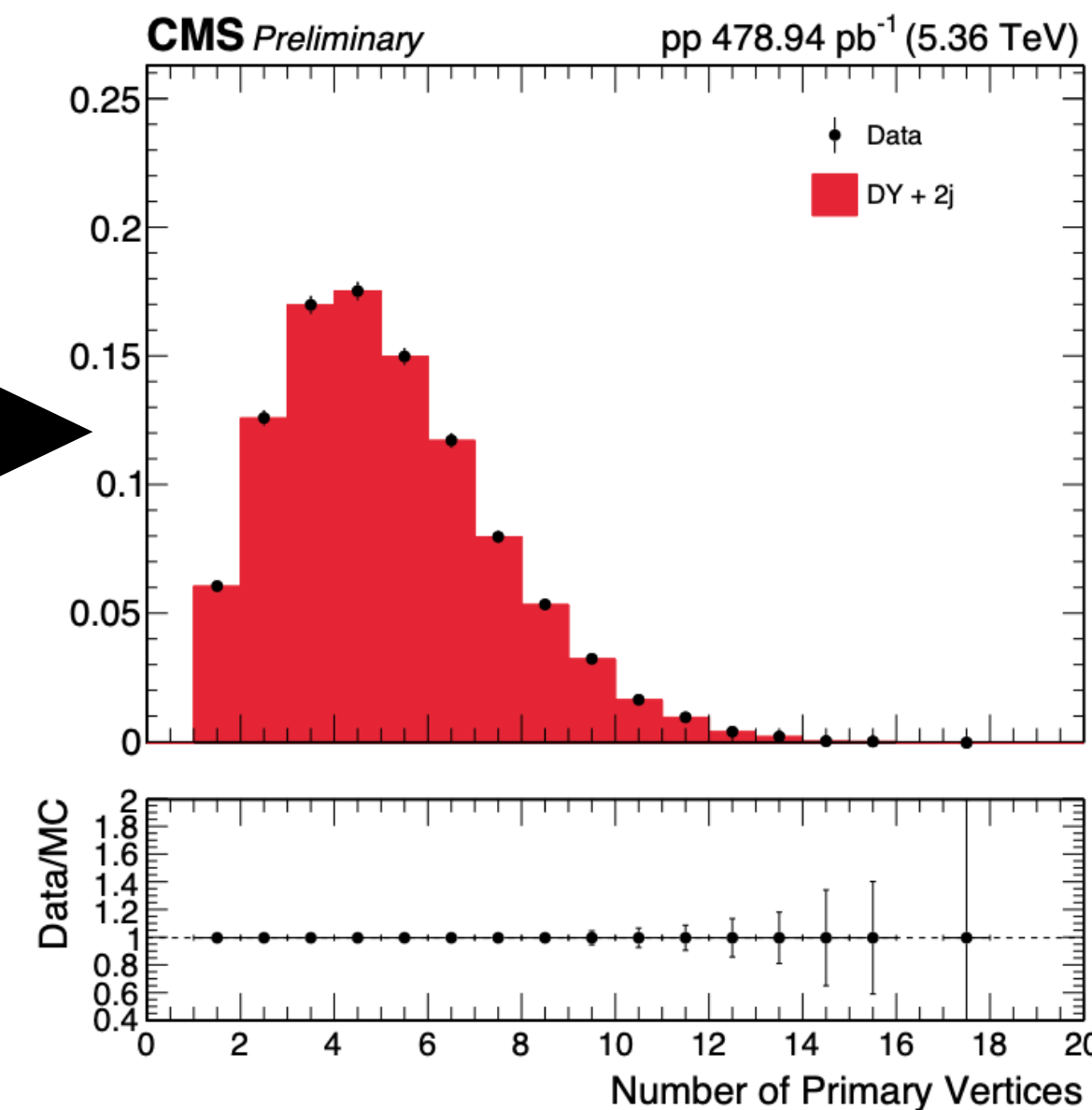
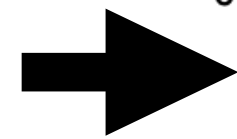
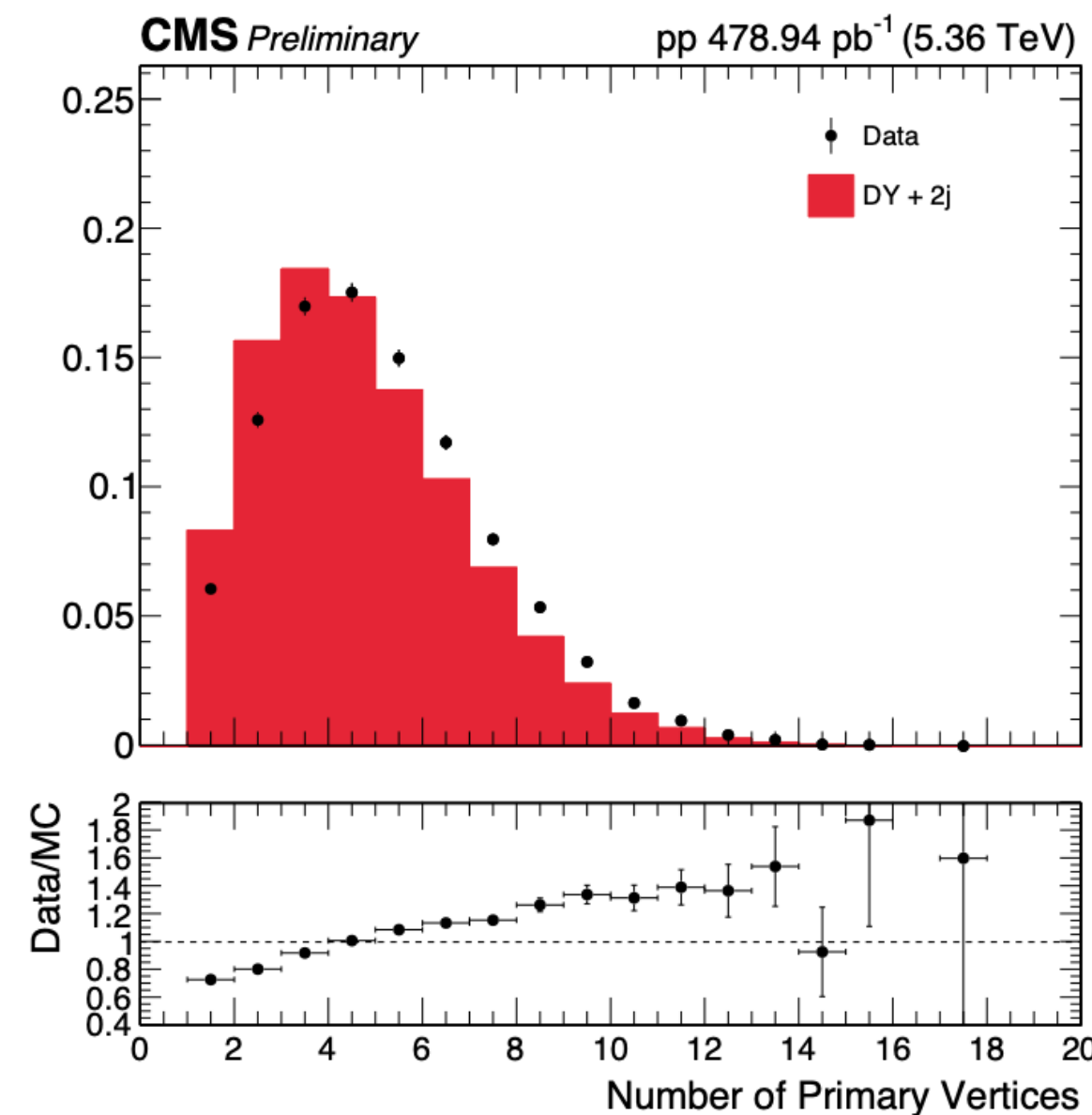
MC corrections

- We need to reweight MC, because they typically assume ideal conditions, for UE activity (ρ) and vertex position (v_z) for **PbPb**
- For **pp**, pileup weight and v_z reweighting
- **Rho reweighting** (bin distributions of $Z \rightarrow \mu\mu$ events) in PbPb:
 - In simulated PbPb events, average transverse energy density ρ (i.e the transverse momentum per unit area in the detector) is not well modeled due to soft, uncorrelated particles of UE alongside the hard scattering
 - Extracted from the ratio of average ρ distribution between central data events (0 – 30%) and centrality unbinned MC



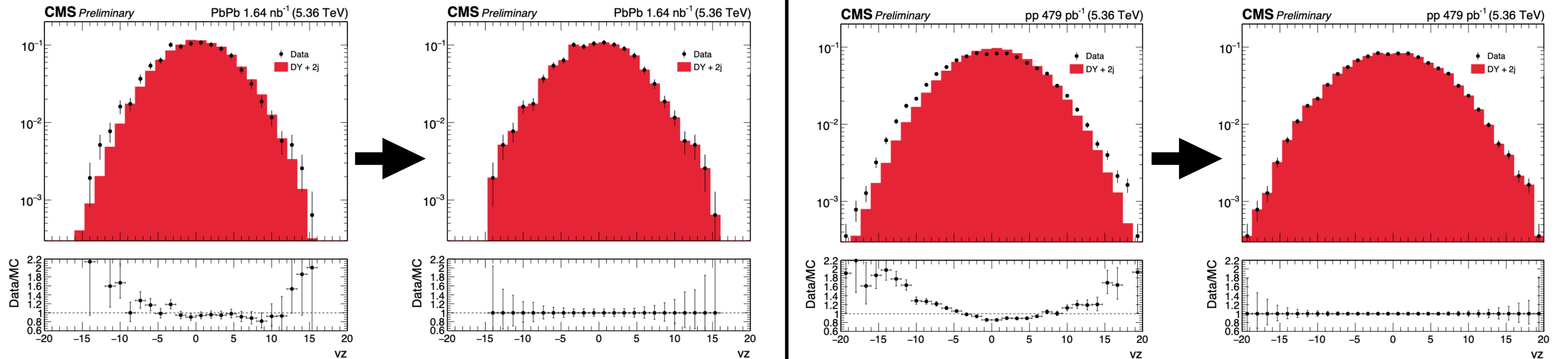
MC corrections

- We need to reweight MC, because they typically assume ideal conditions, for UE activity (ρ) and vertex position (v_z) for **PbPb**
- For **pp**, pileup weight and v_z reweighting
- **PU reweighting** (bin distributions of $Z \rightarrow \mu\mu$ events) in pp:
 - In Run 3 pp ref run, LHC operated under exceptionally low pileup conditions, with $\langle \mu \rangle \sim 4$
 - The total number of reconstructed primary vertices serves as a direct physical proxy for the amount of in-time pileup in a given event



MC corrections

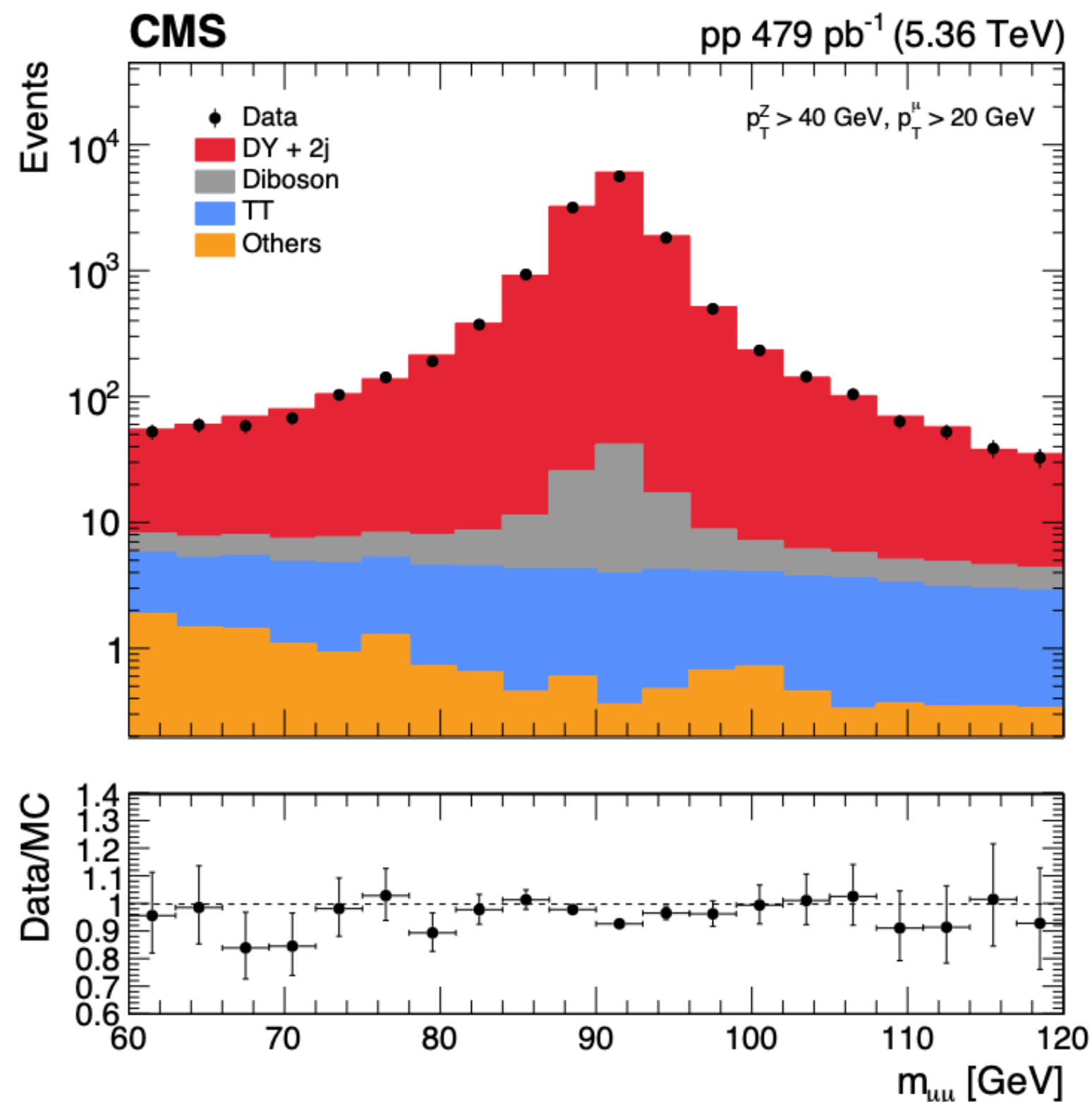
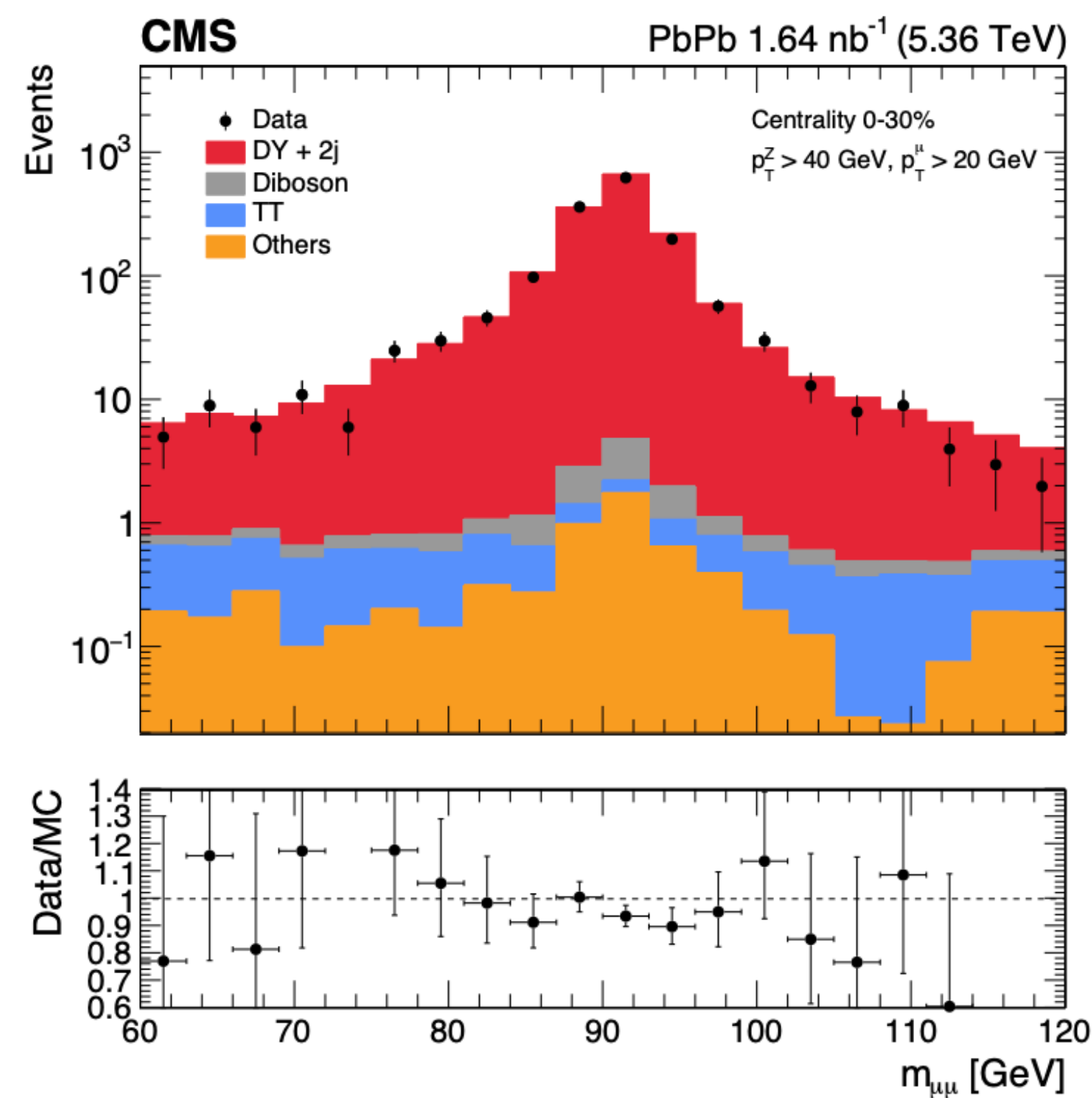
- We need to reweight MC, because they typically assume ideal conditions, for UE activity (ρ) and vertex position (v_z) for **PbPb**
- For **pp**, pileup weight and v_z reweighting
- v_z **reweighting** (bin distributions of $Z \rightarrow \mu\mu$ events):
 - The vertex distribution in the generated MC samples may be different from that in data, which affects the acceptance of Z-jet events
 - Reweight the MC so that the v_z matches that of the data in both PbPb and pp



Detector-level distributions

Z boson reconstruction

- Z mass and p_T for data compared to MC stacked histograms for signal and bkg
- MC distributions normalised using lumi, σ_{gen}^{pp} , σ_{gen}^{NN} (scaled by $A^2 = 208^2$) and final MC event weights



Event count		
	PbPb 23	pp 24
DATA	1547	13787
DY+2jet	1609	14202
Diboson	8	68
TT	8	69
Others	7	15
Bkg around 1%		

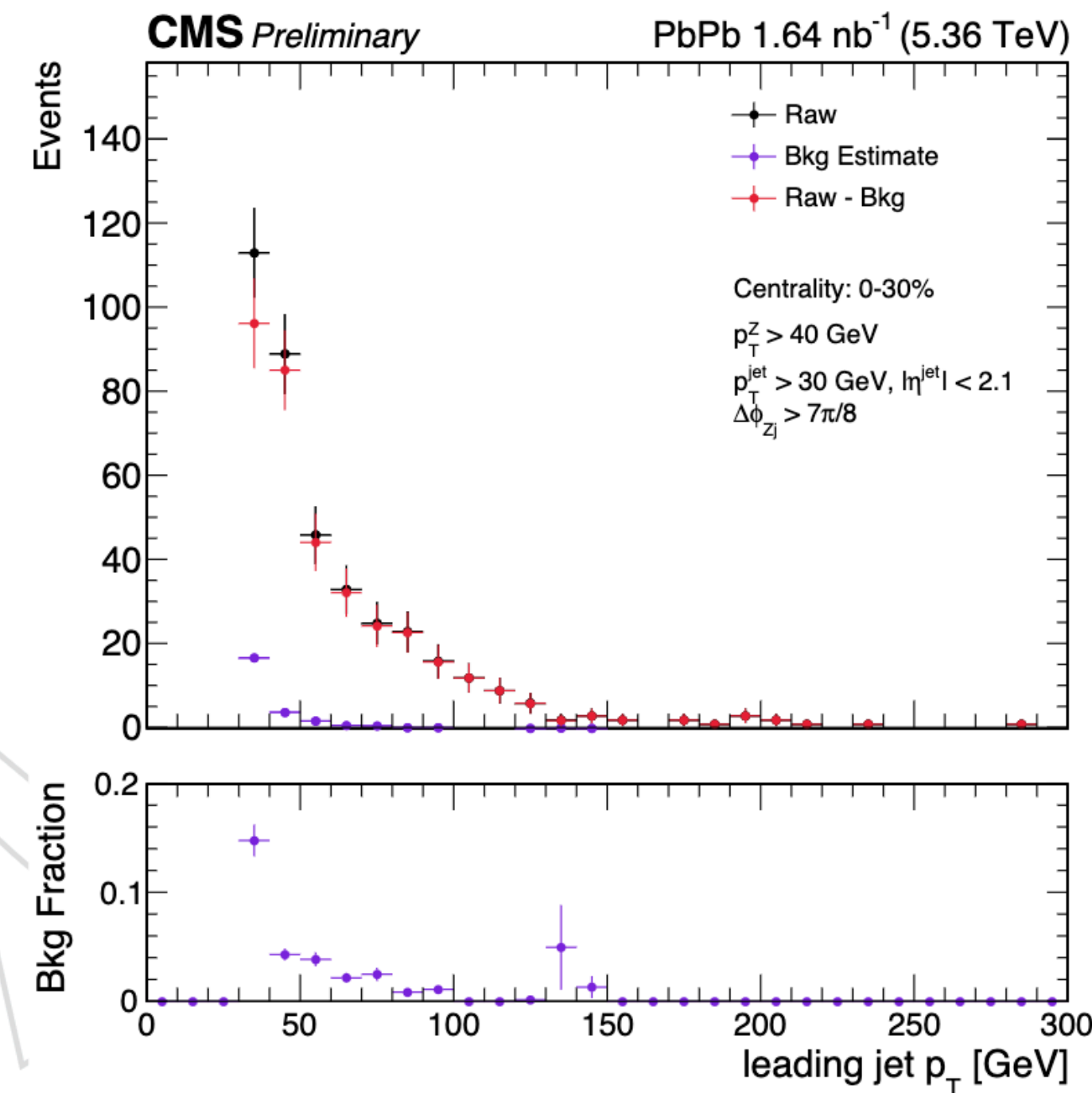
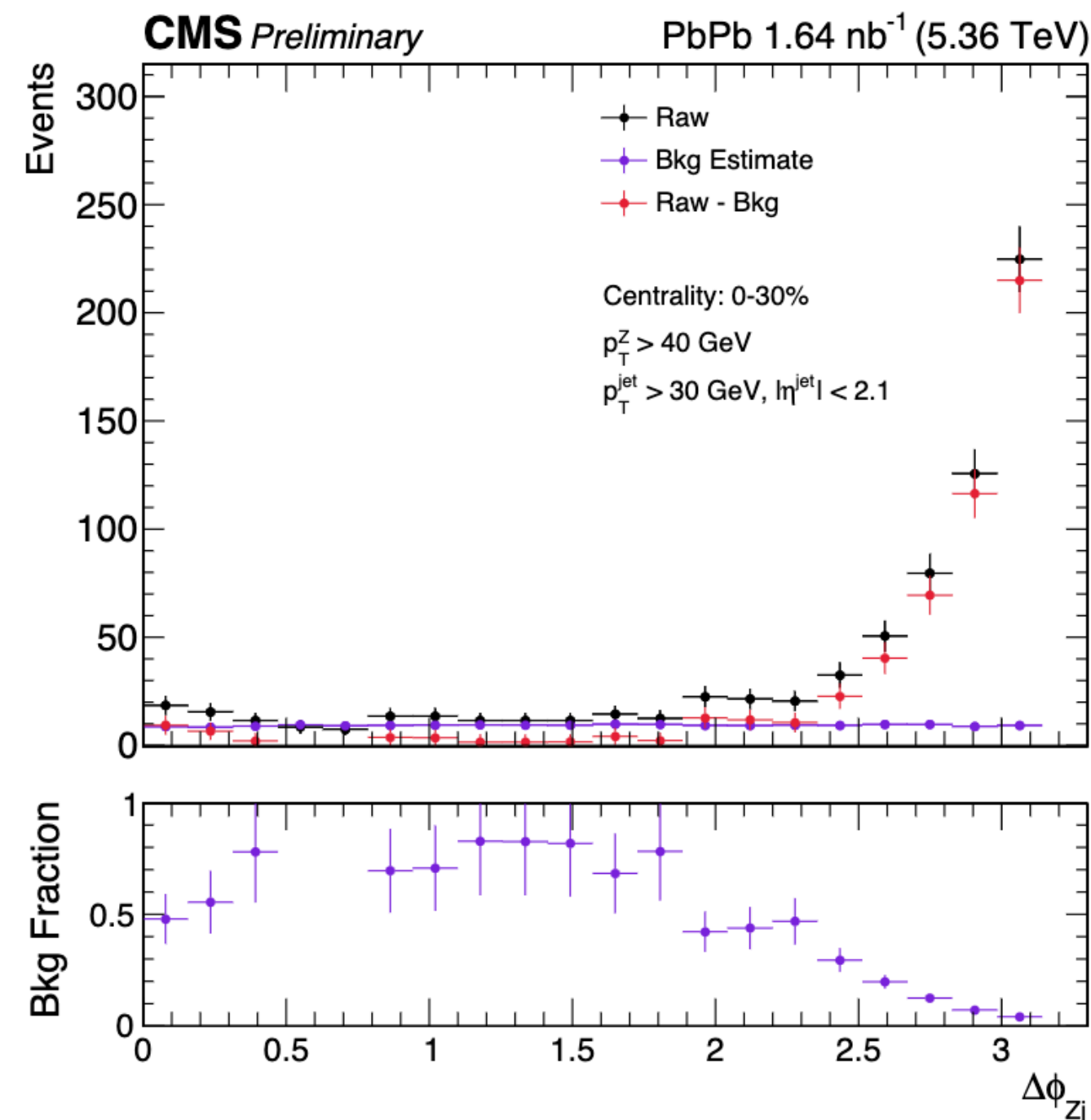
UE background Subtraction

- Minimum bias event mixing
 - Data-driven technique applied for PbPb collisions only
 - Fake jets are not correlated to the Z boson, therefore their distribution is statistically identical to jets found in MB events, used to estimate the contribution of bkg jets
- MB events are:
 - required to pass the **same offline event selection** as the Z-jet candidate events
 - selected in order to have the same centrality (0-30% in bin of 1% of centrality) and to come from the same vertex bin v_z [-15,5], [-5,5], [5,15] cm, so that they have **similar underlying event activity**

Set	Process	Sample (MINIAOD)
Data	HIMinimumBias0	HIMinimumBias0/HIRun2023A-PromptReco
MC	MinBias_Drum5F_5p36TeV_hydjet	MinBias_Drum5F_5p36TeV_hydjet/HINPbPbSpring23MiniAOD-NoPU_132X_mcRun3_2023_realistic_HI_v9-v2

UE background Subtraction

- Each Z+jet signal event is correlated with 100 MB events in the same ν_z -cen bin
- Divide the bkg histogram by 100 before subtracting from the signal histogram
- Final bkg-subtracted spectrum N_{corr} obtained as $N_{corr} = N_{raw} - N_{bkg}$
- Closure tests performed by using alternative matching criterium (based on HF matching) and also by comparing subtracted spectra with reco jets matched with truth in MC simulations



Estimated fraction
of background
under recoiling peak
 $\sim 6.2\%$

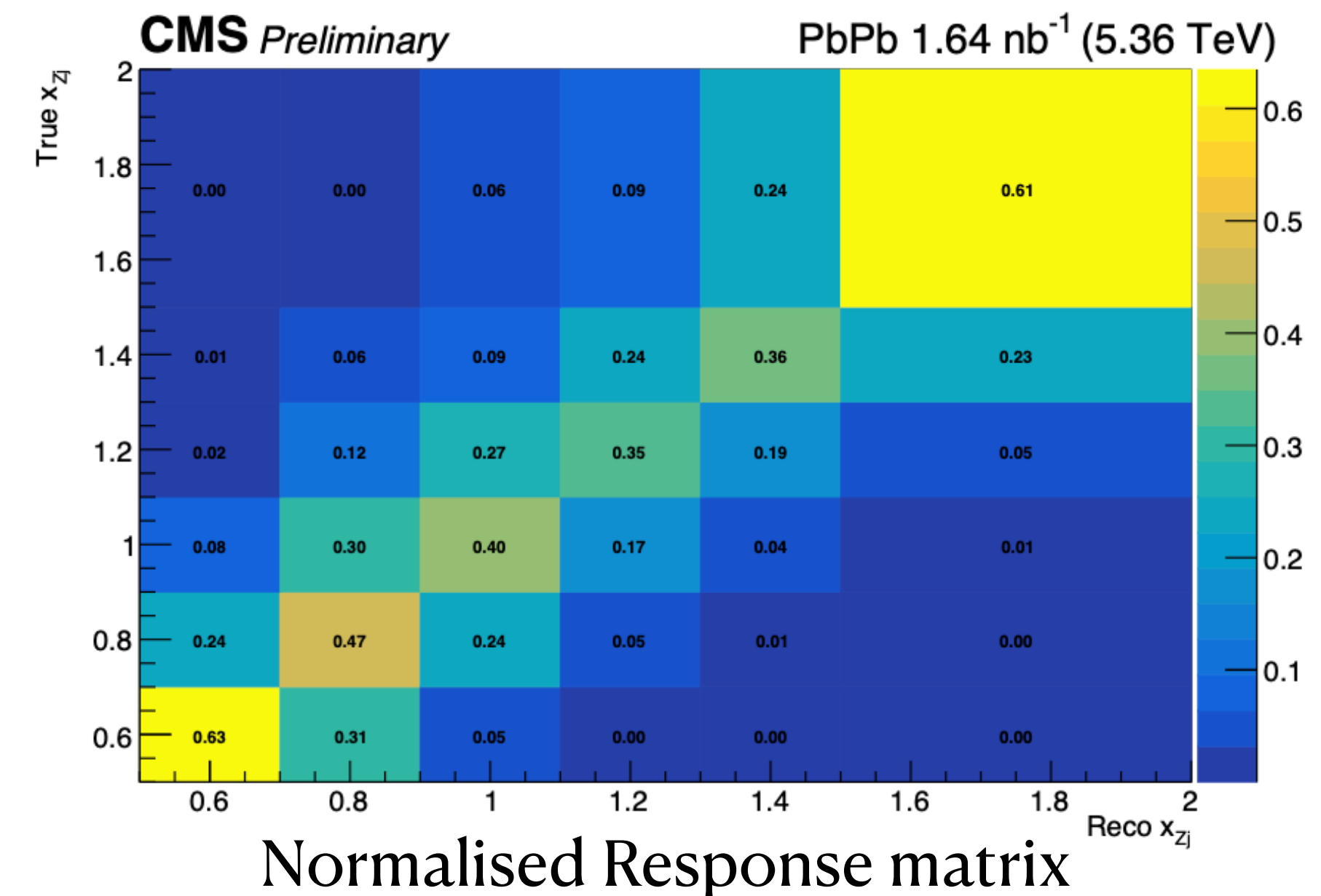
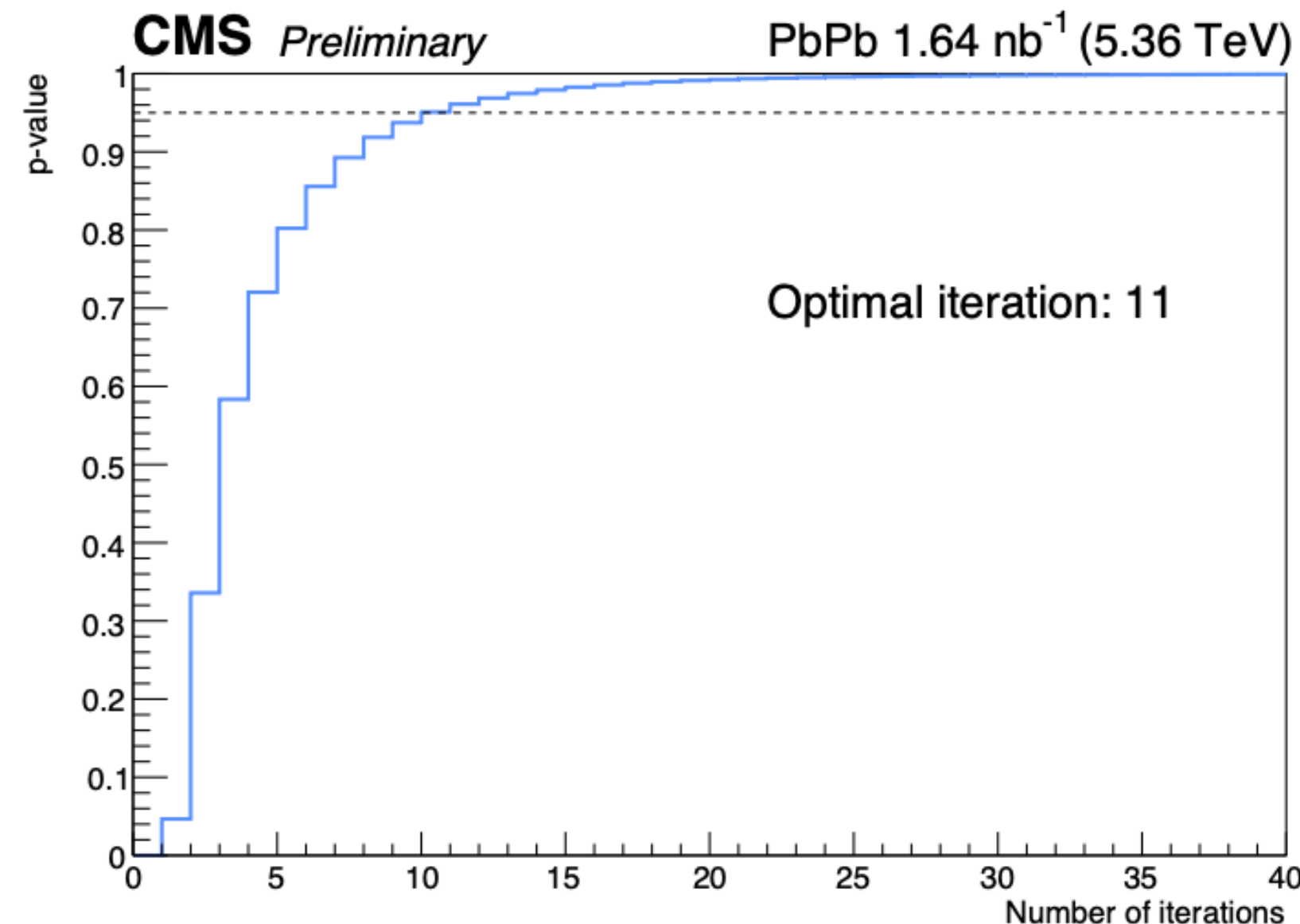
Unfolding

- In order to compare to theoretical predictions or to other experiments, measured spectra (detector-level) x_{Zj} are unfolded to the **particle level** to clean them from
 - Detectors effect
 - Acceptance and efficiency corrections
 - Bins migration effects
- **D'Agostini iterative unfolding** (Bayesian approach) with **early stopping** implemented in the **ROOUNFOLD** package
- The binning choice ensures a sufficiently large number of counts per bin for stable unfolding corrections
- The unfolded solution is stable at the chosen number of iterations, used as **regularising parameter**

$$\overset{\text{Unfolded data}}{y} = \underset{\text{Response matrix}}{A(x, y)} \overset{\text{Measured data}}{x}$$

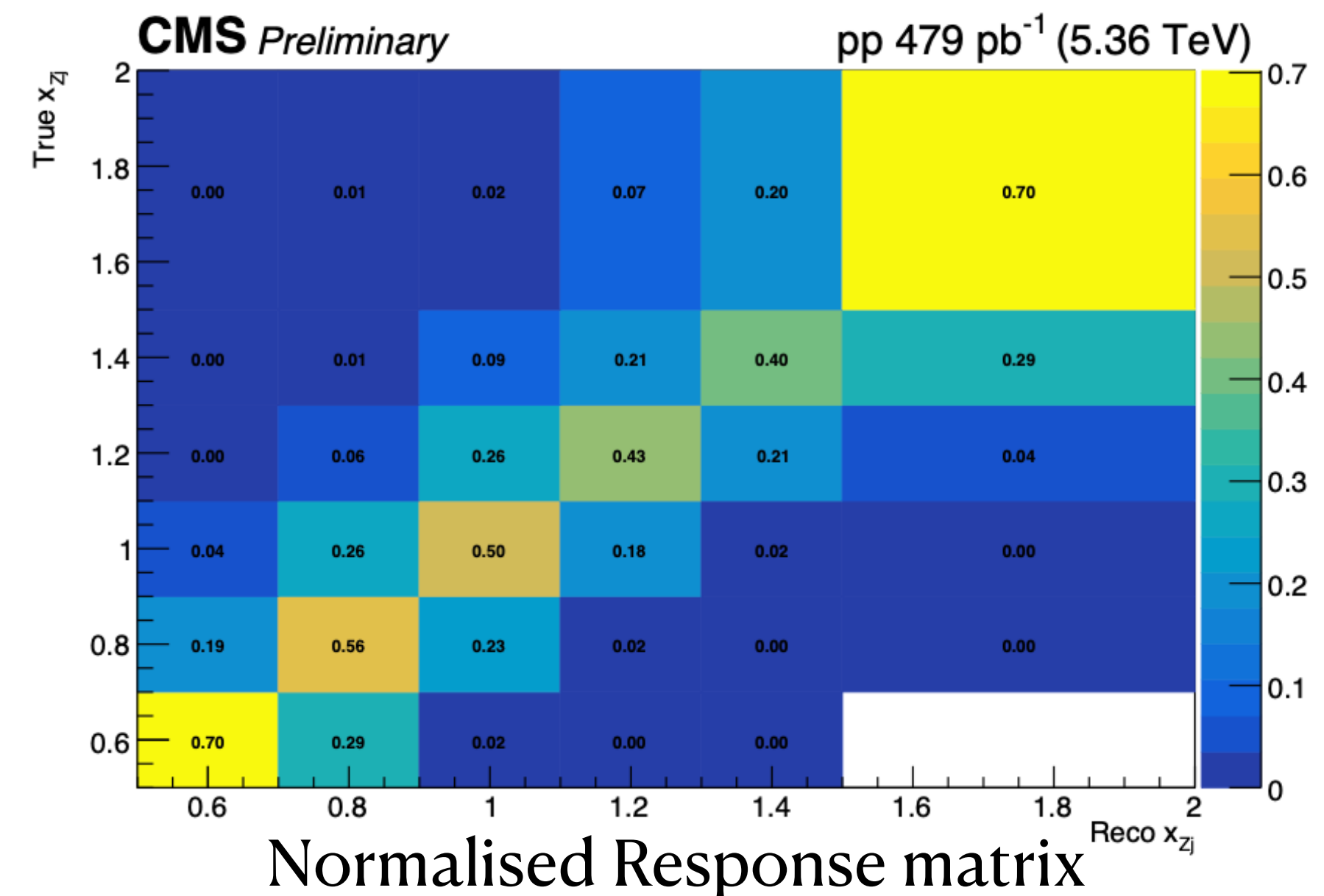
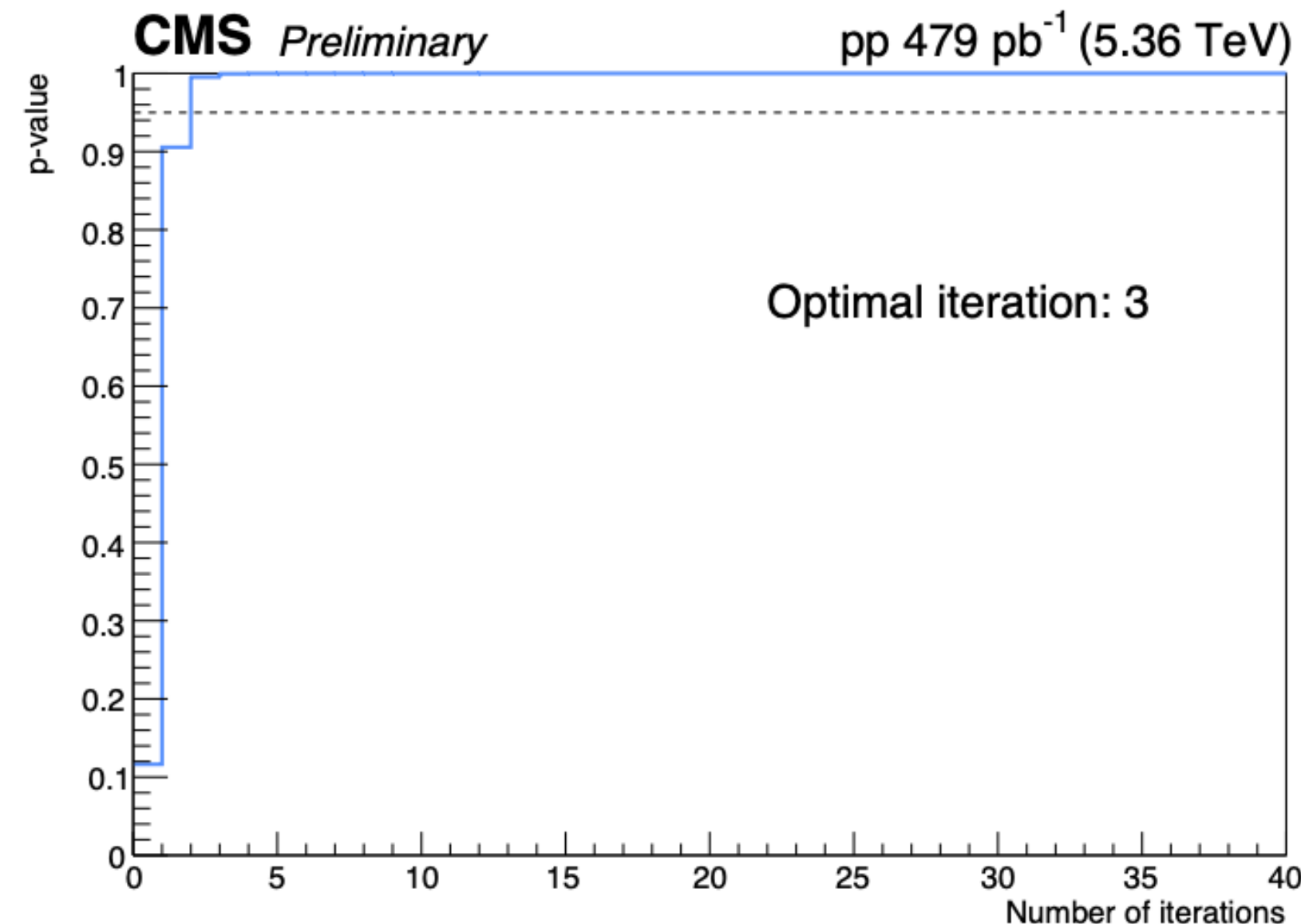
Unfolding

- **Binning** choice dictated by the sample size (sufficient counts per-bin for stable unfolding):
 - 6 bins in x_{Zj} [0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 2] at **reco-** and **gen- level**
- **Early stopping** as **regularisation** parameter (based on **goodness-of-fit** tests, **refold** the unfolded distribution at each iteration, stop when p-value with respect to the input distribution > 0.95)
- Sanity checks performed: trivial identity test, split test (60% – 40 %), cross-folding test for MC modelling, stability with the number of iteration



Unfolding

- **Binning** choice dictated by the sample size (sufficient counts per-bin for stable unfolding):
 - 6 bins in x_{Zj} [0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 2] at **reco-** and **gen- level**
- **Early stopping** as **regularisation** parameter (based on **goodness-of-fit** tests, **refold** the unfolded distribution at each iteration, stop when p-value with respect to the input distribution > 0.95)
- Sanity checks performed: trivial identity test, split test (60% – 40 %), cross-folding test for MC modelling, stability with the number of iteration



Unfolding tests

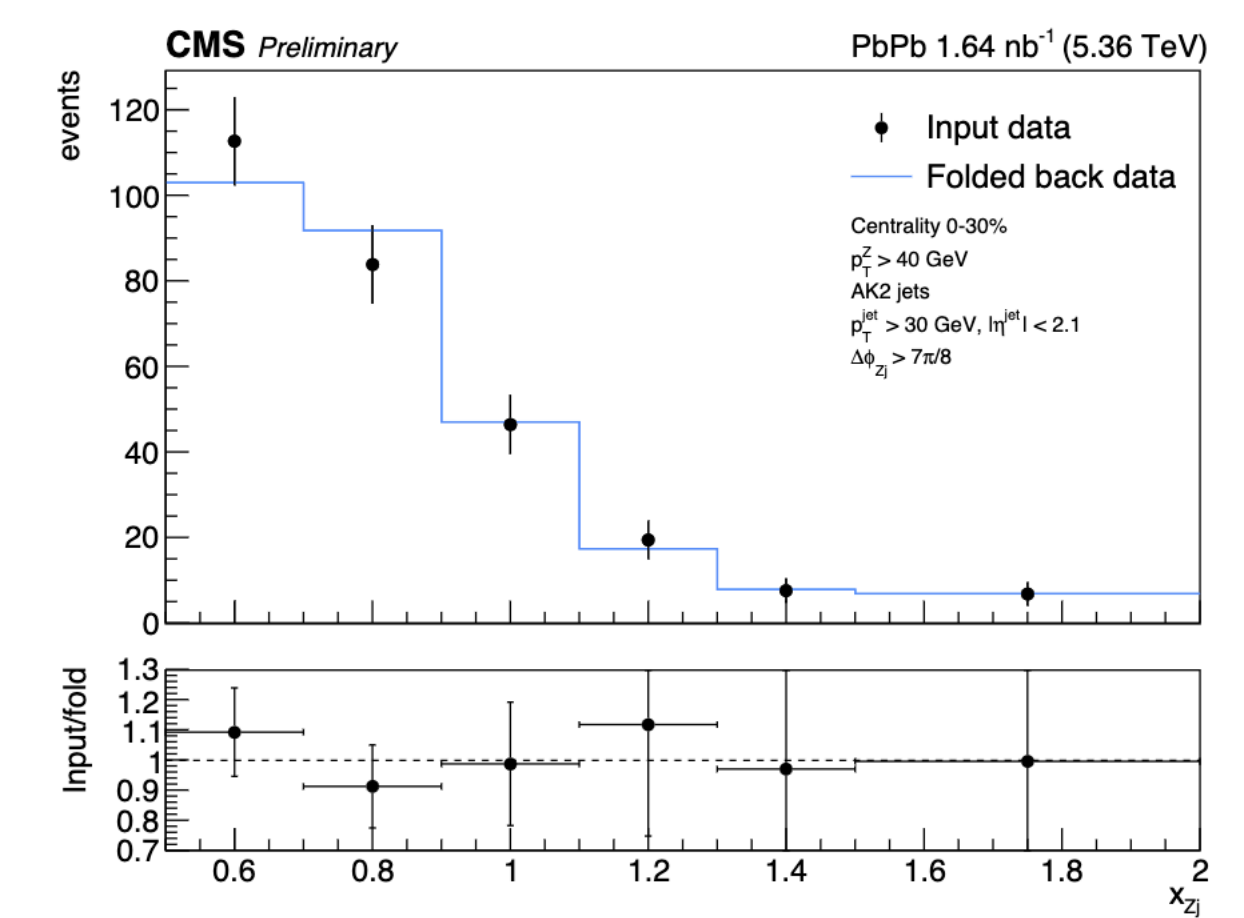
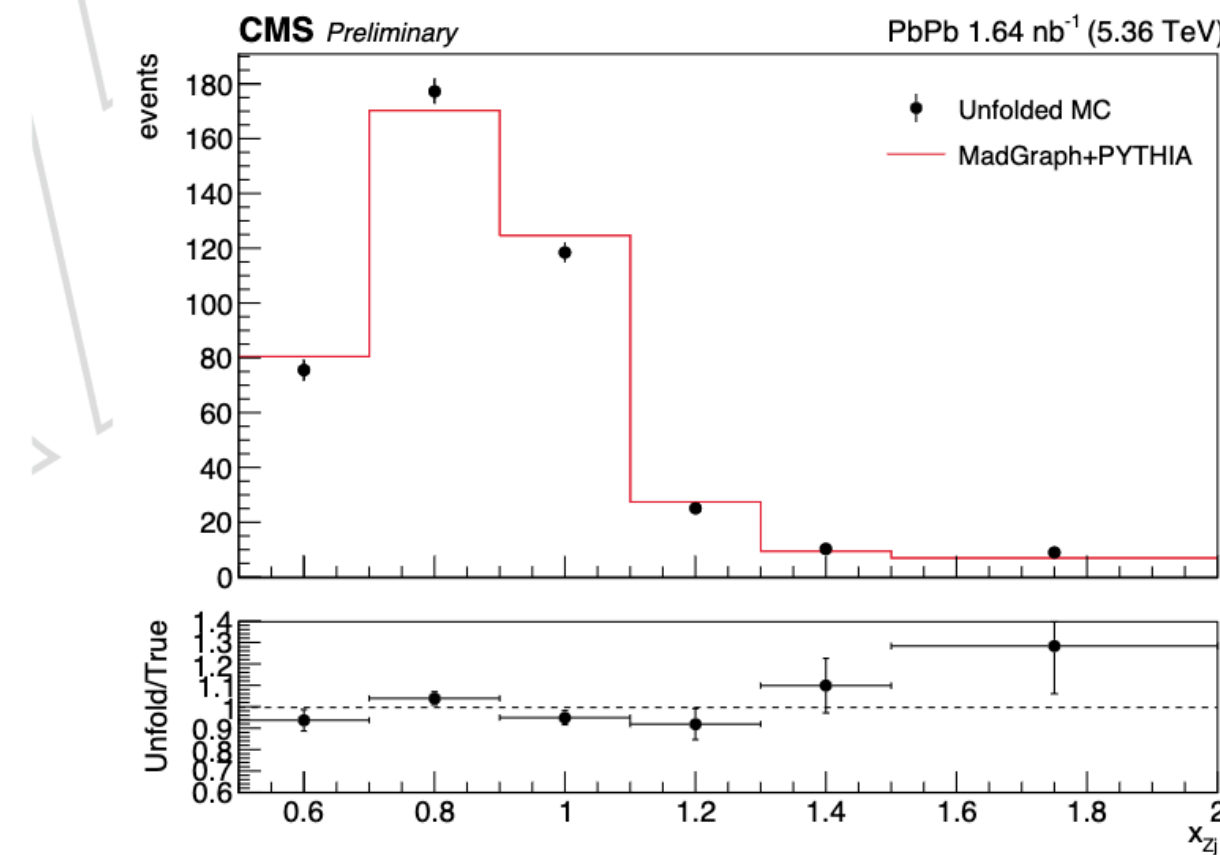
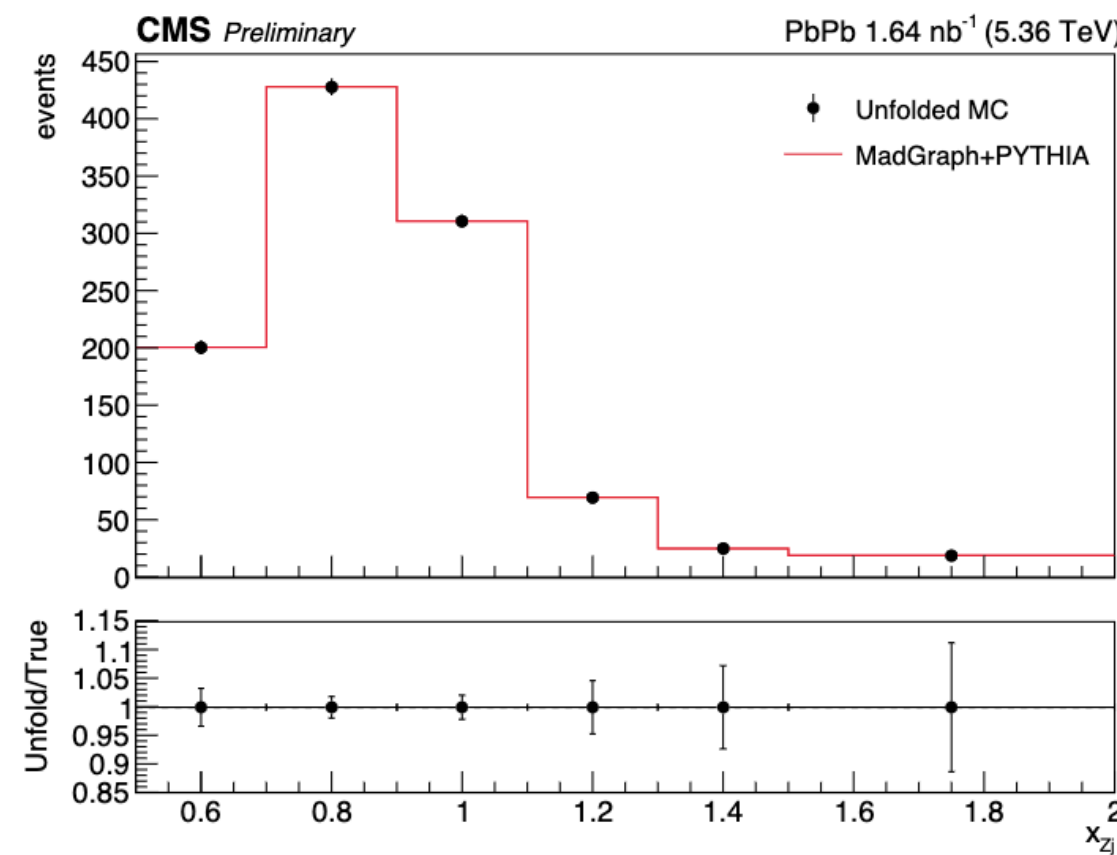
- A number of tests is performed to check stability and robustness of the procedure

Trivial

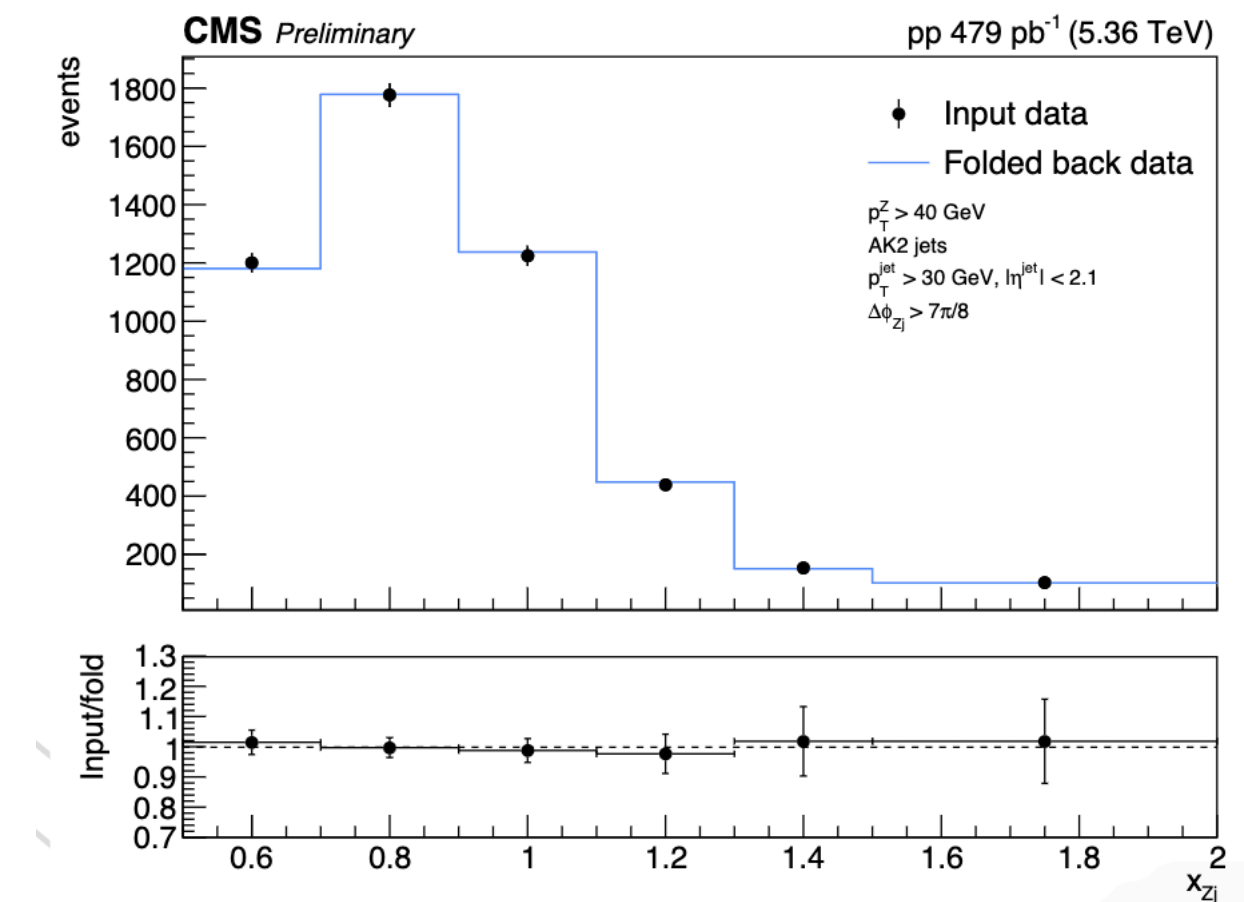
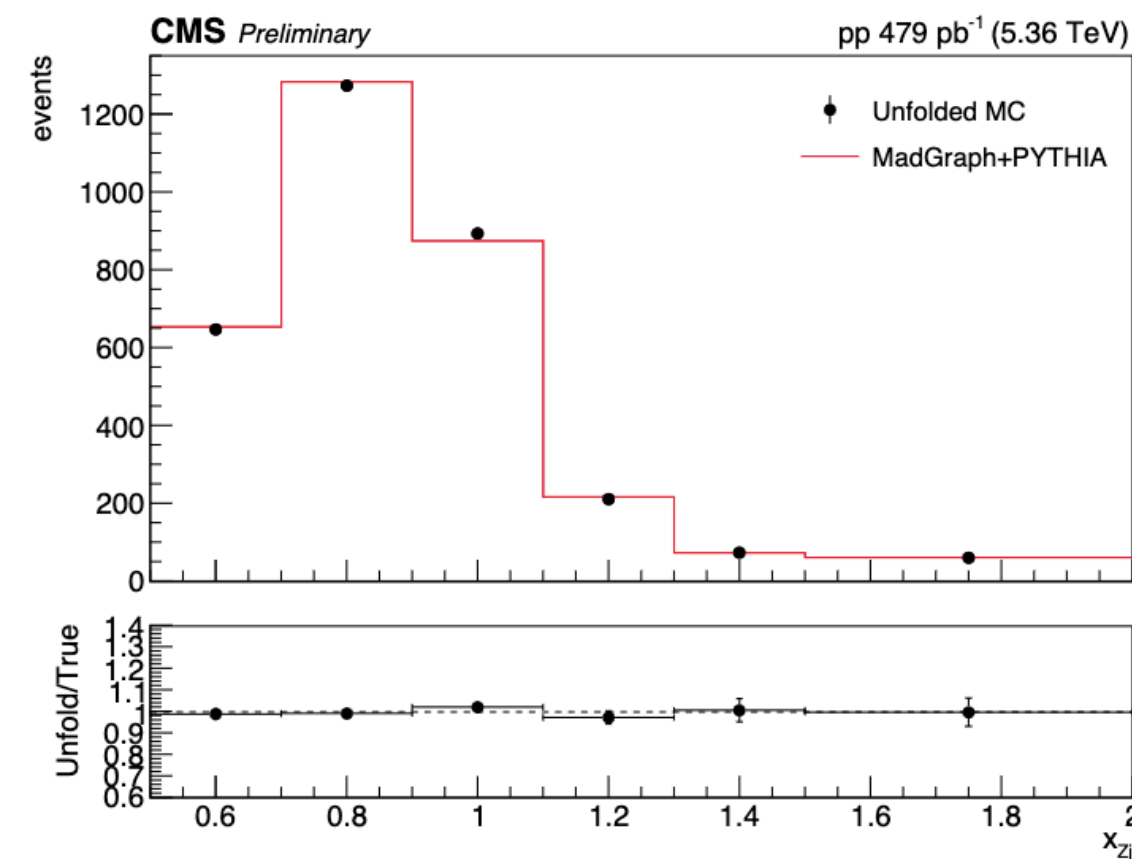
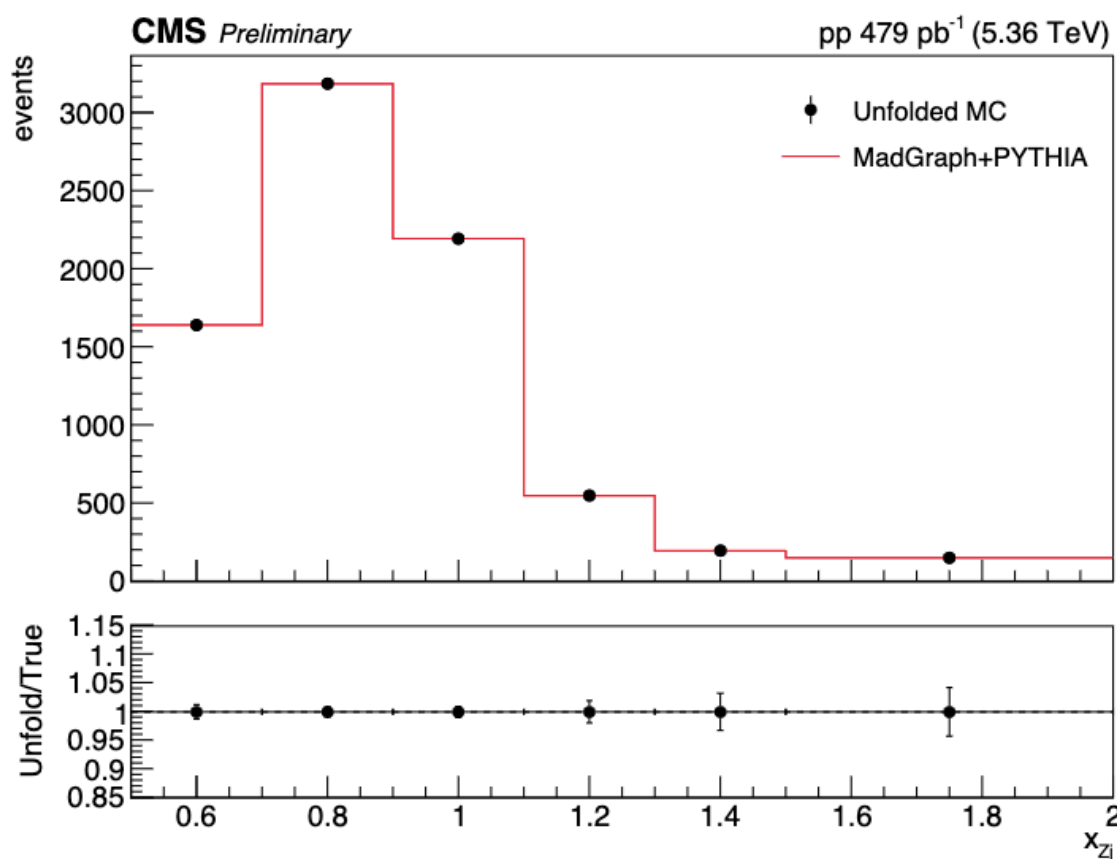
Split

Refolding

Pb 2023



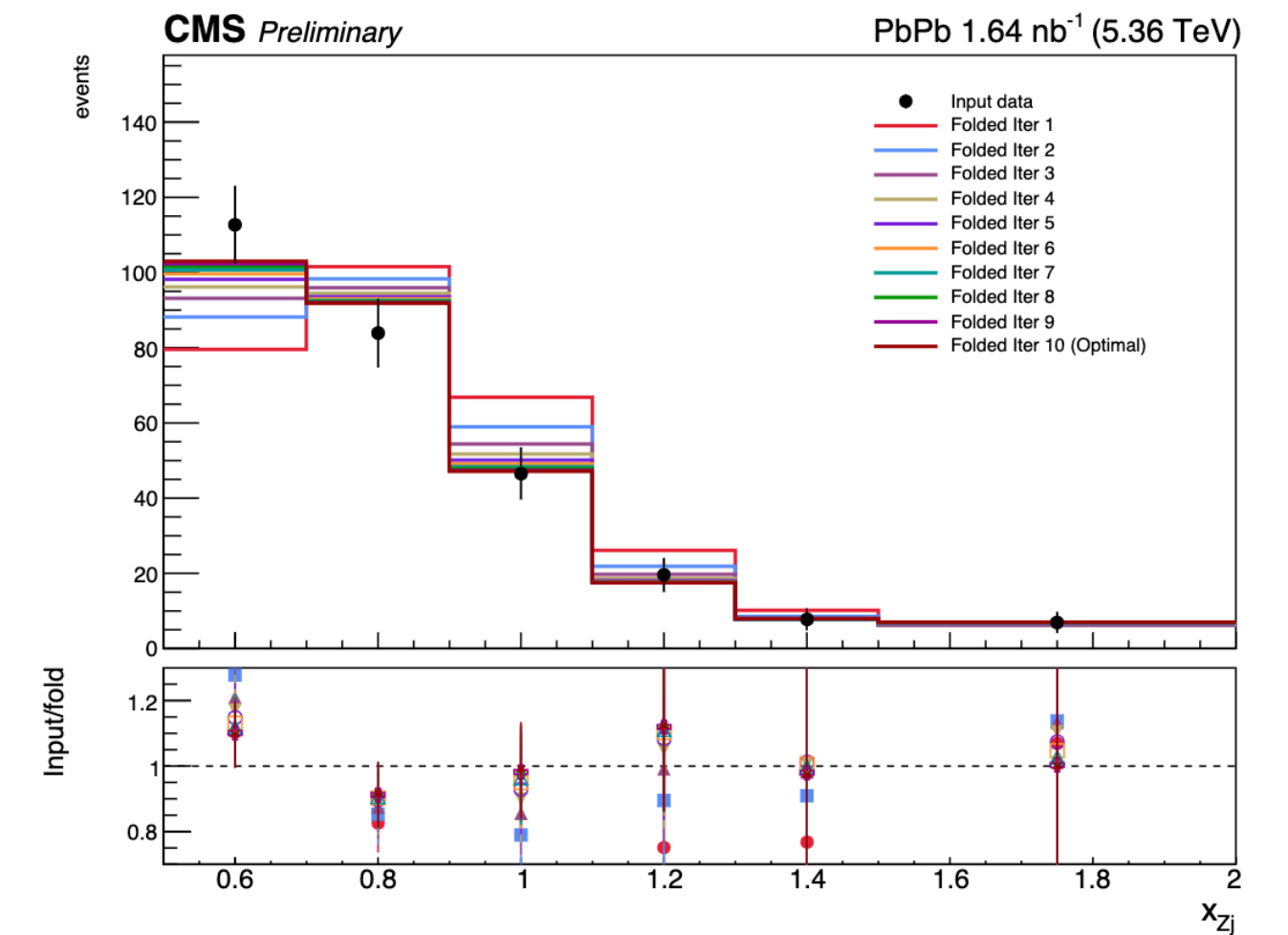
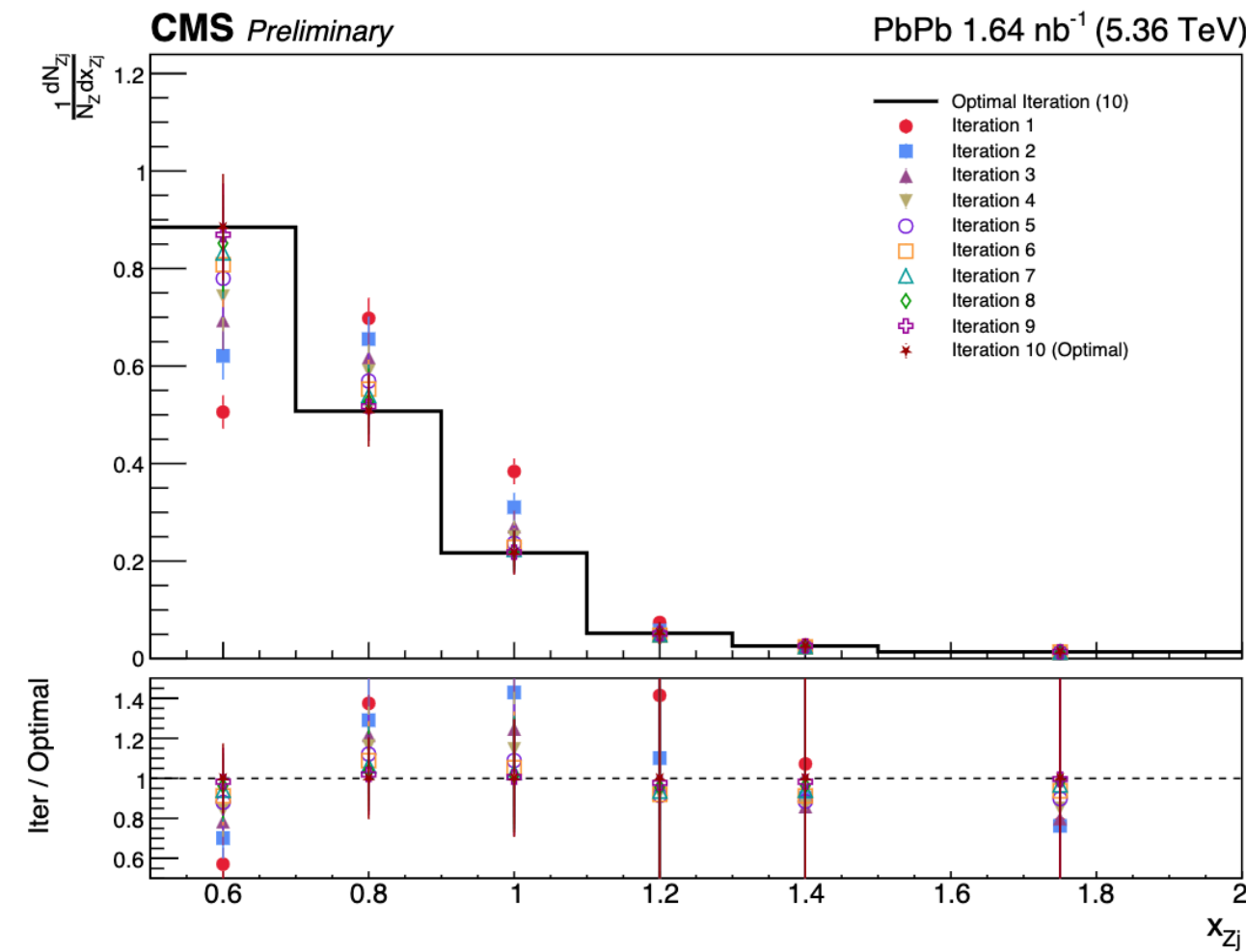
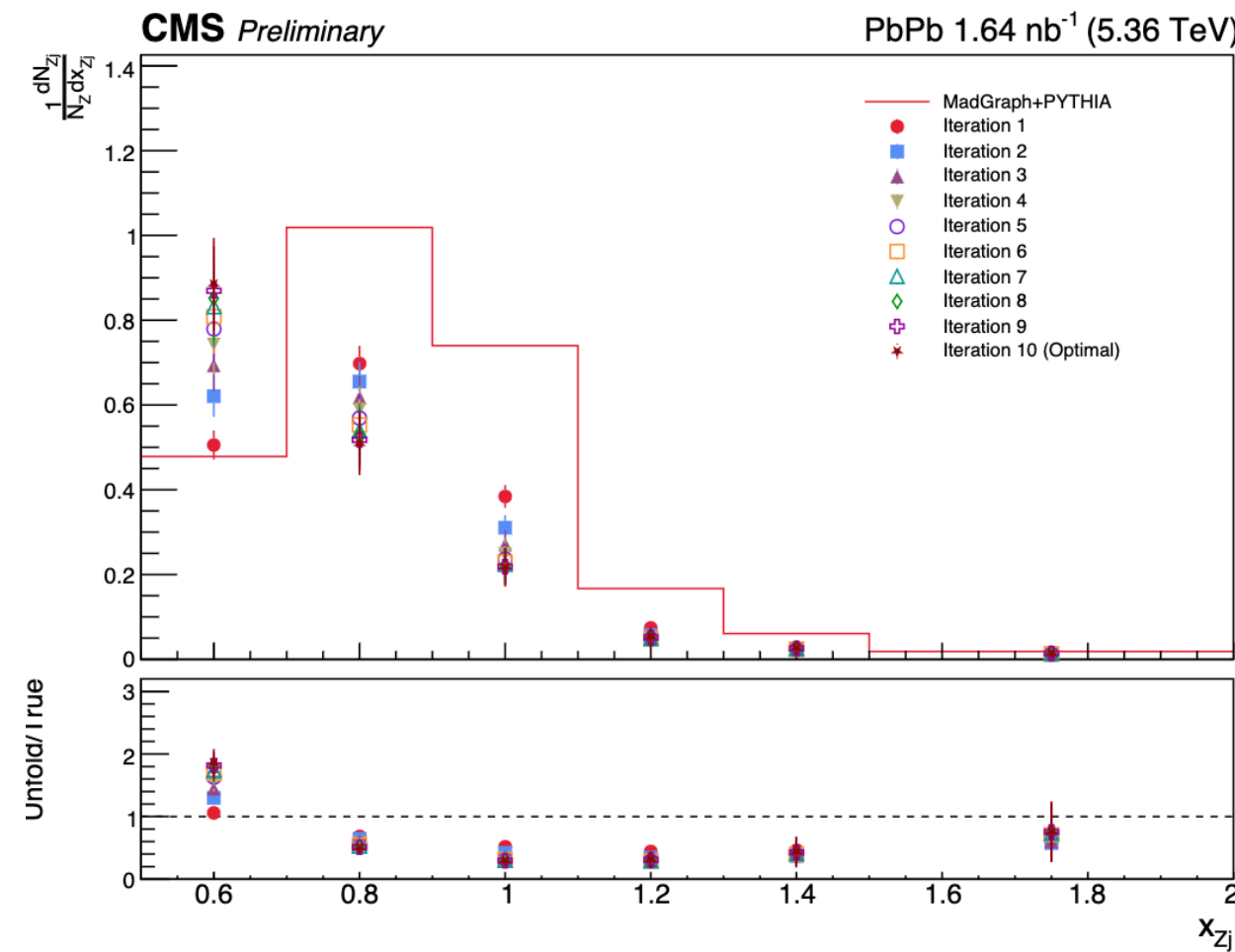
pp 2024



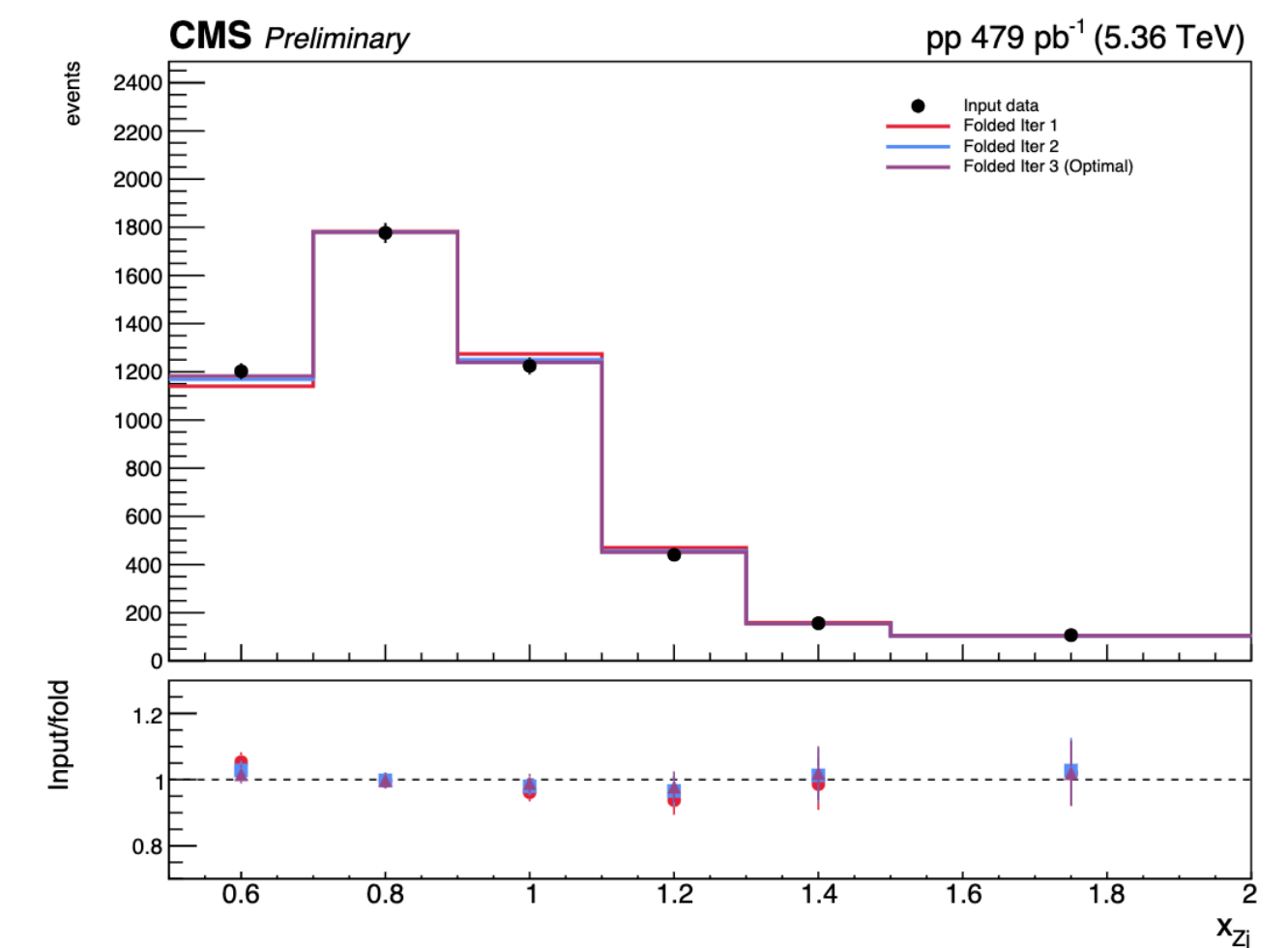
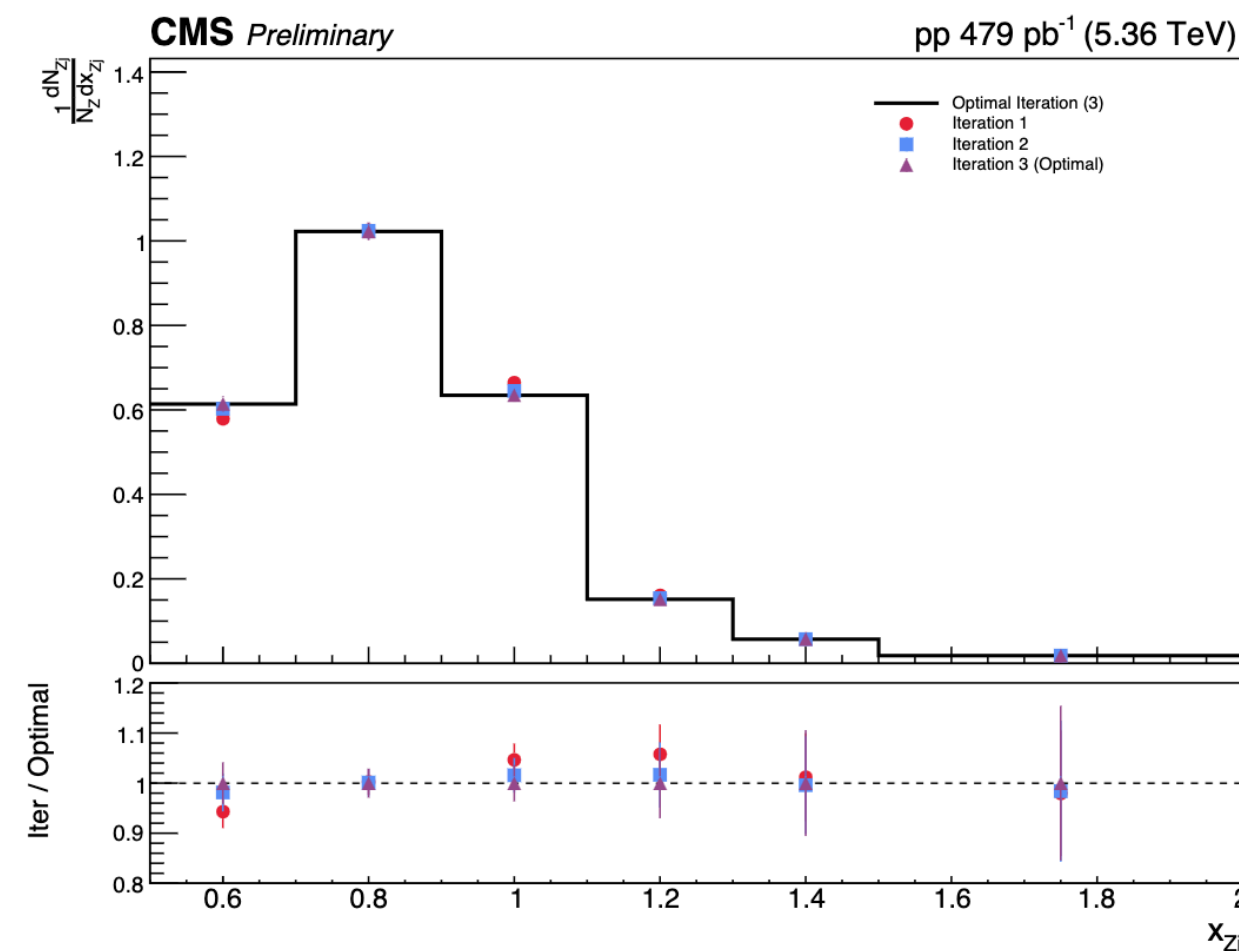
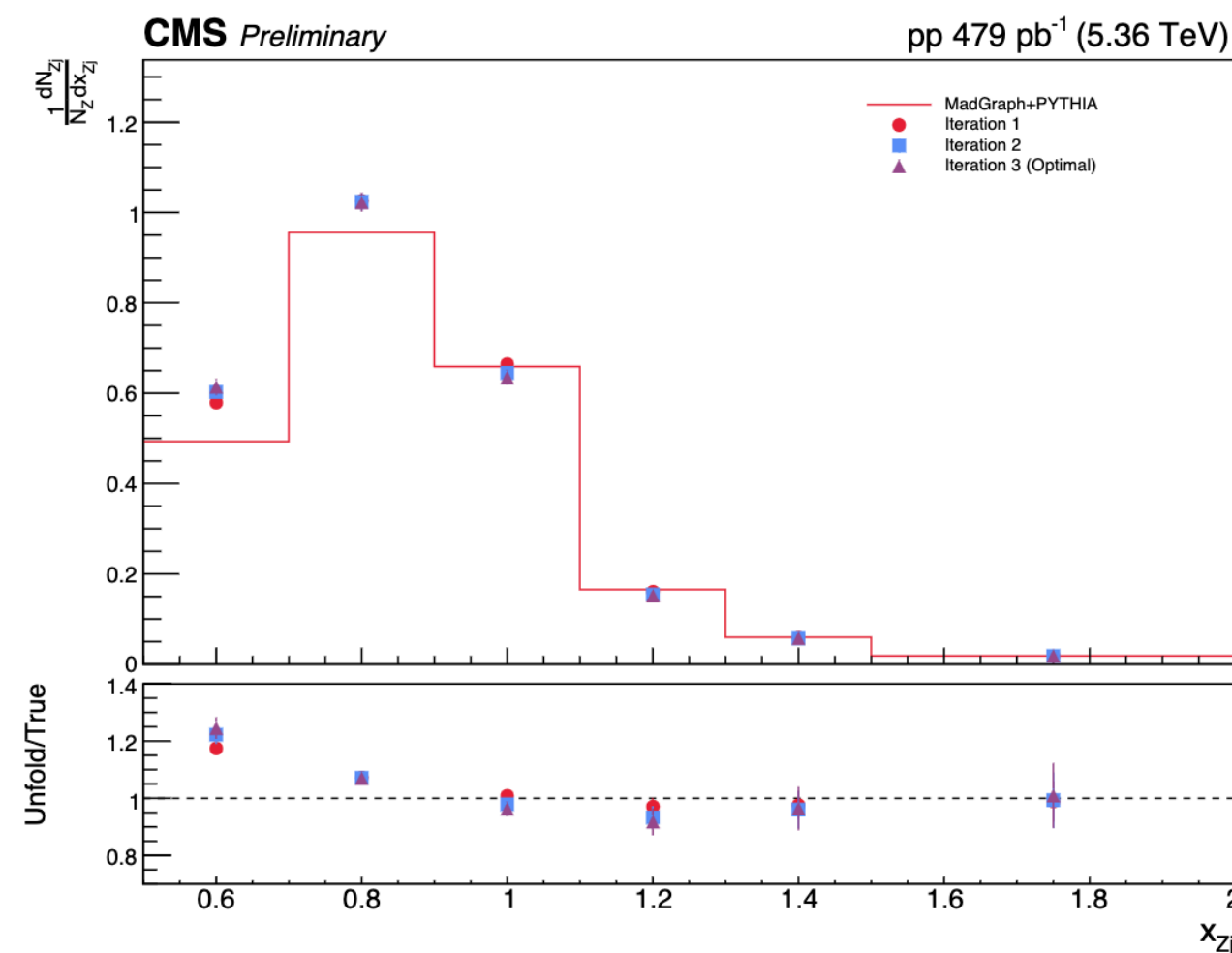
Unfolding tests

- A number of tests is performed to check stability and robustness of the procedure

Pb 2023



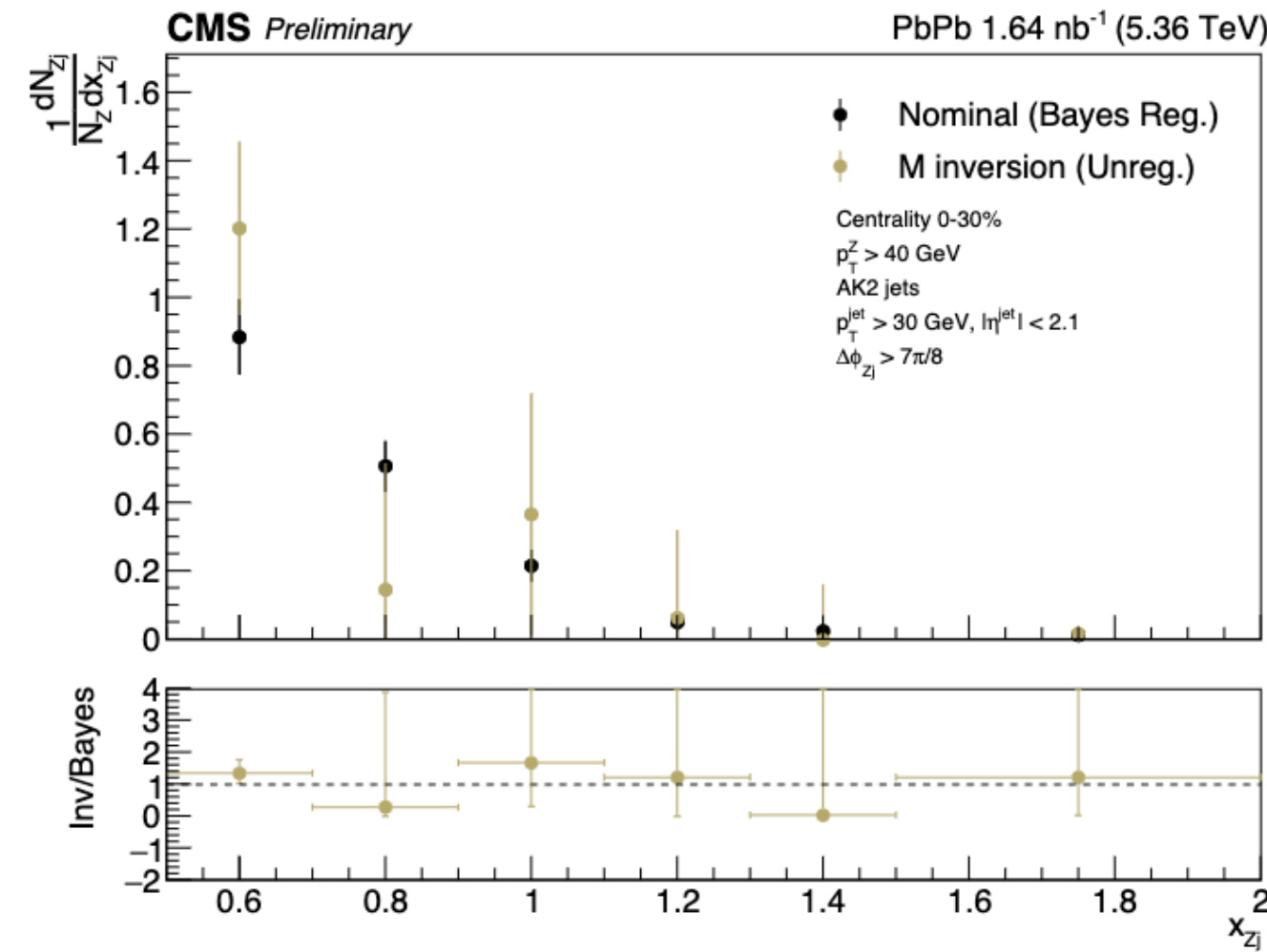
pp 2024



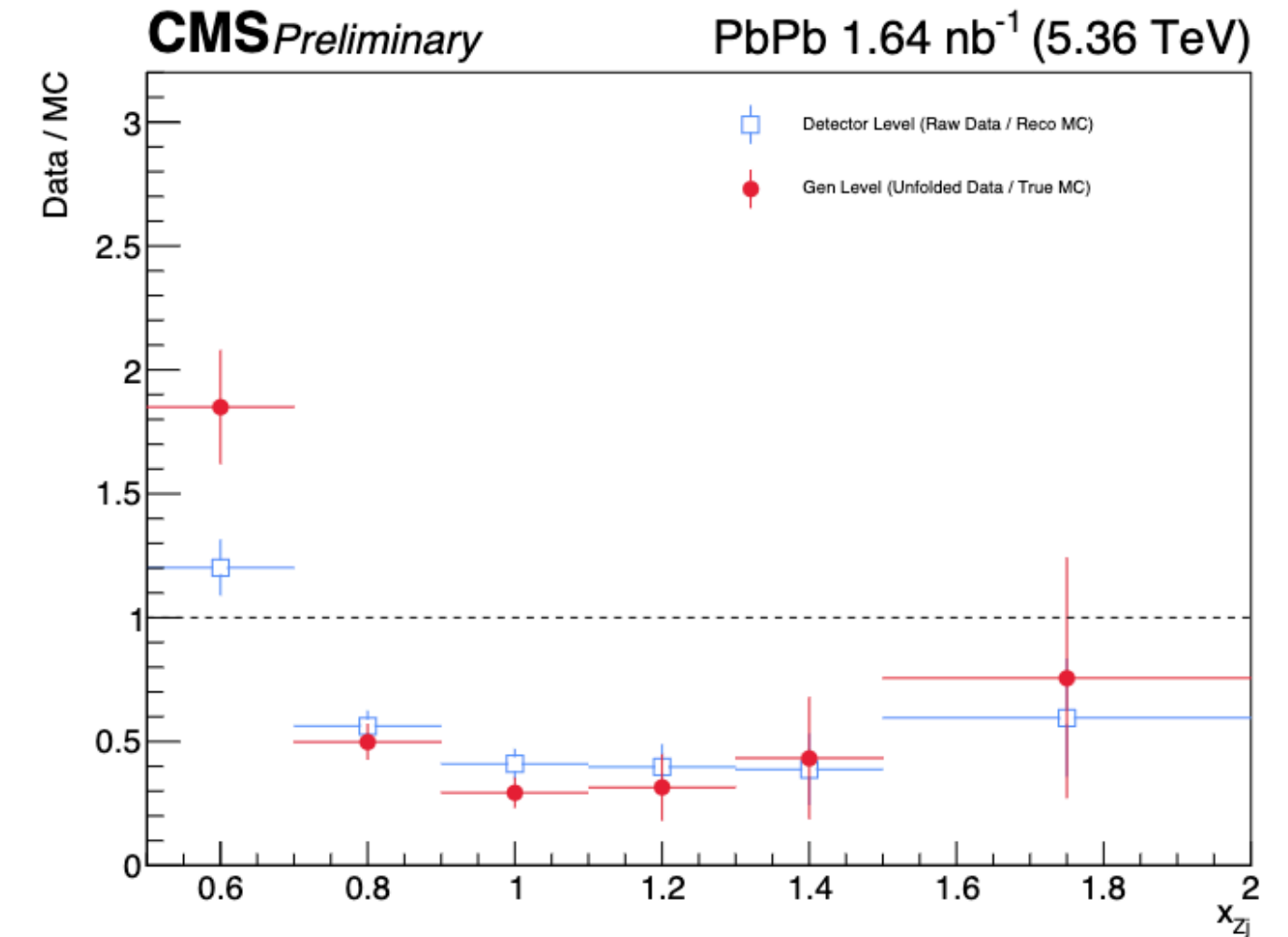
Unfolding tests

- A number of tests is performed to check stability and robustness of the procedure

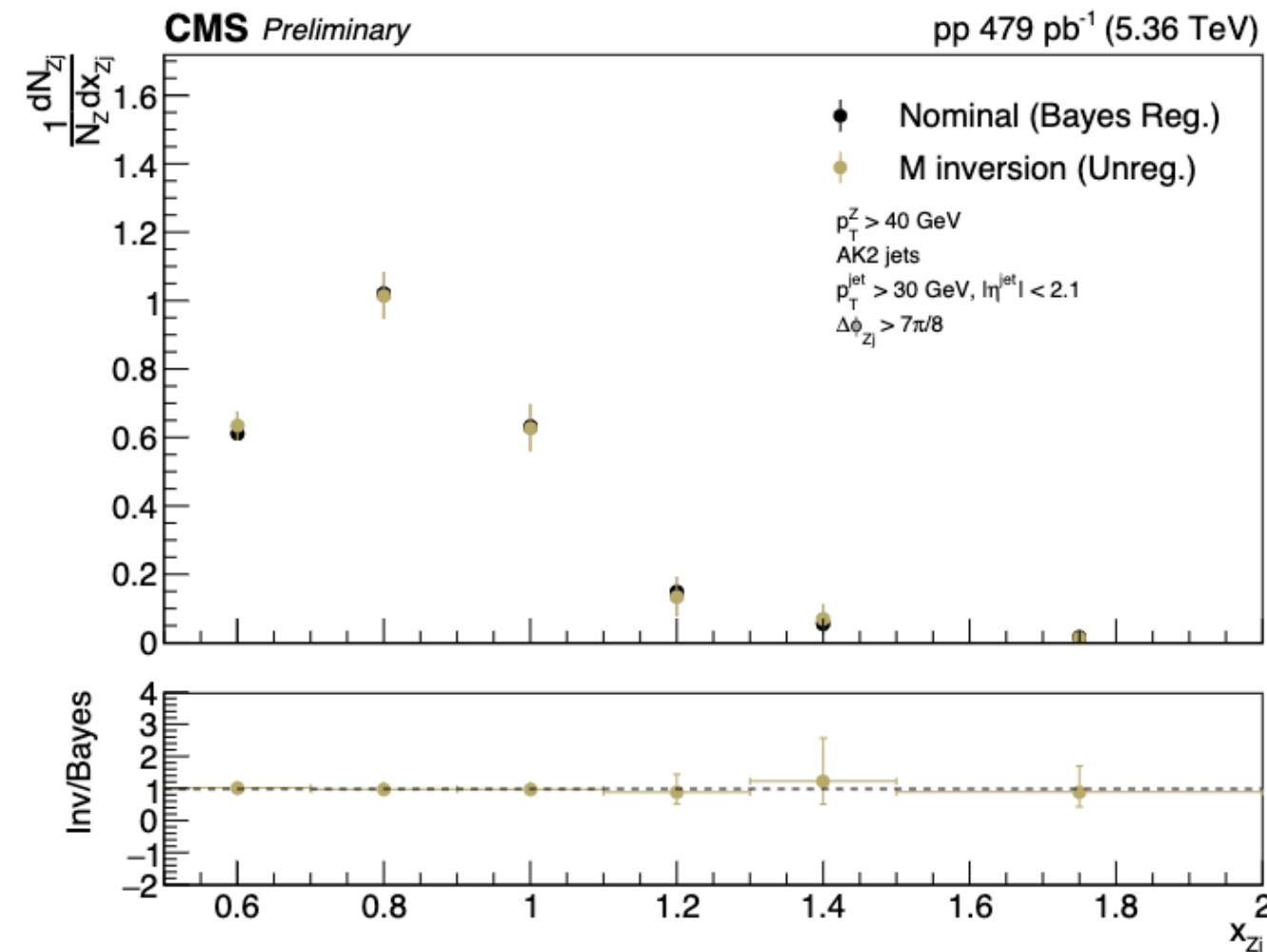
Pb 2023



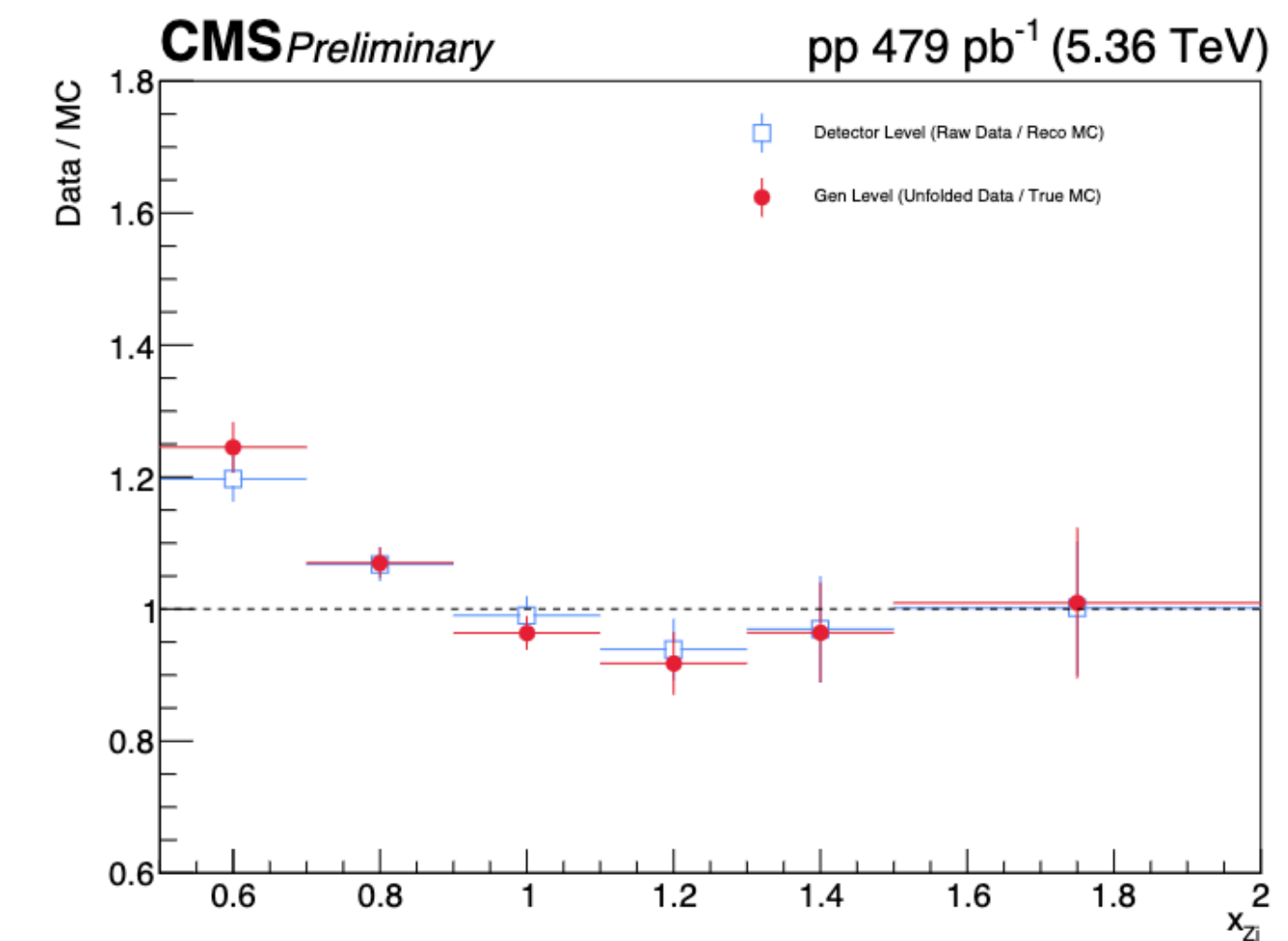
- The condition number of the response matrix (determined using the TDecompSVD class in ROOT) indicate whether regularization is needed or not
- It is calculated by decomposing the matrix into its singular value and taking the ratio of the largest to the smallest non-zero singular value



pp 2024



- If close to 1, the matrix is well-conditioned (regularization not needed matrix inversion works fine)
- We obtain 30.4 for PbPb and 8.9 for pp (we need to perform regularization, in particular in Pb collisions)



Cancellation of uncertainties

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

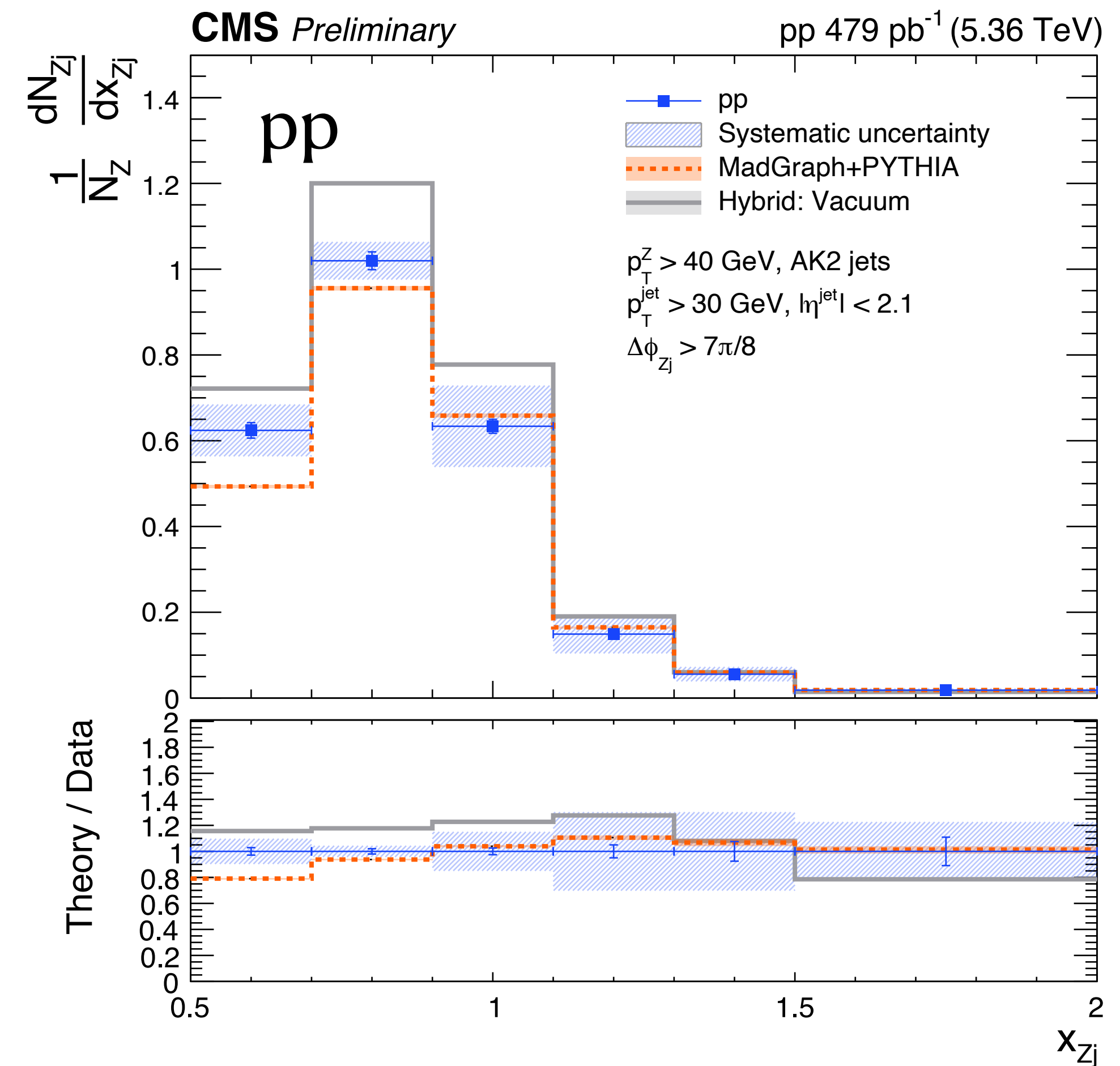
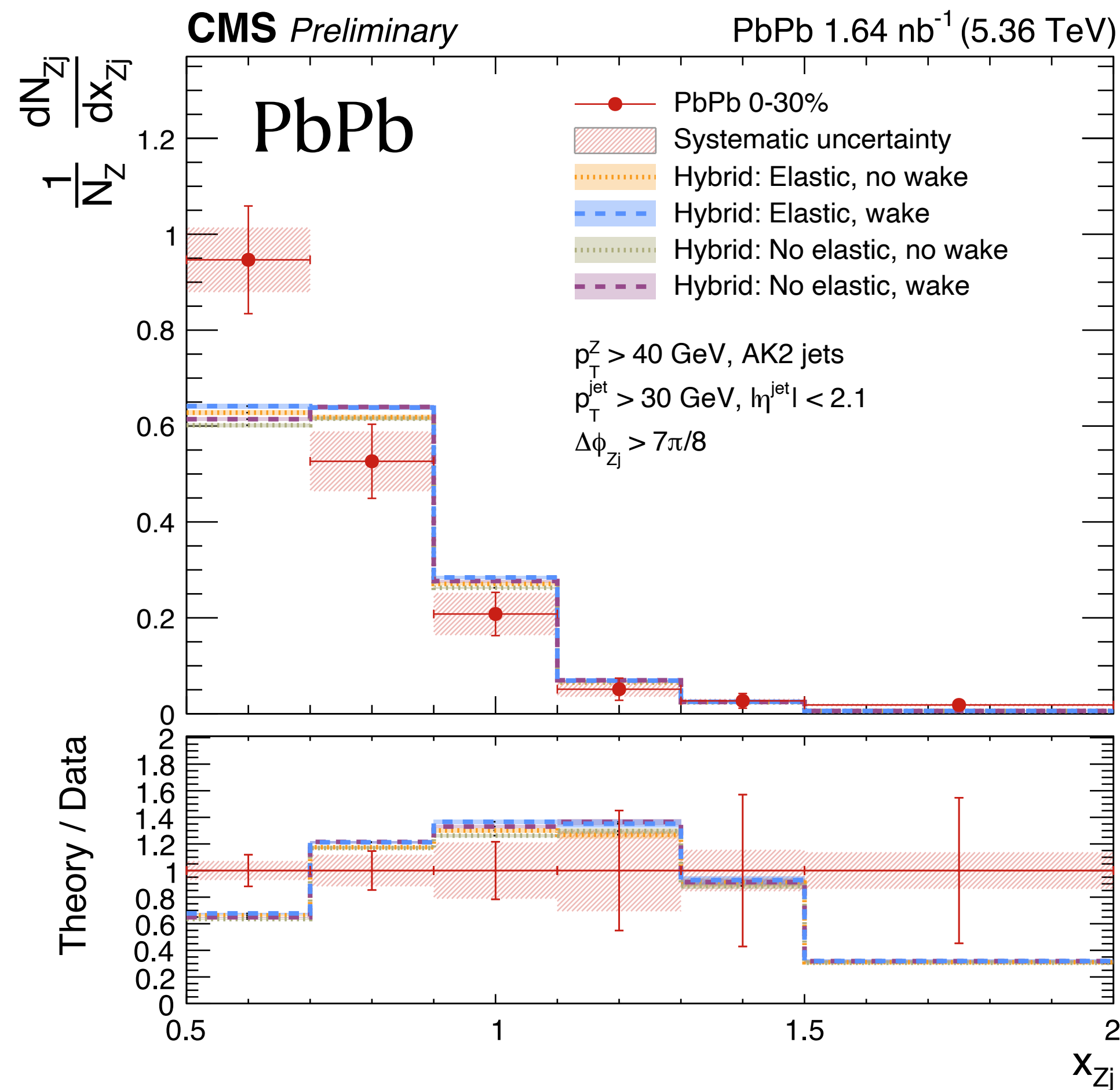
First measurement of jet axis decorrelation with
photon-tagged jets in pp and PbPb collisions at 5.02 TeV

The CMS Collaboration*

The total systematic uncertainty is calculated by summing the symmetrized contributions from each source listed above in quadrature. The maximum value of the deviation is taken if the sources are mutually exclusive up/down variations of the same quantity, such as for the photon purity, JEC, centrality, and iteration choice systematics. When the ratio of PbPb to pp is constructed, the systematic uncertainties are taken as completely uncorrelated and added in quadrature, since the data were taken in different years. The dominant systematics in both pp and PbPb collisions are the JEC, the unfolding prior, and the response matrix statistics. Additionally, the mixed-event background subtraction systematic is significant in central PbPb collisions for jet $p_T < 60$ GeV.

Comparison to theory predictions

- **Absolute comparisons to unfolded pp and PbPb data**
 - the inclusive observable x_{Zj} using small-radius jets ($R = 0.2$) is insensitive to Molière scattering and the medium wake



Fisher

- **The χ^2 Test on Integrated Yields (Normalization)**
- Answers the question: Is the total number of Z+jet events significantly different between PbPb and pp?
- The code treats the total integral of the histograms as a single data point and performs a Z-test (which is mathematically equivalent to a χ^2 test with 1 degree of freedom).
- The total uncertainty for each collision system (s) is the sum of statistical and systematic errors in quadrature

$$s = \sqrt{\sigma_{stat}^2 + \sigma_{syst}^2}$$

- Where the total syst err for the yield is obtained considering syst as bin-by-bin fully correlated
- The script calculates the absolute difference between the two yields and divides it by the combined uncertainty of that difference to get the Z-score:

$$Z = \frac{|Y_{pp} - Y_{PbPb}|}{\sqrt{s_{pp}^2 + s_{PbPb}^2}}$$

- then converts this Z-score into a 2-tailed p-value using the complementary error function

Fisher

- **The Kolmogorov-Smirnov (KS) Test on Shape**
- Question: are the relative shapes of the distributions different, disregarding the total number of events?
- The null hypothesis assumes that both PbPb and pp data originate from the exact same underlying distribution. To represent this, normalize both the PbPb and pp histograms, add them and divide by 2 to create an "Average Shape"
- Use the standard ROOT function to calculate the maximum vertical distance between the cumulative distribution functions of the normalized, real PbPb and pp data.
- Generating Pseudo-Data (Toy MC). In each iteration, generate a "fake" PbPb histogram and a "fake" pp histogram.
- For every bin, take the expected value from H_0 histogram, compute total error for the bin (stat+syst) and randomly fluctuate it
- Each pair of pseudo-histograms is normalized to 1, and their KS distance (D_{toy}) is calculated. If $D_{toy} \geq D_{obs}$, it means the random fluctuations of the null hypothesis produced a difference as large as or larger than what we saw in the real data. Increment a counter $n_{extreme}$
- Calculating the Shape P-value: The final shape p-value is simply the fraction of toys that produced a distance greater than or equal to the observed data:

$$p_{shape} = \frac{n_{extreme}}{N_{toys}}$$

Conclusions

- **First unfolded measurement** of the x_{Zj} distribution in $Z (\rightarrow \mu\mu) + \text{jets}$ events using 2023 PbPb and 2024 pp reference at 5.36 TeV
- **Observation of jet quenching effects** in 0 – 30 % PbPb collisions relative to pp reference
- Measurements compared with theory predictions from the **Hybrid coupling model**, which reproduces the suppression of balanced jets in PbPb collisions, but fails to describe the migration of jets toward low x_{Zj}
- Additionally, the comparison reveals that the inclusive observable x_{Zj} using small-radius jets ($R = 0.2$) is **insensitive to Molière scattering and the medium wake**
- **Future studies**, including the exploration of larger jet radii and **jet substructure observables**, will be instrumental in further disentangling macroscopic bulk energy loss from microscopic quasiparticle interactions within the QGP