Recent jet measurements in CMS

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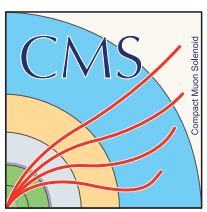
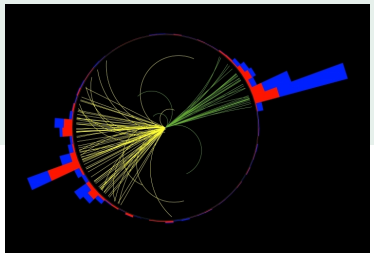


Outline

Several latest CMS measurements on jets (PAS released since May 6, 2025) are presented in this talk. In particular:

- SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets (CMS-PAS-SMP-25-005)
- SMP-24-010: Triple-differential $Z + \text{jets}$ cross section (CMS-PAS-SMP-24-010)
- SMP-25-006: Gluon-induced spin correlations in parton showers (arXiv:2603.03689, submitted to PRL)
- SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets (arXiv:2604.25538, submitted to JHEP)
- SMP-24-012: Boosted W jet mass distributions (arXiv:2603.19963, submitted to JHEP)

Jet as a key physics object in CMS



- A jet is a collimated spray of hadrons produced by the hadronization of a high-energy quark or gluon, and provides an experimental proxy for the underlying parton.
- Jets are reconstructed from particle-flow (PF) candidates, which combine information from all CMS subdetectors to identify individual particles.
- The clustering is performed using the anti-k_{T} algorithm with a distance parameter of e.g., $R = 0.4$.
- The jet momentum is defined as the vector sum of all constituent particle momenta and approximates the momentum of the initiating parton.
- Pileup effects are reduced by removing tracks associated with secondary vertices and correcting residual energy contributions.
- Jet energy corrections are applied to account for detector response.

SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

CMS-PAS-SMP-25-005

Motivation:

- Heavy-flavour hadrons in jets sensitively probe nonperturbative QCD via fragmentation functions $D_q^h(z, Q^2)$, describing the probability for a quark q to fragment into a hadron h carrying momentum fraction z at scale Q^2.
- Observables: longitudinal momentum fraction z and transverse component $p_{\mathrm{T}}^{\mathrm{rel}}$ relative to the jet axis.

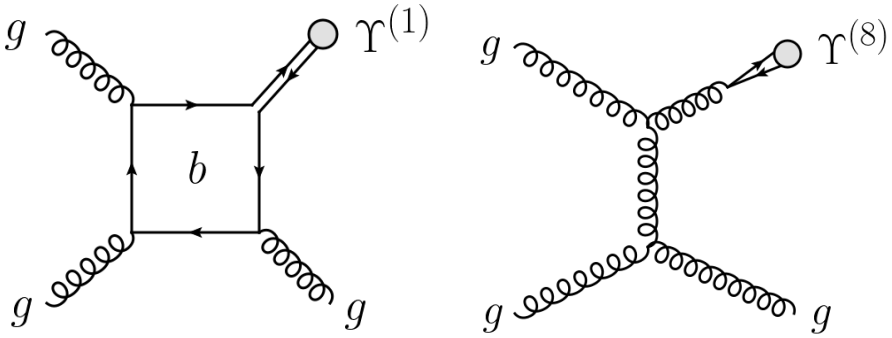
Measumenent:

- Measure $d^3\sigma/(dp_{\mathrm{T}}^{\mathrm{jet}}\, dz\, dp_{\mathrm{T}}^{\mathrm{rel}})$ for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons inside jets (CMS Run 2, $\sqrt{s} = 13$ TeV, $138\ \mathrm{fb}^{-1}$).
- Compare with various MC predictions to test and constrain quarkonium production modelings.

SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

CMS-PAS-SMP-25-005

Event generation and selection:



- Both the singlet and octet NRQCD production mechanisms are included in the MC.
- Data selection isolates dimuon events and reconstructs $\Upsilon(nS)$ candidates inside jets using kinematic and quality cuts, defining the analysis phase space.

- Dimuon triggers (8–12 GeV)
- Opposite-charge $\mu^+\mu^-$, vertex fit
- $7 < m_{\mu\mu} < 13$ GeV $\rightarrow \Upsilon$ candidates
- Muon cuts: $p_{\mathrm{T}} > 6$ GeV, $|\eta| < 1.4$, $|\Delta\eta| < 1.6$
- Dimuon cuts: $p_{\mathrm{T}}^{\mu\mu} > 15$ GeV, $|y^{\mu\mu}| < 1.2$
- Tight mass window: $8.7 < m_{\mu\mu} < 11.3$ GeV
- Best vertex (χ^2) if multiple candidates
- Υ inside jet (both muons in jet)
- Muon subtraction + jet calibration
- Jets: $p_{\mathrm{T}} > 60$ GeV, $|\eta| < 1.5$

SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

CMS-PAS-SMP-25-005

Analysis:

- Yield determination is performed via fits to the dimuon invariant mass spectrum in bins of jet p_{T}, z, and $p_{\mathrm{T}}^{\mathrm{rel}}$, separating $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and background contributions (figures below).
- Unfolding corrects detector-level distributions to particle level using response matrices derived from MC, accounting for efficiency, resolution, and bin migration effects.

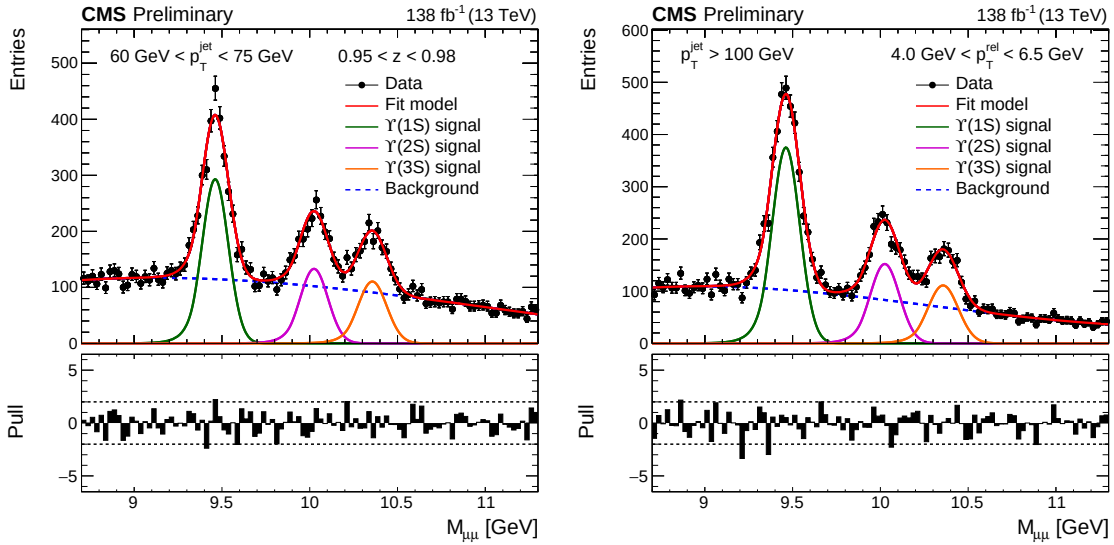
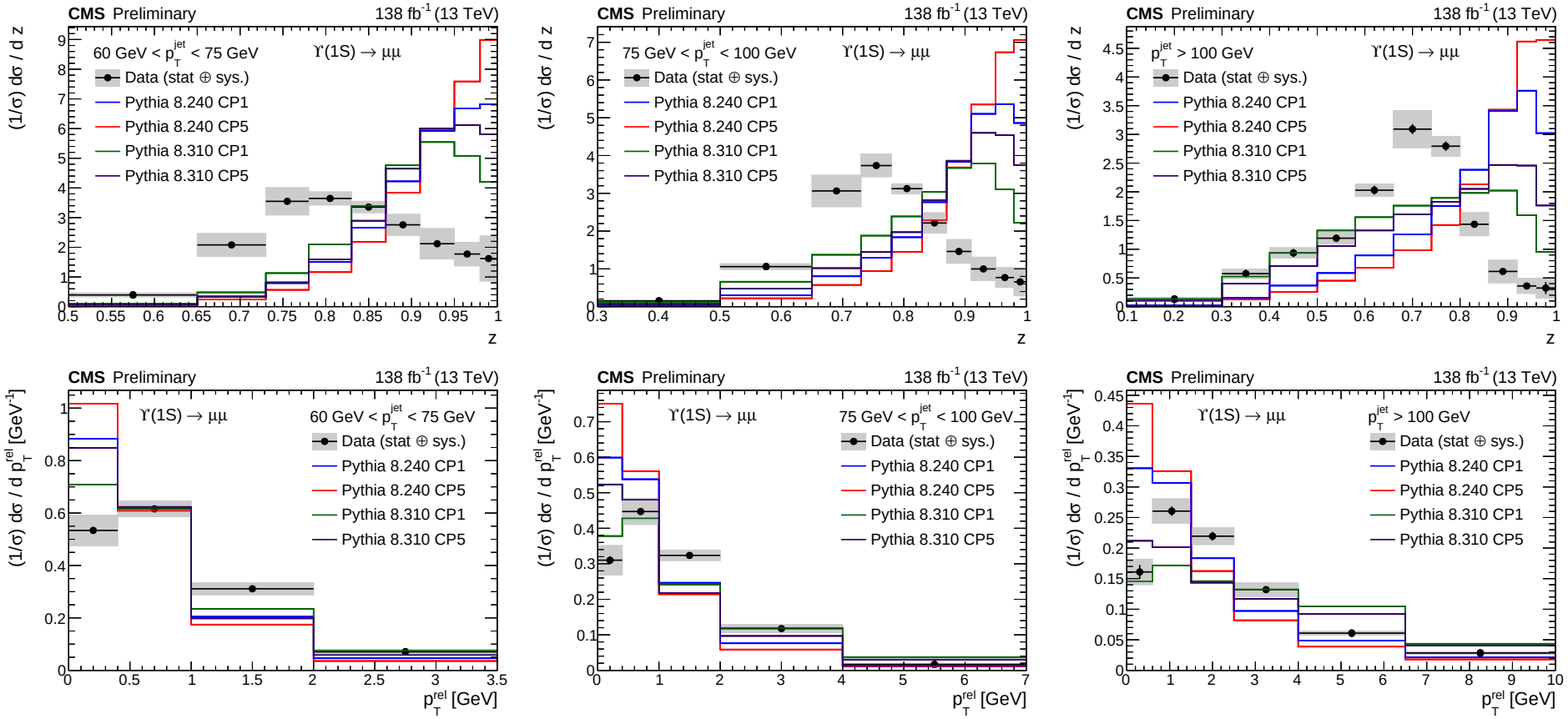


Figure: Fits to the invariant mass distributions of Υ candidates in two representative regions.

SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

CMS-PAS-SMP-25-005

Unfolded results (see similar results for $\Upsilon(2S)$ and $\Upsilon(3S)$ in backup):



- MC generally predicts too isolated Υ mesons (larger z, smaller $p_{\mathrm{T}}^{\mathrm{rel}}$).
- Newer PYTHIA versions show only limited improvement.

SMP-24-010: Triple-differential $Z + \text{jets}$ cross section

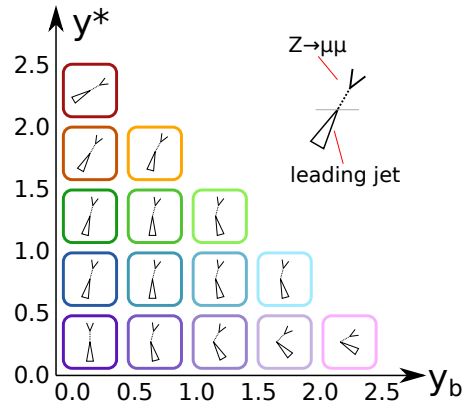
CMS-PAS-SMP-24-010

Motivation:

- $Z(\mu^+\mu^-) + \text{jets}$ is a precisely calculable process in perturbative QCD
- Provides constraints on parton distribution functions (PDFs)

Key observables optimized for PDF sensitivity:

- p_{T}^{Z}: sets the energy scale
- $y^* = \frac{1}{2}\left|y_Z - y_{\mathrm{jet}}\right|$ (probes the scattering angle)
- $y_{\mathrm{b}} = \frac{1}{2}\left|y_Z + y_{\mathrm{jet}}\right|$ (probes initial-state momentum imbalance)
- (Linking observables to PDF) $x_{1,2} = \frac{2\,p_{\mathrm{T}}^{Z}}{\sqrt{s}}\cosh(y^*)\,e^{\pm y_{\mathrm{b}}}$ (in the LO)



Goal:

- Measure $d^3\sigma/(dp_{\mathrm{T}}^{Z}\,dy^*\,dy_{\mathrm{b}})$ using CMS Run 2 data ($\sqrt{s} = 13$ TeV, 138 fb^{-1})
- Compare with NNLO predictions and various PDF sets

SMP-24-010: Triple-differential $Z + \text{jets}$ cross section

CMS-PAS-SMP-24-010

Unfolded data/MC comparisons:

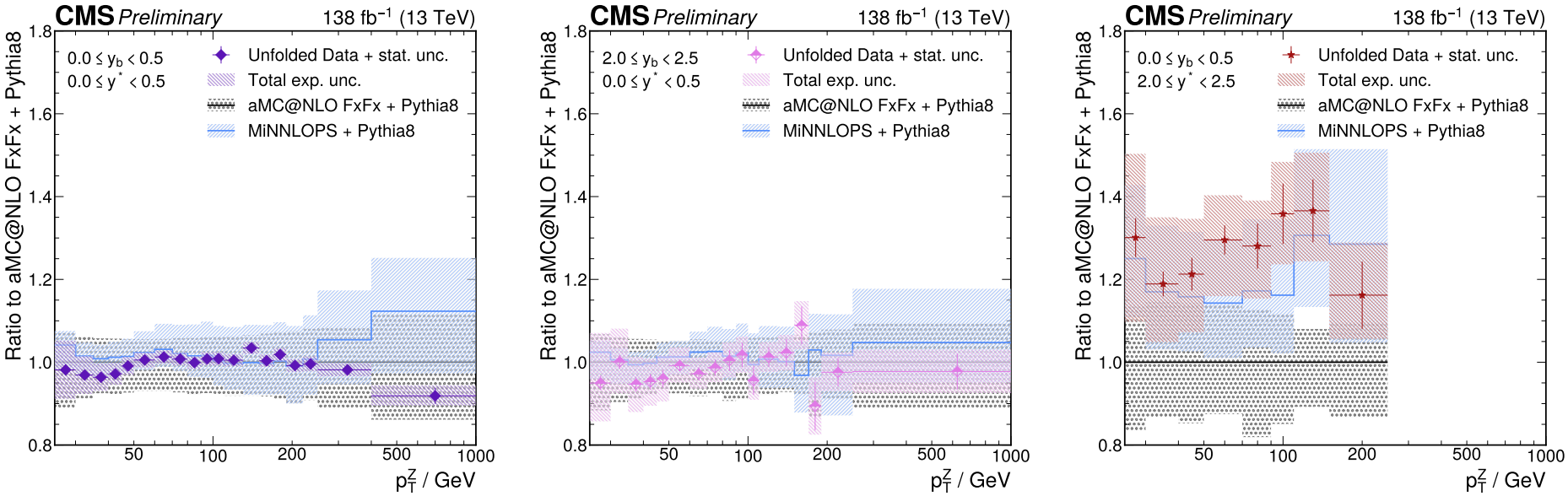


Figure: Ratio of unfolded $Z(\to \mu\mu) + \text{jets}$ cross section to MadGraph5_aMC@NLO + PYTHIA 8 vs p_{T}^{Z} in three (y_b, y^*) regions.

- Good overall agreement; POWHEG MiNNLOPS slightly better at large y^*.
- MC uncertainties from scales, PDFs, and parton shower.

SMP-24-010: Triple-differential $Z + \text{jets}$ cross section

CMS-PAS-SMP-24-010

Unfolded data/various PDF prediction comparisons:

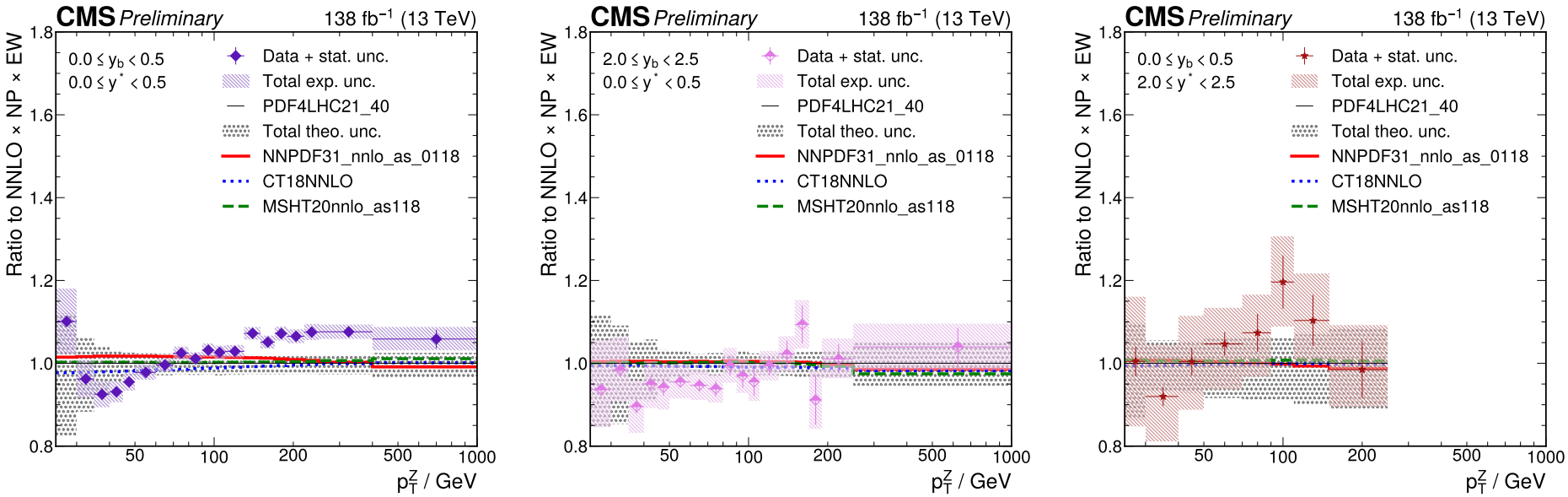


Figure: Ratio of unfolded $Z(\to \mu\mu) + \text{jets}$ cross section to NNLO prediction corrected for electroweak and nonperturbative effects as a function of p_{T}^{Z} in three phase space regions.

- Alternative PDF sets shift NNLO predictions by up to $\sim 7\%$.
- None of the PDFs fully describe the data within uncertainties.
- Provides valuable input for future PDF and α_s determinations.

SMP-25-006: Gluon-induced spin correlations in parton showers

arXiv:2603.03689, submitted to PRL

Motivation:

- Parton showers typically neglect or approximate spin correlations in QCD radiation.
- Gluon splittings induce non-trivial spin correlations affecting final-state observables.
- Need to test and validate spin-correlation effects in modern parton showers.

Measurement:

- Measure $\Delta\phi$ between two successive branchings inside jets (CMS Run 3, 34.7 fb^{-1}).
- Decluster AK8 jets with Cambridge–Aachen to access parton branching chain.
- ML categorization enhances specific splittings ($X \to Xg$, $g \to q\bar{q}$).
- First observation of gluon-polarization-induced angular correlations in soft and collinear jet emissions.

SMP-25-006: Gluon-induced spin correlations in parton showers

arXiv:2603.03689, submitted to PRL

Reco-level results:

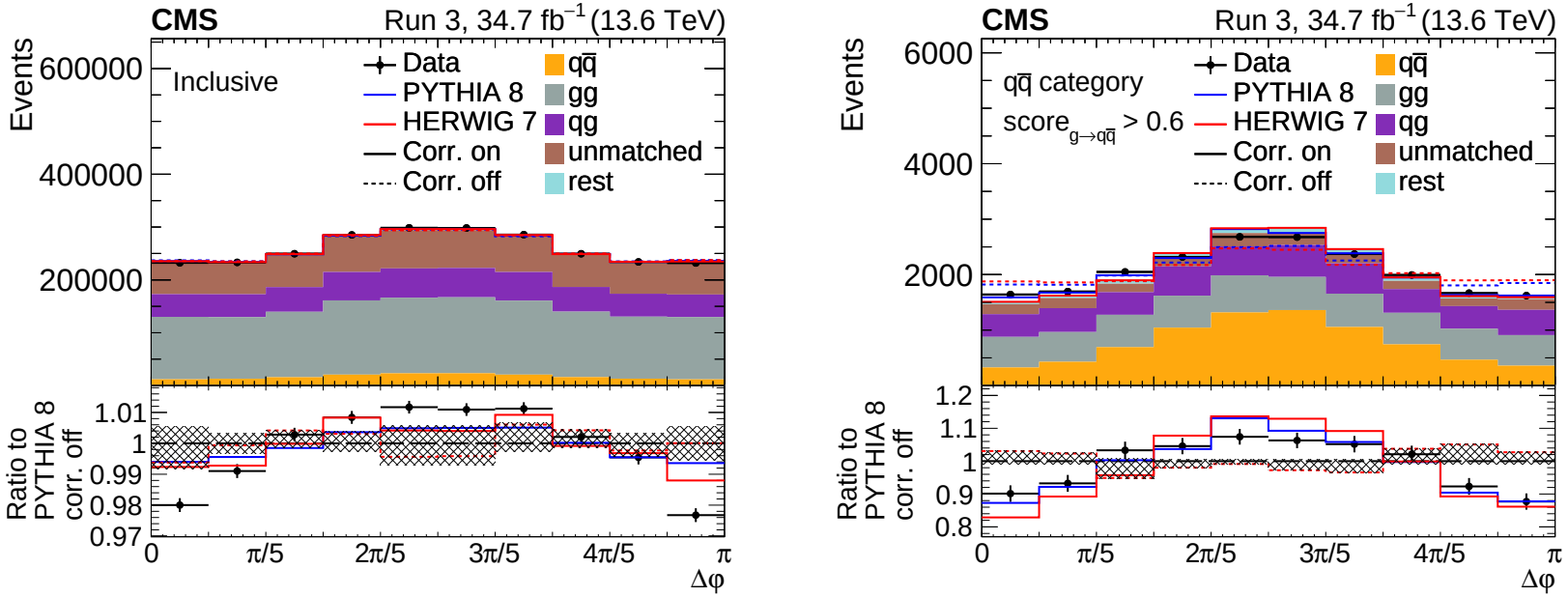


Figure: Reconstructed $\Delta\phi$ distributions in data (points) and MC (histograms) for the inclusive sample (left) and the qq-enriched region ($s_{qq} > 0.6$, right).

Spin-correlation effects in $\Delta\phi$ are negligible in inclusive jet samples but become clearly visible (up to $\sim$12% differences) after selecting a qq-enriched topology using a DNN, with data favoring models including gluon polarization effects.

SMP-25-006: Gluon-induced spin correlations in parton showers

arXiv:2603.03689, submitted to PRL

Reco-level hypothesis tests:

- Strong preference for spin correlations: $6.8\,\sigma$ vs correlation-off; $1.9\,\sigma$ against correlation-on.

Unfolded results:

- Detector effects corrected via unfolding to particle level with bin migrations $< 10\%$ and total uncertainties of 4–8%.
- Unfolded results favor PYTHIA8 correlation-on.

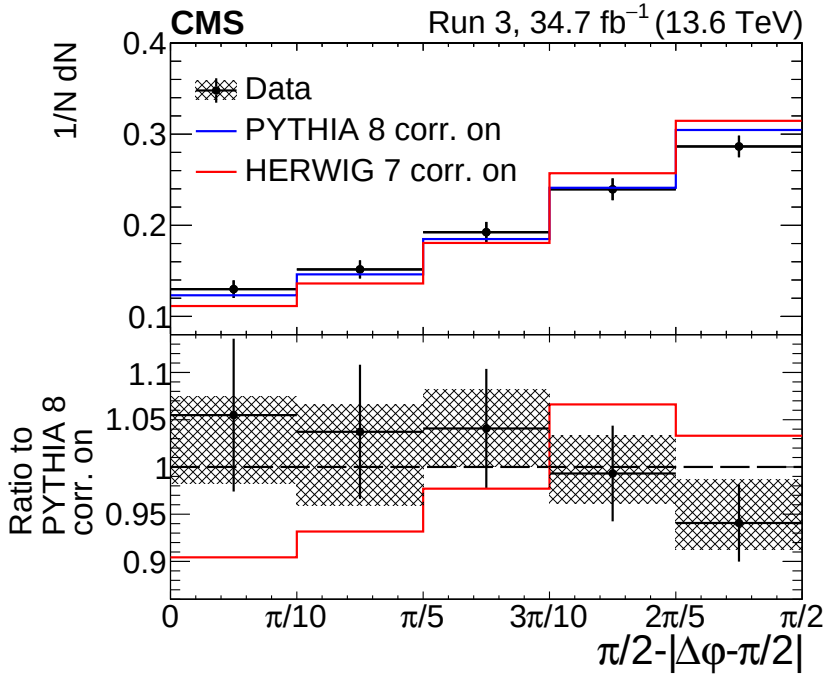


Figure: Unfolded $\Delta\phi$ distribution for events with $s_{qq} > 0.6$; both correlation-on MC.

Overall, data show evidence for gluon spin-induced angular correlations, with models including polarization describing the measurement best but still not fully capturing the observed shape.

SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

Introduction:

- Jet substructure probes QCD radiation patterns inside high-p_{T} AK8 jets.
- Boosted W bosons and top quarks produce multi-prong jet topologies.
- N-subjettiness:

$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min\left\{\Delta R_{1i}^{\beta}, \ldots, \Delta R_{Ni}^{\beta}\right\}.$$

  $p_{T,i}$: transverse momentum of particle i; ΔR_{ki}: angular distance to subjet axis k; $d_0 = \sum_i p_{T,i} R^{\beta}$ (with $R = 0.8$ here) normalizes the observable. It measures how compatible a jet is with an N-prong structure: the smaller, the better; usually used in ratios like $\tau_{21} = \tau_2/\tau_1$ to discriminate between 1-prong and 2-prong jets.

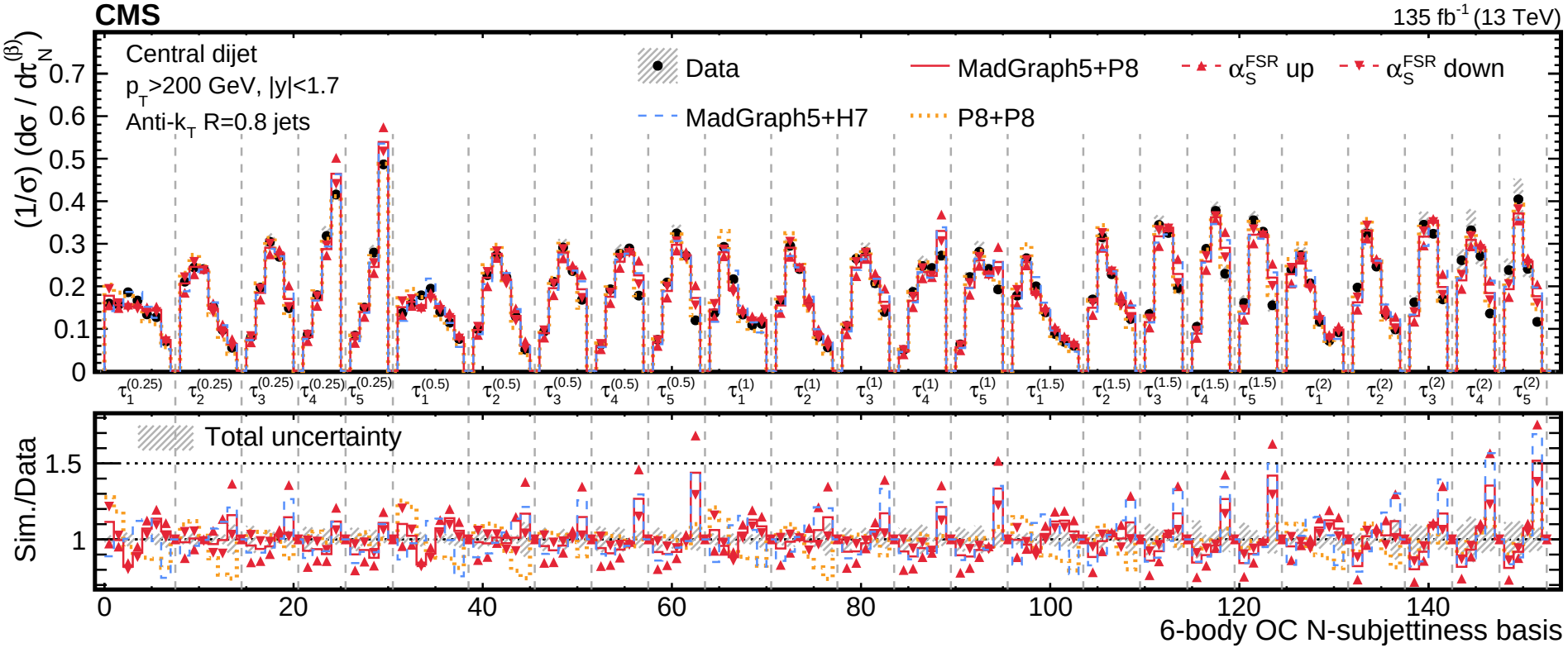
Outline:

- A simultaneous measurement of 25 jet substructure observables was performed using CMS Run 2 data in q/g, W, and t-enriched jet samples.
- Unfolded measurements test parton shower and hadronization modelling.

SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

Unfolded results for q/g jets:



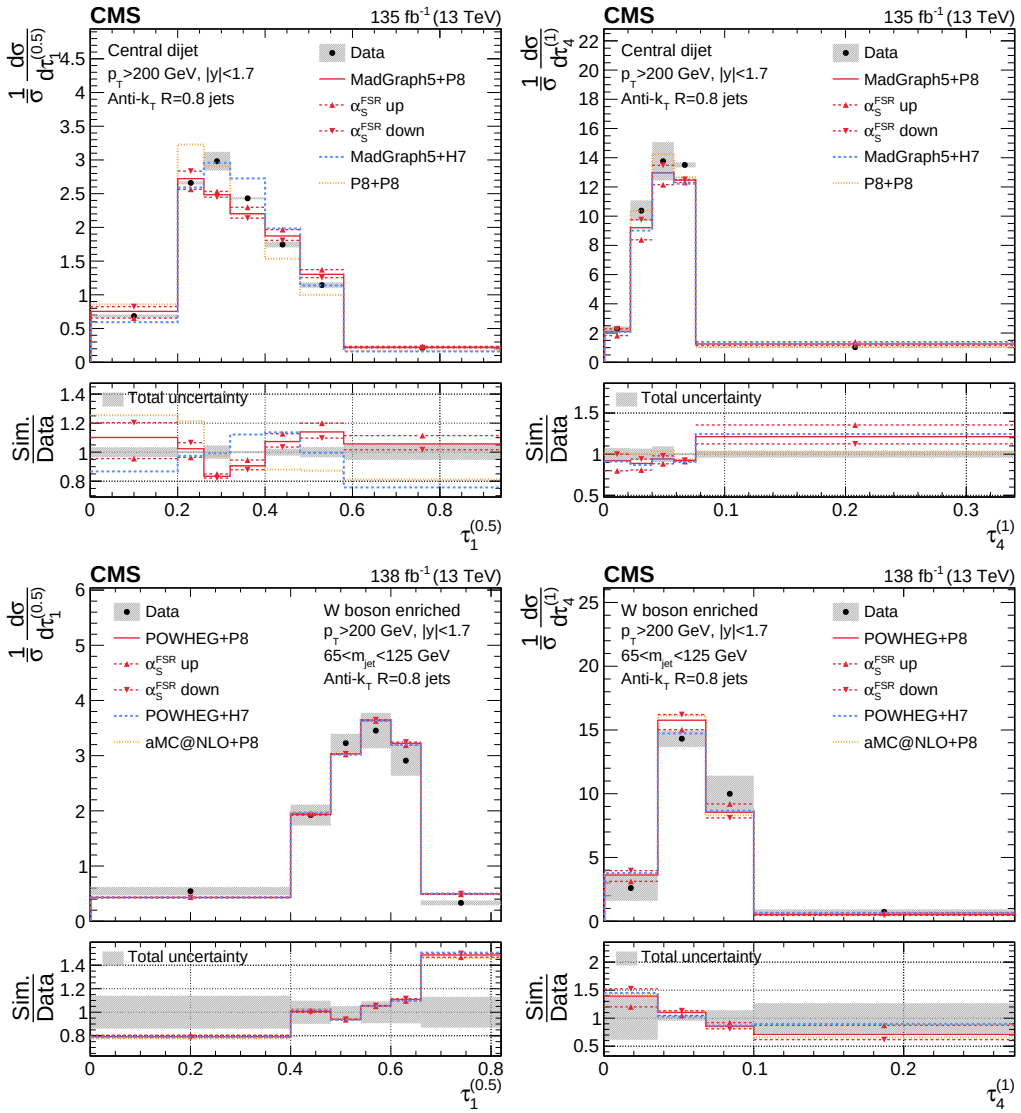
While all models describe peak regions well, the variation with lower $\alpha_s^{\mathrm{FSR}} = 0.115$ best matches data overall, though noticeable discrepancies remain across the bulk—especially for observables sensitive to $\geq$3-body structure. See backup for W/t results.

SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

Unfolded results (t results in backup):

- QCD dijet jets: ∼10% agreement between data and simulation
- Boosted W and top jets: larger deviations (∼5–20%), especially for large N
- No single MC model describes all regions consistently
- Sensitivity to parton shower modelling, in particular α_s^{FSR}
- Systematics dominated by shower/hadronization

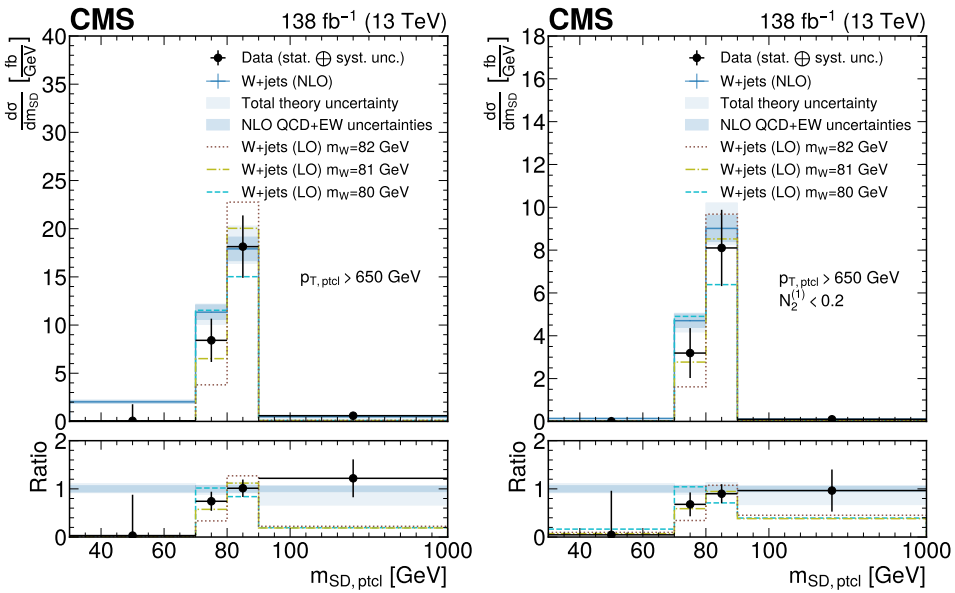


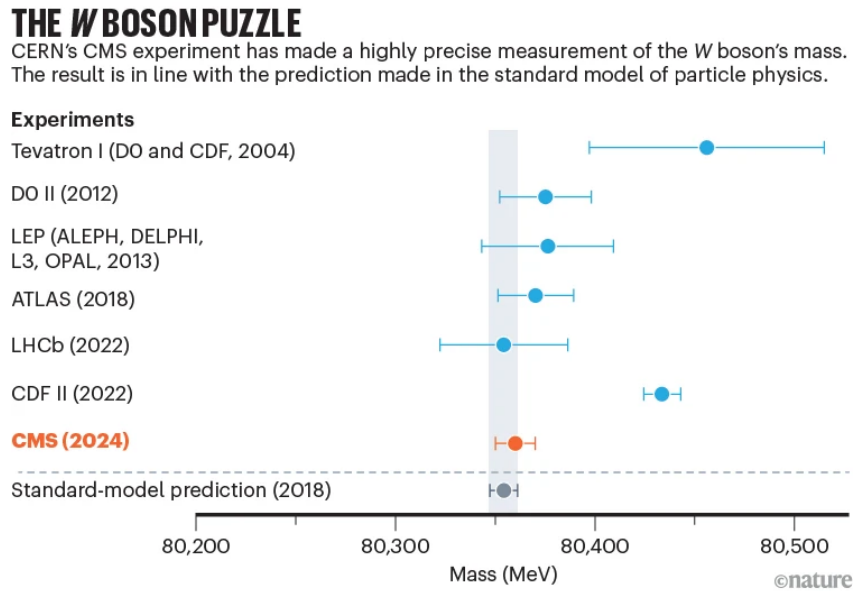
SMP-24-012: Boosted W jet mass distributions

arXiv:2603.19963, submitted to JHEP

Motivation:

- At high p_{T}, hadronic $W \to q\bar{q}$ decays are reconstructed as a single large-R jet.
- Jet substructure and groomed jet mass enable identification of boosted W bosons over large QCD backgrounds.
- Provides a test of jet substructure modeling using CMS Run 2 data ($\sqrt{s} = 13$ TeV, $138\ \mathrm{fb}^{-1}$); m_W is extracted as a benchmark, not a precision measurement.

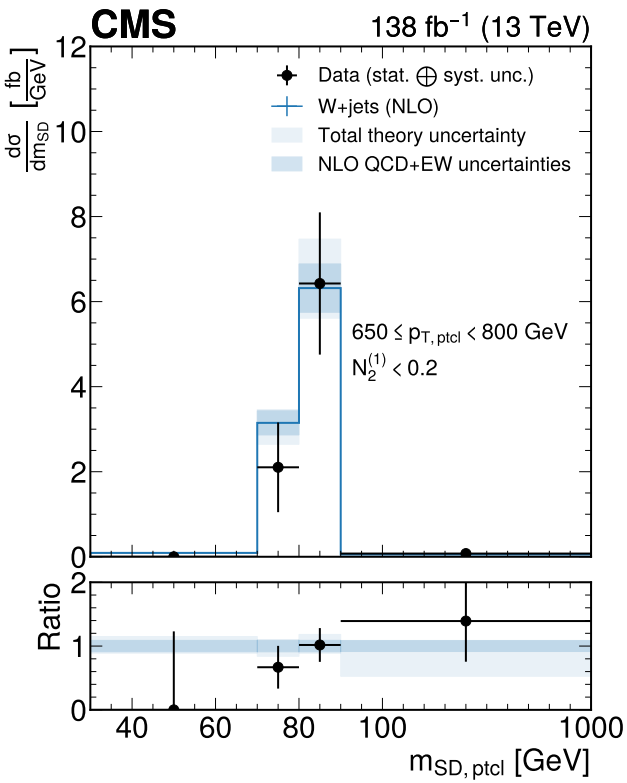


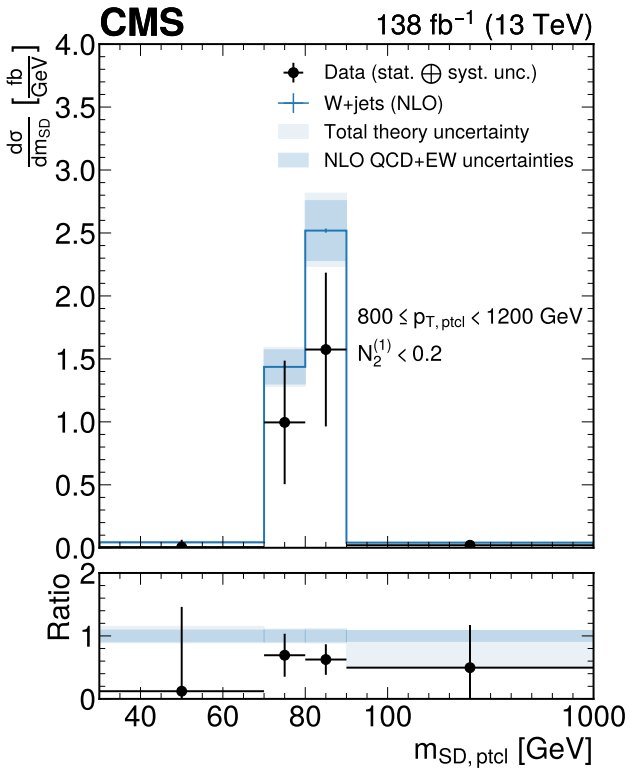


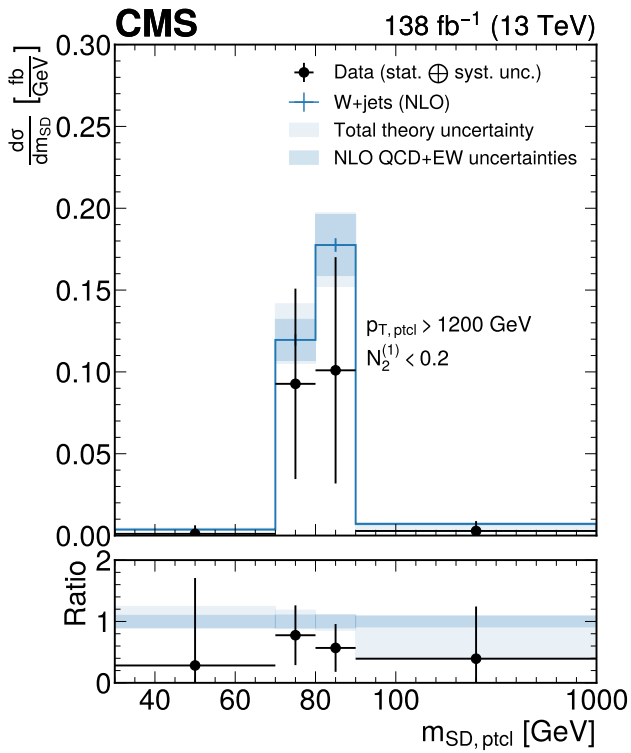
SMP-24-012: Event generation and selection

arXiv:2603.19963, submitted to JHEP

Unfolded Results:



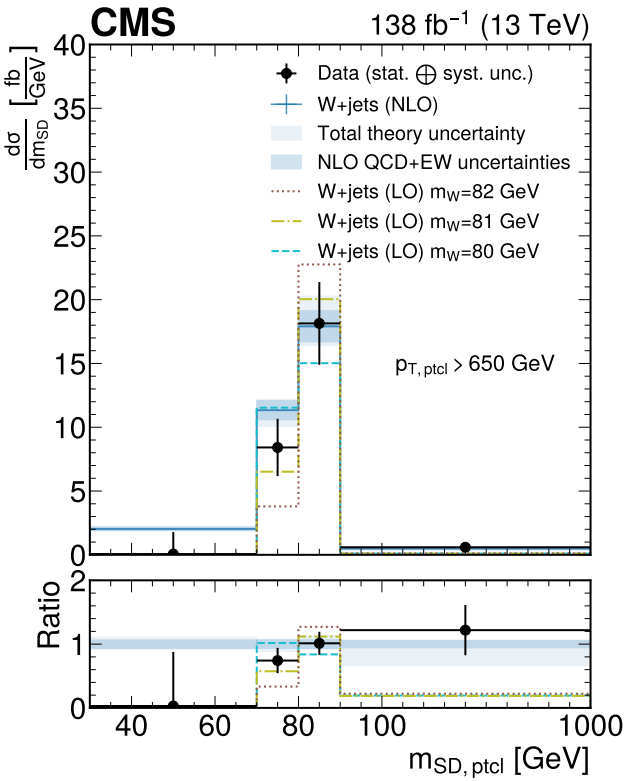


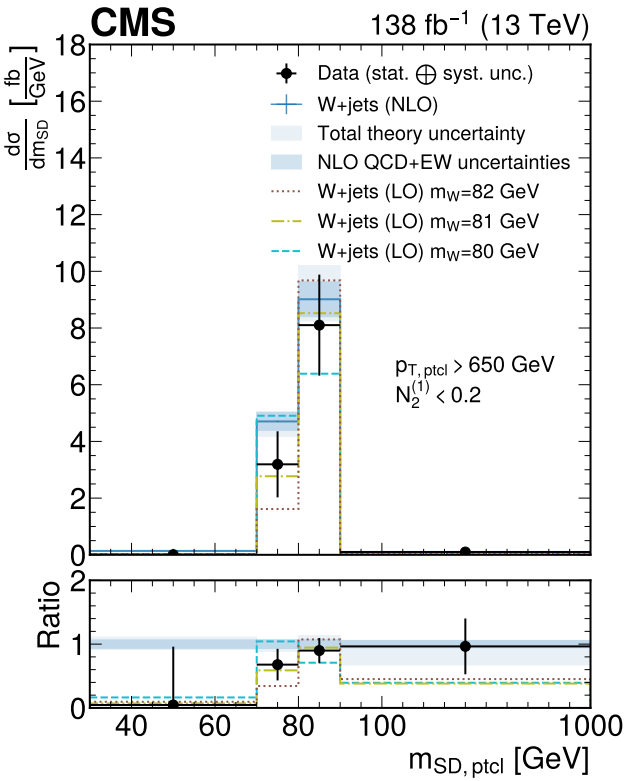


Good agreement is observed within uncertainties, with small deviations in the high p_{T} bins (middle and right figures), consistent with statistical and modeling effects.

SMP-24-012: Event generation and selection

arXiv:2603.19963, submitted to JHEP





Low/high m_{SD} regions are dominated by recoil jets and sensitive to nonperturbative modeling; applying the cut $N_2^{(1)} < 0.2$ reduces this contamination and enhances the W peak.

The jet mass distribution is used to extract m_W via template fits, yielding $m_W = 80.81 \pm 0.55$ GeV, consistent with previous measurements but not yet competitive.

Summary

- CMS jet measurements probe QCD radiation and hadronization across a wide range of processes: q/g jets, boosted W bosons, top quarks, quarkonium, $Z + \text{jets}$, and jet substructure observables.
- Precision unfolded measurements (cross sections, jet substructure, fragmentation, and angular correlations) are used to directly compare data with modern simulation results.
- Across all analyses, no single MC setup fully describes the data:
  - QCD jets: sensitivity to soft/collinear radiation and shower modelling
  - Boosted W/t: larger deviations in multi-prong (high-body) phase space
  - $Z + \text{jets}$: small but systematic tensions with NNLO+PDF predictions
  - Spin correlations: data favour models including gluon polarization effects
- Common picture: jet substructure and QCD radiation modelling remain the dominant limitation in precision description across processes.
- These measurements provide input for tuning parton showers, testing QCD, and improving future simulations and PDFs.

Thanks for your attention!

Backup

SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

CMS-PAS-SMP-25-005

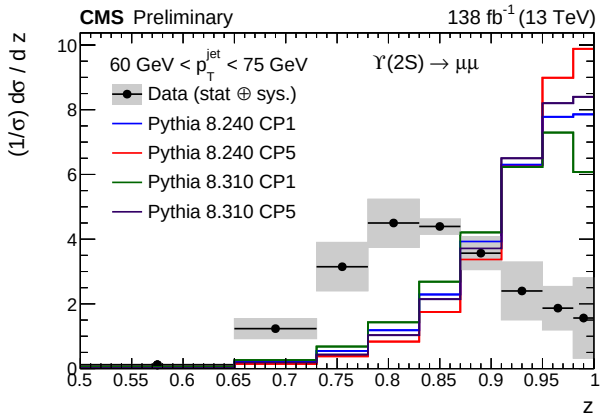
Motivation:

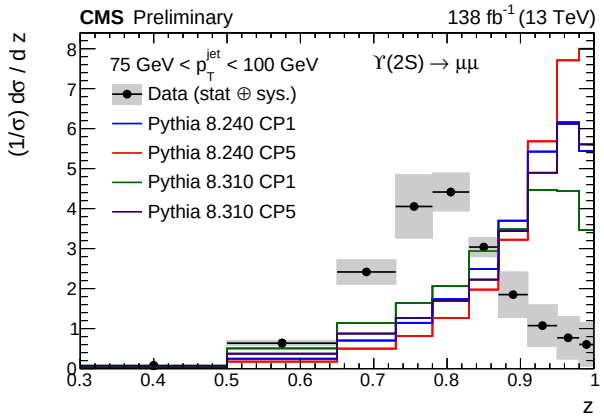
- Heavy-flavour hadrons in jets sensitively probe nonperturbative QCD via fragmentation functions $D_q^h(z, Q^2)$, describing the probability for a quark q to fragment into a hadron h carrying momentum fraction z at scale Q^2.
- Quarkonia polarization puzzle: discrepancy between NRQCD predictions of strong transverse polarization at high p_{T} and experimental results from the LHC, which show little or no polarization.
- The discrepancies are strongly sensitive to long-distance effects in NRQCD, especially the modelling of nonperturbative matrix elements.
- These tensions have motivated improvements in parton-shower quarkonium production models and tuning of NRQCD implementations.
- This work: measure $\Upsilon(nS)$ fragmentation in jets (CMS Run 2, $\sqrt{s} = 13$ TeV).
- Observables: longitudinal momentum fraction z and transverse component $p_{\mathrm{T}}^{\mathrm{rel}}$ relative to the jet axis.

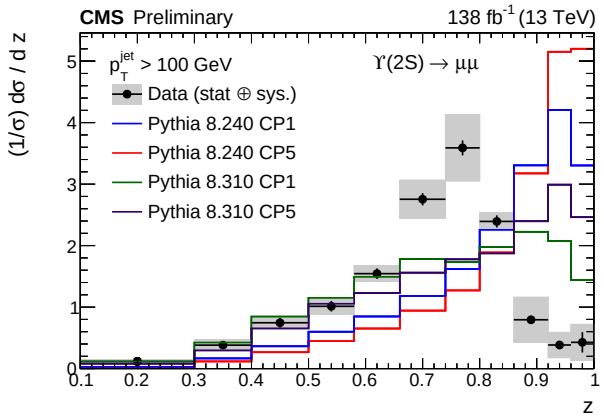
SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

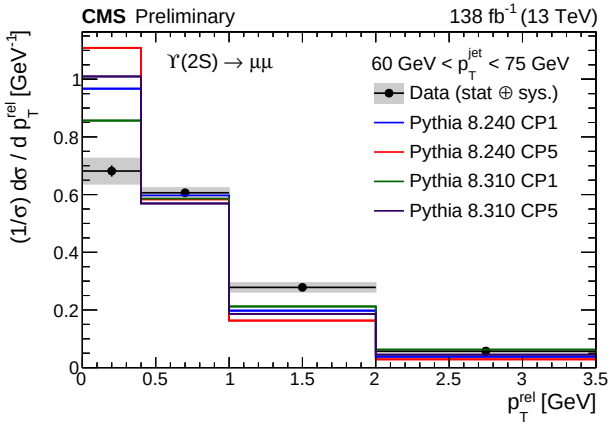
CMS-PAS-SMP-25-005

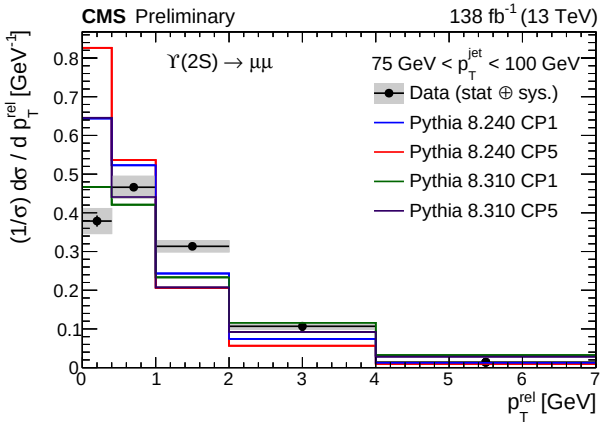
Unfolded results ($\Upsilon(2S)$):

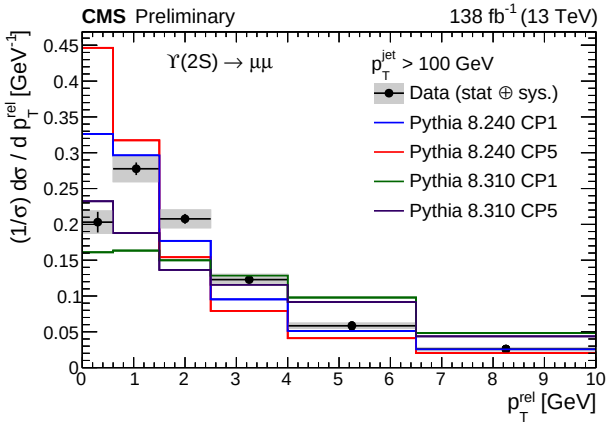








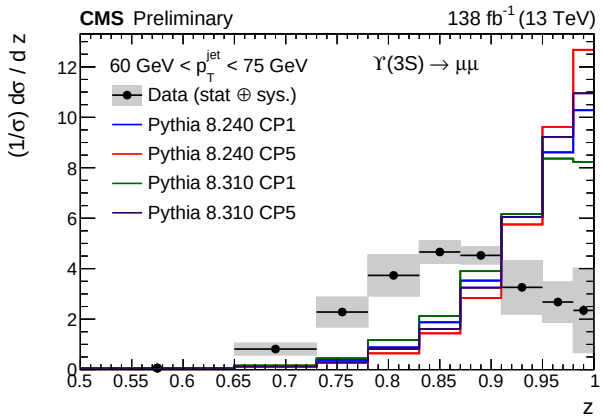


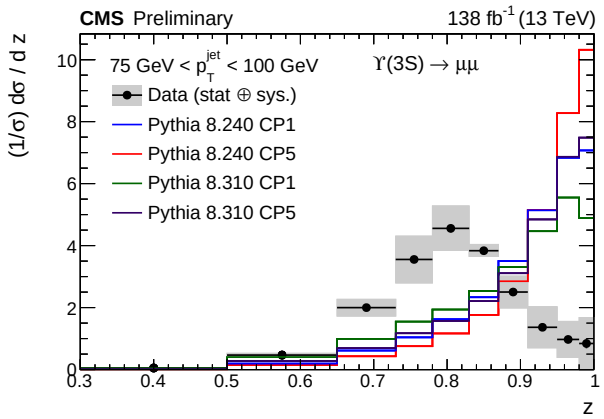


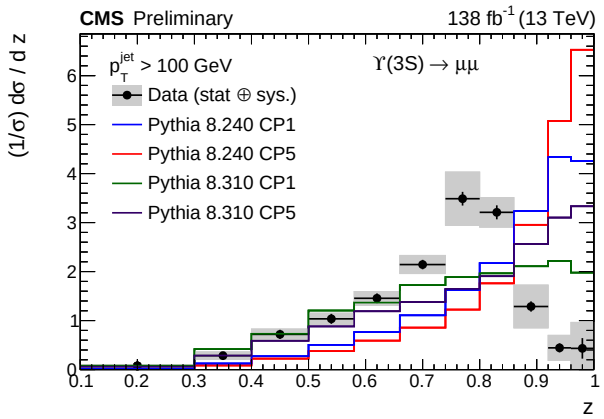
SMP-25-005: Fragmentation of $\Upsilon(nS)$ mesons in jets

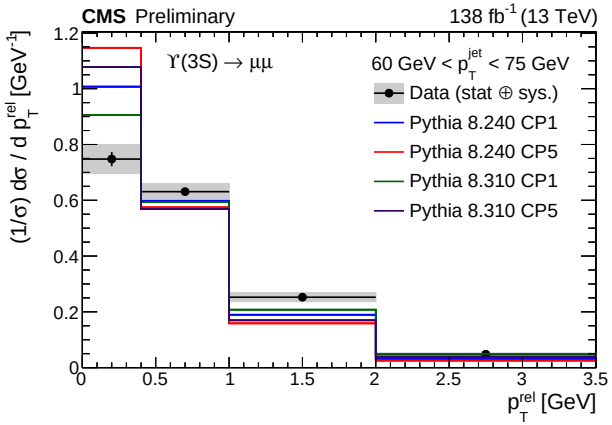
CMS-PAS-SMP-25-005

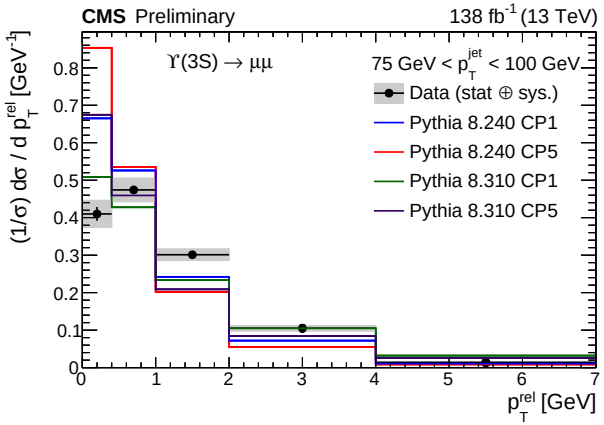
Unfolded results ($\Upsilon(3S)$):

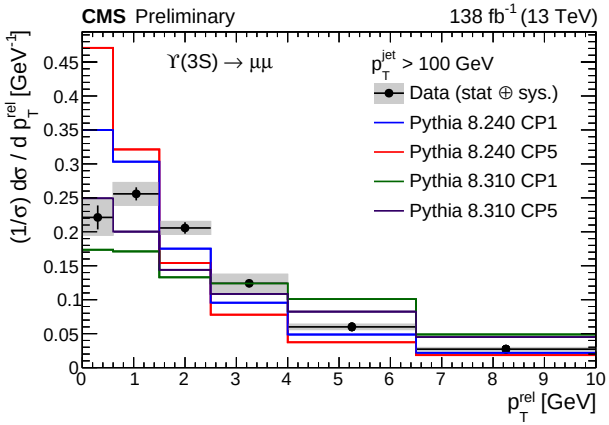










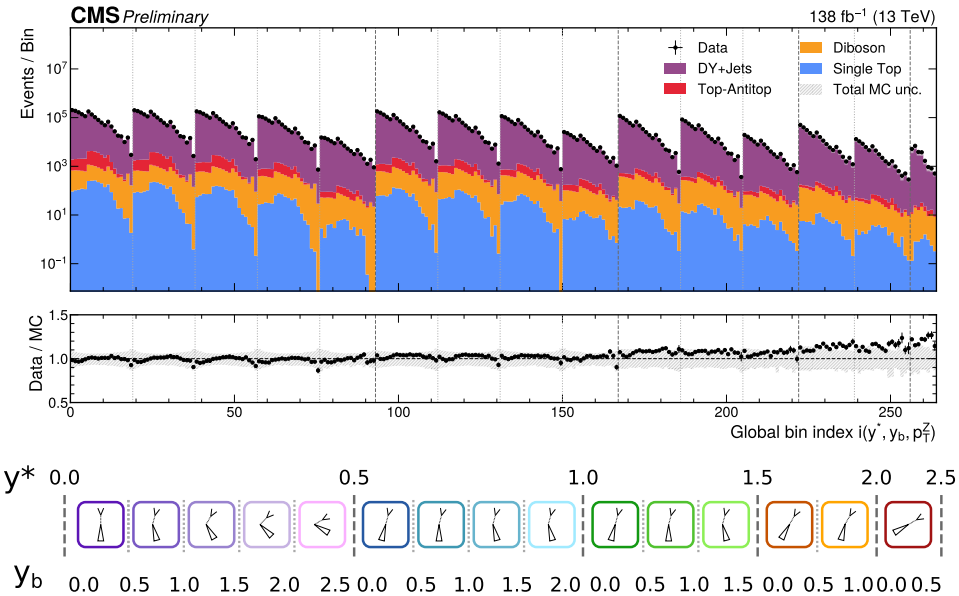


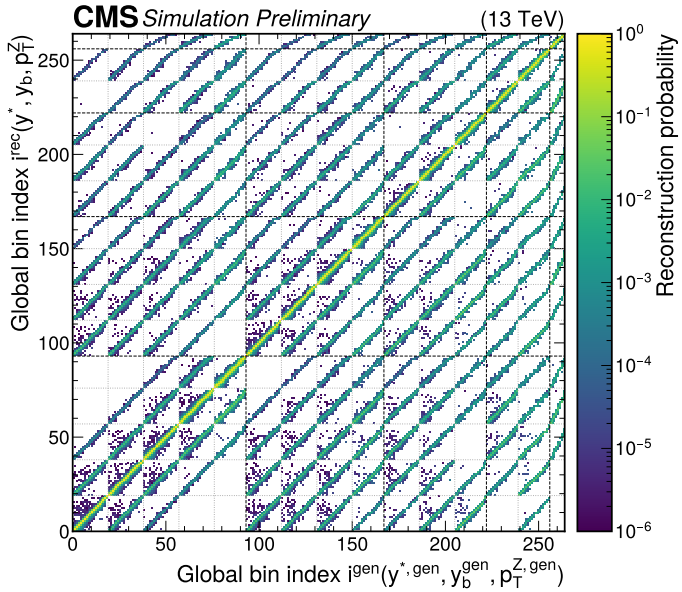
SMP-24-010: Triple-differential Z + jets cross section

CMS-PAS-SMP-24-010

Event generation, selection, and unfolding:

- Signal simulation: MG5_aMC@NLO (NLO, up to 2 jets, FxFx), normalized to NNLO (FEWZ—Fully Exclusive W and Z production, fixed-order)
- Backgrounds: $t\bar{t}$, single top (POWHEG, NNLO normalization), Diboson (NLO)
- Event selection:
  - $\mu^+\mu^-$: $p_{\mathrm{T}} > 29$ GeV, $|\eta| < 2.4$, opposite charge, $|m_{\mu\mu} - m_Z| < 20$ GeV, $p_{\mathrm{T}}^Z > 25$ GeV
  - ≥ 1 jet: $p_{\mathrm{T}} > 20$ GeV, $|y| < 2.4$, $\Delta R(\mu, \mathrm{jet}) > 0.4$





SMP-24-010: Triple-differential $Z + \text{jets}$ cross section

CMS-PAS-SMP-24-010

Unfolded data/baseline (PDF4LHC21) NNLO prediction comparisons:

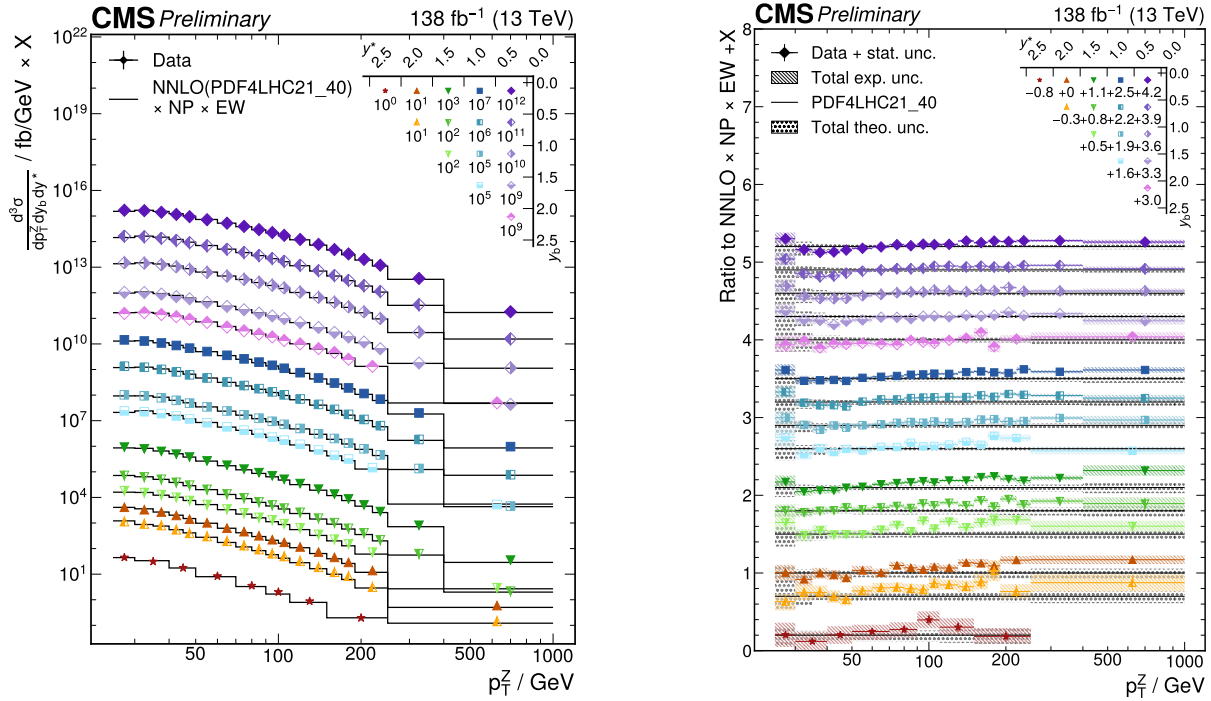


Figure: Unfolded $Z(\to \mu\mu) + \text{jets}$ cross section vs p_{T}^{Z} compared to NNLO QCD predictions with EW and NP corrections (shifted for visibility).

- Agreement generally good.
- Theory uncertainties from scales, PDFs, and corrections included.

SMP-25-006: Gluon-induced spin correlations in parton showers

arXiv:2603.03689, submitted to PRL

Modeling and selection:

- LO dijet MC: PYTHIA8 (p_{T}-ordered, CP5) and HERWIG7 (angular-ordered, CH3), both with NNPDF3.1 NNLO PDFs.
- Select high-p_{T} dijet events: AK8 jets with $p_{\mathrm{T}} > 700$ GeV, $|\eta| < 1.7$, $\Delta\phi_{jj} > 2$.
- Jets are declustered with Cambridge–Aachen (CA) to reconstruct the parton branching chain, providing a proxy for the parton shower history:
  - Clusters particles by smallest angular distance (ΔR), reflecting angular ordering.
  - Uses particles with $p_{\mathrm{T}} > 1$ GeV inside jets.
- Select two successive splittings using highest k_{T} (a "hardness" variable):

$$k_{\mathrm{T}} = p_{\mathrm{T}}^{\text{soft daughter}} \times \Delta R(\text{daughter 1}, \text{daughter 2}).$$

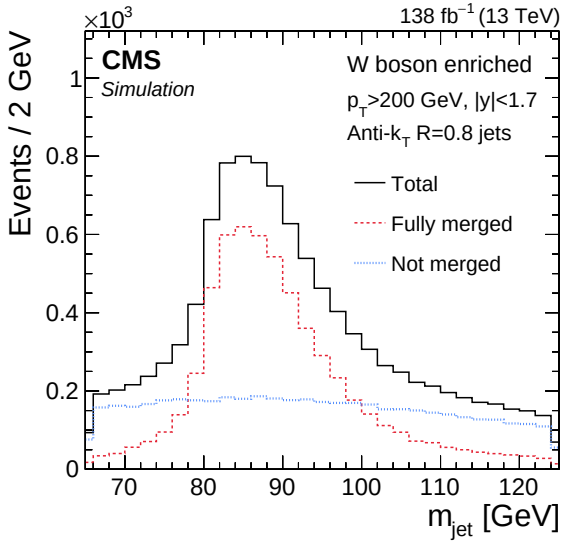
  The softer daughter of the primary splitting must satisfy $p_{\mathrm{T}} > 130$ GeV.
- A DNN is trained to classify jets into qg, gg, qq, and unmatched categories, enhancing the selection of the rare signal topologies sensitive to spin correlations.

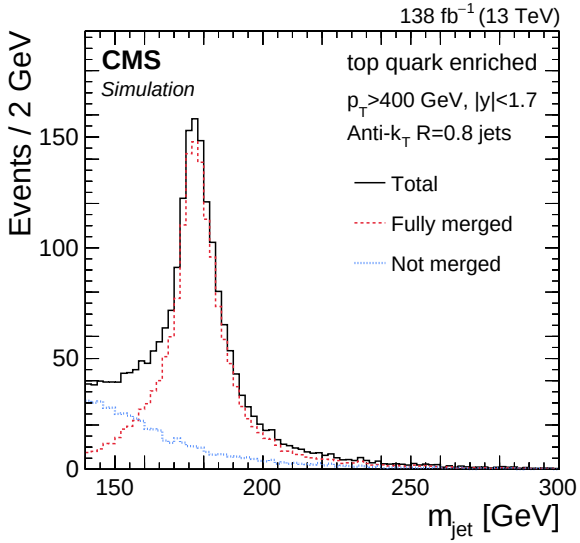
SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

Event generation and selection:

- Event categories include QCD dijet events and μ+jets $t\bar{t}$ production, targeting boosted hadronic W bosons and top quarks.
- Fiducial selections define boosted regimes using AK8 jets ($R = 0.8$):
  - $p_{\mathrm{T}}^{\mathrm{AK8}} > 200$ GeV, $|y| < 1.7$
  - W-enriched: $65 < m_{\mathrm{jet}} < 125$ GeV
  - top-enriched: $140 < m_{\mathrm{jet}} < 300$ GeV, $p_{\mathrm{T}} > 400$ GeV
- In μ+jets: exactly one muon with $p_{\mathrm{T}} > 55$ GeV, $|\eta| < 2.4$, and $\Delta\phi(\mu, \mathrm{AK8}) > 2$.
- Simulated samples use POWHEG and MG5_aMC matched to PYTHIA or HERWIG, with NLO QCD+EW corrections and alternative shower/hadronization models for systematics.

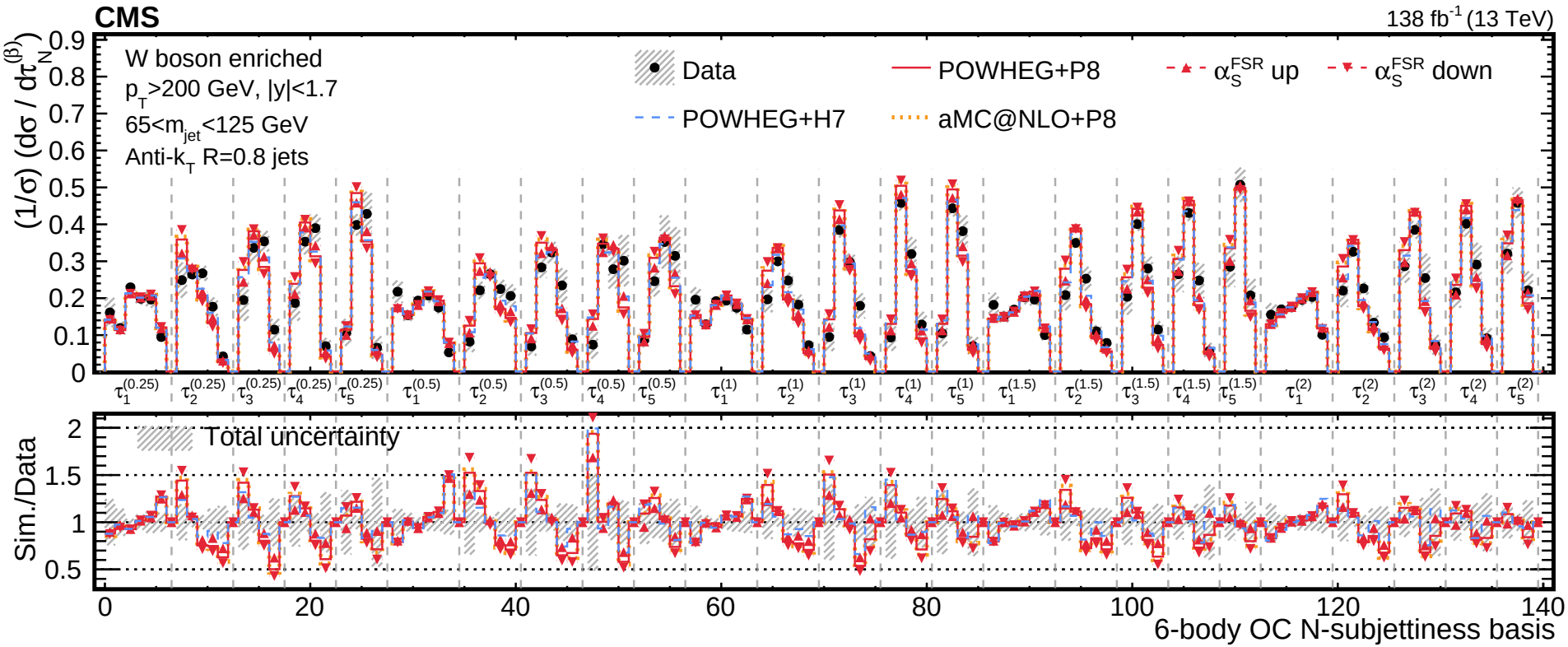




SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

Unfolded results for W jets:

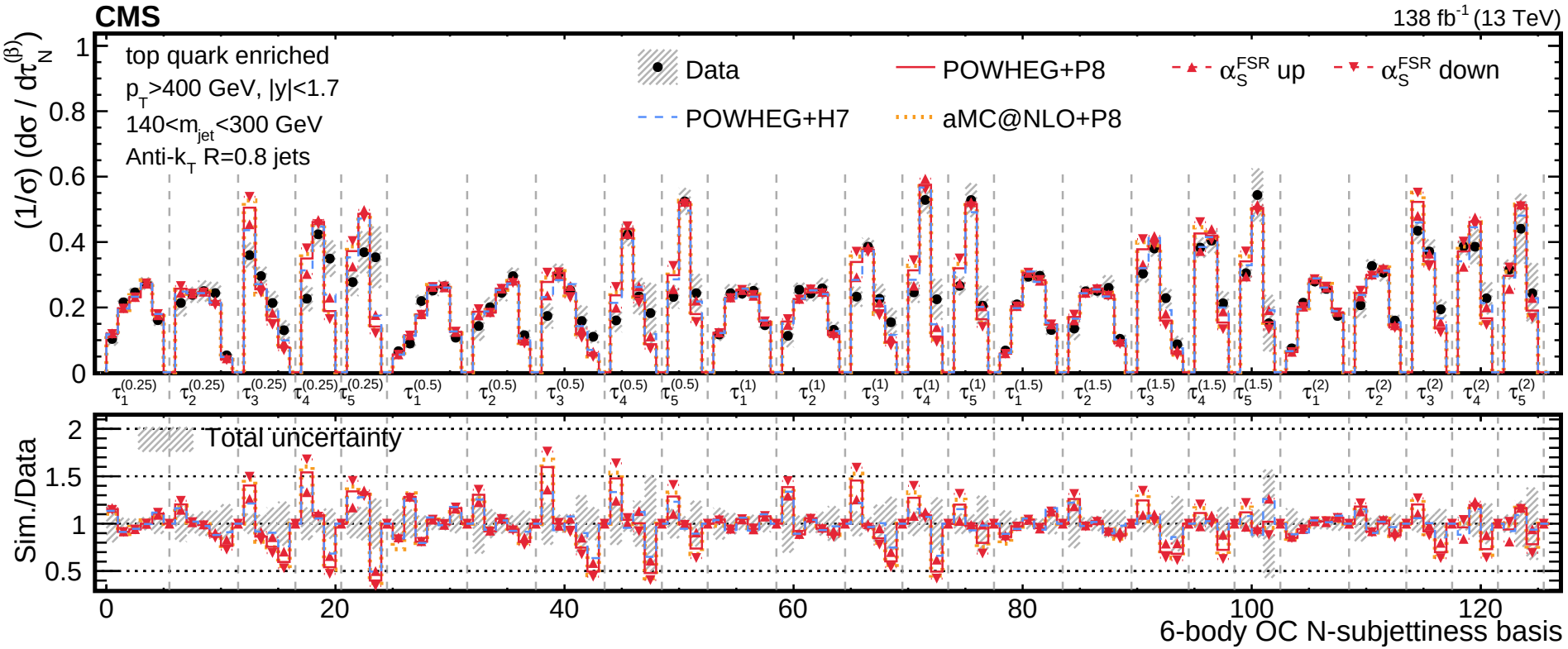


Simulations with a higher $\alpha_s^{\mathrm{FSR}} = 0.122$ provide better overall agreement with data, while discrepancies of $\mathcal{O}(5-20\%)$ remain in regions sensitive to ≥ 3-body radiation, despite good modelling of 1-subjettiness peaks.

SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

arXiv:2604.25538, submitted to JHEP

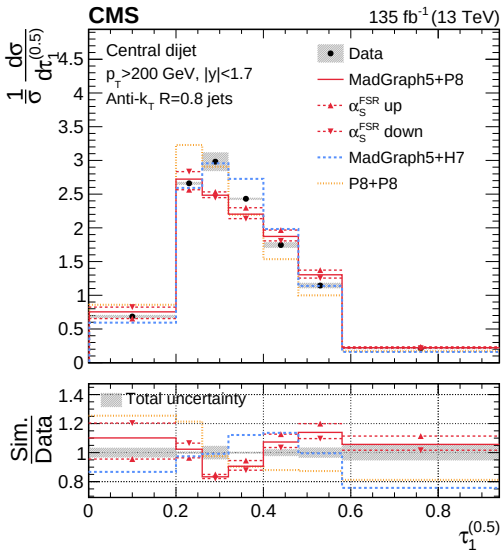
Unfolded results for t jets:

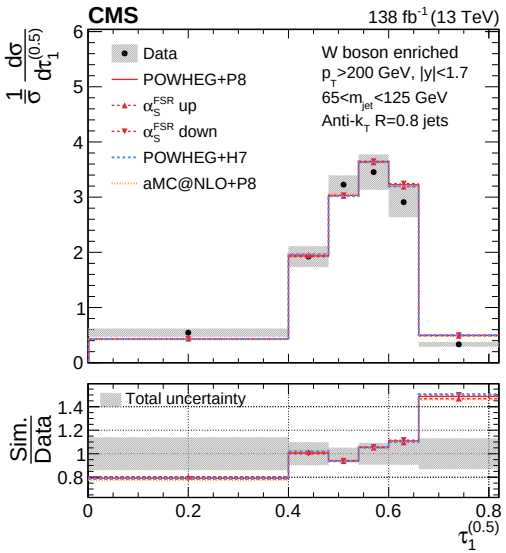


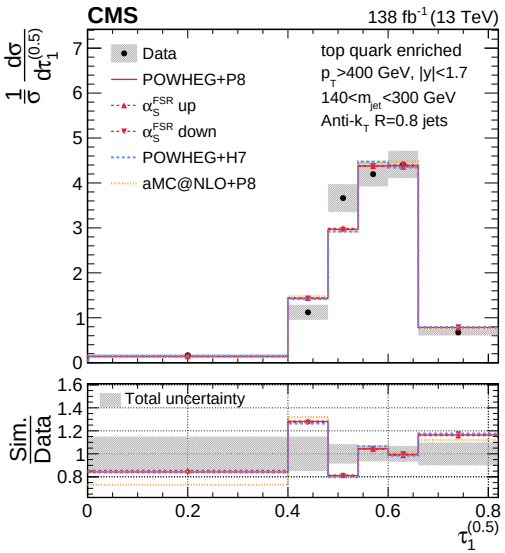
$\alpha_s^{\mathrm{FSR}} = 0.122$ also yields better agreement with data overall, but noticeable discrepancies persist in observables sensitive to ≥ 3-body radiation, while 1-subjettiness regions are generally well described.

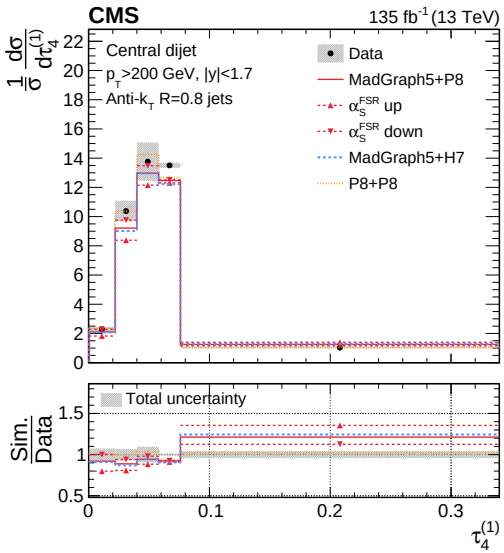
SMP-22-003: N-subjettiness observables in q/g and boosted W/t jets

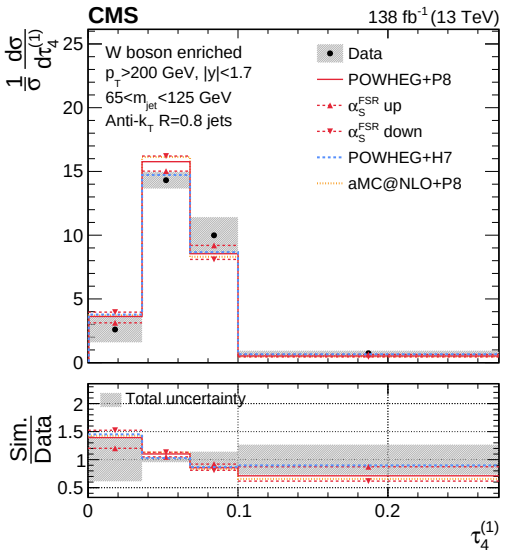
arXiv:2604.25538, submitted to JHEP

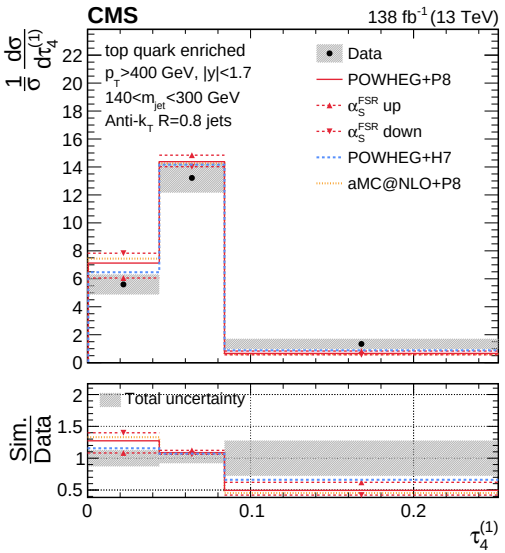












SMP-24-012: Event generation and selection

arXiv:2603.19963, submitted to JHEP

Event generation:

- LO: $W/Z + \text{jets}$ (MG5_aMC@NLO + PYTHIA 8, CP5, MLM), with NLO QCD+EW reweighting; QCD multijet.
- NLO: $t\bar{t}$ (POWHEG v2 + PYTHIA 8).

Reconstruction and selection:

- Leading anti-k_{T} jet is taken as boosted W candidate.
- Jet constituents reclustered with Cambridge–Aachen and groomed using Soft Drop: $\min(p_T^{(1)}, p_T^{(2)})/(p_T^{(1)} + p_T^{(2)}) > z_{\mathrm{cut}}(\Delta R_{12}/R)^{\beta_{\mathrm{SD}}}$, with $z_{\mathrm{cut}} = 0.1$ and $\beta_{\mathrm{SD}} = 0$.
- Groomed jet mass used after calibration from standard CMS samples.
- W tagging via ECF* $N_2^{(1)}$ and ParticleNet classifiers.
- AK8 jet selection: $p_{\mathrm{T}} > 575$ GeV, $|\eta| < 2.4$, with binning up to ∞.
- Jet quality cuts and lepton veto (e/μ with $p_{\mathrm{T}} > 10$ GeV).

*ECF: energy correlation functions.