STANDARD MODEL MEASUREMENTS IN ATLAS AND CMS (Z,W,QCD)

RENCONTRES DE LA THUILE 2022

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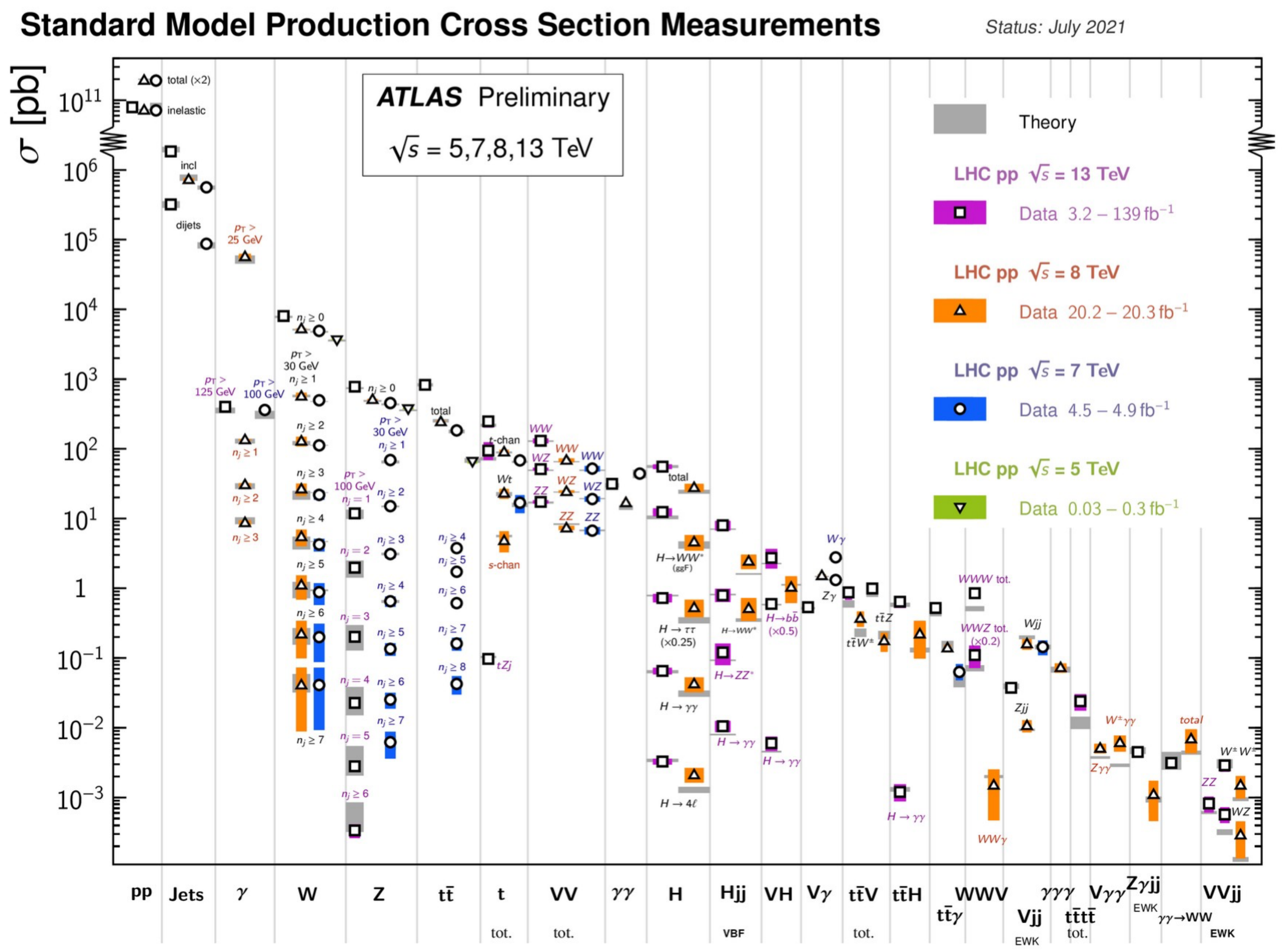
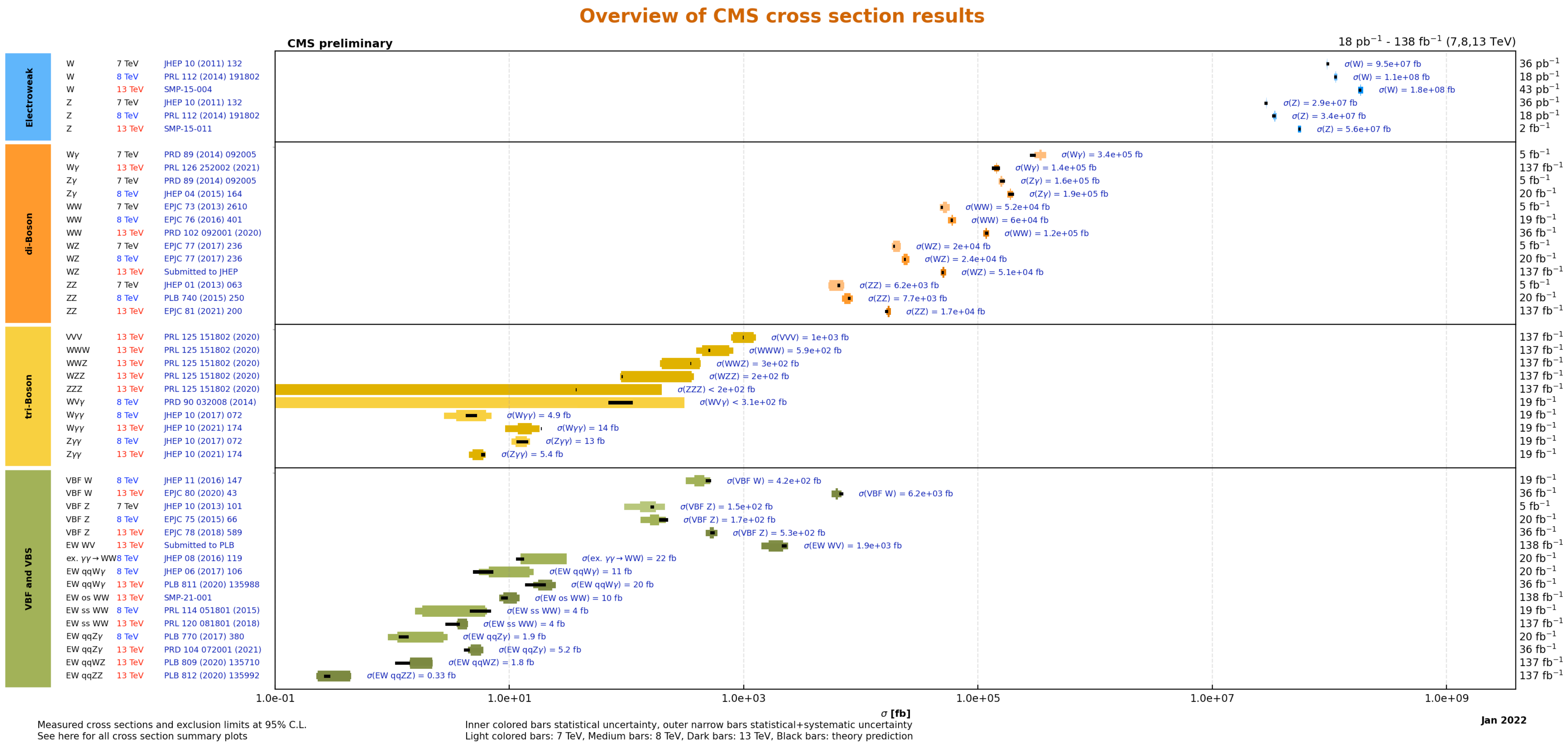
On behalf of ATLAS and CMS collaborations

(*) Supported by US NSF PHY-2011848 and PHY-1707666

OUTLINE

- **Exploring processes spanning a production rate of 9 orders of magnitude**
  - Precision measurements test higher order QCD calculations and constrain PDFs
  - Search for effects of new physics, using the EFT formalism



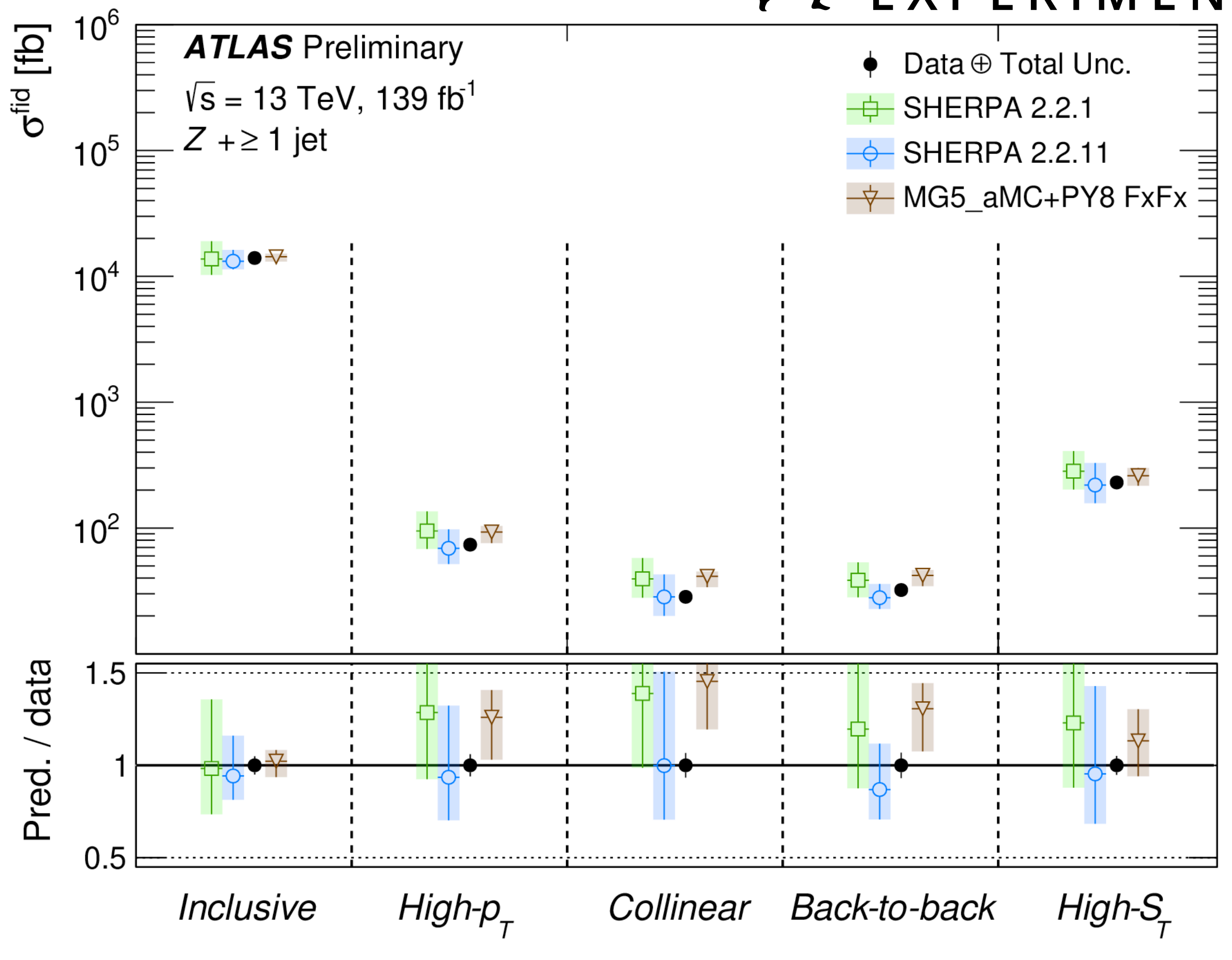


V + JETS

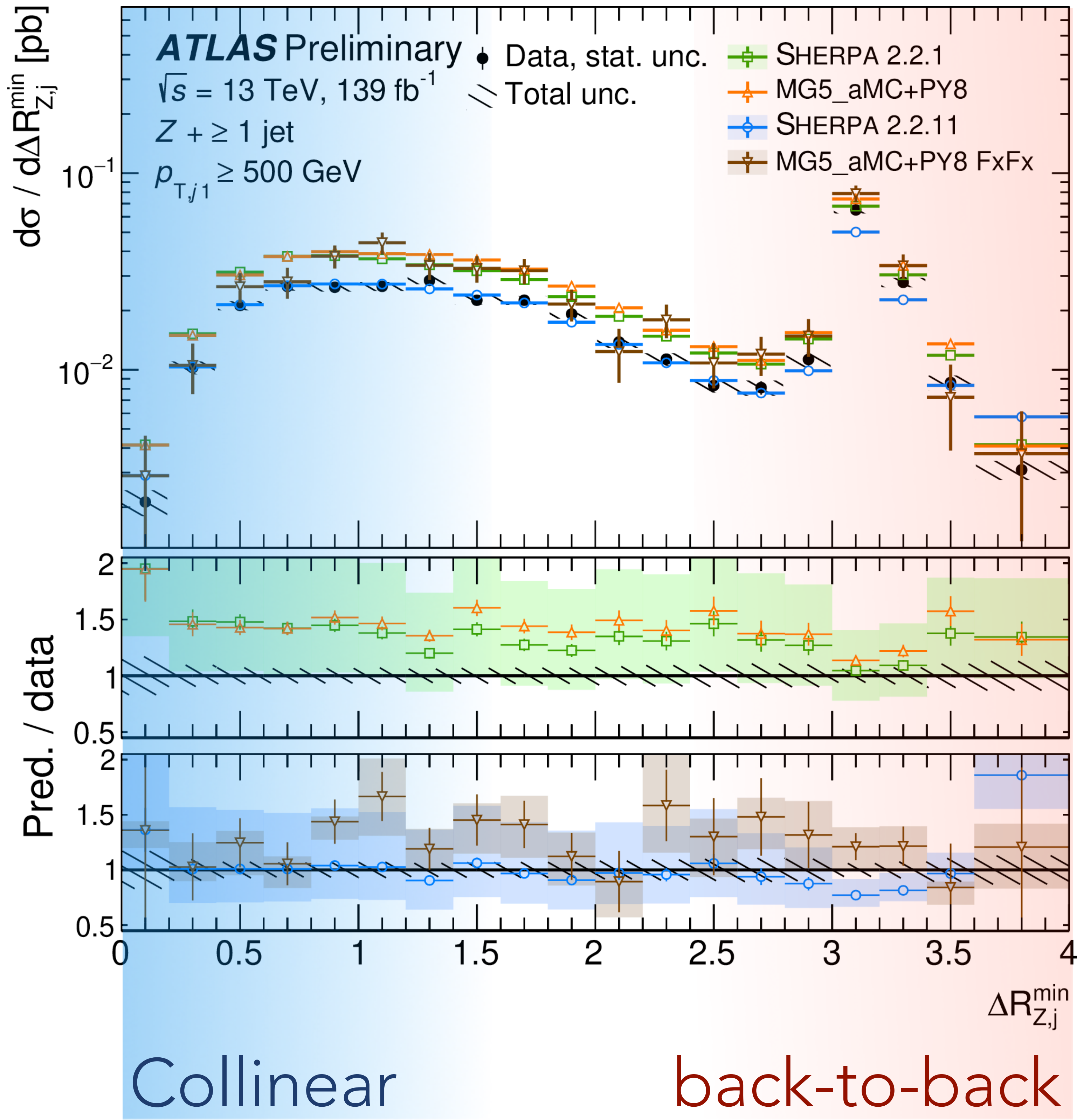
Z + HIGH P_T JETS

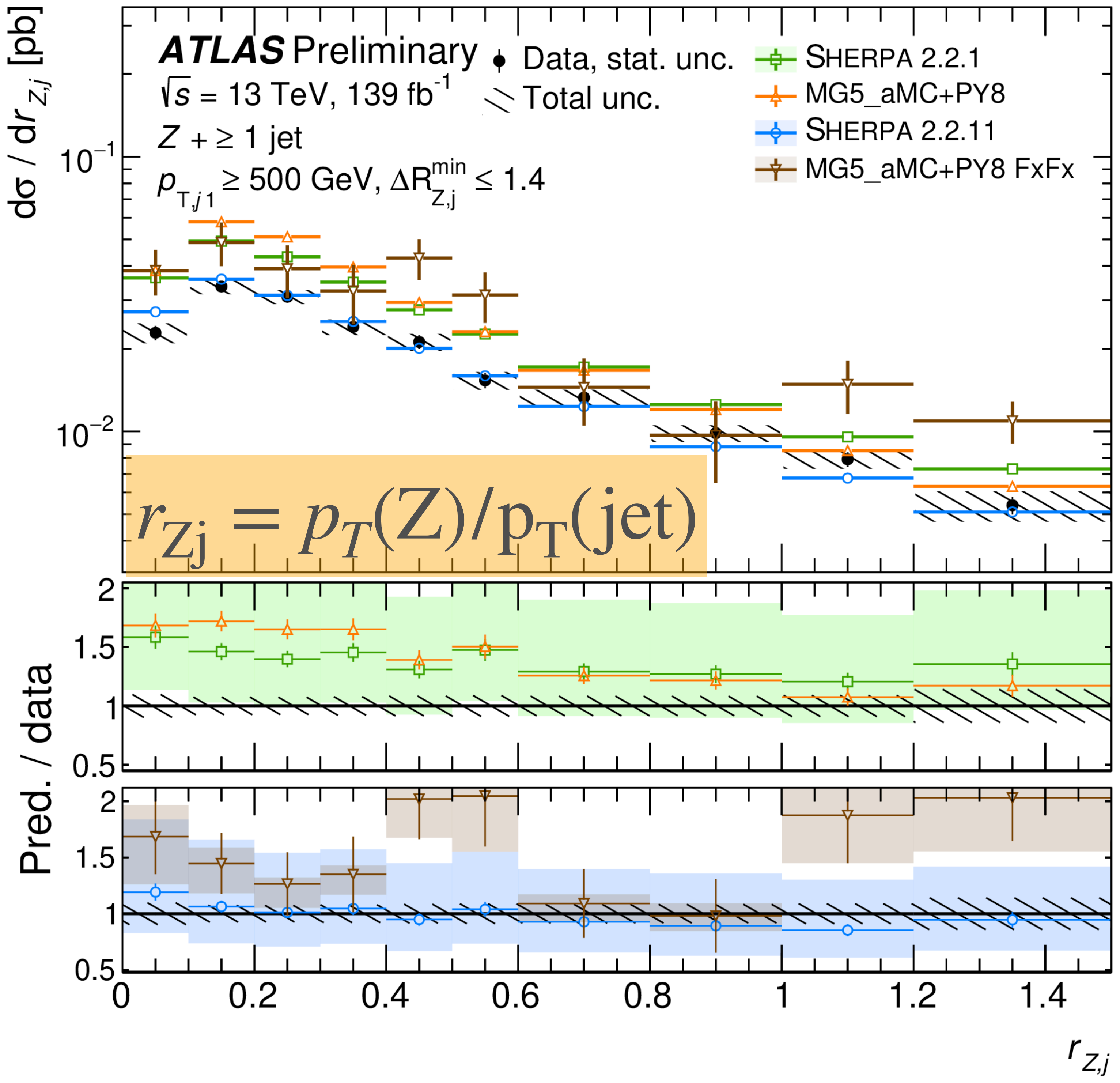
ATLAS-CONF-2021-033

- 13 TeV full run II data with 139/fb. Combines ee & μμ channels
  - Inclusive : Jet pT > 100 GeV & |y|<2.5
  - High pT ("Collinear" & "back-to-back"): Jet pT > 500 GeV
    High-ST : ST > 600 GeV
- Differential cross-sections in all regions for several observables



- Agrees best with Sherpa 2.2.11
- Overestimation from Sherpa 2.2.1 and MG5_aMC





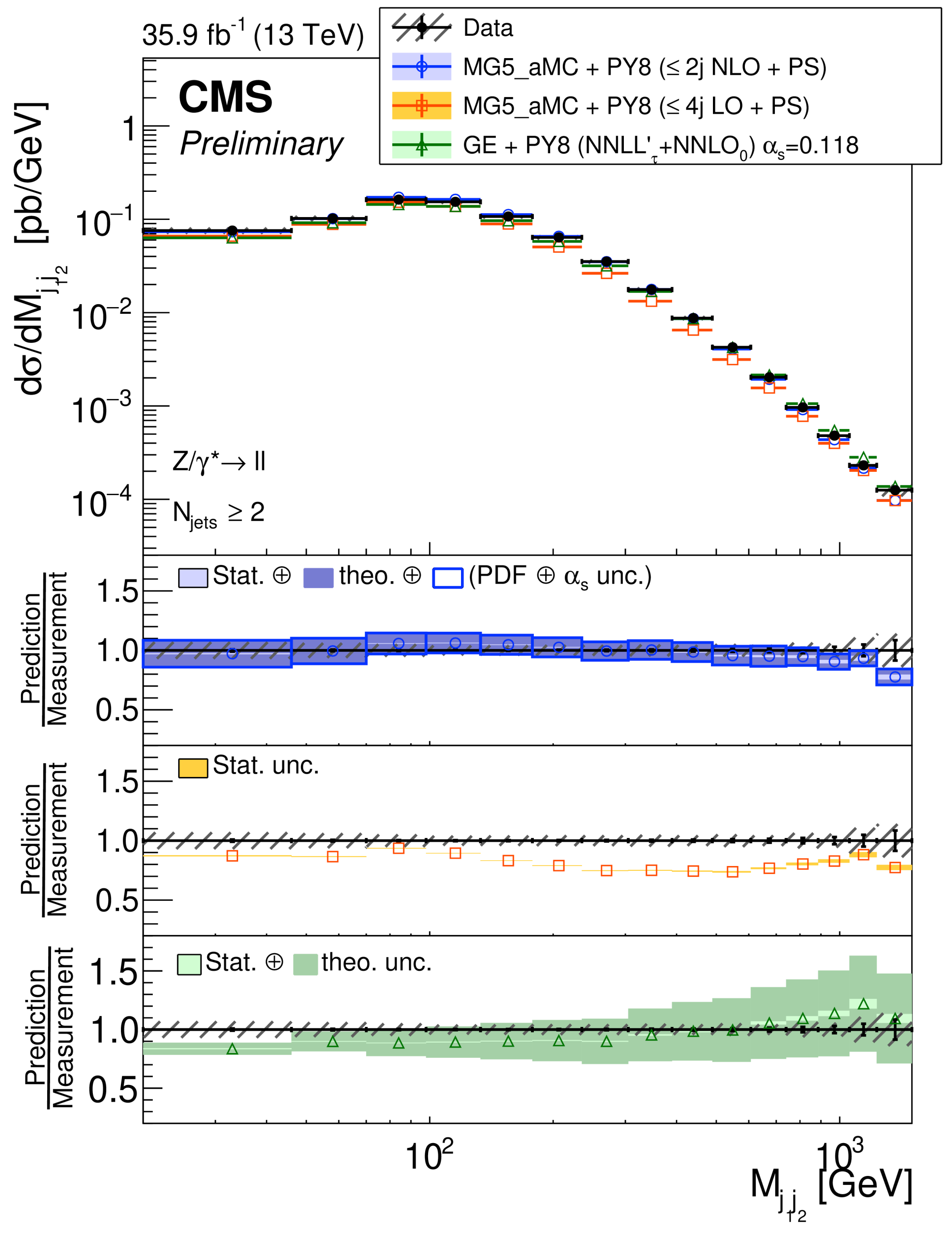
$r_{Zj} = p_T(Z)/p_T(jet)$

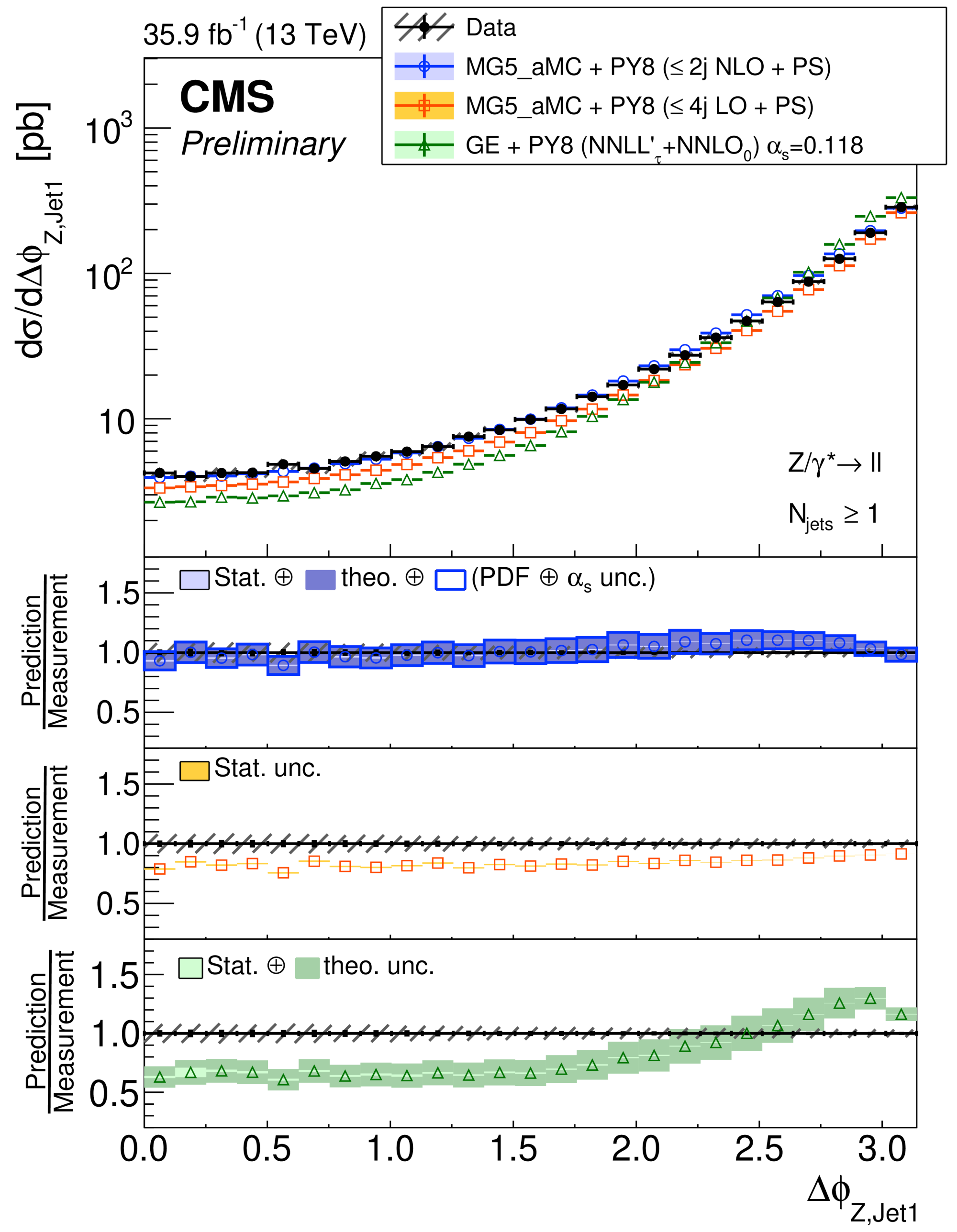
Z + JETS

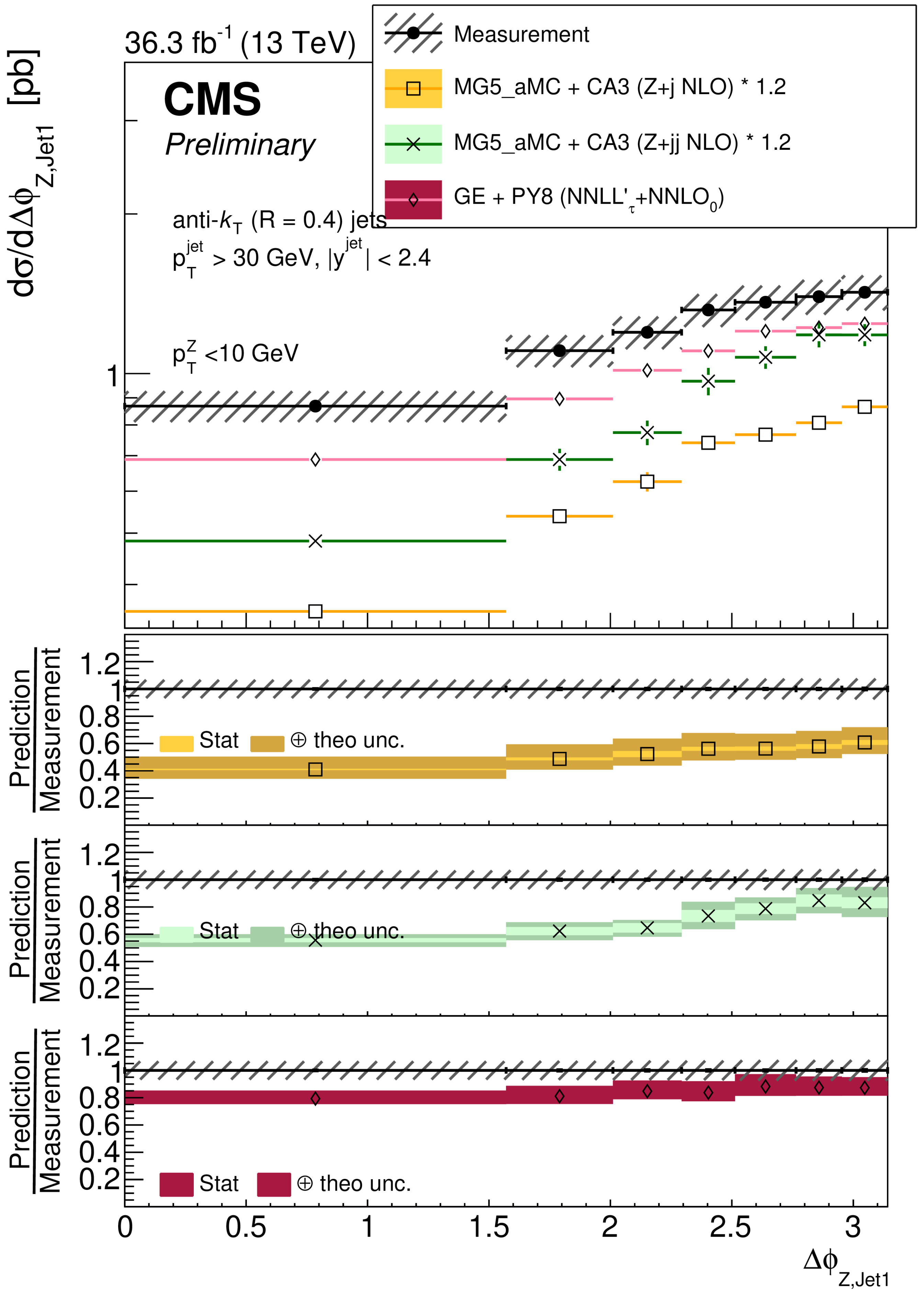
CMS-PAS-SMP-19-009

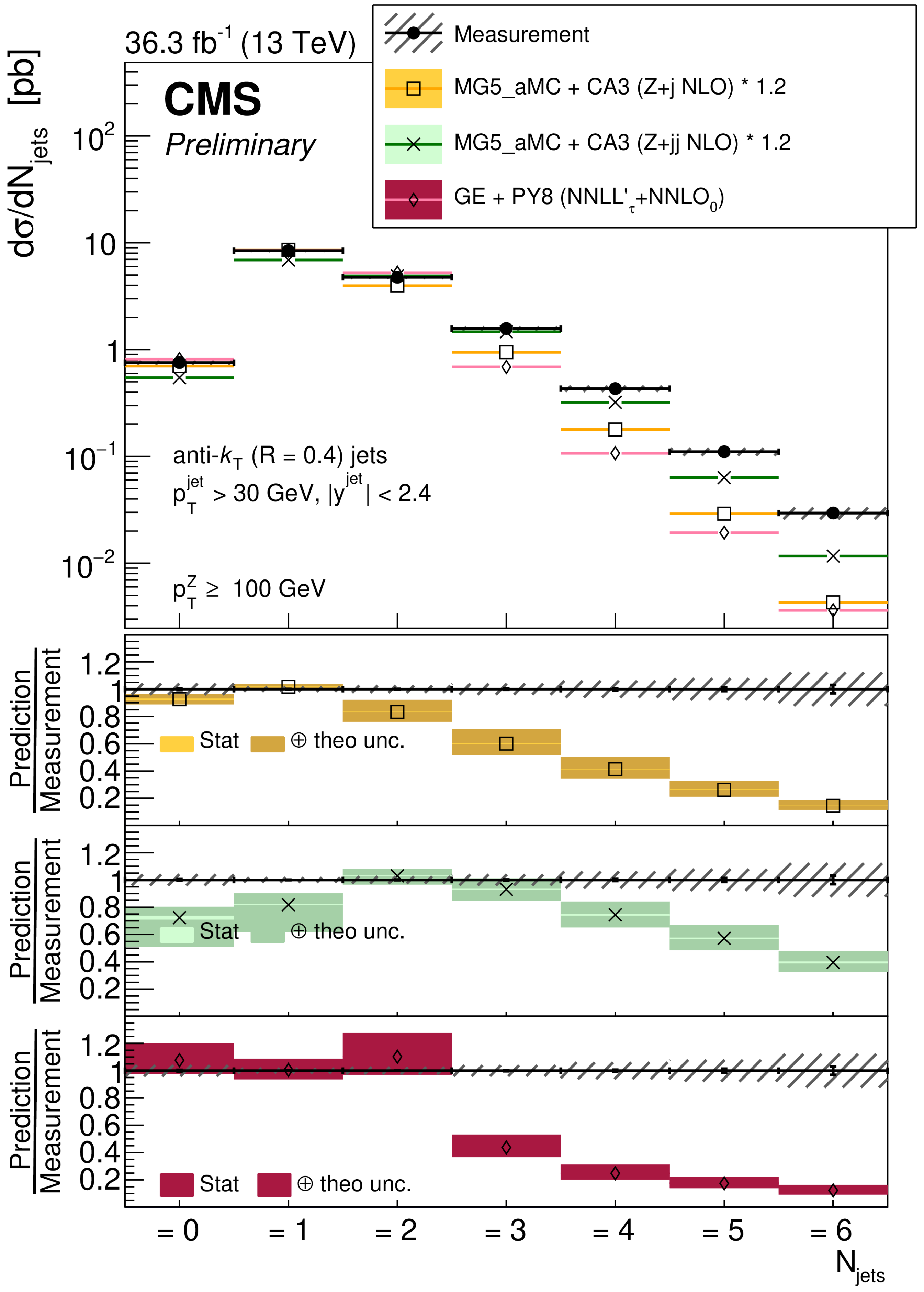
CMS-PAS-SMP-21-003

- **13 TeV data with 35.9/fb** combined ee and μμ channels
  - jet p_T > 30 GeV & |y|<2.5
  - Results unfolded to particle-level
  - N_{jets}, $\Delta\phi(Z, j_1; j_1, j_2)$ Differential distributions in different $p_T(Z)$ regions
  - Results compared to:
    - MG5_aMC: LO & NLO + PS without MPI
    - GENEVA: NNLO with NNLL$'_\tau$ resummation with MPI









- **Best descriptions in most regions is from Geneva NNLO using:**
  - matrix elements at NNLO for Z production + NNLL' resummation
  - Parton Shower and MPI from PYTHIA 8
- Agreement fails for $N_{\text{jets}} \geq 3$

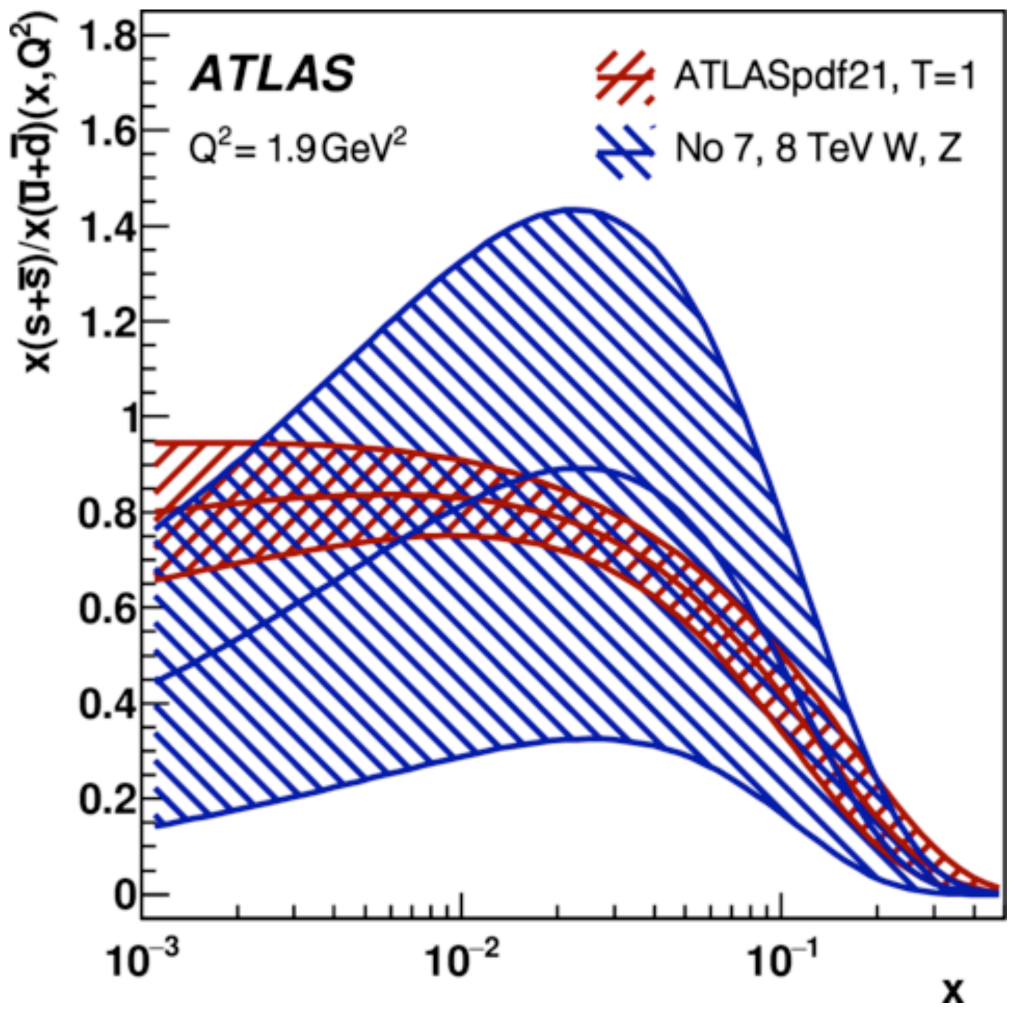
Z/W + JETS

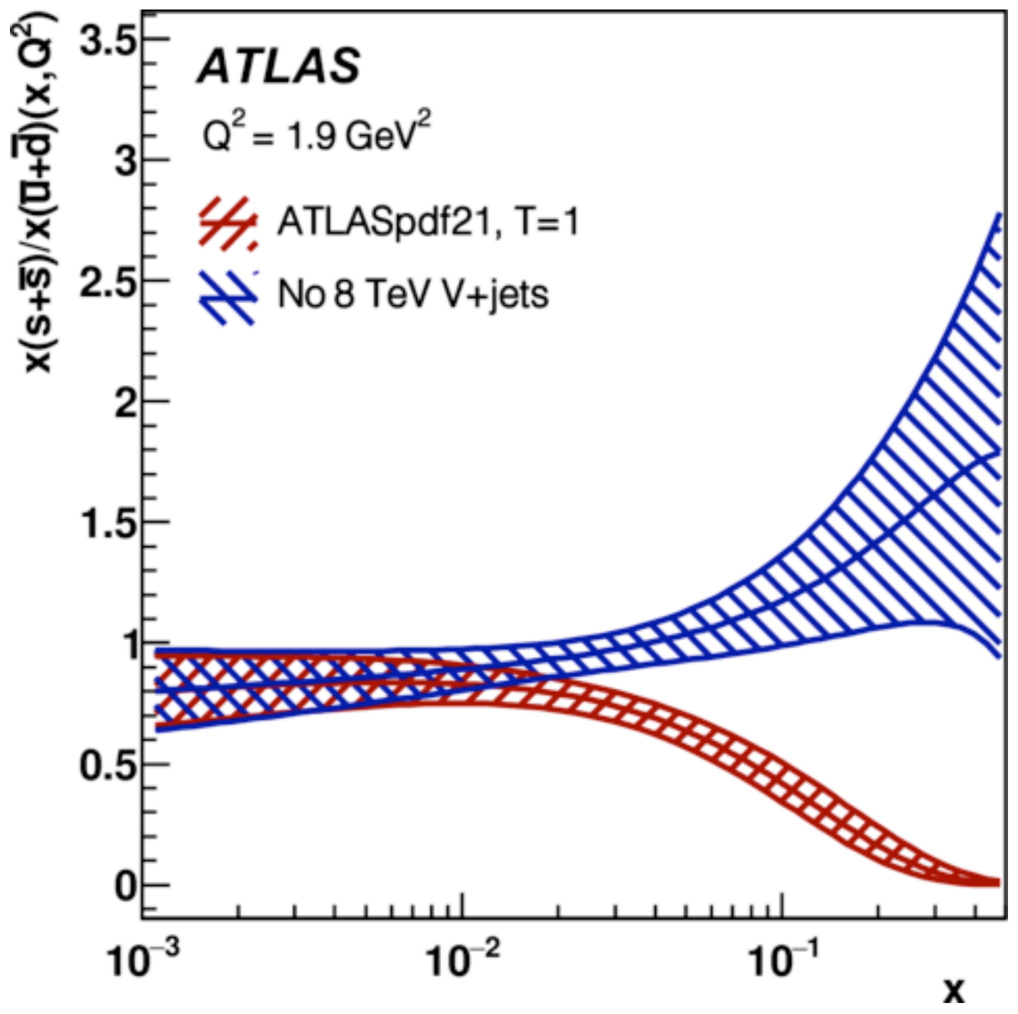
arXiv:2112.11266

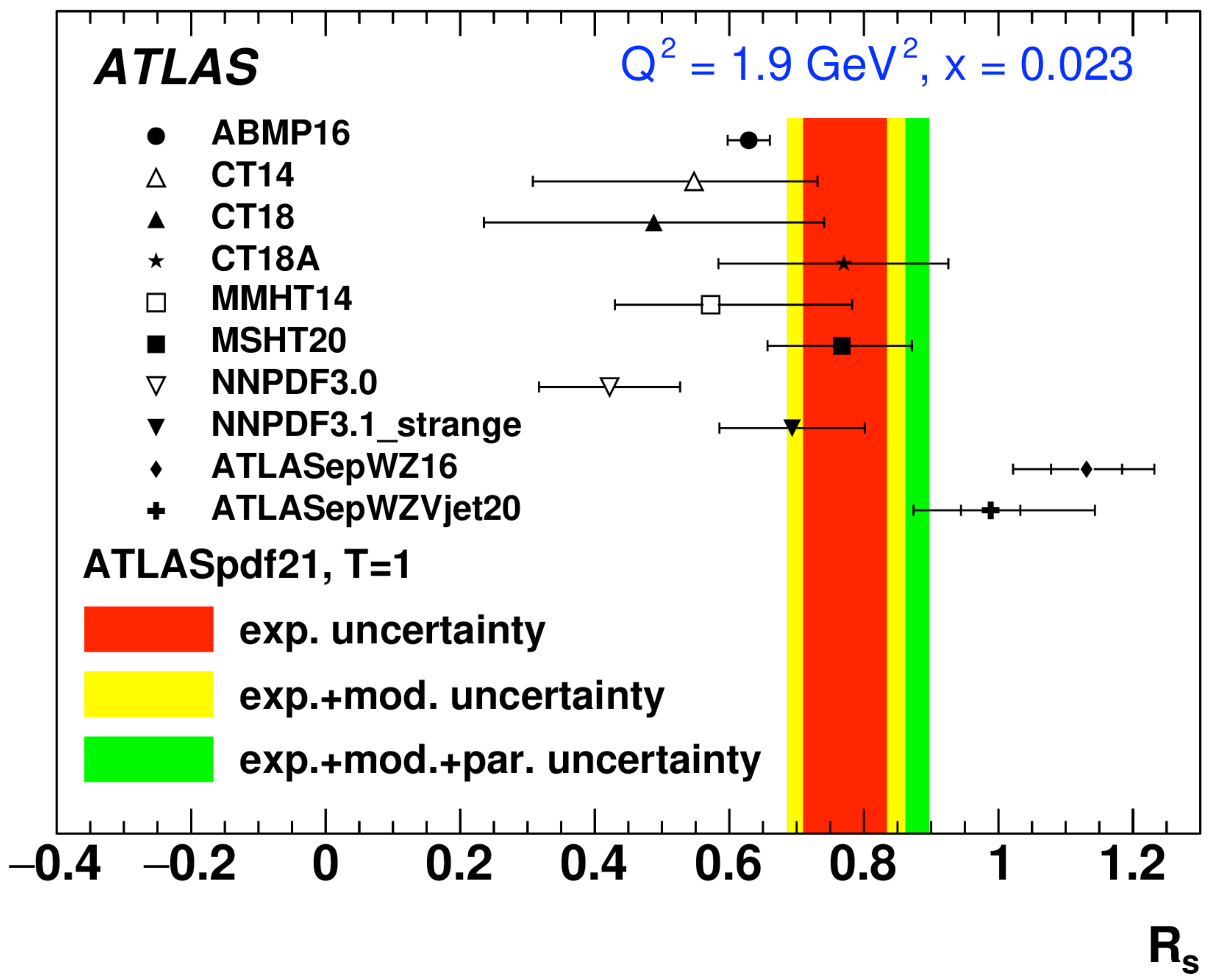
ATLAS EXPERIMENT

- **Combined 7, 8 & 13 TeV data (4.6, 20.2 & 3.2/fb).**
  - ATLASpdf21 fits to all PDF-sensitive ATLAS data sets that have information on correlated systematic uncertainties and NNLO QCD +NLO EW predictions
  - First ATLAS PDF fit which includes 13 TeV data
    - Very wide portfolio of ATLAS data from different years, and across the whole spectrum of QCD processes

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}, m_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [24]	8	20.2	e	p_T^W
Z + jets [25]	8	20.2	e	p_T^{jet} in bins of $\lvert y^{jet}\rvert$
$t\bar{t}$ [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}, p_T^t, y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}, p_T^t, y_t, y_{t\bar{t}}^b$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_T^γ in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	p_T^{jet} in bins of $\lvert y^{jet}\rvert$





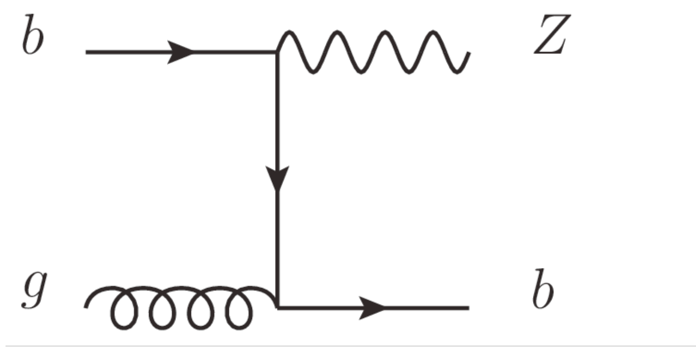


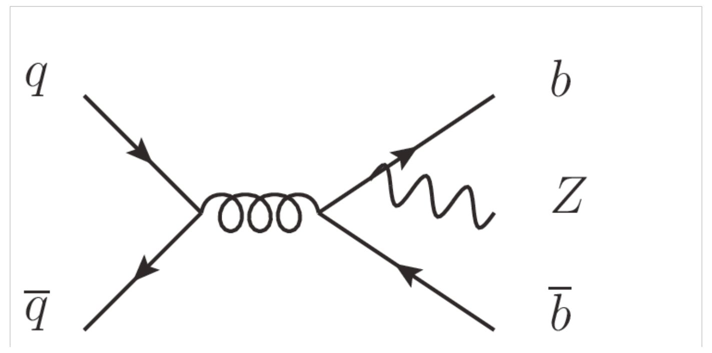
- W/Z data allow to remove constraints on $x\bar{u}$, $x\bar{d}$, $x\bar{s}$ and confirm unsuppressed strangeness at low x
  - Without W/Z data, ratio of strange to light sea quarks very poorly determined
- V+jets data constraint light-sea quarks and gluon at higher x
  - Without V+jets data little information of R_s at high x
- jets, $t\bar{t}$ and photon data constrain gluon PDF
- Reasonable agreement with modern PDF sets

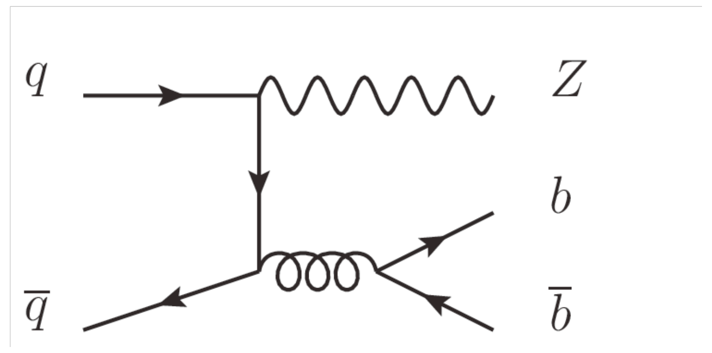
$$R_s(x) = \frac{s(x) - \bar{s}(x)}{\bar{u}(x) + \bar{d}(x)}$$

Z + B JETS

CMS-SMP-20-015

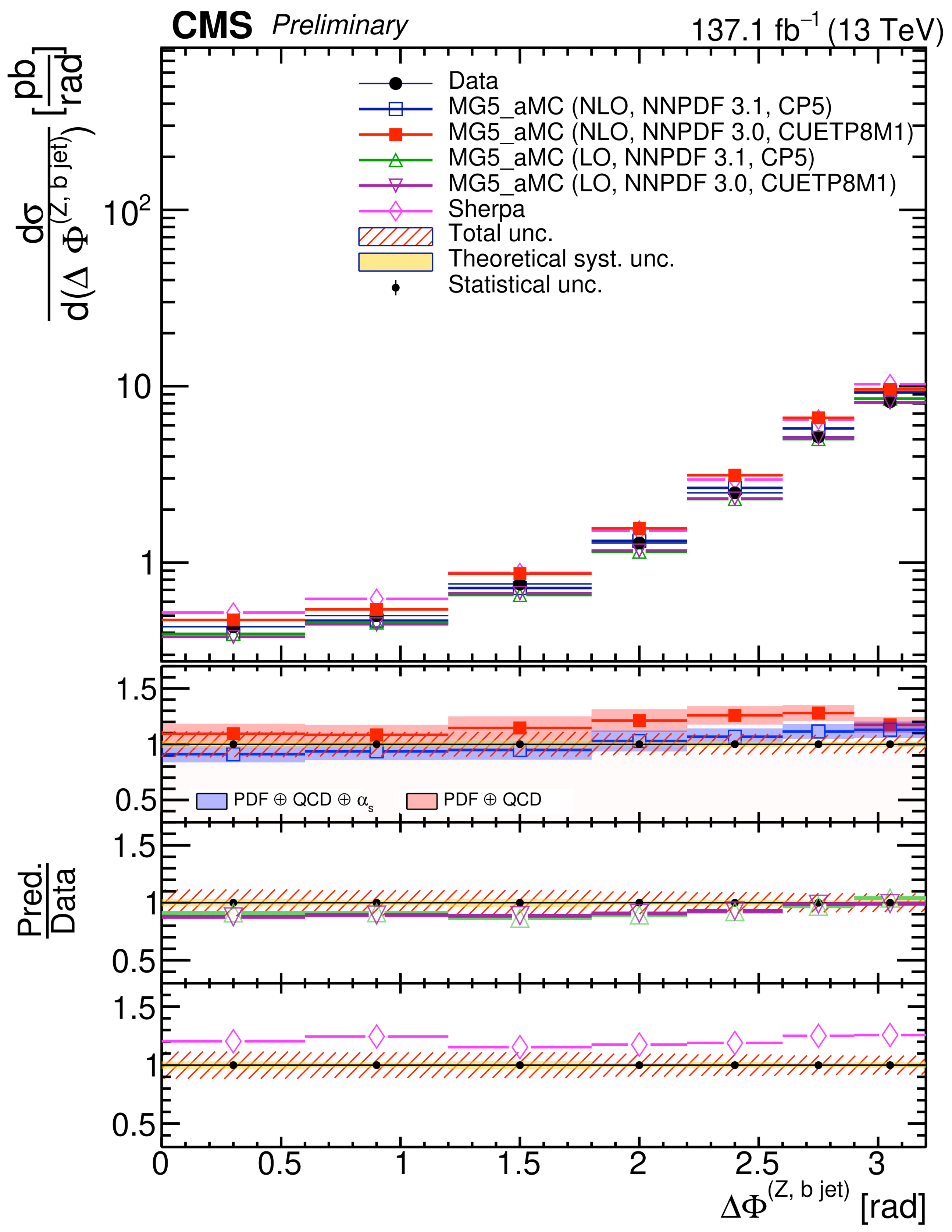


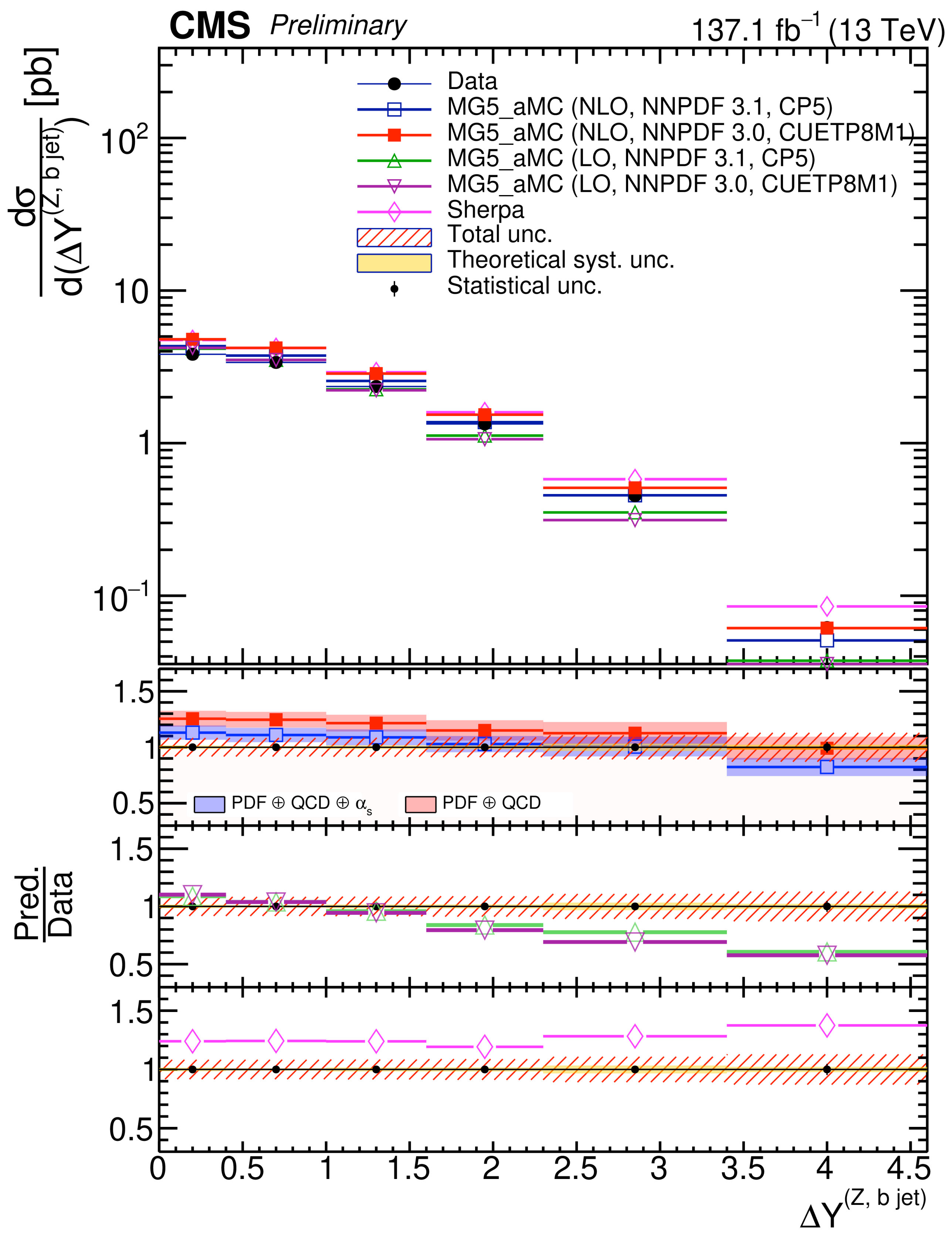


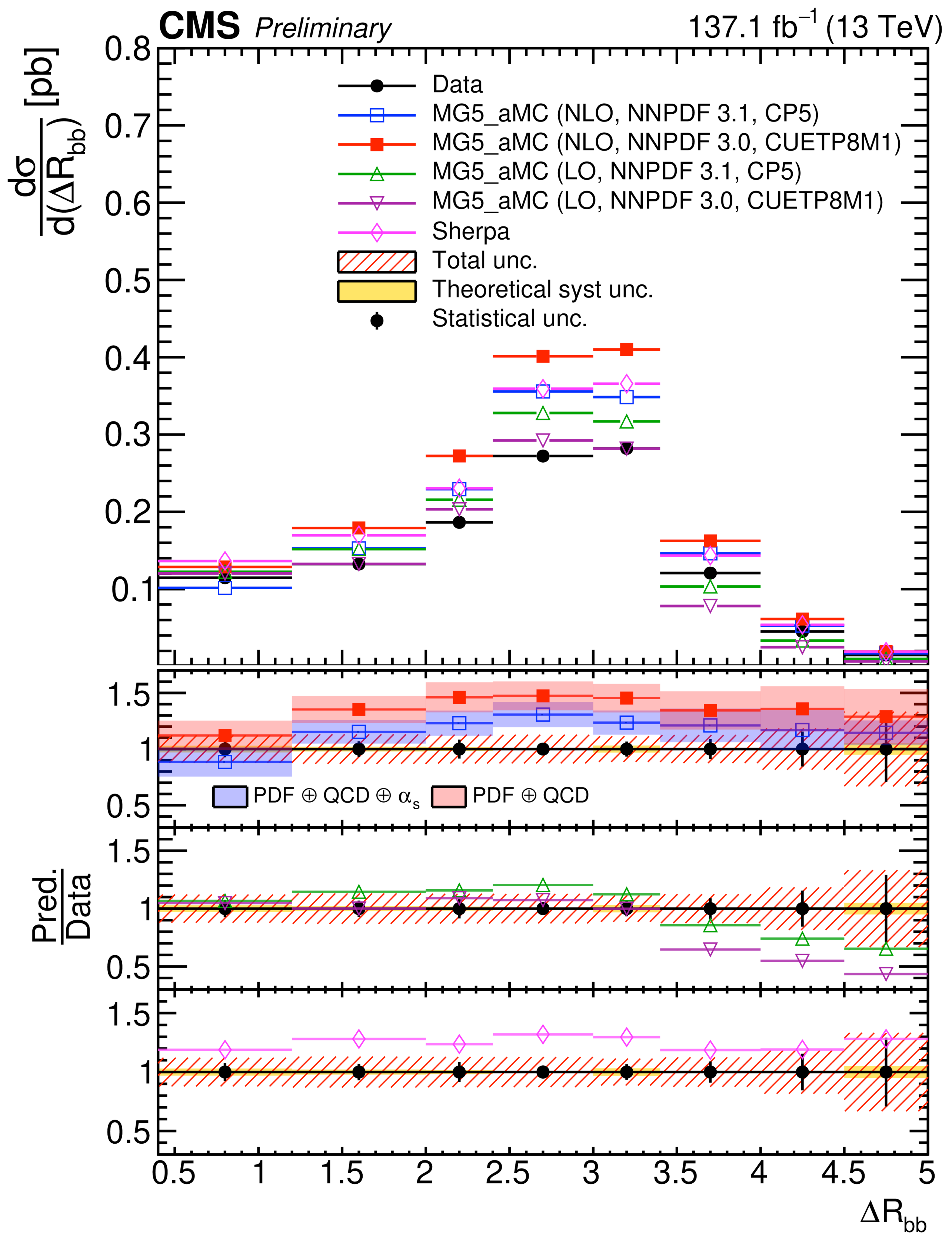


Channel		Measured	MG5_aMC LO NNPDF 3.0 CUETP8M1	MG5_aMC LO NNPDF 3.1 CP5	MG5_aMC NLO NNPDF 3.0 CUETP8M1	MG5_aMC NLO NNPDF 3.1 CP5	SHERPA
$Z + \geq 1$ b jet	ee	$6.45 \pm 0.06 \pm 0.49 \pm 0.17$	6.25	6.33	7.86 ± 0.52	7.05 ± 0.48	8.05
	$\mu\mu$	$6.55 \pm 0.05 \pm 0.39 \pm 0.19$	6.26	6.34	7.86 ± 0.51	7.02 ± 0.47	7.98
	$\ell\ell$	$6.52 \pm 0.04 \pm 0.40 \pm 0.14$	6.25	6.34	7.86 ± 0.51	7.03 ± 0.47	8.02
$Z + \geq 2$ b jets	ee	$0.66 \pm 0.05 \pm 0.07 \pm 0.02$	0.62	0.72	0.89 ± 0.08	0.77 ± 0.07	0.84
	$\mu\mu$	$0.65 \pm 0.04 \pm 0.06 \pm 0.02$	0.64	0.71	0.91 ± 0.09	0.77 ± 0.07	0.84
	$\ell\ell$	$0.65 \pm 0.03 \pm 0.07 \pm 0.02$	0.63	0.71	0.90 ± 0.09	0.77 ± 0.07	0.84
Ratio	ee	$0.102 \pm 0.008 \pm 0.008 \pm 0.004$	0.100	0.113	0.113 ± 0.016	0.110 ± 0.013	0.104
	$\mu\mu$	$0.100 \pm 0.006 \pm 0.006 \pm 0.004$	0.103	0.112	0.116 ± 0.016	0.110 ± 0.013	0.105
	$\ell\ell$	$0.100 \pm 0.005 \pm 0.007 \pm 0.003$	0.102	0.112	0.114 ± 0.016	0.110 ± 0.013	0.105

- **Full Run II 13 TeV data with 137/fb**. Combines ee & μμ channels
  - Results unfolded to particle-level b-jet $p_T > 30$ GeV & |η|<2.4
  - Compared to: MG5 (LO/NLO) + Pythia8 and Sherpa v.2.2



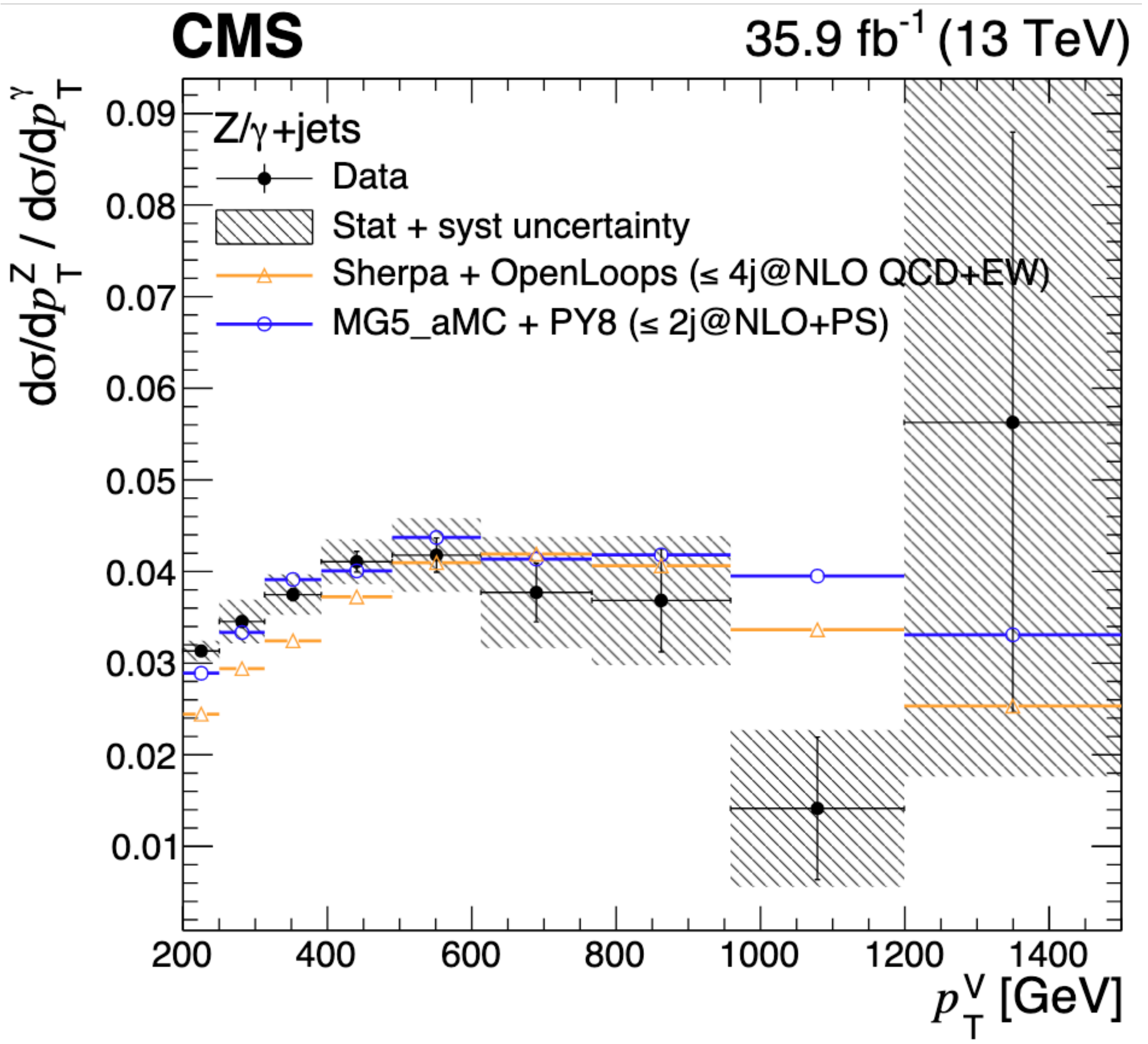


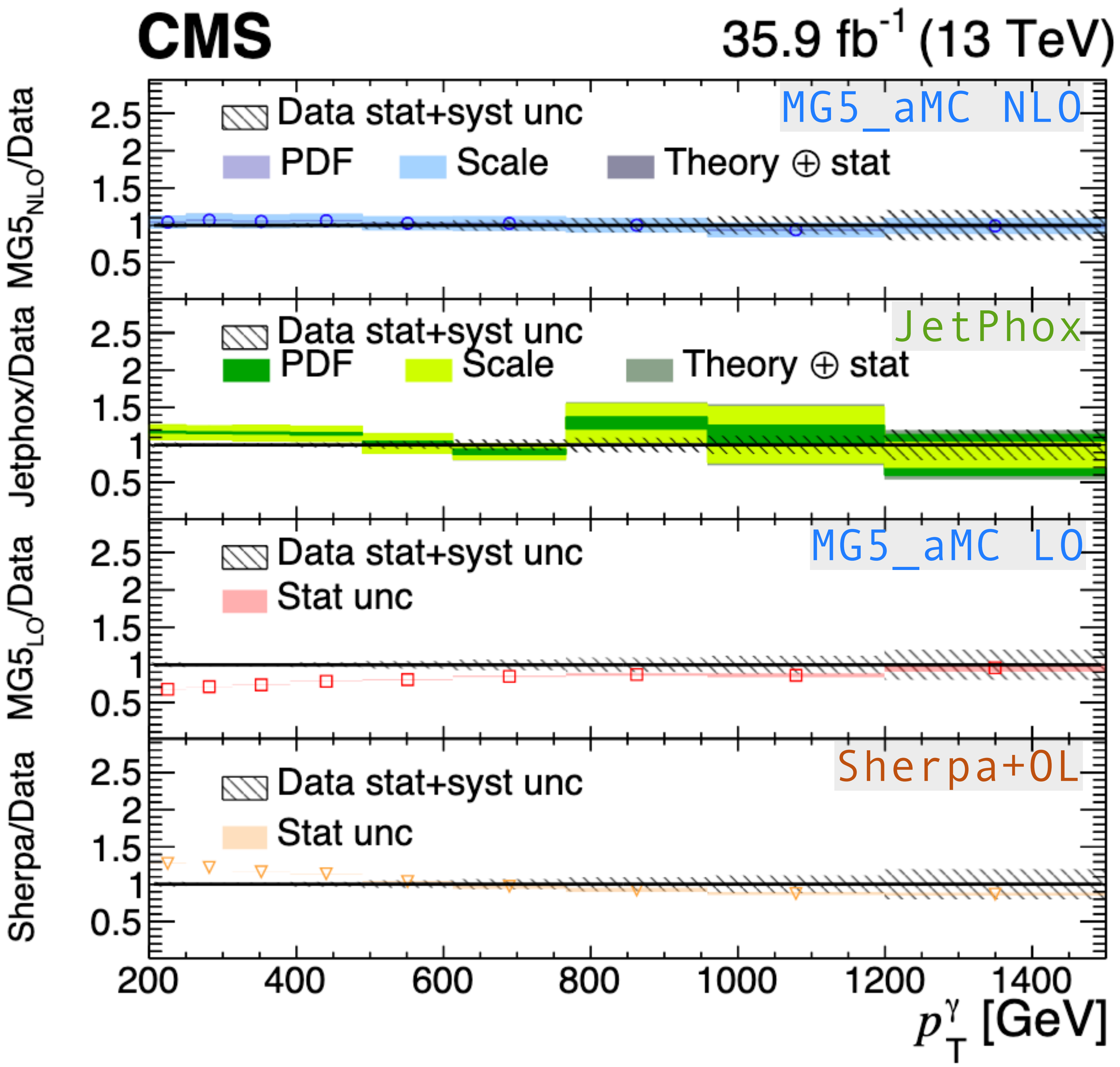


- Integrated cross-section better described by MG5_aMC at LO but overestimated by both MG5_aMC at NLO and SHERPA
- Shapes better described by MG5_aMC at LO rather than NLO
- Sherpa overestimates the integrated cross-section, but described well shapes

DIFFERENTIAL Z/GAMMA JETS

- **Run II 13 TeV data with 35.9/fb**.
  - First measurement of the differential cross section ratio of Z/gamma at 13 TeV.
  - Z/gamma is sensitive to higher order EW corrections at high pT.
  - First explicit study of the collinear emission of Z boson at the LHC.
  - The measurement requires leading jet pT>100 GeV and photon pT>200 GeV, testing bosons pT up to 1.5 TeV





- MG5_aMC NLO agrees with data across the full range of pT, while LO MG5_aMC shows a 10-30% disagreement in shapes
- Sherpa+OpenLoops over-predicts the data by 20-30% for pT < 500 GeV.
- NLO prediction from JetPhox is mostly consistent with data, with a general over-prediction 20% for pT < 500 GeV.

DI-PHOTON ($\gamma\gamma$) PRODUCTION

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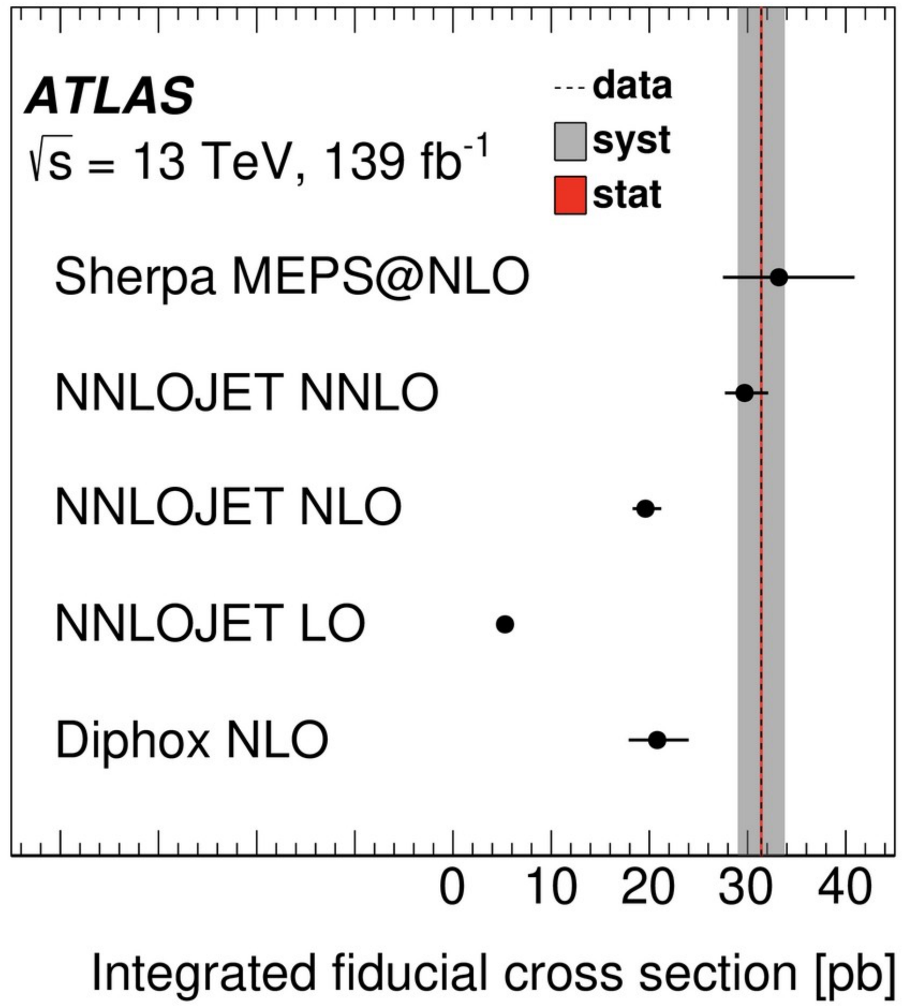
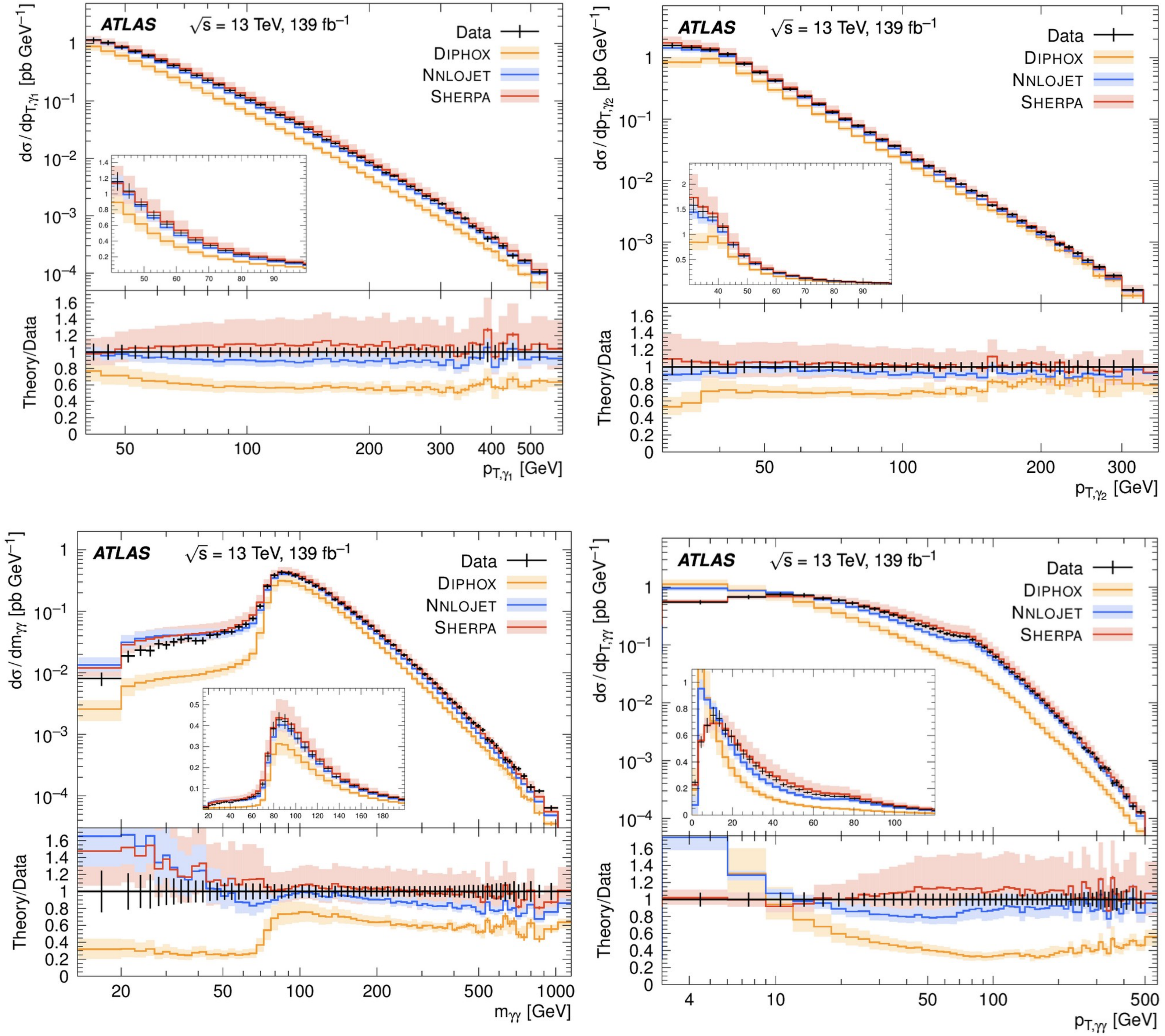
ATLAS EXPERIMENT

- **Full Run II 13 TeV data with 36/fb.**
  - Photon p_T > 40, 30 GeV & |η|<2.37 & $\Delta R_{\gamma\gamma}$> 0.4
  - Main challenge and uncertainty from non-prompt photons; estimated with data-driven methods



Fiducial cross section [pb]	$\sigma_{\gamma\gamma}$	± unc.
SHERPA MEPS@NLO	33.2	$^{+7.7}_{-5.6}$
NNLOJET NNLO	29.7	$^{+2.4}_{-2.0}$
NLO	19.6	$^{+1.6}_{-1.3}$
LO	5.3	$^{+0.5}_{-0.5}$
DIPHOX NLO	20.8	$^{+3.2}_{-2.9}$
Data	31.4	2.4



- Differential distributions in agreement with Sherpa MEPS and Fixed Order NNLO

QCD

EVENT SHAPE

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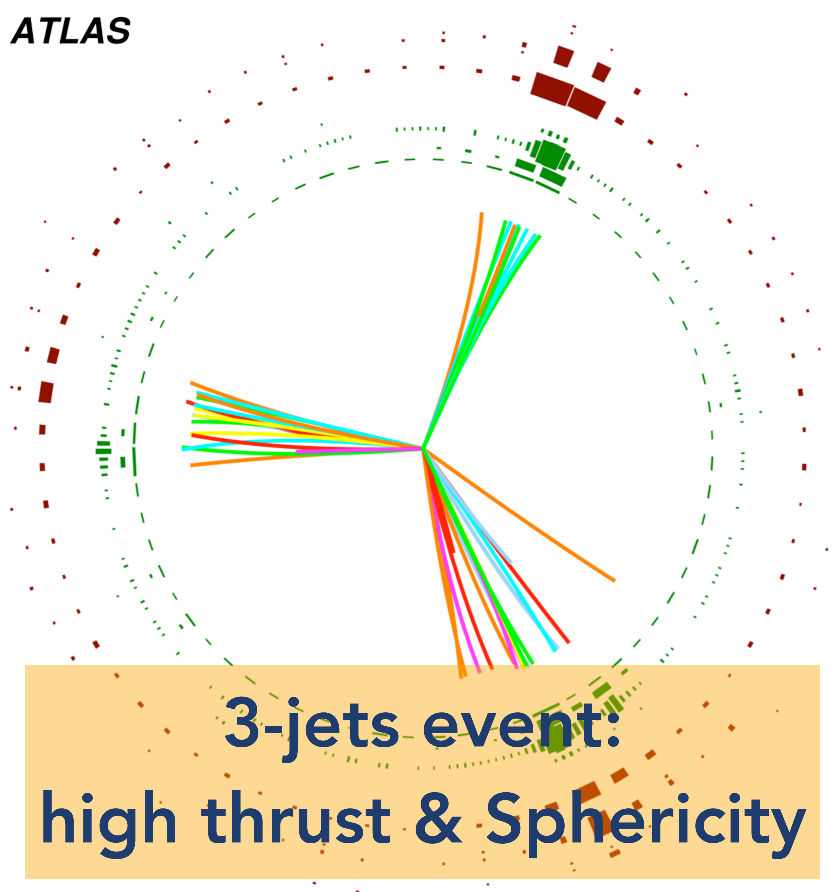
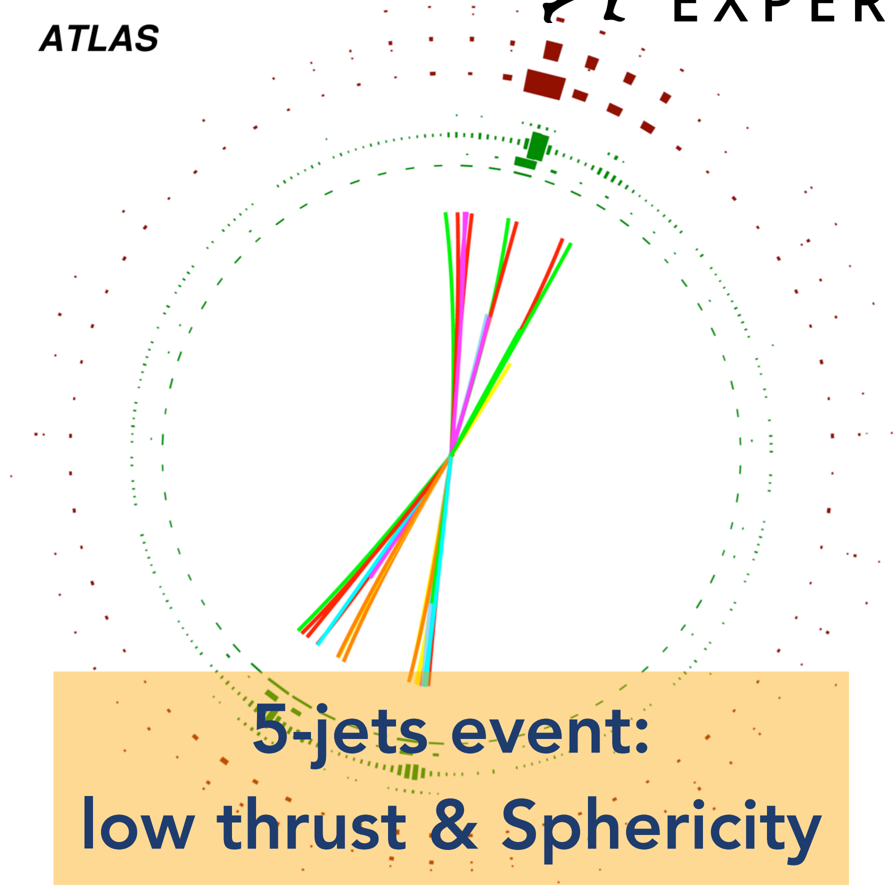
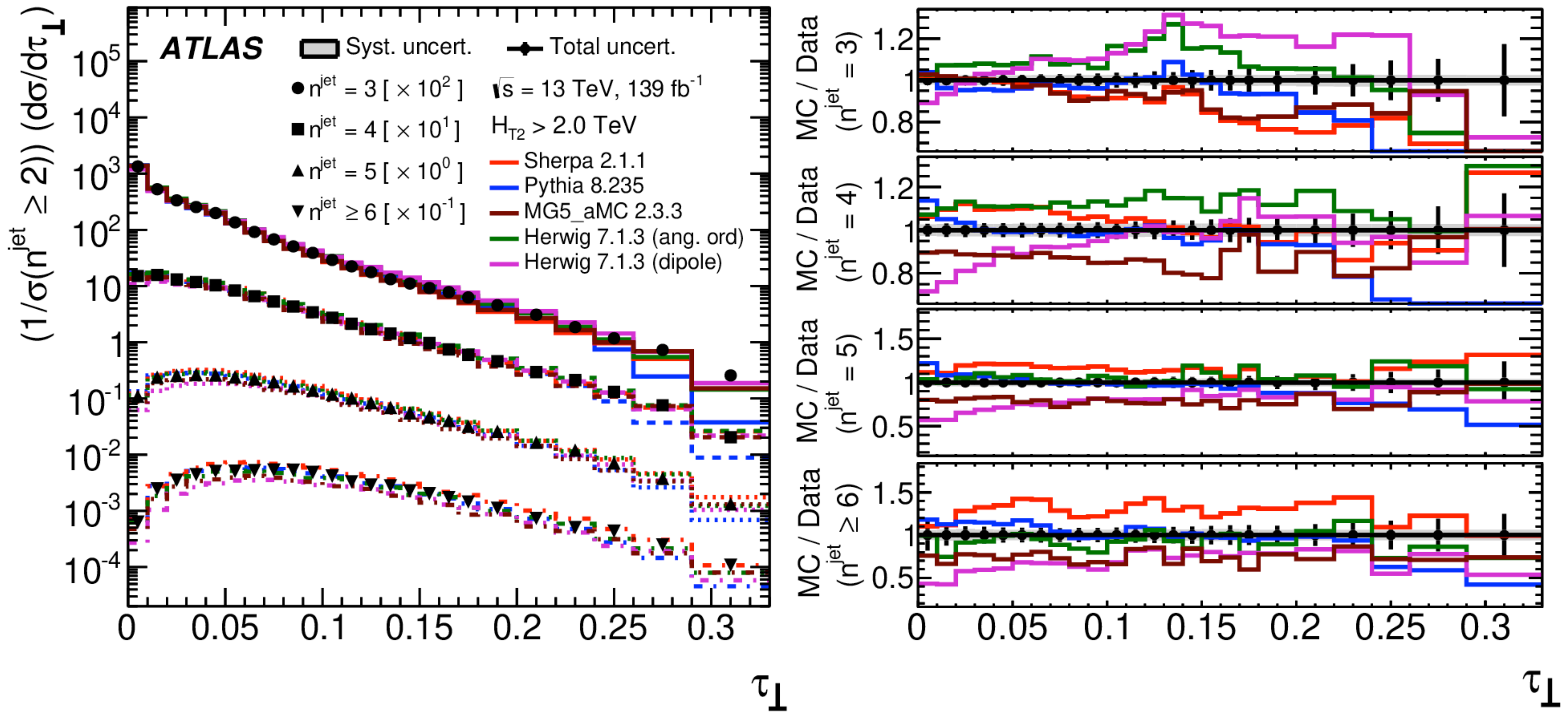
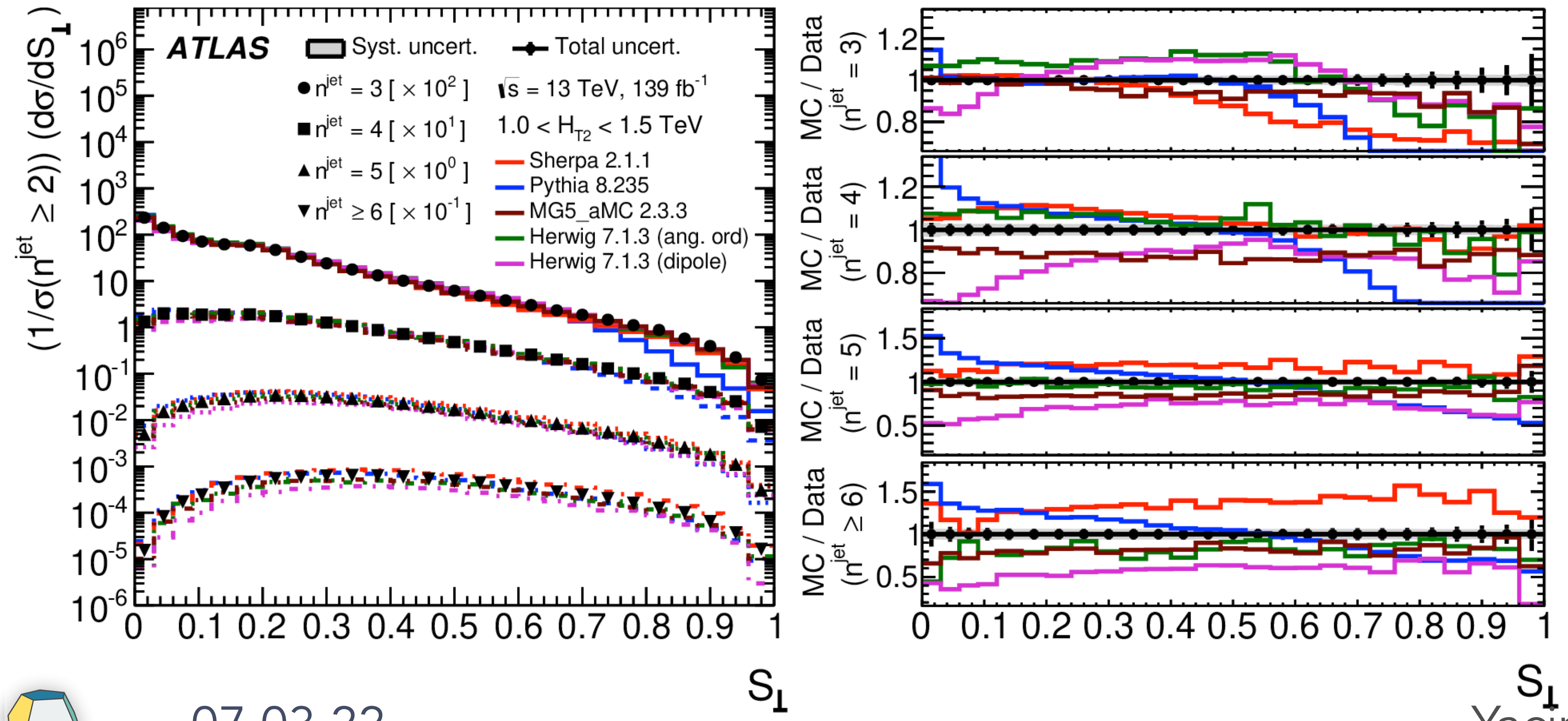
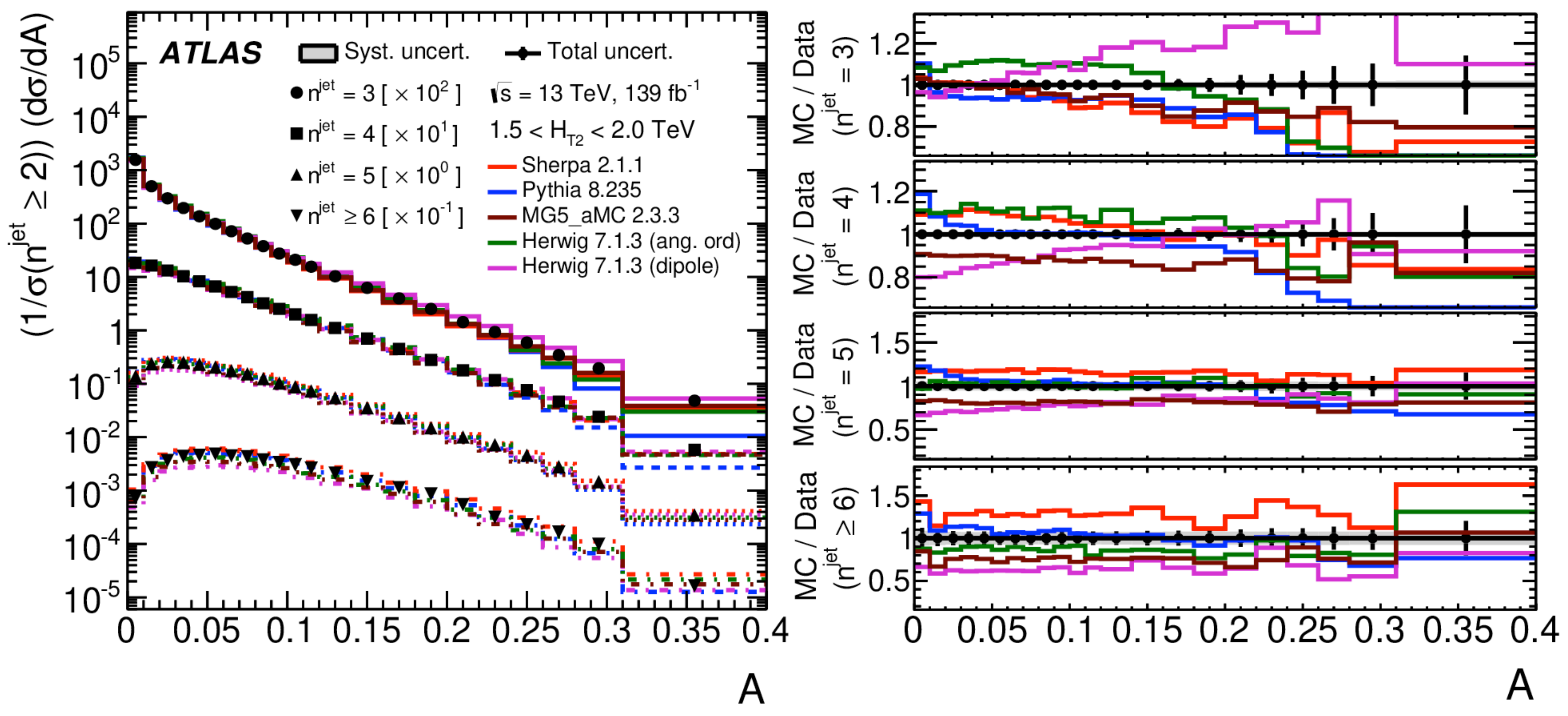
- Full Run II 13 TeV data 139/fb
- Measurements in various event-shape variables:
  - i.e, transverse thrust (τ_T), Sphericity (S), Aplanarity (A) …
  - Done in bins of N_{jets} & in different ranges of $H_{T2} = \sum_{\text{leading 2j}} |p_T|$
- Measurements compared to MC with LO & NLO ME matched to PS at LL accuracy











- At low N_{jets}: shape discrepancies are observed
- At high N_{jets}: better agreement in shapes, but discrepancies observed in normalisation.

INCLUSIVE & MULTI-JET PRODUCTION

CMS-PAS-SMP-21-009

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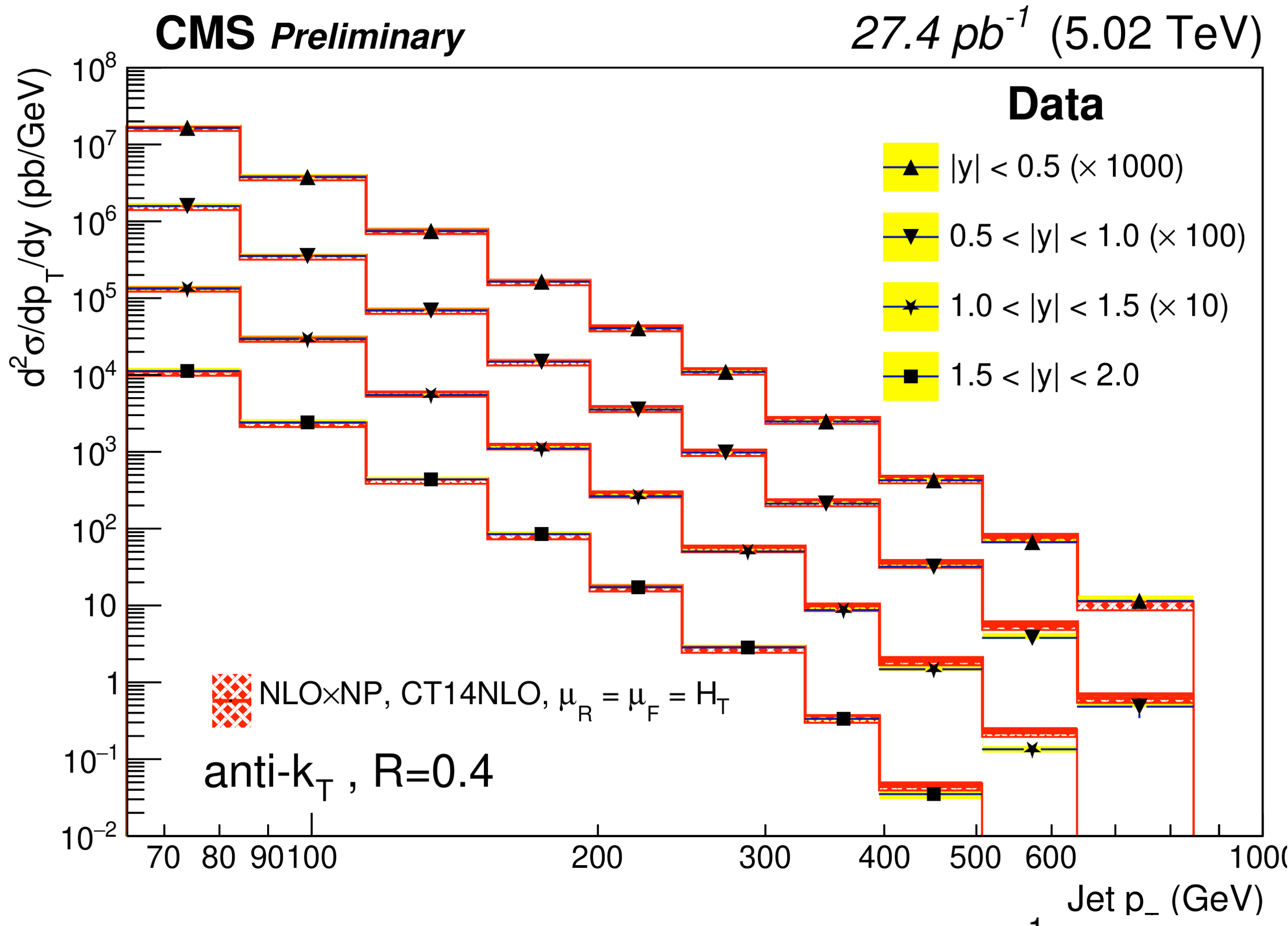
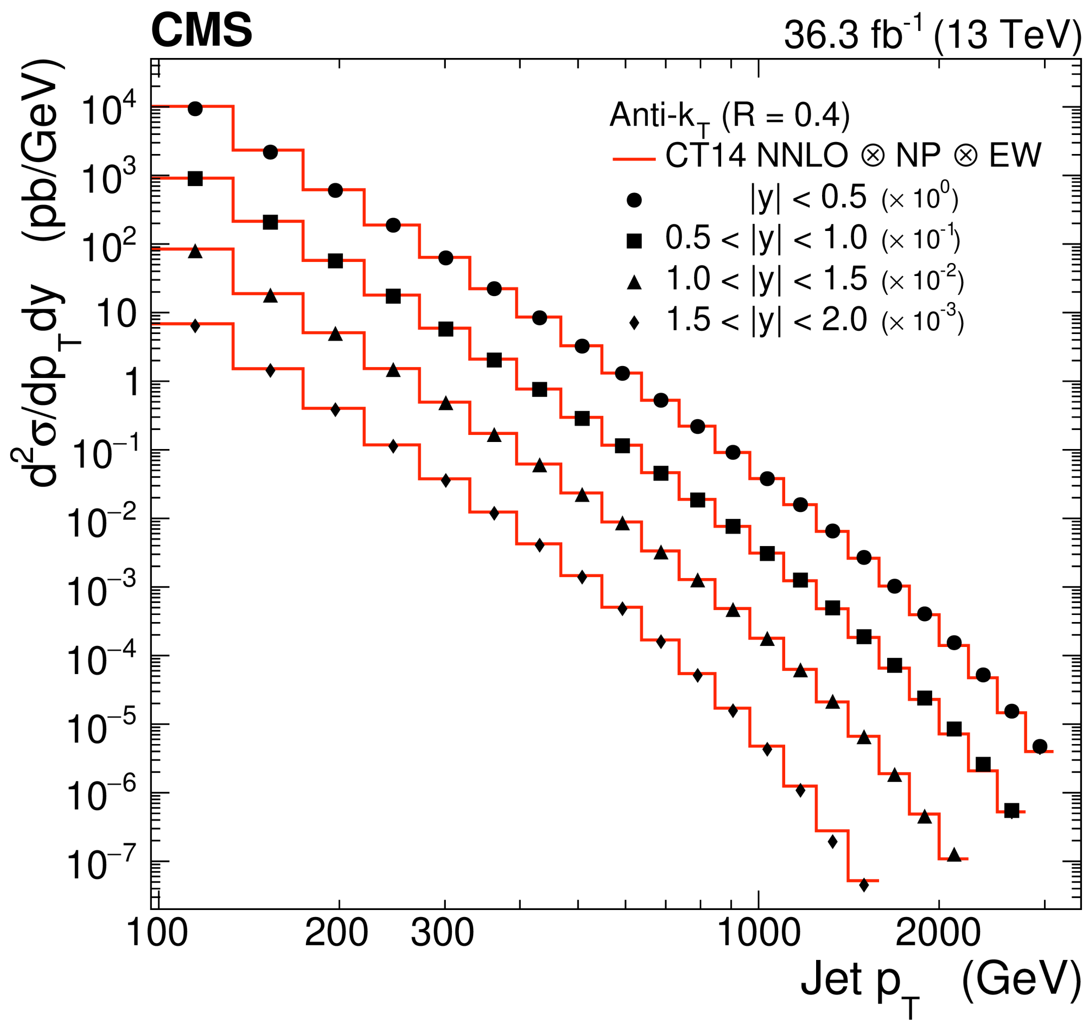
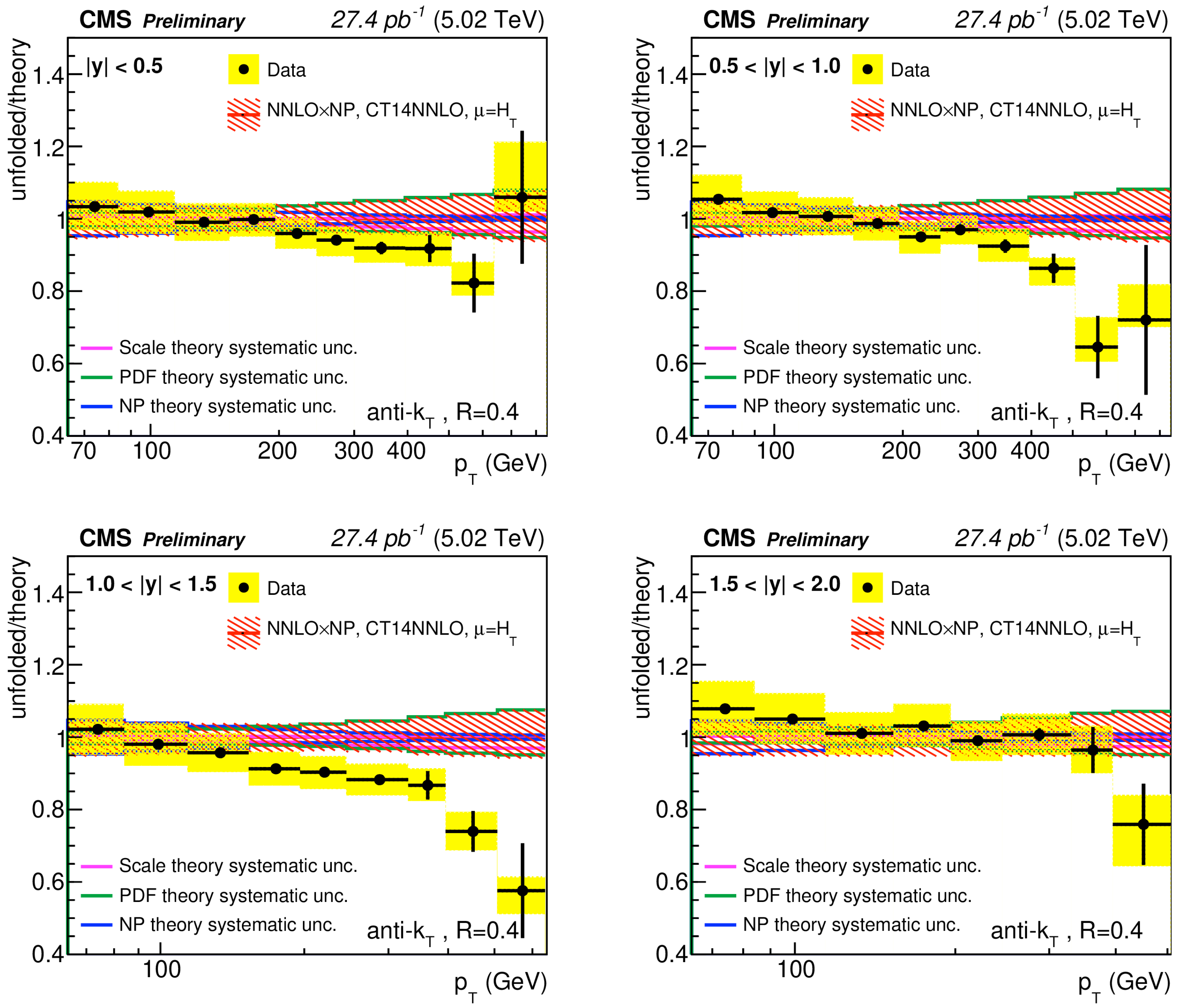
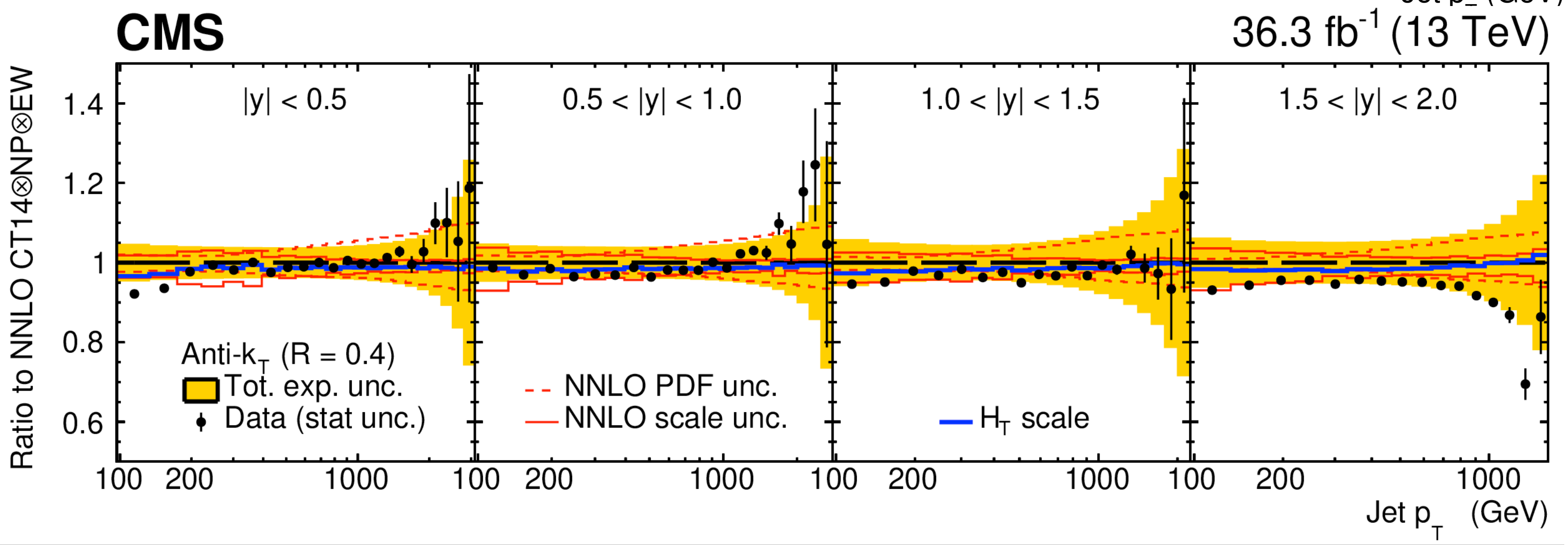
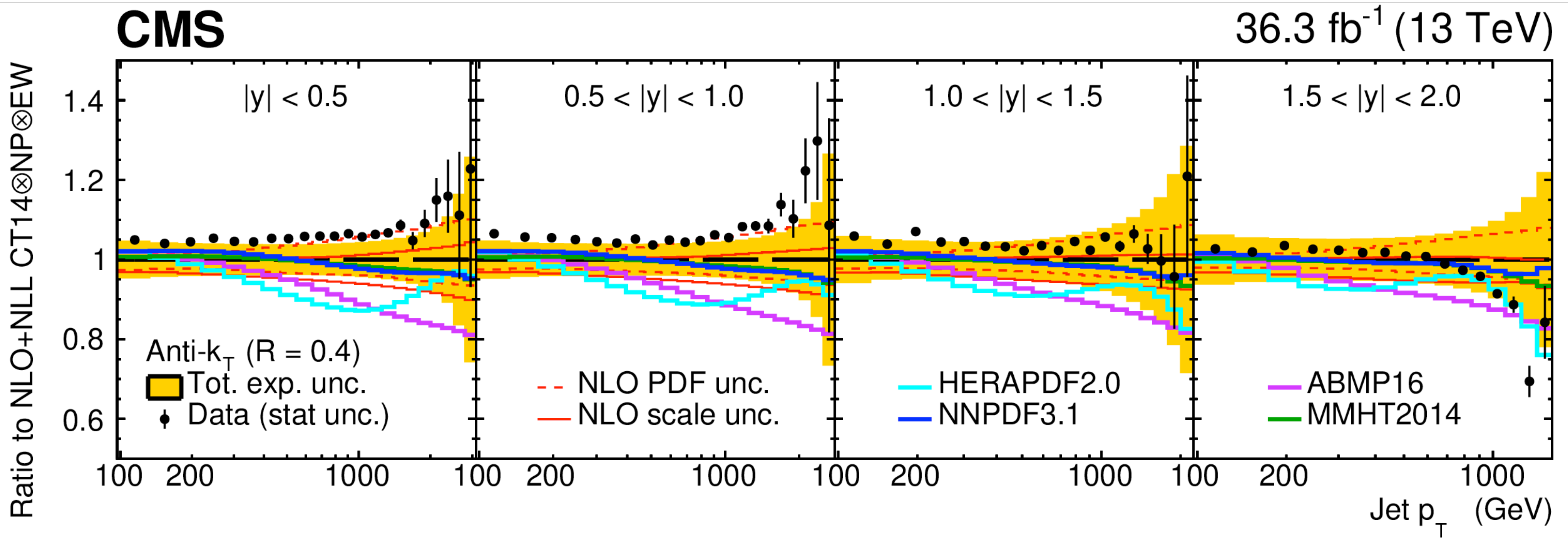
- **5 TeV data with 27.4/pb and 13 TeV data with 33.5/fb**
  - Anti-k_T jets with R=0.4/0.7 @ 5 & 13TeV
  - Measurements done for inclusive jet production and differential cross-section unfolded to particle-level jets with |y|<2









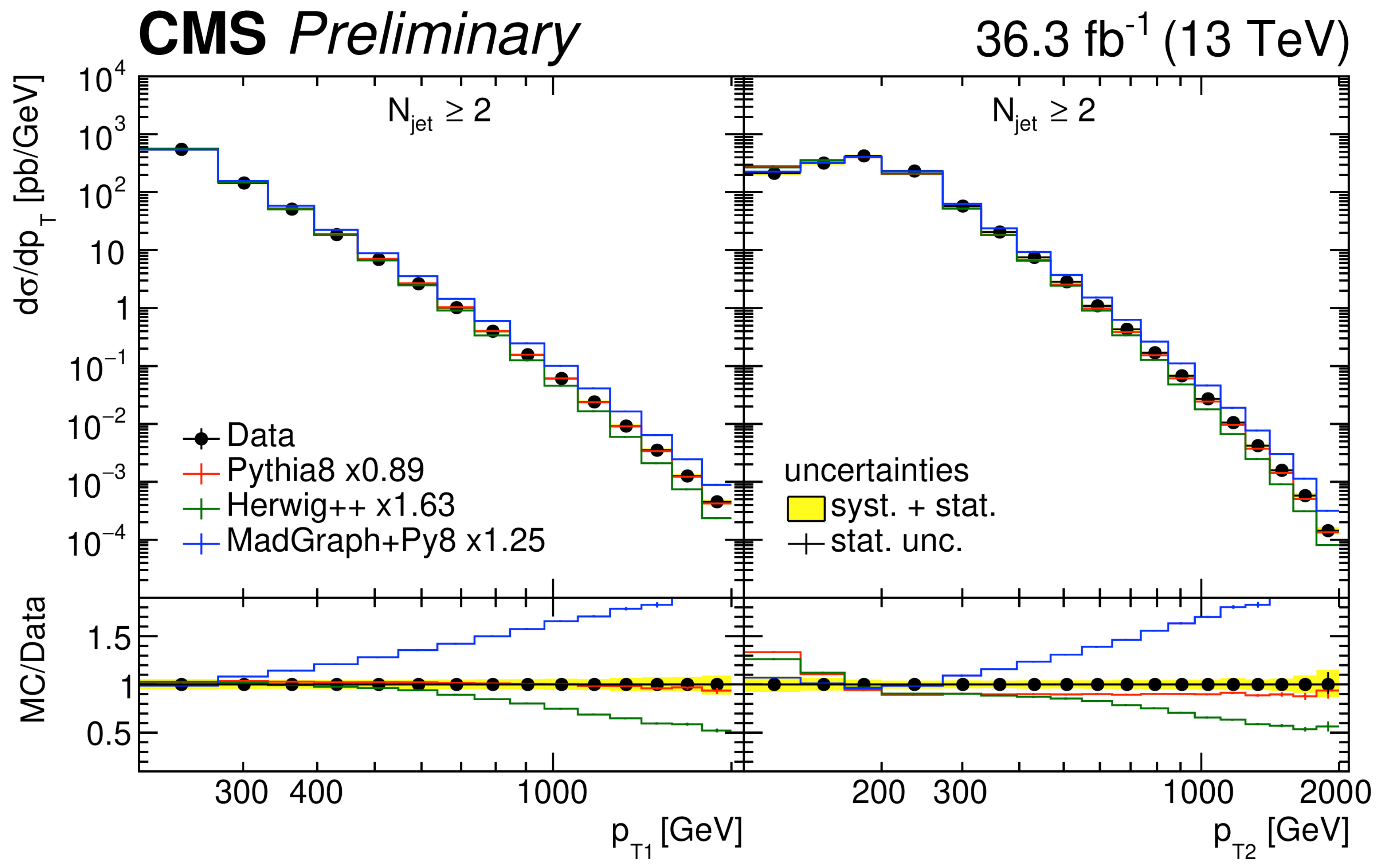


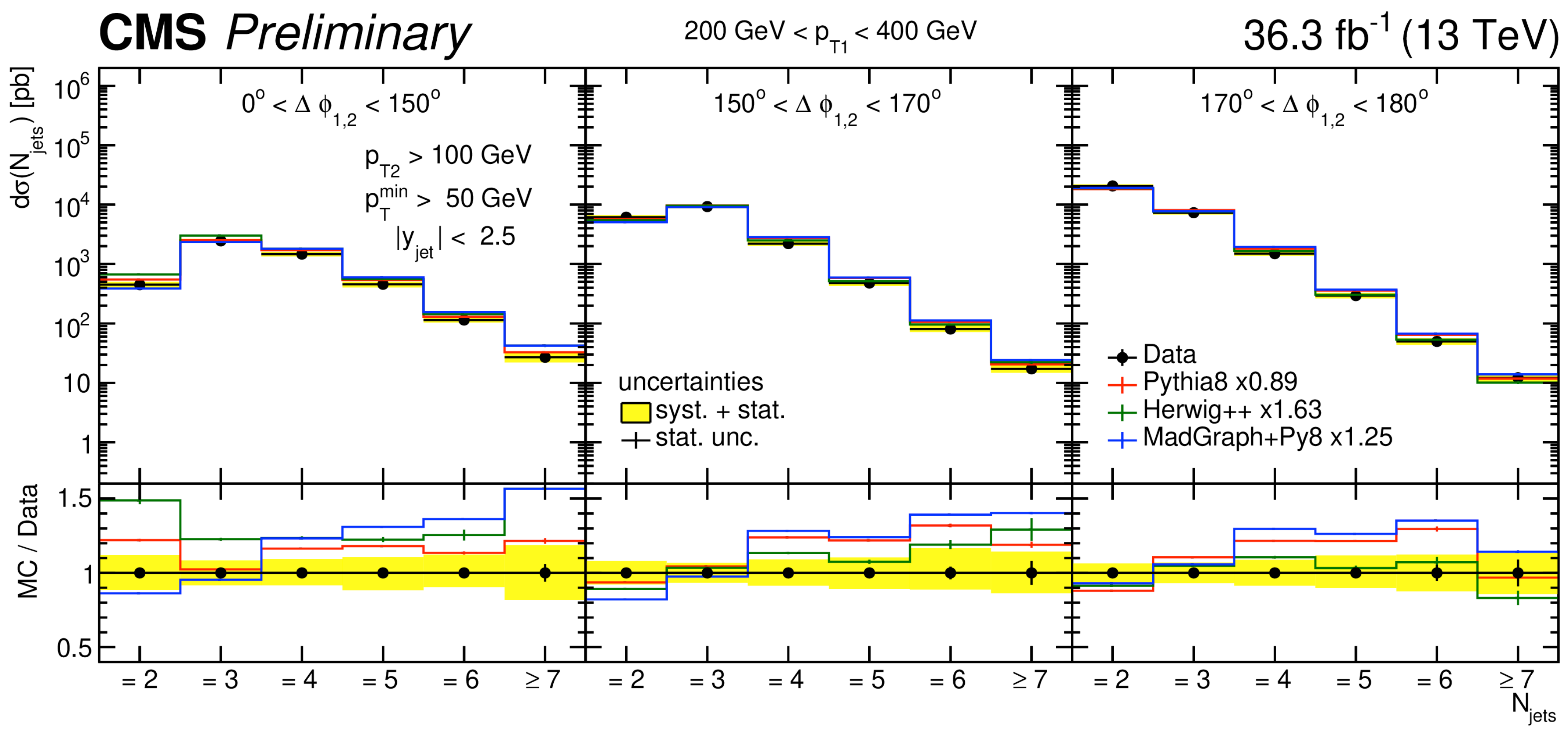
- Results compared to NLO and NNLO QCD predictions H_T scale where $H_T = \sum_{\ell,\text{jets}} |p_T|$

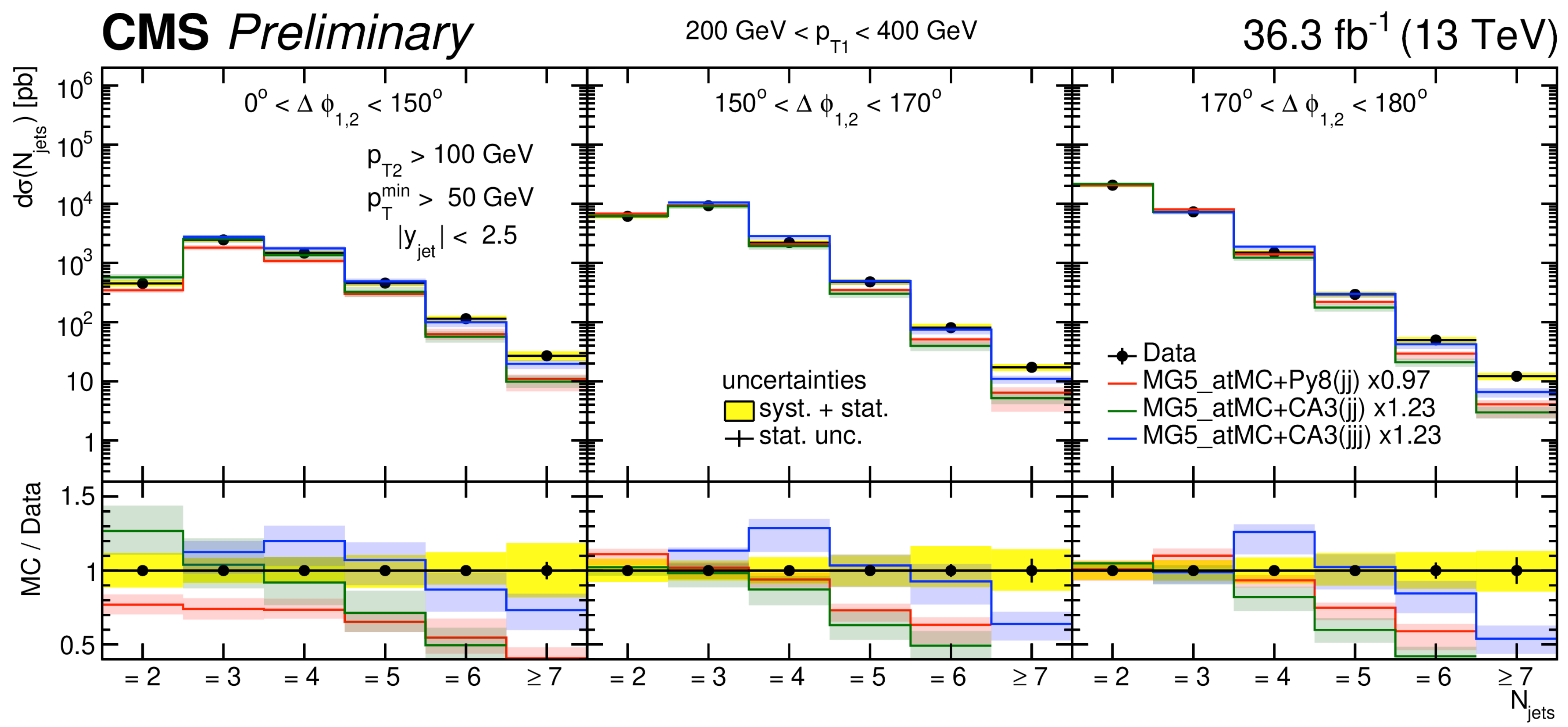
INCLUSIVE & MULTI-JET PRODUCTION

CMS-PAS-SMP-21-006

- **13 TeV data with 36.5/fb**
  - Multi-jet events with p_T(jet)>200, 100, 50 GeV and |y|<2.5
  - Differential measurements in N_{jets}, $p_T(j_1)$, $\Delta\phi_{1,2}$
  - Data compared to
    - LO predictions
    - NLO dijet predictions of MG5_aMC+Py8 (jj) & MG5_aMC+CA3 (jj)
    - NLO three-jet prediction of MG5_aMC+CA3 (jjj)
    - All Normalised to measured inclusive dijet cross-section







- Better agreement at lower jet multiplicities, but prediction for high jet multiplicities disagree with data

INCLUSIVE & MULTI-JET PRODUCTION

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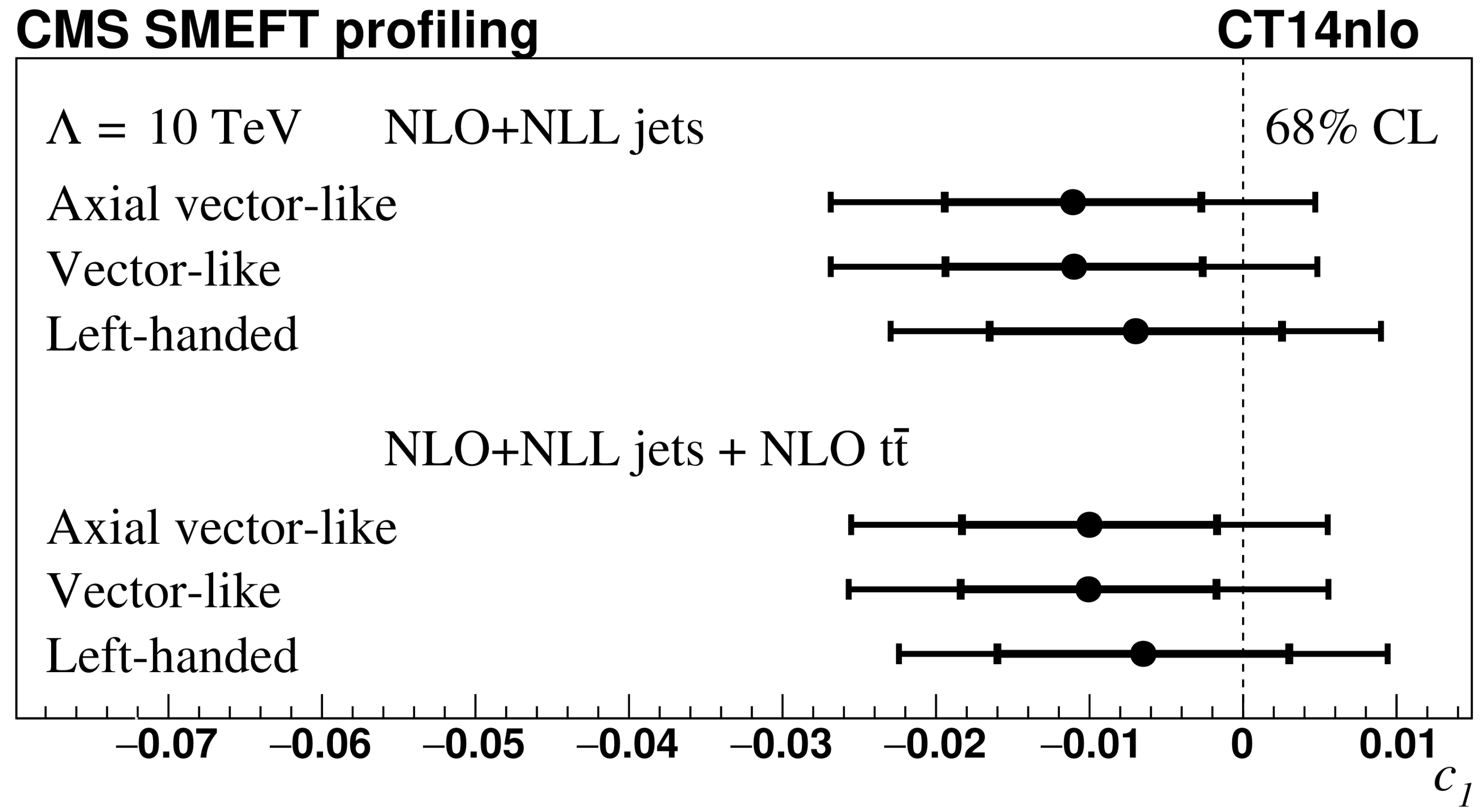
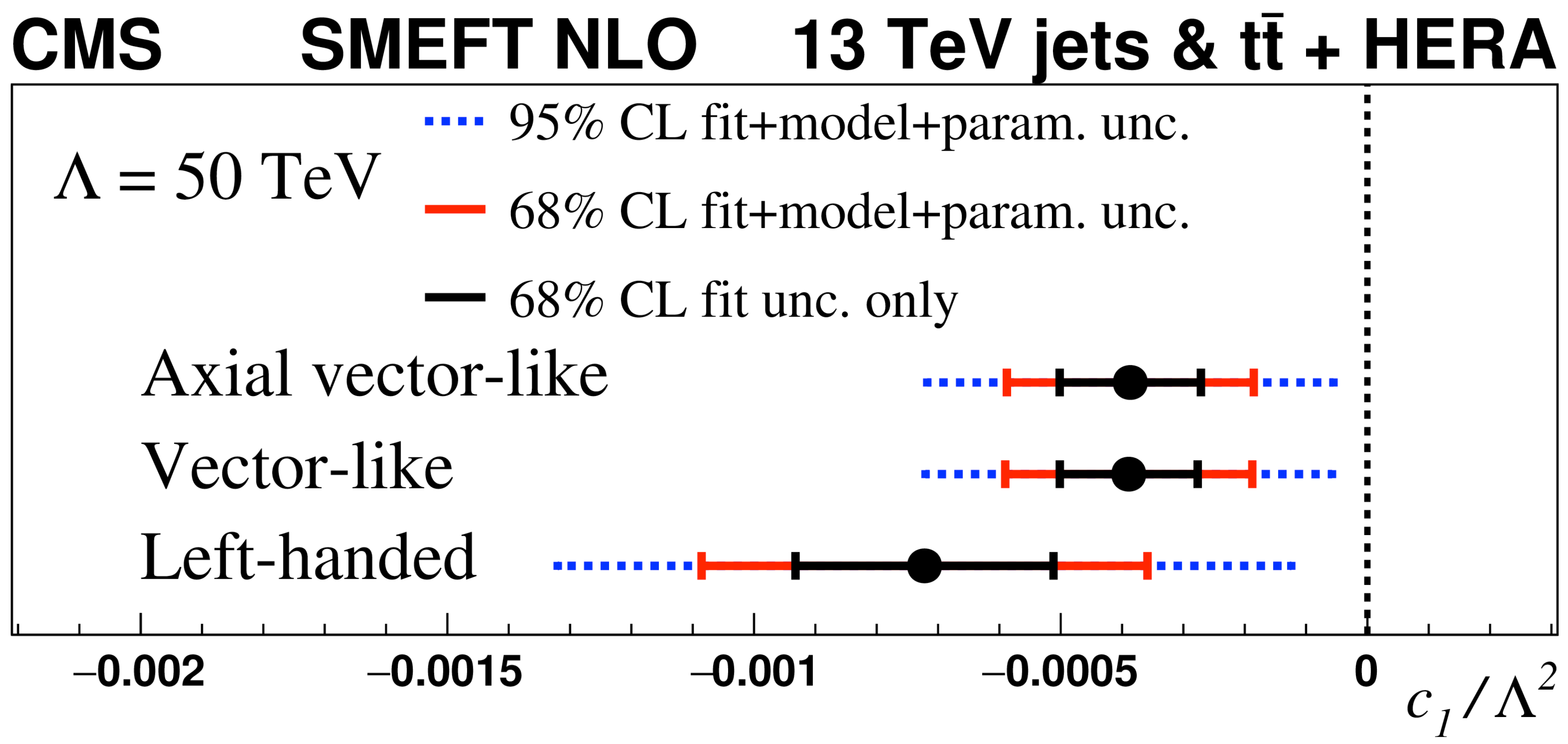
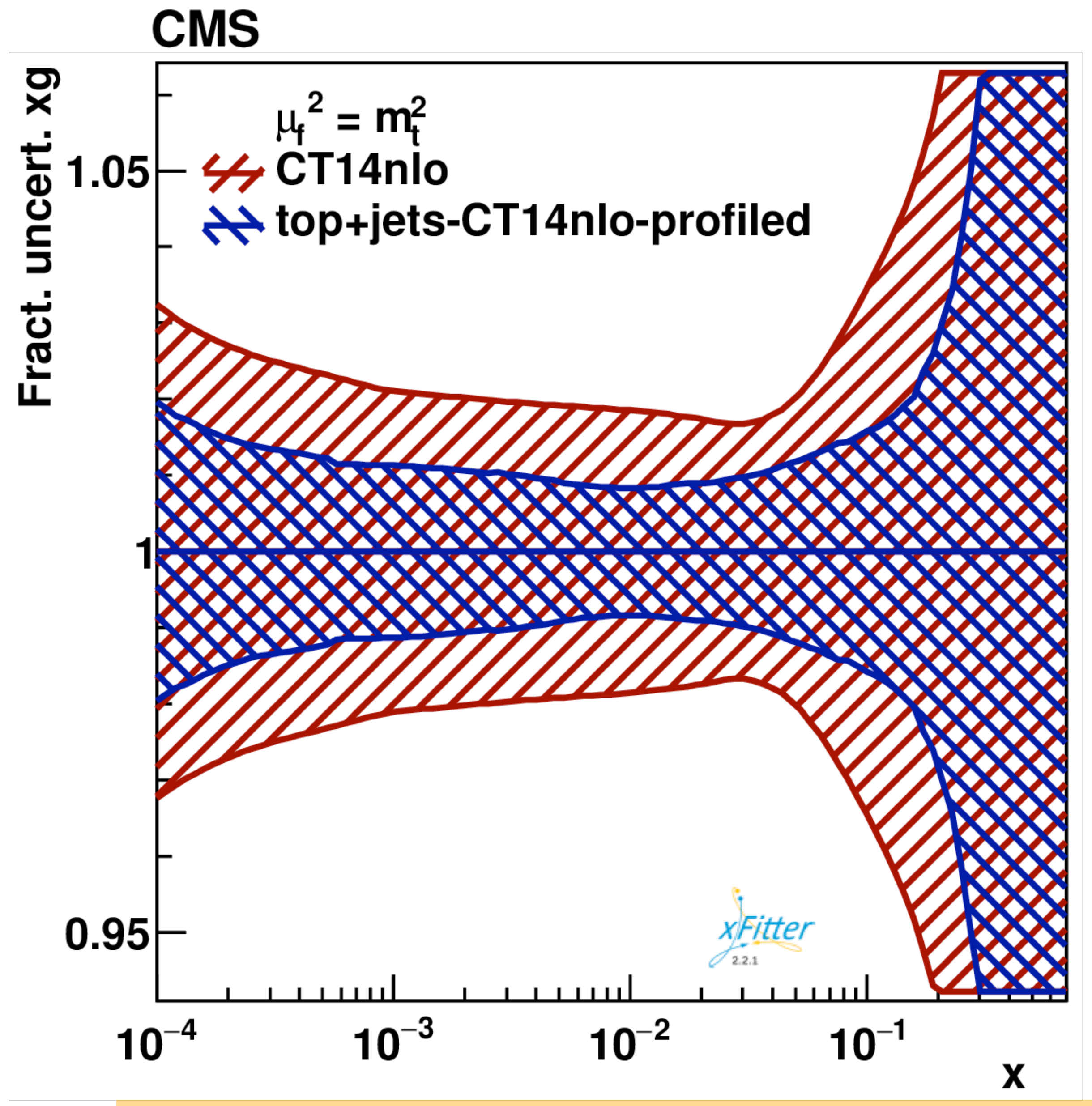
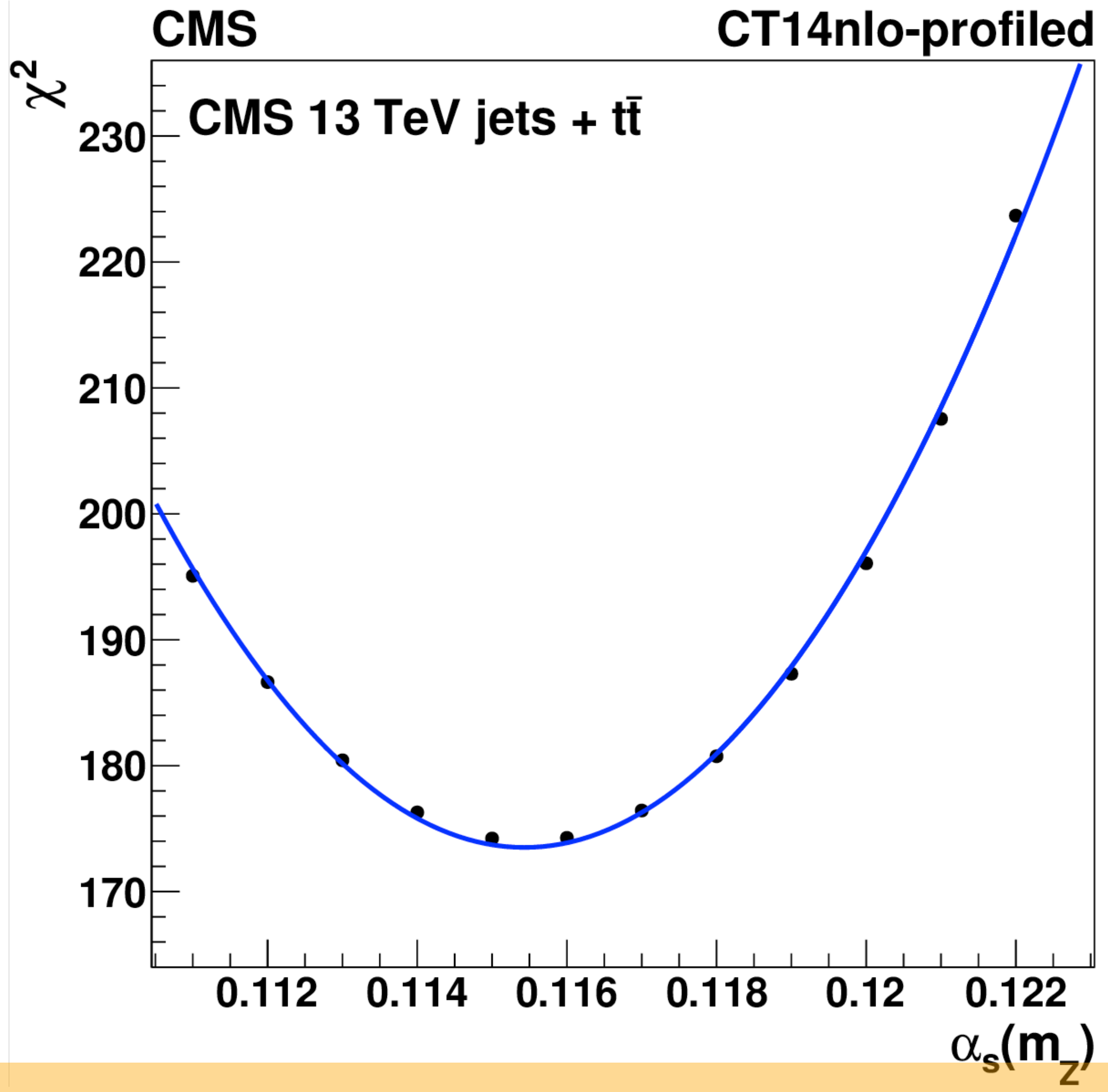
- **13 TeV data with 36/fb.**
- CMS jet and top cross sections + HERA DIS measurements
- Determine: PDFs, α_s, m_{top}, limits on Wilson coefficients for quark Contact-Interactions (CI)









$$\alpha_S(m_Z) = 0.1154 \pm 0.0009 \text{ (PDF)} \pm 0.0015 \text{ (scale)}$$
$$m_t^{\text{pole}} = 170.3 \pm 0.5 \text{ (PDF)} \pm 0.2 \text{ (scale) GeV}$$

- Considerable improvement on gluon PDFs knowledge
- Results of profiling and full fit show agreement between the measurements and the SM prediction

B FRAGMENTATION

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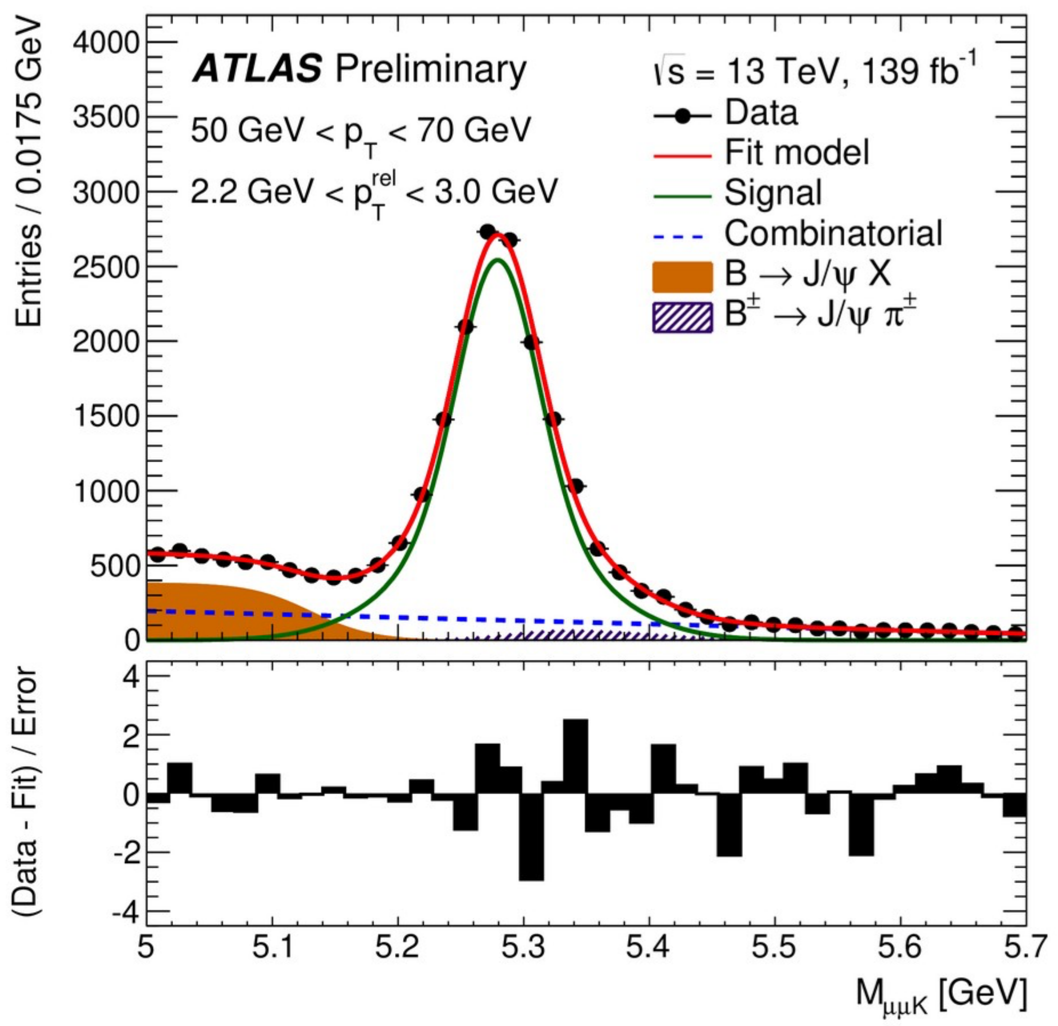
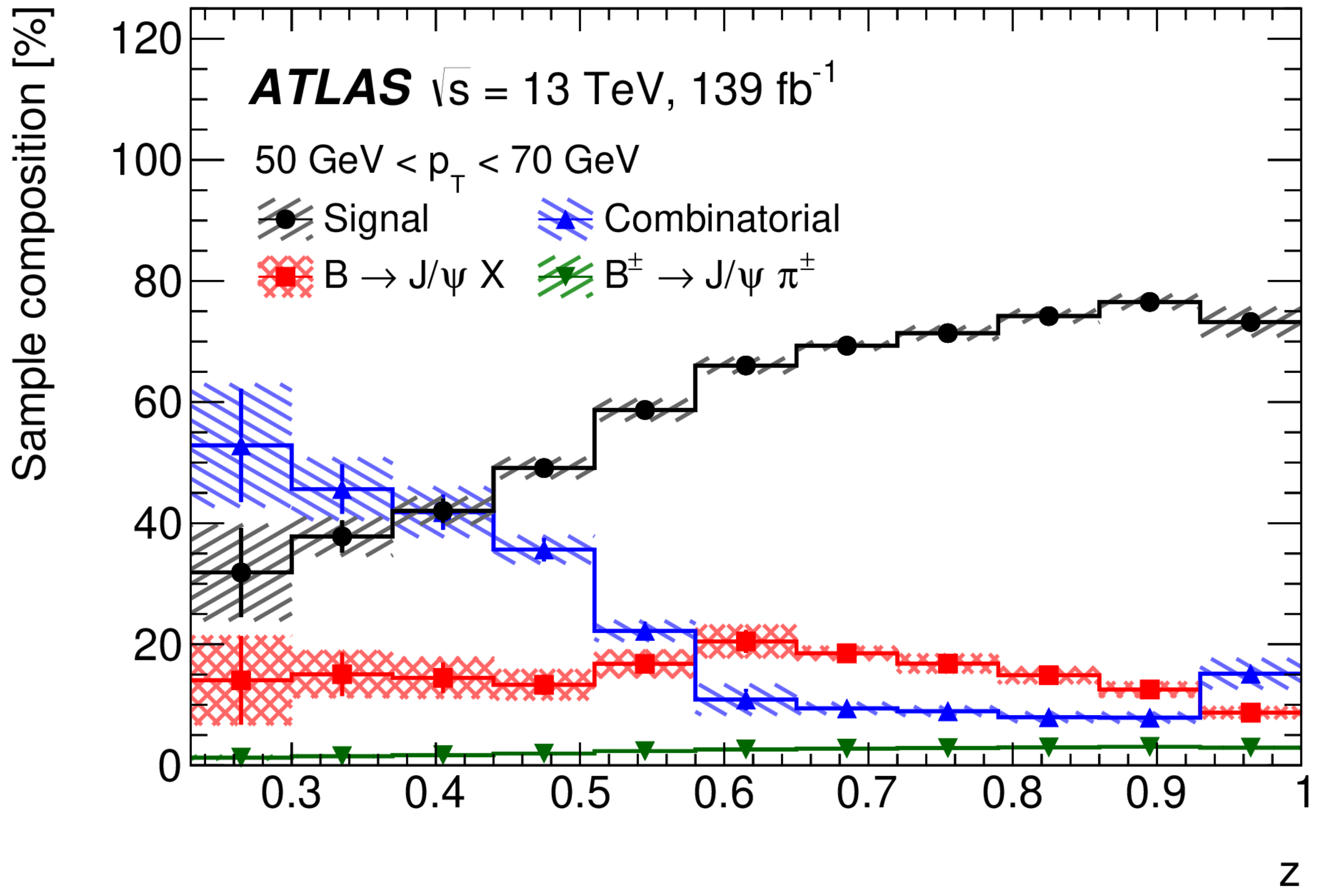
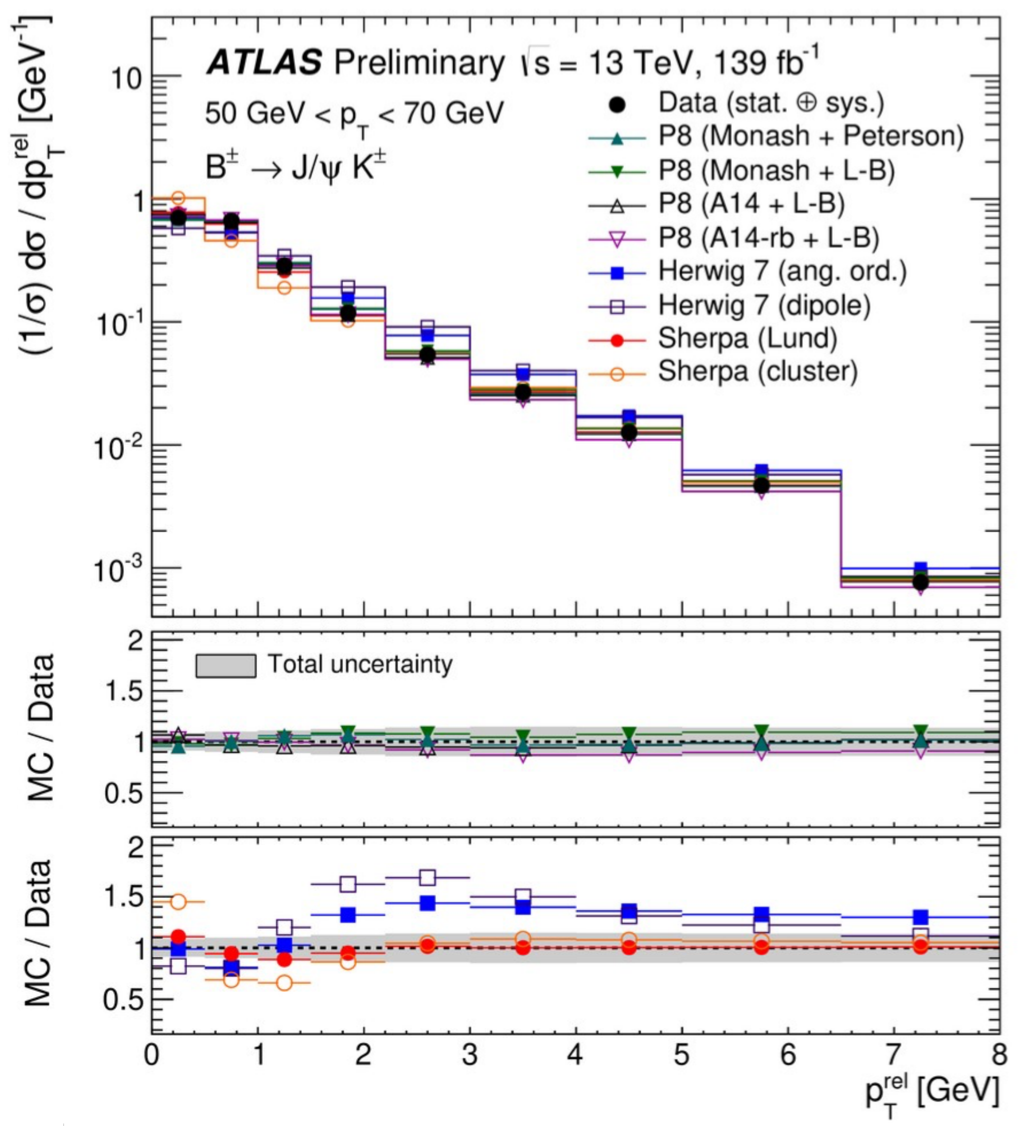
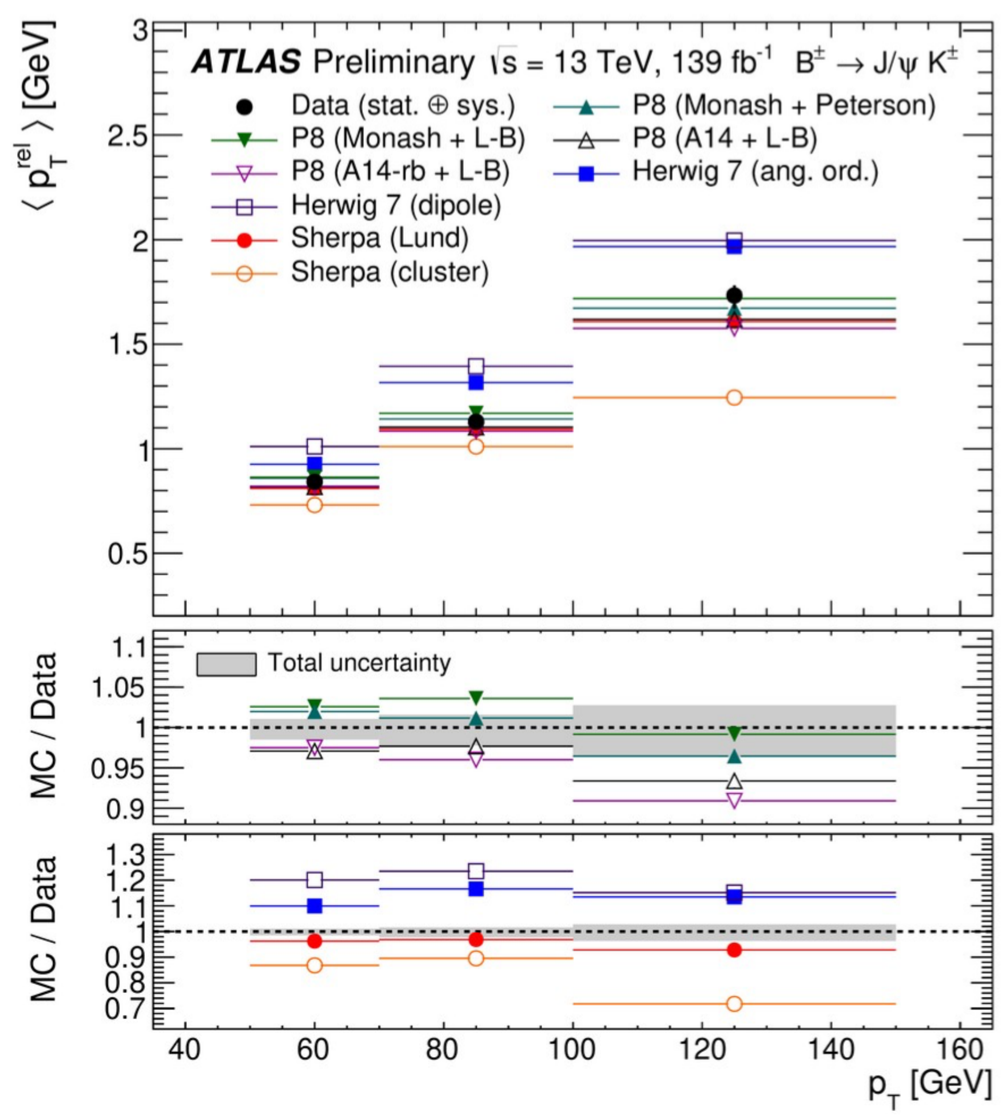
ATLAS EXPERIMENT

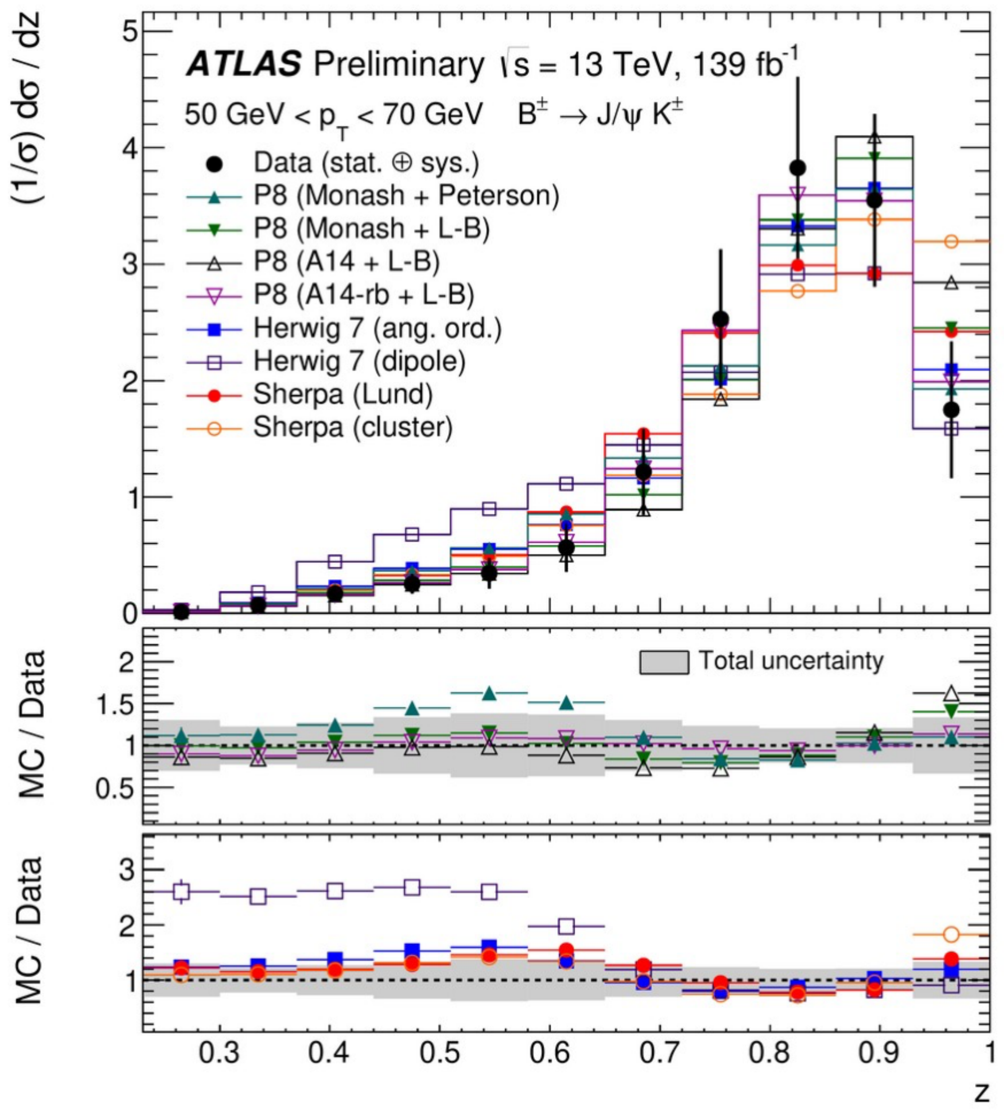
- **Full run II 13 TeV data with139/fb**
  - Fit in M_B in every z, p_T^{rel} and p_T^j bin using MC templates for signal and background
  - Differential cross sections in z and p_T^{rel}

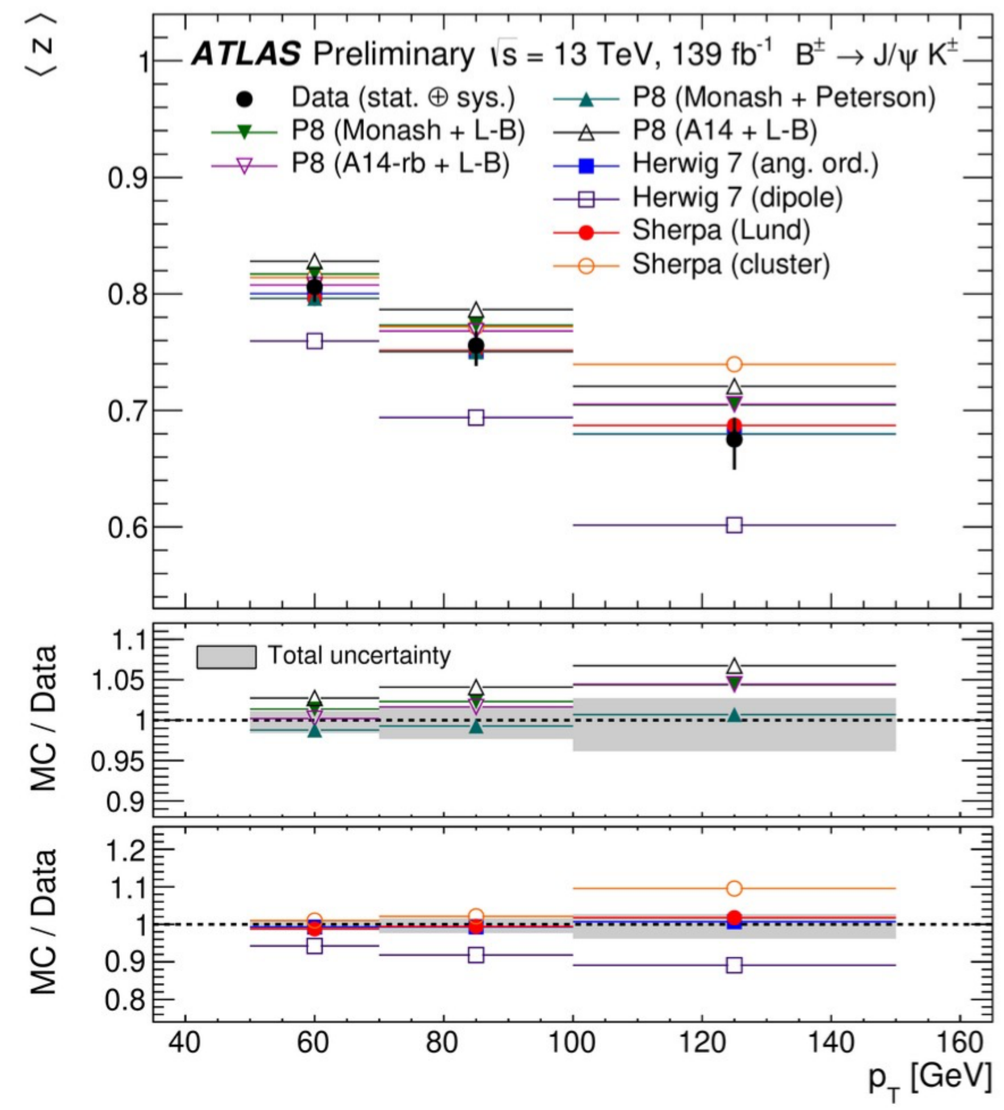












- Pythia fragmentation models tend to give a decent description of the data.
- HERWIG 7 (dipole shower) is off in different regions.

JET SUBSTRUCTURE MEASUREMENTS

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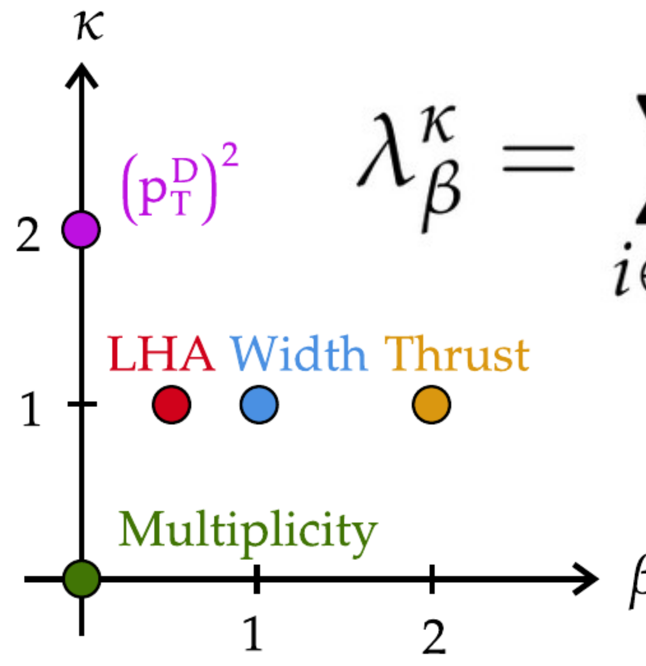
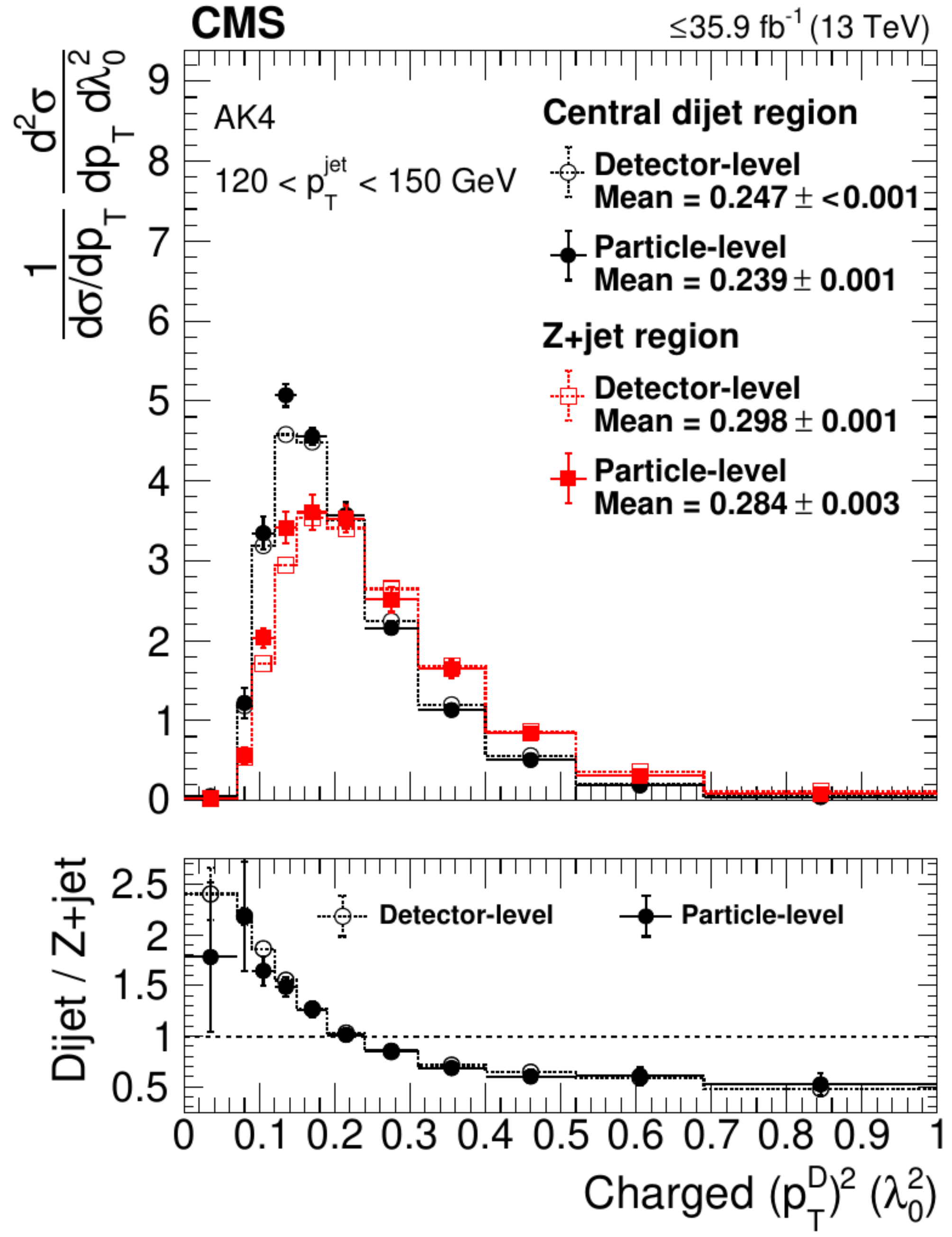
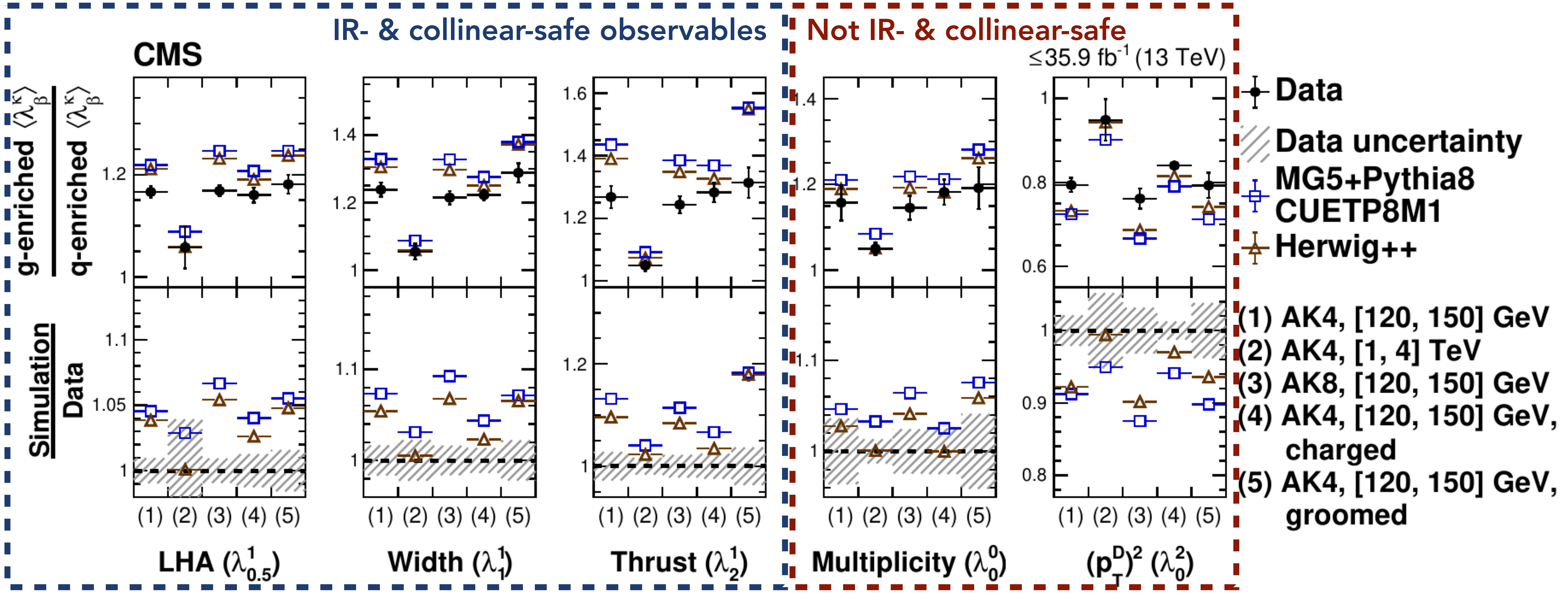
- **13 TeV data with 35.9/fb**
  - Useful tool for distinguishing between quark/gluon jets and evaluating MC simulations
  - Regions: dijet (gluon-jet-enriched) vs Z+jets (quark-jet-enriched)
  - Observable: **generalised angularities** = weighted sums of jet constituents by momentum fractions z and angular distance ΔR to jet axis
  - Jet substructure predictions from MC generators at NLO are compared to measurements



$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$





- MC generators systematically overestimate ratio of λ_β^κ in g-/q-jet samples
  - Improved modelling needed to fully describe jet substructure

CONCLUSION

- Showed recent SM results from ATLAS and CMS
  - Investigating V+jet and QCD processes
  - Run 2 dataset (~140/fb) has allowed precision measurements in both ATLAS and CMS
- Test higher order QCD calculations and constrain PDFs Search for effects of new physics, using the EFT formalism
  - Test higher order QCD calculations and constrain PDFs
  - Search for effects of new physics, using the EFT formalism
- Run 3 (starting soon) will double the data sample
  - Important for reducing systematic uncertainties (theoretical & experimental)
- Precision measurements can lead to (indirect) discoveries
  - New physics may hide behind error bars

BACKUP