Measurements of vector bosons (W/Z) + heavy flavour jets

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On behalf of the ATLAS and CMS collaborations

QCD@LHC
University of Freiburg, Germany
Oct 7–11, 2024

Outline

- W and Z production in association with b or c quarks, i.e. Heavy Flavour (HF) quarks, is a key probe of fundamental physics at collider experiments:
  - Test of HF quark mass (mc~1.4 GeV, mb~4 GeV) treatment in perturbative QCD (pQCD) calculations
  - Flavour of the final state can be related to flavour content of the initial state proton PDFs
  - Major background for Higgs and BSM analyses:
    - Provide guidance on MC generators modelling

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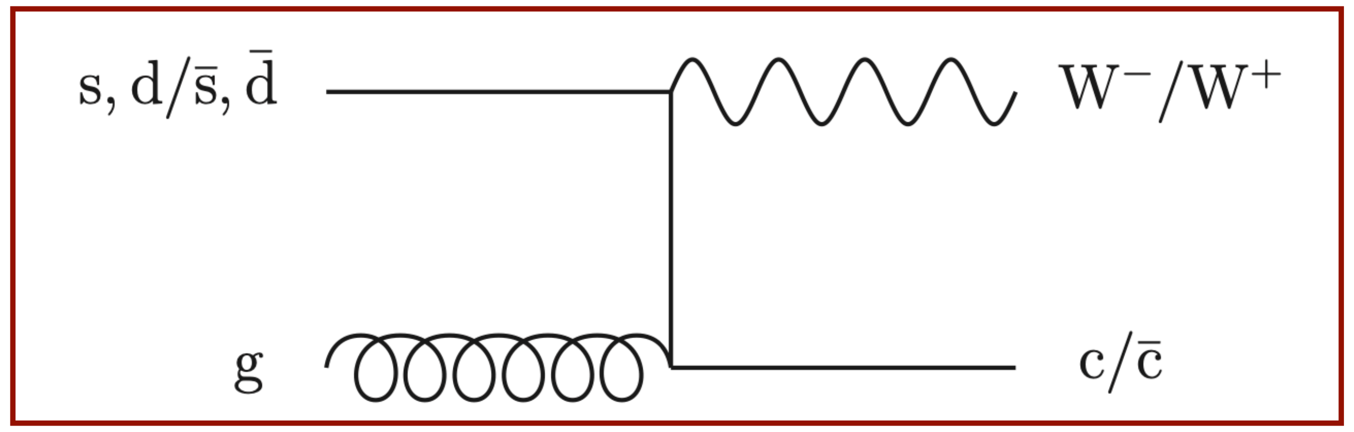
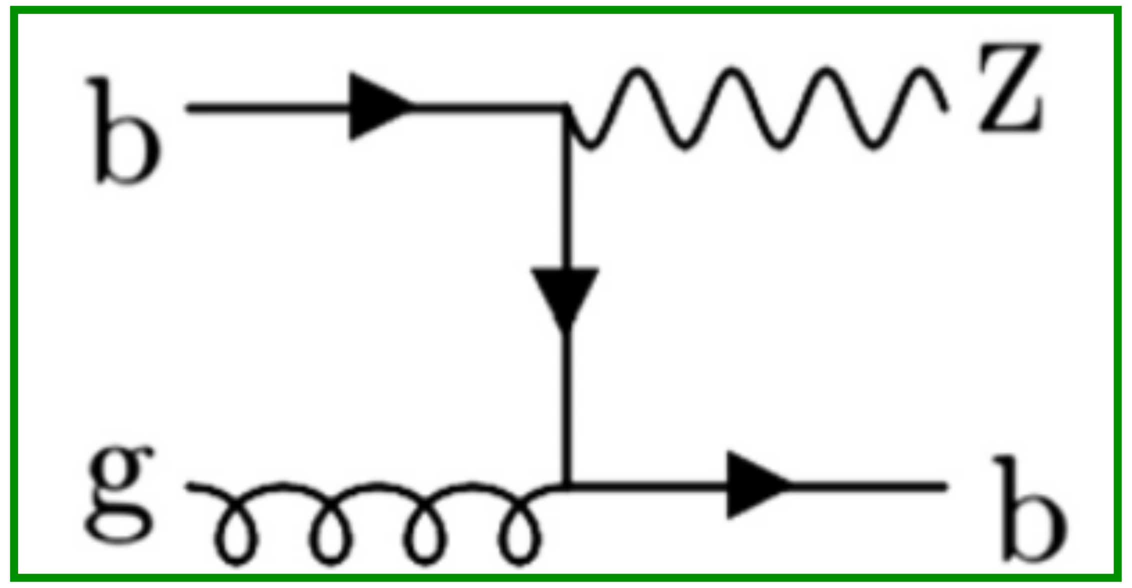
W+c-jet

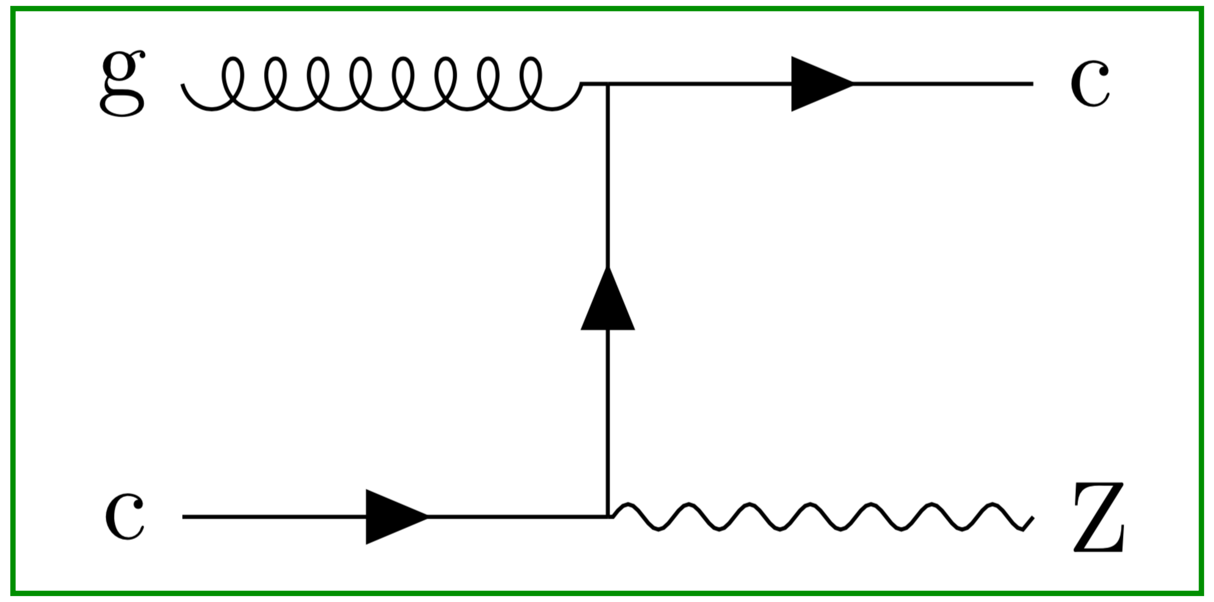




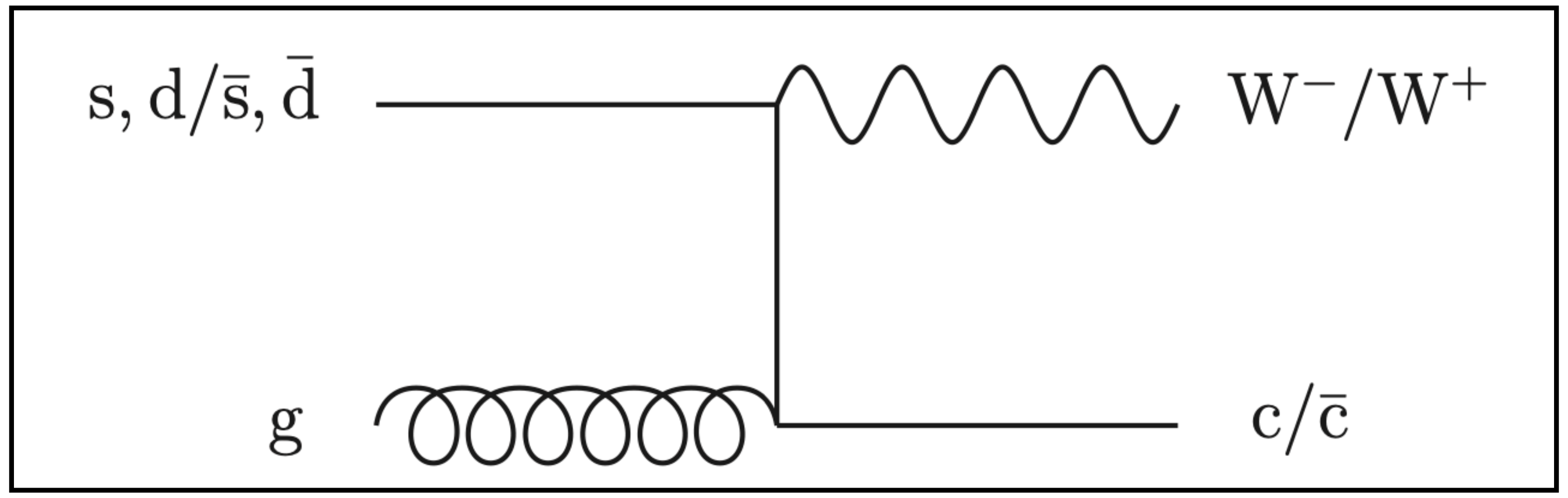
Z+b-jet

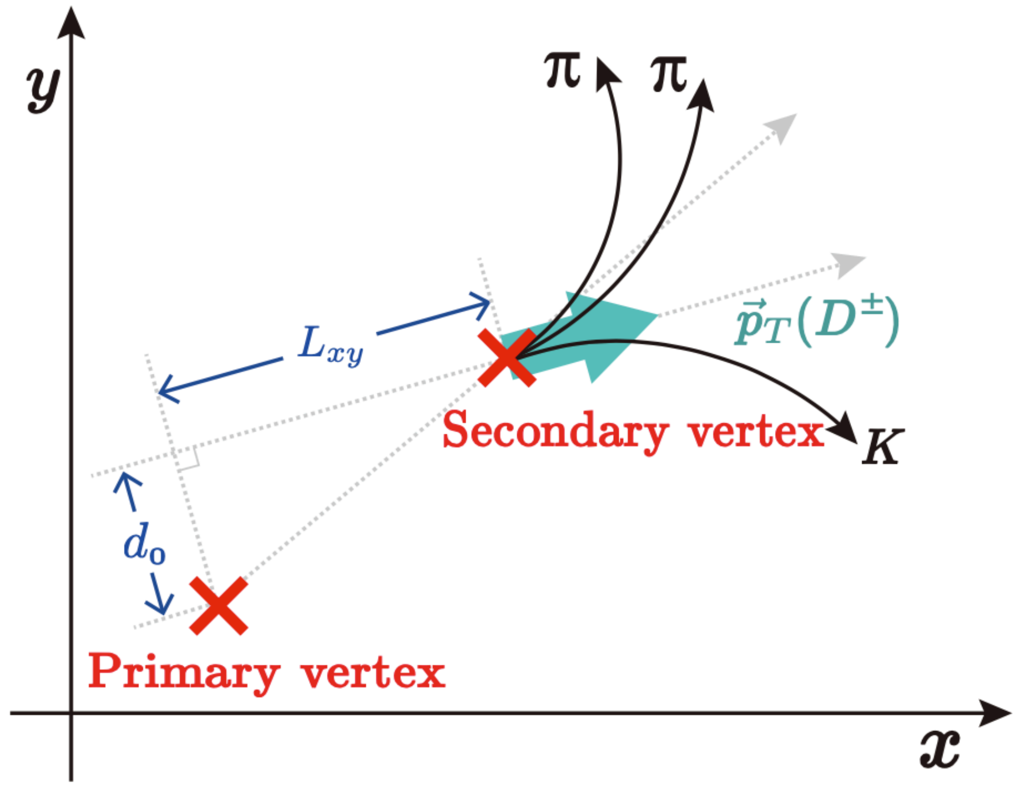
- Today's talk focused on recent measurements at 13TeV:
  - W boson in association with a charm quark:
    - ATLAS: PRD 108 (2023) 032012 , CMS: EPJC 84 (2024) 27
  - Z boson in association with b- or c-jets:
    - ATLAS: arXiv:2403.15093, Phys. Rev. Lett. 130 (2023) 161901
    - CMS: Phys. Rev. D 105 (2022) 092014, JHEP 04 (2021)109

Z+c-jet



W+charm production





- Excellent probe of the strange quark PDF

Analysis strategy:

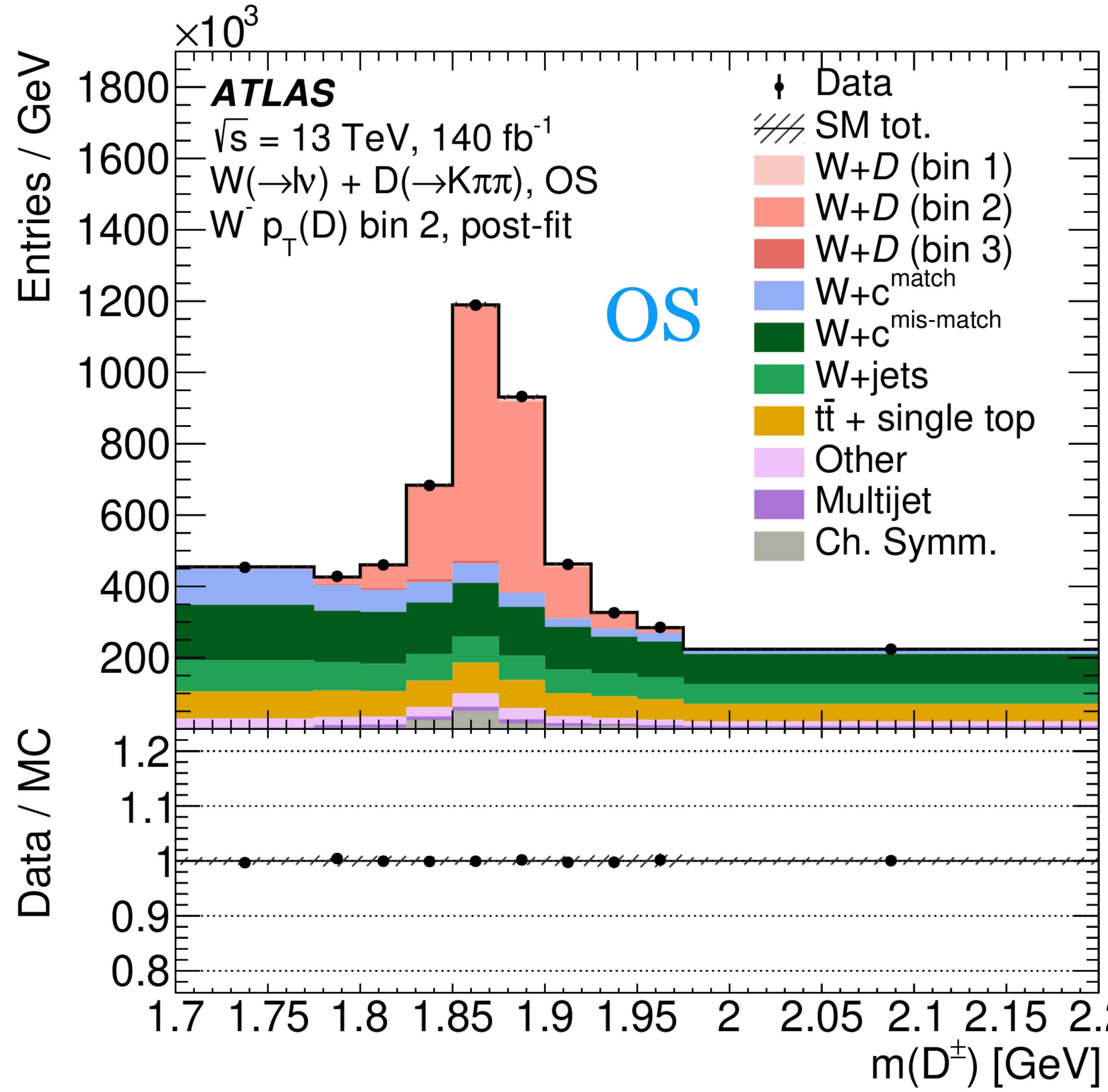
- $W^\mp$ with $D^\pm$ or $D^{*\pm}$ (ATLAS), **c-tagged jet** (CMS)
- Signal extracted as OS (Sig+Bkg) – SS (Bkg)

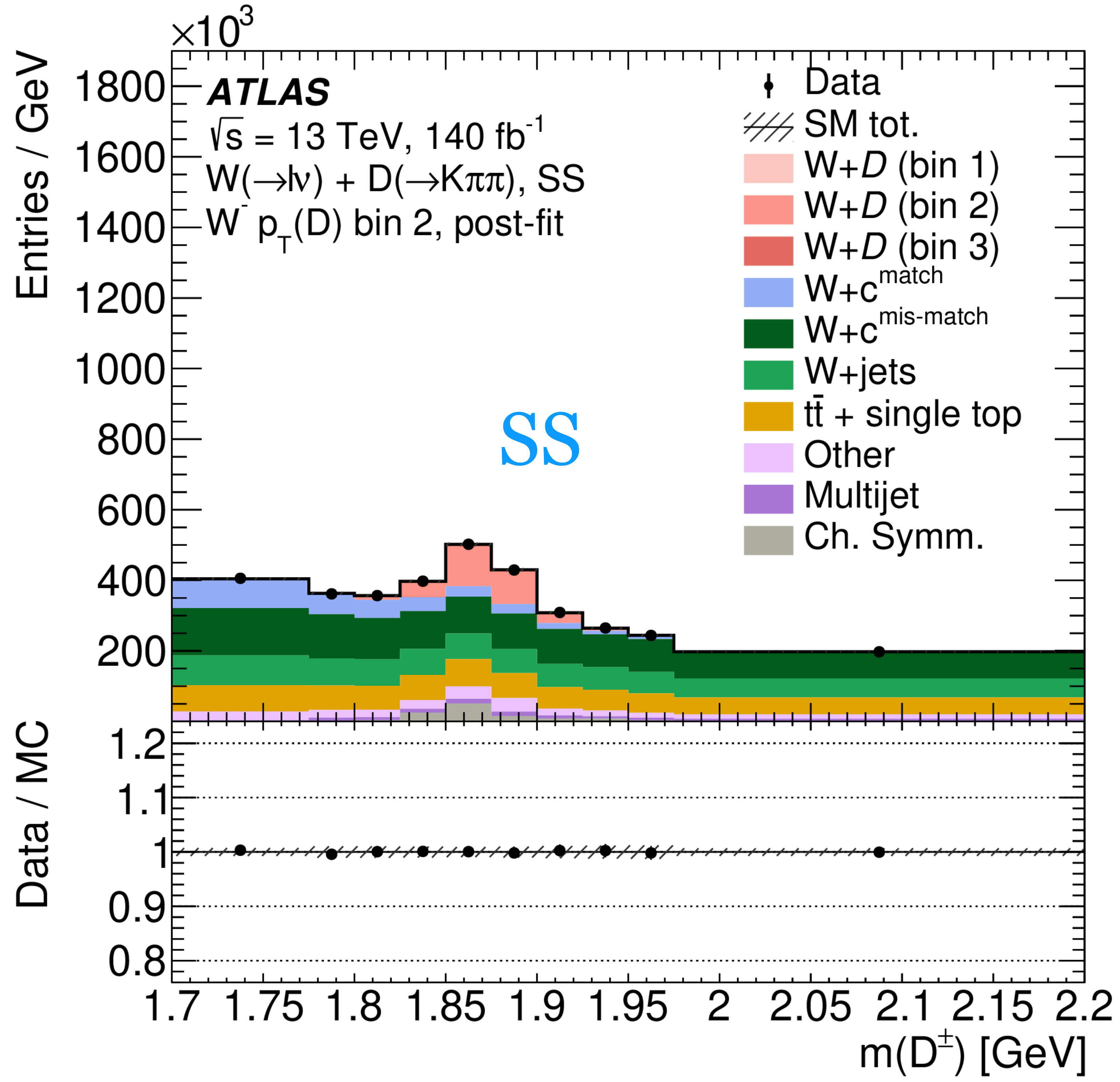
ATLAS: PRD 108 (2023) 032012 **CMS:** EPJC 84 (2024) 27

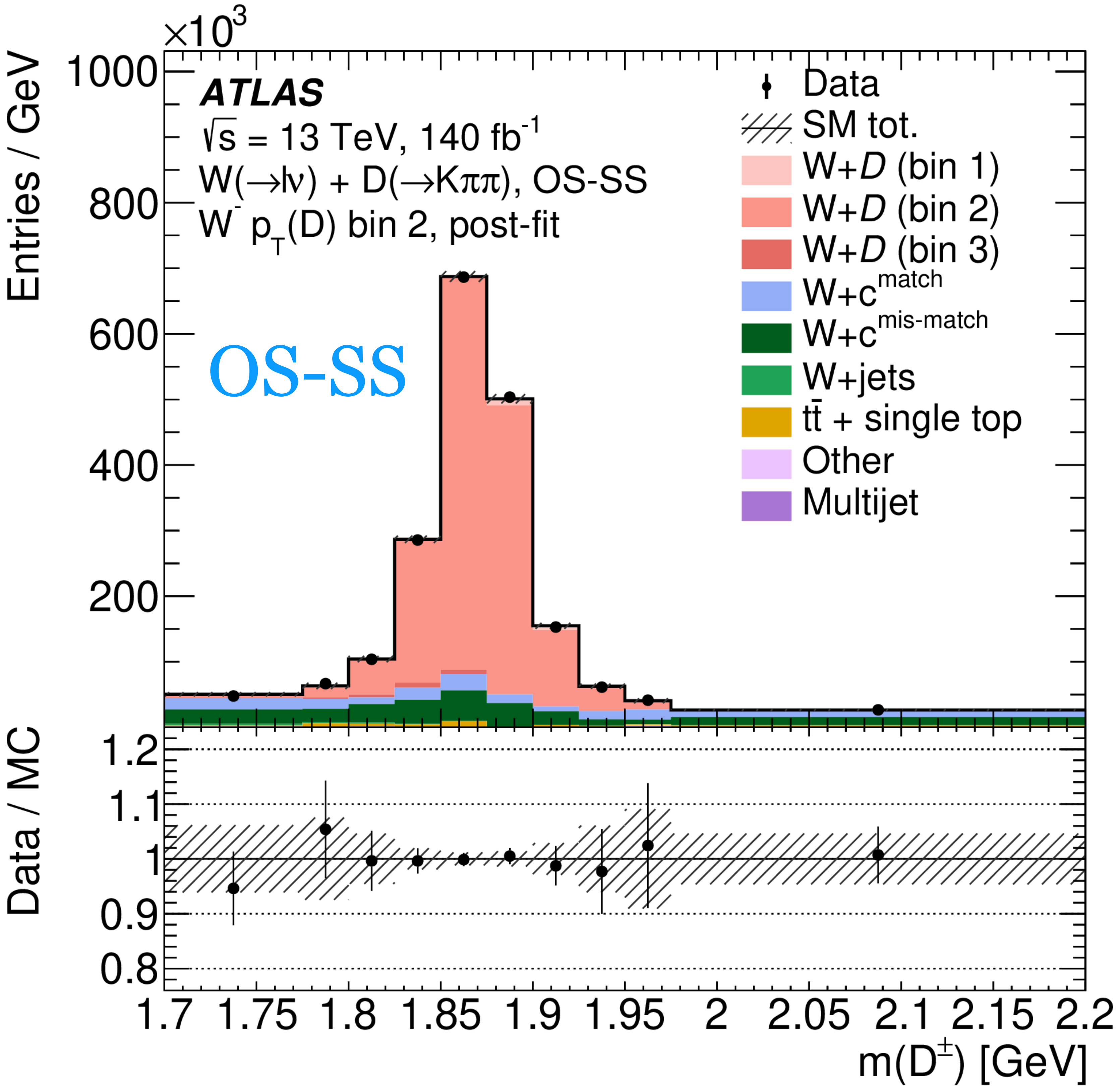
Decay modes:

(i) $D^+ \to K^-\pi^+\pi^+$ and

(ii) $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$

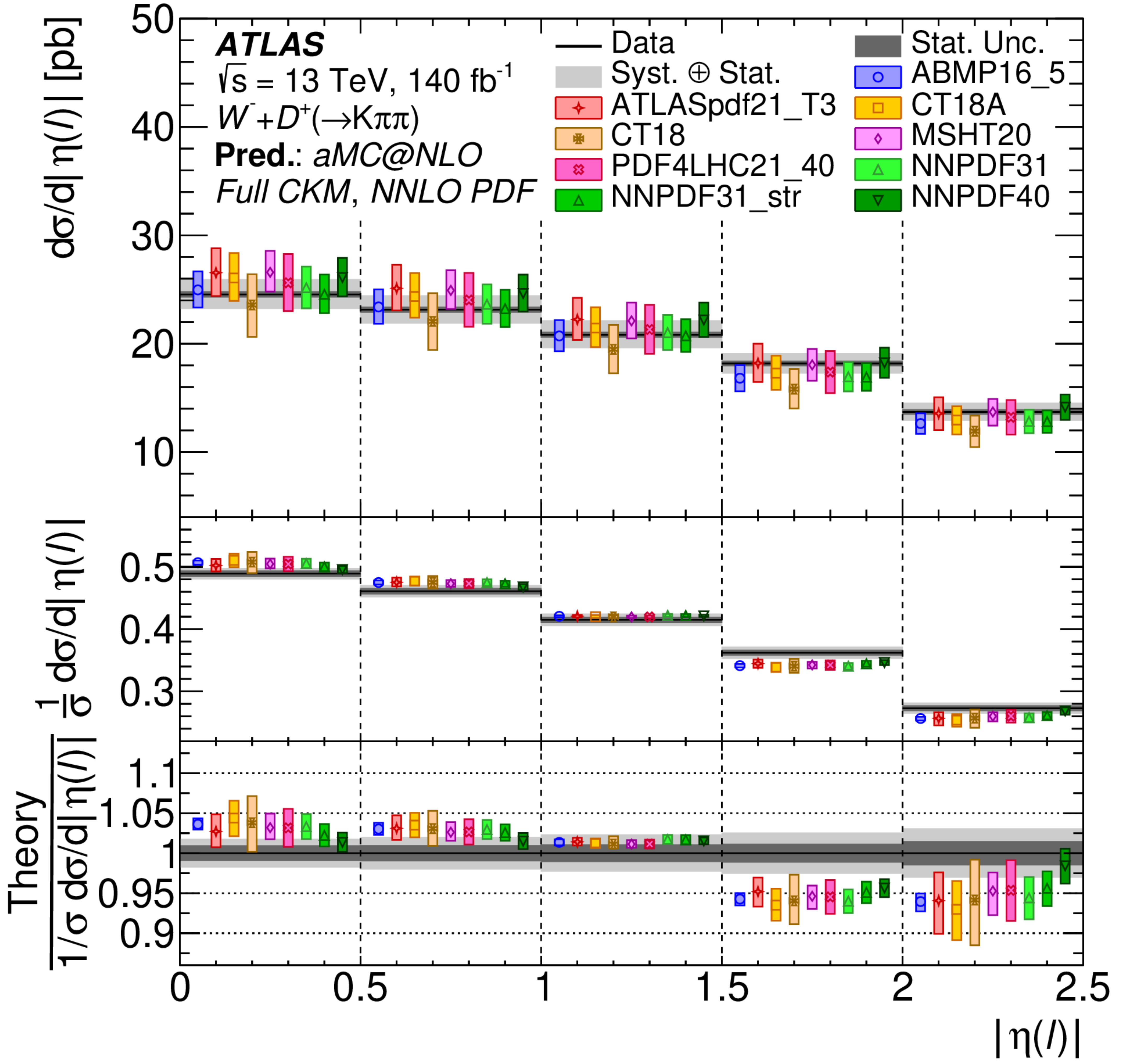


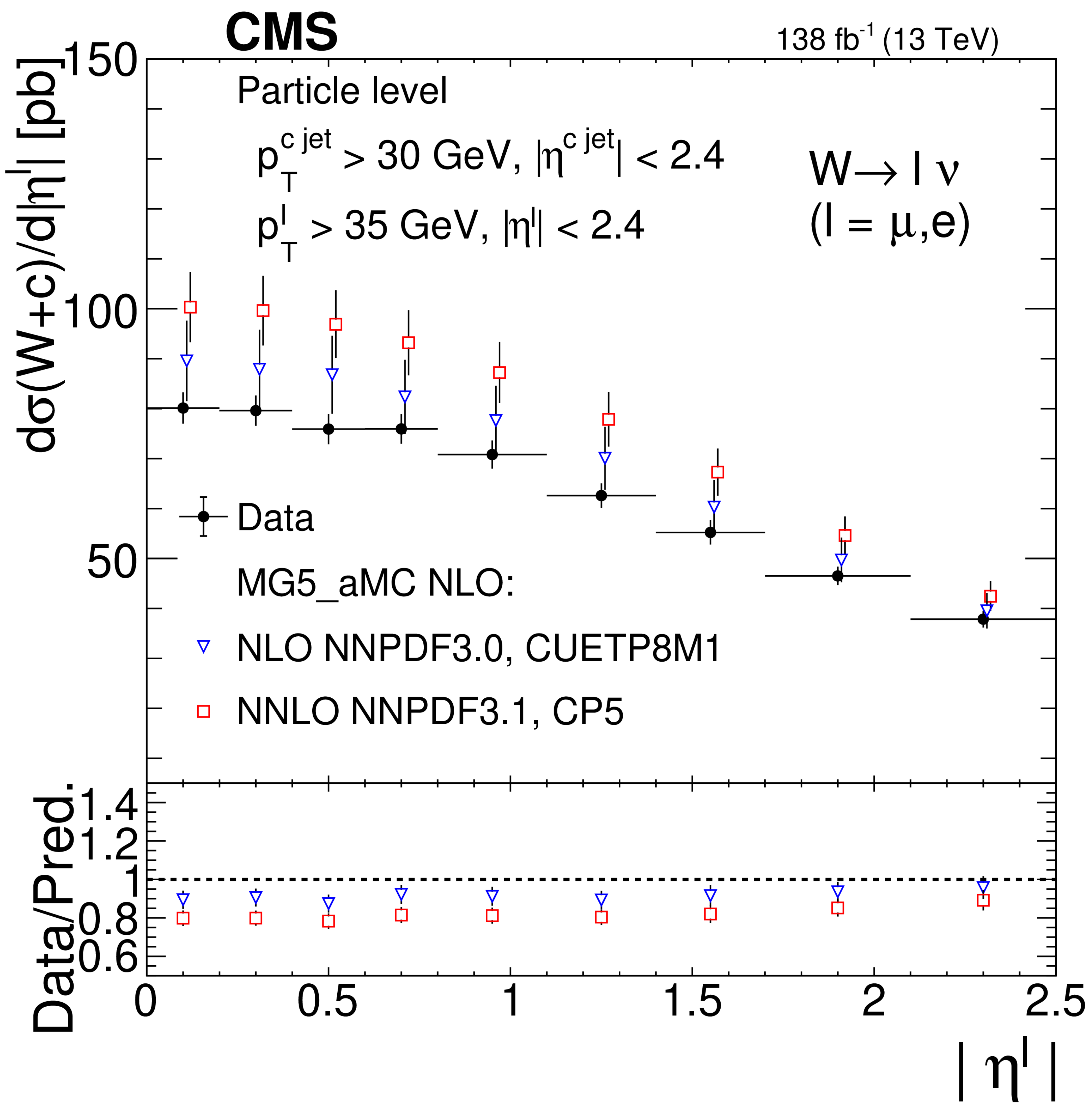




W+charm production: η dependence

► Sensitive to $s, \bar{s}$ PDF → constraints for global PDF fits





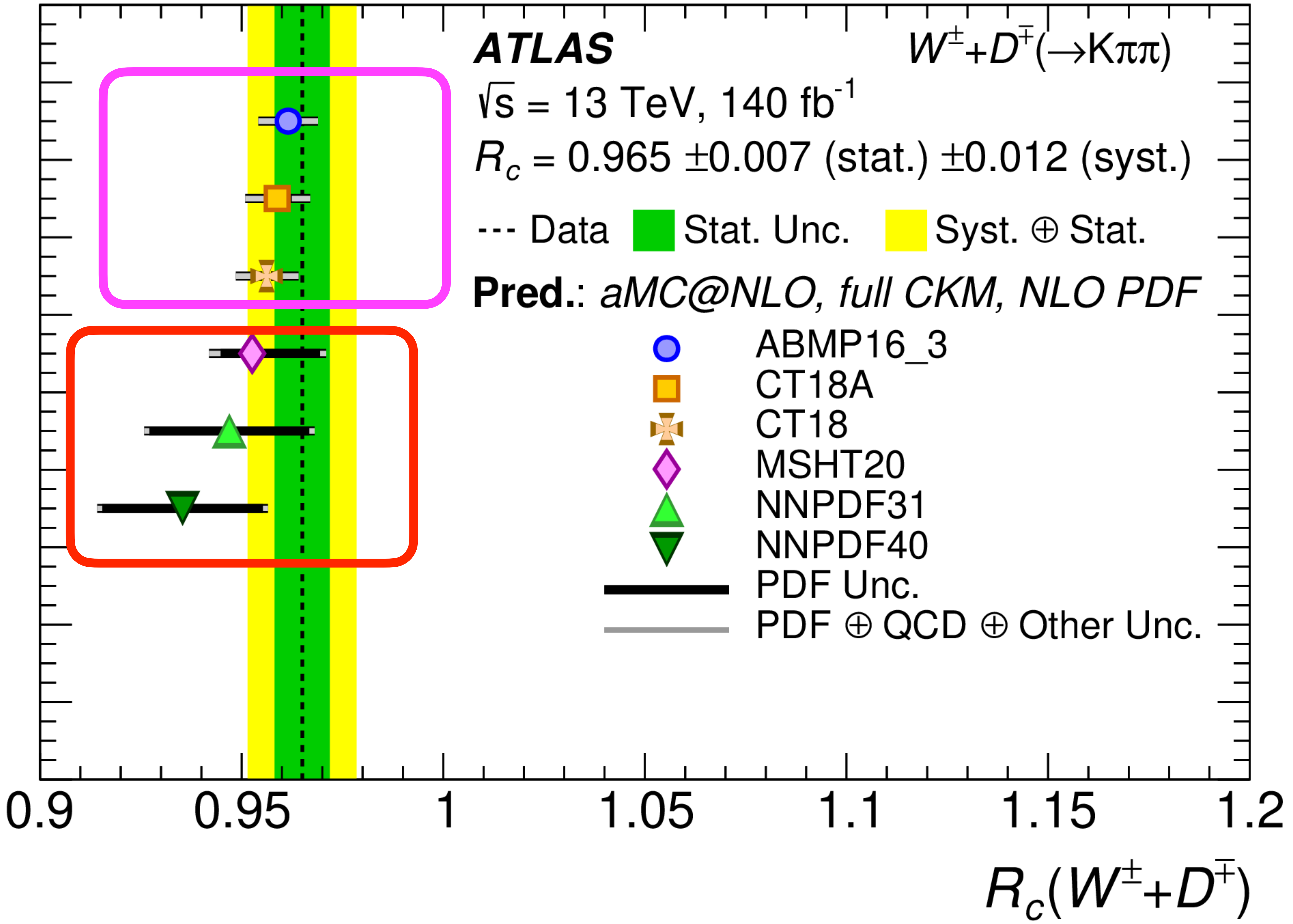
ATLAS: Data with broader η distribution than nominal MG5_aMC@NLO predictions but consistent when including PDF uncertainties

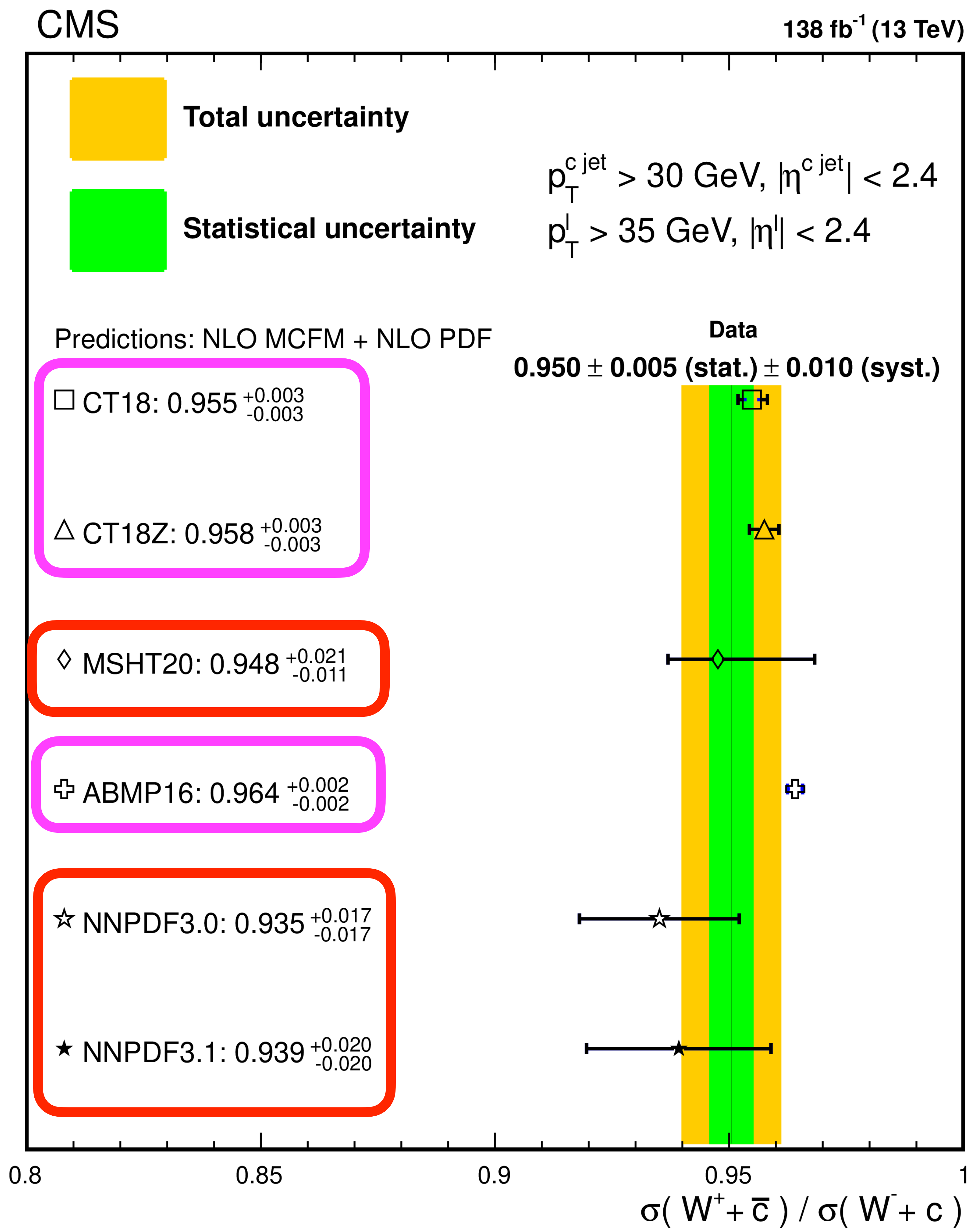
CMS: Similar trend. Data in agreement with MCFM within total uncertainties.

W+charm production: Charge ratio

- Sensitive to difference between s *and* $\bar{s}$ PDFs
- Experimental precision ~ 1%

$$R_C = \frac{\sigma(W^+\bar{C})}{\sigma(W^-C)}$$





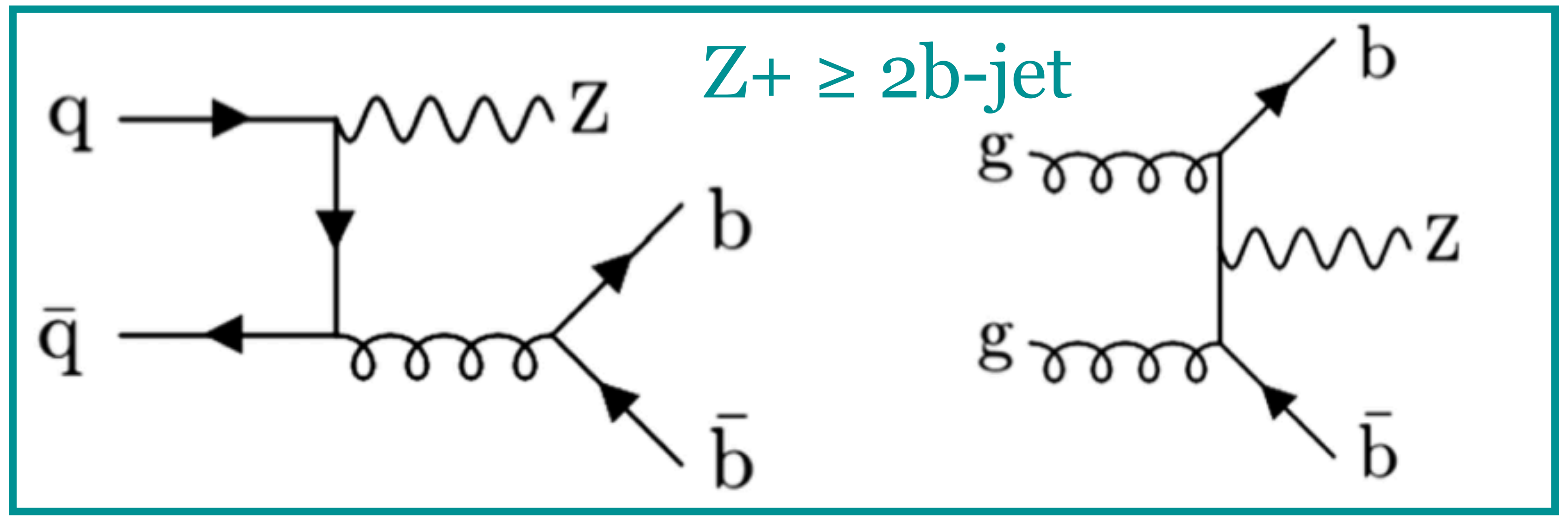
ATLAS: Consistent with PDFs that constrain the strange-quark sea to be symmetric at the starting scale

- PDFs allowing s *and* $\bar{s}$ distributions to differ have larger uncertainties

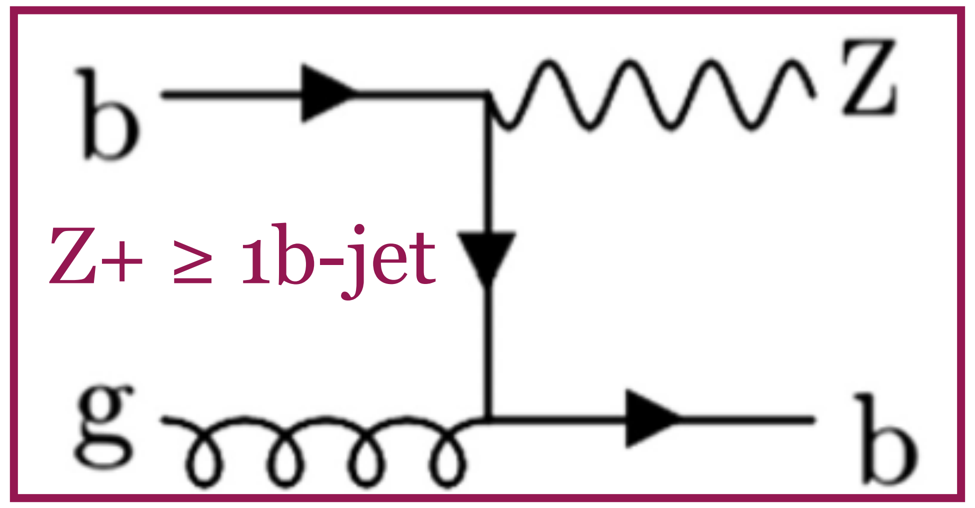
CMS: Data consistent with all PDF, 0.2% uncertainty, 2% uncertainty

Z+b(b) measurements

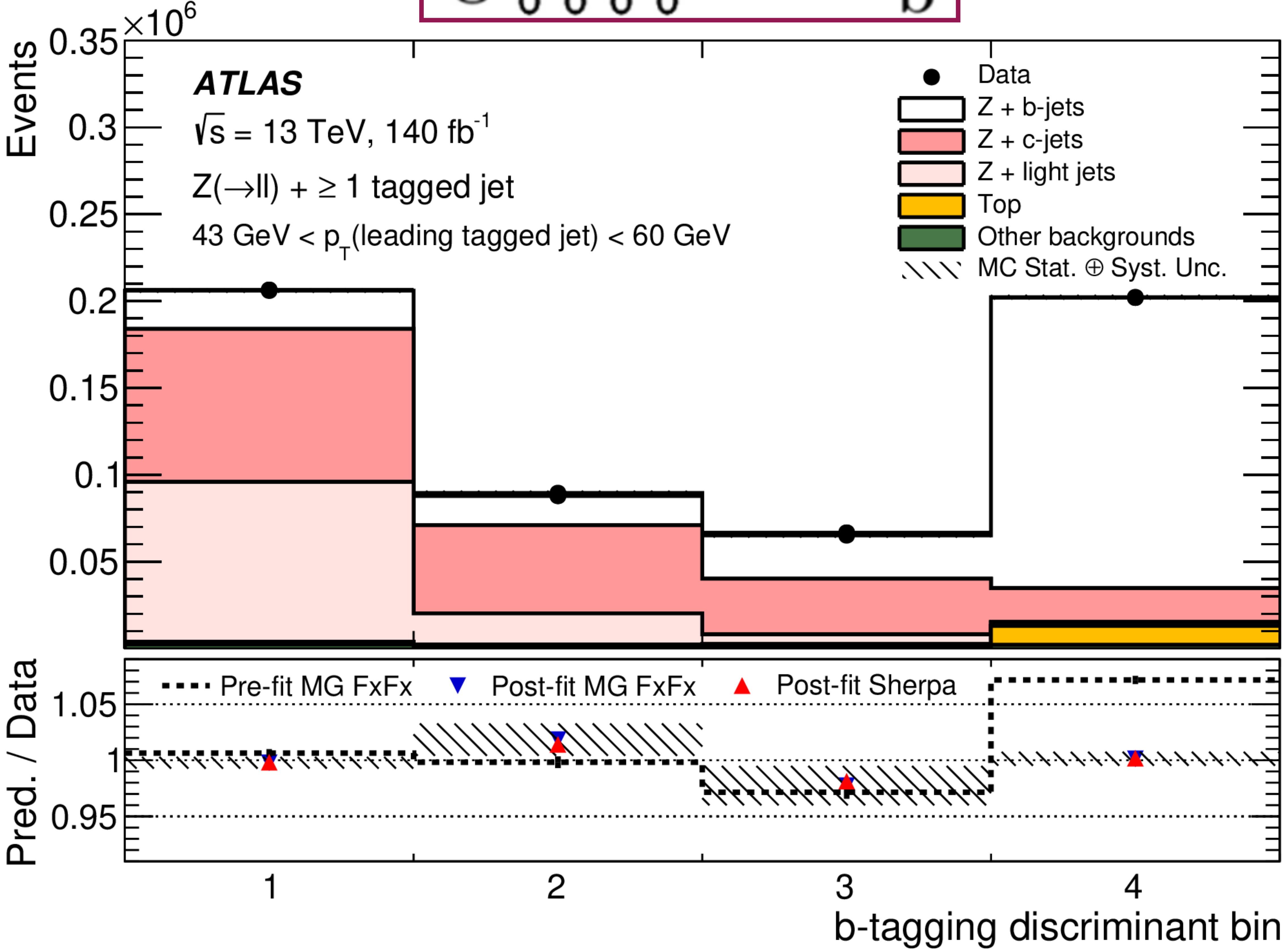
- Flavour/mass schemes, pQCD, IRC-safe b-jets, PDFs
- Important background for VH→***bb*** and BSM searches



Final states: Z + ≥ 1b-jet, Z + ≥ 2b-jets,
pT(b-jet) > 20 GeV, $|y|<2.5$ (ATLAS) ↔ 30 GeV, $|\eta|<2.5$ (CMS)



- Theory: 5F NLO multi-leg ME+PS (MGaMC FxFx or Sherpa)
  - CMS: older versions
  - ATLAS: NNLO Z+1b with IRC safe flavor dressing algorithm Phys. Rev. Lett. 130 (2023) 161901



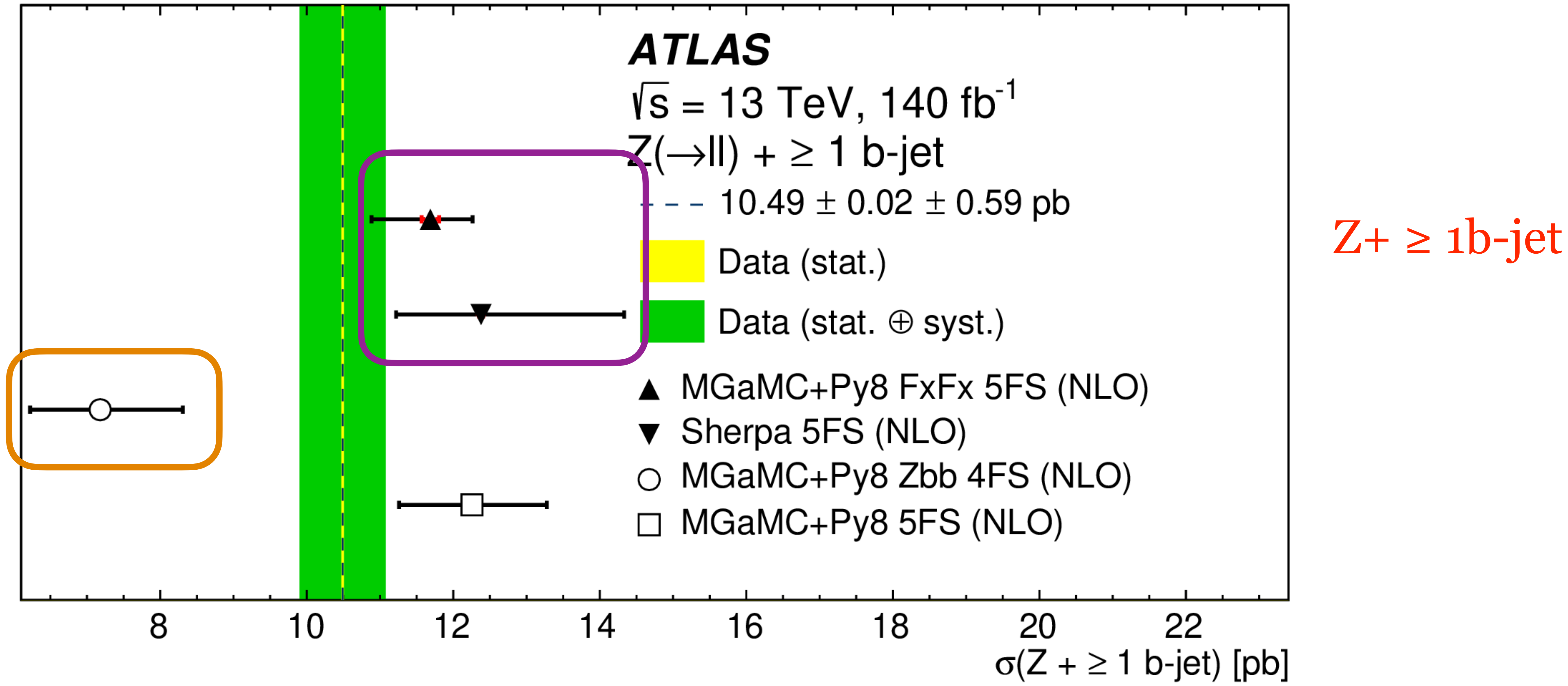
CMS: Phys. Rev. D 105 (2022) 092014
ATLAS: EPJC 84 (2024) 984

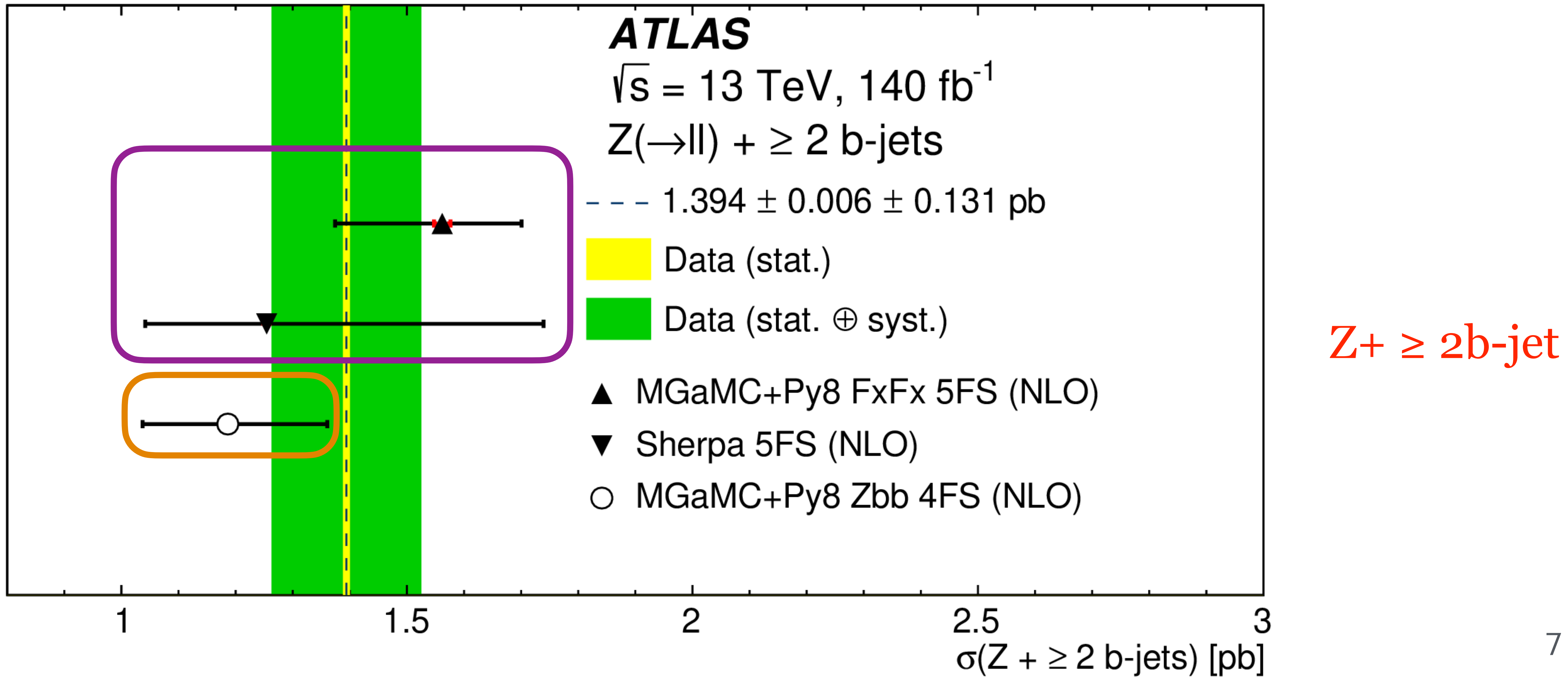
Z+b(b) measurements: Inclusive cross sections

ATLAS: **EPJC 84 (2024) 984**

- 5FS NLO multi-leg MC predictions describe both Z+b and Z+bb measurements
- 4FS Zbb NLO prediction describes Z+bb, while undershoots data in case of Z+b
- Uncertainties: Z+b: 6%, Z+bb: 9%

Results consistent with previous ATLAS measurement with 36 fb^{-1}
[2x better precision]





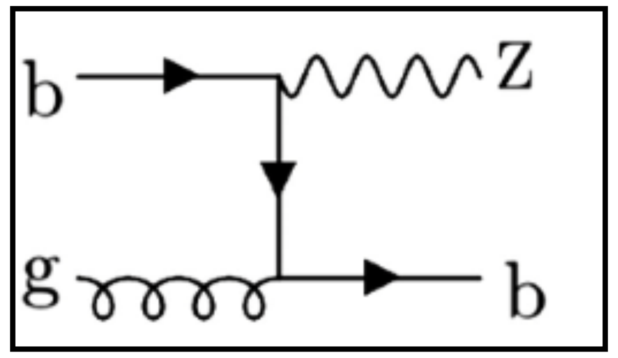
Z+b(b) measurements: Inclusive cross sections

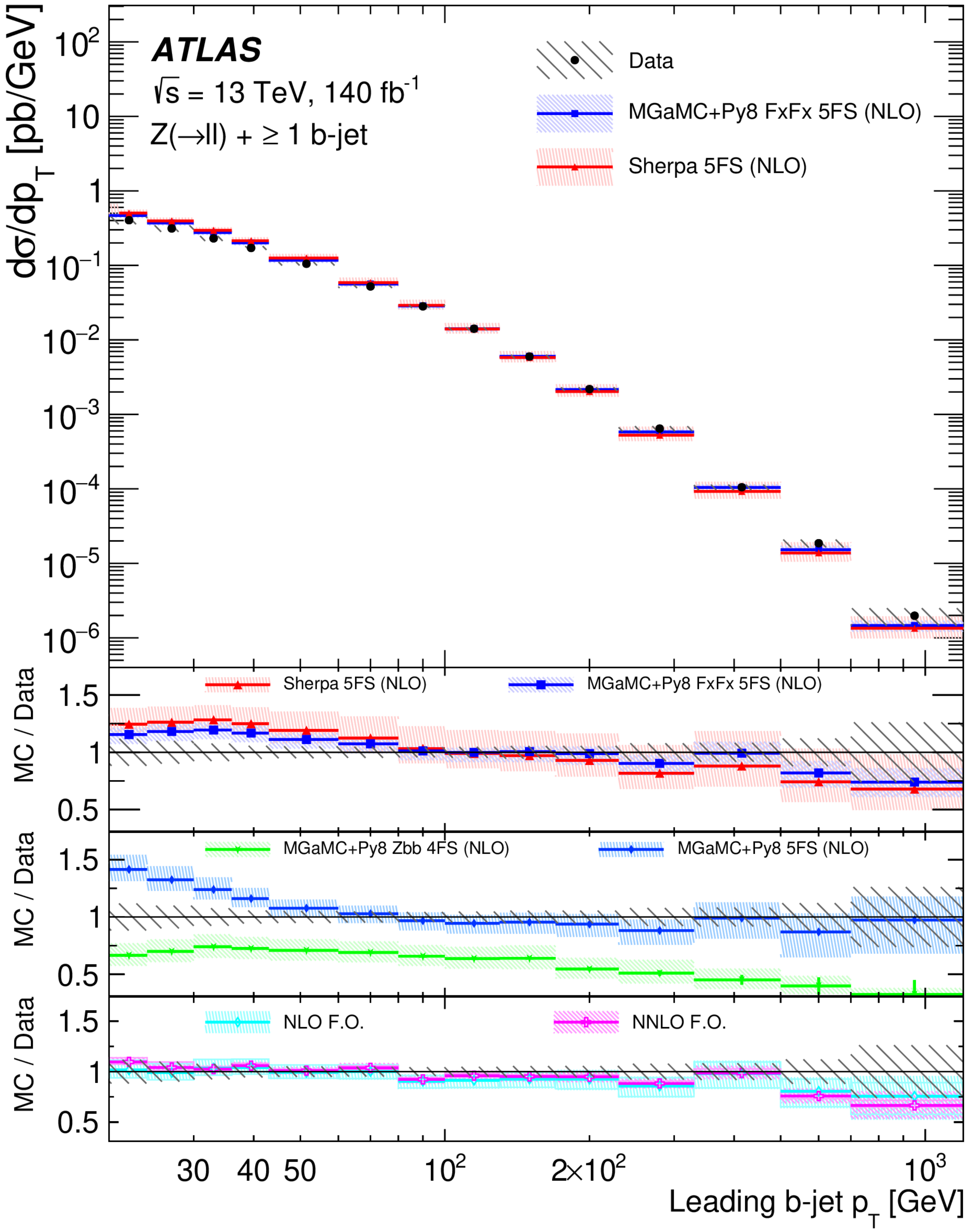
CMS: PRD 105 (2022) 092014

- LO multi-leg predictions describes the data best
- NLO predictions overestimate
- Uncertainties: Z+b: 7%, Z+bb: 12%

	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

Z+b differential cross sections: pT(b-jet)

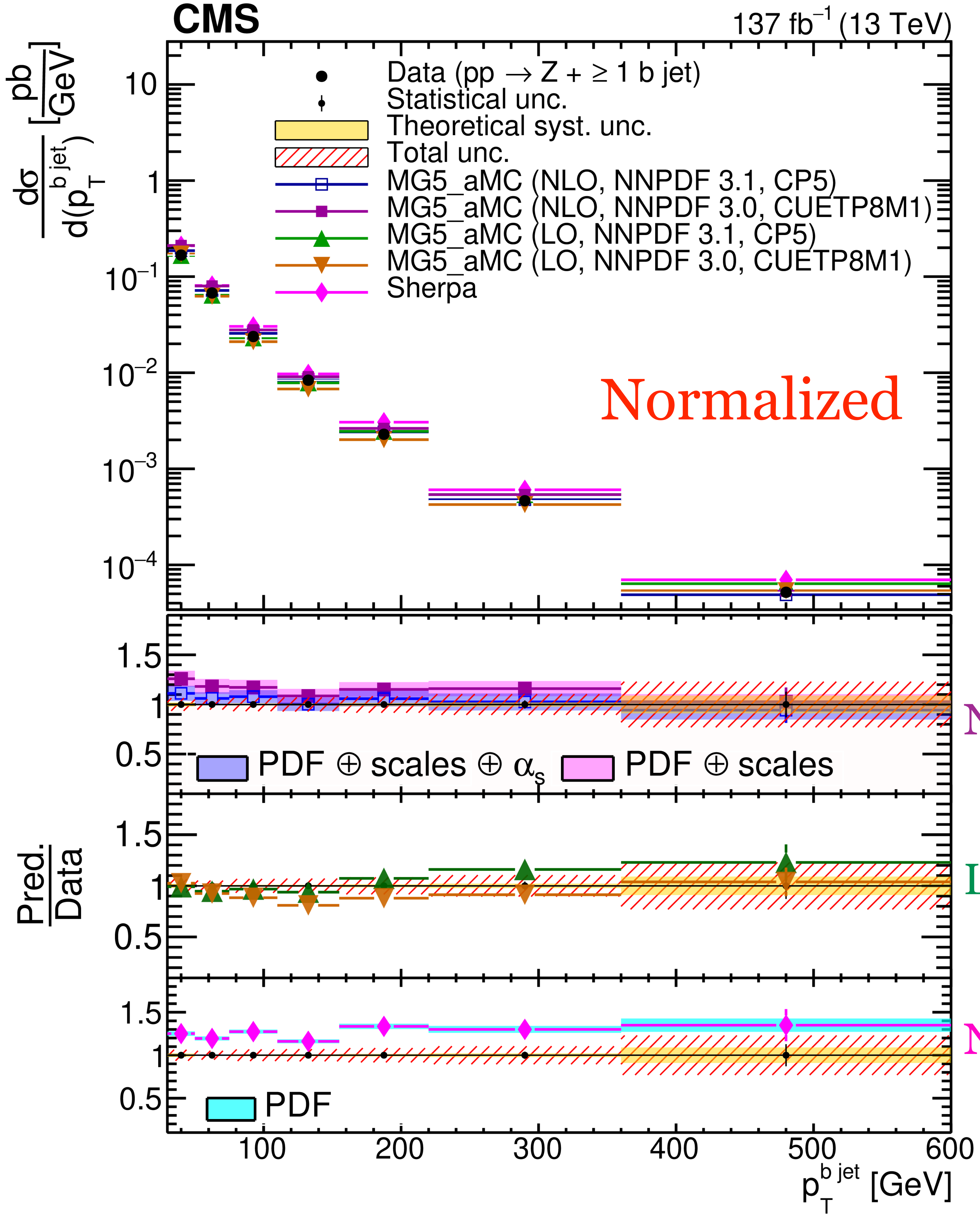




5FS, NLO multileg

4FS, NLO multileg

NNLO, fixed order



NLO MGaMC

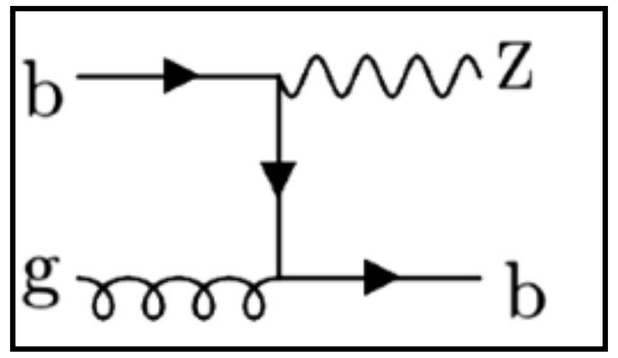
LO MGaMC

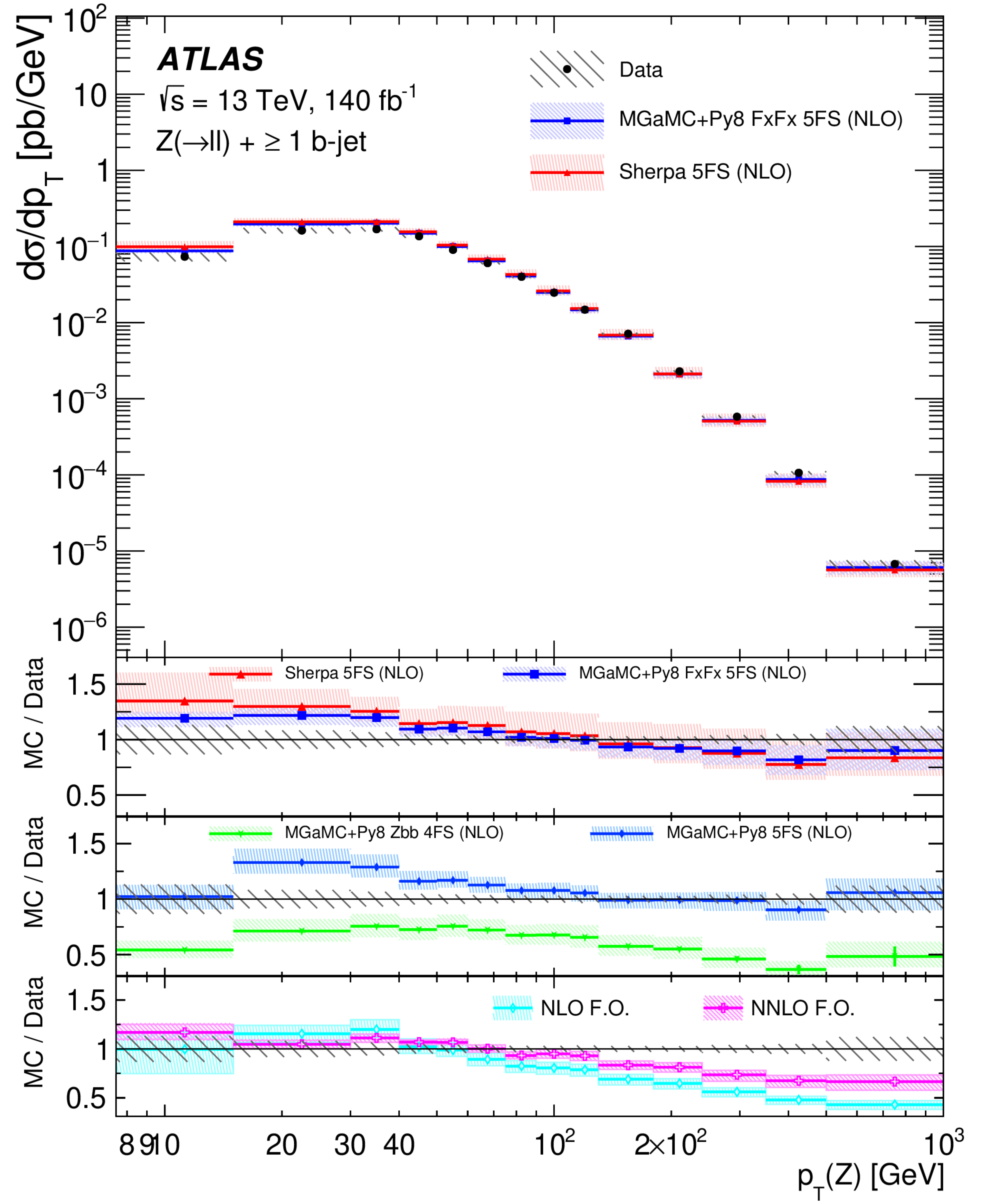
NLO Sherpa

ATLAS: 5FS, NLO multileg and fixed order NNLO describe the data

CMS: NLO shape ok, LO too hard

Z+b differential cross sections: pT(Z)





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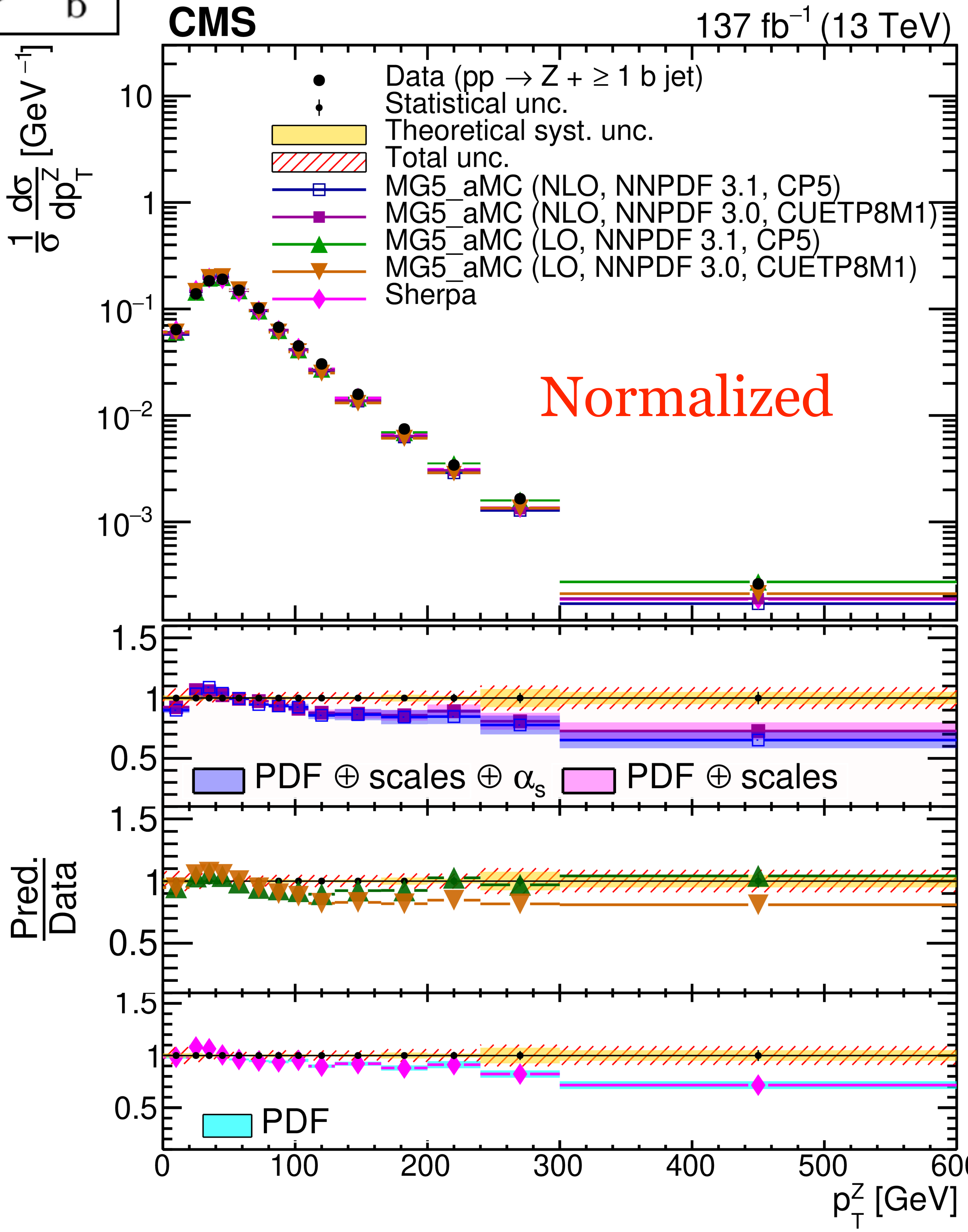


NLO MGaMC

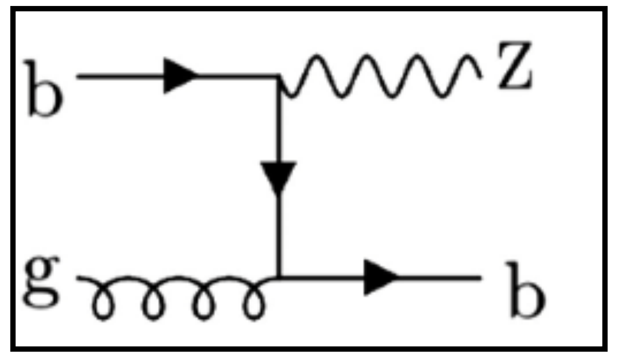
LO MGaMC

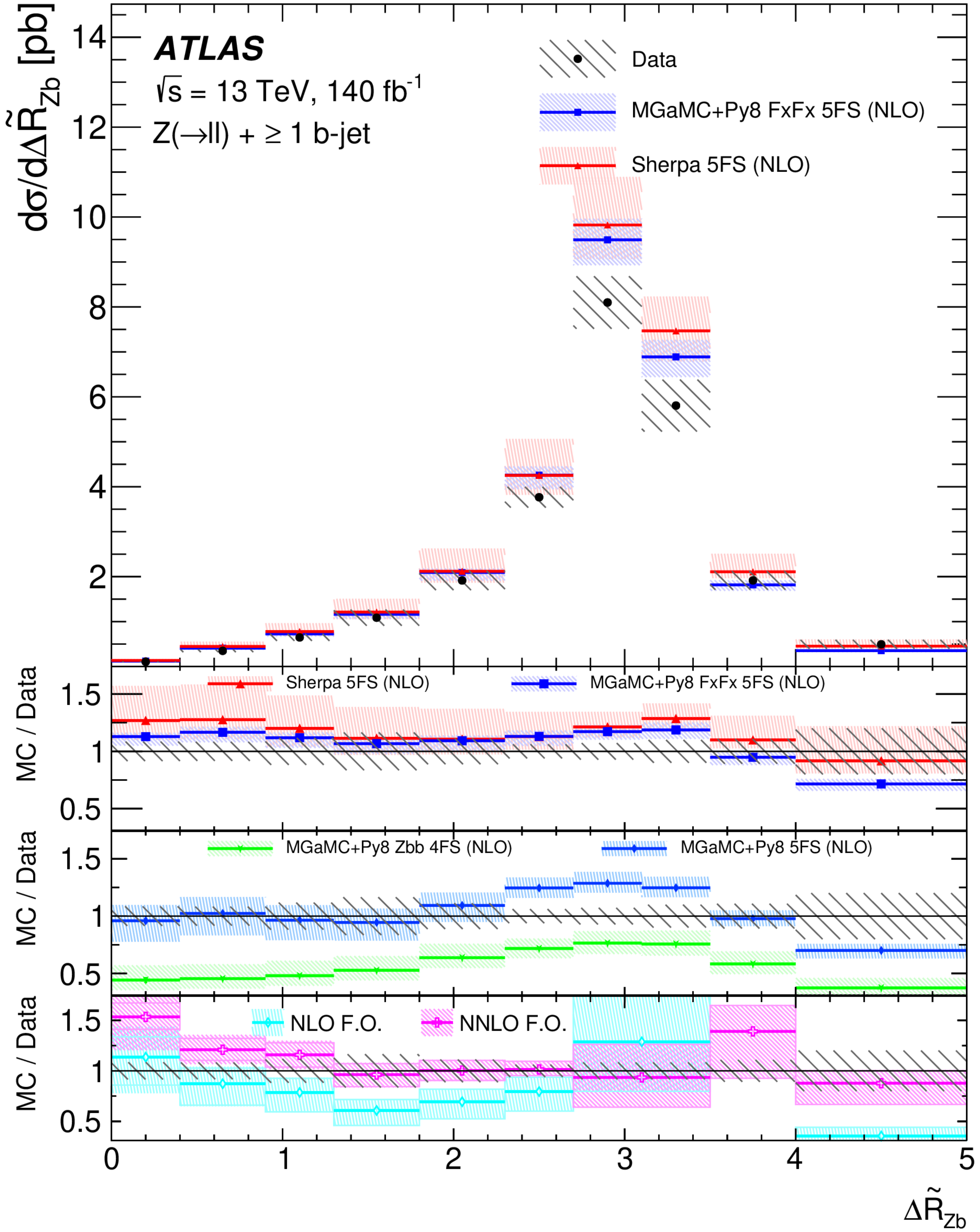
NLO Sherpa

ATLAS: 5FS NLO multileg and NNLO predict soft spectrum

CMS: NLO multileg too soft, LO multileg shape ok

Z+b differential cross sections: ΔR(Z,b)





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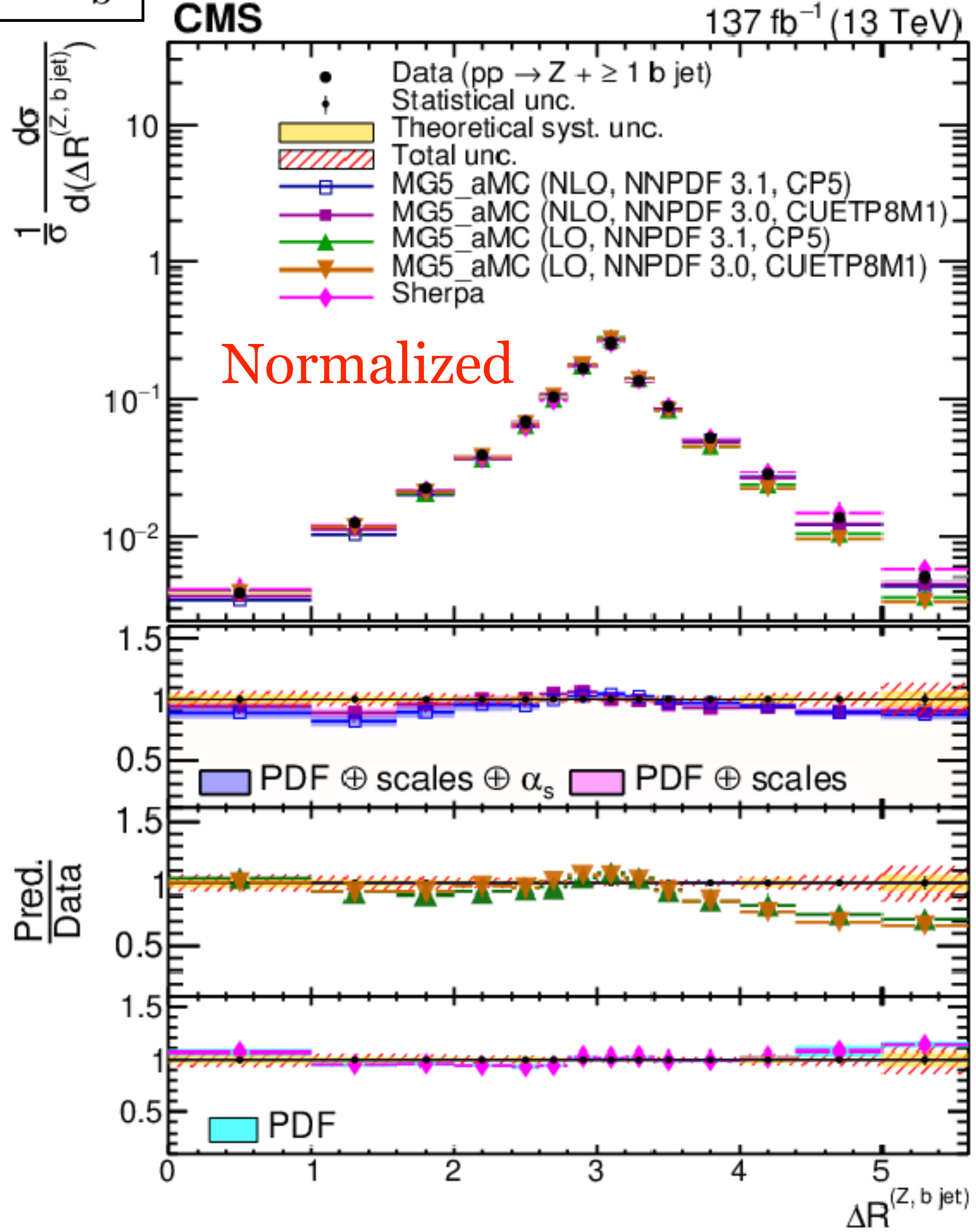

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LO MGaMC

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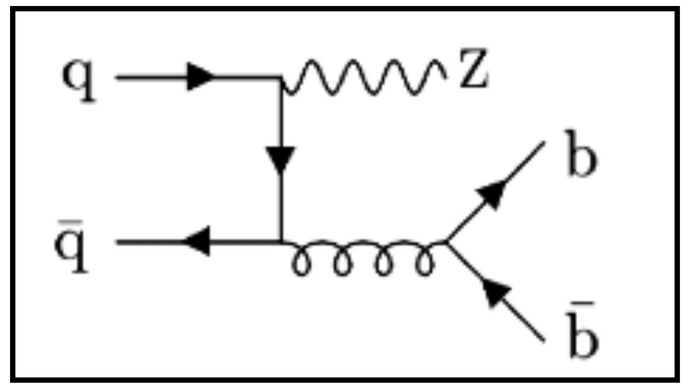
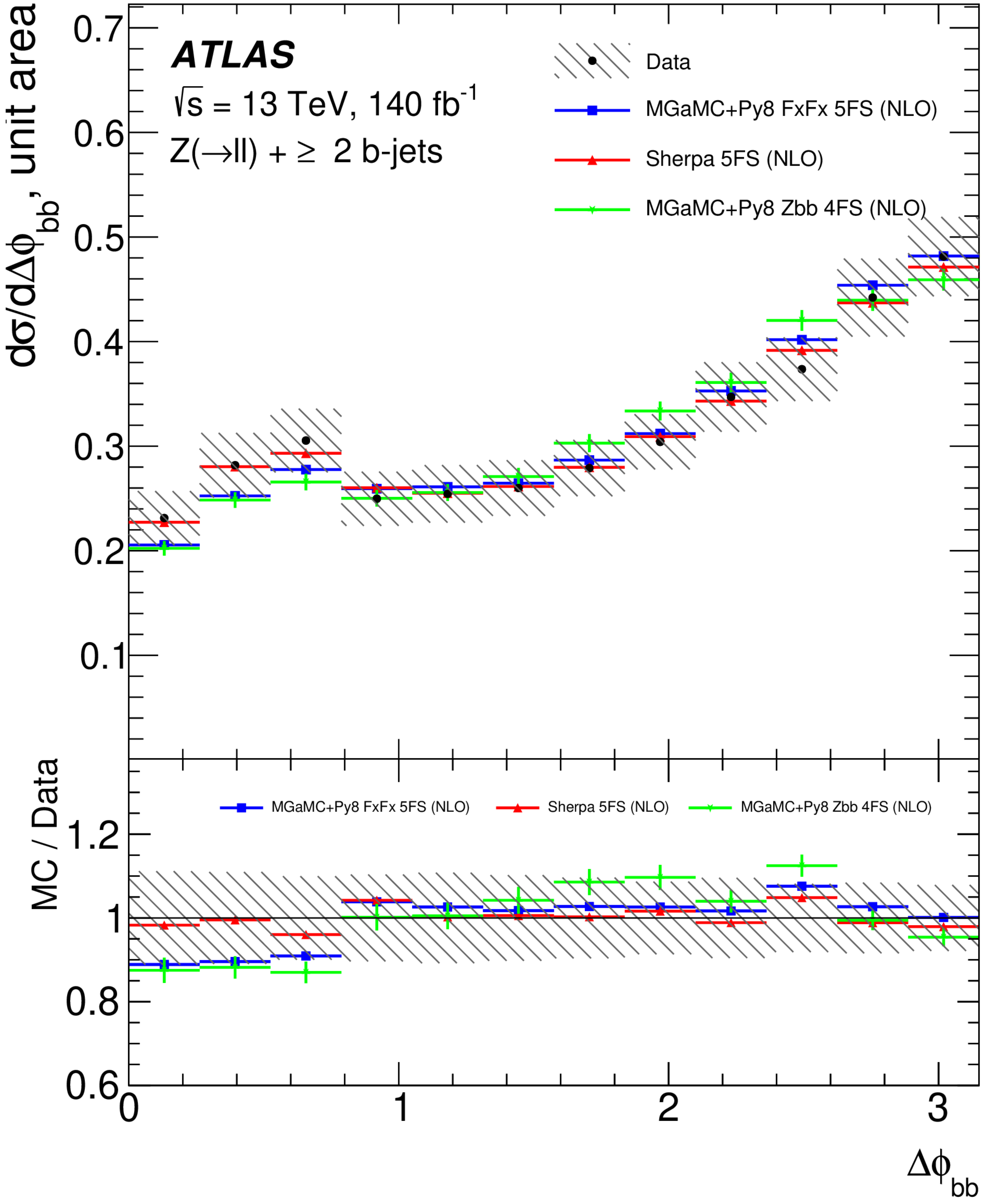
Z+bb measurements: $\Delta\phi_{bb}$ (ATLAS) - ΔR_{bb} (CMS)

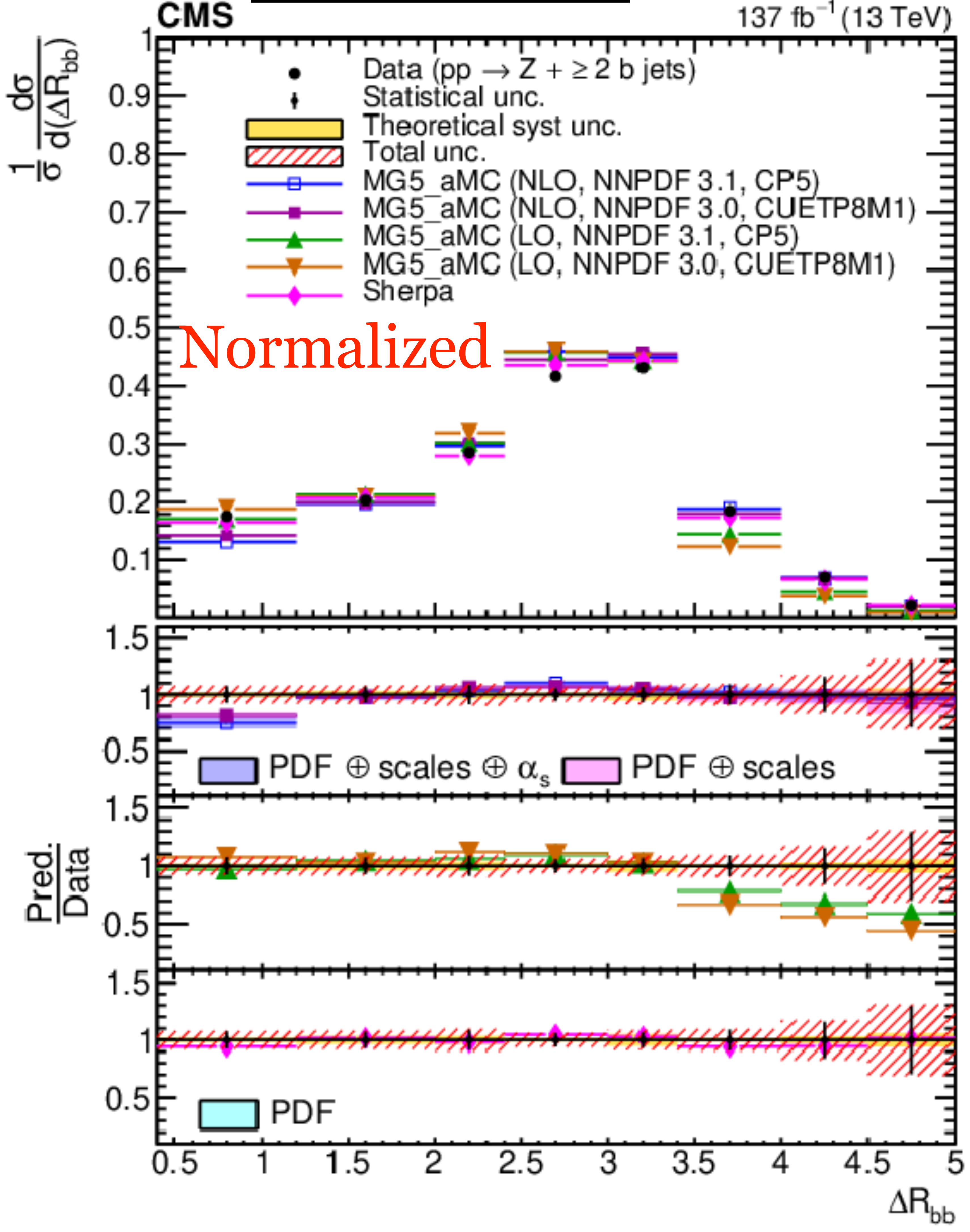




NLO
5FS MGaMC

5FS Sherpa

4FS MGaMC



NLO
MGaMC

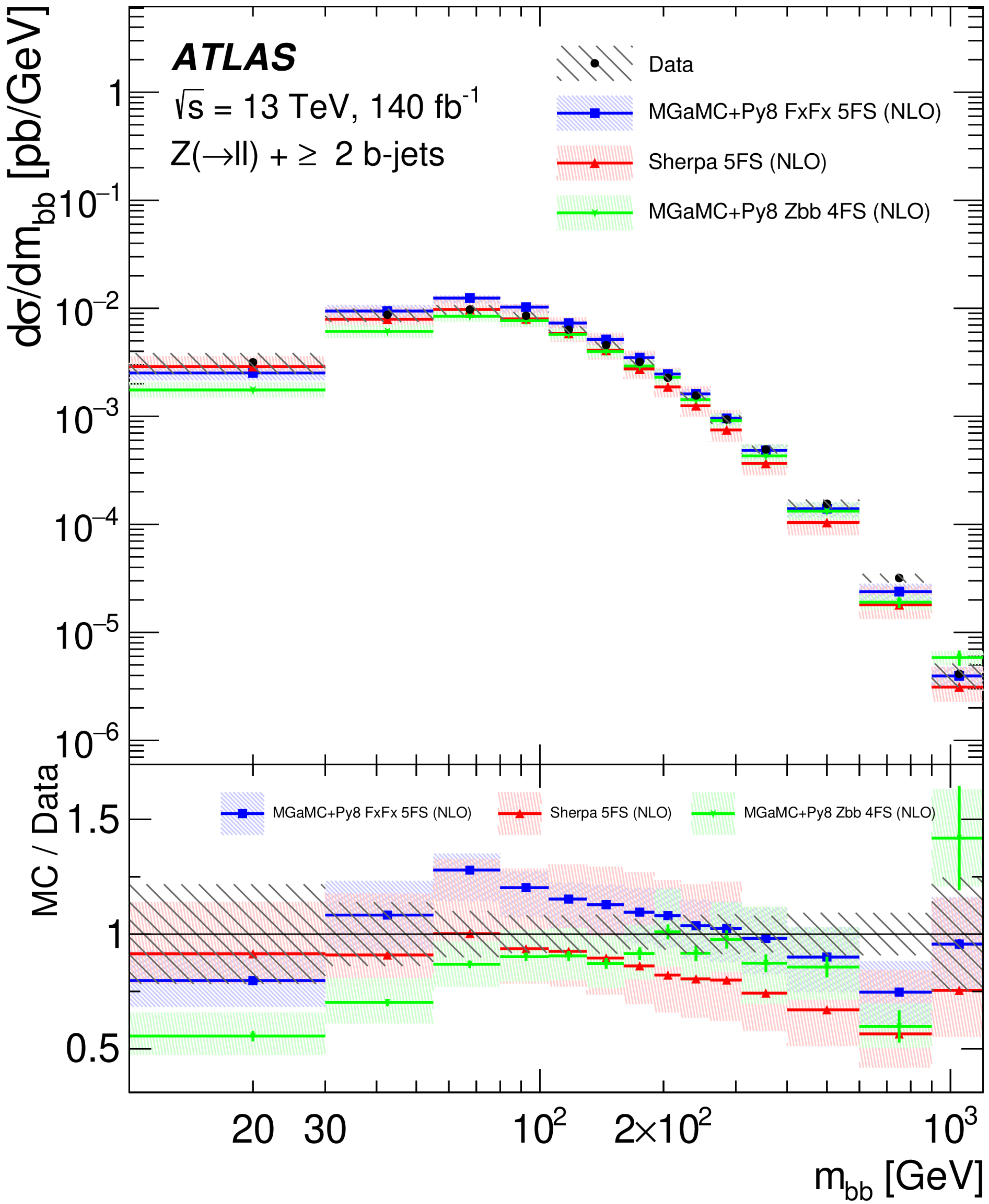
LO
MGaMC

NLO
Sherpa

ATLAS: 5FS NLO multi-leg and Sherpa described the shape, while 4FS NLO underestimate at small and large angles

CMS: NLO MG: sharper peak, underestimates cross section at small ΔR_{bb}, LO MC underestimates large ΔR_{bb}

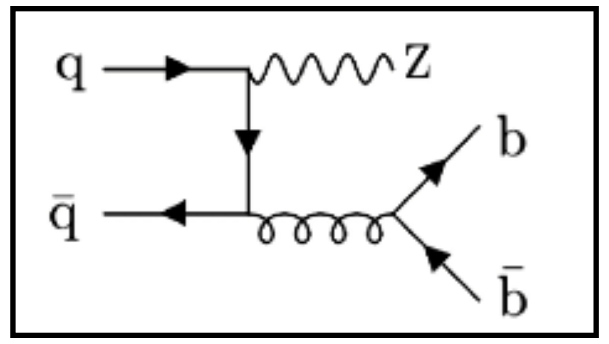
Z+bb measurements: m(bb)

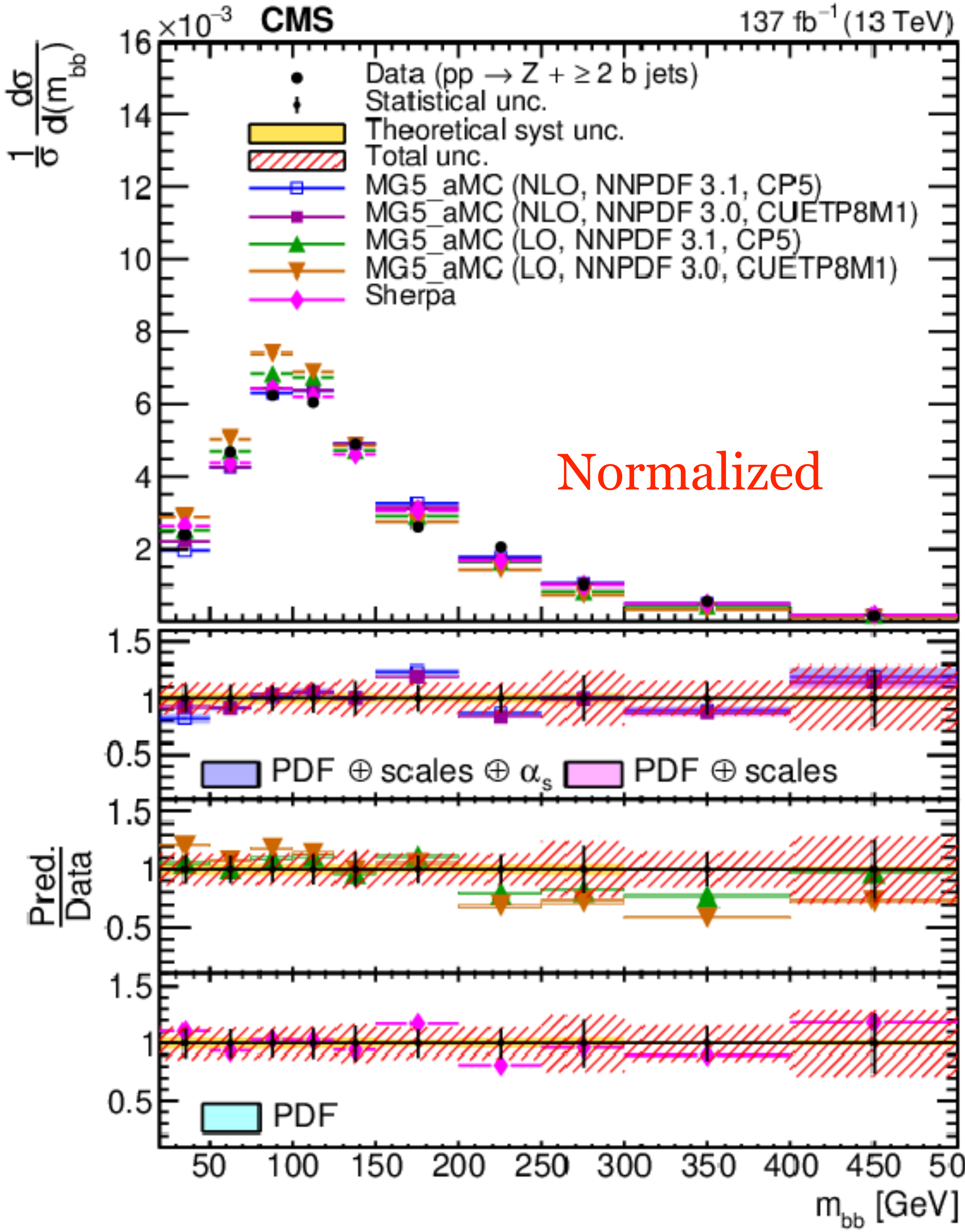


NLO
5FS MGaMC

5FS Sherpa

4FS MGaMC





NLO
MGaMC

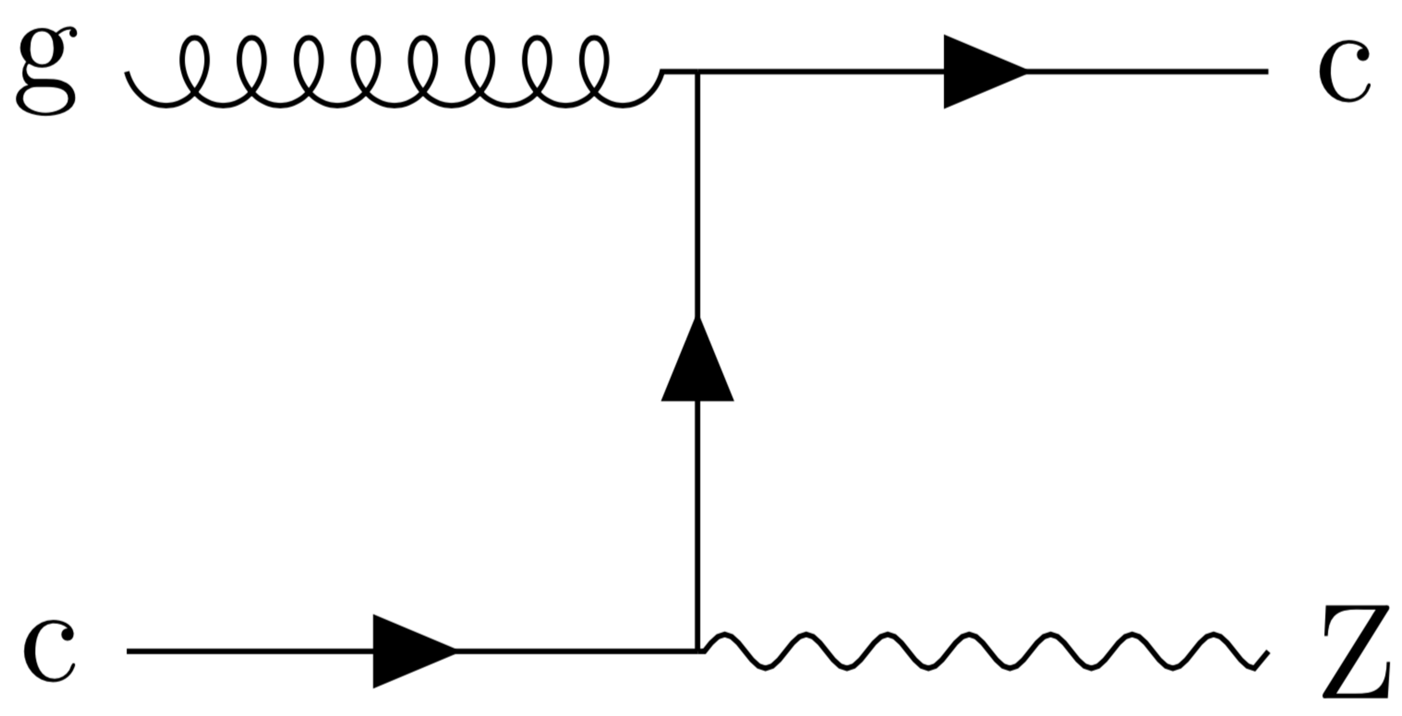
LO
MGaMC

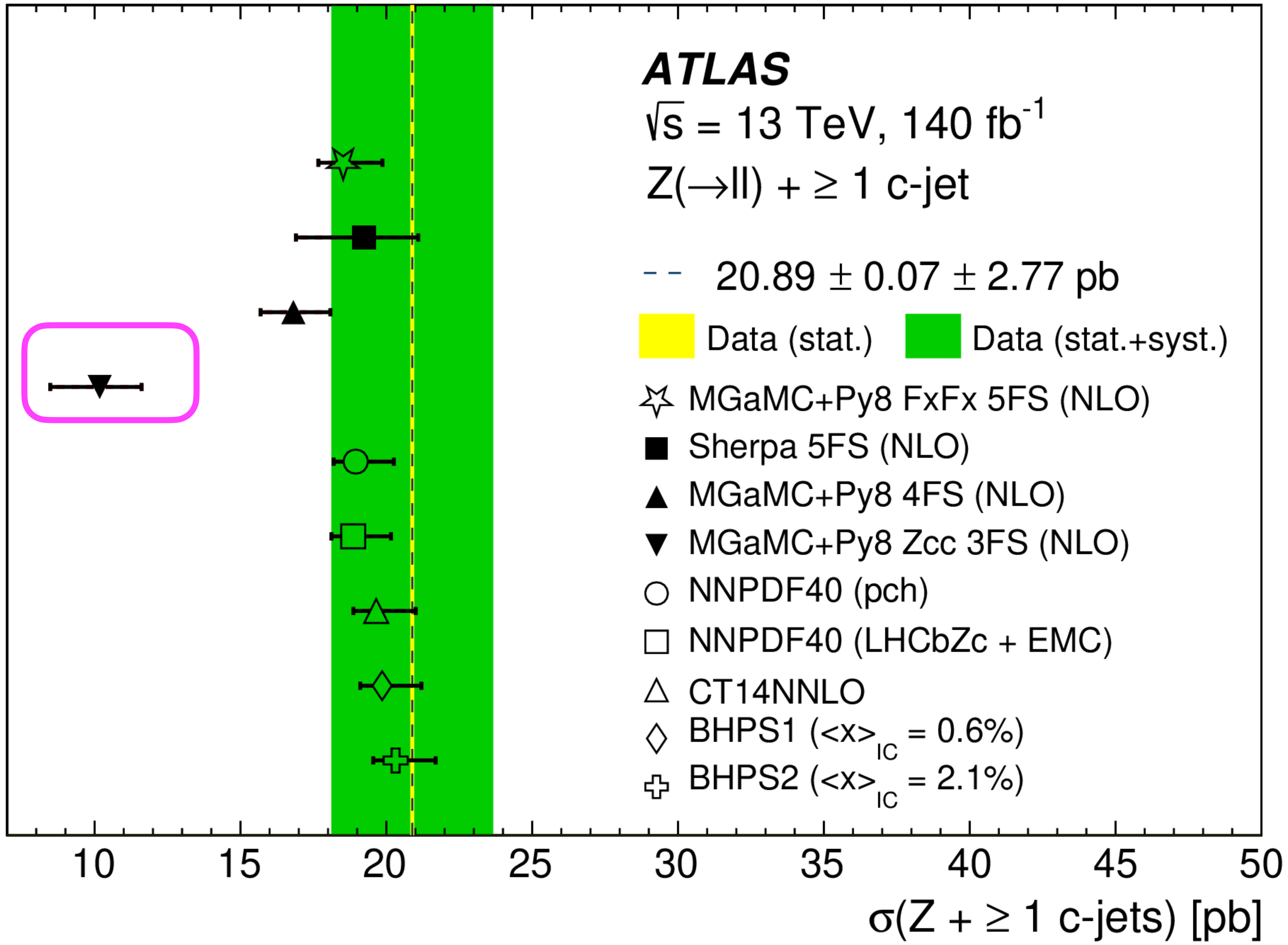
NLO
Sherpa

ATLAS: 4F/5F MC predict m_{bb} peak with steeper slopes

CMS: NLO MC: shape ok, LO underestimates high m_{bb}

Z+c measurements





➡ **Flavour/mass schemes, pQCD, PDF Intrinsic charm (IC)**

Selections:

- ATLAS: pT(c-jet) > 20 GeV, lepton $|\eta|$< 2.5
- CMS: pT(c-jet) > 30 GeV, lepton $|\eta|$< 2.4
- Backgrounds: Z+l/b, top

ATLAS: @140 fb^{-1}, arXiv:2403.15093

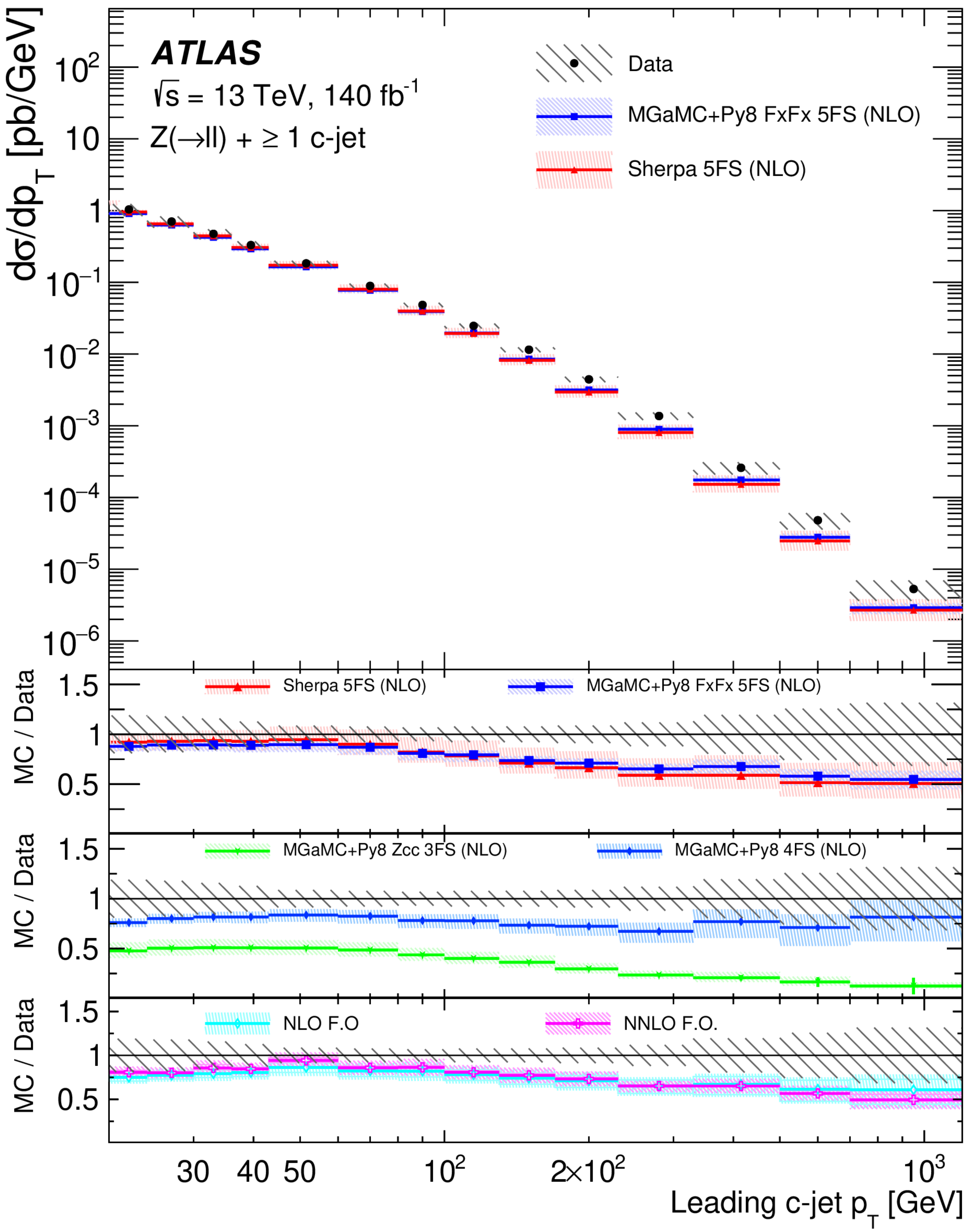
- σ (Z+c) = 20.9 ± 0.1 (stat) ± 2.8 (sys) pb.
- Compatible with all 5F predictions, 3FS Zcc NLO does not describe the data
- 13% uncertainties

CMS*: @36 fb^{-1}, JHEP 04 (2021) 109

- σ(Z+c)=13.6±0.2(stat)±0.8(sys)pb
- Discrepancy with (older) MG5_aMC (NLO) prediction of 17.6 ± 0.4 (theory) pb
- 6%, with tight charm trigger

*Translated from published σ (Z+c)/BF(Z→ll)

Z+c differential cross sections: pT(c-jet)



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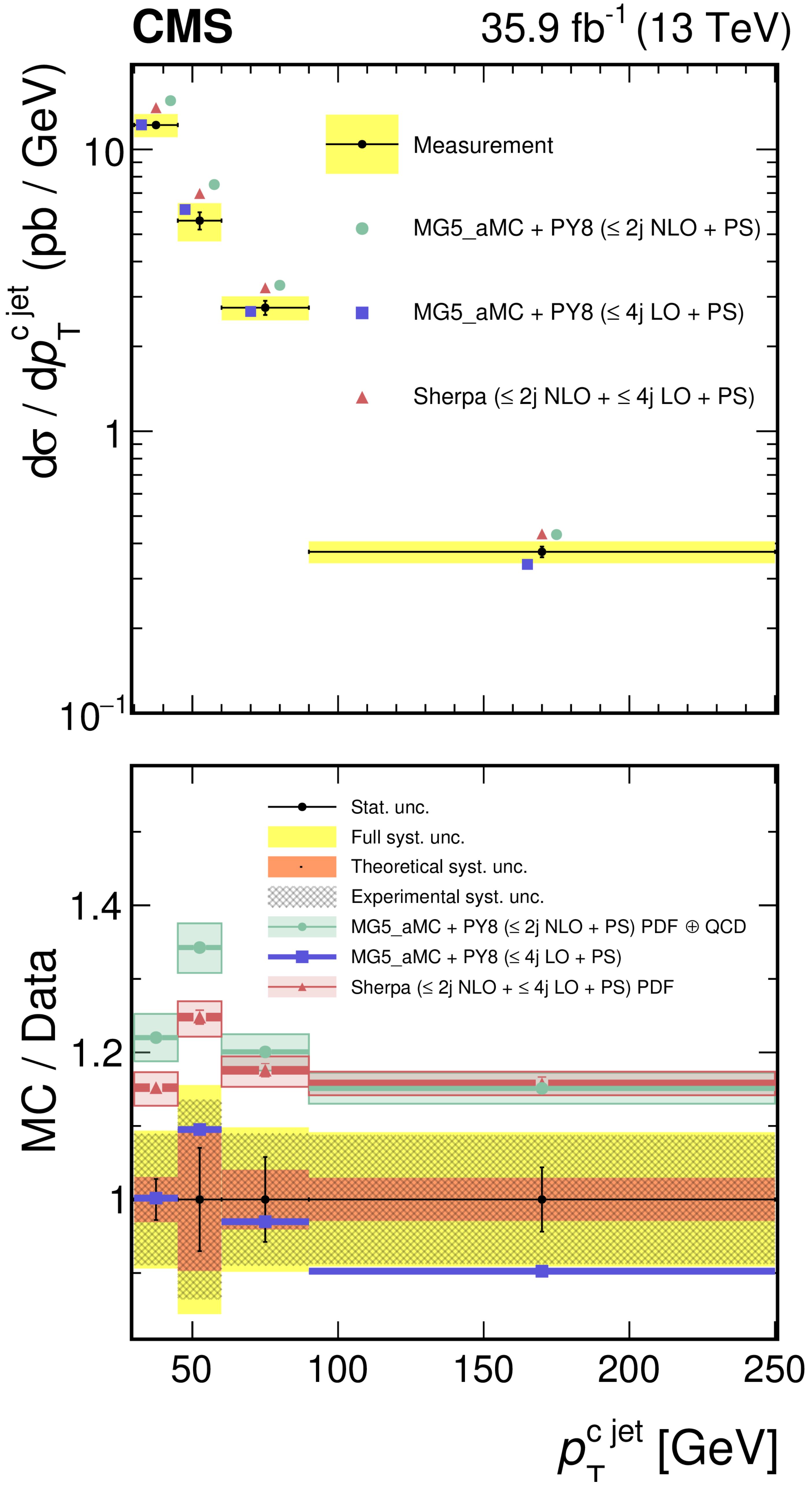
4FS NLO

3FS NLO

NNLO fixed order



NLO MGaMC

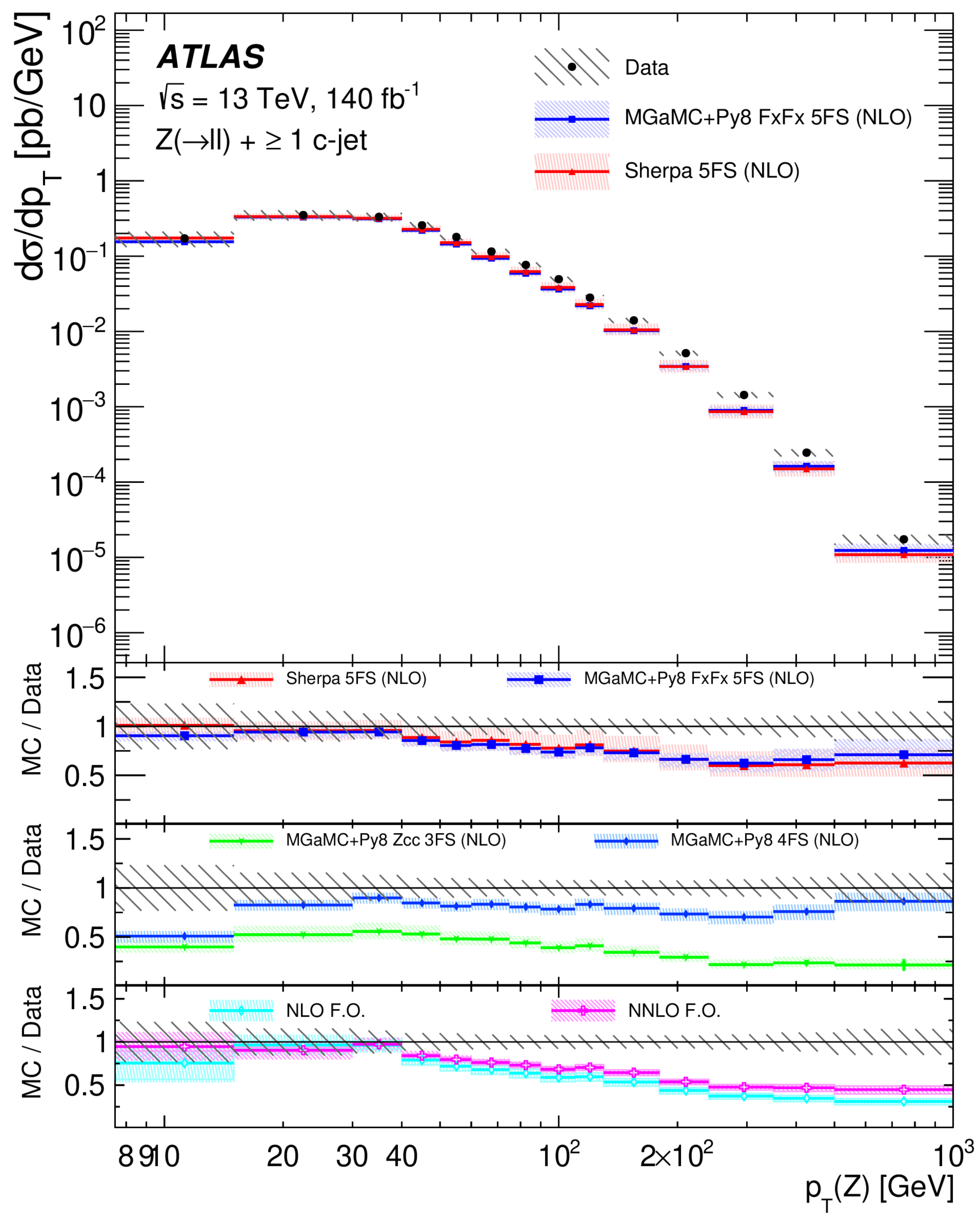
NLO Sherpa

LO

ATLAS: 5FS NLO multi-leg MC and NNLO describe soft end but underestimate large pT(c-jet). 4FS NLO shape ok but offset.

CMS: All MC with too soft pT(c-jet) shape.

Z+c differential cross sections: pT(Z)



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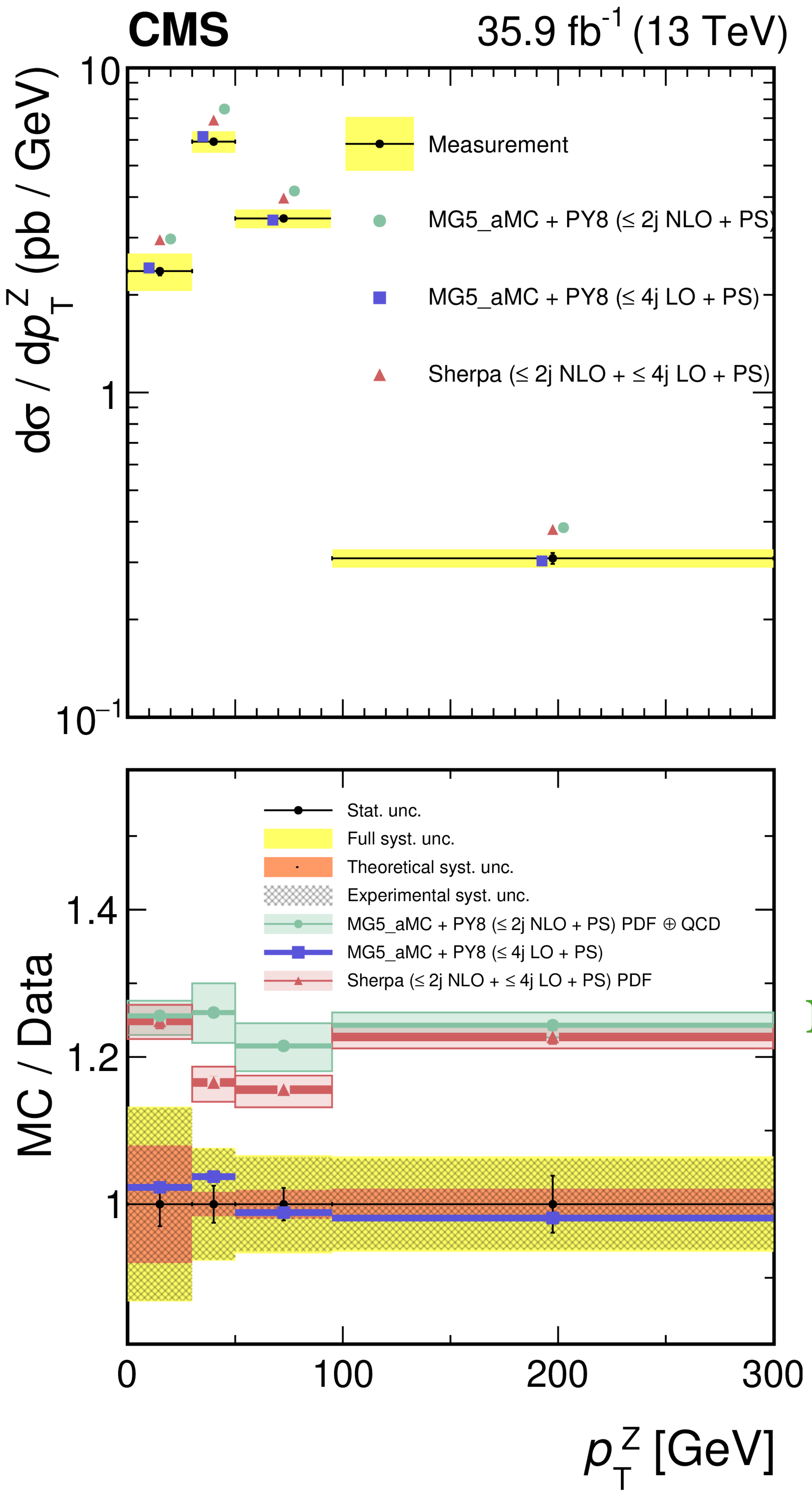

NLO MGaMC

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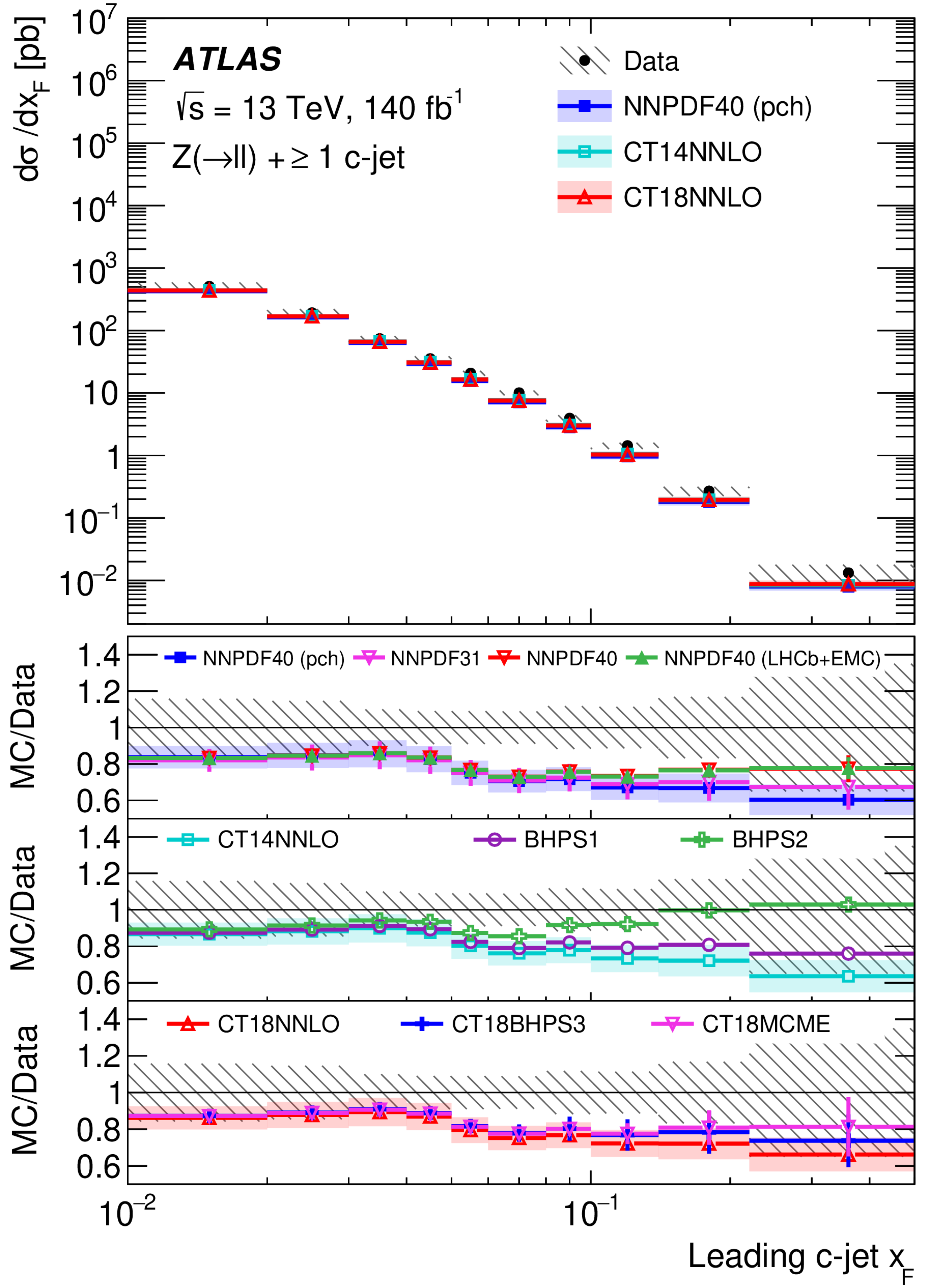
CMS: All MC describes the shape well.

Charm PDF studies by ATLAS

$$x_F = 2|p_z(c)|/\sqrt{s}$$

5FS multi-leg MGaMC+Py8 FxFx, using different PDFs testing the several IC models



Charm PDF studies by ATLAS

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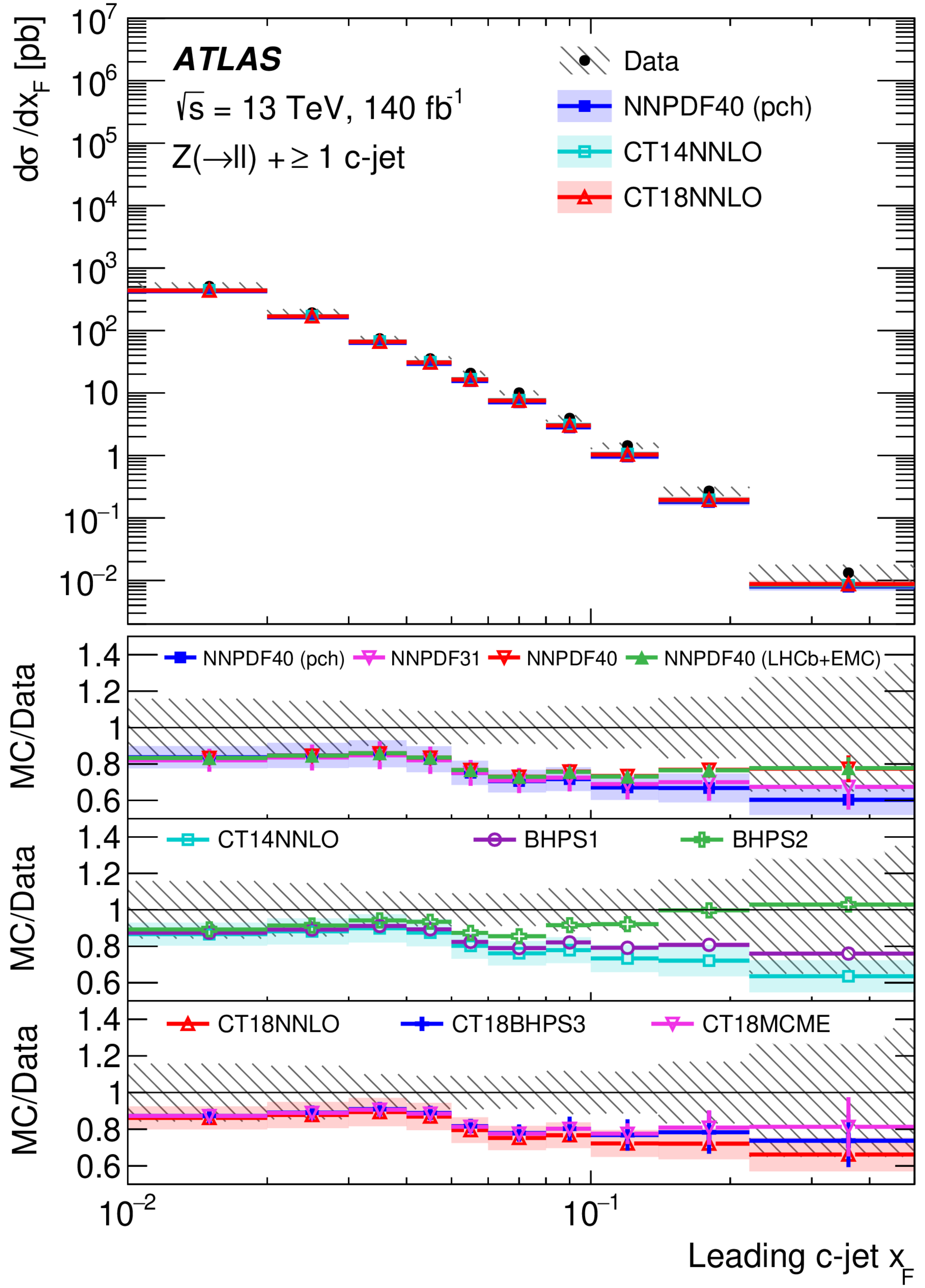
5FS multi-leg MGaMC+Py8 FxFx, using different PDFs testing the several IC models

Mismodelling at large xF:

- Only CT14 BHPS2 (2.1% IC) clearly improves large xF
- More realistic PDF fits: only marginal improvement
- For IC PDFs (e.g. NNPDF4.0 EMC+LHCbZc , last bins)



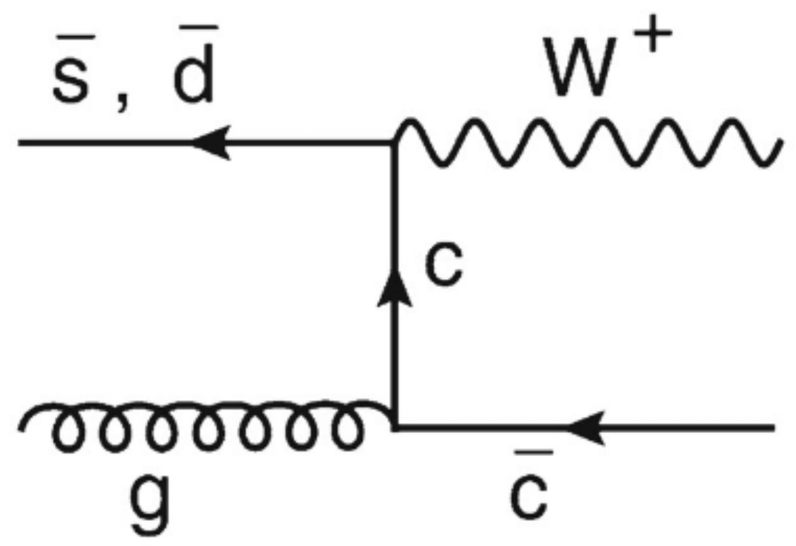
NNPDF4.0 w LHCbZc

BHPS2

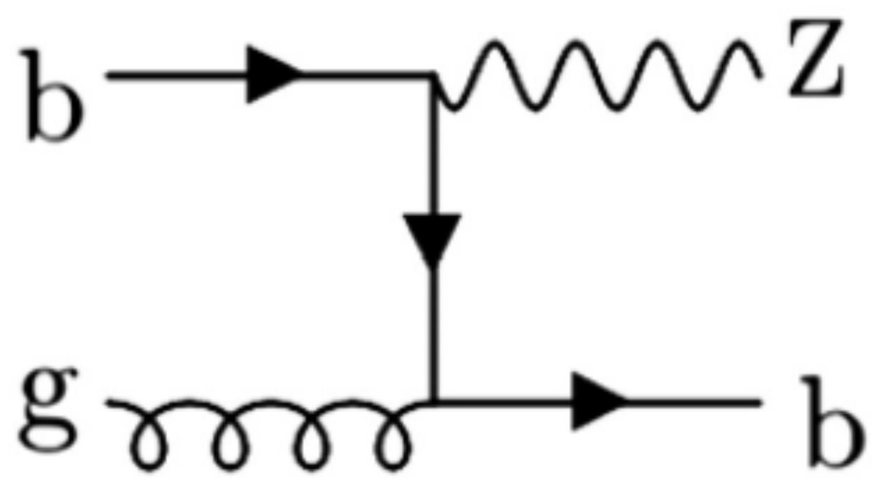
(2.1% IC)

Summary (1/2)

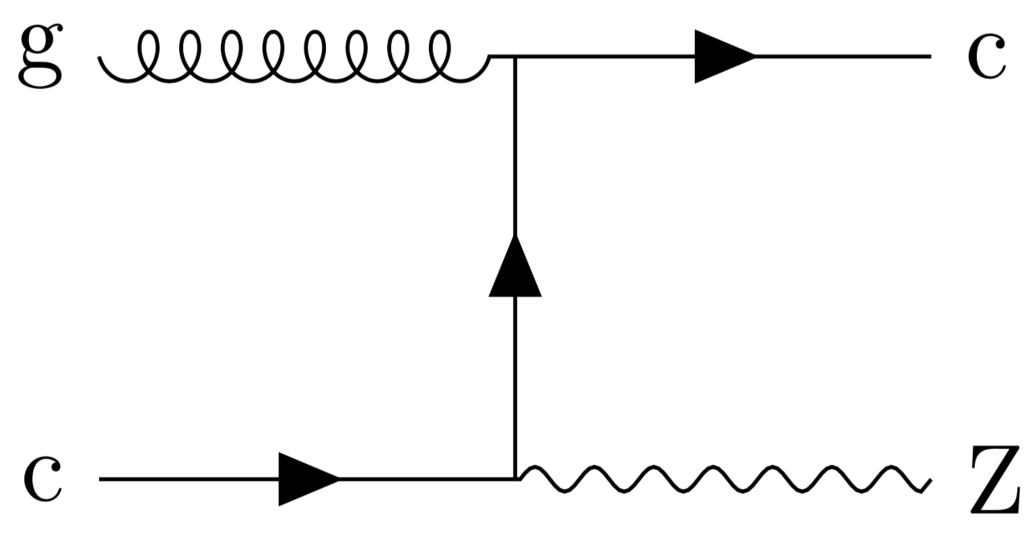
- W+Charm
  - ➡ With Run2 precision W+c becomes sensitive to PDFs



- Z+b(b):
  - ➡ Results updated with full Run-2 dataset, new flavour tagging algorithm
  - ➡Higher precision and larger data sets allow to probe different flavour/mass schemes, pQCD and IRC safe b-jet definitions
  - ➡ Allows precise differential cross-section measurements



- Z+charm: First time in ATLAS
  - ➡ Test effect of missing higher-order terms in QCD
  - ➡ Investigate different Flavour-Schemes in predictions
  - ➡ Explore possible sensitivity to Intrinsic-Charm



Summary (2/2)

- V+HF measurements have profited significantly from flavour-tagging improvements in LHC Run2 and from the larger data set

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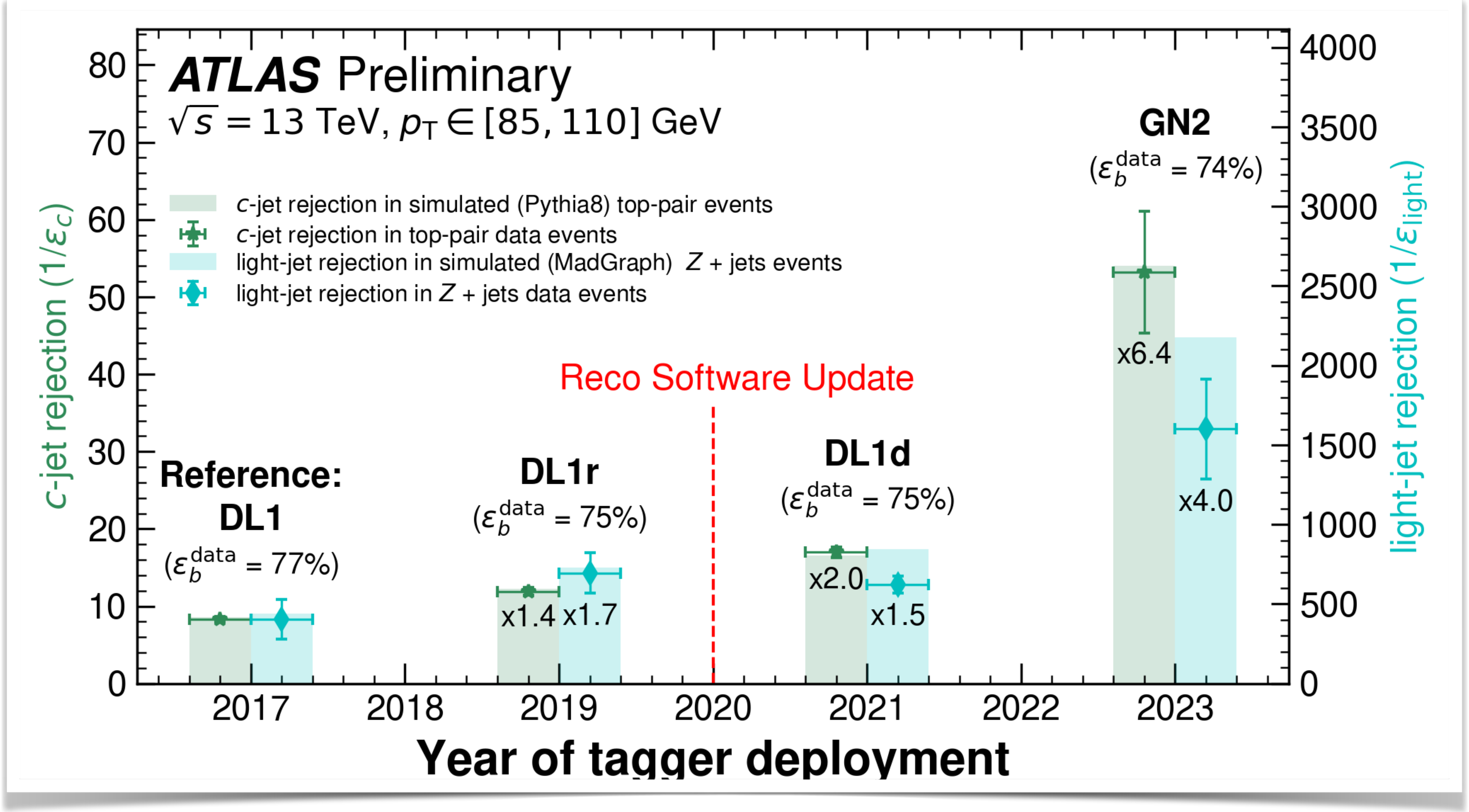
- V+HF measurements have profited significantly from flavour-tagging improvements in LHC Run2 and from the larger data set

- Future prospective:
  - Intrinsic charm and quark/gluon PDF constraints
  - Improved jet flavour algorithm performance, jet substructures for α_S
  - Gluon splitting pattern, fragmentation etc.
  - Precision measurements:
    - Ratio characterized by cancellation of large scale uncertainties
    - Improved predictions—NNLO QCD, N3LO PDF , PS model



Summary (2/2)

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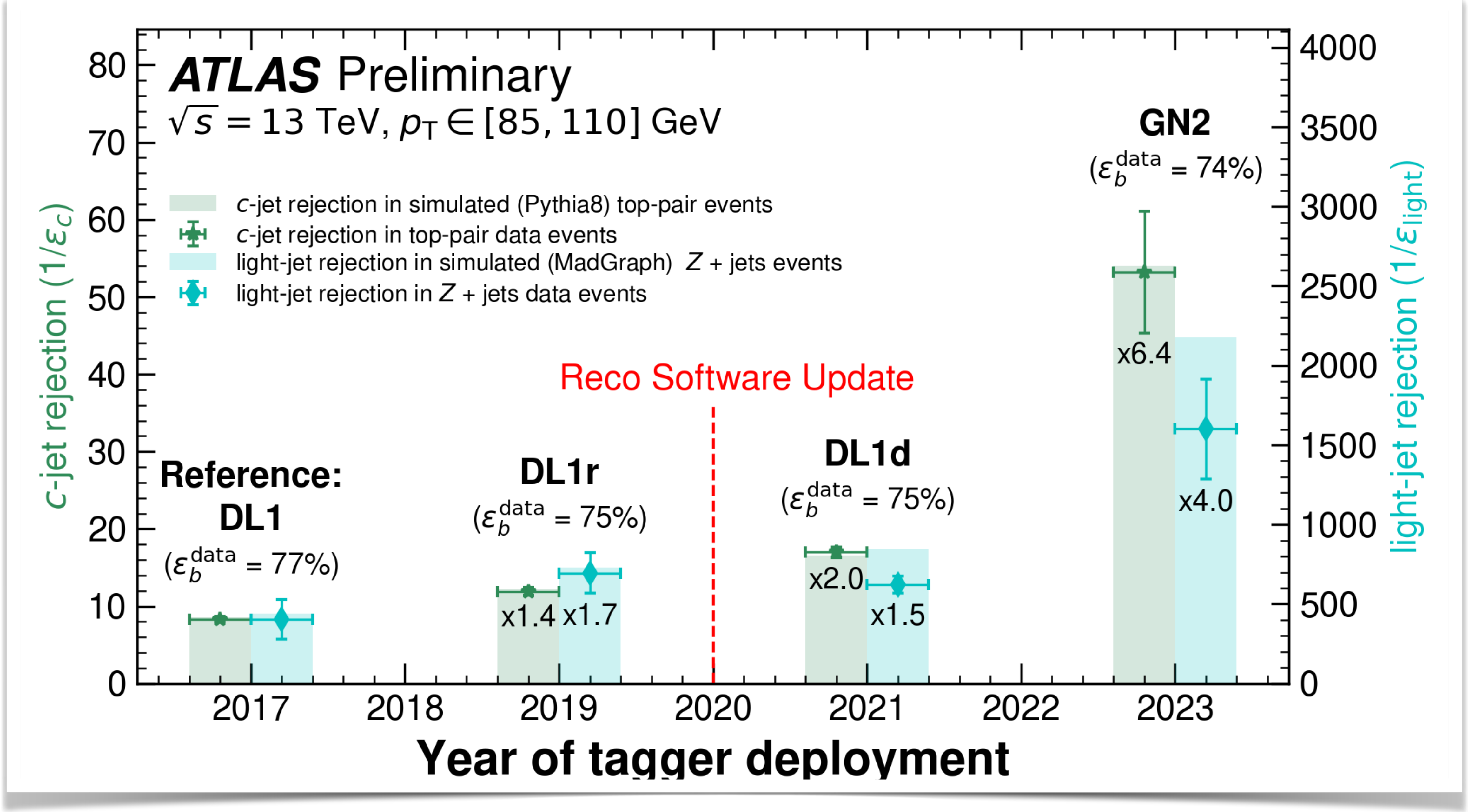

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Thank you for listening…

Back-up

NLO MC generators

- CMS

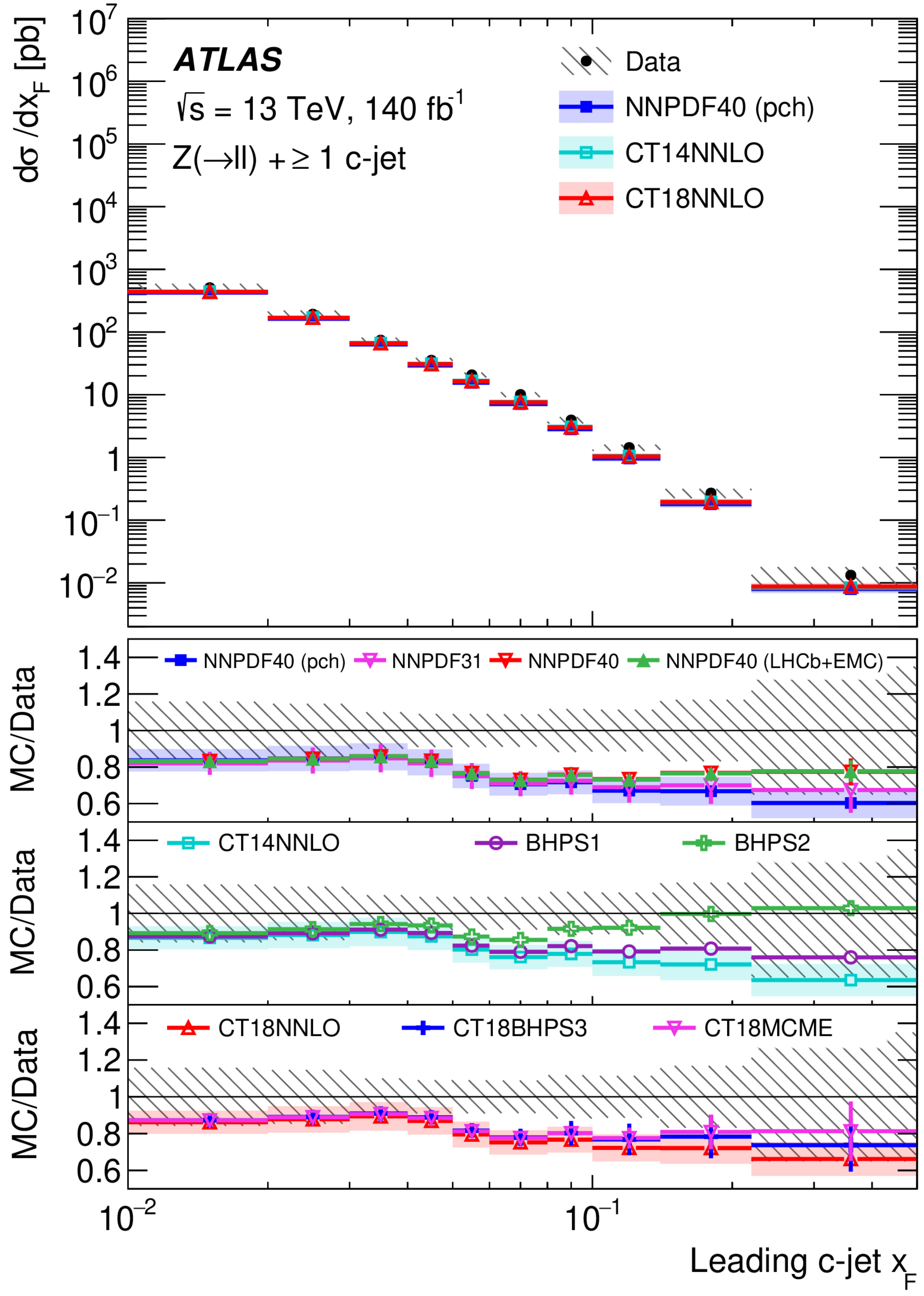
The Drell–Yan (DY) process with exclusive jet multiplicity up to 2 is simulated at next-to-leading order (NLO) precision by MADGRAPH5_aMC@NLO (denoted MG5_aMC) [16] version 2.3.2.2 for 2016 data and version 2.6.0 for the 2017–2018 data with the FXFX [17] matching between the jets from matrix element calculations and parton showers. The NNPDF 3.0 NLO and NNPDF 3.1 next-to-NLO (NNLO) PDF sets [18] are used for the 2016 and 2017–2018 data-taking periods, respectively.

A third inclusive sample has been produced with SHERPA v2.2.4 [23] to generate pp $\rightarrow$ Z + n jets events, with $n \leq 2$ at NLO and $n = 3, 4$ at LO. The merging with the SHERPA parton shower is done via the MEPS@NLO prescription [24–26] with a matching scale of 20 GeV. The NNPDF 3.0 NLO PDF and a dedicated set of tuned parton shower parameters developed by the SHERPA authors are used. In the matrix element calculation, the value of the NNPDF 3.0

- ATLAS

Process	Generator	Order of pQCD in ME (FS)
$Z \rightarrow \ell\ell$	MGAMC+PY8 FxFx v2.6.5	0–3p NLO (5FS)
$Z \rightarrow \ell\ell$	SHERPA 2.2.11	0–2p NLO, 3–5p LO (5FS)

Z+c measurements: more details on x_F



Comparison with 5F multi-leg MGaMC+FxFx with PDF corresponding to different IC predictions

- NPDF31 (default)
- **NNPDF4.0 (NNLO)PCH(no IC): no intrinsic charm**
- NNPDF4.0 (NNLO): baseline, some IC
- **NNPDF4.0 (NNLO) EMC+LHCbZc: incl. LHCb Zc/Zj**

- **CT14 (NNLO) (noIC): no intrinsic charm**
- CT14 (NNLO) IC-BHPS1, older PDF, fixed 0.6% IC
- **CT14 (NNLO) IC-BHPS2, older PDF, fixed 2.1% IC**

- CT18 (NNLO) (no IC)
- CT18FC-CT18 BHPS3: BHPS3 model
- CT18FC-CT18 MCM-E: Meson-Baryon model, based on effective mass