Measurement of *W* and *Z* boson production in association with jets in ATLAS

Camilla Vittori

camilla.vittori@cern.ch

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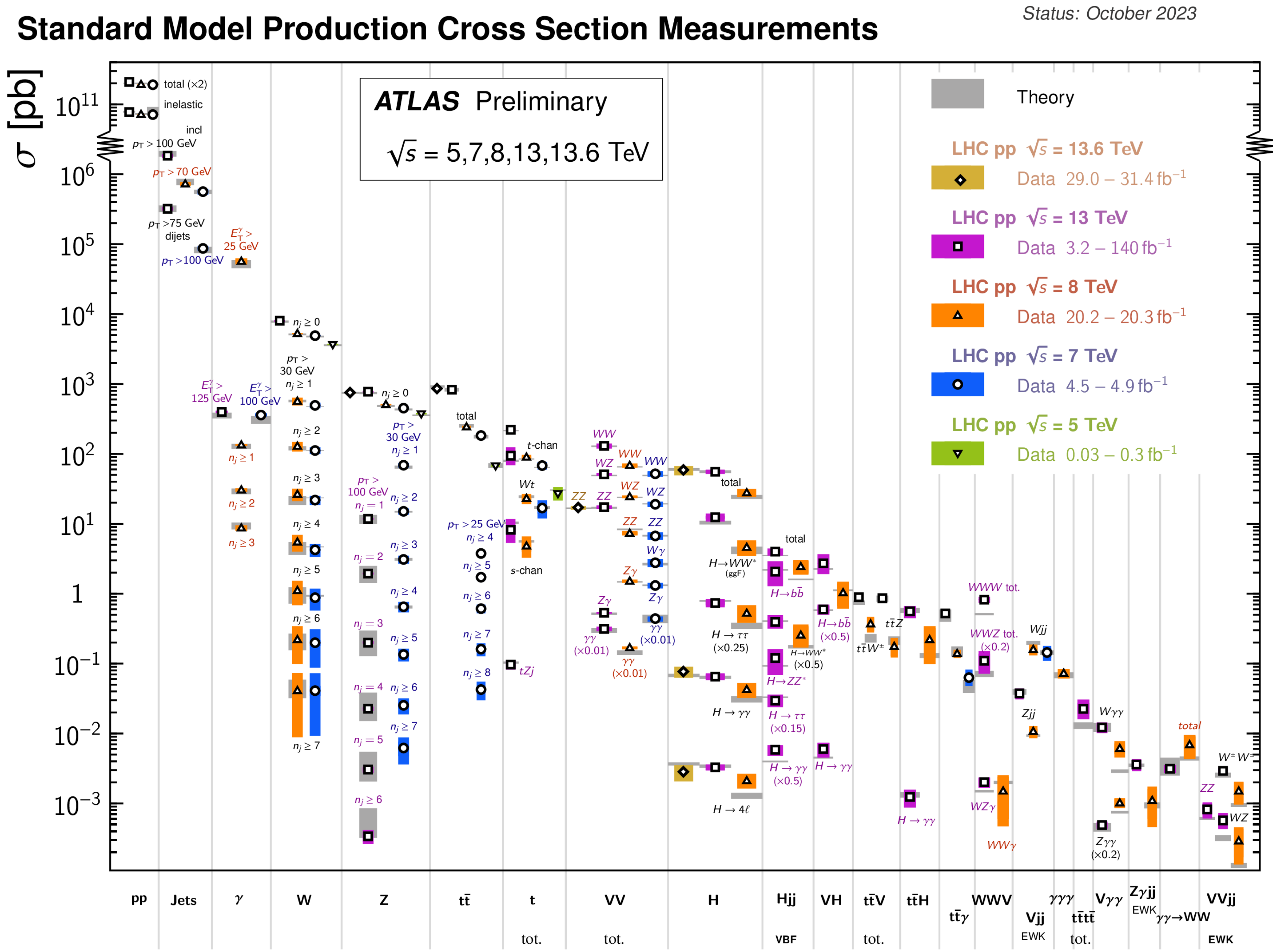
Outline

- V (*W* or *Z*) in association with (heavy-flavour) jets or hadrons production:
  - Precise **test of perturbative QCD** (pQCD)
    - ➡ test state-of-art predictions
  - **Sensitive to Parton Distribution Functions** (PDFs)
  - **Tune predictions and improve Monte Carlo** (MC) simulations
    - ➡ background to other physics processes
    - ➡ reduce modelling/theoretical uncertainty



<u>Today's focus on newest ATLAS results:</u>

- ★ **p_T^{miss} + jets**
- ★ **Z +≥ 1, 2 b-jets and Z+≥ 1 c-jet**
- ★ W + D in backup

Measurement of p_T^{miss} + jets

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

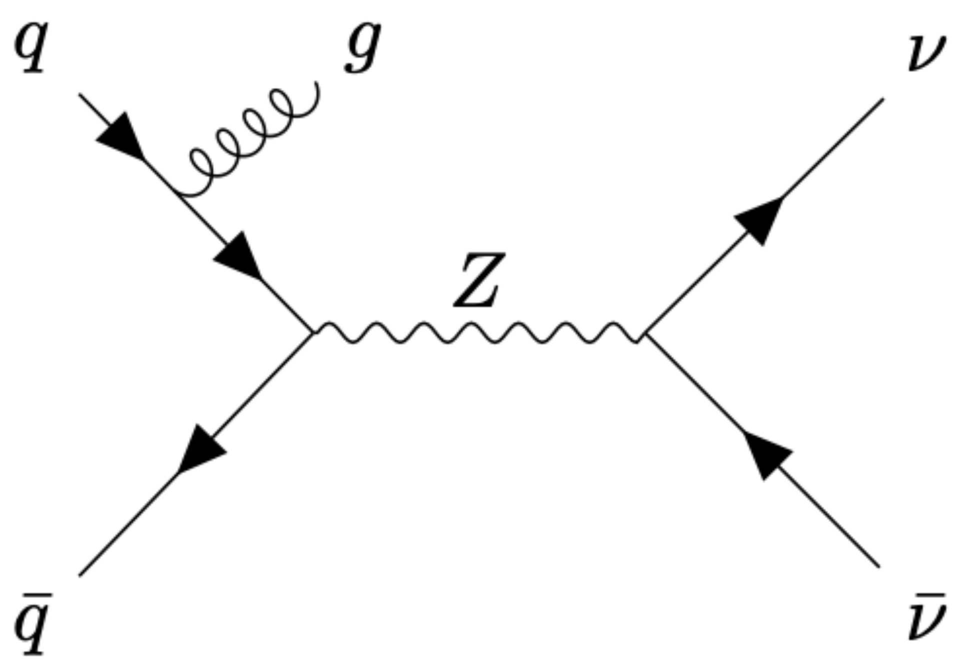
arXiv:2403.02793
Submitted to JHEP

Unfolded differential measurements of p_T^{miss} produced in association with jets

- Two types of measurements:
  - **Z(→$\nu\nu$) + jets "process-specific"** - after subtraction of all sub-dominant processes
  - **p_T^{miss} + jets "final state driven"**- only fakes are subtracted from data
    →**highly re-interpretable in various Beyond-SM (BSM) searches (i.e. Dark Matter)**
- **Differential cross sections measurements in two phase-spaces:**
  - Inclusive: p_T^{miss}
  - Vector Boson Fusion (VBF) - enhanced: p_T^{miss}, $\Delta\phi_{jj}$ and m_{jj}

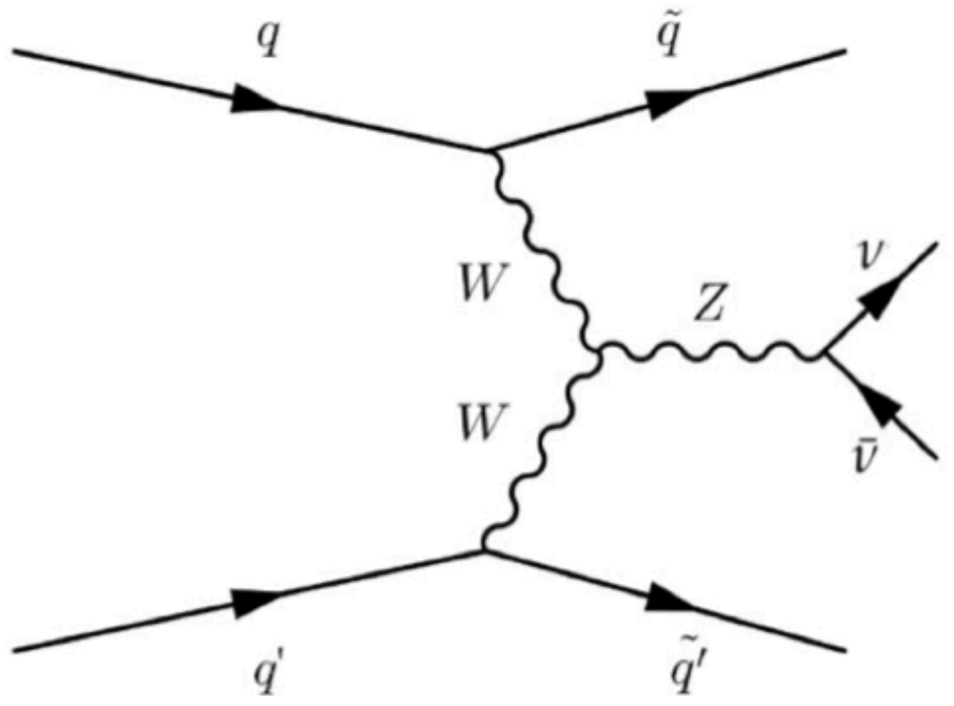
Inclusive

- **≥ 1 jet**
- lead-jet p_T > 120 GeV



VBF

- **≥ 2 jets**
- lead-jet p_T > 80 GeV
- sub-lead jet p_T > 50 GeV
- m_{jj} > 200 GeV



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Measurement of p_T^{miss} + jets

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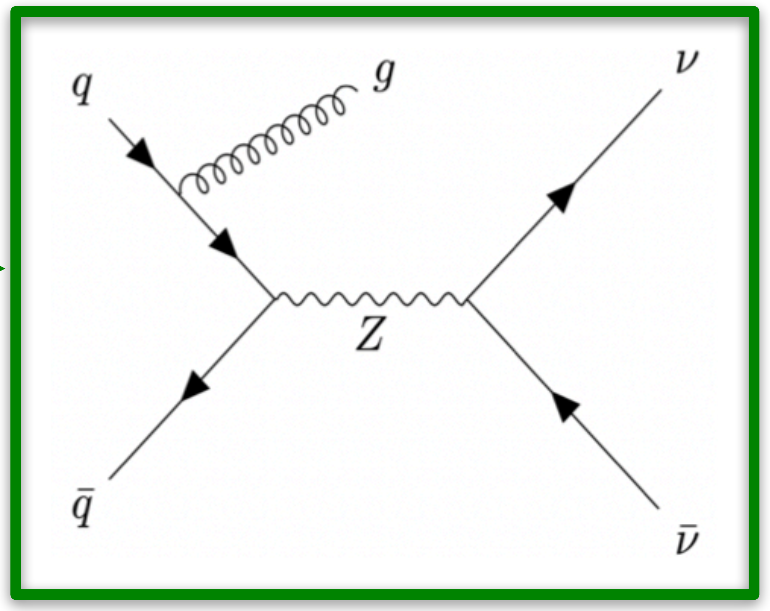
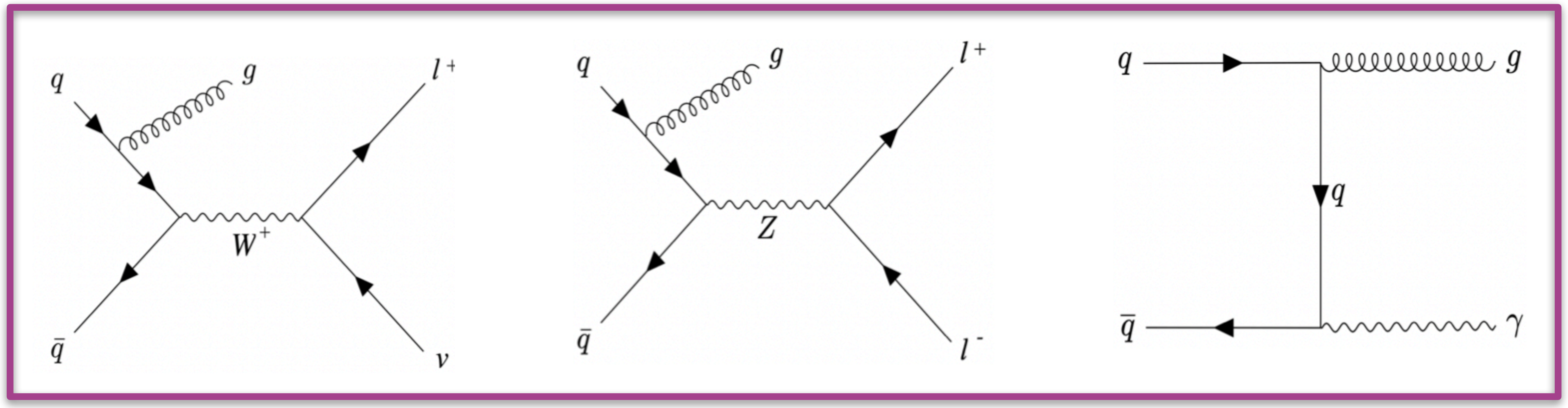
- Measurements performed in:
  - **Signal Region (SR)**: p_T^{miss} + jets
  - **5 Auxiliary Regions (AR)**:
    1 lepton+jets, 2 leptons+jets, photon+jets





- Measure regions individually and as ratios

$$\mathbf{R_{miss}} = \sigma(\mathbf{SR})/\sigma(\mathbf{AR})$$

- R_{miss} allow cancellation of systematics and modelling effect

Regions

SR: p_T^{miss} + jets	Aux: μ + jets
Aux: e + jets	Aux: 2μ + jets
Aux: 2e + jets	Aux: γ + jets

Phase-spaces	**Observables**
>= 1 jet	p_T^{miss}
VBF, >= 2 jets	p_T^{miss}, m_{jj} and $\Delta\Phi_{jj}$

Measurement of p_T^{miss} + jets

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- Background contributions:
  - **Non collision background**: removed by jet identification + data-driven approach using jet timing
  - **QCD multijet**: suppressed by $\Delta\phi(jet, p_T^{miss})$ + data-driven technique
  - **SM processes**: shape is taken from the MC simulation and normalisation is derived from fit to data in specific control regions

	Final-state event selection					
Production process	p_T^{miss}+jets	$2e$+jets	2μ+jets	e+jets	μ+jets	γ+jets
$Z \to \nu\nu$ + jets	55%	–	–	–	–	–
$Z \to ee$ + jets	–	94%	–	–	–	–
$Z \to \mu\mu$ + jets	–	–	95%	–	2%	–
$W \to e\nu$ + jets	6%	–	–	68%	–	–
$W \to \mu\nu$ + jets	9%	–	–	–	67%	–
$W \to \tau\nu$ + jets	20%	–	–	5%	7%	–
γ + jets	–	–	–	–	–	>99%
Top	7%	3%	2%	25%	21%	–
Multi-boson	3%	3%	3%	2%	3%	<1%

P_T^{miss} + jets Results

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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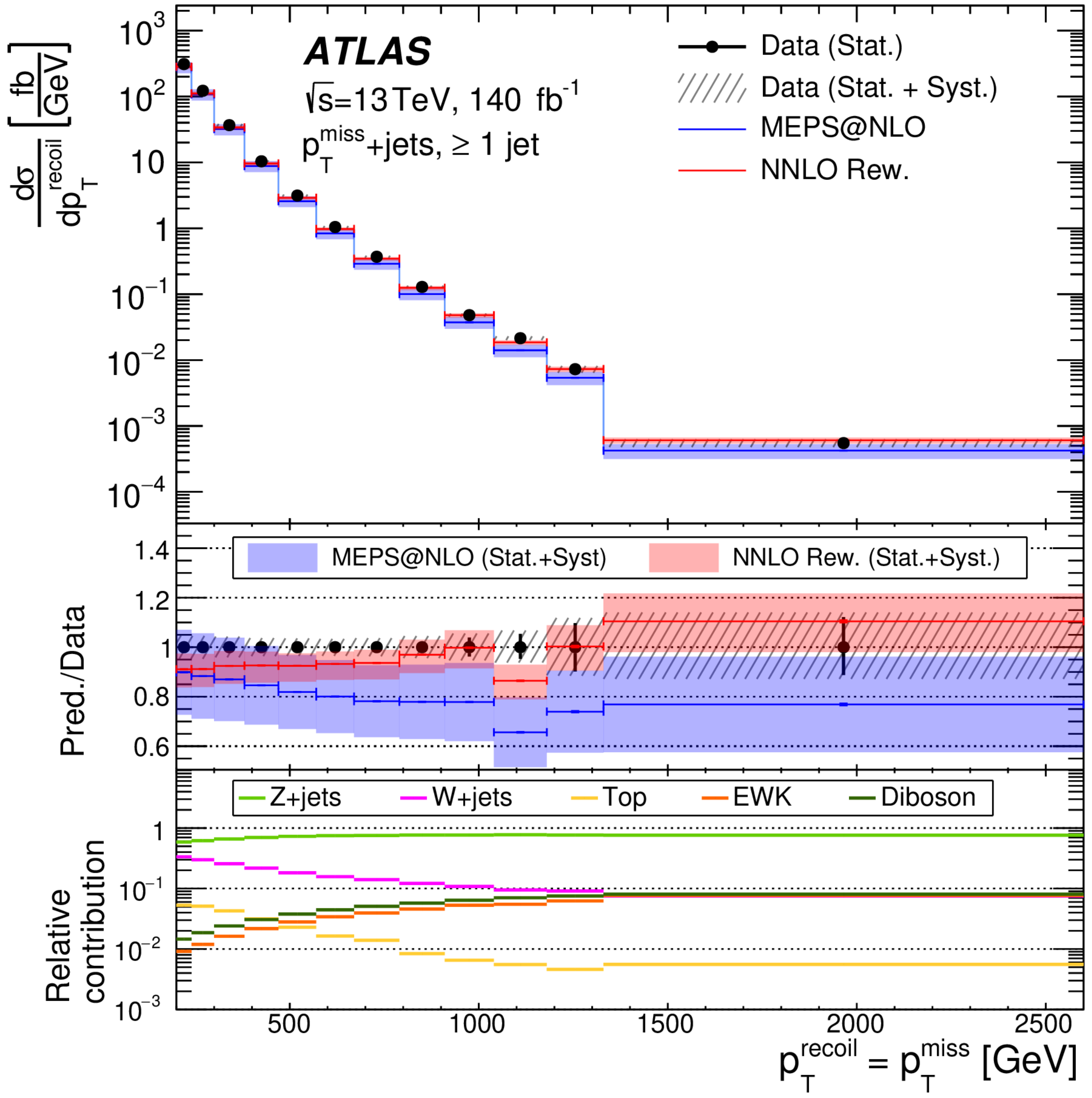
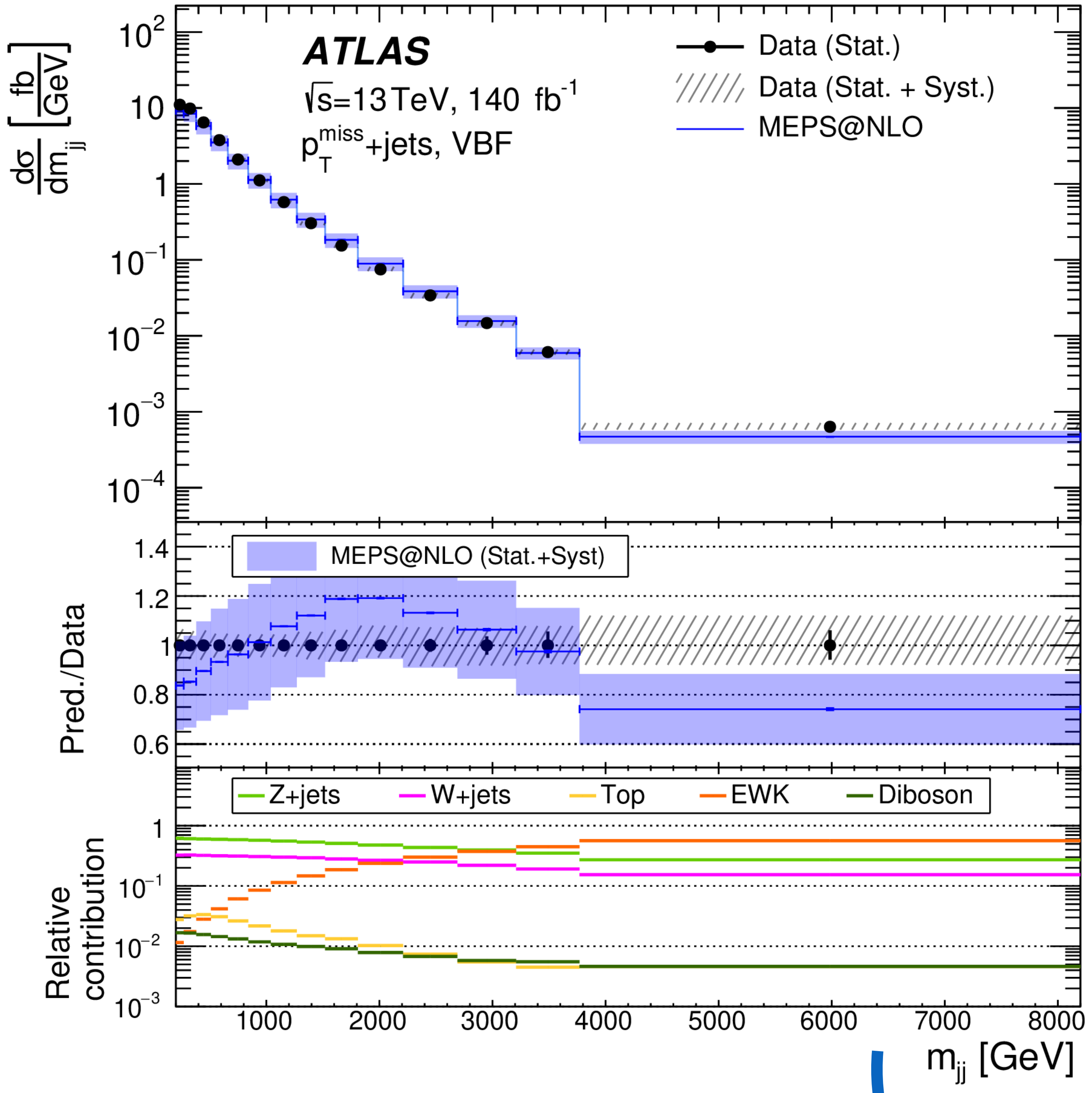
p_T^{miss} + jets, inclusive

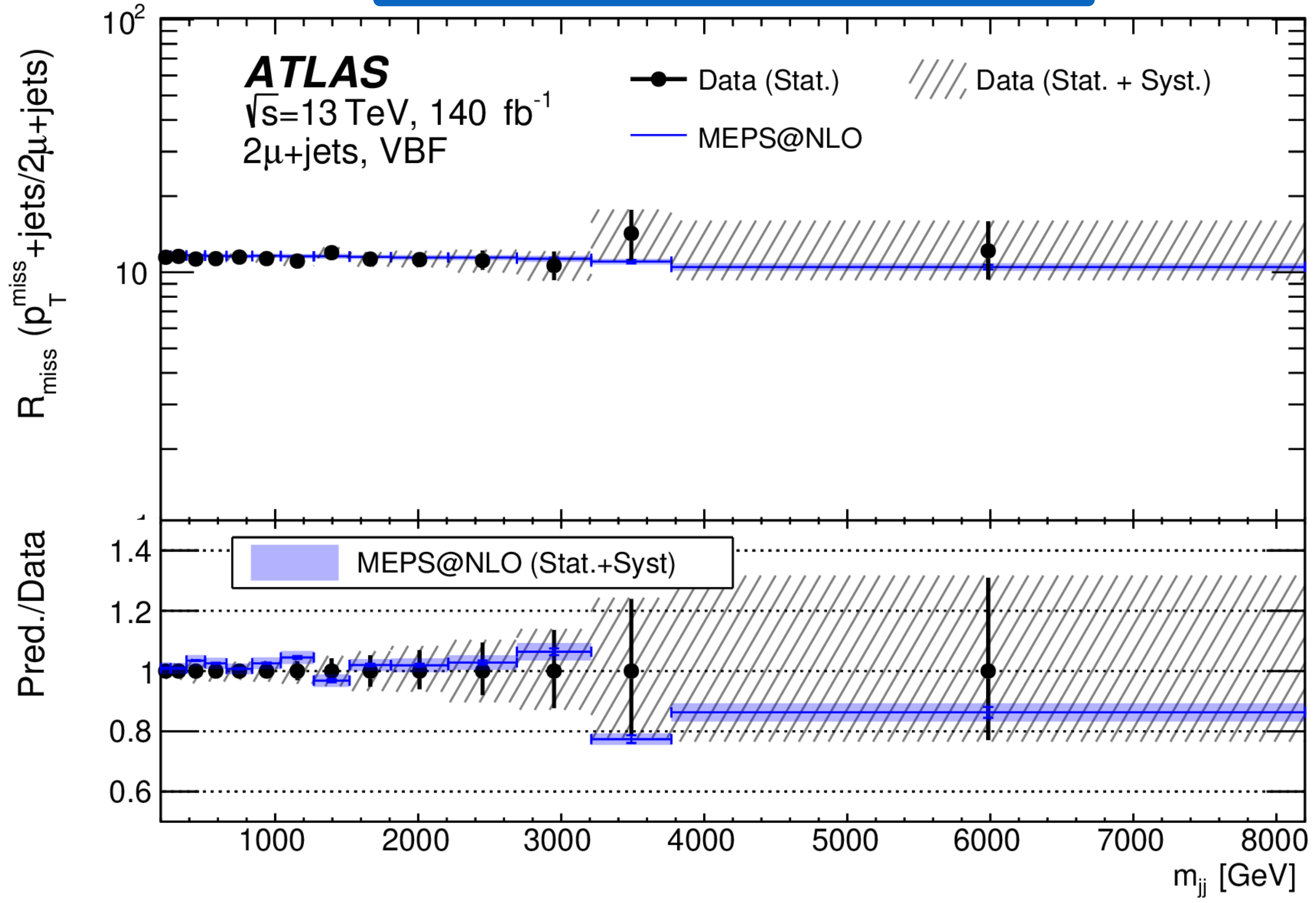


p_T^{miss} + jets, VBF



- ✦ Reasonable agreement with state-of-art SM predictions *backup*
- ✦ **m_{jj} not well described in VBF phase-space (≥2 jets)**

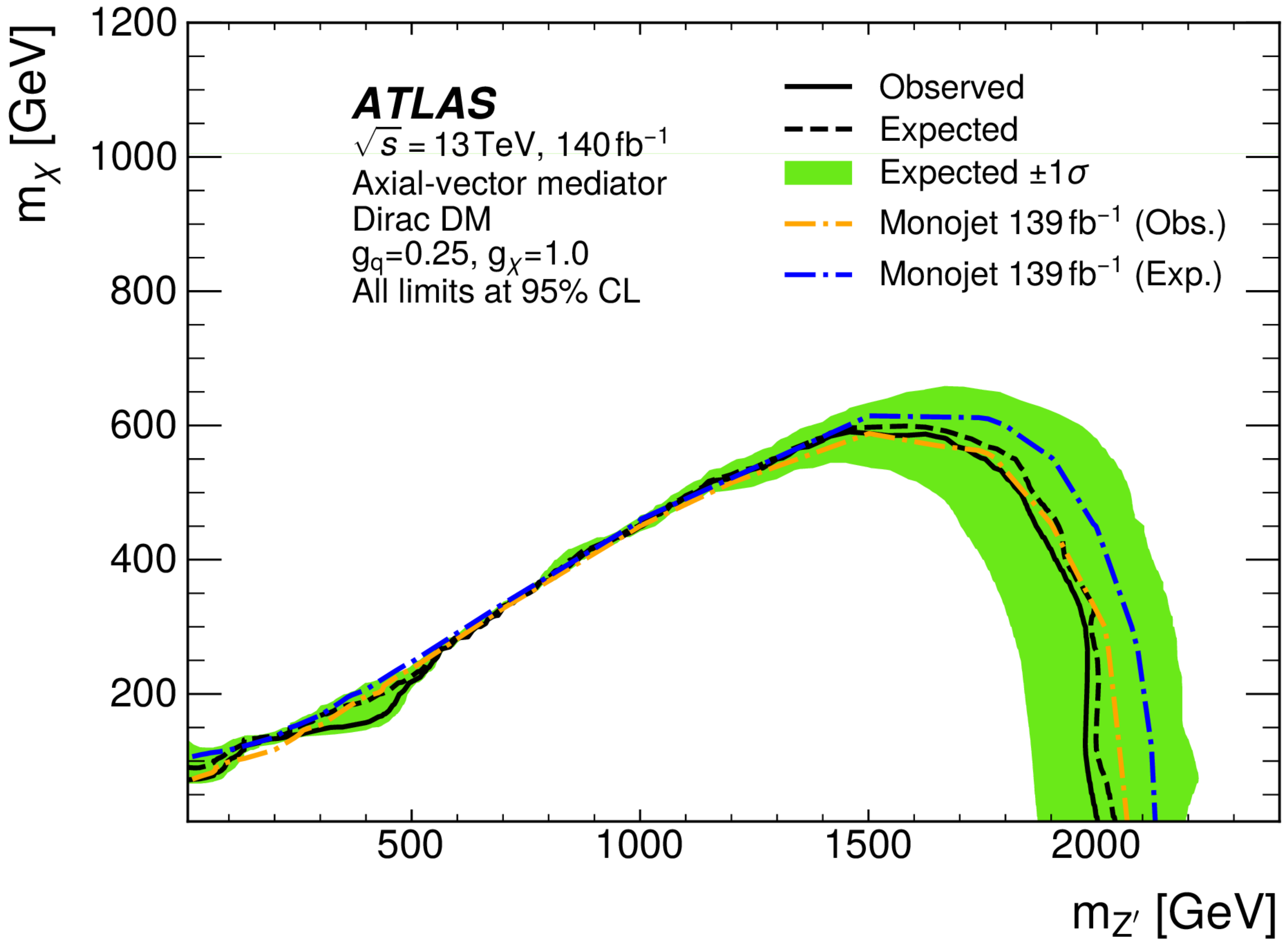
p_T^{miss} + jets, VBF

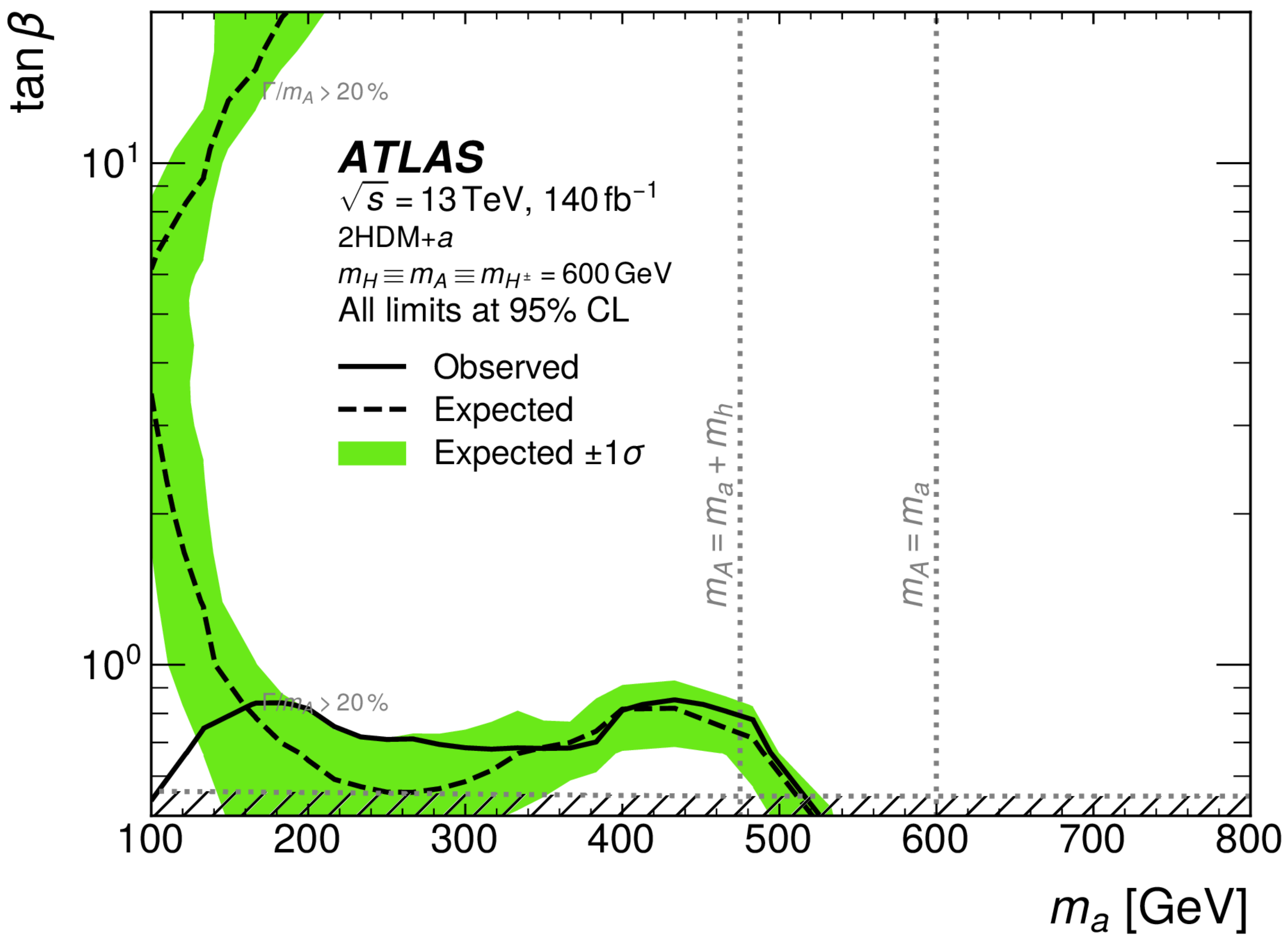


- ✦ **R_{miss}** benefit from the partial cancellation of both systematics and discrepancies in modelling *backup*
- ✦ Most noticeable example from **m_{jj} in VBF**

P_T^{miss} + jets Interpretations

- **Interpretation of the unfolded data in DM-searches - 2 models tested!**
- Measured R_{miss} are used to test **axial-vector mediator Dirac DM model**
  - comparable sensitivity with dedicated DM-searches [Phys. Rev. D 103 (2021) 112006]
- Limits also on **2HDM+a model**, where the Higgs doublets and a pseudo-scalar couple with DM





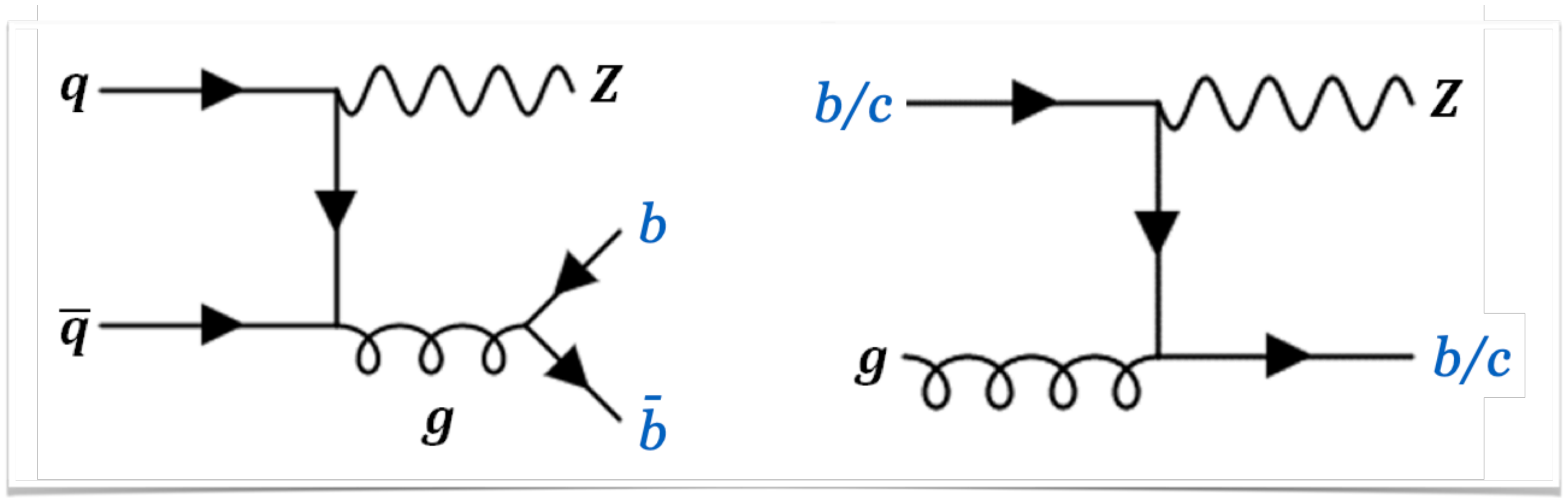
Z + HF-jets measurements

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

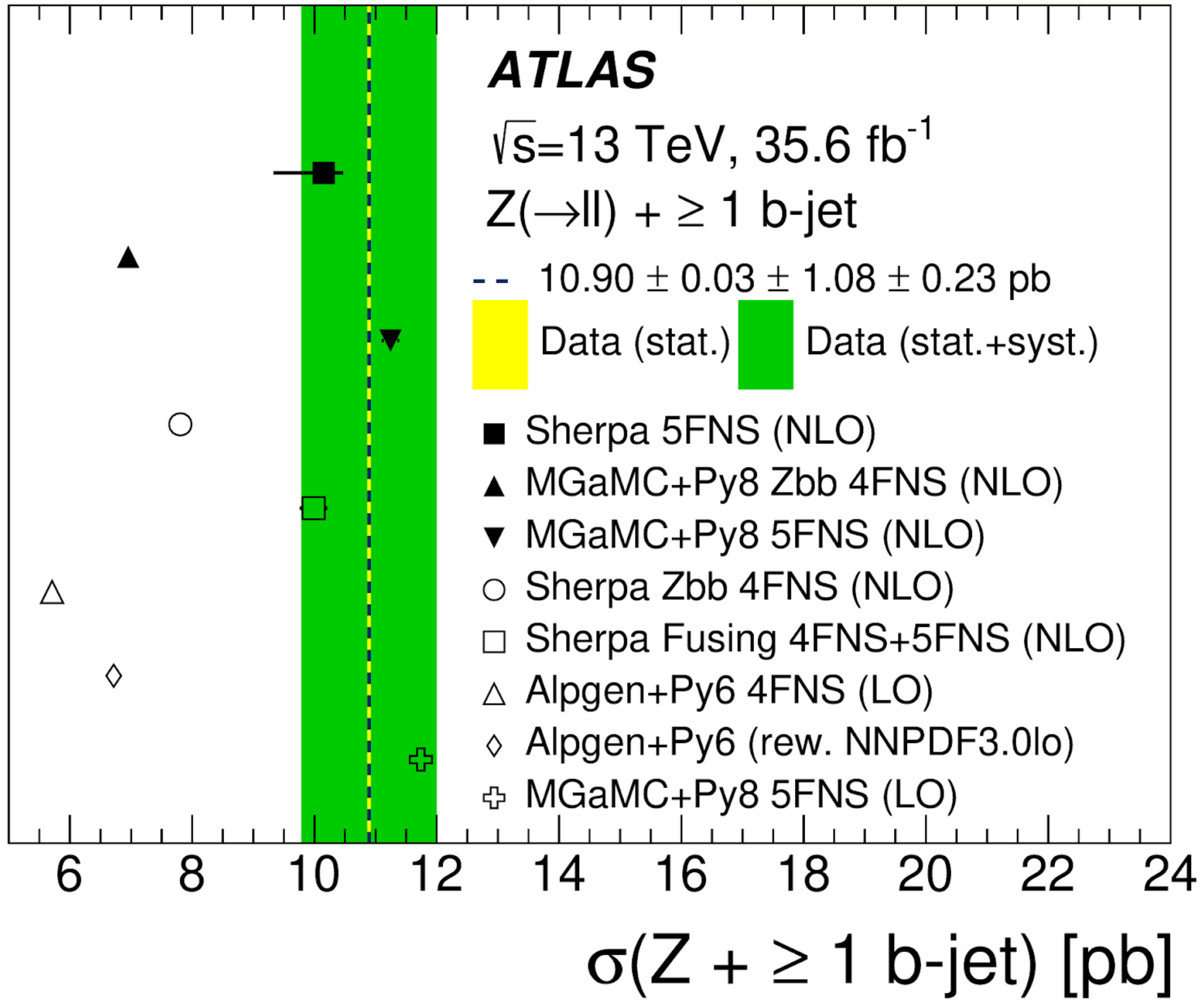
arXiv:2403.15093
Submitted to EPJC

Inclusive and differential *Z*+≥1 *b*-jet, *Z*+≥2 *b*-jets, *Z*+≥1 *c*-jet cross-sections

- Precise test of **pQCD predictions** (NNLO available)
- Unique access to ***b*-, *c*-quark and gluon PDFs**
  - Explore possible sensitivity to Intrinsic Charm (*IC*) component
- Sensitive to **different Flavour number Schemes (FS)** in the predictions
- Inputs for **MC modelling tuning**
  - *Z*+HF background in *VHbb* analyses and BSM searches



JHEP 07 (2020) 044



★ ***Z*+≥1 *b*-jet and *Z*+≥2 *b*-jets:** update 36 fb^{-1} results with larger statistics, new b-tagging algorithm and optimised strategy

★ ***Z*+≥1 *c*-jet:** **first time in ATLAS!**

Z + HF-jets analysis strategy

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

arXiv:2403.15093
Submitted to EPJC

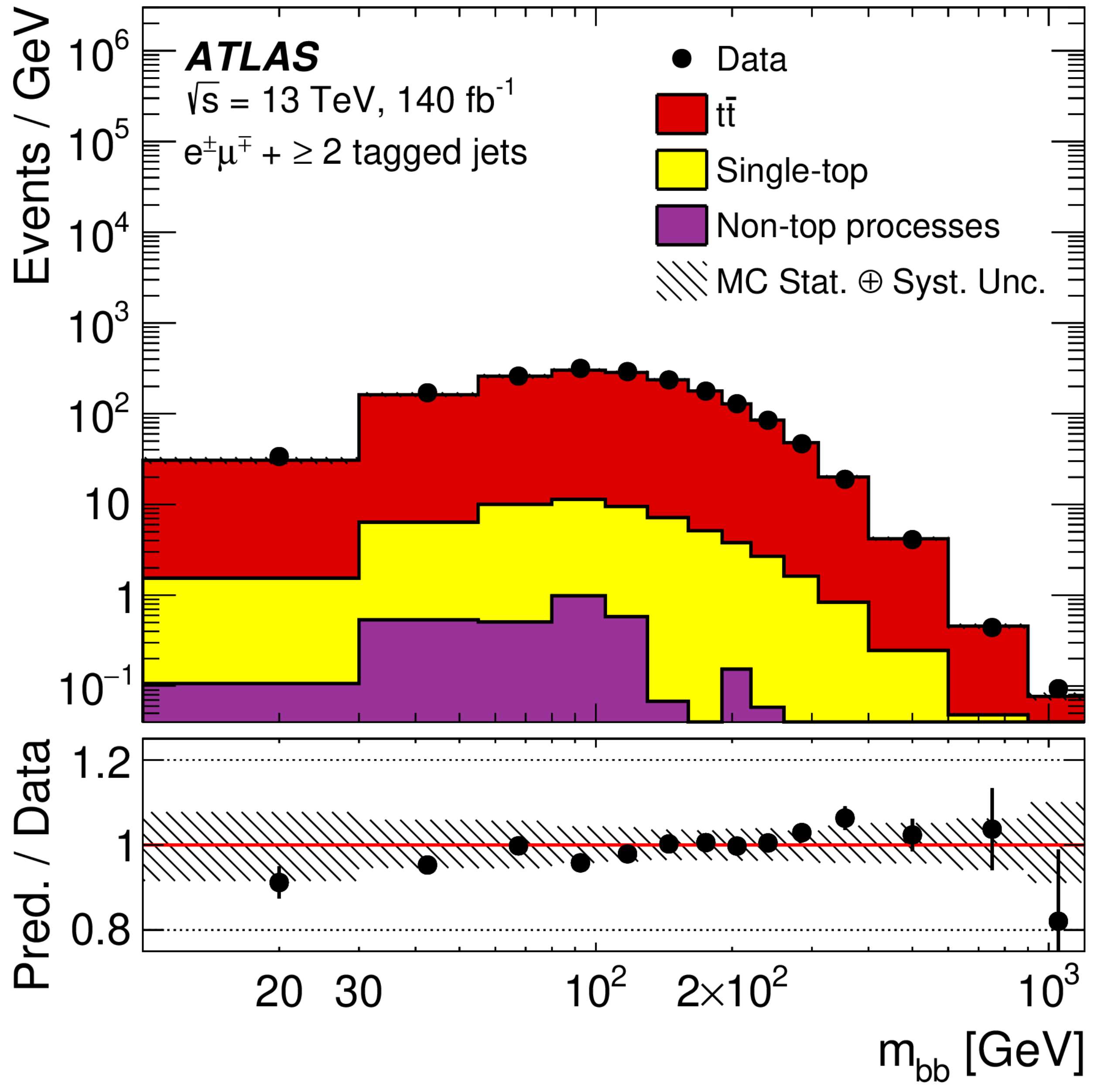
✦ **Select *Z*(→*μμ*, *ee*) + 1 or 2 flavour-tagged jets, with 85% DL1r** (30% efficiency on c-jets)

Define 2 Signal Regions (SR):

1-tag: *Z*+≥1 *b*-jet and *Z*+≥1 *c*-jet measurements

2-tag: *Z*+≥2 *b*-jets measurement

✦ data-driven **$t\bar{t}$ background in e±*μ*∓ CR** **backup*
→ avoid large modelling uncertainties



✦ ***Z*+jets background with bin-wise "flavour fit" of flavour sensitive observable**
→ correct shape and normalisation

✦ **Correct** detector level distributions **to particle level in fiducial phase space** (unfolding) **backup*

✦ **Fwd/central ratio of *Z* p_T in *Z*+≥1 *c*-jet events:**

- keep correlations and migrations into account

Z + HF-jets Flavour-fit

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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✦ *Z*+jet with flavour different from the one measured is the largest source of background

	1-tag SR		2-tag SR
Analysis	*Z*+≥1 *b*-jet	*Z*+≥1 *c*-jet	*Z*+≥2 *b*-jets
***Z*+jets bkg**	*Z*+*c*, *Z*+l	*Z*+*b*, *Z*+l	*Z*+1*b*, *Z*+*c*, *Z*+l

*backup

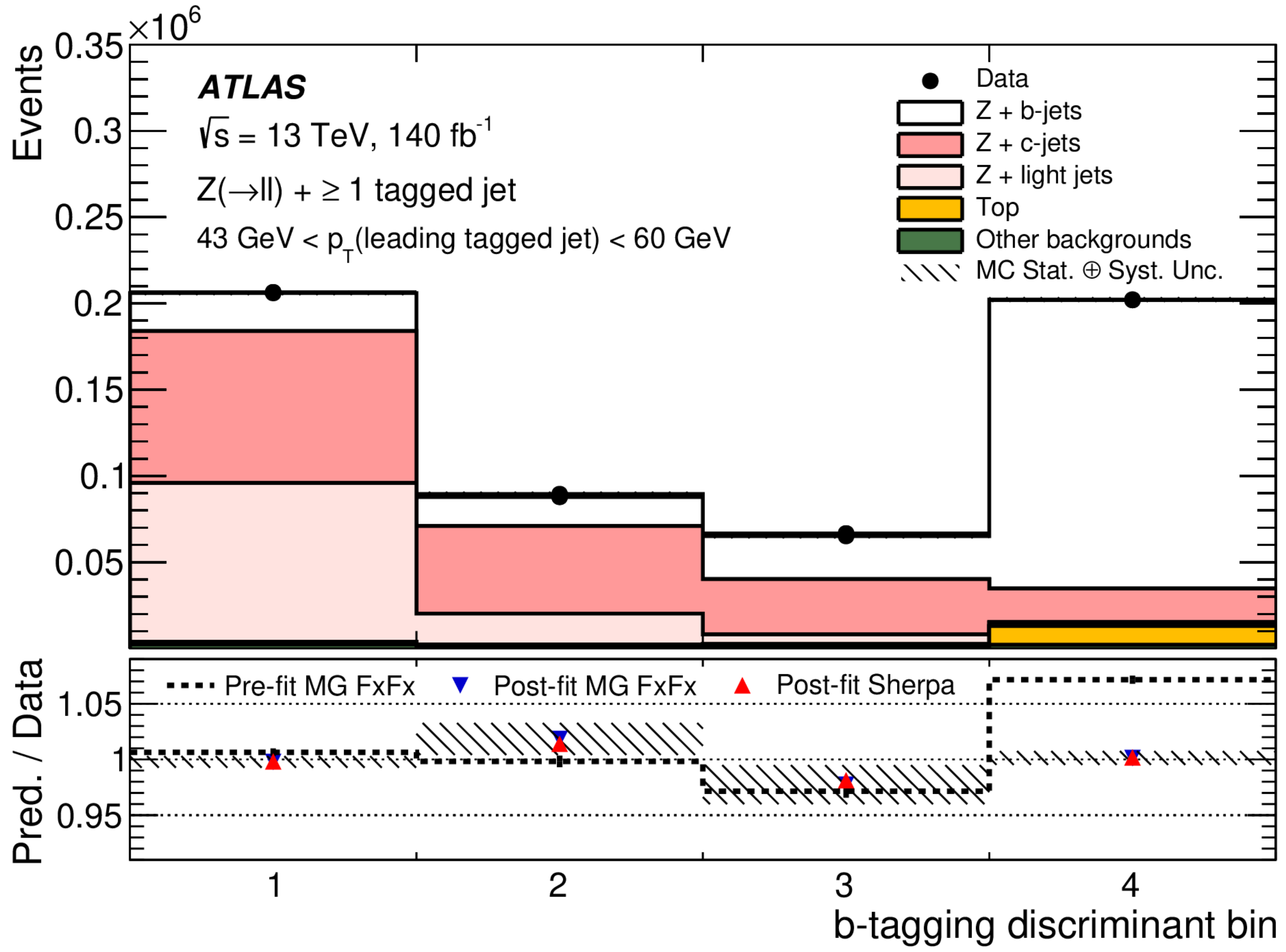
➡ **Correct *Z*+jets flavour components** and constrain systematics **with "flavour-fit"**

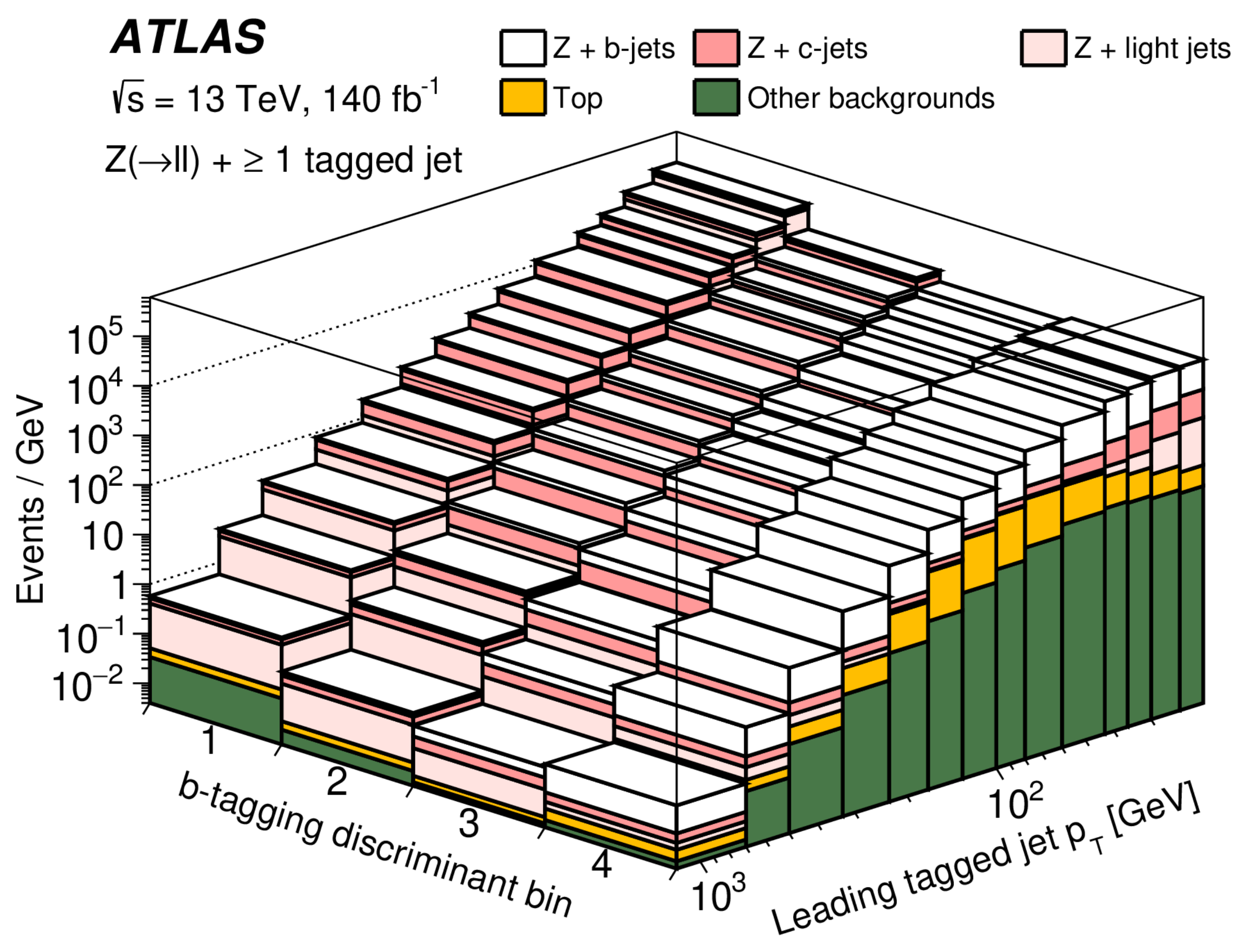
Maximum-likelihood fit to data based on flavour sensitive distribution

✦ **fit performed in individual (optimised) bins of each measured observable**

Example for 1-tag SR:

- Fit of **flavour-tagging score (DL1r) in calibrated bins**
- 3 free parameters corresponding to ***Z*+≥1 *b*-jet**, ***Z*+≥1 *c*-jet** and ***Z*+≥light jets** normalisation





✦ **Factor 2 improved precision** with respect to previous 36 fb^{-1} Z+b results

✦ Dominant uncertainty contributions from: flavour-tagging, jet energy scale and resolution and unfolding *backup*

Source of uncertainty	$Z(\to \ell\ell) + \geq 1$ b-jet [%]	$Z(\to \ell\ell) + \geq 2$ b-jets [%]	$Z(\to \ell\ell) + \geq 1$ c-jet
Flavour tagging	3.6	5.7	10.3
Jet	2.4	4.3	6.5
Lepton	0.3	0.3	0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	0.5	0.3
Z+jets background	0.6	1.5	1.6
Top background	0.1	0.3	<0.1
Other backgrounds	<0.1	0.2	0.1
Pile-up	0.6	0.6	0.2
Unfolding	3.3	5.8	5.0
Luminosity	0.8	0.9	0.7
Total [%]	5.6	9.4	13.2

Inclusive cross-sections:

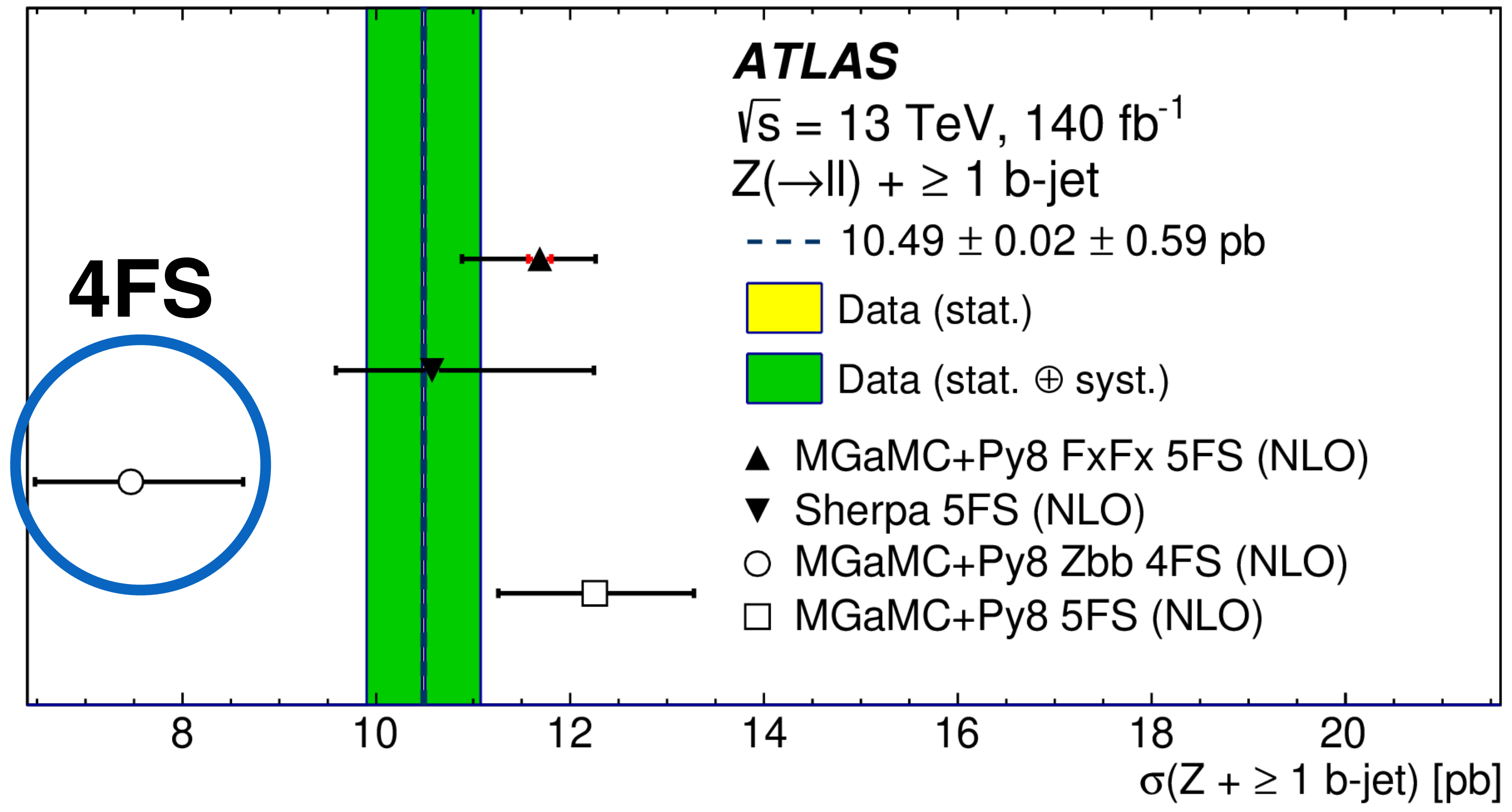
✦ 5FS better describes data

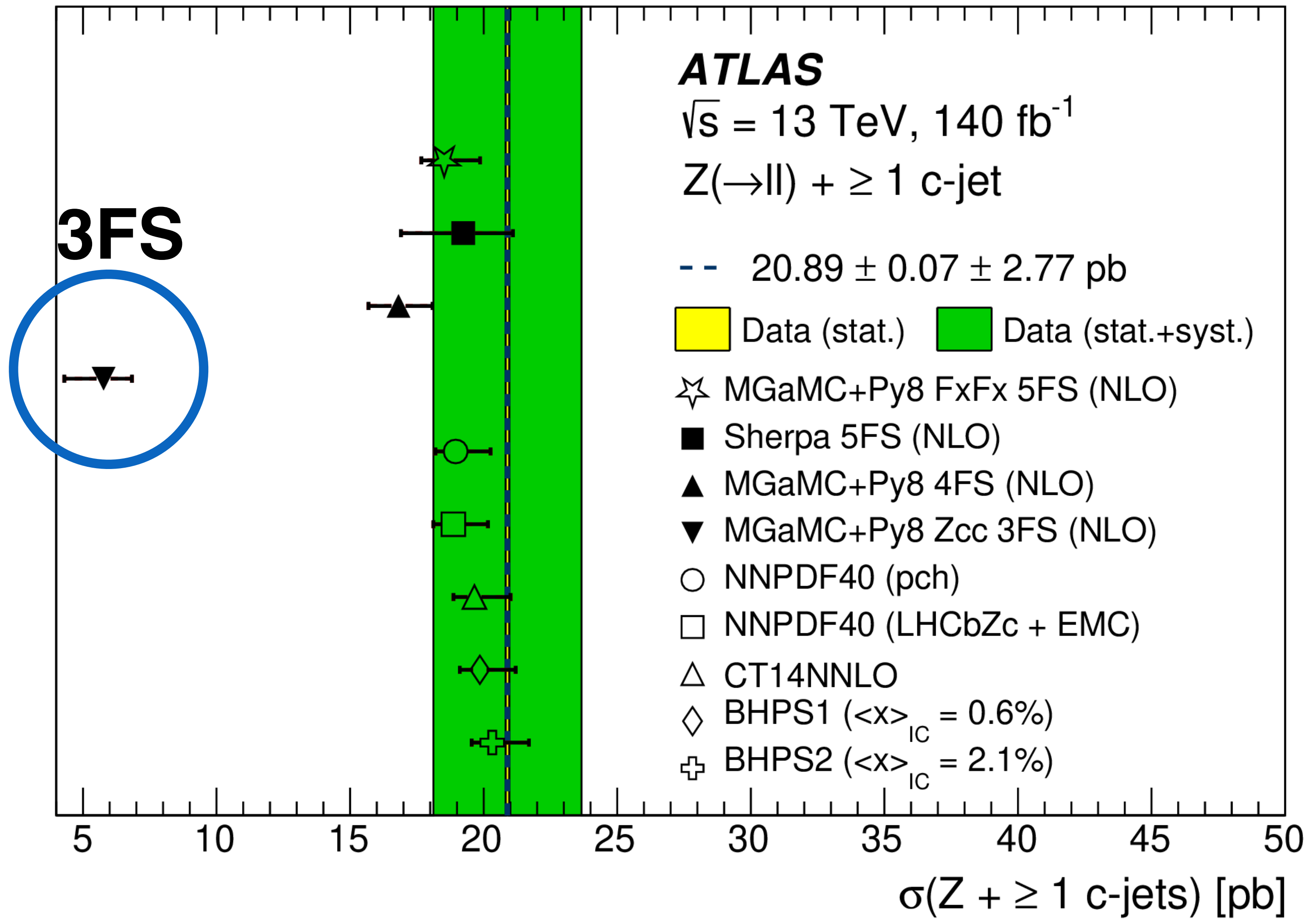
✦ Large underestimation from:
- 4FS of Z+1 b-jet
- 3FS of Z+1 c-jet

→ **lack of log-resummation in PDF evolution**

$$ln(Q^2/m_c^2)$$

Results consistent with previous 36 fb^{-1} measurement





Z + HF-jets Results

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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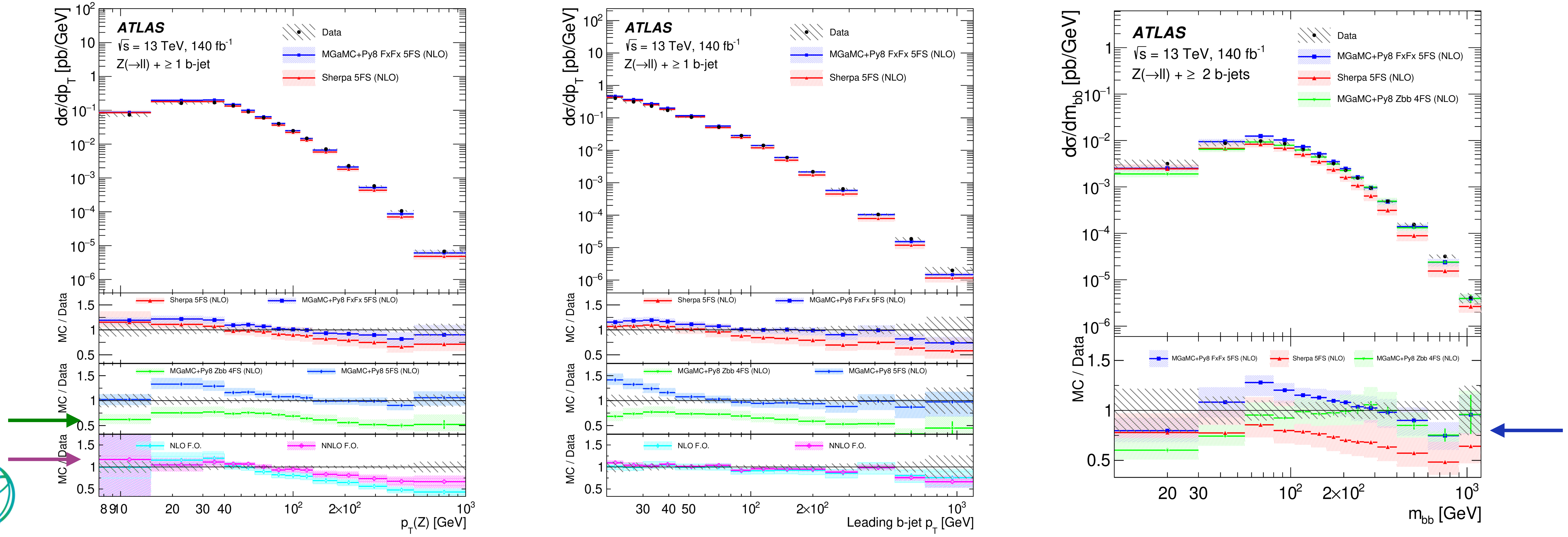
- **5FS:** good description of data by both MGAMC+PY8 FXFX and SHERPA 2.2.11
- **4FS:** MGAMC+PY8 underestimates data in the full spectra - **no log-term resummation in PDF evolution!**
- **Fixed-order:** NLO discrepancies are improved with NNLO
  Large uncertainty on NNLO due to correction for different flavour jet classification
  → **importance of using IRC-safe jet flavour algorithm already in measurements**
- **m_{bb}:** none of the predictions in agreement with data in the full spectrum

*backup



Z + HF-jets Results

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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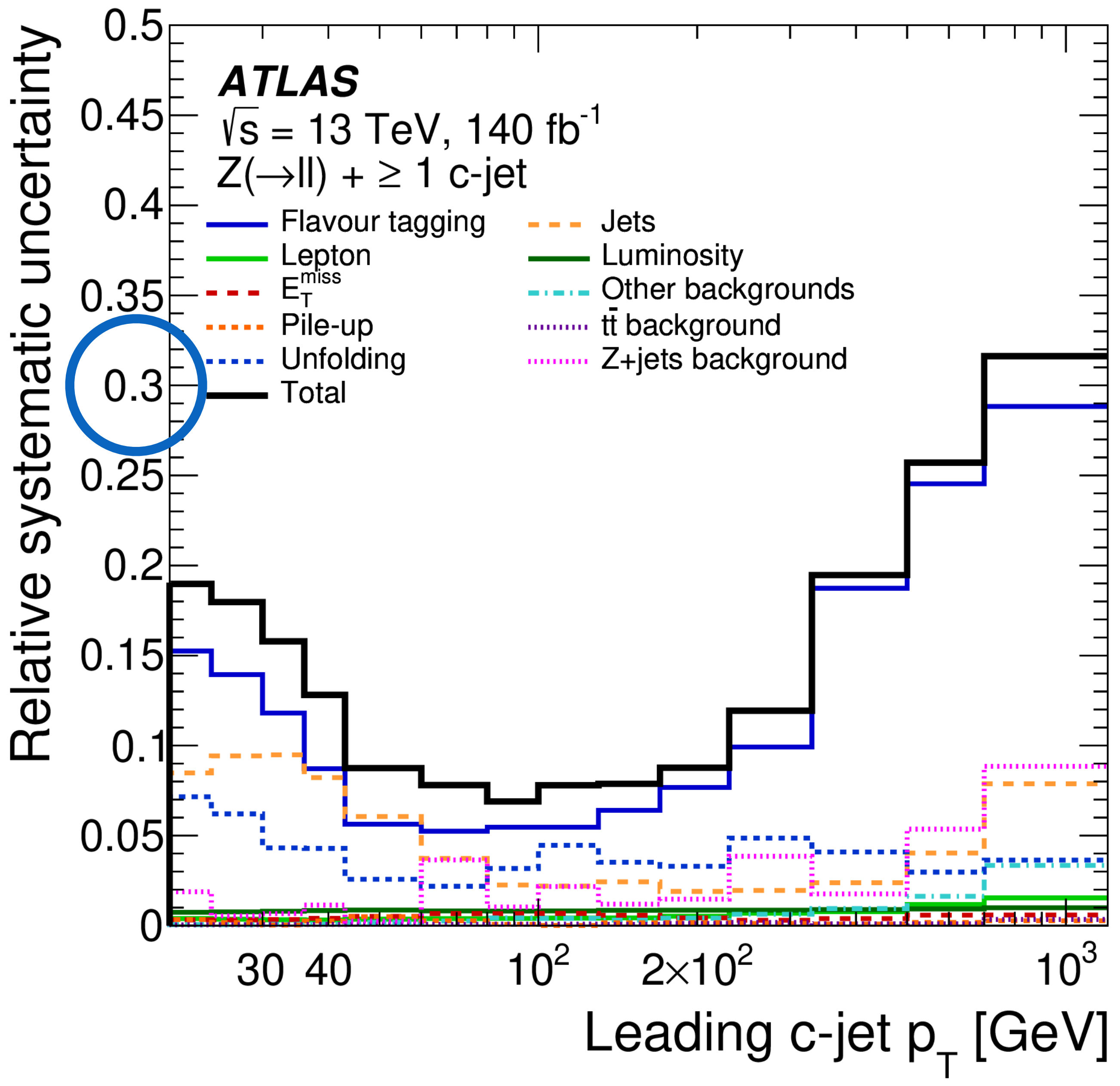
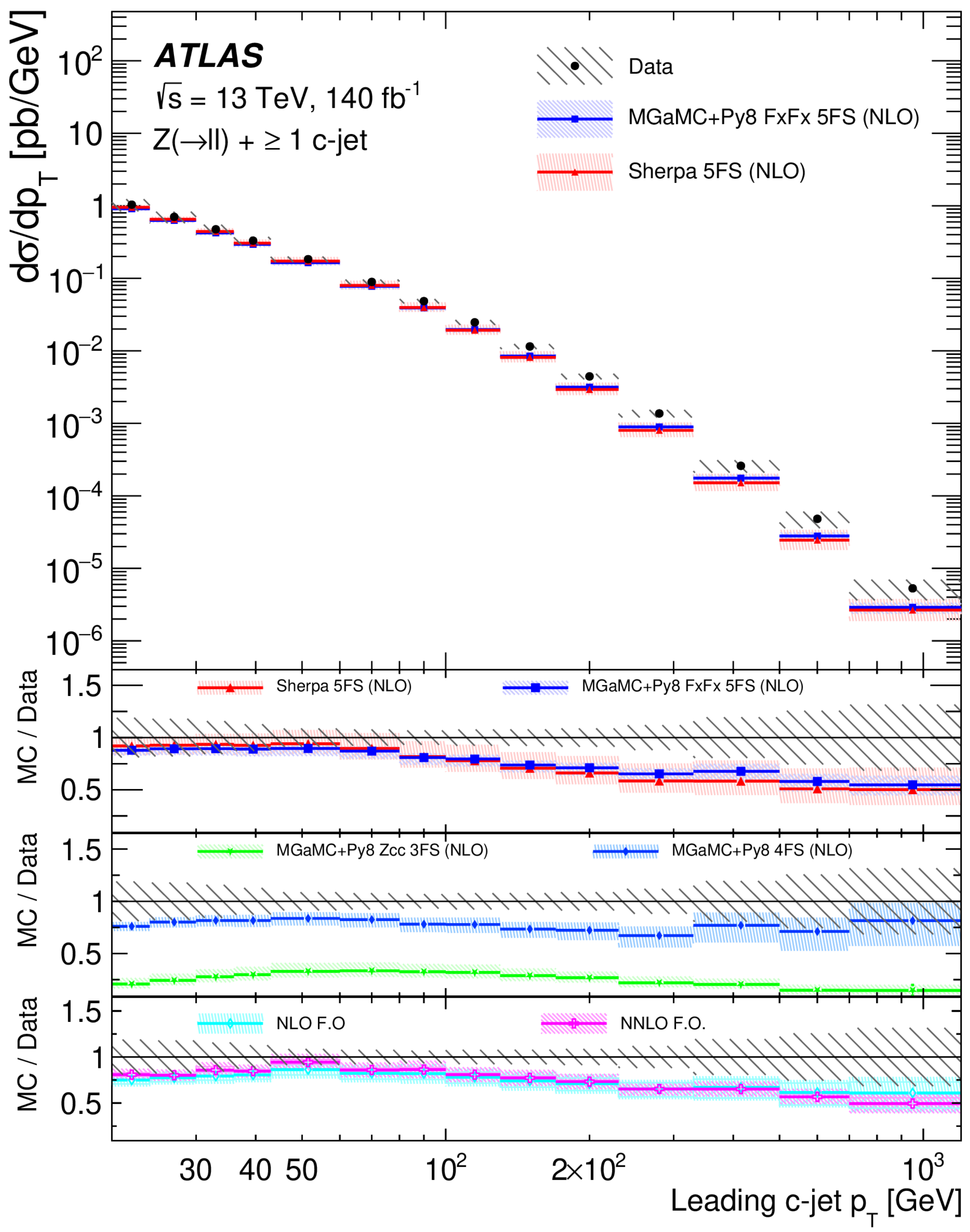
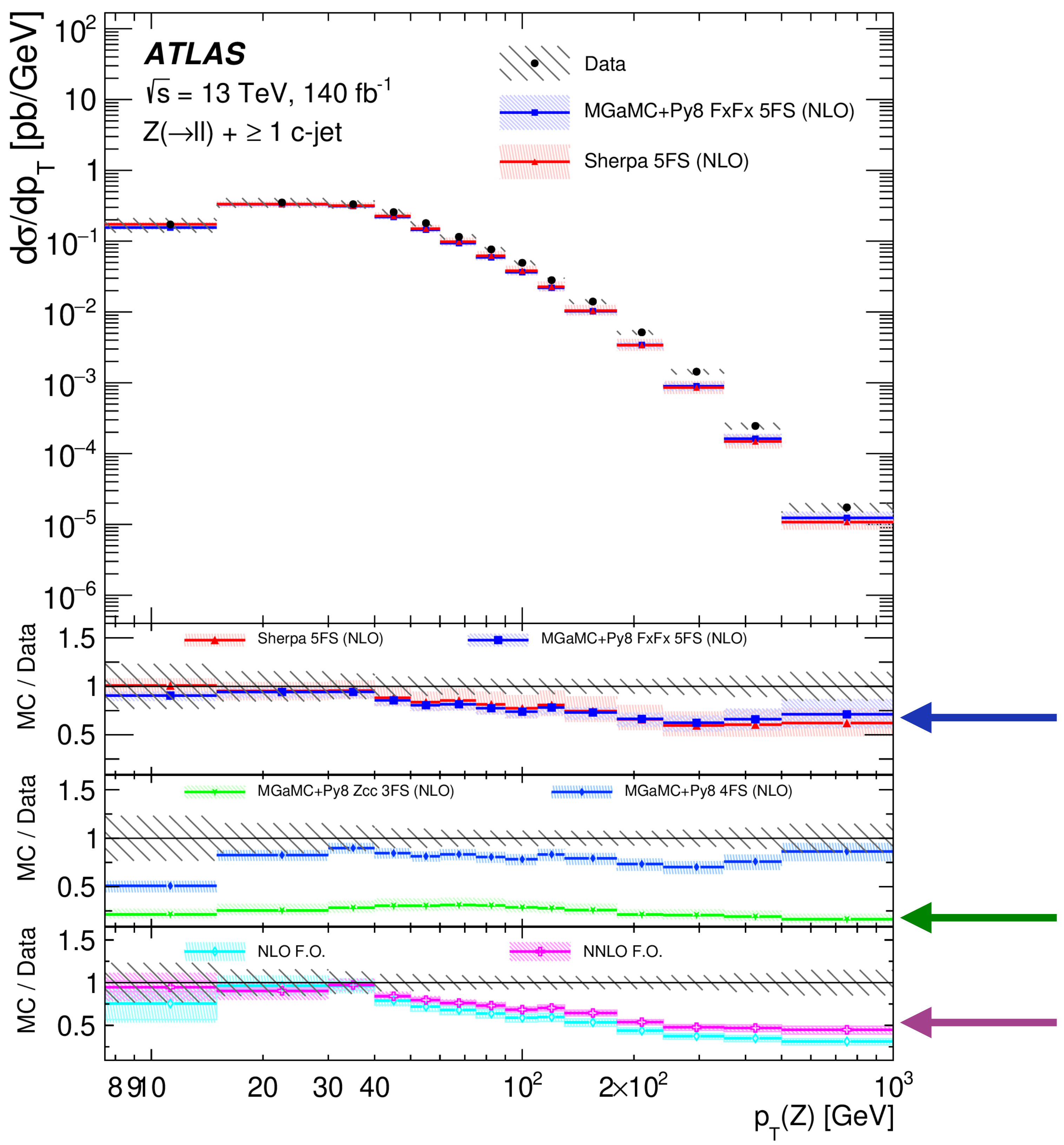
- Larger experimental uncertainties in *Z*+≥1 *c*-jet measurement due mostly to flavour-tagging
- **5FS**: soft p_T spectra well described by MGAMC+PY8 FXFX and SHERPA 2.2.11, not true for p_T>100 GeV
- **4FS:** reasonable p_T modelling by MGAMC+PY8
- **3FS:** MGAMC+PY8 underestimates data by a factor ~3 - **no log-term resummation in PDF evolution!**
- **Fixed-order:** NLO predicts softer p_T spectra, small improvement with NNLO

*backup







Z + HF-jets Results

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$\mathcal{L}$ = 140 fb^{-1}

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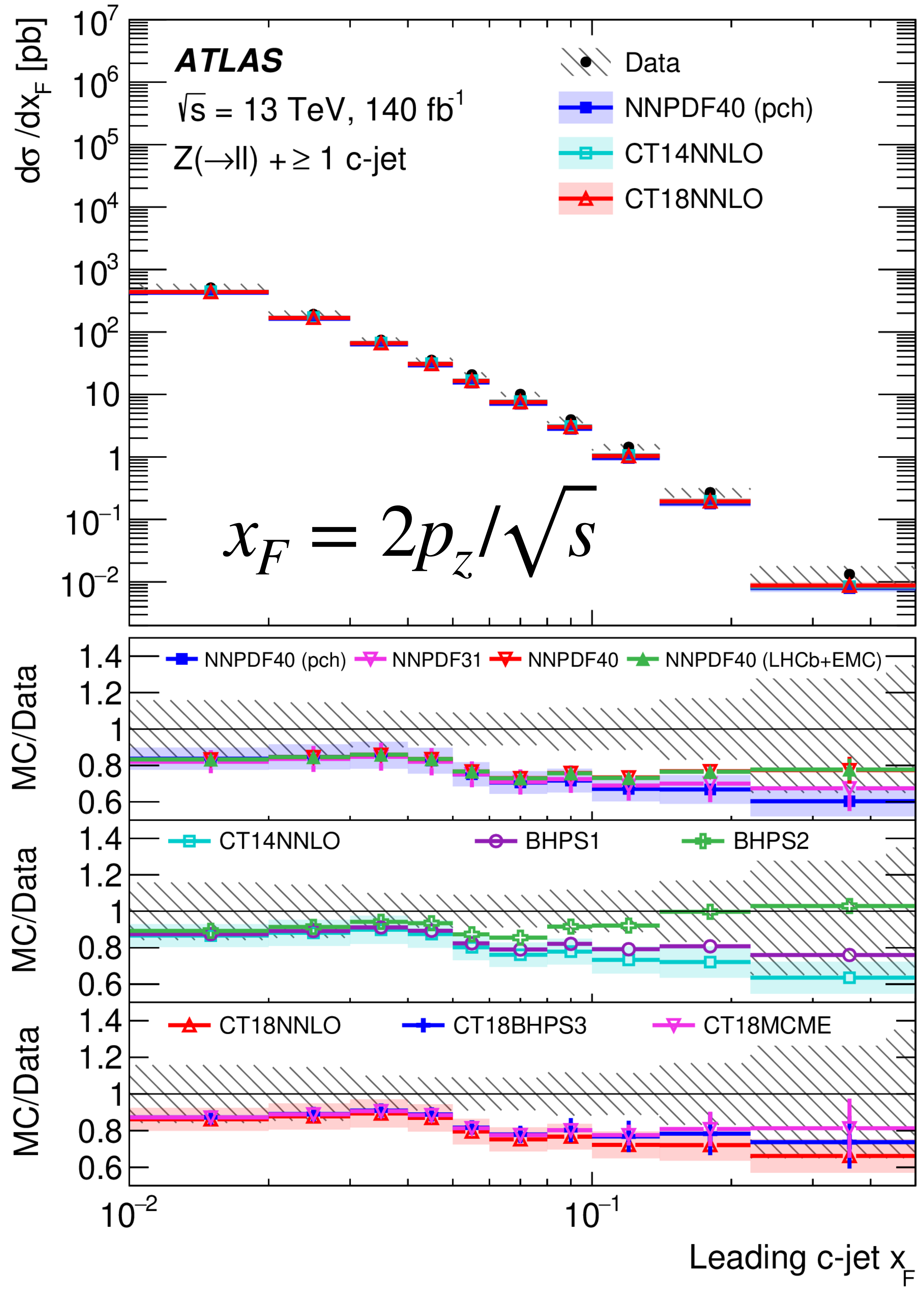
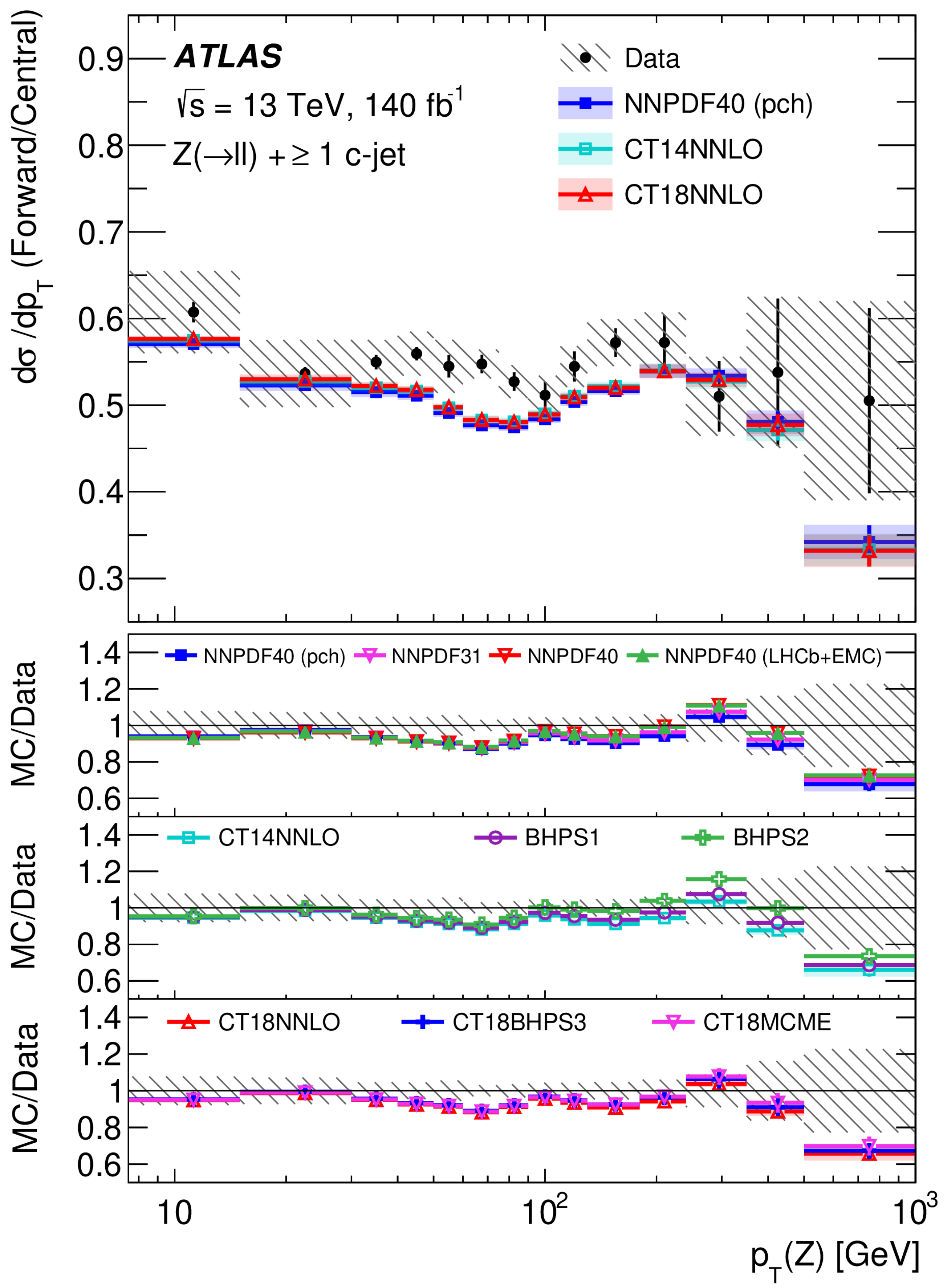
- Experimental and theoretical systematics reduced in Fwd/central ratio of Z p_T (~8%)
- Similar trend with respect to data by all *IC* models from NNPDF, CT14 and CT18
- The measurement has small sensitivity to *IC*
- BHPS2 (with $\langle x_c \rangle$~2%) improves the description of data
- In more realistic scenarios (BHPS1, NNPDF and CT18) the improvement is still marginal



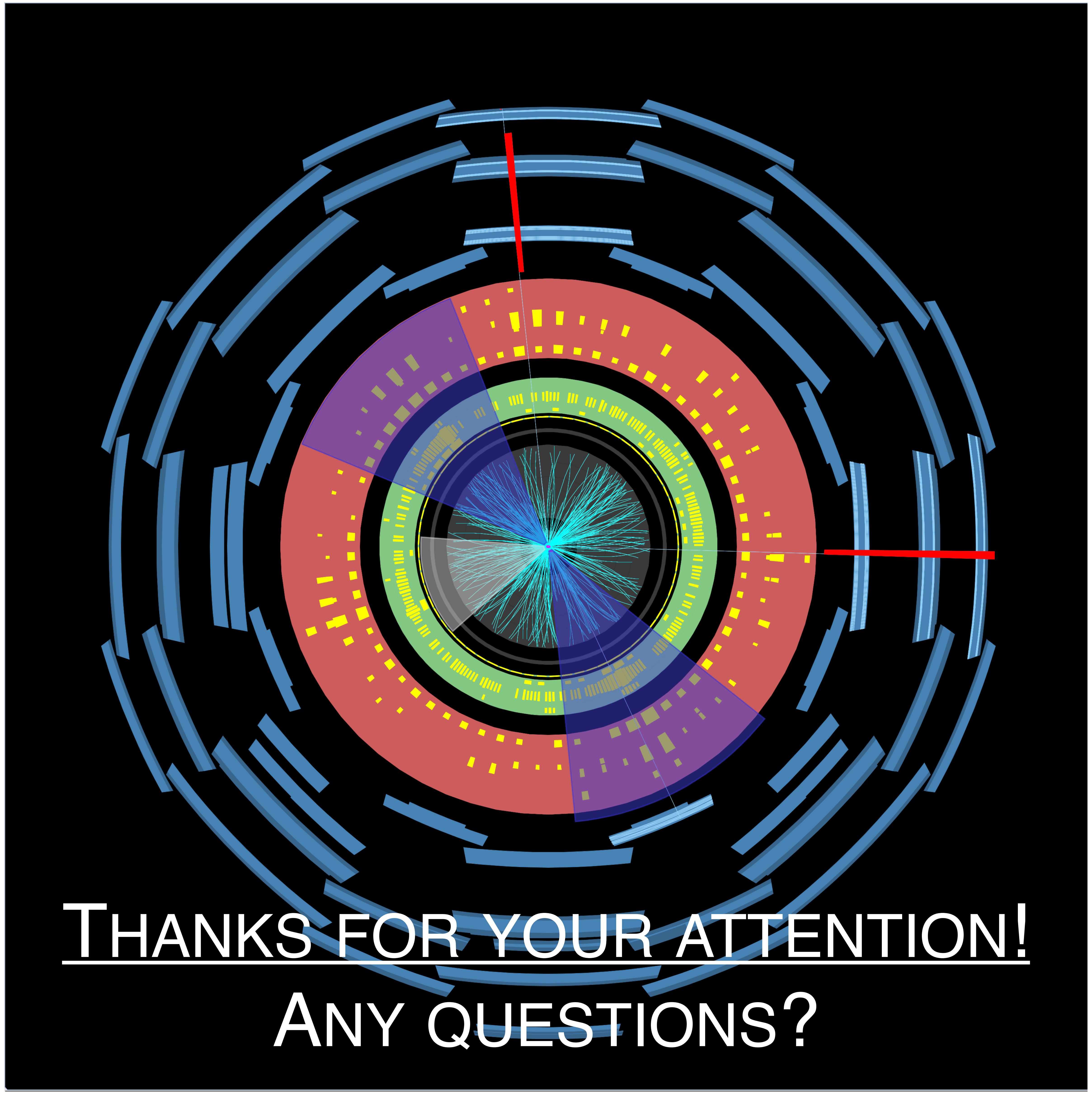
MGAMC+PY8 with different PDF sets testing several *IC*-models (PDF reweighting)

IC is a "valence-like" contribution expected at high Bjorken-*x*



Conclusions

- ***V*+jets and *V*+HF jets** represent an essential ingredient of Standard Model, with **very complex phenomenology**
- The interplay between **theoretical** and **experimental effort** allows to reach **high precision and high sensitivity**
- **Improved knowledge of proton PDF is crucial** to progress further in many precision analyses

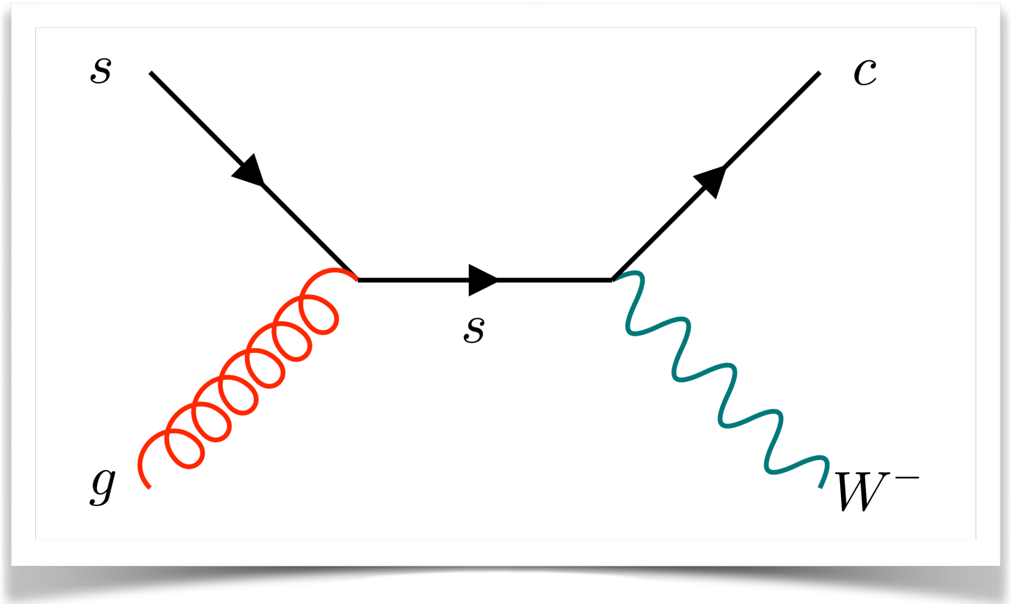


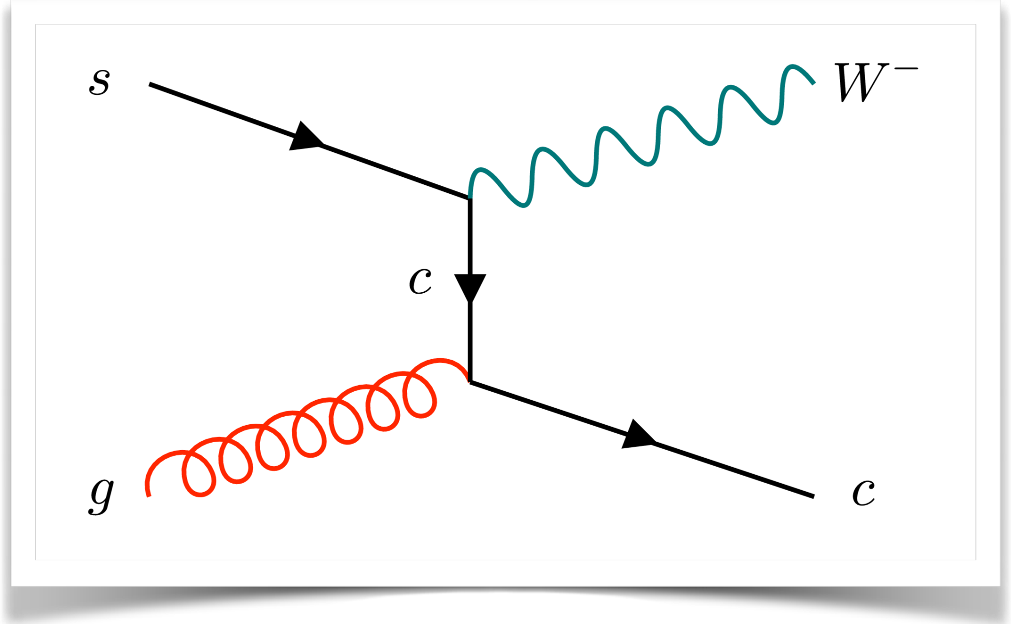
BACKUP

Measurement of $W+D$

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

Phys. Rev. D 108 (2023) 032012

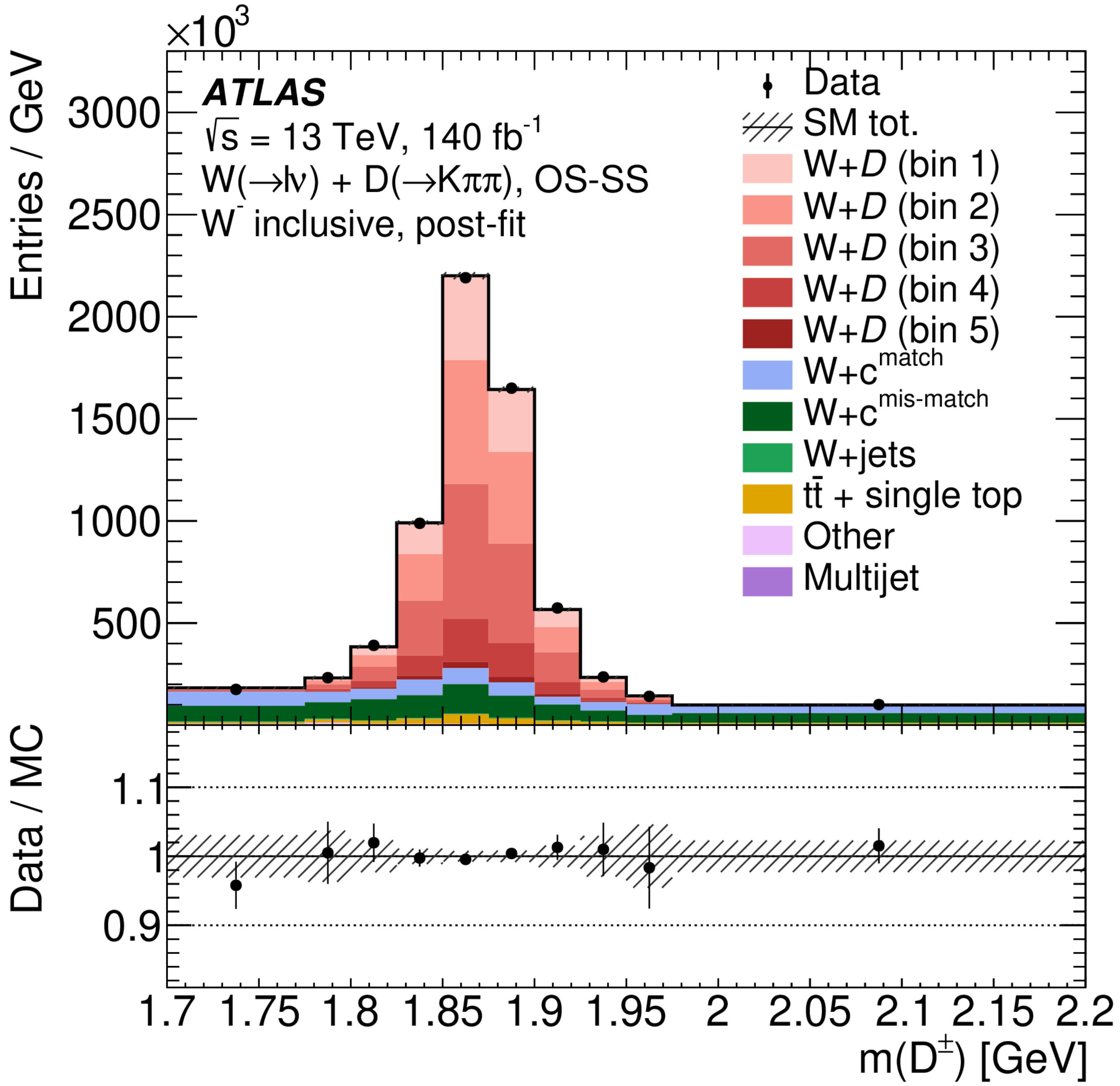




- **Motivations**:
  - W + charmed mesons as **probe of *s*-quark PDF**
    - constraints for future PDF fits
  - Comparison with state-of-art **NLO MCs**
  - **Probe $s - \bar{s}$ quark asymmetry with R_c**

- **W+D(*) with D→Kππ and D*→D₀π→Kππ**
- Secondary vertex fit to reconstruct D-decays
- W and D with opposite sign (OS), while background charge symmetric (SS)
  - OS-SS event correlation to suppress background
- Measurement of integrated cross-sections
- Differential W+D(*) cross sections
  - with binned profile likelihood fit of m(D) in p_T(D) and η^{lep} bins simultaneously in SS and OS
- Cross section ratio **R_c**:

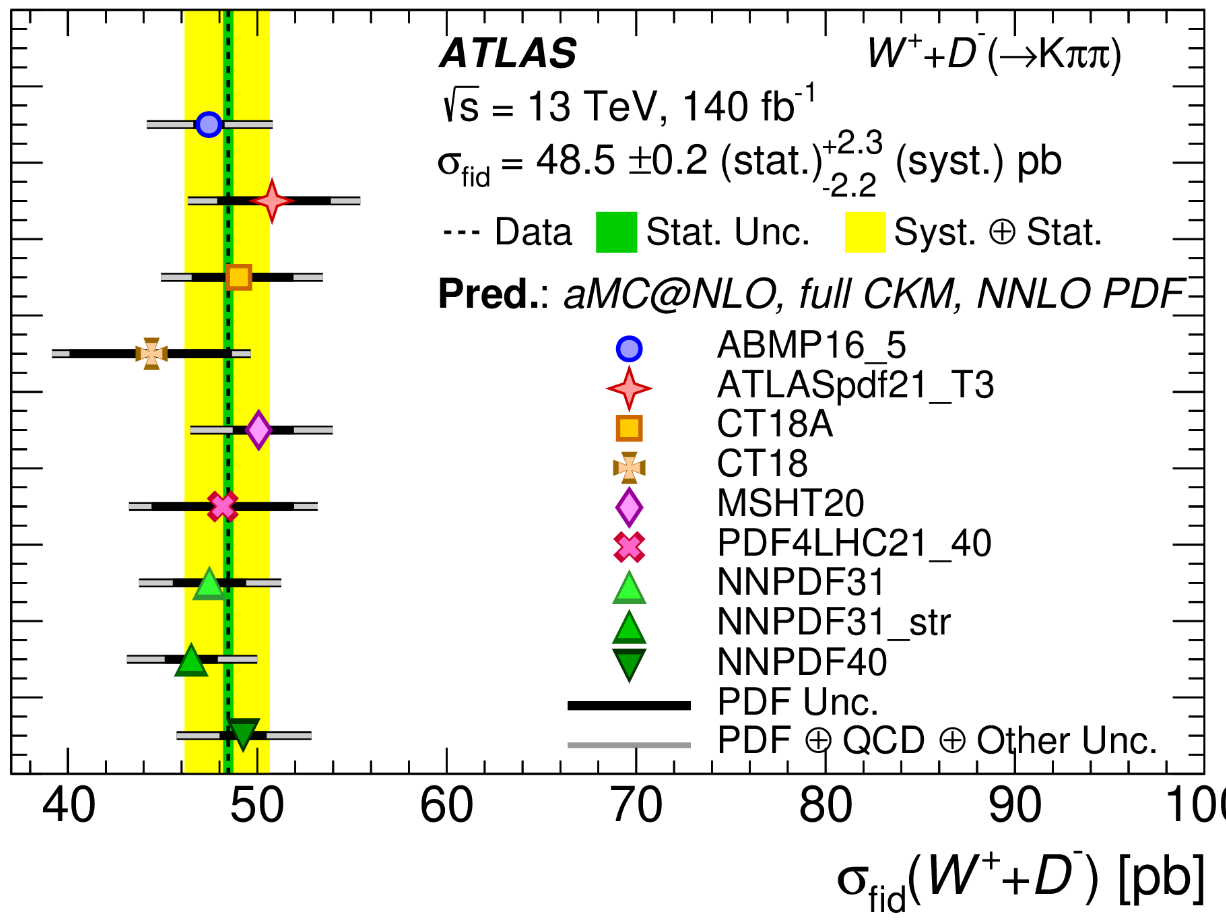
$$R_c^{\pm} = \frac{\sigma_{fid}^{OS-SS}(W^+D^{(*)-})}{\sigma_{fid}^{OS-SS}(W^-D^{(*)+})}$$

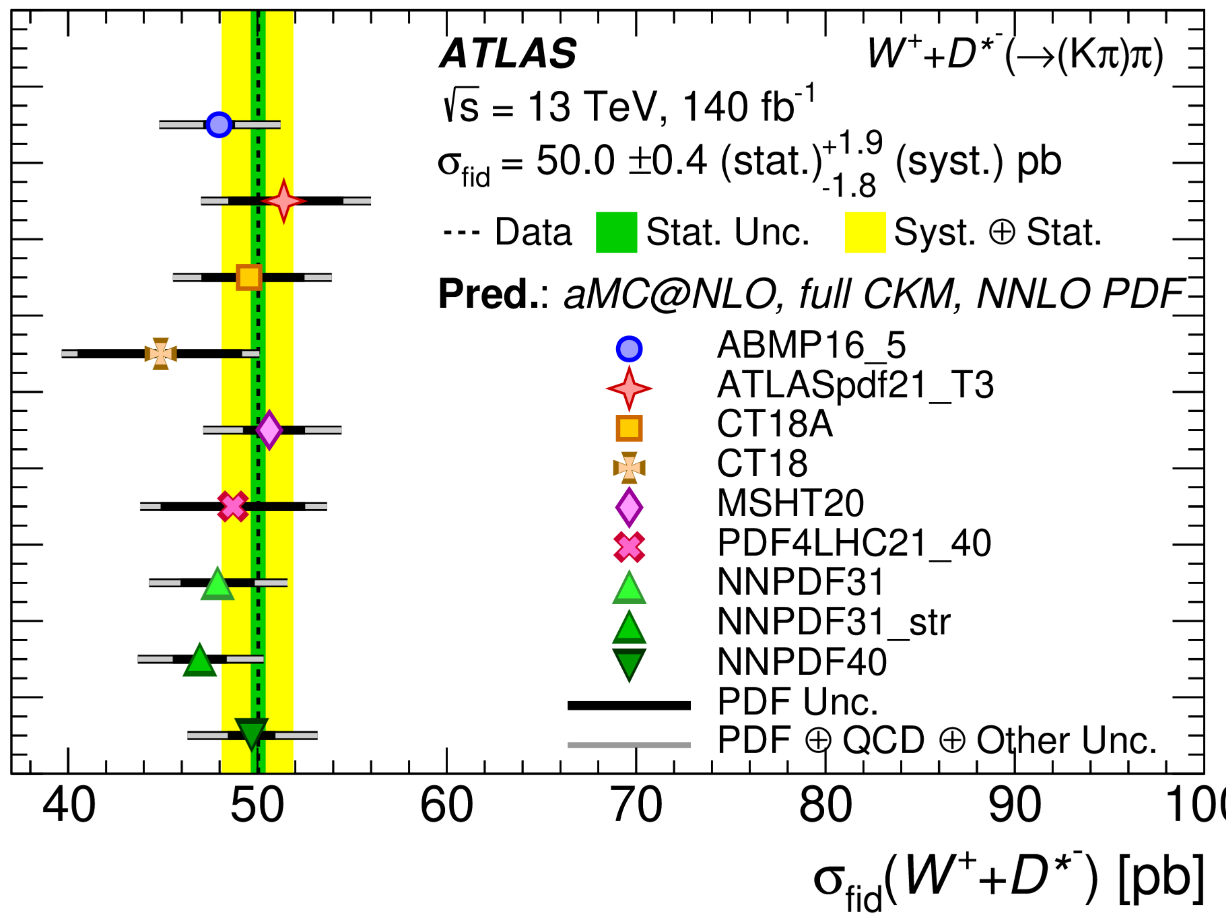


W+D Results

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

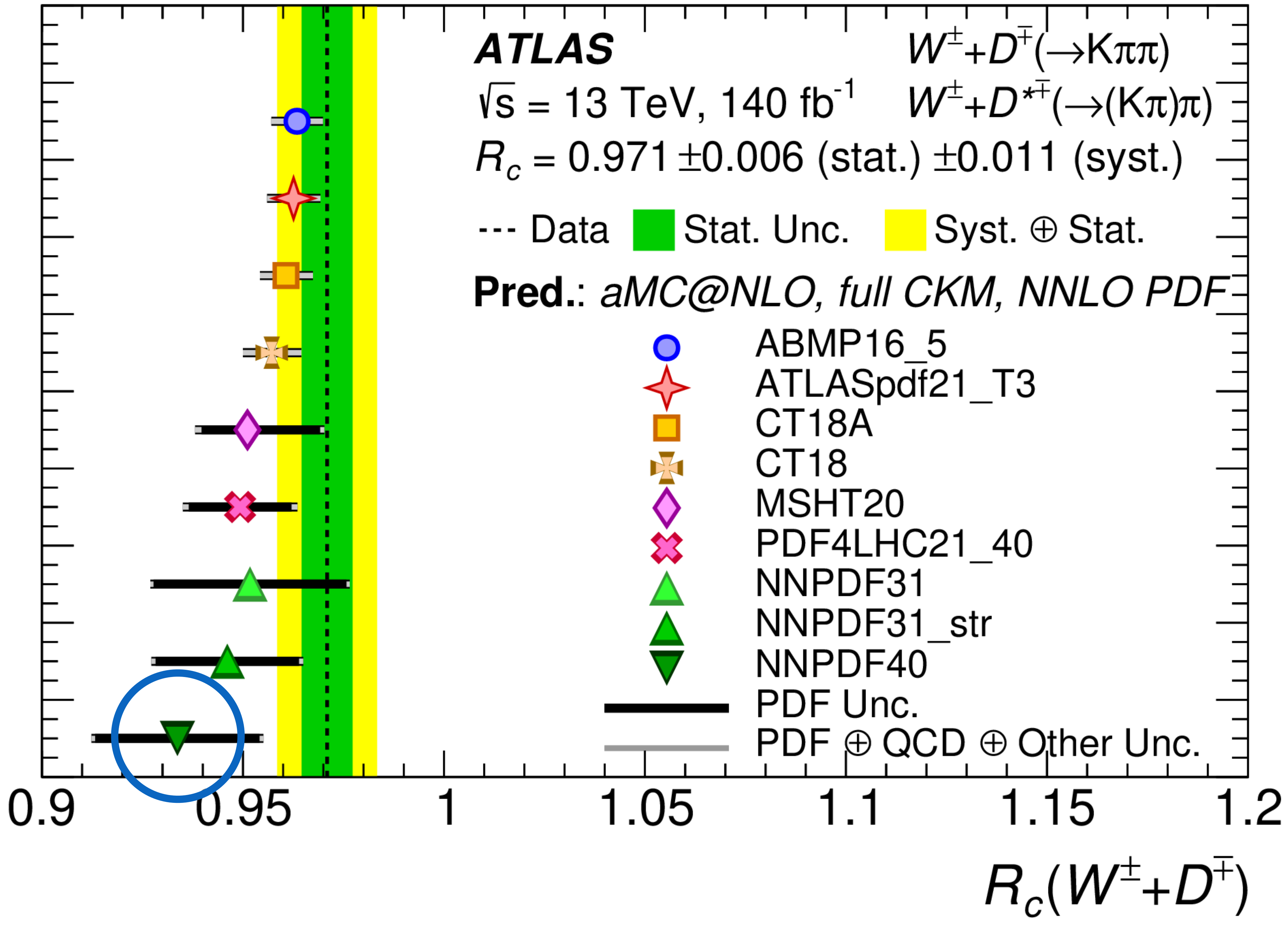
Phys. Rev. D 108 (2023) 032012





- **Integrated cross-sections:**
  - 5% exp. precision (syst. dominated)
    → comparable with PDF-syst
  - Great agreement with all PDF sets!

- **R_c:**
  - %-level exp. precision
  - NNPDF40 NNLO in tension with measured data
  - ABMP16 and CT18 impose $s = \bar{s}$
  - NNPDF and MSHT allow s and $\bar{s}$ to differ
  - Measurements are more in agreement with ABMP16 and CT18
    - **$s - \bar{s}$ asymmetry small in the Bjorken-*x* region probed by this measurement**

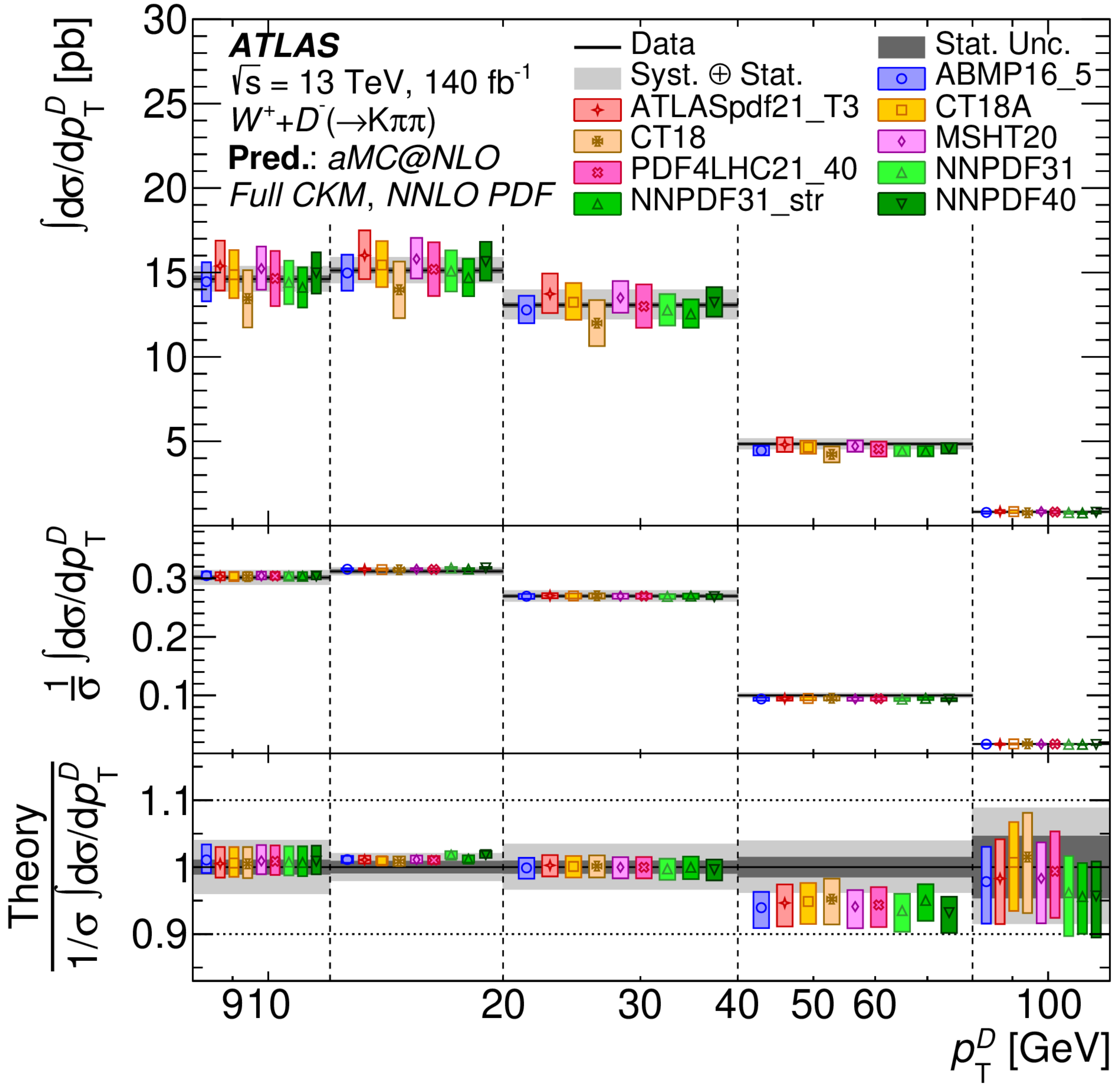


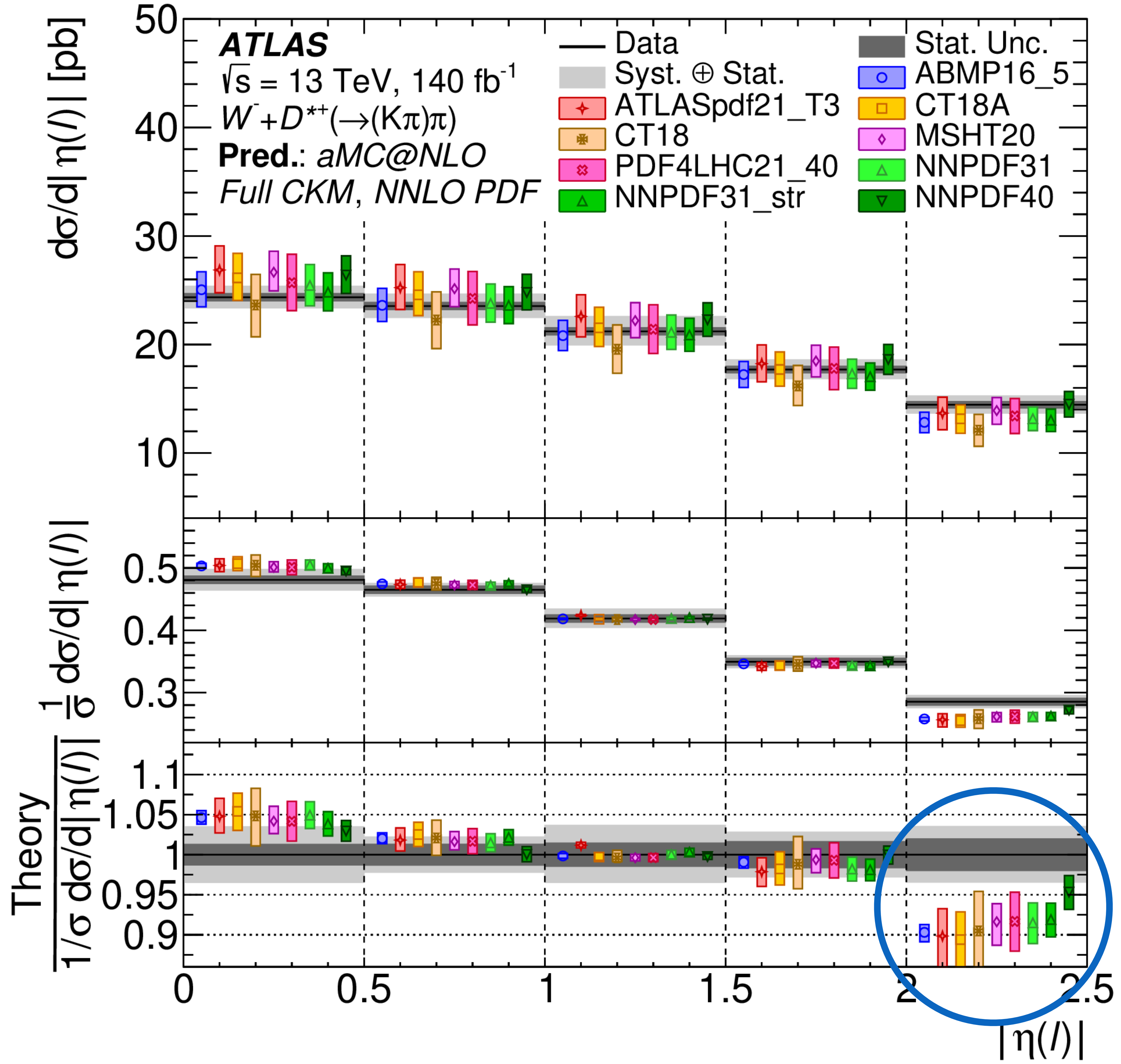
W+D Results

pp **collisions at √s = 13 TeV**
ℒ = 140 fb⁻¹

Phys. Rev. D 108 (2023) 032012

- p_T(D) distributions not sensitive to PDFs
- η^{lep} with small systs provide good sensitivity to PDF variations
- broader η^{lep} in Data than predictions - **discrepancy reduced if considering PDF unc.**
  → **measurements provide useful constraints for global PDF fits**





Measurement of W+D

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

Phys. Rev. D 108 (2023) 032012

Channel	D^+ $\lvert\eta(\ell)\rvert$			
p-value for PDF [%]	Exp. Only	⊕ QCD Scale	⊕ Had. and Matching	⊕ PDF
ABMP16_5_nnlo	7.1	11.8	12.9	19.8
ATLASpdf21_T3	9.0	9.7	11.5	84.7
CT18ANNLO	0.7	1.0	1.1	76.0
CT18NNLO	1.4	6.1	6.3	87.6
MSHT20nnlo_as118	2.7	2.9	3.3	45.6
PDF4LHC21_40	3.9	5.3	5.6	75.8
NNPDF31_nnlo_as_0118_hessian	1.5	2.6	2.8	50.7
NNPDF31_nnlo_as_0118_strange	9.1	14.7	15.2	59.9
NNPDF40_nnlo_as_01180_hessian	9.9	10.2	10.2	43.7

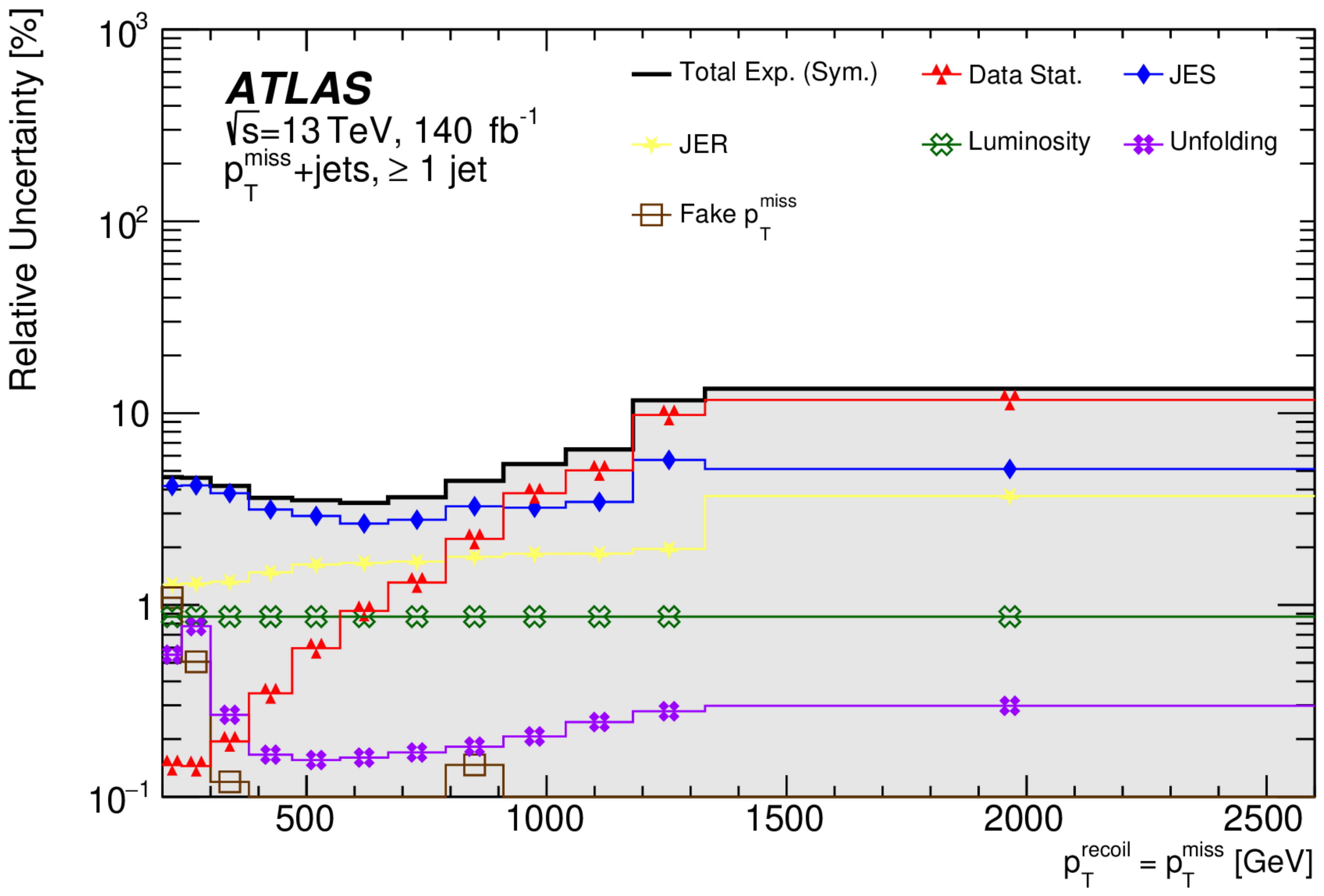
Attribute	p_T^{miss}+jets	e+jets	$2e$+jets	μ+jets	2μ+jets	γ+jets
Lepton or photon rapidity	–	$\|y\| \leq 1.37$ or $1.52 \leq \|y\| \leq 2.47$		$\|y\| \leq 2.5$		$\|y\| \leq 1.37$ or $1.52 \leq \|y\| \leq 2.47$
Leading lepton or photon p_T [GeV]	–	> 30	> 80	> 7	> 80	> 160
Sub-leading lepton p_T [GeV]	–	–	> 7	–	> 7	–
Dilepton mass, $m_{\ell\ell}$ [GeV]	–	–	$m_{\ell\ell} \in (66, 116)$	–	$m_{\ell\ell} \in (66, 116)$	–
(Additional) muons	None with $p_T > 7$ GeV, $\|\eta\| < 2.5$					
(Additional) electrons	None with $p_T > 7$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$					
m_T [GeV]	–	$m_T \in (30, 100)$	–	–	–	–
p_T^{miss} [GeV]	> 200	> 60	–	–	–	–
p_T^{recoil} [GeV]	> 200	> 200	> 200	> 200	> 200	> 200

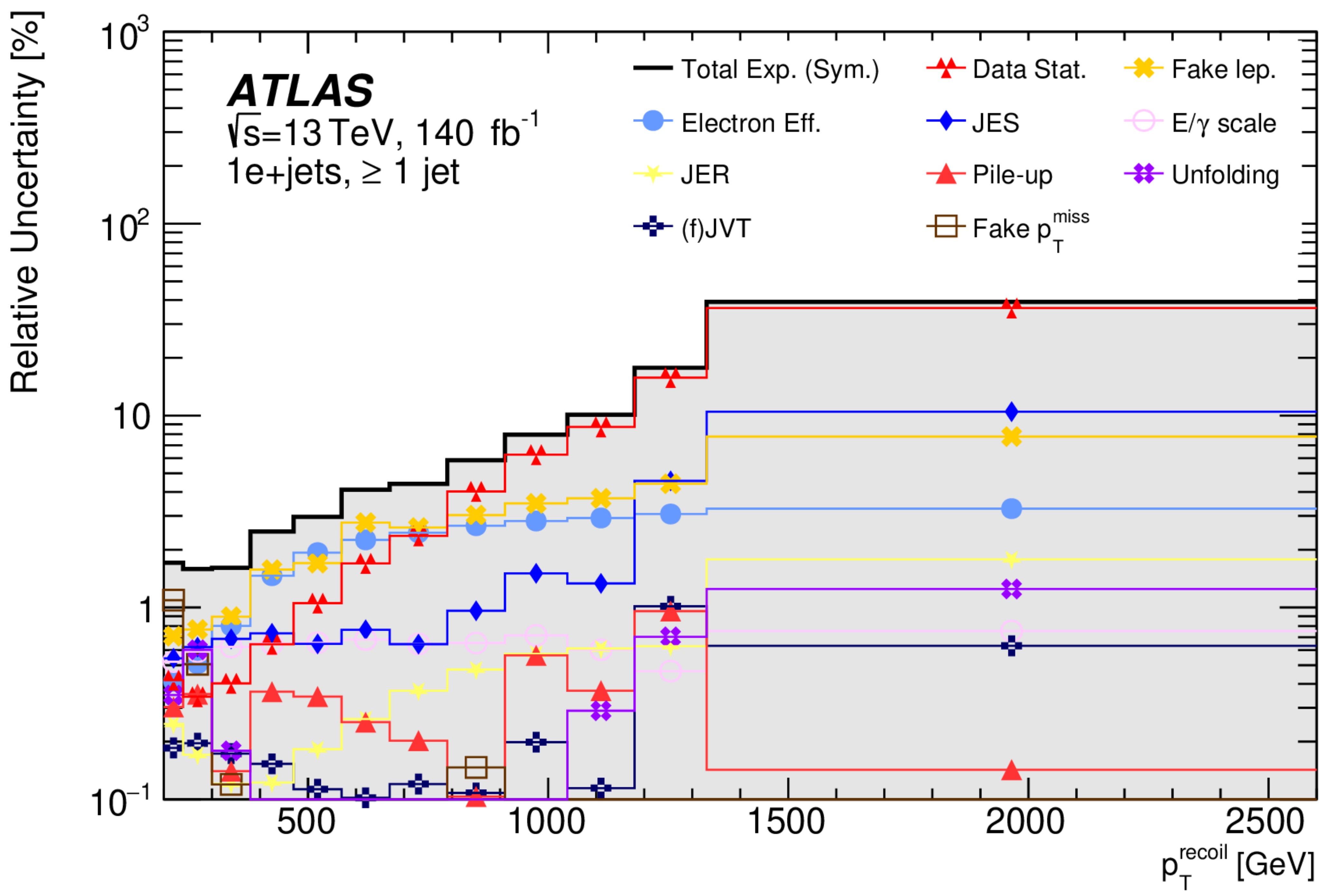
Attribute	≥ 1 jet	VBF
$\Delta\phi\left(\text{jet}, p_T^{miss}\right)$	> 0.4 for four leading p_T jets	
Hadronic τ-lepton	None with $p_T > 20$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	
Leading jet p_T [GeV]	> 120	> 80
Sub-leading jet p_T [GeV]	–	> 50
Leading jet $\|y\|$	< 2.4	< 4.4
Sub-leading jet $\|y\|$	–	< 4.4
Dijet invariant mass m_{jj} [GeV]	–	> 200
$\|\Delta y_{jj}\|$	–	> 1
In-gap jets	–	None with $p_T > 30$ GeV

P_T^{miss}+jets · Uncertainties

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

arXiv:2403.02793
Submitted to JHEP





P_T^{miss}+jets · Results

pp collisions at √s = 13 TeV
ℒ = 140 fb⁻¹

arXiv:2403.02793
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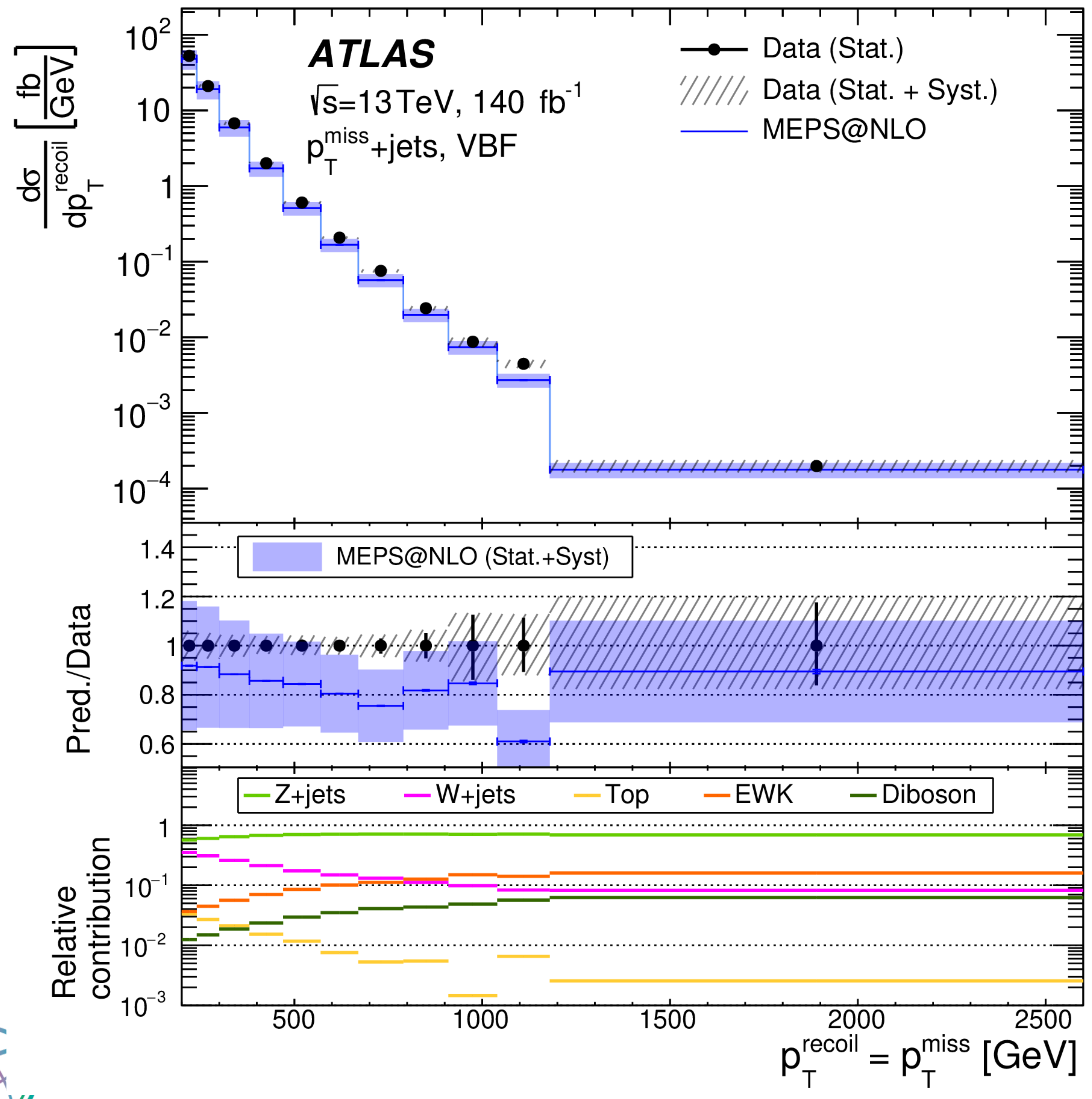
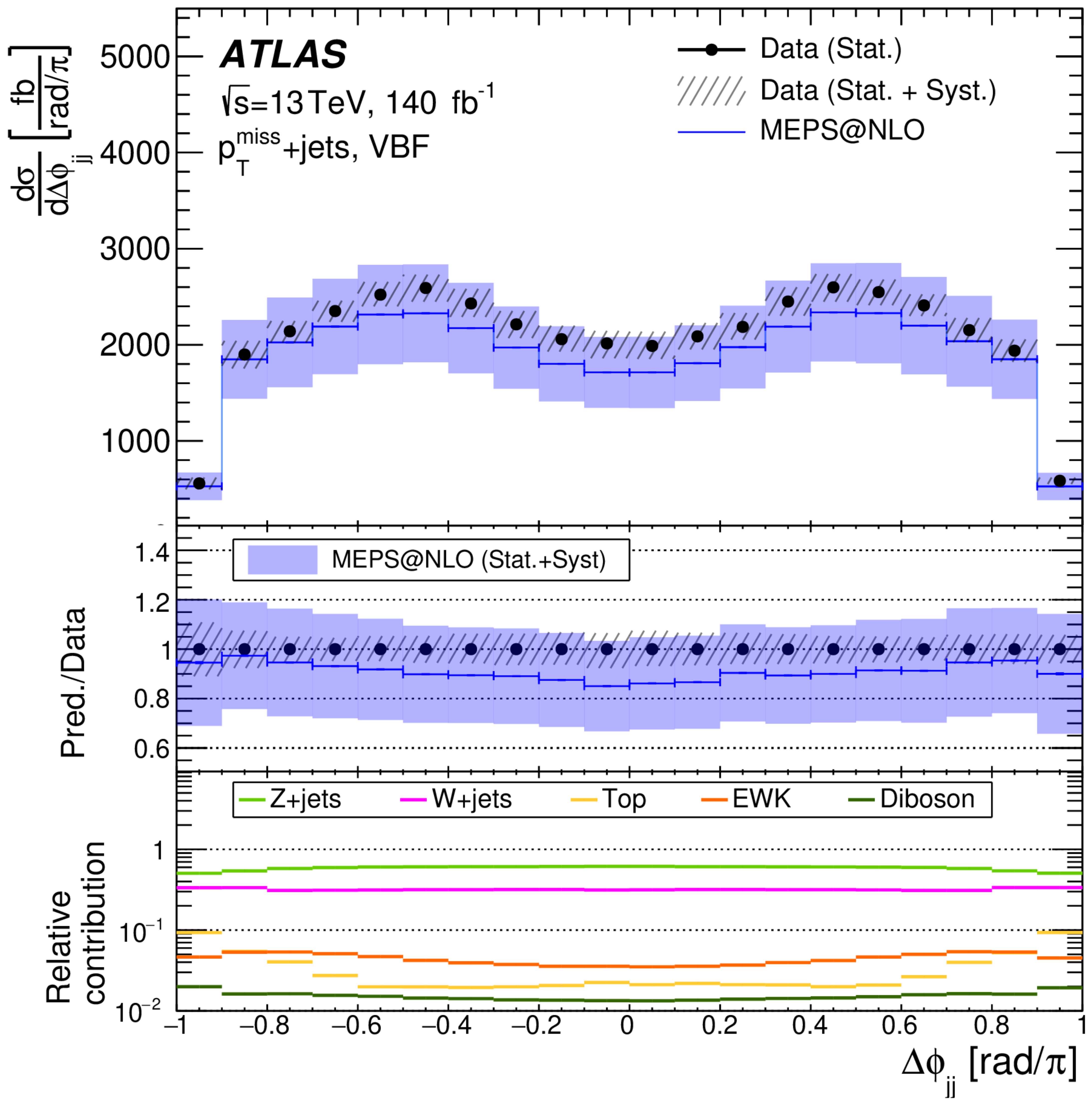
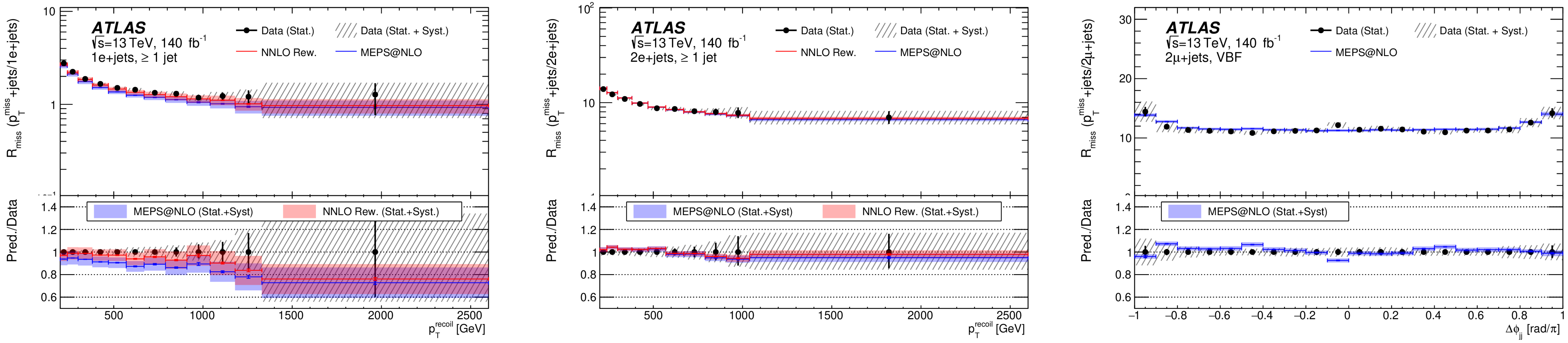




P_T^{miss}+jets · R_{miss}

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb⁻¹

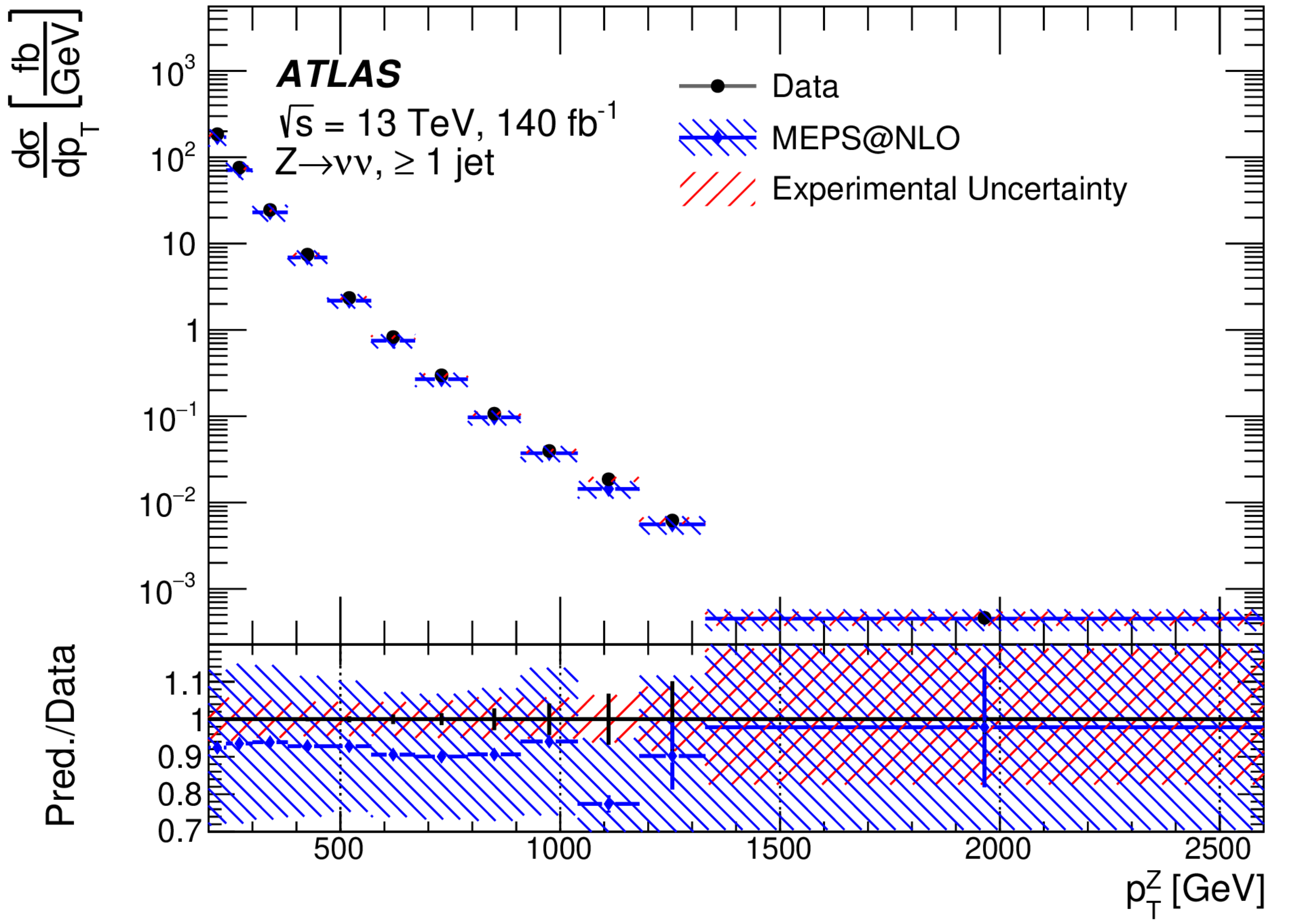
arXiv:2403.02793
Submitted to JHEP

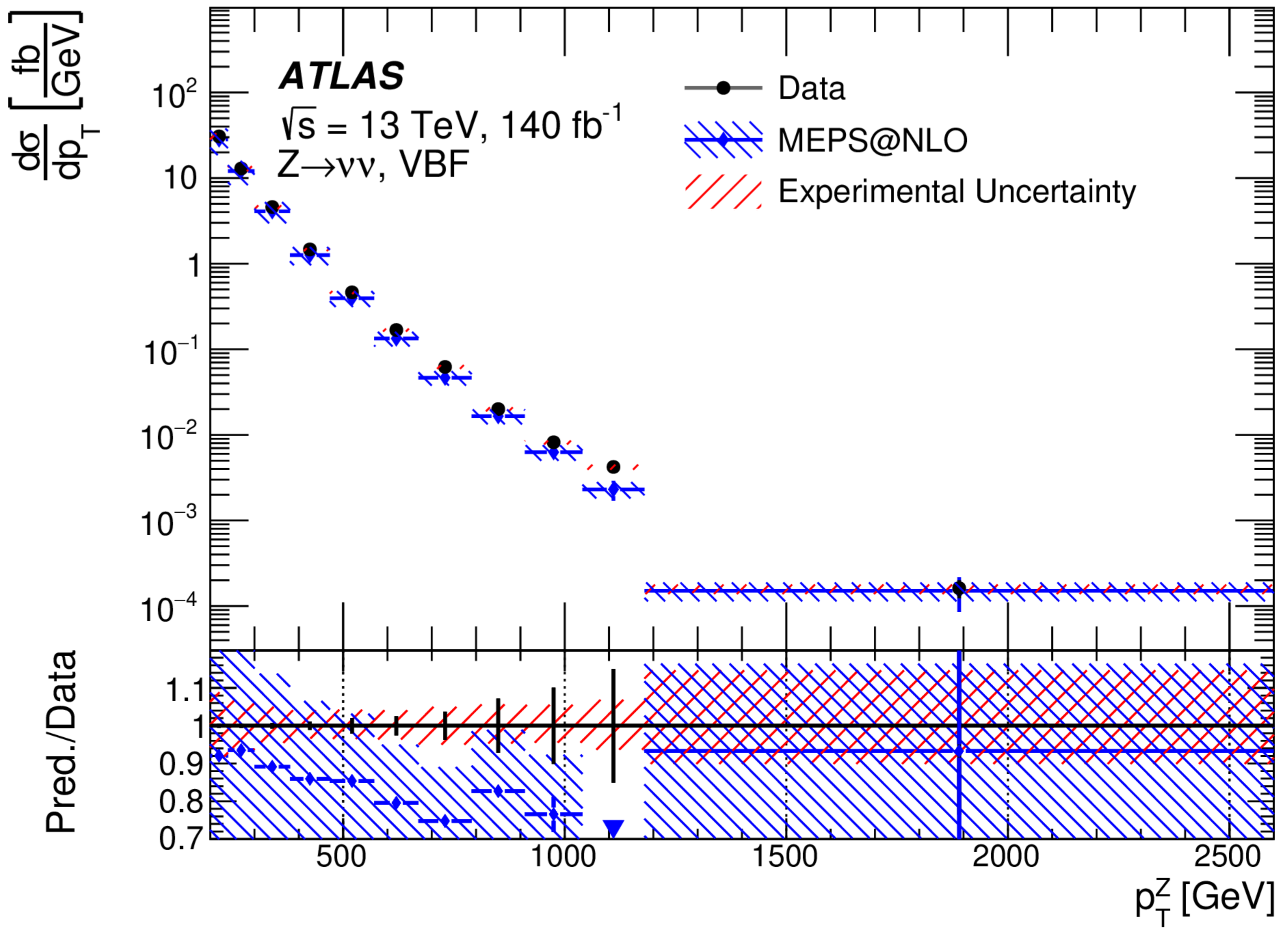


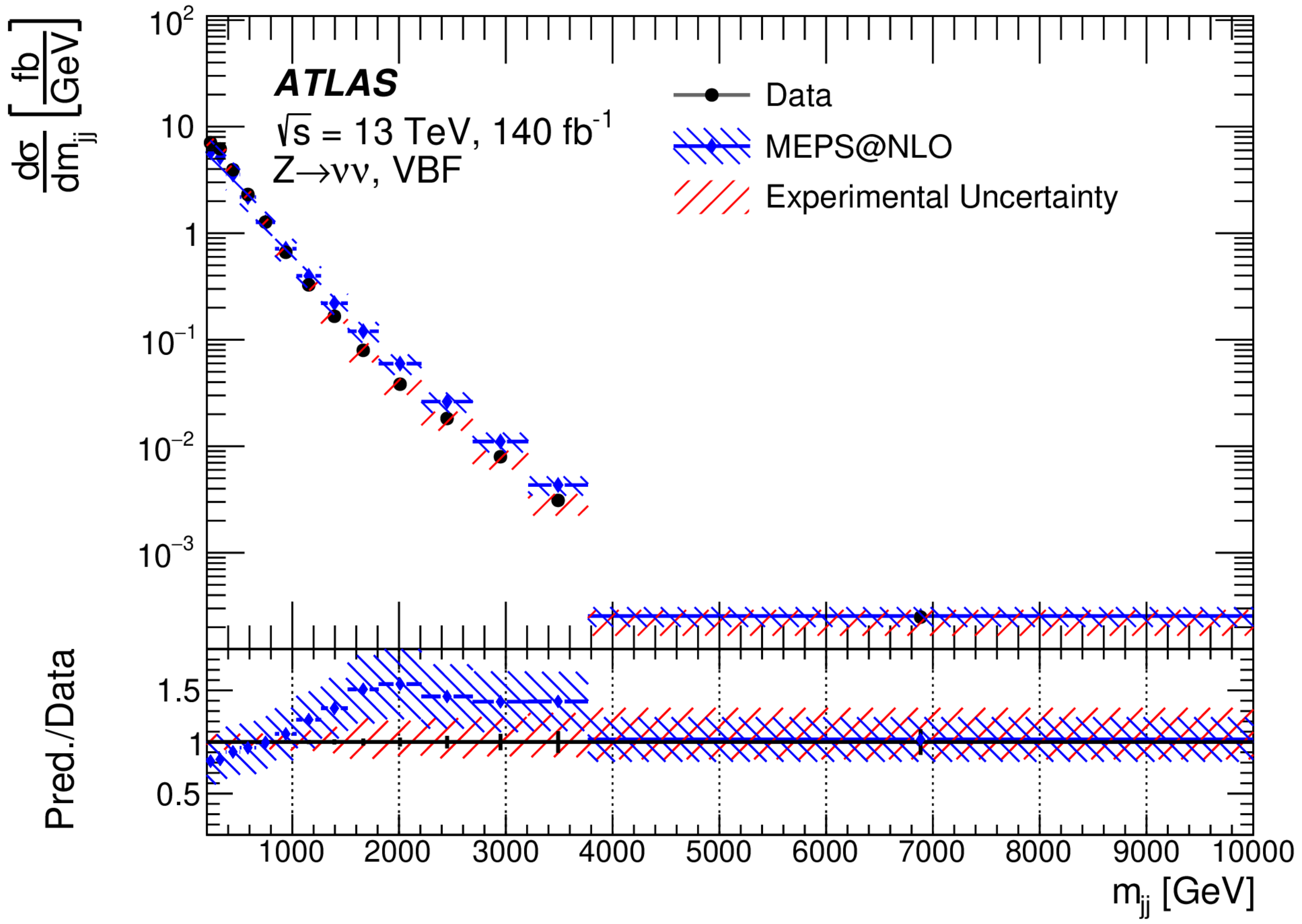
P_T^{miss}+jets · Results Z(→$\nu\nu$)+jets

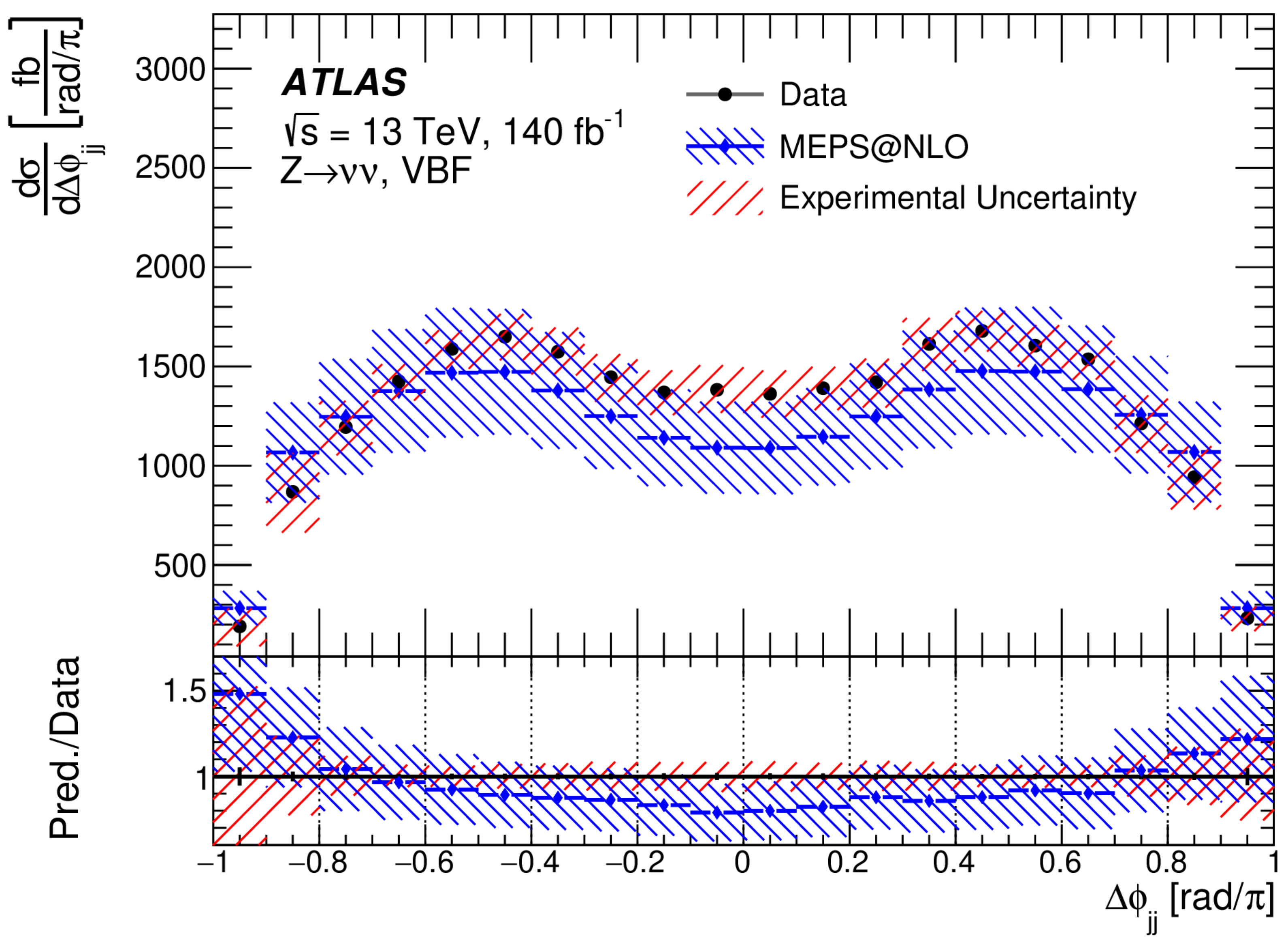
***pp* collisions at √s = 13 TeV**
$\mathcal{L}$ = 140 fb⁻¹

arXiv:2403.02793
Submitted to JHEP









Z + HF · Samples

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

arXiv:2403.15093
Submitted to EPJC

✦ Data

- full Run-2, L = 140 fb^{-1}

✦ MC samples

- State of art MCs for signal and Z+jets bkg:
  - **MGAMC@NLO+PY8 with FXFX merging** - up to 3 partons in NLO ME (nominal)
  - **SHERPA 2.2.11** - up to 2 partons in NLO ME (alternative)

	Process	Generator	Order of pQCD in ME (FNS)	Order σ_{prod} calculation
Signal & Z+jets bkg	$Z \rightarrow \ell\ell$	MGAMC+PY8 FXFX	0-3p NLO (5FNS)	NNLO
	$Z \rightarrow \ell\ell$	SHERPA 2.2.11	0-2p NLO, 3-5p LO (5FNS)	NNLO
$t\bar{t}$	$t\bar{t}$	POWHEG+PY8	NLO	NNLO+NNLL
single-top	single top (s/t/Wt-channel)	POWHEG+PY8	NLO	NLO
diboson	$qg/q\bar{q} \rightarrow VV \rightarrow \ell\ell/\ell\nu/\nu\nu + q\bar{q}$	SHERPA 2.2.1	1p NLO, 2-3p LO	NLO
ZH	$qq \rightarrow ZH \rightarrow \ell\ell/\nu\nu + b\bar{b}$	POWHEG+PY8	NLO	NNLO(QCD),NLO(EW)
	$gg \rightarrow ZH \rightarrow \ell\ell/\nu\nu + b\bar{b}$	POWHEG+PY8	NLO	NLO+NLL

$Z + \mathrm{HF} \cdot t\bar{t}$ background

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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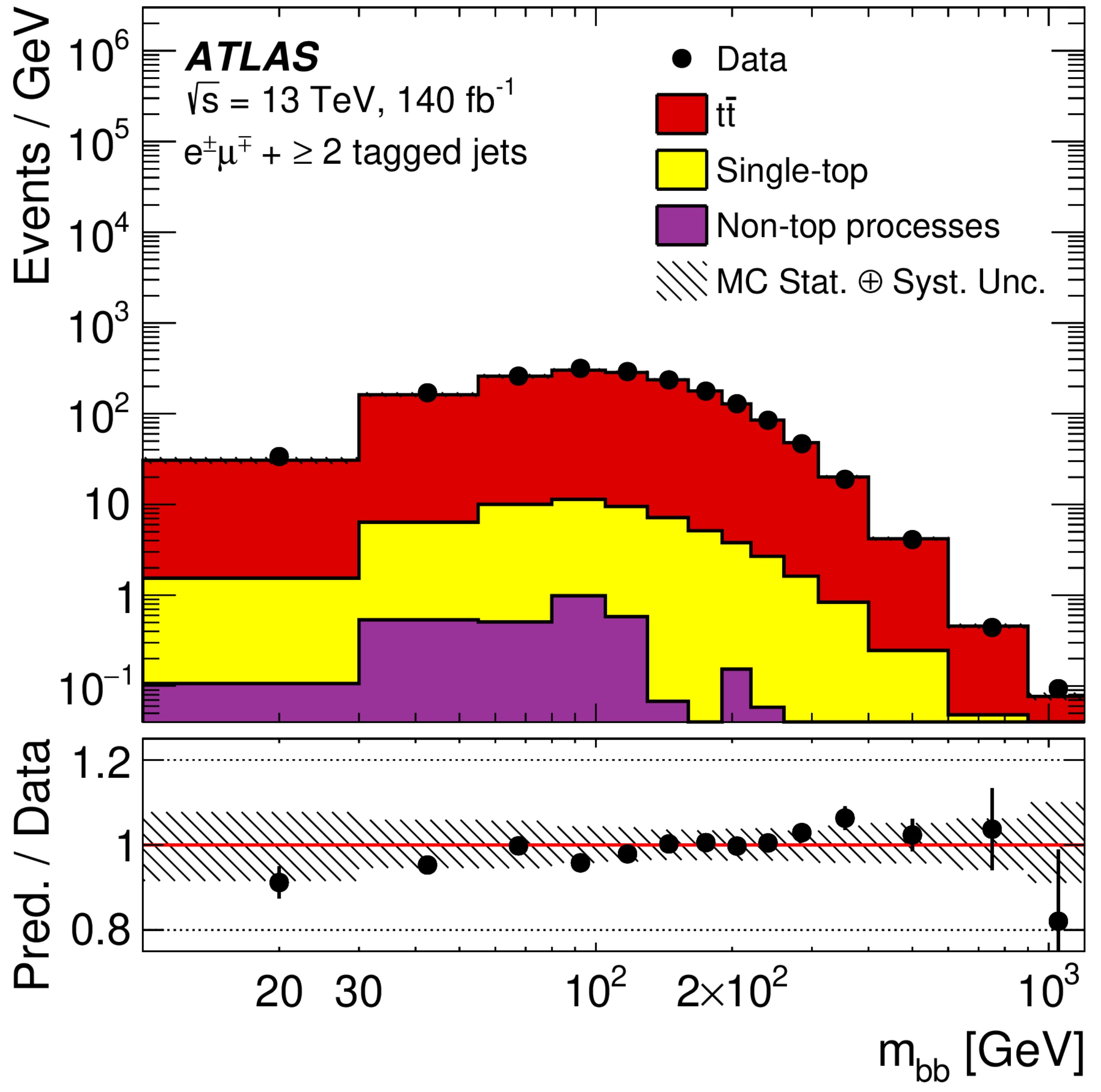
- Dileptonic $t\bar{t}$ events represent the second largest background
- **Data-driven determination in $e^{\pm}\mu^{\mp}$ CR in 71 GeV≤m_{ll}≤111 GeV**
  - avoid large (up to 70% in Z p_T) modelling uncertainty on MC samples

ttbar = Data-MC in $e\mu$ CR

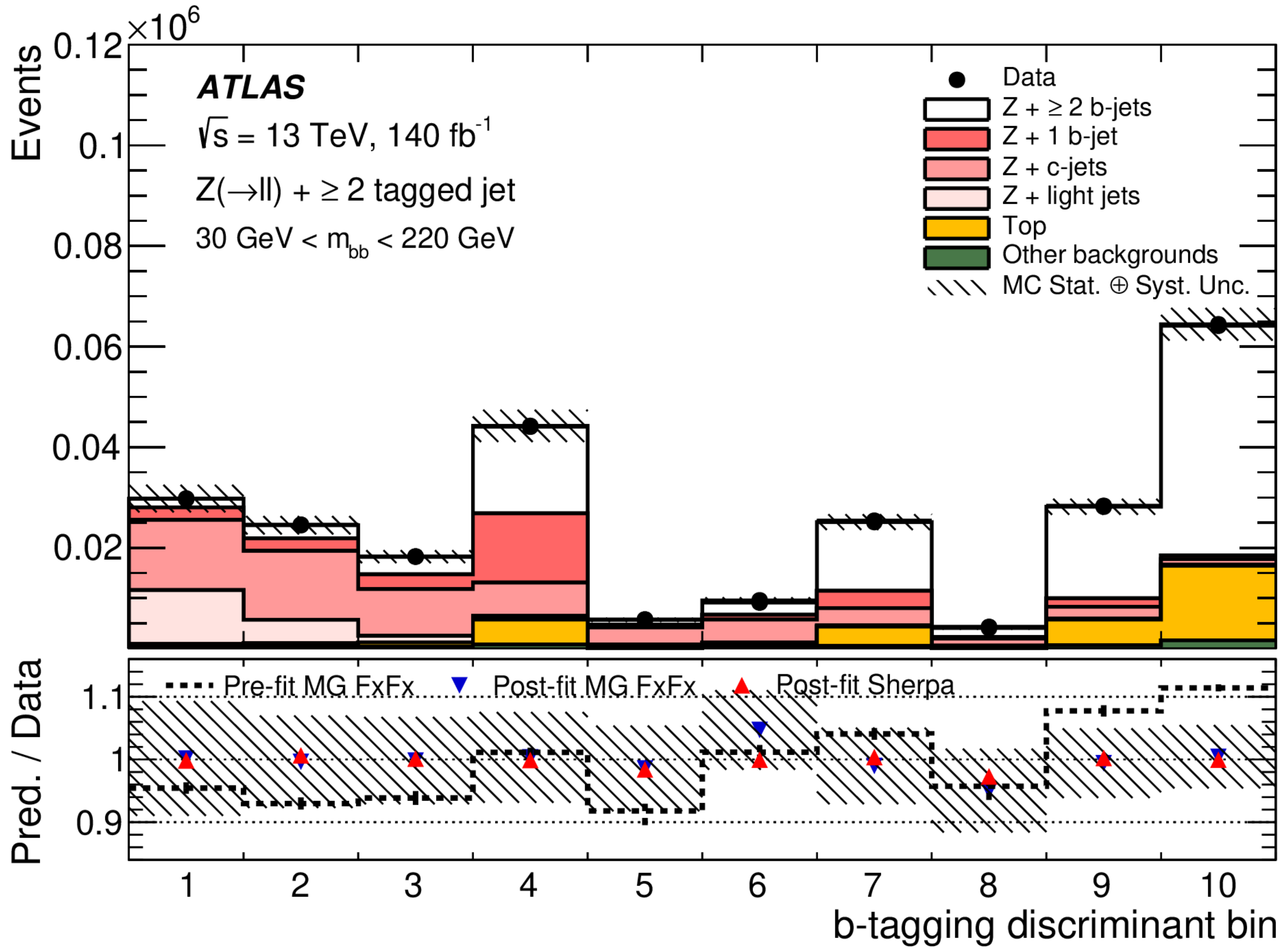
Transfer Factor (TF) correction from CR to SR

$$ttbar^{SR}_{Data} = ttbar^{CR}_{Data} * TF^{CR\rightarrow SR}$$

$$TF^{CR\rightarrow SR} = \frac{ttbar^{SR(ee/\mu\mu)}_{MC}}{ttbar^{CR(e\mu)}_{MC}}$$

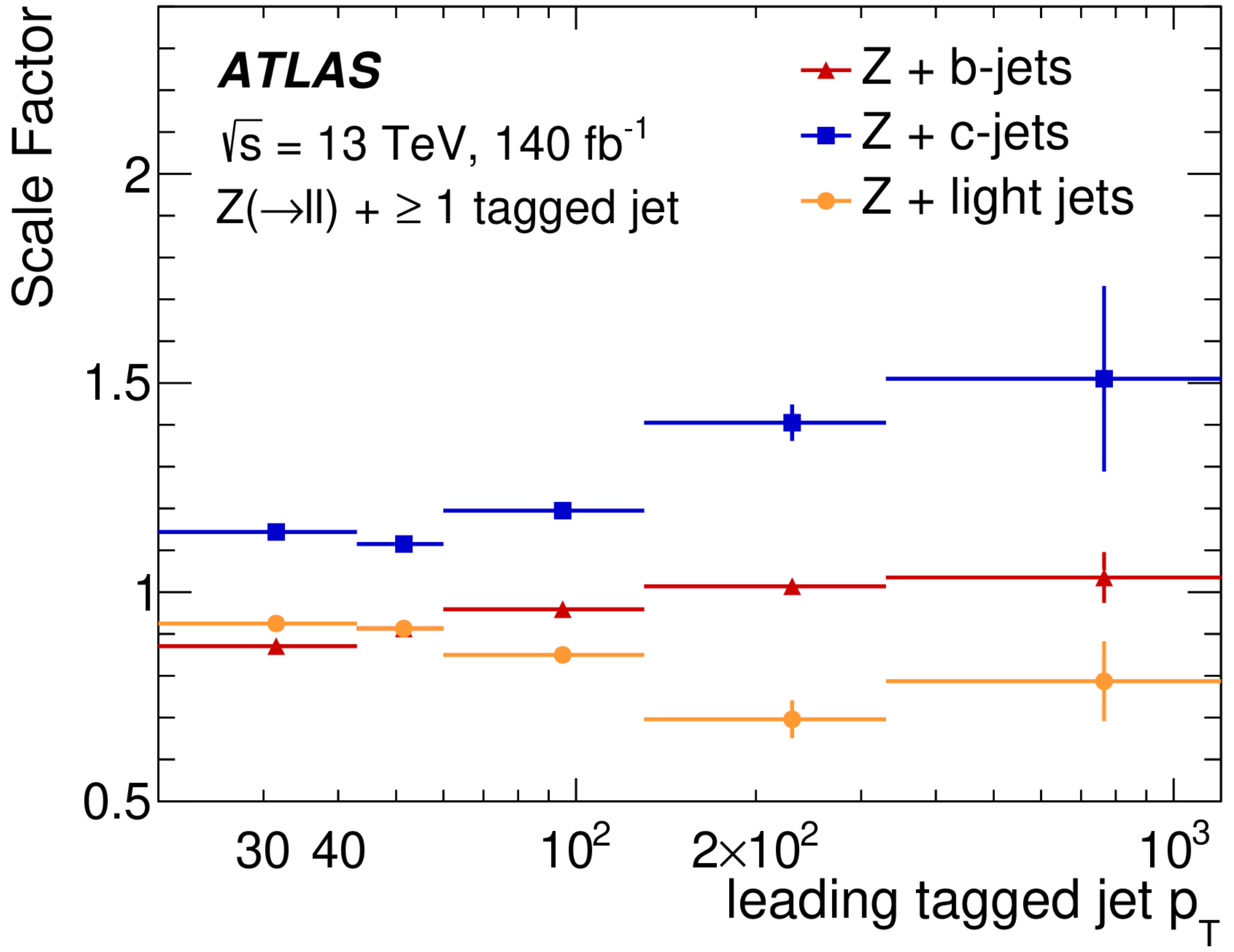


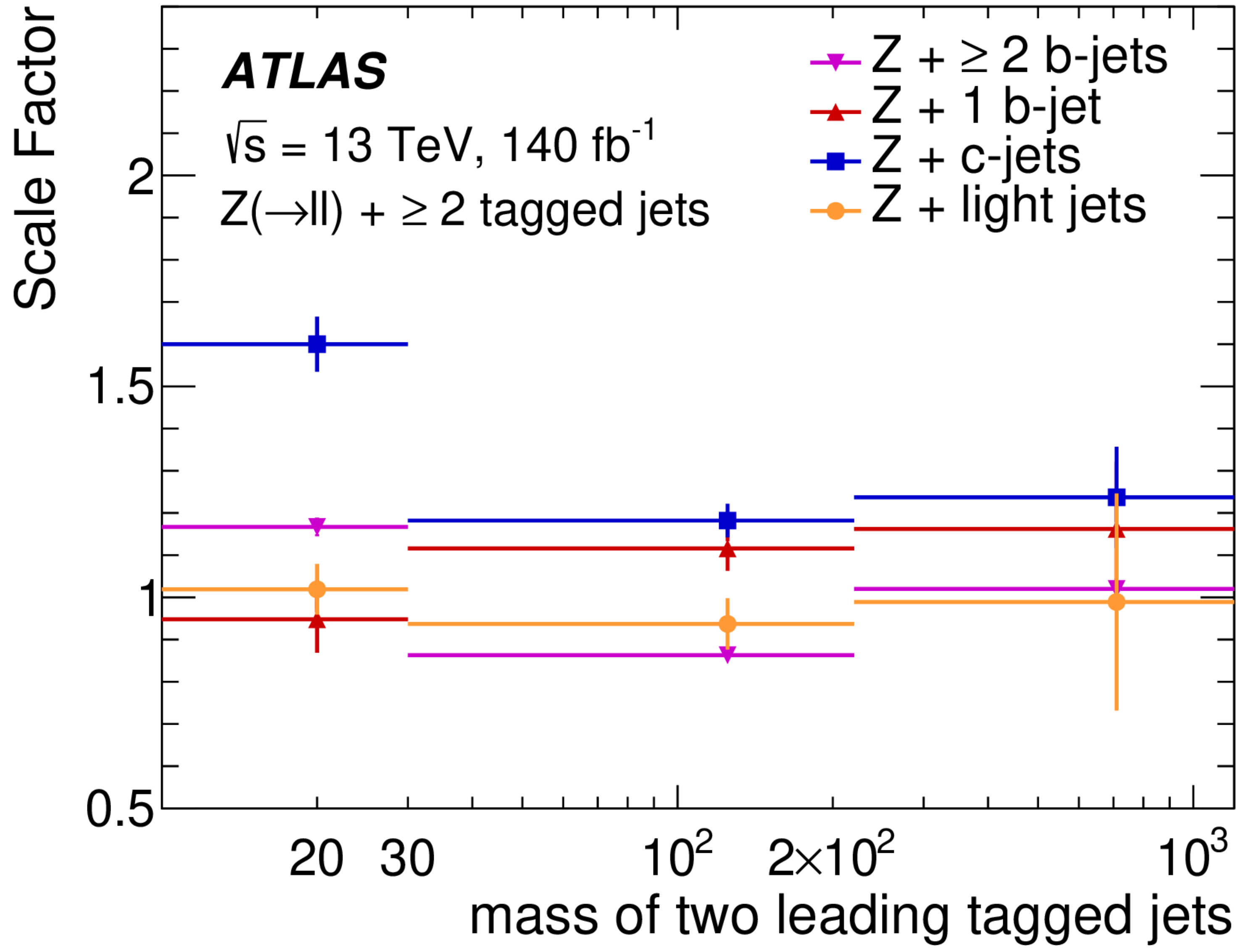
- Detector-level systematics propagated through $TF^{CR\rightarrow SR}$
- **CR→SR extrapolation uncertainty**
  - **validation region (VR):** E_T^{miss} ≥ 60 GeV in 71 GeV< m_{ll} <76 GeV or 106 GeV< m_{ll} <111GeV
  - difference between $t\bar{t}$ estimates from CR→VR and Data-MC in VR



2-tag SR:

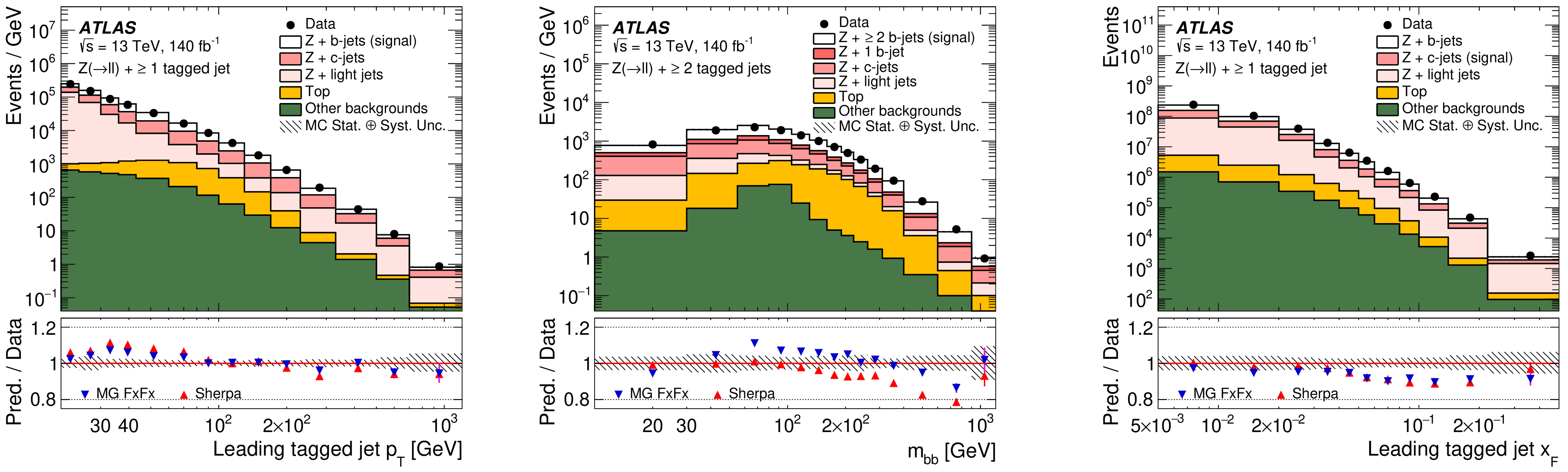
- Fit of **combination of leading and sub-leading flavour-tagged jet DL1r score**
- 4 free parameters corresponding to ***Z*+≥2 *b*-jets**, ***Z*+1 *b*-jet**, ***Z*+≥1 *c*-jet** and ***Z*+≥light jets** normalisation





Z + HF · Detector level

✦ ***Z*+jets background are scaled by the scale factors from *flavour-fit***



1-tag region	
Signal Z + ≥ 1 *b*-jet	
$Z + b$, $Z + bb$	34%
Backgrounds	
$Z + c$	29%
$Z + l$	35%
Top	2%
Others	1%
Total predicted	4 294 900 ± 2100
Data	4 145 168

2-tag region	
Signal Z + ≥ 2 *b*-jets	
$Z + bb$	46%
Backgrounds	
$Z + b$	11%
$Z + c$	23%
$Z + l$	7%
Top	12%
Others	2%
Total predicted	325 300 ± 600
Data	309 199

1-tag region	
Signal Z + ≥ 1 *c*-jet	
$Z + c$	28%
Backgrounds	
$Z + b$, $Z + bb$	33%
$Z + l$	37%
Top	2%
Others	1%
Total predicted	3 994 400 ± 2000
Data	4 145 168

Z + HF · Unfolding

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

arXiv:2403.15093
Submitted to EPJC

Z+≥1 *b*-jet, *Z*+≥1 *c*-jet and *Z*+≥2 *b*-jets cross sections measured at **particle level** in **fiducial phase space** →

Object Selection	Acceptance cuts
Lepton	$p_T > 27$ GeV, $\lvert\eta\rvert < 2.5$
	2 same flavour and opposite charge, 76 GeV $< m_{\ell\ell} <$ 106 GeV
b-jet	$p_T > 20$ GeV, $\lvert y\rvert < 2.5$, $\Delta R(b\text{-jet}, \ell) > 0.4$
c-jet	$p_T > 20$ GeV, $\lvert y\rvert < 2.5$, $\Delta R(c\text{-jet}, \ell) > 0.4$
Event Selection	**Acceptance cuts**
$Z+\geq 1$ *b*-jet	$Z+\geq 1$ *b*-jet and a *b*-jet is the leading heavy-flavour jet
$Z+\geq 2$ *b*-jets	$Z+\geq 2$ *b*-jets and a *b*-jet is the leading heavy-flavour jets
$Z+\geq 1$ *c*-jet	$Z+\geq 1$ *c*-jet and a *c*-jet is the leading heavy-flavour jet
Rapidity regions	**Acceptance cuts**
Central rapidity	*Z* boson rapidity $\lvert y(Z)\rvert < 1.2$
Forward rapidity	*Z* boson rapidity $\lvert y(Z)\rvert \geq 1.2$

- (Data-Bkg) corrected for selection efficiency, resolution effects and differences between detector level and fiducial phase spaces
- **Differential cross sections** corrected to particle level with **iterative Bayesian unfolding**
- For *Z*+≥1 *c*-jet events: central and fwd *Z* p_T are unfolded simultaneously (unrolled distribution). The **fwd/central *Z* p_T ratio** is then evaluated from the unfolded unrolled distribution.
- **Inclusive fiducial cross sections** measured in 1-bin observables and corrected to particle level by dividing for $N^{\text{detector-level}}/N^{\text{particle-level}}$.
- Measurements are performed separately in the electron and muon channels and then combined (agreement within $1\sigma/2\sigma$ in 1-tag/2-tag SRs).

Z + HF · Uncertainties

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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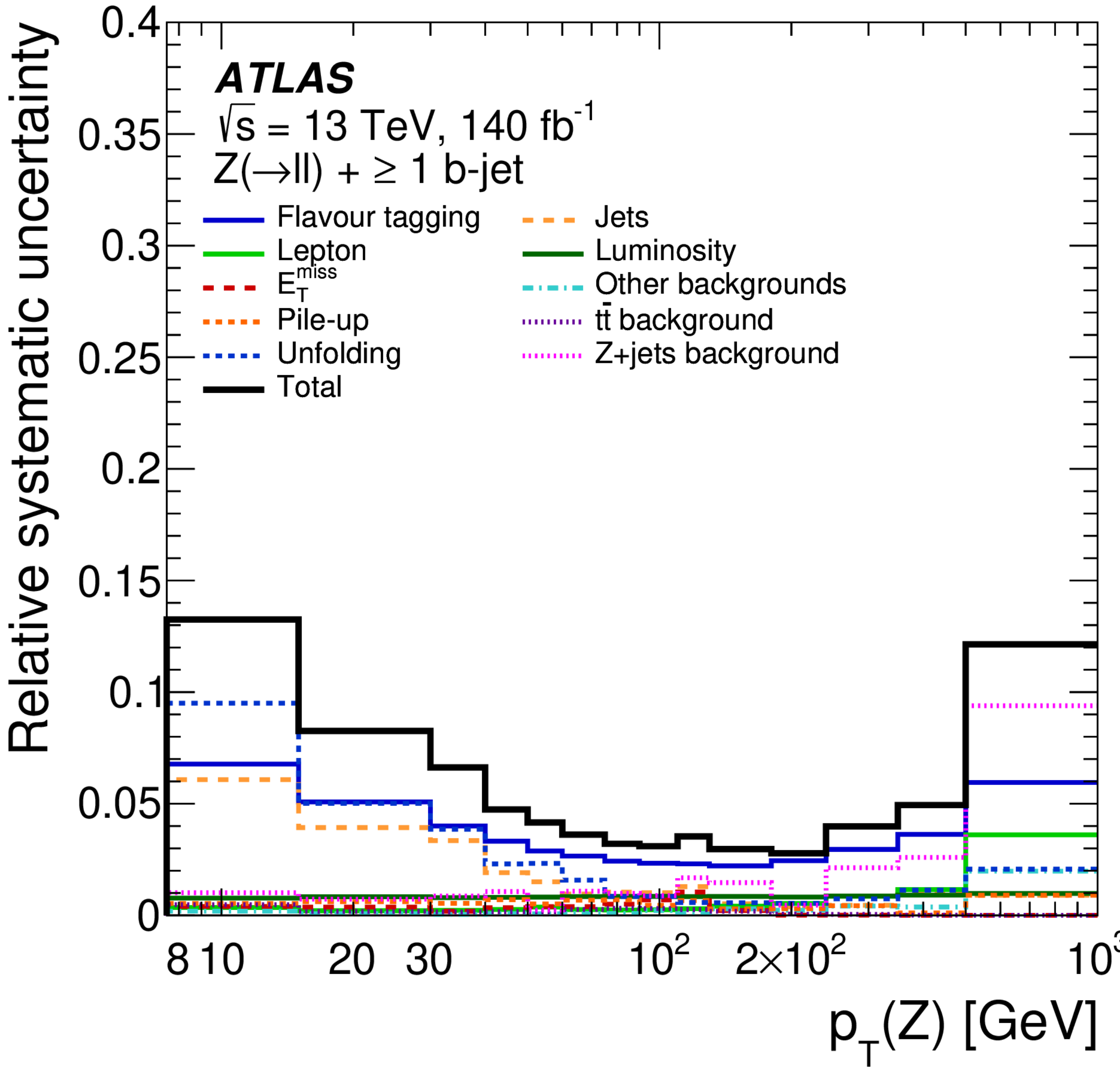
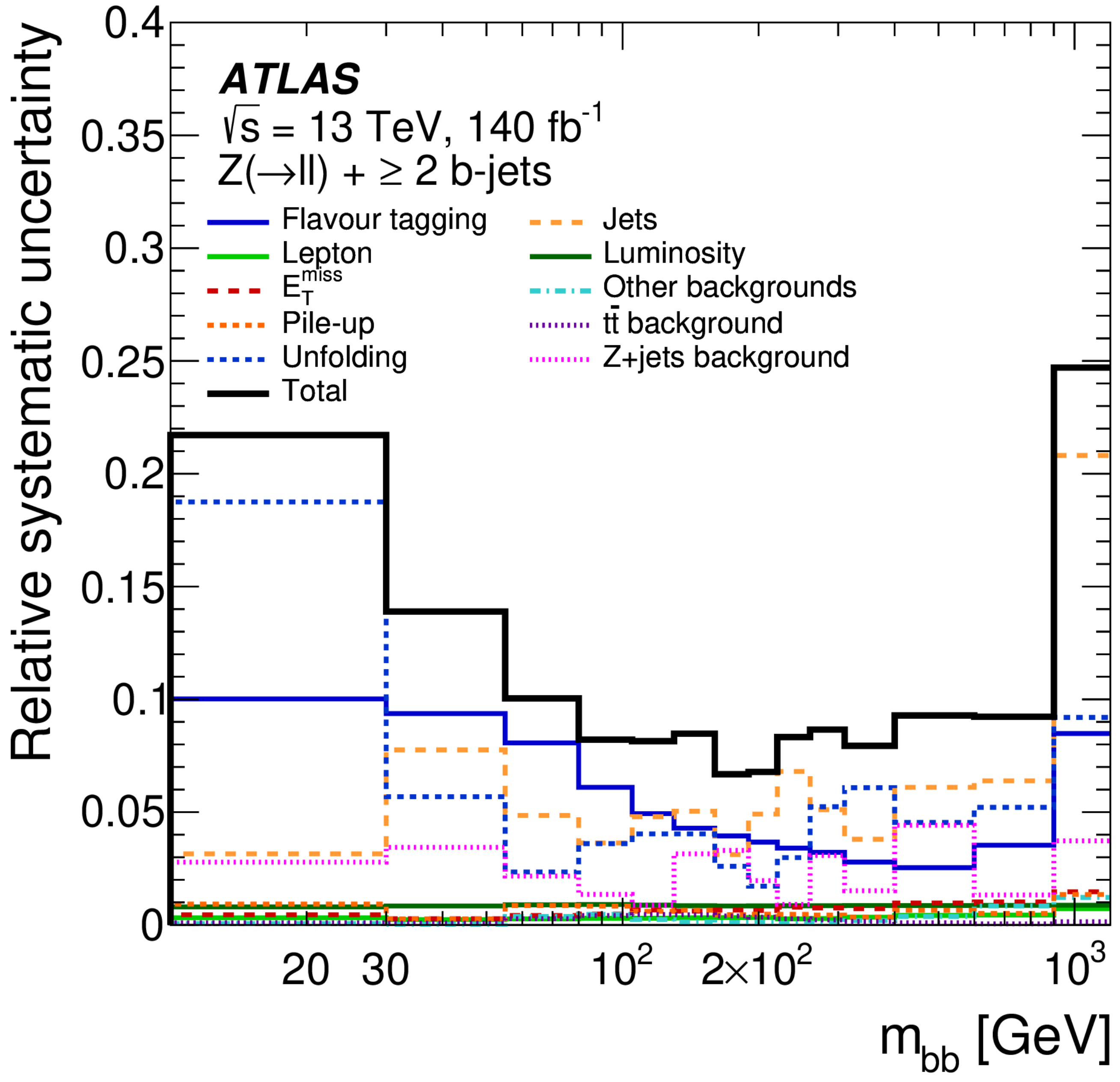
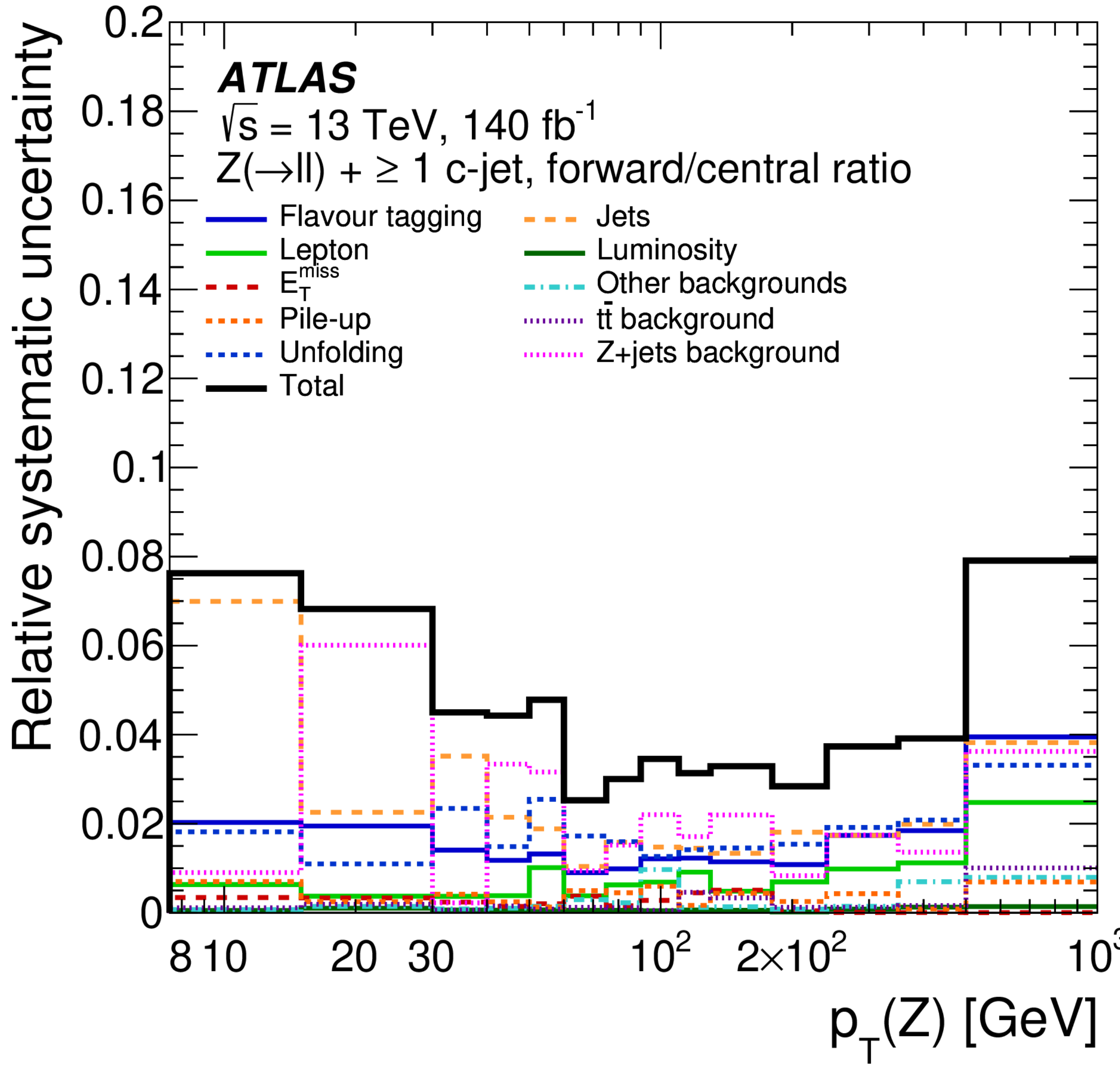
- ***b*-jet tagging**, **Jet**, Lepton, E_T^{miss}, Pile-up and Luminosity
- **Z+jets bkg**: (i) post-fit MGAMC+PY8 FXFX vs SHERPA 2.2.11 difference and (ii) MGAMC+PY8 FXFX QCD scale
- $t\bar{t}$ **bkg**: extrapolation from $e\mu$-CR to SR
- **Other bkg**: QCD scale for diboson and overall normalisation for ZH, single-top and $Z\to\tau\tau$
- **Unfolding**: (i) MGAMC+PY8 FXFX statistics, (ii) data-driven unfolding-bias and (iii) modelling from comparison with SHERPA
- **Statistical uncertainty on data** from 1000 pseudo-experiments (<1%)

Differential distributions: total systematic uncertainties **<5% in *Z*+≥1 *b*-jet** (except some bins in Z p_T), **~10-15% in *Z*+≥2 *b*-jets and *Z*+≥1 *c*-jet** (except some bins at the edges)







Z + HF · Predictions

pp collisions at √s = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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Submitted to EPJC

✦ Measured cross-sections compared with several predictions, **test sensitivity to**:

- different FS in ME
- *IC*-component in proton PDFs
- higher order in QCD

ATLAS official ME+PS samples

Z+*bb* and *Z*+*cc* MGAMC+PY8 with 2 partons in NLO ME

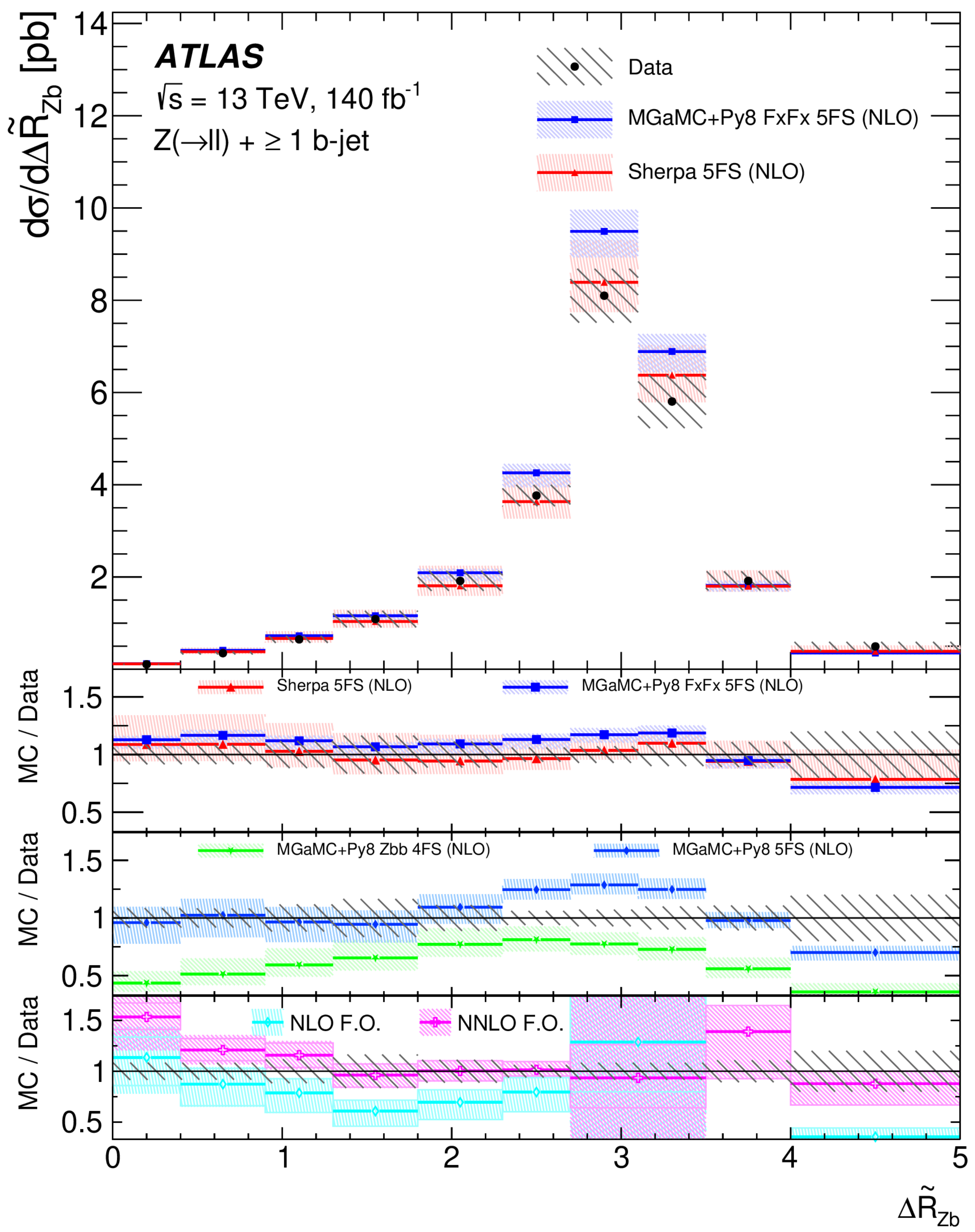
MGAMC+PY8 with different PDF sets testing several *IC*-models (PDF reweighting)

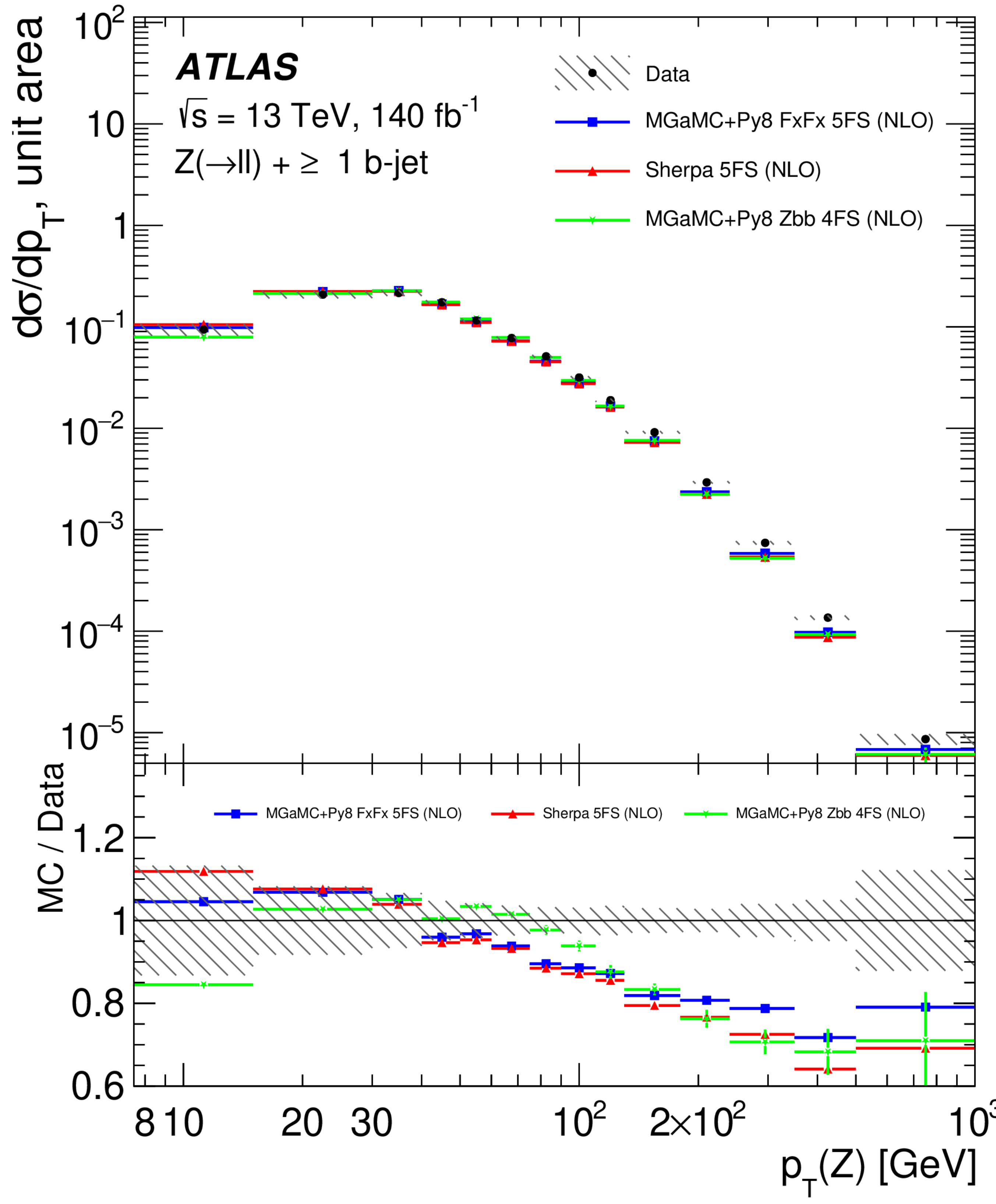
Fixed-order predictions with jet flavour dressing
2 corrections applied: (i) parton→hadron level and (ii) different jet flavour classifications

‘ Generator/settings	Flav. scheme	PDF	LHAPDF ID
		Main MC samples	
MGAMC+PY8 FxFx	5FS	NNPDF3.1 (NNLO) LuxQED	325100
SHERPA 2.2.11	5FS	NNPDF3.0 (NNLO)	303200
		Predictions to test various flavour schemes	
MGAMC+PY8	5FS	NNPDF2.3 (NLO)	229800
MGAMC+PY8 *Zbb*	4FS	NNPDF3.1 (NLO) PCH	321500
MGAMC+PY8 *Zcc*	3FS	NNPDF3.1 (NLO) PCH	321300
		Intrinsic charm (IC) predictions	
MGAMC+PY8 FxFx	5FS	NNPDF4.0 (NNLO) PCH (no IC)	332100
		NNPDF4.0 (NNLO)	331100
		NNPDF4.0 (NNLO) EMC+LHCbZc	–
		CT18 (NNLO) (no IC)	14000
		CT18FC – CT18 BHPS3	14087
		CT18FC – CT18 MCM-E	14093
		CT14 (NNLO) (no IC)	13000
		CT14 (NNLO)IC – BHPS1	13082
		CT14 (NNLO)IC – BHPS2	13083
		Fixed-order predictions	
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

Z + HF · Results

- **5FS**: good description of data by both MGAMC+PY8 FXFX and SHERPA 2.2.11
  MGAMC+PY8 with higher ΔR(*Z*, *b*-jet)~π production (back-to-back)
- **Fixed-order:** Large uncertainty on NNLO due to correction for different flavour jet classification
- **$\Delta\phi_{bb}$**: good description of data by all predictions
  4FS MGAMC+PY8 slightly underestimates collinear and back-to-back *b*-jets





Z + HF · Results

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

arXiv:2403.15093
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- **5FS**: good description of data by both MGAMC+PY8 FXFX and SHERPA 2.2.11
  MGAMC+PY8 with higher ΔR(*Z*, *b*-jet)~π production (back-to-back)
- **Fixed-order:** Large uncertainty on NNLO due to correction for different flavour jet classification
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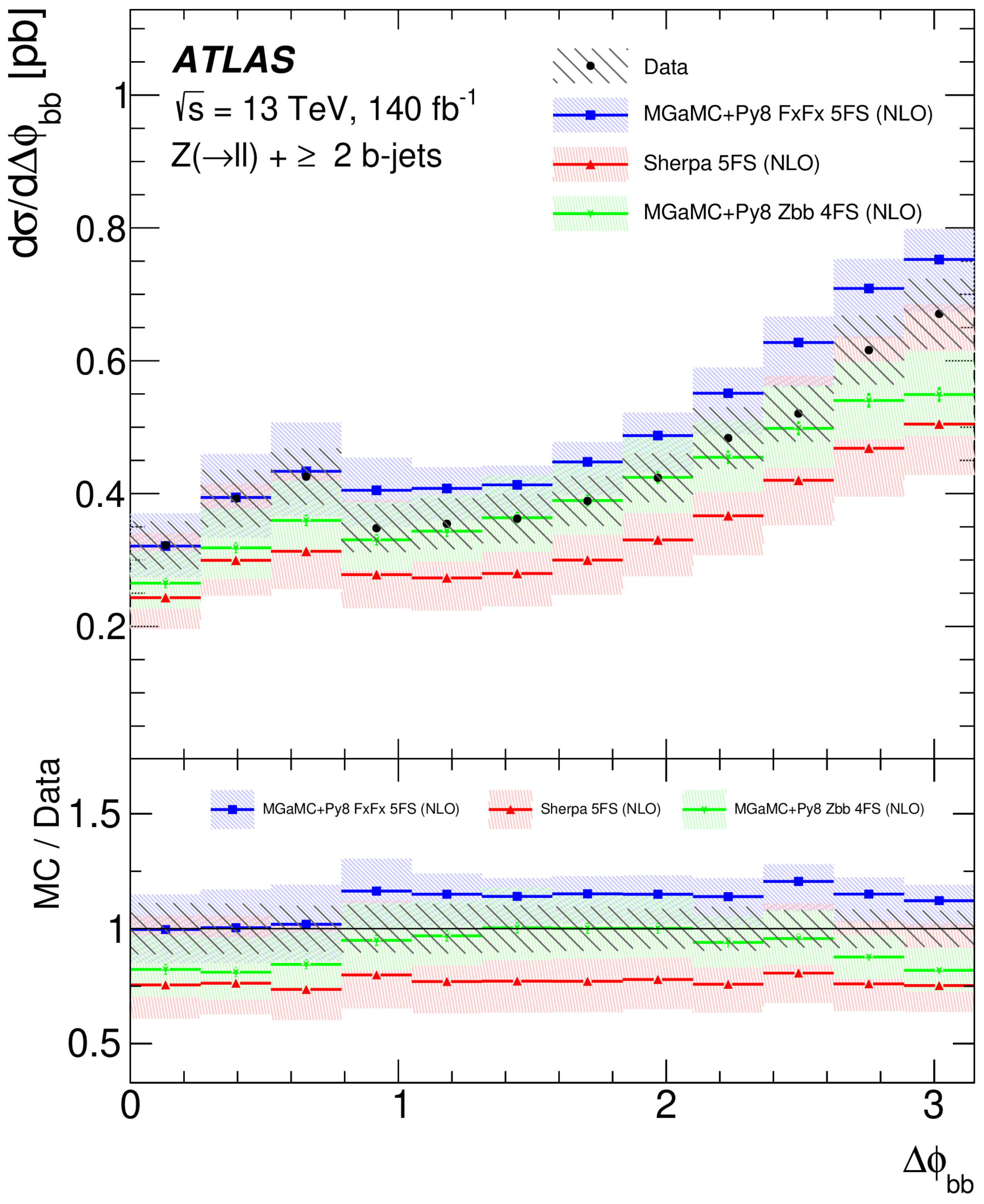

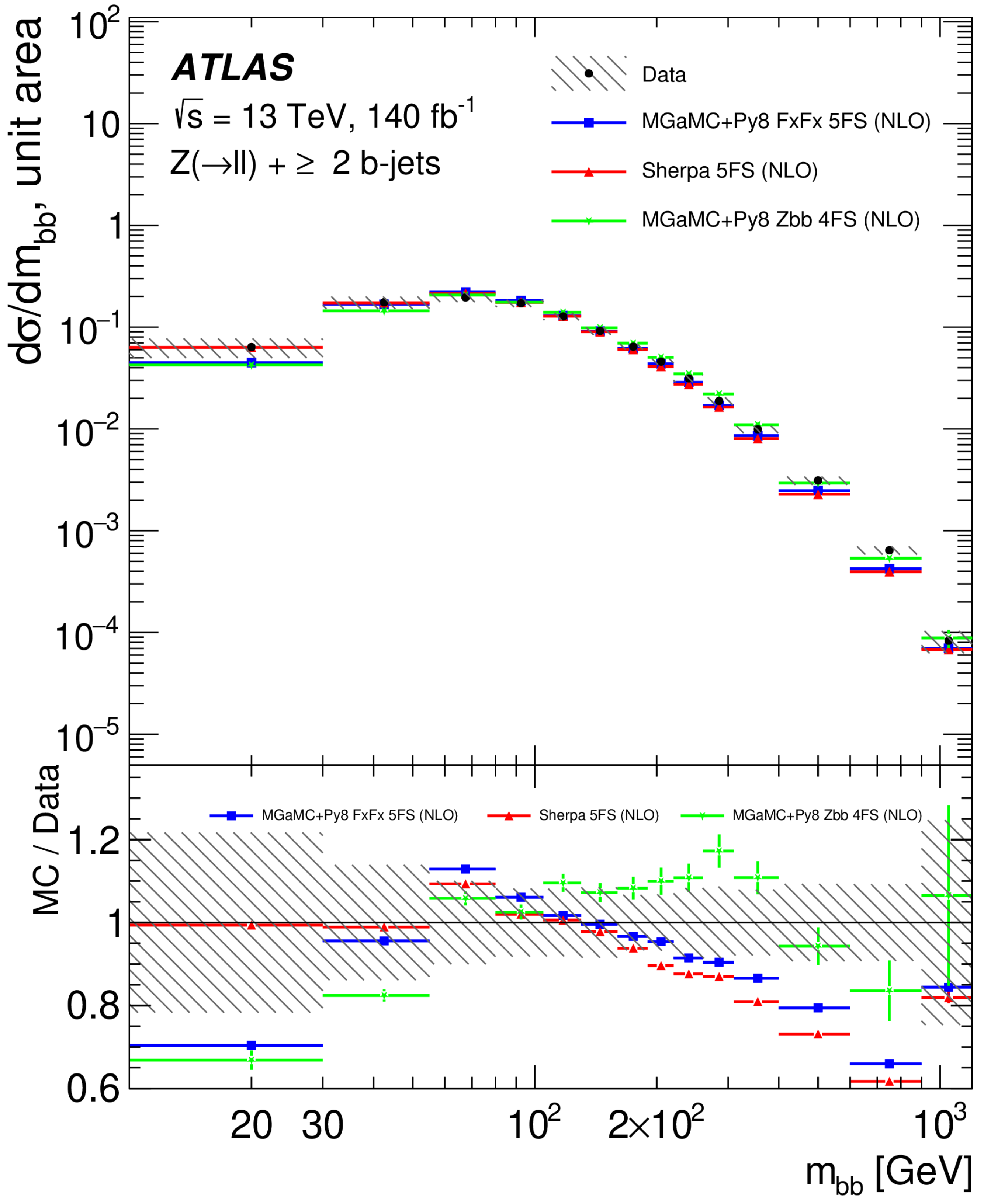

Z + HF · Results

pp collisions at $\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = 140 fb^{-1}

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- **5FS:** soft p_T spectra well described by MGAMC+PY8 FXFX and SHERPA 2.2.11, which underestimate data for p_T>100 GeV. Reasonable agreement with data for x_F.
- **4FS:** reasonable p_T and x_F modelling by MGAMC+PY8
- **3FS:** MGAMC+PY8 underestimates data by a factor ~3 - **lack of logarithmic resummation in PDF evolution**
- **Fixed-order:** NLO predicts softer p_T spectra, small improvement with NNLO. Reasonable description of x_F.