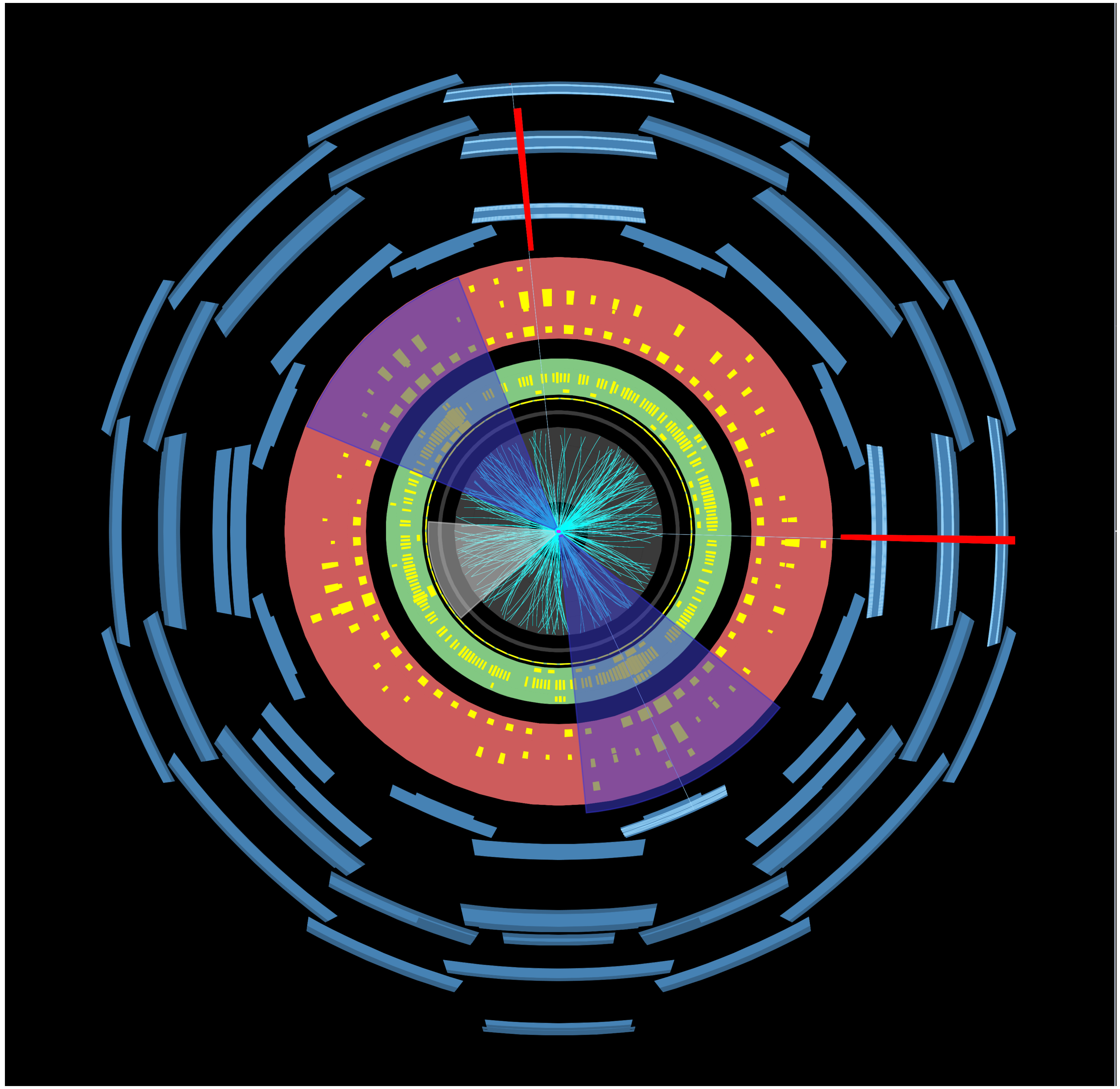
The *charm* and the *beauty* associated with the EWK gauge bosons



Camilla Vittori

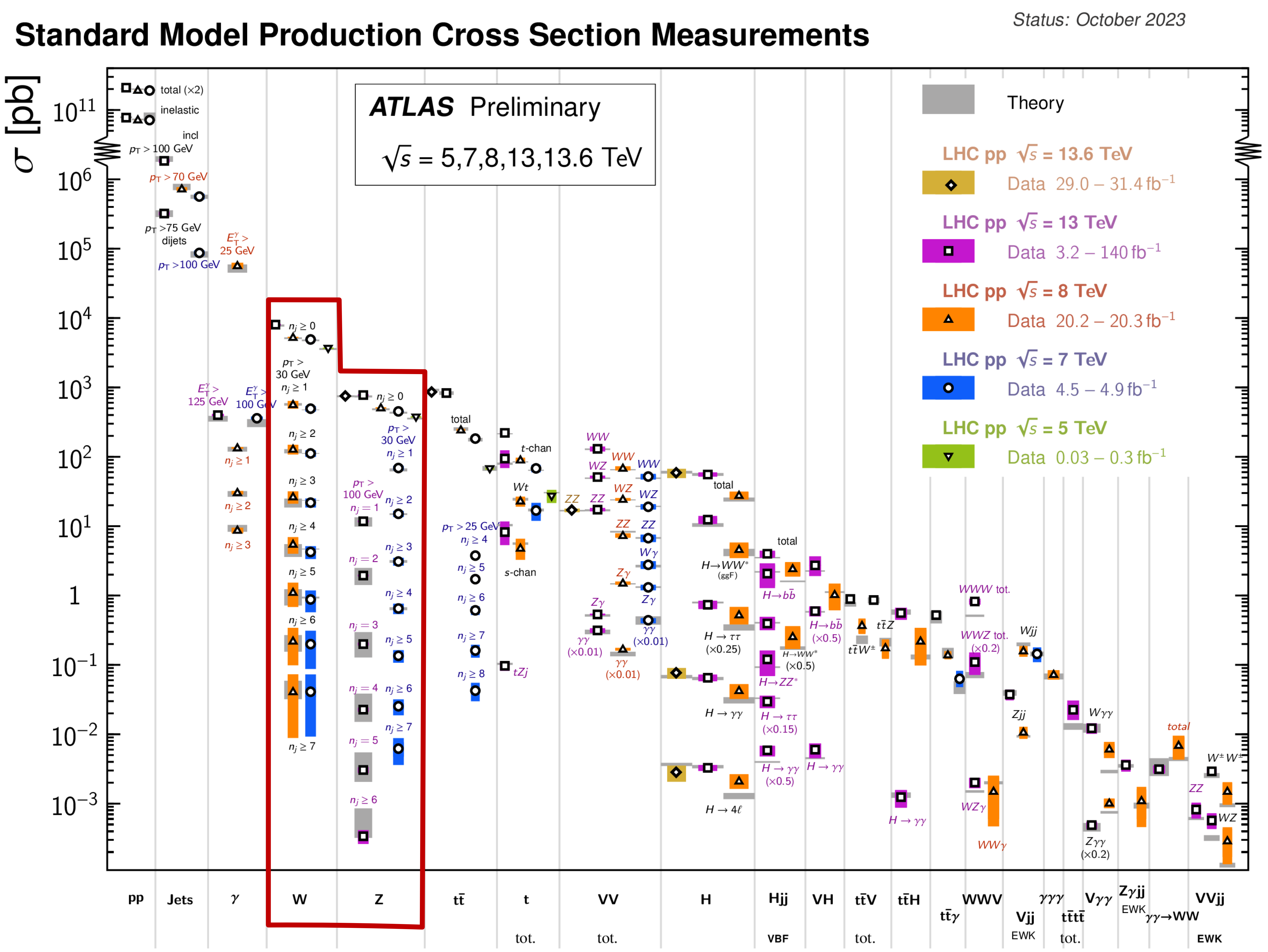
camilla.vittori@cern.ch

on behalf of the ATLAS Collaboration

CERN Seminar

30 April 2024

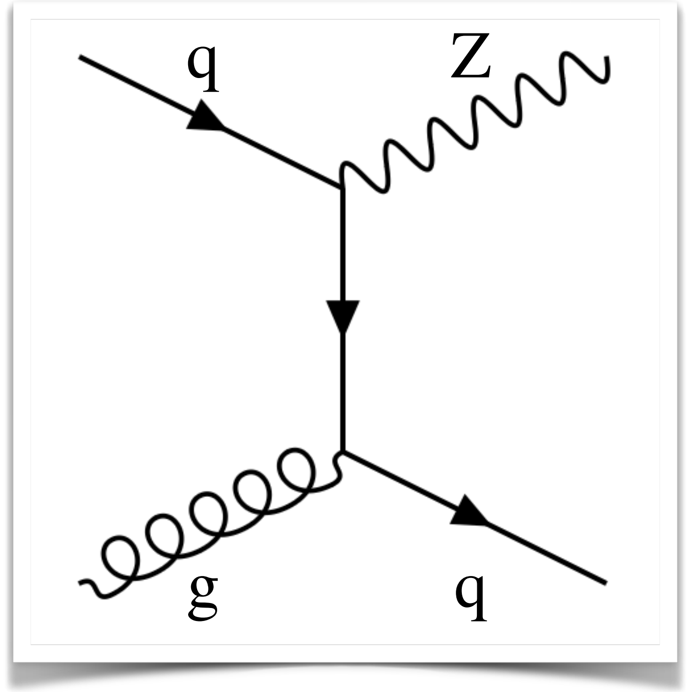
V + jets at hadron collider



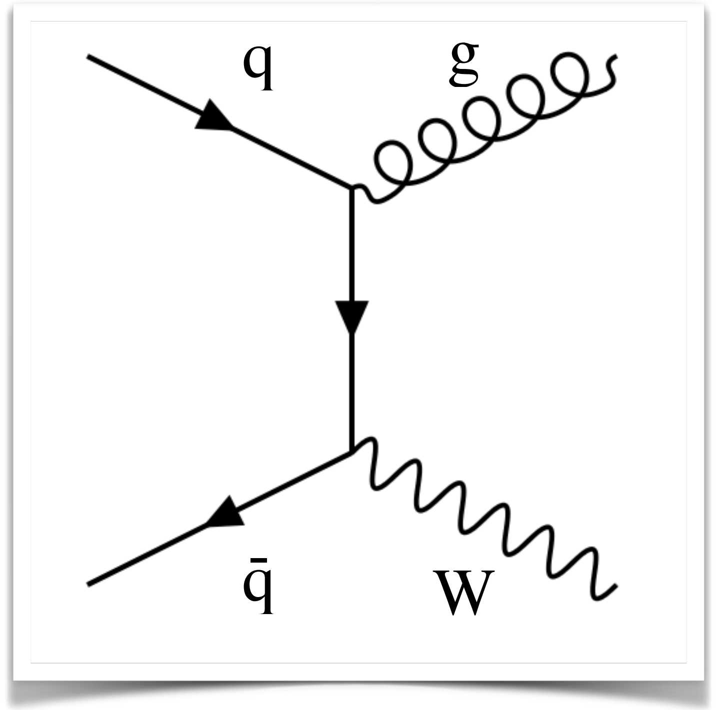
W/Z+jets

- ***V*(=*W*/*Z*) + jets** production has the largest cross-section after multijet and inclusive *V*-boson production
- At LHC, 1/3 of *W*/*Z* production is in association with a jet (p_T>30 GeV)

qg initial state

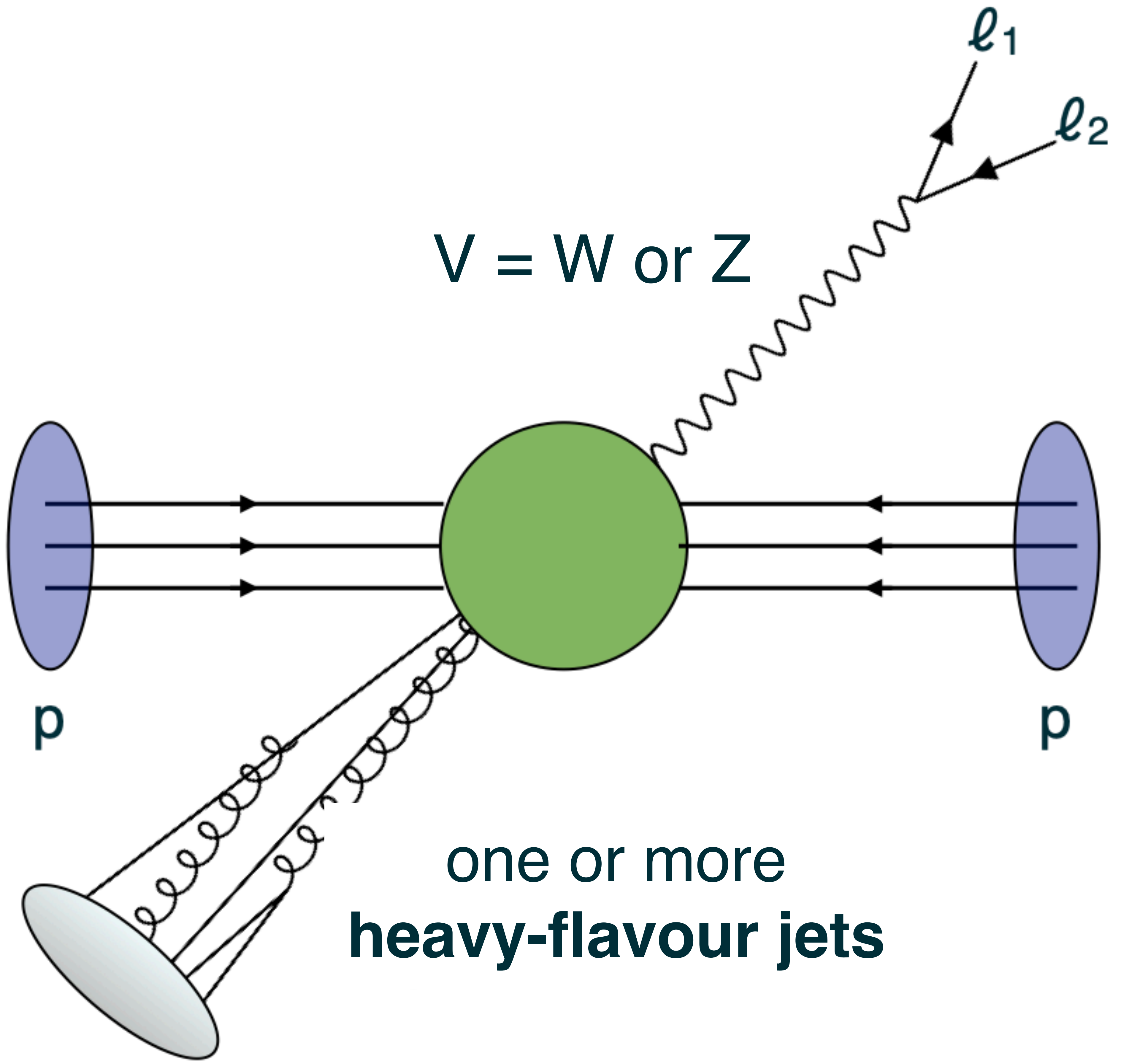


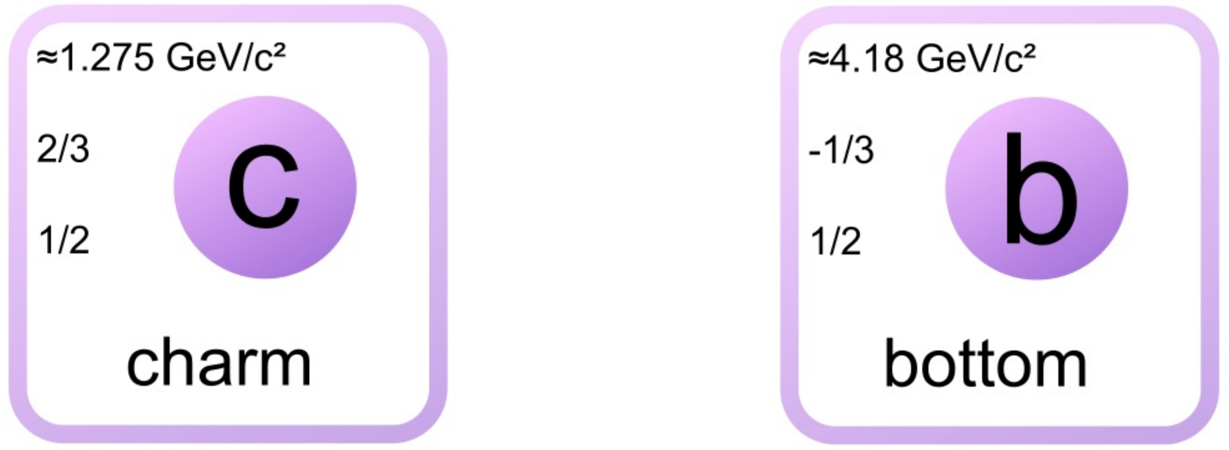
qq̄ initial state



V + HF jets at hadron collider

Heavy-Flavour (HF) jets = jets originating from the hadronisation of *c*- and *b*-quarks



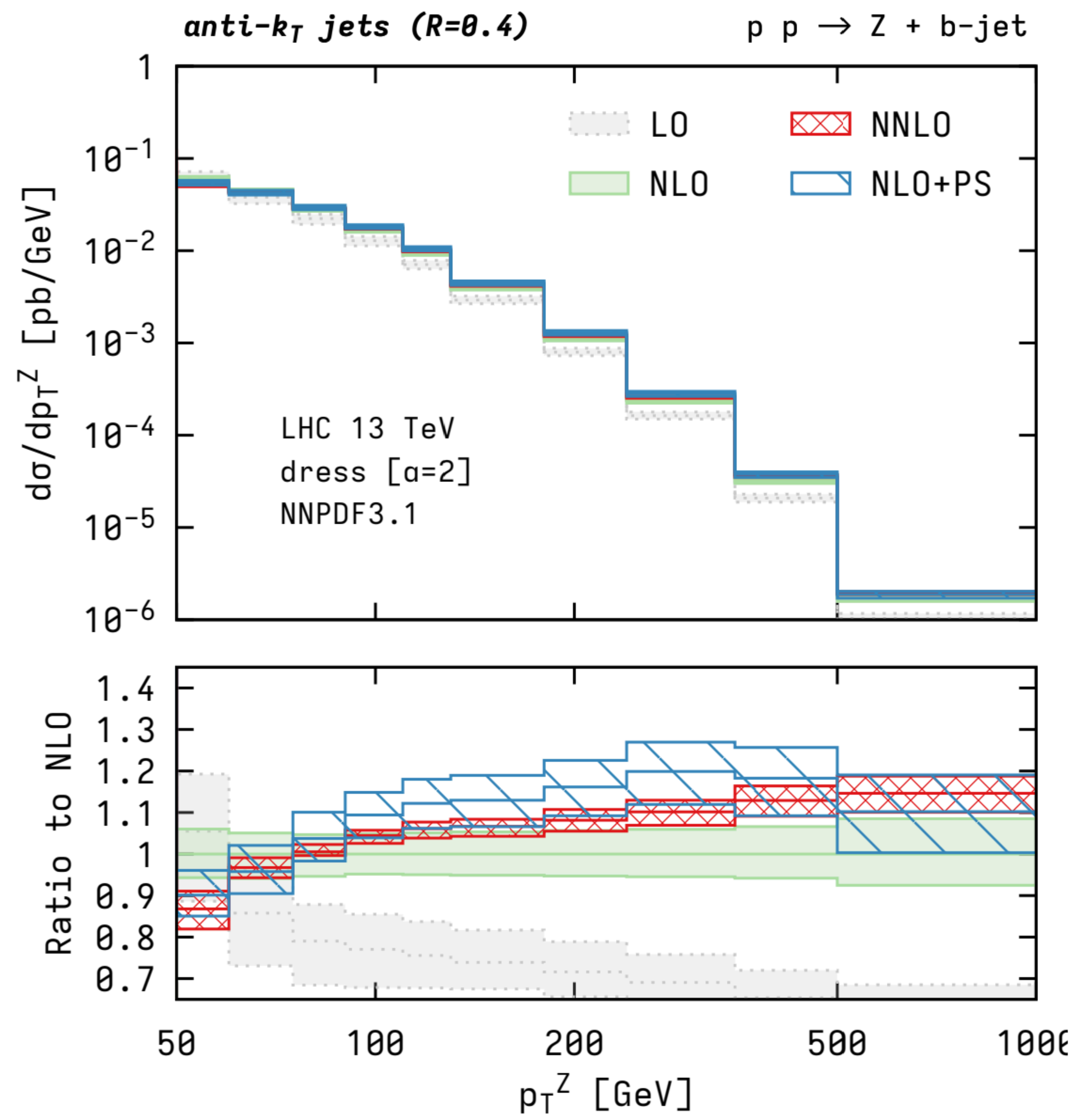


- **Perform perturbative-QCD** (**pQCD**) studies at a wide kinematic range and jet multiplicities
- Increase our understanding of **Parton Distribution Functions** (**PDFs**)
- Improve **background modelling** in Monte Carlo (**MC**) simulation in New Physics (NP) searches

High-order QCD calculations

- The complexity of *V*+HF processes requires calculations with **high order precision in QCD**
- State of the art **MC generators** with **matrix-element** (**ME**) calculations at **NLO in QCD, interfaced with parton-shower (PS)** for the description of the soft QCD emissions
  - **MADGRAPH + PYTHIA** (MGAMC@NLO + PY8 with FXFX merging) - up to 3 partons in NLO ME
  - **SHERPA 2.2.11** - up to 2 partons in NLO ME + 3,4,5 jets at LO
- Fixed-order **theoretical predictions** available up to **NNLO in QCD**
- **Effect of missing higher order terms** not negligible
- Ambiguity in the algorithm used to identify the jet-flavour
  - in the measurements the definition of the jet-flavour is not infrared and collinear (IRC) safe
  - direct comparison with theoretical predictions not possible
  - ➡ **add corrections which affect the precision of the results**

Phys. Rev. Lett. 130 (2023) 161901



Flavour Schemes

- Different theoretical approximations - **Flavour Schemes (FS)** - in the ME of the calculations **related to the treatment of the *c*- and *b*-quark masses**

Example for *Z* + *b*-jets:

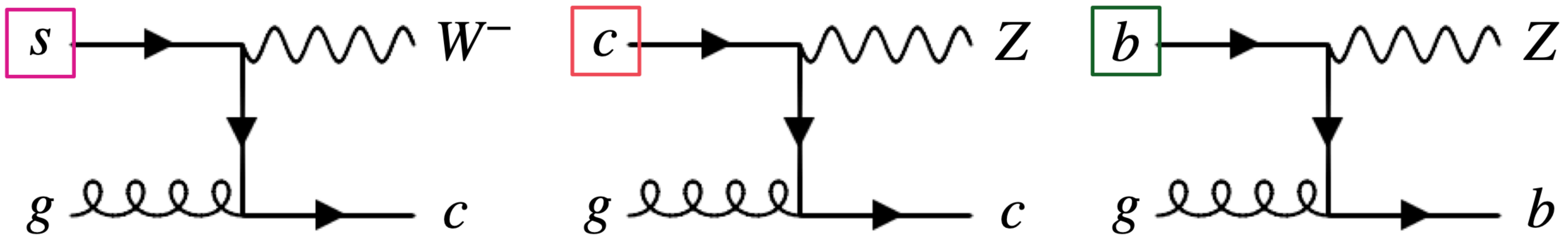
- **4FS**: massive *b*-quarks → *b*-quarks do not contribute to proton wave functions
  - *b*-quarks can only be generated in the hard scattering by **gluon splitting** ($g \rightarrow b\bar{b}$)
  - *b*-quarks **do not enter in pQCD calculations and PDF evolution**
  - $ln(Q^2/m_b^2)$ terms appear at any order in pQCD
  - suitable for kinematic region with energy scale $\mathbf{Q^2 \sim m_b^2}$

- **5FS**: massless *b*-quarks → *b*-quark density is allowed in the initial state via a *b*-quark PDF
  - $ln(Q^2/m_b^2)$ terms affect the convergence of the perturbative expansion ($m_b \rightarrow 0$)
  - resummation of $\alpha_s ln(Q^2/m_b^2)$ to all orders in α_s into b-quark PDF with DGLAP evolution
  - suitable for kinematic region with $\mathbf{Q^2 >> m_b^2}$

- The ambiguity between the FSs is expected to reduce including higher oder pQCD corrections
  - Both schemes have pros and cons and should be chosen according to the scale of the process

PDFs

- V + HF data probe proton PDFs at medium and high x-Bjorken and momentum transfer (Q^2)
- Precise measurements allow to **constrain PDF uncertainties**
- Unique access to ***s***-, ***c***- and ***b***-quark PDFs in proton



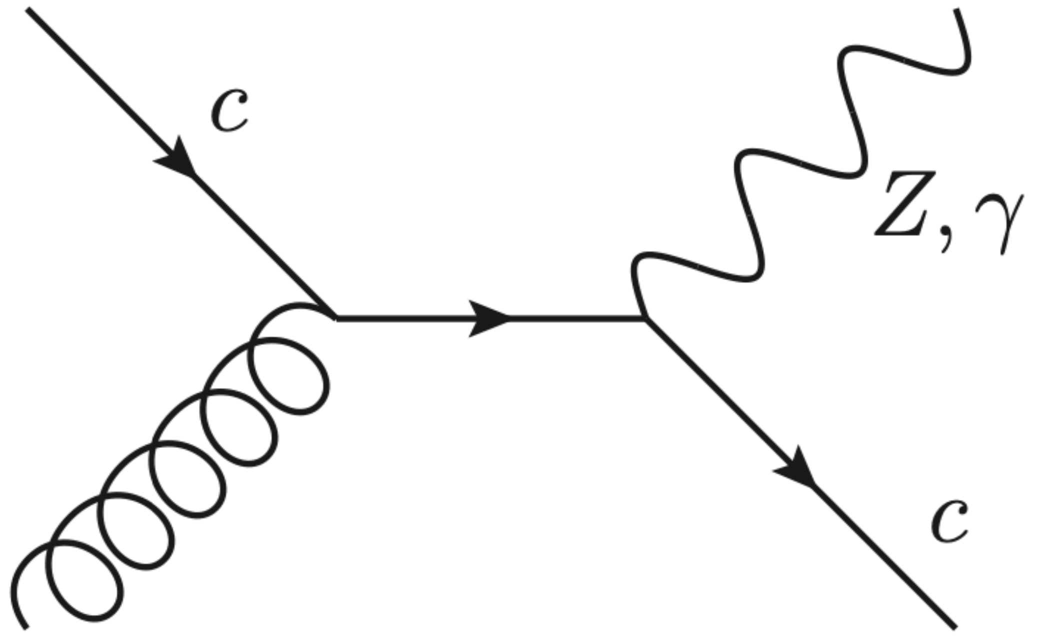
- ***W + c*** production sensitive to ***s*-quark PDF** in the proton
  - It allows to study the *s*-quark asymmetry at the initial scale in PDF evolution
    - At NNLO in QCD, $s - \bar{s}$ asymmetry appears as intrinsic property of the DGLAP evolution
    - Various PDF fits assume **different hypotheses on the $s - \bar{s}$ asymmetry at the initial state**:
      - NNPDF: $s \neq \bar{s}$ coming from independent fit of s and $\bar{s}$
      - CT18: $s = \bar{s}$ at low scale

    ➡ Precise measurements allow to test the $s - \bar{s}$ at the analysed Bjorken-x regions

PDFs

- ***Z* + *c*** production sensitive to ***c*-quark PDF** in the proton
  - It allows to explore the sensitivity to *Intrinsic-Charm* (*IC*) component in the proton
    - Hypothesis of *IC*-existence postulated 40 years ago
    - ***c*-quarks pairs** not only generated perturbatively by gluon splitting (short-time scale), **contribute to the proton structure**
    - IC assumed to exist over a timescale independent of any probed Q^2
    - ***c*-quarks pairs are considered as part of the proton wave function at rest**
    - *Z* + *c* is expected to enhance IC-sensitivity at high Bjorken-*x* (>0.1):
      - larger production of hard *c*-jets in the forward region

➡ Open research field since *IC* has never been observed experimentally!

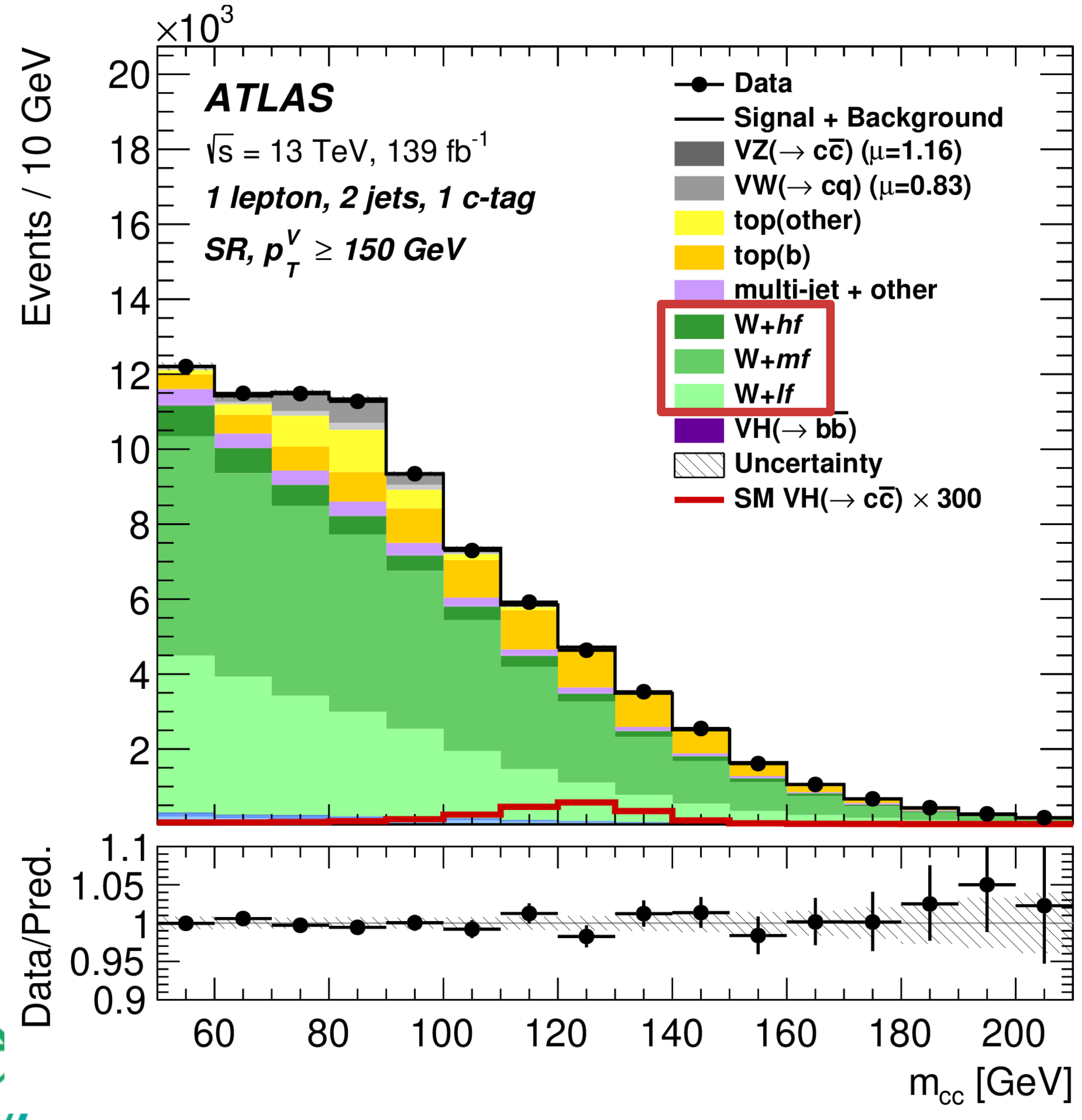


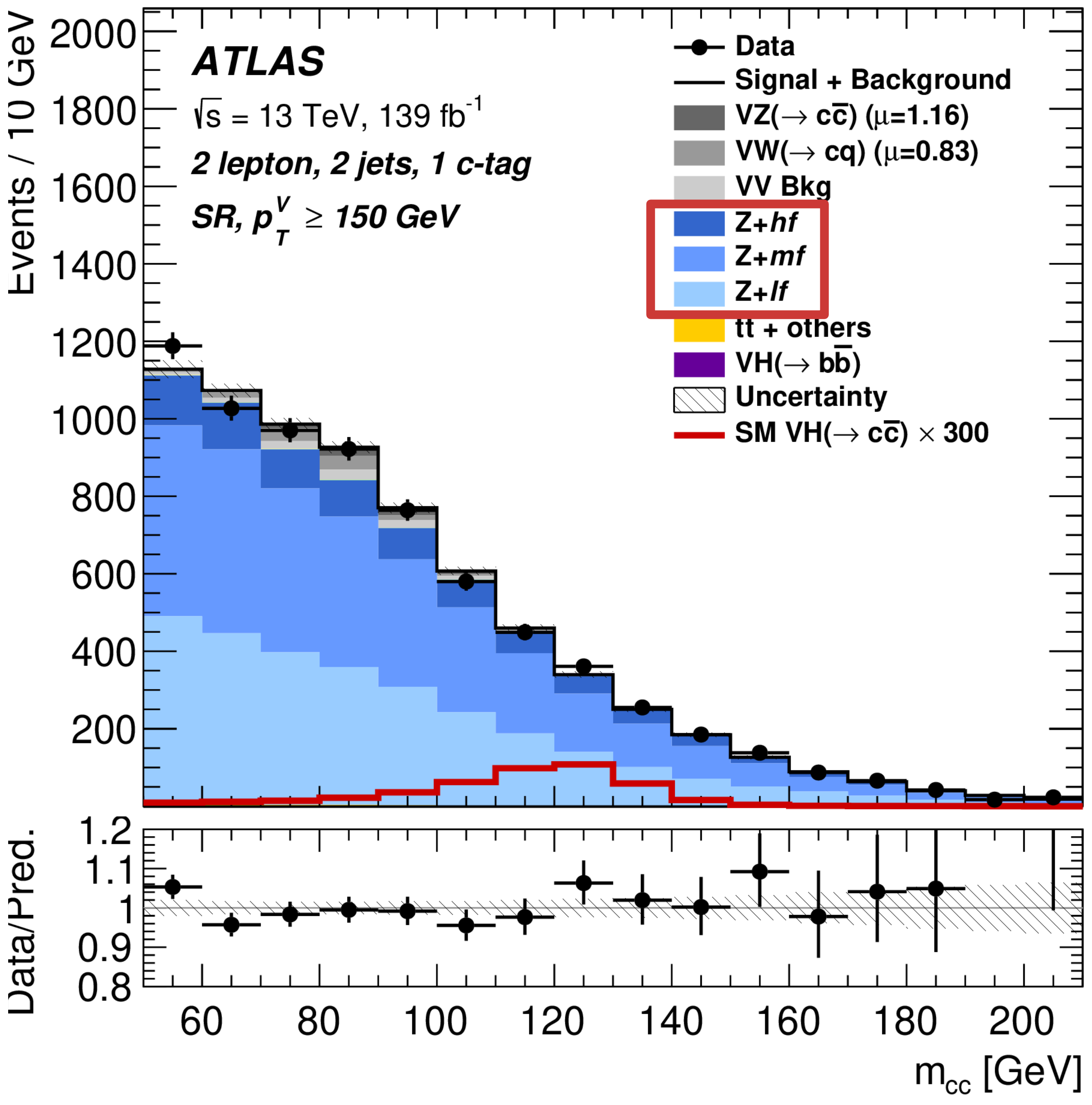
IC: $\psi_p = |uudc\bar{c}\rangle$
not only via $g \to c\bar{c}$

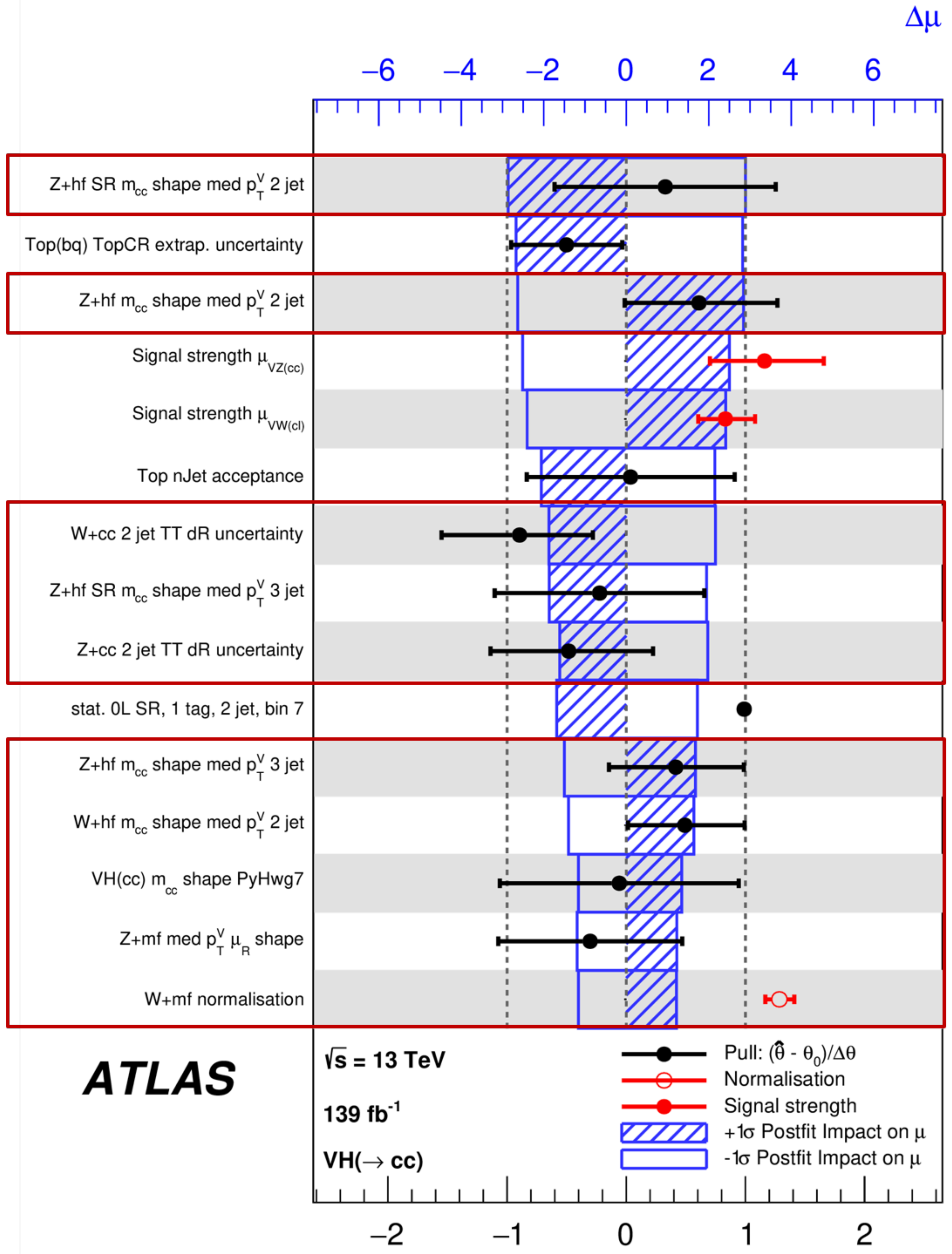
V + HF jets as background for other processes

- Example $VH(\rightarrow b\bar{b}, c\bar{c})$:
  - V+HF jets dominant background
  - jet multiplicity and kinematics used to distinguish the signal from V+HF jets background processes
  - V+HF jets modelling limiting factor

Eur. Phys. J. C 82 (2022) 717







Are high precision measurements possible?

- Performing high precision measurements of *V*+HF QCD production is **challenging**…
  - final state selection strongly relies on the **reconstruction of *b*- and *c*-quarks**
  - poor **modelling** description **by MC generators**
- …**but possible**
  - typically 5-10% precision in cross-sections and down to percent level in normalised cross-sections

Need for:

- **Precise calibrations** for electrons, muons, MET, jets and flavour tagging
- MC generators with **precise modelling** for large jet multiplicities, gluon splitting

Heavy flavours tagging

Inclusive tagging

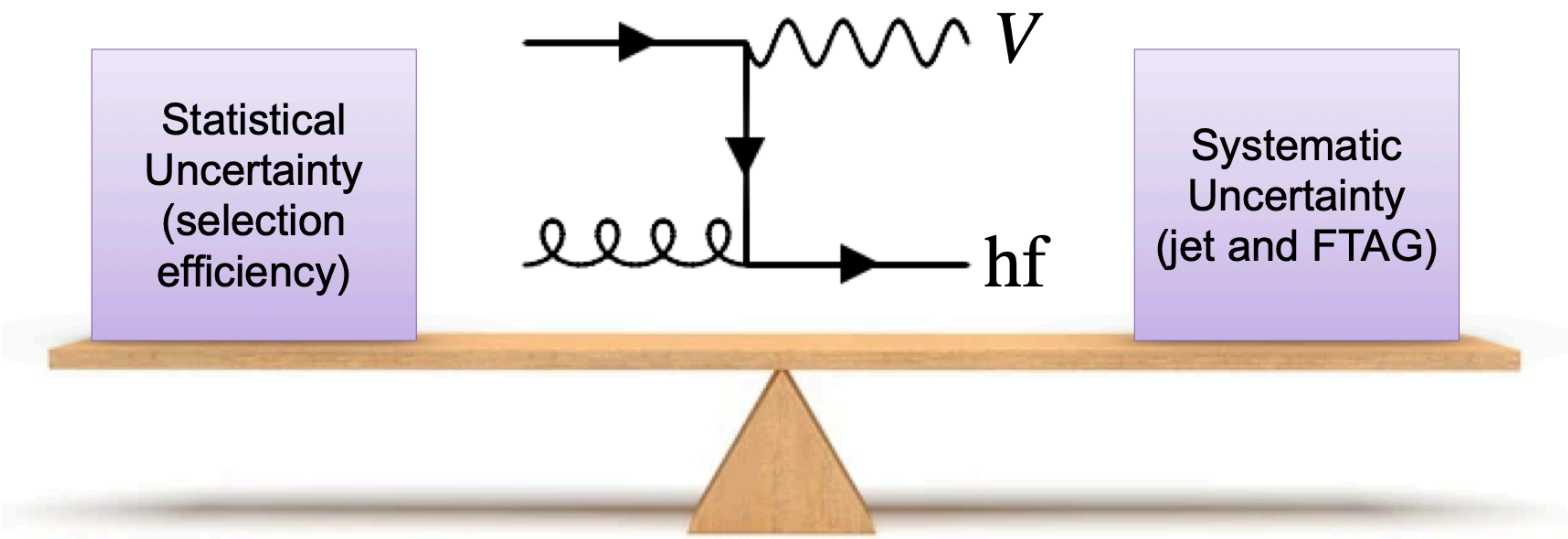
Using jet reconstruction and flavour tagging (FTAG) algorithms

- ✗ Rely on jet reconstruction, FTAG and the related uncertainties
- ✓ Large selection efficiency for *b*-jets and *c*-jets
- ✗ The information on the quark charge is lost
- ✓ Measurements can be used in PDF fits

Exclusive tagging

Using specific heavy hadrons decays (e.g. $D \to \mu X$ or $D \to K\pi\pi$)

- ✓ No (less) need for jet reconstruction and FTAG
- ✗ Low selection efficiency
- ✓ Very reliable determination of the quark charge
- ✓ Measurements with high precisions, requires to include Fragmentation Functions



Today's focus

Two recents results from the **ATLAS experiment** are presented:

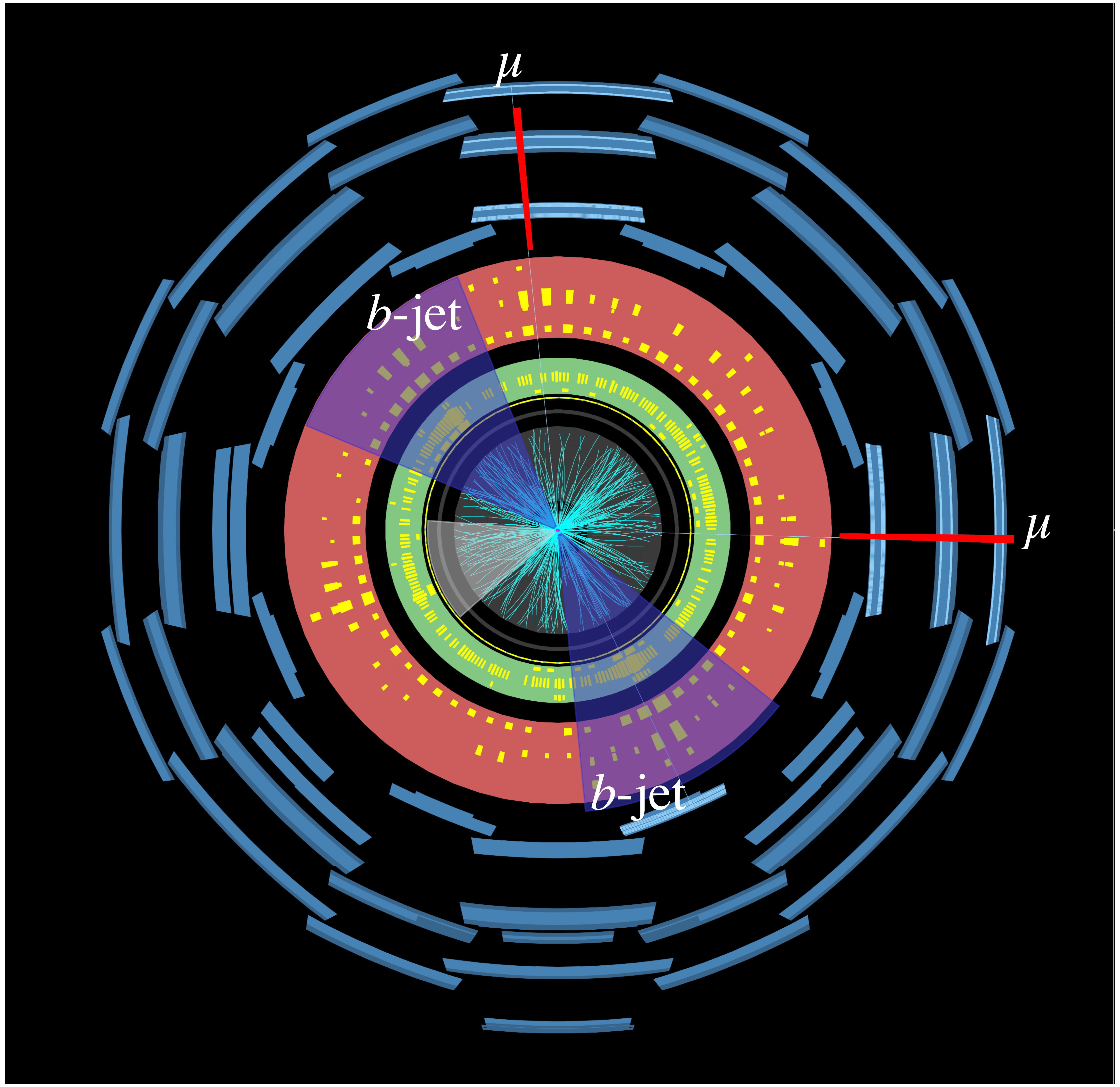
★ **W production in association with charmed-hadron**

Phys. Rev. D 108 (2023) 032012

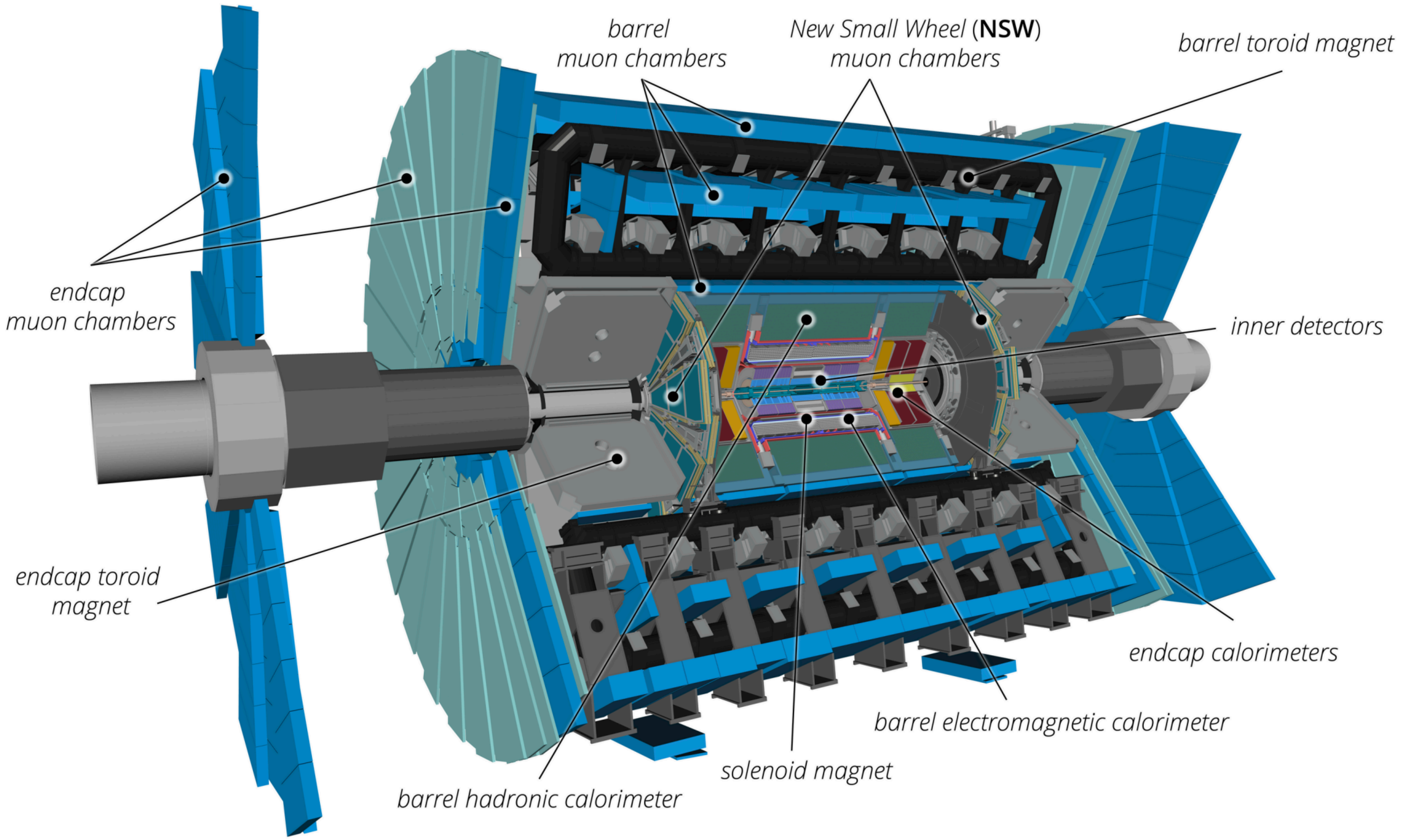
★ ***Z* production in association with 1 or 2 *b*-jets and with *c*-jets**

Submitted to EPJC, arXiv:2403.15093

performed with data from *pp* collisions at $\sqrt{s}$ = 13 TeV, $\mathcal{L}$ = 140 fb^{-1}

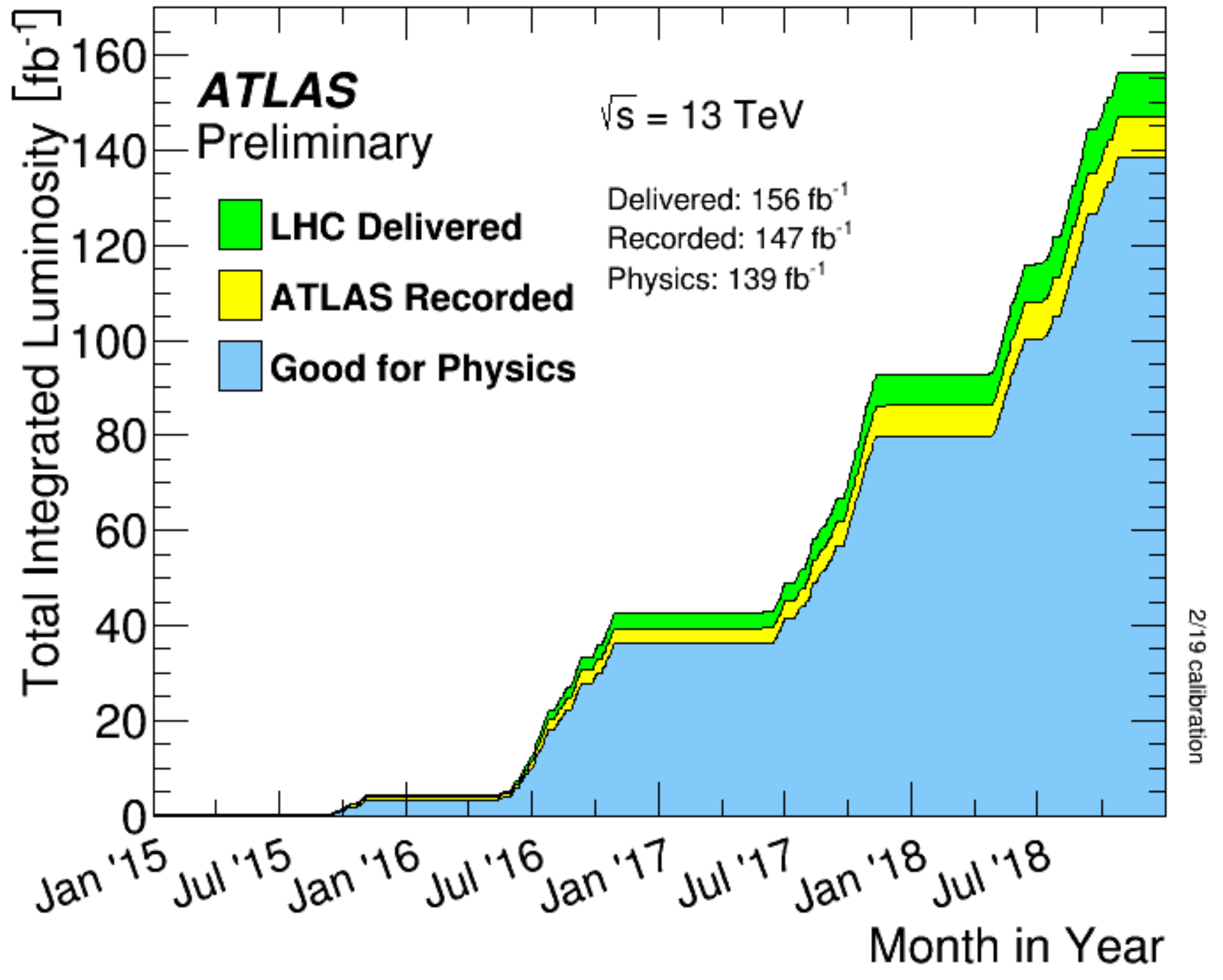


The ATLAS Detector



Run-2 with largest dataset available for physics

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

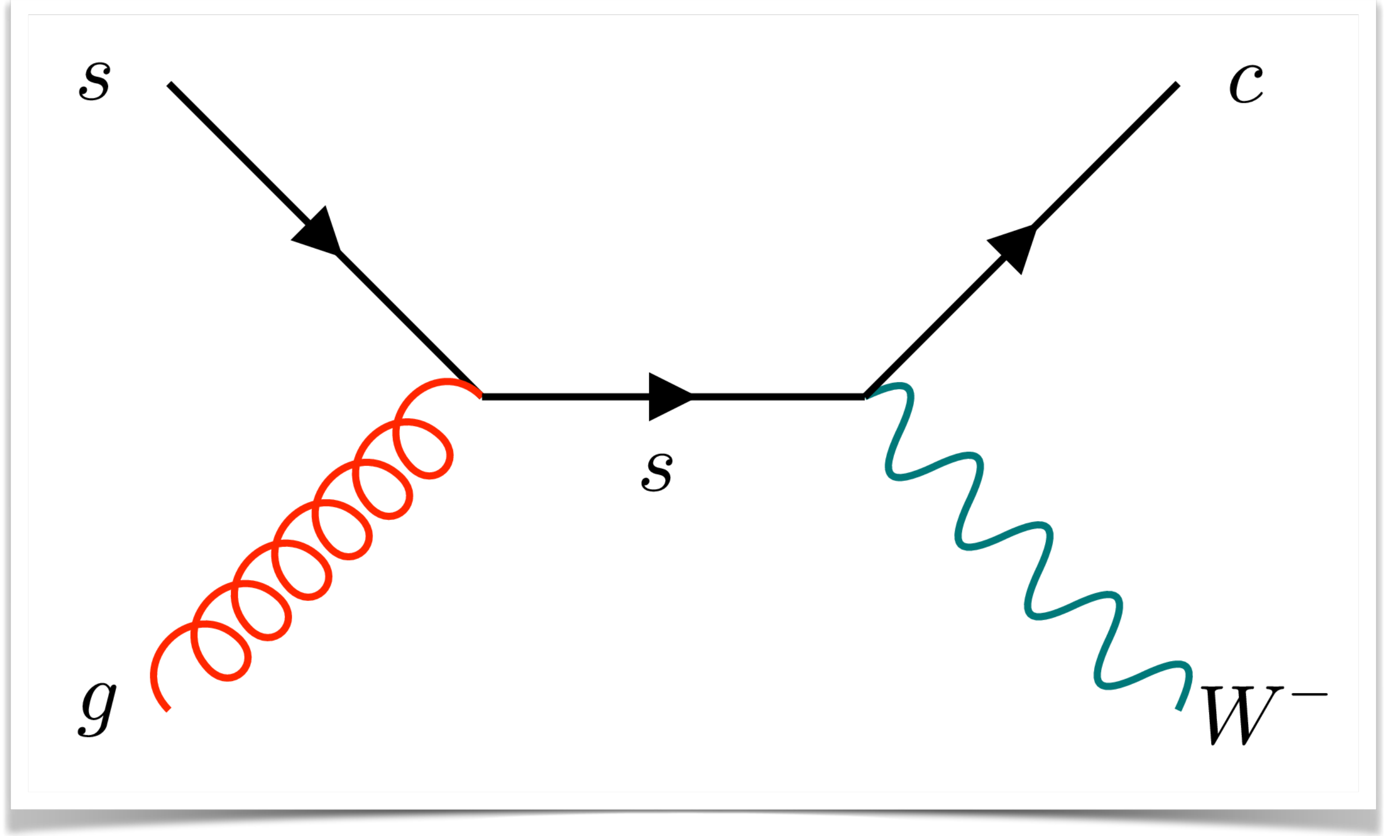


W + charmed hadron

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

Phys. Rev. D 108 (2023) 032012

Measurements of the W boson production in association with charmed hadrons



- Dominant *W+c* production mode at LO from: $gs \rightarrow W^{-}c$
  - ➡ **unique sensitivity to *s*-quark PDF**
  - ➡ crucial measurement for **constraining the PDF uncertainties**
  - ➡ constrain $s - \bar{s}$ asymmetry

- **Reconstruct the *c*-quark exploiting the charmed-hadron decays:**

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

★ **Integrated cross-section** $\sigma(W + D)$

★ **Normalised differential cross-sections** in bins of D-meson p_T and lepton η

★ **Cross-section ratio** $R_c = \sigma(W^{+} + D^{-})/\sigma(W^{-} + D^{+})$

Analysis strategy

Reconstruct $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to (K^-\pi^+)\pi^+$ with a Second Vertex (SV) fit

↓

Control background by using the **charge correlation** between *c*-quark and *W*-boson, always opposite sign

↓

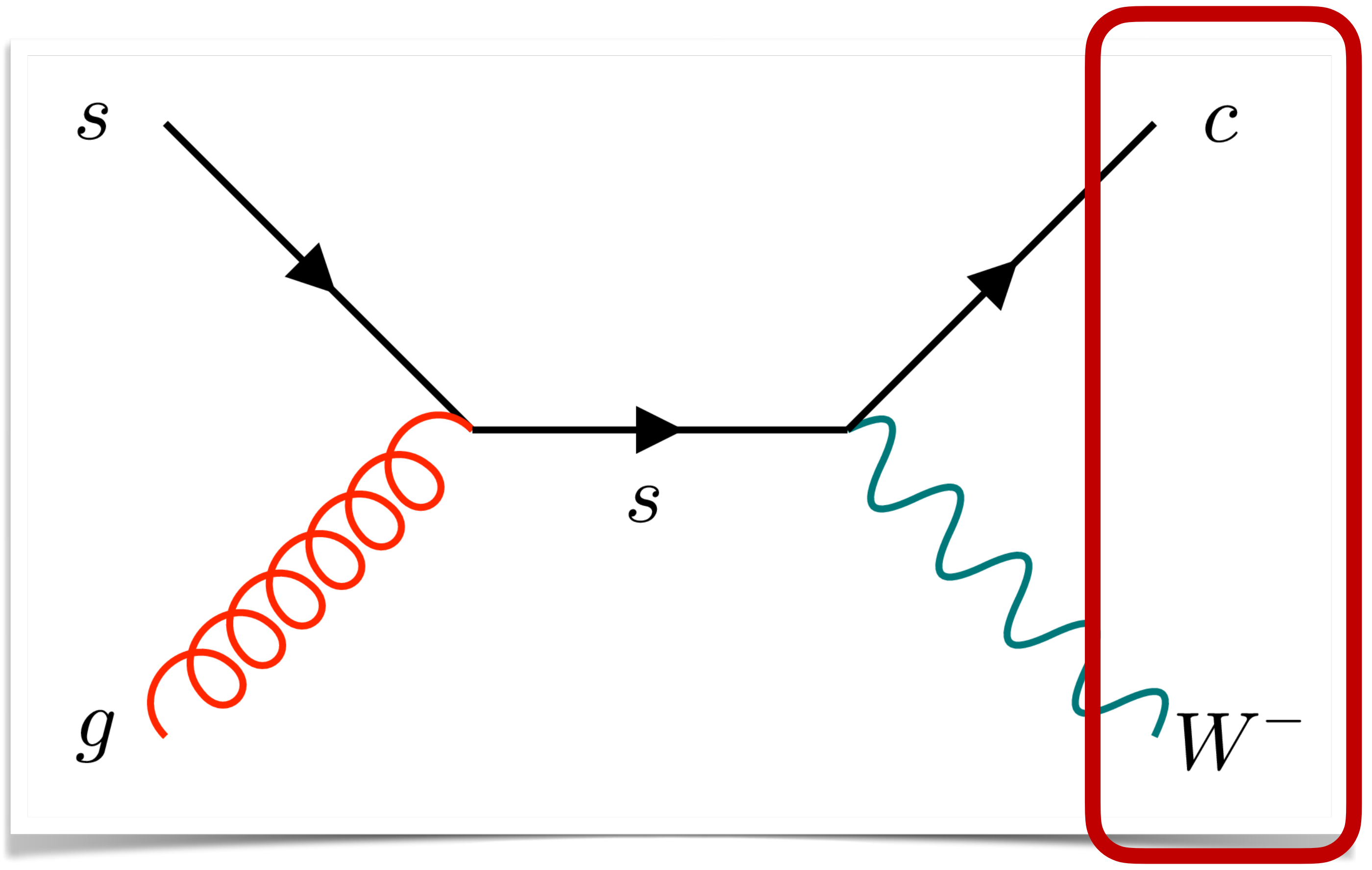
Differential cross sections from likelihood fits of invariant mass $m(D^+)$ or $m(D^{*+} - D^0)$ in several p_T(D) and |η(lep)| bins

↓

Systematics treated as nuisance parameters

↓

Cross-section measurements and comparison with several PDF sets

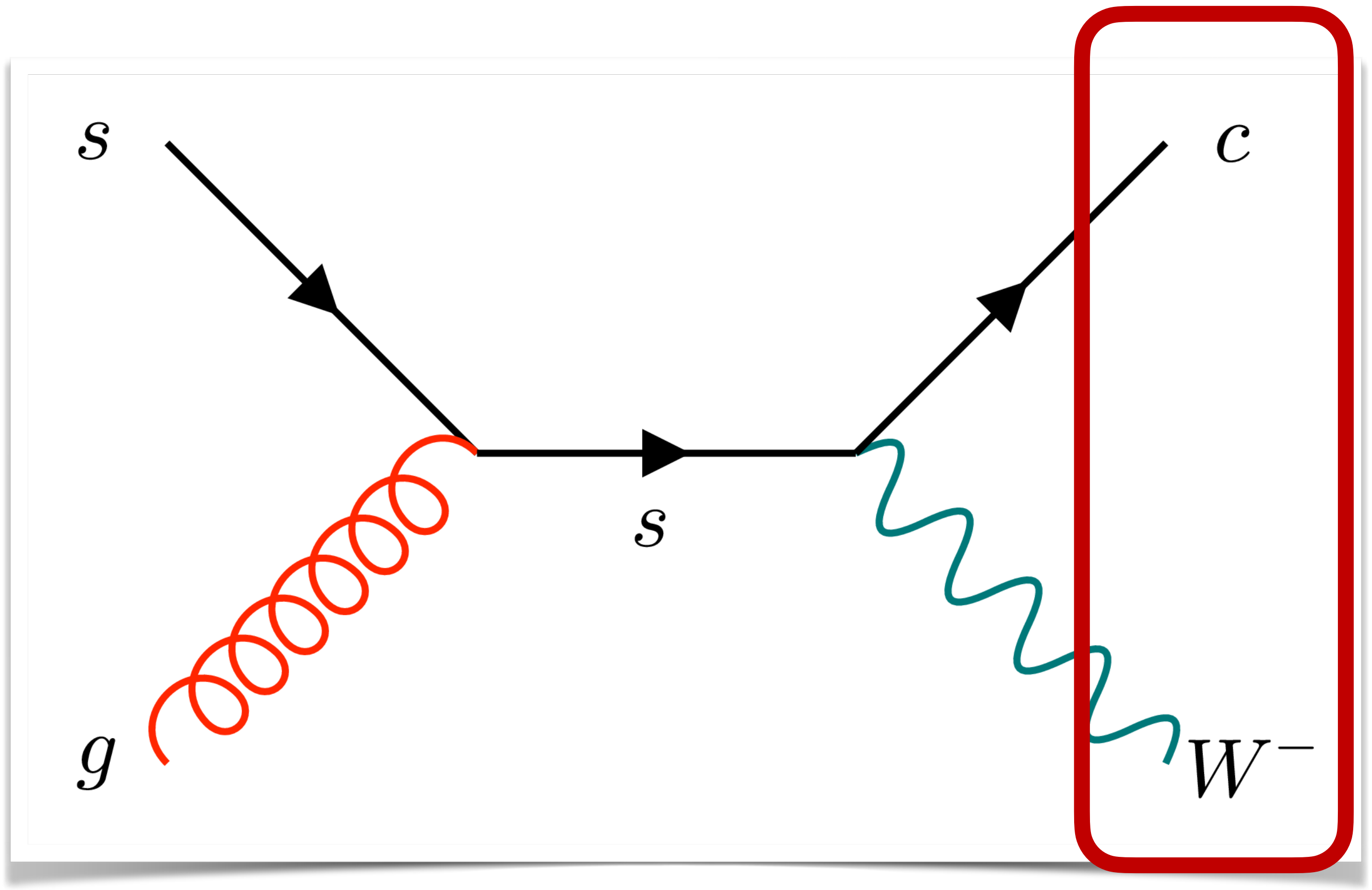


★ **Main challenges:**

➡ correctly reconstruct *D*-meson decays

➡ estimate background from mis-reconstructed D^+ and D^*, $t\bar{t}$ and multijet

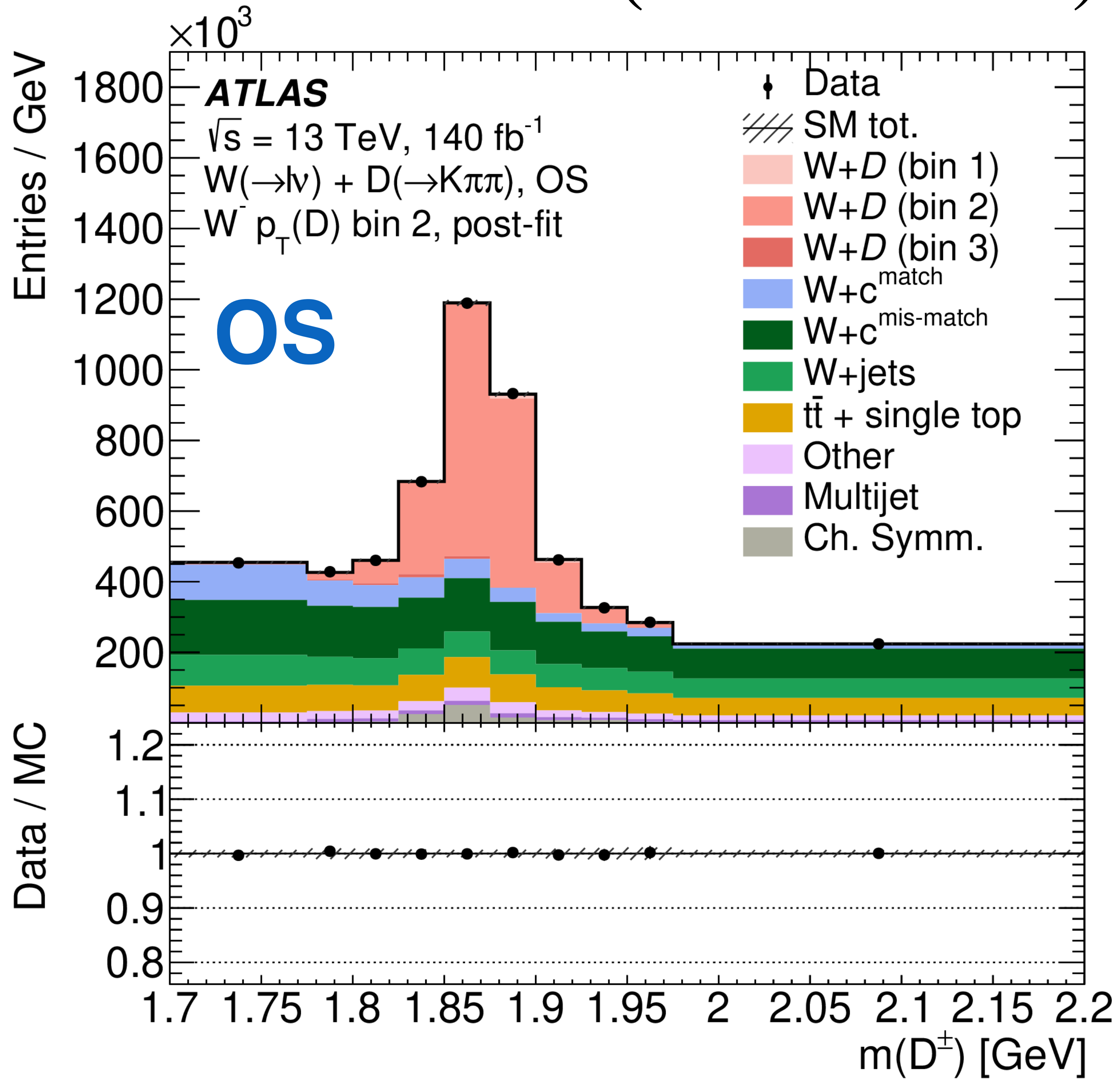
Analysis strategy



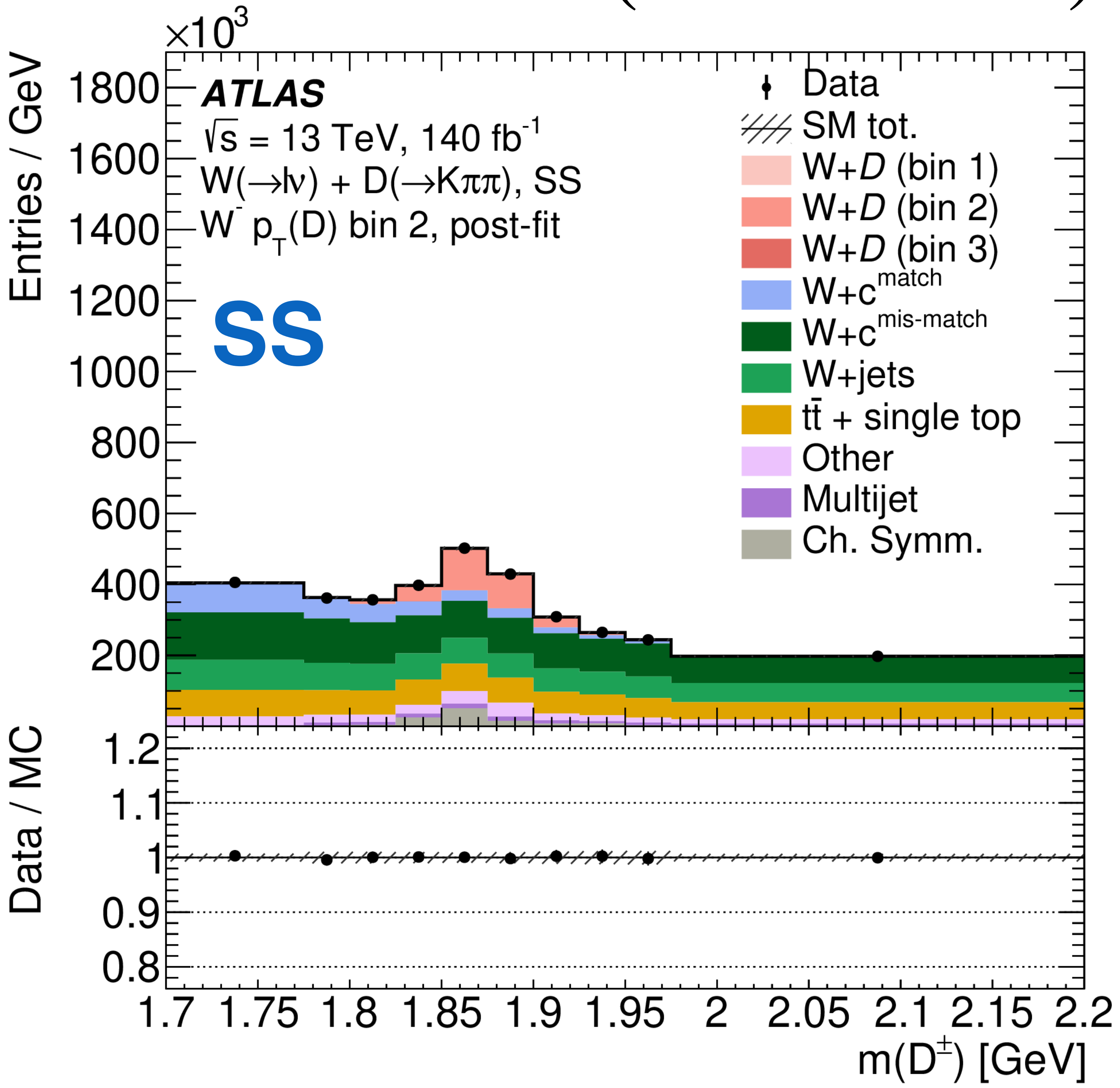
- **Signal signature with opposite-signed (OS) *W* and *D*-meson**
- Backgrounds are mostly charge-symmetric - same contribution of opposite-signed and same-signed (SS) W+D
  - Example: $W + c\bar{c}/b\bar{b}$ where the *D*-meson is not connected to the *s*-quark in the proton

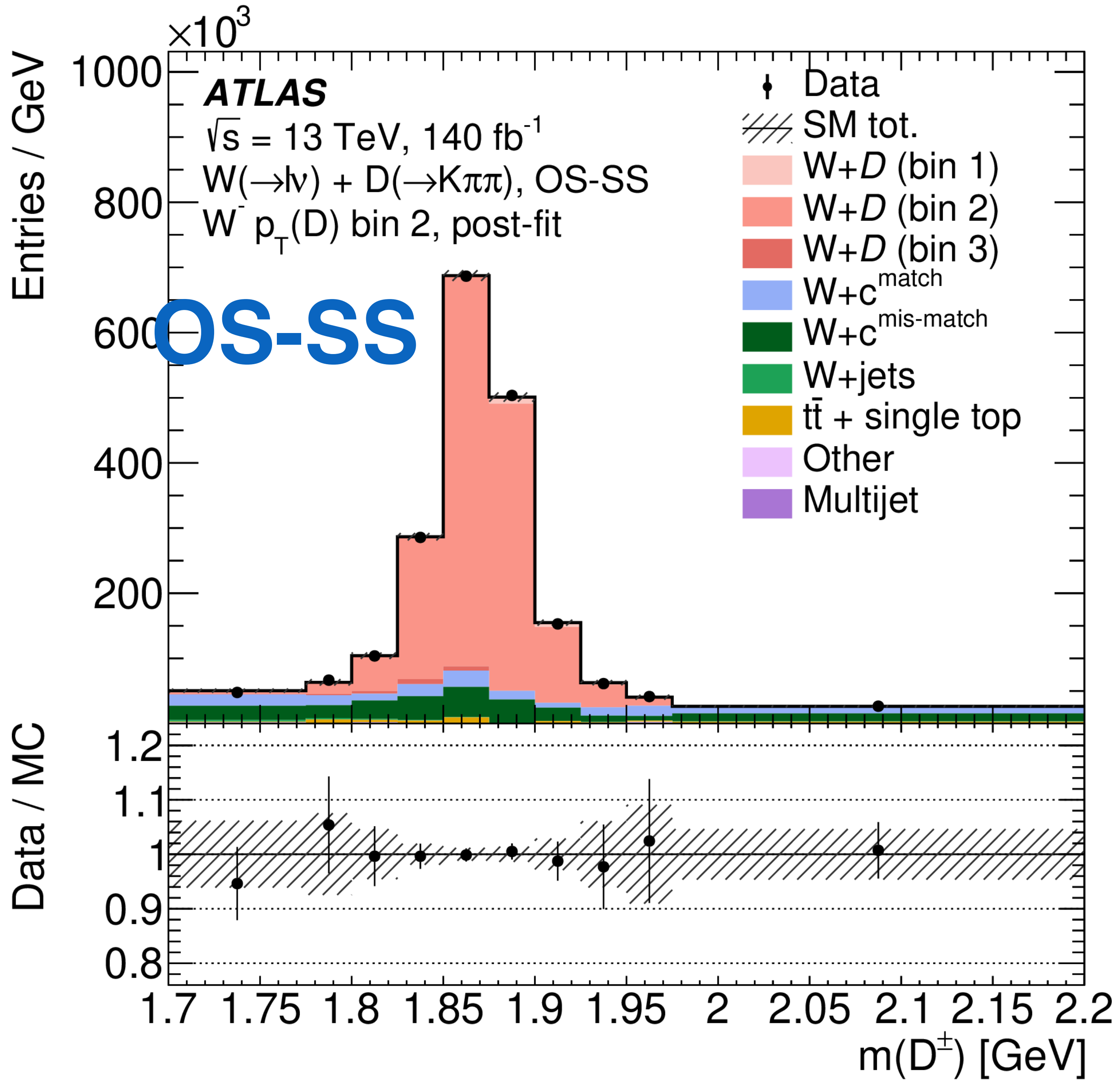
➡ ***Exploit OS-SS strategy to reduce the background contribution***

$W^- + D^+(\rightarrow K^-\pi^+\pi^+)$



$W^- + D^-(\rightarrow K^+\pi^-\pi^-)$





Dataset and event selection

✦ Dataset:

- full Run-2 data, L = 140 fb^{-1}
- Monte Carlo samples:
  - **NLO ME+PS** state-of-the art generators with high parton-multiplicity in ME (SHERPA 2.2.11 and MGAMC@NLO + PY8 with different setups)

✦ Event selection:

veto on *b*-jets to reduce $t\bar{t}$ background

Reconstruction of *W* decay
with E_T^{miss} and m_T cuts to reduce multijet background

Reconstruction of *D*-meson decay

Detector-level selection		
Requirement	W+$D^{(*)}$ SR	Top CR
$N(b\text{-jet})$	0	≥ 1
E_T^{miss}	> 30 GeV	
m_T	> 60 GeV	
Lepton p_T	> 30 GeV	
Lepton $\|\eta\|$	< 2.5	
$N(D^{(*)})$	≥ 1	
$D^{(*)}$ p_T	> 8 GeV and < 150 GeV	
$D^{(*)}$ $\|\eta\|$	< 2.2	

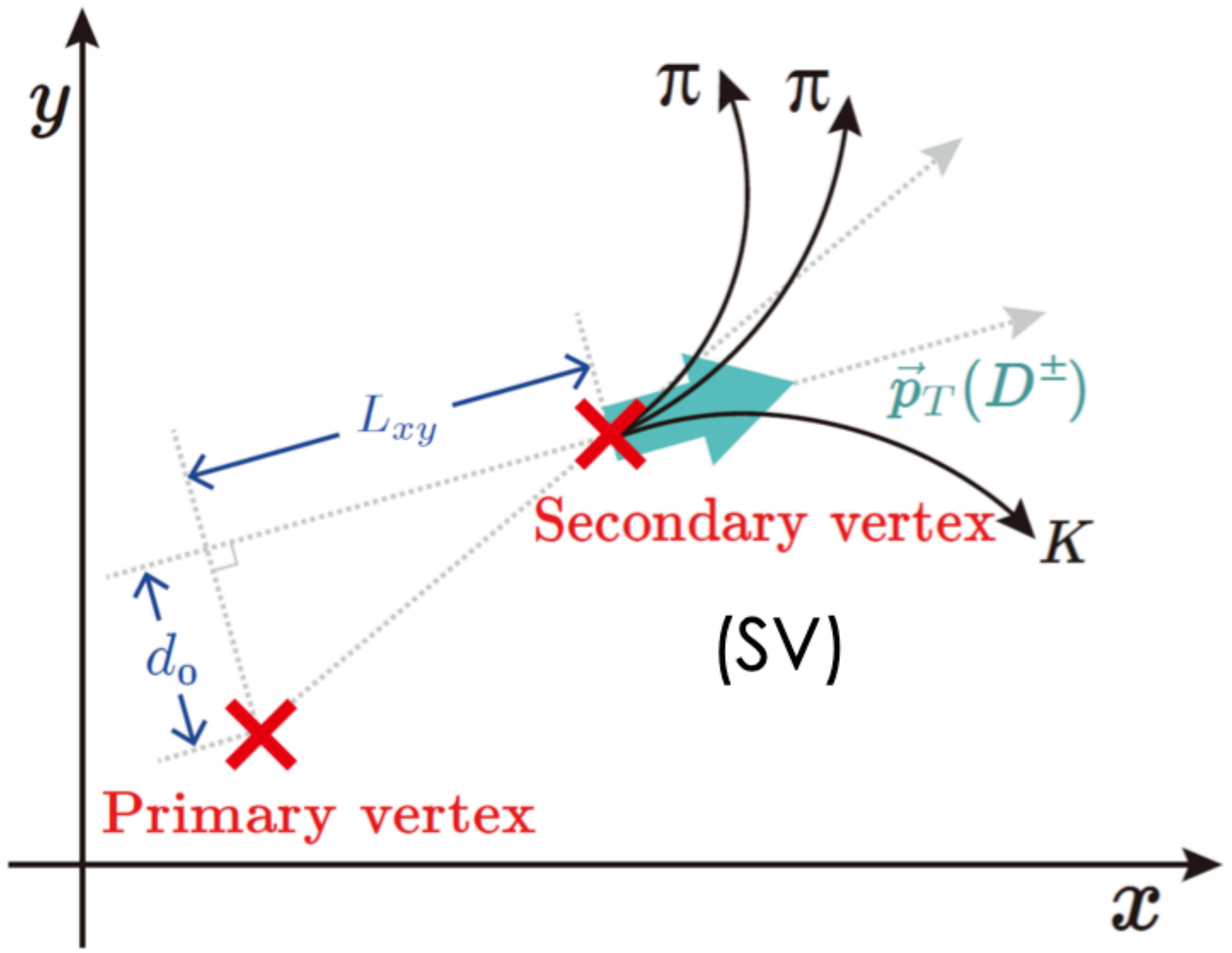
Exclusive D-meson decay reconstruction

- **Identify events with *c*-quarks by reconstructing the charmed-hadron decays**

$$D^+ \rightarrow K^-\pi^+\pi^+ \text{ and } D^{*+} \rightarrow (K^-\pi^+)\pi^+$$

- Tracks from the Inner Detector are used
  - **several SV-based requirements to distinguish signal from background**
    - Example: N_{tracks}, charge of tracks, flight-length L_{xy} , d_0, etc
- **Candidates K/π are assigned based on the charge of the track**
  - D^+: N_{tracks} = 3, 2 tracks with same charge assigned to π and the other to K
  - D^0: N_{tracks} = 2, matching with prompt π from D^{*+} decay
- **Tracks from the $\mathbf{D^+(D^0)}$ candidates are inputs to Kalman-Filter algorithm which fits tracks to SV**

D+ meson



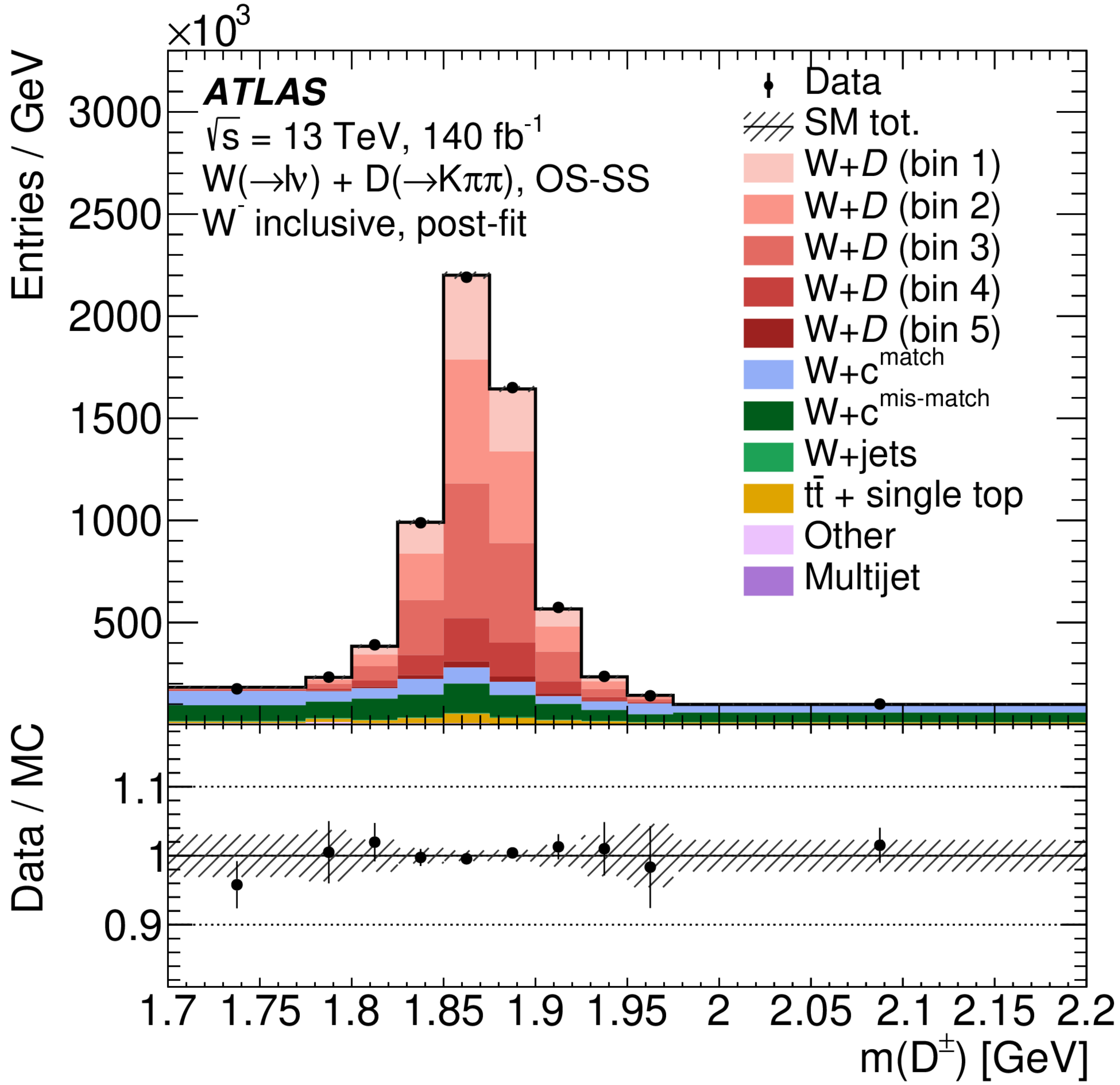
Signal and background modelling

✦ **MC samples are used to model signal and background mass templates** (except for multijet)

✦ <u>*W+D*(*)</u>:

MC truth information is used to categorise *W+D*(*) events according to the **origin of the tracks used to reconstruct D(*) decays** (track-based truth matching):

- ***W+D*(*) signal** = all tracks belong to a *D*-meson decaying $K^-\pi^+\pi^+$
- ***W+c* (match)** = tracks belong to different decays modes of *D-meson* or to different charmed-hadrons ($D_s^+ \to K^+K^-\pi^+$ or $D^+ \to K^+K^-\pi^+$)
- ***W+c* (mis-match)** = not all tracks truth-matched to a *D*-meson
- ***W+jets***: no tracks are matched to a truth *D*-meson



✦ <u>Additional background from:</u>

✦ Top ($t\bar{t}$, single-top and $t\bar{t}X$) constrained in control region (CR) with ≥ 1 b-jet

✦ Other: diboson, Z+jets

✦ Multijet determined from data in enriched CR

Likelihood fit unfolding

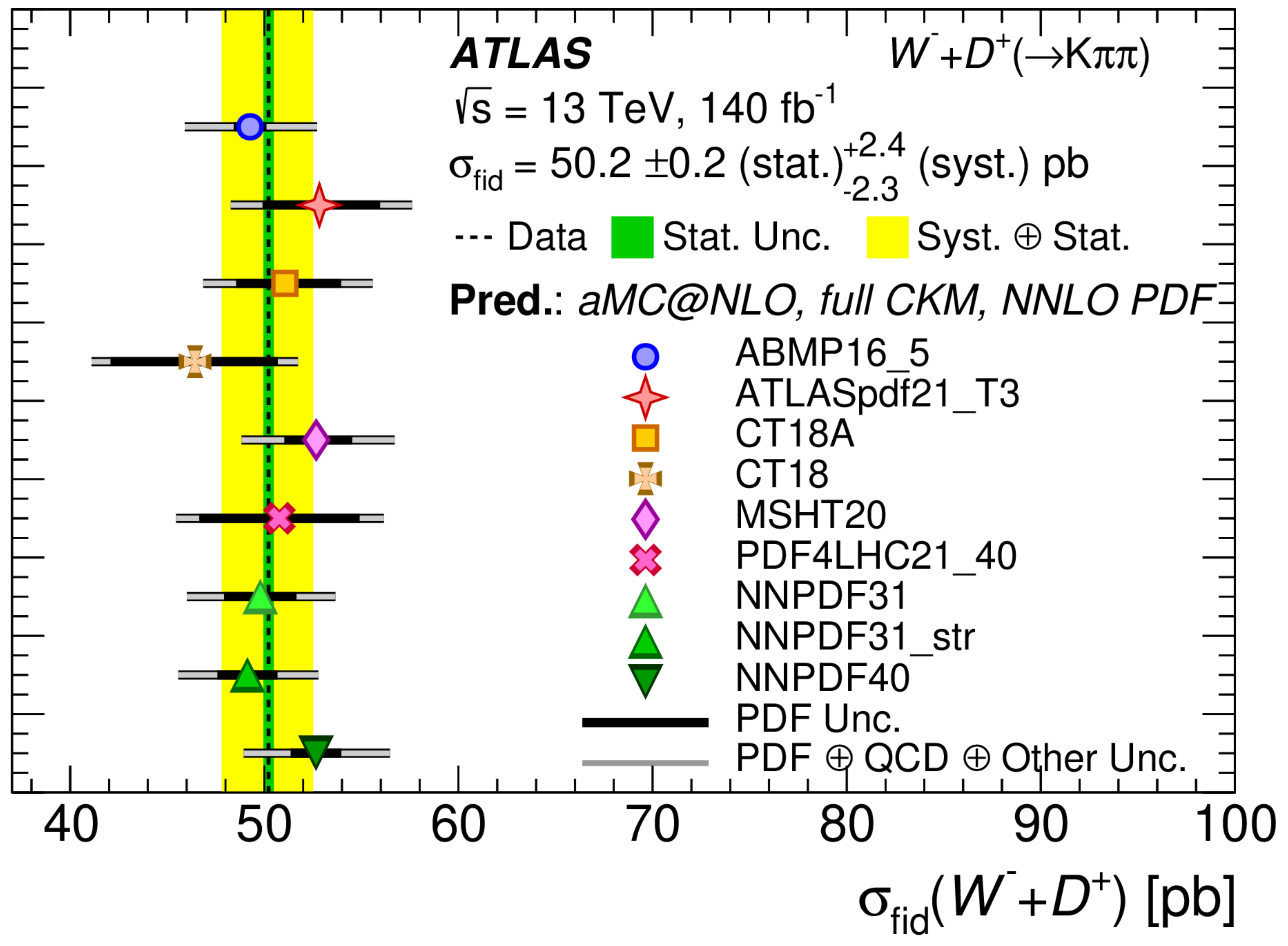
- **Cross sections are extracted with likelihood fits at particle level**
- **Differential cross-sections are measured in $p_T(D)$ and |η(lep)| bins**
  - OS and SS regions fitted simultaneously
  - To measure R_c, W^+ and W^- regions fitted at the same time
    → **10 Parameters of Interest (POIs) in the fit**
- Systematics implemented as Nuisance Parameters (NPs) in the likelihood fit

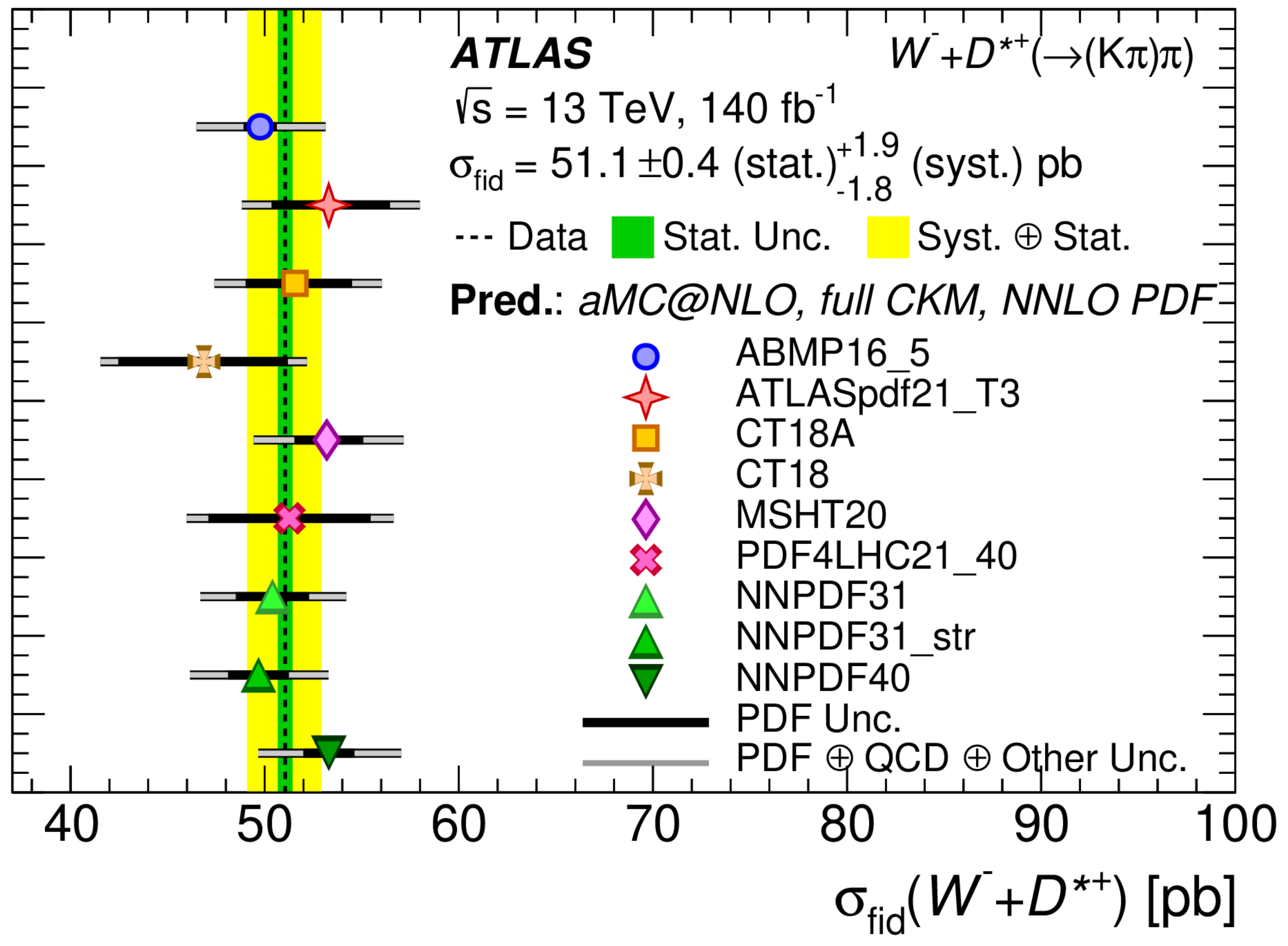
	D^+ channel			D^{*+} channel		
Uncertainty [%]	$\sigma^{\text{OS-SS}}_{\text{fid}}(W^-+D^+)$	$\sigma^{\text{OS-SS}}_{\text{fid}}(W^++D^-)$	$R_c^{\pm}(D^+)$	$\sigma^{\text{OS-SS}}_{\text{fid}}(W^-+D^{*+})$	$\sigma^{\text{OS-SS}}_{\text{fid}}(W^++D^{*-})$	$R_c^{\pm}(D^{*+})$
SV reconstruction	3.0	2.9	0.5	2.3	2.3	0.4
Jets and E_T^{miss}	1.7	1.9	0.2	1.5	1.5	0.4
Luminosity	0.8	0.8	0.0	0.8	0.8	0.0
Muon reconstruction	0.6	0.7	0.3	0.7	0.7	0.3
Electron reconstruction	0.2	0.2	0.0	0.2	0.2	0.0
Multijet background	0.2	0.2	0.1	0.1	0.1	0.1
Signal modeling	2.1	2.1	0.1	1.2	1.2	0.0
Signal branching ratio	1.6	1.6	0.0	1.1	1.1	0.0
Background modeling	1.1	1.2	0.3	1.3	1.3	0.5
Finite size of MC samples	1.2	1.2	1.1	1.4	1.4	1.3
Data statistical uncertainty	0.5	0.5	0.7	0.7	0.7	1.0
Total	4.6	4.6	1.4	3.7	3.7	1.7

- Precision on **inclusive cross section ~5%**
- **Precision on R_c ~1%** for cancellation of correlated systematics in W^+ and W^-

Inclusive cross-section results

- Results in good agreement with predictions from different PDF sets
- **Experimental precision** (~5% syst-dominated) is comparable to the PDF uncertainties (*black*) and **smaller than total theoretical uncertainty** (*grey*)
- High-precision measurements can constrain theoretical predictions

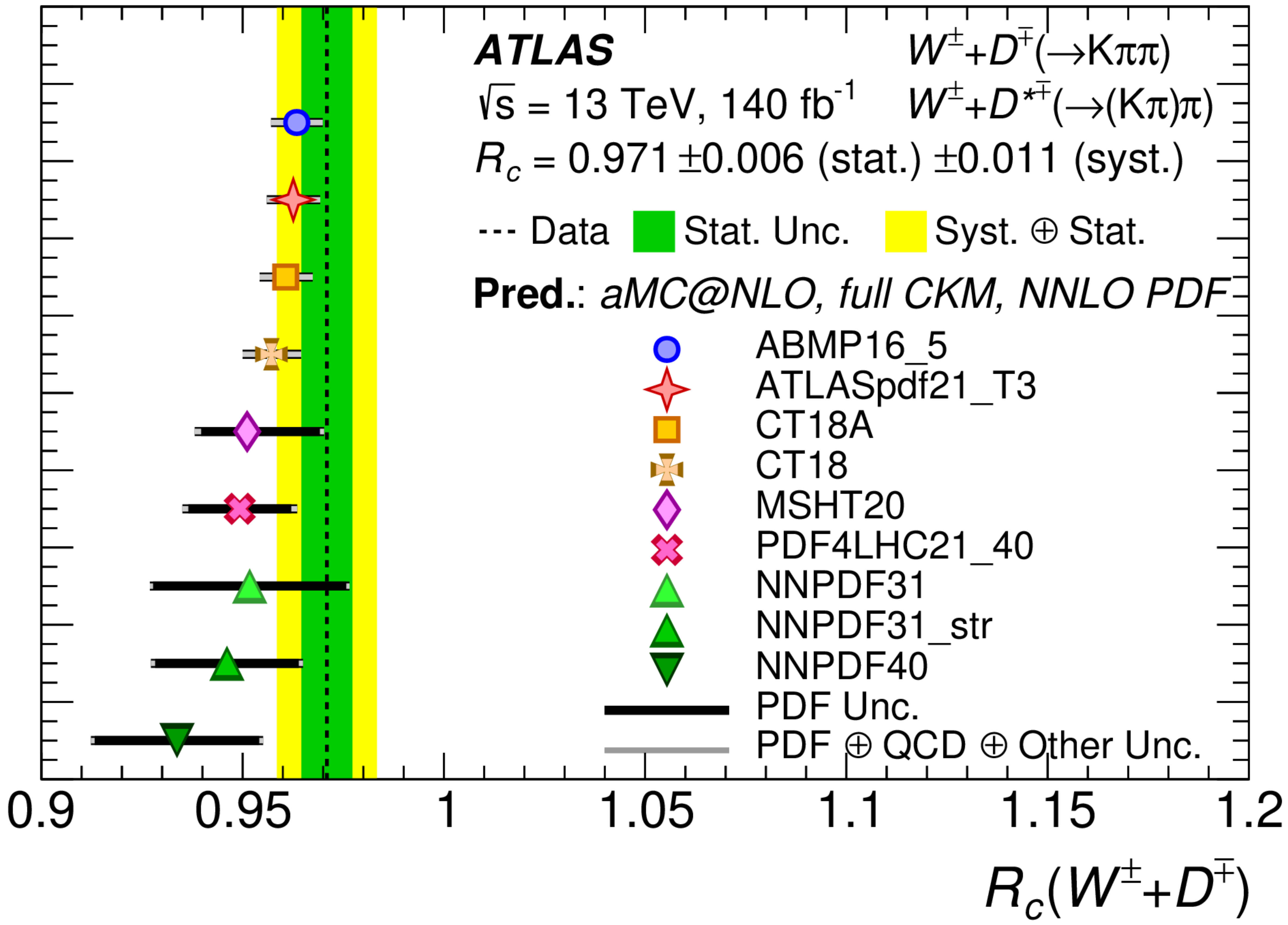




Cross-section ratio results

- **R_c with experimental precision ~1%**, comparable contribution from statistical and systematic uncertainties
- PDFs imposing symmetric strange-sea ($s = \bar{s}$) have smaller uncertainties: i.e. CT18, AMBP16 and ATLASpdf21_T3
- predictions with $s - \bar{s}$ asymmetry at the initial scale largely dominated by PDF uncertainty
  - ➡ $s - \bar{s}$ asymmetry small in the Bjorken-x region probed by this measurement

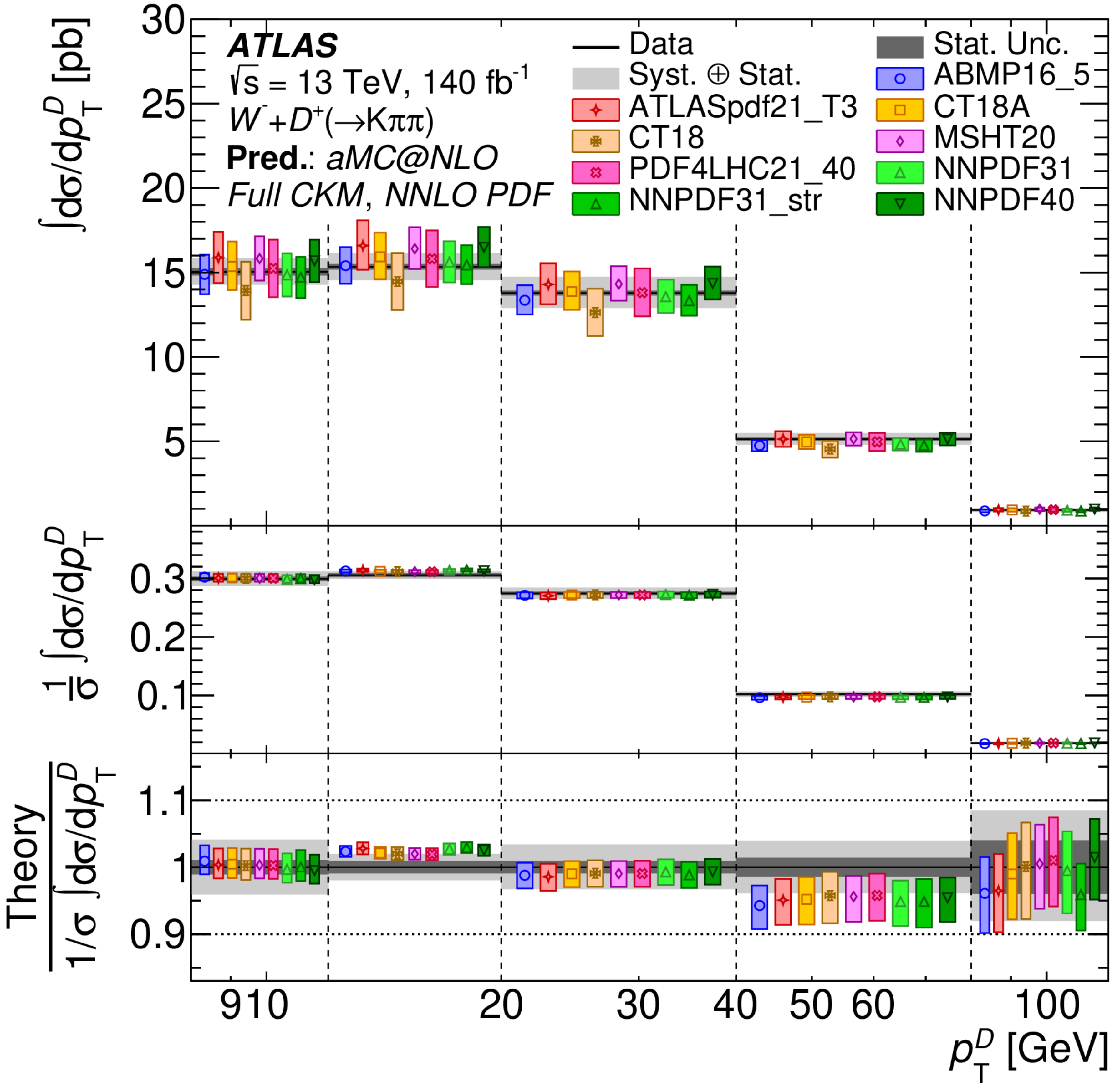
$$R_c = \sigma(W^+ + D^-)/\sigma(W^- + D^+)$$



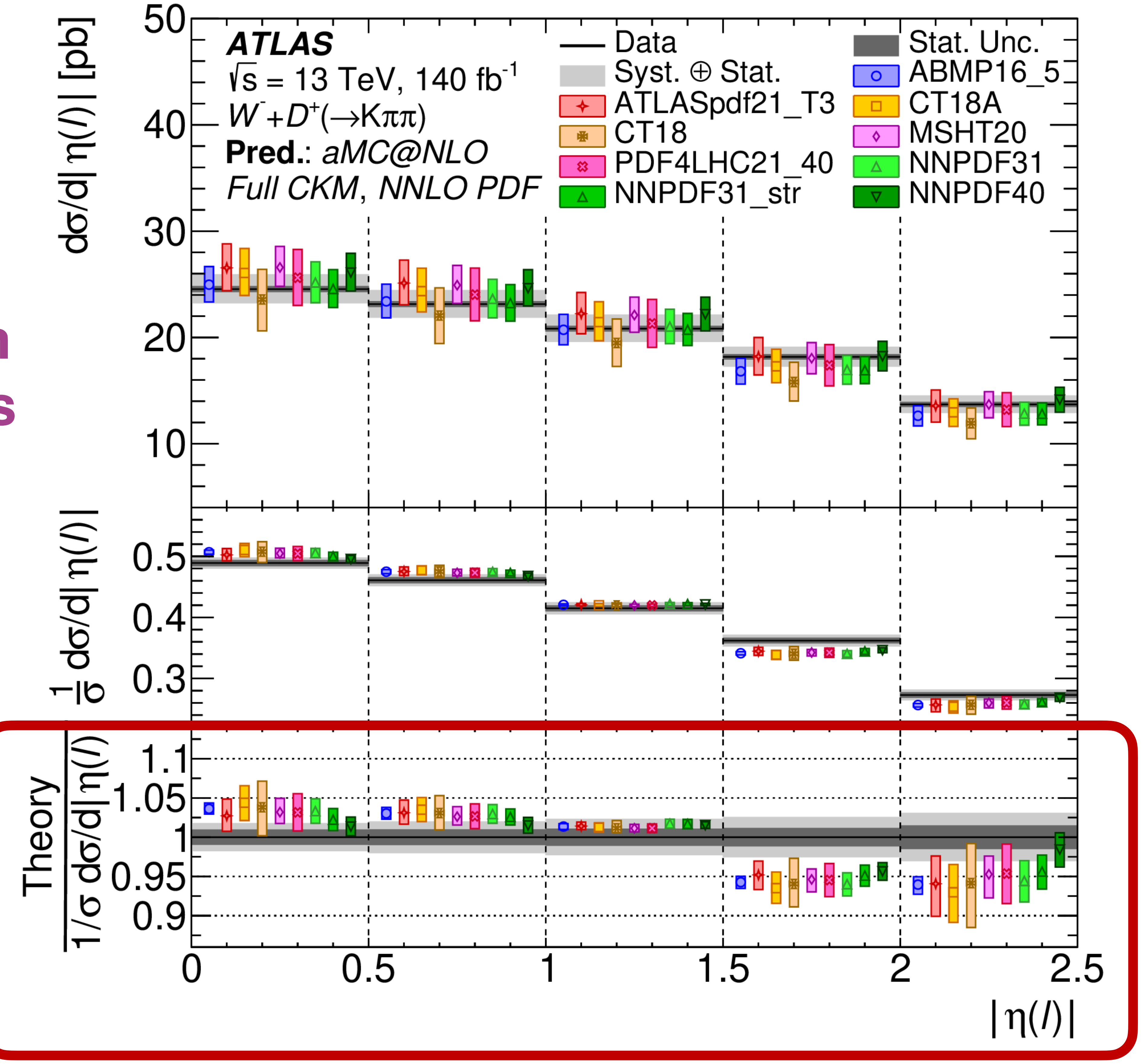
➡ **Uncertainty on R_c smaller than PDF uncertainties without $s = \bar{s}$ asymmetry**

Differential cross-section results

- All predictions have similar **p_T(D)** shape, **not sensitive to PDFs**
- **|η(lep)|** has smaller systematics and **good sensitivity to PDF variations**
- broader |η(lep)| in data than predictions - **discrepancy covered by PDF uncertainties**
  → **measurements provide useful constraints for global PDF fits**



MGAMC+PY8 with different PDF sets



Comparison with several PDF sets

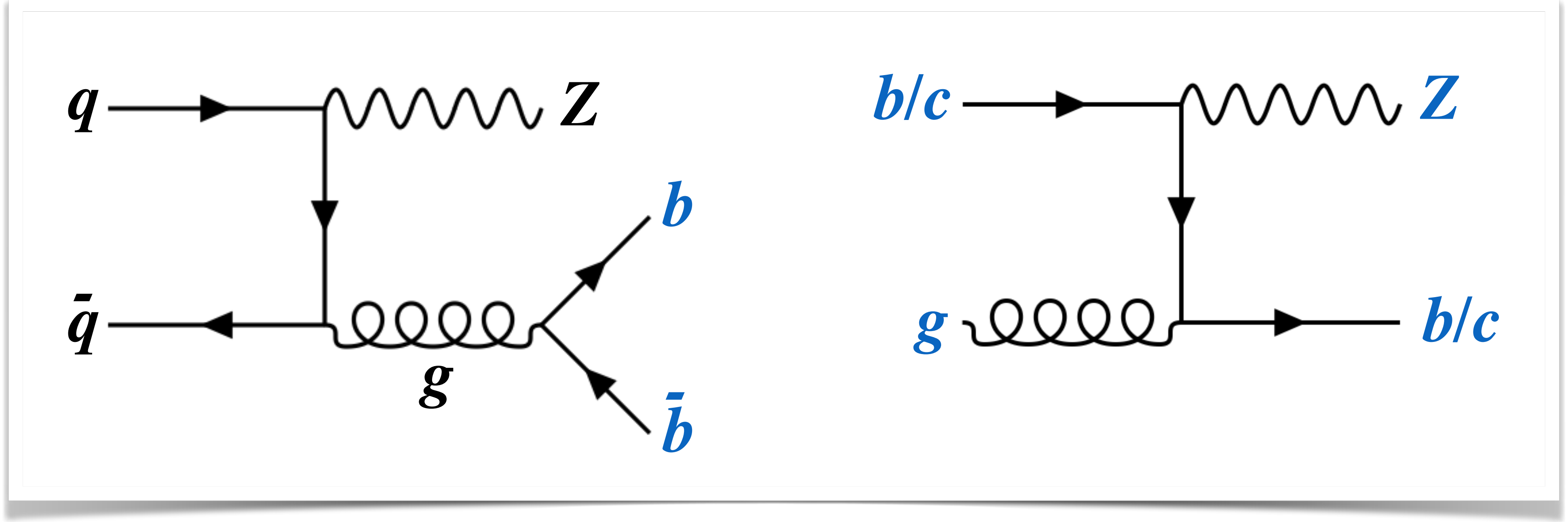
- The compatibility between measurements and predictions is tested with a χ^2 test
- **Adding the PDF uncertainty largely increase the p-value**
  - PDF uncertainty has significant impact on the shape of |η(lep)| differential measurements
  - **This measurement can provide useful constraints on PDF uncertainties in a global PDF fit**

Channel	D^+ $\|\eta(\ell)\|$			
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

Z + HF jets

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

arXiv:2403.15093
Submitted to EPJC

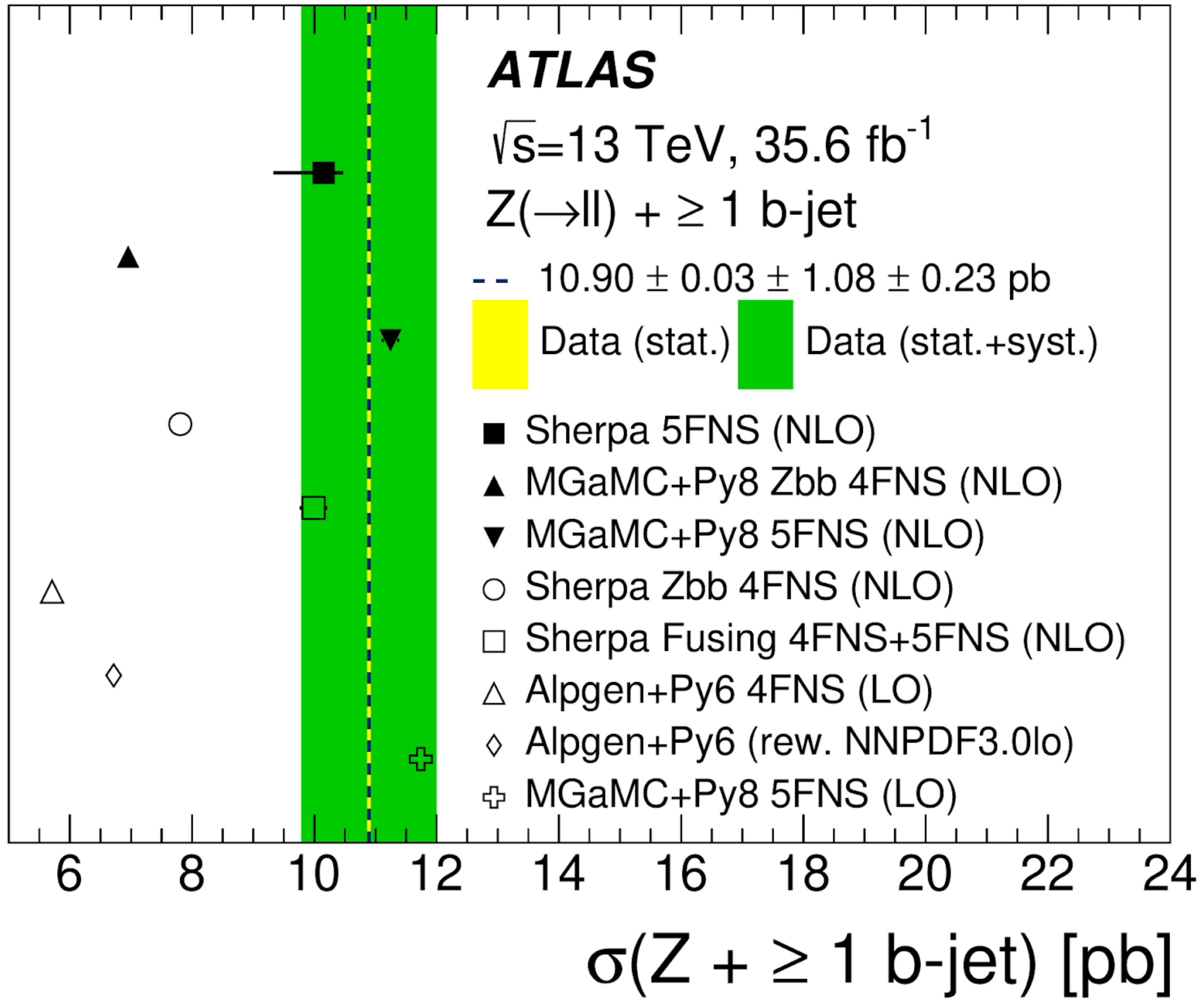


Inclusive and differential cross-sections of *Z*+≥1 *b*-jet, *Z*+≥2 *b*-jets and *Z*+≥1 *c*-jet

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

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

JHEP 07 (2020) 044



➡ Test effect of missing higher-order terms in QCD
➡ Investigate different Flavour-Schemes in predictions
➡ Explore possible sensitivity to *Intrinsic-Charm*

Analysis strategy

Event selection:
select **Z(→μμ,ee)+ flavour-tagged jets candidates**

↓

Background estimation:
- data-driven $t\bar{t}$ in dedicated CR
- *Z*+jets from fit to data ("***flavour-fit***")
- other minor backgrounds from MC samples

↓

From detector to **particle level**:
correction for resolution and efficiency effects with Bayesian unfolding

↓

Cross-section measurements

↓

Comparison with theoretical predictions

★**Main challenge:**
correctly reconstruct the flavour of the jet

➡ dedicated categorisation of the events at both reconstructed and particle level

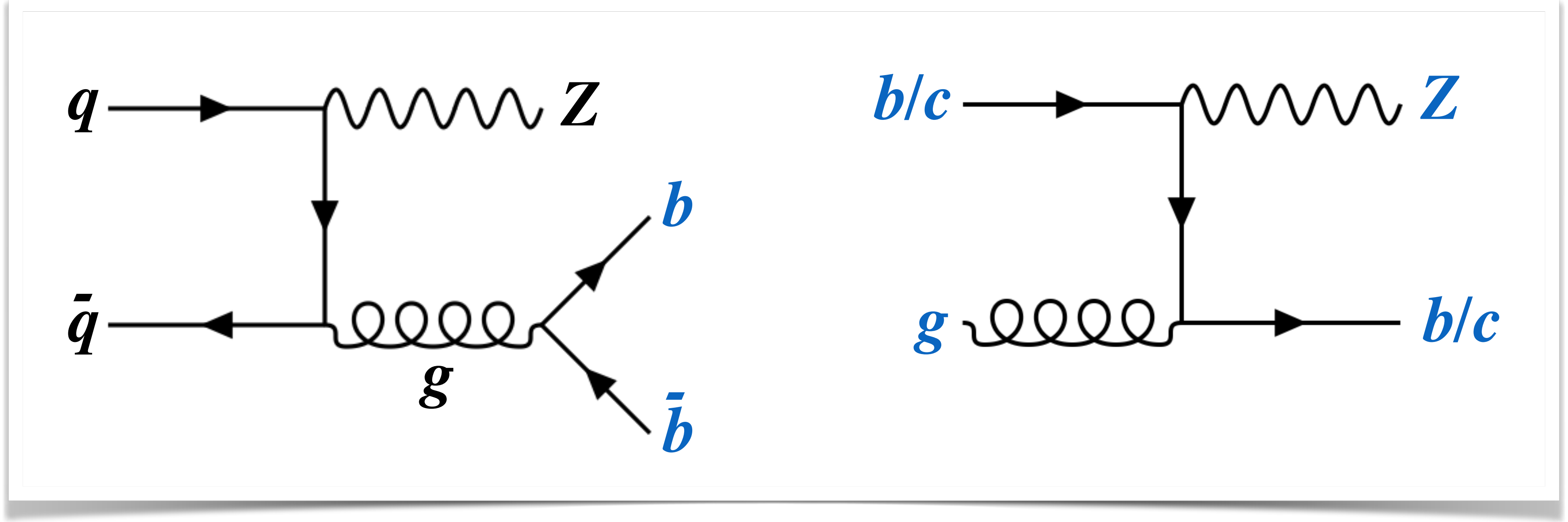
➡ fit to data ("flavour fit") to correct shape and normalisation of measured observables

Dataset and event selection

✦ Dataset:

- full Run-2 data, L = 140 fb^{-1}
- Monte Carlo samples:
  - **NLO ME+PS** state-of-the art generators with high parton-multiplicity in ME (MGAMC@NLO + PY8 with FXFX merging and SHERPA 2.2.11)

✦ Event selection:



2 good leptons: e^+e^- $\mu^+\mu^-$ with p_T>27 GeV, |η|<2.5
76 GeV < m_{ll} < 106 GeV

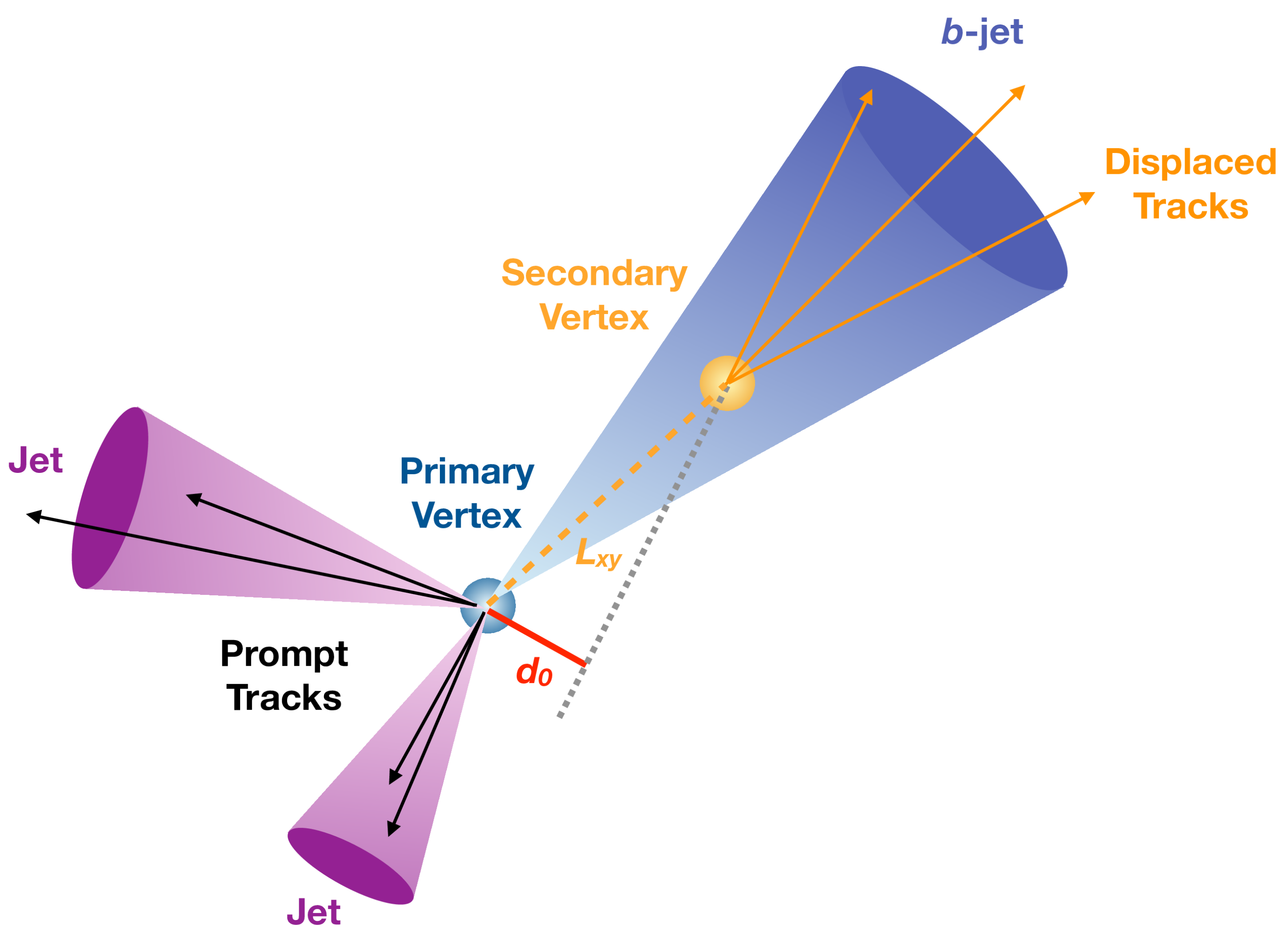
≥ 1 good jet with p_T>20 GeV, |y|<2.5
flavour-tagging DL1r @ 85%

Define 2 Signal Regions (SR) based on the number of flavour-tagged jets:

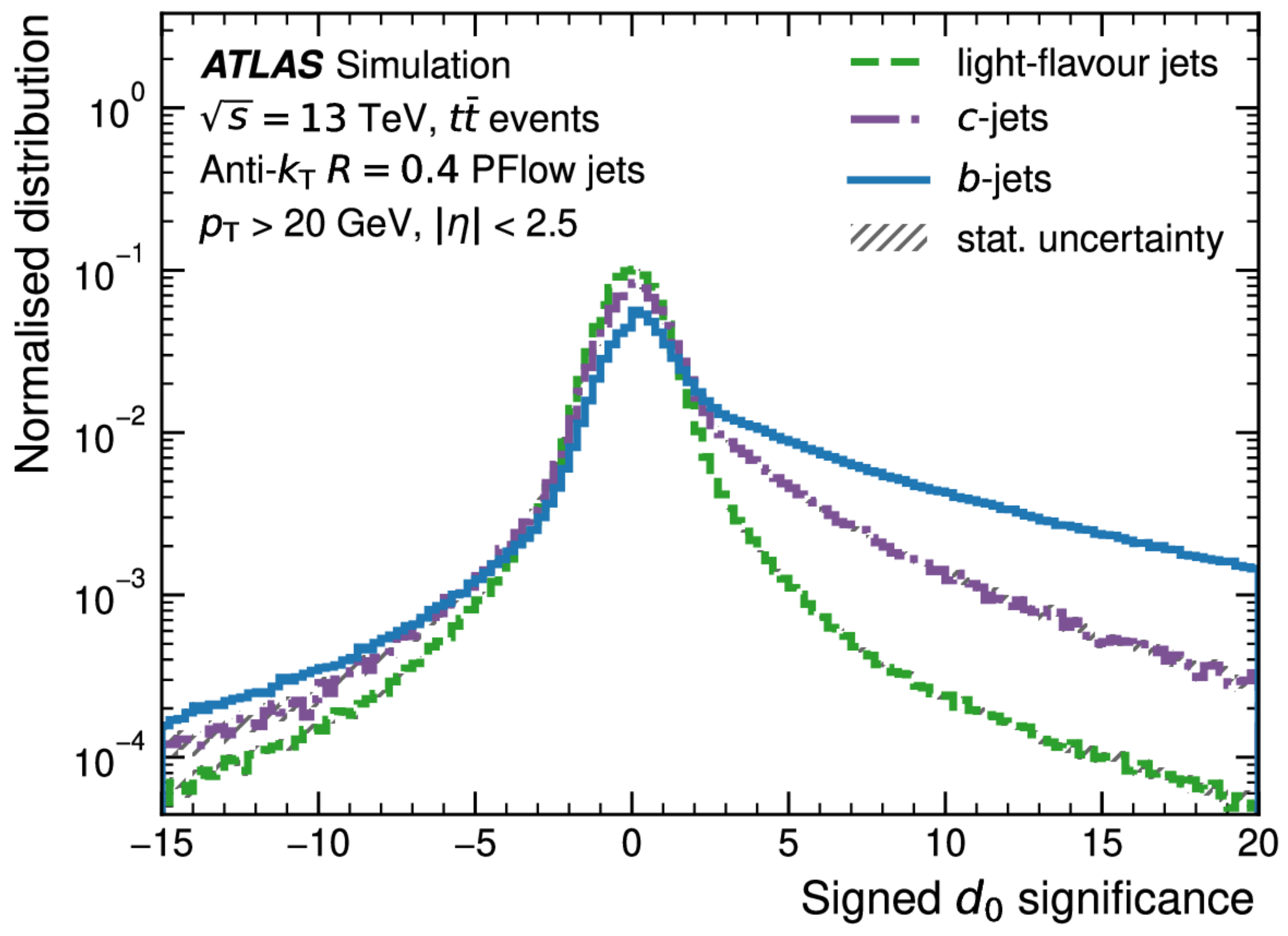
1-tag: Z+≥1 b-jet and Z+≥1 c-jet measurements

2-tag: Z+≥2 b-jets measurement

Inclusive flavour-tagging



Eur. Phys. J. C 83 (2023) 681



- Flavour of the jets determined with DL1r @ 85% algorithm

DL1r:

- high level algorithm operating on outputs from intermediate track and vertex algorithms
  - **based on *b*-hadron decay signature:** displaced tracks, secondary vertex, high-track multiplicity, longitudinal impact parameter, semi-leptonic decays

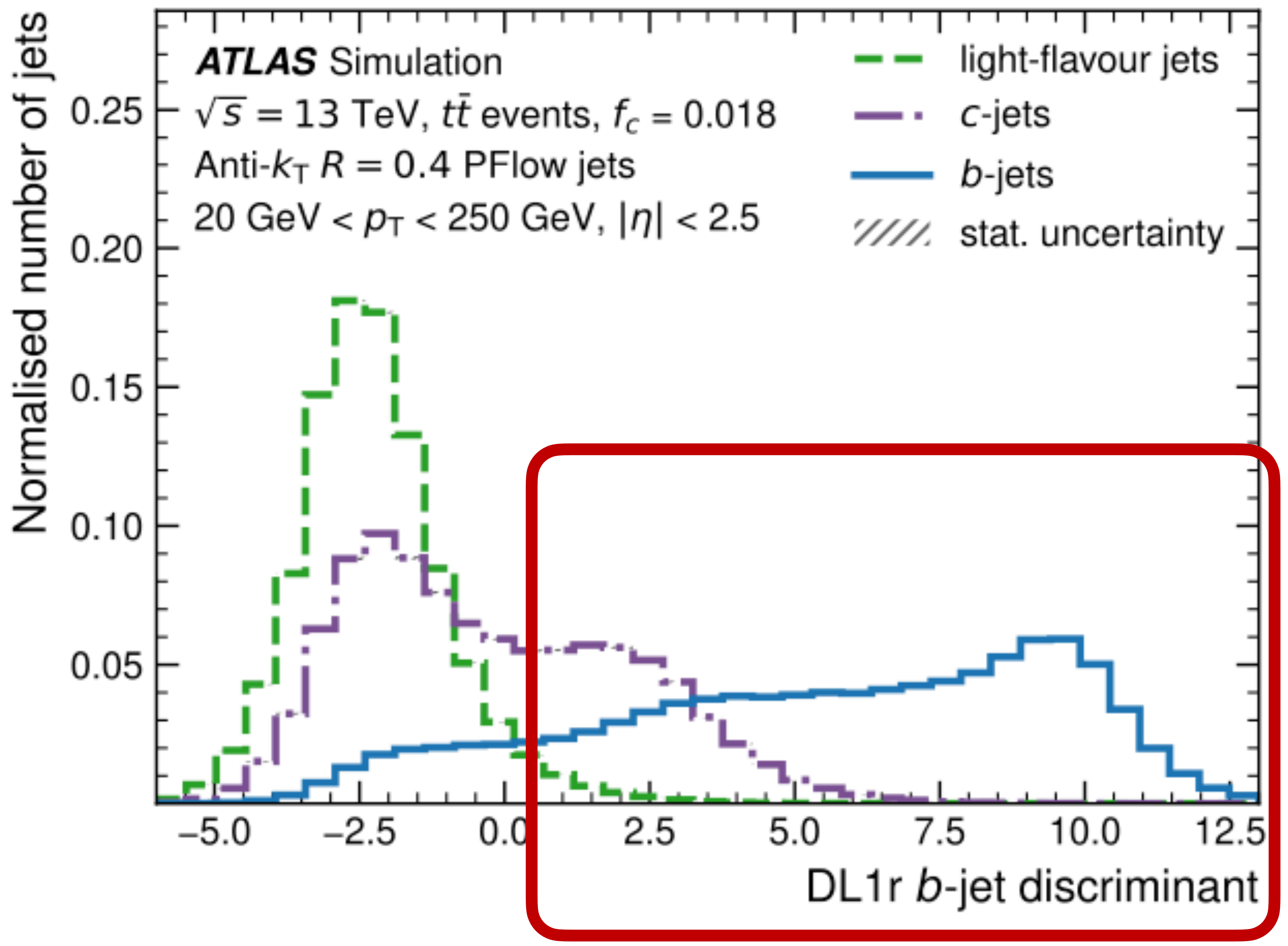
$$D_{\text{DL1r}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c \cdot p_{light})}\right)$$

- DL1r discriminant calculated from p_b, p_c and p_{light} which are the *b*-, *c*- and light-jet probabilities

Inclusive flavour-tagging

- Different selections (working-points WP) are provided based on DL1r values:
  - 60%, 70%, 77% and 85% efficiency WPs
  - 5 exclusive bins, with **calibrated b-tagging** and **c/light-jet mis-tagging efficiency**

Eur. Phys. J. C 83 (2023) 681



Eur. Phys. J. C 79 (2019) 970

ϵ_b	DL1			
	Selection	Rejection		
		c-jet	τ-jet	Light-flavour jet
60%	> 2.74	27	220	1300
70%	> 2.02	9.4	43	390
77%	> 1.45	4.9	14	130
85%	> 0.46	2.6	3.9	29

DL1r @ 85% WP retains **85% b-jets** and (1/2.6=) **38% c-jets**

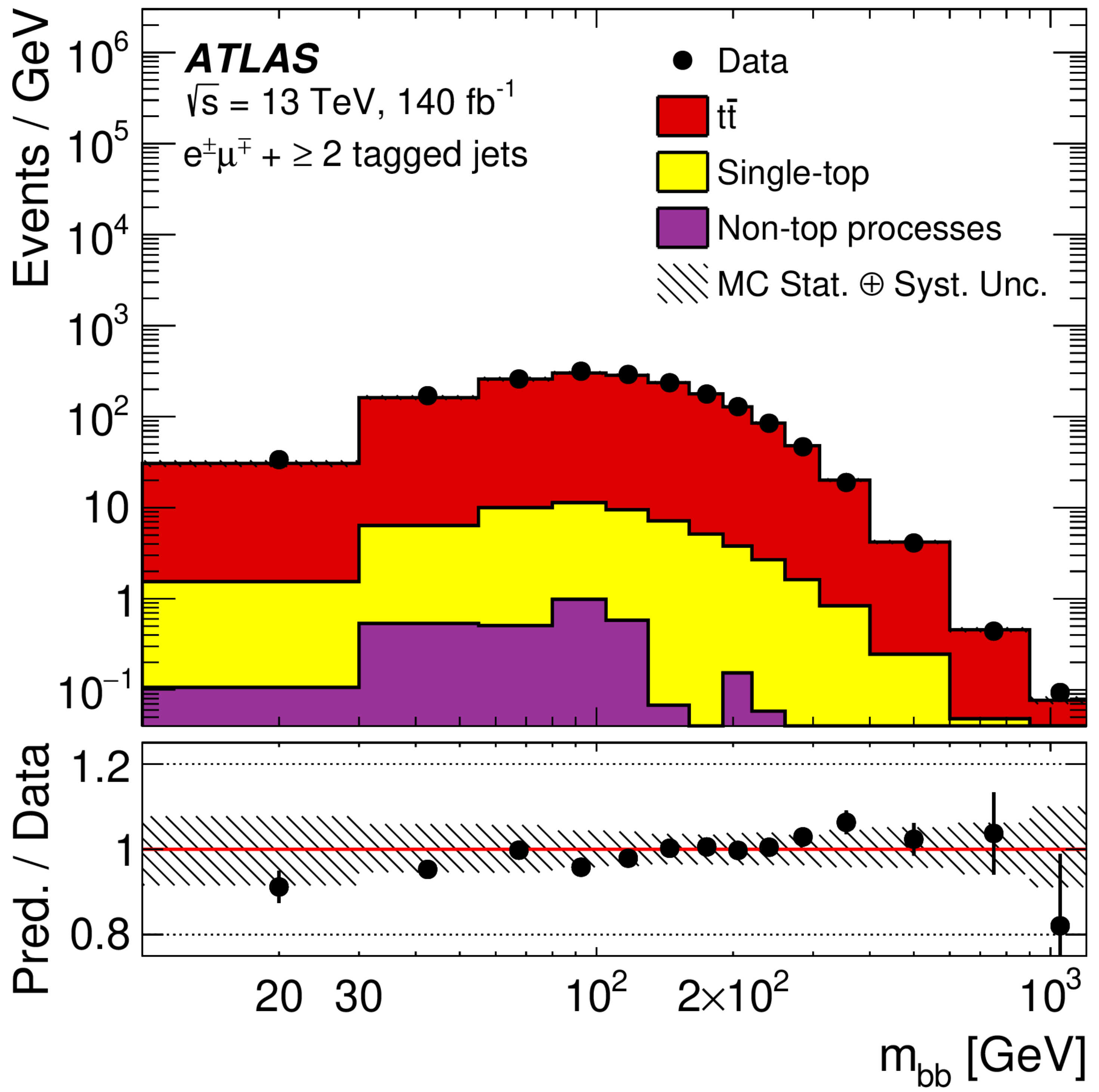
Data-driven $t\bar{t}$ background

- Dileptonic $t\bar{t}$ events represent the second largest background
- Using **data-driven technique** to avoid large modelling uncertainties (up to ~70% at high Z p_T)

Method of the Transfer Factors

- **opposite flavour $e\mu$ CR** enhanced with $t\bar{t}$ events (>90%)
- $t\bar{t}$ template **ttbar^{CR}_{Data}**: by **subtracting from data** all MC **in CR**
- $t\bar{t}$ **normalisation in SR**: by multiplying for **Transfer Factors (TFs)** obtained from MC

$$t\bar{t}^{SR} = t\bar{t}^{CR}_{Data} \cdot TR^{CR\to SR}$$



$$TF^{CR\to SR} = \frac{t\bar{t}^{SR\,(ee/\mu\mu)}_{MC}}{t\bar{t}^{CR\,(e\mu)}_{MC}}$$

- Systematics:
  - Strong reduction of detector-level systematics propagated through TFs
  - CR→SR extrapolation uncertainty

Z+jets background and flavour fit

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

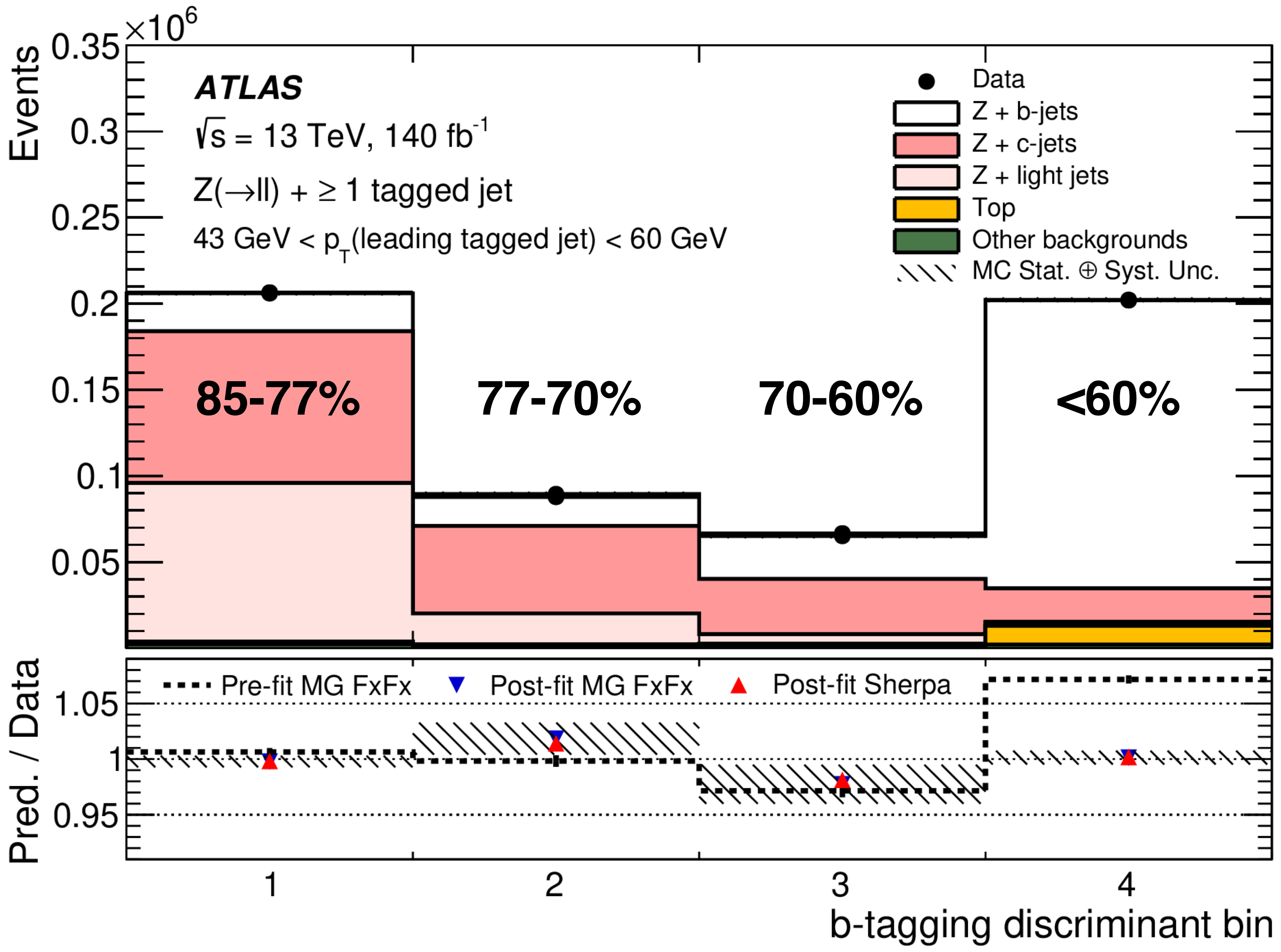
	1-tag SR		**2-tag SR**
Analysis	*Z*+≥1 *b*-jet	*Z*+≥1 *c*-jet	*Z*+≥2 *b*-jets
Z+jets bkg	*Z*+*c*, *Z*+l	*Z*+*b*, *Z*+l	*Z*+1*b*, *Z*+*c*, *Z*+l

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

Maximum-likelihood fit to data based on flavour sensitive distribution

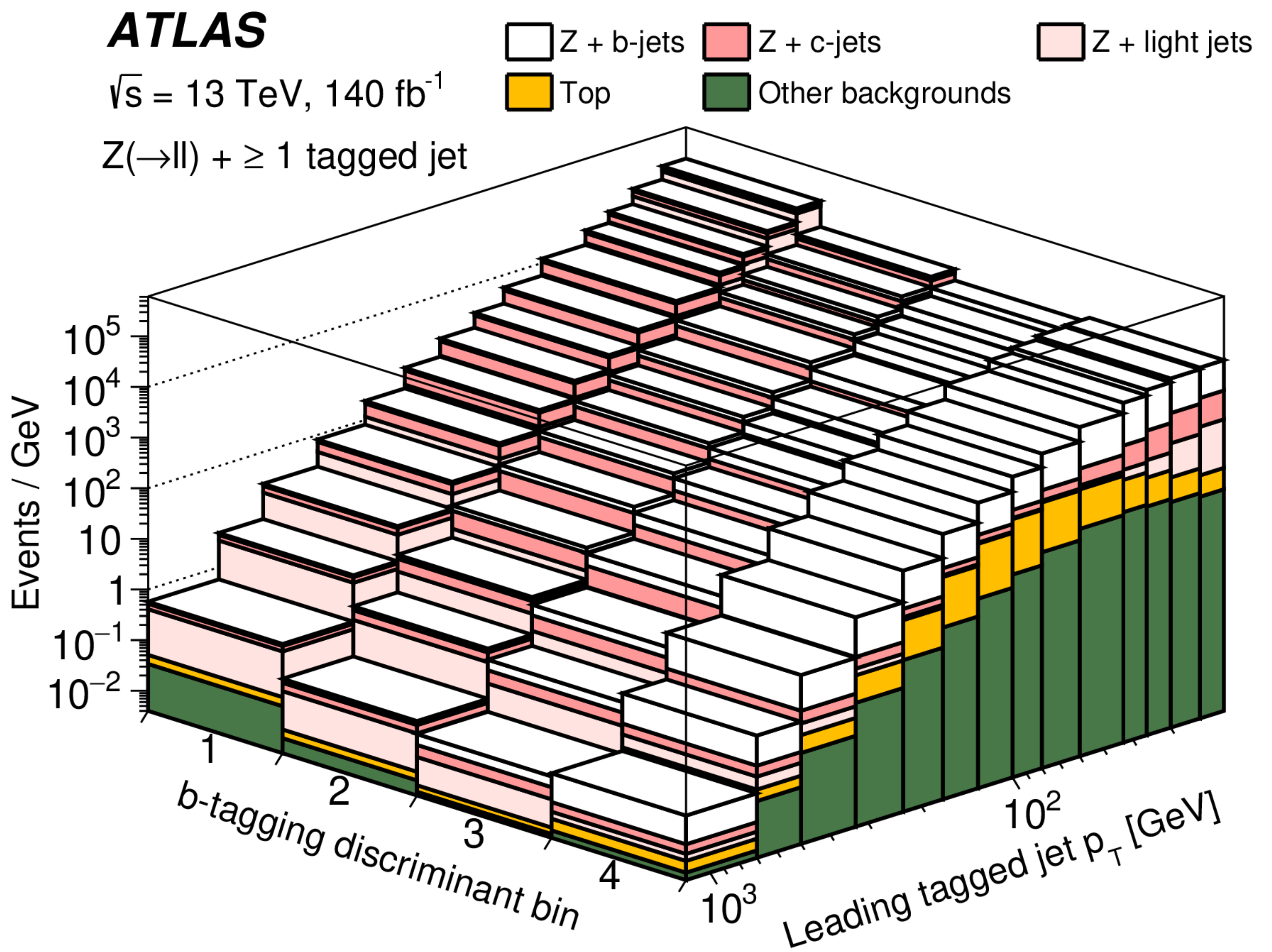
Example for 1-tag SR:

- 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

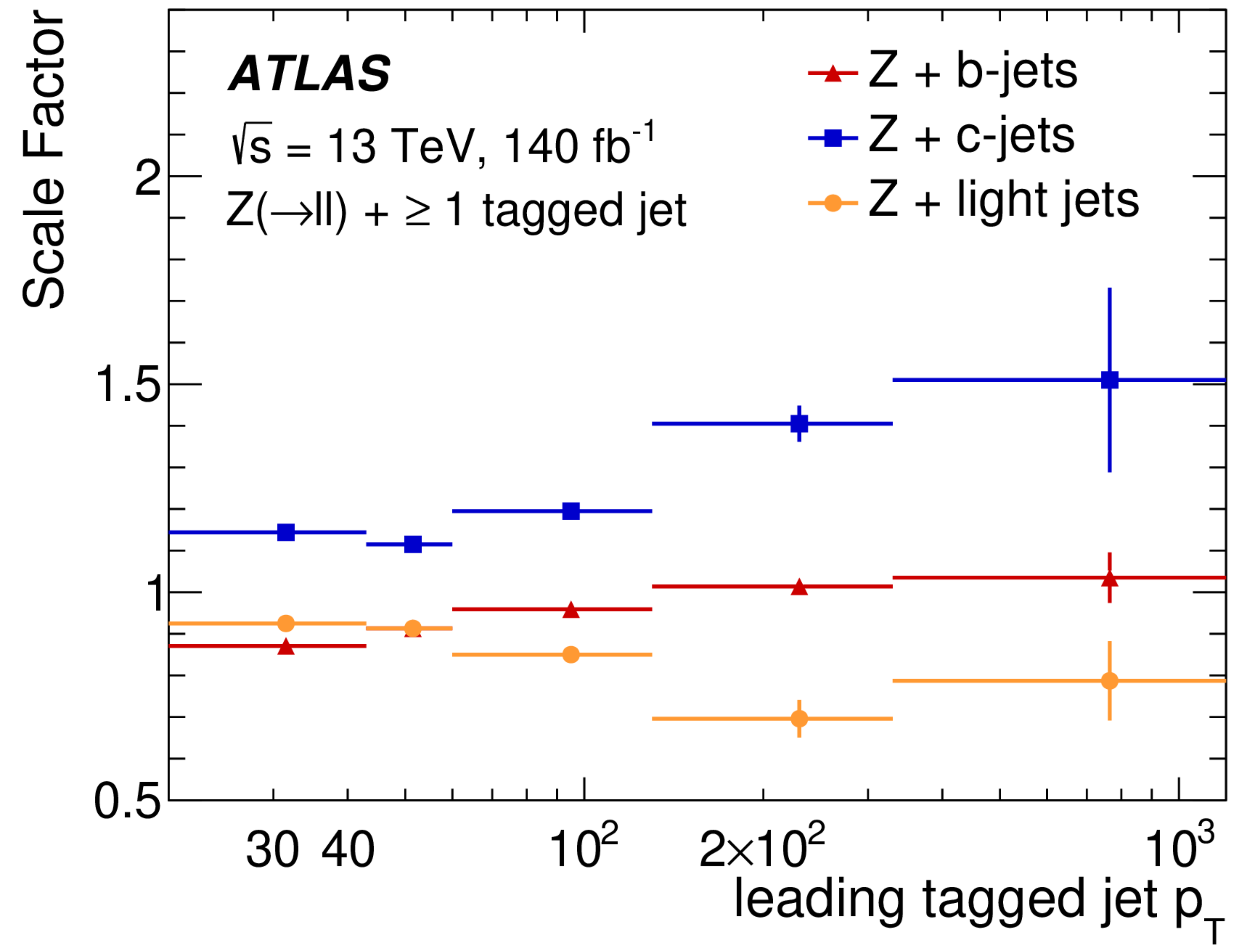


Z+jets background and Flavour Fit

- **Fit performed in individual** (optimised) **bins of each measured observable**



- **Bin-by-bin scale factors** allow to **correct** both **normalisation** and **shape** of *Z*+flavoured-jets contributions

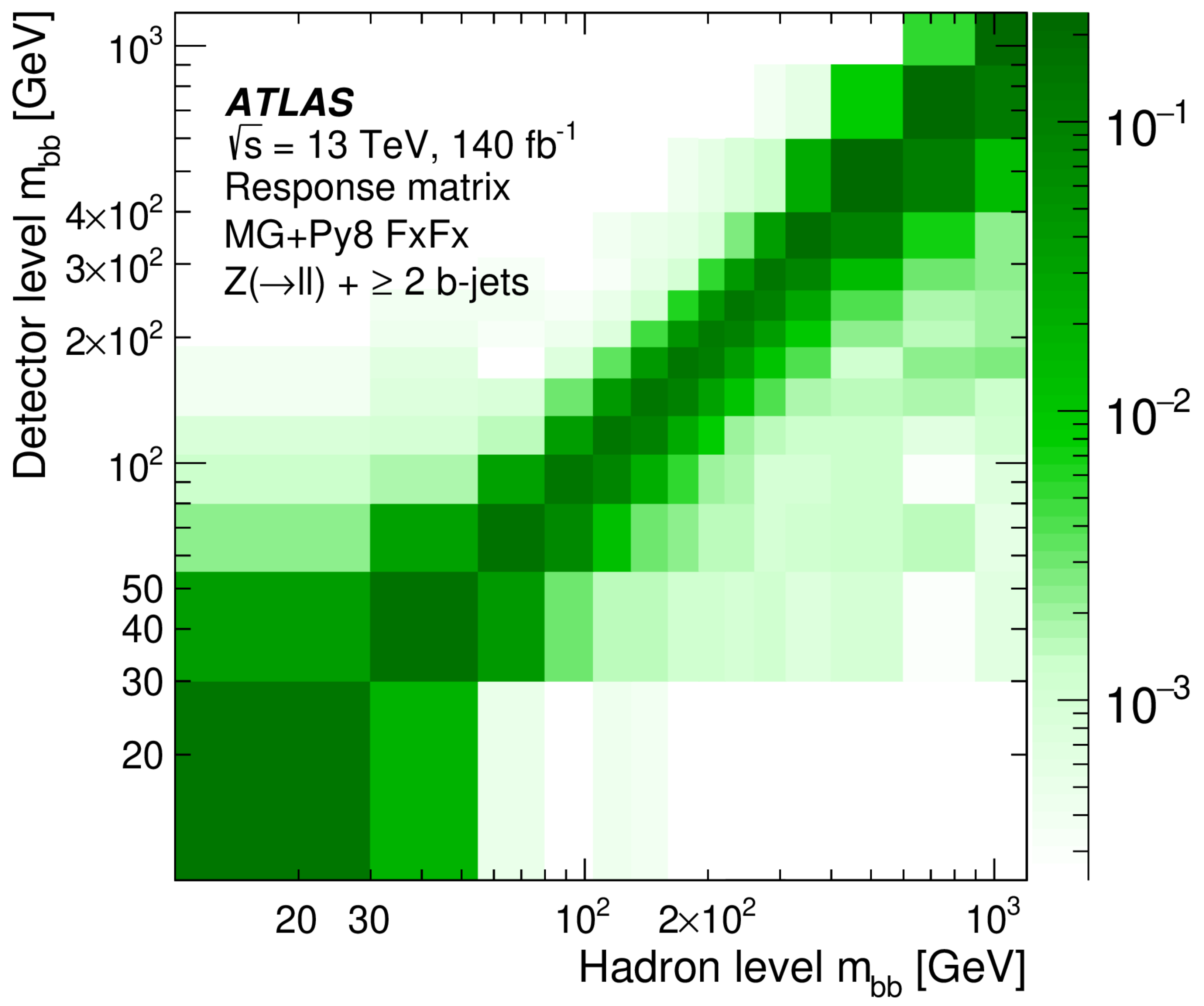


- Systematics:
  - Detector-level systematics affect *Z*+jets templates - repeat flavour fit
  - uncertainty on *Z*+jets background yields from comparison of two MCs

From detector to particle level

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 $\lvert y(Z)\rvert \geq 1.2$



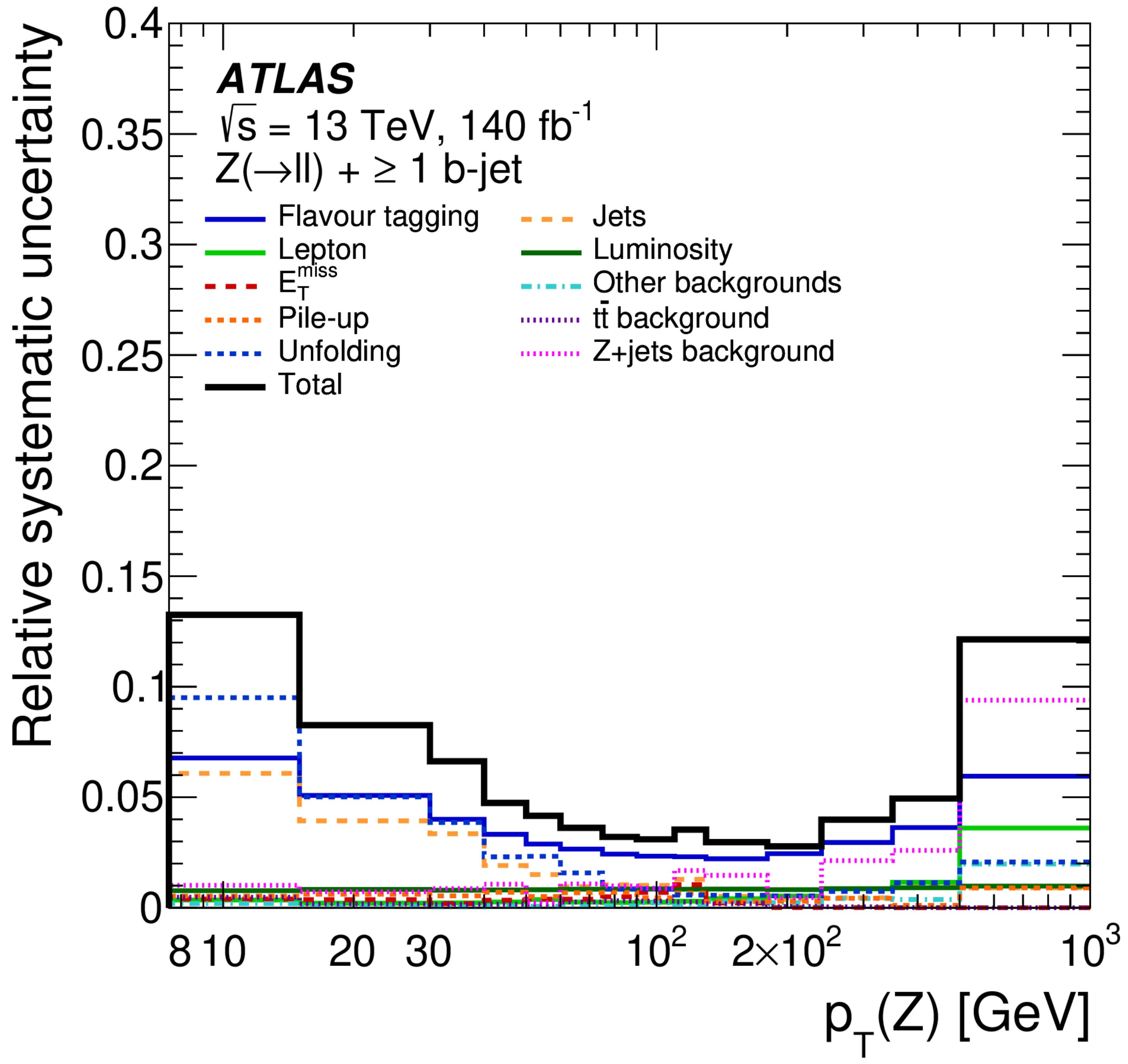
- (Data-Bkg) corrected for selection efficiency, resolution effects and differences between detector level and fiducial phase spaces
- **Differential cross sections** corrected to particle level with **iterative Bayesian unfolding**

Uncertainties on the cross section measurements

- **x2 improved precision on $Z + b$-jets** measurements with respect to previous ATLAS results
- Dominant uncertainty contributions from:
  flavour-tagging, jet energy scale and resolution and unfolding
- Statistical uncertainty on data <1%

Differential distributions: total unc. **<5% in Z+≥1 b-jet, ~10-15% in Z+≥2 b-jets and Z+≥1 c-jet**

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_T^{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



Theoretical predictions

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

Different FS in matrix-element calculation

***IC*-component in proton PDFs**

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

Higher order terms in QCD

Fixed-order predictions with jet flavour dressing (infrared and collinear safe)

‘ Generator/settings	Flav. scheme	PDF
		Main MC samples
MGAMC+PY8 FxFx	5FS	NNPDF3.1 (NNLO) LuxQED
SHERPA 2.2.11	5FS	NNPDF3.0 (NNLO)
		Predictions to test various flavour schemes
MGAMC+PY8	5FS	NNPDF2.3 (NLO)
MGAMC+PY8 Zbb	4FS	NNPDF3.1 (NLO) PCH
MGAMC+PY8 Zcc	3FS	NNPDF3.1 (NLO) PCH
		Intrinsic charm (IC) predictions
MGAMC+PY8 FxFx	5FS	NNPDF4.0 (NNLO) PCH (no IC)
		NNPDF4.0 (NNLO)
		NNPDF4.0 (NNLO) EMC+LHCbZc
		CT18 (NNLO) (no IC)
		CT18FC – CT18 BHPS3
		CT18FC – CT18 MCM-E
		CT14 (NNLO) (no IC)
		CT14 (NNLO)IC – BHPS1
		CT14 (NNLO)IC – BHPS2
		Fixed-order predictions
NLO	5FS	PDF4LHC21
NNLO	5FS	PDF4LHC21

Inclusive cross-section results

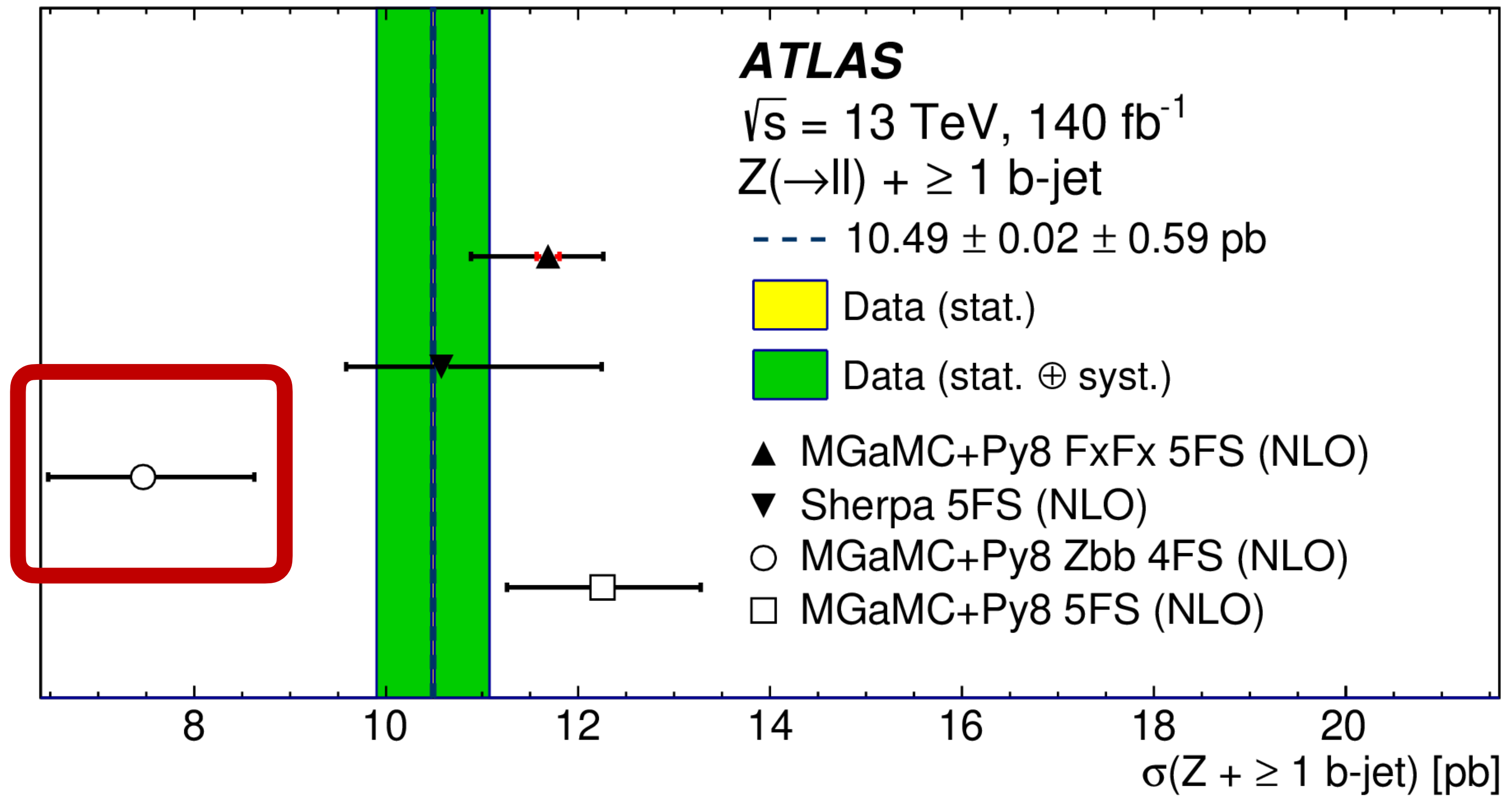
$$\sigma(Z{+}\geq 1\ b\text{-jet}) = 10.49 \pm 0.02\ (\text{stat.}) \pm 0.59\ (\text{syst.})\ \text{pb}$$

$$\sigma(Z{+}\geq 2\ b\text{-jets}) = 1.39 \pm 0.01\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{pb}$$

$$\sigma(Z{+}\geq 1\ c\text{-jet}) = 20.89 \pm 0.07\ (\text{stat.}) \pm 2.77\ (\text{syst.})\ \text{pb}$$

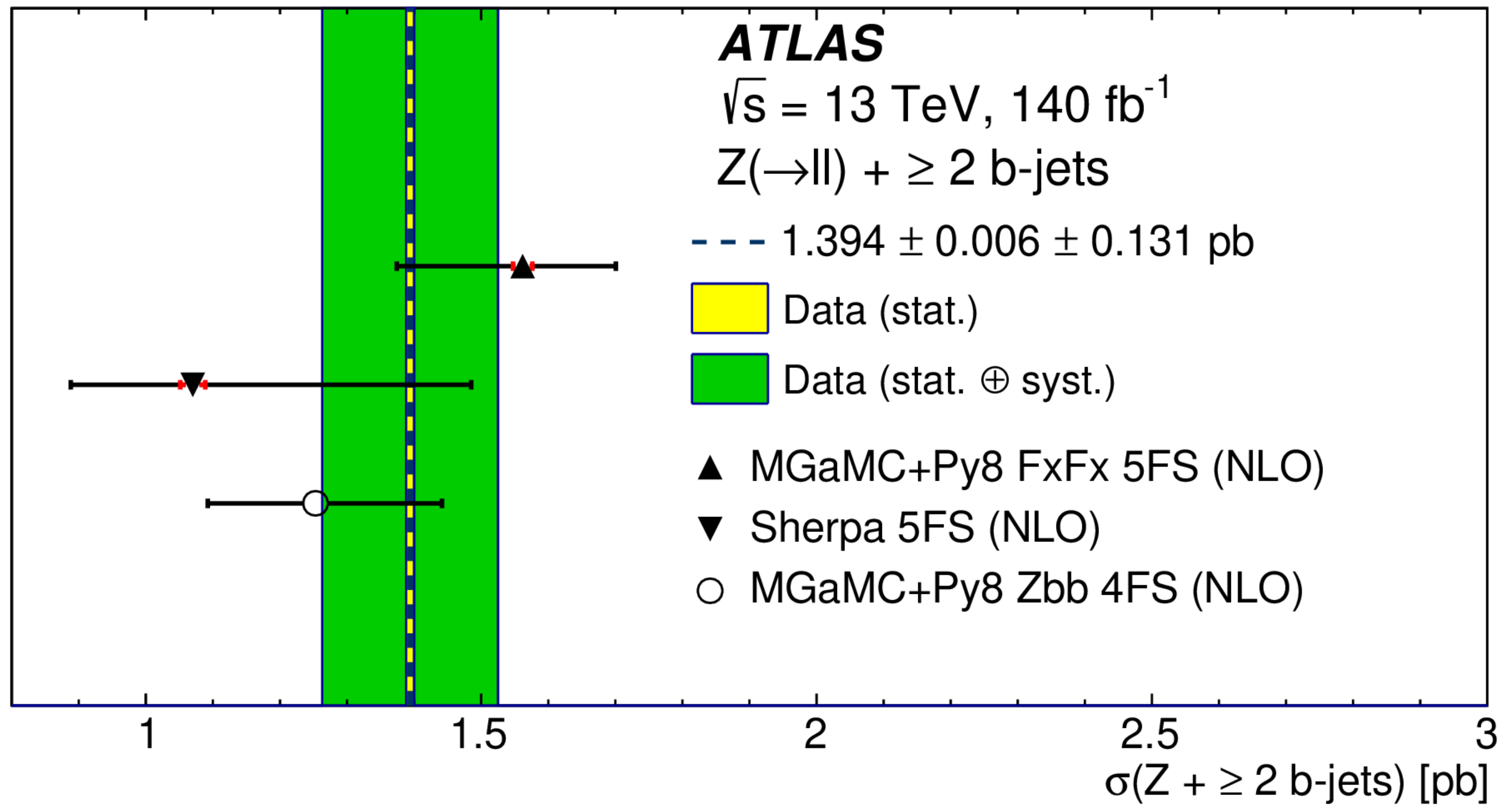
Z+≥1 b-jet

- Good description from 5FS
- 4FS with large underestimation



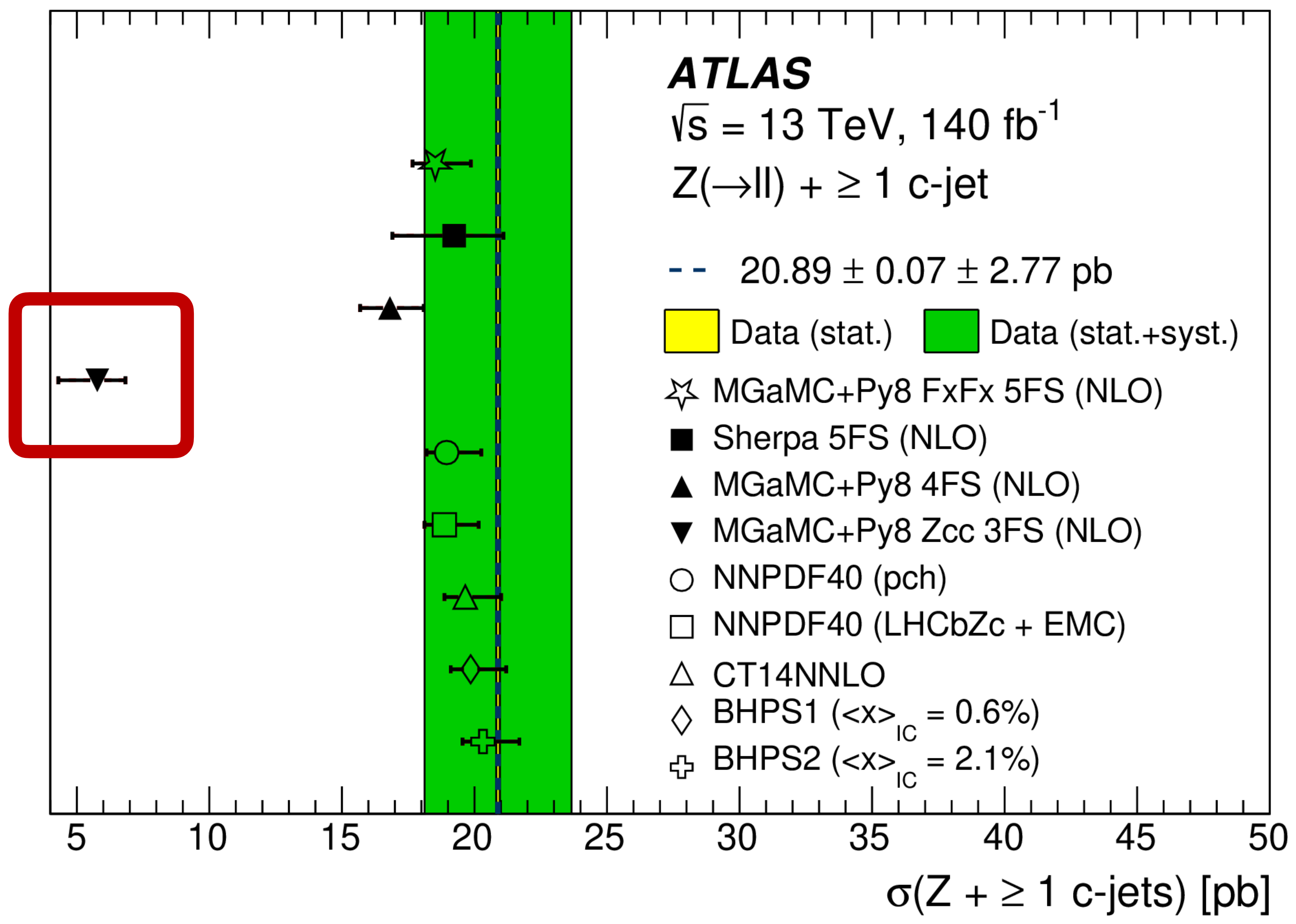
Z+≥2 b-jets

- 4FS and 5FS in agreement with data



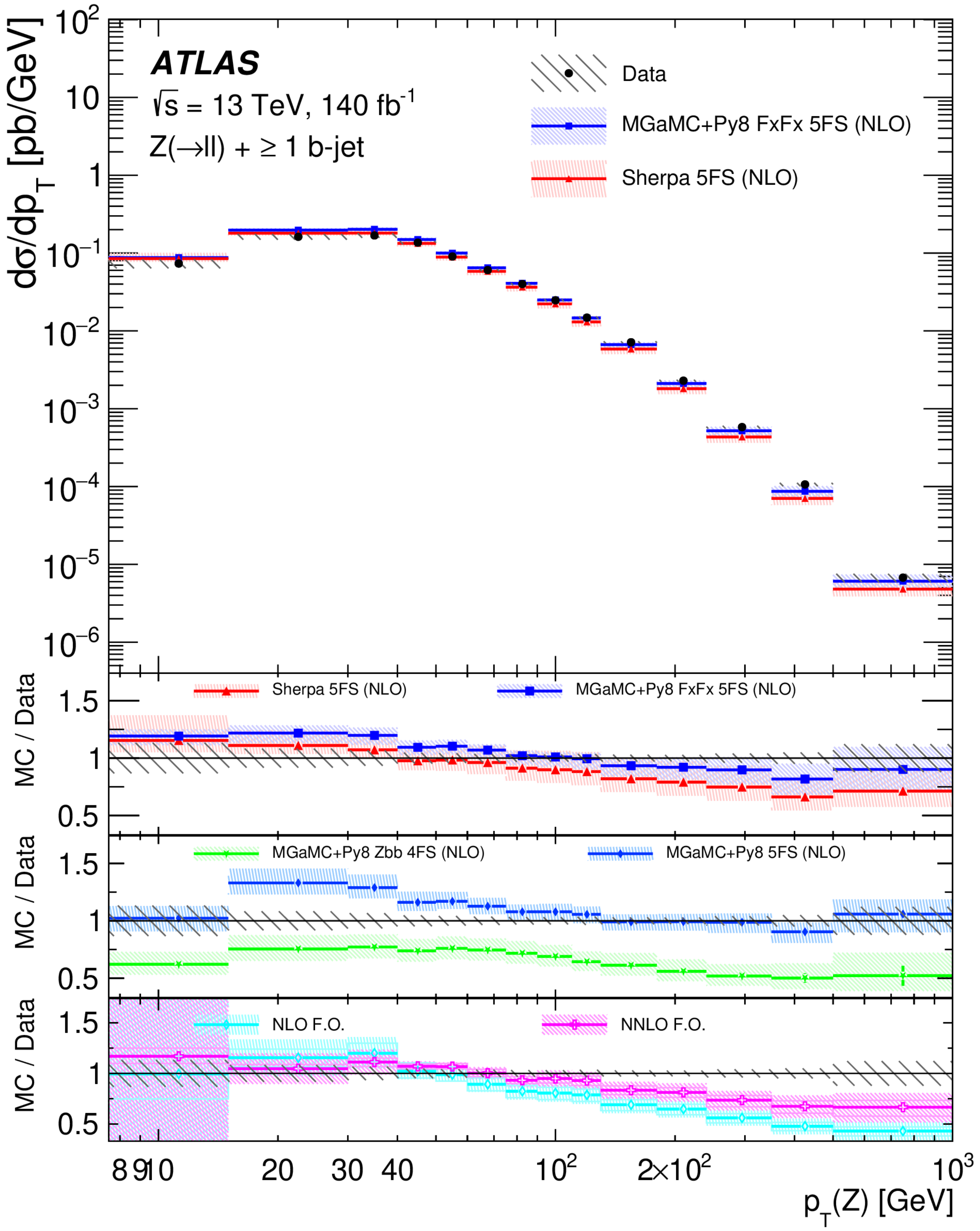
Z+≥1 c-jet

- 5FS in agreement with data
- 3FS with large underestimation



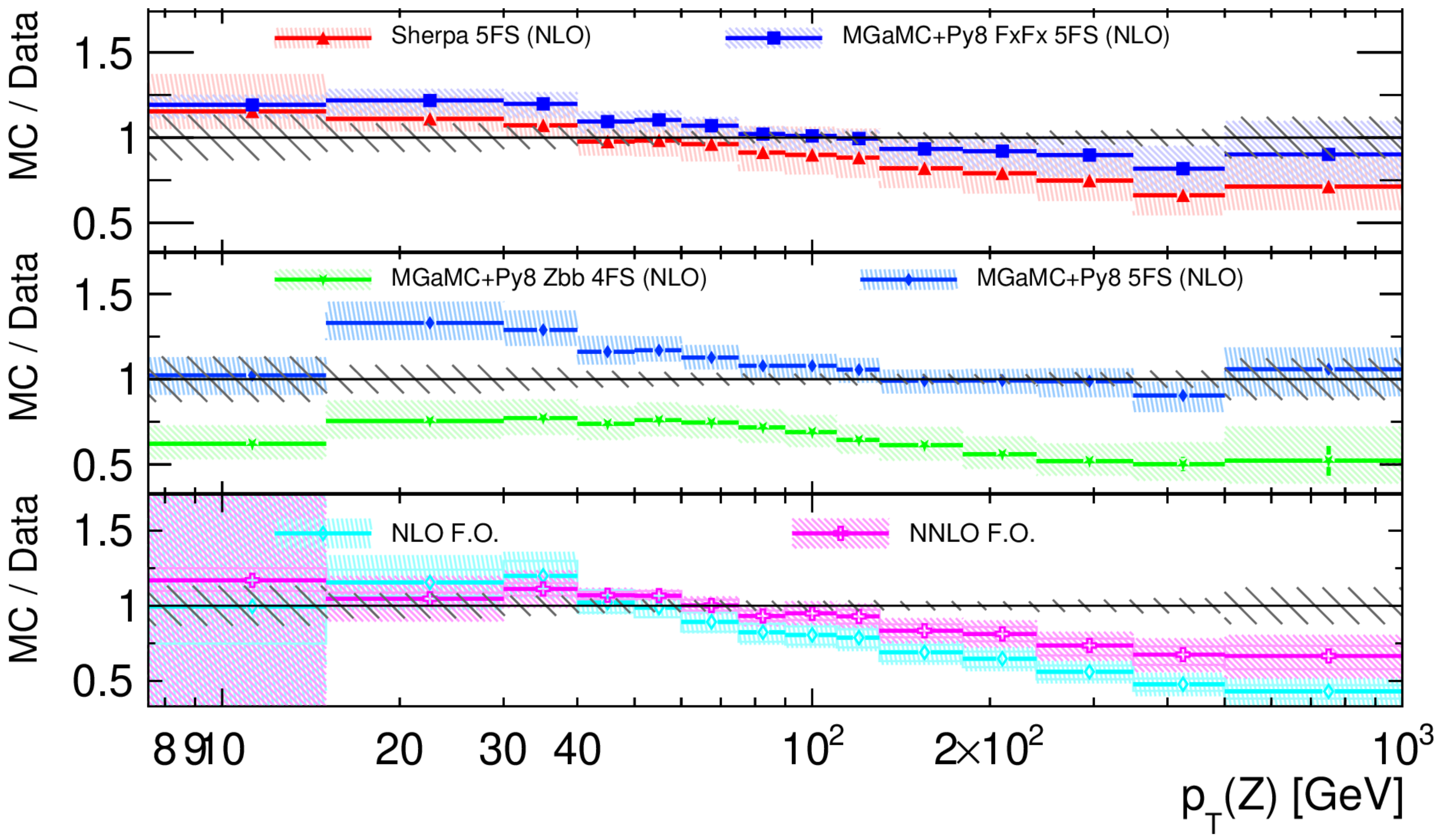
Results consistent with previous ATLAS measurement with 36 fb^{-1}

Differential *Z*+≥1 *b*-jet cross-section results



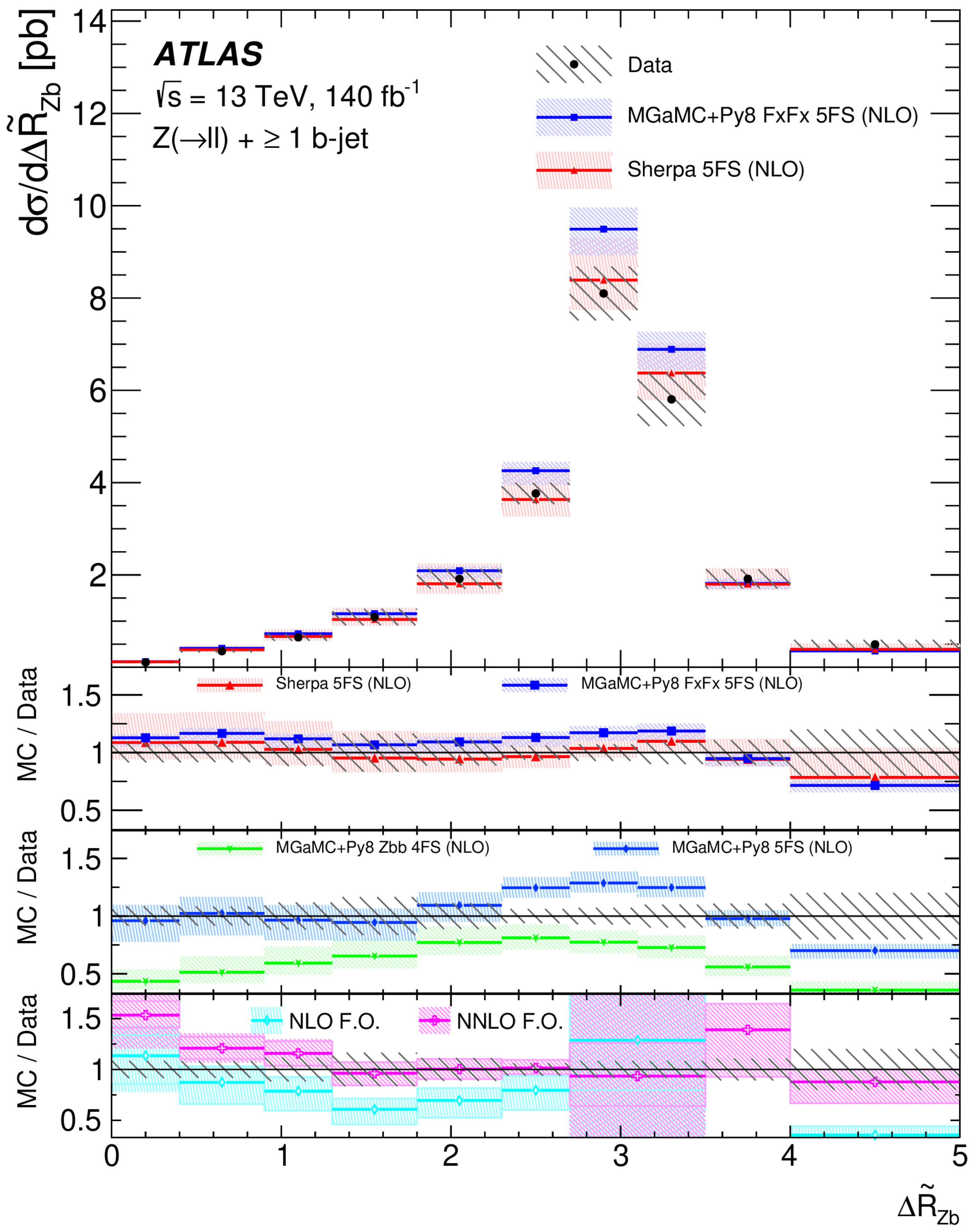
5FS: good description by both NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

4FS: similar modelling of 5FS, but large underestimation of data - **no log-term resummation in PDF evolution!**



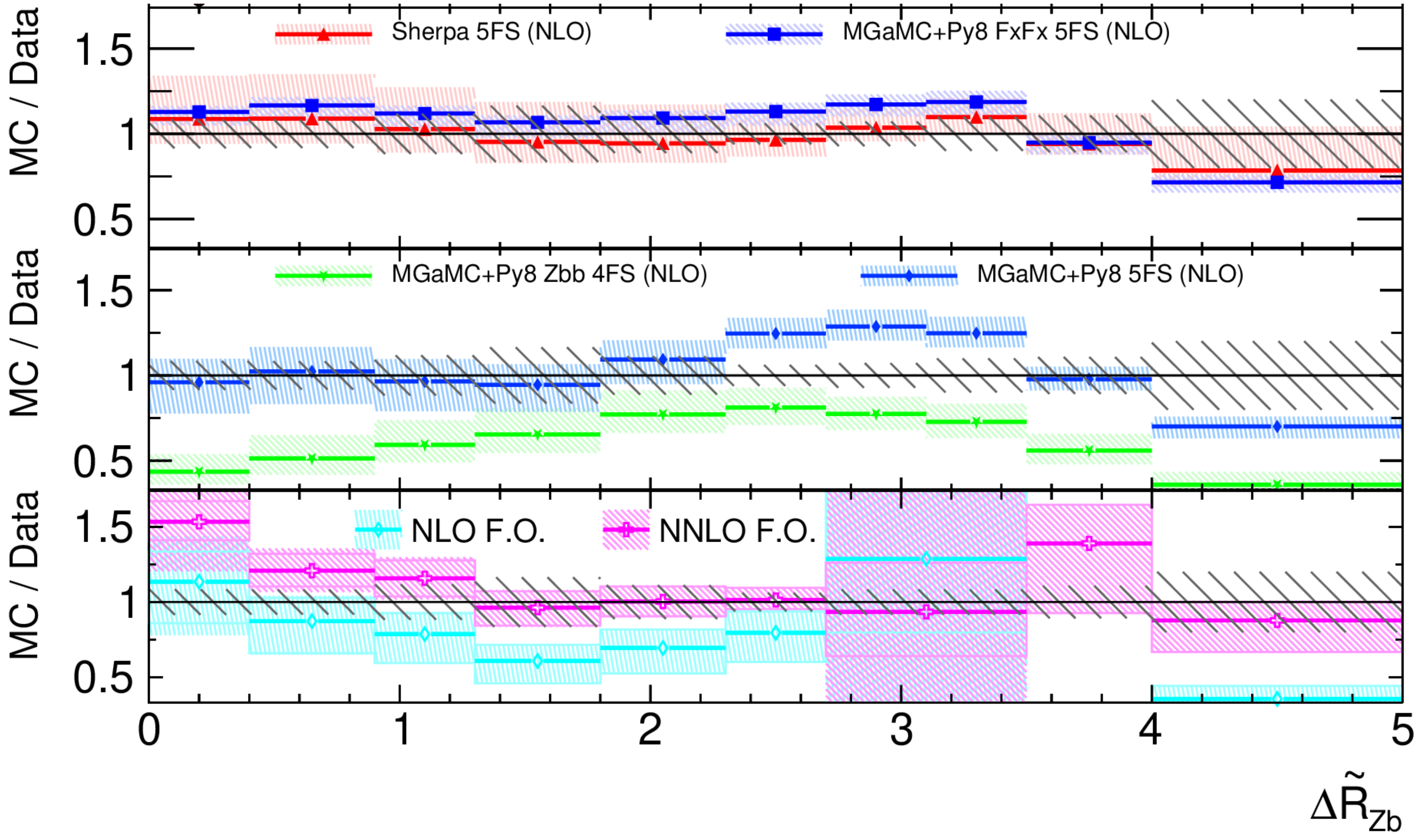
Fixed-order: at high p_T NNLO calculations in worst agreement than NLO ME+PS. Large uncertainty on NNLO due to **different jet flavour algorithms** → importance of using IRC-safe jet-flavour algorithm in measurements

Differential $Z+\geq1$ *b*-jet cross-section results



5FS: good description by both NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

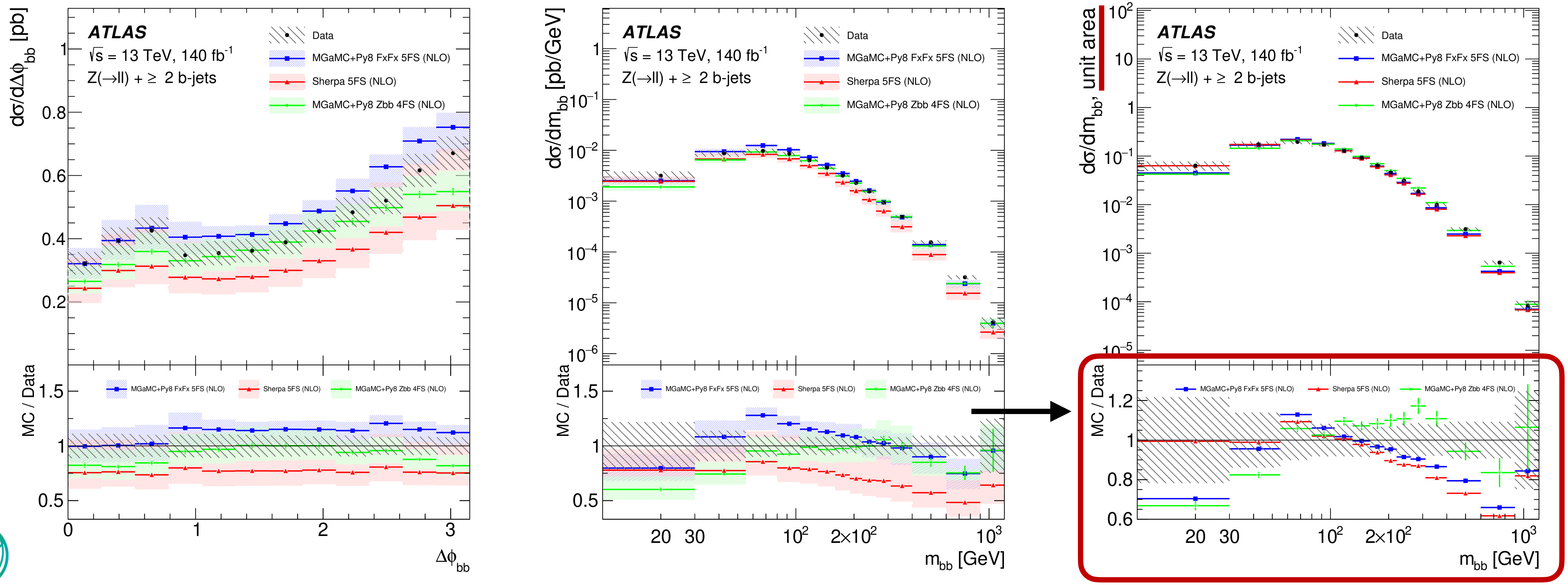
4FS: mismodelling of collinear and large $\Delta\mathrm{R}(Z, b-\mathrm{jet})$



Fixed-order: NLO discrepancies improved with NNLO. Calculations suffer from divergences at $\Delta\mathrm{R}(Z, b-\mathrm{jet}) \sim \pi$, where uncertainties increase

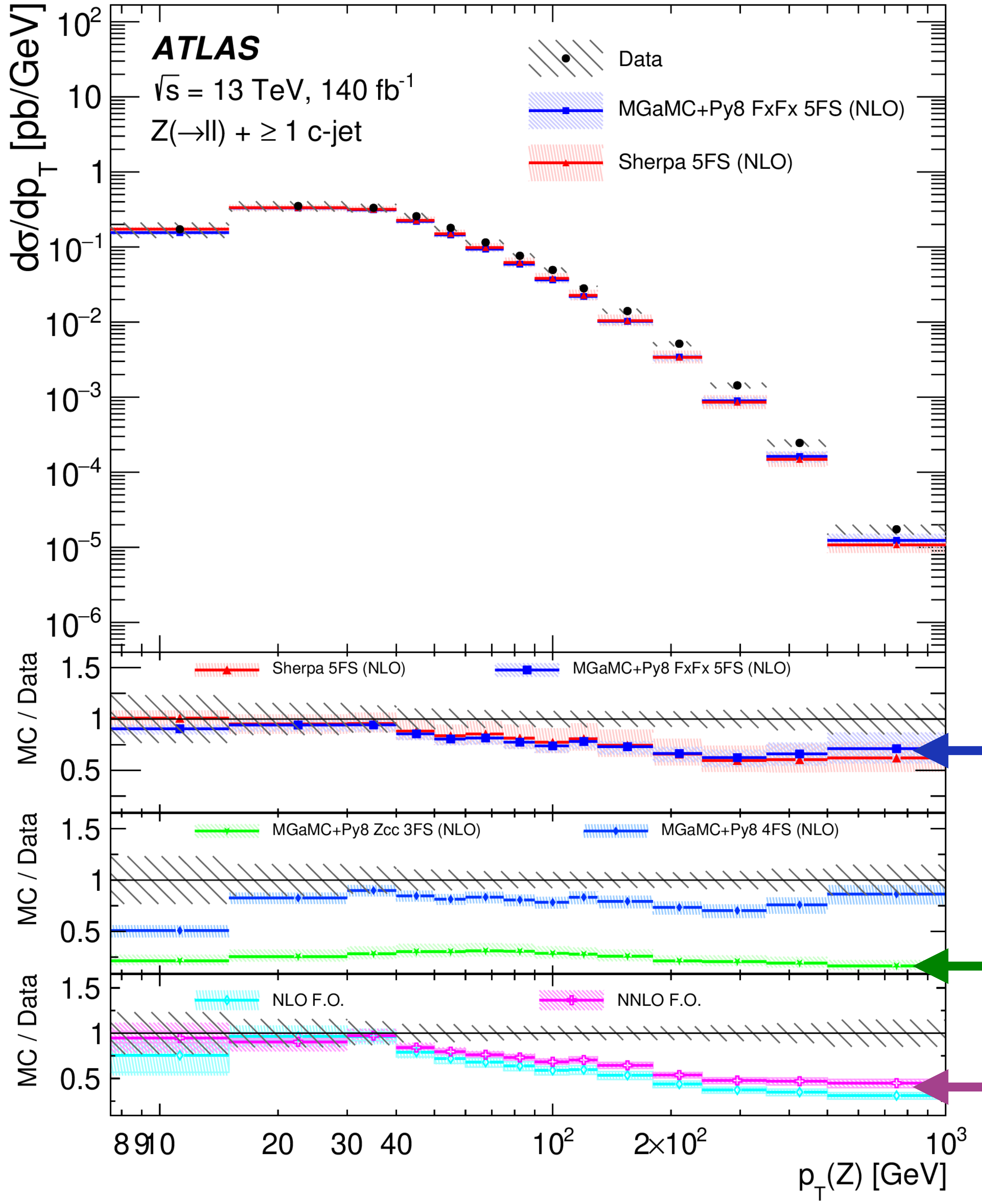
Differential Z+≥2 b-jets cross-section results

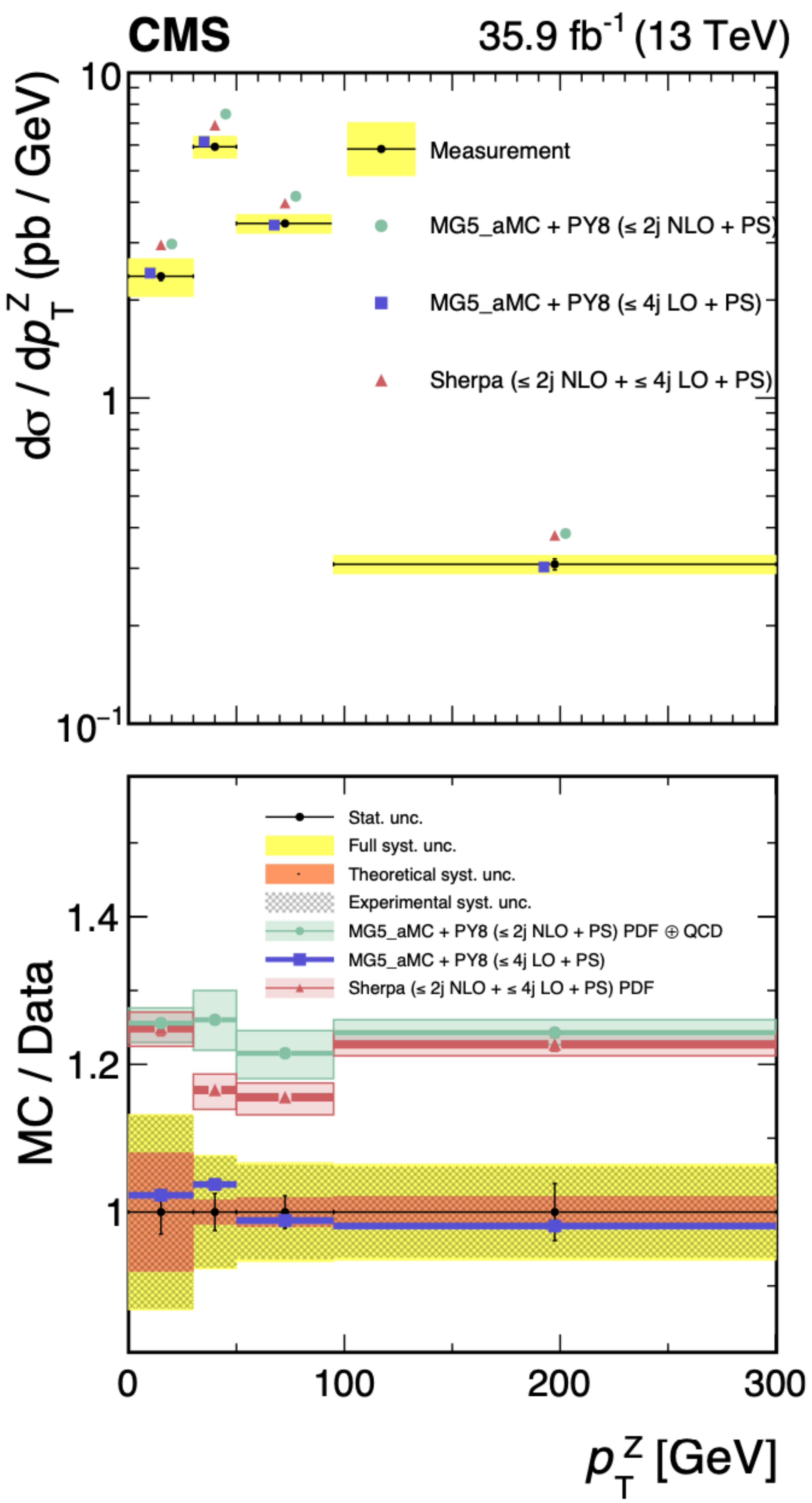
- **$\Delta\phi_{bb}$:** good modelling by all predictions
- **m_{bb}:** similar description by all predictions, with steep decrease for m_{bb}>80 GeV
  none of the predictions in agreement with data in the full spectrum



Differential Z+≥1 *c*-jet cross-section results

- **5FS**: soft p_T spectra well described by NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)
  - Different results from CMS: better modelling from LO MCs, NLO up-to-date MCs with off normalisation
- **3FS**: better modelling than 5FS but large underestimation of normalisation by a factor ~3 - **no log-term resummation in PDF evolution!**
- **Fixed-order**: NLO predicts softer p_T spectra, small improvement with NNLO

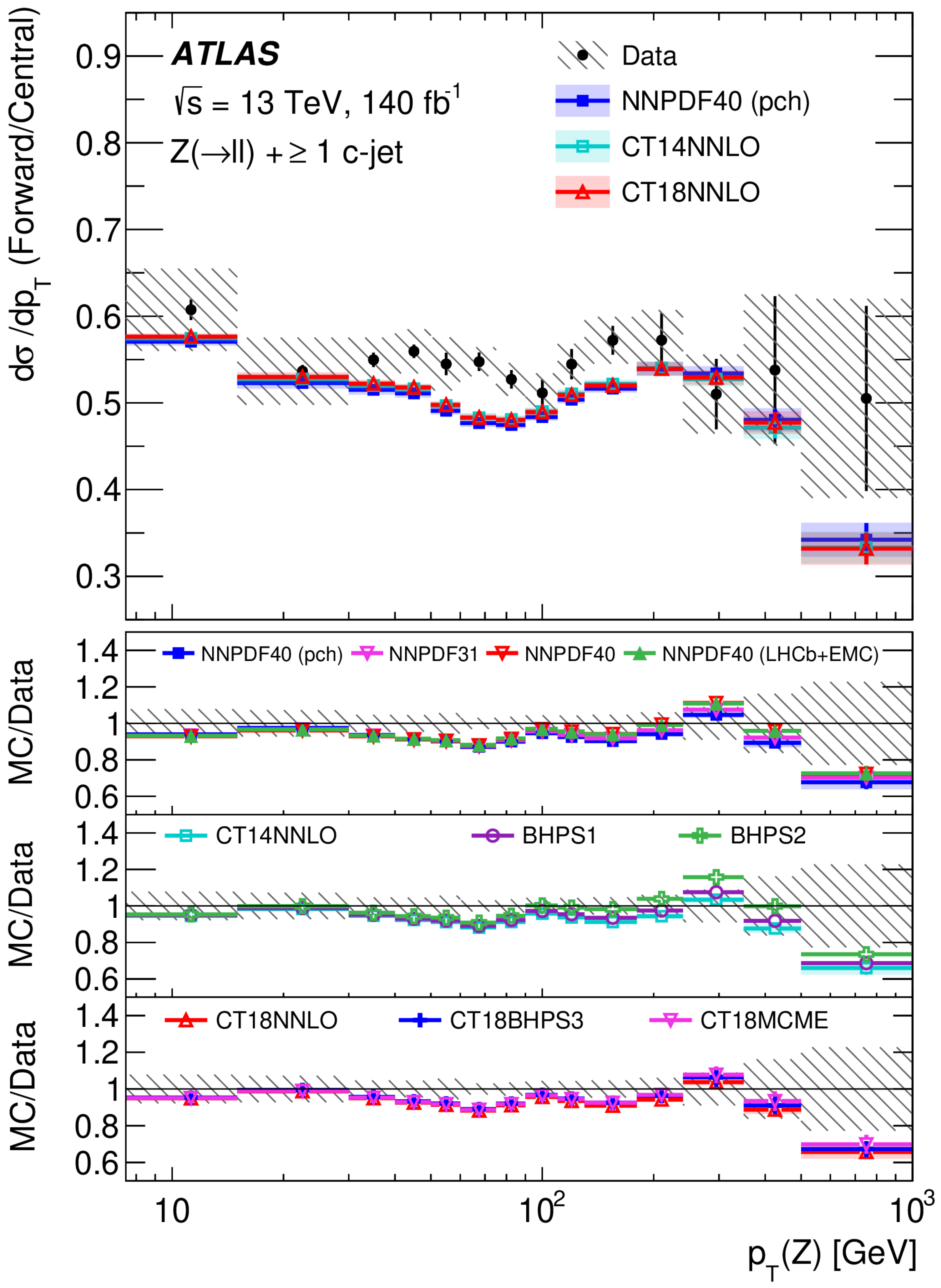




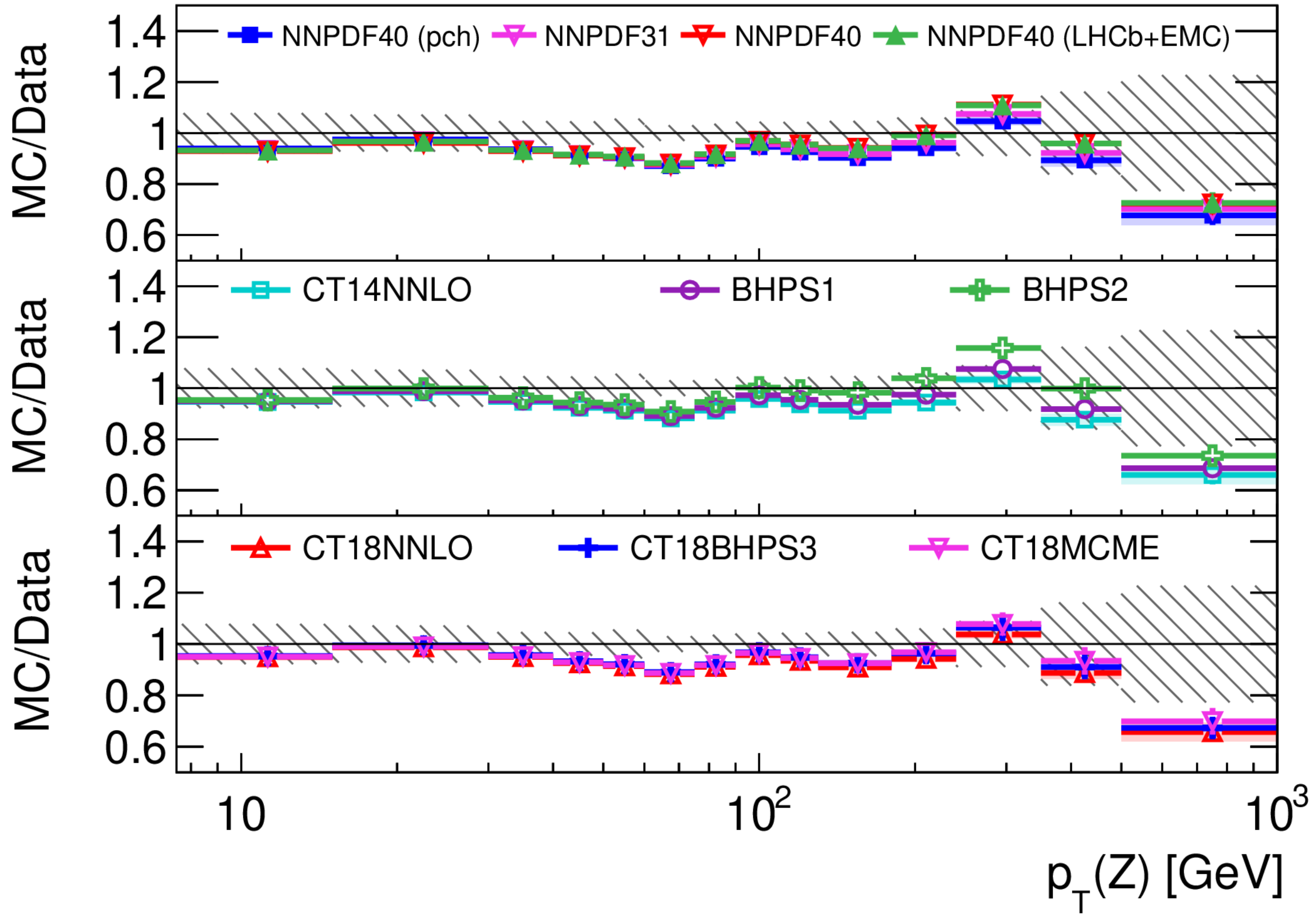
Differential $Z+\geq1$ *c*-jet cross-section results

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

Forward/Central ratio of Z p_T



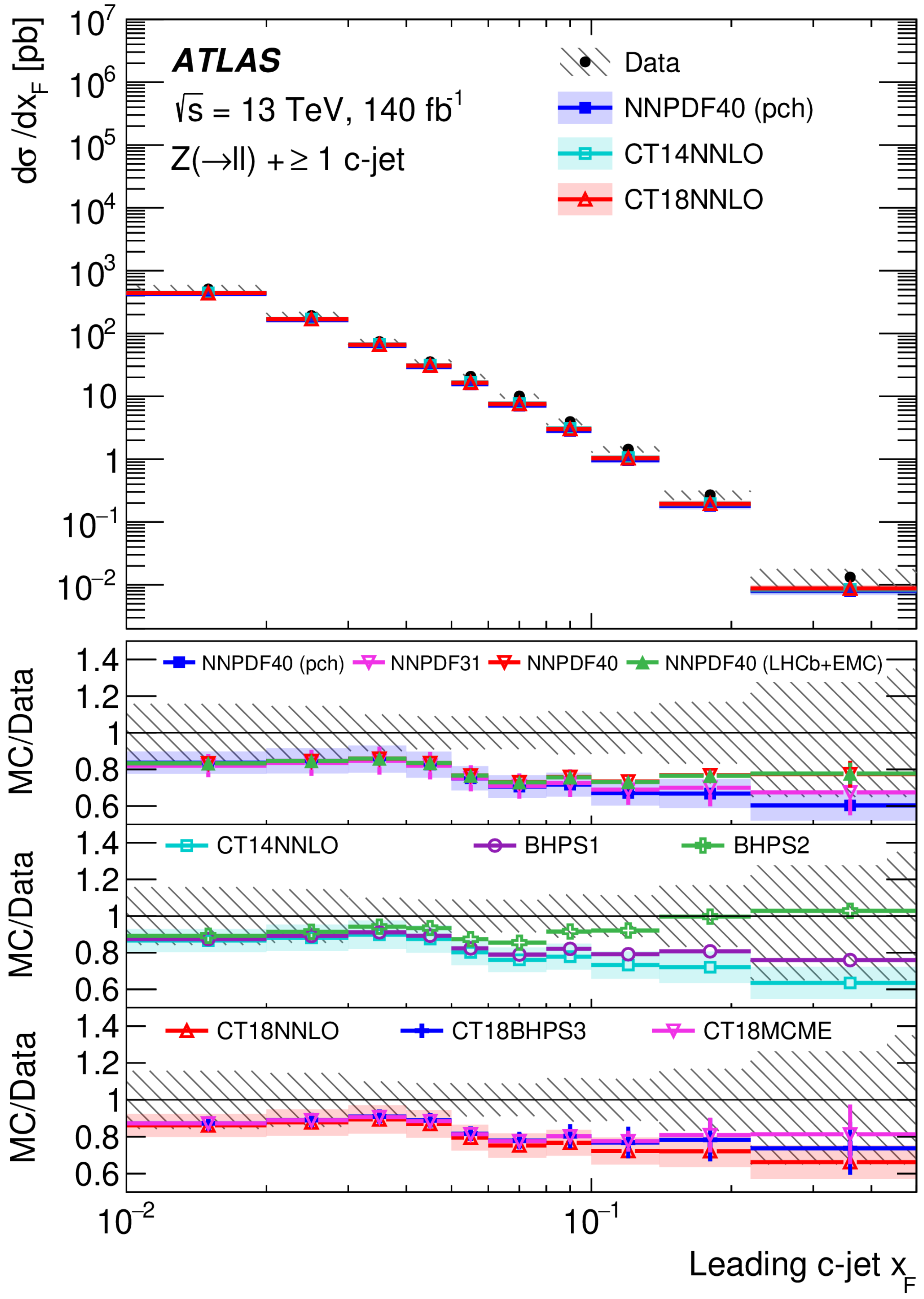
- Large reduction of systematics in the ratio (~8%)
- **Similar trend by all *IC* models** from NNPDF, CT14 and CT18
  - PDF sets with only perturbative charm (no *IC*): NNPDF40 (pch), CT14NNLO and CT18NNLO
  - ➡ **The measurement has small sensitivity to *IC***



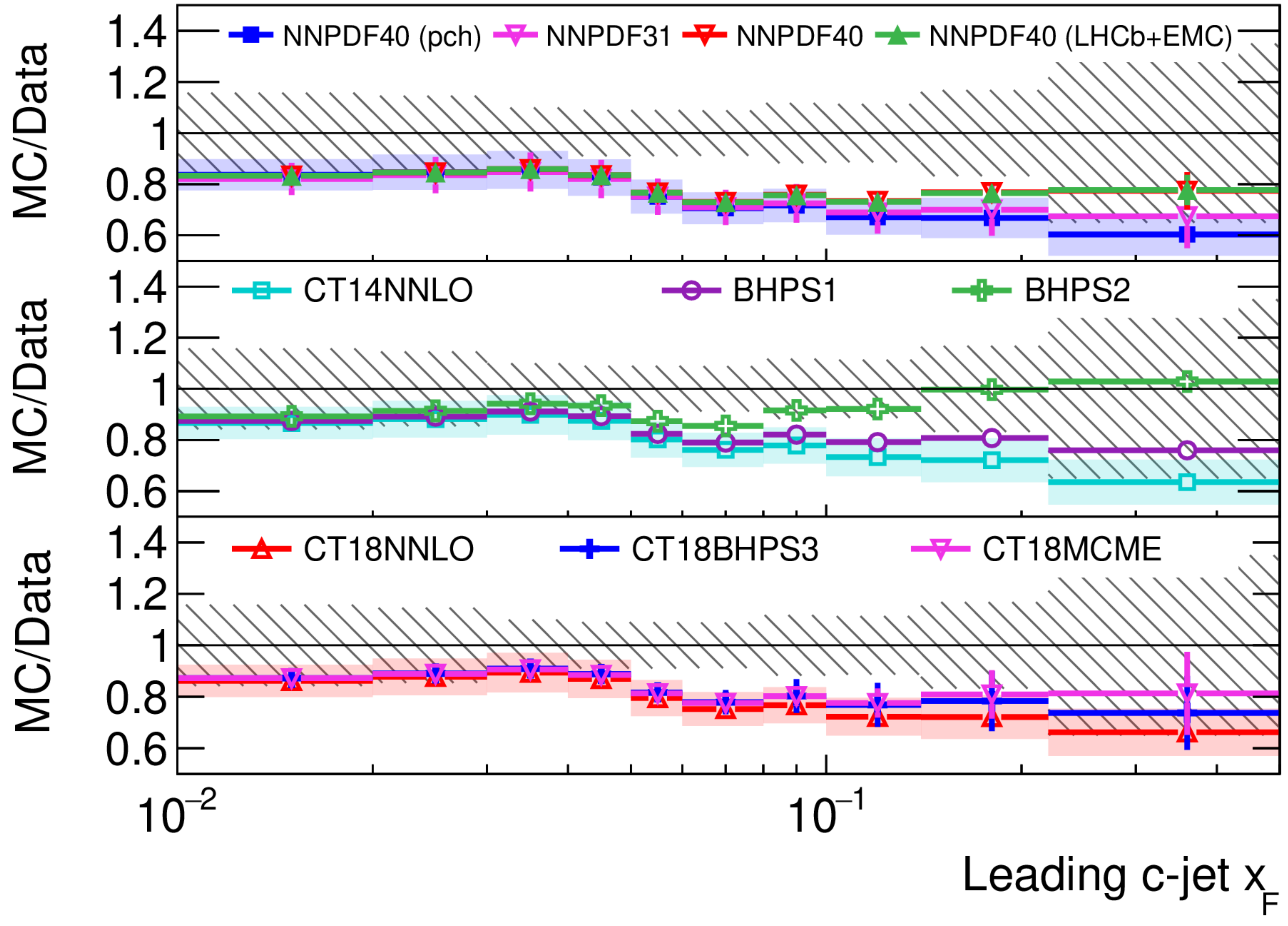
Differential $Z+\geq 1$ *c*-jet cross-section results

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

Feynman-variable $x_F = 2p_z/\sqrt{s}$



- **Similar trend by all *IC* models**
  - ➡ **The measurement has small sensitivity to *IC***
- BHPS2 (with <x_c>~2%) improves the description of data
  - In more realistic scenarios (NNPDF and CT18) the improvement is still marginal



Conclusions

- Associated production of EWK gauge bosons with *c*- or *b*-quarks represents an essential ingredient of Standard Model

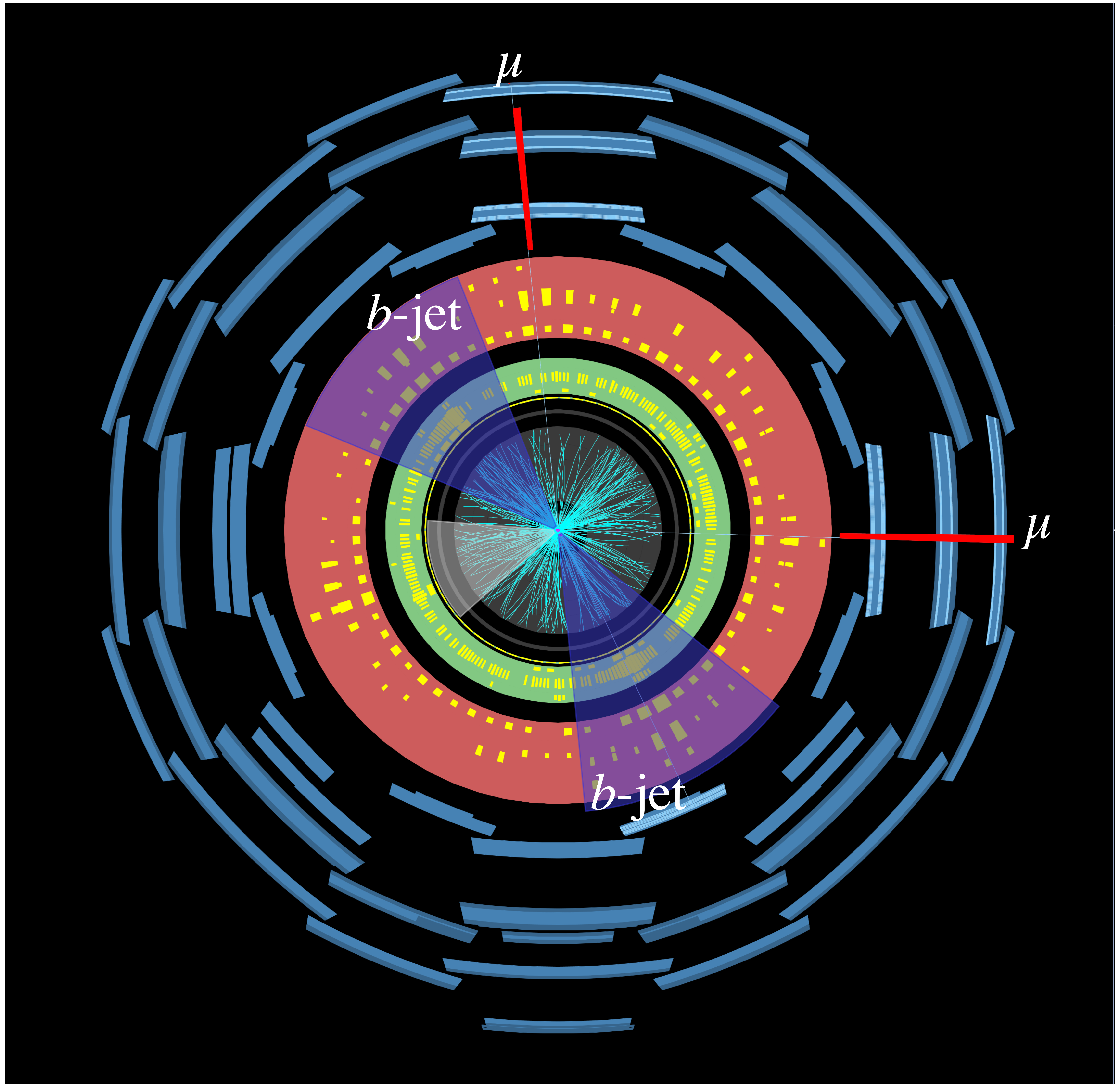
- **The era of high precision measurements with c- and b-quarks has started**
  - requires good performance in reconstructing final state objects and precise modelling by Monte Carlo generators

- **ATLAS *W*+*D* and *Z*+HF jets measurements with 140 fb^{-1} (*pp* collisions) reach high precision results**
  - useful inputs for global fit PDF, sensitive to s-, c- and b-quark PDF
  - benchmarks for Monte Carlo simulations and theoretical predictions available at NNLO
  - explore the sensitivity to new phenomenon, i.e. *IC*

- The interplay between theoretical and experimental effort is necessary to progress even further

THANK YOU FOR THE ATTENTION!

ANY QUESTIONS?

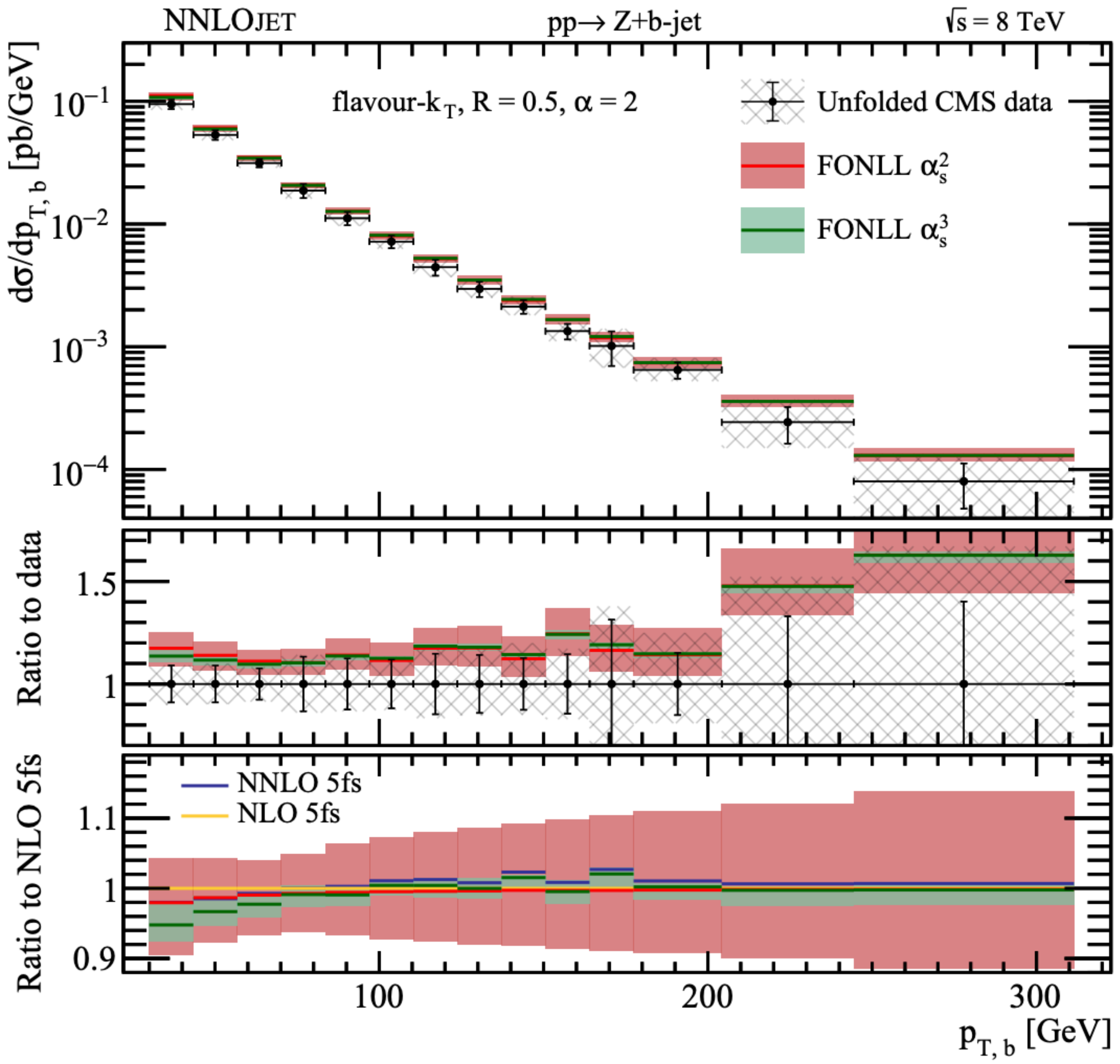


Backup

High-order QCD calculations

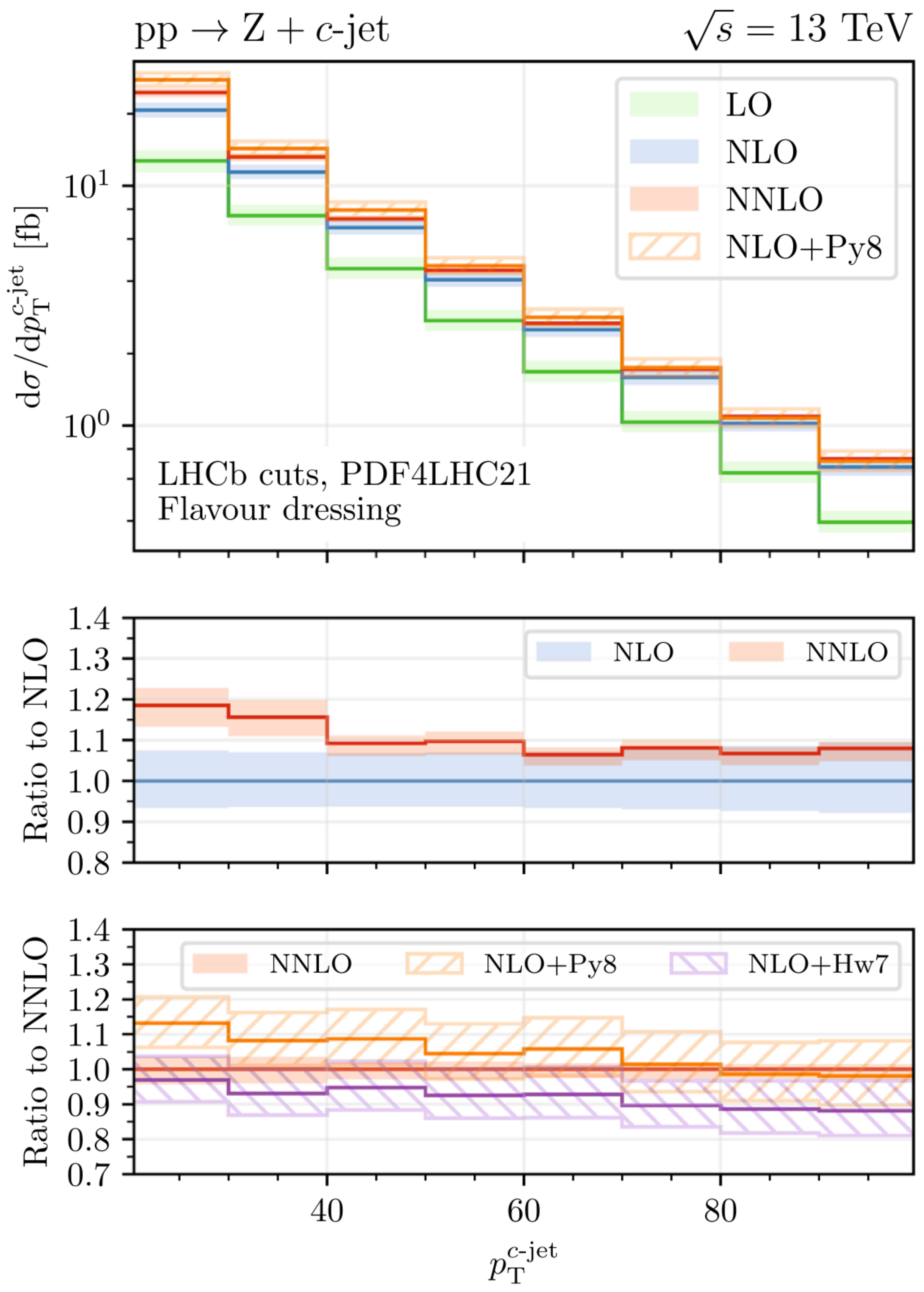
- ***Z + b*-jets** NNLO predictions compared with CMS results at 8 TeV

Phys. Rev. Lett. 125(22), 222002 (2020)



- ***Z + c*-jets** NNLO predictions in LHCb fiducial phase space

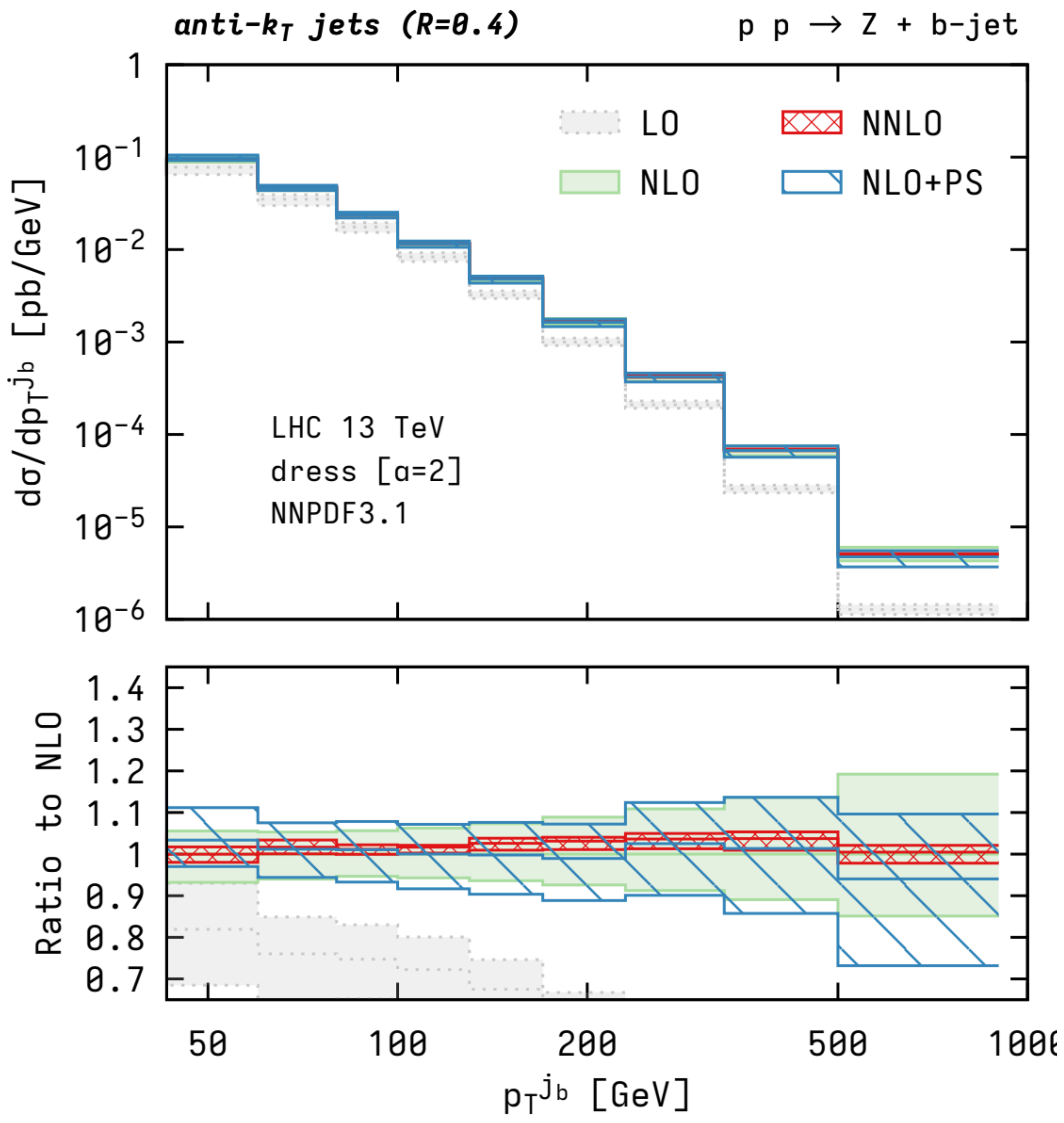
Eur. Phys. J. C (2023) 83:336



Jet-flavour algorithms

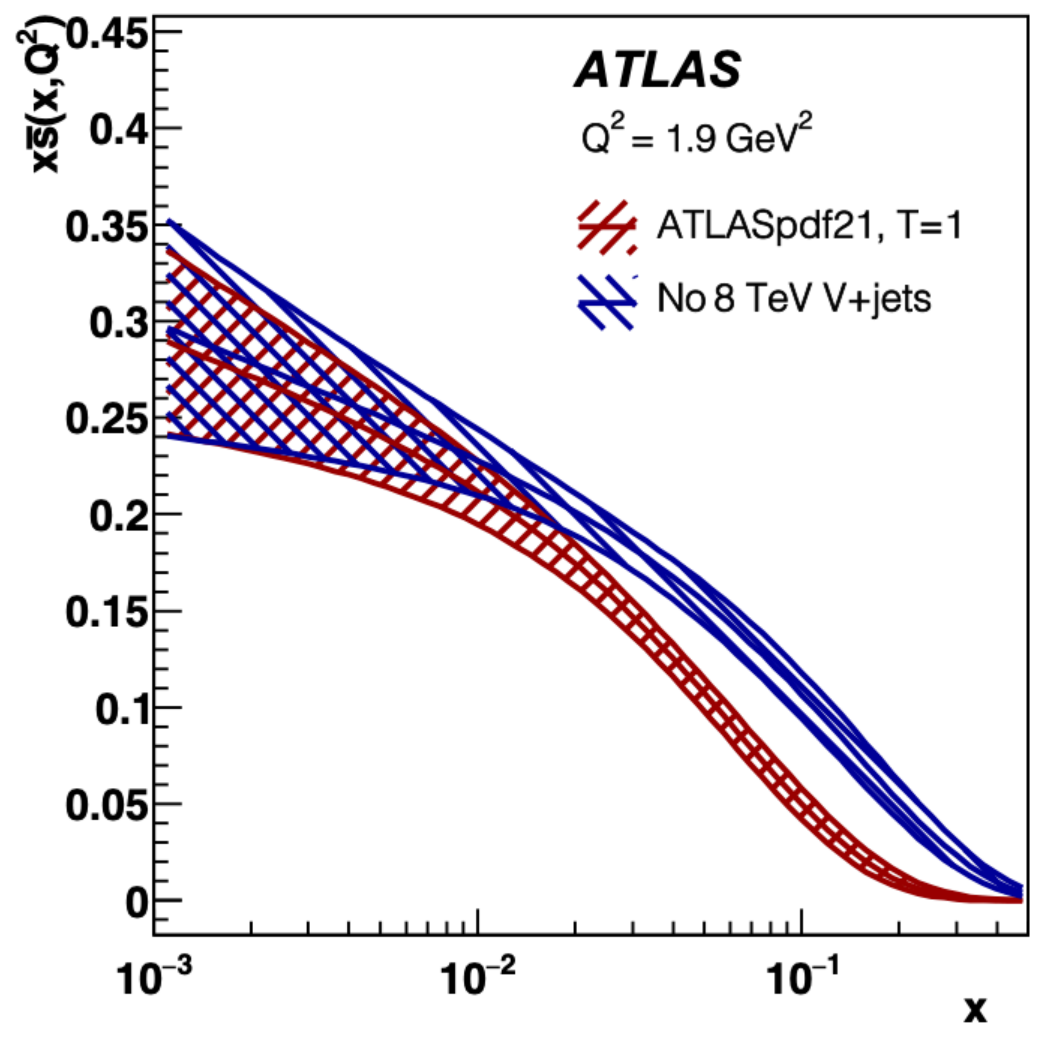
- **Difficult to have a definition of a flavoured jet which is infrared and collinear safe** (= insensitive to soft emissions and collinear splittings) due to large singularities
- Different flavour-dressing algorithms in literature:
  - **flavour-kt** [Banfi, Salam, Zanderighi]
    Eur.Phys.J.C47:113-124,2006
  - **flavour dressing** [Gauld, Huss, Stagnitto]
    Phys. Rev. Lett. 130 (2023) 161901
    - IRC safe to all orders in pQCD → applied to fixed-order-predictions
    - combined with any IRC safe definition of a jet, such as anti-kT
    - flavour assignment can be applied to quarks, HF-hadrons
  - **flavoured anti-kT** [Czakon, Mitov, Poncelet]
    JHEP 04 (2023) 138
  - **flavour nautralisation** [Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler]
    arXiv:2306.07314
  - **practical jet flavour through NNLO** [Caletti, Larkoski, Marzani, Reichelt]
    Eur. Phys. J. C 82 (2022), 632

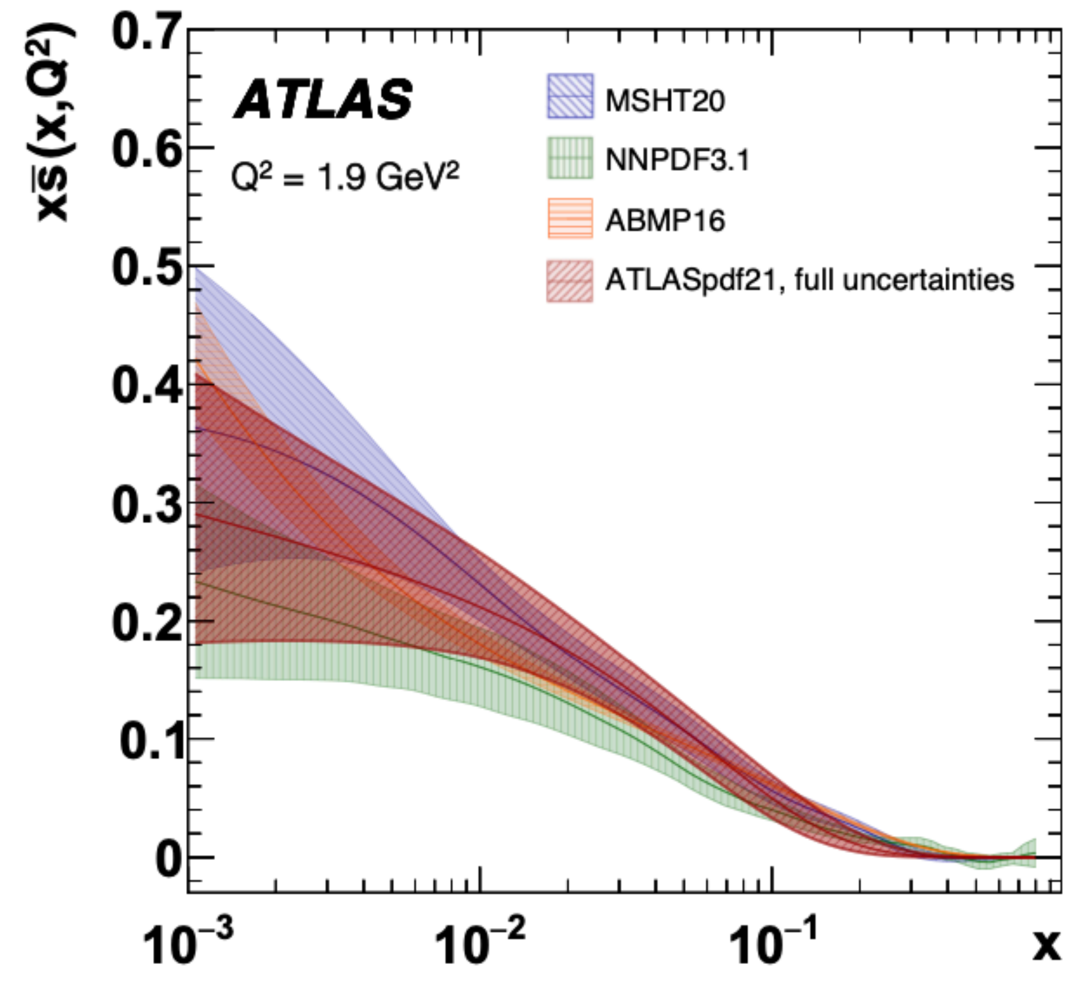
Phys. Rev. Lett. 130 (2023) 161901



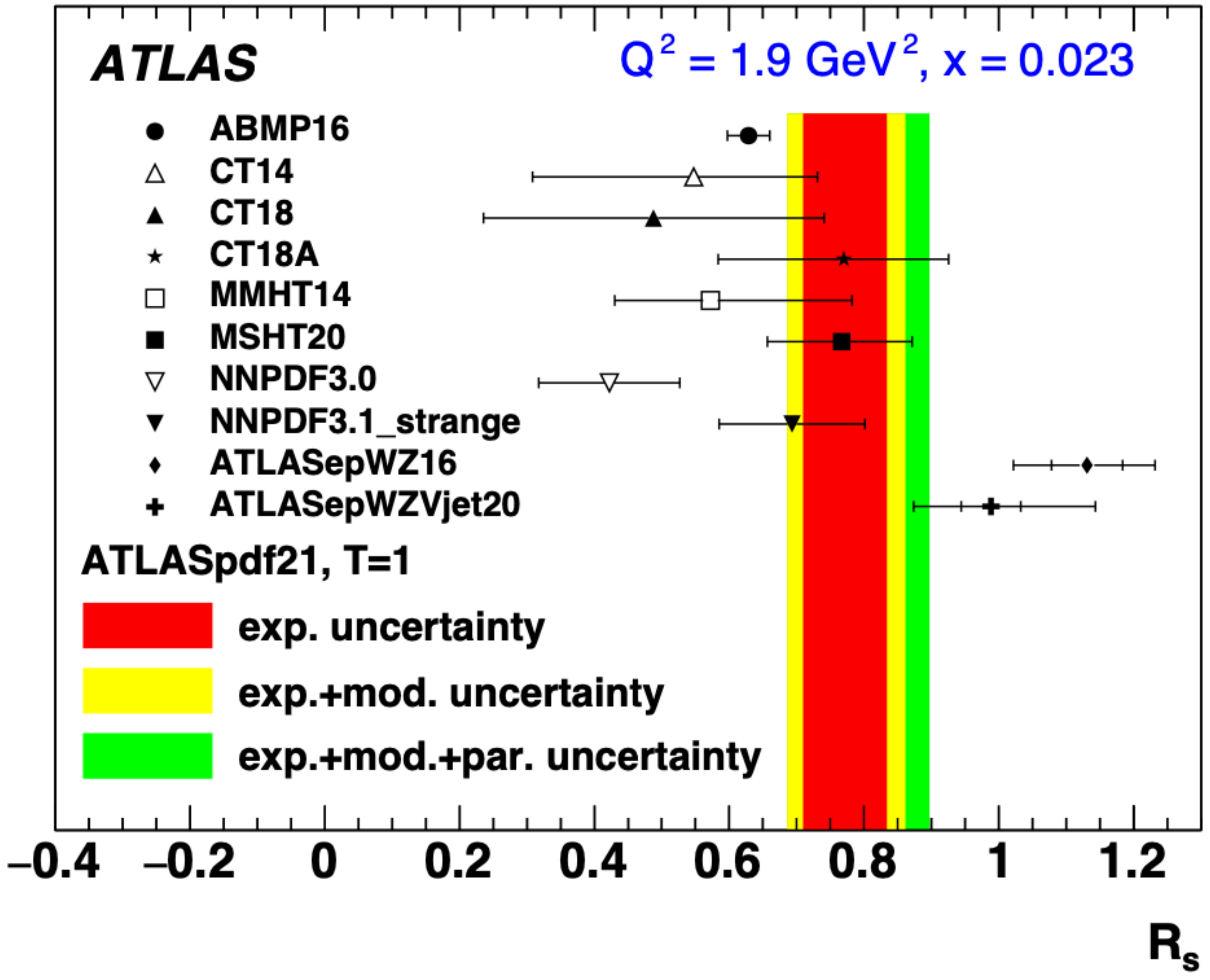
ATLASpdf21

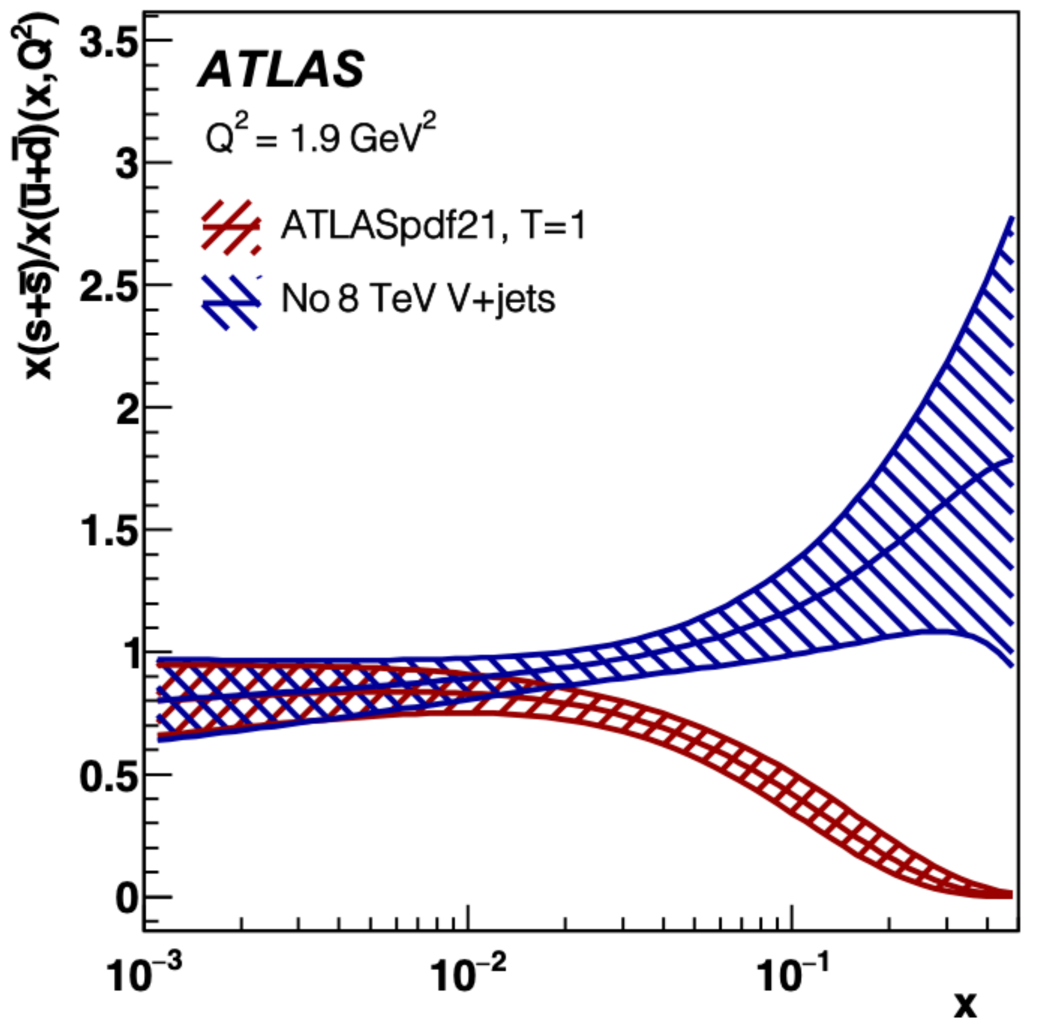
Eur. Phys. J. C 82 (2022) 438

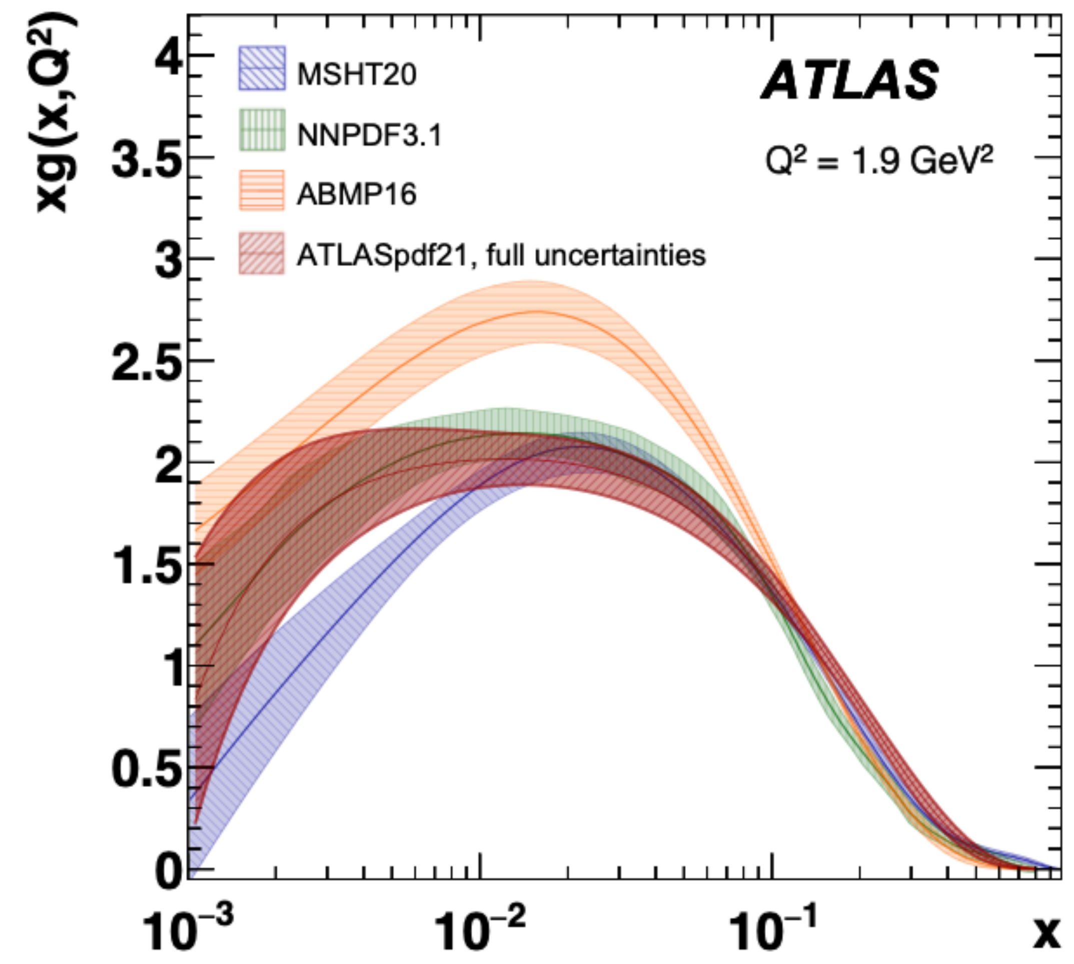




$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$







$s - \bar{s}$ asymmetry

- **At NNLO in QCD, $s - \bar{s}$ asymmetry appears as intrinsic property of the DGLAP evolution**
  - to different probability $q \to q'$ of and $q \to \bar{q}'$ splitting
  - role of u and d-quark valence densities at high Bjorken-*x*

- Various PDF fits assume **different hypotheses on the $s - \bar{s}$ asymmetry at the initial state**:
  - NNPDF: $s \neq \bar{s}$ coming from independent fit of s and $\bar{s}$
  - CT18: $s = \bar{s}$ at low scale

$$R_c = \frac{\sigma(W^+ + D^-)}{\sigma(W^- + D^+)}$$

JHEP 06 (2021) 100

PDF set	V_{cd}	$\sigma_{W^+ j_c}$ [pb]	$\sigma_{W^- j_c}$ [pb]	$R_{W^\pm j_c}$
NNPDF31 LO	$= 0$	9.8395(4)	10.4654(4)	0.94020(5)
	$\neq 0$	12.0725(4)	14.2624(5)	0.84646(4)
NNPDF31 NLO	$= 0$	22.593(2)	23.718(2)	0.95260(6)
	$\neq 0$	24.500(9)	27.29(1)	0.8977(5)
CT18 NLO	$= 0$	21.675(2)	21.675(2)	1.0000(1)
	$\neq 0$	23.477(9)	25.252(8)	0.9297(5)

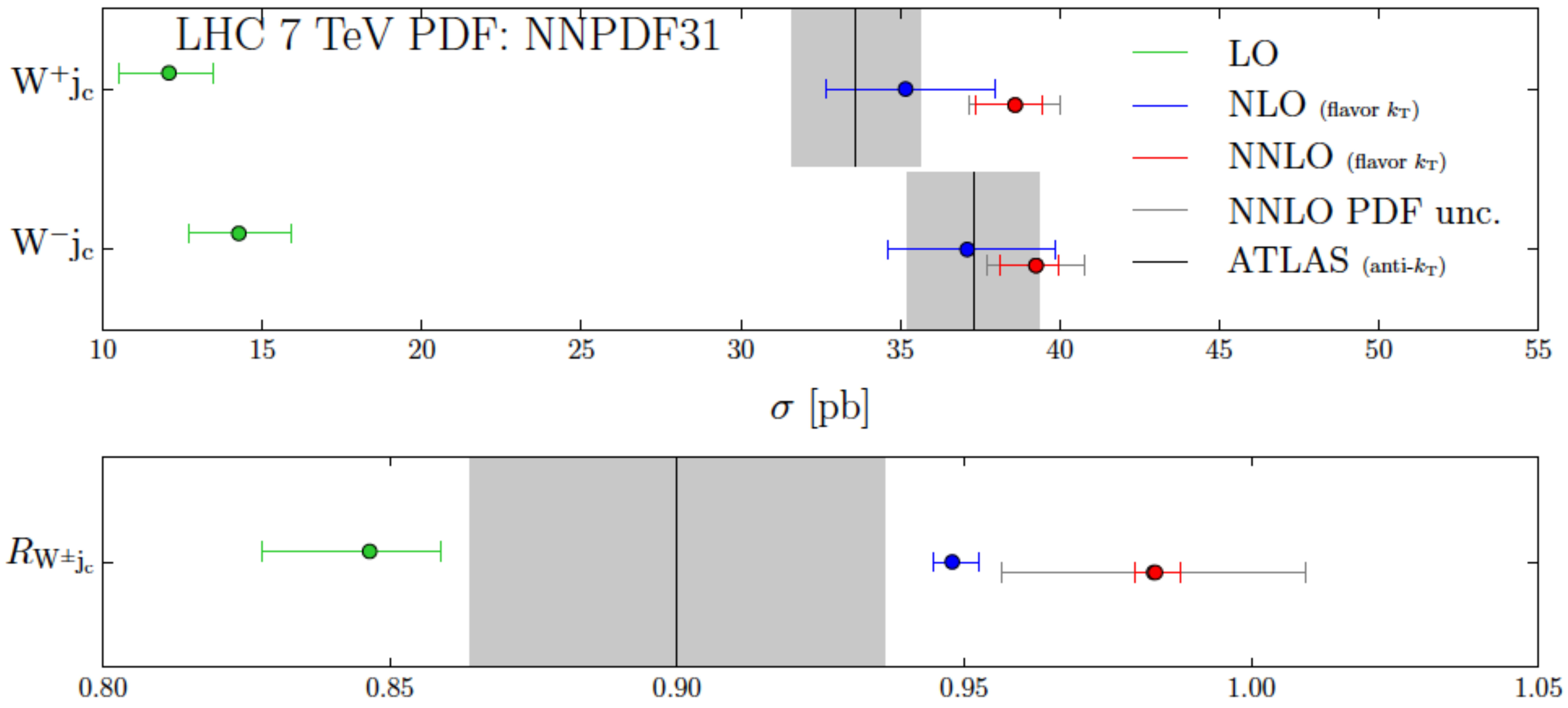
- $V_{cd}=0$:
  - in NLO CT18 prediction, $R_c = 1$ since no $s - \bar{s}$ asymmetry is considered
  - in NLO NNPDF31, $R_c < 1$

- $V_{cd} \neq 0$:
  - reduced the sensitivity to $s - \bar{s}$

$s - \bar{s}$ asymmetry

- ✦ Scale uncertainty decreases with the inclusion of NNLO corrections
  - ➡ **significant reduction of the theoretical uncertainty due to missing order terms**
- ✦ Large uncertainty from PDF
  - ➡ **unique opportunity for high quality fitting of the *s*-quark PDF and test $s - \bar{s}$ asymmetry**
- ✦ NNLO PDF not in good agreement with ATLAS 7 TeV data:
  - different jet-flavour algorithm
  - |Vcd|≠0 only at LO in calculations
  - large PDF uncertainty

JHEP 06 (2021) 100



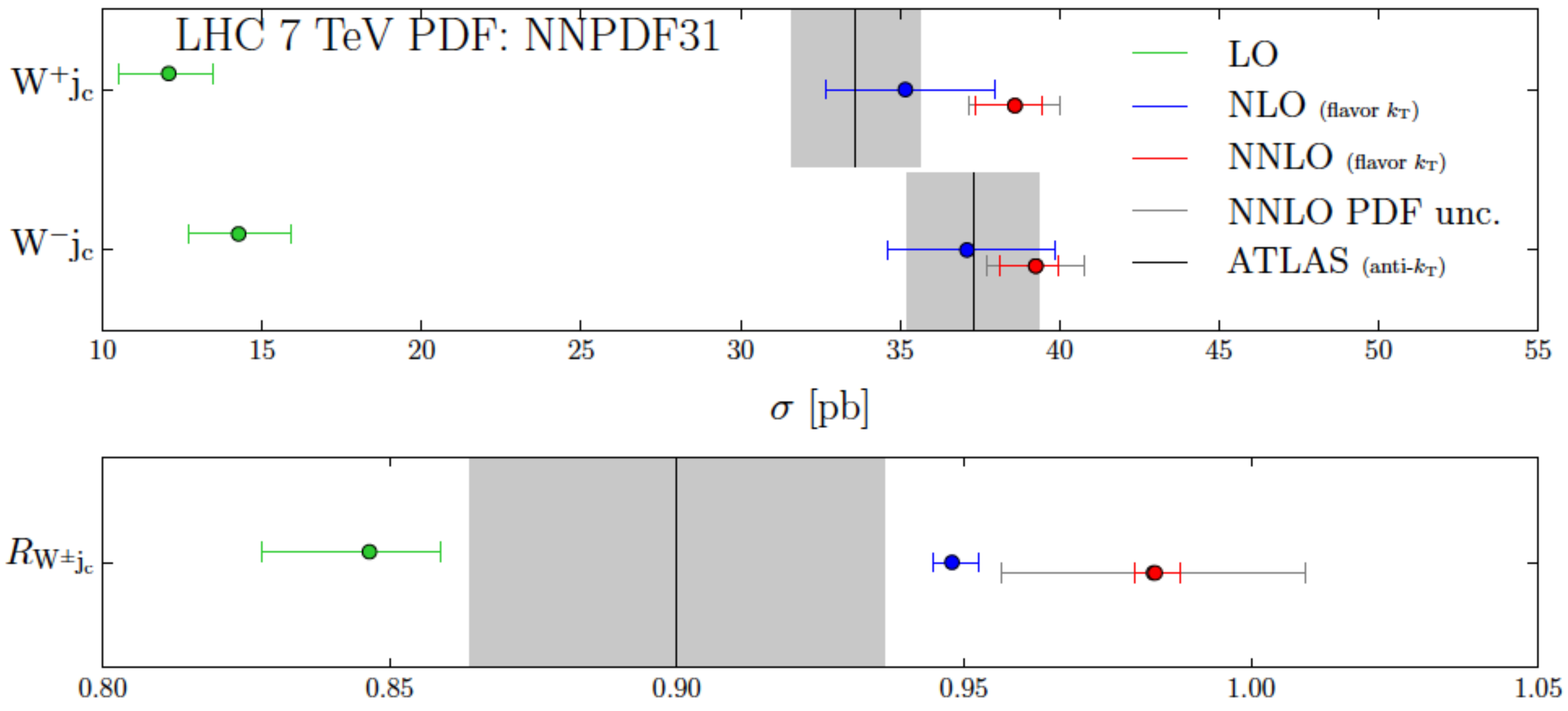
(a)

R_c in *W+D* production

- W+D production:
  - dominated by CKM diagonal terms (|Vcs|~90%), |Vcd|~10% at LO
  - off-diagonal |Vcd|~10% at LO (negligible at higher orders)
  - ➡ **$R_c < 1$ due to valence *d*-quark contribution**
  - ➡ $R_c \rightarrow 1$ including higher order corrections

$$\text{LO}: \quad R_c = \frac{|V_{cs}|\bar{s} + |V_{cd}|\bar{d}}{|V_{cs}|s + |V_{cd}|d}$$

JHEP 06 (2021) 100

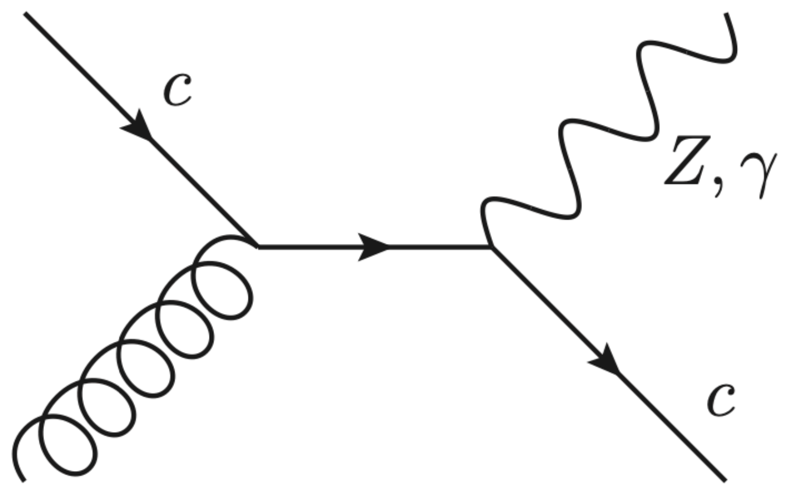


(a)

Intrinsic-Charm

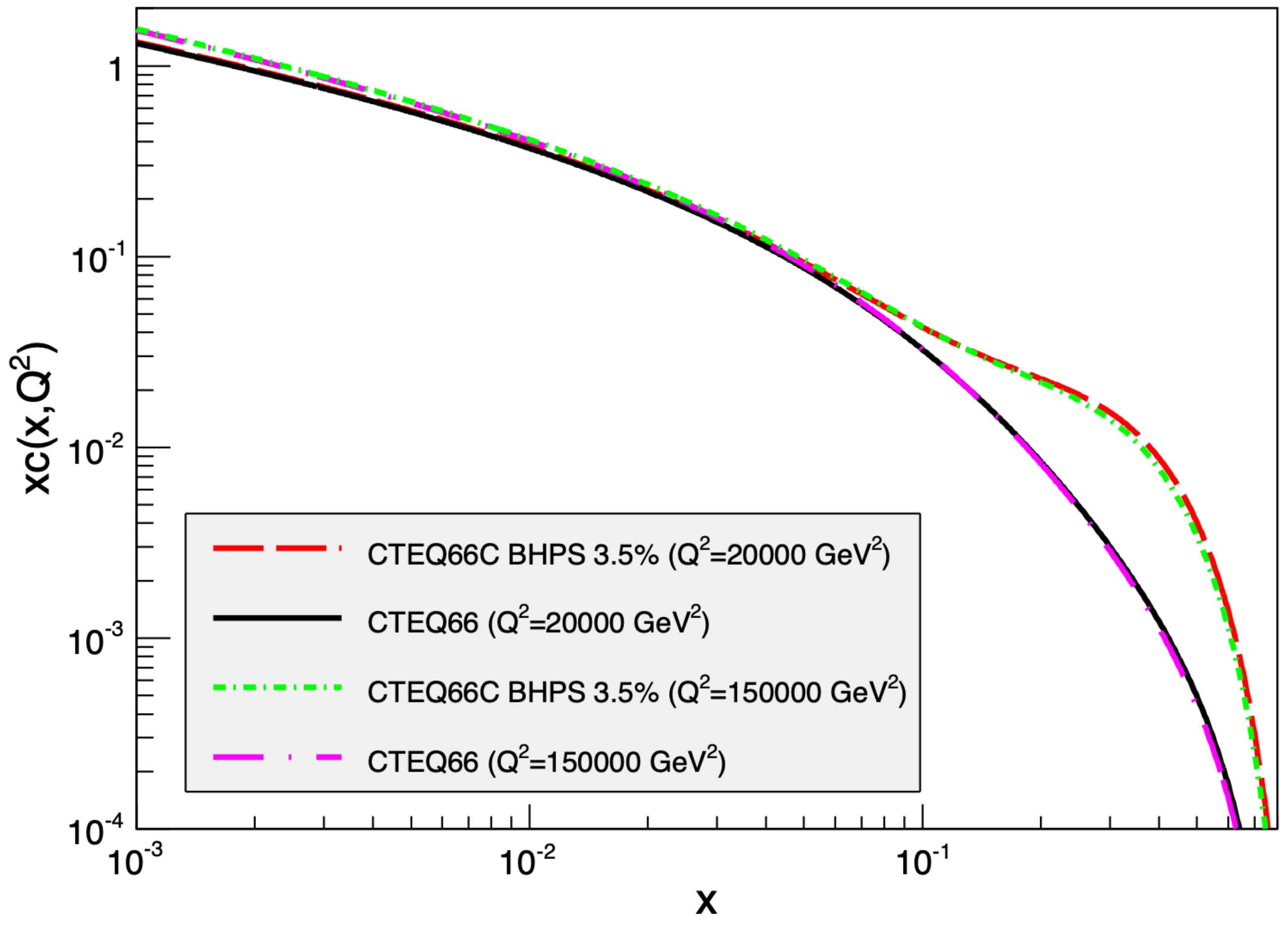
- PDFs give the probability of finding a parton with a certain momentum fraction x at a given scale μ
  - for $\mu < 1/\mu_0$ (long-distance scale): PDF cannot be calculated from QCD
  - for $\mu > \mu_0$ (short-distance scale): PDF can be calculated within pQCD (DGLAP evolution)
- Global analyses usually assume the HF-content of the proton to be negligible at $\mu = m_{s,c,b}$
  - ➡ HF-quarks arise only perturbatively through gluon-splitting
- 40 years ago the coexistence of an *extrinsic* and *intrinsic* contribution to the structure of the proton was postulated
  - *extrinsic* (ordinary) HF-quarks generated on a short -time scale → PDFs satisfy QCD evolution equations
  - *intrinsic* HF-quarks are assumed to exist over a timescale independent of any probed Q^2

- **Intrinsic Charm:** *c*-quark pairs as part of proton wave function at rest
  - ➡ *IC* expected at high Bjorken-x (>0.1)
  - ➡ expected higher sensitivity with hard *c*-jets in the forward region



IC: $\psi_p = |uudc\bar{c}\rangle$
not only via $g \to c\bar{c}$

Phys. Rev. D 92 (2015) 034014



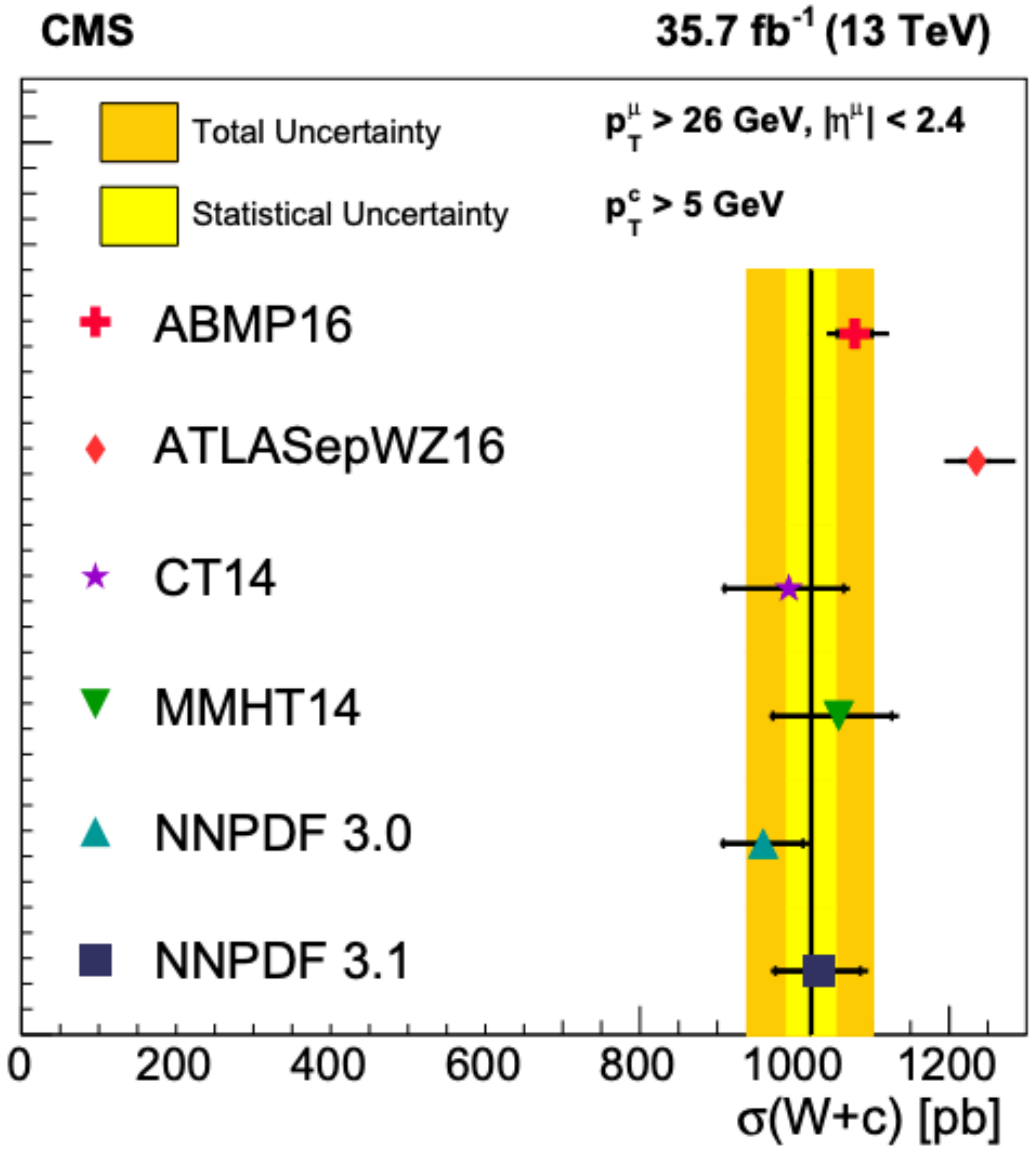
W + charmed hadron

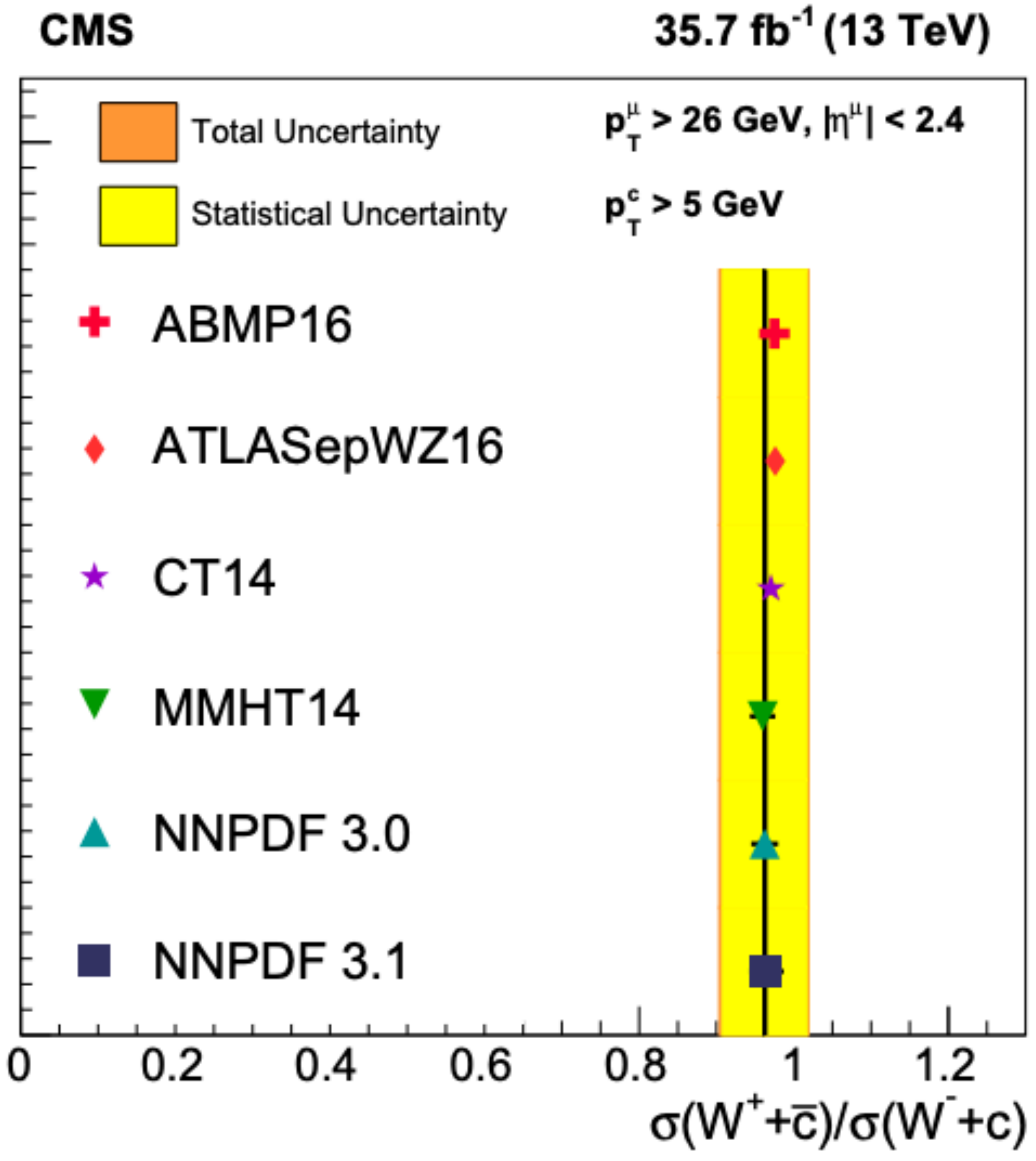
State of the art

Eur. Phys. J. C 79 (2019)269

$$\sigma(\mathrm{W{+}c}) = 1026 \pm 31\,(\mathrm{stat})^{+76}_{-72}\,(\mathrm{syst})\,\mathrm{pb}$$

$$\frac{\sigma(\mathrm{W^{+}{+}\bar{c}})}{\sigma(\mathrm{W^{-}{+}c})} = 0.968 \pm 0.055\,(\mathrm{stat})^{+0.015}_{-0.028}\,(\mathrm{syst})$$





MC Samples

- **SHERPA 2.2.11** - up to 2 partons in NLO Matrix Element (ME) - nominal MC
- alternative MCs: **MGAMC@NLO+PY8 with different setups** (multi-jet merged with FxFx or CKKW and NLO with finite *c*-quark mass)
- Samples generated by requiring the presence of a single lepton and $D^{+(*)}$, the latter forced to decay into $K^{-}\pi^{+}\pi^{+}$ mode

Process	ME generator	QCD accuracy	ME PDF	PS generator	UE tune	HF decay
W+jets (background modeling)						
W+jets	SHERPA 2.2.11	0–2j@NLO+3–5j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA
W+jets	aMC@NLO (CKKW-L)	0–4j@LO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
W+jets	aMC@NLO (FxFx)	0–3j@NLO	NNPDF3.1NNLO_luxqed	PYTHIA 8	A14	EVTGEN
W+$D^{(*)}$ (signal modeling and theory predictions)						
W+$D^{(*)}$	SHERPA 2.2.11	0–1j@NLO+2j@LO	NNPDF3.0NNLO	SHERPA	Default	EVTGEN
W+$D^{(*)}$	aMC@NLO (NLO)	NLO	NNPDF3.0NNLO	PYTHIA 8	A14	EVTGEN
W+$D^{(*)}$	aMC@NLO (FxFx)	0–3j@NLO	NNPDF3.1NNLO_luxqed	PYTHIA 8	A14	EVTGEN
Backgrounds						
Z+jets	SHERPA 2.2.11	0–2j@NLO+3–5j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA
$t\bar{t}$	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, Wt	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, t-channel	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, s-channel	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
$t\bar{t}V$	aMC@NLO	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Diboson fully leptonic	SHERPA 2.2.2	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA
Diboson hadronic	SHERPA 2.2.1	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA

Event Selection

	Electrons			Muons		
Features	`baseline`	`loose`	`tight`	`baseline`	`loose`	`tight`
p_{T}	$> 20\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$		$> 20\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$	
$\lvert\Delta z_0^{\mathrm{BL}} \sin(\theta)\rvert$	< 0.5 mm			< 0.5 mm		
$\lvert d_0^{\mathrm{BL}}/\sigma(d_0^{\mathrm{BL}})\rvert$	< 5			< 3		
Pseudorapidity	$(\lvert\eta\rvert < 1.37) \lvert\rvert (1.52 < \lvert\eta\rvert < 2.47)$			$\lvert\eta\rvert < 2.5$		
Identification	Tight			Tight		
Isolation	No		Yes	No		Yes

D Meson Properties

D Species	D Mass [GeV]	Production Fraction (%)	Final State	BR (%)
D^+	1.87	24.04	$K^- \pi^+ \pi^+$	9.46
$D^{*+} \to D^0 \pi^+$ (D^* properties)	1.86 (2.01)	60.86 (24.29)	$(K^- \pi^+)\, \pi^+$	67.7 × 3.95

$D^{(*)}$ cut	D^+ cut value	D^{*+} cut value ($D^0\pi \to (K\pi)\pi$)
N_{tracks} at SV	3	2
SV charge	± 1	0
SV fit quality	$\chi^2 < 8$	$\chi^2 < 10$
Track p_{T}	$p_{\mathrm{T}} > 800\,\mathrm{MeV}$	$p_{\mathrm{T}} > 600\,\mathrm{MeV}$
Track angular separation	$\Delta R < 0.6$	$\Delta R < 0.6$
Flight length	$L_{xy} > 1.1\,\mathrm{mm}\ (p_{\mathrm{T}}(D^+) < 40\,\mathrm{GeV})$ $L_{xy} > 2.5\,\mathrm{mm}\ (p_{\mathrm{T}}(D^+) \geq 40\,\mathrm{GeV})$	$L_{xy} > 0\,\mathrm{mm}$
SV impact parameter	$\lvert d_0\rvert < 1\,\mathrm{mm}$	$\lvert d_0\rvert < 1\,\mathrm{mm}$
SV 3D impact significance	$\sigma_{3D} < 4.0$	$\sigma_{3D} < 4.0$
Combinatorial background rejection	$\cos\theta^*(K) > -0.8$	—
Isolation	$\Sigma p_{\mathrm{T}}{}^{\Delta R<0.4}_{\mathrm{tracks}}/p_{\mathrm{T}}(D^+) < 1.0$	$\Sigma p_{\mathrm{T}}{}^{\Delta R<0.4}_{\mathrm{tracks}}/p_{\mathrm{T}}(D^{*+}) < 1.0$
$D_s^{\pm} \to \phi\pi^{\pm}$ rejection	$m(K^+K^-) > \lvert m_\phi - 8\rvert$ MeV	—
D^{*+} background rejection	$m(K\pi\pi) - m(K\pi) > 160\,\mathrm{MeV}$	—
D^0 mass	—	$\lvert m_{K\pi} - m_{D^0}\rvert < 40\,\mathrm{MeV}$
π_{slow} p_{T}	—	$p_{\mathrm{T}} > 500\,\mathrm{MeV}$
π_{slow} angular separation	—	$\Delta R(\pi_{\mathrm{slow}}, D^0) < 0.3$
π_{slow} d_0	—	$\lvert d_0\rvert < 1\,\mathrm{mm}$
QCD background rejection	$\Delta R(D^+, \ell) > 0.3$	$\Delta R(D^{*+}, \ell) > 0.3$
$D^{(*)}$ p_{T}	$8\,\mathrm{GeV} < p_{\mathrm{T}}(D^+) < 150\,\mathrm{GeV}$	$8\,\mathrm{GeV} < p_{\mathrm{T}}(D^{*+}) < 150\,\mathrm{GeV}$
$D^{(*)}$ η	$\lvert\eta(D^+)\rvert < 2.2$	$\lvert\eta(D^{*+})\rvert < 2.2$
Invariant mass	$1.7\,\mathrm{GeV} < m(D^+) < 2.2\,\mathrm{GeV}$	$140\,\mathrm{MeV} < m(D^{*+}{-}D^0) < 180\,\mathrm{MeV}$

Multijet background

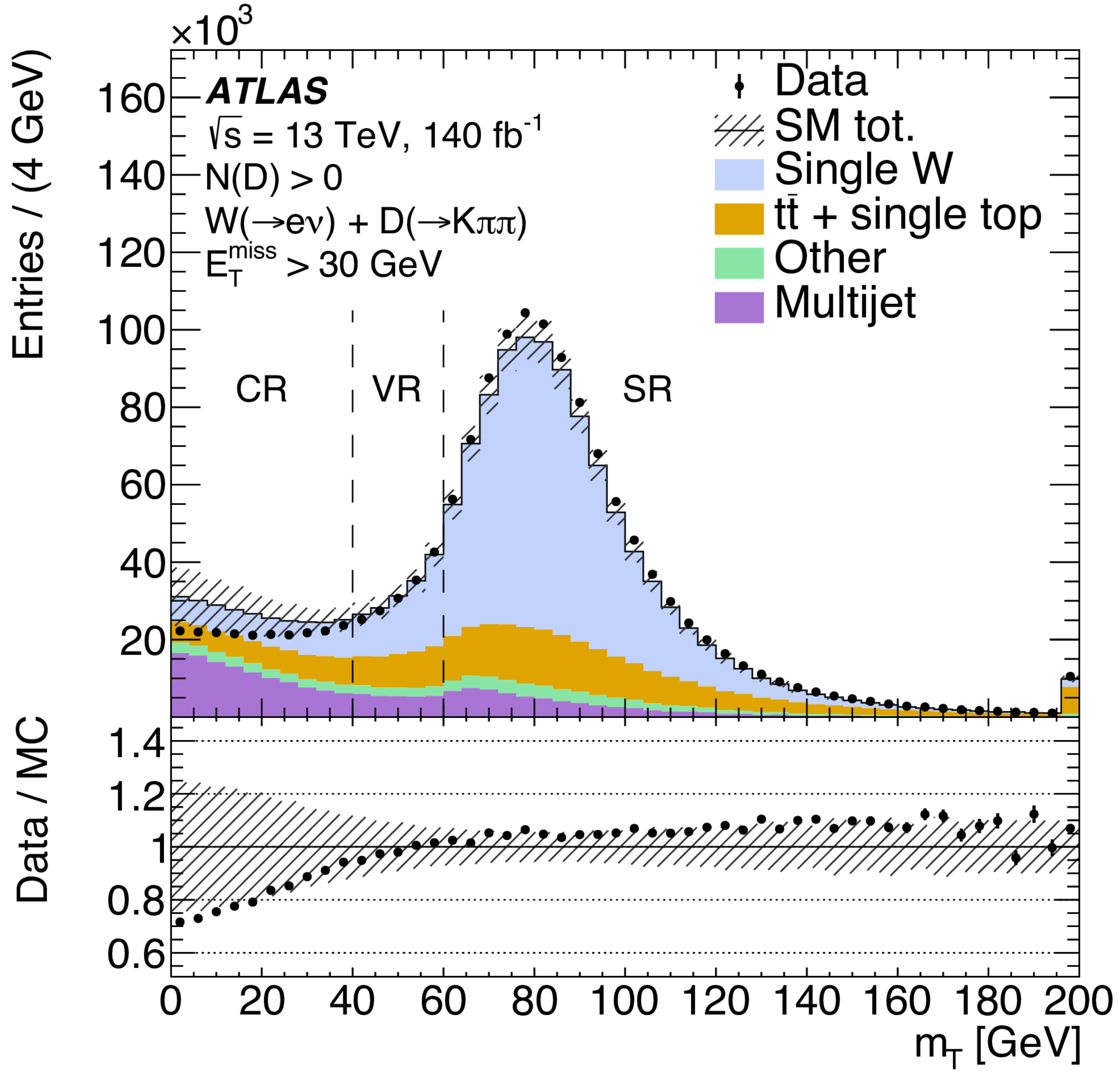
✦ **Multijet (MJ) background modelled using Matrix-Method (data-driven)**

✦ Matrix-method measures **fake/real lepton efficiencies** and estimates MJ from anti-Tight data

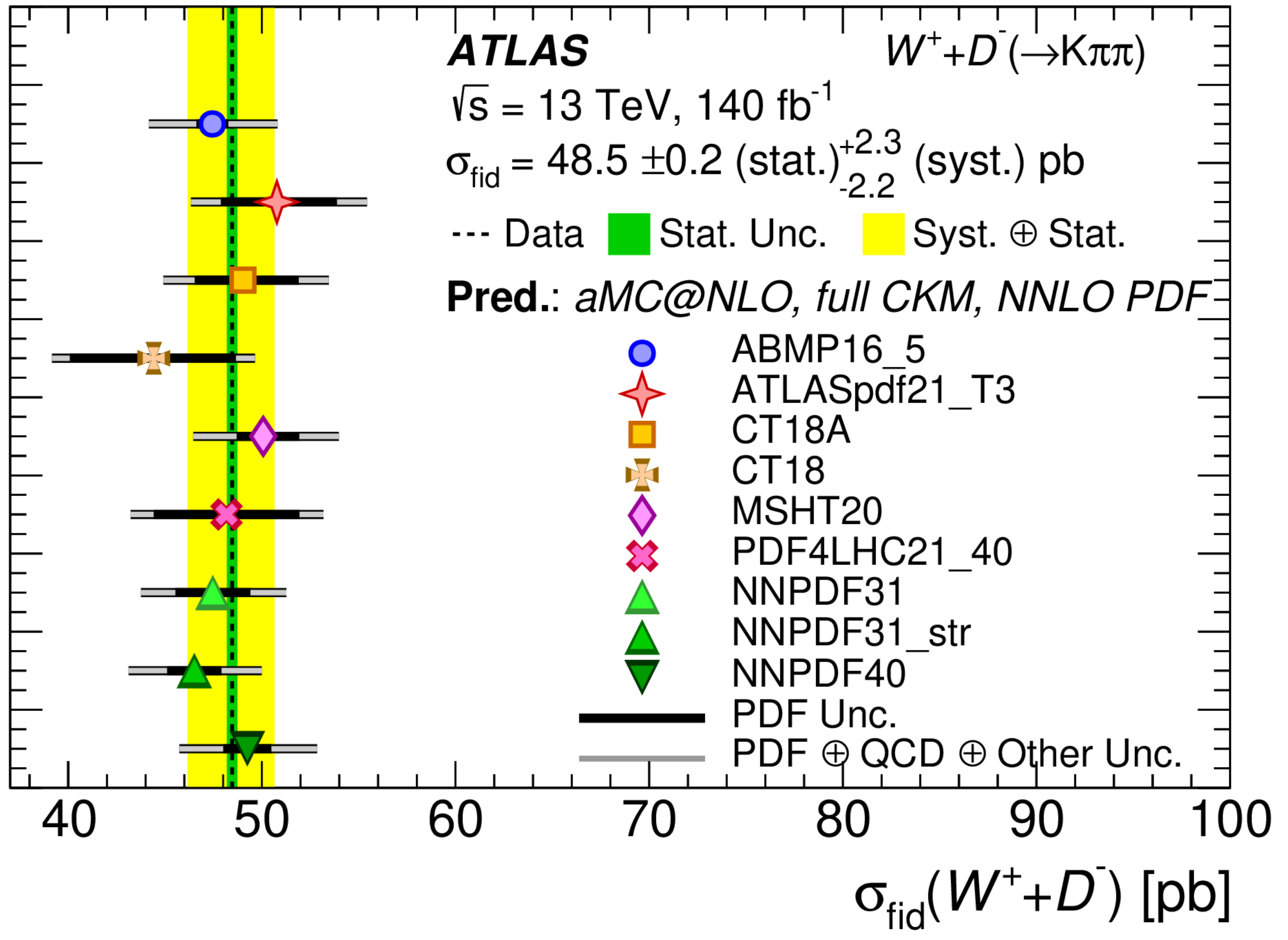
- ✦ real lepton efficiencies - in *W*+*D* SR
- ✦ fake lepton efficiencies - measured in CR defined by
  - ✦ inverted *W* selection (E_T^{miss}<30 GeV, m_T<40 GeV)
  - ✦ inverting isolation

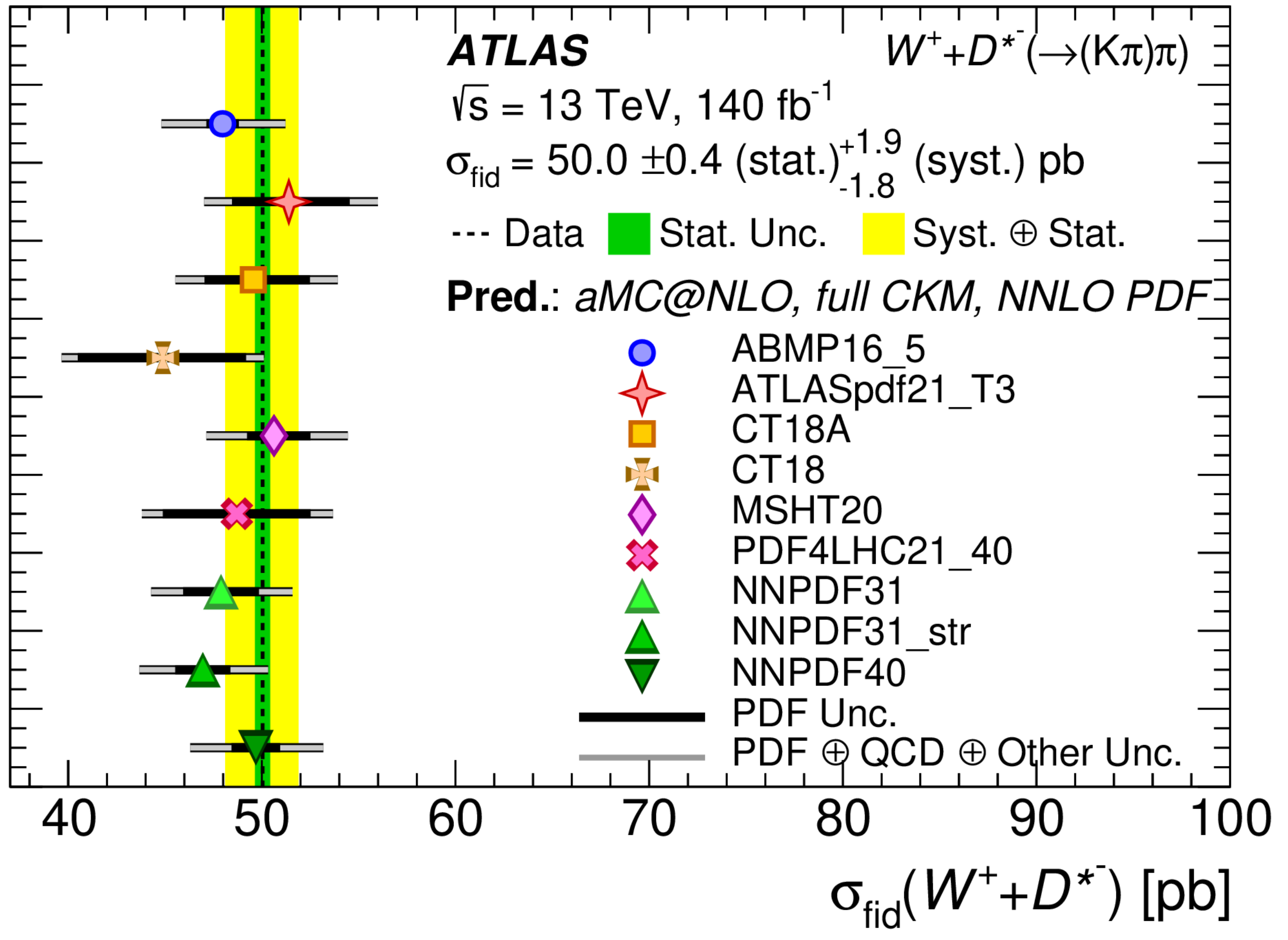
✦ systematics on the dependence of the fake efficiency from E_T^{miss} ~ 50-60%

➡ **MJ contribution at ~% level**, so the large associated uncertainties are subdominant in the fit



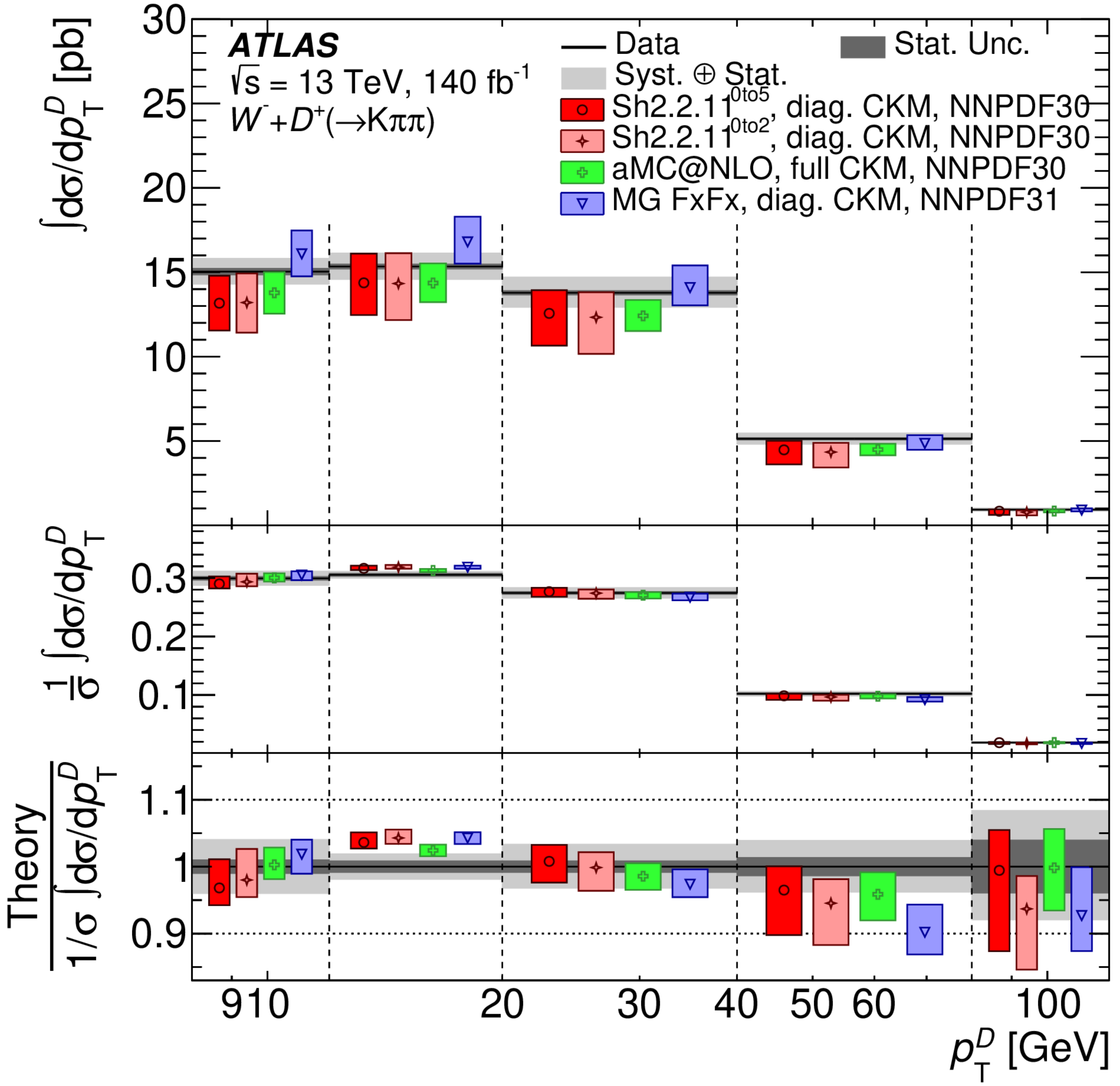
Inclusive cross-section results

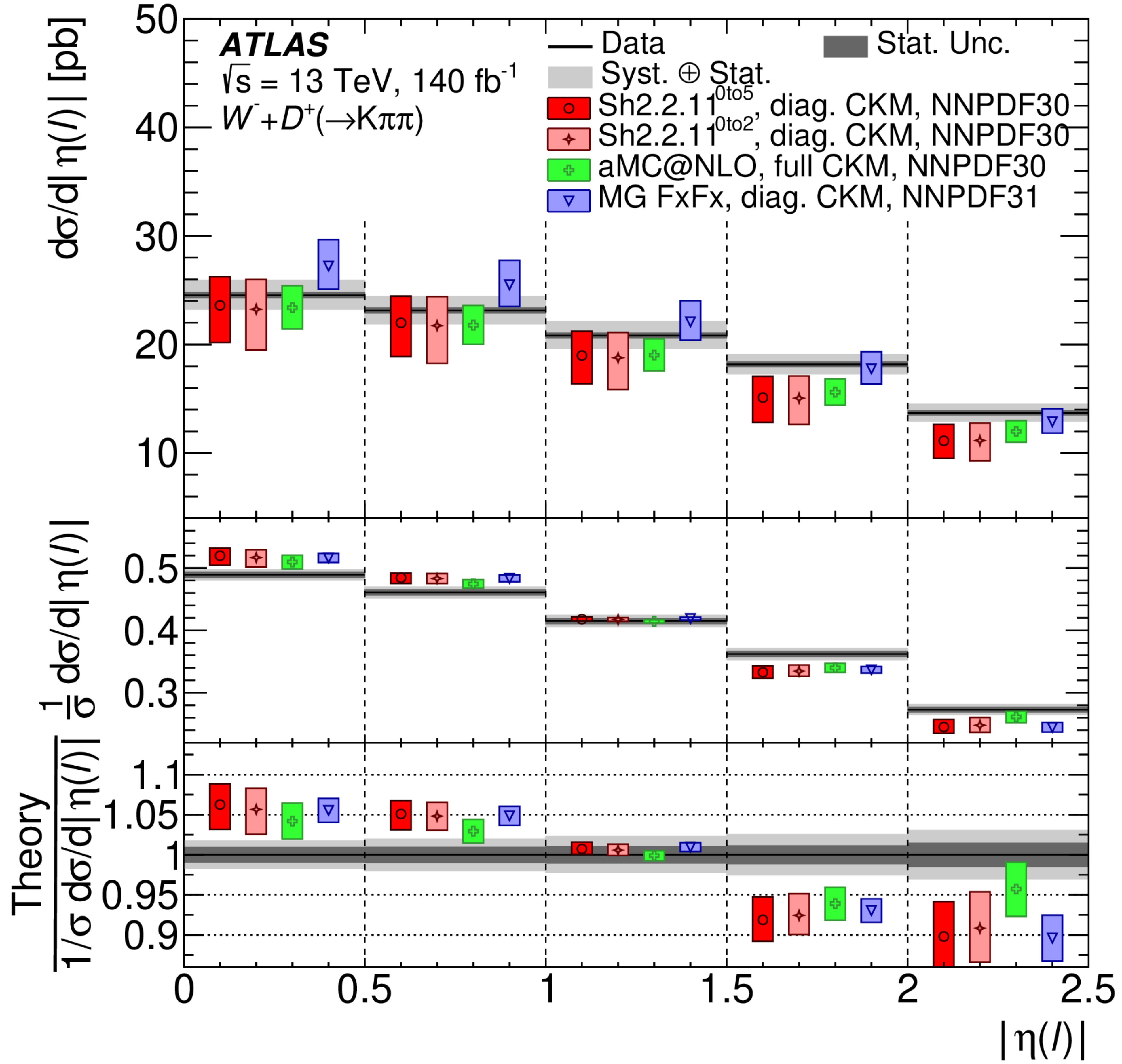




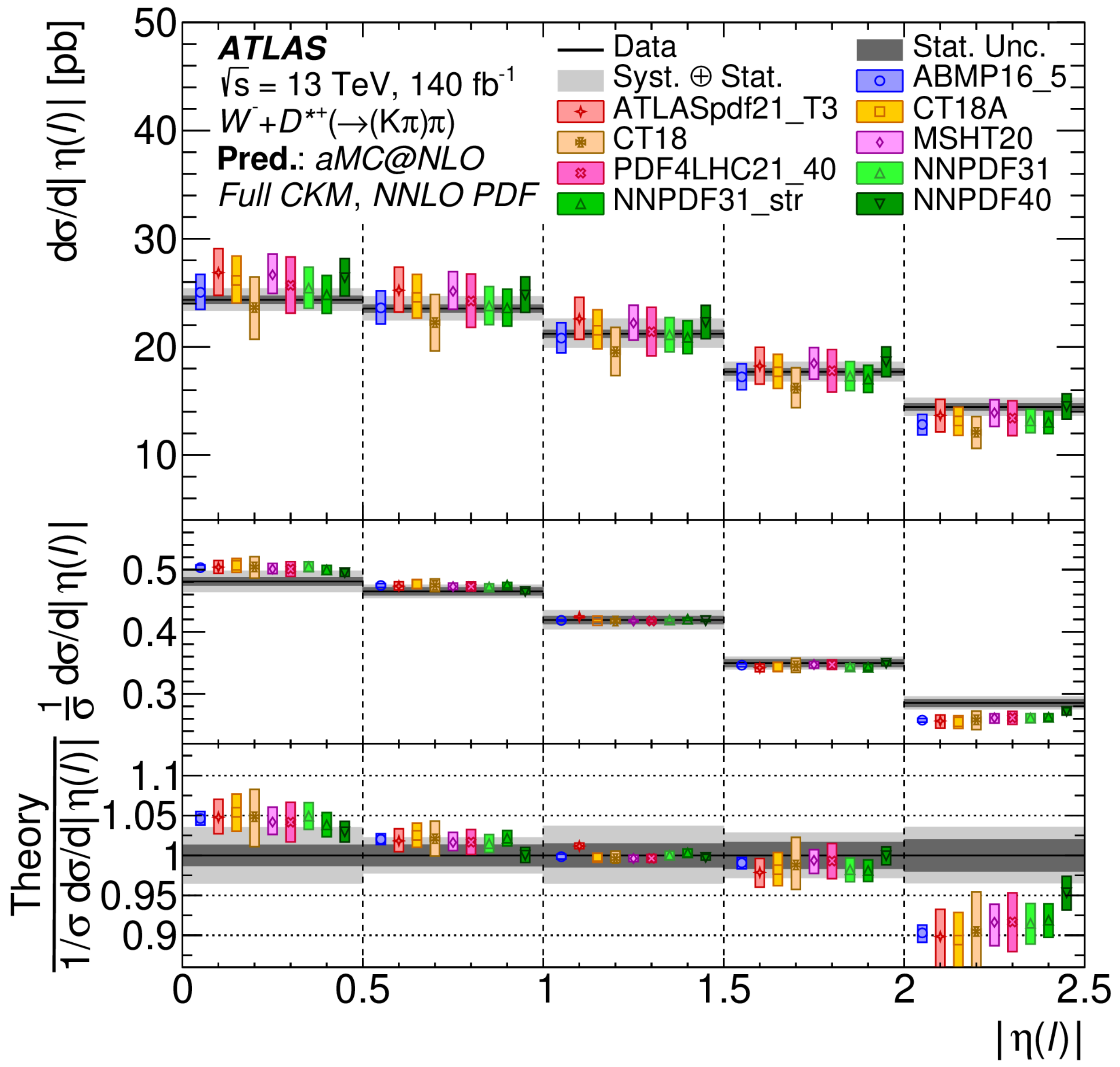
Channel	$\sigma_{\text{fid}}^{\text{OS-SS}}(W{+}D^{(*)}) \times B(W \to \ell\nu)$ [pb]
$W^-{+}D^+$	50.2 ± 0.2 (stat.) $^{+2.4}_{-2.3}$ (syst.)
$W^+{+}D^-$	48.5 ± 0.2 (stat.) $^{+2.3}_{-2.2}$ (syst.)
$W^-{+}D^{*+}$	51.1 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
$W^+{+}D^{*-}$	50.0 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
	$R_c^{\pm} = \sigma_{\text{fid}}^{\text{OS-SS}}(W^+{+}D^{(*)}) / \sigma_{\text{fid}}^{\text{OS-SS}}(W^-{+}D^{(*)})$
$R_c^{\pm}(D^+)$	0.965 ± 0.007 (stat.) ± 0.012 (syst.)
$R_c^{\pm}(D^{*+})$	0.980 ± 0.010 (stat.) ± 0.013 (syst.)
$R_c^{\pm}(D^{(*)})$	0.971 ± 0.006 (stat.) ± 0.011 (syst.)

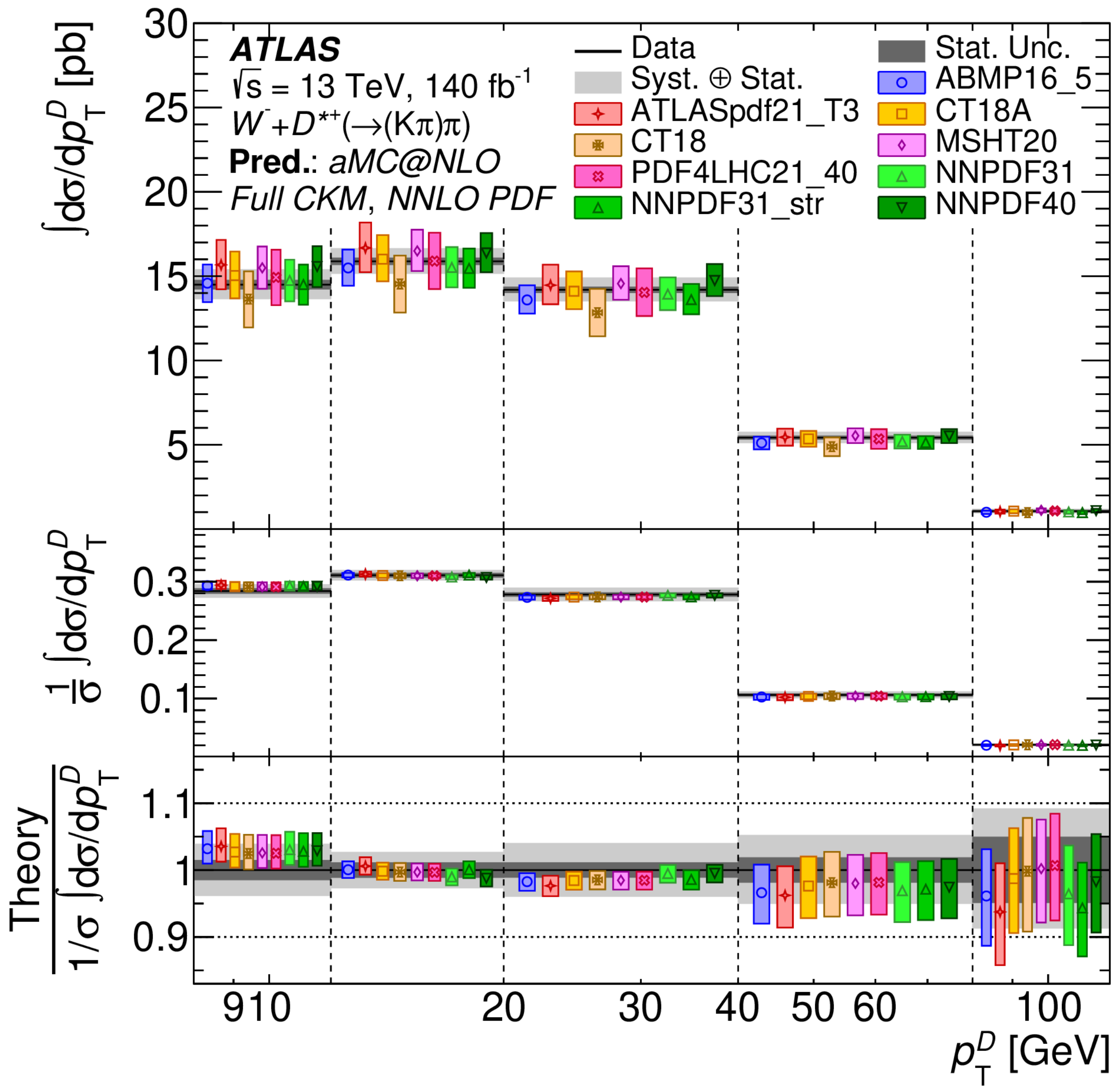
Differential cross-section results

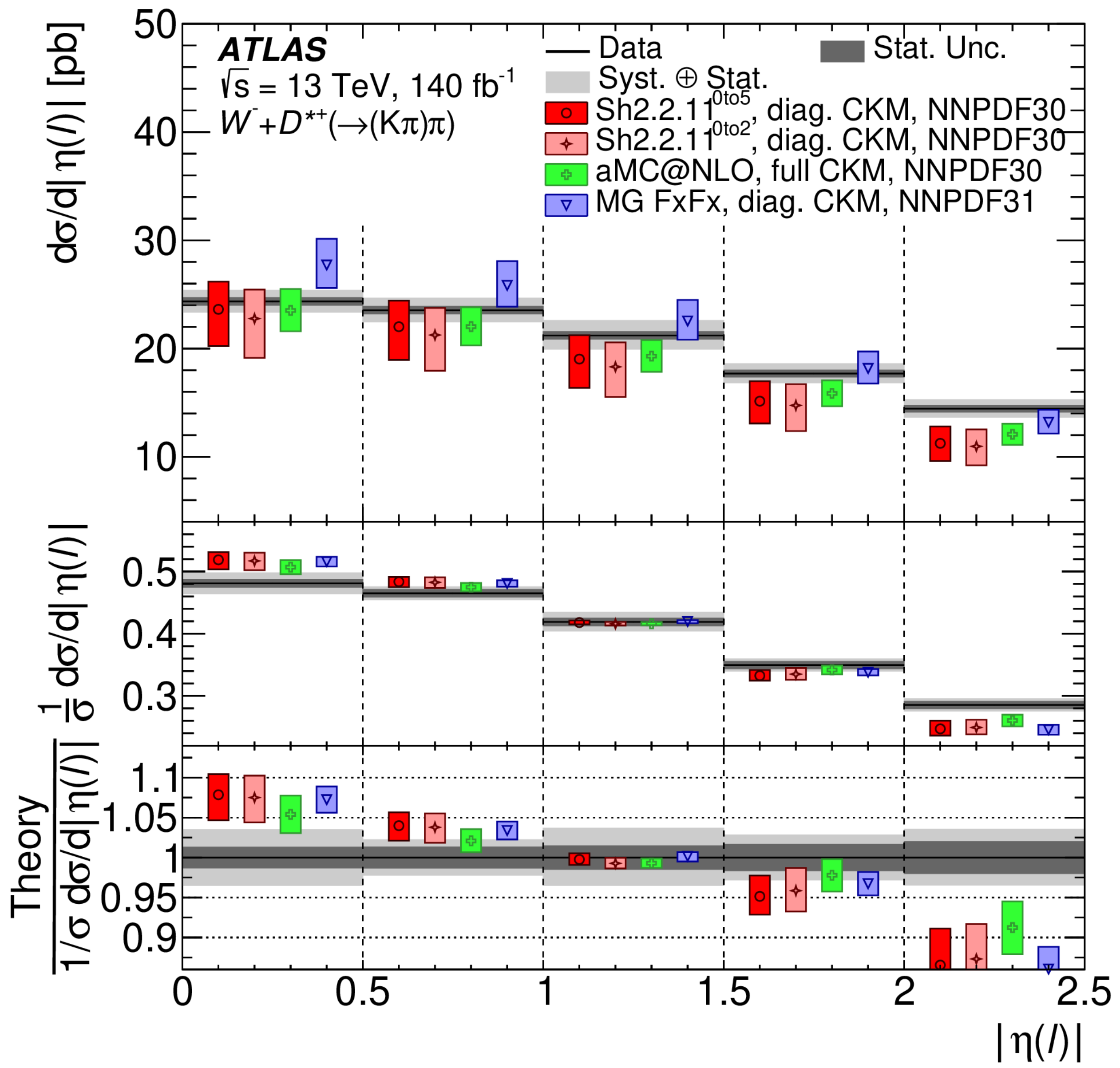


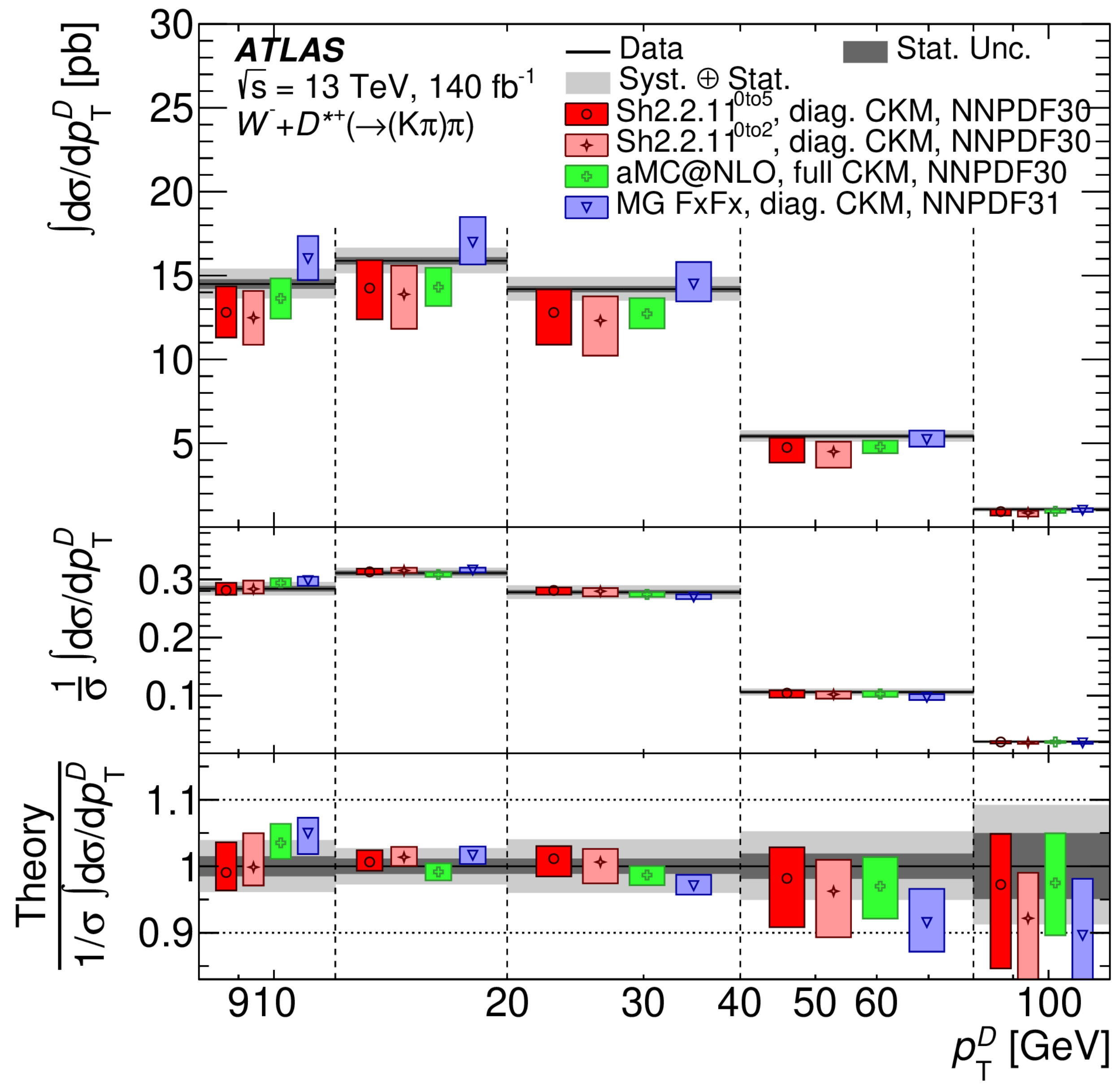


Differential cross-section results









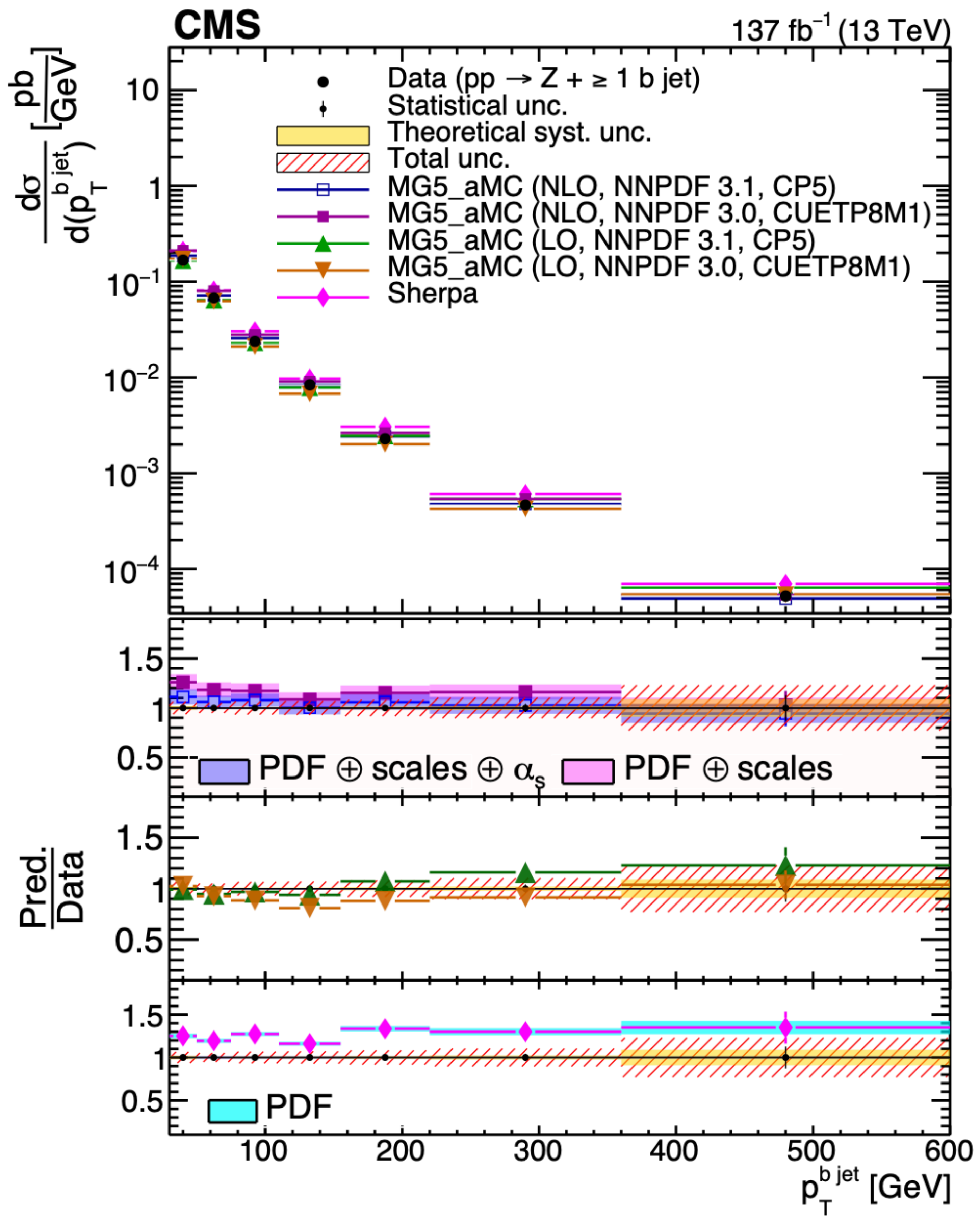
Z + HF jets

State of the art

Z + b-jet

- ✦ **ATLAS:** resolved and boosted with 36 fb^{-1}
- ✦ **CMS:** with 137 fb^{-1}

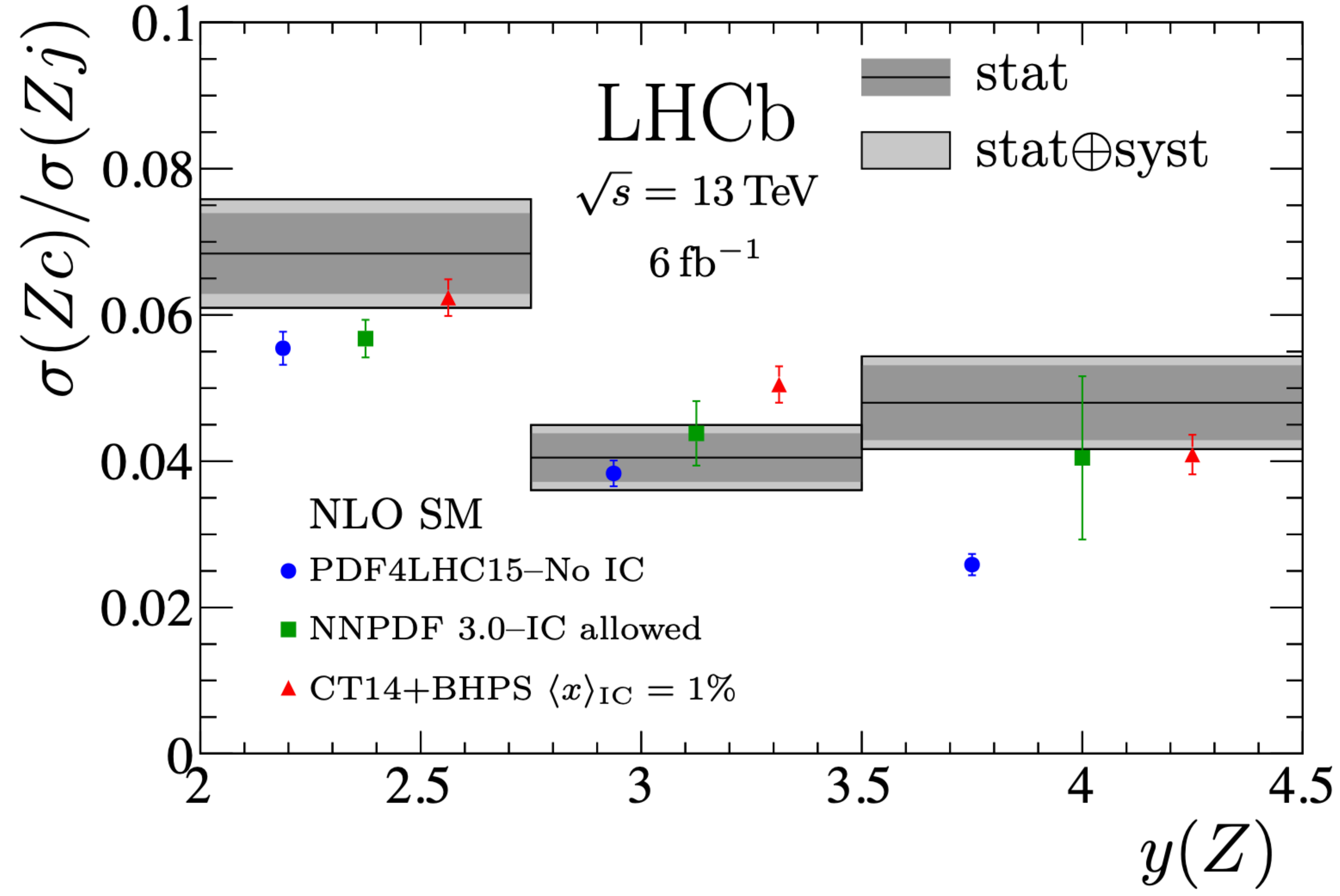
Phys. Rev. D 105, 092014



Z + c-jet

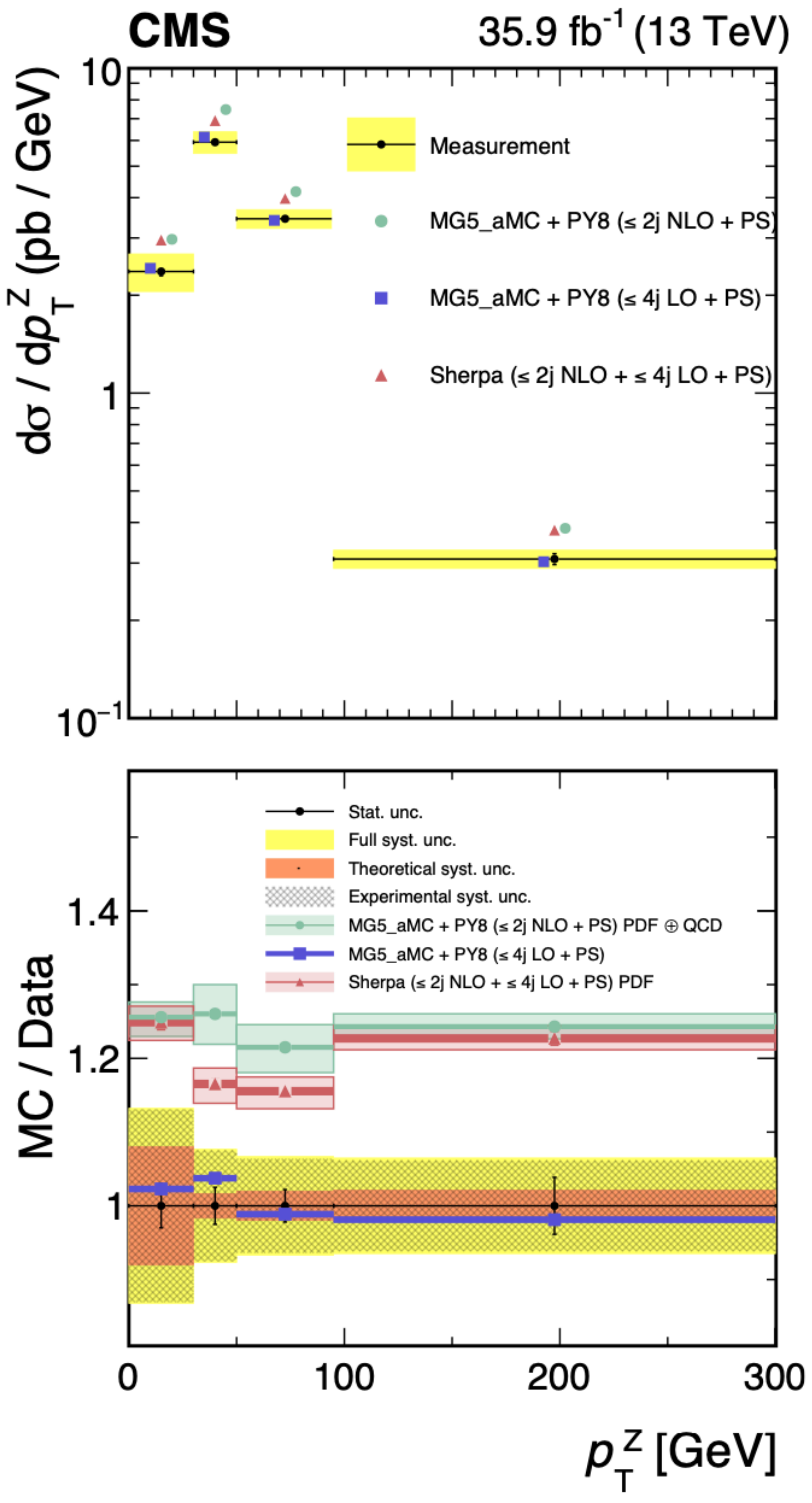
- ✦ **LHCb:** with 6 fb^{-1}

Phys. Rev. Lett. 128 (2022) 082001



- ✦ **CMS:** with 36 fb^{-1}

JHEP 04 (2021) 109



Event selection

Object definition		
	Electron channel	Muon channel
Leptons	Single electron trigger Tight Isolated $d_0/\sigma_{d_0} < 5$, $\|z_0 \sin(\theta)\| < 0.5$ mm $p_T > 27$ GeV $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	Single muon trigger Medium Isolated $d_0/\sigma_{d_0} < 3$, $\|z_0 \sin(\theta)\| < 0.5$ mm $p_T > 27$ GeV $\|\eta\| < 2.5$
Jets	$p_T > 20$ GeV and $\|y\| < 2.5$ $\Delta R(\text{jet}, \ell) > 0.4$	
Flavour-tagged jets	$p_T > 20$ GeV and $\|y\| < 2.5$ DL1r@85%	

Event selection	
Leptons	Exactly 2, same-flavour, opposite-charge
$m_{\ell\ell}$	76 GeV $< m_{\ell\ell} <$ 106 GeV
E_T^{miss}	$E_T^{miss} < 60$ GeV if $p_T^{\ell\ell} < 150$ GeV
Flavour-tagged jets	≥ 1 or ≥ 2 jets, DL1r@85%
Signal regions	
1-tag	≥ 1 flavour-tagged jets
2-tag	≥ 2 flavour-tagged jets
Rapidity regions	
Central rapidity	Z boson rapidity $\|y(Z)\| < 1.2$
Forward rapidity	Z boson rapidity $\|y(Z)\| \geq 1.2$

Jet flavour algorithm

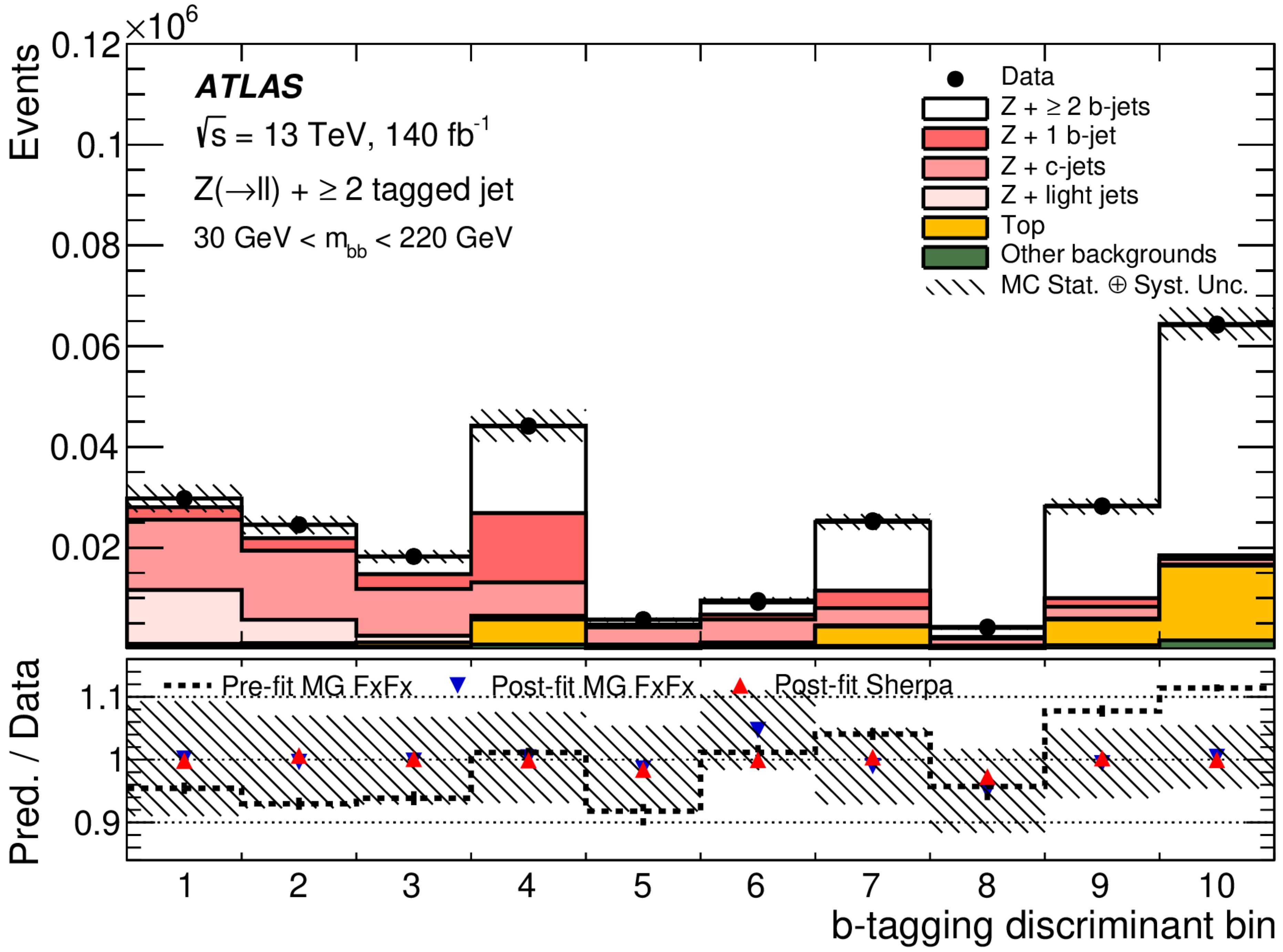
- **Jet flavour classification in measurement: cone-based algorithm**
  - *b*-jets = jets lie within ΔR=0.3 of at least one *b*-hadron with p_T> 5 GeV. If a *b*-hadron matches two jets, only the closest in ΔR is taken
  - *c*-jets = jets not classified as b-jets, are considered to be c-jets if they lie within ΔR=0.3 of at least one *c*-hadron with p_T> 5 GeV.
  - light-jets = all the others

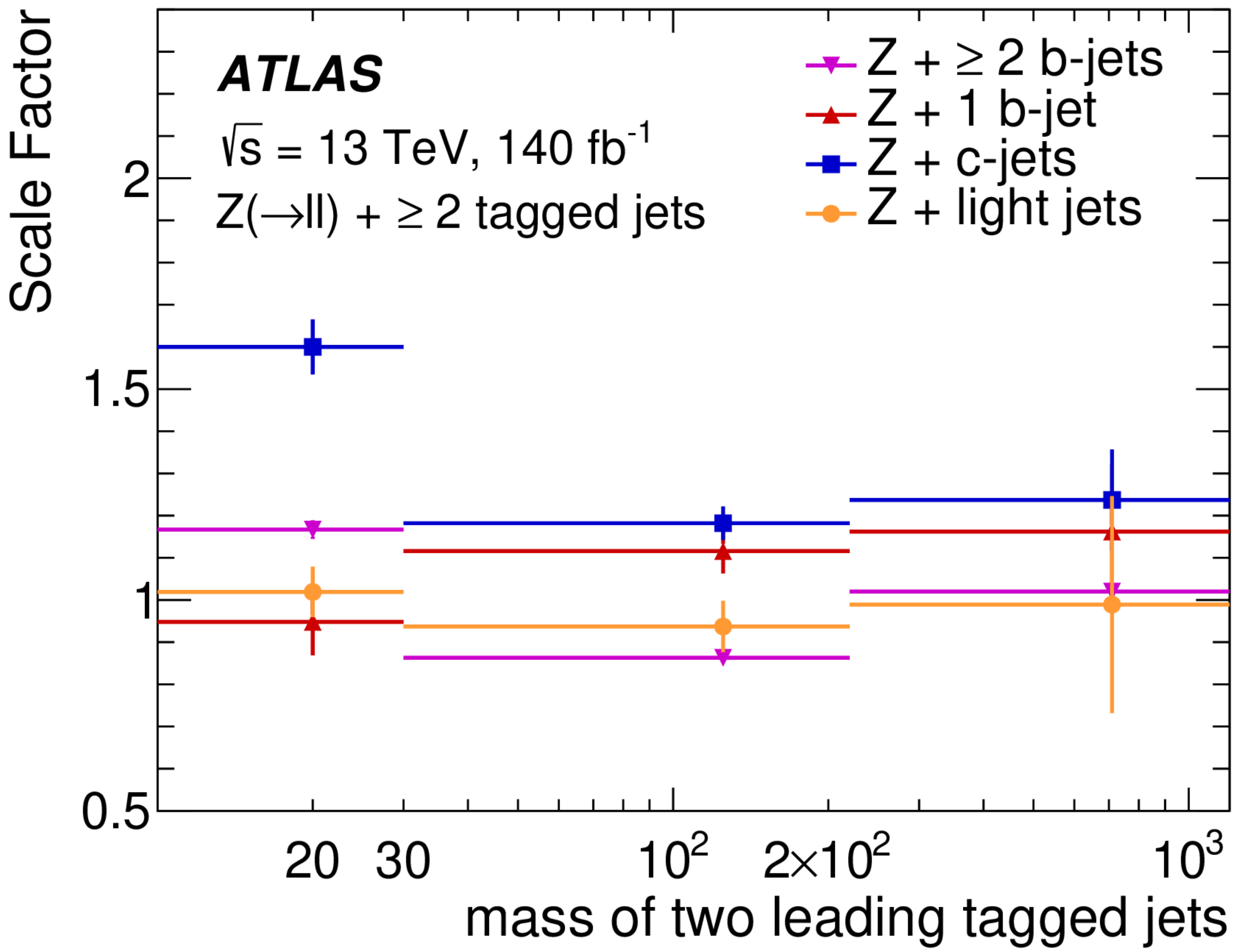
- **Corrections to fixed-order predictions to compare with measurements**
  - hadronisation and multi-parton interactions (MPI)
    - hadron-level / parton-level distributions of PYTHIA 8.3831 samples
  - **jet flavour definition**
    - hadron level distributions with cone-based algorithm / flavour-dressing algorithm
    - derived with MGAMC@NLO+PY8 FXFX and SHERPA and the difference is taken as systematic

Flavour fit in 2-tag SR

2-tag SR:

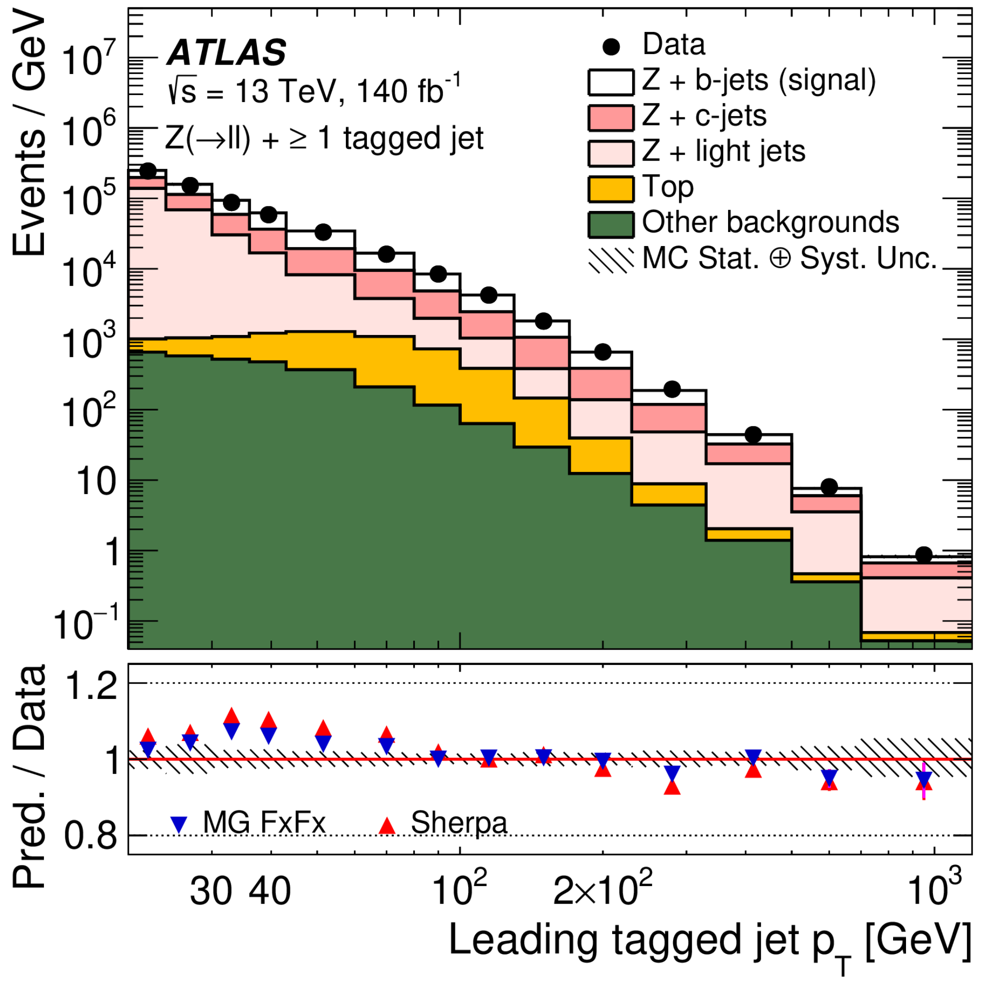
- Discriminating variable: **combination of leading and sub-leading flavour-tagged jet DL1r score**
- 4 free parameters corresponding to ***Z*+≥2 *b*-jets**, ***Z*+1 *b*-jet**, ***Z*+≥1 *c*-jet** and ***Z*+≥light jets** normalisation

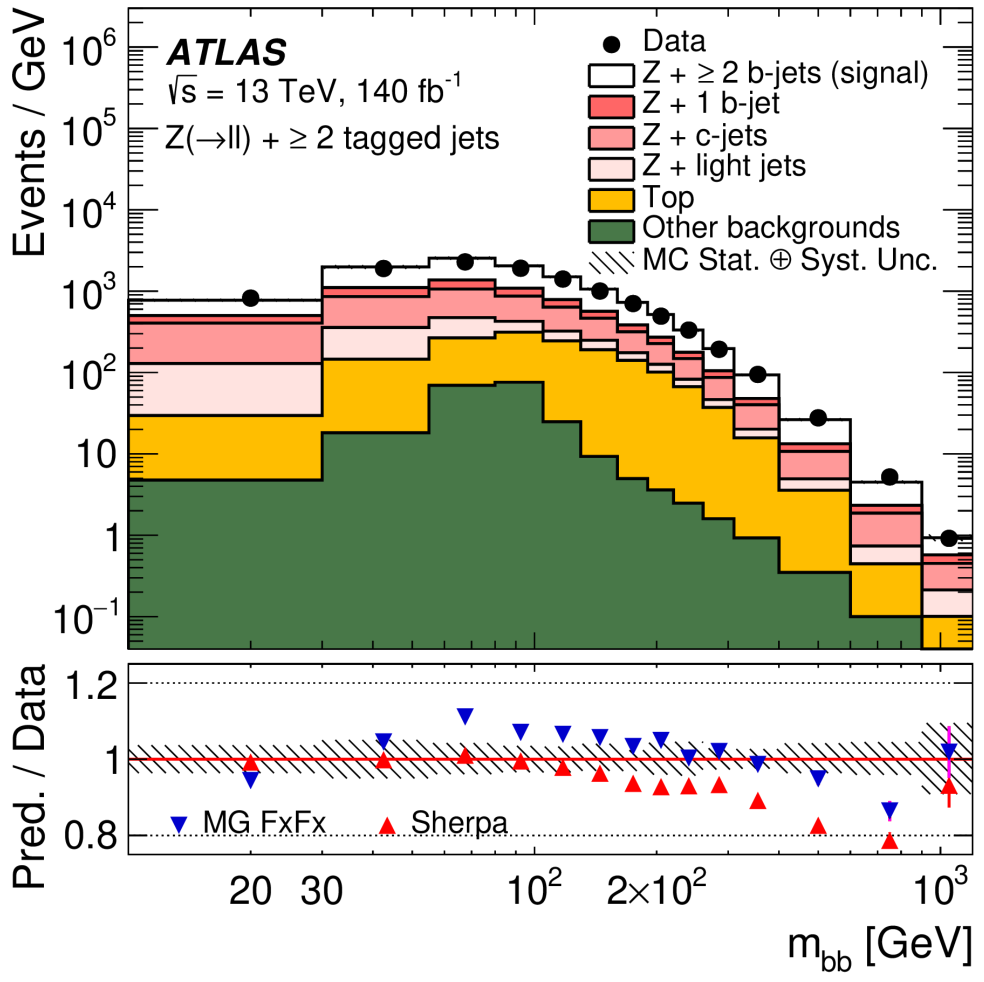


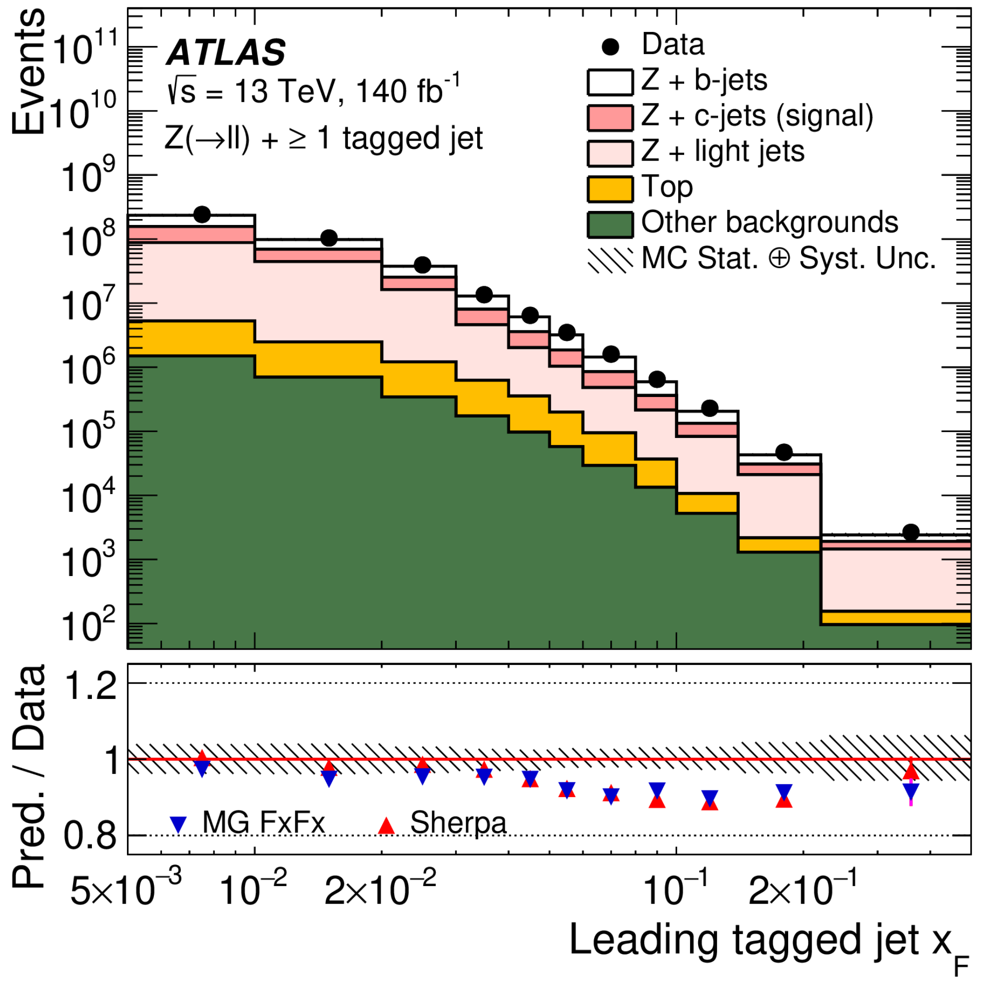


Post-fit signal and background contribution

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







1-tag region	
Signal $Z + \geq 1$ 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

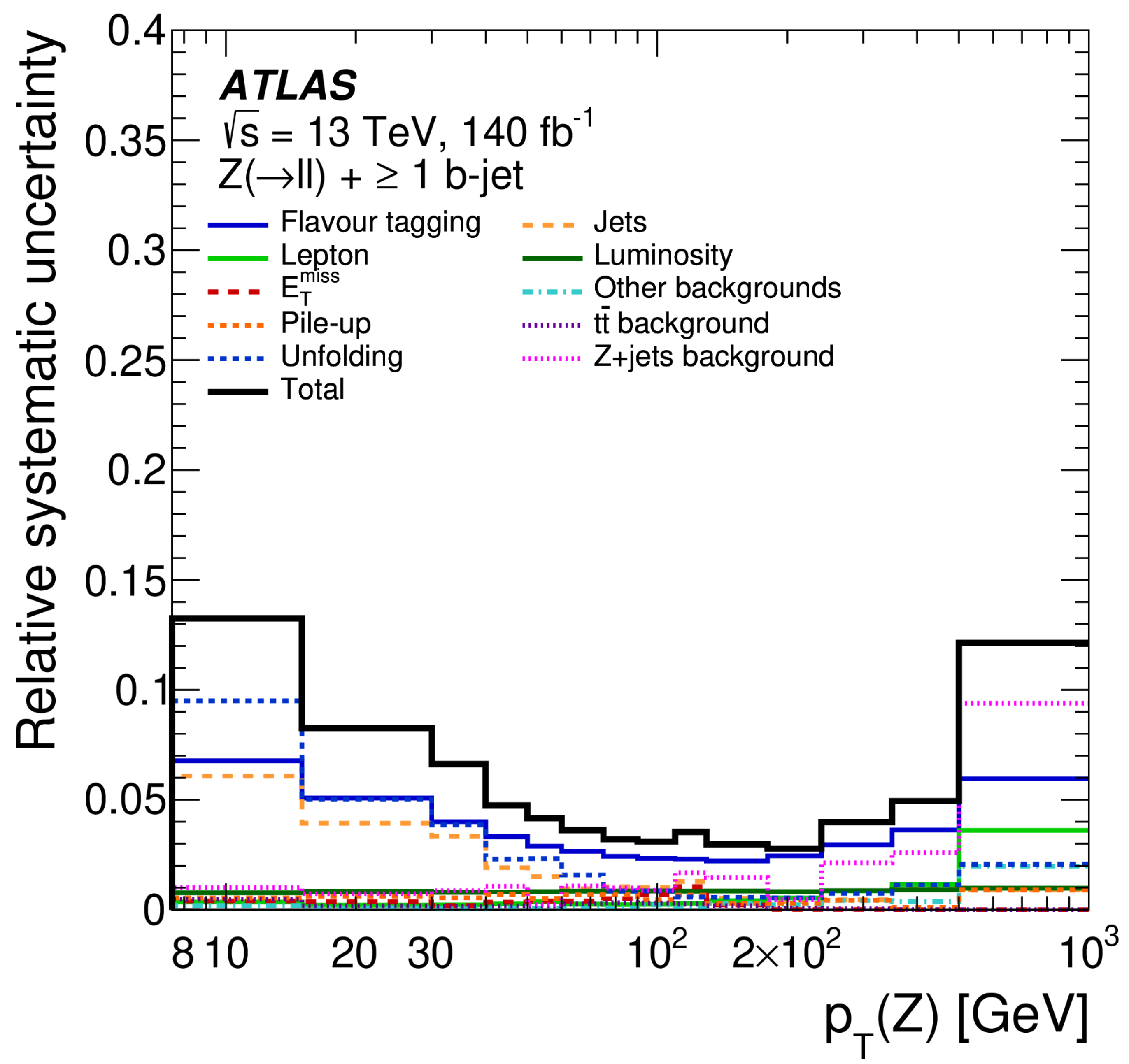
2-tag region	
Signal $Z + \geq 2$ b-jets	
$Z+bb$	46%
Backgrounds	
$Z+b$	11%
$Z+c$	23%
$Z+l$	7%
Top	12%
Others	2%
Total predicted	325 300 ± 600
Data	309 199

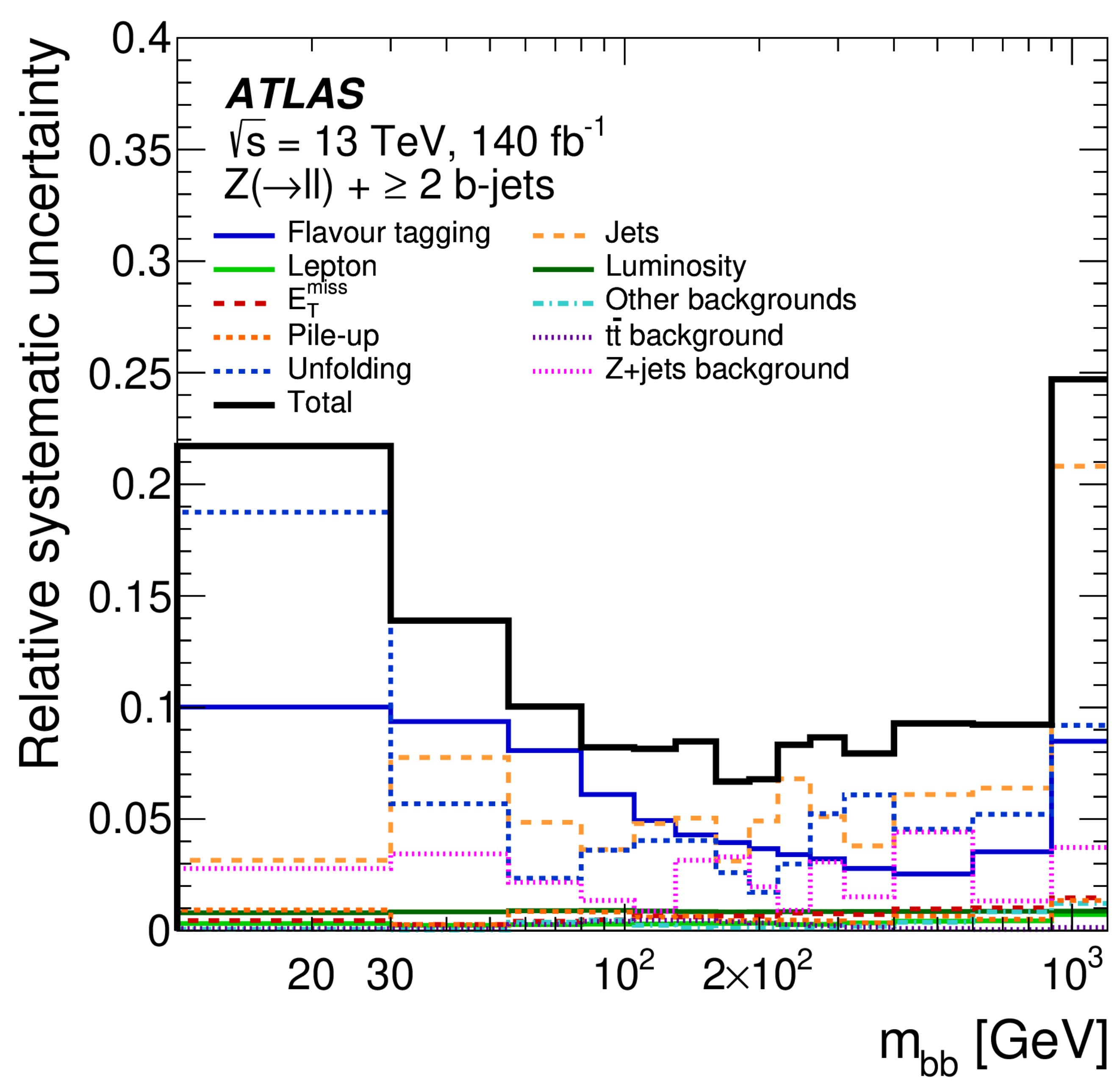
1-tag region	
Signal $Z + \geq 1$ c-jet	
$Z+c$	28%
Backgrounds	
$Z+b$, $Z+bb$	33%
$Z+l$	37%
Top	2%
Others	1%
Total predicted	3 994 400 ± 2000
Data	4 145 168

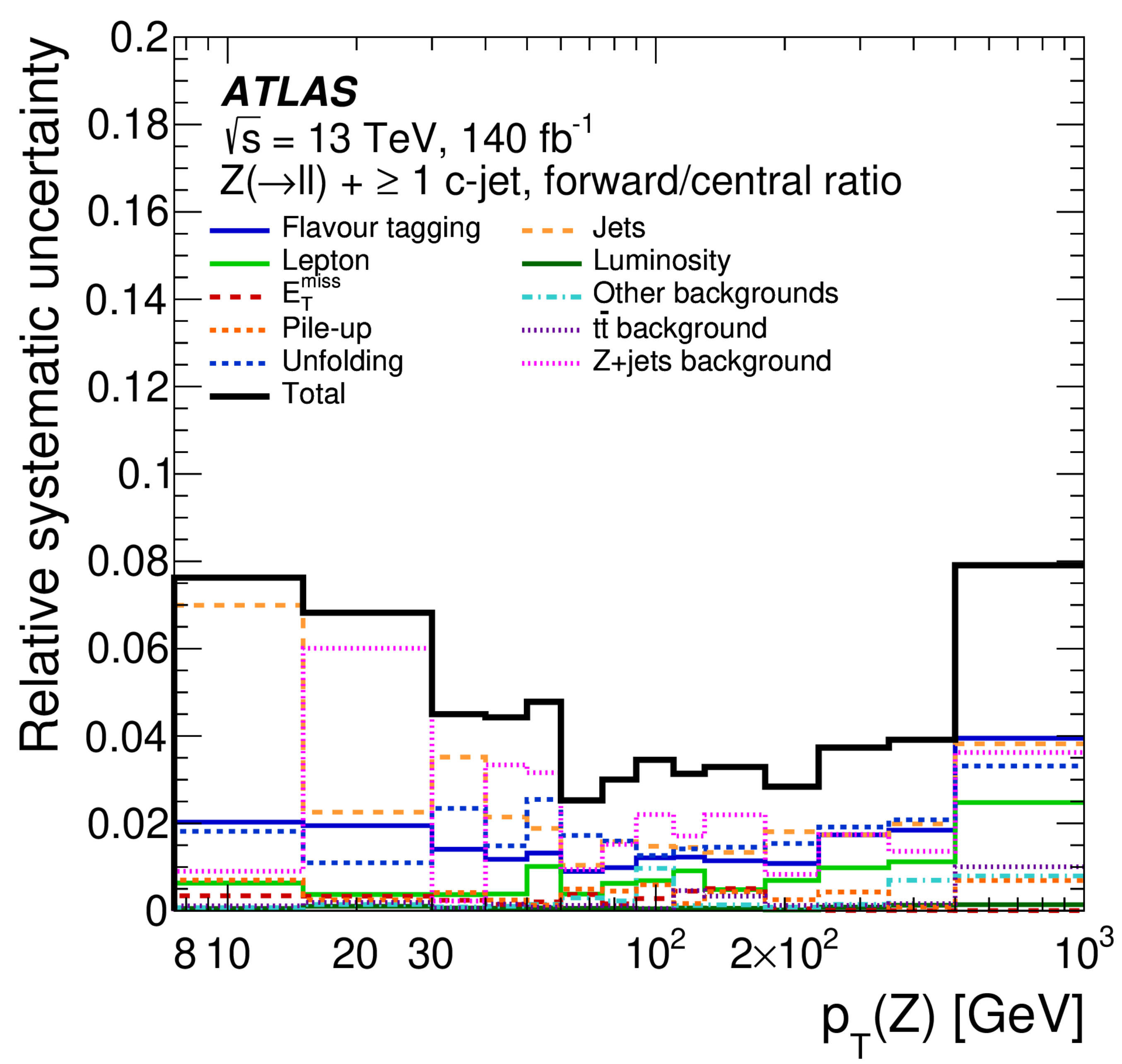
Uncertainties on the cross section measurements

- **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)

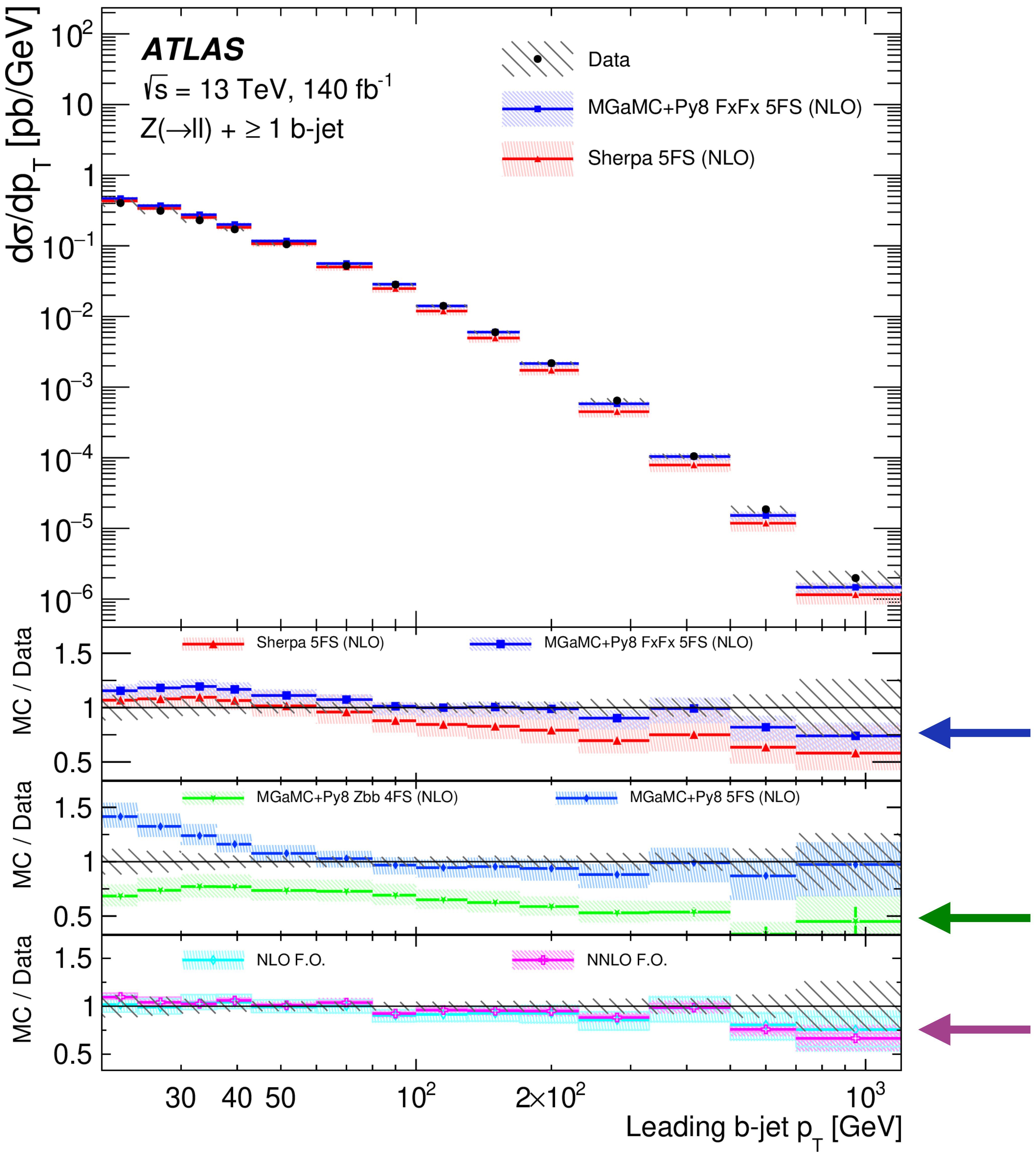






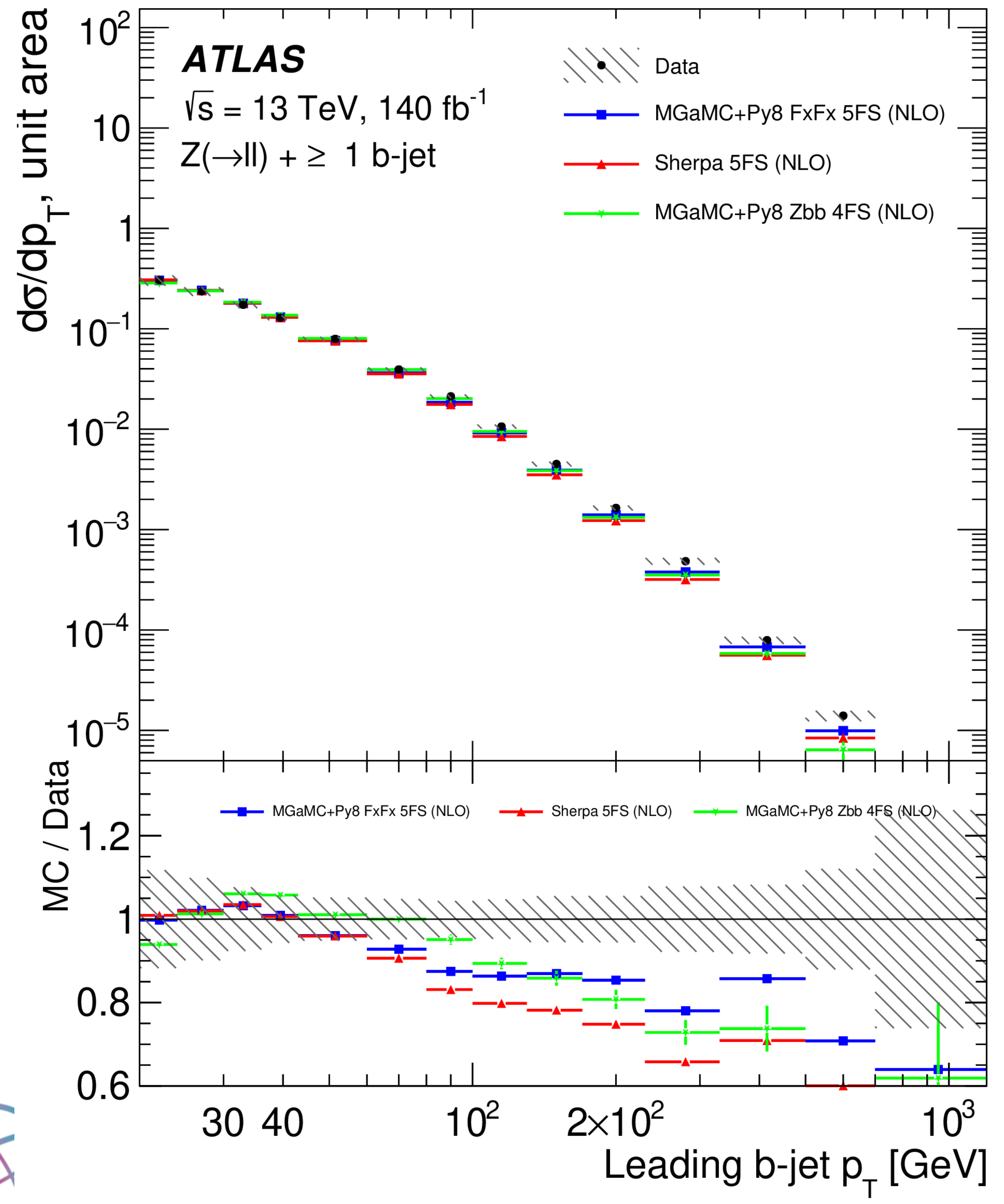
Differential Z+≥1 b-jet cross-section results

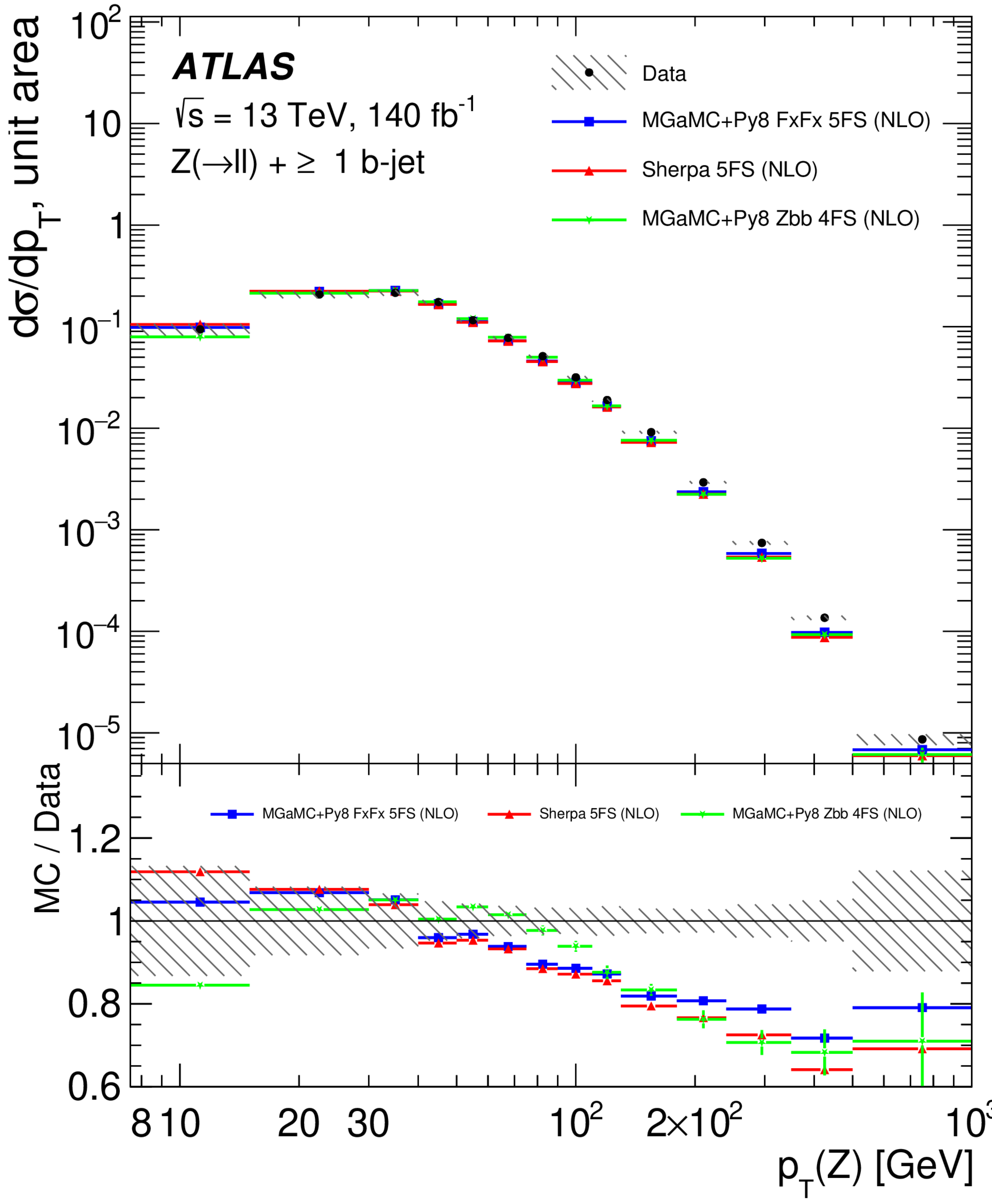
- **5FS:** good description of data by both MGAMC+PY8 FXFX and SHERPA 2.2.11
  MGAMC+PY8 with softer leading b-jet p_T and higher $\Delta R(Z, b\text{-jet}) \sim \pi$ production (back-to-back)
- **4FS:** MGAMC+PY8 underestimates data in the full spectra - **no log-term resummation in PDF evolution!**
- **Fixed-order:** very good descrition

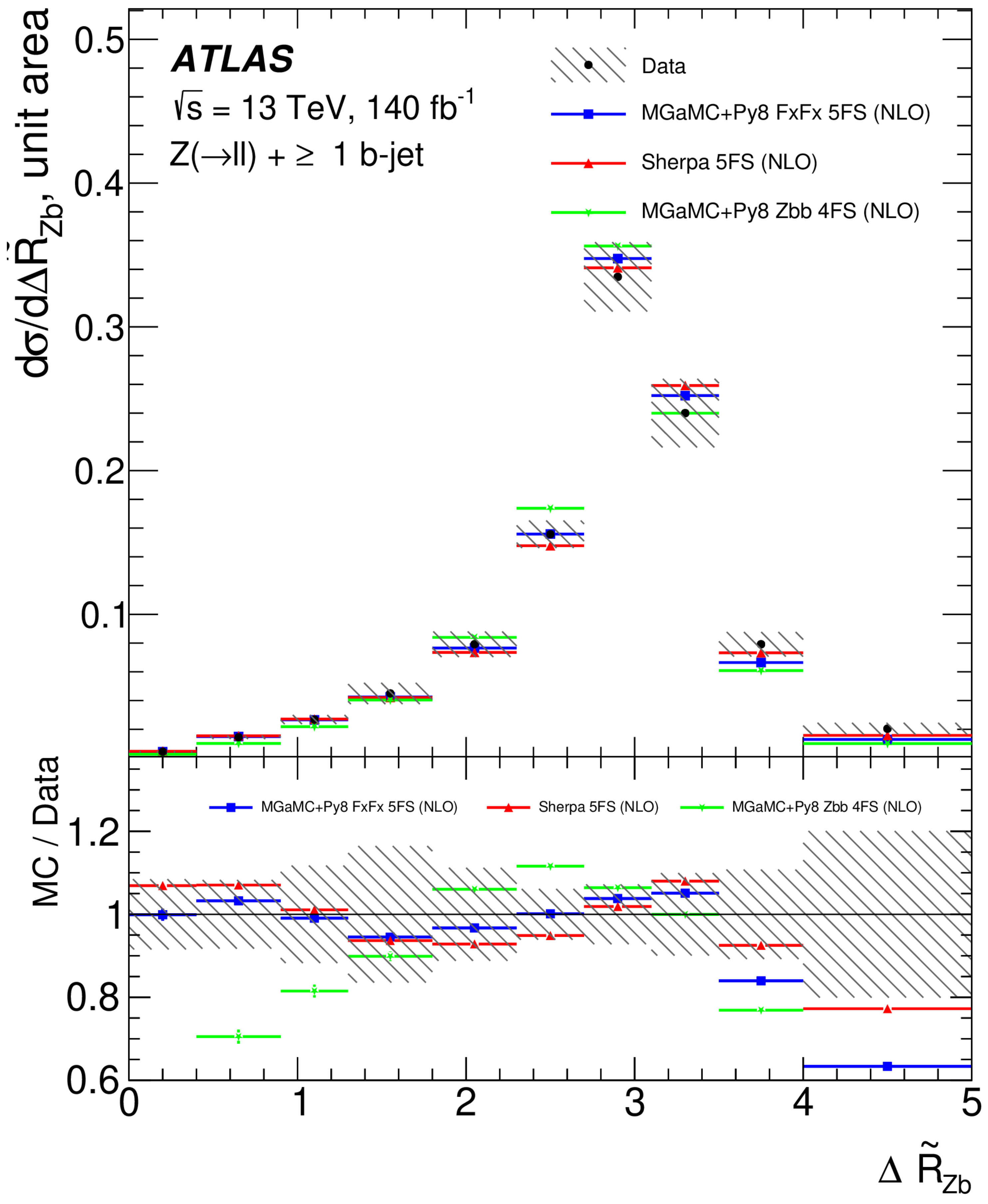


Differential Z+≥1 b-jet cross-section results

- **5FS:** good description of soft p_T spectrum by both MGAMC+PY8 FXFX and SHERPA 2.2.11
- **4FS:** similar p_T modelling than 5FNS, large underestimation of collinear Z-bjet emission



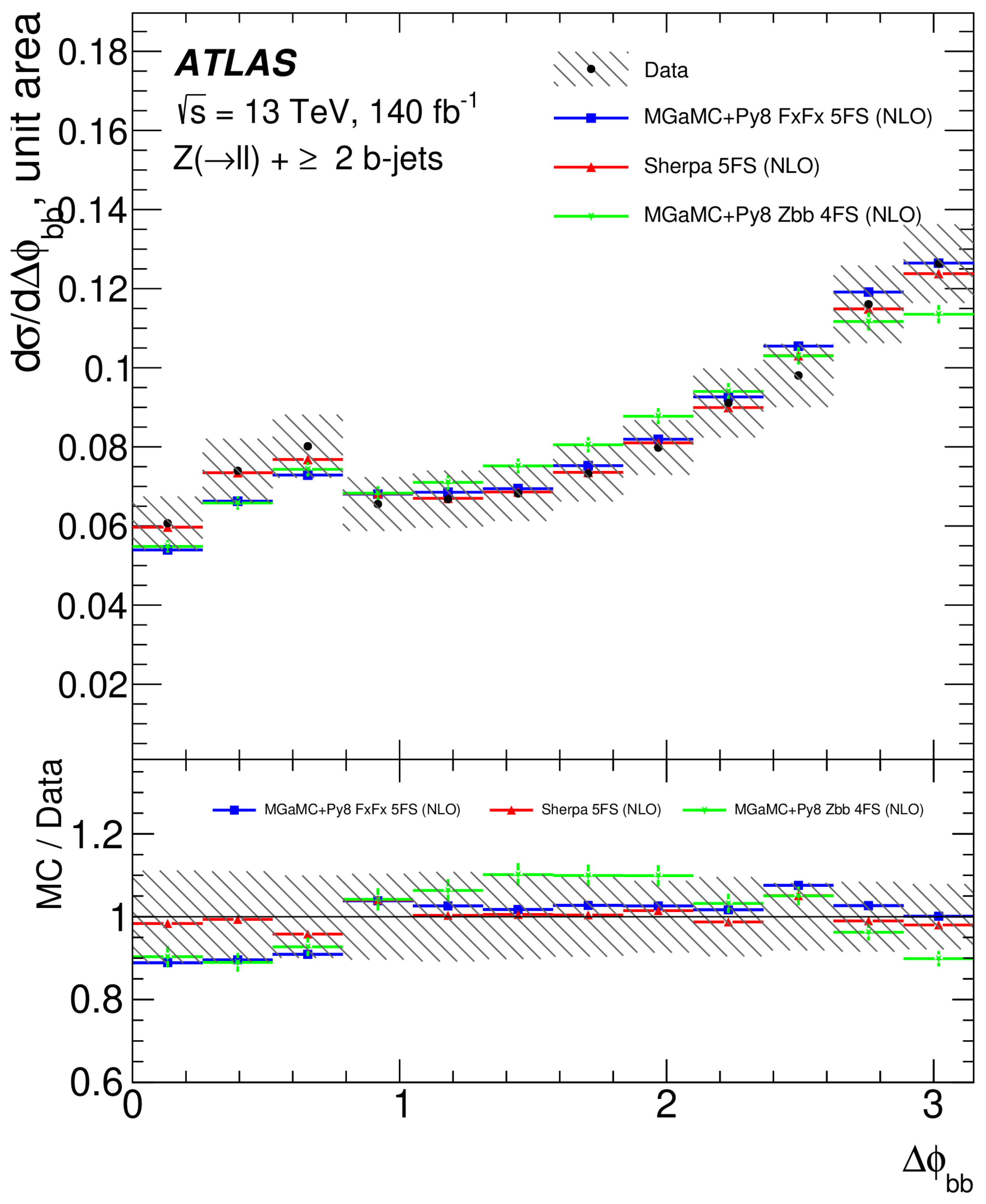


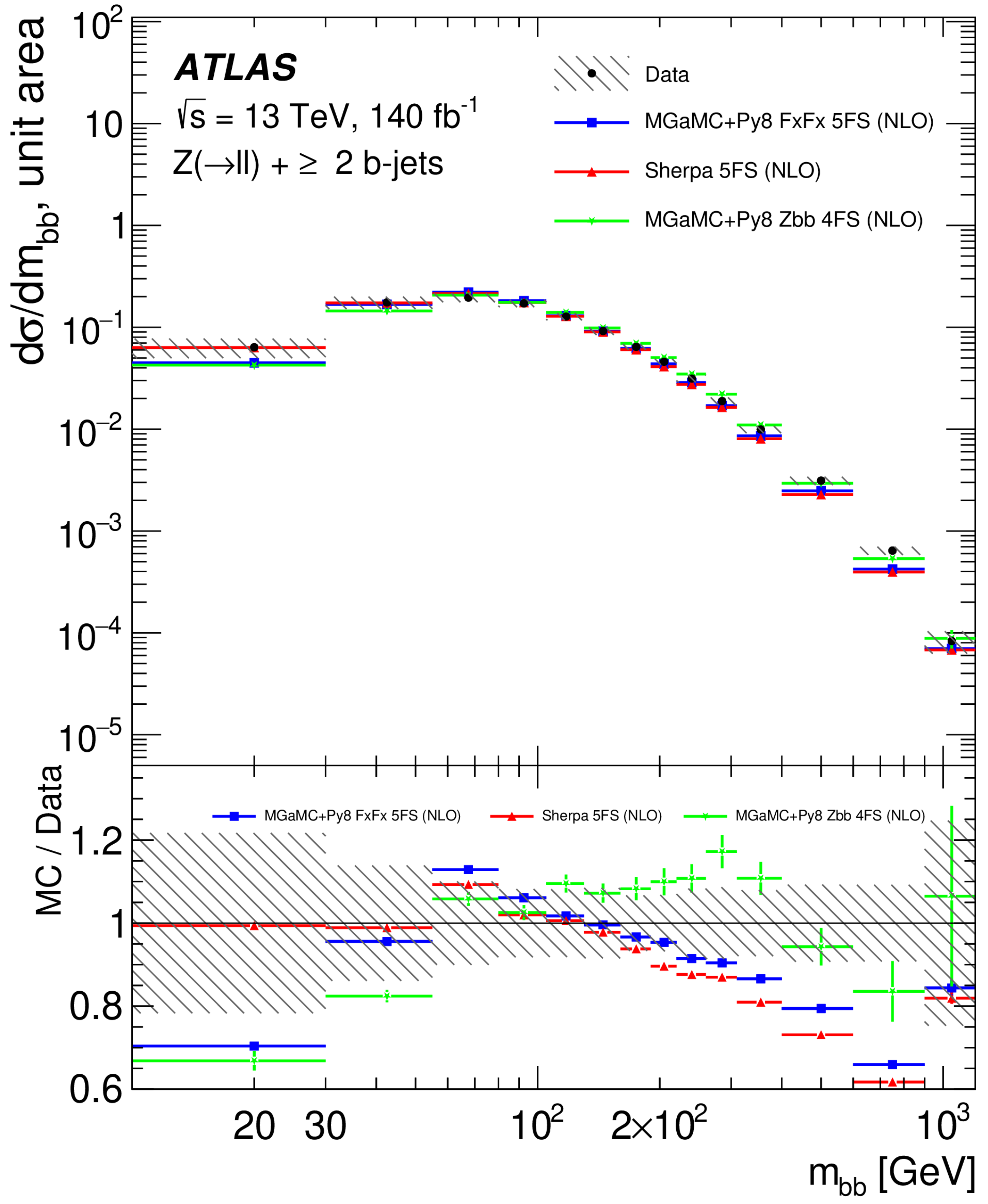


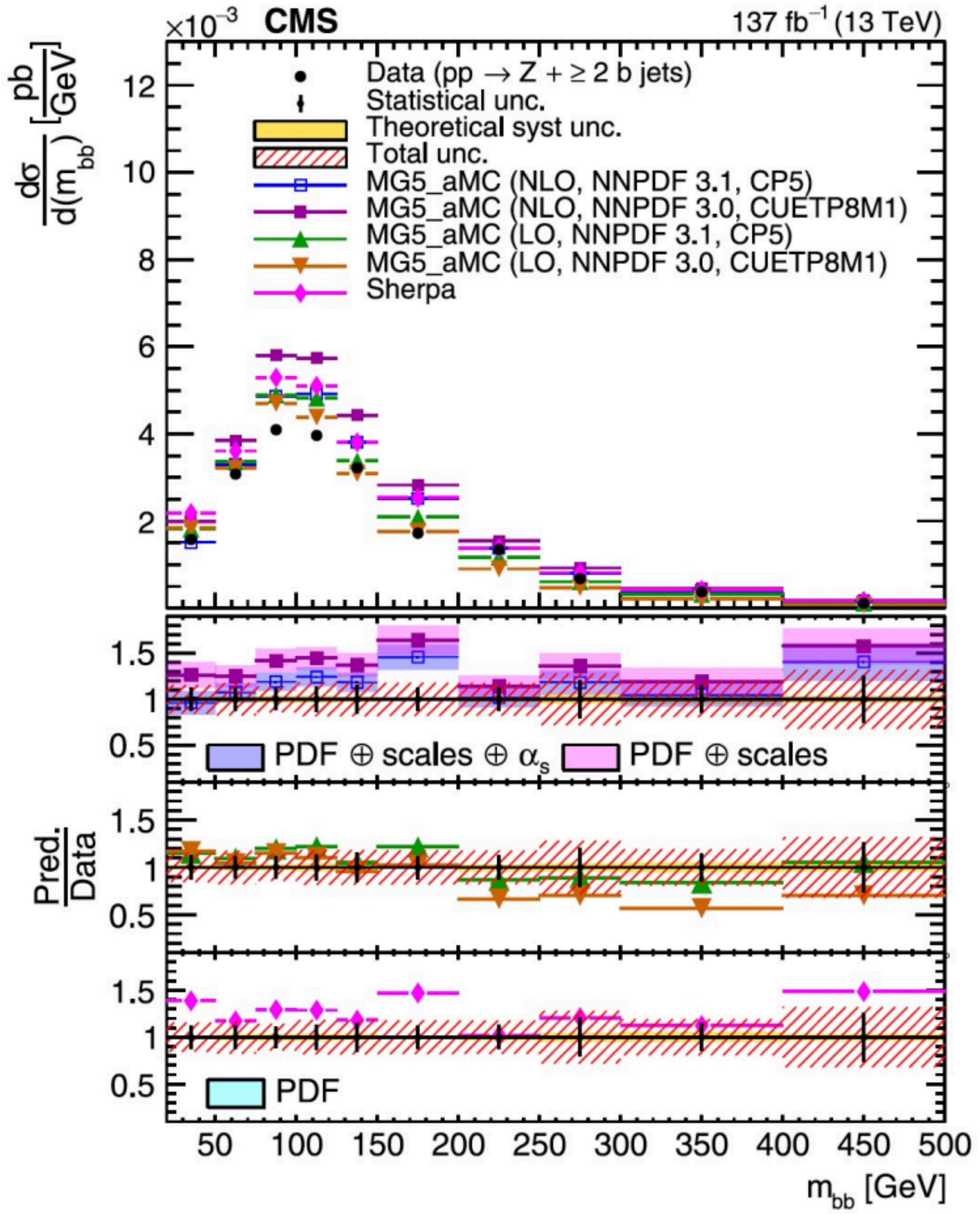
Differential *Z*+≥2 *b*-jets cross-section results

- **$\Delta\phi_{bb}$:** good description of data by all predictions
- **m_{bb}: Soft m_{bb} well described by** SHERPA 2.2.11, while MGAMC+PY8 descriptions are off in the ful spectrum

CMS results of m_{bb} better described by LO MGAMC+PY8.

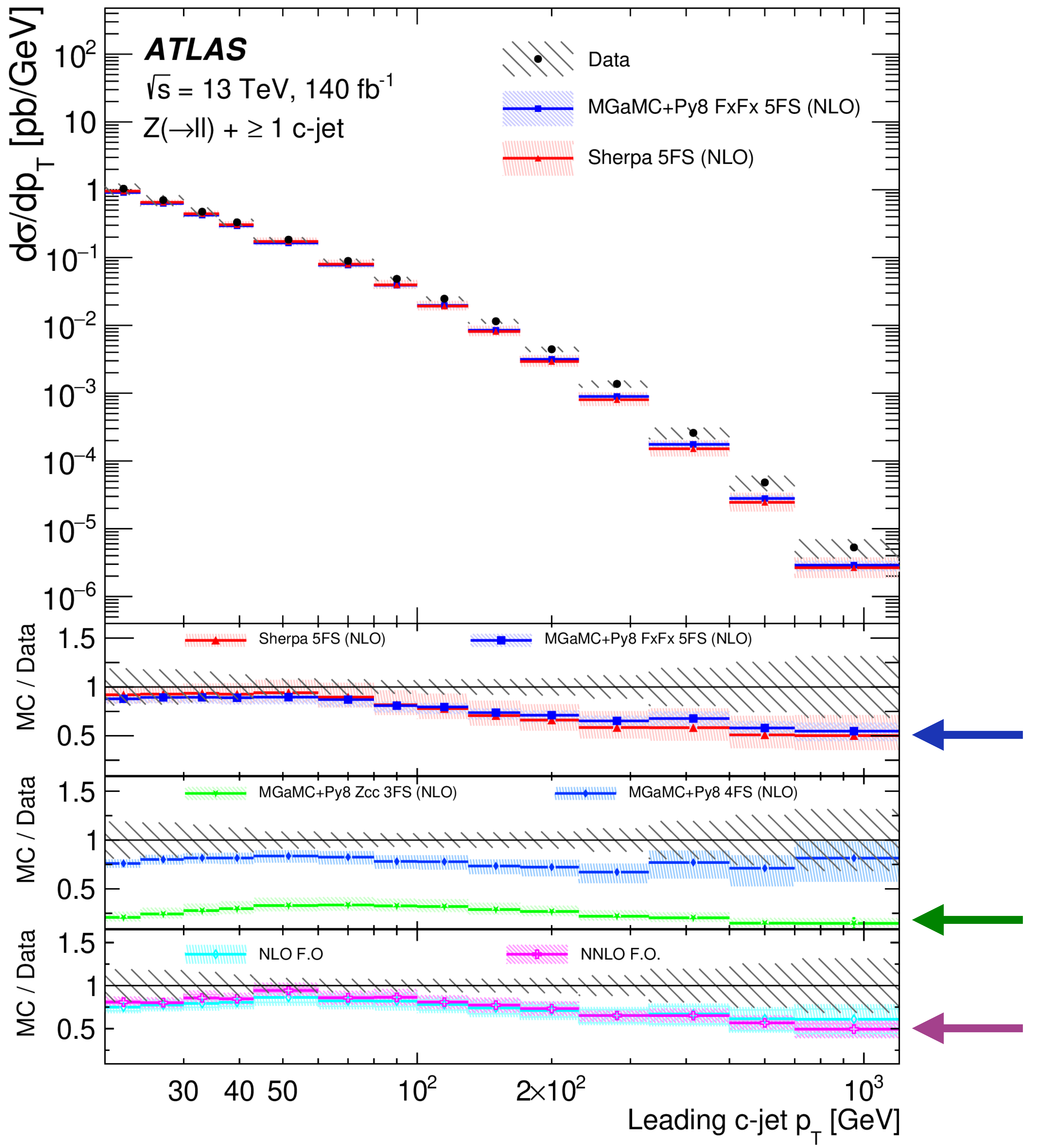






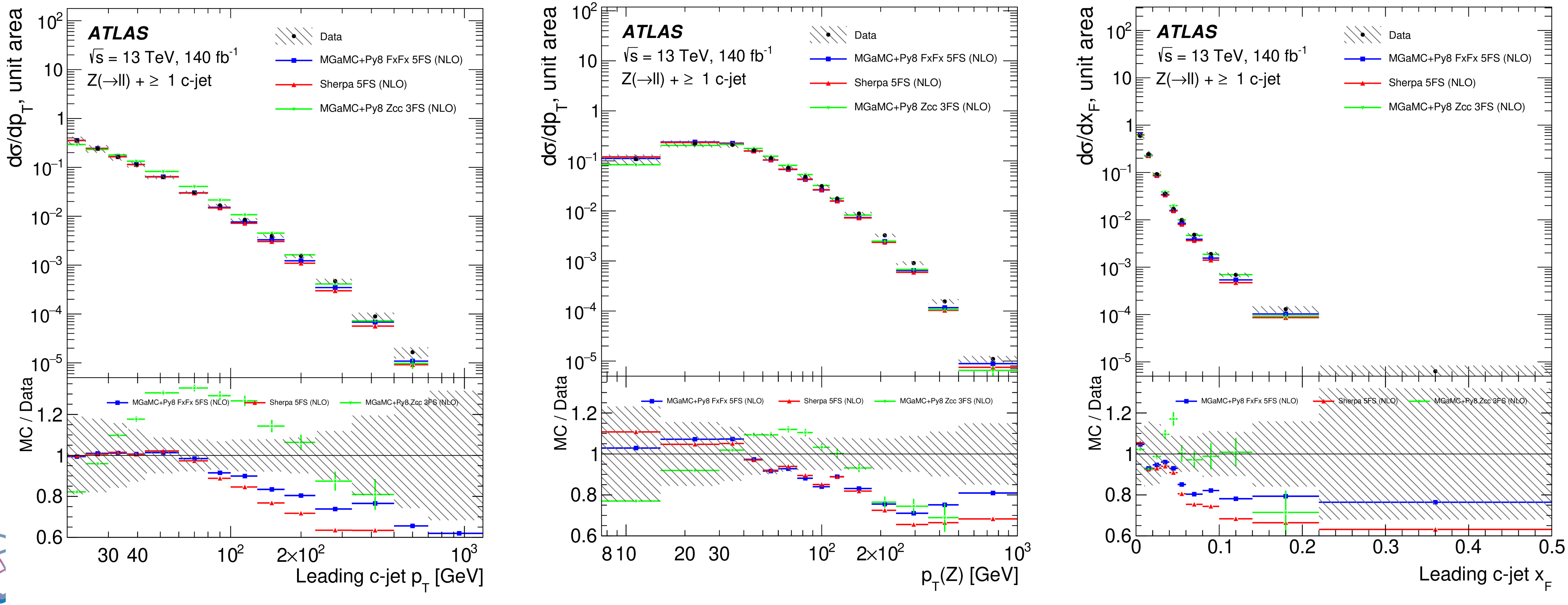
Differential $Z+\geq 1$ *c*-jet cross-section results

- **5FS**: soft p_T spectra well described by MGAMC+PY8 FXFX and SHERPA 2.2.11, not true for p_T>100 GeV
- **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



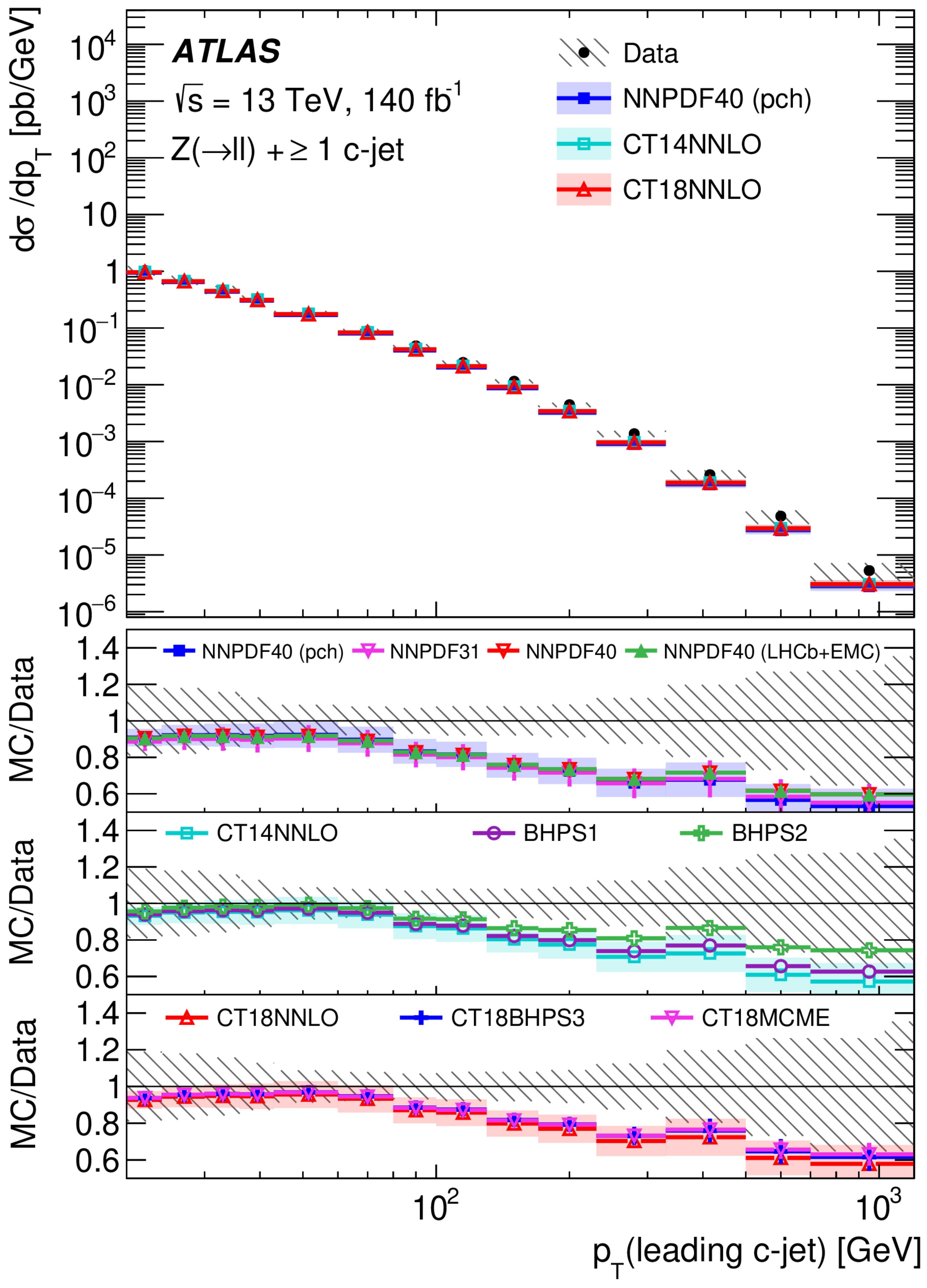
Differential Z+≥1 c-jet cross-section results

- **5FS:** soft p_T spectra well described by MGAMC+PY8 FXFX and SHERPA 2.2.11, not true for p_T>100 GeV
- **3FS:** large mismodelling of all observables

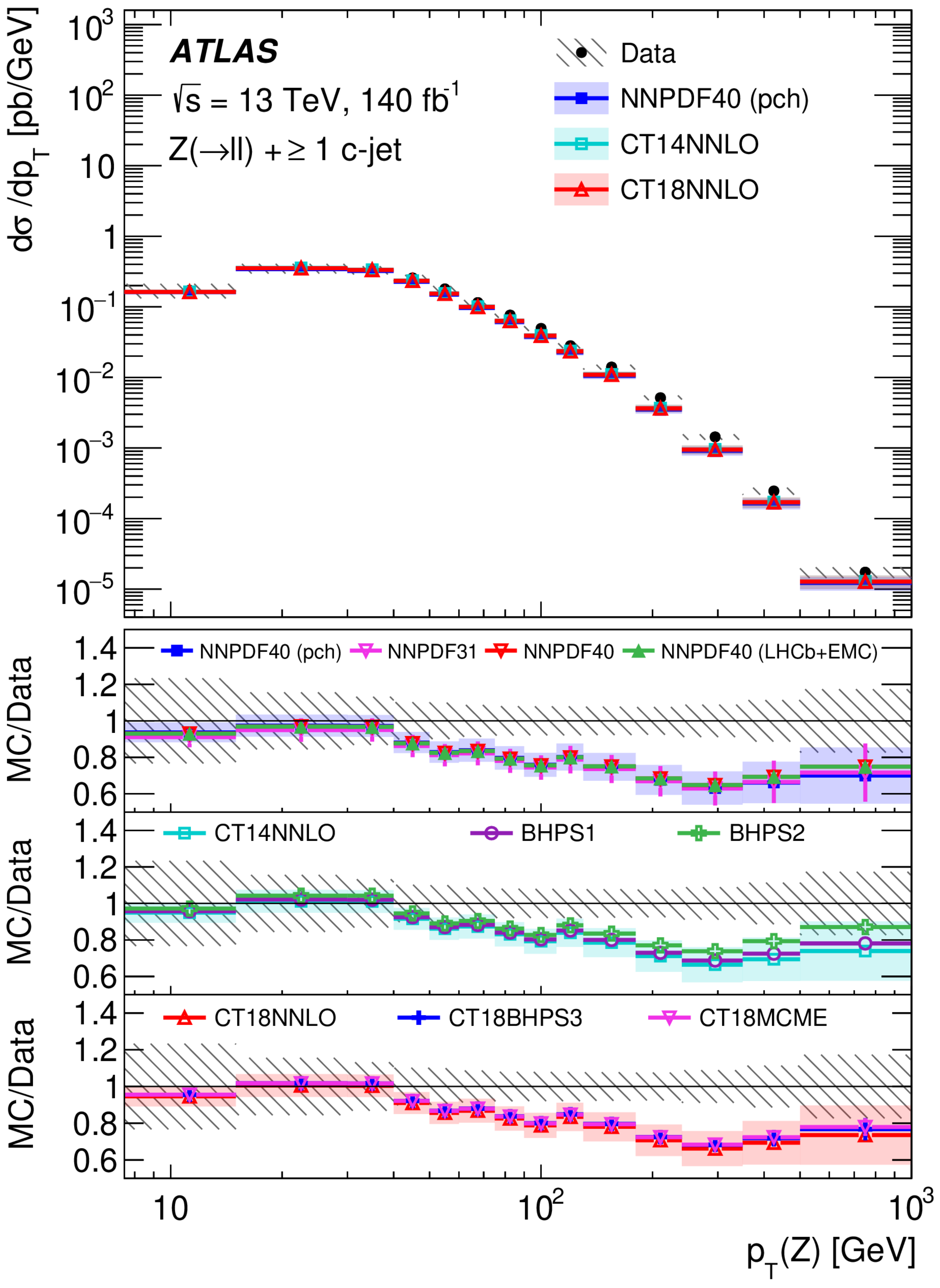


Differential $Z+\geq 1$ *c*-jet cross-section results

- Similar trend with respect to data by all *IC* models from NNPDF, CT14 and CT18
- The measurement has small sensitivity to *IC*



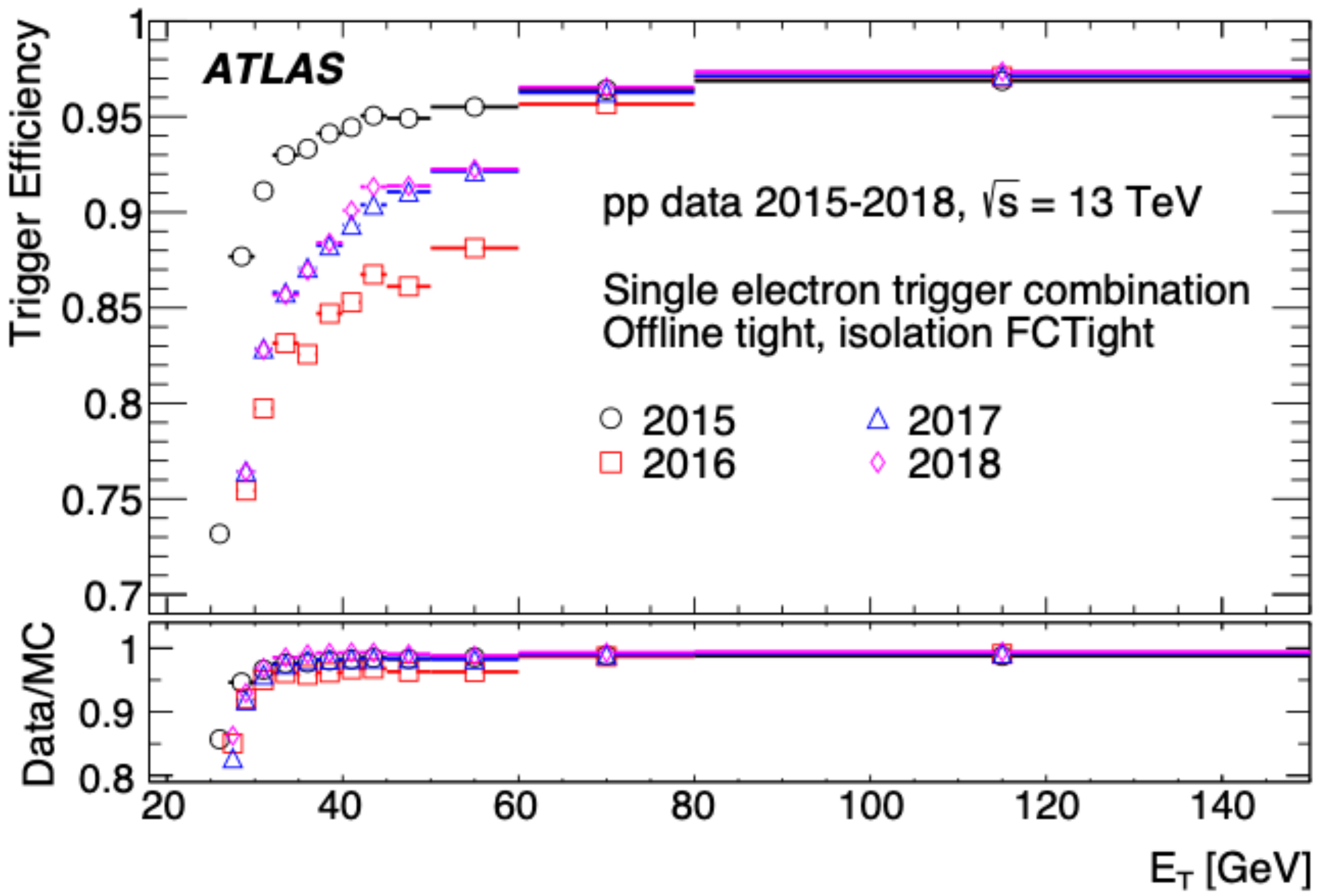
MGAMC+PY8 with different PDF sets testing several *IC*-models (PDF reweighting)



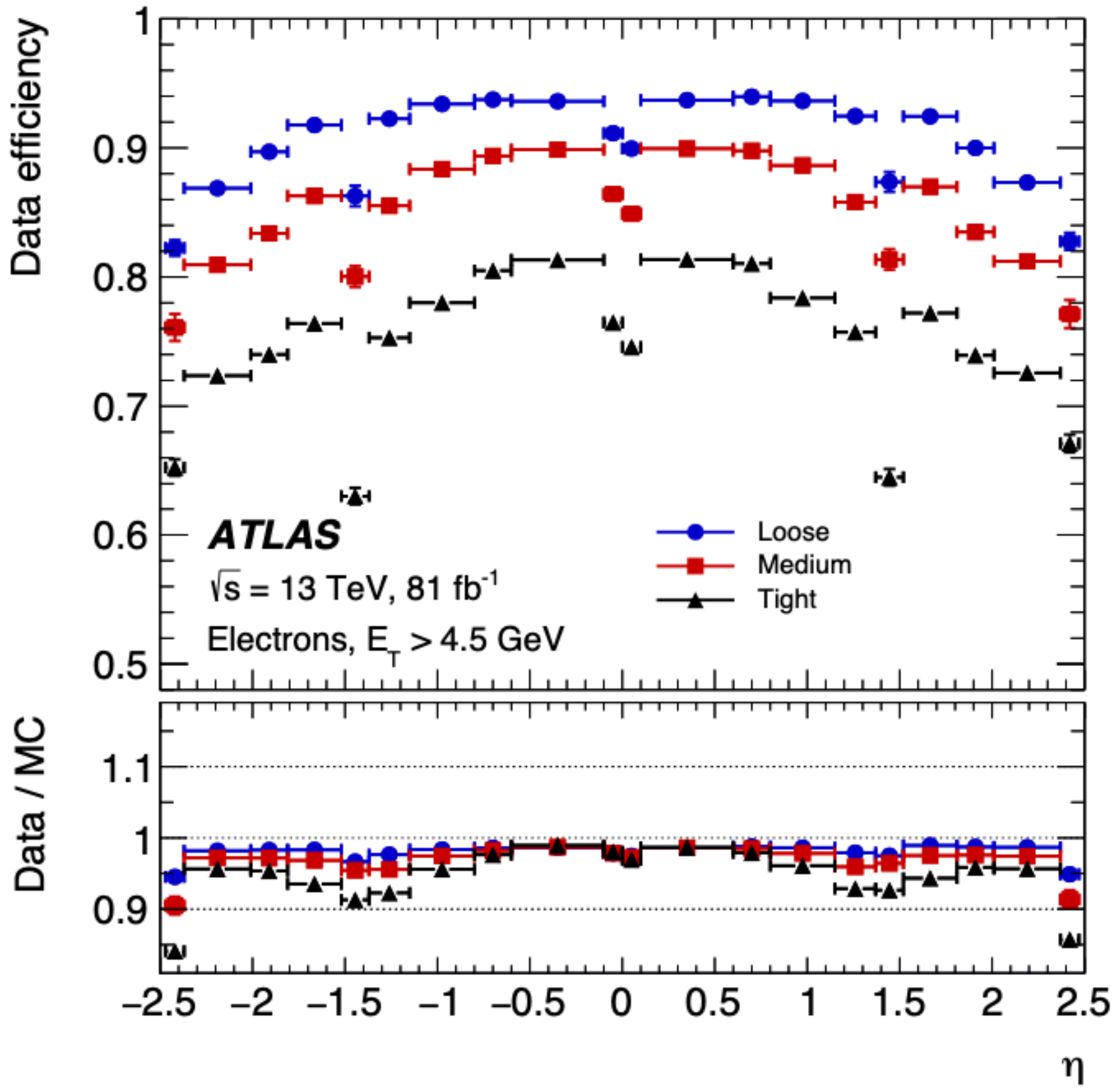
Performances

Electrons and muons

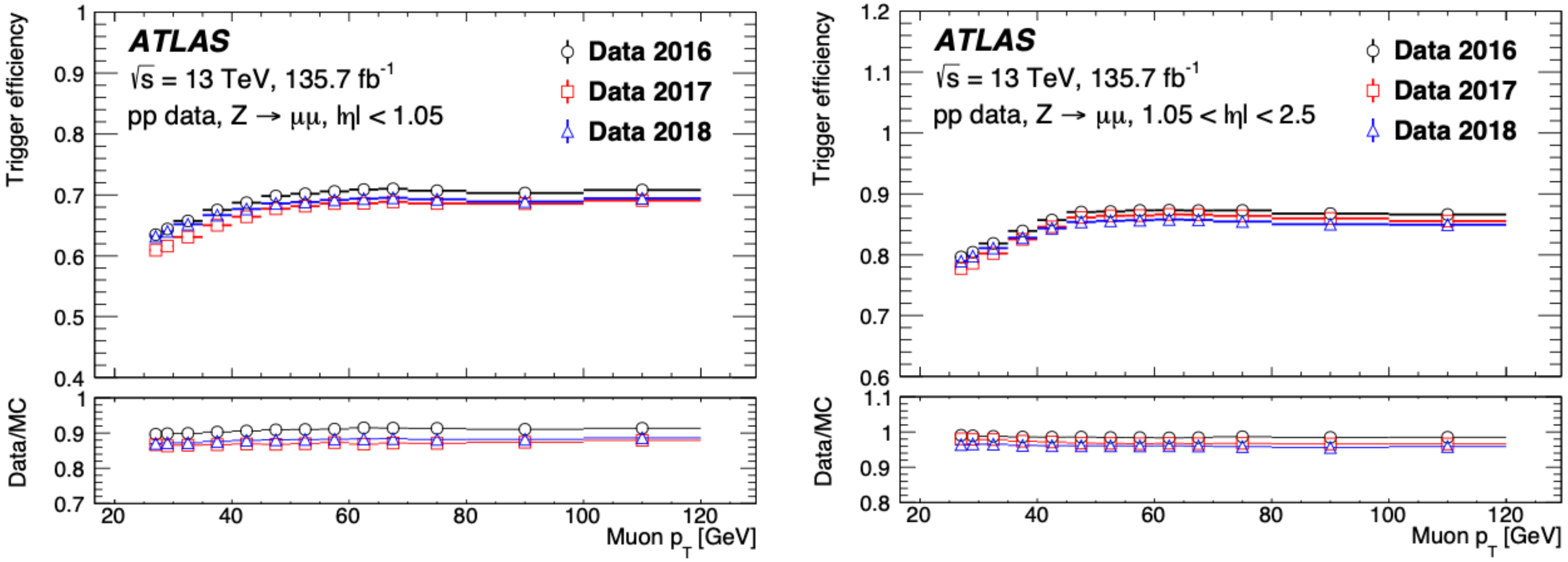
Eur. Phys. J. C 80 (2020) 47



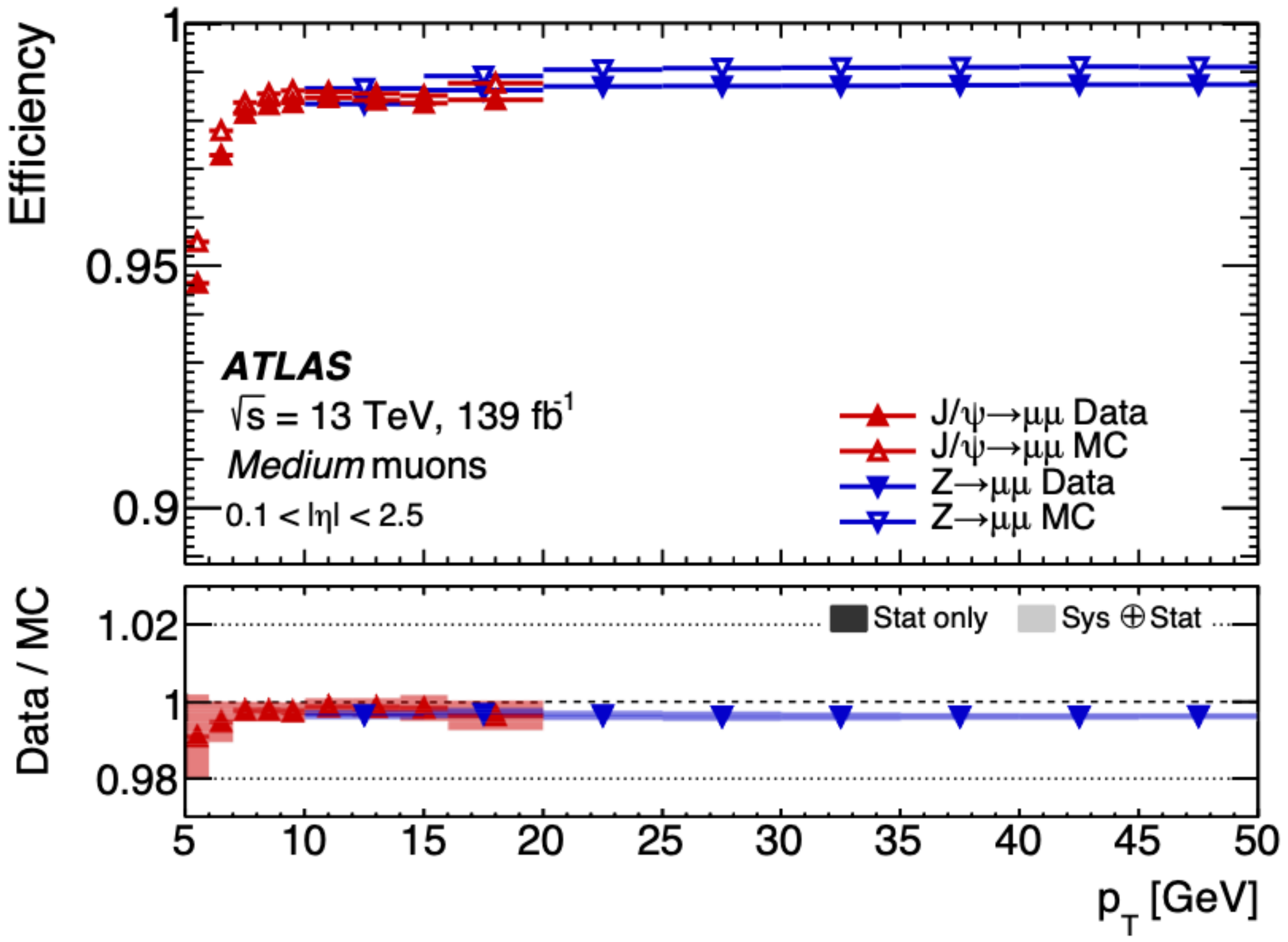
JINST 14 (2019) P12006



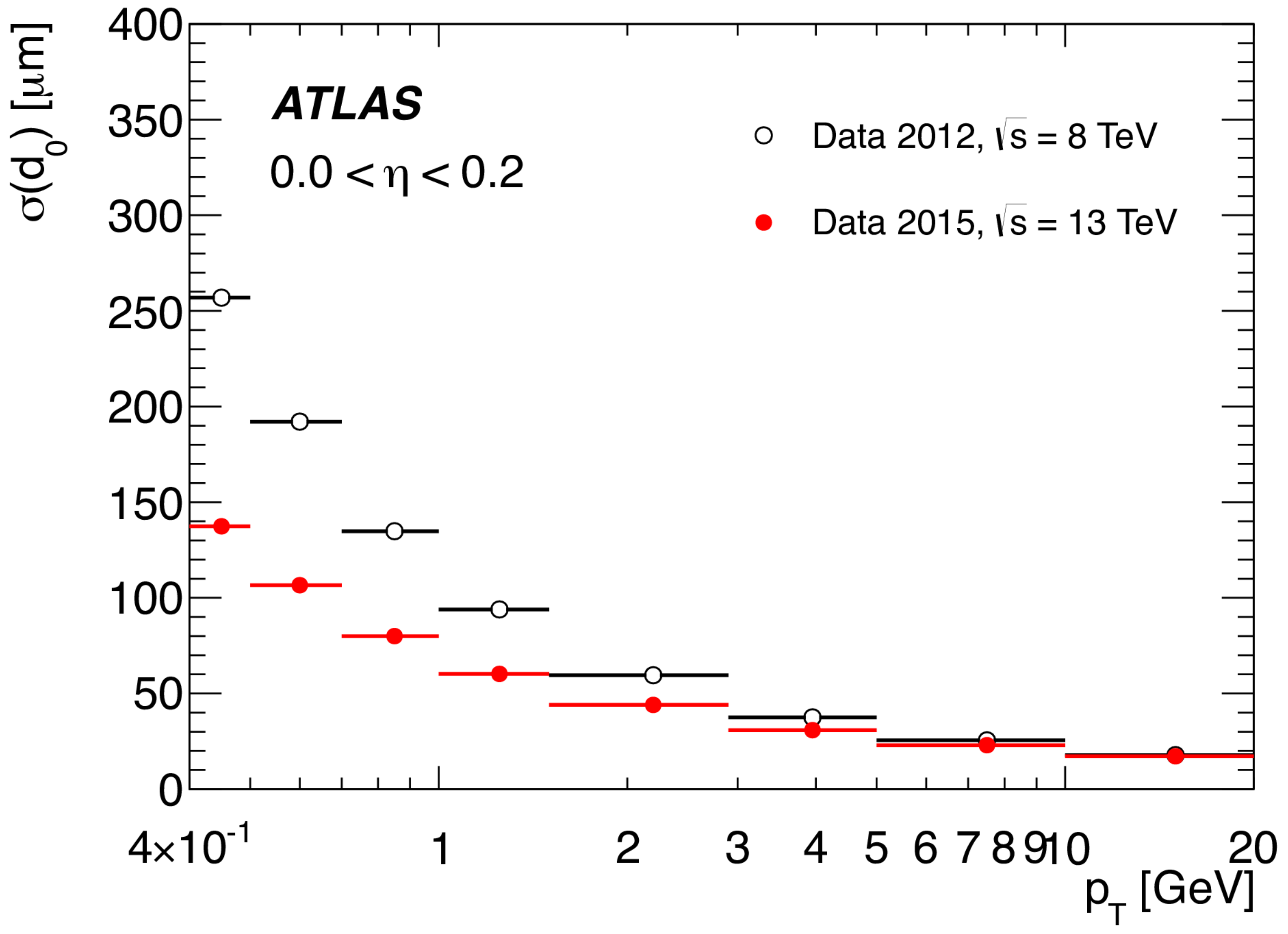
JINST 15 (2020) P09015

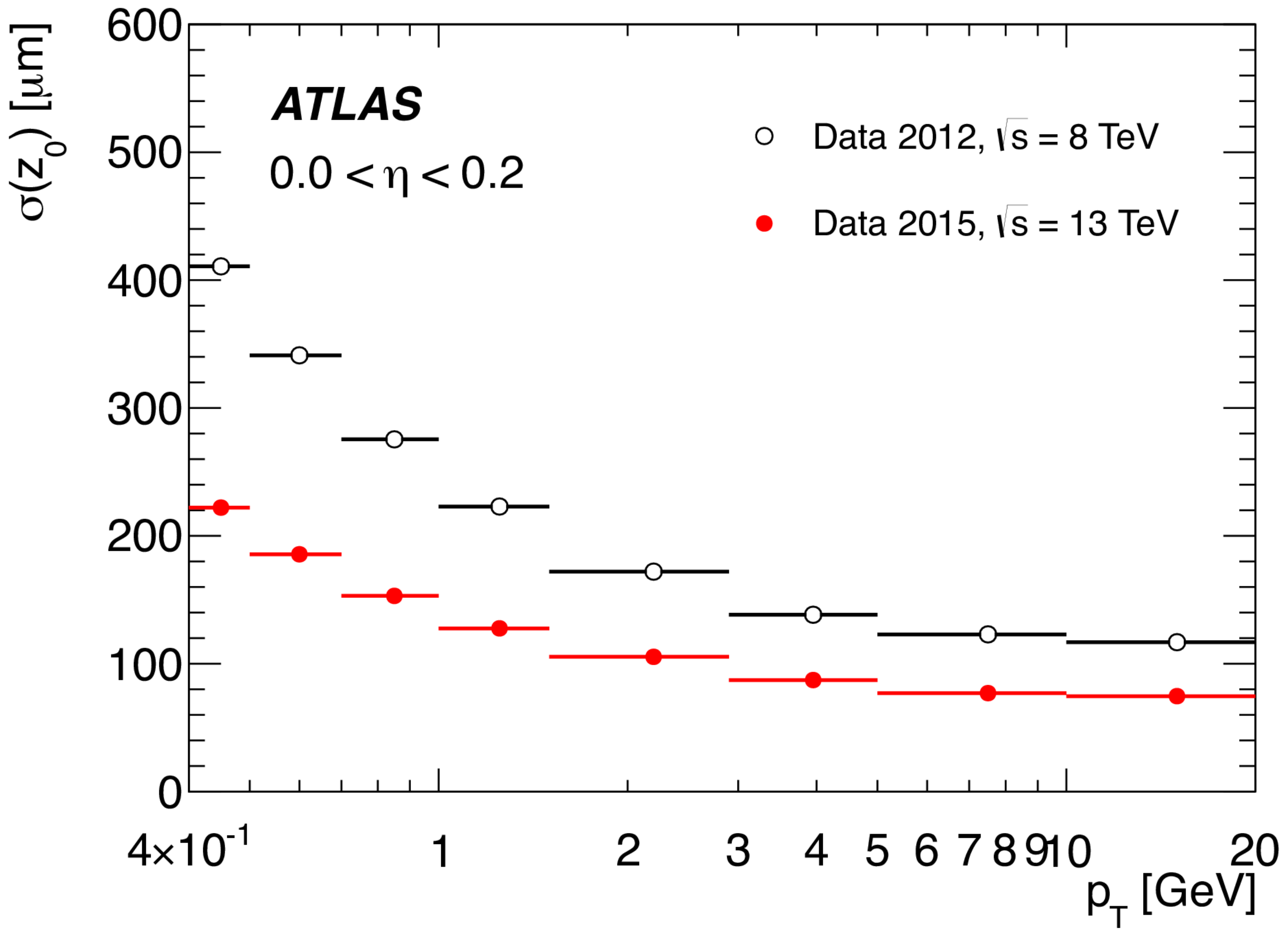


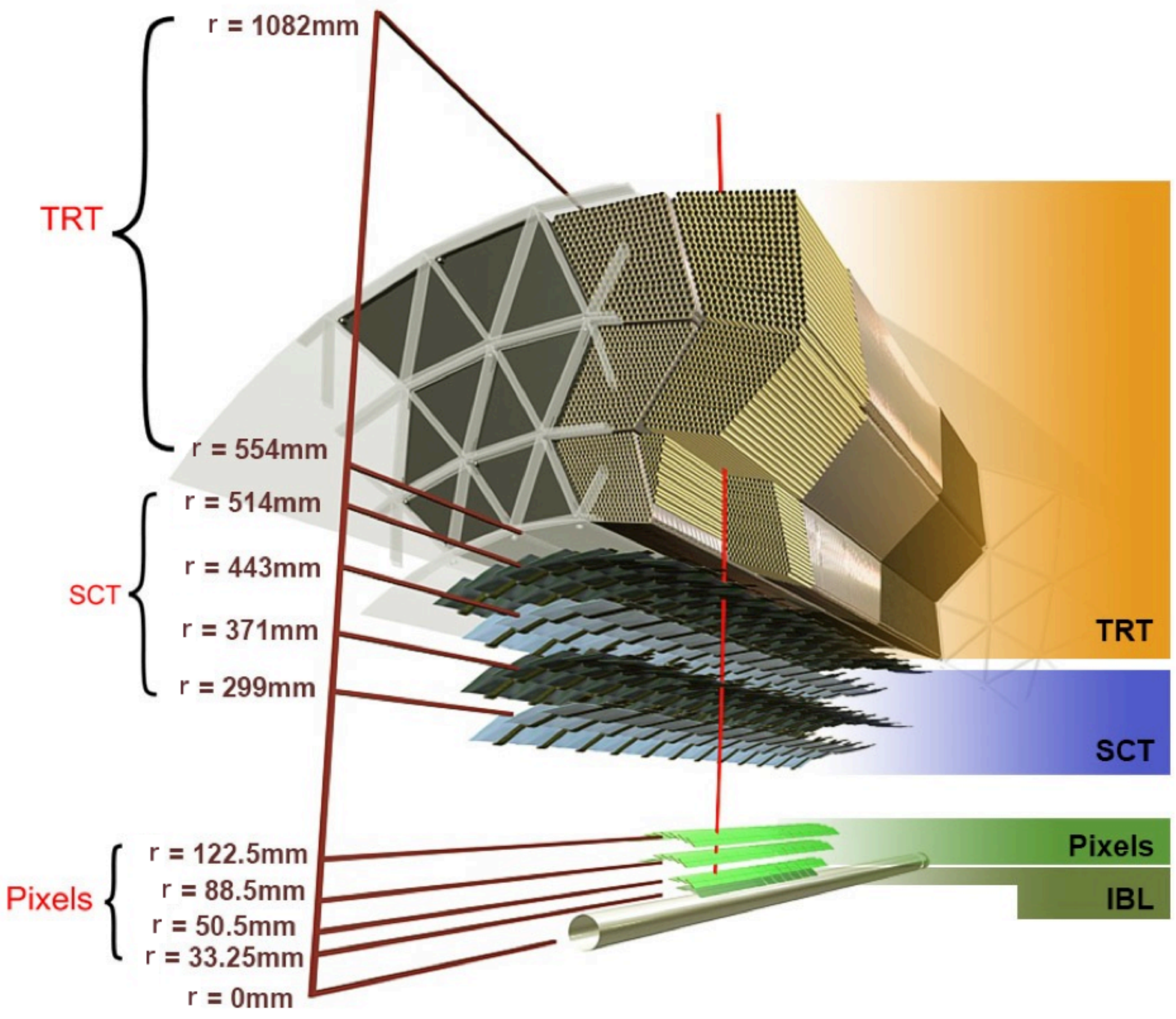
Eur. Phys. J. C 81 (2021) 578



submitted to JINST, arXiv:2305.16623v1





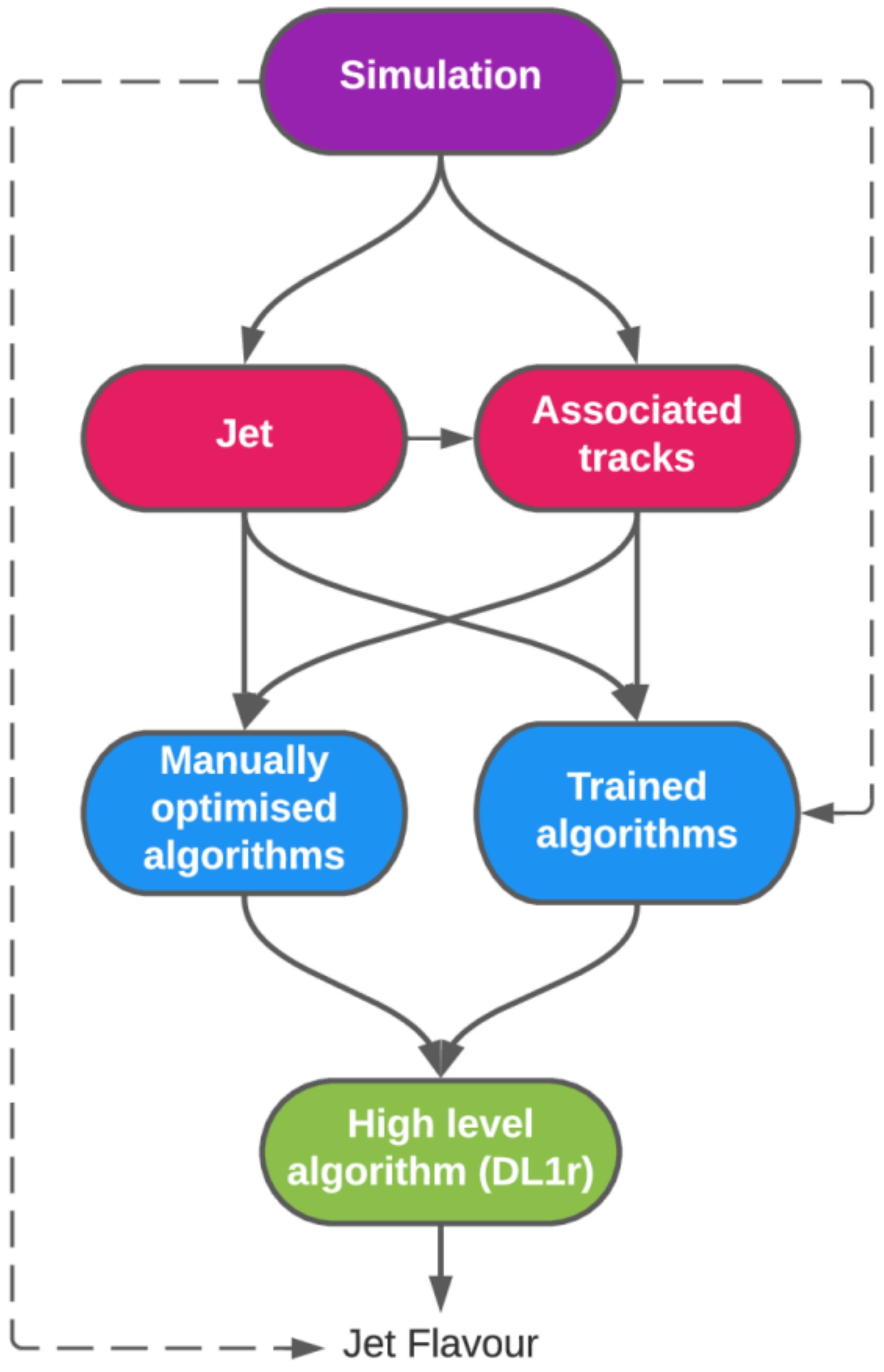


Flavour tagging

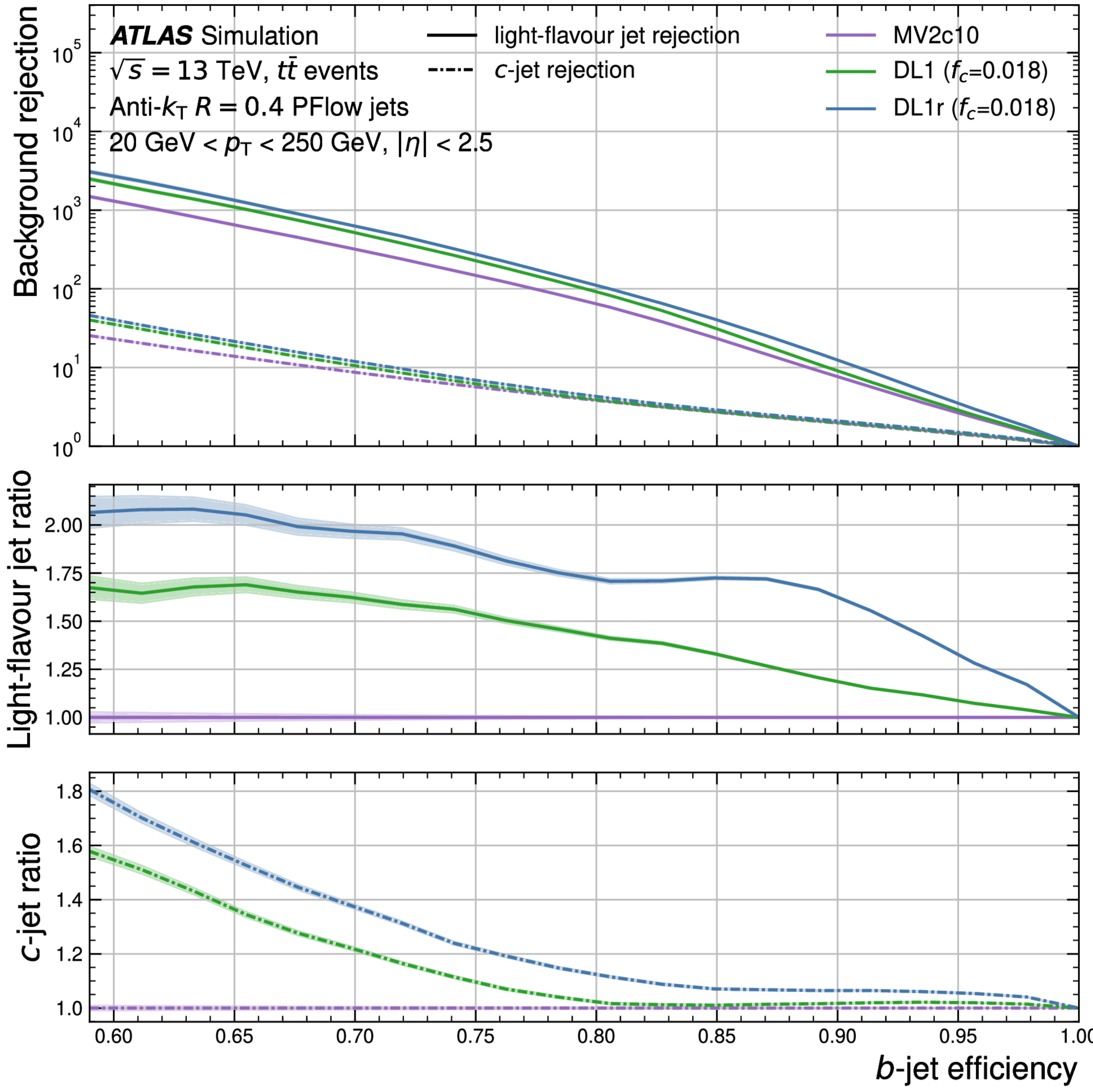
- ✦ Using unique characteristics of b-hadron decays
  - ✦ long lifetime (~1.5 ps →~ 3 mm decay length)
  - ✦ high-mass (~5 GeV)
  - ✦ number of tracks per jet (~5 per b-jets)

High-level DL1r algorithm operating on outputs from layer of intermediate algorithms

- Secondary vertex based: SV1 and JetFitter
- Track IP based: IP3D and RNNIP (RNN based)



Eur. Phys. J. C 83 (2023) 681



Flavour tagging

Eur. Phys. J. C 83 (2023) 681