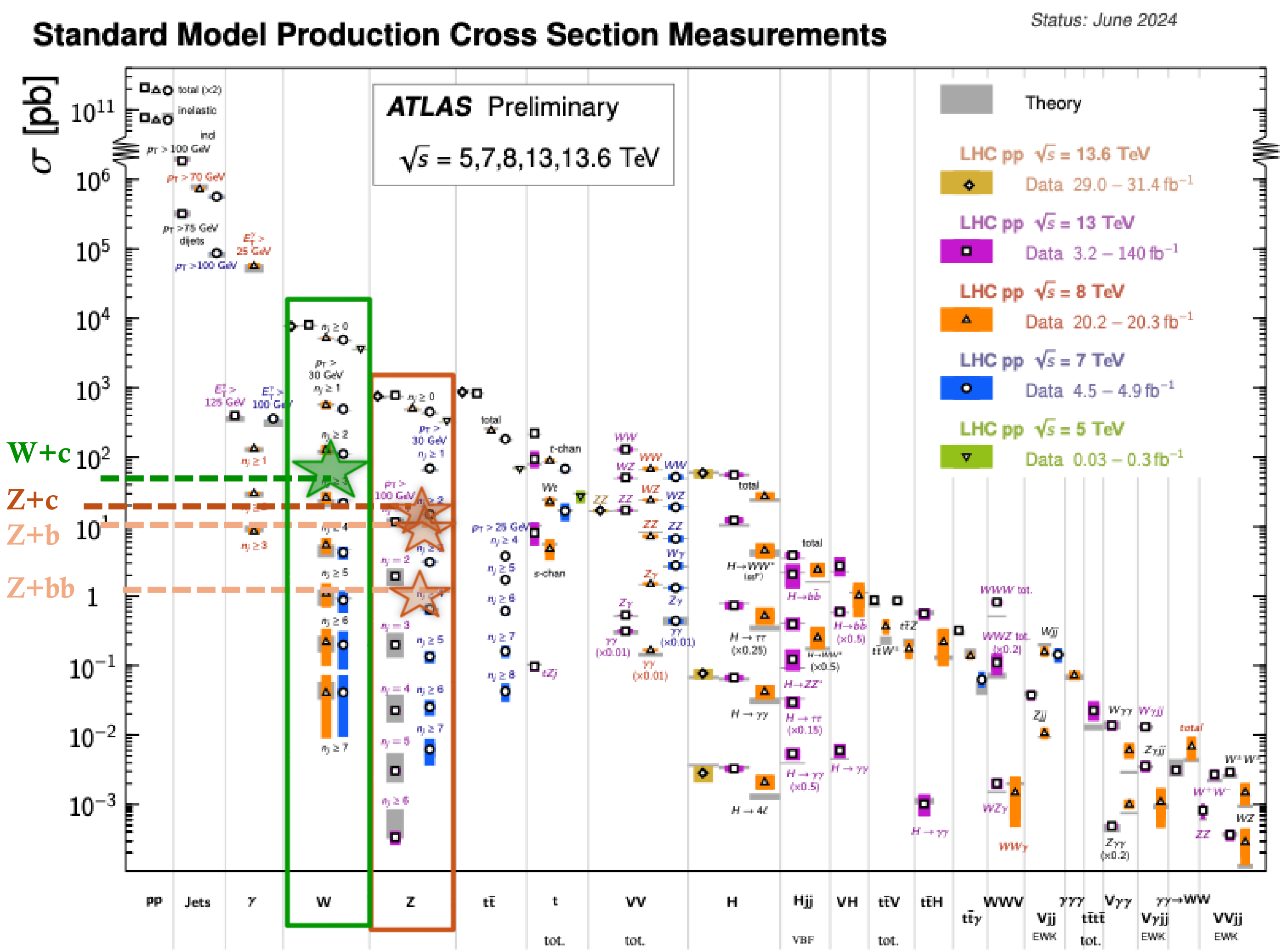
V+heavy flavour measurements at ATLAS

E. Meoni
(Università della Calabria & INFN)

on behalf of the ATLAS Collaboration

New Trends in High-Energy and Low-x Physics 2024,
1–5 Sept 2024, Sfantu Gheorghe, Romania

Introduction



V(=W/Z) + (inclusive) jets abundantly produced at the LHC and measured up to a large jet multiplicities and in extreme phase spaces already in Run-1 (7 TeV and 8 TeV)

V + heavy flavours (= c- and b-quarks) more challenging to measure and to predict

2 recent ATLAS V+HF measurements with Run-2 dataset (13 TeV, 140 fb^{-1}):

- **W + ≥1 charmed hadron (Phys. Rev. D 108 (2023) 032012)**
- **Z + ≥1 c-jet or ≥ 1 b-jet or ≥ 2 b-jets (arXiv:2403.15093)**

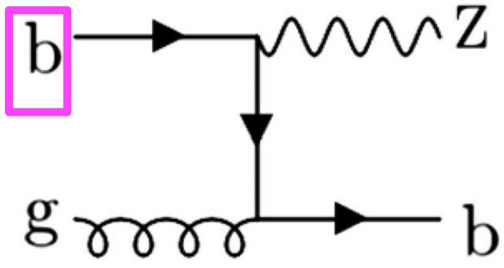
Motivations

V+HF measurements :

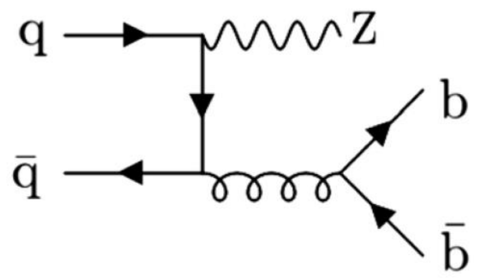
- Precision test of the perturbative QCD:
  - fixed order calculations up to NNLO and MCs with multileg NLO matrix elements (ME) + Parton Showers (PS)
  - various flavour schemes (FS) in ME with different c- and b-mass treatments

- Inputs to improve the understanding of proton structure (PDFs):
  - W+c sensitive to s-quark content of the proton
  - Z+c sensitive to Intrinsic Charm component of the proton (IC: $|p> = |uudc\bar{c}>$)

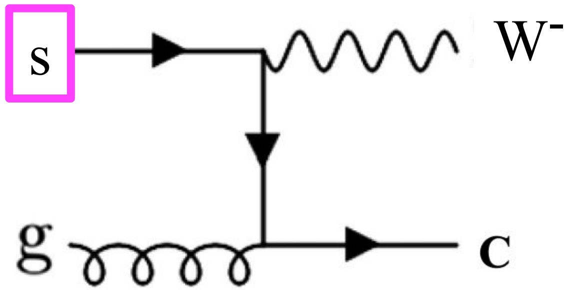
- Inputs to improve the background modelling in MCs for Higgs-boson measurements and searches of New Physics

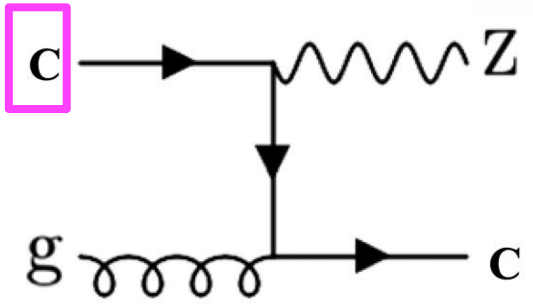


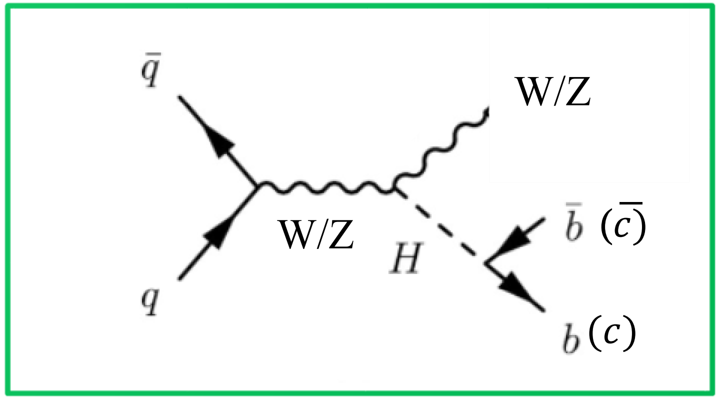
Present only in 5 FS



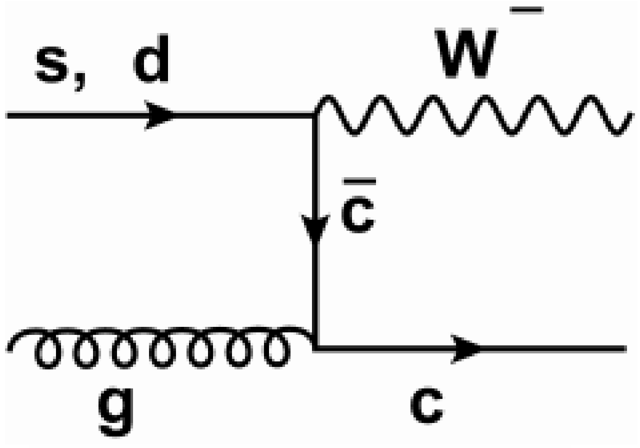
Present in 4 and 5 FS

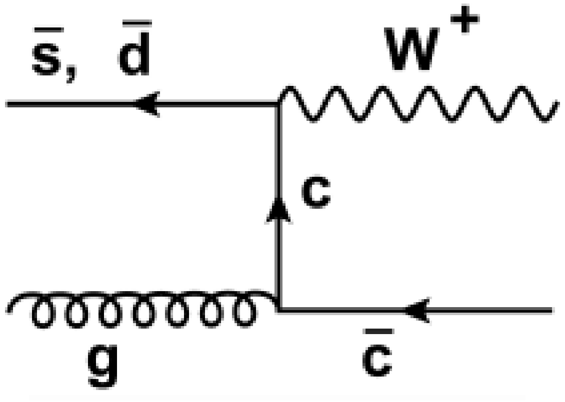






W plus a c-quark identified via reconstruction of a charmed hadron (Phys. Rev. D 108 (2023) 032012)





$sg \to W^- c \sim 90\%\ @LO$
$dg \to W^- c \sim 10\%\ @LO$

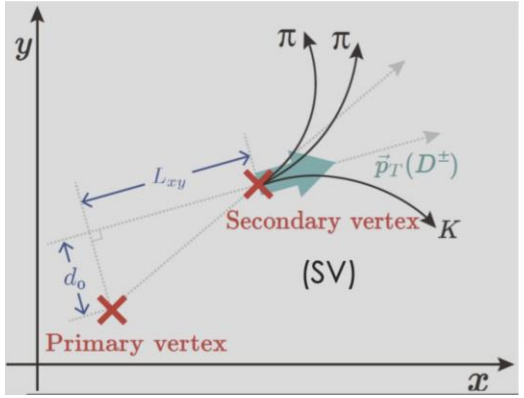
-W^+ and W^- measurements allow to study the $s - \bar{s}$ asymmetry

-W and c-quark always have opposite charge (OS), while backgrounds are mostly symmetric in charge (SS)

Strategy of the measurement

W (→ lν) selection

- 1 isolated *e* or μ with p_T> 30 GeV and central (|η|< 2.5) , E_T^{miss}>30 GeV, m_T^W>60 GeV
- b-jet veto (to reject top background)



c-quark identified via:
$D^+ \rightarrow K^-\pi^+\pi^+$
$D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$
and their charge conjugates

- $D^+(D^0)$ candidate reconstructed with a fit of the associated tracks to a common SV
- ≥ 1 isolated $D^{(*)}$ with 8 GeV< p_T <150 GeV |η|<2.2

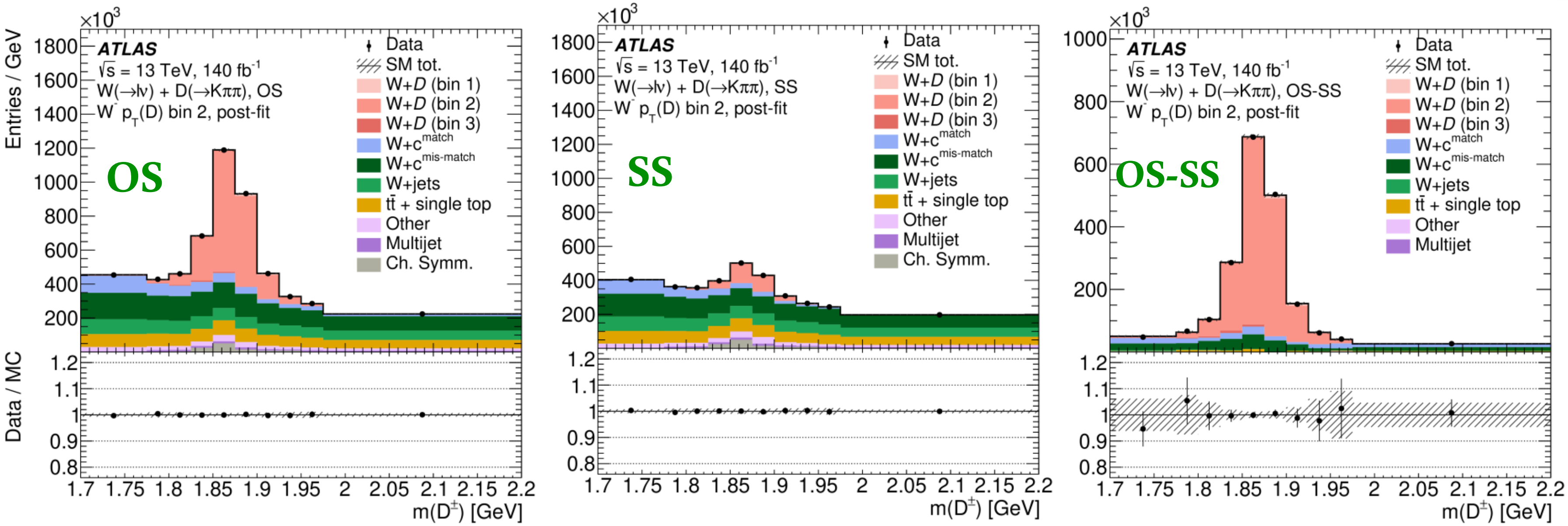
Signal (S) and background (B) extraction

- Likelihood fit of $m(D^+)$ for D^+ and of $m(D^{*+} - D^0)$ for D* in Signal Region (SR) and N_{evt} in top control region (≥ 1 b-jet CR)
- OS and SS fitted simultaneously and S extracted from the OS-SS difference

Fit done in bins of p_T^D or $|\eta^{lep}|$

Templates for W+c - signal, W+c background (but diverse final state from signal), W+jets (no c-jets), top and minor background from MC

Multijet: determined from data in enriched CR

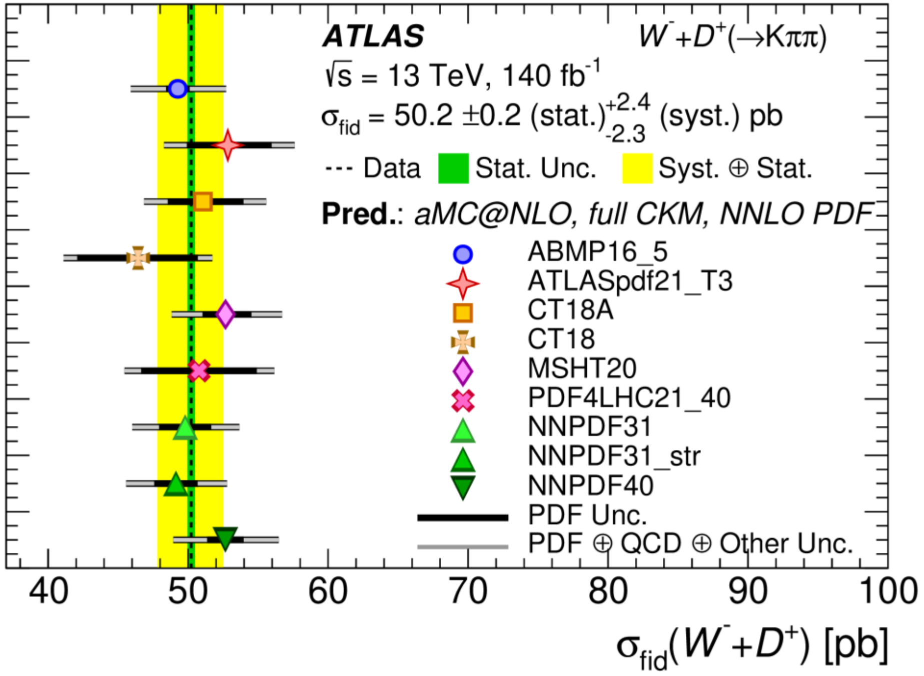


Inclusive W+D cross-section

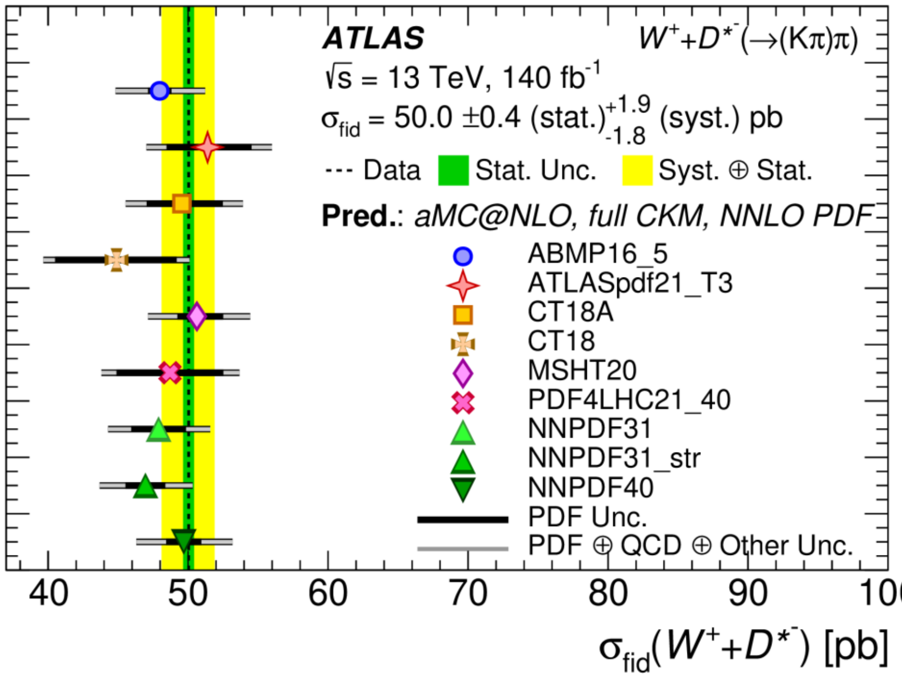
Cross-section measurement

- W^+ and W^- inclusive cross-sections, cross-section ratios and differential cross-sections extracted from the likelihood fit
- Fiducial phase-space at particle level close to detector level one:

1 e or μ with $p_T > 30$ GeV $|\eta| < 2.5$,
≥ 1 $D^{(*)}$ with $p_T > 8$ GeV $|\eta| < 2.2$



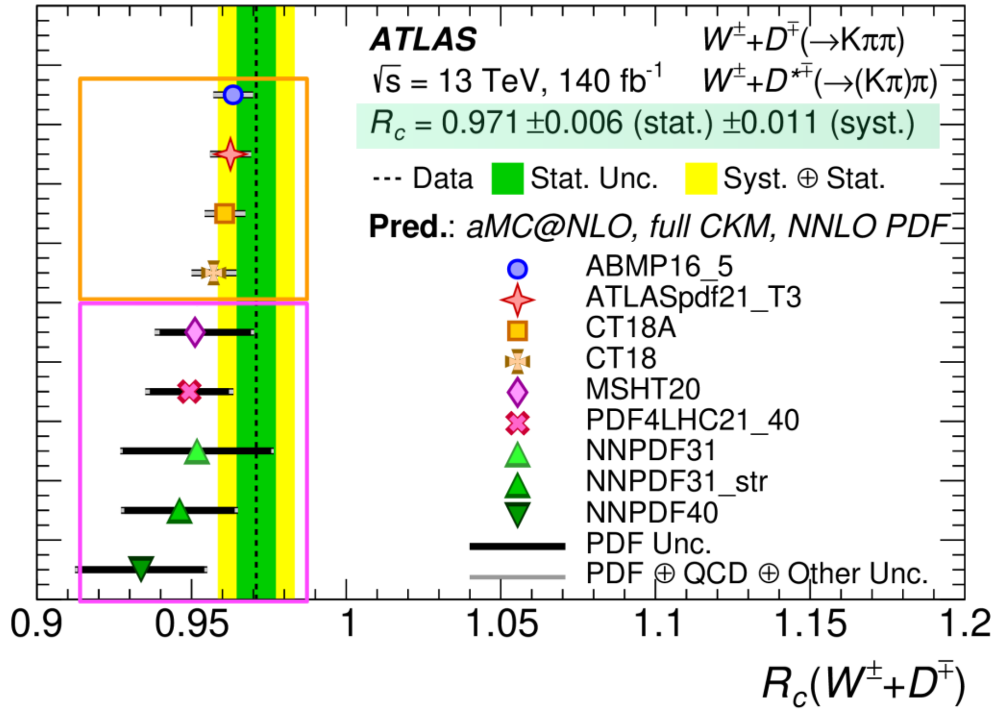
Data compared with predictions from NLO ME+PS MC with different NNLO PDFs (w/wo symmetric strange quark sea)



Uncertainty of the measurement (~5%) smaller than theoretical precision of the predictions
Data in good agreement with predictions from different PDF sets

R_c ratio

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



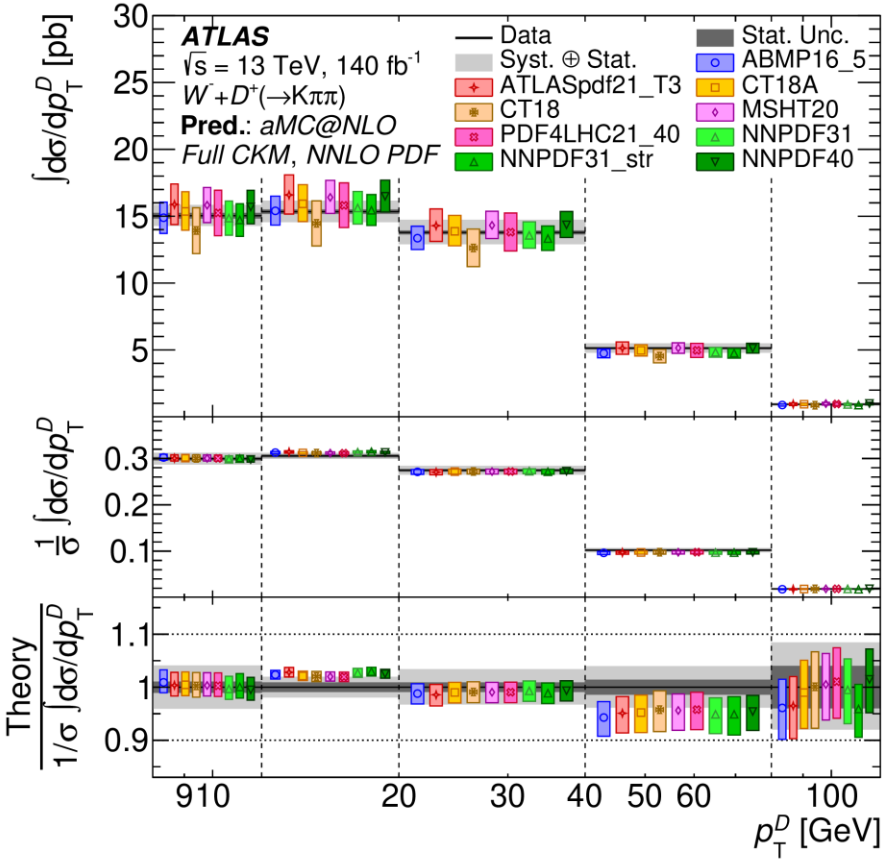
Precision of measured R_c ~1%

Smaller uncertainties for PDF sets with symmetric strange-quark sea ($s = \bar{s}$, ABMP16 and CT18) than sets allowing asymmetry (NNPDF or MSHT), data more precise than predictions in this second case

Data agree with all PDF sets within the uncertainties, although some tension shown with NNPDF 4.0

Small $s - \bar{s}$ asymmetry in the region probed by this measurement

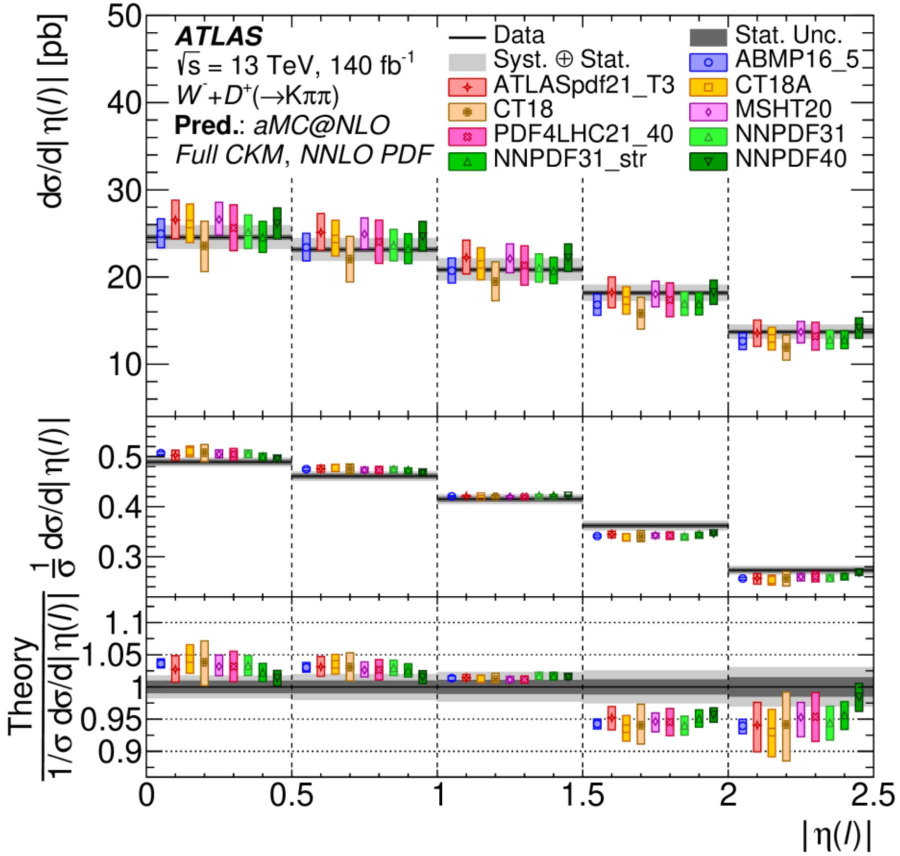
W+D differential cross-sections



→ Absolute cross-section ←

→ Normalised cross-section ←

→ Prediction to data ratio ←



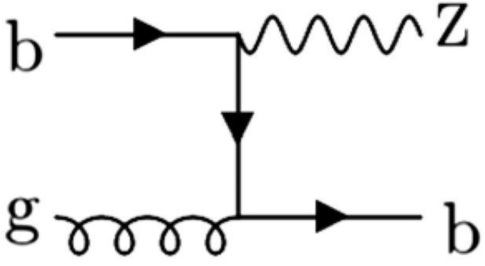
All predictions with different PDFs have similar p_T^D shape → observable sensible to MC modelling not to PDFs

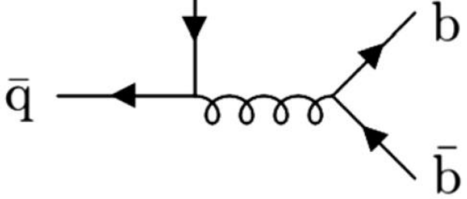
|η(lep)| has smaller systematics and good sensitivity to PDFs

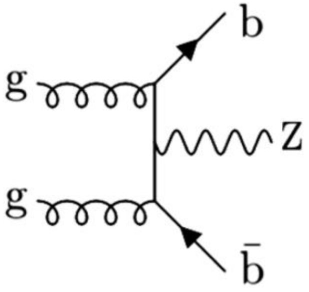
η distribution broader in data than predictions but consistent when including uncertainties

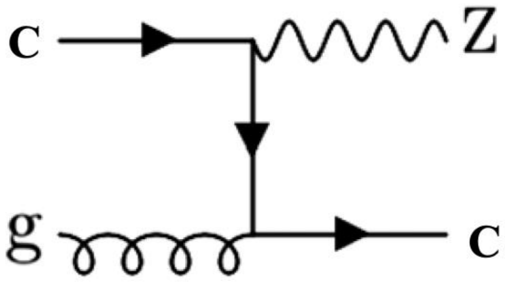
Z + ≥ 1 b-quark , Z + ≥ 2 b-quarks, Z + ≥ 1 c-quark, b- and c-quark identified with jet reconstruction and a flavour tagging algorithm

(arXiv:2403.15093)









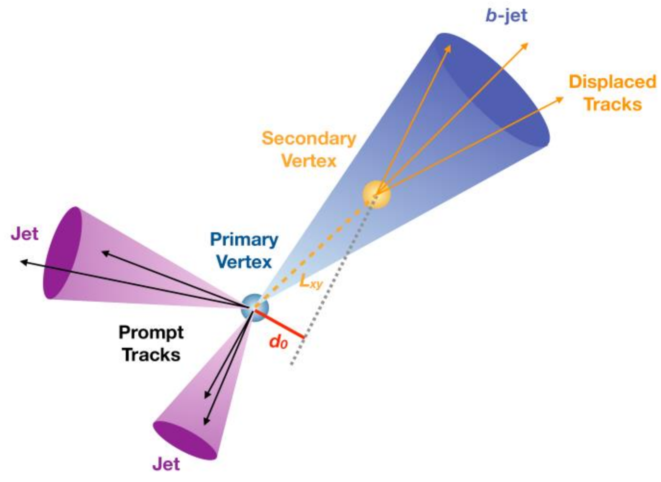
Strategy of the measurement

Z (→ ll) selection

2 isolated OS *e* or μ with p_T> 27 GeV and central,
76GeV<m_{ll} <106GeV

c- and b-quark identified via flavour tagging

≥ 1 or ≥ 2 flavour-tagged jets with p_T>20 GeV |y|<2.5

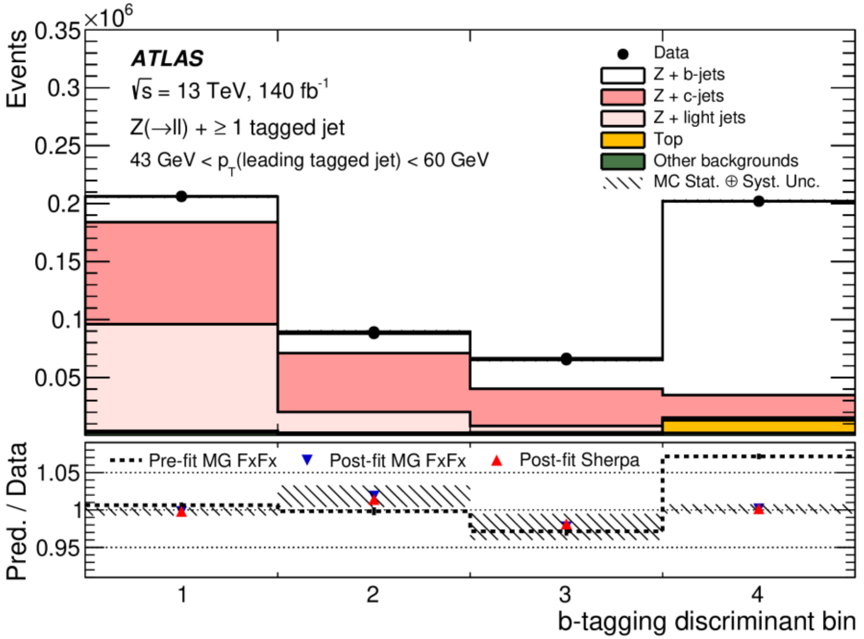


DL1r algorithm exploits b-quark properties (i.e. long lifetime and heavy mass) relying on track-based observables (displaced tracks, secondary vertex, longitudinal impact parameter, decay topologies)

DL1r Working Point at 85% b-jets efficiency and 38% c-jets efficiency

Background determination

ttbar: data-driven technique in dedicated CR (1*e*1μ)
Multijet: data-driven technique found negligible
Z+jets components from a fit to data of a flavour sensitive variable, templates from MC, fit performed in individual bins of each observable
Minor backgrounds from MC

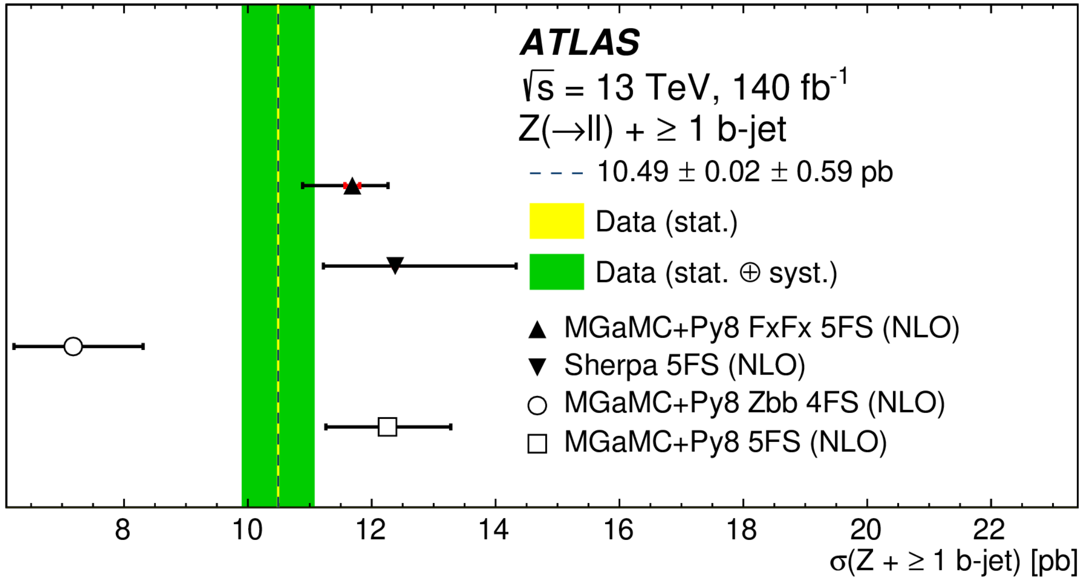


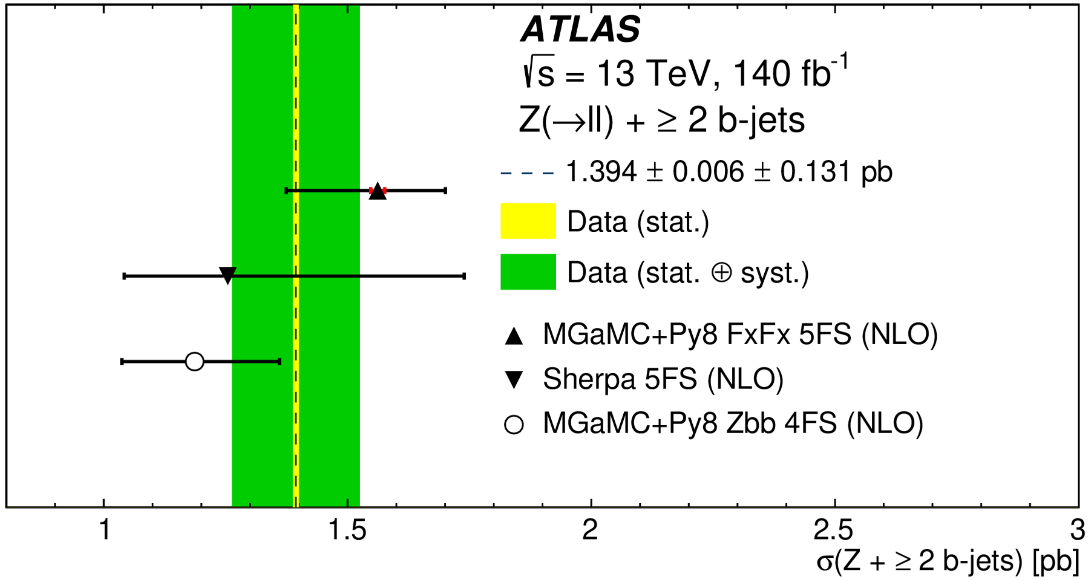
Inclusive Z+ ≥ 1 b-jet and Z+ ≥ 2 b-jet cross-sections

Cross-section extraction

- Bin-by-bin unfolding for inclusive cross-section and iterative bayesian unfolding for differential ones
- Fiducial phase-space at particle-level close to detector level one:

1 e or μ with p_T> 27 GeV |η|< 2.5 , 76GeV<m_{ll}<106GeV
b-jets with p_T>20 GeV |y|<2.5
Z+ ≥ 1 b-jet, or Z+ ≥ 2 b- jets

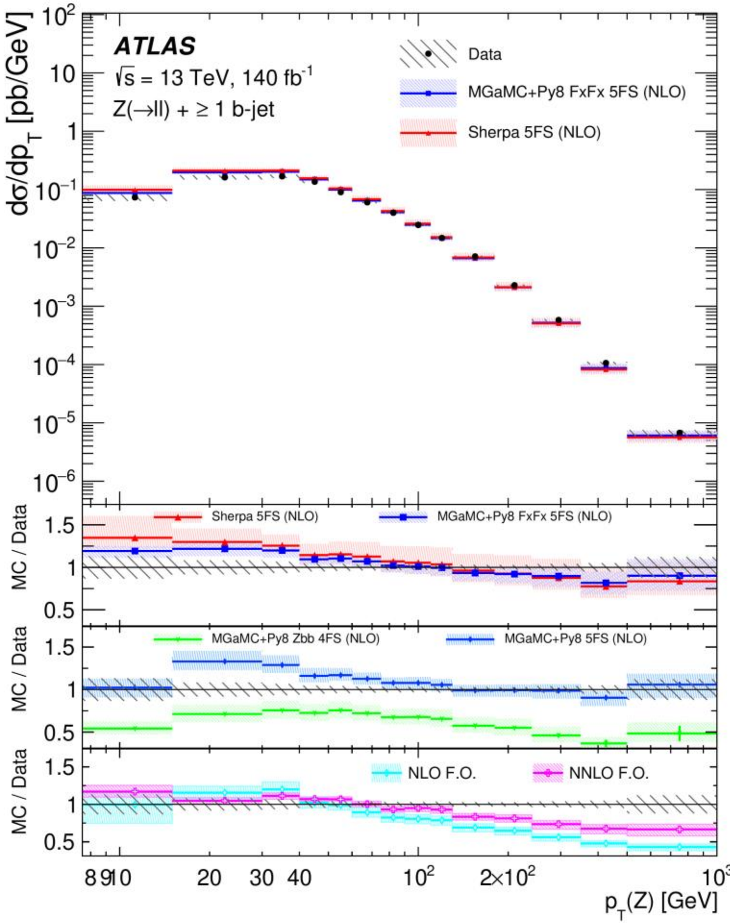




- Uncertainty on the measurement: ∽6% (Z+ ≥ 1 b-jet), ∽10% (Z+ ≥ 2 b- jets)

- Data compared with a variety of MC predictions with different FSs:
5FS NLO ME+PS MCs (MGaMC+Py8 FxFx and Sherpa) describe Z+b and Z+bb,
while 4FS Zbb NLO MC (MGaMC+Py8 Zbb) describes only Z+bb largely underestimating Z+b

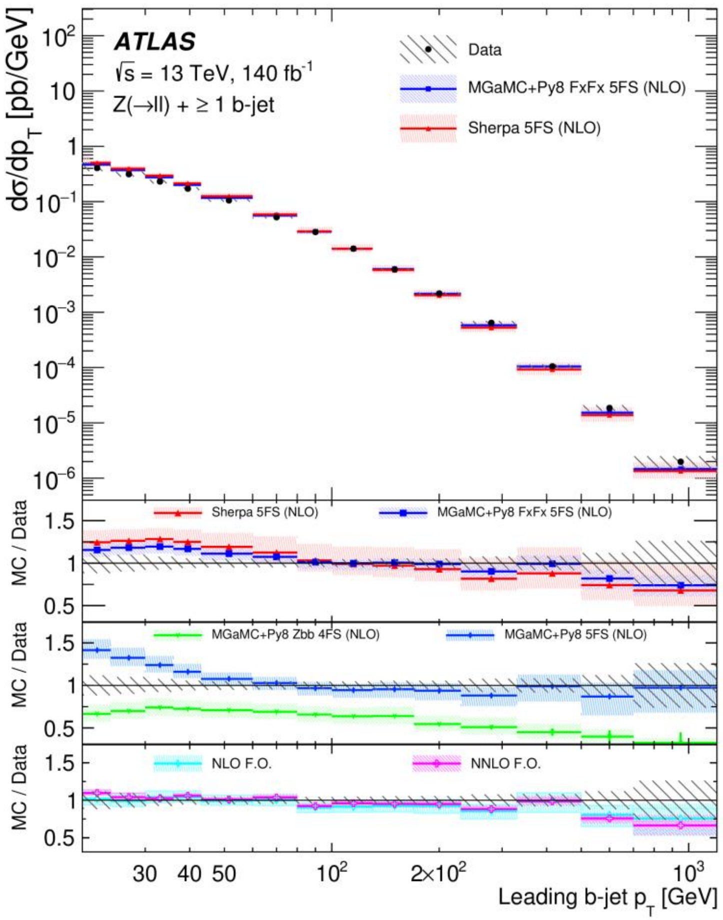
Differential Z+ ≥ 1 b-jet cross-sections



Data compared with:

-a variety of MCs (4FS and 5FS)

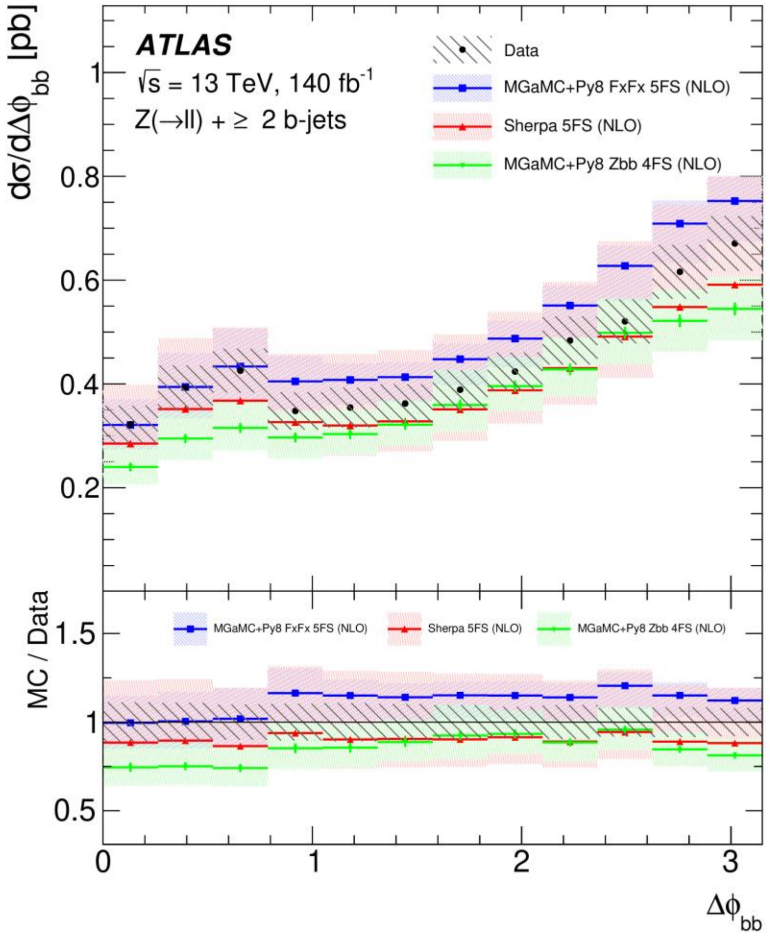
- fixed order calculations (corrected for non-perturbative effects and different jet flavour definition): NLO and NNLO calculations

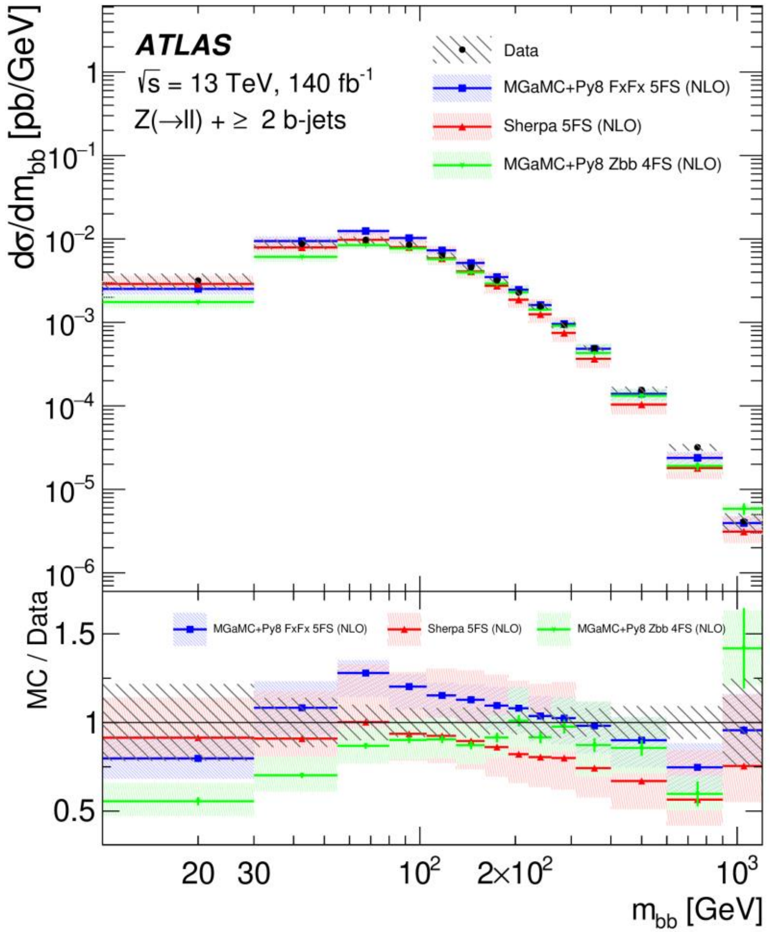


The measured p_T spectra are harder than predicted ones

Fixed-order calculations show discrepancy with data in the high p_T (Z) region

Differential Z+ ≥ 2 b-jets cross-sections

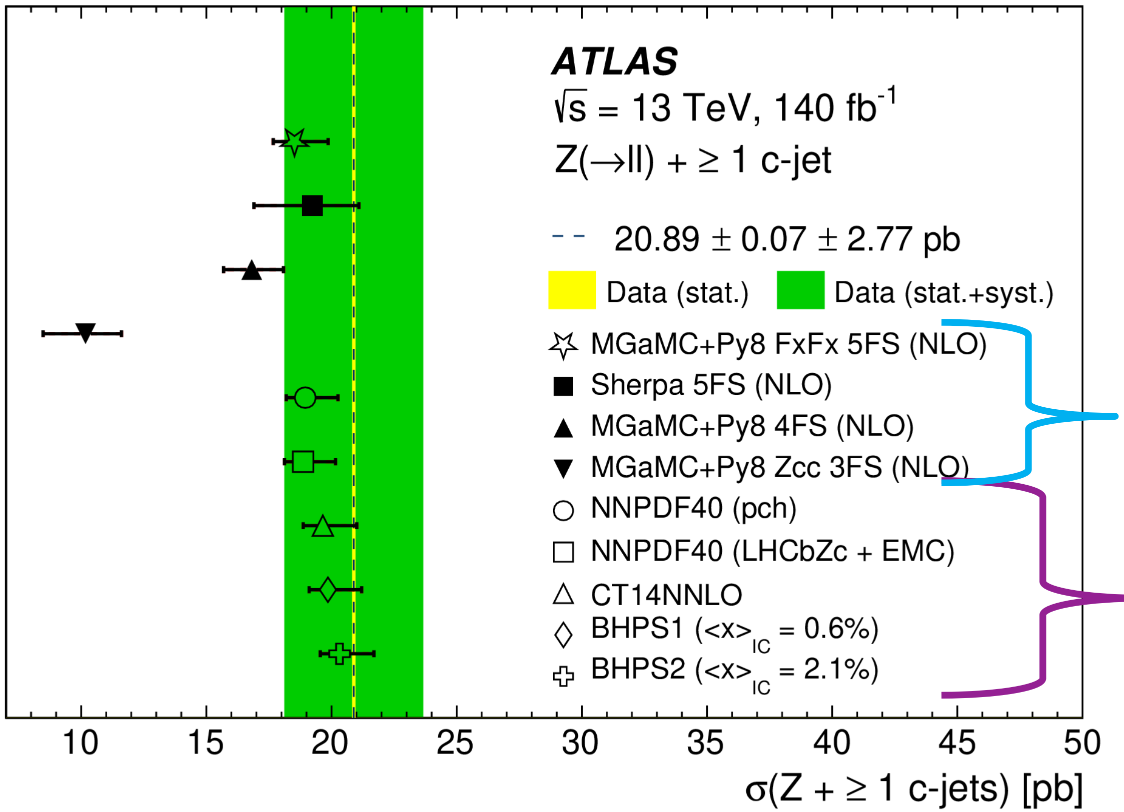




$\Delta\Phi_{bb}$: well described by 5FS NLO ME+PS MCs (MGaMC+Py8 FxFx and Sherpa),

M_{bb} : none of the predictions in agreement with data in the full spectrum

Inclusive Z+ ≥ 1 c-jet cross-section



Uncertainty on the measurement: ∽13%

Data compared with a variety of **MC predictions**:

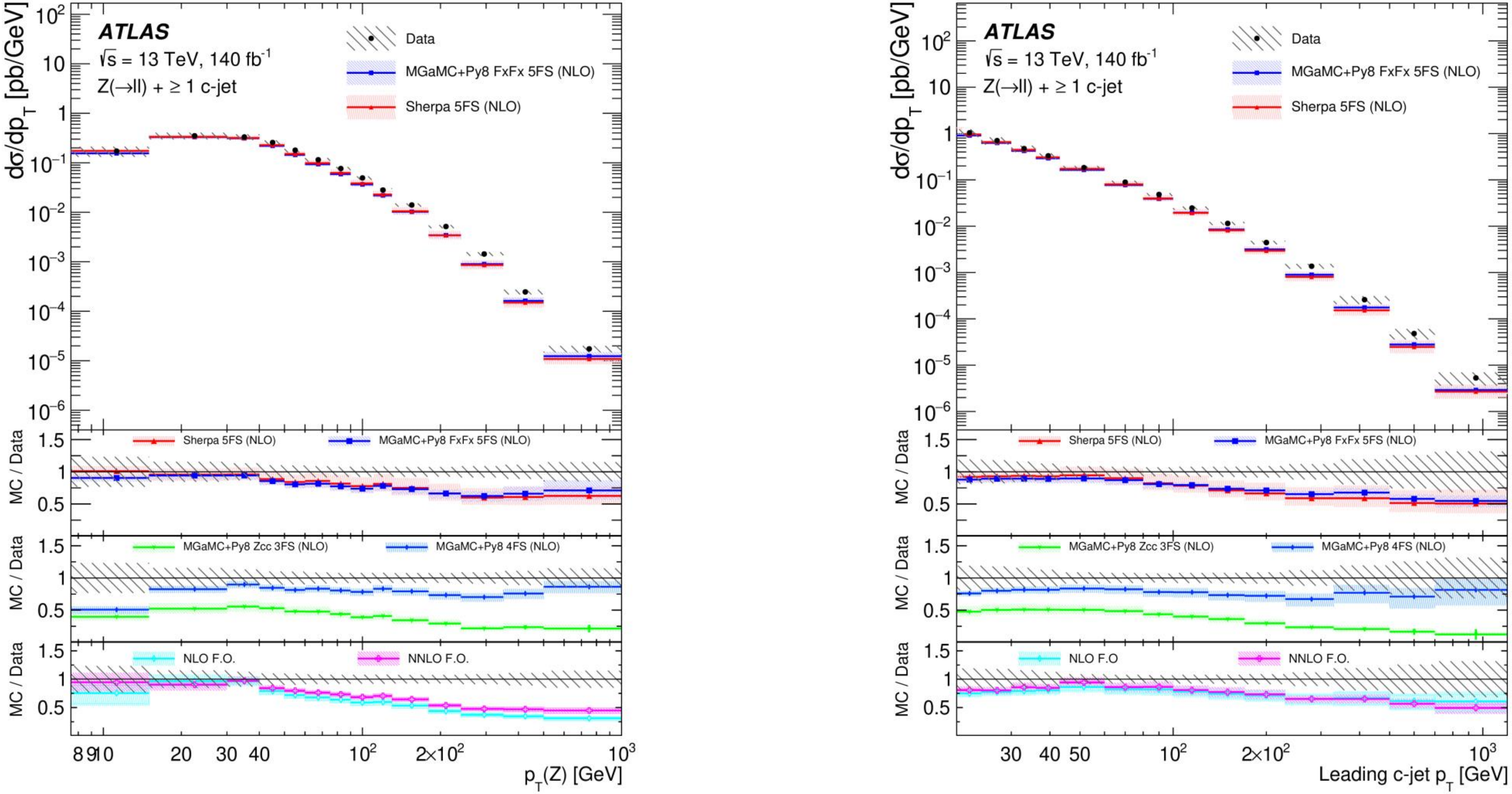
NLO ME+ PS MCs with different FSs

MGaMC+Py8 FxFx (5 FS NLO ME+PS MC) with different PDFs having different IC contributions

3FS Zcc NLO ME+PS MC does not describe the data

5FS NLO ME+PS MCs in agreement with data

Differential Z+ ≥ 1 c-jet cross-sections

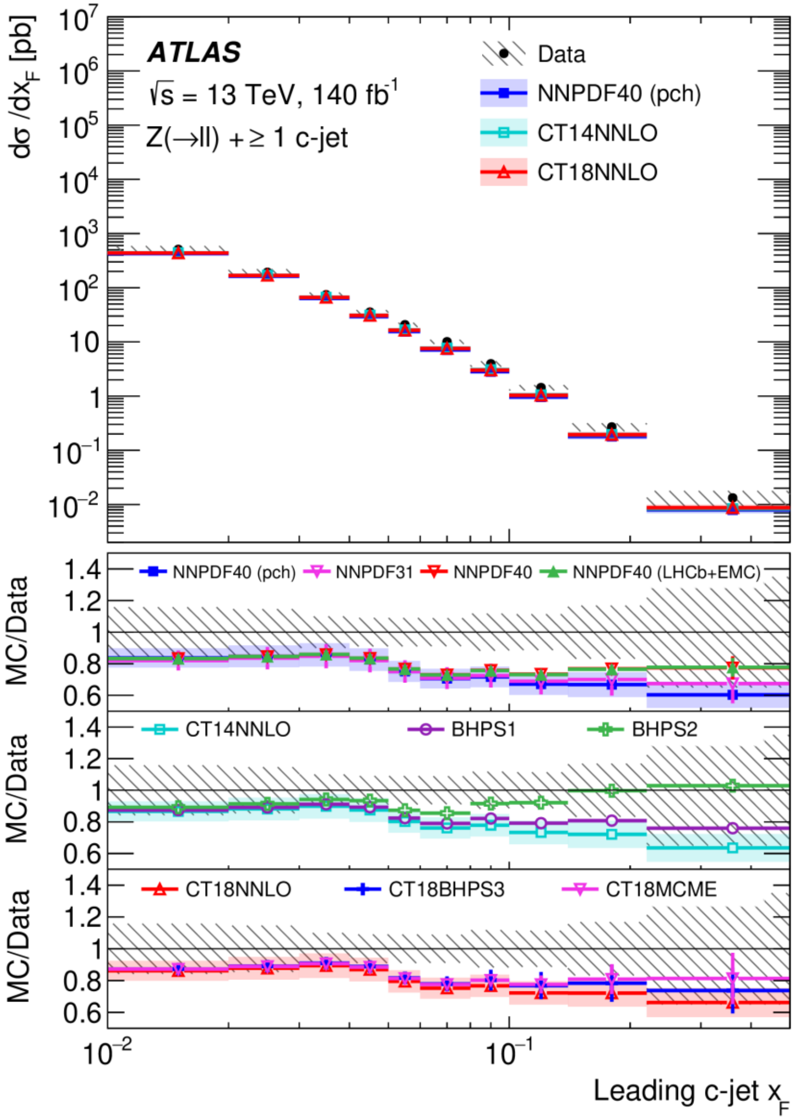


3FS and 4 FS NLO ME+PS MCs largely underestimate data

5FS NLO ME+PS MCs and fixed-order NLO and NNLO calculations describe soft part of the spectra, but underestimate large p_T (larger effect for $p_T(Z)$ with fixed-order calculations)

Differential Z+ ≥ 1 c-jet cross-sections

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



NNPDF4.0 LHCb+EMC

CT14 BHPS2 (2.1% IC)

x_F sensitive to IC

Data compared to MGaMC+Py8 FxFx (5 FS NLO ME+PS MC) with several PDF sets testing different IC-models

Mismodelling at large x_F :

- PDFs with large IC contribution, such as CT14 BHPS2 (2.1% IC), agree at large x_F

- with more realistic PDF fits (NNPDF4.0 LHCb+EMC): only marginal improvement in last bins

Conclusions

- V+HF measurements at the LHC with Run-2 entered in the precision era thanks to large amount of data and improvements in HF- tagging performances

- 2 recent ATLAS measurement presented today: W+D , Z+b(b) and Z+c:

  - W+D: precise measurement able to constraint PDFs fits, data consistent with predictions from various PDFs

  - Z+b(b): 5FS NLO ME+PS MCs describe data within uncertainties, 4FS NLO ME+PS MCs underestimate Z+b data;

  - Z+c: 3FS NLO ME+PS MCs underestimate data; no significant modelling dependence on IC on the measured observables

- Close interactions between experimentalists and theorists, including PDF fitter communities and MC developers, crucial in this kind of studies

BACKUP

W+D: MC predictions

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

Nominal signal MC: SHERPA

Alternative signal MC:
MGAMC@NLO+PY8
with different setups
(multi-jet merged with FxFx or CKKW and NLO with finite c-quark mass)

In all MC samples charmed hadron production fractions corrected to the world-average values

$D^{(*)}$ object selection criteria

Candidates K/π assigned based on the charge of the track:

- D^+: N_{tracks} = 3 tracks with total charge = ±1 with same charge assigned to π and the other to K
- D^0: N_{tracks} = 2 with total charge = 0, matching with prompt π from D^{*+} decay

SV-based cuts applied to improve S/B

D(*) cuts:

η cut to avoid ID edge with large amount of material and reduced reconstruction efficiency

p_T upper cut to reject fake $D^{(*)}$ mesons at high momentum

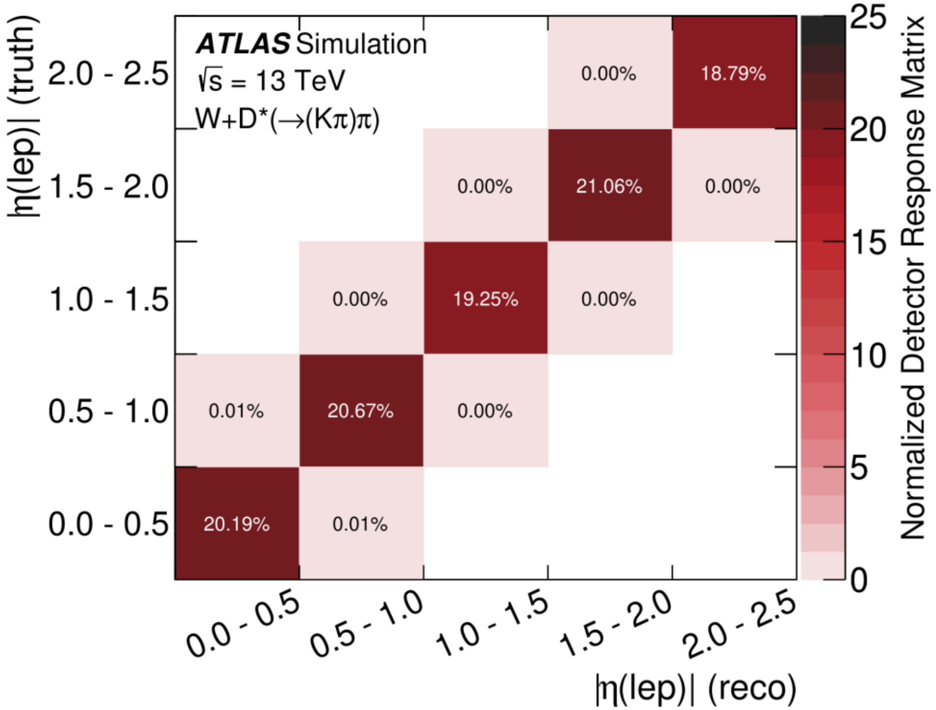
$D^{(*)}$ cut	D^+ cut value	D^{*+} cut value ($D^0\pi \to (K\pi)\pi$)
N_{tracks} at SV	3	2
SV charge	±1	0
SV fit quality	$\chi^2 < 8$	$\chi^2 < 10$
Track p_T	$p_T > 800$ MeV	$p_T > 600$ MeV
Track angular separation	$\Delta R < 0.6$	$\Delta R < 0.6$
Flight length	$L_{xy} > 1.1$ mm $(p_T(D^+) < 40$ GeV$)$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

W+D: Migration matrix

Cross-section extraction

- W^+ and W^- inclusive cross-sections, cross-section ratios and the differential cross-sections also extracted from a likelihood fit

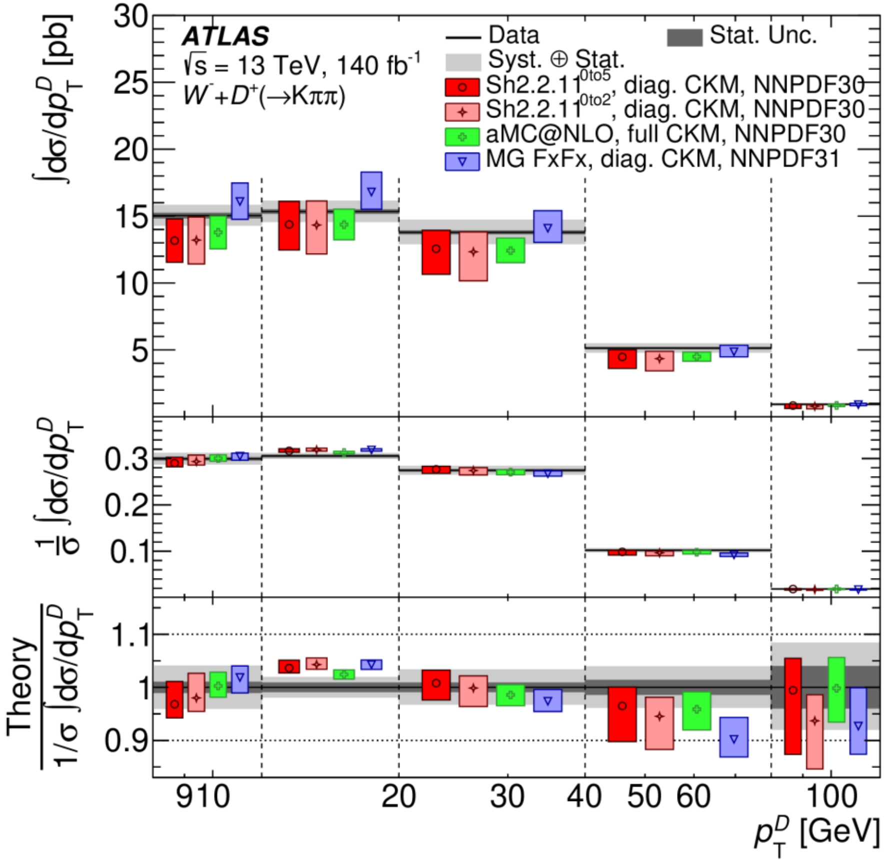
- Fiducial phase-space close to detector level one:
  1 e or μ with $p_T > 30$ GeV $|\eta| < 2.5$
  ≥ 1 $D^{(*)}$ with 8 GeV< p_T >8 GeV $|\eta|<2.2$

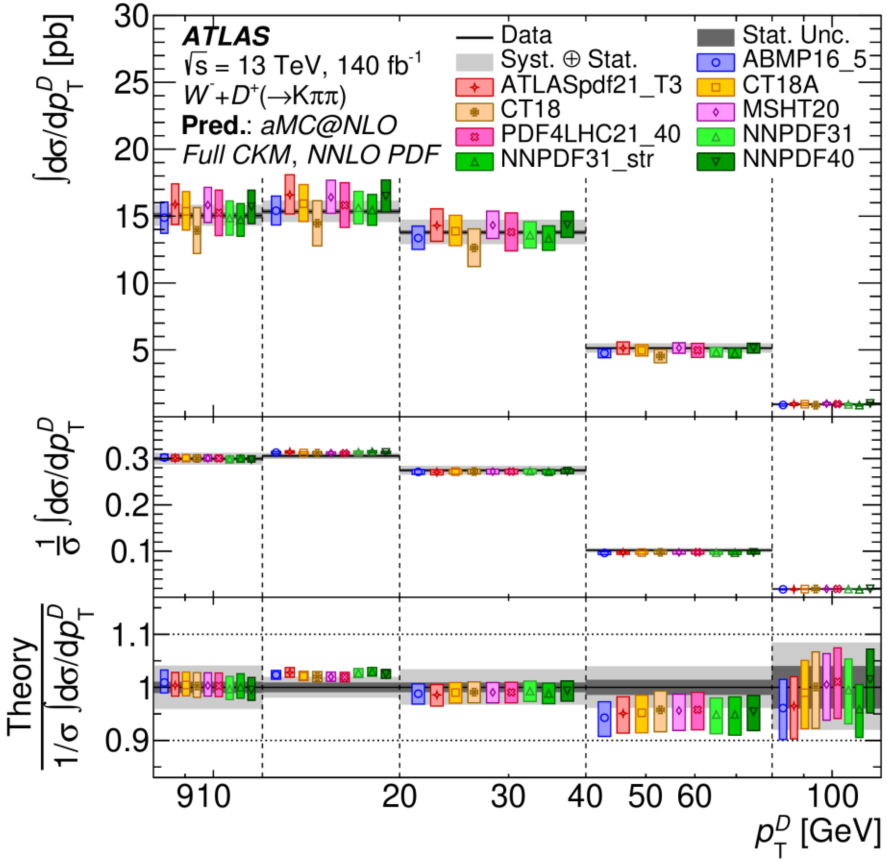


W+D : Uncertainties

	D^+ channel			D^{*+} channel		
Uncertainty [%]	$\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^+)$	$\sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^-)$	$R_c^{\pm}(D^+)$	$\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^{*+})$	$\sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^{*-})$	$R_c^{\pm}(D^{*+})$
SV reconstruction	3.0	2.9	0.5	2.3	2.3	0.4
Jets and $E_{\text{T}}^{\text{miss}}$	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

W+D differential cross-sections





All predictions with different PDFs have similar p_T^D shape → observable sensible to MC modelling not to PDFs

Z+ ≥ 1 b-jet, Z+ ≥ 2 b-jet, Z+ ≥ 1 c-jet: MC Predictions

NLO ME+PS MCs with different FSs

Specific NLO ME+PS MC with different NNLO PDFs having different

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

Z+ ≥ 1 b-jet, Z+ ≥ 2 b-jet, Z+ ≥ 1 c-jet: Fixed order calculations

Fixed order (FO) calculations

	Fixed-order predictions		
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

Corrections from parton-level to particle level to allow comparison with unfolded data:

- *Corrections for non-perturbative effects* :

  bin-by-bin correction with a MC with hadronization and underline event switched on/off

- *Corrections for different jet flavour definition*:

  - FOs use **flavour-dressing algorithm (**Phys. Rev. Lett. 130 (2023) 161901**)** for the assessment of the flavour of the (anti-kt R= 0.4) – IRC safe algorithm

  -In the analysis used **a cone-base algorithm**:

  b-jet= jet within ΔR=0.3 of at least a b-hadron with p_T> 5 GeV. If a b-hadron matches two jets, only the closest is taken

  c-jet = jet not classified as b-jets, within ΔR=0.3 of at least one c- hadron with p_T> 5 GeV.

  light-jet = jet not classified as a b- or a c-jet

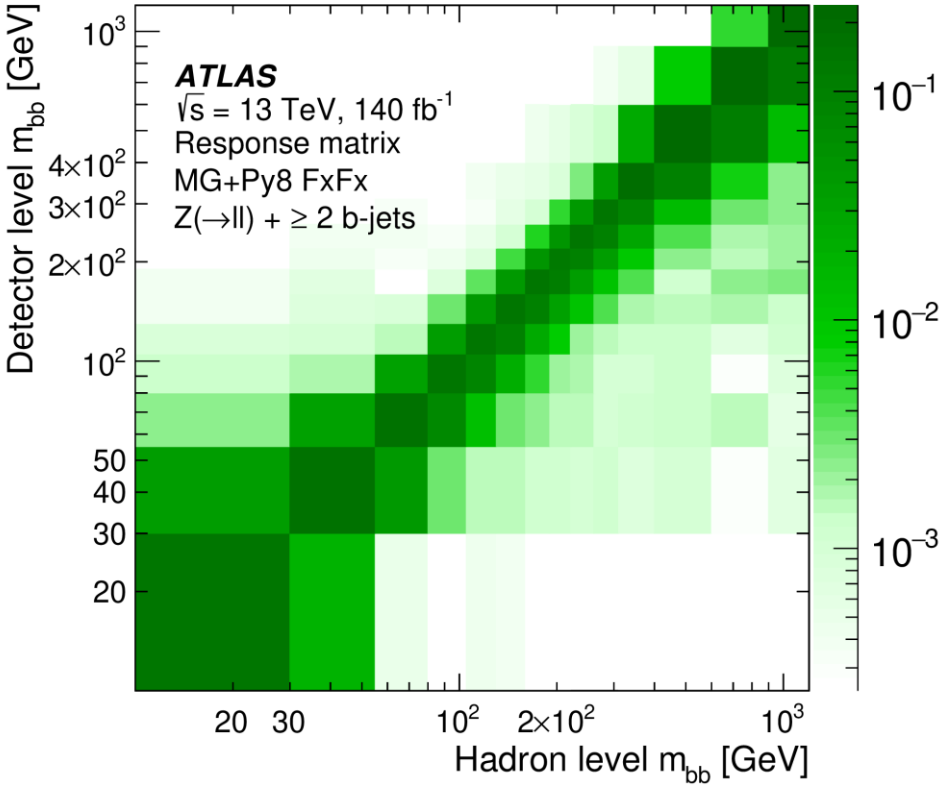
  - bin-by-bin corrections done with MGaMC+Py8 FxFx (ratio of results with cone-base/flavour dress) , difference with Sherpa taken as systematic

Z+ ≥ 2 b-jets : Migration matrix

- Bin-by-bin unfolding for inclusive cross-sections and Bayesian unfolding for differential cross-sections

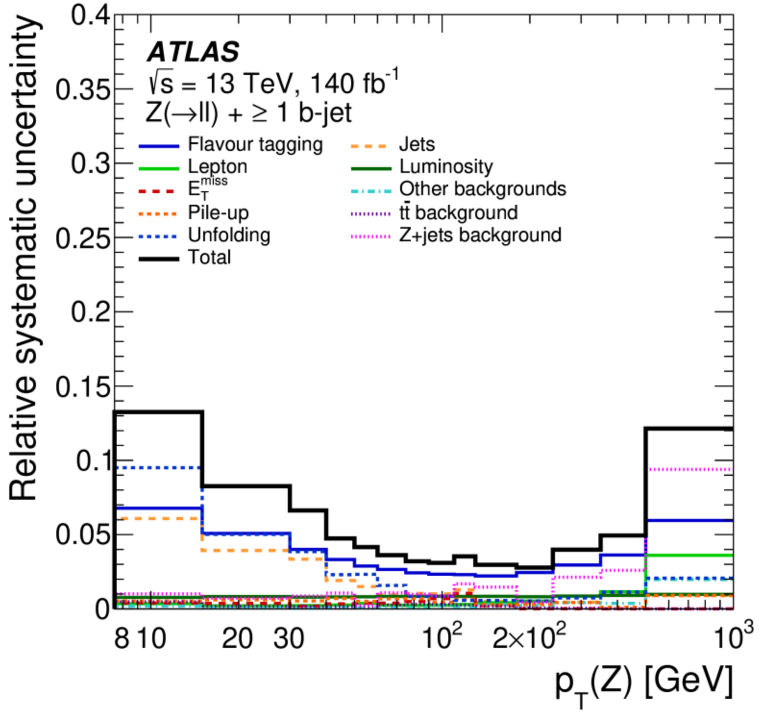
Cross-section extraction

- Fiducial phase-space close to detector level one:
  1 e or μ with p_T> 27 GeV |η|< 2.5 , 76GeV<m_{ll} <106GeV
  b-jets and c-jets with p_T>20 GeV |y|<2.5
  Z+ ≥ 1 b-jet, or ≥Z+ 2 b- jets or Z+ ≥ 1 c-jets



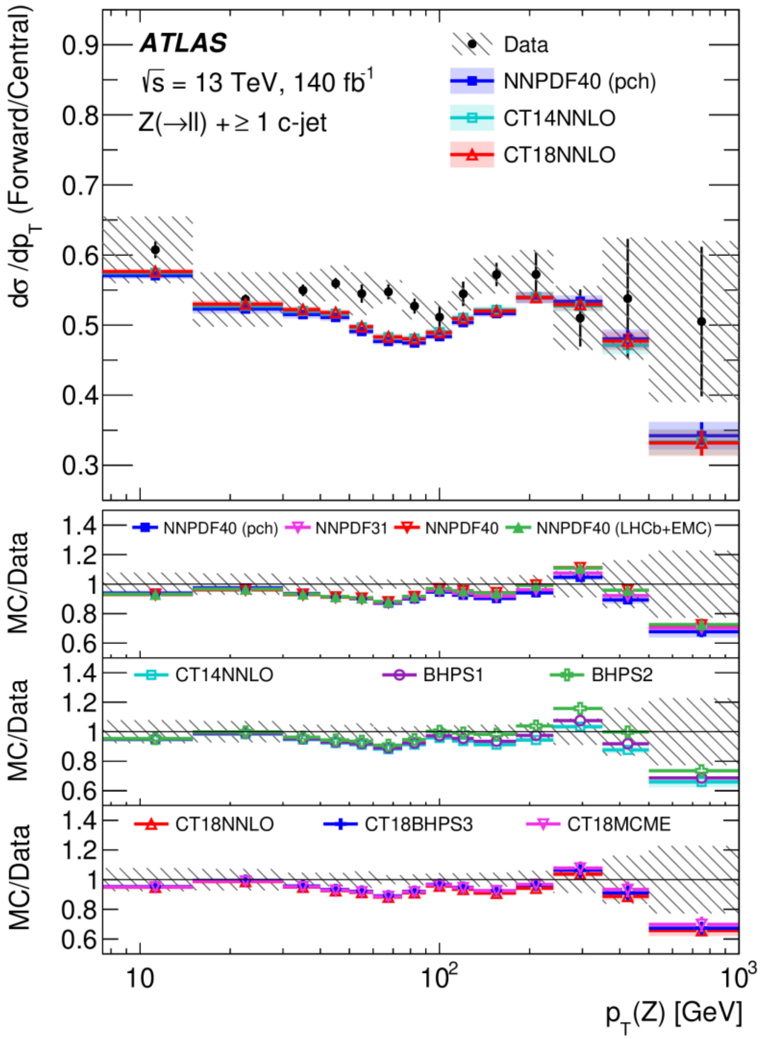
Z+ ≥ 1 b-jet, Z+ ≥ 2 b-jet, Z+ ≥ 1 c-jet: Uncertainties

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



Differential Z+ ≥ 1 c-jet measurements

Ratio of Forward $p_T(Z)$ to Central $p_T(Z)$



Central Z : |y|<1.2
Forward Z: |y|>1.2

- Large reduction of systematics in the ratio (~8%)

- Data compared to MGaMC+Py8 FxFx (5 FS NLO ME+PS MC) with several PDF sets testing different IC-models:

  similar trend by all IC-models
  → The measurement has small sensitivity to IC