Measurements of W and Z boson production in association with jets in ATLAS

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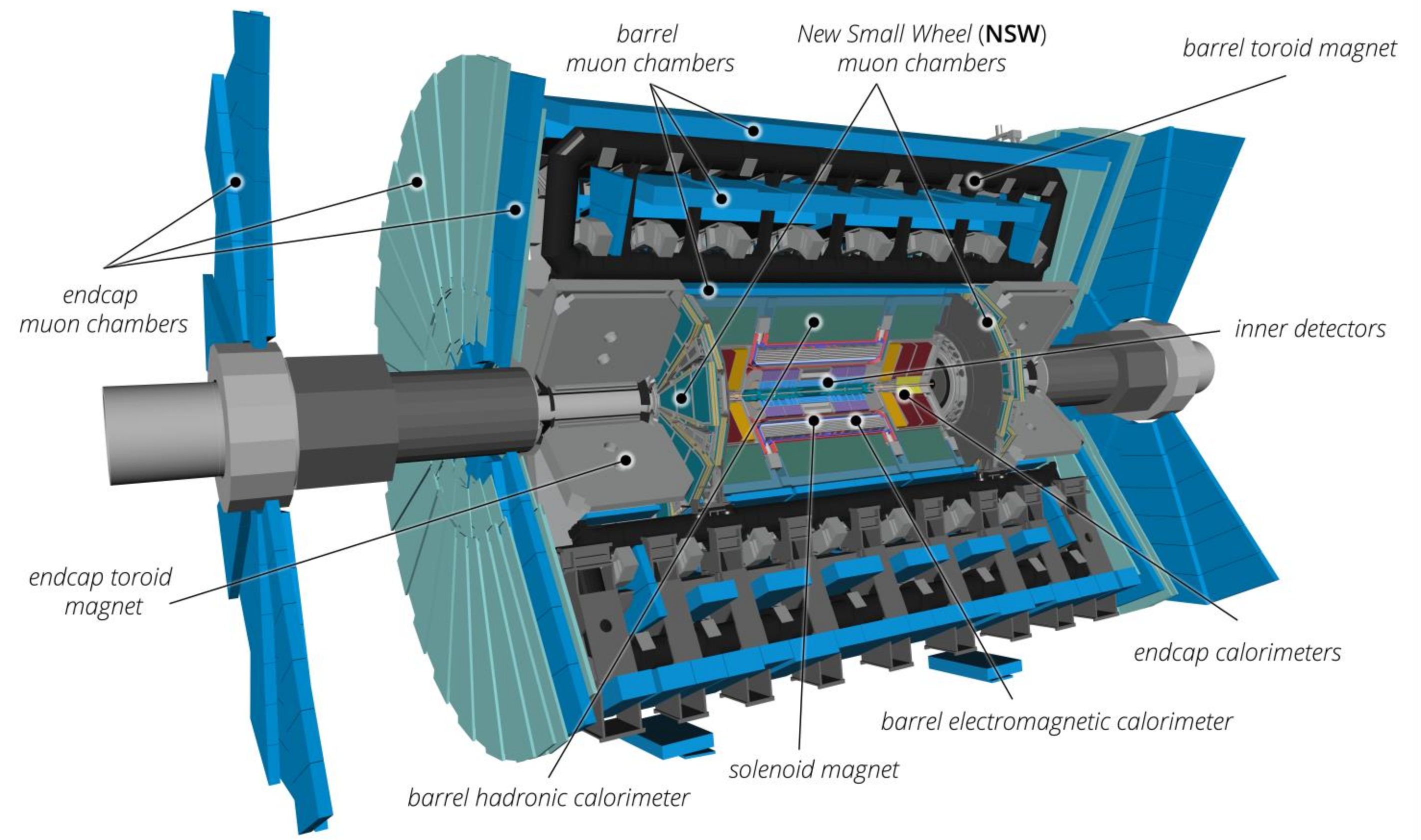
On behalf of the ATLAS collaboration

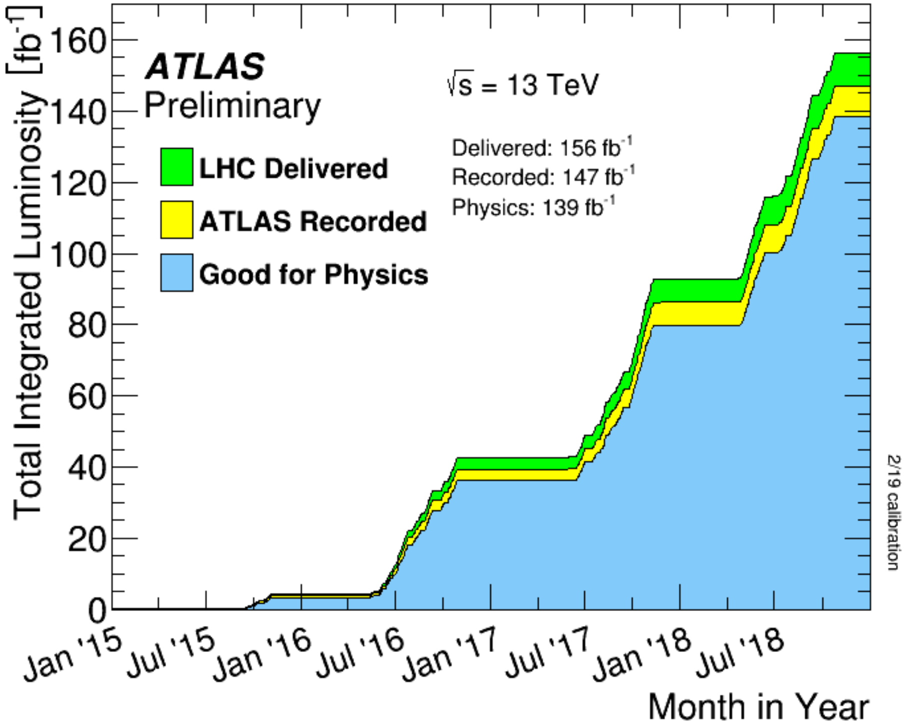
17^{th}-24^{th} July 2024, the 42^{nd} ICHEP, Prague

ATLAS Experiment

- **A priority goal** is to establish to what extent the SM remains valid at accessible energies

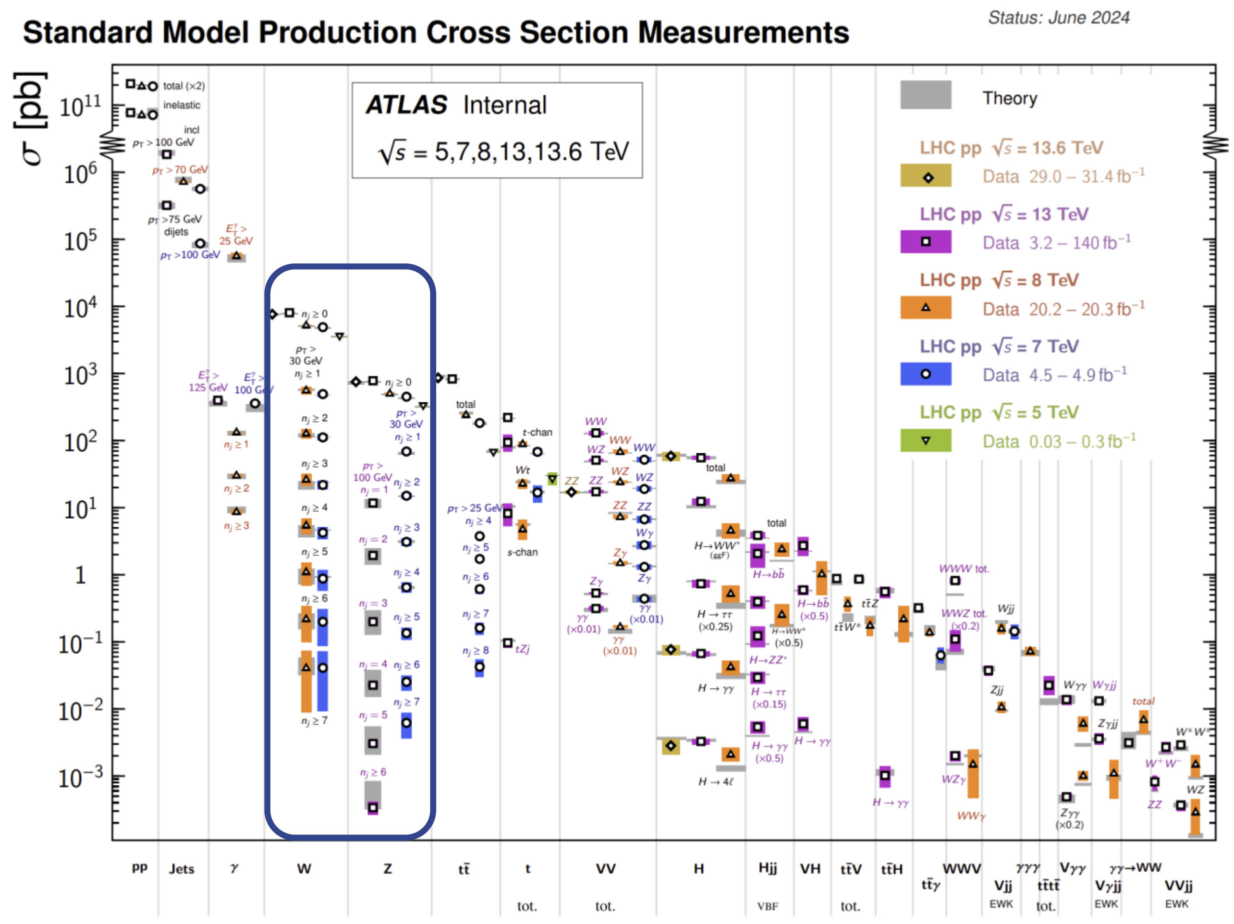


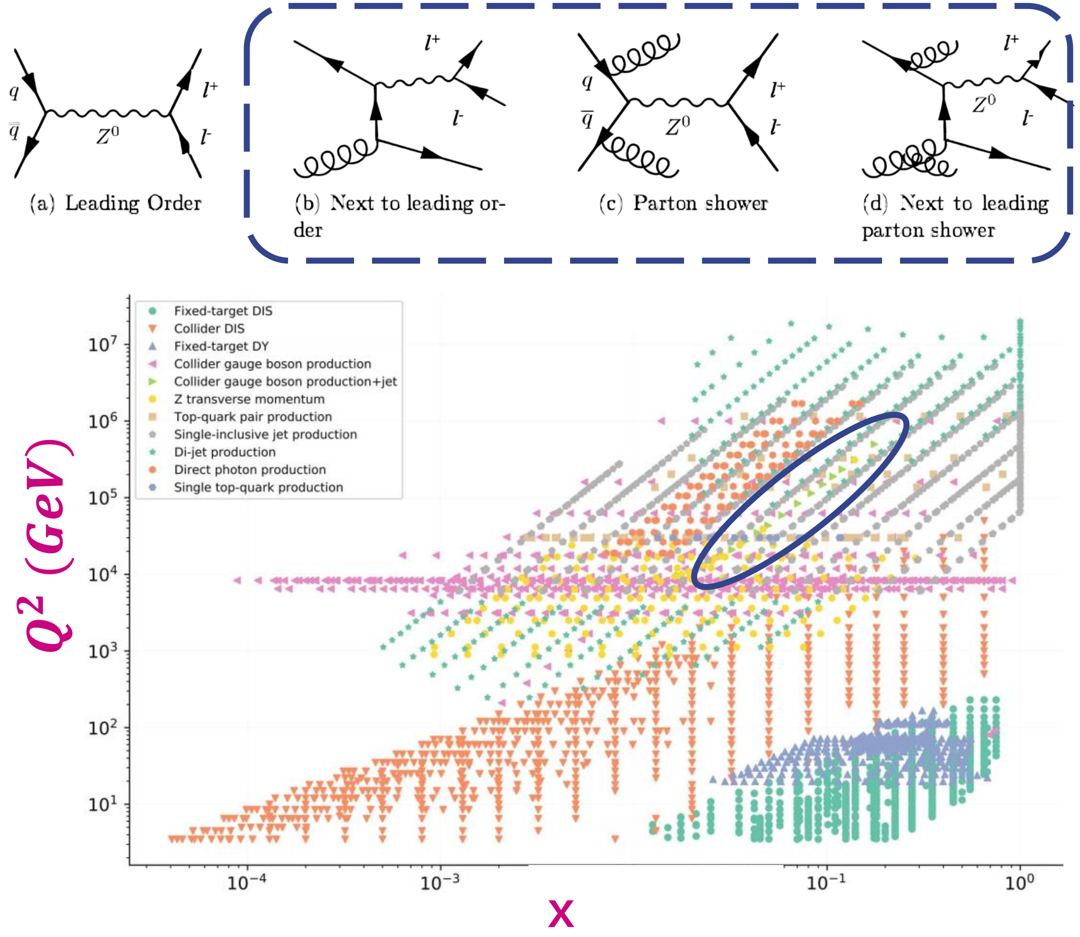
- Run-2 with largest dataset available for physics: $\mathcal{L}$ = 140 fb^{-1} at $\sqrt{s}$ = 13 TeV



V + jets at hadron collider

- **V(=W/Z) + jets** production has the *large cross-section* and a *broad kinematic range*
  - *High order of Drell-Yan process* accounting for 1/3 of W/Z productions at LHC



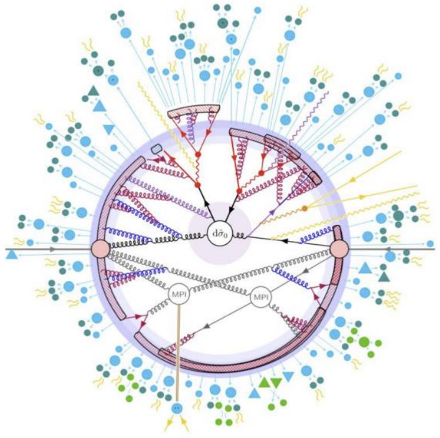


Goals of V + jets measurements

- ✦ 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

Stages of a MC event generator

- Hard Scatter
- Parton Shower (PS)
- Hadronisation (Had)
- Colour Reconnection (CR)
- Multiple Parton Interactions (MPI)

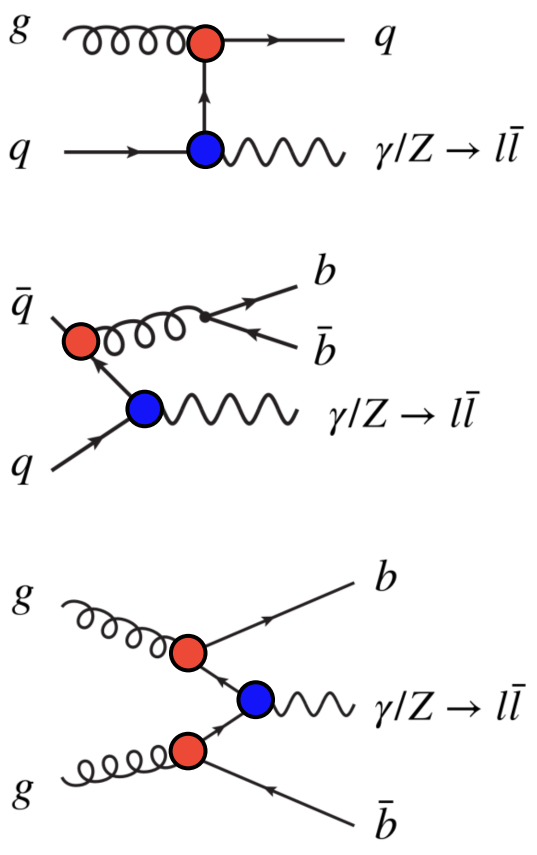


Pythia 8.3 schematic event

qg initial state

$q\bar{q}$ initial state

gg initial state



** Z + bb shown as example*

Today focus on recent ATLAS results

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

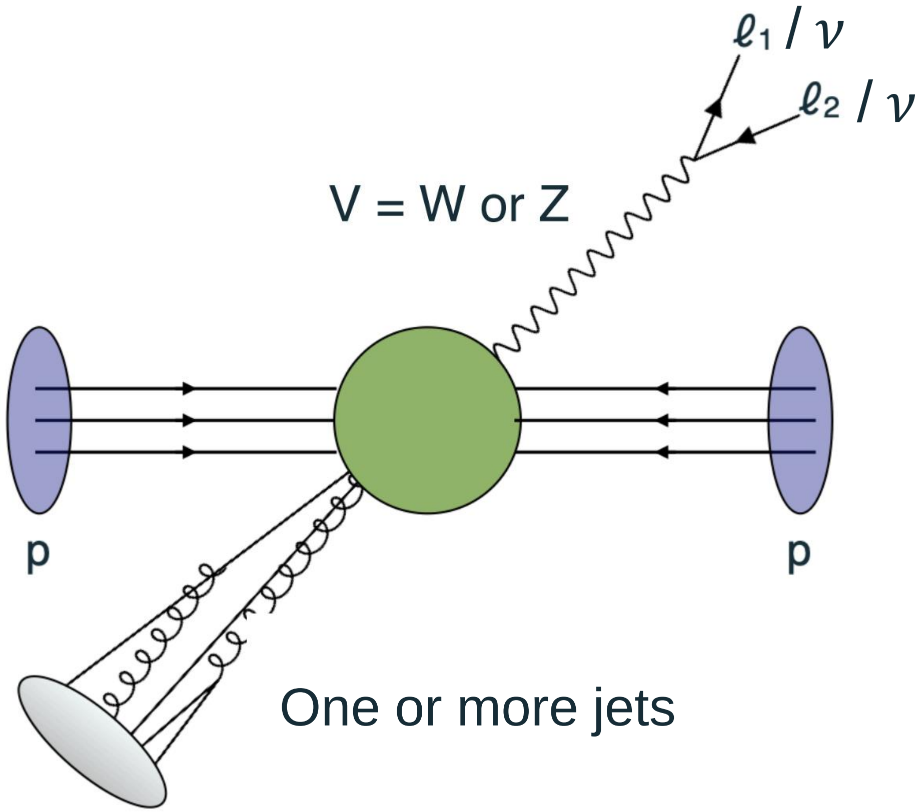
Phys. Rev. D 108 (2023) 032012

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

Submitted to EPJC, arXiv:2403.15093

★ **MET production in association with jets**

Submitted to JHEP, arXiv:2403.02793

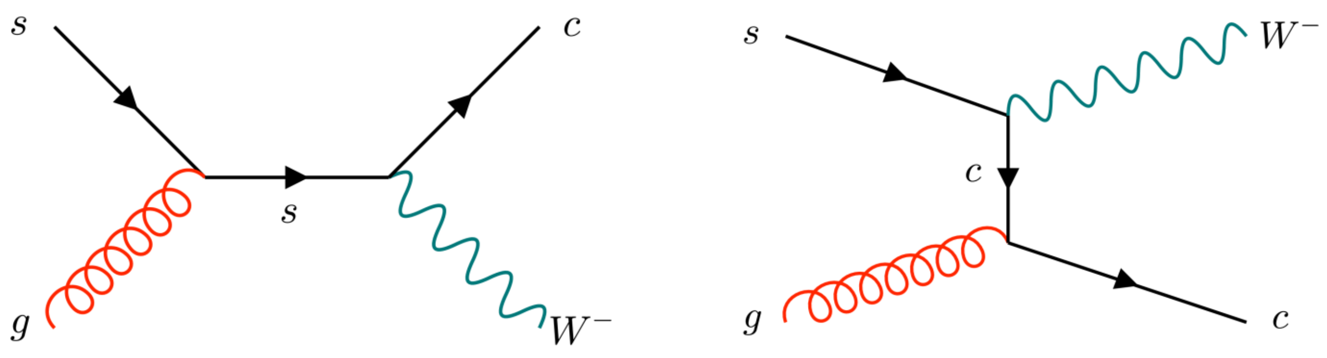


W + Charmed hadron

W + D Measurements

140 fb^{-1}, $\sqrt{s}$ = 13 TeV, ***selections in backup***

✦ **Signal signature with opposite-signed (OS) W and D-meson**



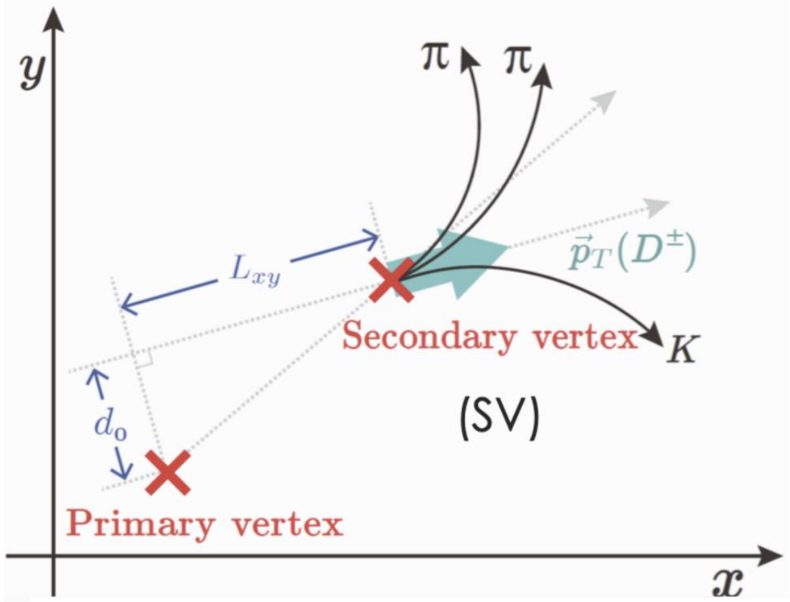
gs → $W^{-}c$ dominant at LO

⇨ unique probe to ***s-quark*** **PDF**

Exclusive D-meson decay reconstruction with fit K/π candidate tracks to the secondary vertex

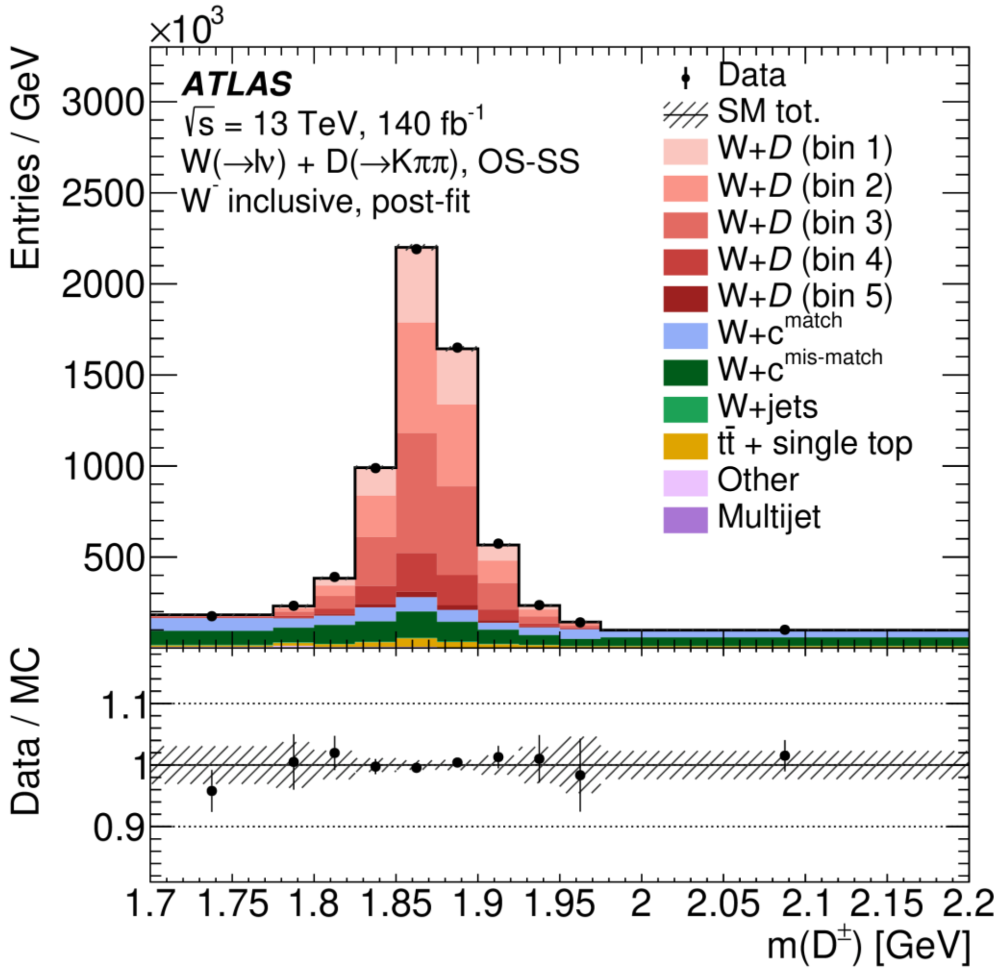
$Targeting\ at\ \boldsymbol{D^{+}} \rightarrow\ \boldsymbol{K^{-}\pi^{+}\pi^{+}} and\ \boldsymbol{D^{*+}} \rightarrow (\boldsymbol{K^{-}\pi^{+}})\boldsymbol{\pi^{-}}$

with the charge conjugate modes



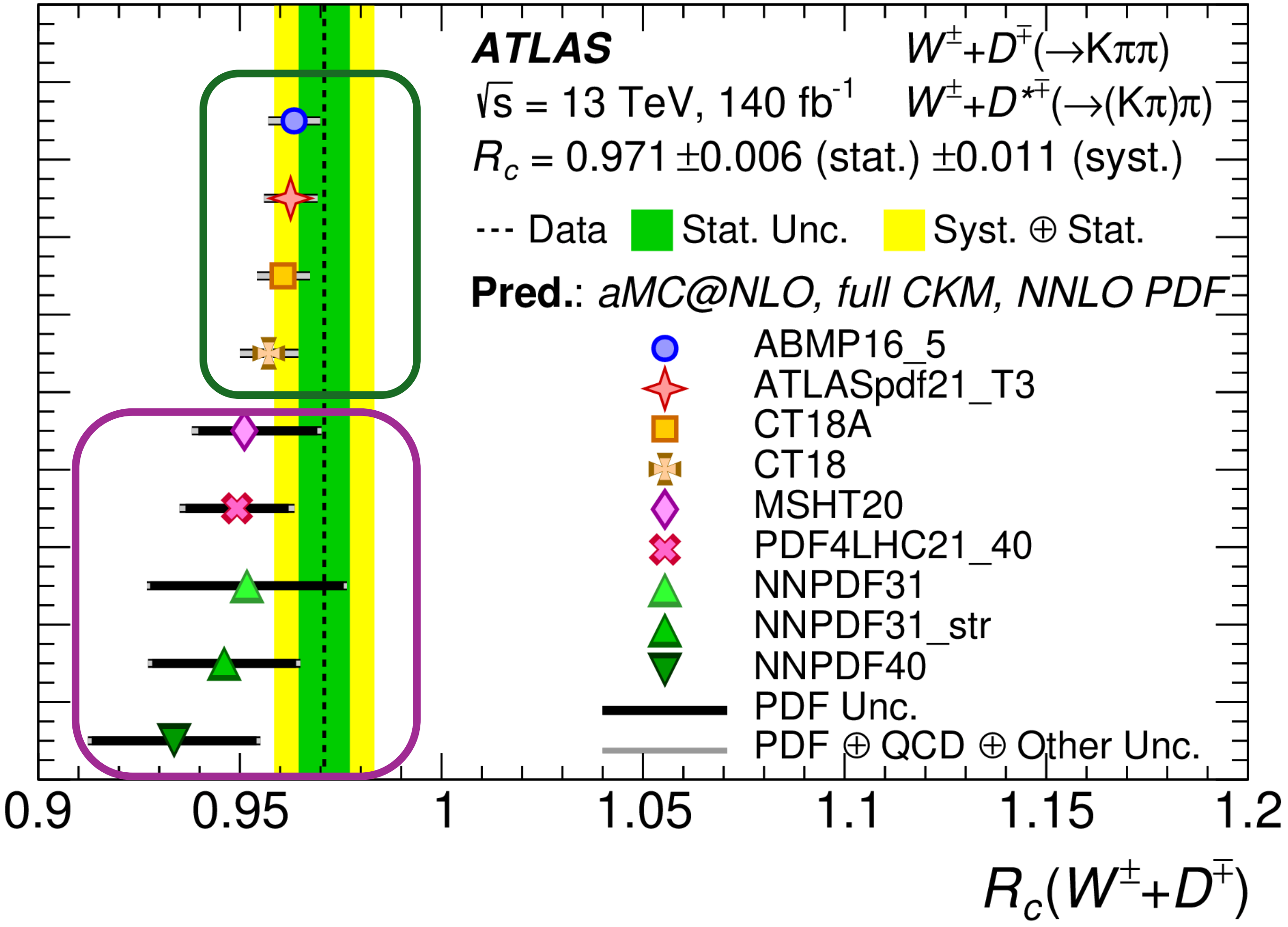
Highlights in Analysis Strategy

- **Control the backgrounds with charge correlation between W and D**
  - Backgrounds mostly have same contribution of OS and SS W+D
    i.e. $W + c\bar{c}$ $(b\bar{b})$, $t\bar{t}$ ⇨ ***OS – SS*** strategy applied
- **Differential cross sections measured with likelihood fits**
  - Binned profile likelihood fit of m_{D^+} or $(m_{D^{*+}} - m_{D^0})$ **in p_T^D and $|\eta(l)|$ bins** simultaneously in SS and OS
- **Results compared with state-of-the-art PDF sets**



Inclusive cross section

✦ **Data obtained from the combination of W+D and W+D* measurements**



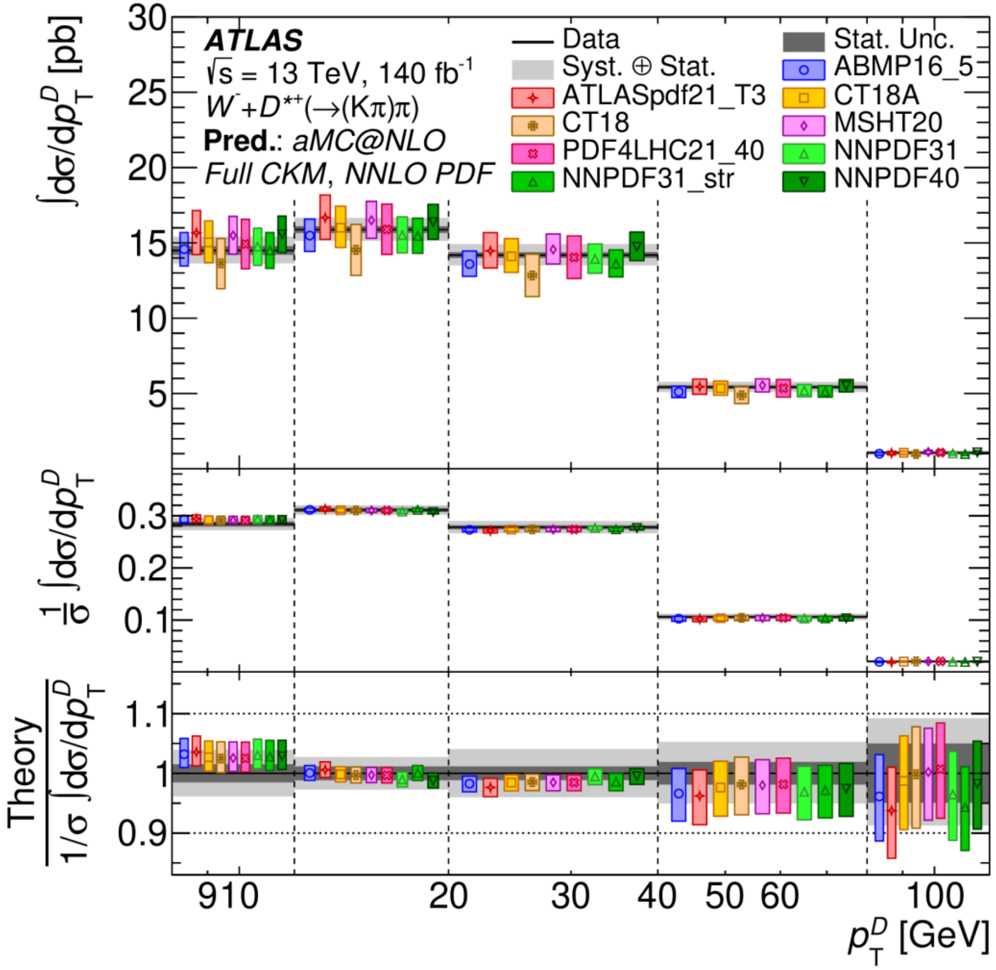
$R_c^{\pm}$ with experimental precision ~ 1%

✦ Consistent with PDF sets imposing a ***symmetric*** $s - \bar{s}$ sea quark

⇨ asymmetry small in the Bjorken-x region probed by this measurement.

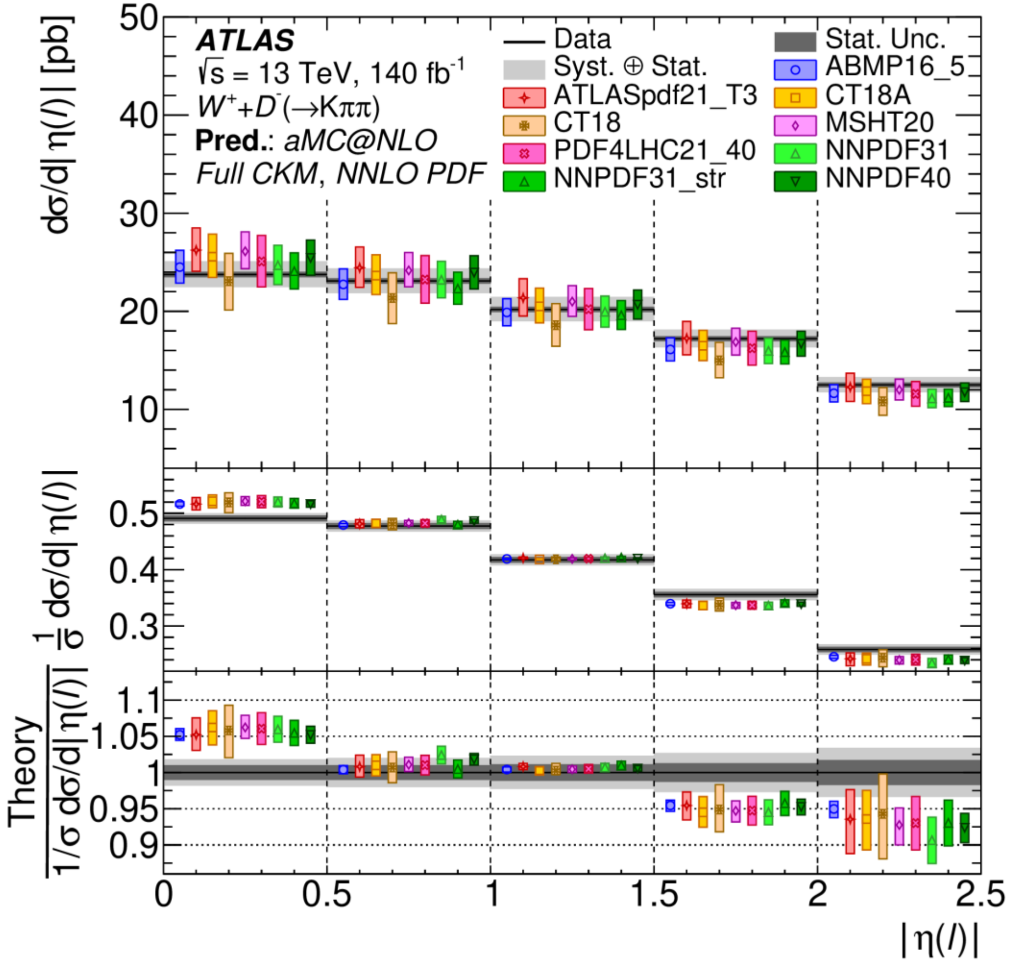
✦ PDF fits that allow the ***s and*** $\bar{s}$ ***distributions to differ*** have larger uncertainties

Differential cross section



Shape Only

- ✦ *Systematic uncertainties for $|\eta(l)|$ are small providing good sensitivity to PDF variations*



- ✦ *Experimental sensitivity reduced by the presence of p_T dependent sys. uncertainties*

Z + HF jets

Z + HF jets Measurements

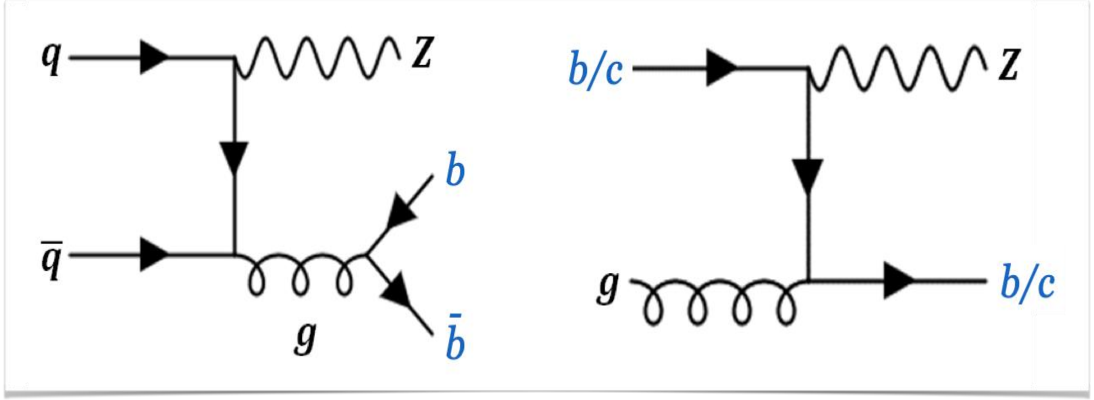
140 fb^{-1}, $\sqrt{s}$ = 13 TeV, *selections in backup*

Inclusive and differential Z+≥1b, ≥2b, ≥1c x-sections and fwd/central ratio for Z+≥1c events with 139 fb^{-1}

- Z+≥1b: Z p_T, lead b-jet p_T and ΔR(Z, lead b-jet)
- Z+≥2b: m_{bb}, $\Delta\Phi_{bb}$
- Z+≥1c: Z p_T, lead c-jet p_T, lead c-jet x_F and fwd/central vs Z p_T

High level neural ***network*** algorithm used for ***flavour tagging***

$\Delta R(jet, hadron) < 0.3$ ***truth match*** used to categorize ***Z+b/c/l jets***



⇨ Test effect of ***missing higher order*** in QCD

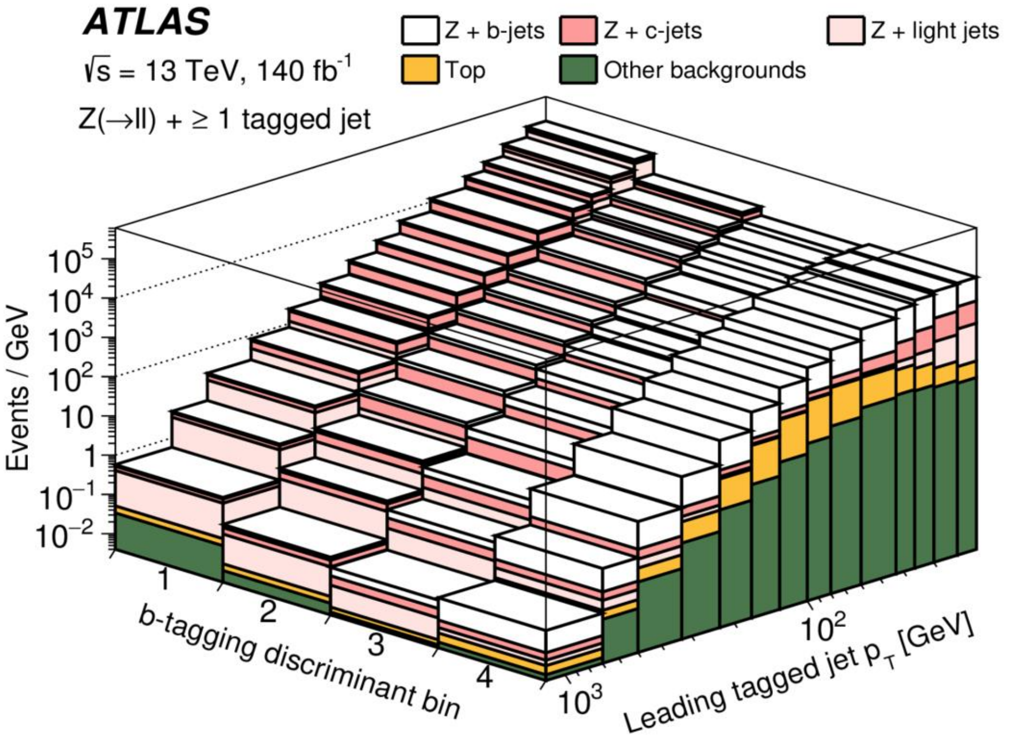
⇨ Investigate different ***Flavour-Schemes***

⇨ Explore possible sensitivity to ***Intrinsic-Charm***

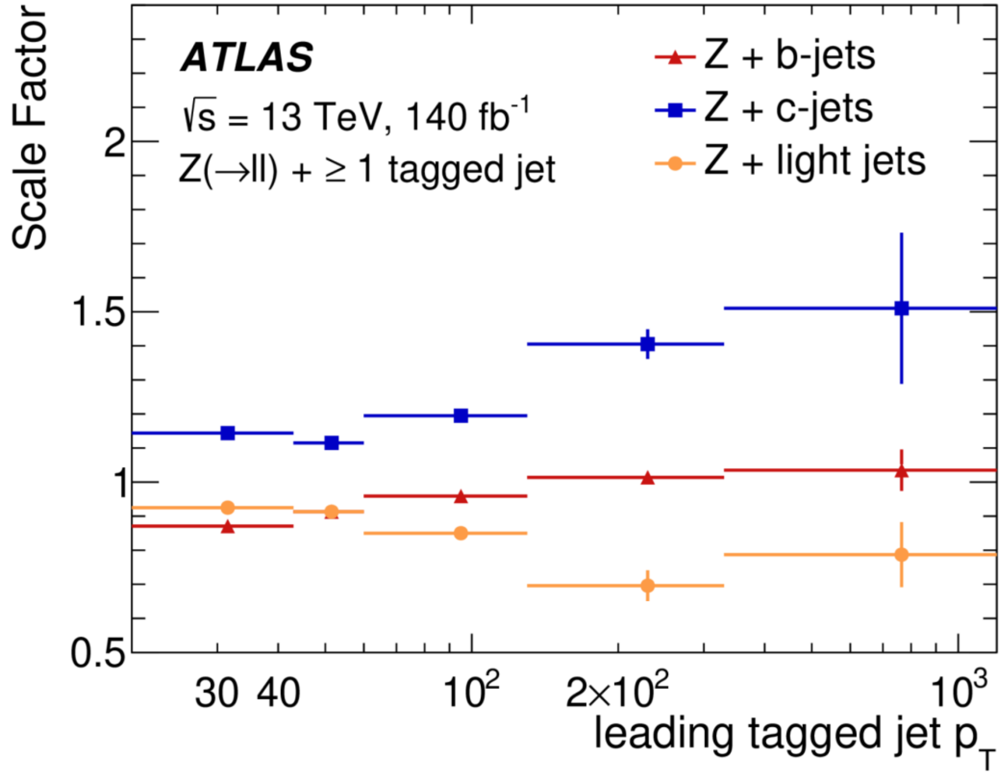
Z+jets background and flavour fit

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

- **Maximum-likelihood fit** to data based on **flavour sensitive distribution**



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



Inclusive cross-section results

$Z + \geq 1\ b$-jet

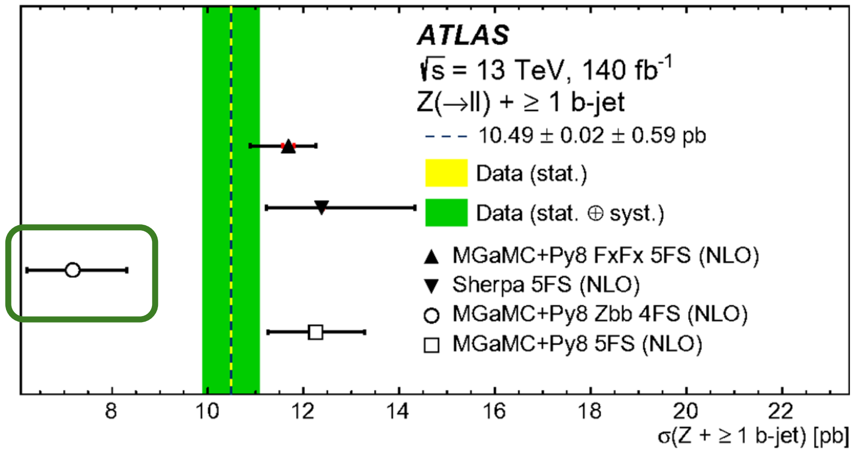
- Good description from *5FS*
- *4FS* with large underestimation

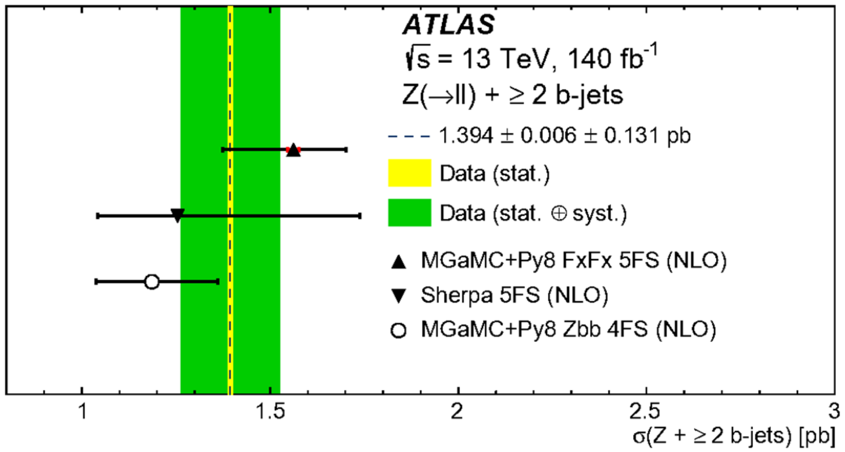
$Z + \geq 2\ b$-jet

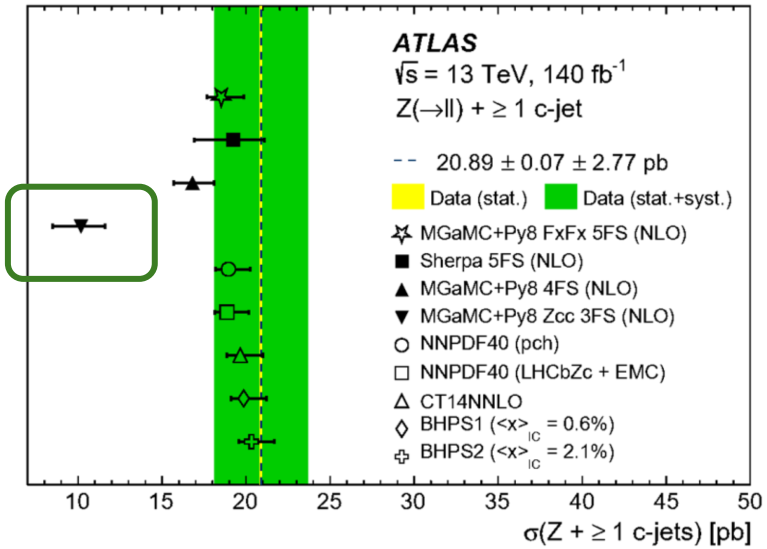
- 4FS and *5FS* agrees with data
- much sizable MHOU for Sherpa

$Z + \geq 1\ c$-jet

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

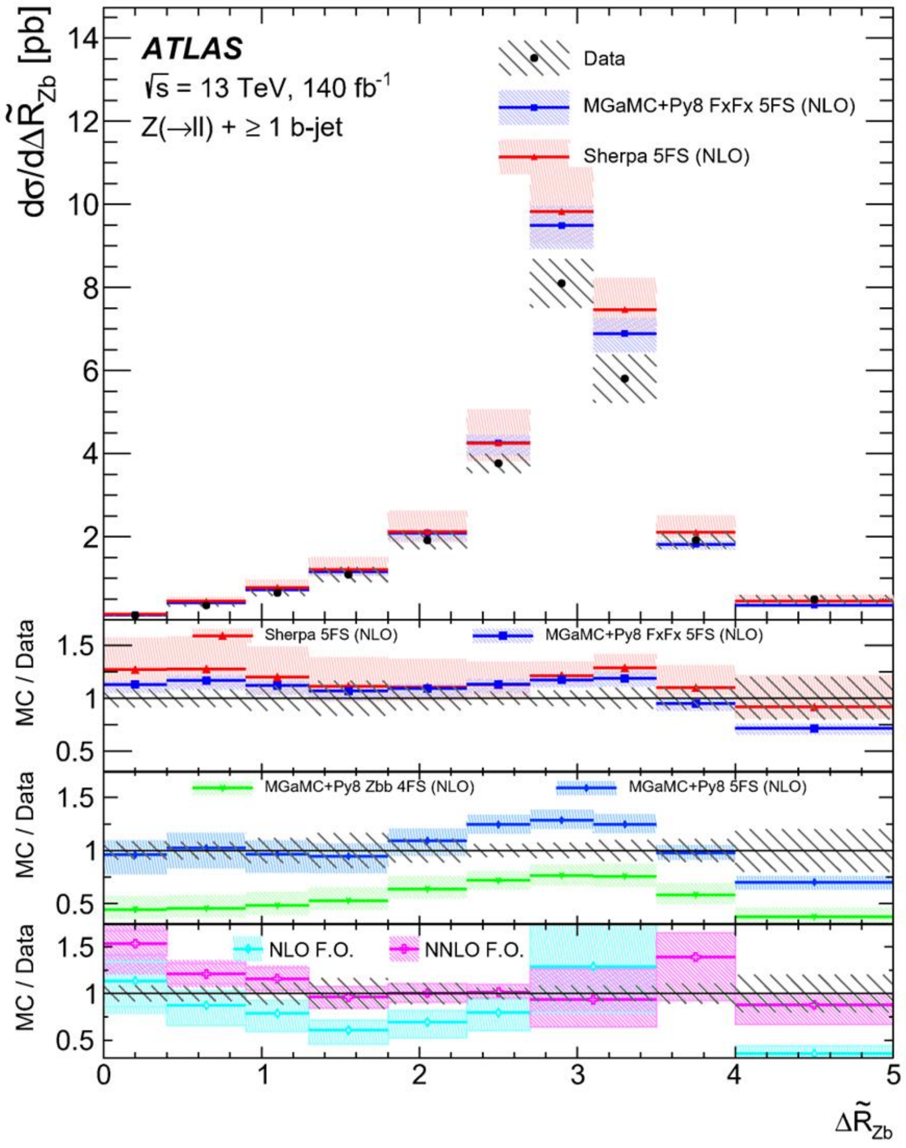






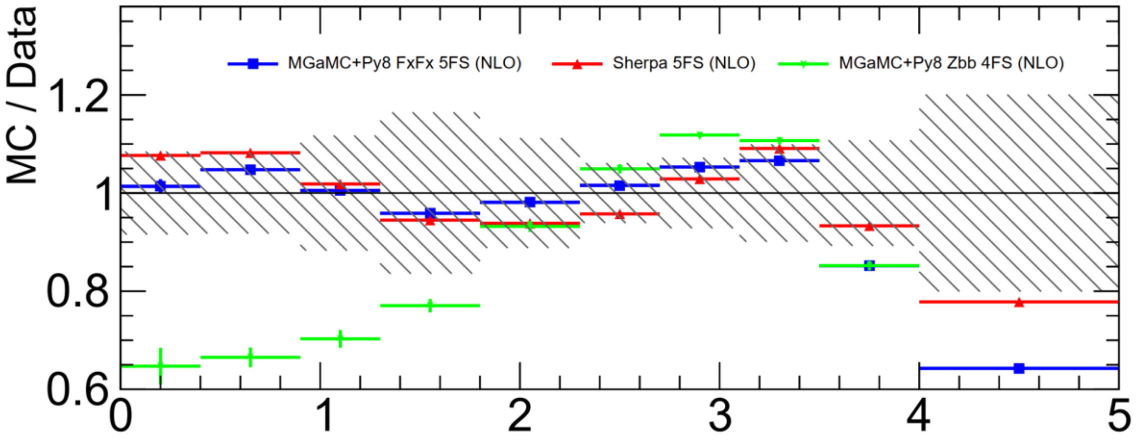
Results consistent with previous ATLAS measurement with 36 fb^{-1} ***[2x better precision]***

Differential Z+>= 1b-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 ΔR(Z, b−jet)



Shape Only

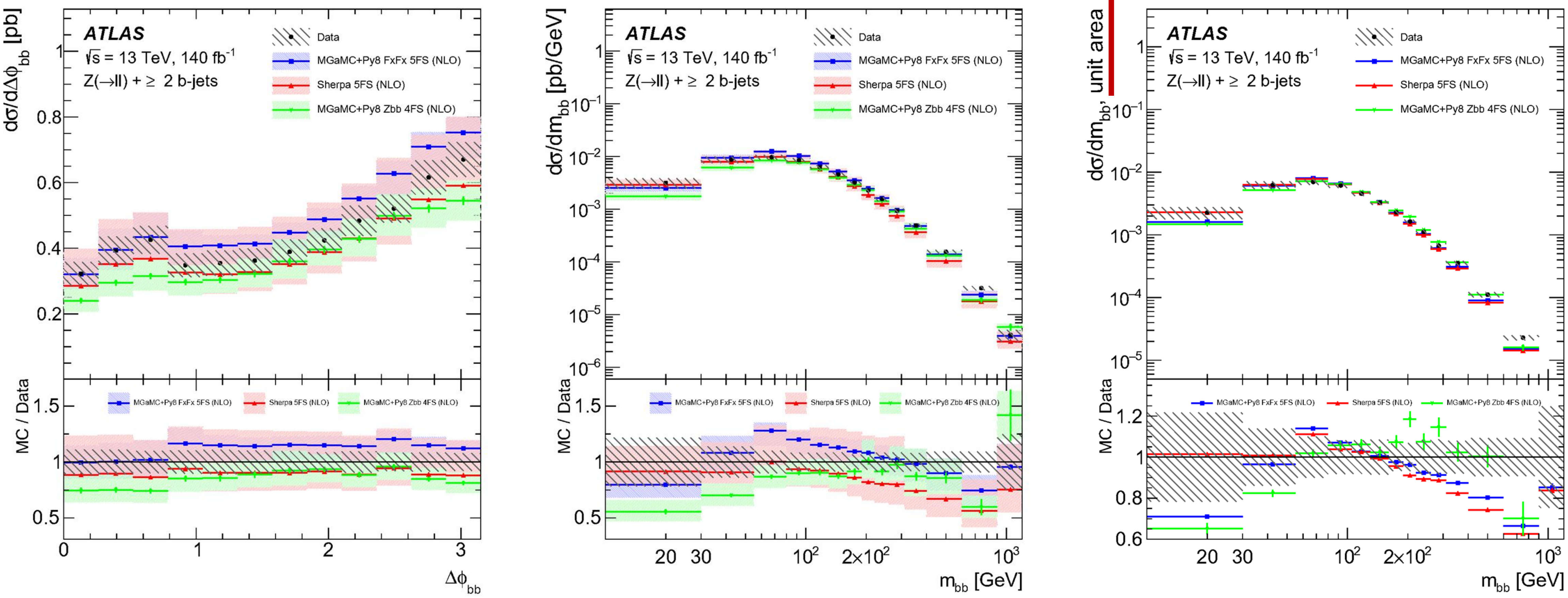
Fixed-order: NLO discrepancies improved with NNLO.
Calculations suffer from divergences at ΔR(Z,b −jet) ~ π uncertainties increase

Differential Z+>= 2b-jet 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

Shape Only

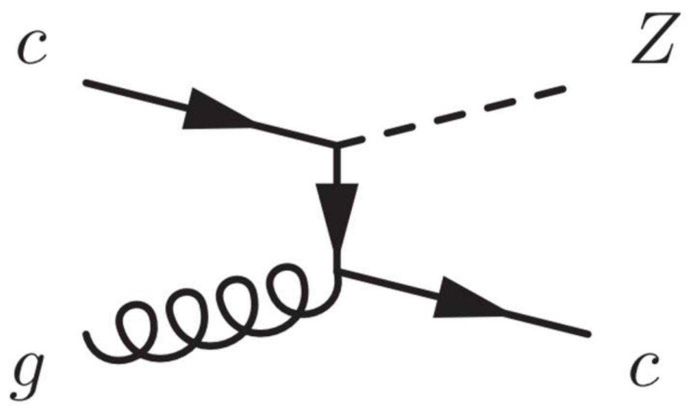


Intrinsic Charm

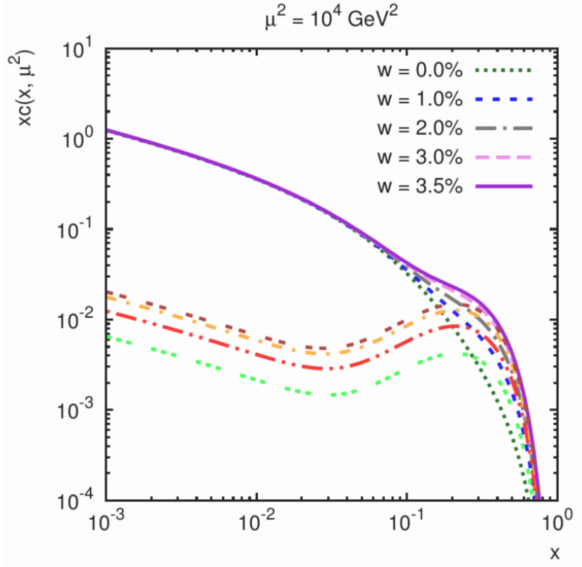
Physical Review Letters 128 (2022)

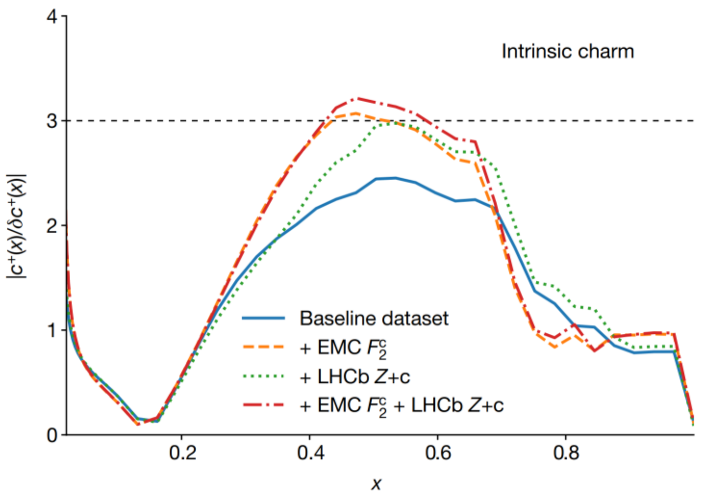
Nature 608, 483–487 (2022)

- ***Intrinsic-Charm (IC)*** component in the proton ~ debated for 40 years
  - c-quarks pairs are considered as part of the proton wave function at rest - valence-like structure
  - upper limits on <x_c> differ from 0.5% to 2%



$\Psi_p = |uudc\bar{c}>$, IC not via $g \to c\bar{c}$



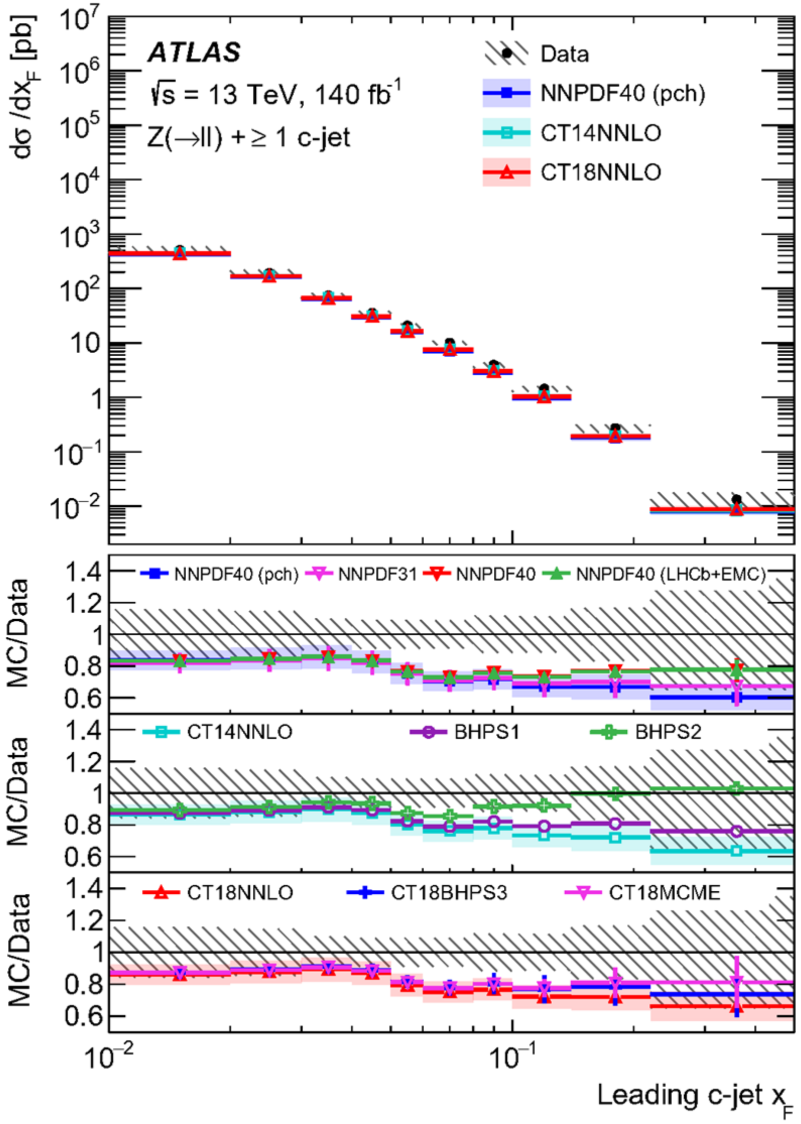


- IC enhanced in x_c > 0.1 accessible via **V+HF in LHC**
- **LHCb** reports an excess in high η region with Z + c
- **NNPDF** gives an evidence on the existence of IC

Differential Z+>= 1c-jet cross-section results

PhysRevD.92.034014

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



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

		Intrinsic charm (IC) predictions	
MGaMC+Py8 FxFx	5FS	NNPDF4.0 (NNLO) pch (no IC)	332100
		NNPDF4.0 (NNLO)	331100
		NNPDF4.0 (NNLO) EMC+LHCbZc	– [25]
		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

- BHPS2 (with $<x_c>\sim 2\%$) improves the description of data
  - In more realistic scenarios (NNPDF and CT18) the improvement is still marginal related to the uncertainties

MET + jets

MET + jets Measurements

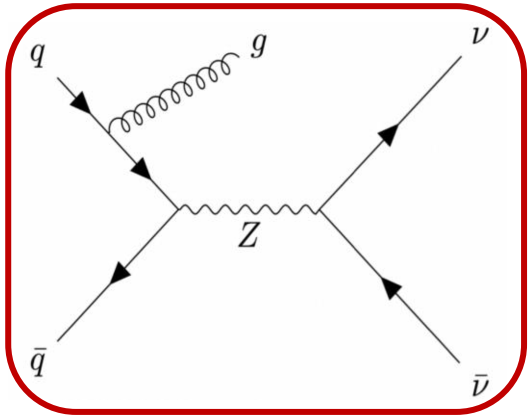
140 fb^{-1}, $\sqrt{s}$ = 13 TeV, *selections in backup*

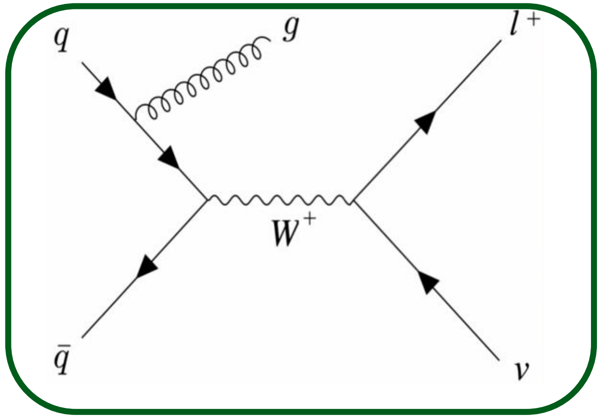
- **Measurement of final state with large p_T^{miss} and at least one energetic jet**

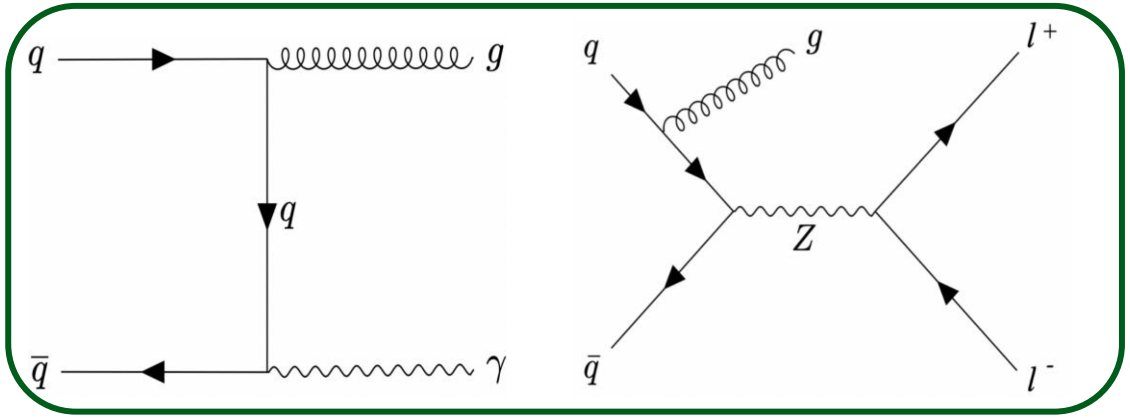
- ***Two jet-topology phase spaces to probe BSM***
  - Mono-jet region: p_T^{miss}
  - VBF region: p_T^{miss}, $\Delta\phi_{jj}$, m_{jj}

- **Signal region (SR): p_T^{miss} + jets**
  - MET + jets

- **Auxiliary measurements (AM): p_T^{recoil} + jets**
  - 2e + jets, 2μ + jets
  - e + jets, μ + jets, γ + jets



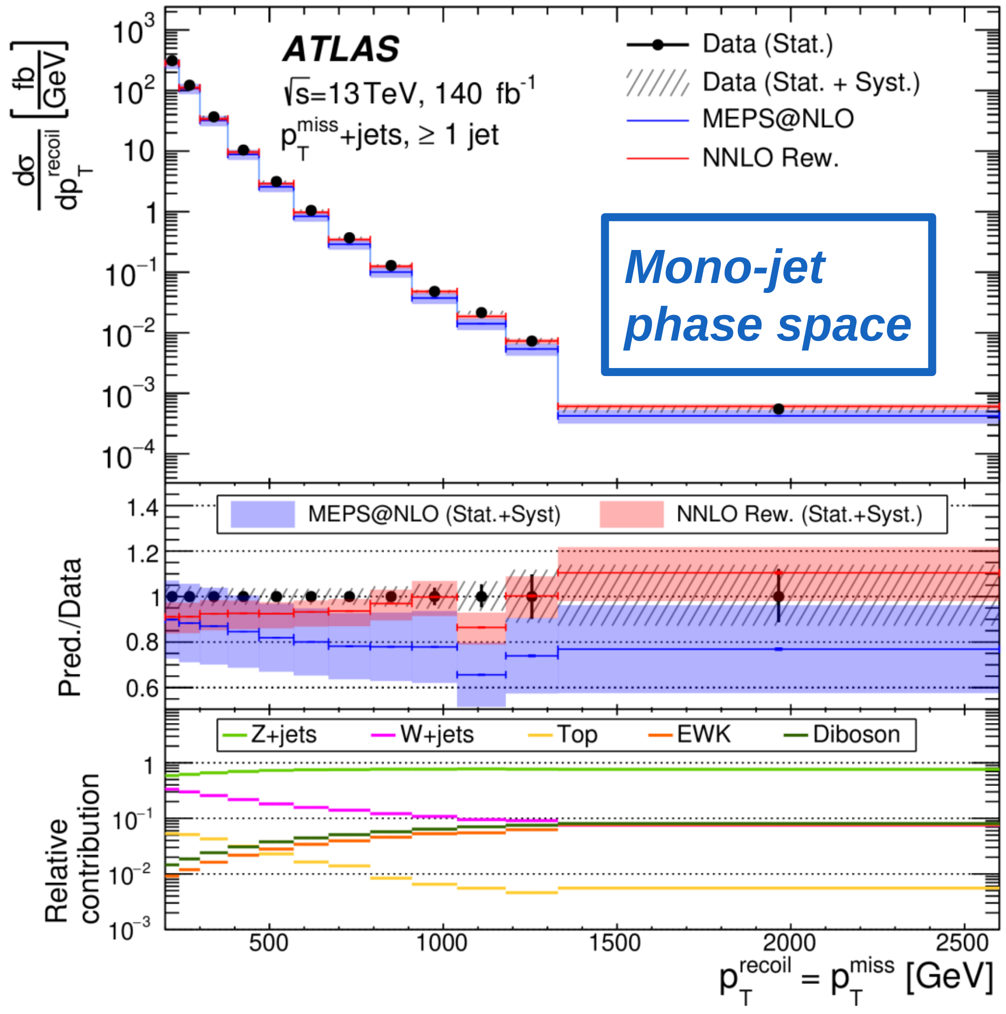


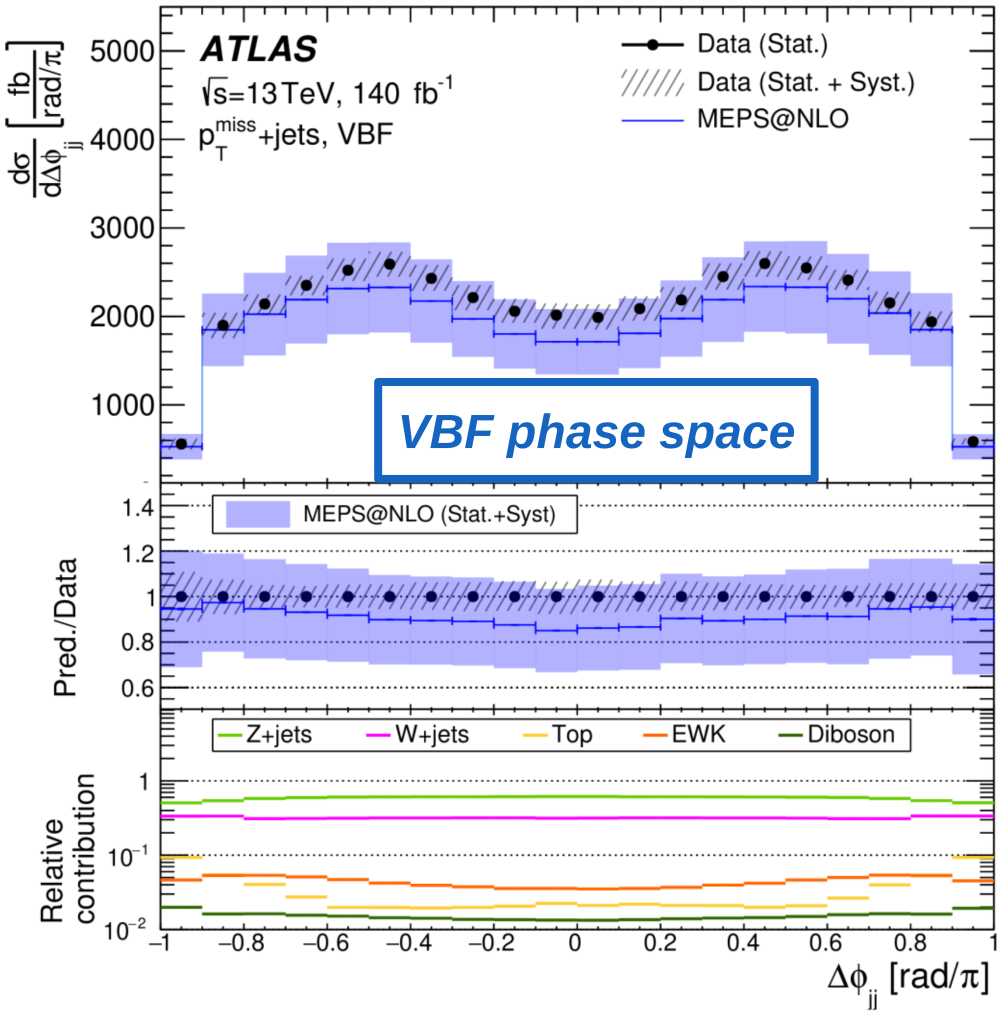


- **Measure regions individually and as ratio R^{miss}: $\sigma(SR)/\sigma(AM)$**

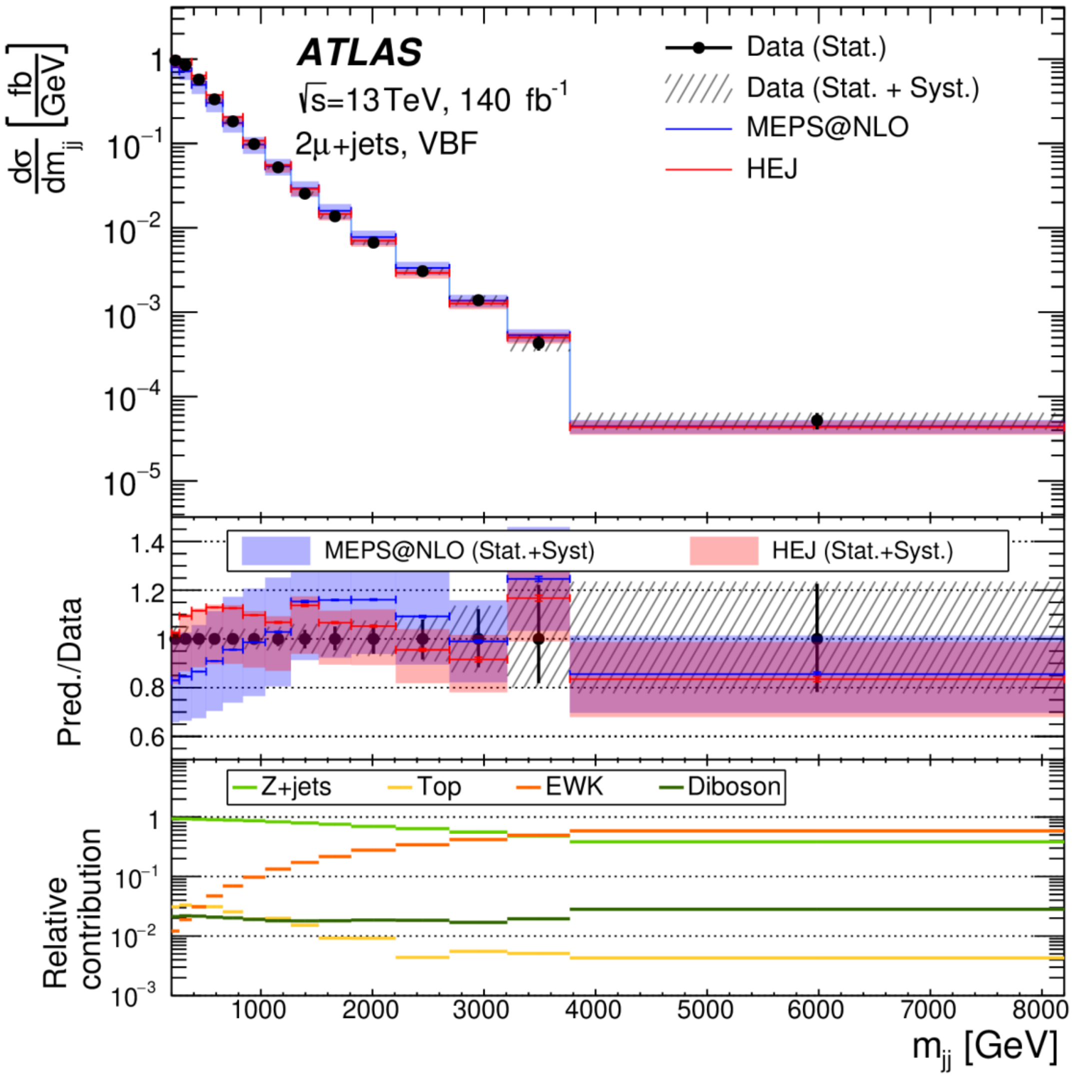
Differential cross sections

- Apart from the ***offset normalizations***, data ***described well*** for p_T^{miss} and $\Delta\phi_{jj}$ in all SR/ARs

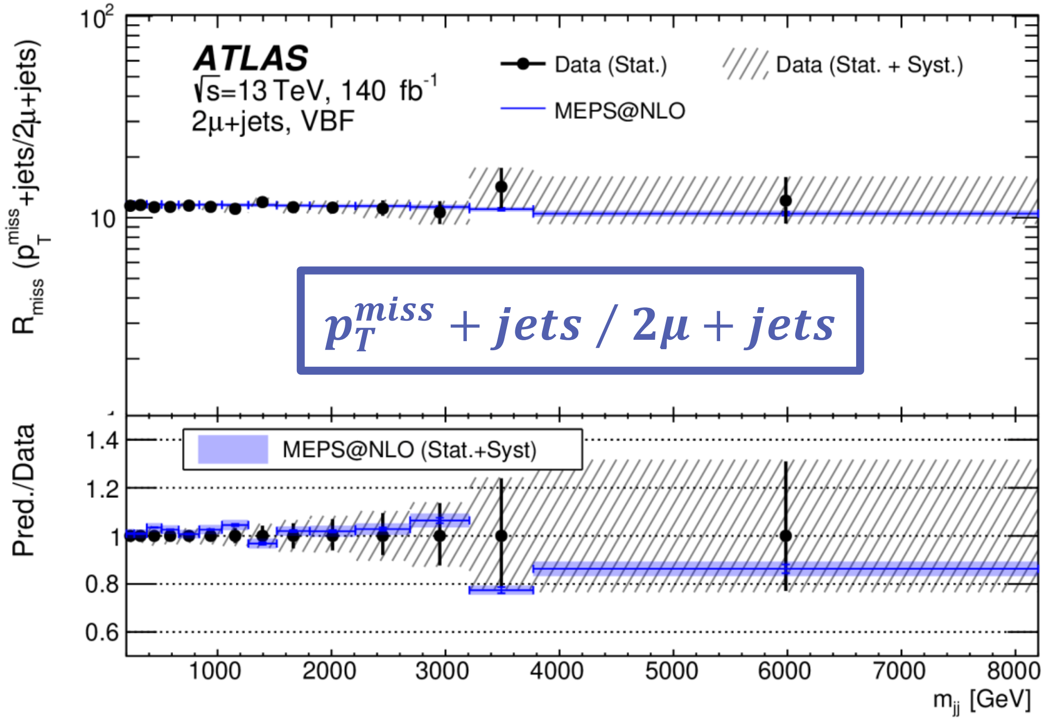




Differential cross sections



- **Discrepancy identified for m_{jj} shape**
  - better modelling given by *a resummation prediction from HEJ*
  - Both of *mis-modelling effects and correlated uncertainties cancel out in R^{miss}*

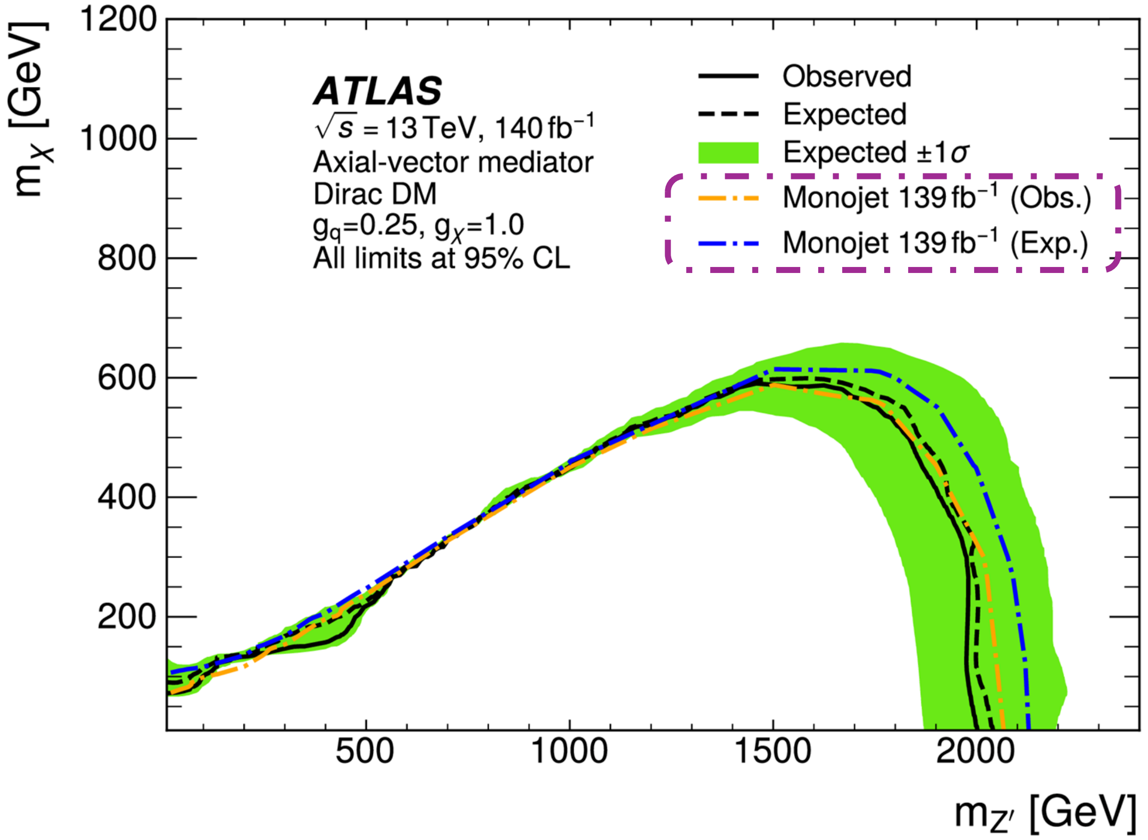


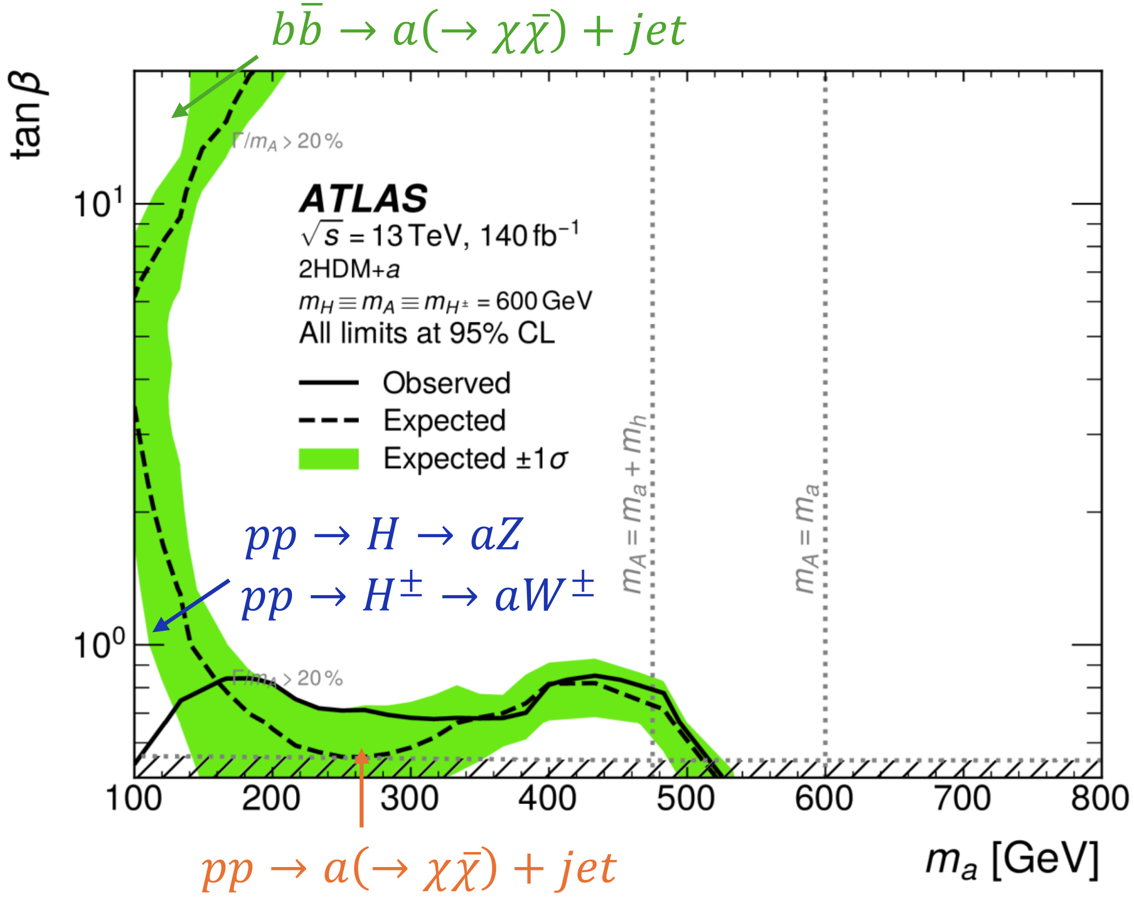
$p_T^{miss} + jets \ / \ 2\mu + jets$

BSM interpretations

- **Interpretation with two benchmark models for dark matter**
  - Z' model: extend SM with the new U(1) symmetry
  - 2HDM+a model: involve an additional Higgs doublet and a pseudoscalar a as the mediator

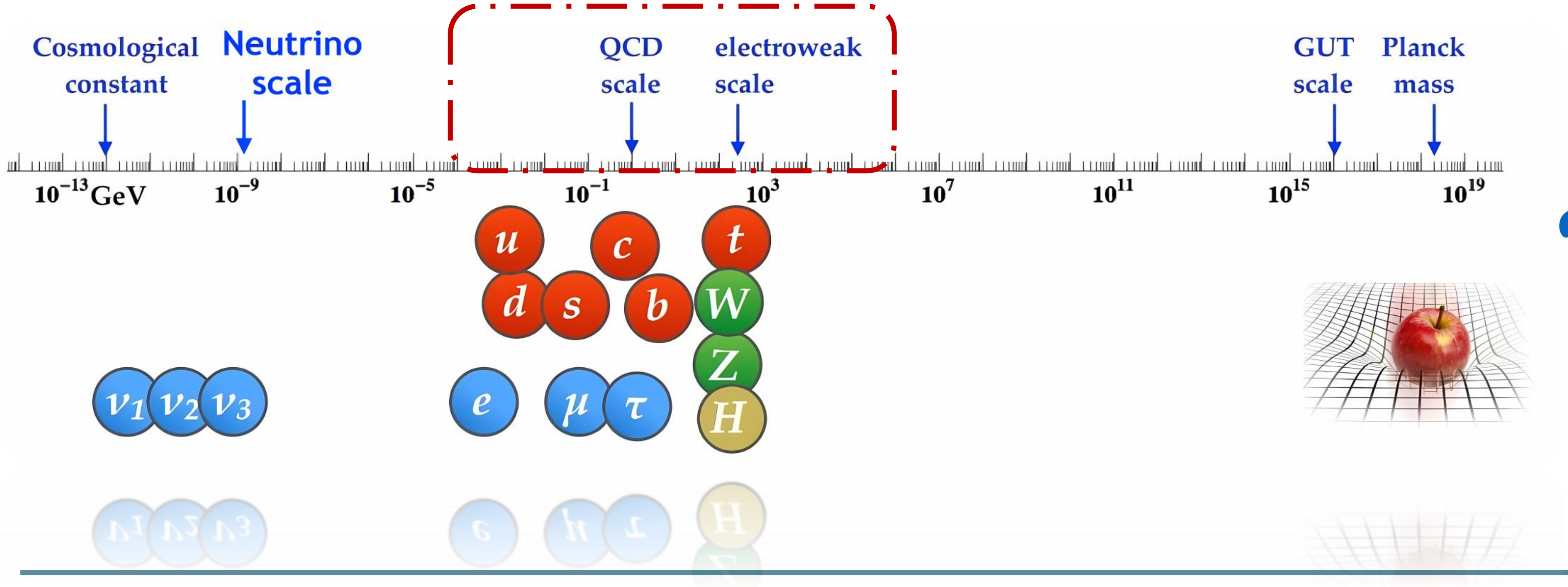
Sensitivity compatible with the MET-based searches!





Conclusion

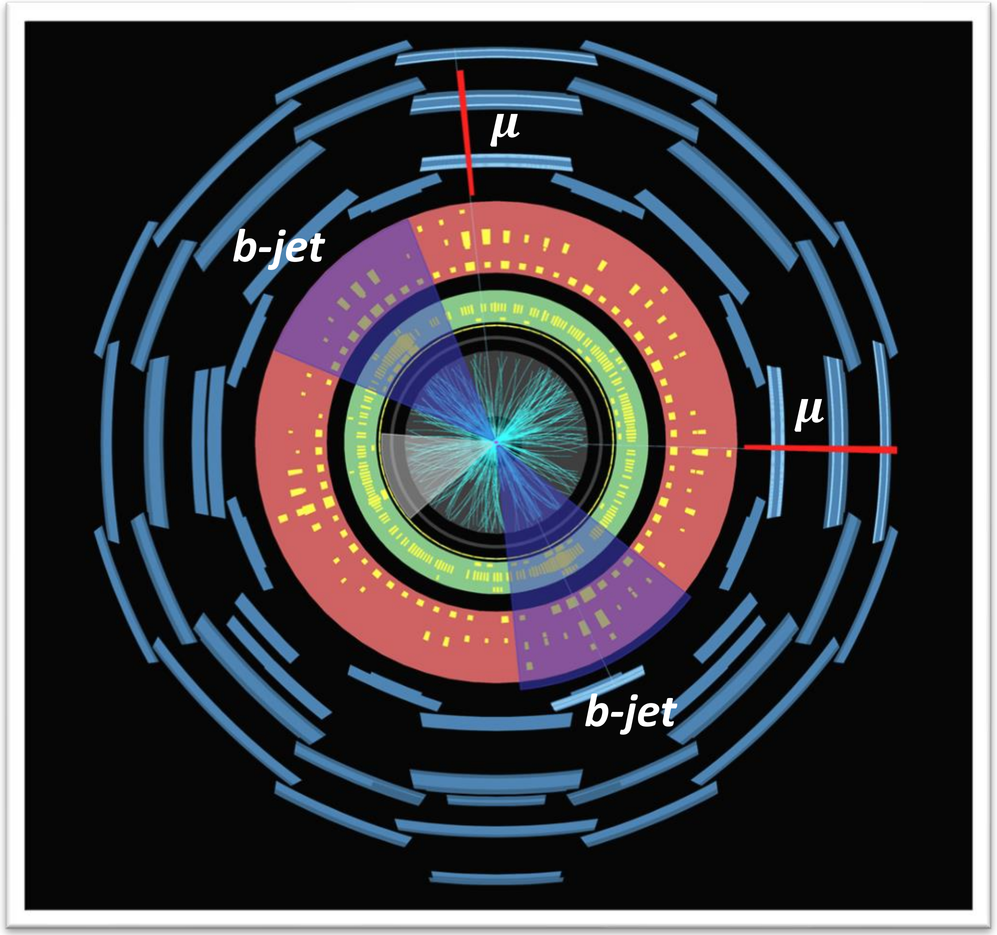
- EWK gauge bosons production associated with jets as an essential ingredient of SM
  - Provide useful inputs for global fit PDF, sensitive to light, c-, b-quark, and gluon PDFs
  - Serve as benchmarks for Monte Carlo simulations and theoretical predictions available at NNLO
  - Allow to explore the sensitivity to new phenomenon, i.e. *intrinsic charm, dark matter*
- BSM searches can benefit from improved modellings of substantial EWK + QCD processes



Thank You!

** Back up*

Event display of Z+>=2b-jets candidate from data recorded by ATLAS



W + Charmed hadron

MC samples

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

A reweighting procedure is applied to all MC samples to correct the charmed hadron production fractions to the world-average values. The change in the individual charmed meson production fractions is as large as 20%, depending on the MC configuration.

EvtGen 1.7.0 is used to force all D0 mesons to decay through the interested mode

As the width of the D^{*+} meson is set incorrectly in Sherpa 2.2.11, the mass shape in the D^{*+} channel is taken from the aMC@NLO+Py8 (NLO) W+ D^{*+}signal sample

Category	Normalization	$m(D^{(*)})$ shape
W+$D^{(*)}$ (D^+ channel)	SHERPA 2.2.11	SHERPA 2.2.11
W+$D^{(*)}$ (D^* channel)	SHERPA 2.2.11	aMC@NLO+PY8 (NLO)
W+c^{match} (D^+ channel)	MG+PY8 (CKKW-L)	MG+PY8 (CKKW-L)
W+c^{match} (D^* channel)	SHERPA 2.2.11	SHERPA 2.2.11
W+$c^{\text{mis-match}}$	SHERPA 2.2.11	LIS SHERPA 2.2.11
W+jets (D^+ channel)	SHERPA 2.2.11	LIS SHERPA 2.2.11
W+jets (D^* channel)	MG+PY8 (CKKW-L)	LIS MG+PY8 (CKKW-L)

Object selection

$D^{(*)}$ 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	$\lvert d_0 \rvert < 1$ mm	$\lvert d_0 \rvert < 1$ mm
SV 3D impact significance	$\sigma_{3D} < 4.0$	$\sigma_{3D} < 4.0$
Combinatorial background rejection	$\cos\theta^*(K) > -0.8$	—
Isolation	$\Sigma p_{T\,\text{tracks}}^{\Delta R<0.4}/p_T(D^+) < 1.0$	$\Sigma p_{T\,\text{tracks}}^{\Delta R<0.4}/p_T(D^{*+}) < 1.0$
$D_s^\pm \to \phi\pi^\pm$ rejection	$m(K^+K^-) > \lvert m_\phi - 8 \rvert$ MeV	—
D^{*+} background rejection	$m(K\pi\pi) - m(K\pi) > 160$ MeV	—
D^0 mass	—	$\lvert m_{K\pi} - m_{D^0} \rvert < 40$ MeV
π_{slow} p_T	—	$p_T > 500$ MeV
π_{slow} angular separation	—	$\Delta R(\pi_{\text{slow}}, D^0) < 0.3$
π_{slow} d_0	—	$\lvert d_0 \rvert < 1$ 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	$\lvert \eta(D^+) \rvert < 2.2$	$\lvert \eta(D^{*+}) \rvert < 2.2$
Invariant mass	1.7 GeV $< m(D^+) <$ 2.2 GeV	140 MeV $< m(D^{*+}-D^0) <$ 180 MeV

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

Event selection

(a)

Detector-level selection		
Requirement	W+$D^{(*)}$ SR	Top CR
$N(b\text{-jet})$	0	≥ 1
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV	
m_{T}	> 60 GeV	
Lepton p_{T}	> 30 GeV	
Lepton $\lvert\eta\rvert$	< 2.5	
$N(D^{(*)})$	≥ 1	
$D^{(*)}$ p_{T}	> 8 GeV and < 150 GeV	
$D^{(*)}$ $\lvert\eta\rvert$	< 2.2	

(b)

Truth fiducial selection	
Requirement	W+$D^{(*)}$
$N(b\text{-jet})$	—
$E_{\mathrm{T}}^{\mathrm{miss}}$	—
m_{T}	—
Lepton p_{T}	> 30 GeV
Lepton $\lvert\eta\rvert$	< 2.5
$N(D^{(*)})$	≥ 1
$D^{(*)}$ p_{T}	> 8 GeV
$D^{(*)}$ $\lvert\eta\rvert$	< 2.2

Highlights in Analysis Strategy

- **Control the backgrounds with charge correlation between W and D**
  - Backgrounds mostly have same contribution of OS and SS W+D i.e. $W + c\bar{c}$ $(b\bar{b})$, $t\bar{t}$ ⇨ ***OS – SS*** strategy applied

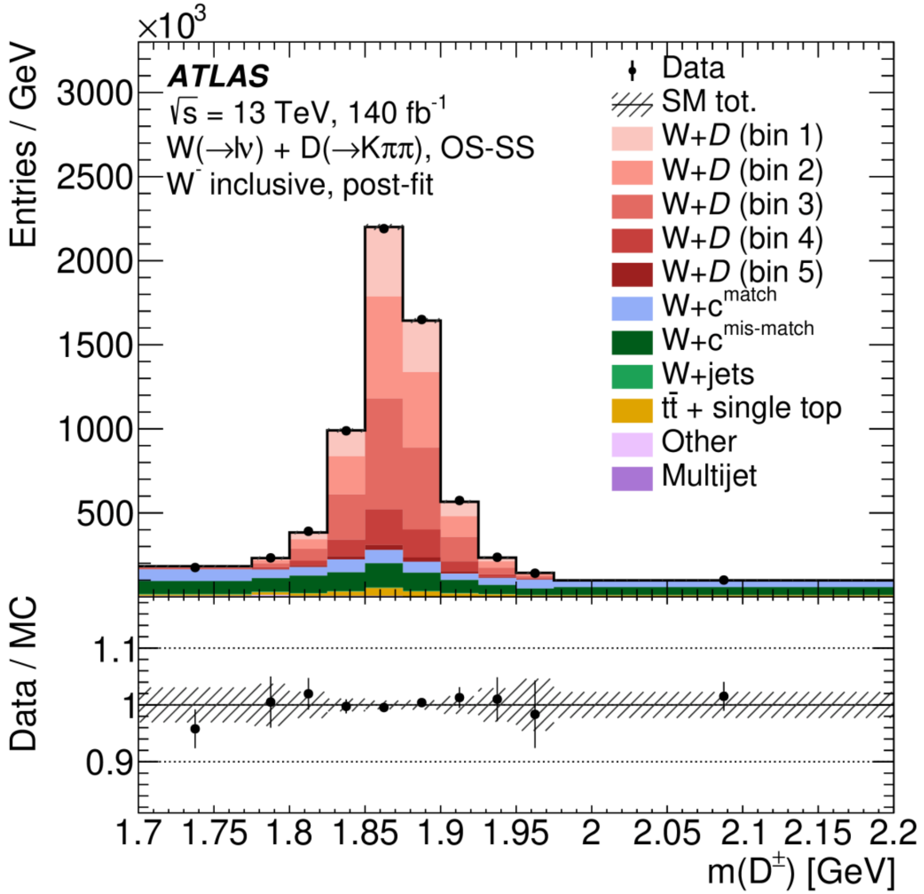
- **Differential cross sections measured with likelihood fits**
  - Binned profile likelihood fit of m_{D^+} or $(m_{D^{*+}} - m_{D^0})$ **in p_T^D and $|\eta(l)|$ bins** simultaneously in SS and OS

- **Comparison with several PDF sets**

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

★ **Normalized differential cross-sections** in bins p_T^D and $|\eta_l|$

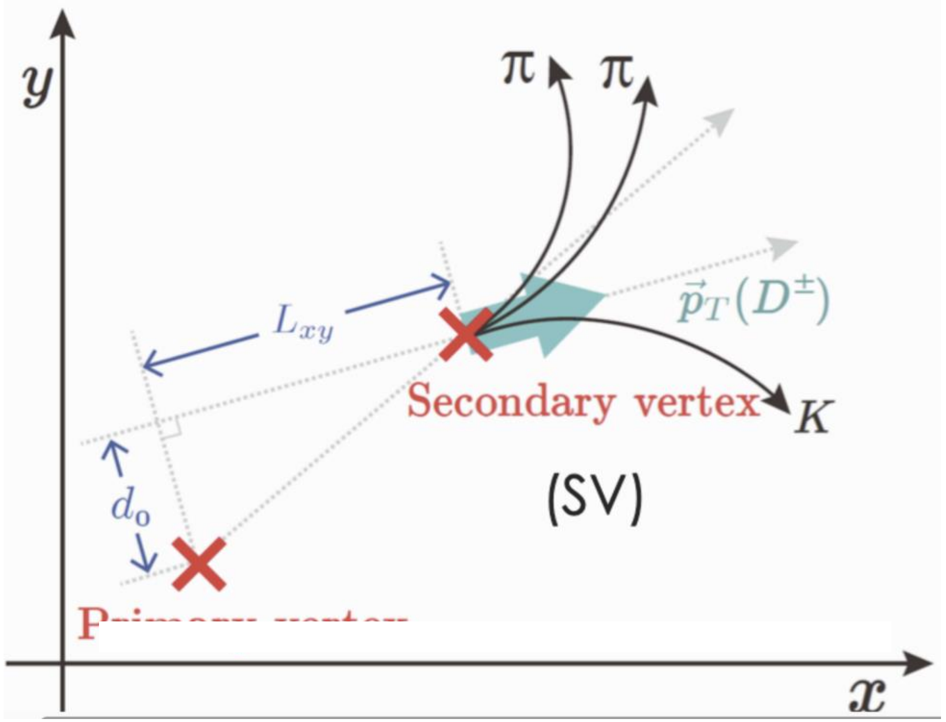
★ **Cross-section ratio** $R_c = \sigma(W^+ + D^-)/\sigma(W^- + D^+)$



track-based truth matching used to categorize reconstructed W+D(*) events into signal, other meson or decay modes and fakes

Exclusive D-meson decay reconstruction

- **D mesons are explicitly reconstructed**
  - Tracks from the ID
  - K/π assigned based on track charge
  - Feed to Kalman Filter (KF) which fits tracks to SV
  - Output is a set of D meson candidates

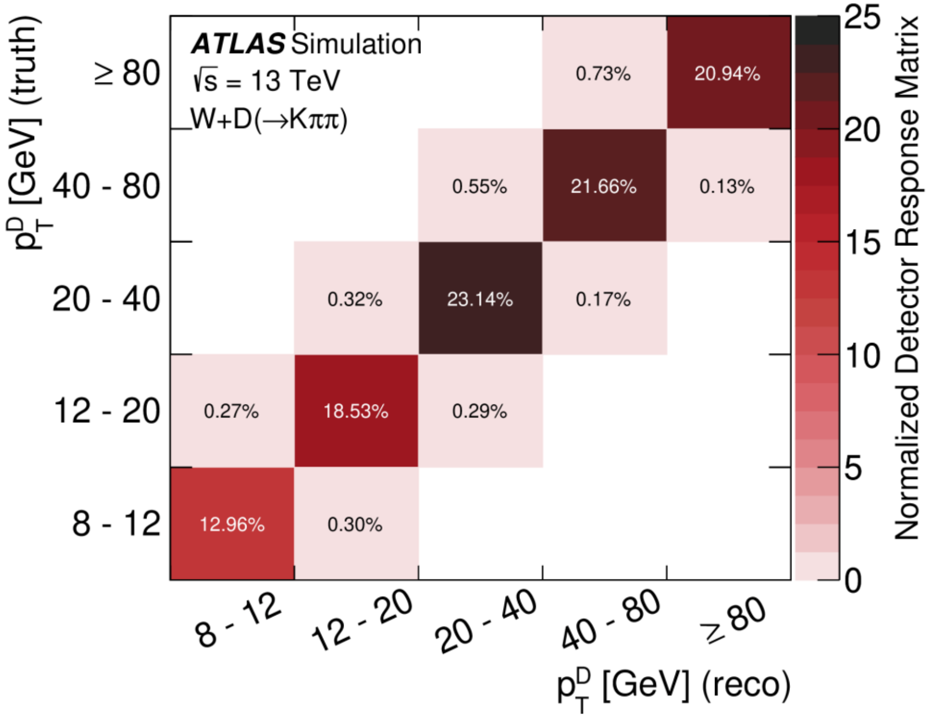


D Meson Properties

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 $\times$ 3.95

Likelihood fit unfolding

- **Binned Profile Likelihood Fit performed on invariant mass m(D^+), or mass difference m(D^*- D^0), to extract cross-sections**
  - Fit templates split in differential bins of $p_T(D) or\ |\eta(l)|$
  - Bin edges chosen to give approx. similar stat unc. in each bin
- **Truth bins distributed in reco bins as prescribed by the response matrix**
  - Response matrix very nearly diagonal in both variables (and for both D meson modes)



the sum of all elements is 100 percent

Inclusive cross section and differential in $|\eta(l)|$

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.)

$\|\eta(\ell)\|$	$\int d\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^+)/d(\|\eta(\ell)\|)$ [pb]	$1/\sigma \int d\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^+)/d(\|\eta(\ell)\|)$
[0.0, 0.5]	12.27 ± 0.13 (stat.) $^{+0.67}_{-0.64}$ (syst.)	0.2446 ± 0.0023 (stat.) $^{+0.0036}_{-0.0036}$ (syst.)
[0.5, 1.0]	11.57 ± 0.12 (stat.) $^{+0.63}_{-0.61}$ (syst.)	0.2305 ± 0.0022 (stat.) $^{+0.0040}_{-0.0040}$ (syst.)
[1.0, 1.5]	10.41 ± 0.12 (stat.) $^{+0.64}_{-0.59}$ (syst.)	0.2075 ± 0.0022 (stat.) $^{+0.0042}_{-0.0041}$ (syst.)
[1.5, 2.0]	9.09 ± 0.11 (stat.) $^{+0.45}_{-0.43}$ (syst.)	0.1810 ± 0.0020 (stat.) $^{+0.0041}_{-0.0041}$ (syst.)
[2.0, 2.5]	6.85 ± 0.11 (stat.) $^{+0.39}_{-0.37}$ (syst.)	0.1365 ± 0.0020 (stat.) $^{+0.0037}_{-0.0036}$ (syst.)
	$\int d\sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^-)/d(\|\eta(\ell)\|)$ [pb]	$1/\sigma \int d\sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^-)/d(\|\eta(\ell)\|)$
[0.0, 0.5]	11.87 ± 0.13 (stat.) $^{+0.65}_{-0.62}$ (syst.)	0.2455 ± 0.0024 (stat.) $^{+0.0037}_{-0.0037}$ (syst.)
[0.5, 1.0]	11.55 ± 0.12 (stat.) $^{+0.61}_{-0.60}$ (syst.)	0.2387 ± 0.0023 (stat.) $^{+0.0041}_{-0.0041}$ (syst.)
[1.0, 1.5]	10.09 ± 0.12 (stat.) $^{+0.61}_{-0.57}$ (syst.)	0.2087 ± 0.0023 (stat.) $^{+0.0042}_{-0.0040}$ (syst.)
[1.5, 2.0]	8.60 ± 0.12 (stat.) $^{+0.43}_{-0.41}$ (syst.)	0.1779 ± 0.0022 (stat.) $^{+0.0042}_{-0.0042}$ (syst.)
[2.0, 2.5]	6.25 ± 0.11 (stat.) $^{+0.37}_{-0.35}$ (syst.)	0.1292 ± 0.0022 (stat.) $^{+0.0038}_{-0.0037}$ (syst.)

Uncertainties on inclusive cross sections

	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

Uncertainties on differential cross sections in $|\eta(l)|$

Uncertainty [%]	$d\sigma_{\text{fid}}^{\text{OS-SS}}(W^{-}+D^{+})/d(\|\eta(\ell)\|)$ $(1/\sigma d\sigma/d\eta)$					$d\sigma_{\text{fid}}^{\text{OS-SS}}(W^{+}+D^{-})/d(\|\eta(\ell)\|)$ $(1/\sigma d\sigma/d\eta)$				
$\|\eta(\ell)\|$ bins	[0.0, 0.5]	[0.5, 1.0]	[1.0, 1.5]	[1.5, 2.0]	[2.0, 2.5]	[0.0, 0.5]	[0.5, 1.0]	[1.0, 1.5]	[1.5, 2.0]	[2.0, 2.5]
SV reconstruction	3.2 (0.1)	3.1 (0.2)	3.2 (0.2)	3.2 (0.1)	3.3 (0.2)	3.1 (0.1)	3.0 (0.1)	3.1 (0.2)	3.0 (0.2)	3.1 (0.2)
Jets and $E_{\text{T}}^{\text{miss}}$	1.6 (0.2)	1.9 (0.4)	1.6 (0.2)	1.5 (0.6)	1.7 (0.4)	1.6 (0.2)	1.8 (0.3)	1.8 (0.2)	1.5 (0.4)	1.9 (0.5)
Luminosity	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)
Muon reconstruction	0.5 (0.2)	0.6 (0.1)	0.8 (0.1)	0.8 (0.1)	0.8 (0.2)	0.5 (0.2)	0.6 (0.1)	0.8 (0.1)	0.8 (0.1)	0.9 (0.2)
Electron reconstruction	0.2 (0.2)	0.3 (0.0)	0.3 (0.1)	0.4 (0.1)	0.4 (0.1)	0.2 (0.2)	0.3 (0.0)	0.3 (0.1)	0.4 (0.1)	0.4 (0.2)
Multijet background	0.2 (0.2)	0.2 (0.2)	0.2 (0.2)	0.3 (0.1)	0.9 (0.7)	0.2 (0.3)	0.1 (0.1)	0.1 (0.1)	0.4 (0.3)	0.7 (0.6)
Signal modeling	3.2 (0.4)	2.9 (0.3)	3.9 (1.1)	1.8 (1.4)	2.4 (0.7)	3.2 (0.4)	2.9 (0.3)	3.9 (1.2)	1.9 (1.4)	2.5 (0.7)
Signal branching ratio	1.6 (0.0)	1.6 (0.0)	1.5 (0.0)	1.6 (0.0)	1.5 (0.0)	1.6 (0.0)	1.6 (0.0)	1.6 (0.0)	1.7 (0.1)	1.6 (0.0)
Background modeling	1.5 (0.8)	2.2 (1.2)	1.7 (0.7)	1.2 (0.8)	2.1 (1.3)	1.8 (0.7)	2.0 (1.2)	1.7 (0.8)	1.3 (0.9)	1.9 (1.4)
Finite size of MC samples	1.6 (1.3)	1.8 (1.4)	2.1 (1.6)	1.9 (1.7)	2.7 (2.4)	1.7 (1.3)	1.8 (1.5)	1.9 (1.5)	2.2 (1.8)	3.0 (2.7)
Data statistical uncertainty	1.0 (0.9)	1.1 (1.0)	1.2 (1.1)	1.2 (1.1)	1.6 (1.5)	1.1 (1.0)	1.1 (1.0)	1.2 (1.1)	1.3 (1.2)	1.8 (1.7)
Total	5.5 (1.7)	5.5 (2.0)	6.0 (2.3)	5.0 (2.5)	5.8 (3.0)	5.4 (1.8)	5.4 (2.0)	6.0 (2.3)	5.1 (2.7)	6.0 (3.4)

Uncertainties on differential cross sections in $p_T(D^+)$

Uncertainty [%]	$d\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^+)/d(p_\text{T}(D^+))$ $(1/\sigma d\sigma/dp_\text{T})$					$d\sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^-)/d(p_\text{T}(D^+))$ $(1/\sigma d\sigma/dp_\text{T})$				
$p_\text{T}(D^+)$ bins [GeV]	[8, 12]	[12, 20]	[20, 40]	[40, 80]	[80, ∞)	[8, 12]	[12, 20]	[20, 40]	[40, 80]	[80, ∞)
SV reconstruction	3.1 (1.2)	2.8 (0.6)	3.2 (0.7)	4.7 (2.6)	5.7 (4.3)	2.6 (1.0)	2.5 (0.7)	3.3 (0.7)	4.5 (2.5)	5.8 (3.9)
Jets and E_T^miss	1.8 (0.8)	1.9 (0.4)	1.9 (0.5)	2.0 (1.2)	3.4 (2.4)	2.1 (0.6)	1.9 (0.6)	2.1 (0.7)	2.0 (1.2)	3.7 (2.7)
Luminosity	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)
Muon reconstruction	0.8 (0.2)	0.7 (0.1)	0.6 (0.1)	0.5 (0.3)	0.6 (0.5)	0.8 (0.2)	0.7 (0.1)	0.6 (0.1)	0.5 (0.3)	0.5 (0.4)
Electron reconstruction	0.2 (0.0)	0.2 (0.1)	0.3 (0.0)	0.4 (0.2)	0.5 (0.4)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)	0.4 (0.2)	0.5 (0.4)
Multijet background	0.3 (0.2)	0.3 (0.1)	0.2 (0.1)	0.1 (0.3)	1.1 (1.3)	0.1 (0.1)	0.3 (0.1)	0.2 (0.1)	0.2 (0.1)	0.1 (0.2)
Signal modeling	1.5 (3.2)	2.7 (0.7)	4.6 (2.7)	2.4 (0.4)	3.0 (1.2)	1.5 (3.2)	2.7 (0.7)	4.6 (2.7)	2.3 (0.4)	3.0 (1.1)
Signal branching ratio	1.7 (0.1)	1.6 (0.0)	1.5 (0.1)	1.6 (0.0)	1.7 (0.1)	1.7 (0.1)	1.6 (0.0)	1.5 (0.1)	1.6 (0.0)	1.7 (0.1)
Background modeling	1.7 (1.4)	1.5 (0.8)	1.8 (1.2)	1.8 (1.6)	1.8 (1.7)	1.9 (1.5)	1.6 (1.0)	1.8 (1.3)	1.6 (1.5)	3.5 (3.2)
Finite size of MC samples	2.3 (1.7)	1.7 (1.3)	1.6 (1.3)	2.1 (1.9)	4.6 (4.6)	2.4 (1.8)	1.7 (1.3)	1.7 (1.4)	2.1 (1.9)	4.8 (4.6)
Data statistical uncertainty	1.2 (1.0)	0.9 (0.8)	0.9 (0.9)	1.4 (1.4)	4.0 (4.0)	1.3 (1.1)	1.0 (0.9)	1.0 (0.9)	1.5 (1.5)	4.6 (4.6)
Total	5.1 (4.0)	5.1 (1.9)	6.5 (3.3)	6.5 (3.9)	9.9 (8.2)	5.0 (4.0)	5.0 (2.0)	6.6 (3.4)	6.3 (3.8)	10.6 (8.6)

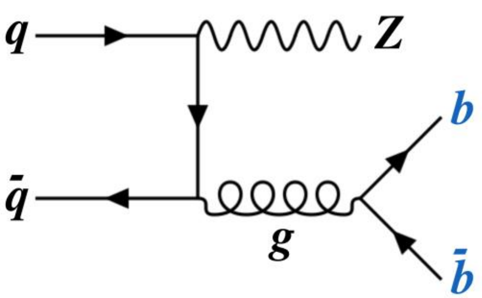
Z + HF jets

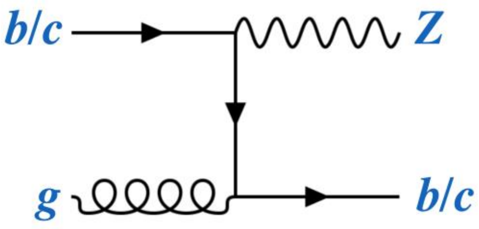
Dataset and event selection

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 μ+μ- with p_T > 27 GeV, $|\eta|$ < 2.5
76 GeV < m_{ll} < 106 GeV

≥ 1 good jet with p_T > 20 GeV, $|y|$ < 2.5
b-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

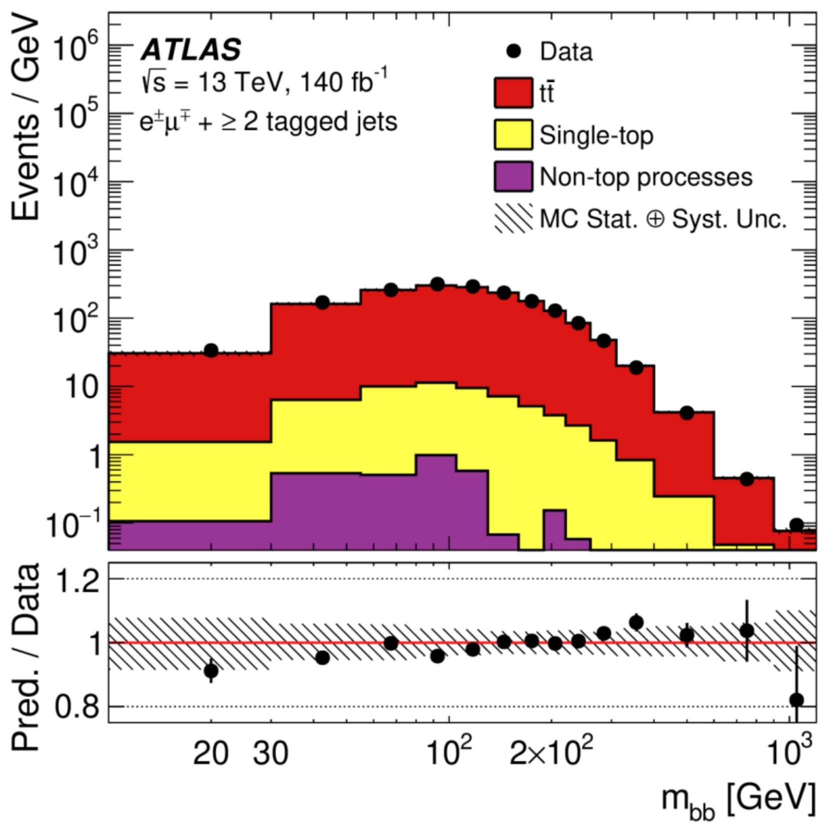
Data-driven $t\bar{t}$ background

- Dileptonic events represent the second largest background
  - Using **data-driven technique** to avoid large modelling uncertainties (up to ~70% at high Z pT)

- **Method of the Transfer Factors**
  - opposite flavour eμ CR enhanced with $t\bar{t}$ events (>90%)
  - **$t\bar{t}$ template in CR** obtained by subtracting other MC from data
  - **Transfer Factors** as ratio of $t\bar{t}$ MC distributions in SR and CR

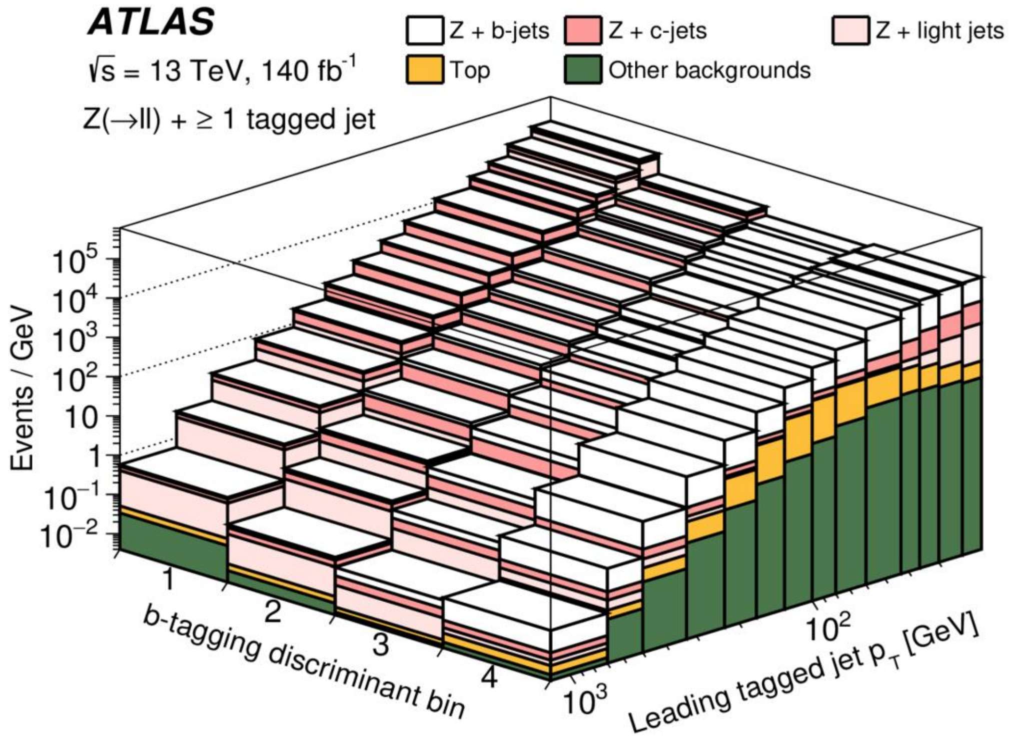
$$t\bar{t}^{SR} = t\bar{t}^{CR}_{Data} \cdot TR^{CR\rightarrow SR}$$

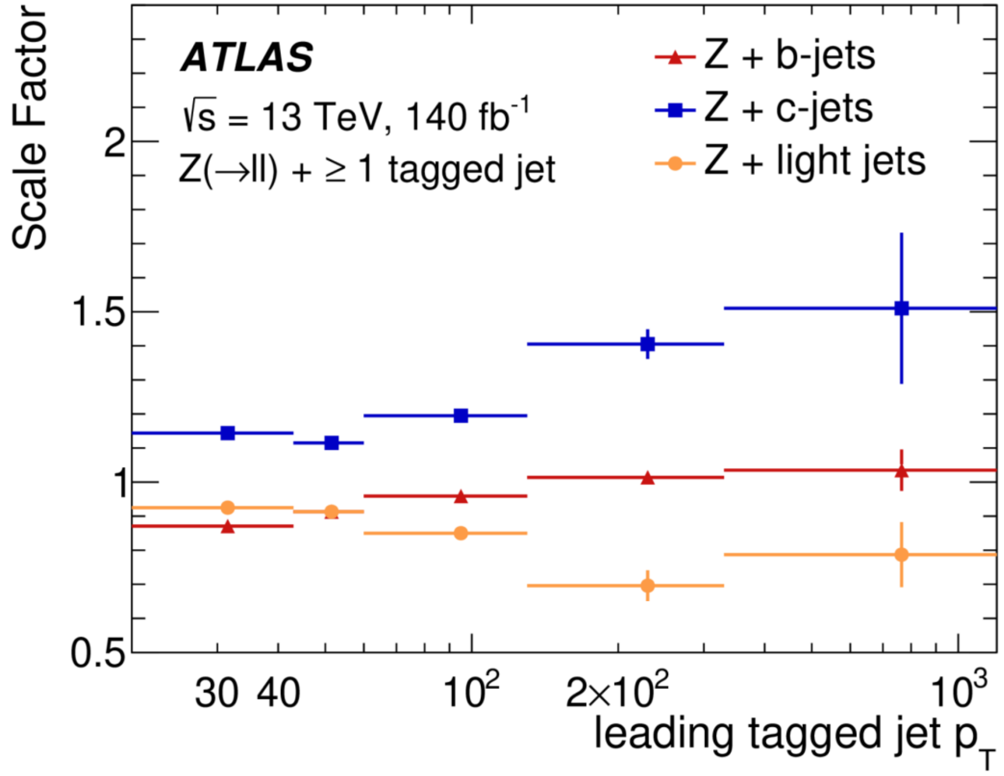
$$TF^{CR\rightarrow SR} = \frac{t\bar{t}^{SR\,(ee/\mu\mu)}_{MC}}{t\bar{t}^{CR\,(e\mu)}_{MC}}$$



Z+jets background and flavour fit

- Z+jet with jet-flavour different from the one measured is the largest source of background
  - **Fit performed in individual** (optimized) **bins of each measured observable**
  - **Bin-by-bin scale factors** allow to **correct both normalization and shape** of Z+flavoured-jets contributions



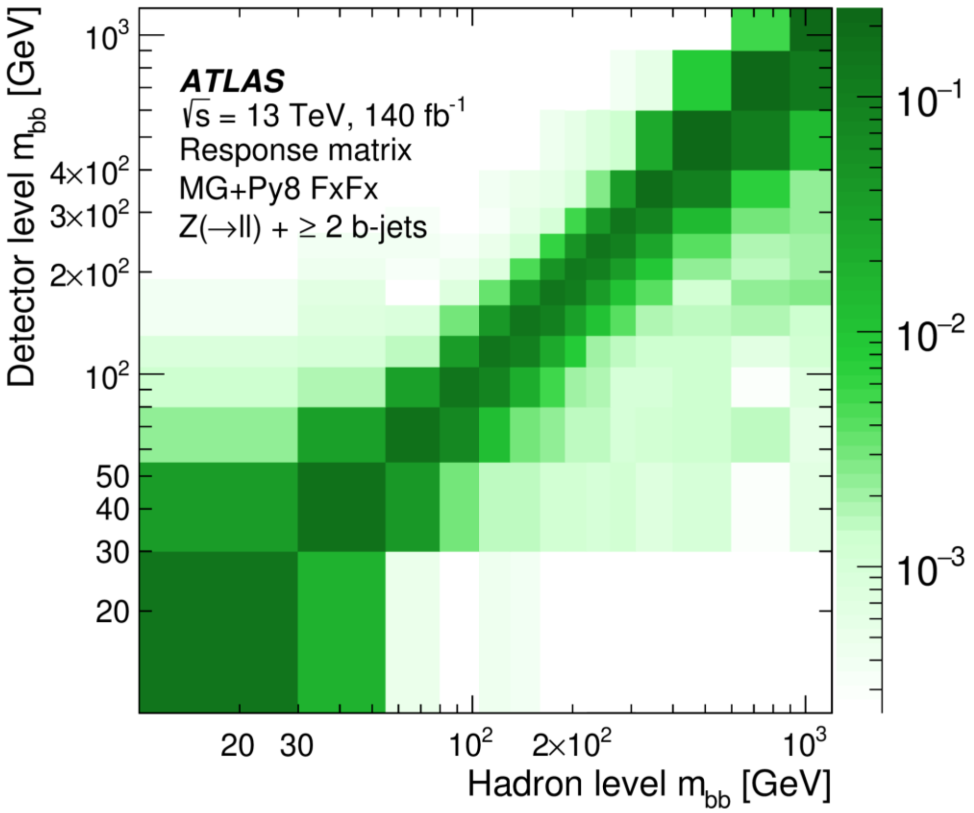


From detector to particle level

✦ **Differential cross sections** corrected to particle level with **iterative Bayesian unfolding**:

selection efficiency, resolution effects and differences between detector level and fiducial phase spaces

Object Selection	Acceptance cuts
Lepton	$p_T > 27$ GeV, $\|\eta\| < 2.5$ 2 same flavour and opposite charge, 76 GeV $< m_{\ell\ell} <$ 106 GeV
b-jet	$p_T > 20$ GeV, $\|y\| < 2.5$, $\Delta R(b\text{-jet}, \ell) > 0.4$
c-jet	$p_T > 20$ GeV, $\|y\| < 2.5$, $\Delta R(c\text{-jet}, \ell) > 0.4$
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 $\|y(Z)\| < 1.2$
Forward rapidity	Z boson rapidity $\|y(Z)\| \geq 1.2$

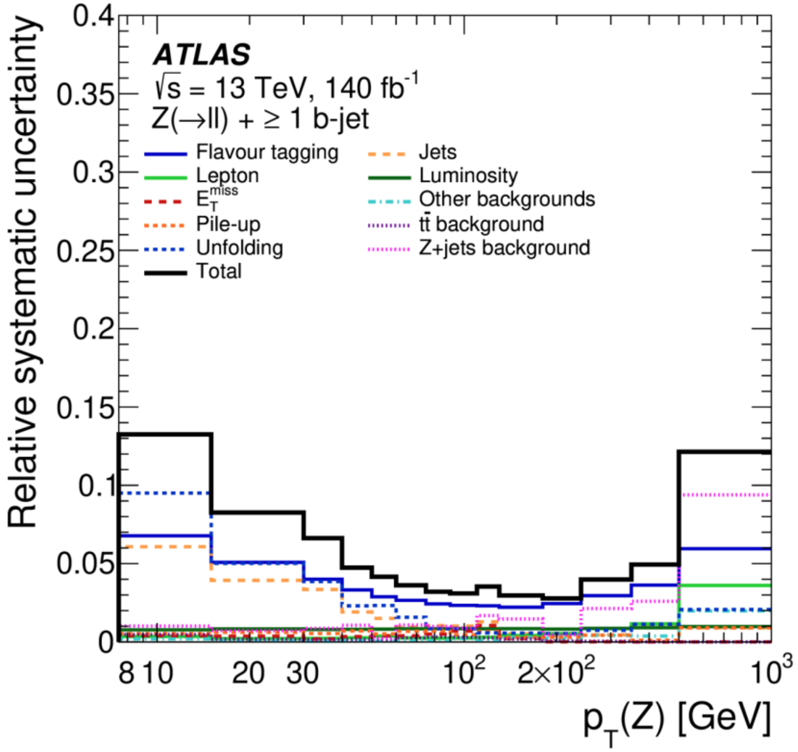


Z+≥1 b-jet, Z+≥1 c-jet and Z+≥2 b-jets cross sections measured at **particle level** in **fiducial phase space**

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** for modest p_T

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



Theoretical predictions

arXiv:2109.02653
Phys. Lett. B 843 (2023)
Eur. Phys. J. C 83, 336
PhysRevLett.130.161901

- 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	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	– [25]
		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 [3]	
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

Flavour Scheme

JHEP07(2012)022

- V+HF production is characterized by ***hard scale*** $\boldsymbol{Q}$ and mass of a ***heavy quark*** $\boldsymbol{m}$
  - **4FS**: massive b-quarks → *b-quark appear only via gluon splitting*
    - power and logarithm corrections appear at fixed order explicitly
    - suitable for $\boldsymbol{Q^2 \sim m_b^2}$
  - **5FNS**: massless b-quarks → *b-quark allowed via intrinsic PDF*
    - $(m_b{}^2/Q^2)^n$ pushed to higher orders
    - $\ln(Q^2/m_b^2)$ resummed to all orders into b-quark PDF → ***collinear logarithms resummation***
    - adequate at $\boldsymbol{Q^2 \gg m_b^2}$

increases in high *Bjorken* x and Q

  - Several key processes at LHC sensitive to FS assumptions: top, Higgs, V+jets
    - discrepancy among flavor schemes converge with increasing pQCD order

Inclusive cross-section results

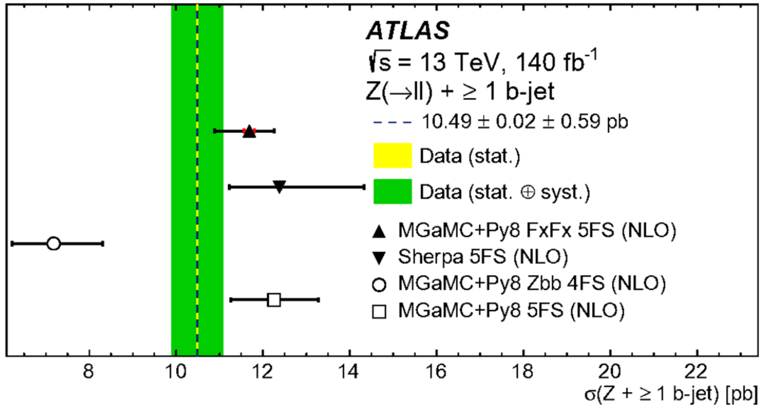
σ(Z+≥1 b-jet) = 10.49 ± 0.02 (stat.) ± 0.59 (syst.) pb

σ(Z+≥2 b-jets) = 1.39 ± 0.01 (stat.) ± 0.13 (syst.) pb

σ(Z+≥1 c-jet) = 20.89 ± 0.07 (stat.) ± 2.77 (syst.) pb

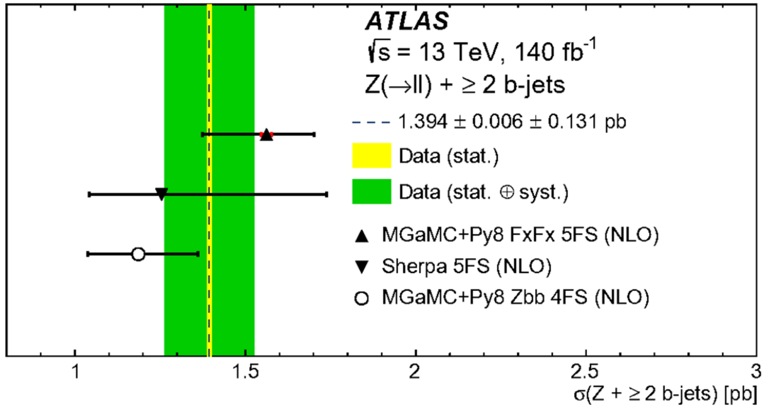
$Z+\geq 1\ b$-jet

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



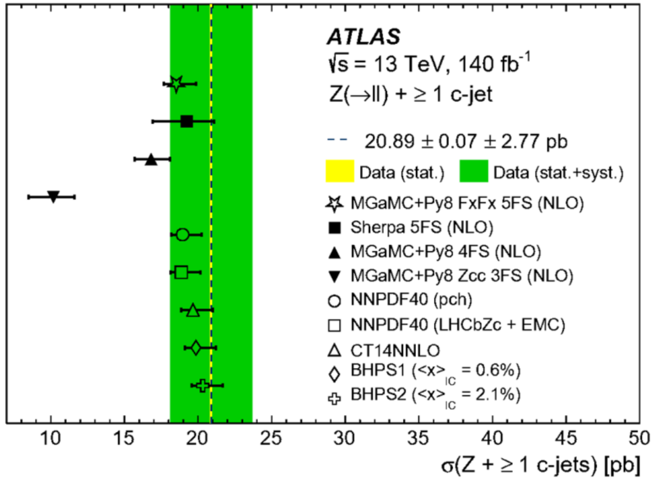
$Z+\geq 2\ b$-jet

- 4FS and 5FS agrees with data
- much sizable MHOU for Sherpa



$Z+\geq 1\ c$-jet

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



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

CT18FC PDF set

- An updated CTEQ paper on IC PDFs: PLB 843 (2023) 137975
  - All PDF sets available at web page, also included in LHAPDF
- Baseline no-IC PDF to be used: **CT18NNLO** (14000)
  - Uncertainties: 58 eigenvector variations
- Four variants including IC:
  1. CT18 BHPS3 (14087) – similar to earlier BHPS variants, different amount of IC (?)
  2. CT18 MBM-C (14090) – *meson-baryon model (confining)*, asymmetric $c\bar{c}$ contributions
  3. CT18 MBM-E (14093) – *meson-baryon model (effective-mass)*, similar to 2, but more constrained
  4. CT18X BHPS3 (14096) – same as 1, but using **CT18XNNLO** fit as a baseline (with DIS data fitted using x-dependent μ_F to model small-x saturation)
- For each of them – two variations with $\Delta\chi^2 = 10, 30$
  - $\Delta\chi^2 = 30$ – standard CT 68% CL tolerance
  - $\Delta\chi^2 = 10$ – more restrictive, compatible with MSHT20 tolerance
- Options suggested by Tim Hobbs:
  - Minimal: use *CT18 BHPS3* and *CT18 MBM-C* in comparison to nominal *CT18NNLO*, evaluate uncertainties with $\Delta\chi^2 = 30$ variations
  - Ideal: test all options (note that for *CT18X BHPS3* need a different nominal *CT18XNNLO*)

MET + jets

Event selection

Attribute	p_T^{miss}+jets	e+jets	$2e$+jets	μ+jets	2μ+jets	γ+jets
Lepton or photon rapidity	–	$\lvert y\rvert \leq 1.37$ or $1.52 \leq \lvert y\rvert \leq 2.47$		$\lvert y\rvert \leq 2.5$		$\lvert y\rvert \leq 1.37$ or $1.52 \leq \lvert y\rvert \leq 2.47$
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, $\lvert\eta\rvert < 2.5$					
(Additional) electrons	None with $p_T > 7$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$					
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, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Leading jet p_T [GeV]	> 120	> 80
Sub-leading jet p_T [GeV]	–	> 50
Leading jet $\lvert y\rvert$	< 2.4	< 4.4
Sub-leading jet $\lvert y\rvert$	–	< 4.4
Dijet invariant mass m_{jj} [GeV]	–	> 200
$\lvert\Delta y_{jj}\rvert$	–	> 1
In-gap jets	–	None with $p_T > 30$ GeV

SM contributions with MC simulation

	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%

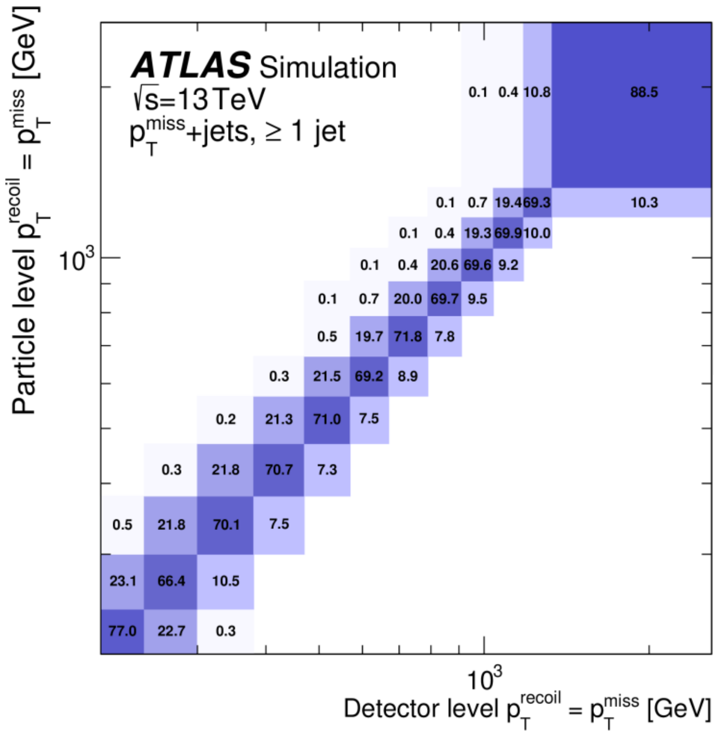
Highlights in Analysis Strategy

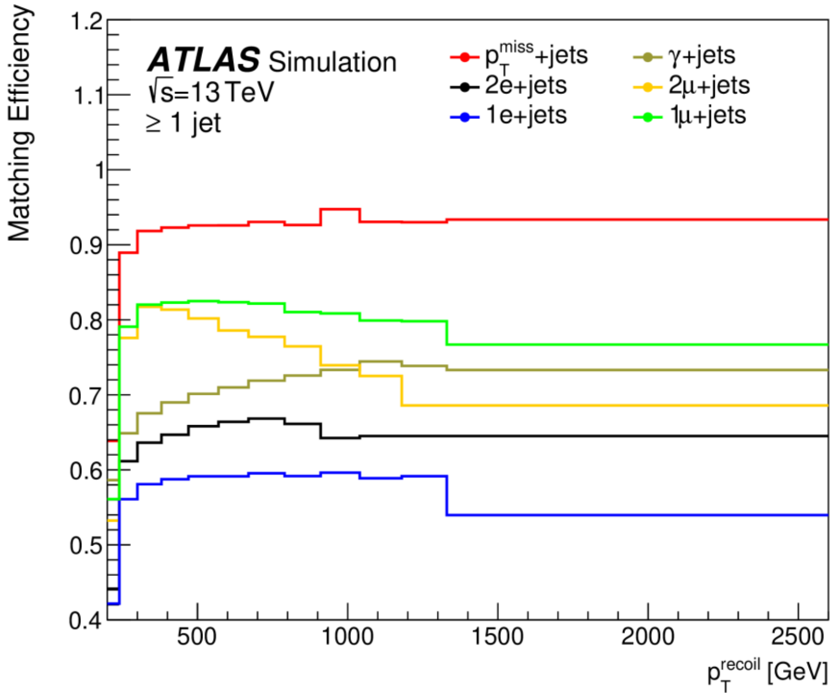
- **Background contribution**
  - *Non collision background*: jet identification + data-driven approach with time differences
  - *Mis-calibrated/identified multi-jets*: $\Delta\phi(jet, p_T^{miss})$+ jet smearing/fake factor methods
  - *Other SM processes*: shape taken from MC with normalization from fit in dedicated CRs

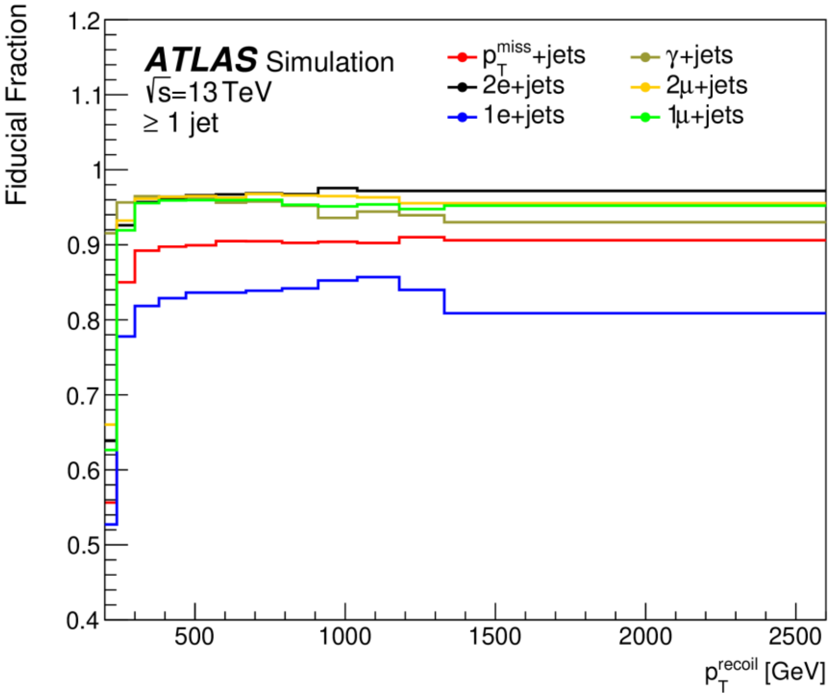
- **Detector effects correction**
  - $Z \rightarrow \nu\nu$ measurements ⇨ correct data subtracting all backgrounds
  - *inclusive* p_T^{miss} measurements ⇨ correct data subtracting fakes only

- **Quantitative comparison to the latest-of-art SM predictions**
  - *Likelihood fit* with uncertainties treated as covariance matrix or nuisance parameters
  - $\chi^2/d.o.f. < 2$ for the post-fit agreement between SM and all measurements except m_{jj}

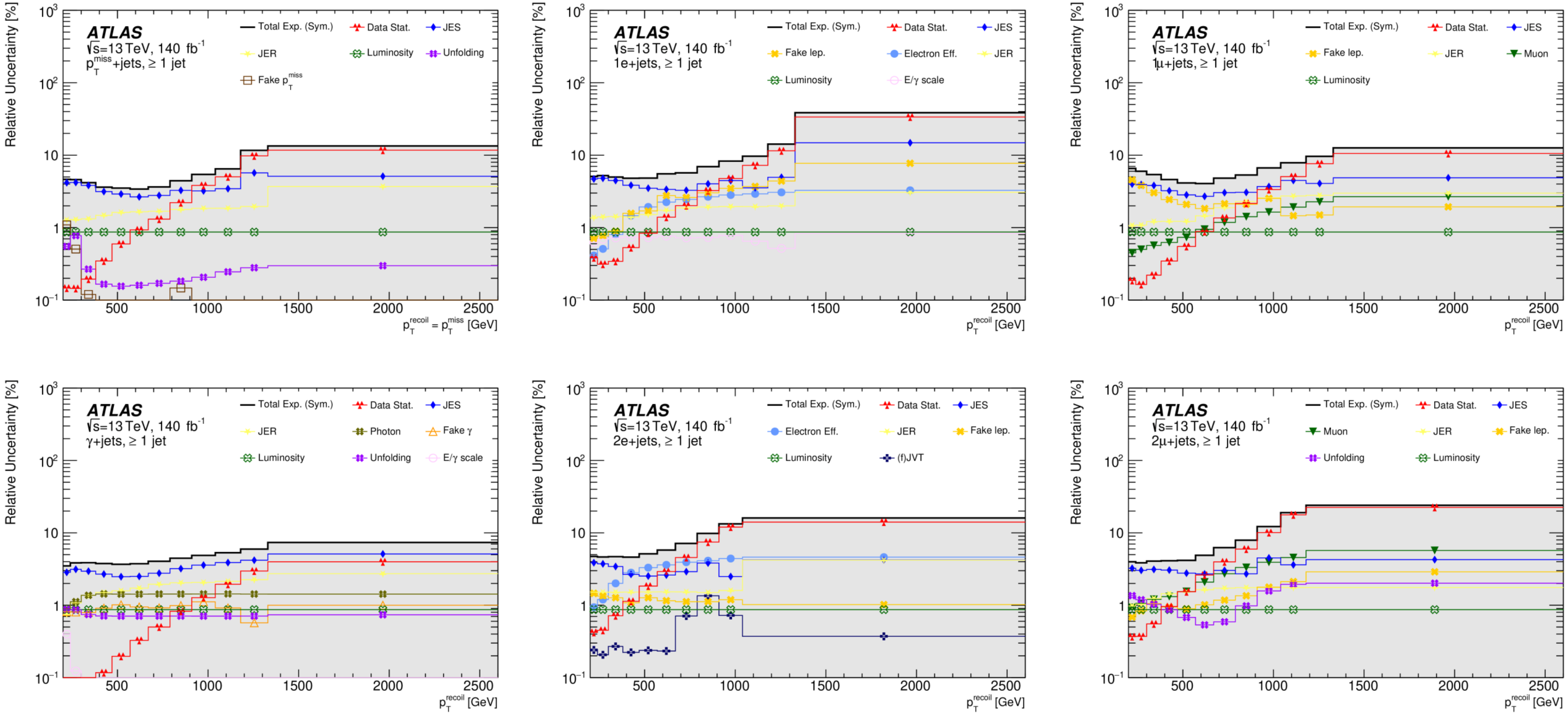
Unfolding


ATLAS Simulation
√s=13 TeV
p_T^{miss}+jets, ≥ 1 jet
Particle level $p_T^{recoil} = p_T^{miss}$ [GeV]
Detector level $p_T^{recoil} = p_T^{miss}$ [GeV]
10^3
77.0 22.7 0.3
23.1 66.4 10.5
0.5 21.8 70.1 7.5
0.3 21.8 70.7 7.3
0.2 21.3 71.0 7.5
0.3 21.5 69.2 8.9
0.5 19.7 71.8 7.8
0.1 0.7 20.0 69.7 9.5
0.1 0.4 20.6 69.6 9.2
0.1 0.4 19.3 69.9 10.0
0.1 0.7 19.4 69.3 10.3
0.1 0.4 10.8 88.5

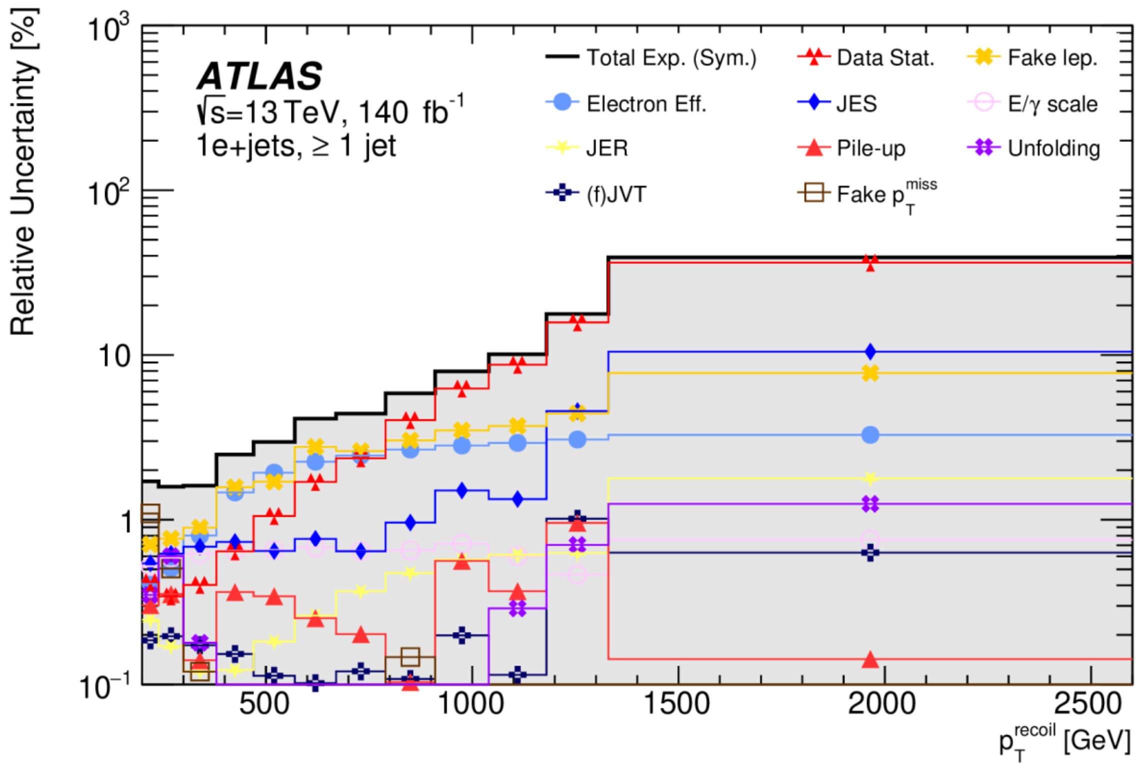

ATLAS Simulation
√s=13 TeV
≥ 1 jet
p_T^{miss}+jets
2e+jets
1e+jets
γ+jets
2μ+jets
1μ+jets
Matching Efficiency
p_T^{recoil} [GeV]

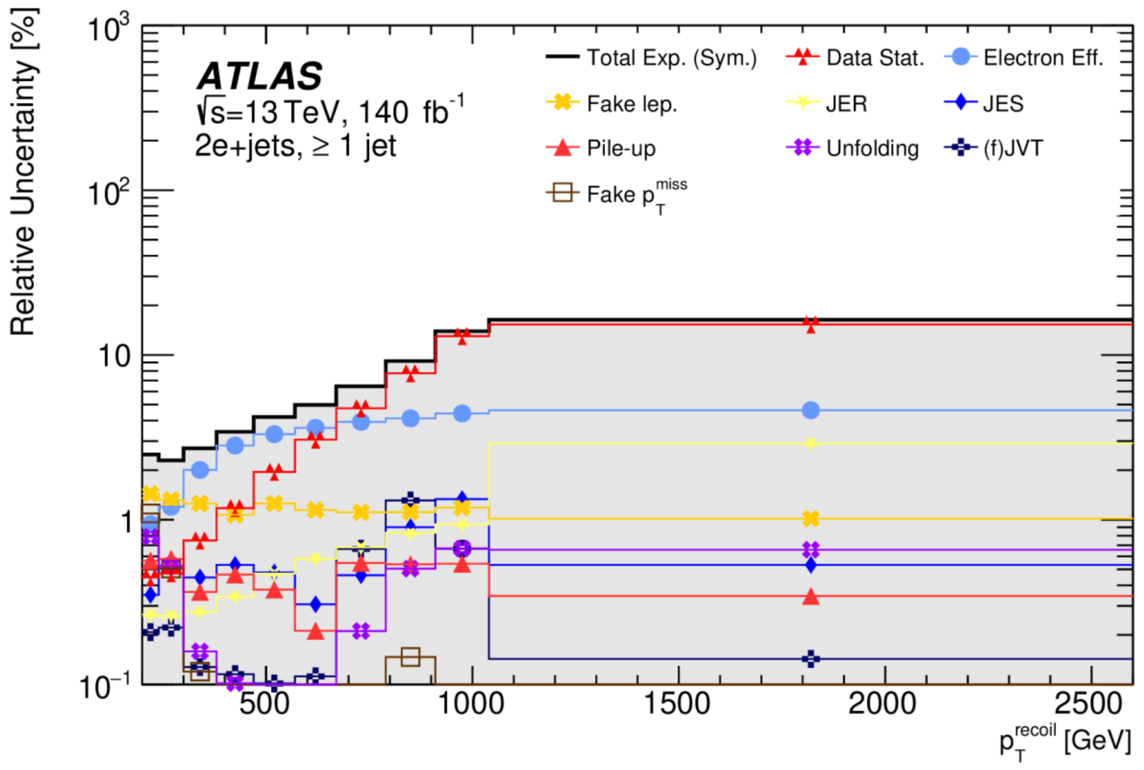

ATLAS Simulation
√s=13 TeV
≥ 1 jet
p_T^{miss}+jets
2e+jets
1e+jets
γ+jets
2μ+jets
1μ+jets
Fiducial Fraction
p_T^{recoil} [GeV]

Relative uncertainties as a function of p_T^{miss} or p_T^{recoil}

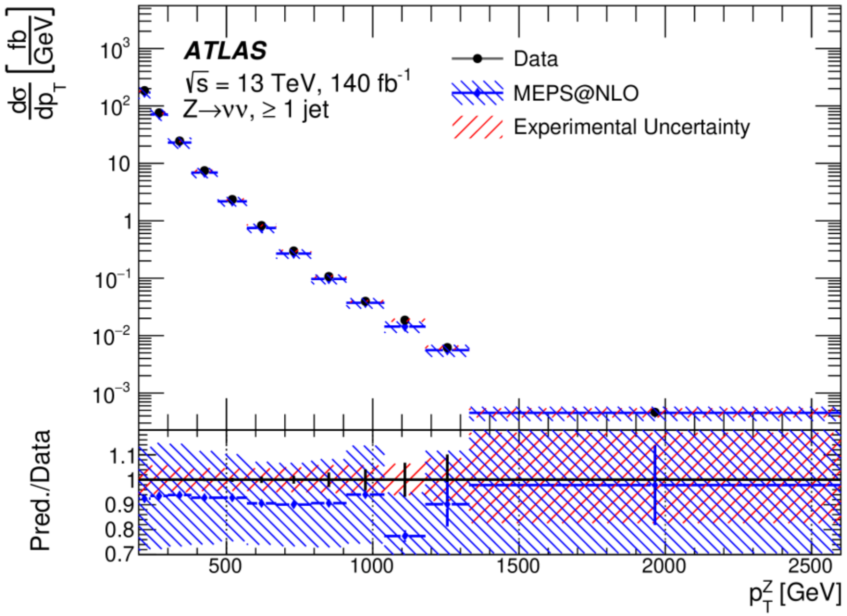


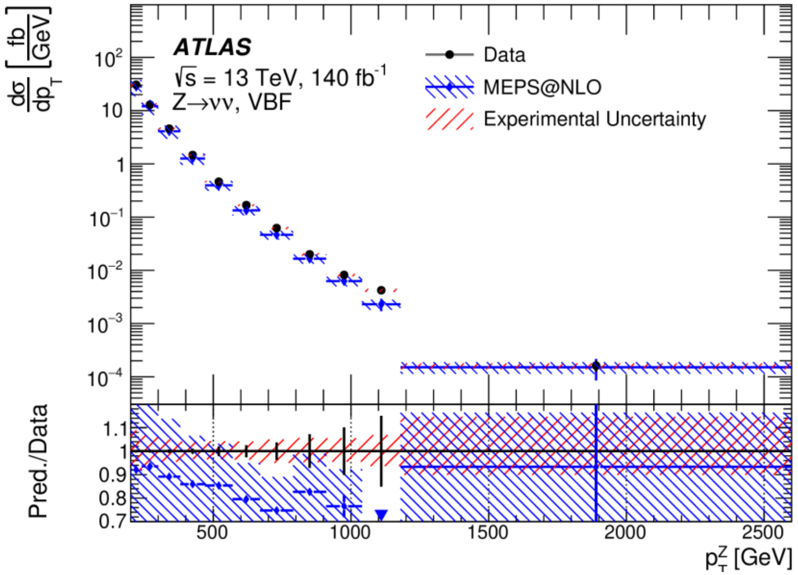
Relative uncertainties as a function of R^{miss}

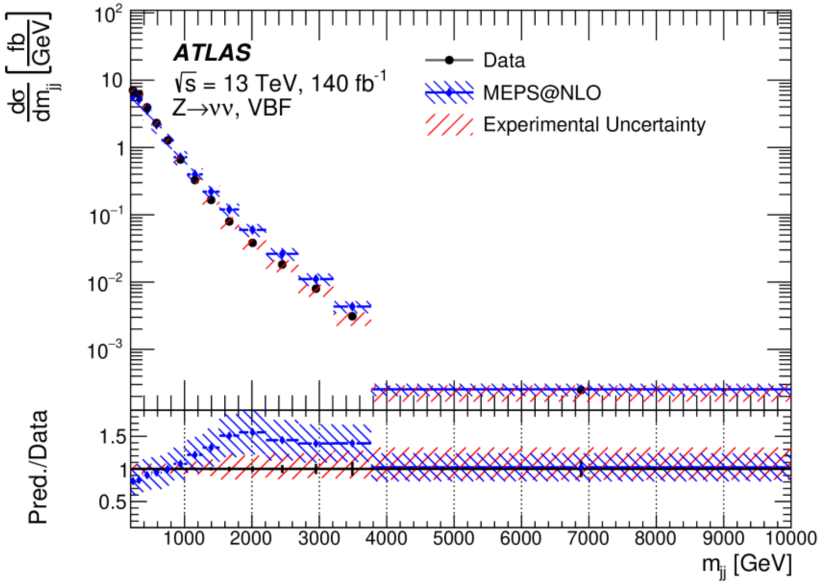


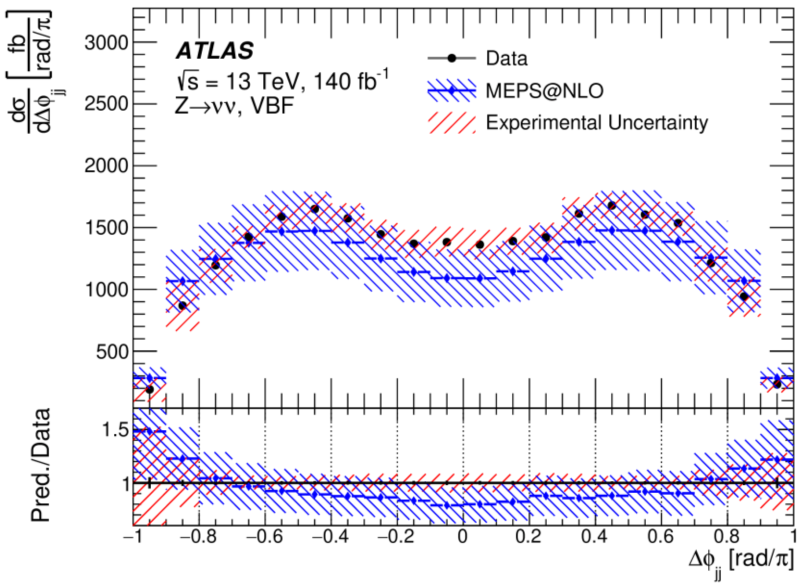


Z(→ $\nu\nu$) measurement results

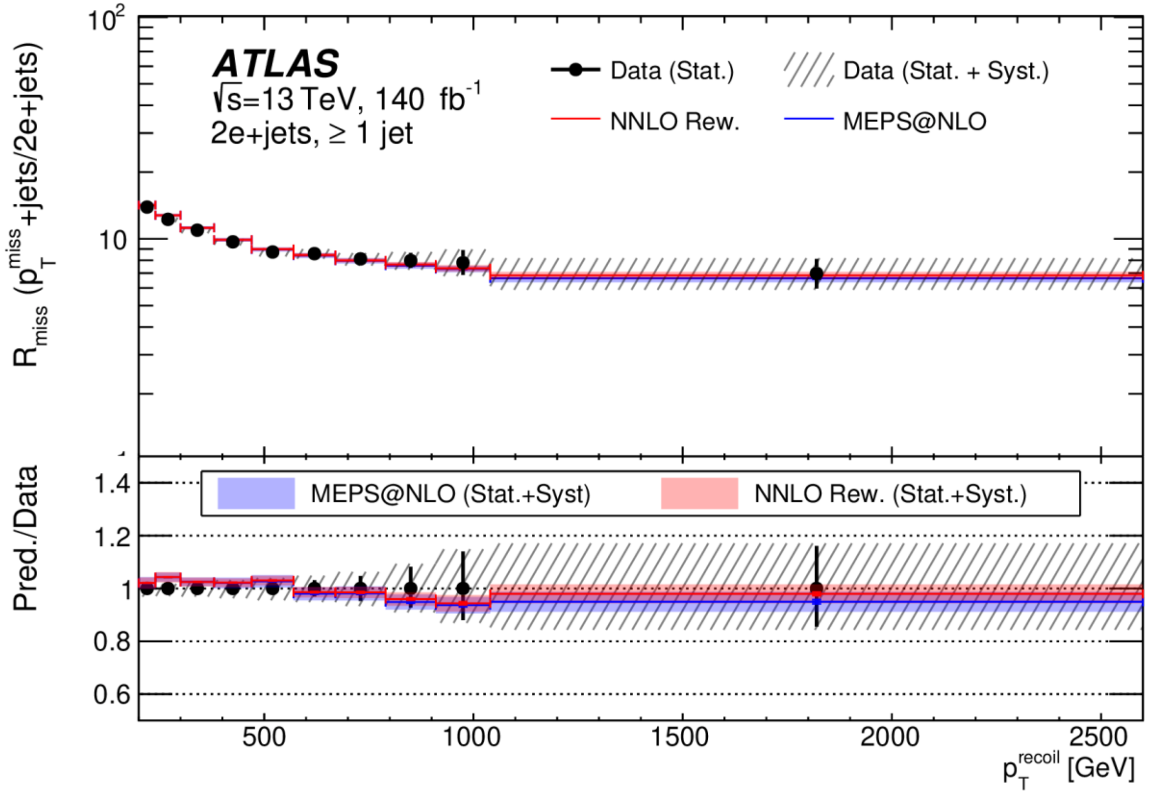


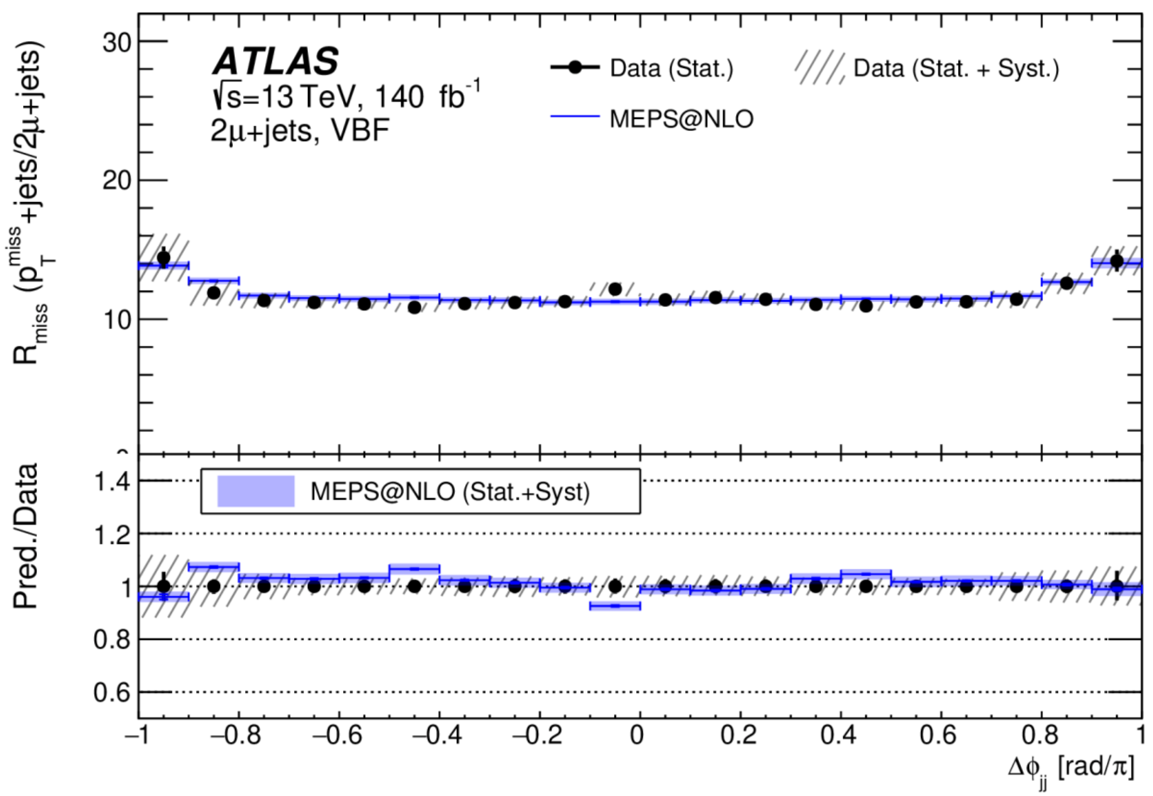






Ratio measurement results





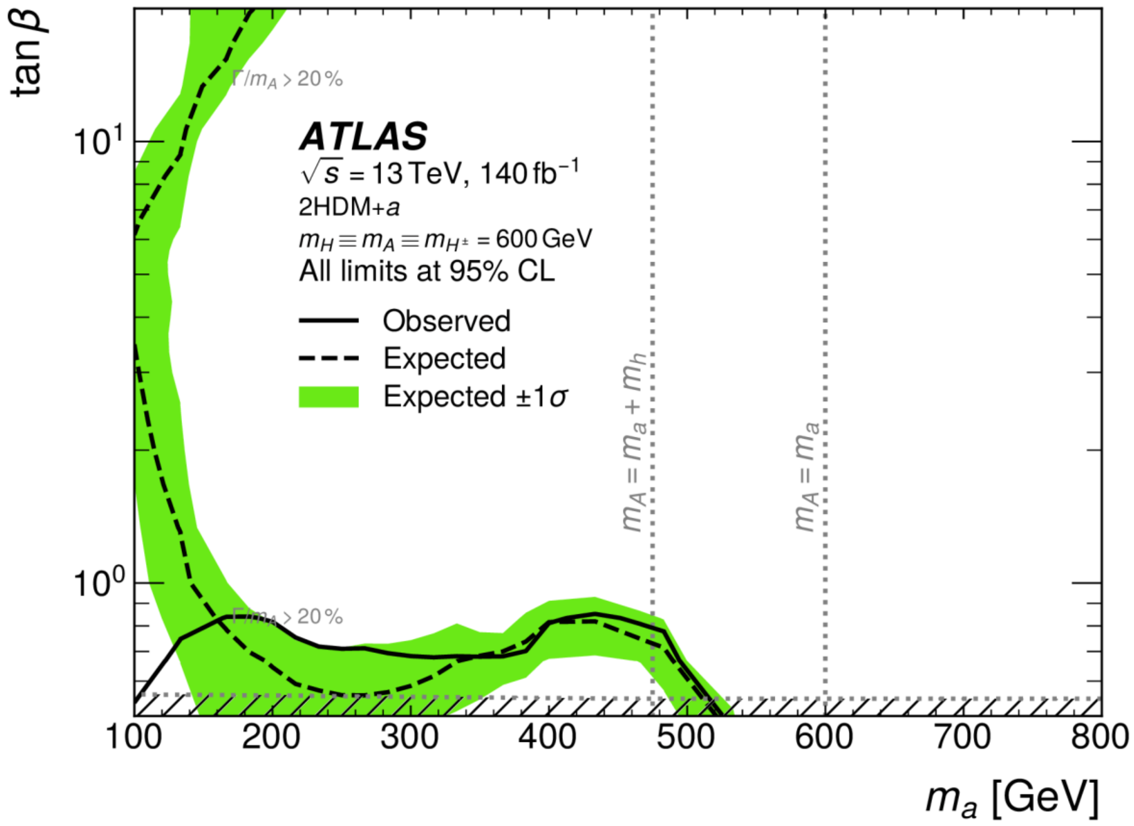
Statistical Test

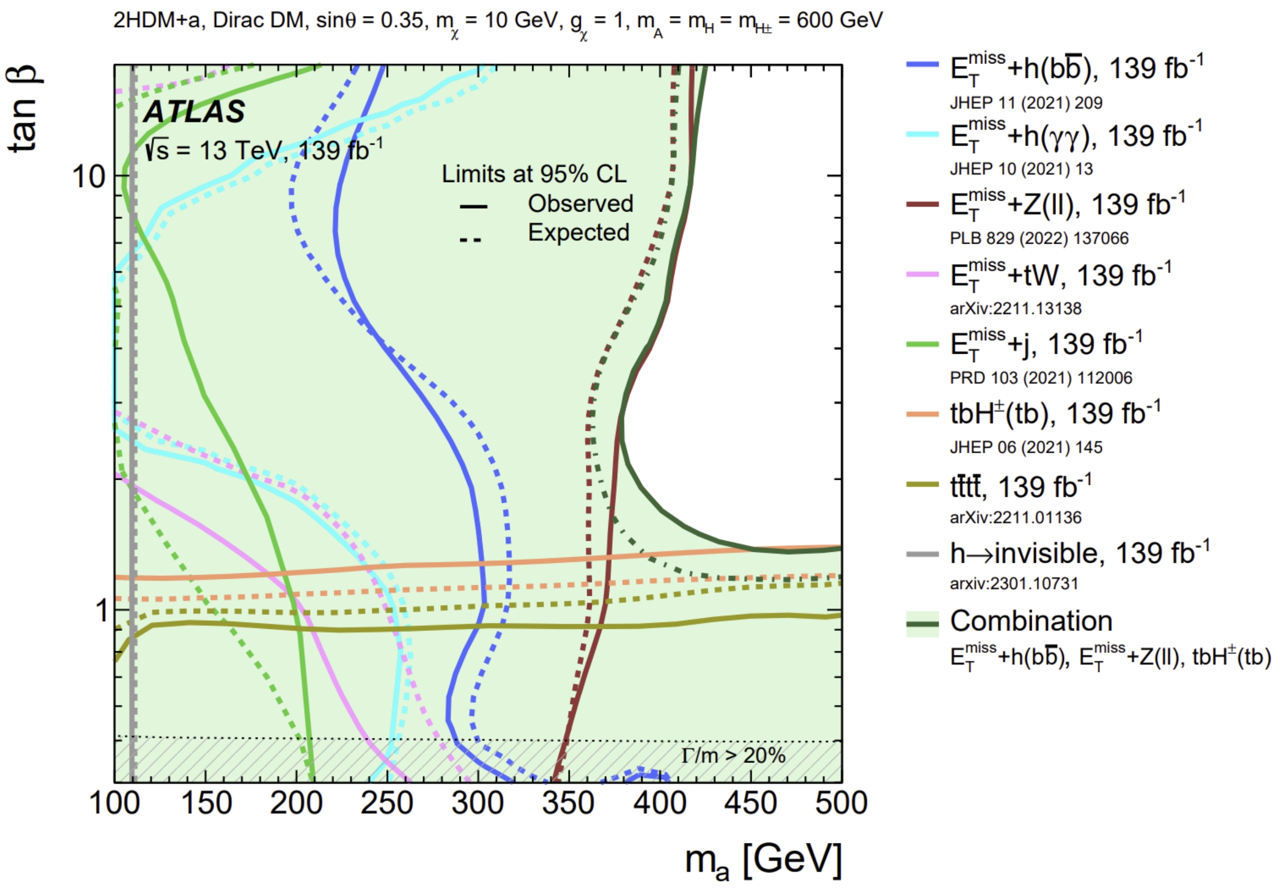
- **Test statistic is defined as -2 times the log of the likelihood ratio**

  Let's call the "SM only hypothesis" H0 and the "BSM hypothesis" with signal strength mu=1 H1.

- **To calculate the confidence level (CL) of exclusion**
  - *we need to know the underlying distribution (p.d.f.) of the test statistic;*
    - to obtain this we generate pseudo-experiments (toys) where we fluctuate data within statistical and systematic covariances.
  - *For the observed limits, we fluctuate experimental data to obtain a p.d.f. for the test statistic under signal hypothesis H1, and ultimately, we calculate the excluded level of CL (in fact CLs) by plugging in the observed value of the test statistic from the experimental data that was actually measured*
  - *For the expected limits, we only use theoretical predictions instead. We fluctuate the theoretical predictions of hypothesis of H1 to get the p.d.f., and then evaluate the expected CL by plugging in the prediction for H0, which answers the following question: "If we measured precisely the SM (background) only prediction with our experiment, how (un)likely are we to exclude this particular model?"*

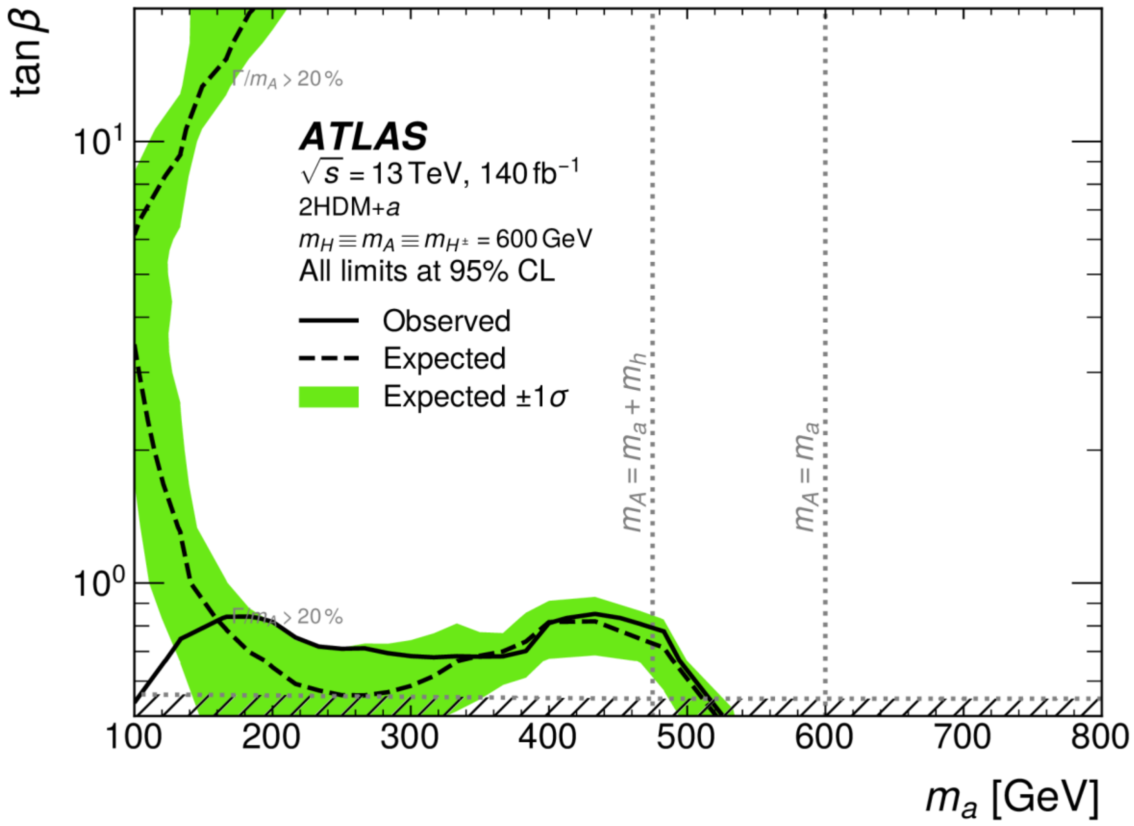
2HDM+a





ATLAS summary plot [2306.00641]

2HDM+a



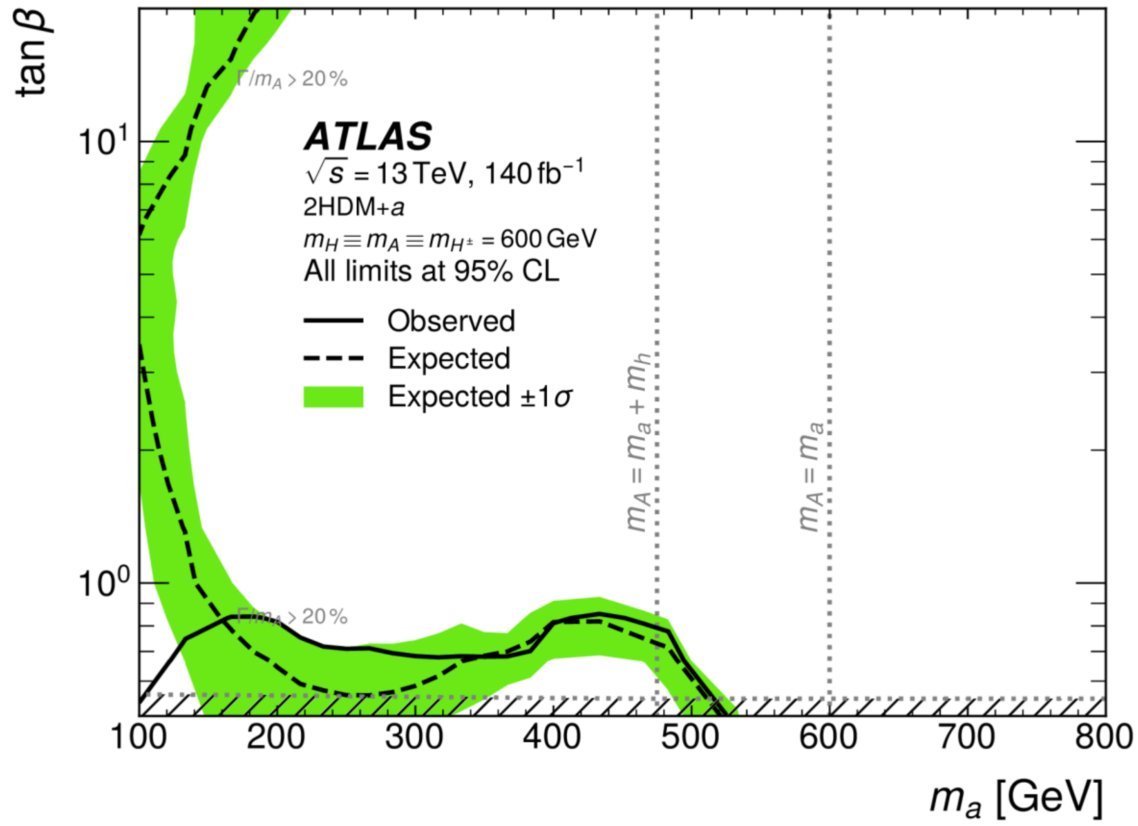
The scan reveals two major regions of sensitivity:

- For **tan β < 0.7**, masses of the pseudoscalar a up to 520 GeV are excluded because of loop-induced production of a and its subsequent decay into DM particles, $p\,p \rightarrow a(\rightarrow \chi\bar{\chi})$+jets. The sensitivity is larger at **m_a > 350 GeV ≈ 2 m_{top}** because here the a can be produced resonantly from top quarks.

For **tanβ > 10**, there is a second island of sensitivity because of b-quark induced production of a and its subsequent decay into DM particles.

- **At small ma**, the expected exclusion limits are generally stronger because of processes almost independent of tan β, e.g., $p\,p \rightarrow H \rightarrow aZ$ and $p\,p \rightarrow H^{\pm} \rightarrow aW^{\pm}$. However, the sensitivity to these processes is not large enough to close the sensitivity gap between small and large values of tan β.

2HDM+a



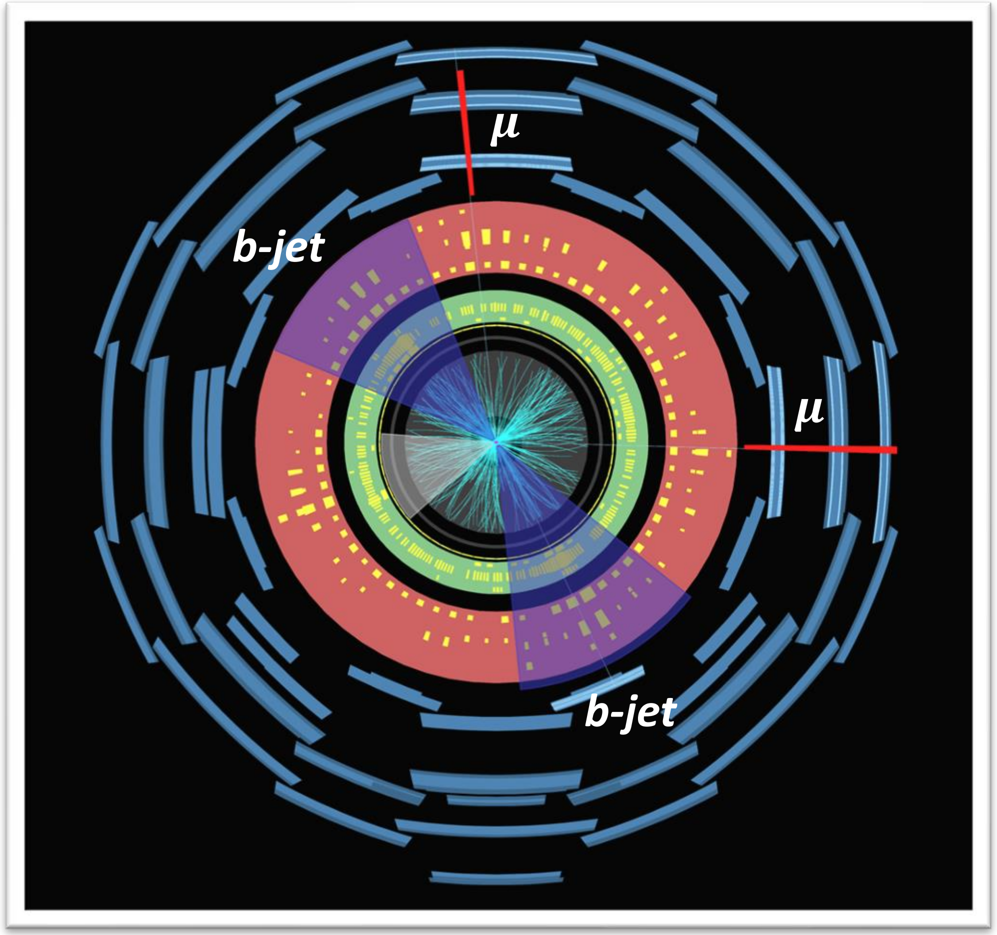
Is there any idea why the observed exclusion limits for the 2HDM+a model are significantly worse than expected at low ma values?

- *In the SM-only case there is pre-fit a significant difference between measured data and SM prediction. This gets considerably reduced post-fit but at the price of a number of large pulls to some nuisance parameters (even for Rmiss).*

- *2HDM+a signal points are generally very broad and not peaky. This means we can reduce remaining normalization discrepancies between data and SM prediction in many regions at once, rendering an exclusion unfeasible.*

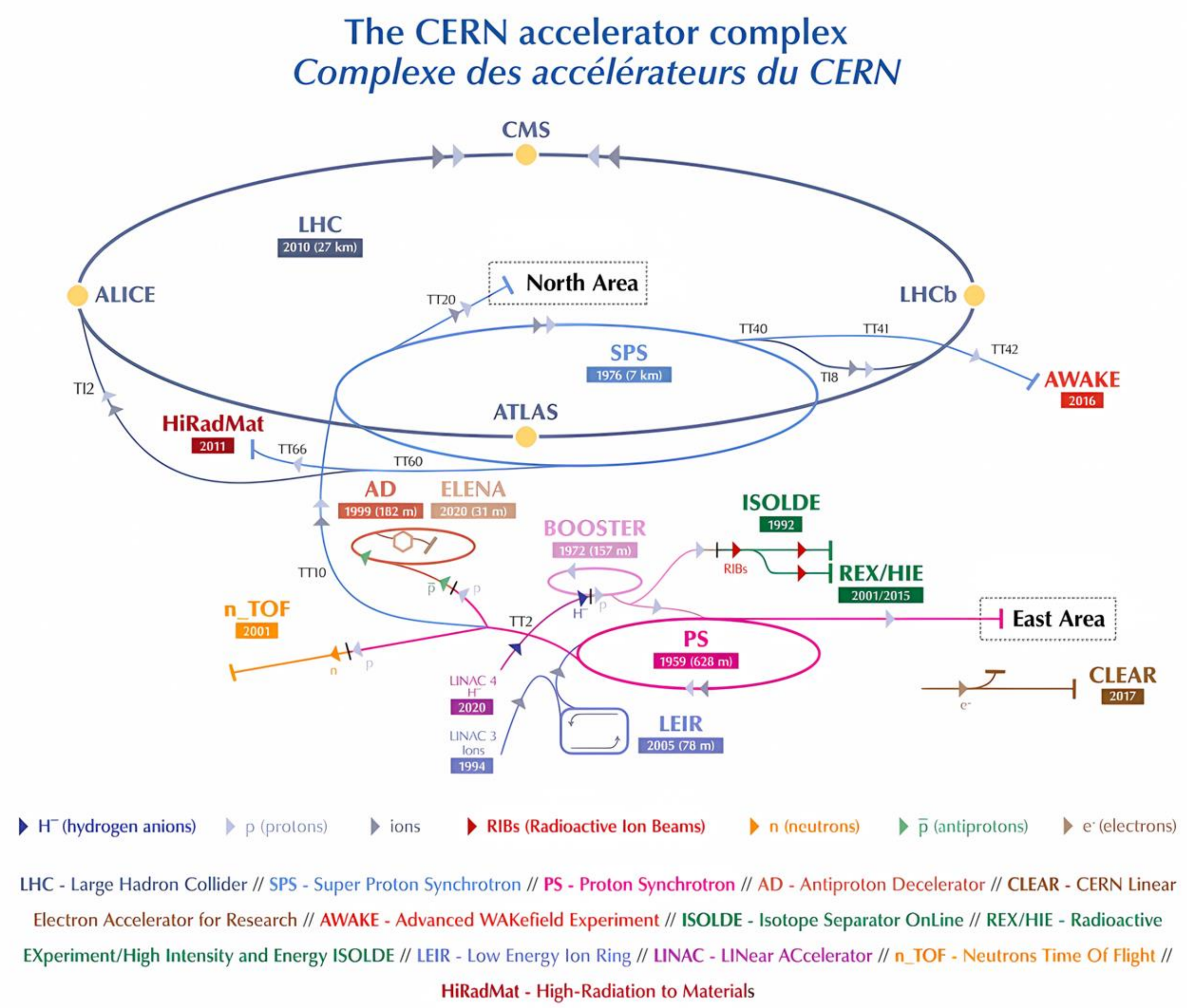
** Back up*

Event display of
Z+>=2b-jets candidate from data recorded by ATLAS



The Large Hadron Collider

Snowmass White Paper Contribution:
Physics with the Phase-2 ATLAS and CMS Detectors

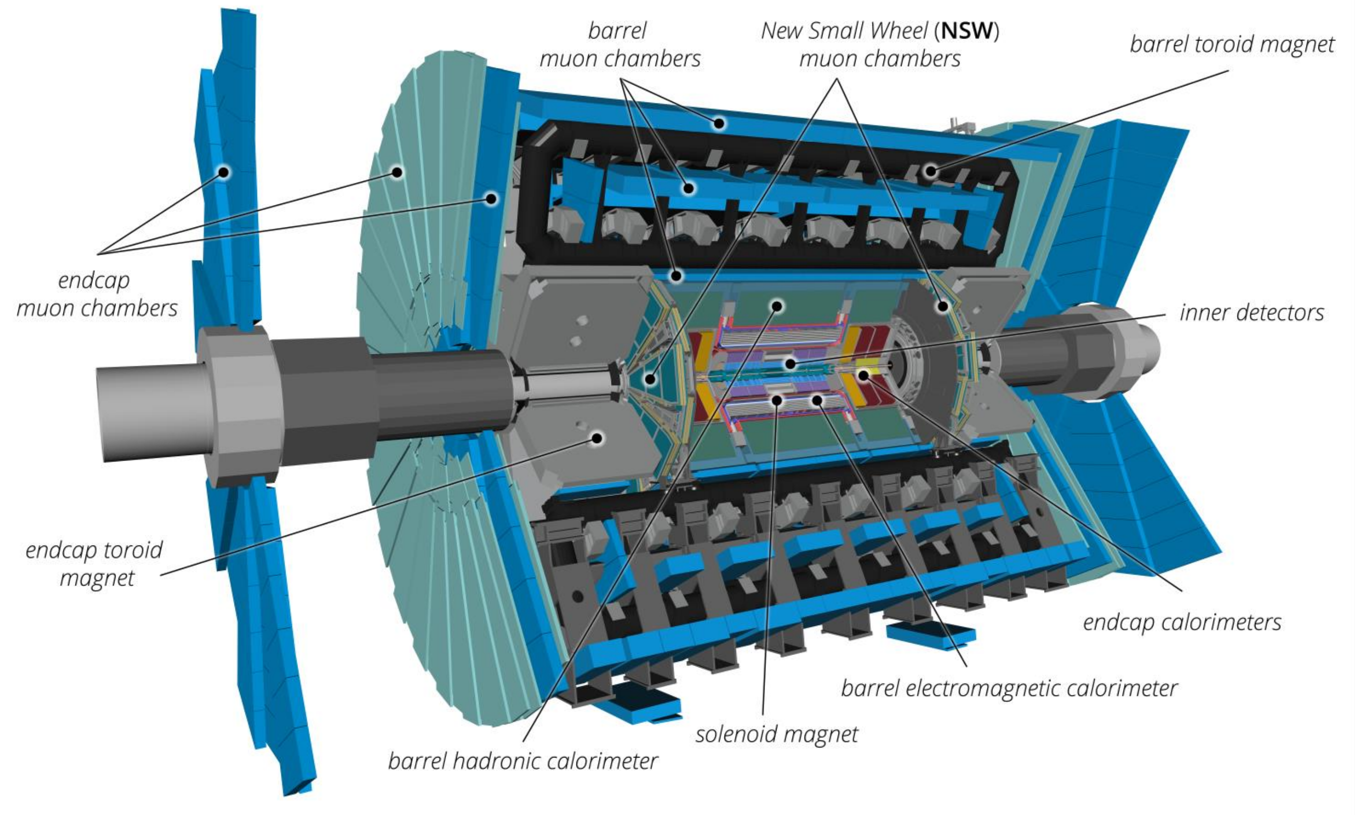


CERN-GRAPHICS-2019-002

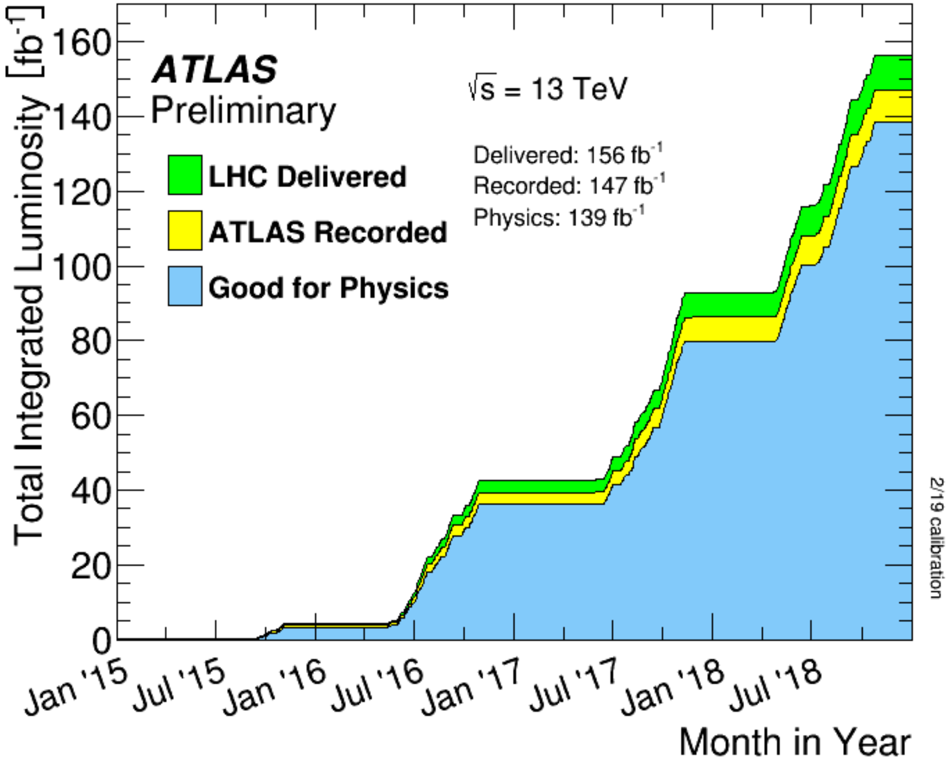
- Frontier particle physics @ TeV scale
  - Higgs physics: Yukawa coupling, self interactions
    - ⇨ mass origin of matter particles
    - ⇨ evolution of vacuum and universe
  - SM precision: bosons, top, fundamental parameters
    - ⇨ confront with PDF, electroweak and QCD theory
  - New physics: dark matter, exotics, symmetry breaking
    - ⇨ search for BSM interaction and particles directly
- Why New Physics?
  - Neutrino mass, baryon asymmetry, dark matter inflation ☜ experimental challenges
  - Fermion/Higgs hierarchy, gauge unification, vacuum stability ☜ theoretical motivation

ATLAS Experiment

- **A priority goal** is to establish to what extent the SM remains valid at accessible energies



- Run-2 with largest dataset available for physics: $\mathcal{L}$ = 140 fb^{-1} at $\sqrt{s}$ = 13 TeV



- Onion layer structure:

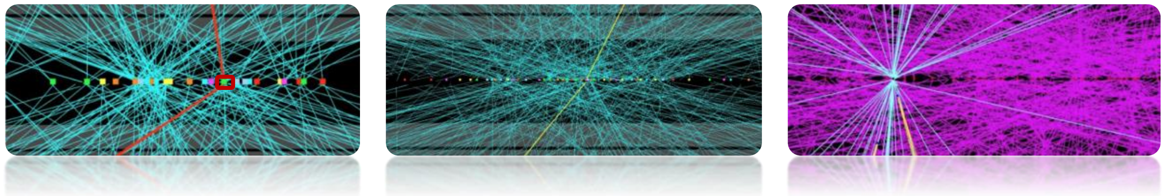
inner detector → calorimeters → muon spectrometer

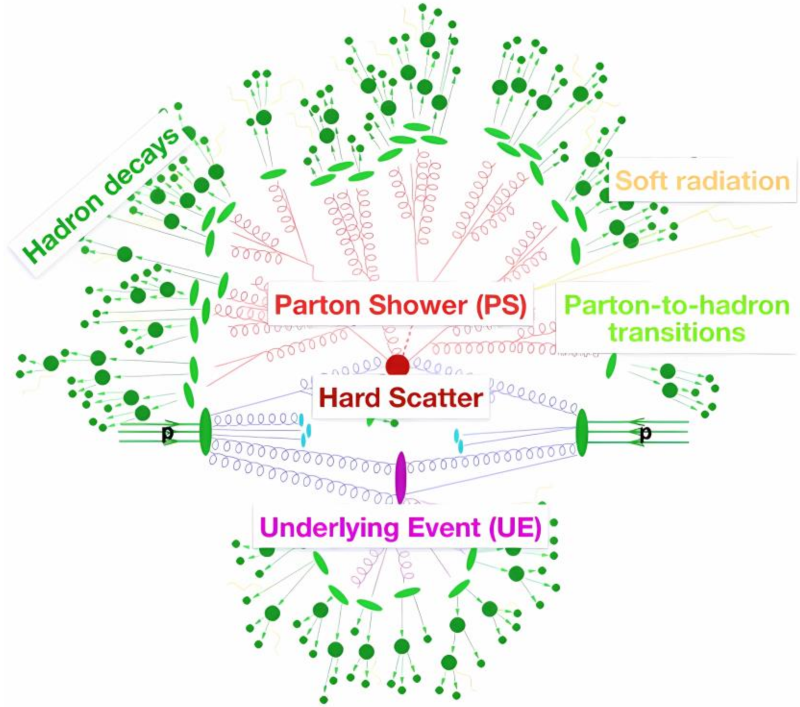
Hard QCD and EWK at ATLAS

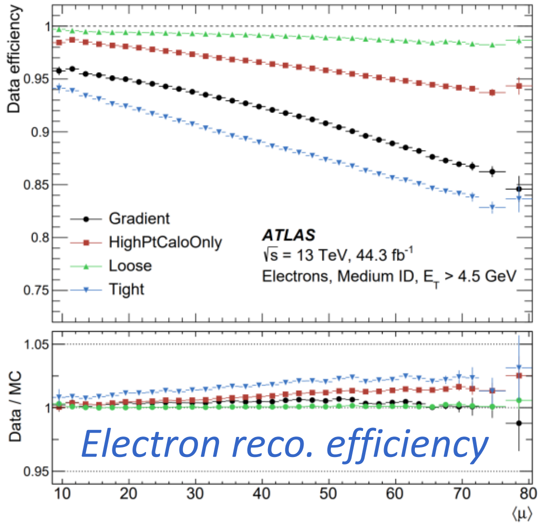
[Muon: Eur. Phys. J. C 81 (2021) 578]
[E/γ: JINST 14 (2019) P12006]
[FT: Eur.Phys.J.C 83 (2023)]

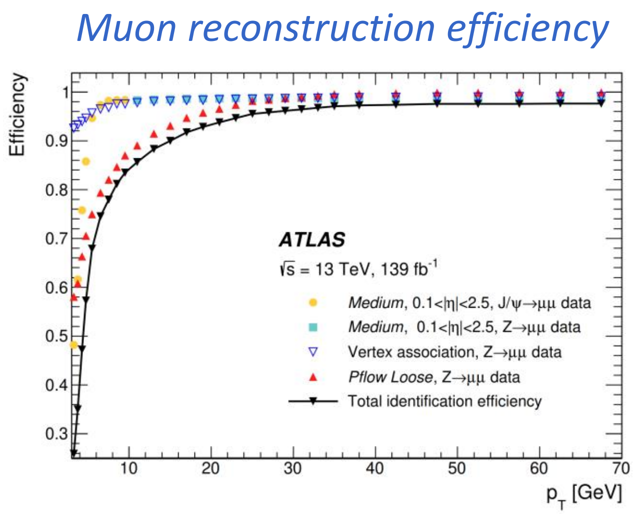
- Hard interactions are challenging at LHC
  - Excellent analysis results depend on the precise *modelling*, *experiment performance*, *analysis strategies*

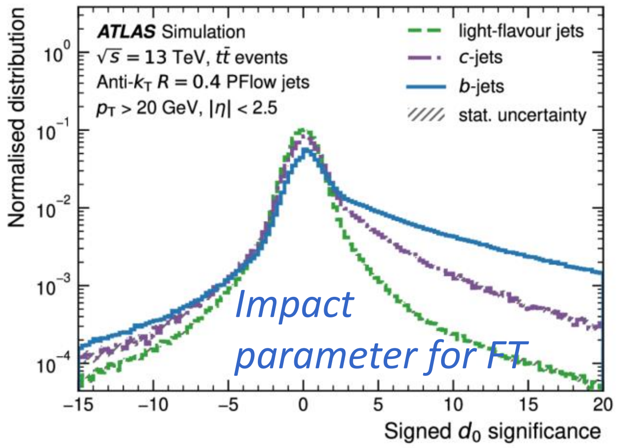
$<\mu> = 30$ $<\mu> = 60$ $<\mu> = 140-200$

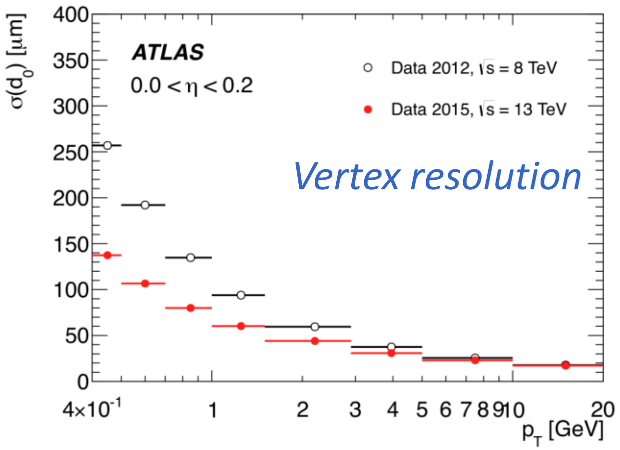






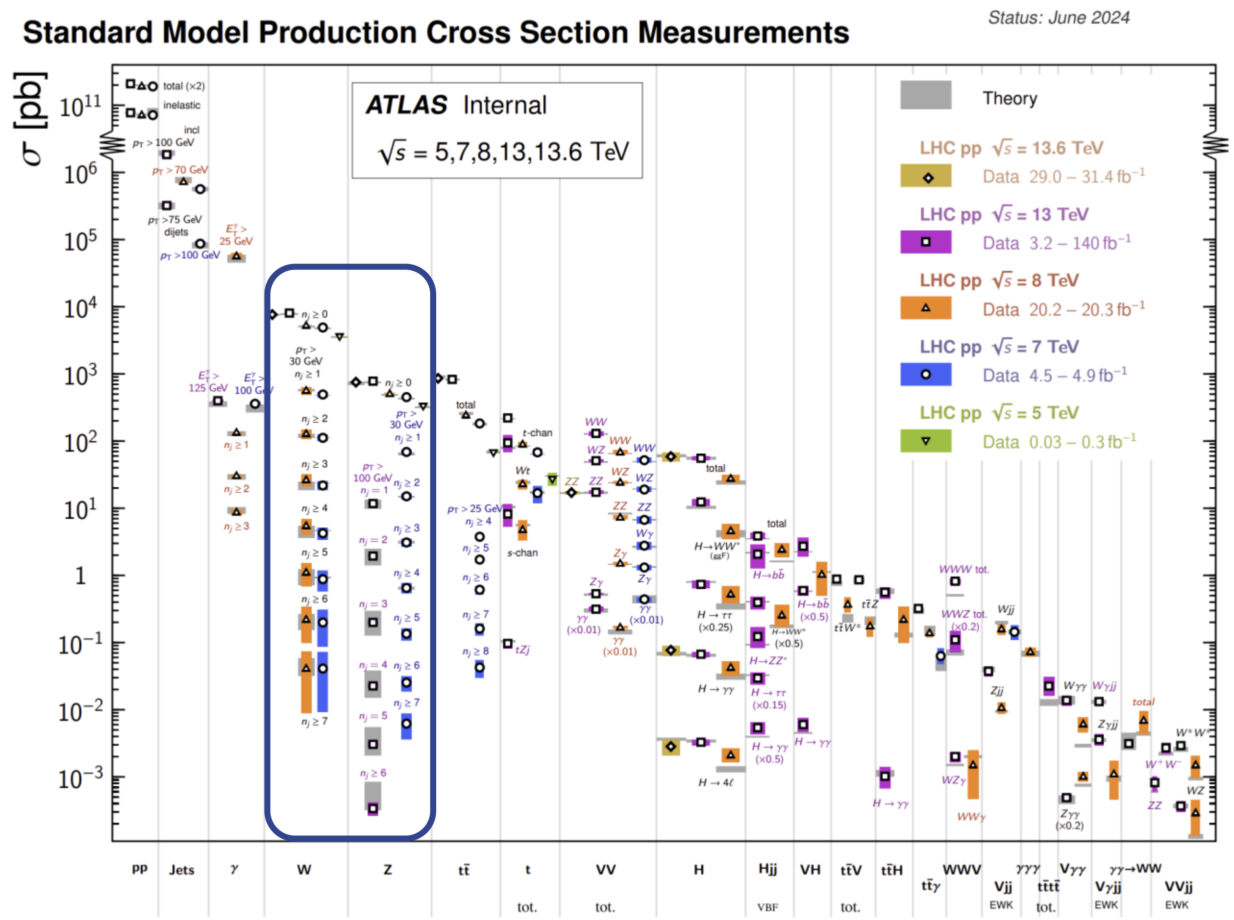


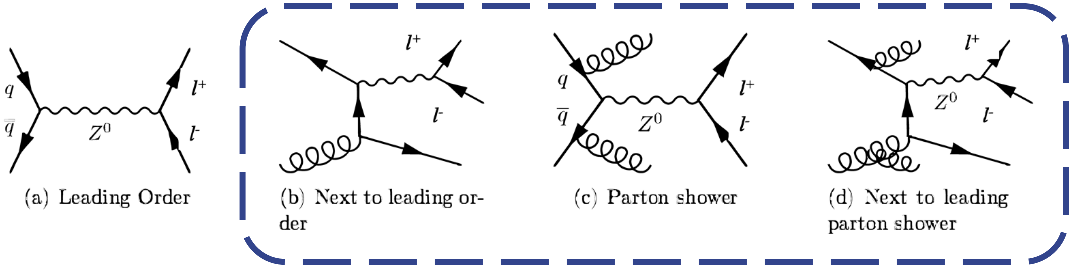


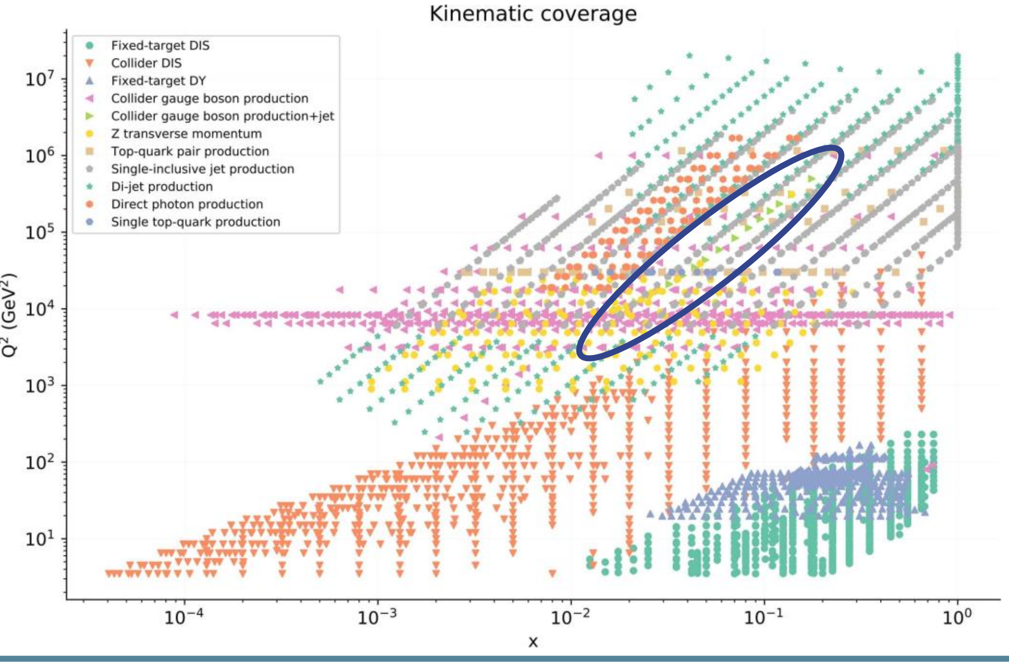


V + jets at hadron collider

- **V(=W/Z) + jets** production has the *large cross-section* and a *broad kinematic range*
  - High order of Drell-Yan process with accounting for 1/3 of W/Z productions at LHC





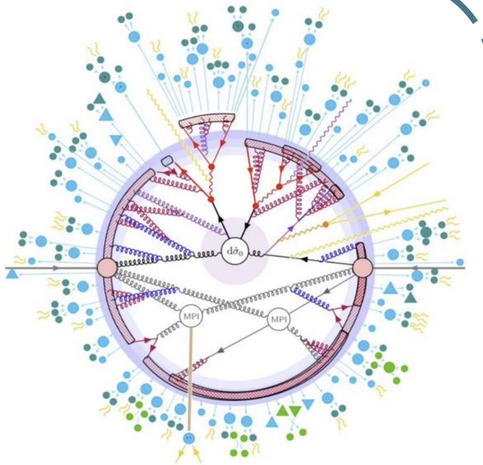


Goals of V + jets measurements

- 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

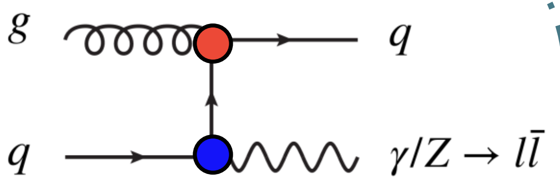
Stages of a MC event generator

- Hard Scatter
- Parton Shower (PS)
- Hadronisation (Had)
- Colour Reconection (CR)
- Multiple Parton Interactions (MPI)

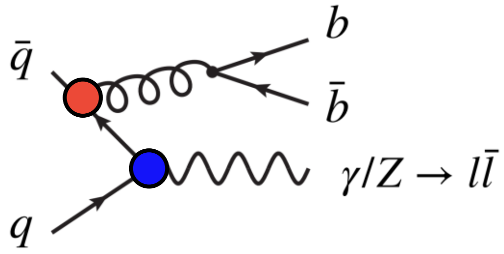


Pythia 8.3 schematic event

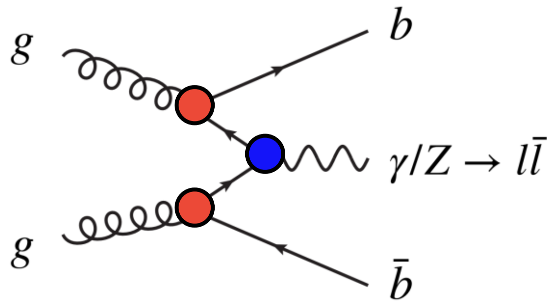
qg
initial state



$q\bar{q}$
initial state



gg
initial state

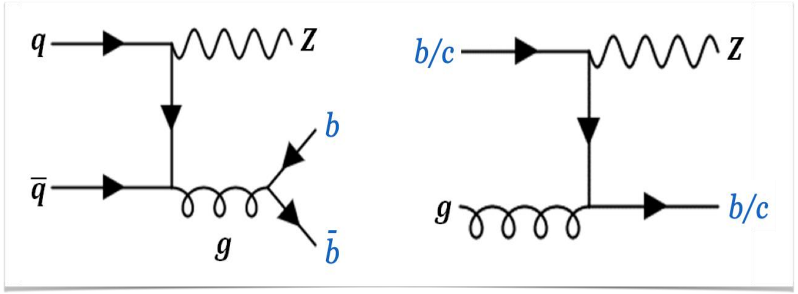


** Z + bb shown as example*

Z + HF jets Measurement

Inclusive and differential Z+≥1b, ≥2b, ≥1c x-sections and fwd/central ratio for Z+≥1c events with 139 fb^{-1}

- Z+≥1b: Z p_T, lead b-jet p_T and ΔR(Z, lead b-jet)
- Z+≥2b: m_{bb}, $\Delta\Phi_{bb}$
- Z+≥1c: Z p_T, lead c-jet p_T, lead c-jet x_F and fwd/central vs Z p_T



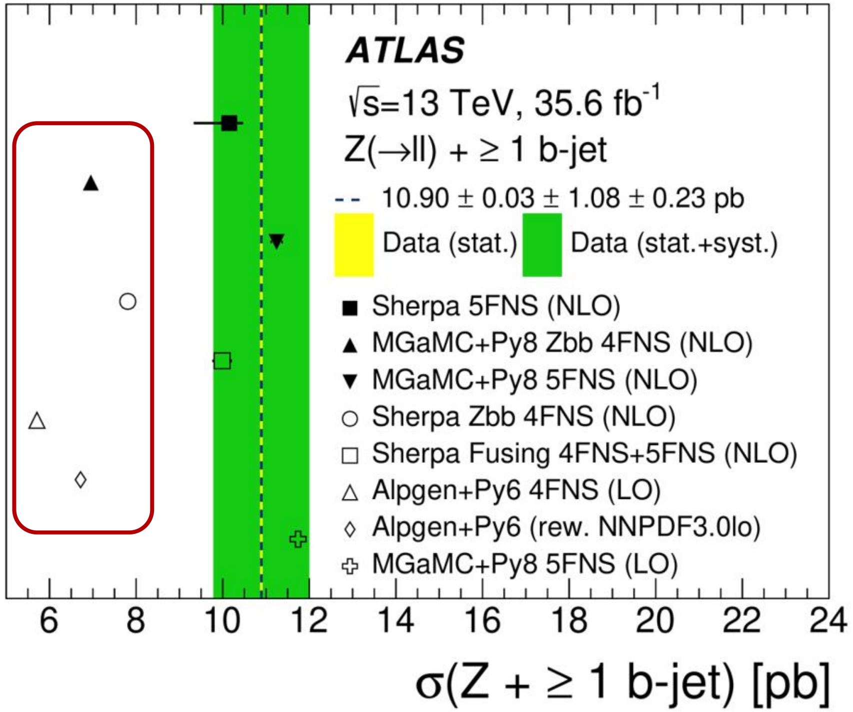
✤ **Z+≥1 b-jet and Z+≥2 b-jets**:
update 36 fb^{-1} results with larger statistics, new FT algorithm and optimized strategy for main backgrounds

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

⇨ Test effect of missing higher-order terms in QCD

⇨ Investigate different Flavour-Schemes in predictions

⇨ Explore possible sensitivity to Intrinsic-Charm



Analysis strategy

Event selection:
select **Z(→$\mu\mu$,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

✦ Z+HF events categorized at both reconstructed and particle level

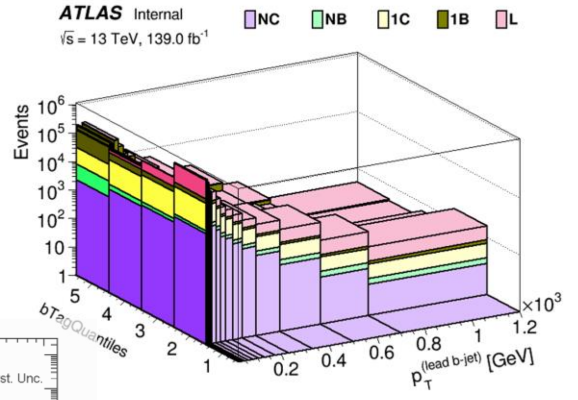
- Single jet flavor classified as B, C, L
  using cone-based (ΔR<0.3) matching between truth hadrons and jets
  correct place to replace with IRC safe jet-flavour algorithm
- Event flavor classified as 1B, NB, 1C, NC, L
  according to the leading jet flavour and number of HF-jets

For the ***background estimation*** and ***detector effect corrections*** to the dedicated HF processes, such as Z+>=1b [1B+NB]

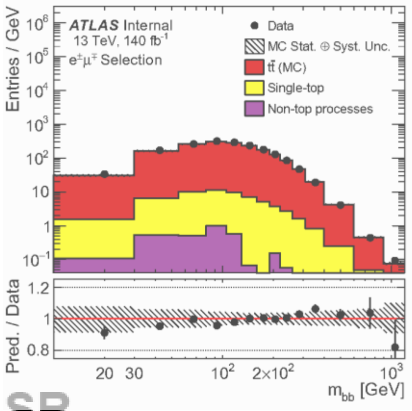
Analysis strategy

SR: 2 leptons (e^+e^- or $\mu^+\mu^-$) with ≥ 1, 2 flavour-tagged jets

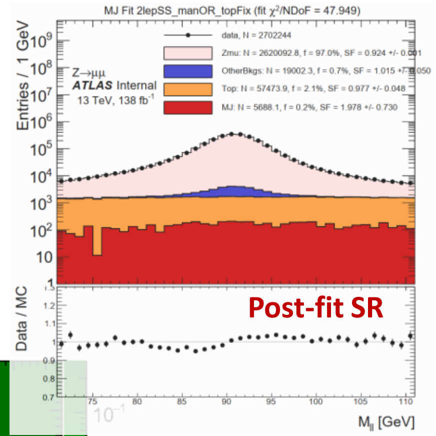
- Loose 85% WP DL1r flavour-tagger to allow a fraction of c-jets



- **Z+jets determined by bin-wise flavour fits**
  - Clear trends of scale factors correct both of shape and norm.

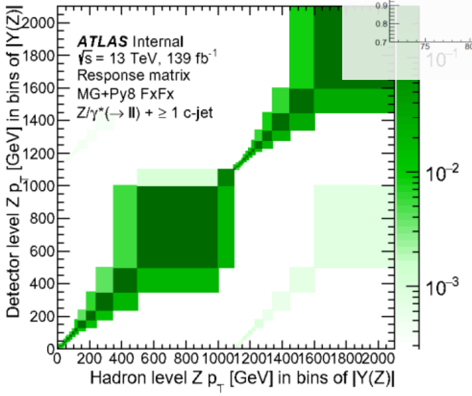


- ***tt* estimated with transfer factors from $e^{\pm}\mu^{\mp}$ CR**
  - Data-driven uncert ~ 25% (7%) of modelling uncert in Z+1b (Z+2b)



- **QCD multi-jets validated by simultaneous fit of anti-iso CR and SR**
  - Permille level in SRs hence neglected in the analysis

- **Central and forward Z pT unfolded at meanwhile to keep correlations**
  - Small forward ↔ central migrations

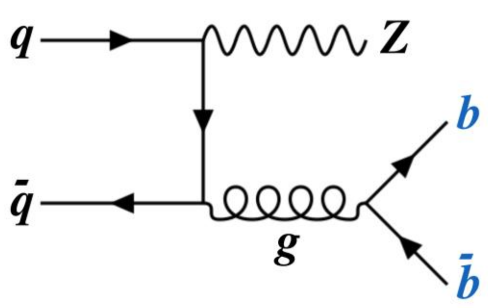


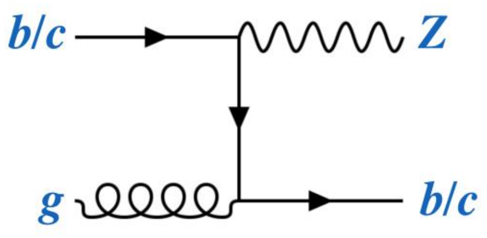
Dataset and event selection

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 μ+μ-
with p_T > 27 GeV, $|\eta|$ < 2.5
76 GeV < m_{ll} < 106 GeV

≥ 1 good jet
with p_T > 20 GeV, $|y|$ < 2.5
b-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

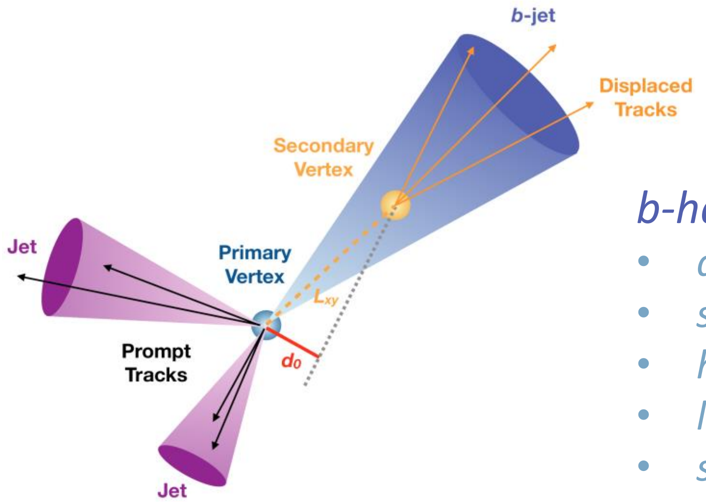
2-tag: **Z+≥2 b-jets** measurement

Flavour Tagging

DL1r

- High level neural network algorithm operating on outputs from intermediate track and vertex algorithms
- DL1r discriminant calculated from the b-, c- and light-jet probabilities

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

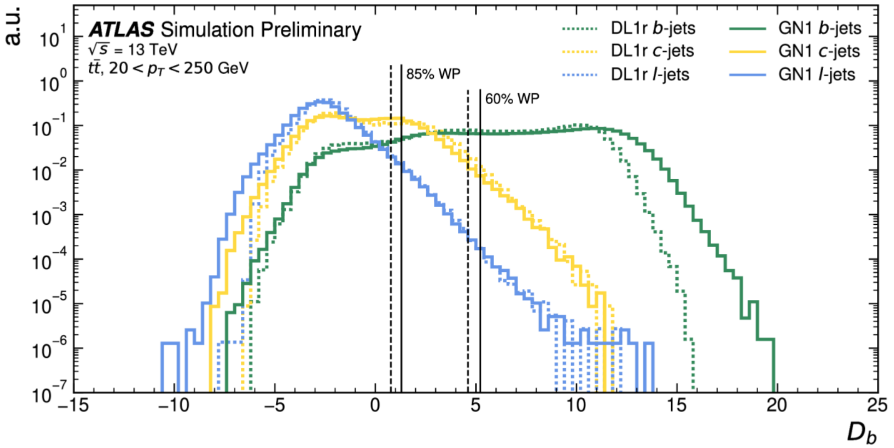


b-hadron decay signature

- *displaced tracks*
- *secondary vertex*
- *high-track multiplicity*
- *longitudinal impact parameter*
- *semi-leptonic decays*

b-tagging based on D_{DL1r}

- Selections provided with 60%, 70%, 77% and 85% b-tagging efficiency
- Flavour-sensitive distribution available with 5 exclusive bins obtained with different b-tagging selections



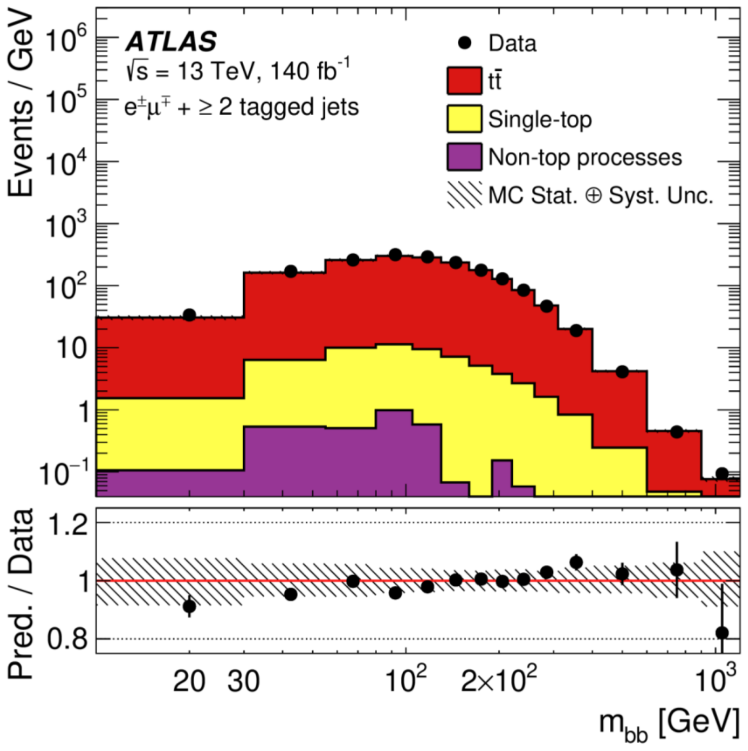
✵ DL1r @ 85% WP retains *85%* b-jets and *38%* c-jets

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

- Dileptonic events represent the second largest background
  - Using **data-driven technique** to avoid large modelling uncertainties (up to ~70% at high Z pT)
- **Method of the Transfer Factors**
  - opposite flavour eμ CR enhanced with $t\bar{t}$ events (>90%)
  - **$t\bar{t}$ template in CR** obtained by subtracting other MC from data
  - **Transfer Factors (TFs)** as ratio of $t\bar{t}$ MC distributions in SR and CR

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

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



- Systematics:

  Strong reduction of detector-level systematics propagated through TFs

  CR→SR extrapolation uncertainty derived via MC v.s. DD $t\bar{t}$ in VR

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

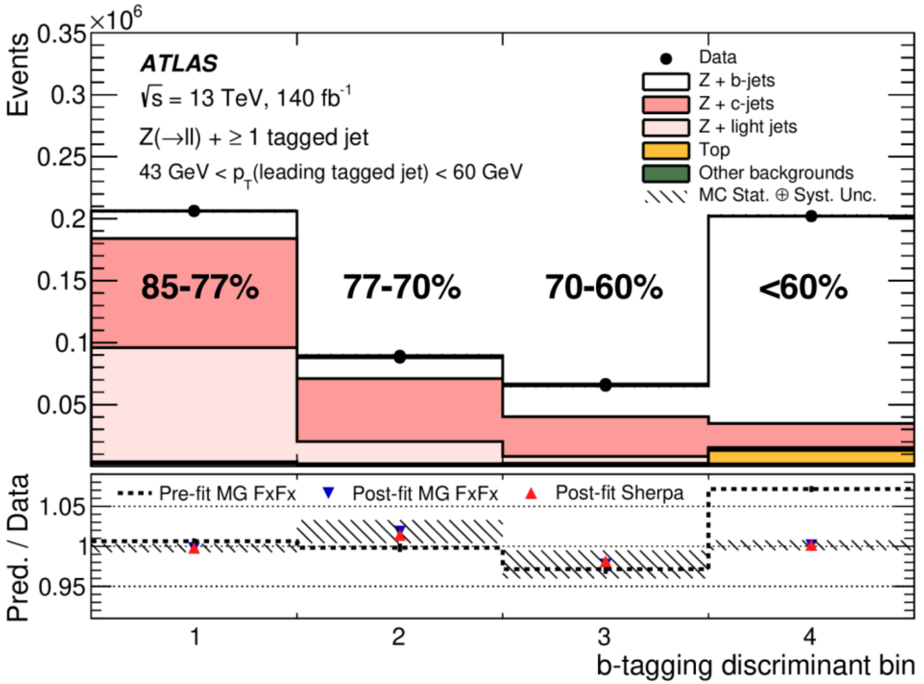
➞ **Correct Z+jets flavour components** and constrain systematics **with flavour-fit**

Maximum-likelihood fit to data based on flavour sensitive distribution

Example for 1-tag SR:

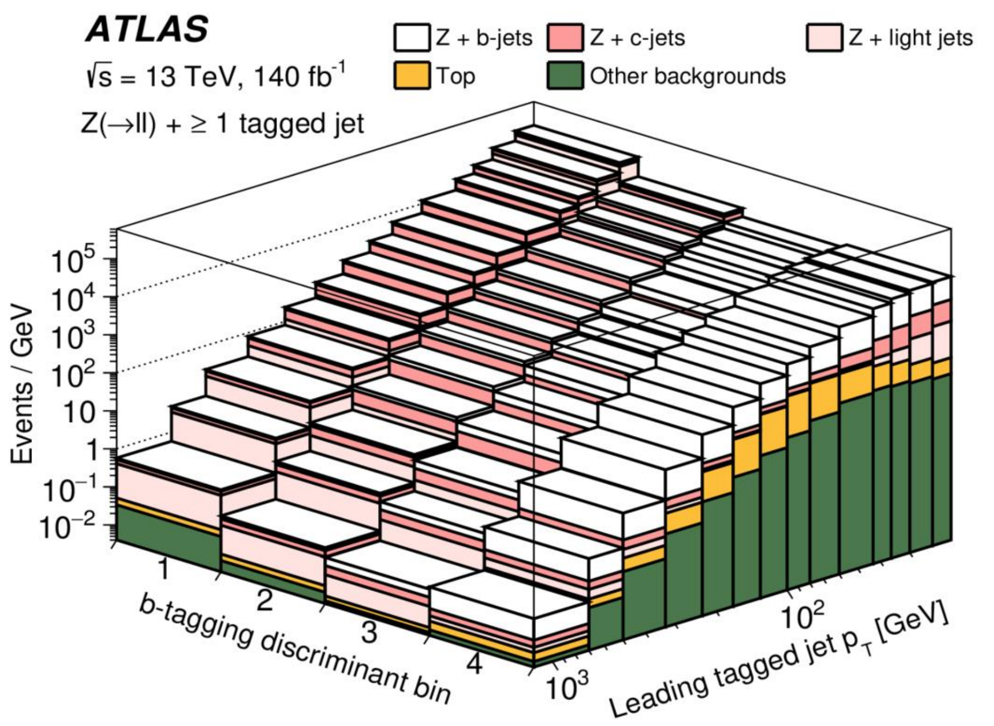
Fit of **flavour-tagging score (DL1r) in calibrated bins**

3 free parameters corresponding to **Z+≥1 b-jet, Z+≥1 c-jet** and **Z+≥light** jets normalization

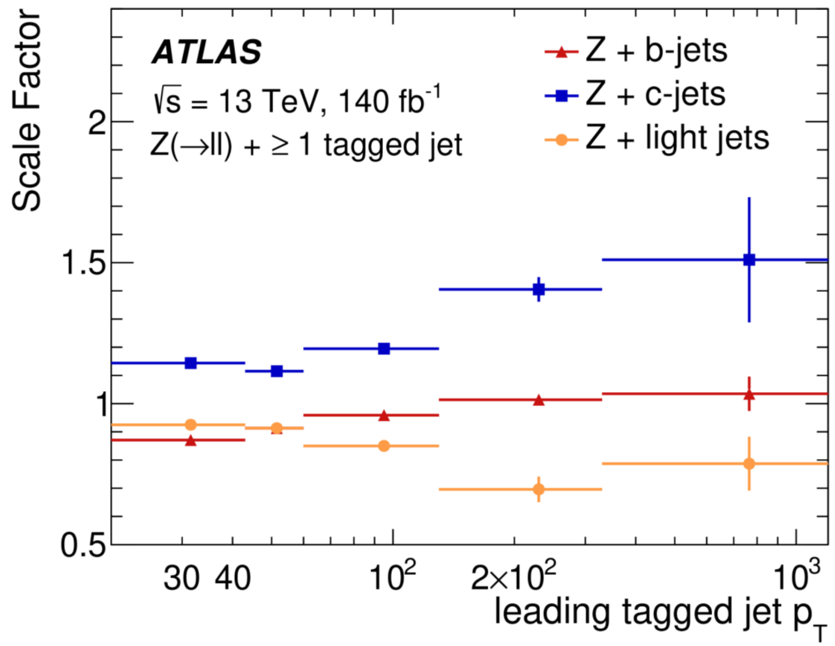


Z+jets background and flavour fit

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



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



- **Systematics**

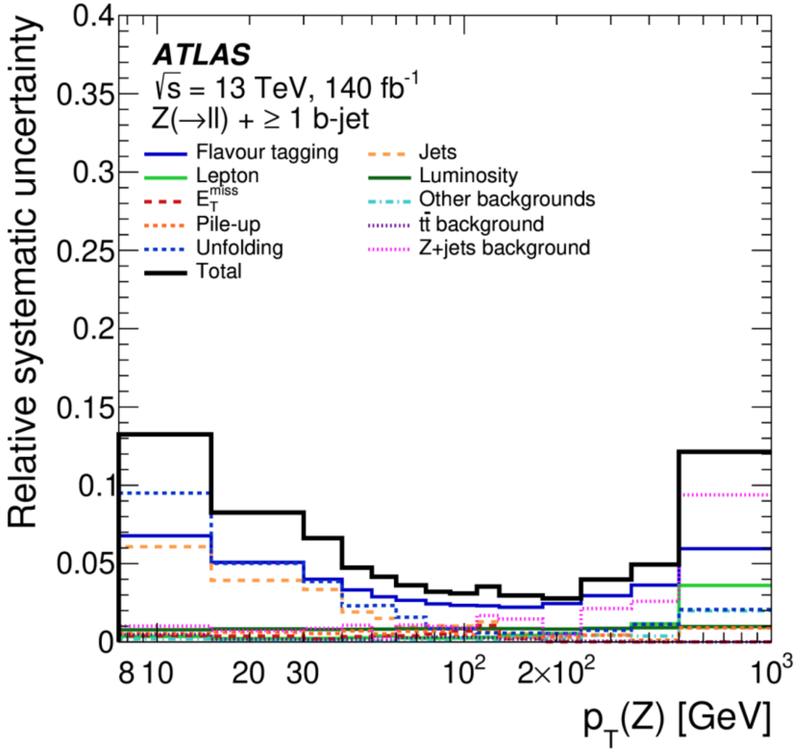
  detector-level systematics affect Z+jets templates - repeat flavour fit

  uncertainty on Z+jets background yields from comparison of two MCs

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** for modest p_T

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

arXiv:2109.02653
Phys. Lett. B 843 (2023)
Eur. Phys. J. C 83, 336
PhysRevLett.130.161901

- 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	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	– [25]
		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 [3]	
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

Flavour Scheme

JHEP07(2012)022

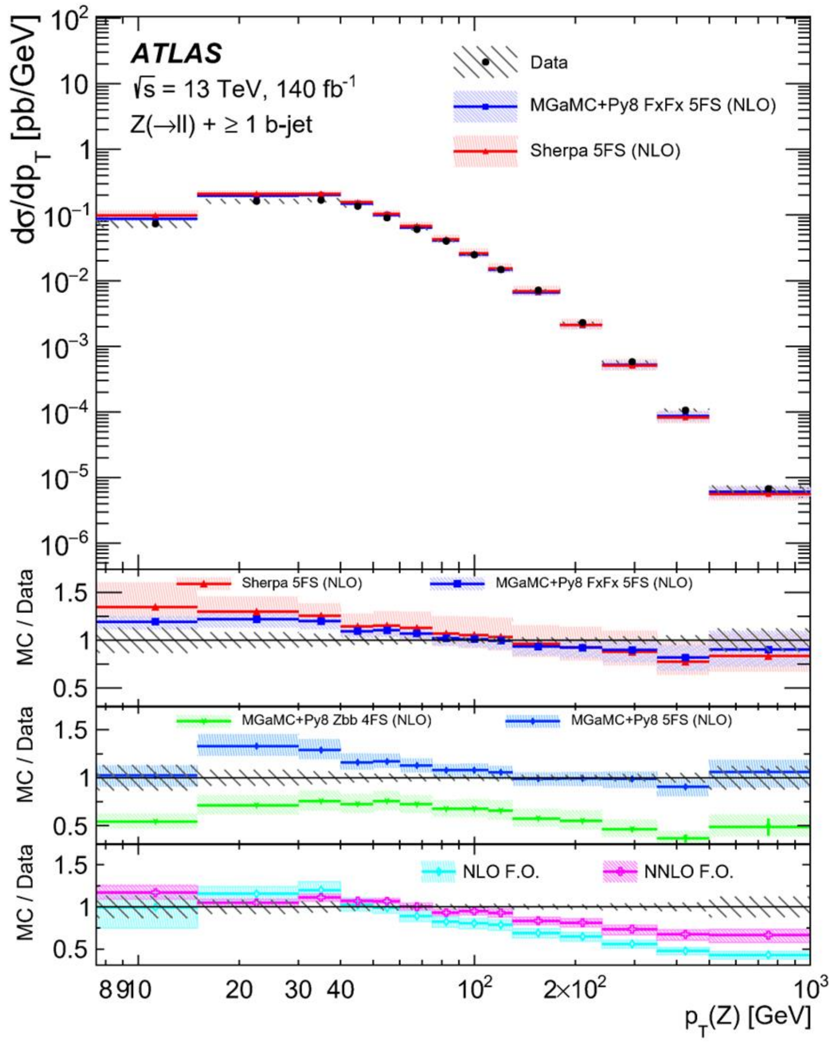
- V+HF is characterized by ***hard scale Q*** and mass of a ***heavy quark m***
  - pQCD calculations contain both powers of m^2/Q^2 and $\ln(Q^2/m_b^2)$ for g/q collinear splitting

- Variety assumptions on dealing with heavy quark masses in ME calculations

  - **3FNS:** massive c-quarks → c-quark appear only via gluon splitting
  - **4FS**: massive b-quarks → *b-quark* appear only via *gluon splitting*
    - power and logarithm corrections appear at fixed order explicitly
    - suitable for $\boldsymbol{Q^2 \sim m_b^2}$
  - **5FNS**: massless b-quarks → *b-quark* allowed via intrinsic *PDF*
    - $({m_b}^2/Q^2)^n$ pushed to higher orders
    - $\ln(Q^2/m_b^2)$ resummed to all orders into b-quark PDF
    - adequate at $\boldsymbol{Q^2 \gg m_b^2}$

  - *Collinear logarithms resummation* affects several key processes in LHC→ *Impact* increases in high *Bjorken x* and Q
    - amounts to adding different O(α_S^{n+1}) higher-order terms at a fixed order n in perturbation theory

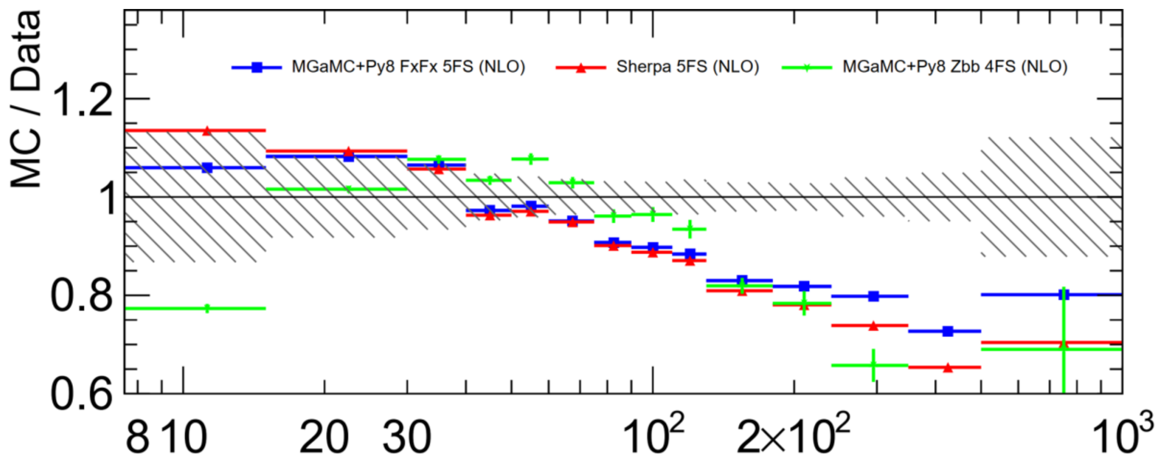
Differential Z+>= 1b-jet cross-section results



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

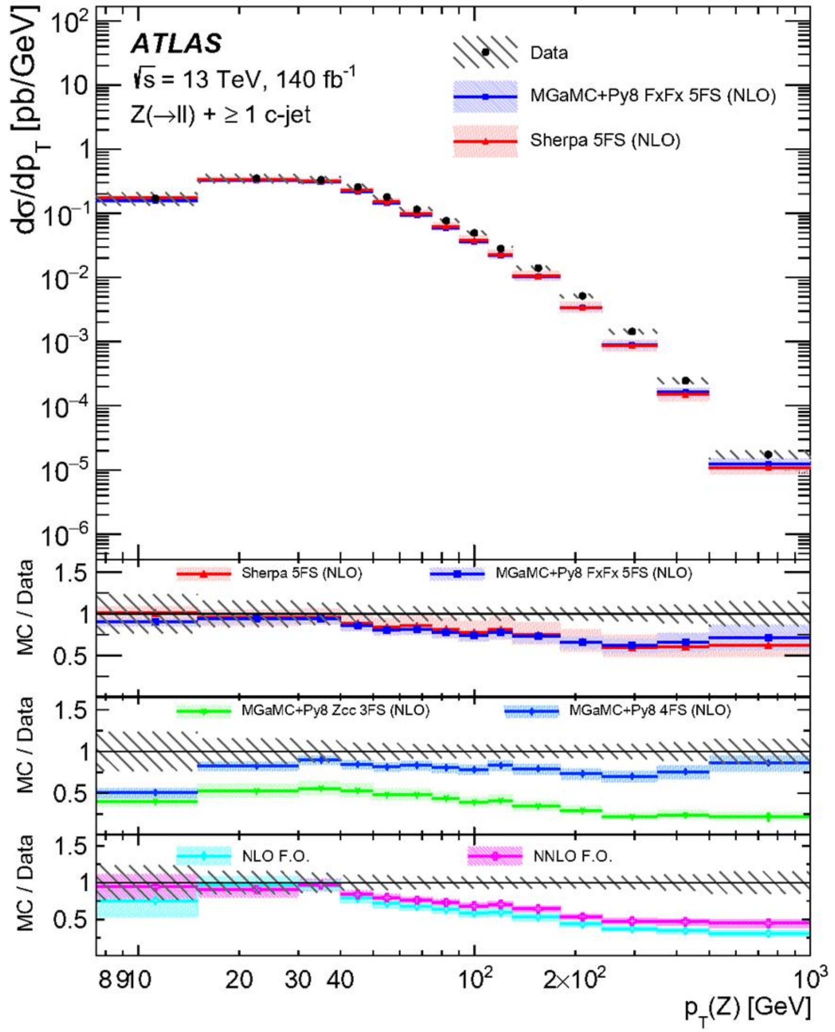
- no log term resummation in PDF evolution!



Shape Only

Fixed-order: Large divergences founded in the high p_T region for all predictions. Uncertainty related to the correction scale factor for different jet algorithms.

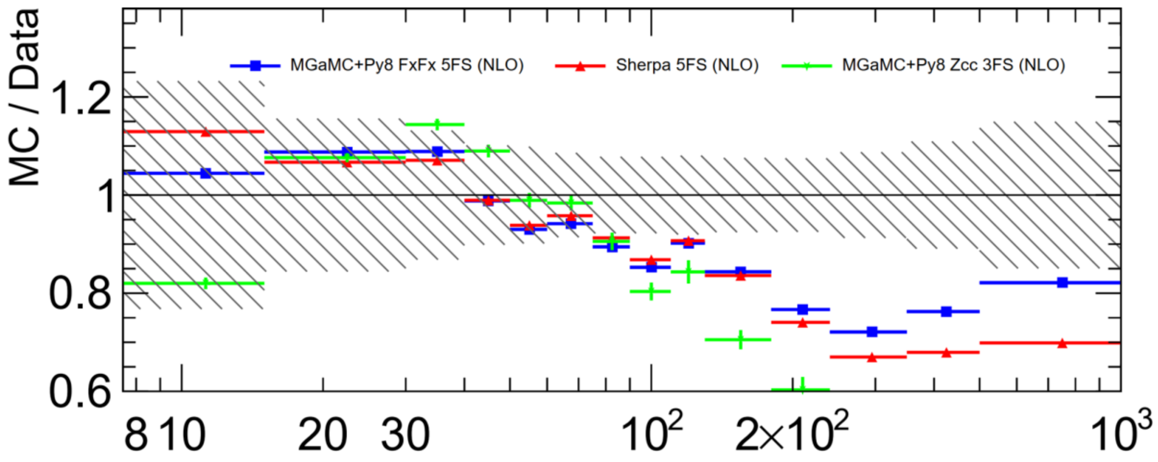
Differential Z+>= 1c-jet cross-section results



5FS: soft pT spectra well described by NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

3FS: large underestimation of normalization by a factor ~3

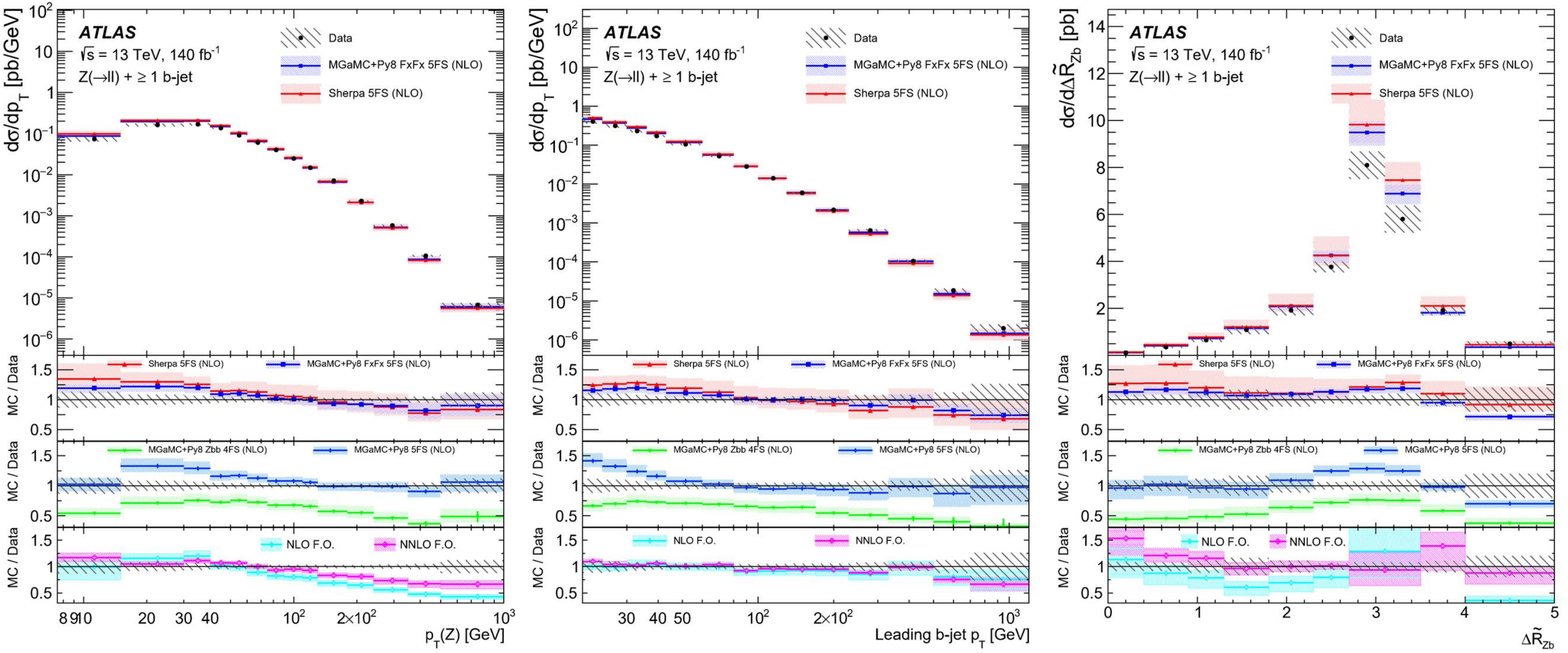
- **no log-term resummation in PDF evolution!**



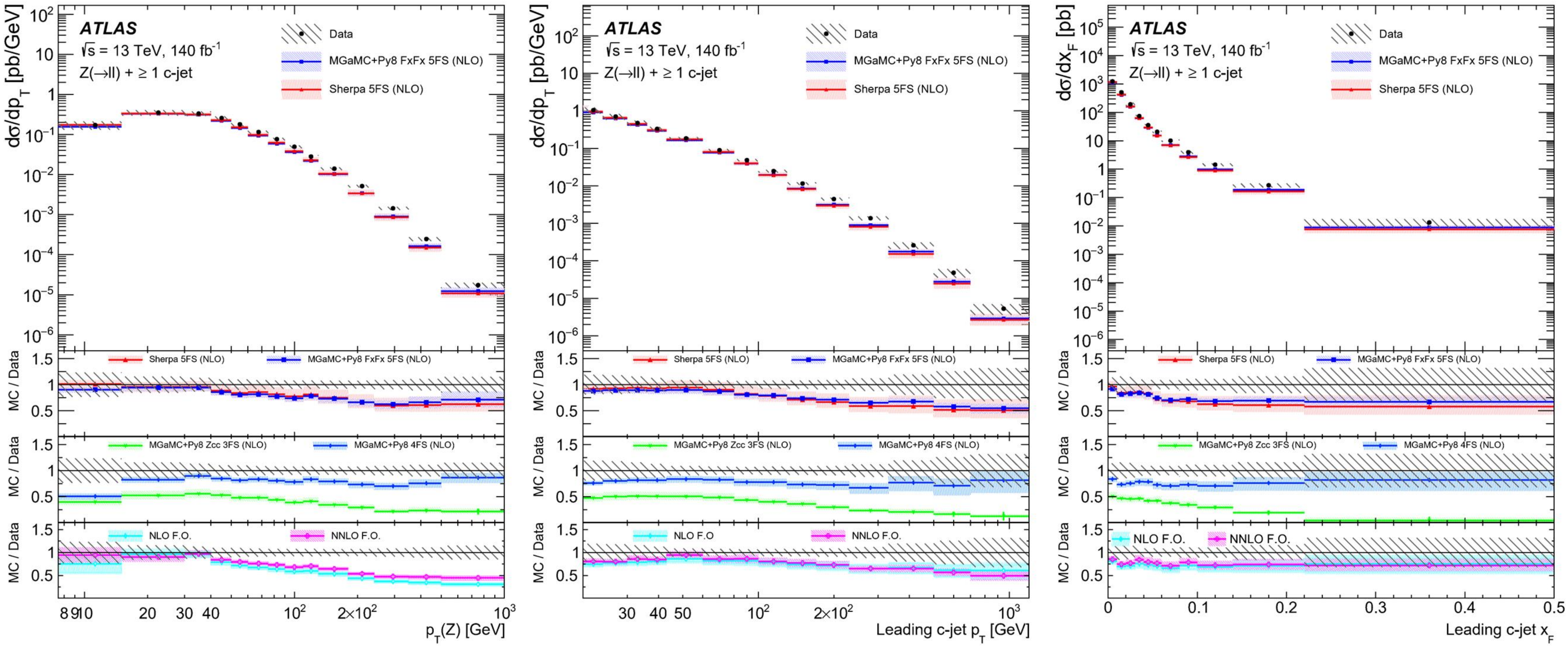
Shape Only

Fixed-order: at high p_T NNLO calculations in worst agreement than NLO ME+PS. NLO predicts softer p_T spectra, which is slightly improved with NNLO

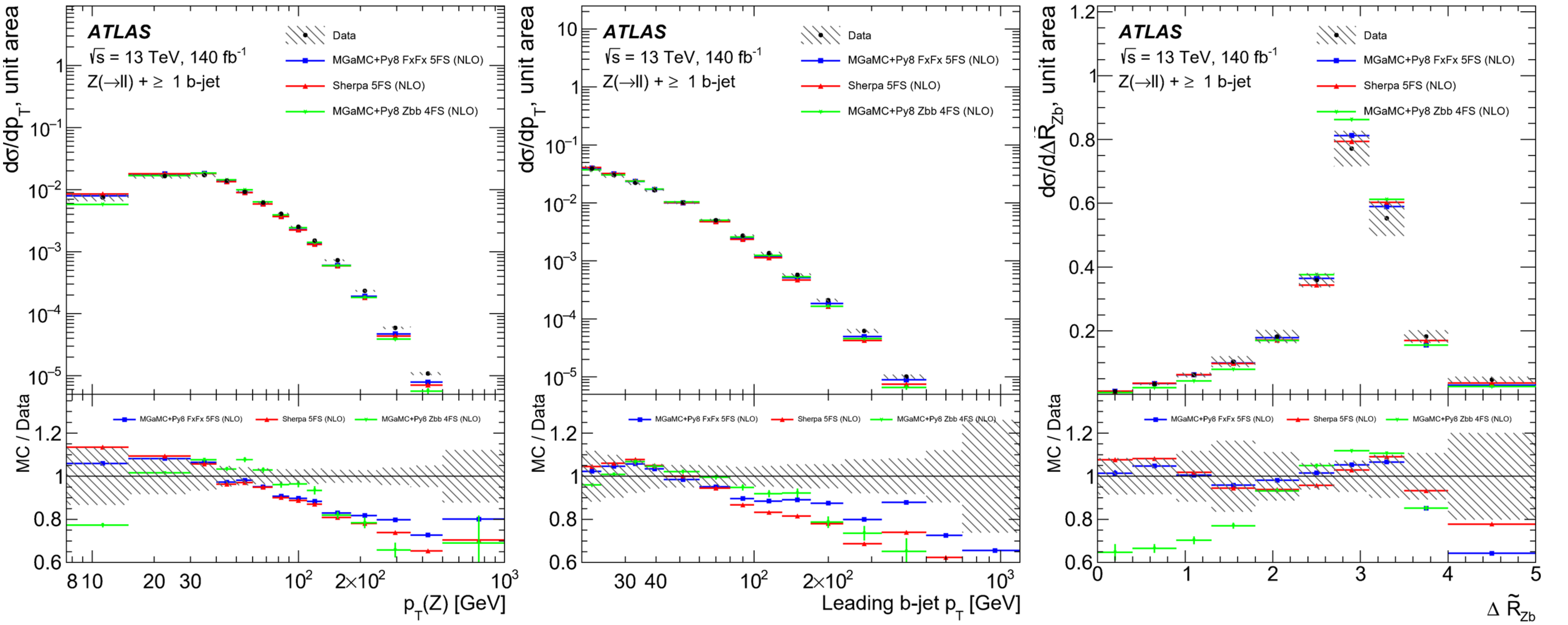
Differential Z+>= 1b-jet cross-section results



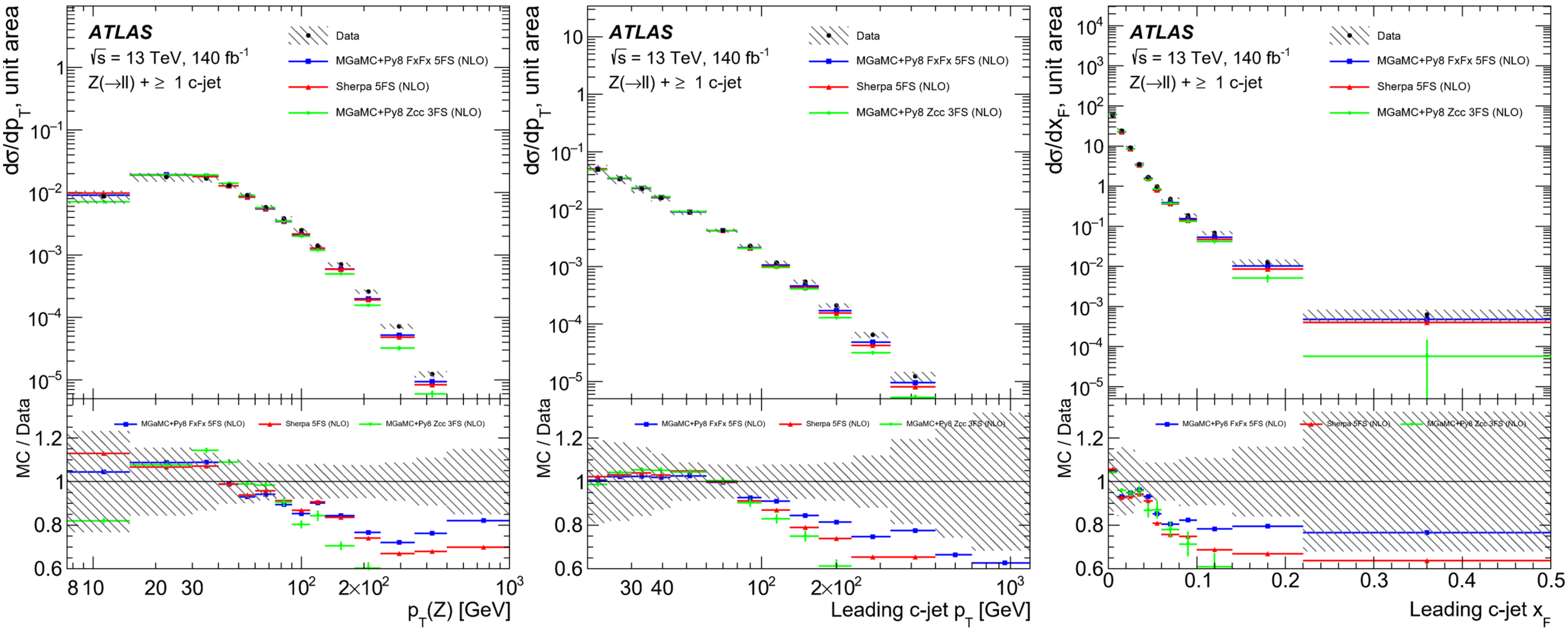
Differential Z+>= 1c-jet cross-section results



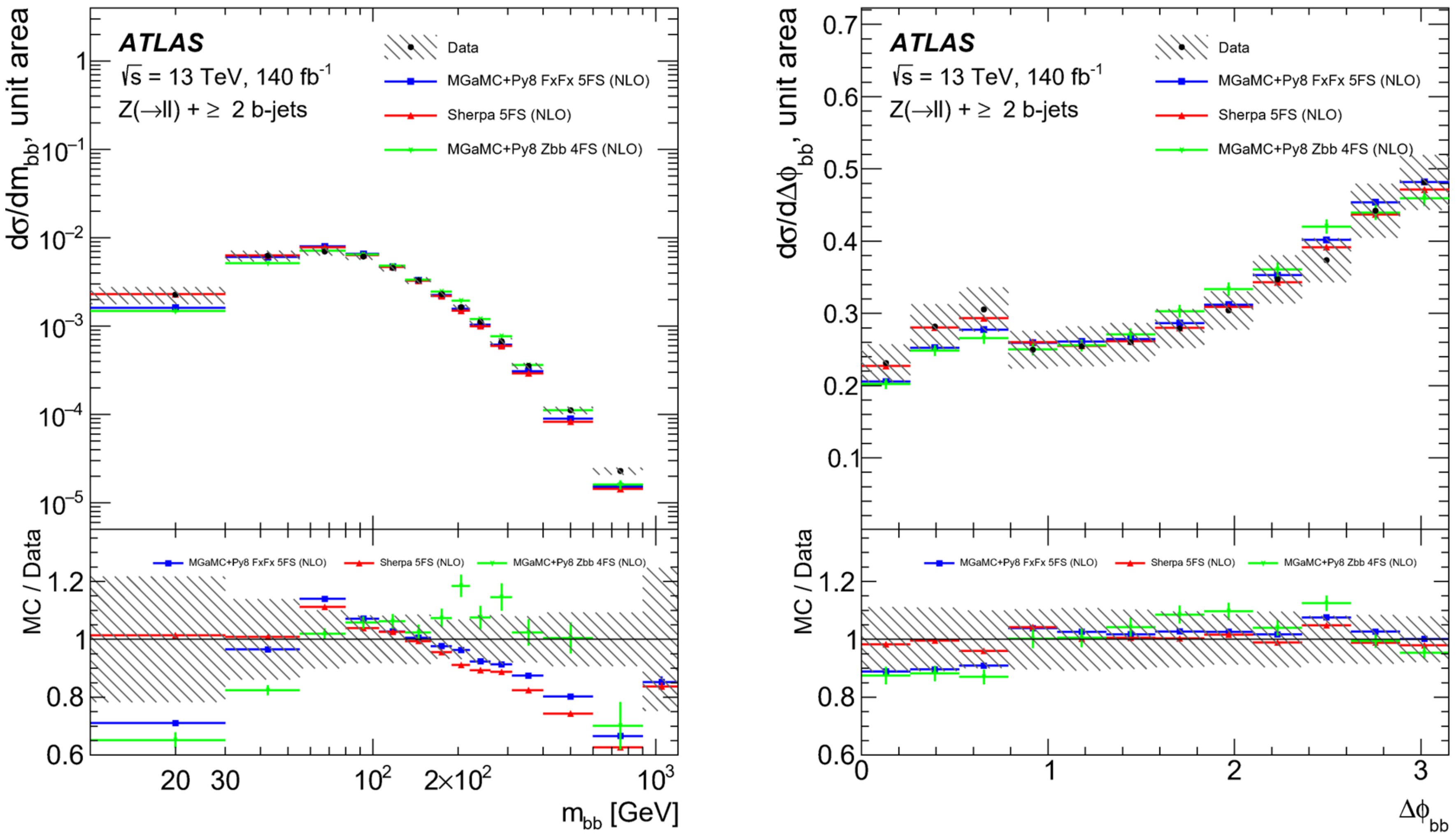
Differential Z+>= 1b-jet cross-section results (Norm.)



Differential Z+>= 1c-jet cross-section results (Norm.)



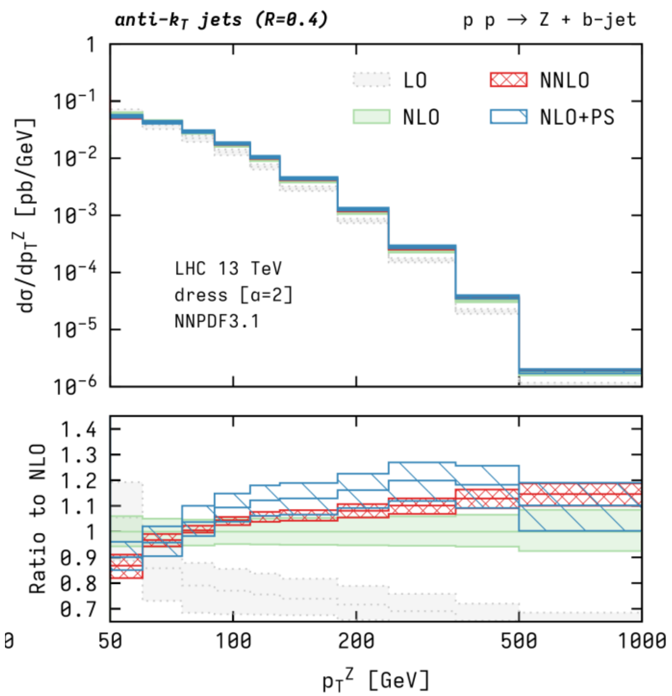
Differential Z+>= 2b-jet cross-section results (Norm.)



High-order QCD calculation

Eur. Phys. J. C 83, 336
SM@LHC 2024

- 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
  - **Fixed-order** theoretical predictions available up to **NNLO** in QCD
    - Effect of missing higher order terms not negligible
    - IRC-safe jet flavour algorithms ⇨ soft flavored pairs clustered without ambiguity



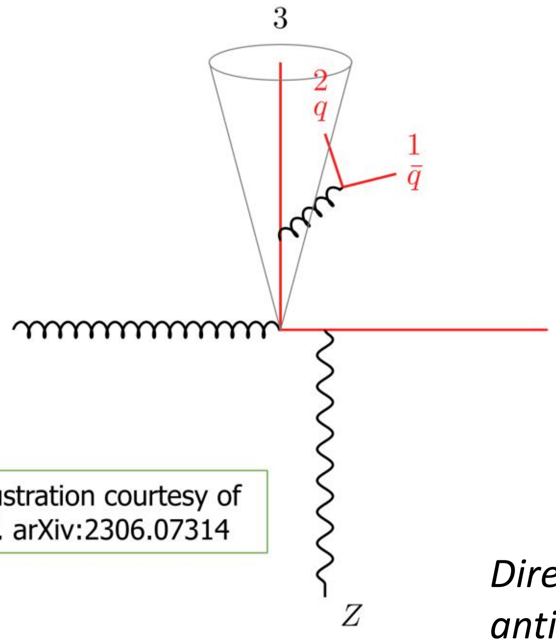


Illustration courtesy of ref. arXiv:2306.07314

- ***partonic ~ hadronic jet-flavour*** duality ambiguous starting from ***NNLO***

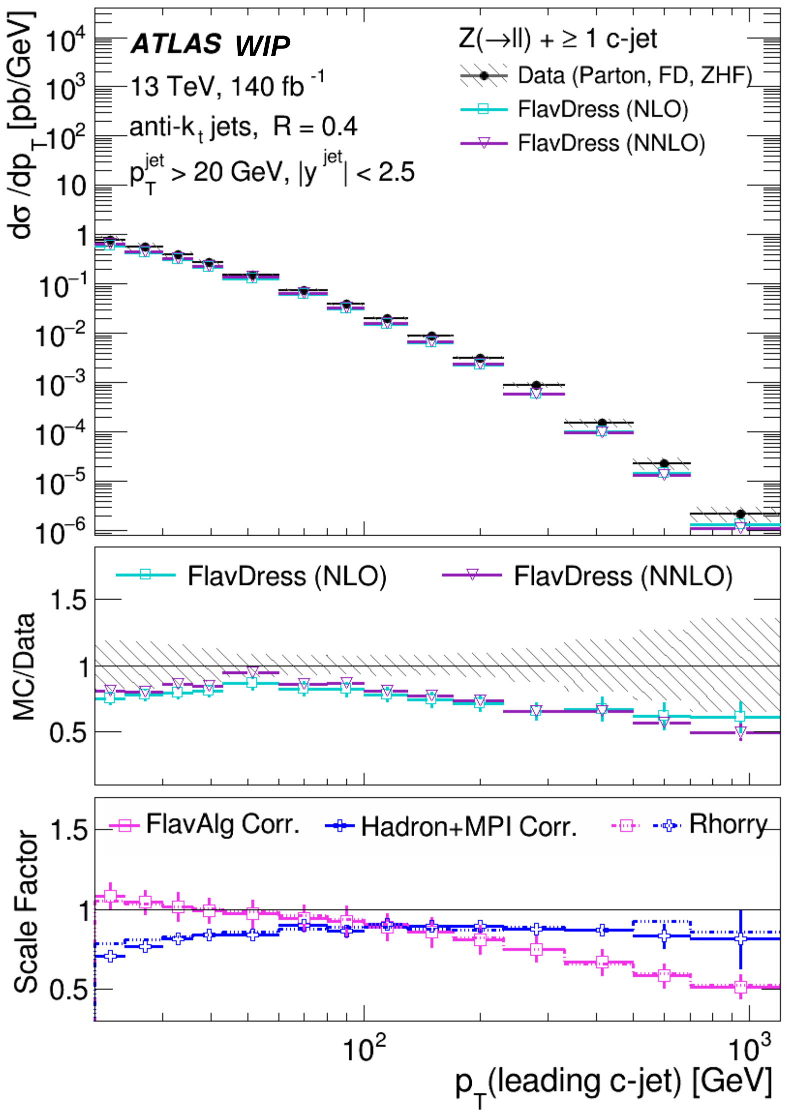
Consider a soft $g \to b\bar{b}$ emission

- If one of them is clustered in an unrelated hard jet, while another one forms its own jet

⇨ kinematic is unchanged but the flavor is (so called as IR unsafe)

Direct comparison of NNLO with data unfeasible:
anti-kt jet algorithm used at LHC is flavor-blind to cluster hadrons

Differential Z+>= 1c-jet cross-section results



Two scale factors used to correct data for a fair comparison with parton-level fixed-order predictions obtained with flavor-dressing algorithm (IRC-safe)

- **Jet flavour** algorithm correction ~ **50% (40%) in high pT region for Z+c (Z+b)**:
  - ratio of *FD-alg.* to *Exp-alg.* predictions

    (obtained with NLO+PS, hadron-level)
- **Hadronization and MPI** effects ~ **20% in low pT region**:
  - ratio of *parton-level* to *hadron-level* predictions

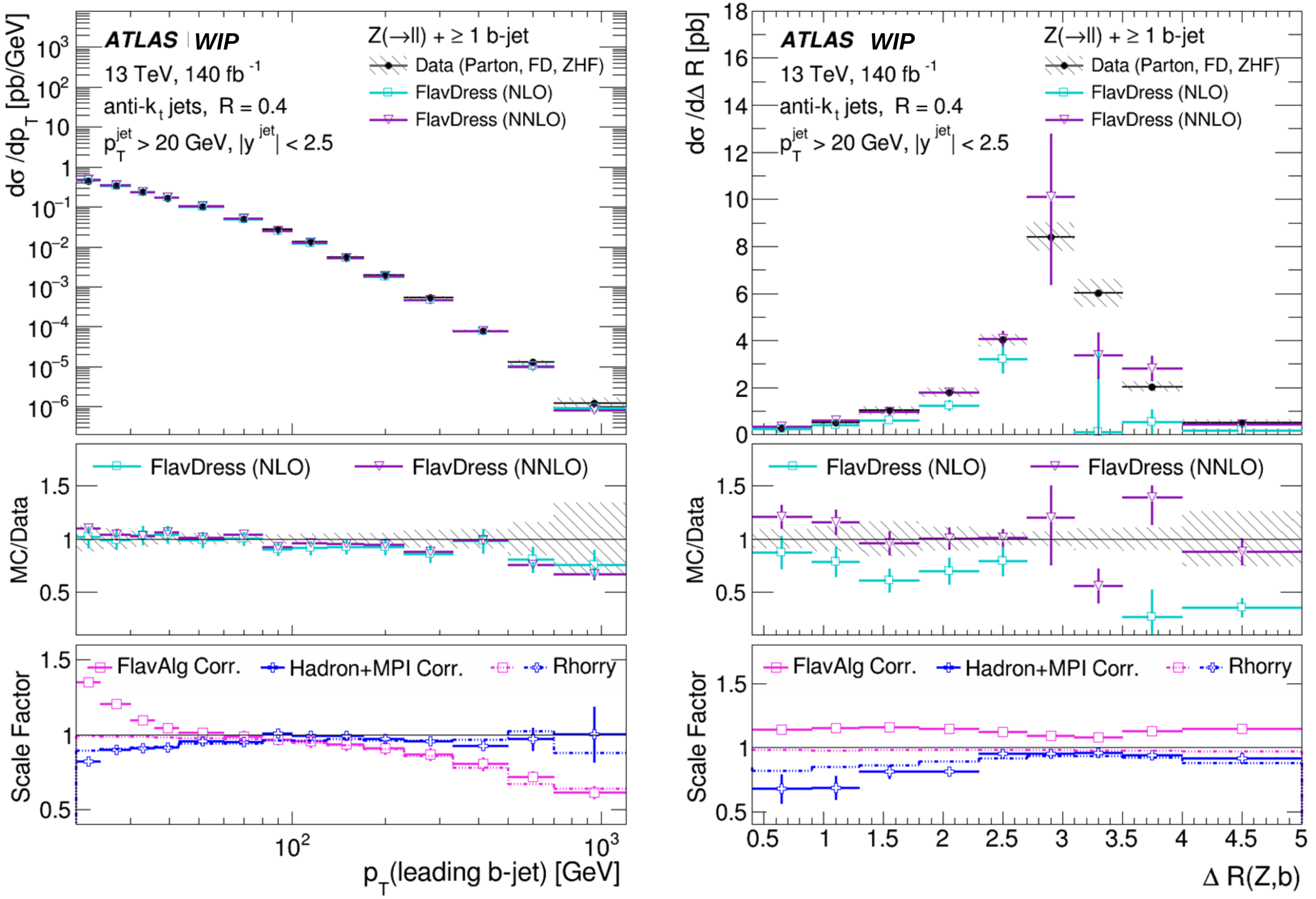
    (obtained with NLO+PS, FD algorithm)

SFs derived with ***MG+ Py8 FxFx (for FlavAlg Corr)***, ***Pythia (for Hadron+MPI Corr.)*** consistent with the one derived with ***MG+Py8 (for both)*** from Rhorry Gauld for Z+c process

Cons.:

- **Additional uncertainties** for the SFs should be been taken counted for the universal purpose
- **Not sure** if the SFs derived at **NLO+PS suitable for NNLO predictions**

Differential Z+>= 1b-jet cross-section results



SFs derived with ***MG+ Py8 FxFx (for FlavAlg Corr)***, ***Pythia (for Hadron+MPI Corr.)***

inconsistent with the one derived with ***MG+Py8 (for both)*** from Rhorry Gauld for **Z+b** process

<u>As it contains one additional correction</u>:

Jet clustering **all particles after b-hadron decay (ATLAS)**

-->

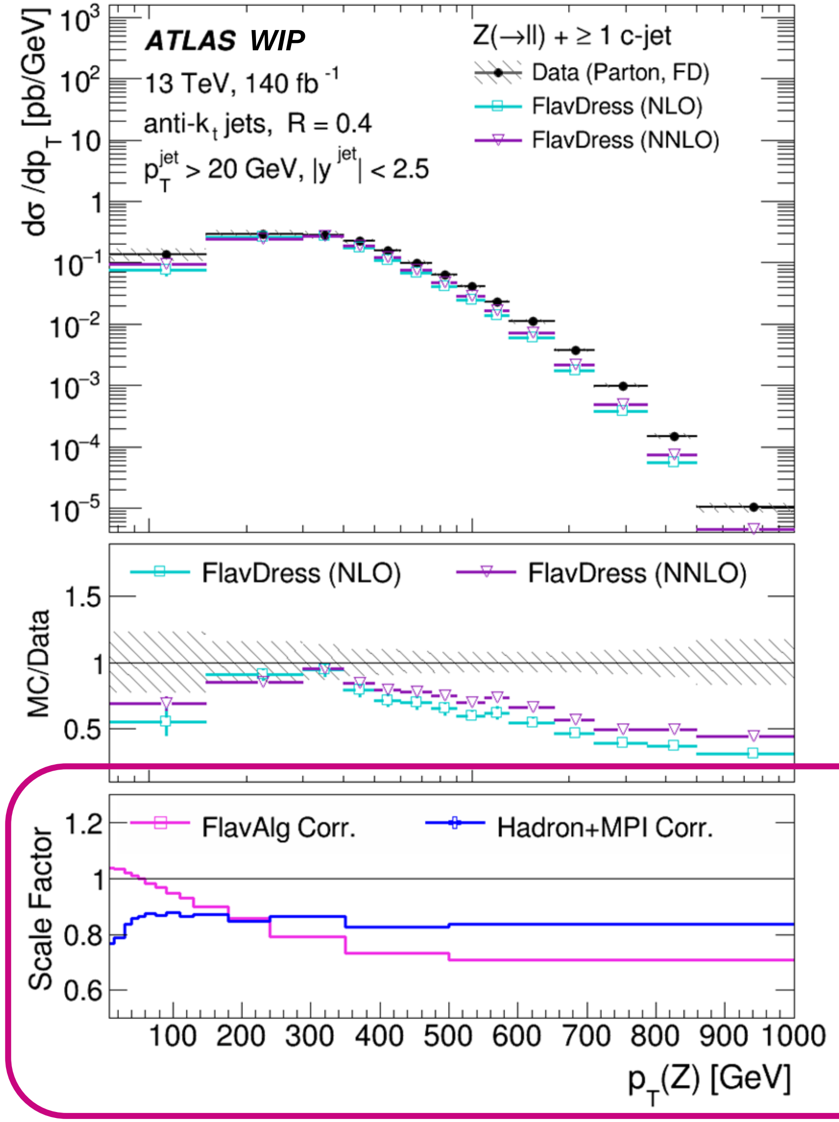
Jet clustering other particles **and stable b-hadrons (R.G.)**

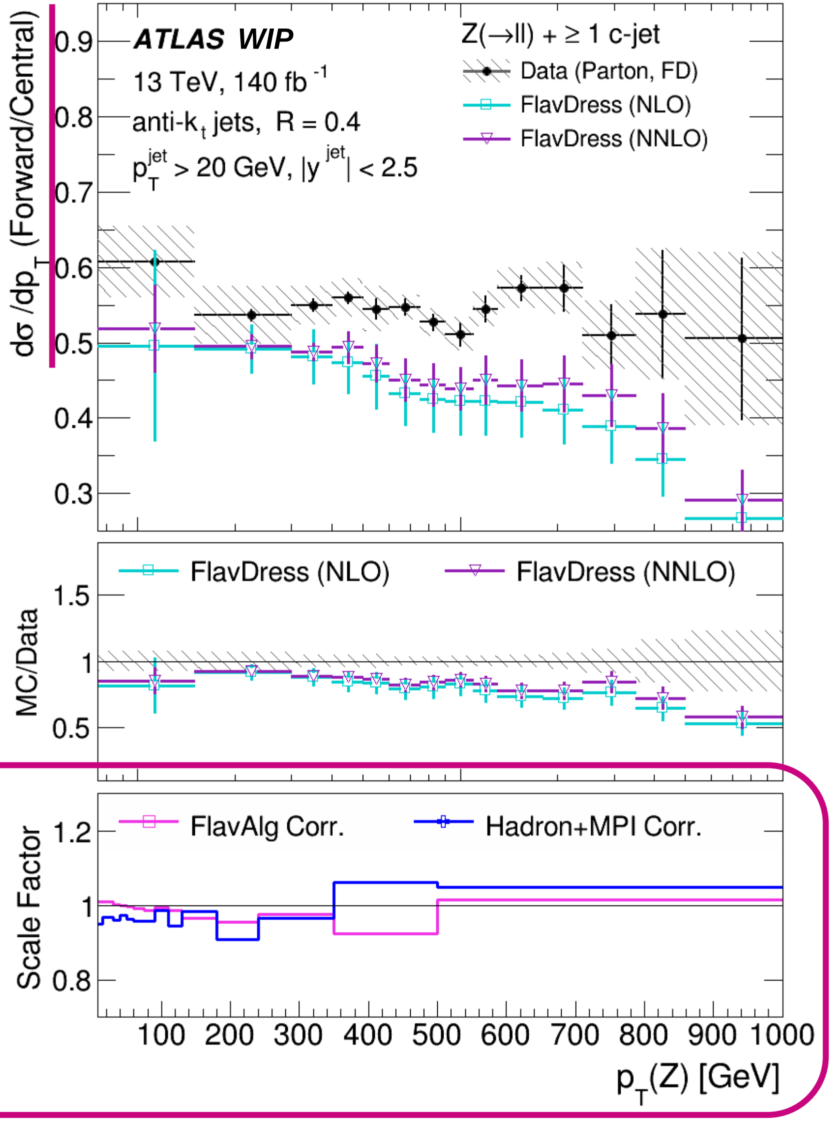
- ✓ Sizable effects for only Z+b results from b hadrons have more cascade decays than c hadrons

Differential Z+>= 1c-jet cross-section results

PhysRevLett.130.161901

Central: $|Y_Z| < 1.2$; Forward: $|Y_Z| > 1.2$





Interesting point:

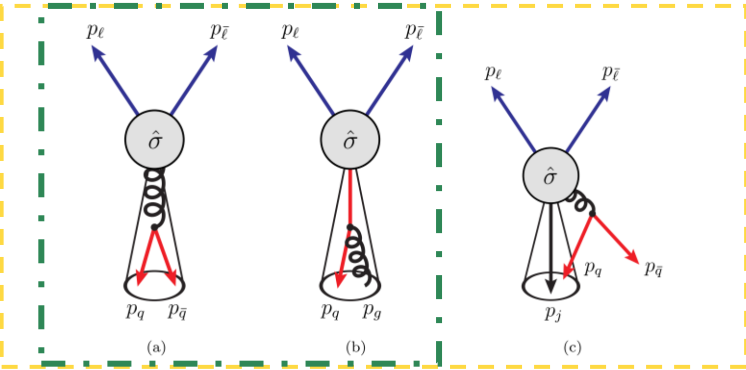
the IRC-unsafe components relevant to the high p_T rather η

HF-quark mass dependent..

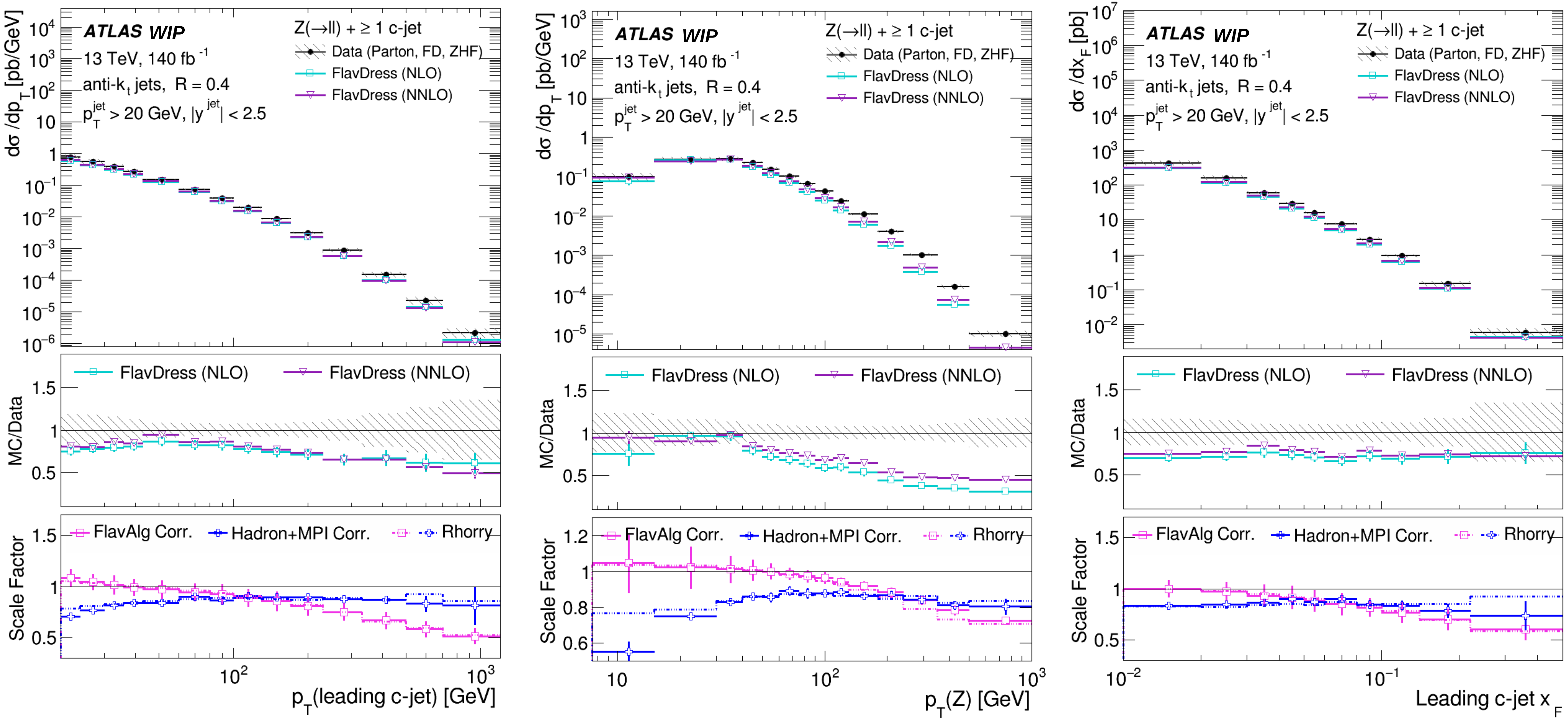
High-Q dependent..

We can image the dynamical origin of IRC-unsafe components are mostly those collinear splittings with the type $\ln(Q^2/m_q^2)$

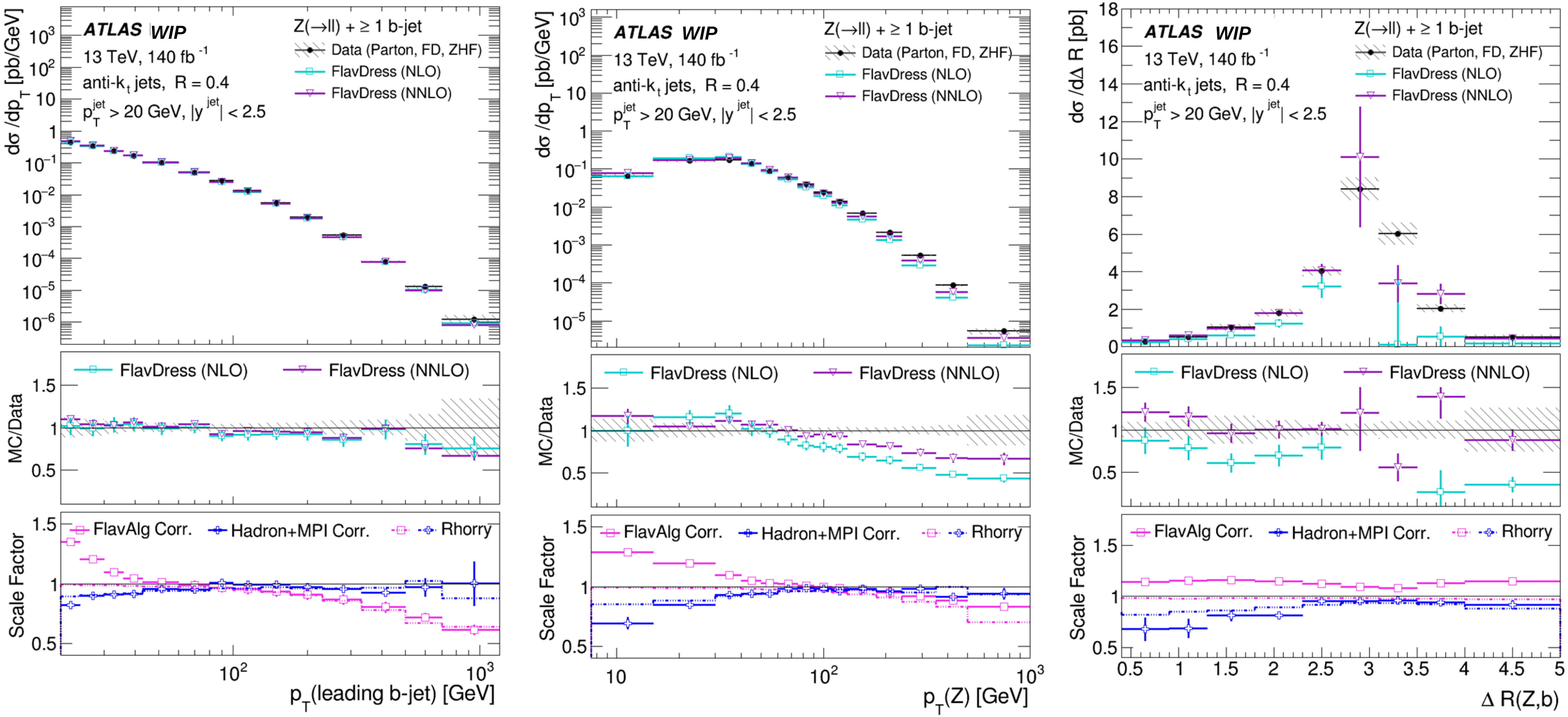
IRC-unsafe components



Differential Z+>= 1c-jet cross-section results



Differential Z+>= 1b-jet cross-section results



NLO+PS (5FNS) + NLO EW Correction

- **Data:** full Run 2, 140 fb^{-1}
- **MC samples**
  - **MGaMC@NLO with FxFx merging** - up to 3 partons in NLO ME!
  - Sherpa 2.2.11 - up to 2 partons in NLO ME
  - Besides the QCD-only nominal, Sherpa provides on-the-fly weights including approximate NLO electroweak corrections using up to three different approaches

⇨ additive, multiplicative, exponentiated

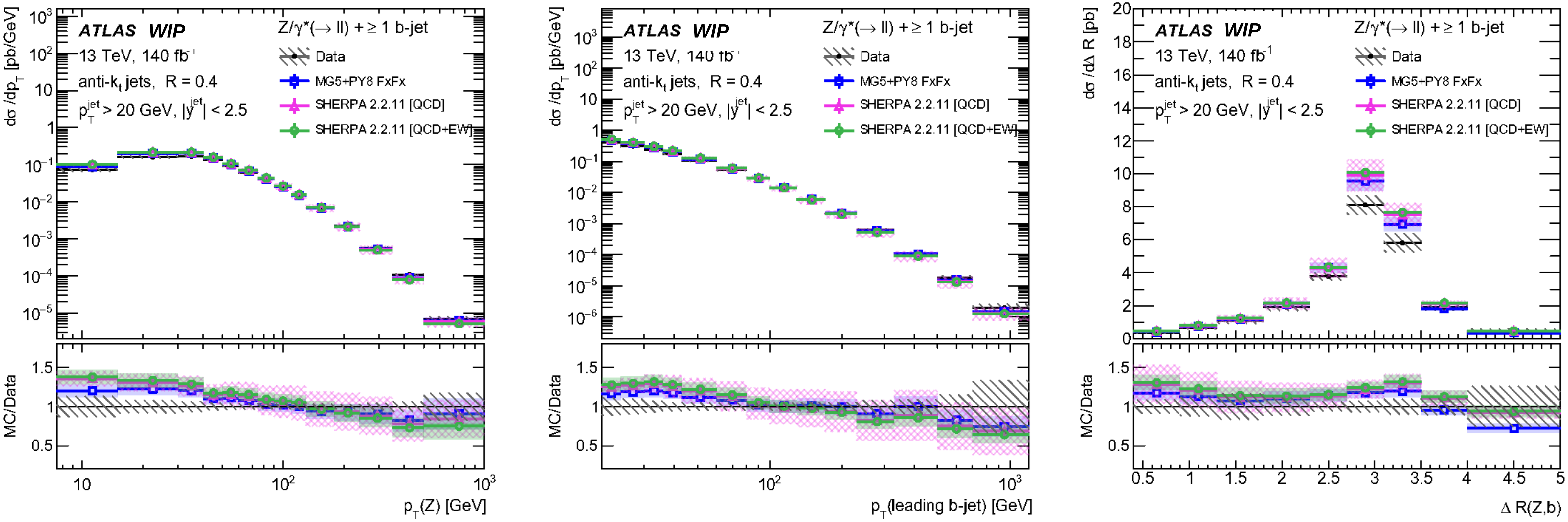
Approach that yields **the smallest overall correction with respect to the QCD-only curve** as the nominal prediction

Assign the difference to the curve with the **largest correction from other approaches as a (symmetrised) uncertainty**

*backup

NLO+PS (5FNS) + NLO EW Correction: Z+≥1b

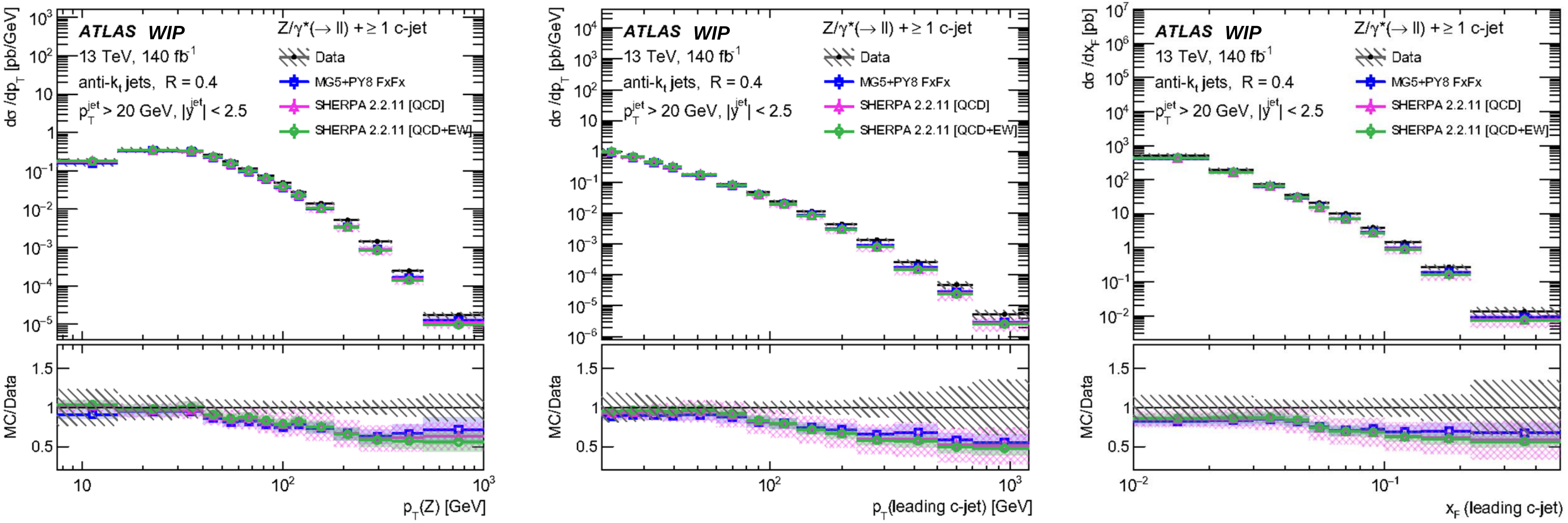
- **Good agreement** for both of MG FxFx and Sherpa 2.2.11, with the former giving better modelling



- **NLO EW correction** is negligible, with difference from QCD-only only visible in the high p_T^Z region (~ 10%)
  - With the uncertainty taken from different EW virtual correction approaches at 10% ~ 20% at the most

NLO+PS (5FNS) + NLO EW Correction: Z+≥1c

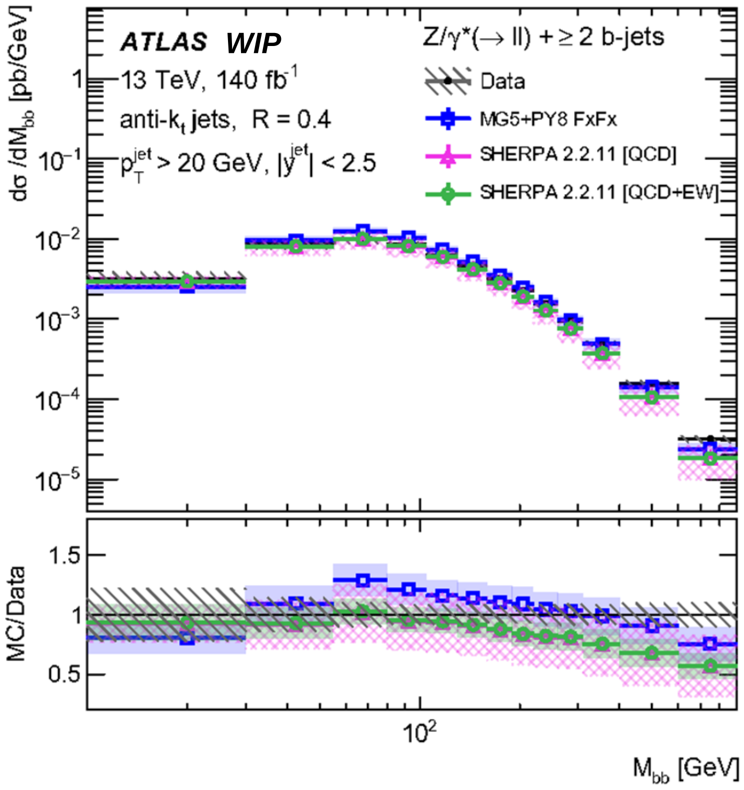
- **Mis-modelling visible in the high p_T^Z tails**, with softer spectrum for lead c-jet pT and xF than data

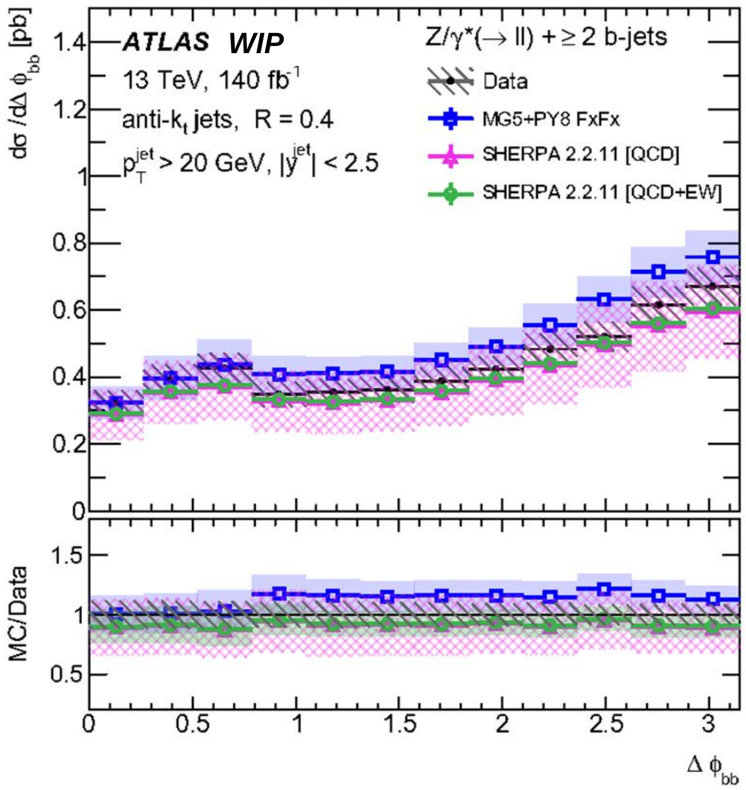


- **NLO EW correction** is negligible, with difference from QCD-only only visible in the high p_T^Z region (~ 10%)
  - With the uncertainty taken from different EW virtual correction approaches at 10% ~ 20% at the most

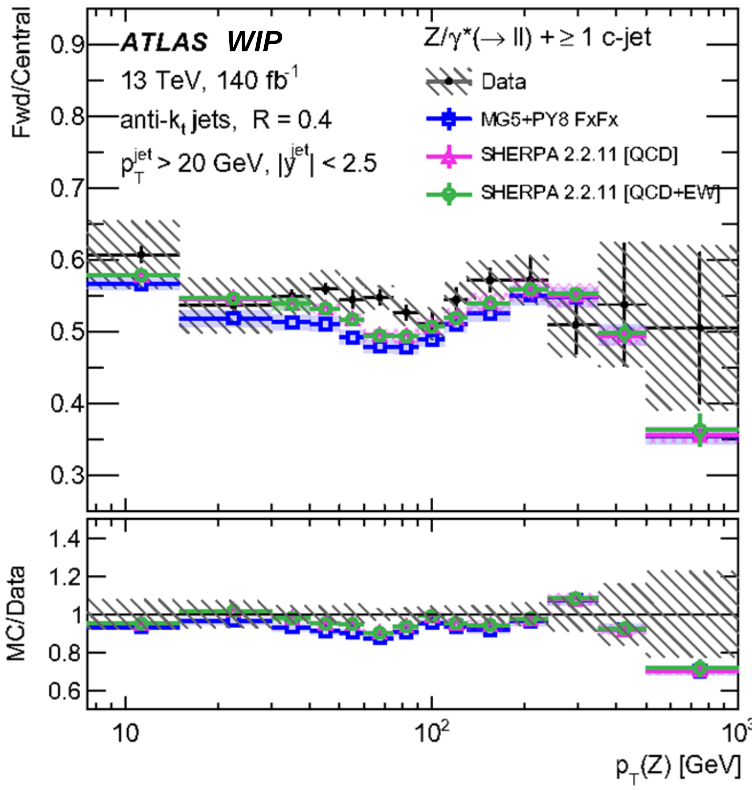
NLO+PS (5FNS) + NLO EW Correction: Z+≥2b

- **Perfect modelling for the shape of $\Delta\phi_{bb}$ and overall agreement for m_{bb}**
  - Sherpa gives much larger theoretical uncertainty as the case in Z+1b





Ratio observable for Z+c



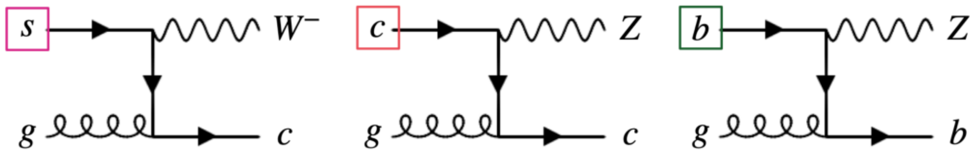
- **QCD scale uncertainty (for missing higher order effects) reduced largely for p_T^Z (fw | cen)**

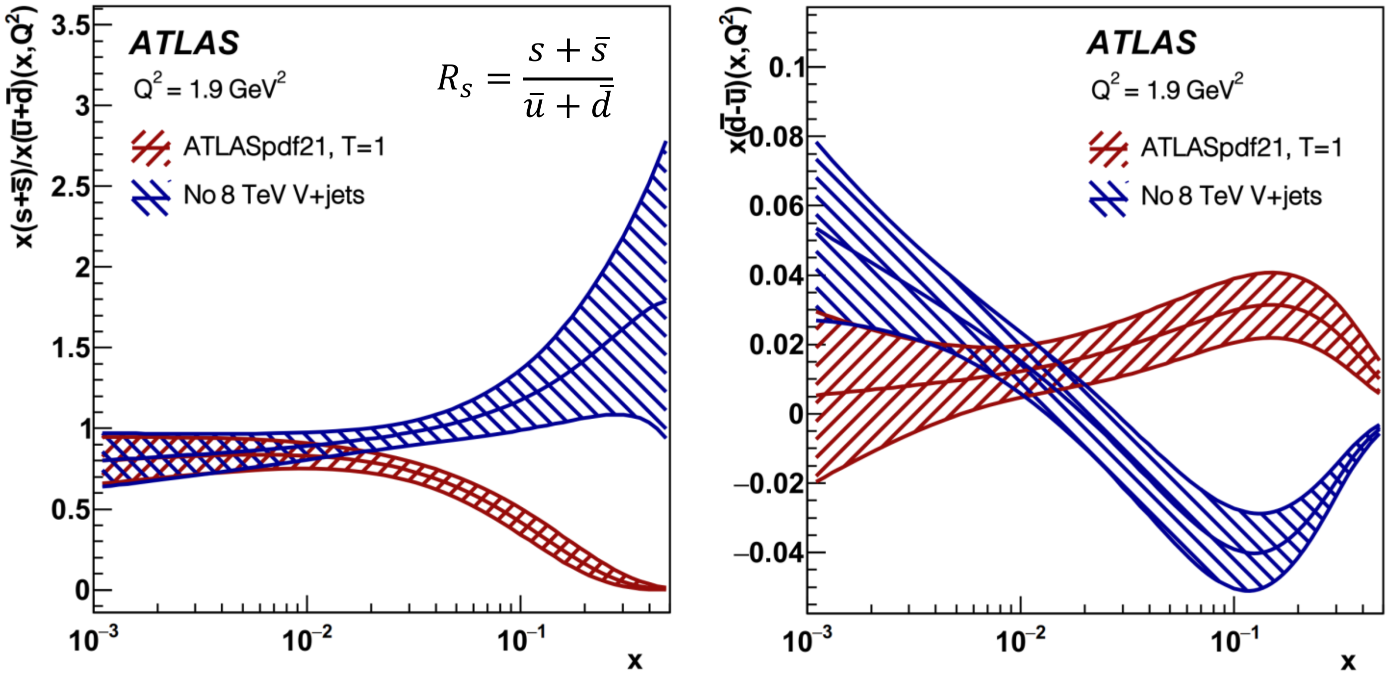
Proton PDFs

Eur. Phys. J. C (2022) 82

- **V + HF** expected to effect at medium and high Bjorken x and momentum transfer Q^2

- Unique access to ***s-, c-, b****-quark* and ***gluon*** PDFs in proton
- Allow to determinate the ***PDF shape*** and ***constrain uncertainties*** further





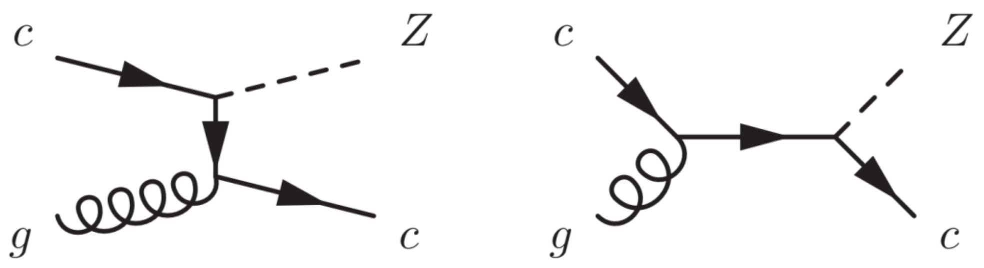
- Vjets play a key role in the R_s and $x(\bar{d}-\bar{u})$ PDF determinations in the high x regions - **ATLASpdf21**

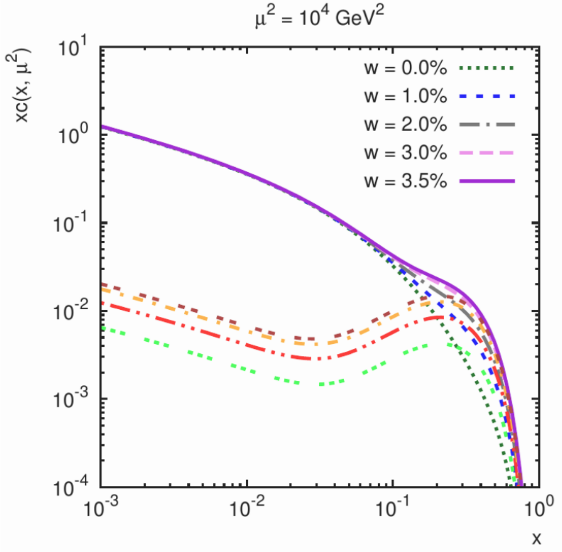
Intrinsic Charm

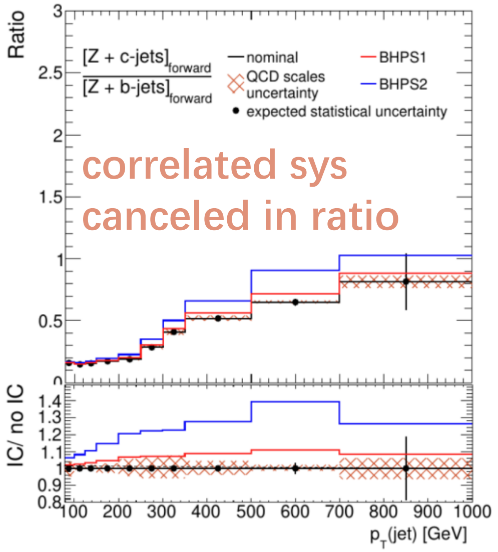
Physical Review Letters 128 (2022)
Nature 608, 483–487 (2022)

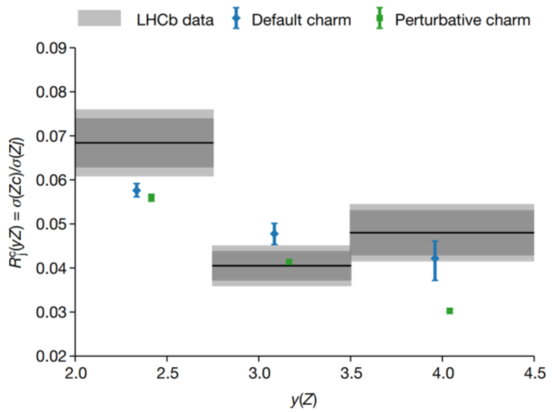
- ***Intrinsic-Charm (IC)*** component in the proton ~ debated for 40 years (upper limits on <x_c> differ from 0.5% to 2%)
  - c-quarks pairs are considered as part of the proton wave function at rest - valence-like structure

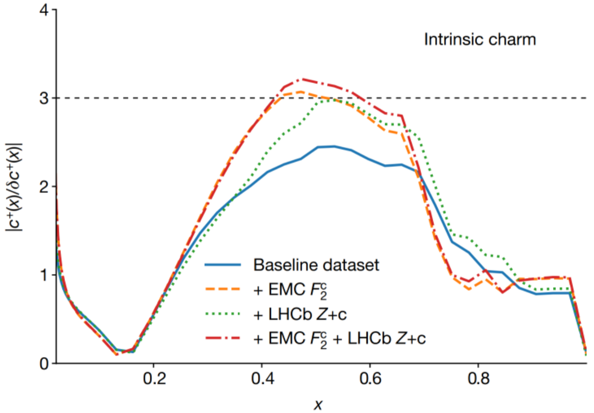
$\Psi_p = |uudc\bar{c}>$, IC not via $g \to c\bar{c}$





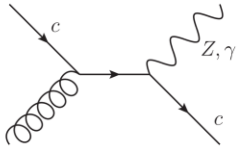






- IC enhanced in x_c > 0.1 accessible via **V+HF in LHC**
- **LHCb** reports an excess in high η region with Z + c
- **NNPDF** gives an evidence on the existence of IC
  - <x_c> = (0.62$\pm$ 0.28) % with peaking at ~ 0.4

Intrinsic Charm

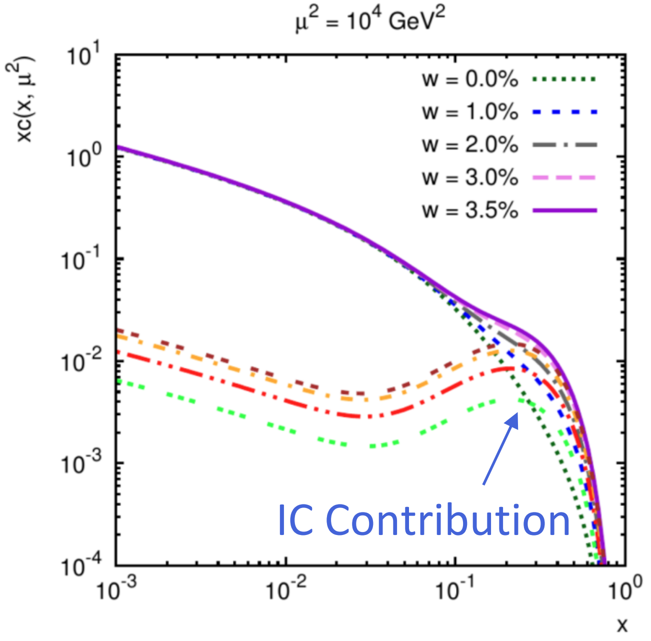


[1] PLB 93 (1980) 451
[2] PRD 92 (2015) 034014

- Idea of intrinsic charm (IC)[1] contribution to proton PDF debated for ~40 years
  - Initially introduced to describe enhanced charmed hadron production at ISR
  - Still no reliable experimental confirmation/exclusion
- Valence-like c quarks have large x ≥ 0.1, unlike perturbative charm with smaller x
  - Understanding of heavy quark PDF is very important for Higgs and BSM background modelling
  - Studying charm associated production with Z or γ more sensitive than inclusive charm production[2]
    - IC sensitive in $x_c > 0.1$, where $x_c \geq x_F^V = \frac{2p_T^V}{\sqrt{s}} \sinh(\eta_V)$
    - Selection criteria - hard c-jet and Z in forward region
- CT14 and NNPDF
  - Provide PDF sets with inclusion of IC in the fits according to BHPS model
  - PDF reweighting is used to model the IC effect with Z+jets NLO sample

	$w(\vert uudc\bar{c}\rangle)$	$\langle x\rangle_{\text{IC}}$
BHPS1	1.1%	0.6%
BHPS2	3.5%	2.1%

$$w(x_1, x_2, Q) = \frac{f_i^{\text{new}}(x_1, Q^2) f_j^{\text{new}}(x_2, Q^2)}{f_i^{\text{old}}(x_1, Q^2) f_j^{\text{old}}(x_2, Q^2)}$$

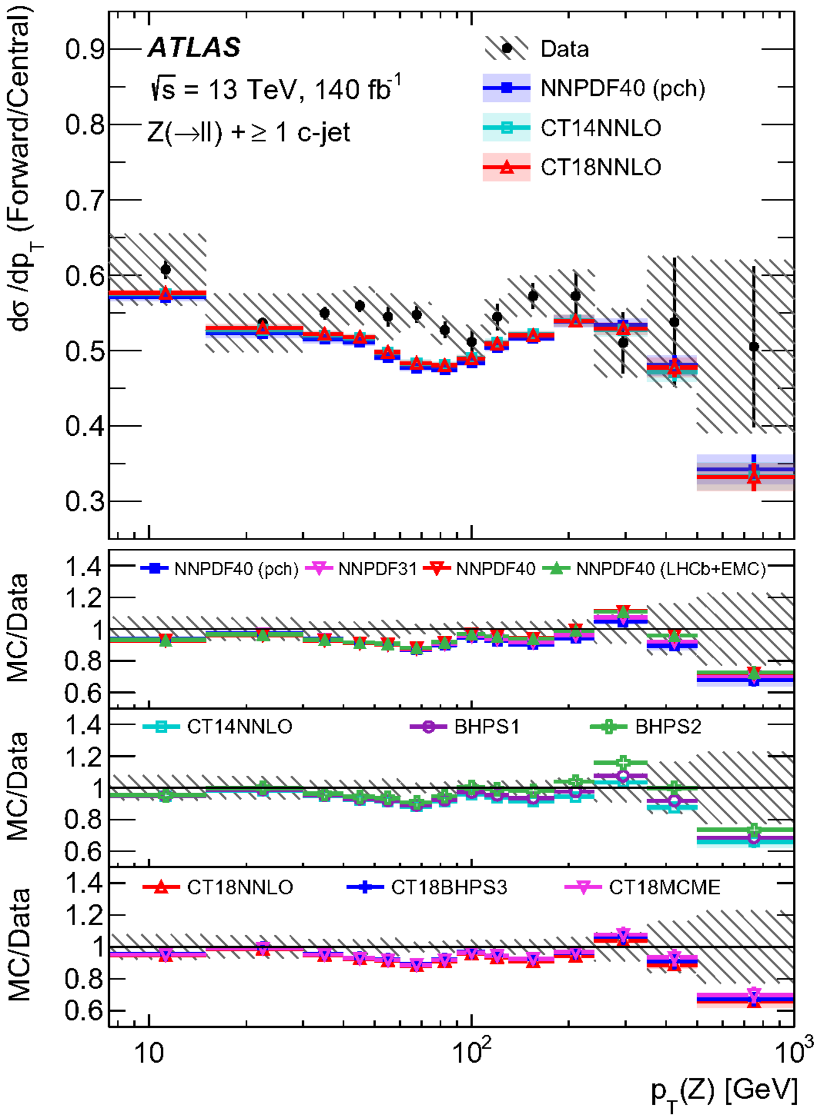


CT18FC PDF set

- An updated CTEQ paper on IC PDFs: PLB 843 (2023) 137975
  - All PDF sets available at web page, also included in LHAPDF
- Baseline no-IC PDF to be used: **CT18NNLO** (14000)
  - Uncertainties: 58 eigenvector variations
- Four variants including IC:
  1. CT18 BHPS3 (14087) – similar to earlier BHPS variants, different amount of IC (?)
  2. CT18 MBM-C (14090) – *meson-baryon model (confining)*, asymmetric $c\bar{c}$ contributions
  3. CT18 MBM-E (14093) – *meson-baryon model (effective-mass)*, similar to 2, but more constrained
  4. CT18X BHPS3 (14096) – same as 1, but using **CT18XNNLO** fit as a baseline (with DIS data fitted using x-dependent μ_F to model small-x saturation)
- For each of them – two variations with $\Delta\chi^2 = 10, 30$
  - $\Delta\chi^2 = 30$ – standard CT 68% CL tolerance
  - $\Delta\chi^2 = 10$ – more restrictive, compatible with MSHT20 tolerance
- Options suggested by Tim Hobbs:
  - Minimal: use *CT18 BHPS3* and *CT18 MBM-C* in comparison to nominal *CT18NNLO*, evaluate uncertainties with $\Delta\chi^2 = 30$ variations
  - Ideal: test all options (note that for *CT18X BHPS3* need a different nominal *CT18XNNLO*)

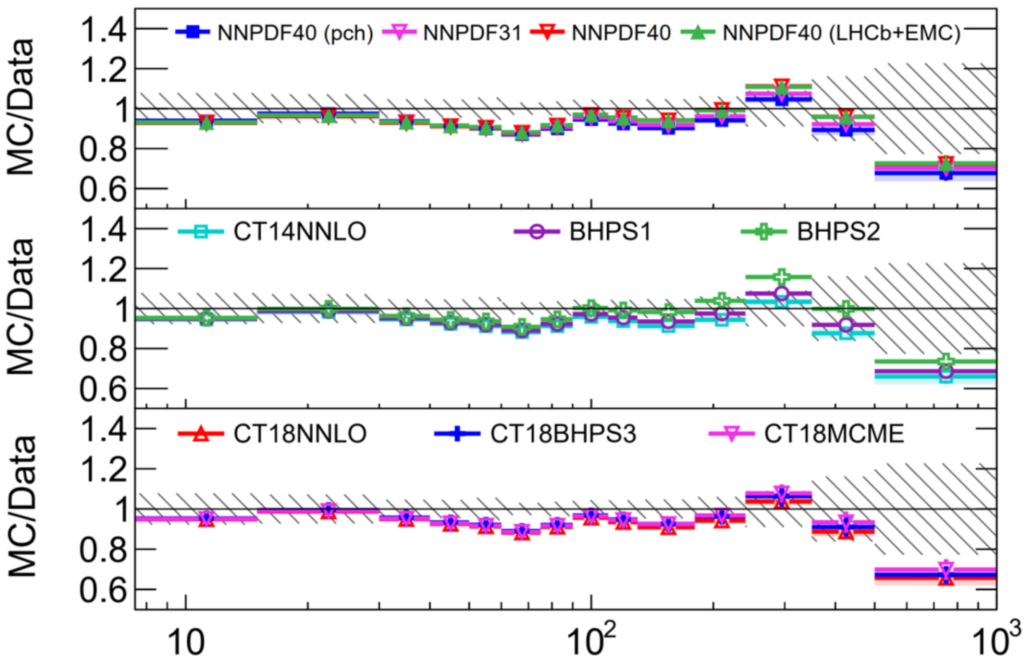
Differential Z+>= 1c-jet cross-section results (ICs)

Forward/Central ratio of Z pT



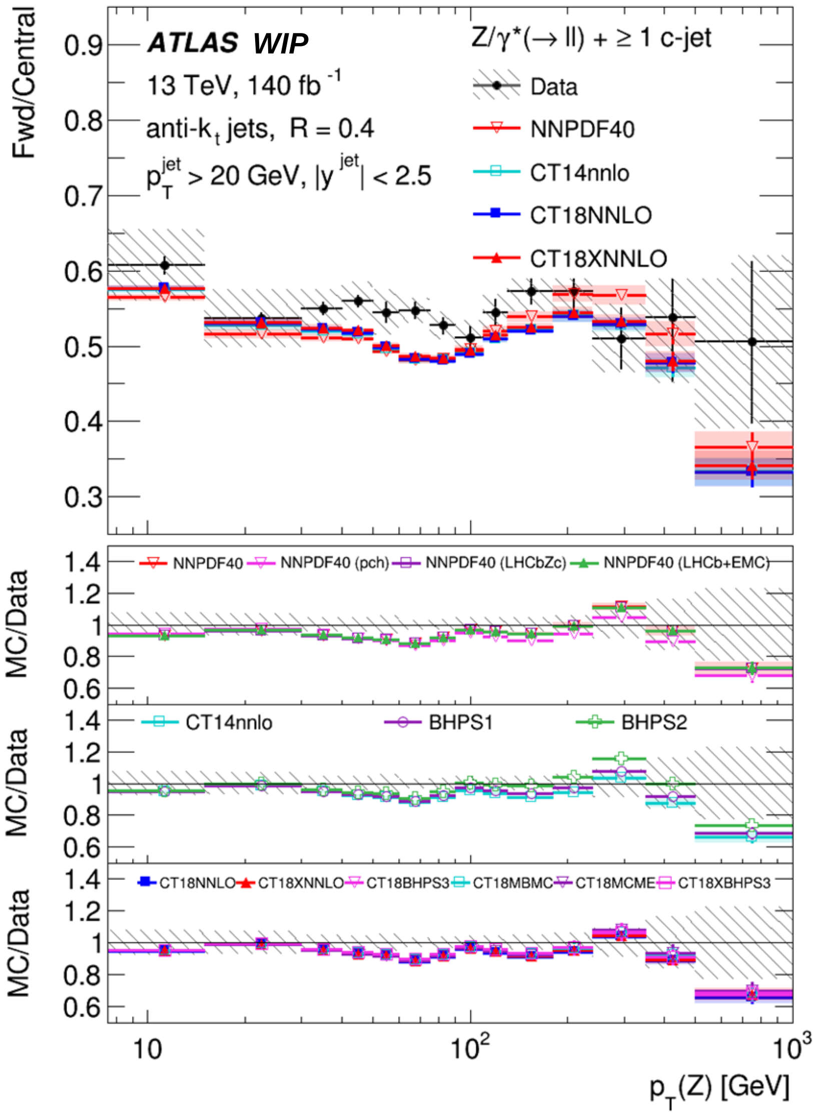
MGAMC+PY8 with **several PDF sets** testing **different IC-models**

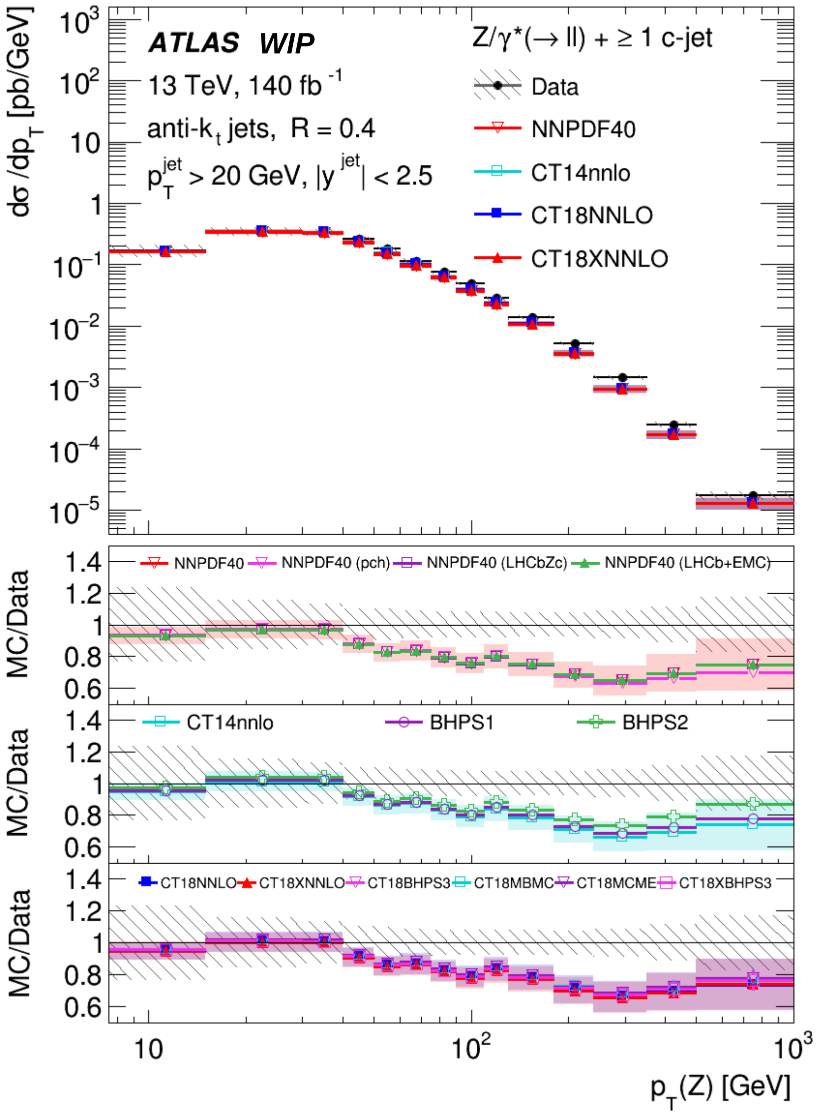
- Large reduction of systematics in the ratio (~8%)
- **Similar trend by all IC models** from NNPDF, CT14 and CT18
  - PDF sets with only perturbative charm (no IC): NNPDF40 (pch), CT14NNLO and CT18NNLO



Differential Z+>= 1c-jet cross-section results (ICs)

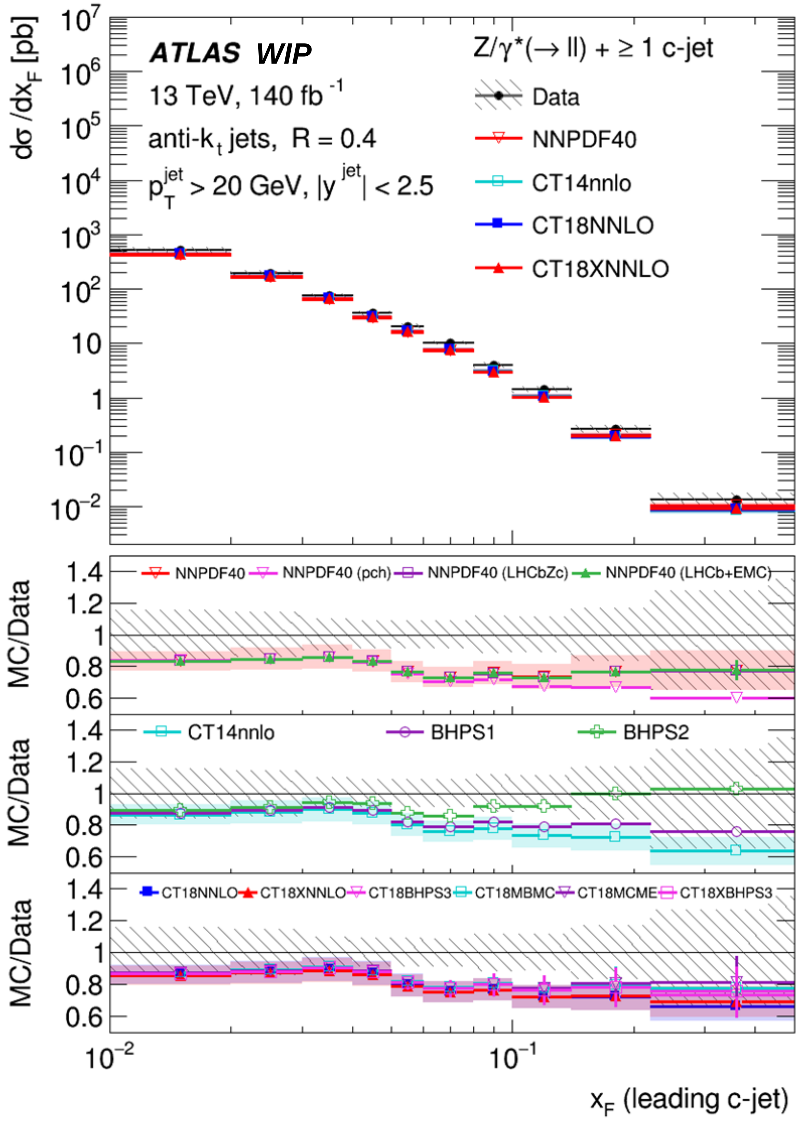
Forward/Central ratio of Z pT

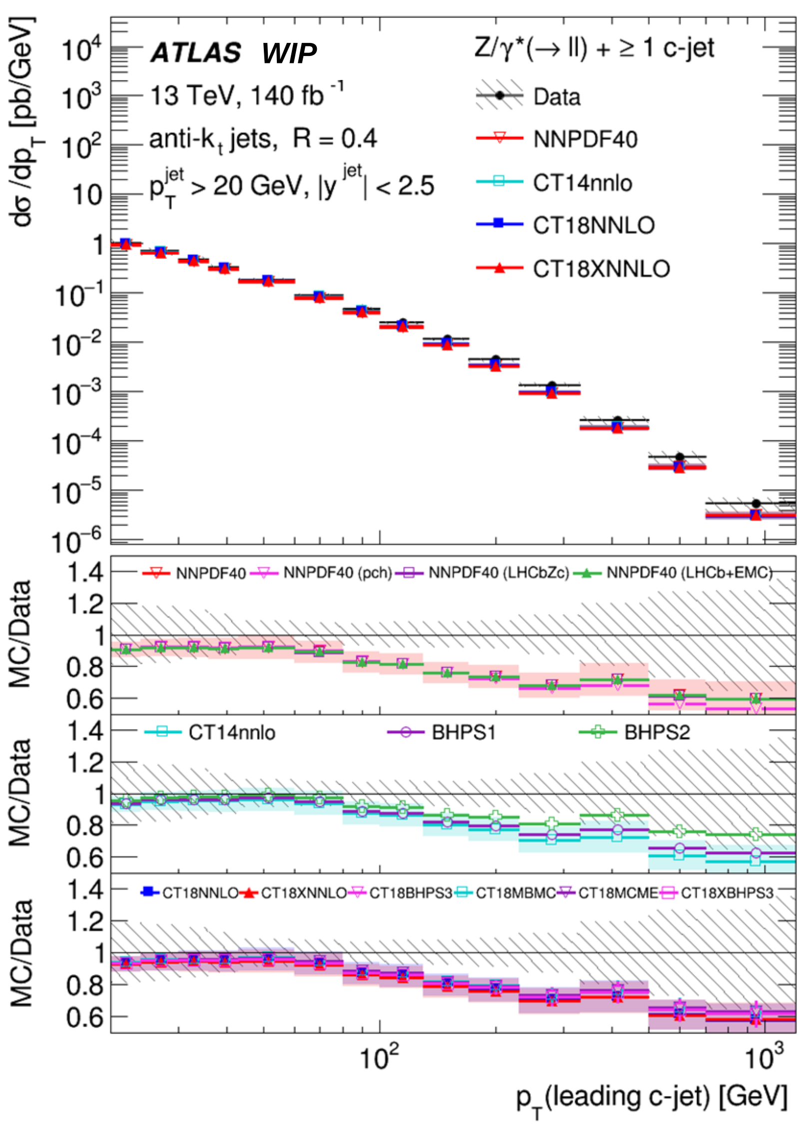




Differential Z+>= 1c-jet cross-section results (ICs)

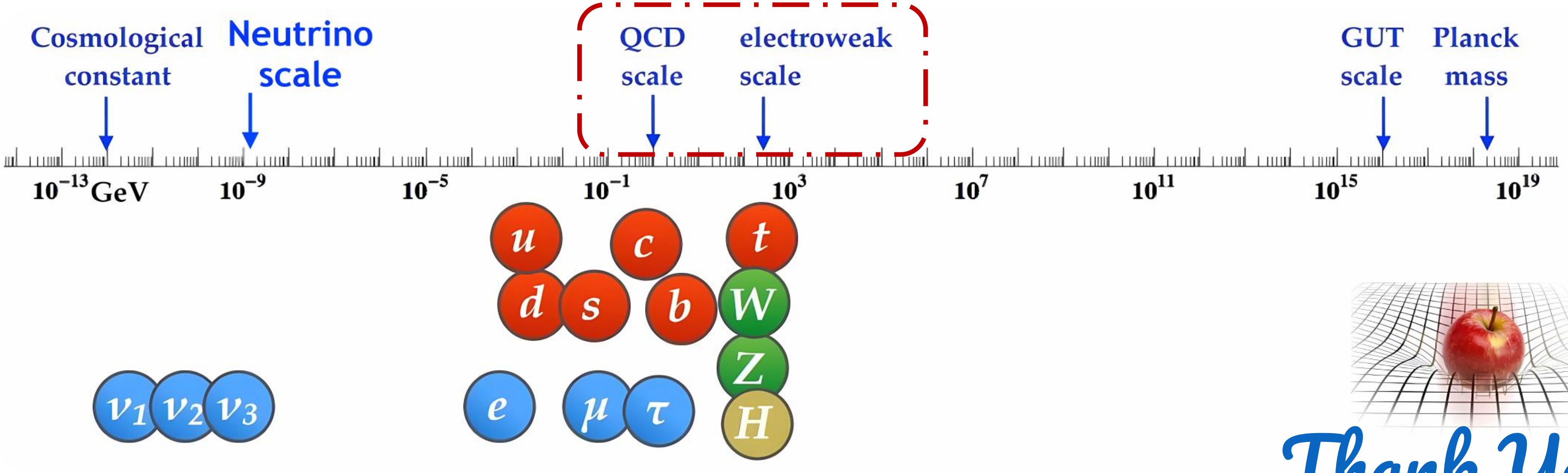
Feynman-variable $x_F = 2p_Z/\sqrt{s}$





Conclusion

- EWK gauge bosons production associated with jets as an essential ingredient of SM
  - Provide useful inputs for global fit PDF, sensitive to light, c-, b-quark, and gluon PDFs
  - Serve as benchmarks for Monte Carlo simulations and theoretical predictions available at NNLO
  - Allow to explore the sensitivity to new phenomenon, i.e. *intrinsic charm, dark matter*
- BSM searches can benefit from improved modellings of substantial EWK + QCD processes



Thank You!

* Back up

Event display of

Z+>=2b-jets candidate from data recorded by ATLAS