ATLAS EXPERIMENT

Measurement of electroweak gauge boson production in association with jets at ATLAS

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On behalf of the ATLAS Collaboration

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Topics Covered

Electroweak gauge boson association with jets measurements including :

- Differential Z+b-jets at high pT [arXiv:2204.12355, accepted by PRD]
- Measurement of the production of a W boson in association with a charm hadron [arXiv:2302.00336, accepted by PRD]
- Differential cross-section for Zγ+jets [arXiv:2212.07184, accepted by JHEP]

Introduction

Electroweak gauge boson production :

- W and Z vector boson, photon (γ)

The measurements of gauge boson in association with jets production cross-sections at the LHC are crucial in the LHC physics and allow :

- Achieve precision tests of perturbative Quantum ChromoDynamics (pQCD)
- Measure fundamental parameters of the Standard Model (SM)
- Improve our understanding of Parton Density Functions (PDF)
- Understand important backgrounds for BSM and Higgs measurement, work as sensitive probes to BSM physics as well
  - New probe to Effective Field Theory (EFT) study

For more information :

- ATLAS : https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Z + b-jets at high pT measurement

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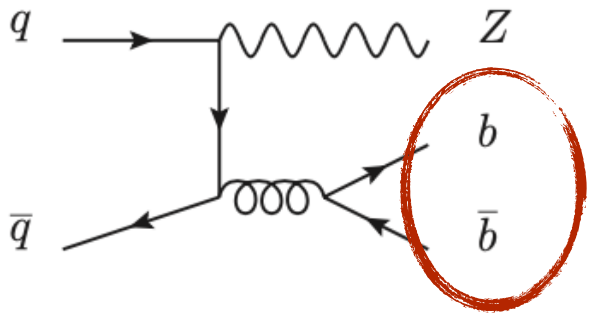
To measure the fiducial cross-sections of Z+≥1 b-jet and Z+≥2 b-jets

ATLAS @ 13 TeV

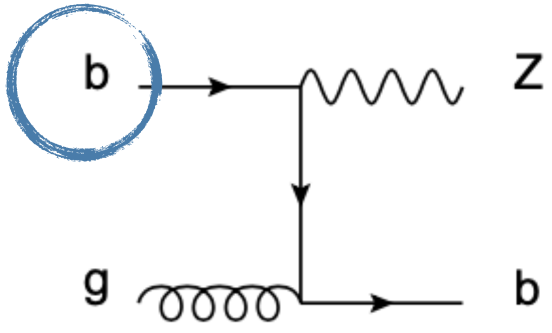
Physics motivation

- Sensitive to the b-flavour component of PDFs
  - Discriminate the effects of the b quark PDF of the proton (4/5 - FS)
- Important test of pQCD : gluon splitting, HF mass, NLO effects
  - The opportunity to study $g \to bb$ splitting helps with Parton-shower modelling
- Important background for $VH(bb)$, $ttH(bb)$, exotics/ resonances searches and measurements

Submitted to PRD, arXiv : 2204.12355

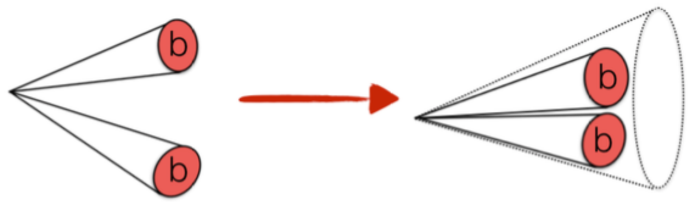


4 Flavour (4F) scheme :
No b-quark in PDF, b-quark in shower



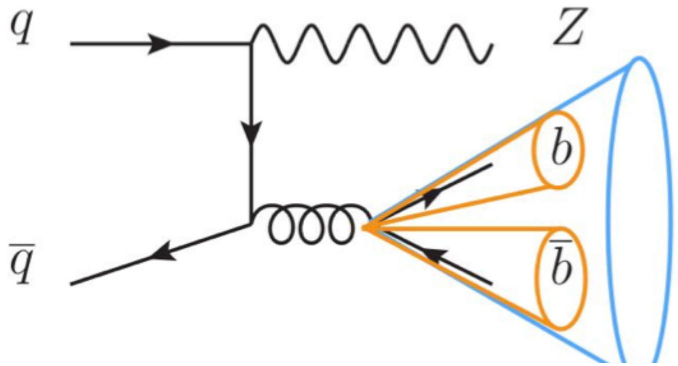
5 Flavour (5F) scheme :
b-quark in PDF and shower

Z + b-jets at high pT measurement



Strategy :

- To measure differential fiducial cross-sections of large-R jets and tagged sub-jet variables in boosted Z+bb events

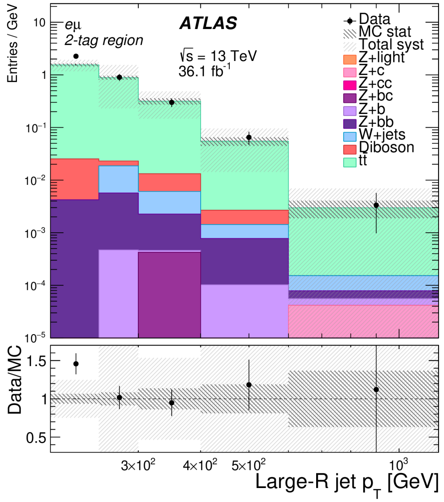


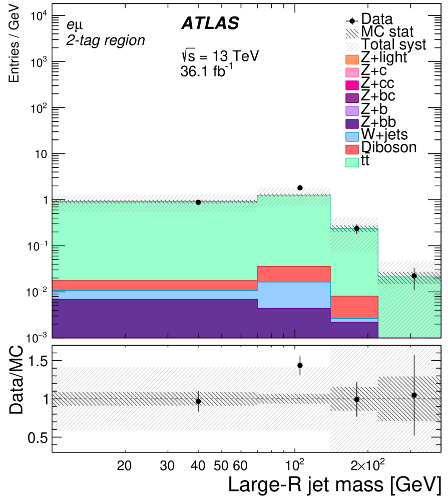
Main observables :

- Large-R jet p_T and mass m_j in the inclusive (no tagging requirements) and 2 b-tag regions
- $\Delta R(b, b)$ via track-jets
- Mis-modelling motivated : $p_T(J+Z), \Delta\Phi(J+Z)$ in inclusive selection without b-tags

Backgrounds :

- $t\bar{t}$ control region : $e\mu$ CR to assess modelling of $t\bar{t}$, main background in 2 b-tag region
- Fake lepton : access modelling of W+jets
- Multi-jet estimated from fake-enriched region





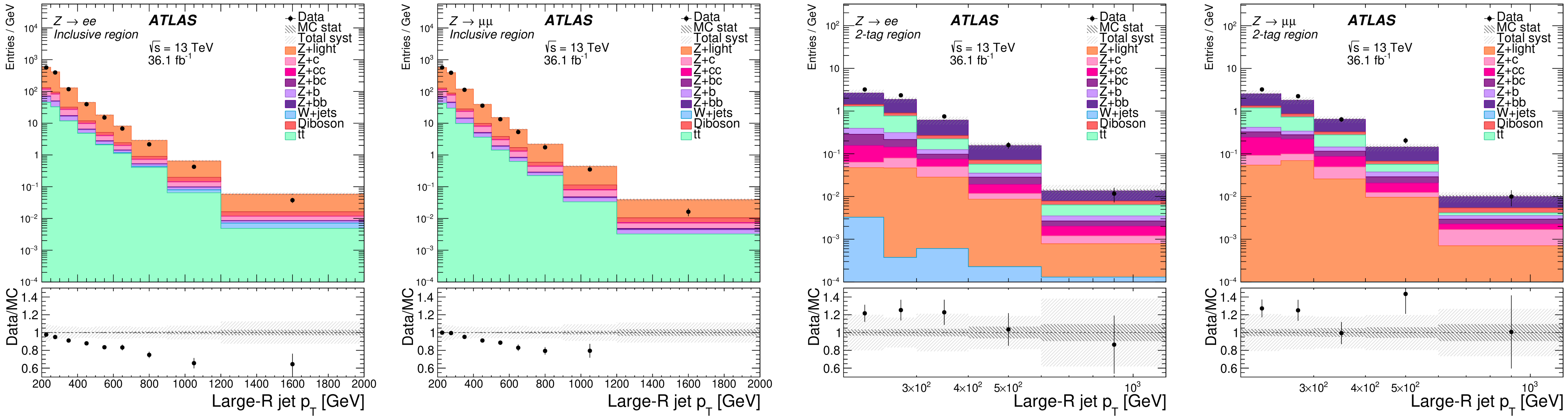
Submitted to PRD, arXiv : 2204.12355

Z + b-jets at high pT measurement

Data/MC comparison

Submitted to PRD, [arXiv : 2204.12355](https://arxiv.org/abs/2204.12355)

- Inclusive region :
  - Z+light dominates as expected, too much diffuse QCD activity in MC :mis-modelling in inclusive $p_T(J)$
- 2 b-tag region
  - Shape modelling much improved, significant $t\bar{t}$ acceptance



Z + b-jets at high pT measurement

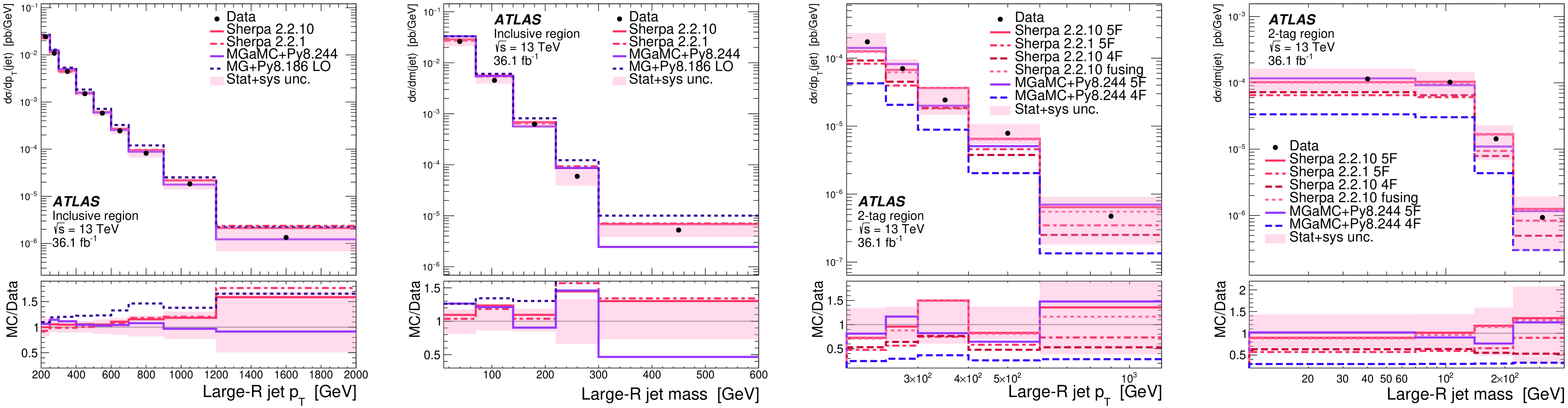
Submitted to PRD, arXiv : 2204.12355

Fully-bayesian unfolding method is used to unfold the distributions

- Sherpa 2.2.1 (NLO) samples used to produce response matrices for correcting detector responses
- Both electron and muon channels are unfolded together

In inclusive region : MG5aMC + PY8 (LO) describes all distribution shapes well, while others have mis-modelling of QCD activity

In 2 b-tag region : good shape agreement between the data and all MC models, 4FS underestimate the rate of $b\bar{b}$ boosted-jet production, 5FS is much better



[PDF constraints] W + charmed hadron measurement

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Dominant production mode : $gs \to Wc$

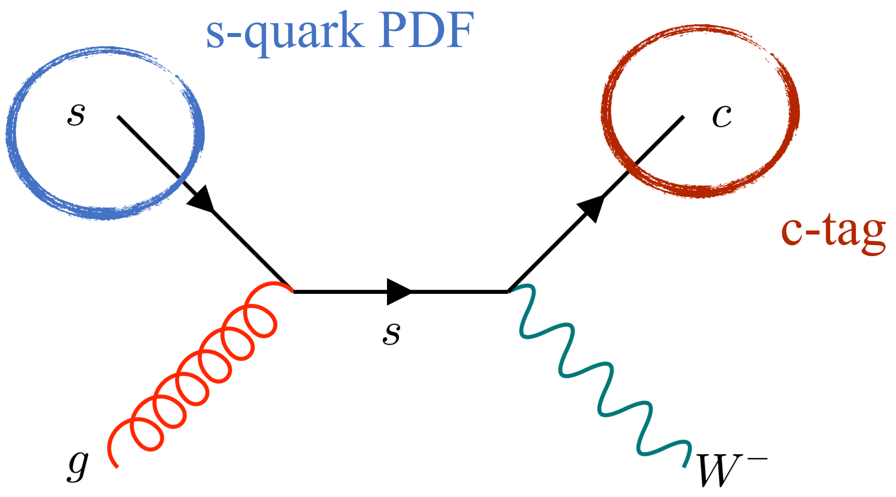
- Sensitive to s-quark PDF
- 90% of this signature produced by a s-quark initiated process at LO

Submitted to PRD, [hep-ex/2302.00336](hep-ex/2302.00336)

Crucial measurement for constraining PDF uncertainties

- PDFs sensitive to the eta distribution of the lepton in W+D
- Measurement in this variable can be used to improve PDF fit
- Constrain $s - \bar{s}$ asymmetry and help to tune MC simulation

The leading-order diagram for $W^- + c$ production



MC modelling of V+HF generator (e.g. backgrounds in $H \to bb/cc$)

[PDF constraints] W + charmed hadron measurement

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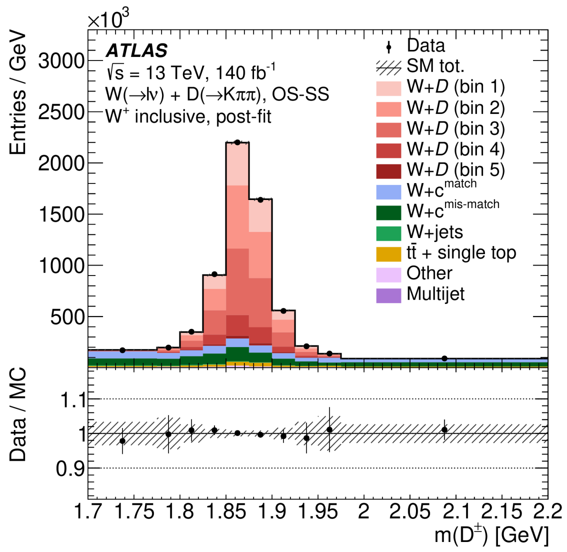
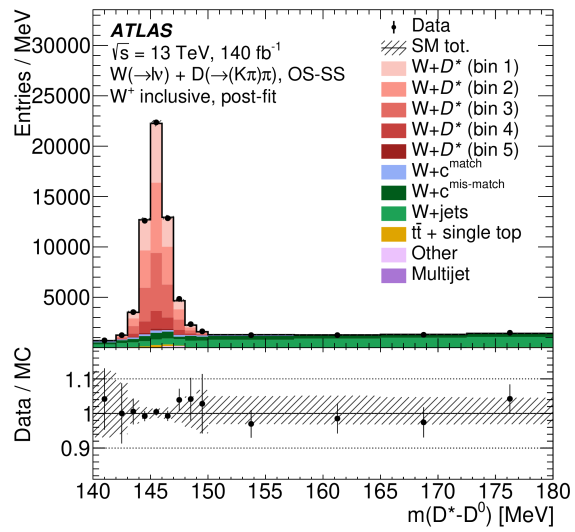
Strategy

- **Identify c via charmed-hadron reconstruction**

  (using **S**econd **V**ertex mass distribution)
- $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$ via $m(D^{\pm})$
- $D^{*\pm} \rightarrow D^{0}\pi^{\pm} \rightarrow (K^{\mp}\pi^{\pm})\pi^{\pm}$ via $m(D^{*\pm} - D^{0})$

Both e and μ W decays

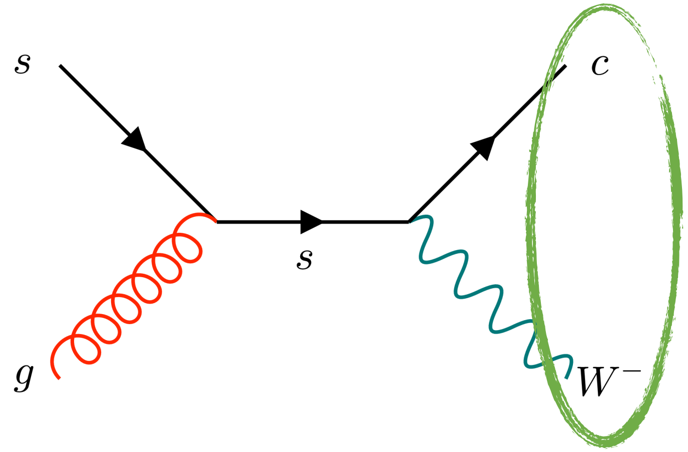




Submitted to PRD, [hep-ex/2302.00336](hep-ex/2302.00336)

Exploit charge correlation between c-quark and W to control the background : " OS - SS subtraction "

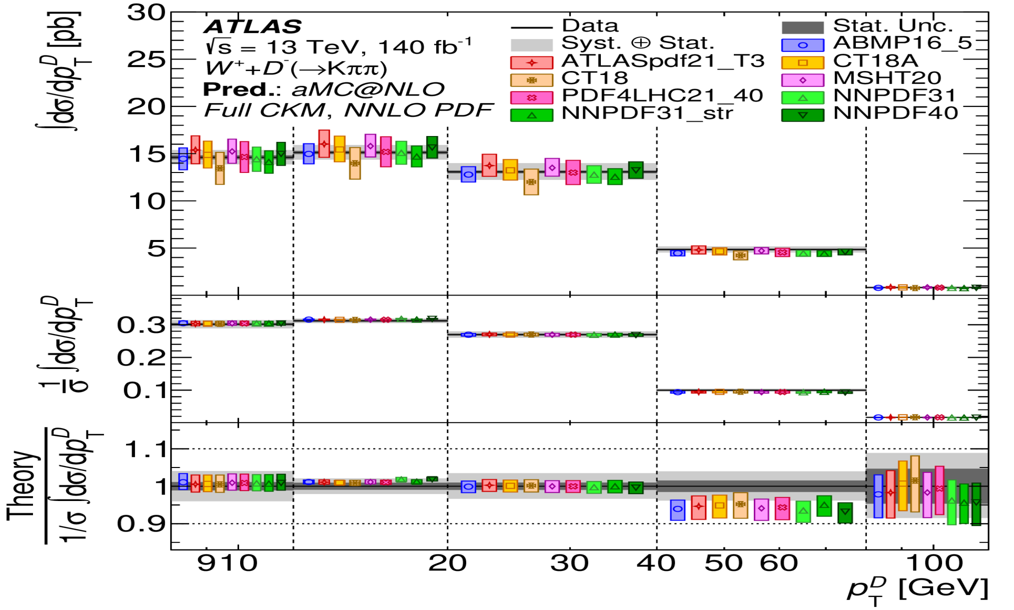
- $W + c^{match}$: tracks in SV belong to different c-hadron or decay mode
- $W + c^{mis-match}$: not all tracks belong to $D^{\pm *}$ candidate
- W + jets : no track belong to $D^{\pm *}$ candidate
- Top constrained in data region with $\geq$ 1 b-jet
- Multi-jet from fake-enriched events in data



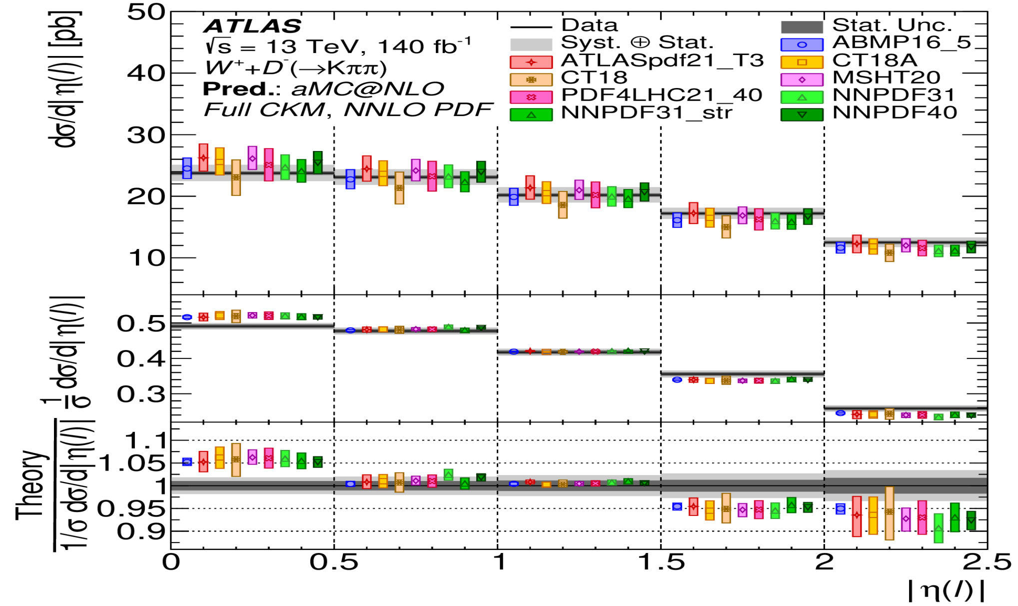
Always Opposite-Sign

[PDF constraints] W + charmed hadron measurement

- All observables (cross-sections and ratio of cross-sections : $\sigma(W^+ + D^-)/\sigma(W^- + D^+)$) are extracted with likelihood fits
- Background normalisation and systematics constraints via likelihood fit of 5 $p_T(D^{\pm(*)})$ or $|\eta(l)|$ bins, and control regions



- Differential unfolded σ measurement : smaller systematics in $|\eta(l)|$ than $p_T(D^{\pm(*)})$ (SV reconstruction independent of $\eta(l)$)
  - p_T^D useful for MC modelling (e.g. discern different hard scatter generators)
  - $|\eta(l)|$ is the most sensitive variable to the PDFs



Submitted to PRD, [hep-ex/2302.00336](hep-ex/2302.00336)

[PDF constraints] W + charmed hadron measurement

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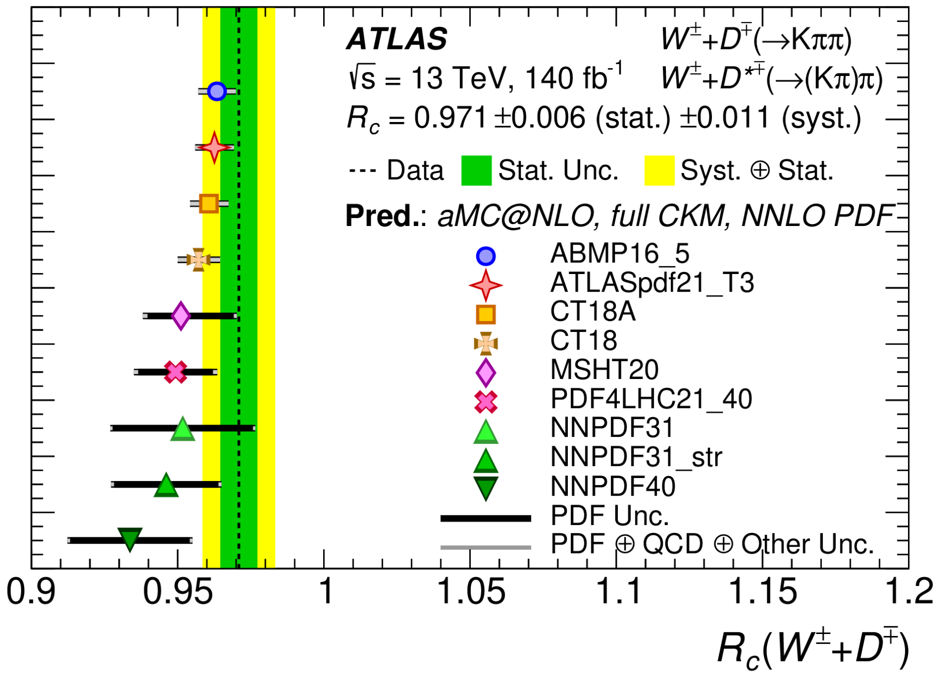
- Ratio of σ ($\sigma(W^+ + D^-)/\sigma(W^- + D^+)$) in 2 decay channels in agreement with world average : 1.021 ± 0.034
- Systematics in "+" and "-" channels mostly cancel out in $R_C^\pm$. MC and Data statistics dominate with 1.1-1.3% and 0.7-1.0% respectively
- $R_c^\pm$ in agreement with NLO prediction, and with higher precision using CT18 and AMBP16 (assume $s = \bar{s}$), which suggests $s - \bar{s}$ asymmetry is small
- Global PDF fit ATLASSpdf21 agrees well

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.)



Submitted to PRD, [hep-ex/2302.00336](hep-ex/2302.00336)

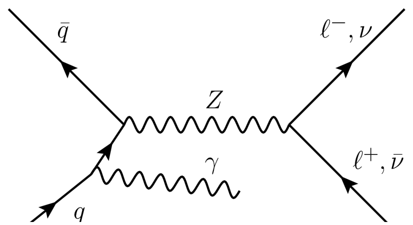
Zγ + jets measurement — Physics motivation

First measurement of Z(ll)γ + jets

Submitted to JHEP, [hep-ex/2212.07184]

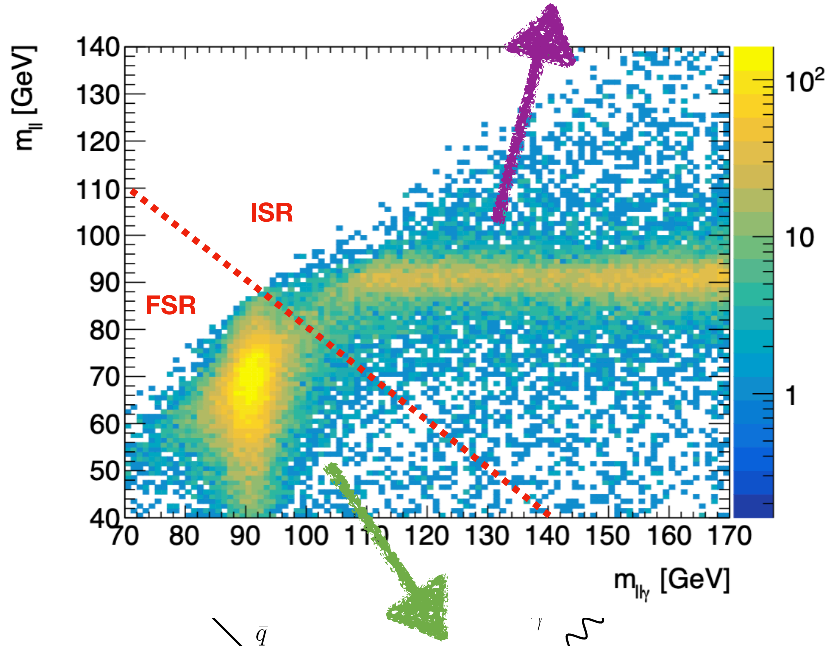
Z(ll)γ + jets measurement provides **large statistics** but with **small background contribution**

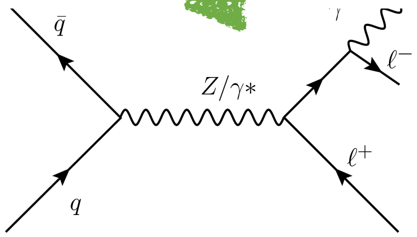
Measuring **ISR** contribution



Differential distributions can be used to

- Constrain parameters of the SM Lagrangian
- Test of parton density function, parton shower predictions
- Test fixed-order QCD calculations with resummation of Sudakov logarithms
- To search for physics beyond the SM (e.g. ALP, EFT)
- Provide possibility of Z boson polarisation measurement





Process: Z(ll)γ production in association with hadronic jets

(recent FSR Z(ll)γ measurement at 8TeV [ATLAS-CONF-2022-046])

$Z(ll)\gamma$ + jets measurement — Strategy

Event signature :

- 2 OSSF leptons + $\geq$ 1 signal photon + jets
- Low-mass resonances is avoid by requiring $m_{ll} >$ 40GeV, e.g. $\gamma *$
- FSR events are reduced by requiring $m_{ll} + m_{ll\gamma} >$ 182GeV

Backgrounds

- Jet fake photon : estimated by 2D sideband method based on photon ID and Isolation (11%)
- $t\bar{t}\gamma$ shape from MC, normalisation from data in $e\mu\gamma$ CR (4%)
- Pileup photon : estimated by data-driven method (3%)
- Multi-boson events with $e \to \gamma$, directly estimated from MC (1%)

Submitted to JHEP, hep-ex/2212.07184

Different variables have been measured

1D observables :

- Interesting for QCD studies : $N_{jets}, p_T^{jet1}, p_T^{jet2}, p_T^{jet1}/p_T^{jet2}$, $m_{ll\gamma j}$, m_{jj}
- Used in other analysis : $H_T, p_T^{\gamma}/H_T, \Delta\Phi(j,\gamma), \Delta R(l,l), p_T^{ll}$

QCD-sensitive 2D variables

- $p_T^{ll\gamma}/m_{ll\gamma}$ in 3 slices of $m_{ll\gamma}$
- $p_T^{ll} - p_T^{\gamma}$ in 3 slices of $p_T^{ll} + p_T^{\gamma}$
- $p_T^{ll\gamma j}$ in 3 slices of $p_T^{ll\gamma}$
- $p_T^{ll} - p_T^{\gamma}$, $p_T^{ll} + p_T^{\gamma}$, $p_T^{ll\gamma j}$ are also measured inclusively

Hard variables : represent the hard scale of the process (non-zero at LO)
Resolution variables : sensitive to additional QCD variations

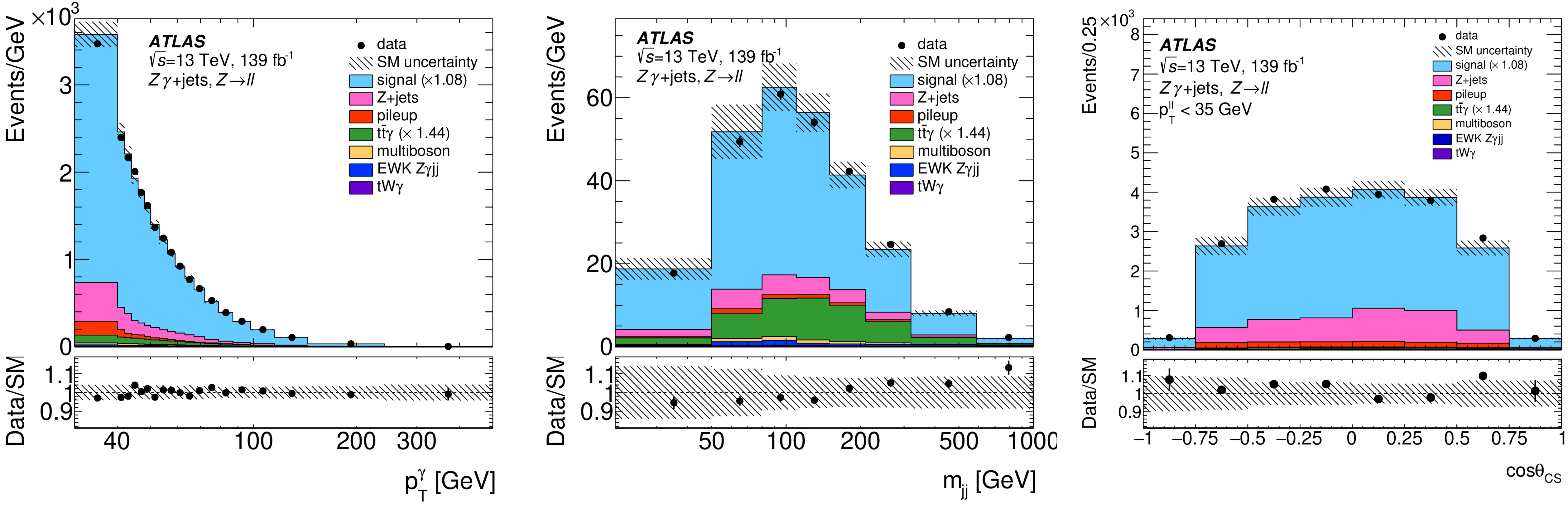
Polarisation-sensitive 2D variables

- $cos\theta_{CS}$ in 5 bins of p_T^{ll}
- ϕ_{CS} in 5 bins of p_T^{ll}
- First time to measure the lepton angular coefficient in DY events with γ

Z$(ll)\gamma$ + jets measurement — Results

Good agreement observed between the measured data and SM predictions

- The Sherpa 2.2.11 signal sample is scaled by a normalisation factor of 1.08 to match the data
- A total uncertainty is ～4% of the total prediction



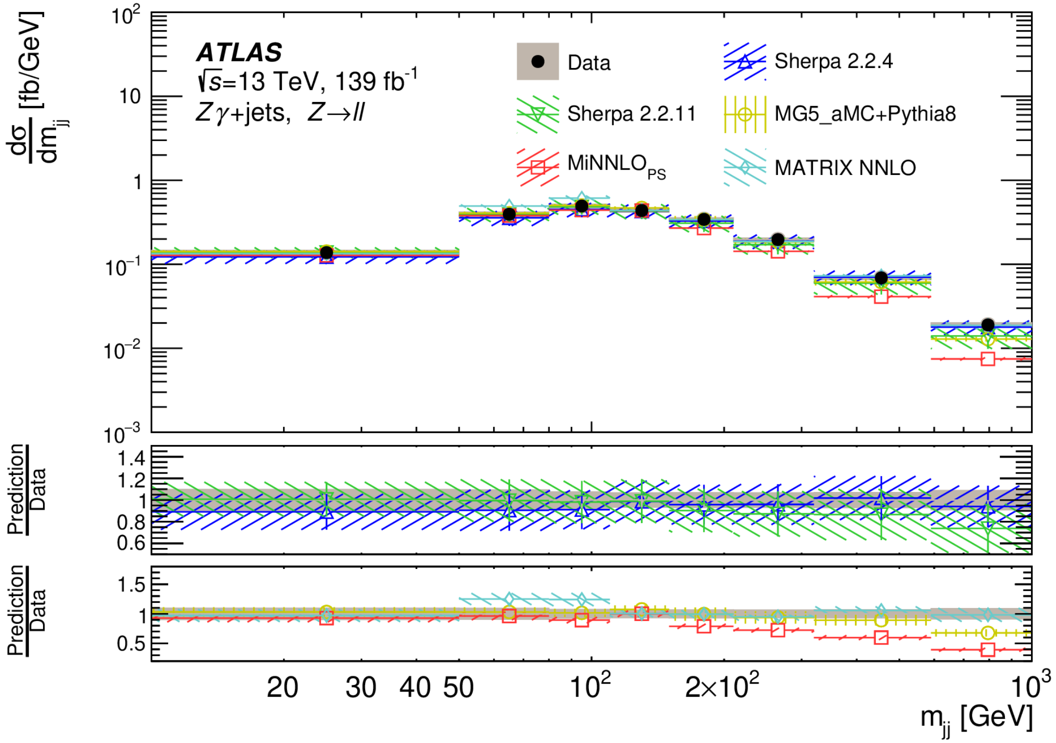
Submitted to JHEP, hep-ex/2212.07184

Z(ll)γ + jets measurement — Results

Iterative Bayesian method is used to unfold the distribution

- Two iterations bayesian method used as nominal value (best compromise between bias and statistical uncertainty)
- Sherpa 2.2.11 used to produce the response matrices for the migration correction in the detector-level and particle-level distributions

- Unfolded results are compared with different theoretical predictions, including :
  - Calculation of Sherpa and MadGraph
  - NNLO predictions of MiNNLO$_{PS}$
  - NNLO fixed order calculation MATRIX
- **Sherpa and MadGraph generally describe well data**
  - Sherpa 2.2.11 has a better agreement in shapes
- **MiNNLO$_{PS}$** and **NNLO MATRIX** predict accurately the observables, but with some discrepancy at high jet multiplicity



Submitted to JHEP, hep-ex/2212.07184

Summary

Recent results from ATLAS experiment of gauge boson production in association with jets are presented here

- Differential measurement Z + b-jets at high pT
- Differential measurement W + charm hadron production
- Differential measurement of $Z\gamma$ + jets

Fiducial and unfolded differential production cross-sections have been determined for multiple processes of the SM

Different final states were analysed with different analysis method applied and new techniques are also pushed forward

The increase of luminosity will benefit to rare processes, and understand systematics in a better way

As Run3 data-taking already starts → Let's looking forward to the new results !

Backup

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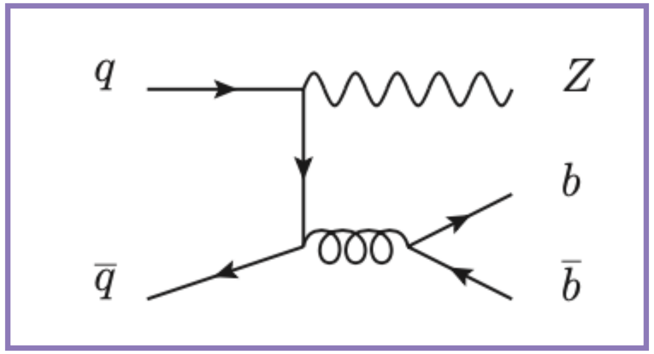
Z + b-jets at high pT measurement

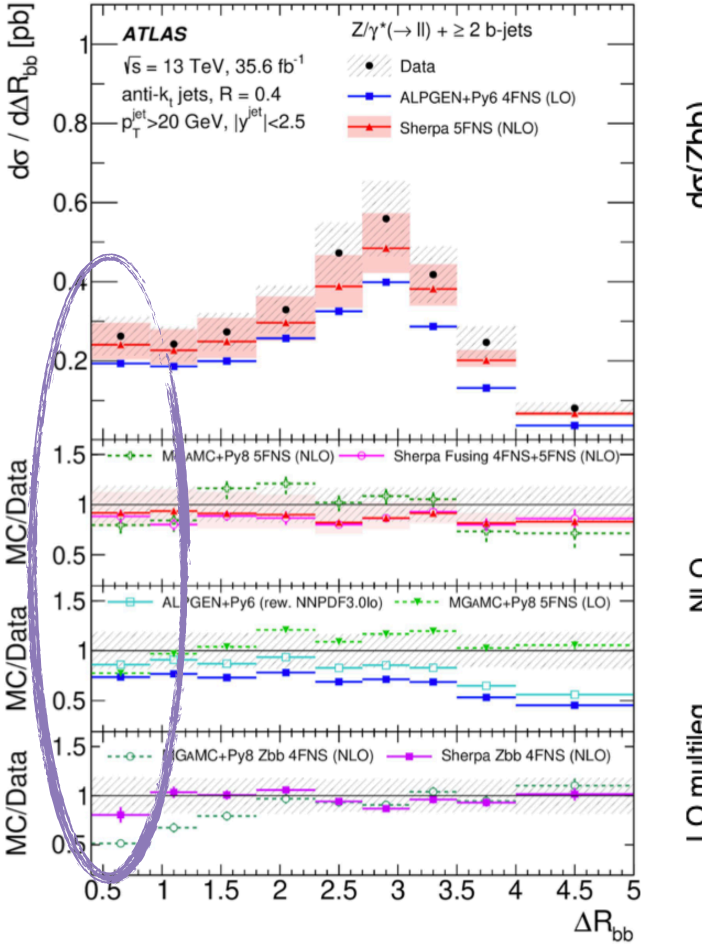
Important test of pQCD :

- The study of $g \to bb$ splitting helps with Parton-shower modelling
- $\Delta R(b,b)$ sensitive to the $Z + bb$ production mechanism
- And low $\Delta R(b,b)$ sensitive to gluon splitting in b-quarks
- Mis-modelling by MG5aMC+PY8 $Z \to bb$ 4FS in the phase space dominated by $g \to bb$



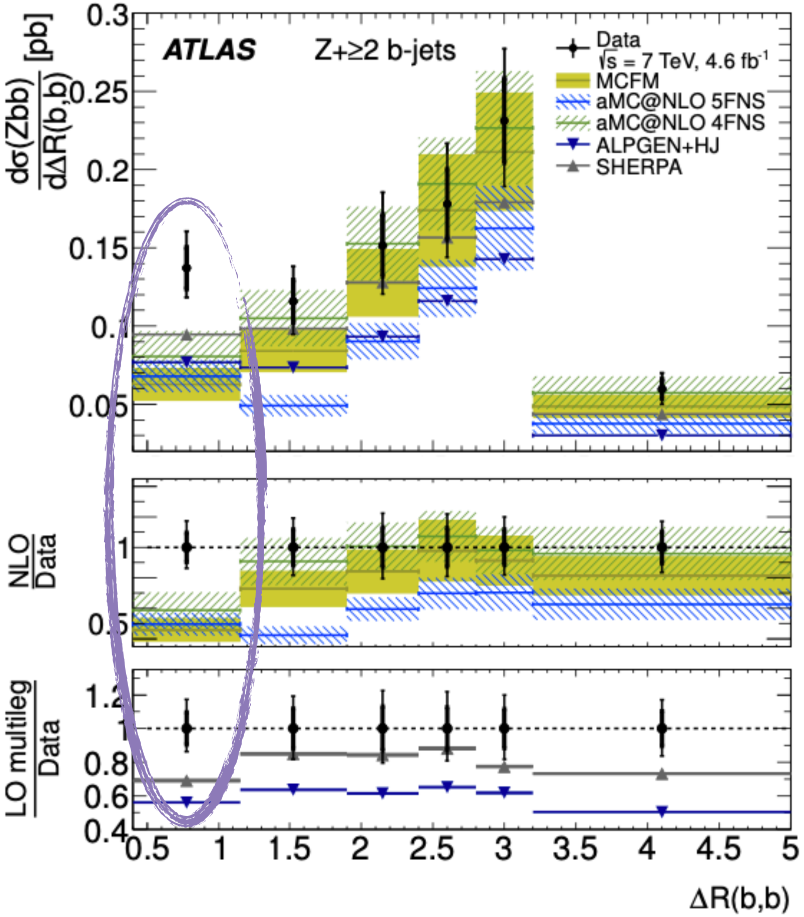
JHEP 07 (2020) 44

ATLAS @ 13 TeV



JHEP 10 (2014) 141

ATLAS @ 7 TeV



Z + b-jets at high pT measurement backup

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Additional plots — events yields

Inclusive :

No track jet cut — MC overestimate

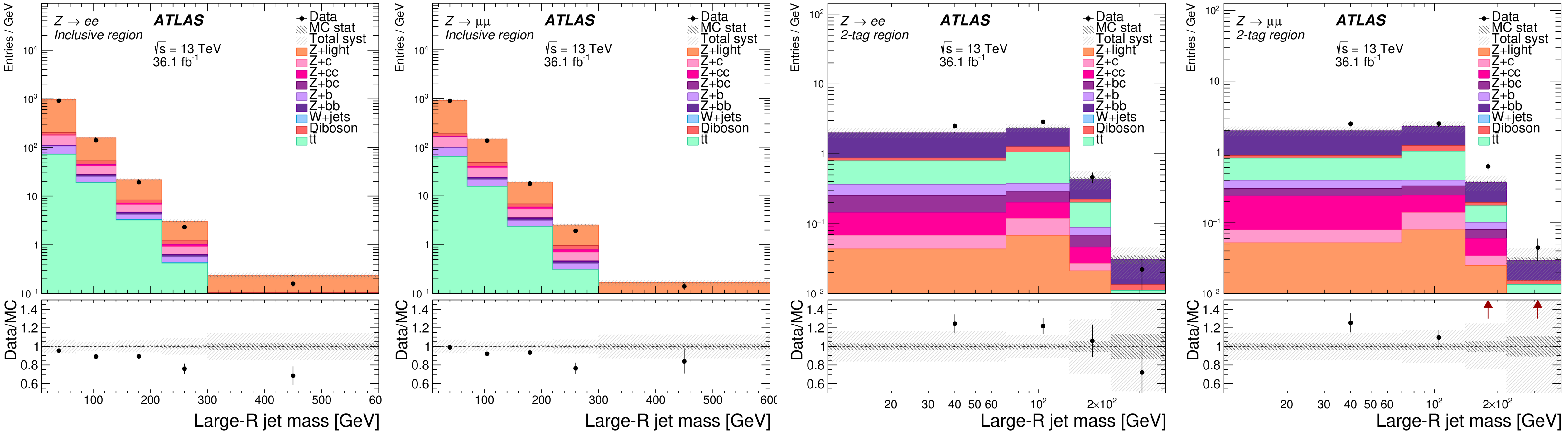
2 b-tag :

2 b-trackjets in $\Delta R(b, j) < 0.8$ — MC underestimate

	Inclusive		2-tag	
	ee	$\mu\mu$	ee	$\mu\mu$
$Z{+}b\bar{b}$	324 ± 4	305 ± 4	163.8 ± 2.6	157.2 ± 2.5
$Z{+}c\bar{c}$	536 ± 10	530 ± 9	12.3 ± 1.8	19.3 ± 2.0
$Z{+}bc$	89 ± 2	81 ± 2	14.6 ± 1.2	12.1 ± 0.9
$Z{+}b$	2588 ± 13	2423 ± 12	14.8 ± 1.1	12.4 ± 1.3
$Z{+}c$	5073 ± 32	4862 ± 39	5.5 ± 1.3	6.9 ± 1.7
$Z{+}$light	$53\,808 \pm 164$	$51\,206 \pm 145$	9.4 ± 1.1	11.1 ± 1.5
$t\bar{t}$	5960 ± 46	5204 ± 43	82.7 ± 5.3	75.4 ± 5.6
$W{+}$jets	73 ± 4	7 ± 1	0.4 ± 0.1	< 0.1
Diboson	2042 ± 17	1834 ± 16	21.5 ± 1.4	20.7 ± 1.4
MC total	$70\,493 \pm 175$	$66\,452 \pm 158$	324.9 ± 6.8	315.1 ± 7.2
Data	66 481	65 034	391	384

Z + b-jets at high pT measurement backup

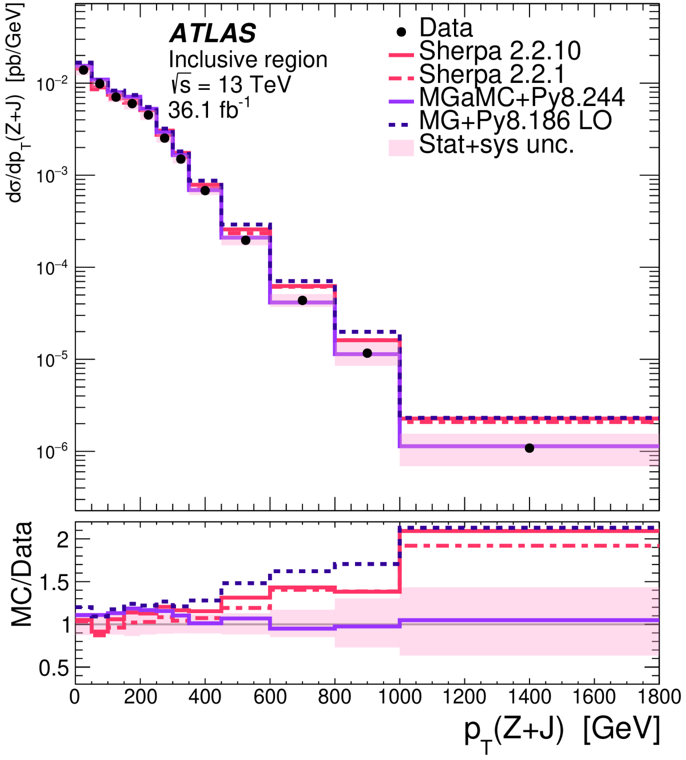
Additional plots — Data/MC comparison

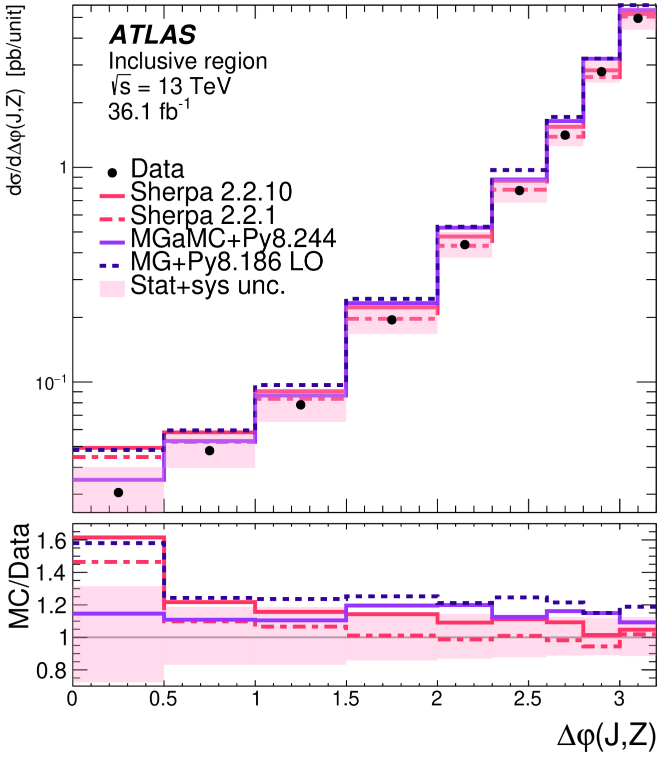


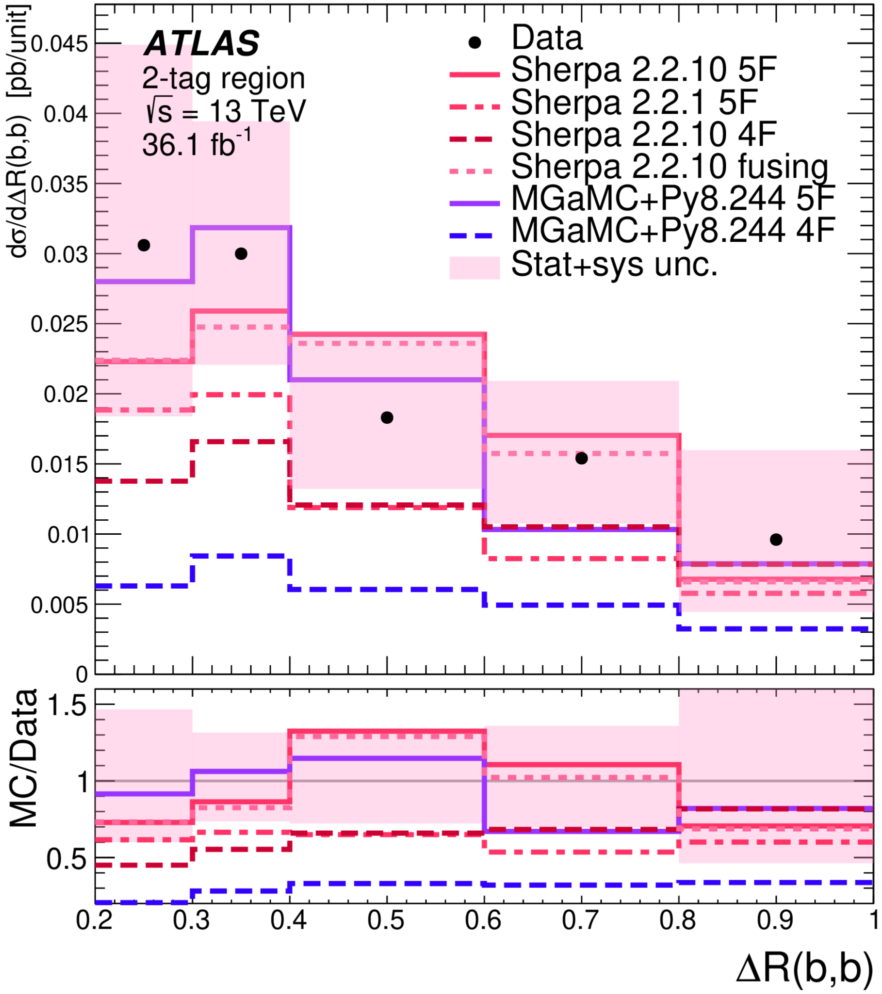
Z + b-jets at high pT measurement backup

Additional plots — Unfolded results

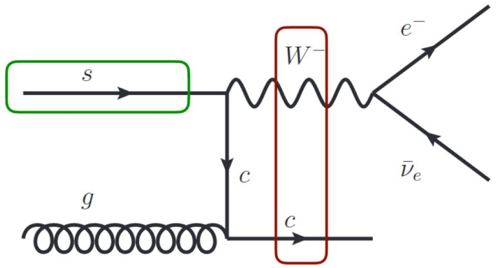
- Sherpa 2.2.1 (+ 0,1,2 jets at NLO and 3,4 jets at LO)
- MG5aMC + PY8.186 (+ 0,1,2,3,4 jets at Leading Order)







W + charm hadron measurements backup



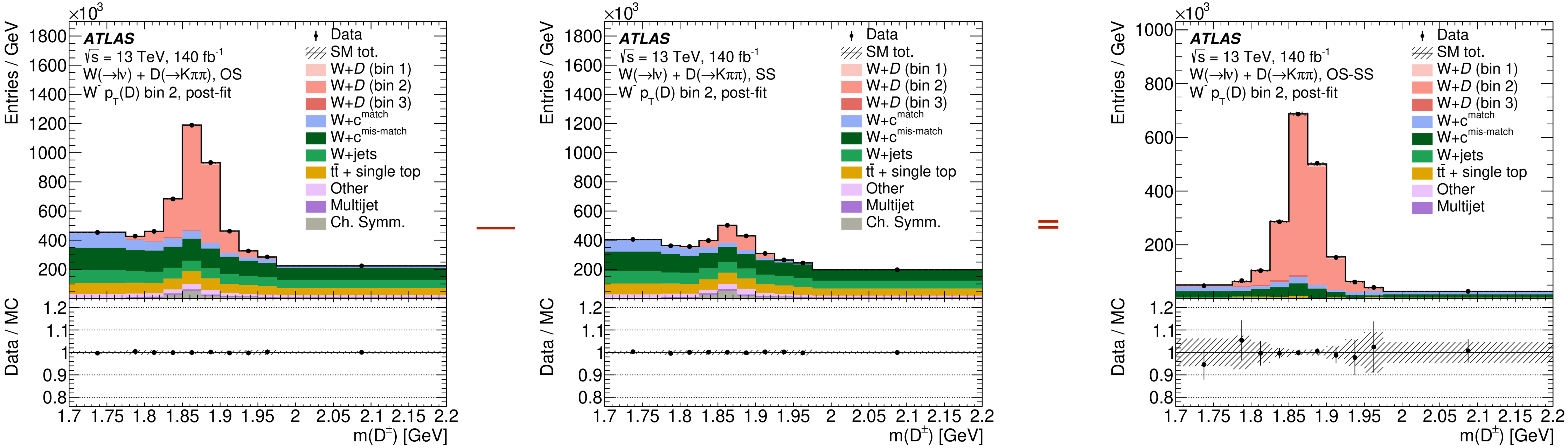
OS - SS subtraction

- OS : opposite-sign (OS) W+D (c and l from W have opposite sign)
- SS : same-sign (SS) W+D (bkg $W + c\bar{c}$ and $t\bar{t}$ suppressed by same sign subtraction)

Signal signature : an oppositely-signed (OS) W boson and D meson

Statistical “subtraction” performed that removes most background while preserving signal

All cross-sections have been measured in this analysis are “OS-SS” measurements

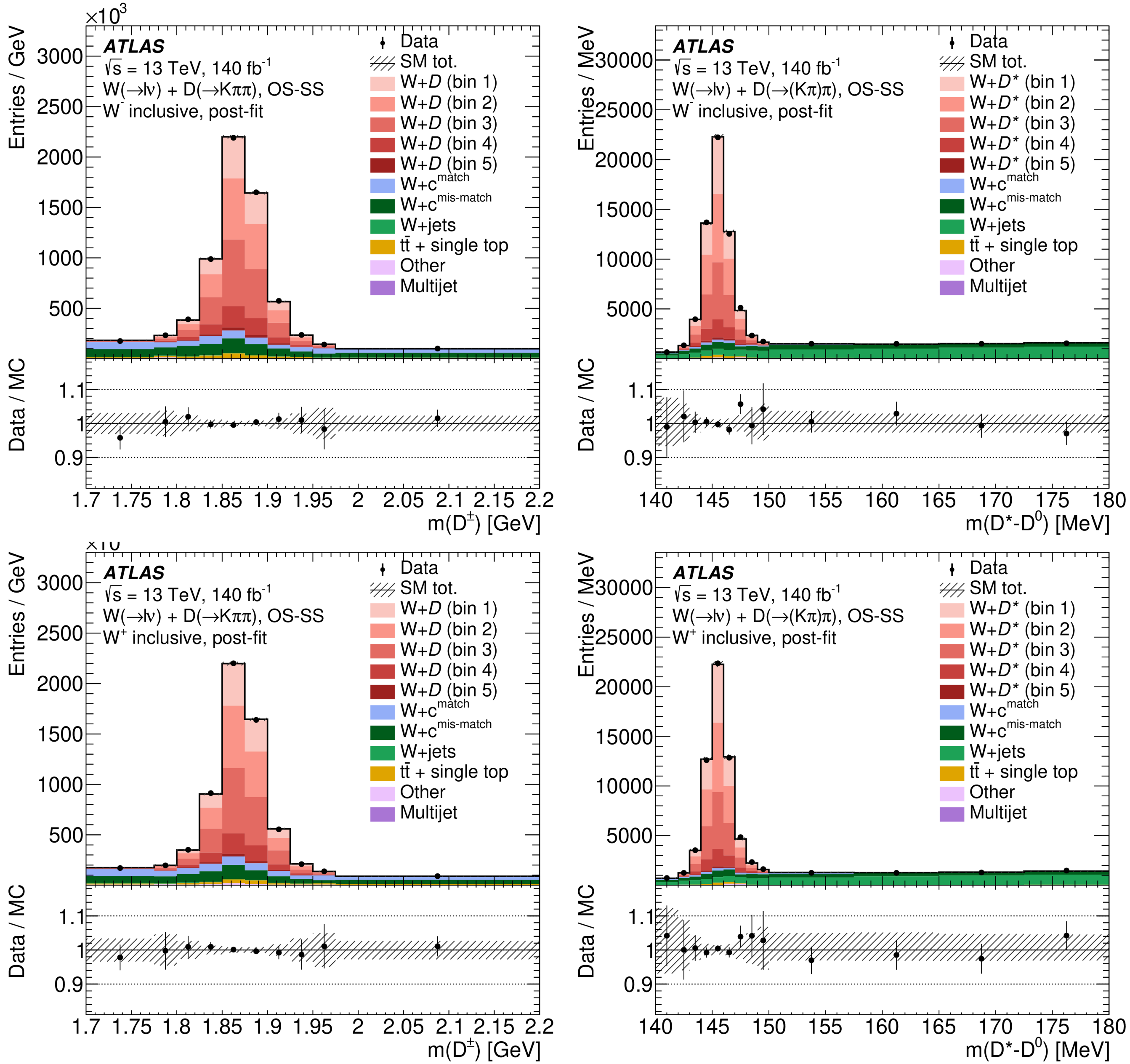


W + charm hadron measurements backup

Additional plots — post-fit mass plots

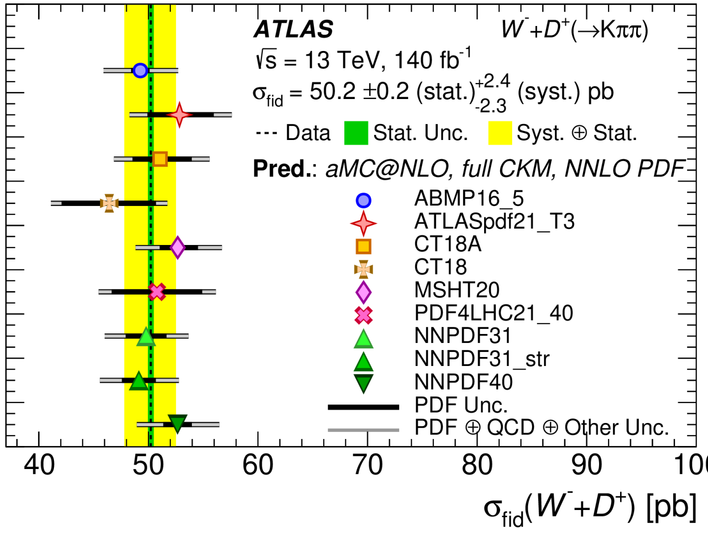
Percent-level Data/MC agreement in the post-fit invariant mass plots

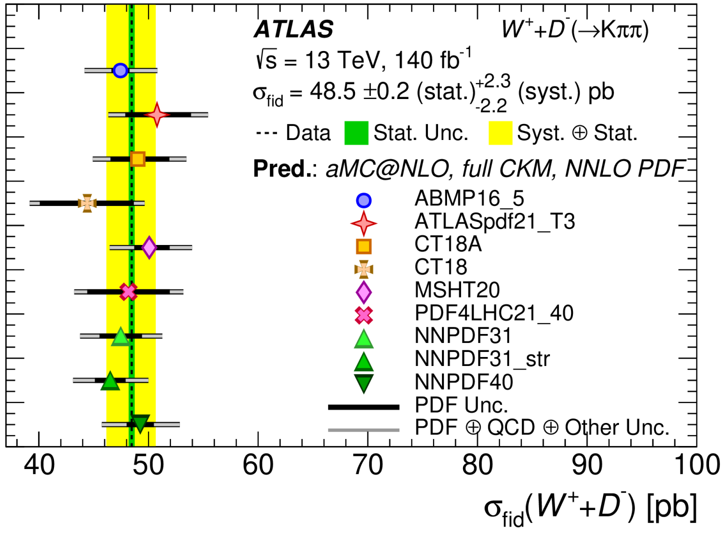
- 4 invariant mass plots provided ($[W^-, W^+] \times [D^+, D^*]$)
- Post-fit plots for all individual different bins provided in STDM-2019-22
- Good agreement observed !

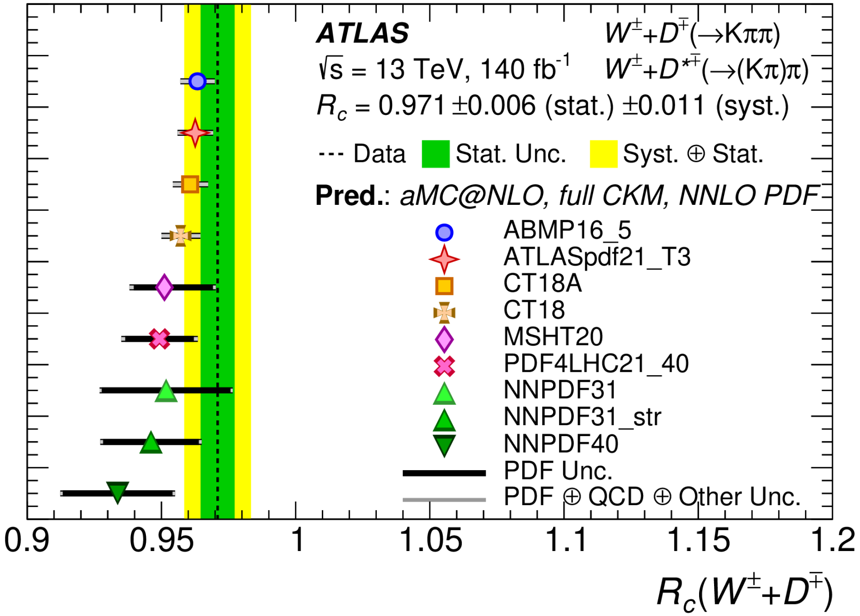


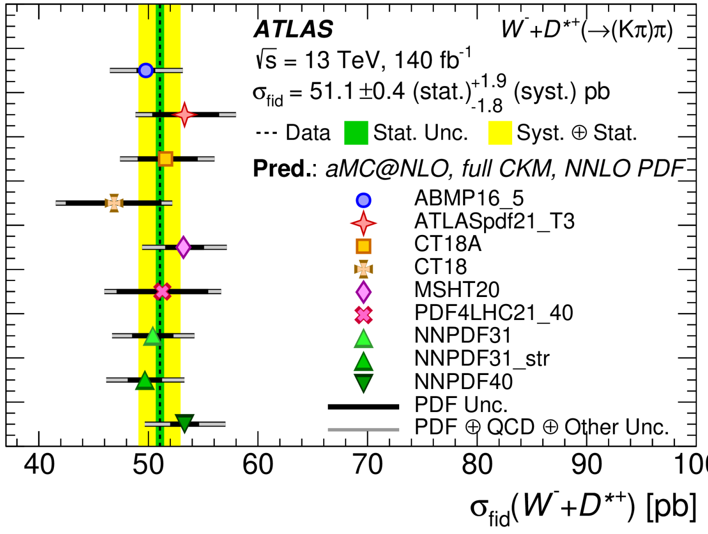
W + charm hadron measurements backup

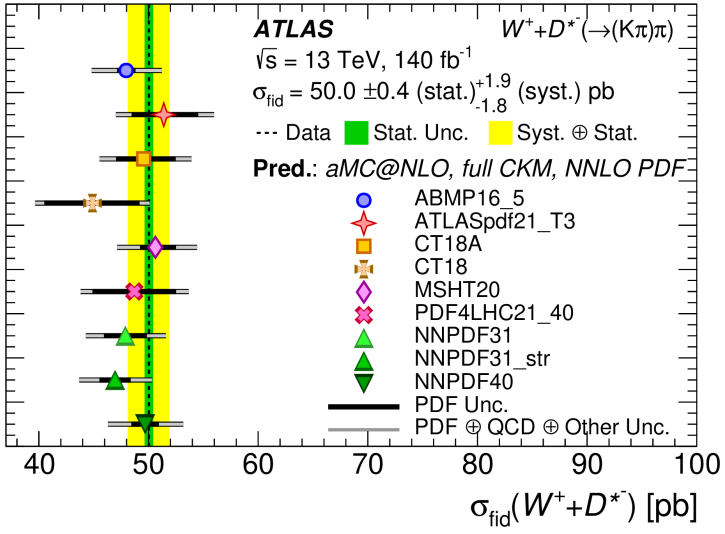
Additional plots — ladder plots for integrated cross sections of $[W^-, W^+] \times [D^+, D^*]$







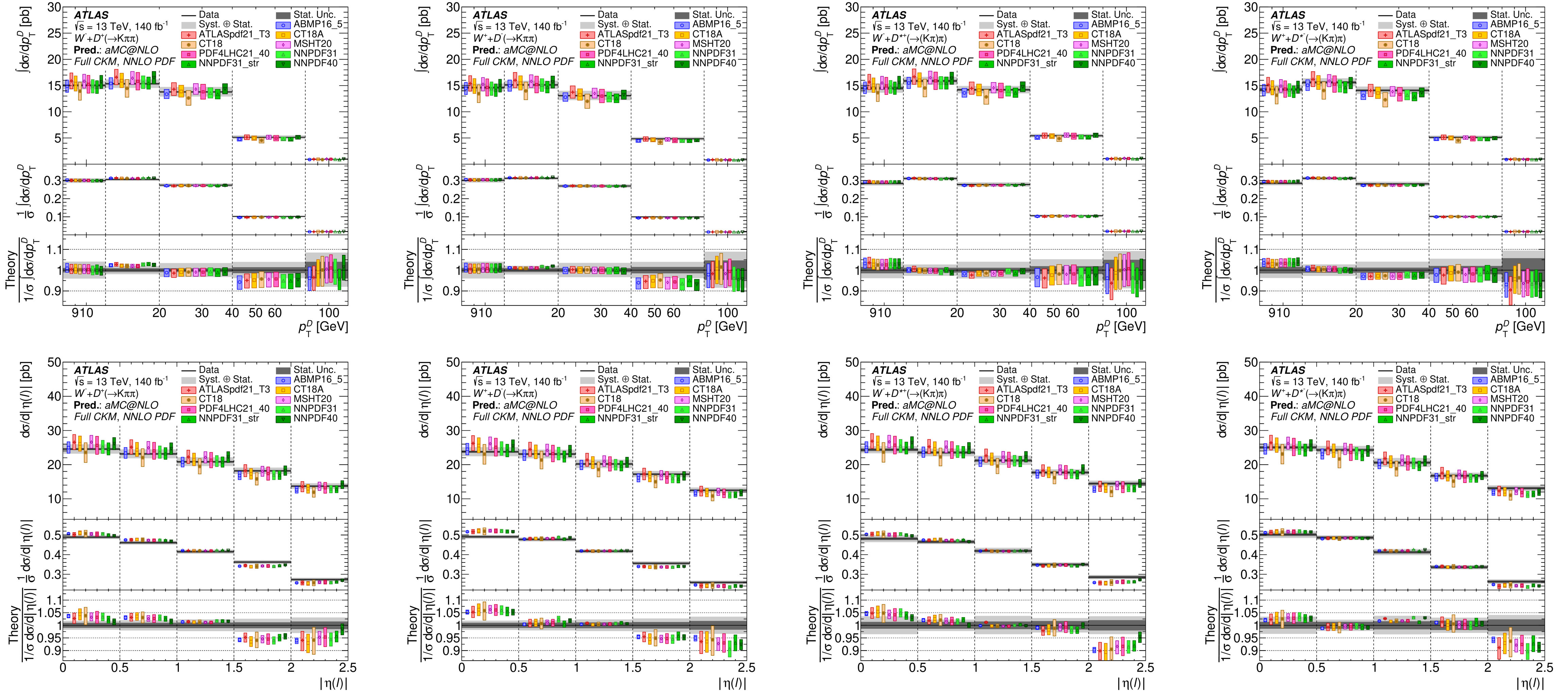




W + charm hadron measurements backup

Additional plots — differential cross-section measurements

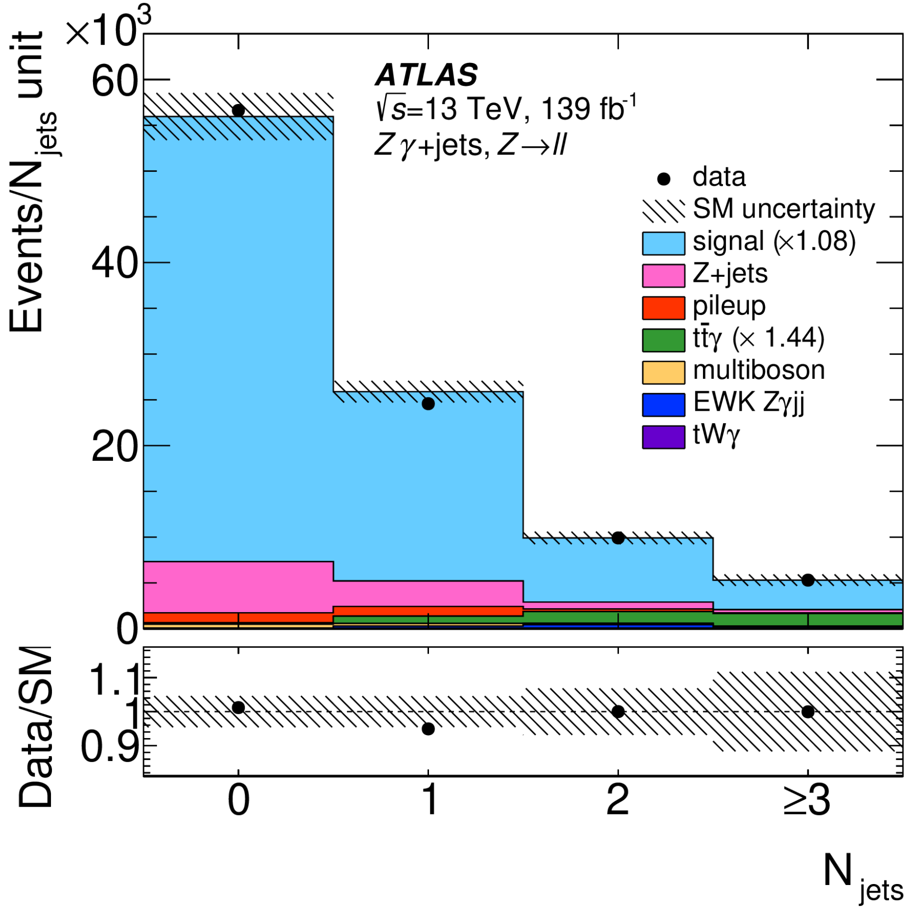
- 8 differential cross-section plots $[W^-, W^+] \times [D^+, D^*] \times [p_T(D), \eta(l)]$



$Z(ll)\gamma$ + jets backup

Additional plots for data/MC comparison at Reconstructed Level

Good agreement observed between measured data and SM predictions



Source	ee + $\mu\mu$	
$Z\gamma$+jets signal	73 500	± 50 (stat.) $\pm$ 2 600 (syst.)
Z + jets	9 800	± 460 (stat.) $\pm$ 2 100 (syst.)
$t\bar{t}\gamma$	3 600	± 10 (stat.) $\pm$ 540 (syst.)
pile-up	2 500	± 70 (stat.) $\pm$ 700 (syst.)
multiboson	950	± 5 (stat.) $\pm$ 160 (syst.)
$tW\gamma$	150	± 1 (stat.) $\pm$ 45 (syst.)
Total prediction	90 500	± 500 (stat.) $\pm$ 3 500 (syst.)
Data	96 410	

A total uncertainty is ~4% of the total predictions

Z(ll)γ + jets backup

Additional plots