High precision measurement of the differential W and Z boson production cross sections

Deep Inelastic Scattering 2017, Birmingham

Philip Sommer
on behalf of the ATLAS Collaboration

Albert-Ludwigs-Universität Freiburg

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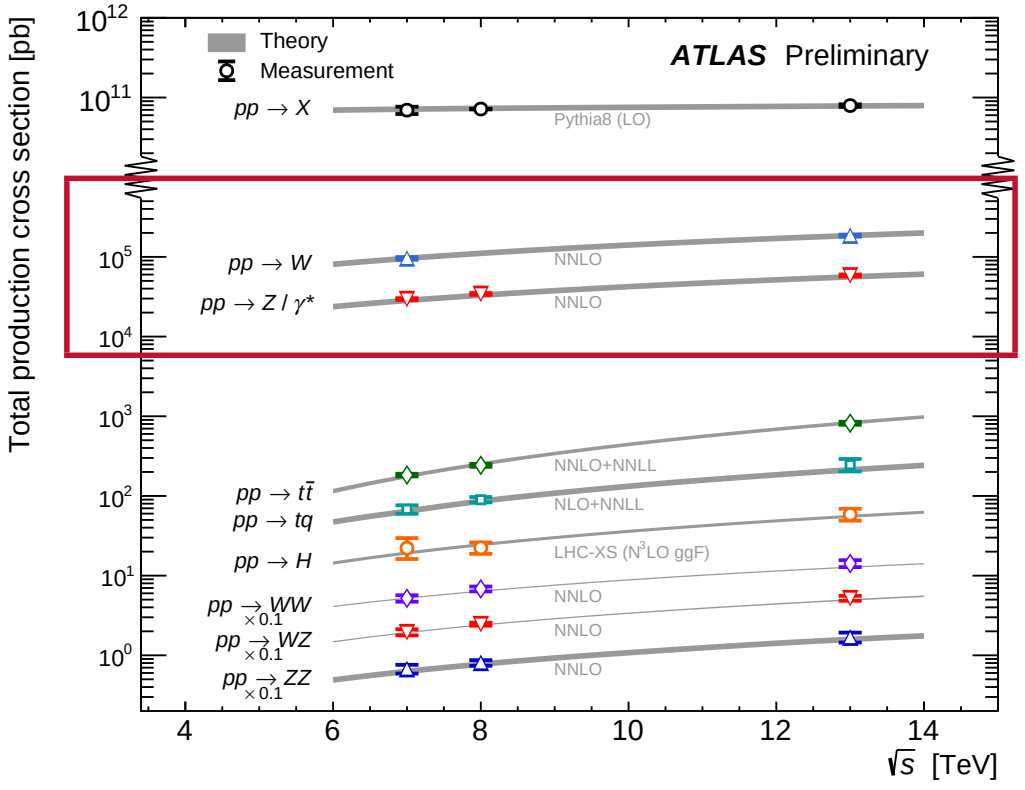
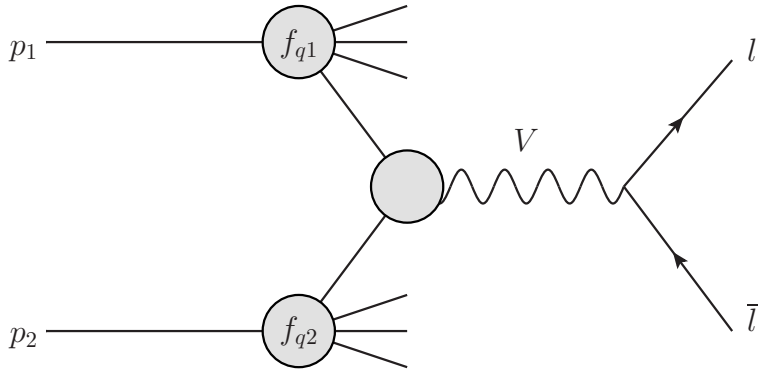
Introduction

- Drell-Yan production is the largest source of isolated leptons at the LHC
- allowing for very precise cross-section measurements

- at the same time the Drell-Yan process is theoretically known extremely well
- calculations at NNLO QCD and NLO EW





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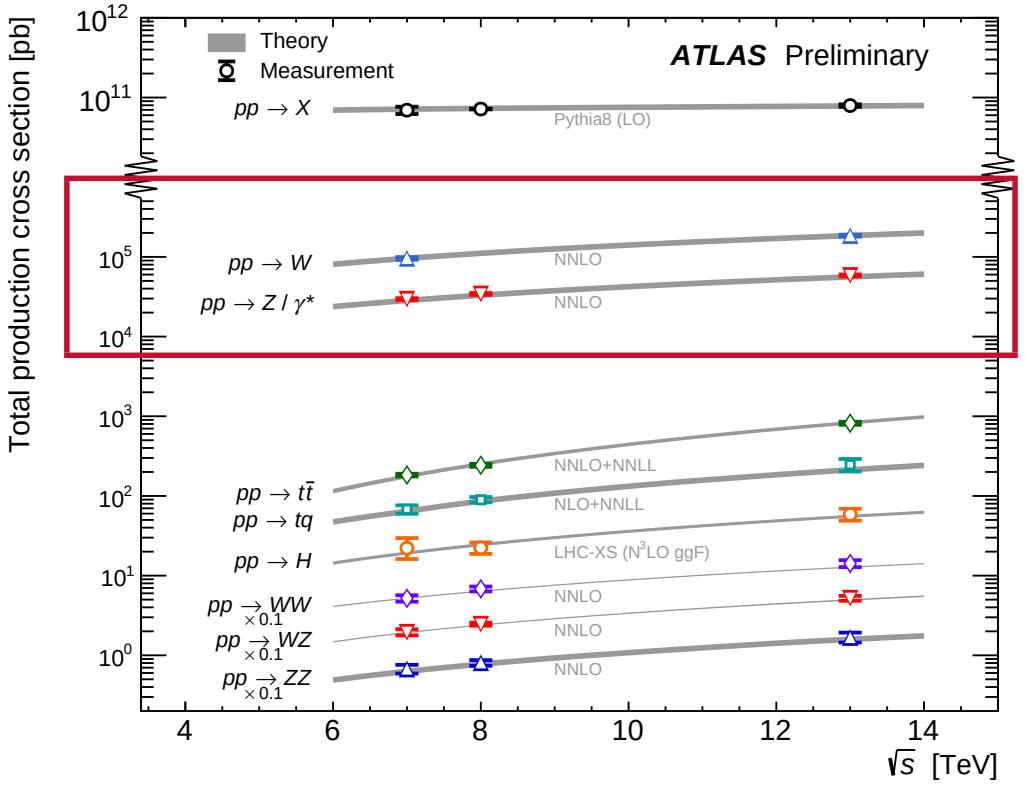
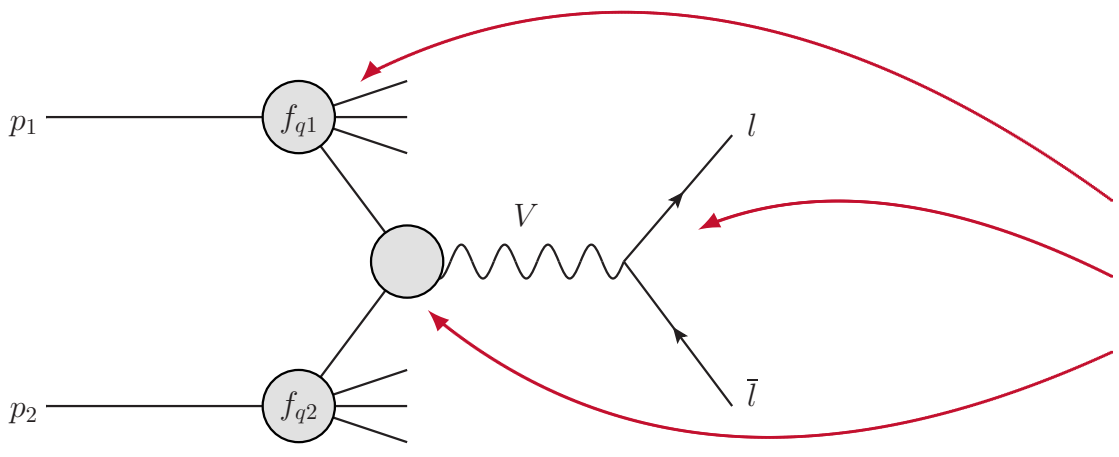
→ use data to infer on the input to the theoretical calculations





- parton distribution functions
- test of lepton universality
- $|V_{cs}|$ CKM matrix element

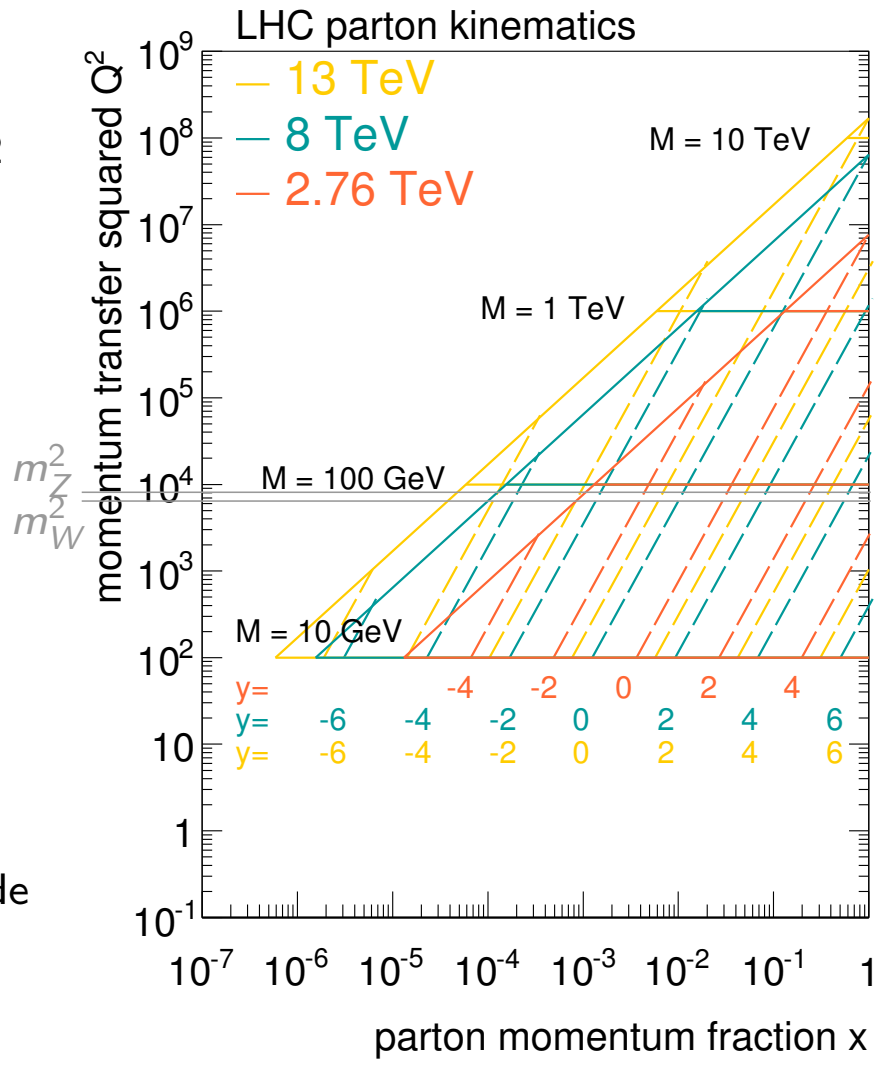
Theoretical Limitations

- fixed order calculations of Drell-Yan production computed using DYNNLO 1.5 and FEWZ 3.1.b2
- with typical systematic uncertainties of

μ_R, μ_F variations (factors of 2, with $0.5 \leq \mu_R/\mu_F \leq 2$)	$\sim 1.1\%$
beam energy	± 0.5-0.6%
PDF (with a spread between PDFs larger than this)	up to $\pm 2.5\%$

- measurement of W and Z production can constrain these uncertainties, in particular those from PDF
- measurement as a function of rapidity can provide information for the parametrisation vs. x

$$y = 0.5 \ln(x_1/x_2)$$



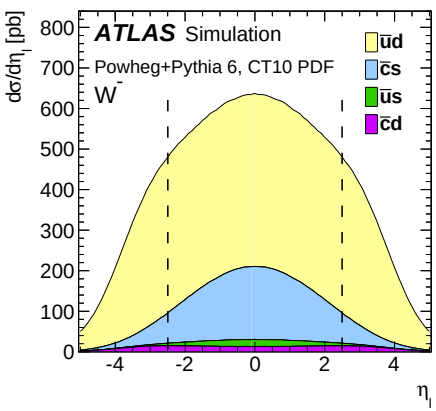
- measurement performed in 4.6 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV

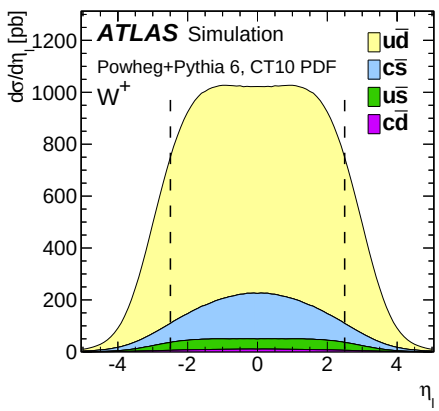
$W \to \ell\nu$ Analysis

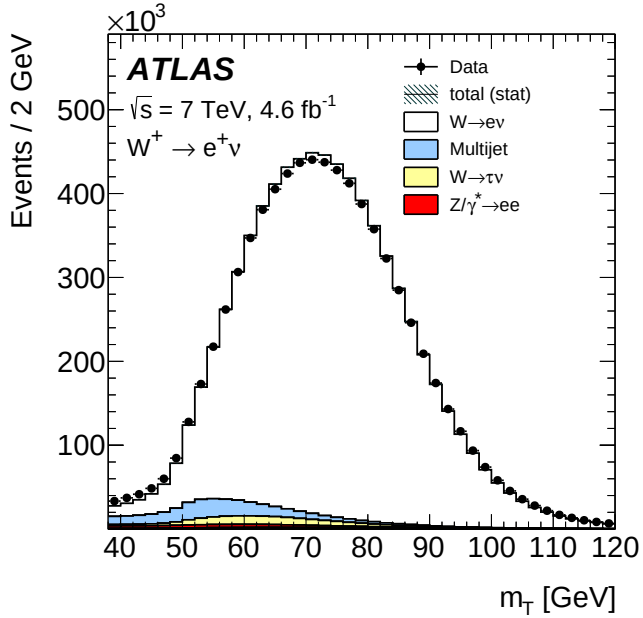
- $\sim 12.7\,\mathrm{M}$ $W \to e\nu$ and $\sim 15.5\,\mathrm{M}$ $W \to \mu\nu$ candidate events
- in a fiducial phase space of $p_{\mathrm{T},\ell} > 25$ GeV, $|\eta_\ell| < 2.5$ GeV, $p_{\mathrm{T},\nu} > 25$ GeV, $m_{\mathrm{T}} > 40$ GeV
- with backgrounds contributing 7.7% and 8.3%, respectively
- pseudo-rapidity of charged lepton provides sensitivity to different initial states

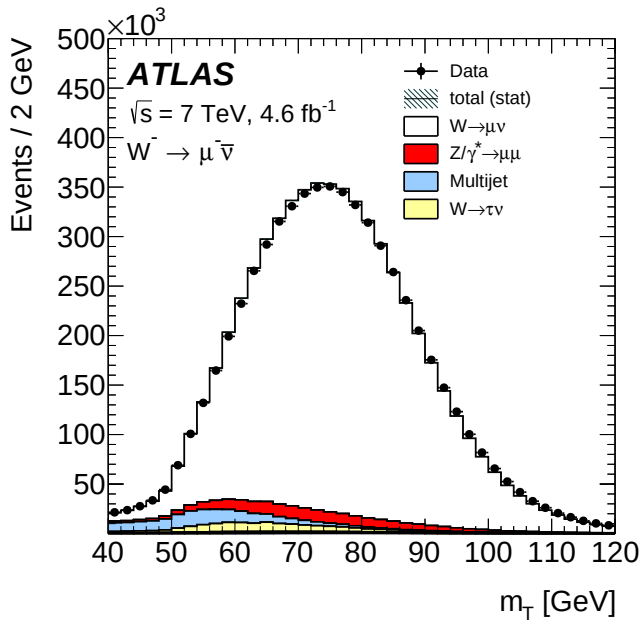
→ measurement is performed in 10 bins of $|\eta_\ell|$

- capture cross-section shape while assuring control of local detector effects



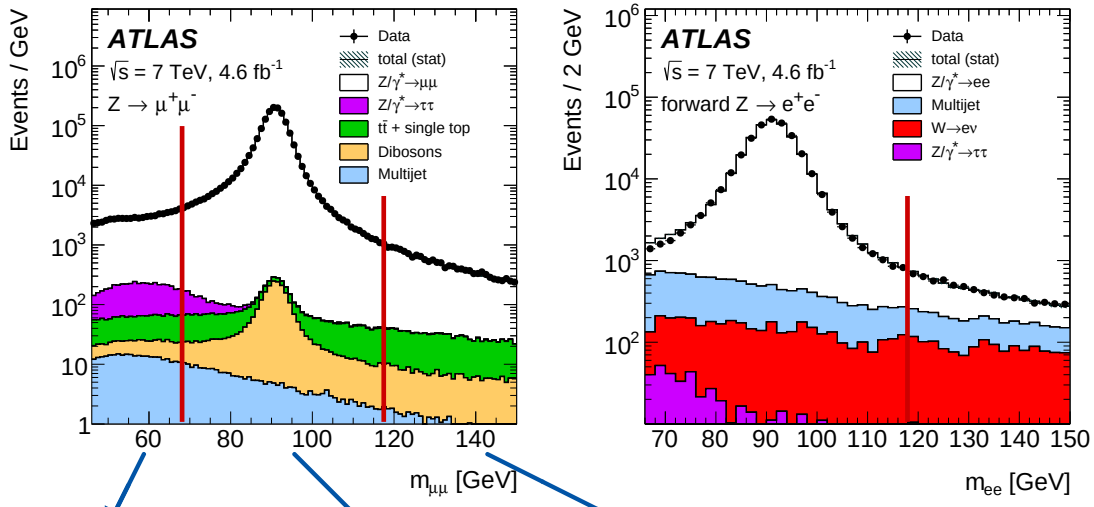


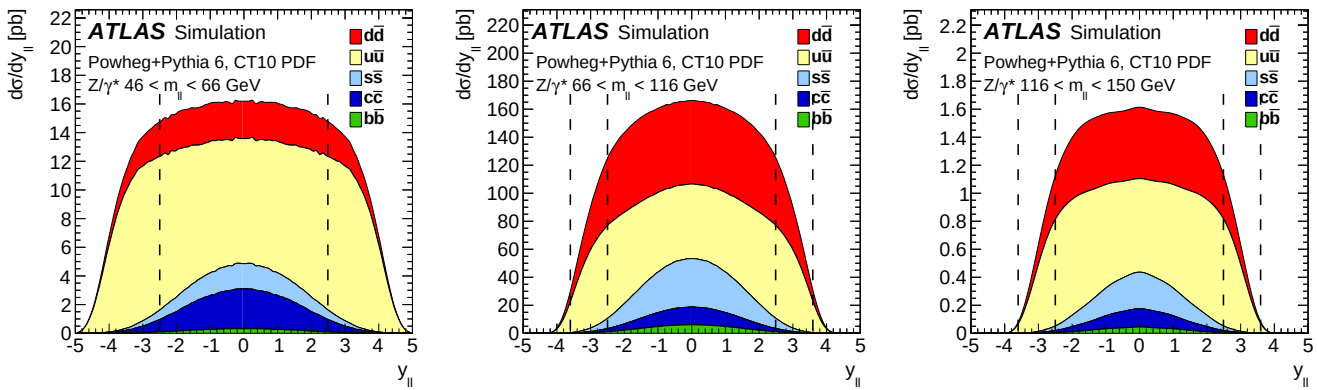




$Z \to \ell\ell$ Analysis

- the analysis of $Z \to \ell\ell$ events is performed in slices of M_{ll}
- using events with central leptons ($|\eta| < 2.5$) and with a central lepton and a forward electron ($2.5 < |\eta| < 4.9$)
- $\sim 1.3\,\mathrm{M}$ $Z \to ee$ and $\sim 1.6\,\mathrm{M}$ $Z \to \mu\mu$ candidate events
- in a fiducial phase space of $p_{\mathrm{T},\ell} > 20$ GeV, and η
- background contributing $< 0.5\%$ (central-central) and 2.9% (central-fwd)





- sensitivity to PDF by performing measurements in bins of $0 < |y_{\ell\ell}| < 2.4$ (central-central)
- by using central-forward events can extend the measurement to $1.2 < |y_{\ell\ell}| < 3.6$

Systematic Uncertainties

- the differential $W \to \ell\nu$ and $Z \to \ell\ell$ cross sections were already measured in 2010 data Phys.Rev. D85 (2012) 072004
- to improve on this measurement requires a better understanding of the detector performance

electrons

2010 data, 36 pb^{-1}	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
QCD background	0.4	0.4	0.4	0.7
E_T^{miss} scale and resolution	0.8	0.7	1.0	—
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity		3.4		

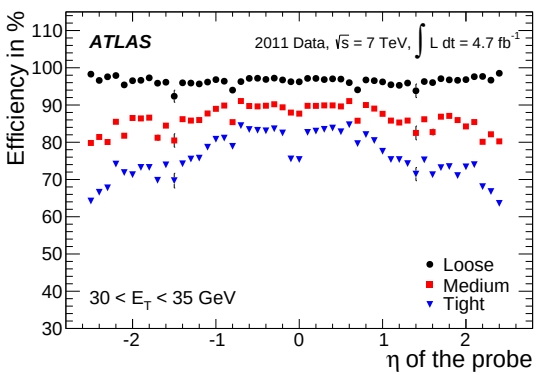
2011 data, 4.6 fb^{-1}	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$	$\delta\sigma_{\text{forward }Z}$
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
E_T^{miss} soft term scale	0.14	0.13	–	–
E_T^{miss} soft term resolution	0.06	0.04	–	–
Multijet background	0.55	0.72	0.03	0.05
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity			1.8	

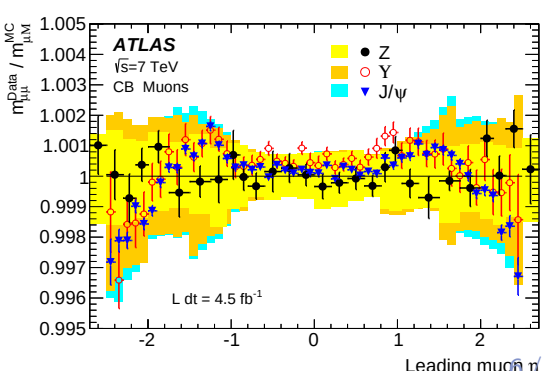
muons

2010 data, 36 pb^{-1}	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_T resolution	0.04	0.03	0.05	0.02
Muon p_T scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity		3.4		

2011 data, 4.6 fb^{-1}	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_T resolution	0.01	0.01	<0.01
Muon p_T scale	0.18	0.17	0.03
Multijet background	0.33	0.27	0.07
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

- dramatic reduction of uncertainties related to lepton and E_T^{miss} reconstruction
- uncertainty on luminosity determination reduced to ±1.8%





Cross Sections & Lepton Universality

- fiducial cross sections are calculated for W^+, W^- and Z production

	$\sigma^{\text{fid}}_{W\to\ell\nu}$ [pb]
$W^+ \to e^+\nu$	$2939 \pm 1\,(\text{stat}) \pm 28\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \mu^+\nu$	$2948 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \ell^+\nu$	$2947 \pm 1\,(\text{stat}) \pm 15\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^- \to e^-\bar{\nu}$	$1957 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 35\,(\text{lumi})$
$W^- \to \mu^-\bar{\nu}$	$1964 \pm 1\,(\text{stat}) \pm 13\,(\text{syst}) \pm 35\,(\text{lumi})$
$W^- \to \ell^-\bar{\nu}$	$1964 \pm 1\,(\text{stat}) \pm 11\,(\text{syst}) \pm 35\,(\text{lumi})$
$W \to e\nu$	$4896 \pm 2\,(\text{stat}) \pm 49\,(\text{syst}) \pm 88\,(\text{lumi})$
$W \to \mu\nu$	$4912 \pm 1\,(\text{stat}) \pm 32\,(\text{syst}) \pm 88\,(\text{lumi})$
$W \to \ell\nu$	$4911 \pm 1\,(\text{stat}) \pm 26\,(\text{syst}) \pm 88\,(\text{lumi})$
	$\sigma^{\text{fid}}_{Z/\gamma^*\to\ell\ell}$ [pb]
$Z/\gamma^* \to e^+e^-$	$502.7 \pm 0.5\,(\text{stat}) \pm 2.0\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \mu^+\mu^-$	$501.4 \pm 0.4\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \ell\ell$	$502.2 \pm 0.3\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 9.0\,(\text{lumi})$

- significant improvement of precision by combining lepton flavours

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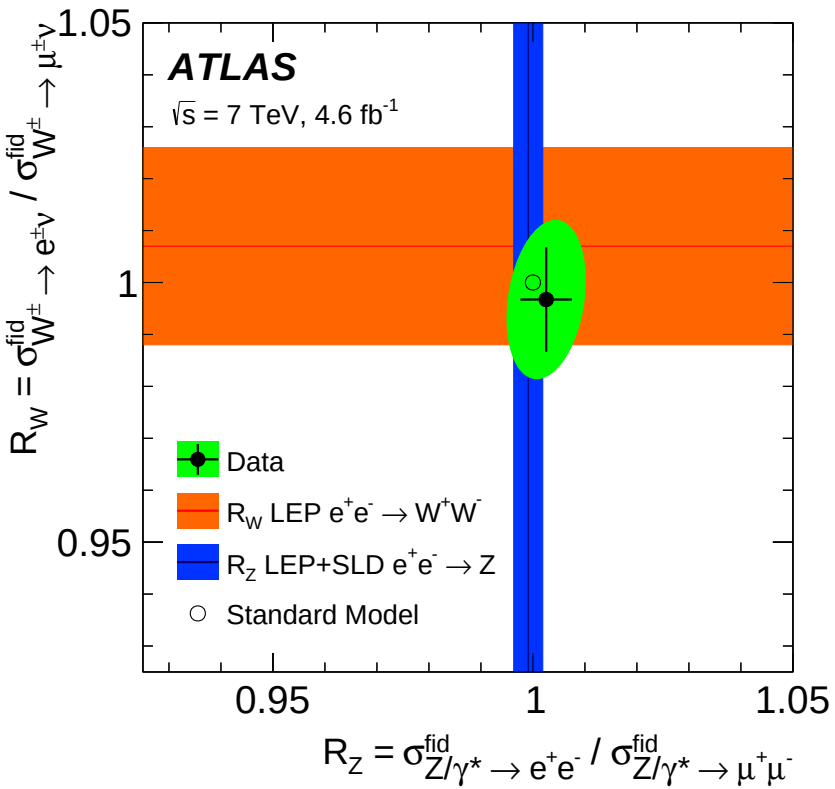
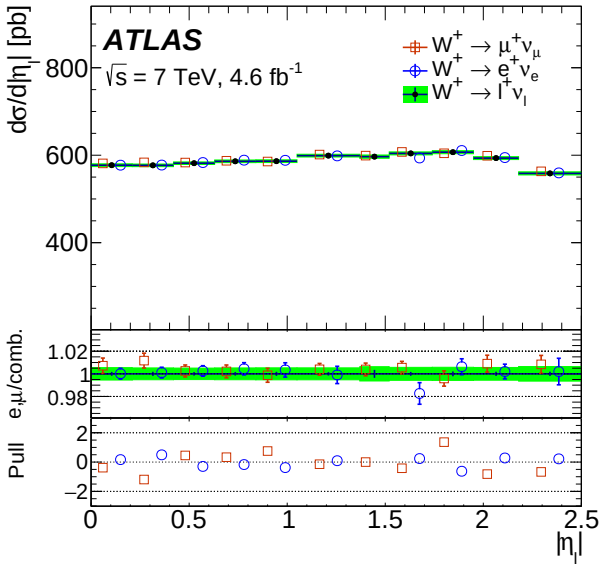
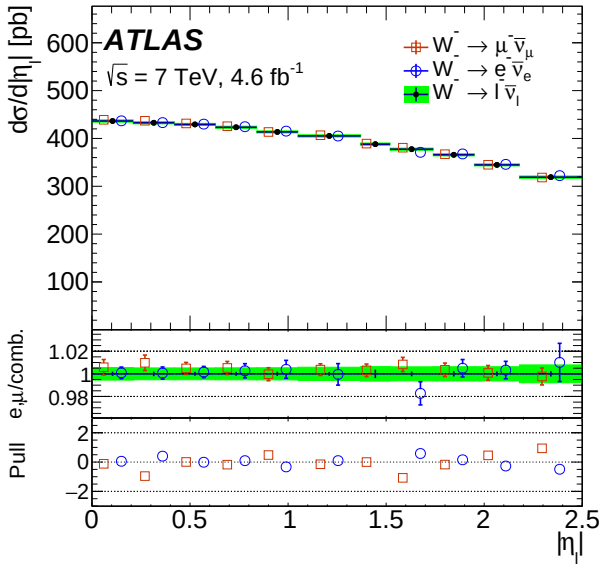


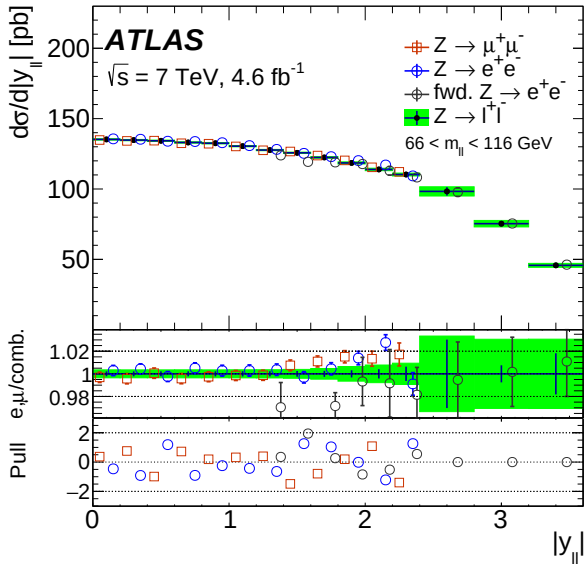
- significant improvement of precision by combining lepton flavours

- ratios of the measured cross sections in electron and muon decay channels are used to measure the relative branching fractions
- due to cancellation of correlated uncertainties reach a precision of 1% and 0.5% for W and Z branching fractions, respectively
- improvement over previous on-shell $W \to \ell\nu$ results from the LEP and LHC experiments

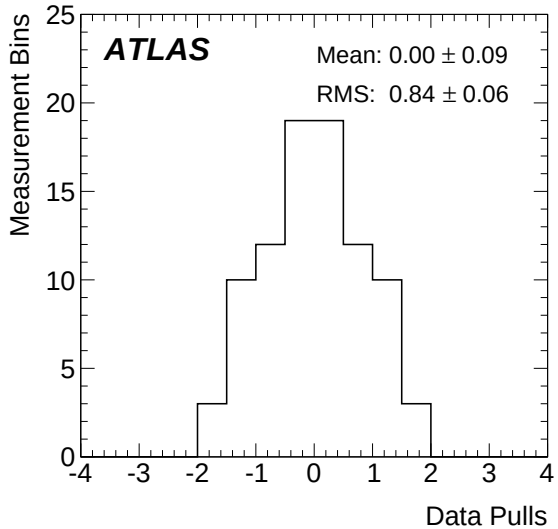
Combination of Measurements







- a χ^2 fit is performed to combine the measurements in e and μ final states (assuming lepton universality)
- small extrapolation to a common e and μ fiducial region for $W \to \ell\nu$, $Z \to \ell\ell$ (central) and $Z \to ee$ (fwd) individually
- excellent agreement found between e and μ final states within the uncorrelated part of the systematic uncertainty



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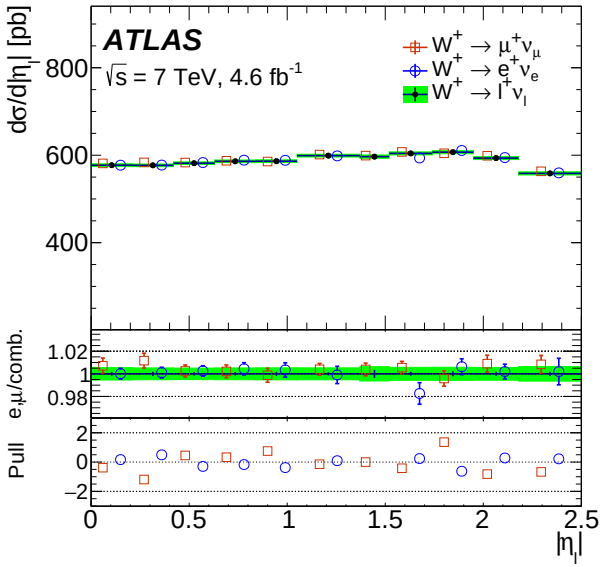

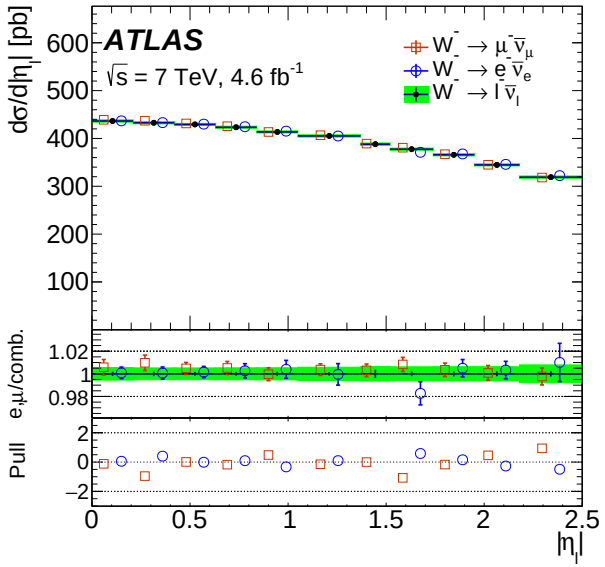

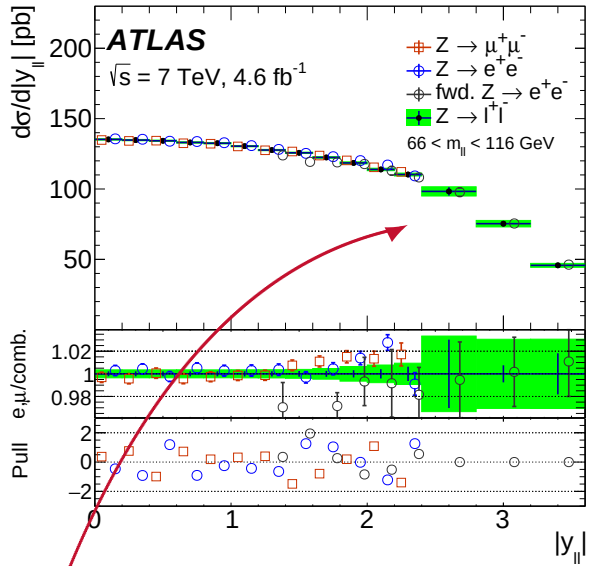

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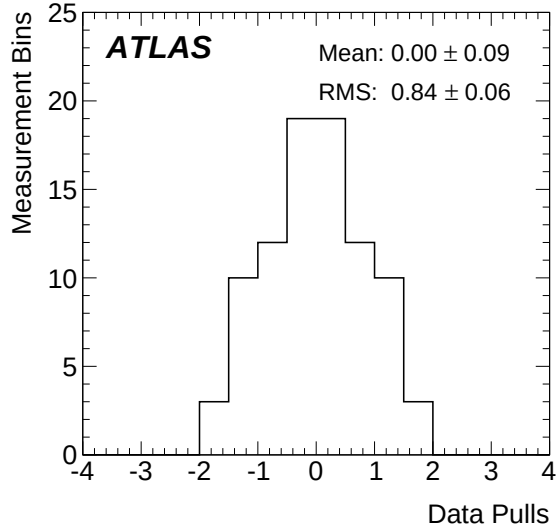
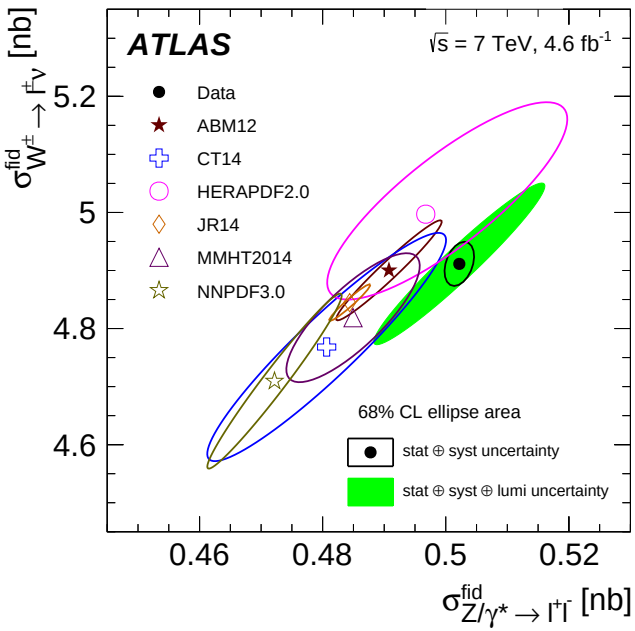
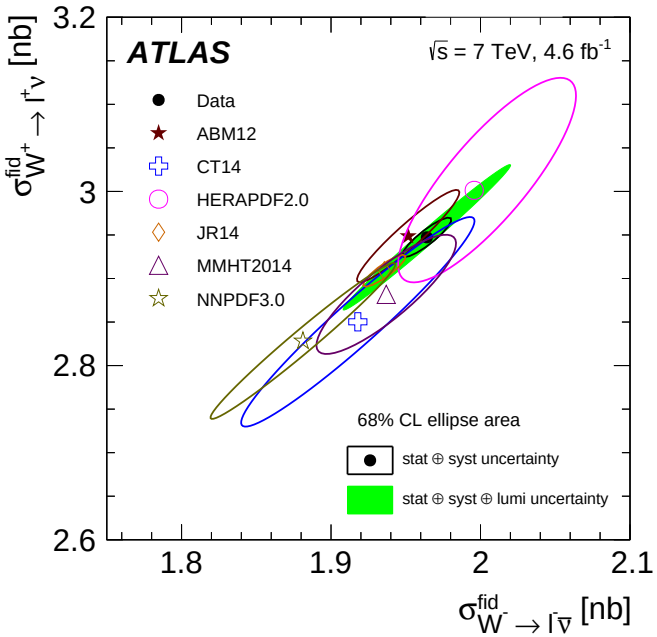
- small extrapolation to a common e and μ fiducial region for $W \to \ell\nu$, $Z \to \ell\ell$ (central) and $Z \to ee$ (fwd) individually
  (only for the purpose of *plotting*, $Z \to \ell\ell$ was extrapolated to "full η")
- excellent agreement found between e and μ final states within the uncorrelated part of the systematic uncertainty

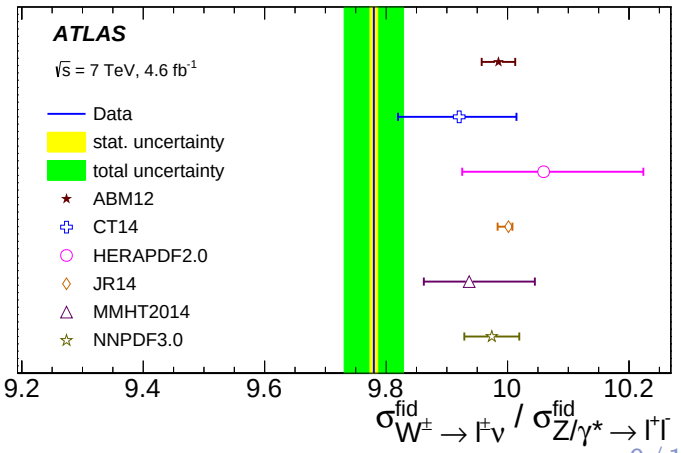


Comparison to Theory



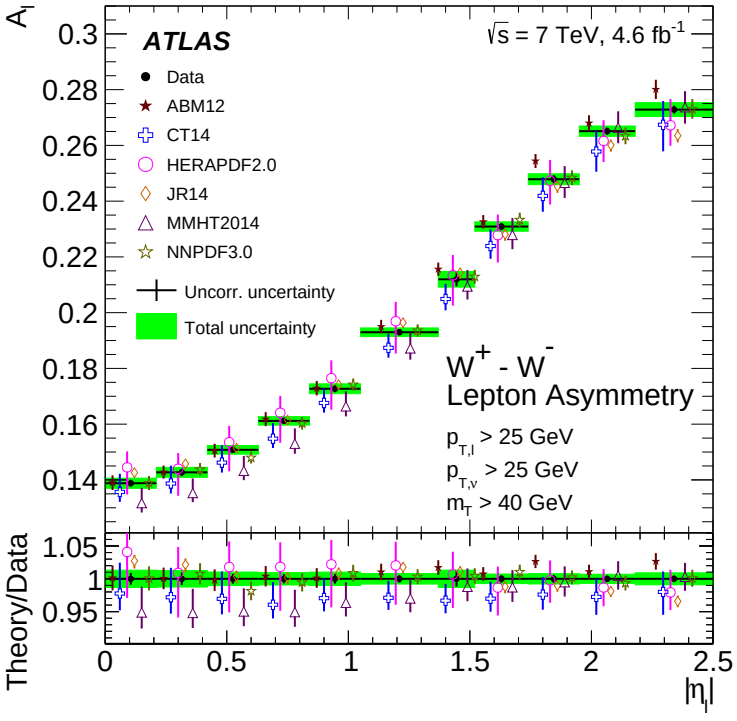


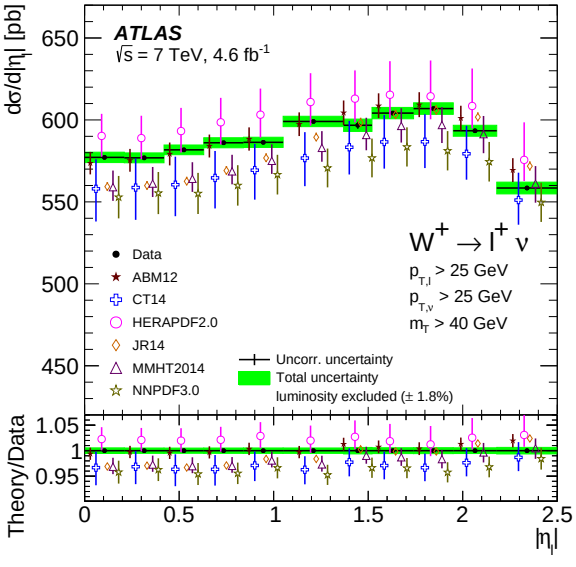
- the small uncertainties on the measured fiducial cross sections allow to discriminate between different PDFs
- due to large correlations this particularly applies to ratios
- predictions for $W^{\pm}/Z$ ratio systematically higher than measured in data
- the W^{+}/W^{-} ratio is generally well reproduced

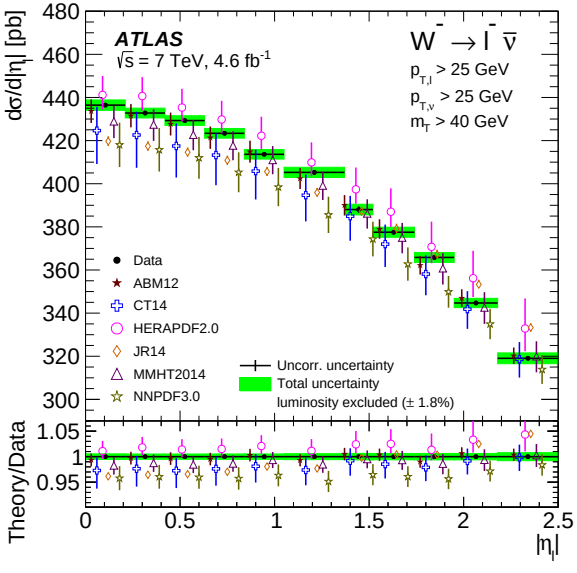


Differential $W \to \ell\nu$ Measurements

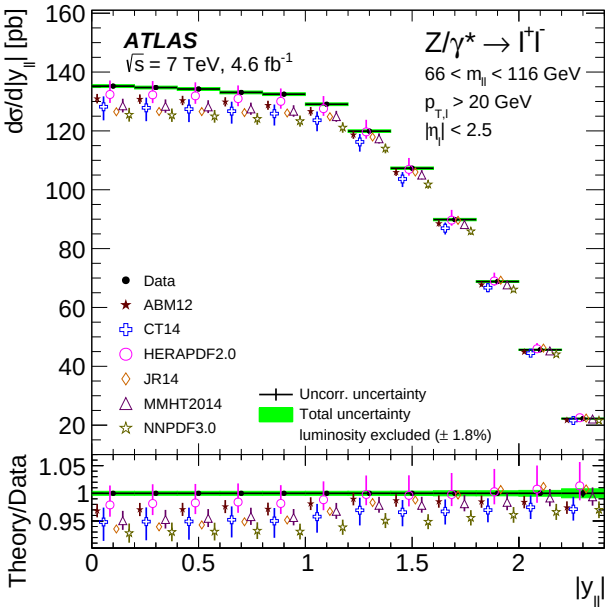
- shape of differential W cross sections generally well described
- particularly good description of the differential lepton charge asymmetry A_ℓ
- differences in PDF sets seen in the overall normalisation
- a precise measurement of the absolute cross section provides valuable information despite larger uncertainties

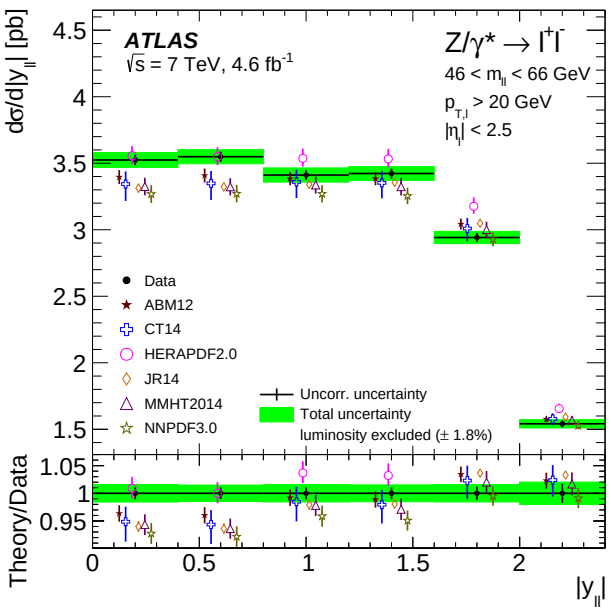


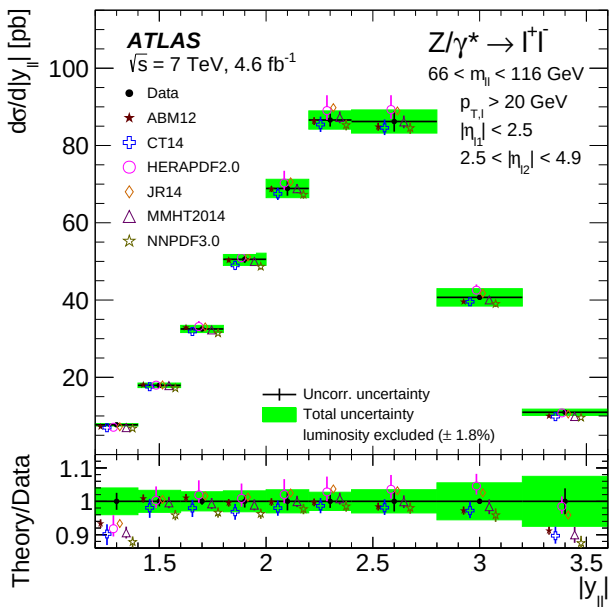




Differential $Z \to \ell\ell$ Measurements

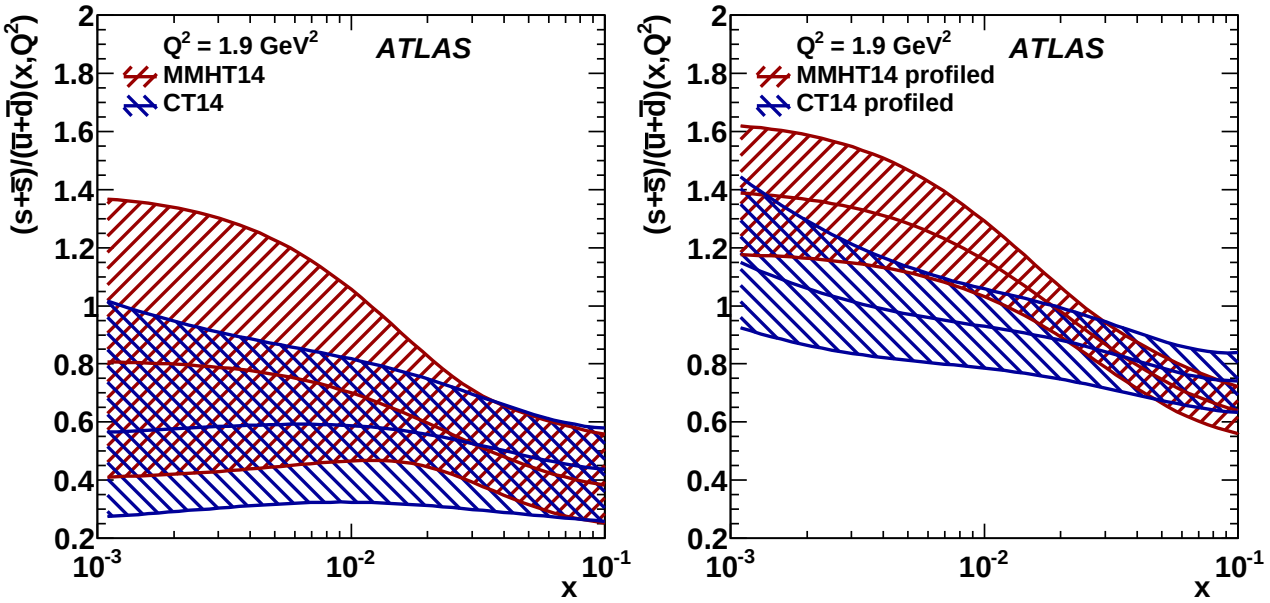




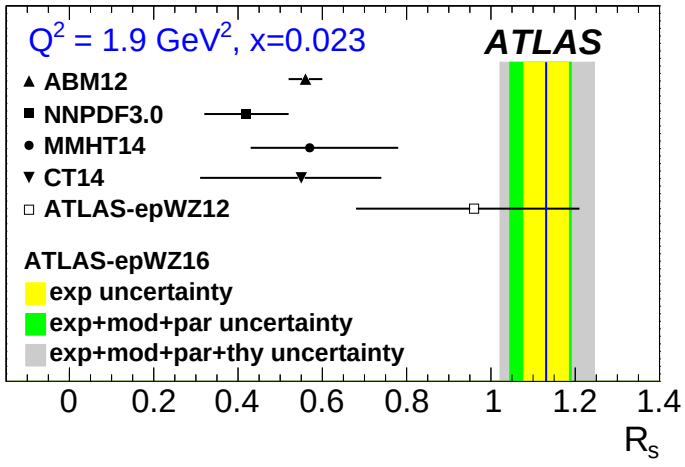


- differences in the rapidity dependence between data and theoretical predictions
- at the Z resonance the data can also provide information on the normalisation
- at central rapidity the theoretical predictions are lower by 3-5%
- in the forward region the measurement is not sensitive to differences between PDFs

PDF Profiling



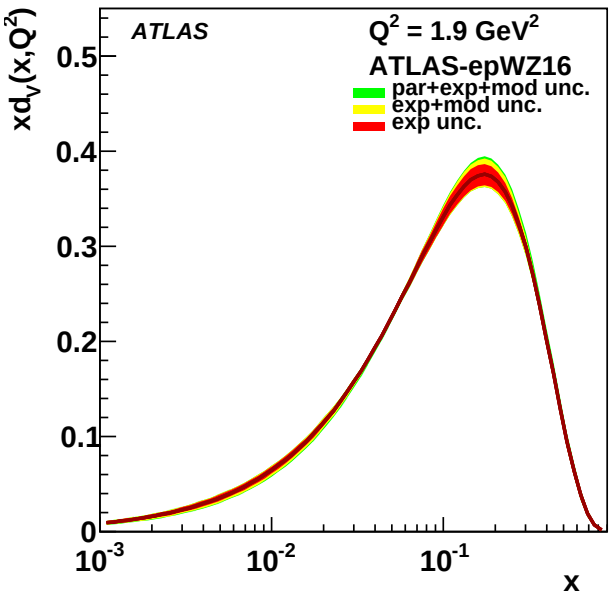
- quantitative assessment of agreement of PDFs with data by profiling PDFs in the fit
- best match: CT14 with $\chi^2/\text{n.d.f.} = 103/61$
  worst match: NNPDF3.0 with $\chi^2/\text{n.d.f.} = 147/61$

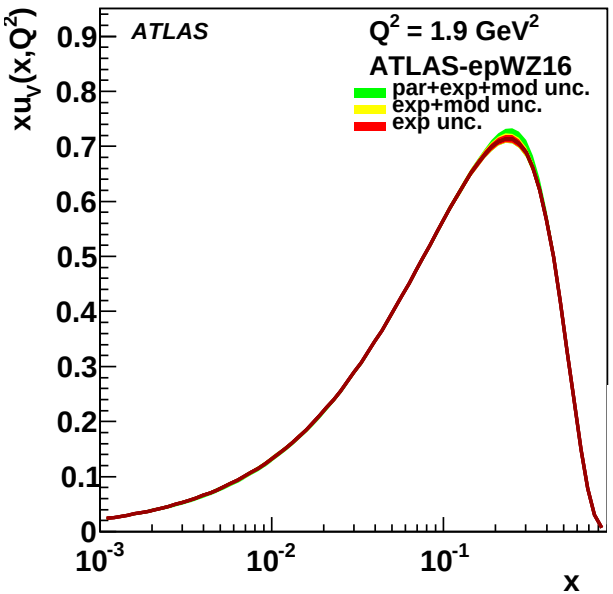


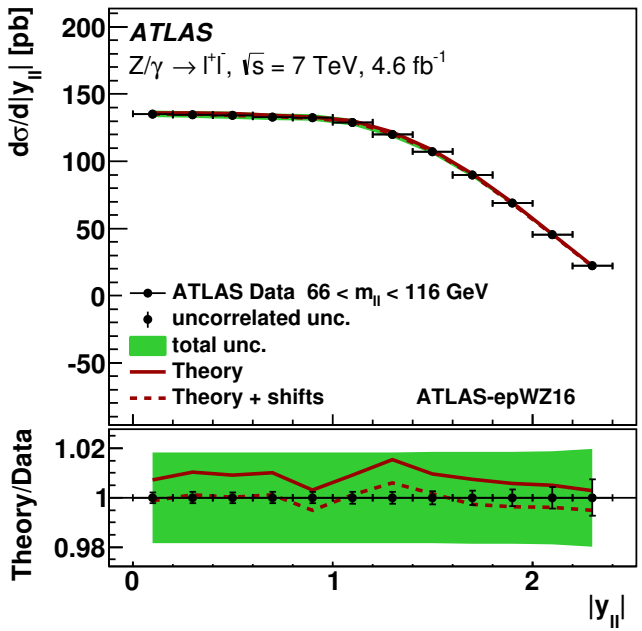
- profiling the PDFs by introducing data provides constraints on the central values and the uncertainties
- most notable is the shift of the strange sea fraction to higher values
- leading to a reduction of the light sea quark density

QCD Analysis

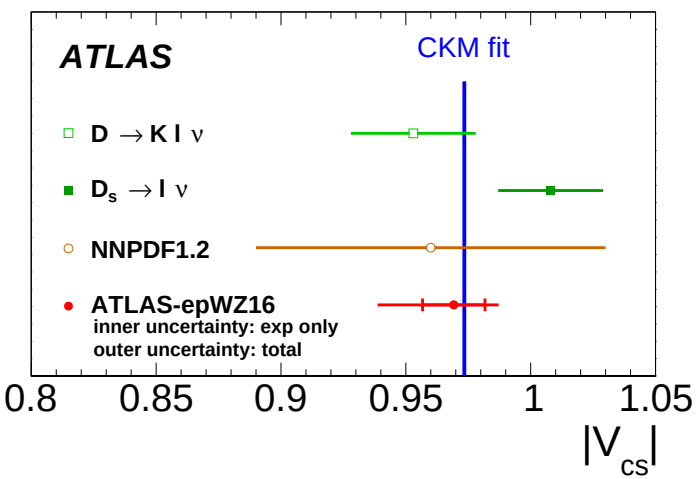
- the data is combined with *ep* data from H1 and ZEUS
- to obtain a new PDF set, ATLAS-epWZ2016





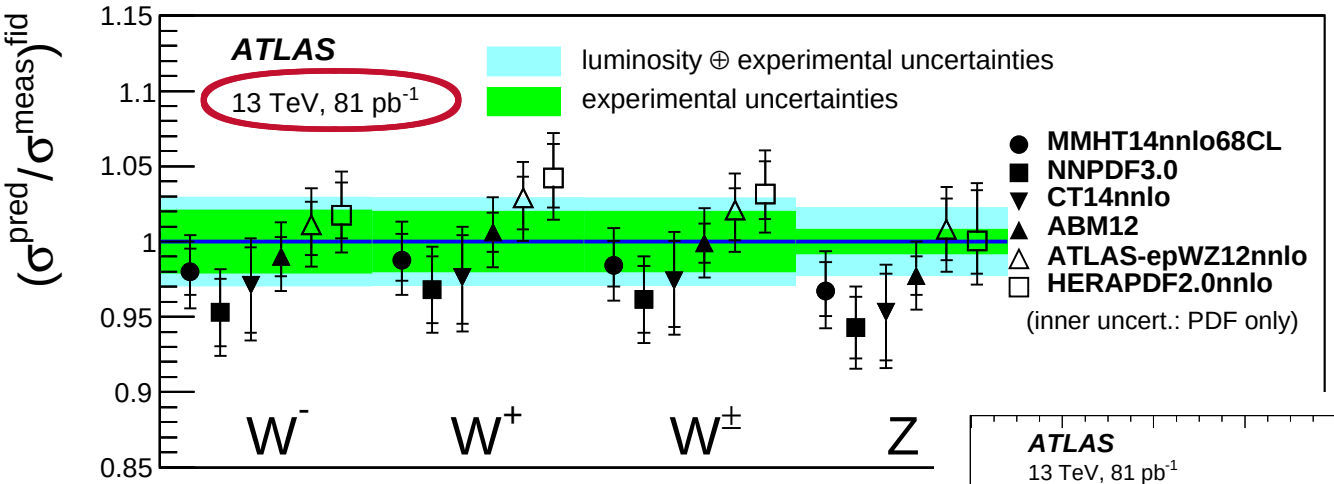


- the ATLAS data adds information on the flavour composition of the quark-sea and the valence-quark distribution at lower x
- letting $|V_{cs}|$ free floating in the fit provides a competitive direct measurement

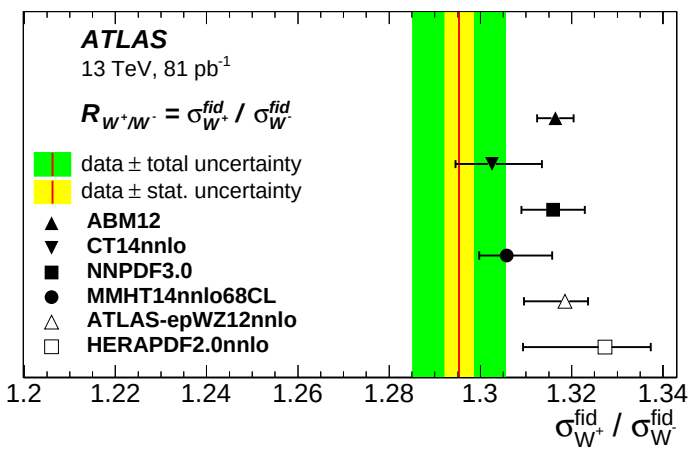


Outlook

- first measurement available at $\sqrt{s} = 13$ TeV, using 81 pb^{-1} of data from 2015
- results on integrated fiducial cross sections and cross section ratios



Phys. Lett. B 759 (2016) 601



- the measurements probe to lower values of x
- confirmation of the trends seen at 7 TeV but results are generally less precise
- by now the data collected at 13 TeV increased by > 400
- our understanding of the detector has since improved considerably but there is a lot of work ahead to bring down the uncertainties to the level of 2011

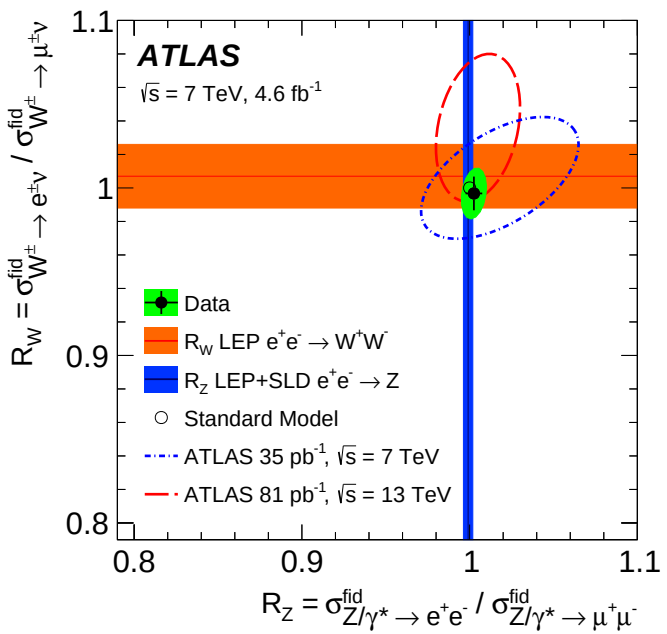
Summary

- measurement of integrated and differential fiducial $W \to \ell\nu$ and $Z \to \ell\ell$ cross sections in pp collisions at $\sqrt{s} = 7$ TeV
- improving precision of previous measurement of fiducial Z (W) cross sections by $\times 10$ ($\times 3.5$)
- one of the most precise measurements at the LHC, more precise than theoretical predictions

- measurement used to derive a set of parton distribution functions ATLAS-epWZ16
- evidence for enhanced strange quark density at low x & Q^2

- much more data have been collected since 2011
- it will take a few years of work to understand them to a level that can improve the precision reached at $\sqrt{s} = 7$ TeV

- for more details see **arXiv:1612.03016**, submitted to EPJC



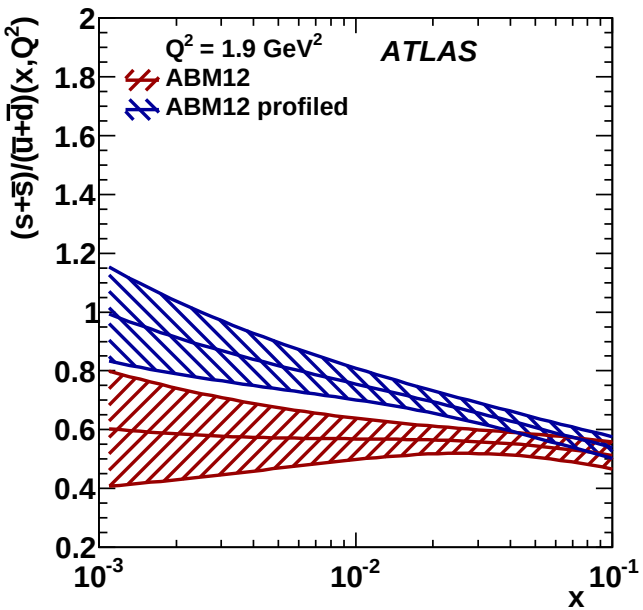
Backup

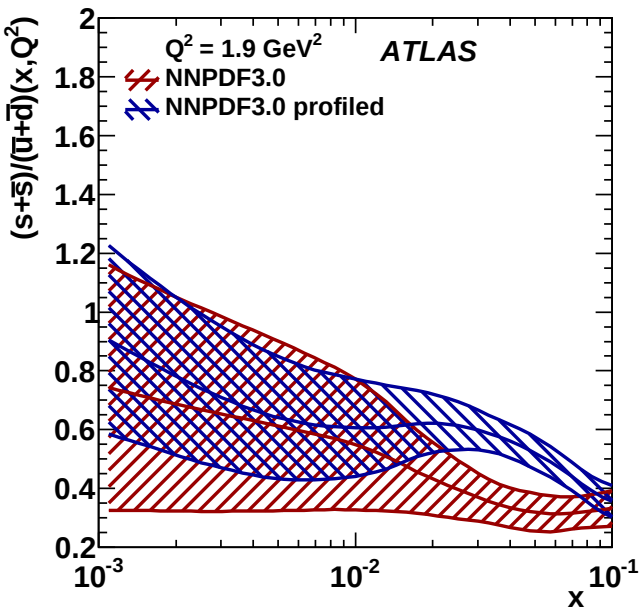
Profiling PDFs

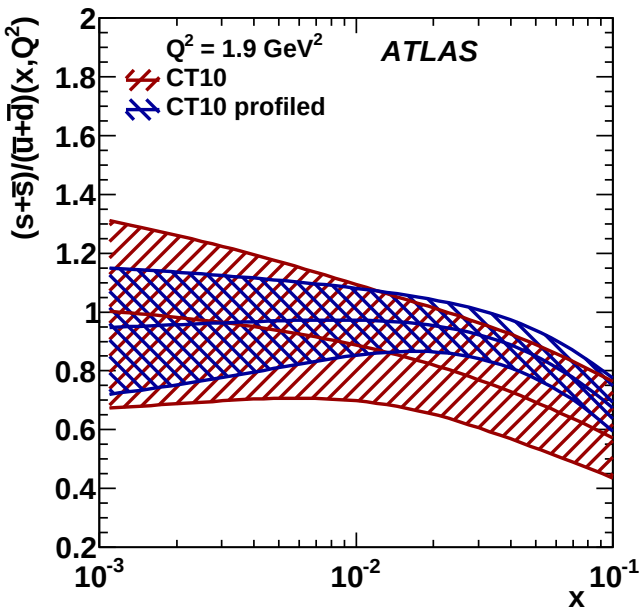
Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+\nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^-\bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46 - 66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

- χ^2 values including | excluding PDF uncertainties

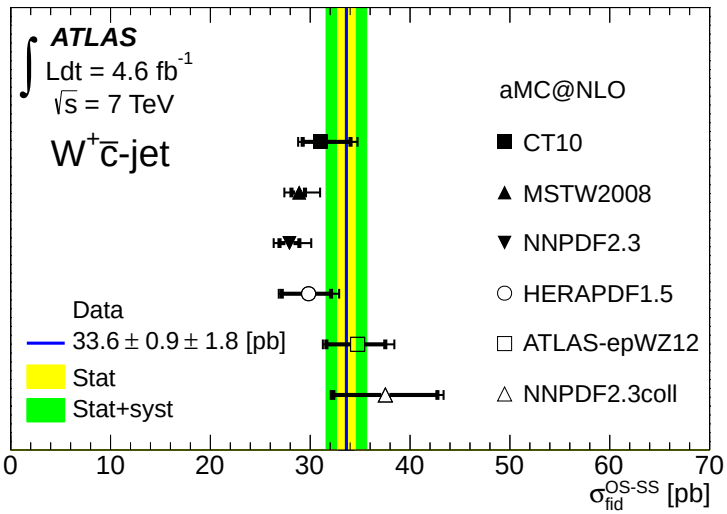
Profiling of the Strange Sea Fraction

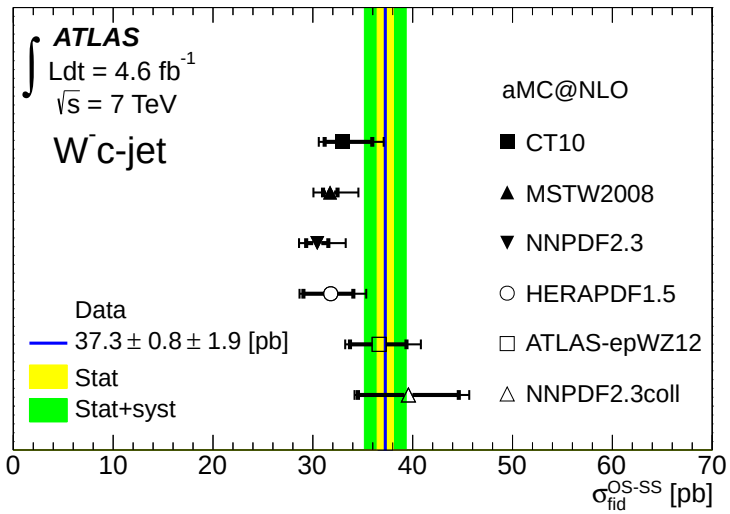






W+charm, JHEP05(2014)068





- theoretical predictions from aMC@NLO at NLO
- uncertainties from μ_R and μ_F variations: $+8/-4\%$
- experimental uncertainty on measurement: $\sim 6\%$

Systematic Uncertainties, Electrons

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]	$\delta\sigma_{\text{forward } Z}$ [%]
Trigger efficiency	0.03	0.03	0.05	0.05
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
Forward identification efficiency	–	–	–	1.51
Isolation efficiency	0.03	0.03	–	0.04
Charge misidentification	0.04	0.06	–	–
Electron p_{T} resolution	0.02	0.03	0.01	0.01
Electron p_{T} scale	0.22	0.18	0.08	0.12
Forward electron p_{T} scale + resolution	–	–	–	0.18
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.14	0.13	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.06	0.04	–	–
Jet energy scale	0.04	0.02	–	–
Jet energy resolution	0.11	0.15	–	–
Signal modelling (matrix-element generator)	0.57	0.64	0.03	1.12
Signal modelling (parton shower and hadronization)	0.24	0.25	0.18	1.25
PDF	0.10	0.12	0.09	0.06
Boson p_{T}	0.22	0.19	0.01	0.04
Multijet background	0.55	0.72	0.03	0.05
Electroweak+top background	0.17	0.19	0.02	0.14
Background statistical uncertainty	0.02	0.03	<0.01	0.04
Unfolding statistical uncertainty	0.03	0.04	0.04	0.13
Data statistical uncertainty	0.04	0.05	0.10	0.18
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity			1.8	

Systematic Uncertainties, Muons

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.19	0.19	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
Signal modelling (parton shower and hadronization)	0.14	0.17	0.22
PDF	0.09	0.12	0.07
Boson p_{T}	0.18	0.14	0.04
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	