Single boson production and differential cross section measurements in ATLAS

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on behalf of the ATLAS Collaboration

The Fifth Annual Large Hadron Collider Physics Conference

Shanghai Jiao Tong University, 15-20 May 2017

Parallel session EWK I

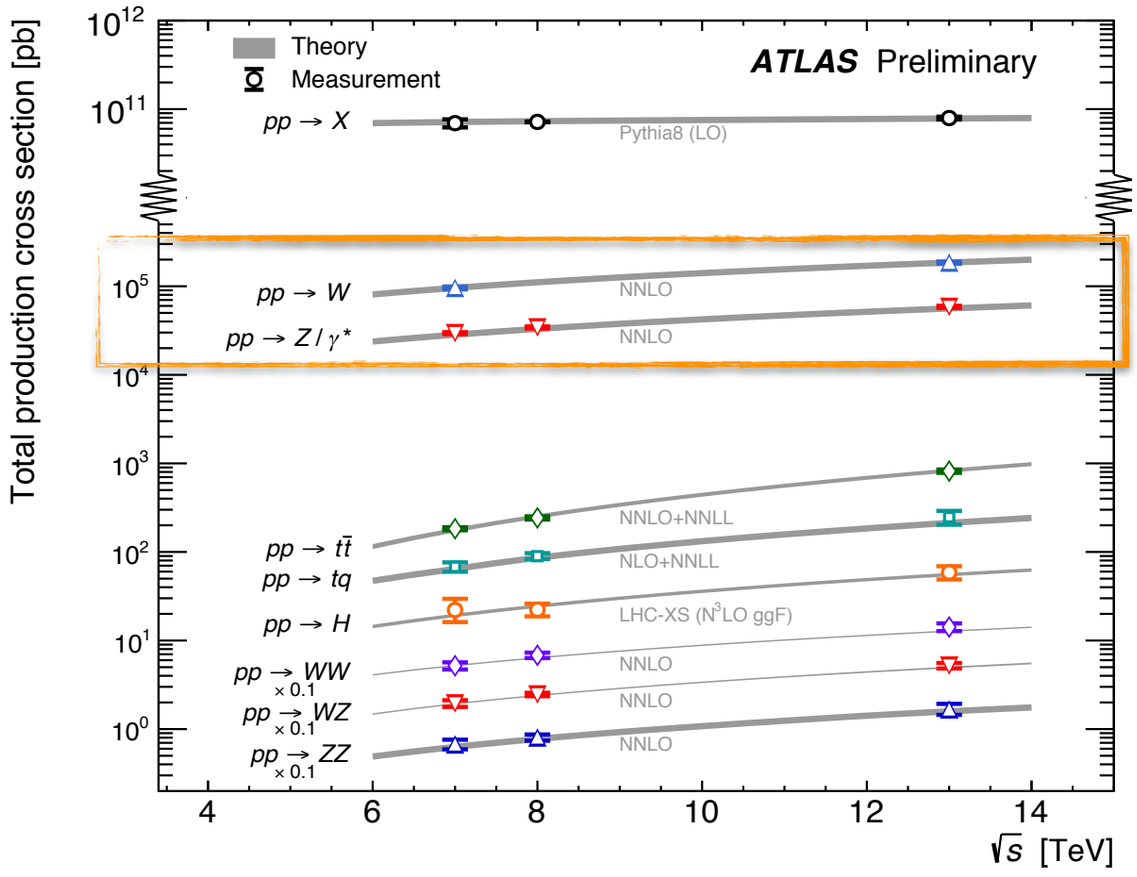
ATLAS EXPERIMENT

UNIVERSITY OF CALIFORNIA SANTA CRUZ

Overview

Drell-Yan production:

- theoretically described at ***NNLO QCD*** and ***NLO EW***
- very ***high-statistics process at LHC*** → reach of ***high experimental precision***
- measurement that can be used to ***extract*** all the relevant ***information on calculation inputs***, to improve their precision
- largest ***DY uncertainties*** (on calculations from FEWZ and DYNNLO)
  - ~1.1% from ***scale*** variations
  - ~2.5% from ***PDFs*** → the measurements can help particularly in constraining these



In this talk:

- W,Z precision measurements @ 7 TeV
- tt/Z ratios @ different √s

Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector

$\sqrt{s}$=7 TeV, 4.6 fb^{-1}

http://inspirehep.net/record/1502620

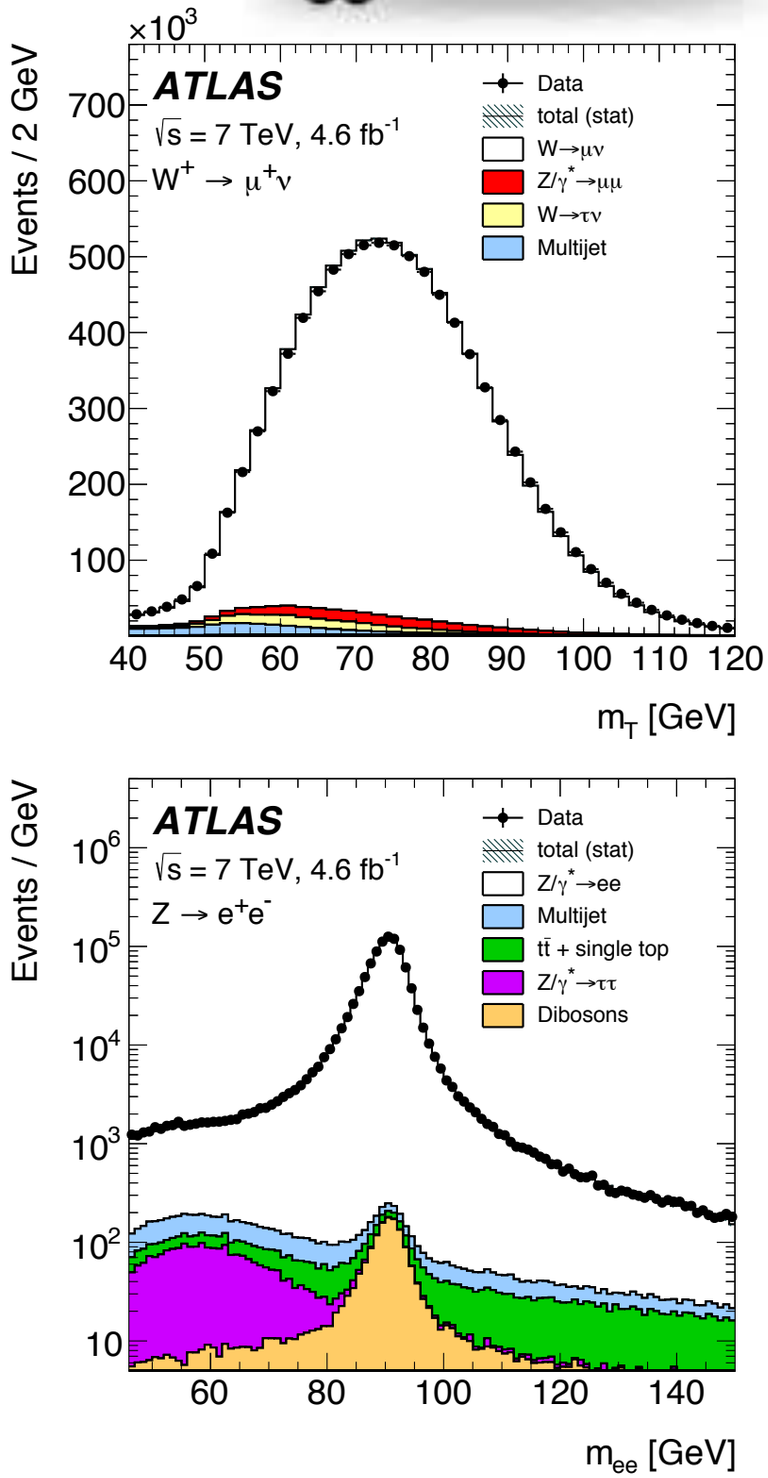
submitted to EPJC

Analysis overview

- Looking at ***~30M candidate W's***, and ***~3M candidate Z's*** (combining e and μ channels)

- ***Fiducial selection:***
  - ***W:*** p_T^ℓ>25 GeV, $|\eta^\ell|$<2.5, p_T^ν>25 GeV, m_T>40 GeV
  - ***Z:*** p_T^ℓ>20 GeV, one lepton with $|\eta^\ell|$<2.5, and another one either in the same η^ℓ range (***CC***-category), or in the forward region: 2.5<$|\eta^\ell|$<4.9 (***CF***)

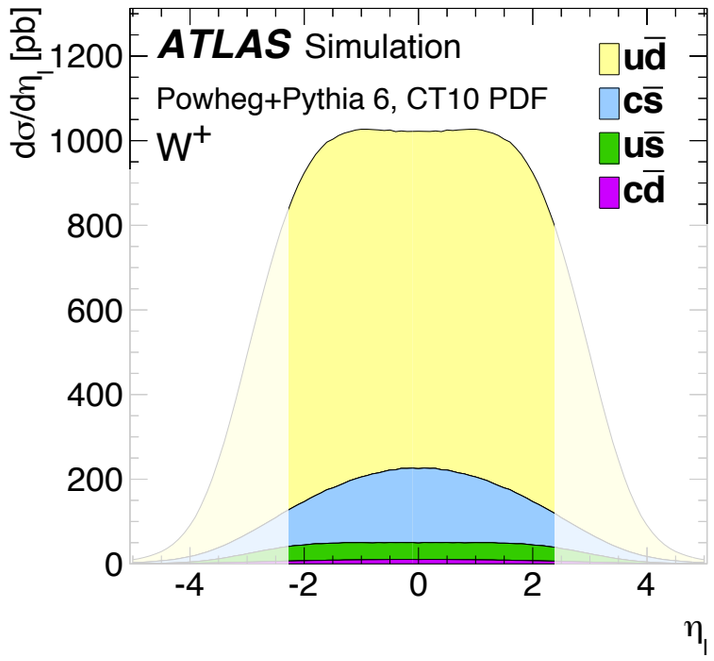
- ***Background*** ~8% in the W case, and <1% (~3%) in Z CC (CF)
  - mostly estimated from Monte Carlo, apart from QCD multijet, using data-driven techniques

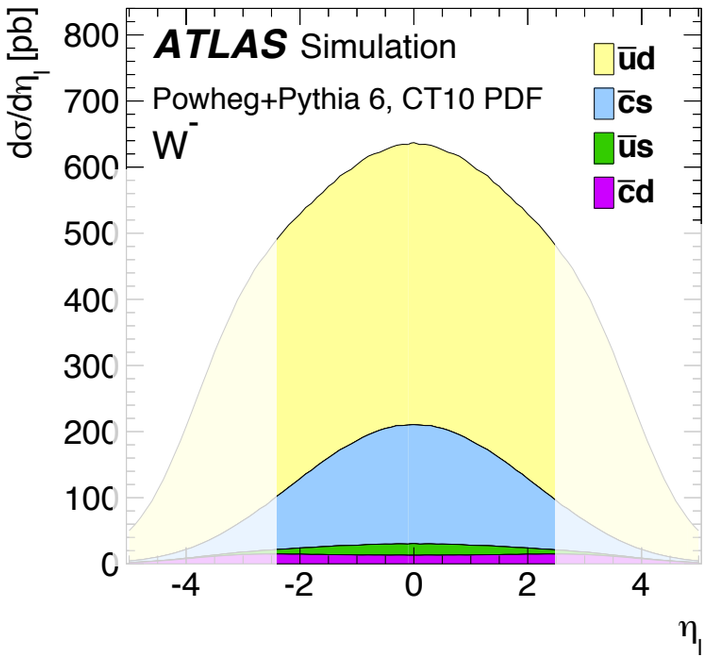


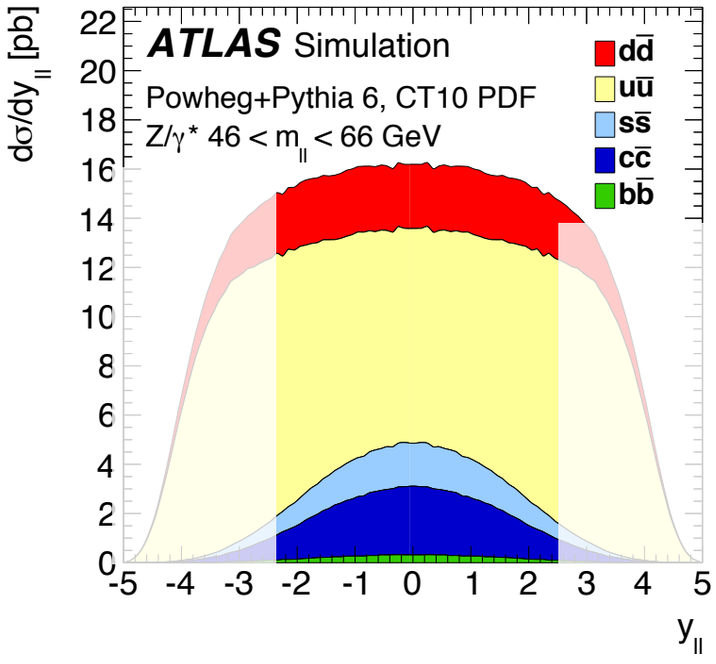
Measurement strategy

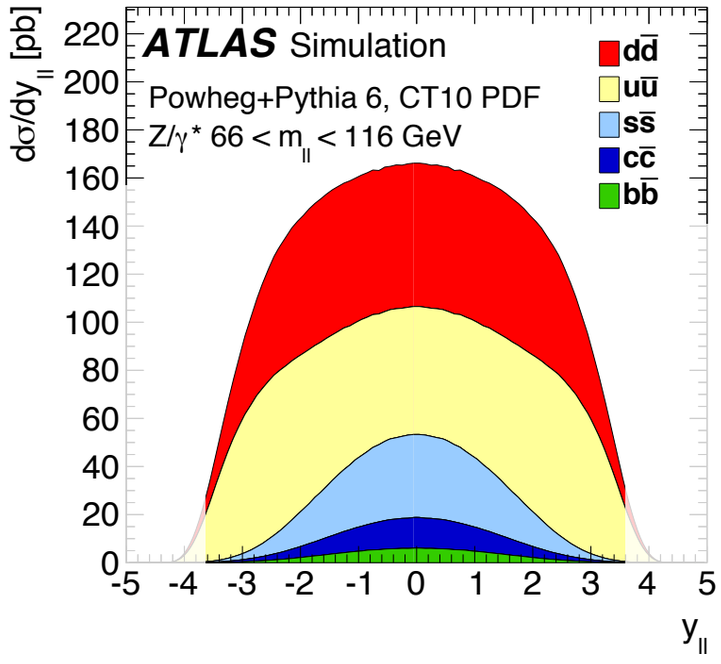
Measurement differential in:

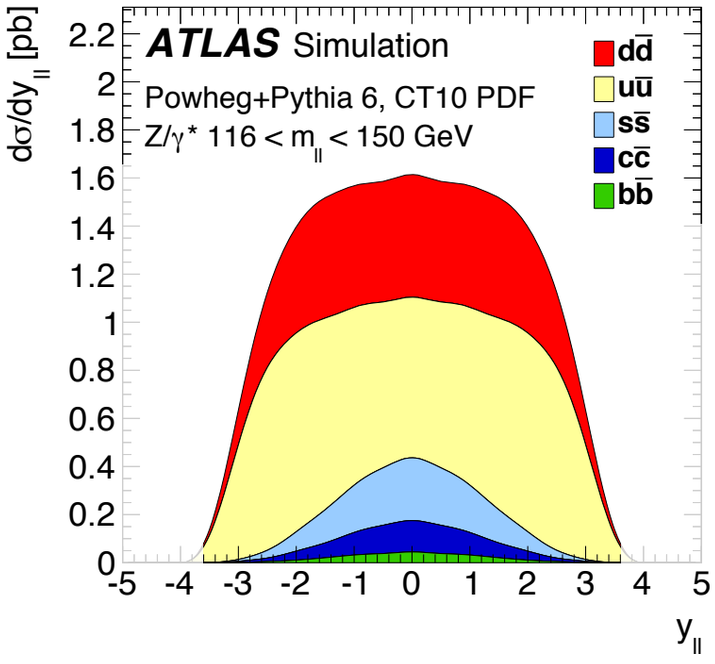
- W analysis: $|\eta^{\ell}|$ → 10 bins, providing information on different initial states
- Z analysis: in 3 $m_{\ell\ell}$ slices [46-66], [66-116], [116-150] GeV → bins of $y_{\ell\ell}$: $0<|y_{\ell\ell}|<2.4$, extended to $1.6<|y_{\ell\ell}|<3.6$ for CF channel











Detector-level uncertainties

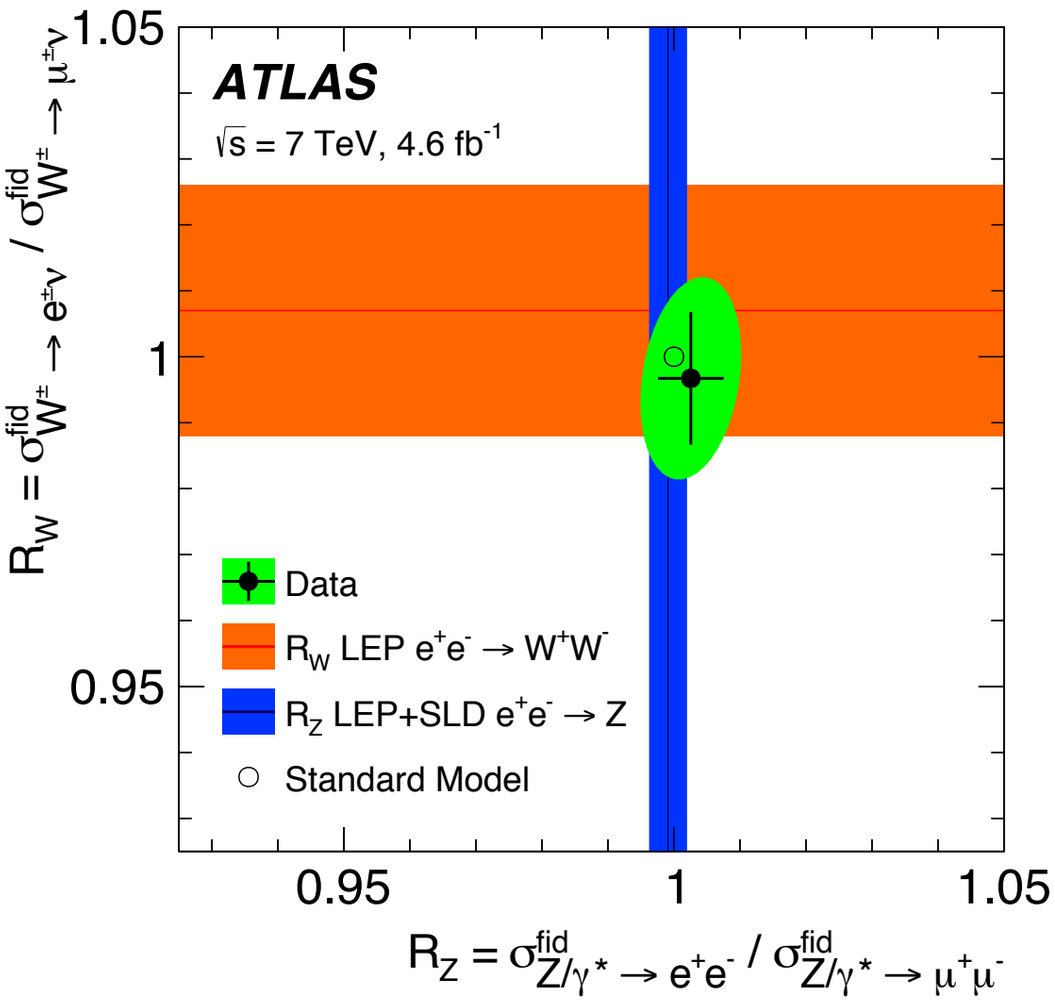
- The ***main*** experimental ***uncertainties*** come from the reconstruction efficiencies of the leptons, the W signal modelling, and the data-driven QCD background estimate

- Very thorough and complex work to achieve ***dramatic uncertainty reduction*** (up to 60% for lepton and missing energy, halved lumi unc), compared to previous W,Z cross section measurement with 7 TeV data by ATLAS (https://inspirehep.net/record/928289)

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
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	

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]	$\delta\sigma_{\text{forward } Z}$ [%]
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	

Lepton universality (& inclusive σ measurement)



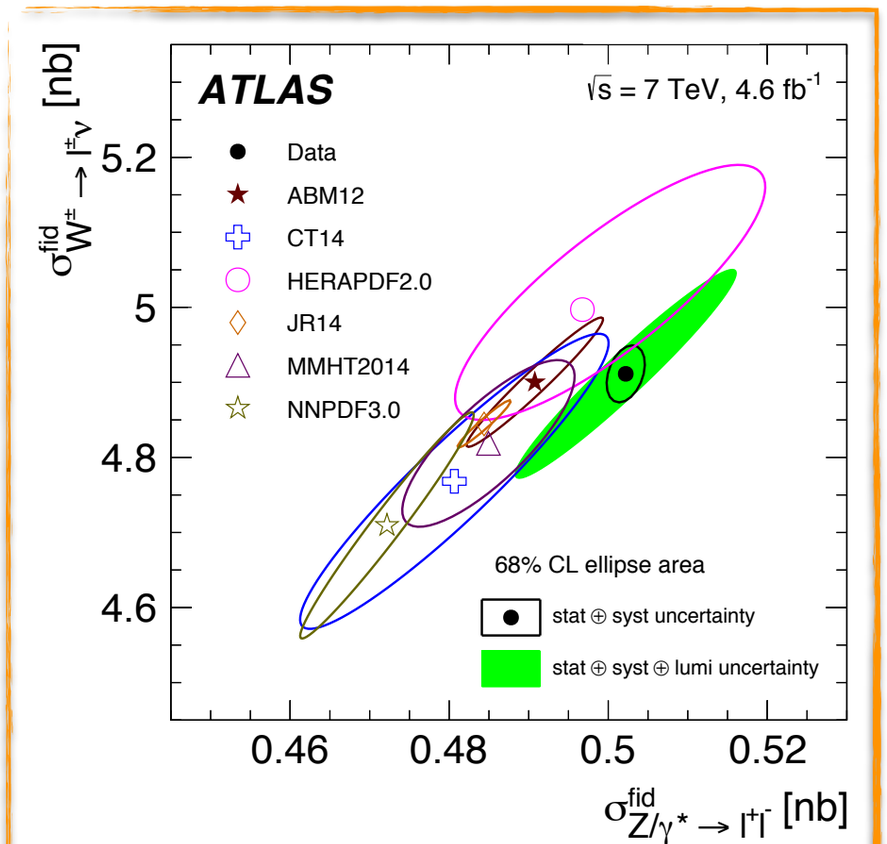
Lepton universality from fiducial measurement in the e and μ channels

- Achieve very high precision, improving previous on-shell W results from LEP, due to cancellations of correlated uncertainties
  - 1% precision on W, 0.5% precision on Z BR's

*The **combination** of fiducial cross sections allows to reach **high precision** in the measurement*

	$\sigma^{\text{fid}}_{W\to\ell\nu}$ [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]
$Z/\gamma^* \to e^+e^-$	$502.7 \pm 0.5\,(\text{stat}) \pm 2.0\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \mu^+\mu^-$	$501.4 \pm 0.4\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \ell\ell$	$502.2 \pm 0.3\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 9.0\,(\text{lumi})$

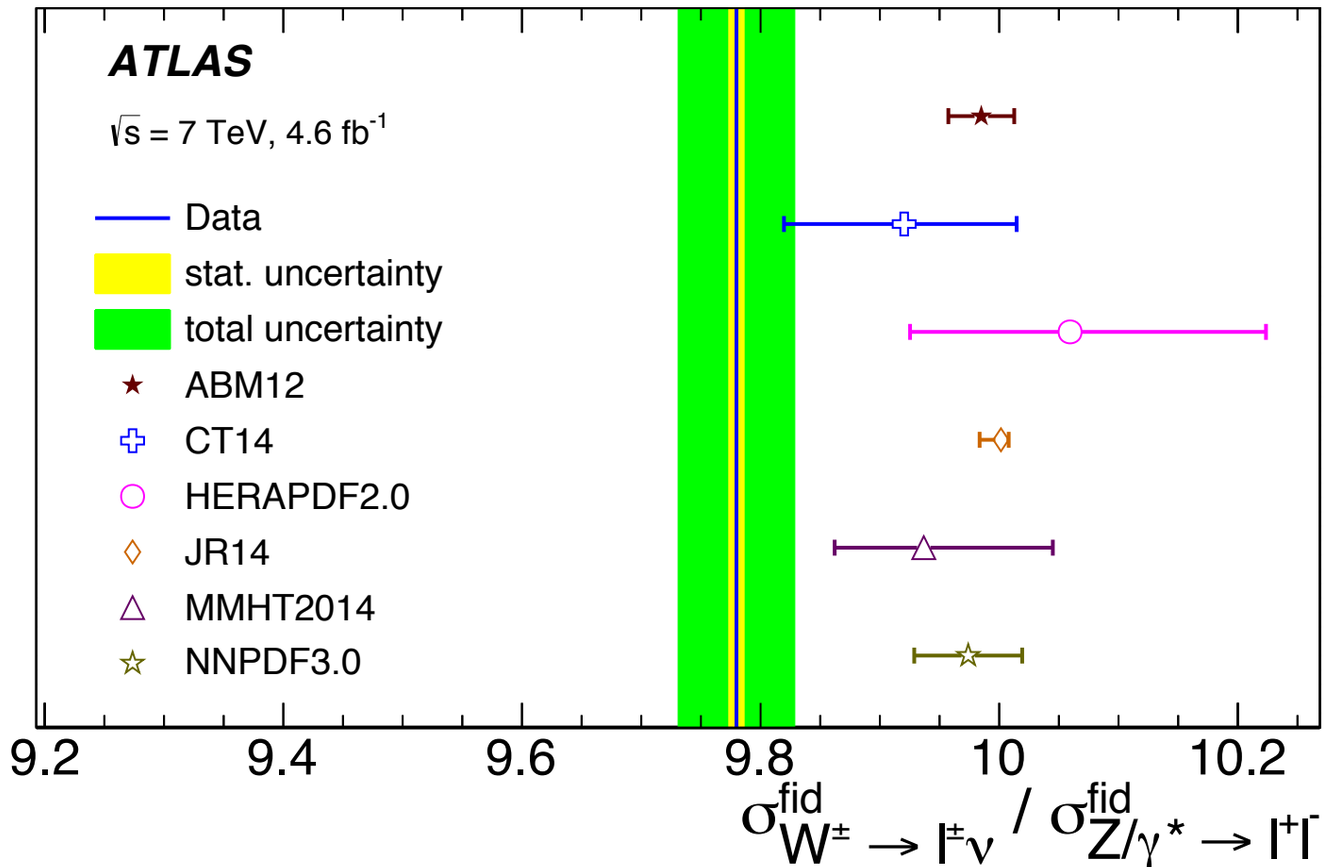
Comparing fiducial σ to theory



Very ***small uncertainty*** achieved → study ***compatibility with pdfs***, with discrimination power

Ratios even more ***powerful***, since uncertainty made smaller by large correlations

- ➡ W^+/W^- well described
- ➡ ***W/Z*** consistently ***overpredicted*** by different pdfs → could indicate that strangeness is enhanced
  - ➡ compatible result in 13 TeV (Phys.Lett. B759 (2016) 601-621)



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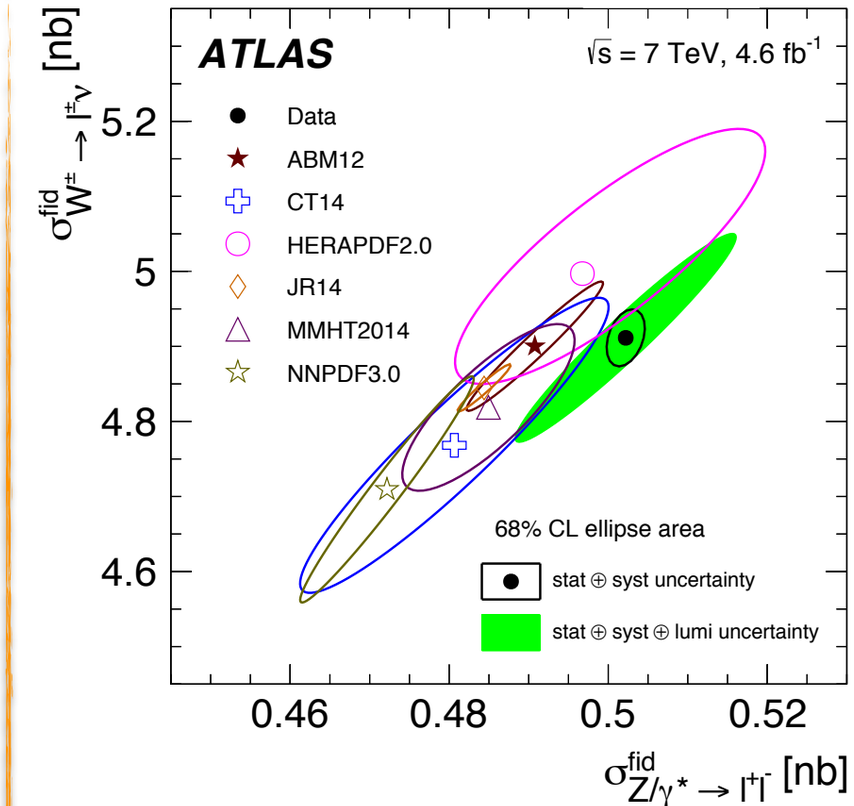

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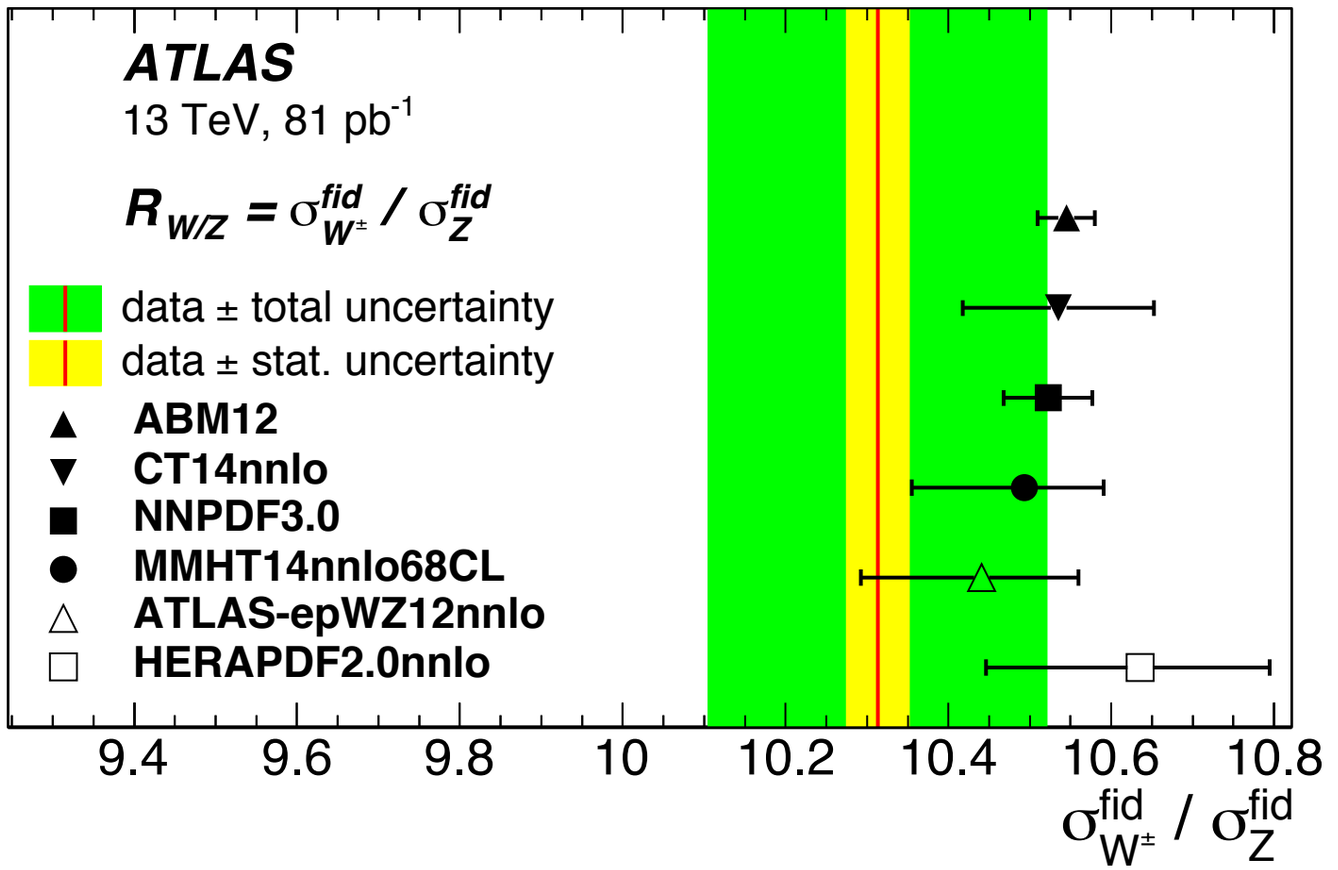
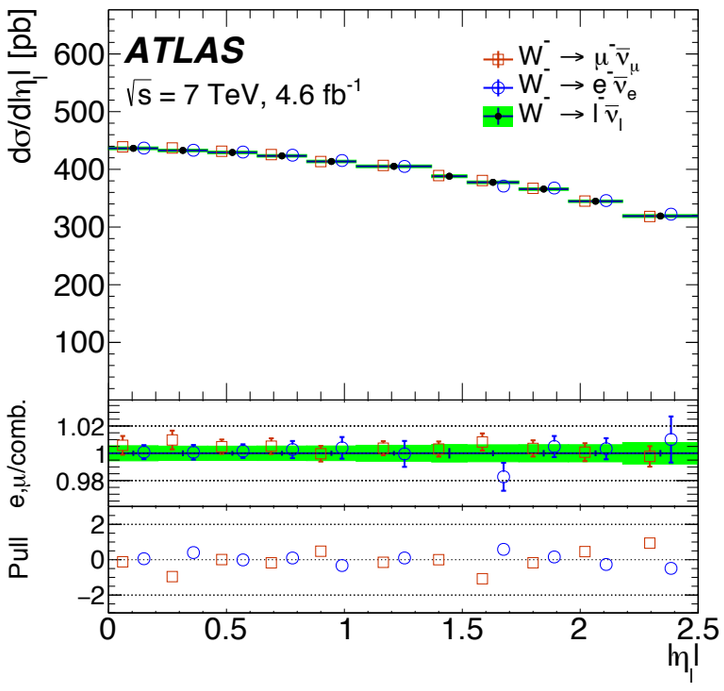


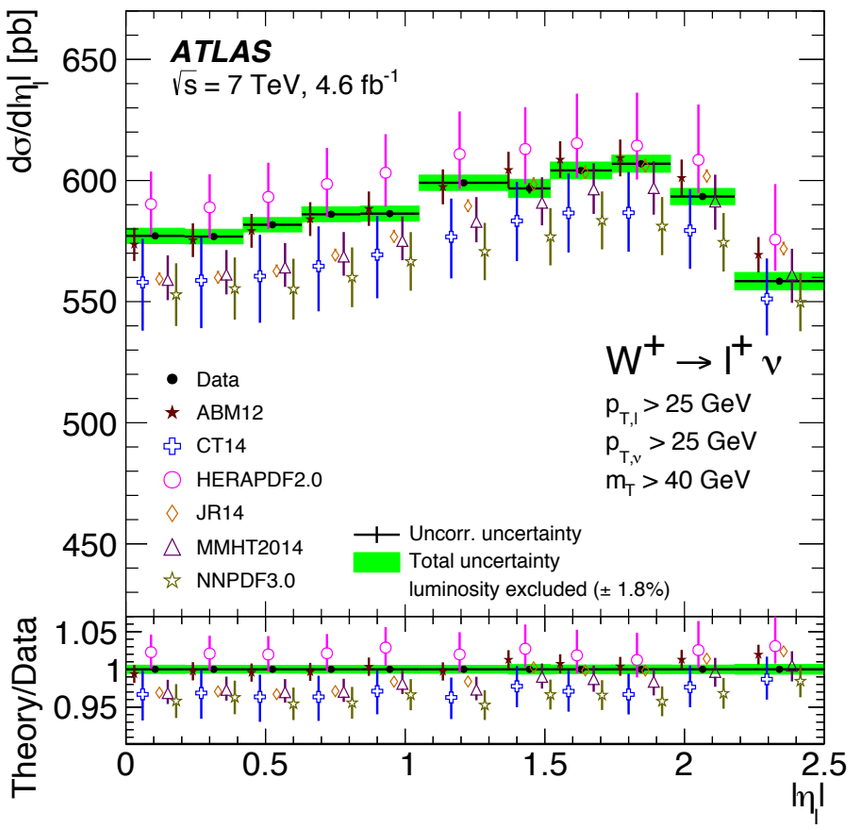
Going differential

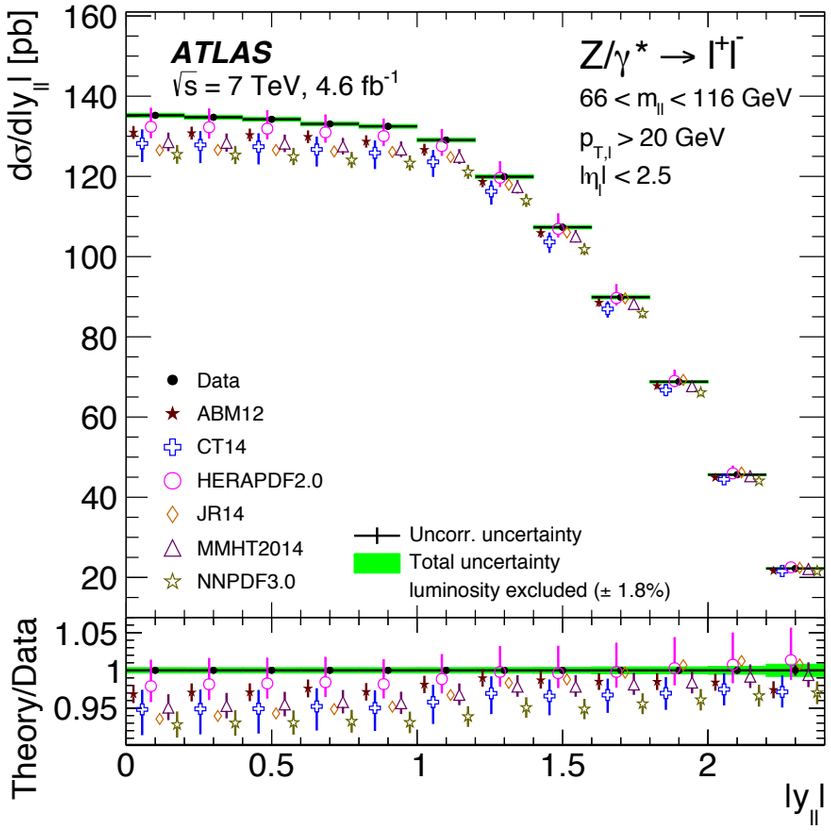
Digression on combination

- channels combined with a χ^2 fit
- very ***good compatibility*** between e and μ channels



- W differential cross section ***shapes well described*** by predictions, although some ***normalisation differences***
- Excellent description of W^+-W^- lepton charge asymmetry vs $|\eta_\ell|$
- Observed $y_{\ell\ell}$ ***dependence differences between data and predictions*** for the Z, in the central rapidity measurements (underestimate of up to 5%)
- No sensitivity to pdfs in forward region

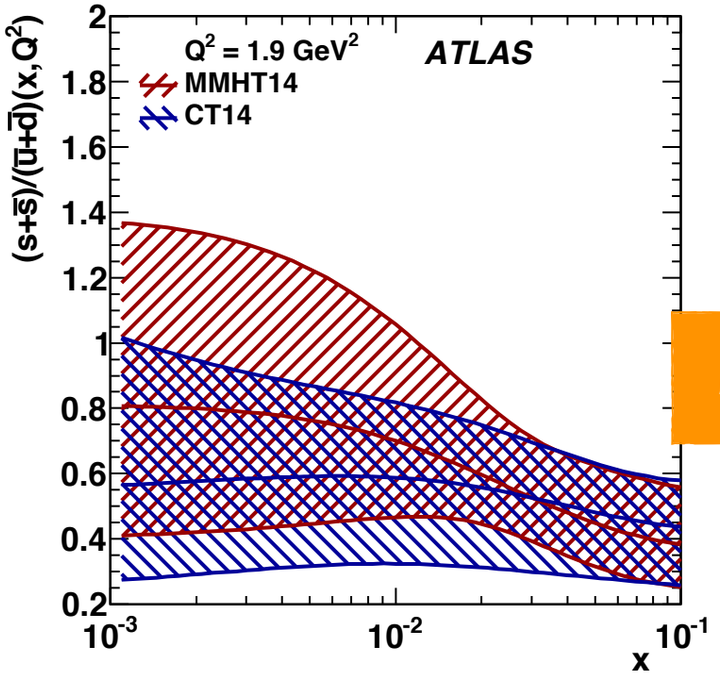




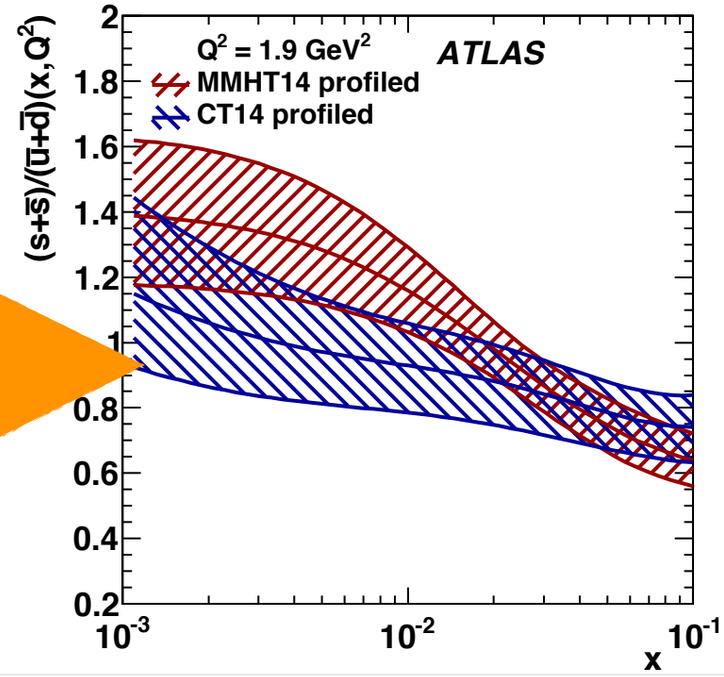
Constraining pdfs

Profile pdfs to test agreement with data from this measurement

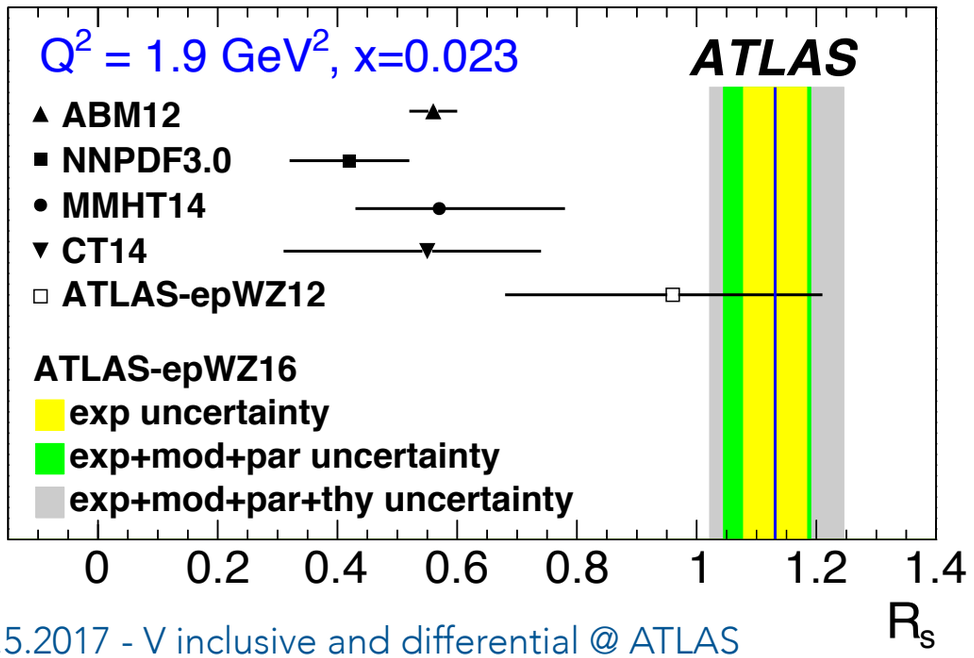
- best match: ATLAS-epWZ12 (χ^2/ndf=113/159)



Profile $R_s(x)=(s(x)+\bar{s}(x))/(\bar{u}(x)+\bar{d}(x))$



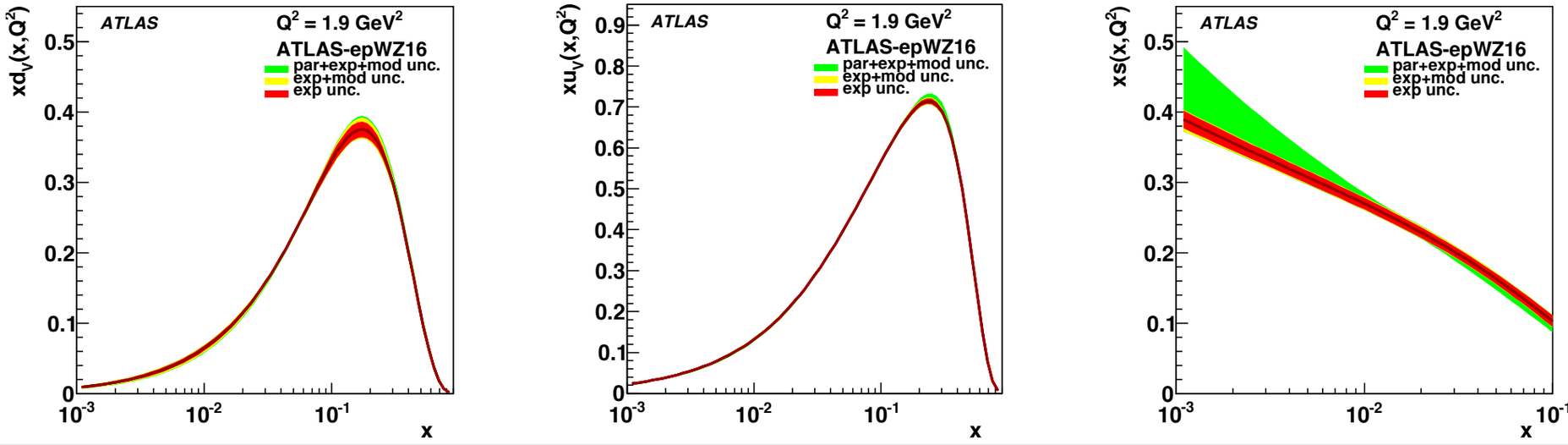
Data provide constraints on both central values and uncertainties, particularly ***shifting the strange fraction at higher values*** (enhancement visible in W/Z ratio)



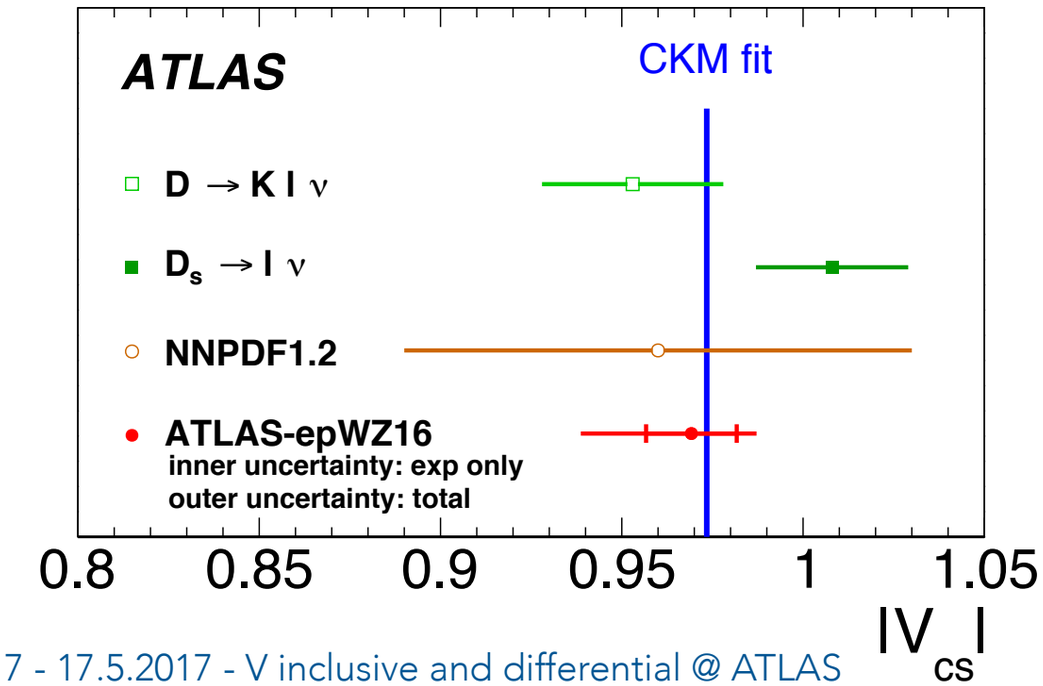
QCD interpretation

Aimed at obtaining a new pdf set: ATLAS-epWZ16

- combine with ep H1 and ZEUS data, new data add info on flavour composition of quark sea, and low-x valence quark distribution



Competitive measurement of $|V_{cs}|$, by floating it freely in the fit



Measurements of top-quark pair to Z-boson cross-section ratios at $\sqrt{s}$=13,8,7 TeV with the ATLAS detector

JHEP 1702 (2017) 117

Analysis overview

Ratios of Z fiducial and tt total cross sections at different sqrt s

$$\rightarrow R^{fid}_{Z_i/Z_j} = \sigma^{fid}_{Z(iTeV)}/\sigma^{fid}_{Z(jTeV)},\ R^{tot}_{t\bar{t}_i/t\bar{t}_j} = \sigma^{tot}_{t\bar{t}(iTeV)}/\sigma^{tot}_{t\bar{t}(jTeV)}$$

$$\rightarrow R^{tot/fid}_{t\bar{t}/Z}(iTeV) = \sigma^{tot}_{t\bar{t}(iTeV)}/\sigma^{fid}_{Z(iTeV)}$$

$$\rightarrow R^{tot/fid}_{t\bar{t}/Z}(i/j) = [\sigma^{tot}_{t\bar{t}(iTeV)}/\sigma^{fid}_{Z(iTeV)}]/[\sigma^{tot}_{t\bar{t}(jTeV)}/\sigma^{fid}_{Z(jTeV)}]$$

stolen from M. Zinser DIS talk

- Take advantage of precision achieved with some detector level systematic uncertainty cancellation to extract information on α_S, m_t, PDFs
  - ***particularly sensitive to g/q ratio***

Measurements and predictions

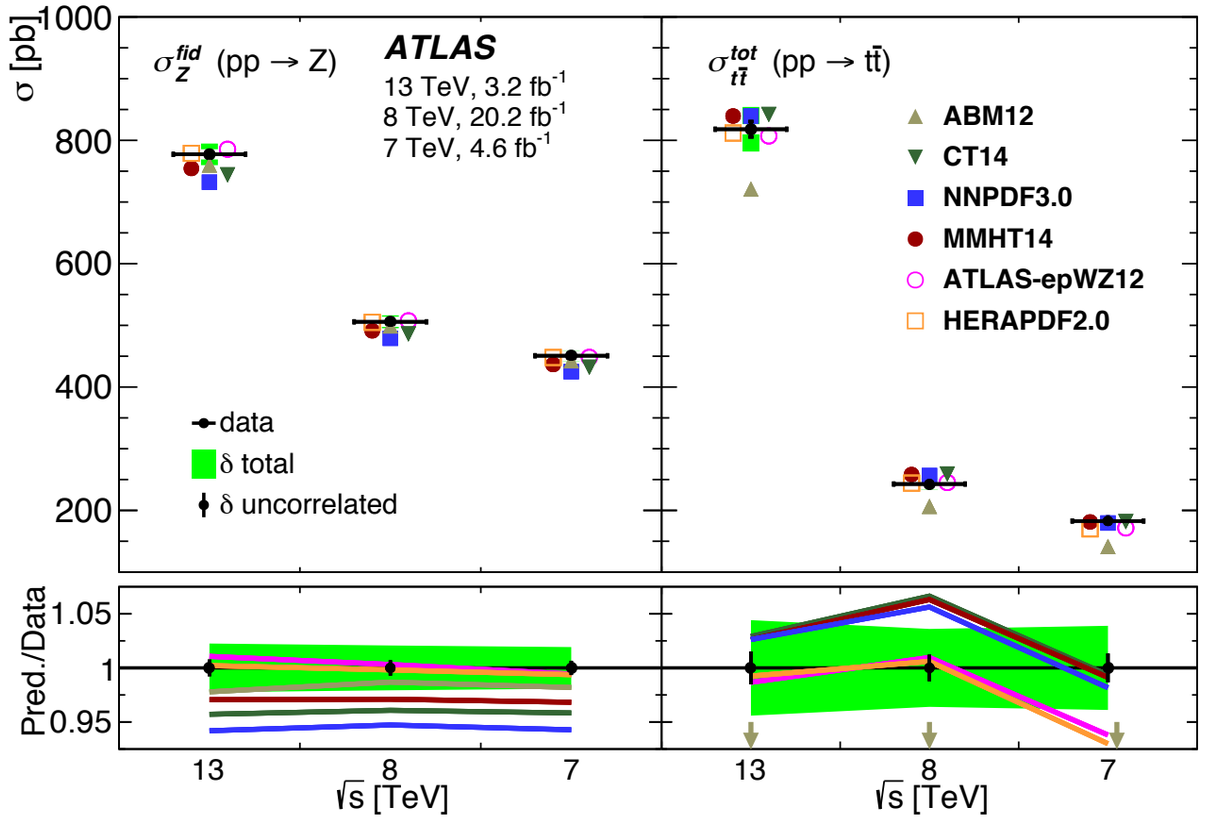
- Using previously measured cross sections, and measure for the paper σ^{Z}_{fid} ***@ 13 TeV with 3.2 fb^{-1}***
  - ***fiducial selection:*** p_T^{ℓ}>25 GeV, $|\eta_\ell|$<2.5, 66<$m_{\ell\ell}$/GeV<116

- ***Predictions*** used:
  - ***Z fiducial:*** DYNNLO(1.5) @ NNLO QCD, and FEWZ(3.1) @ NLO EW
  - ***tt total:*** Top++(2.0) @ NNLO+NNLL
  - ***uncertainties*** on the predicted ratios ranging ***between 0.2 and 2.5%***

	σ_Z^{fid}			$\sigma_{t\bar{t}}^{\text{tot}}$		
$\sqrt{s}$ [TeV]	13	8	7	13	8	7
Central value [pb]	744	486	432	842	259	182
Uncertainties [%]						
PDF	$^{+2.7}_{-3.4}$	$^{+2.5}_{-3.1}$	$^{+2.5}_{-3.0}$	$^{+2.6}_{-2.7}$	$^{+3.9}_{-3.4}$	$^{+4.4}_{-3.7}$
α_S	$^{+0.9}_{-1.1}$	$^{+1.0}_{-0.8}$	$^{+1.0}_{-0.7}$	$^{+1.9}_{-1.8}$	$^{+2.1}_{-2.1}$	$^{+2.2}_{-2.1}$
Scale	$^{+0.5}_{-0.8}$	$^{+0.5}_{-0.5}$	$^{+0.7}_{-0.3}$	$^{+2.4}_{-3.6}$	$^{+2.6}_{-3.5}$	$^{+2.6}_{-3.5}$
Intrinsic Z	$^{+0.7}_{-0.7}$	$^{+0.7}_{-0.7}$	$^{+0.7}_{-0.7}$	N/A	N/A	N/A
m_t	N/A	N/A	N/A	$^{+2.8}_{-2.7}$	$^{+3.0}_{-2.9}$	$^{+3.1}_{-3.0}$
Total	$^{+3.0}_{-3.7}$	$^{+2.8}_{-3.3}$	$^{+2.9}_{-3.2}$	$^{+5}_{-6}$	$^{+6}_{-6}$	$^{+6}_{-6}$

Cross sections and correlation model

Cross section measurements ***dominated by systematic uncertainties*** (luminosity, beam energy, signal modelling)



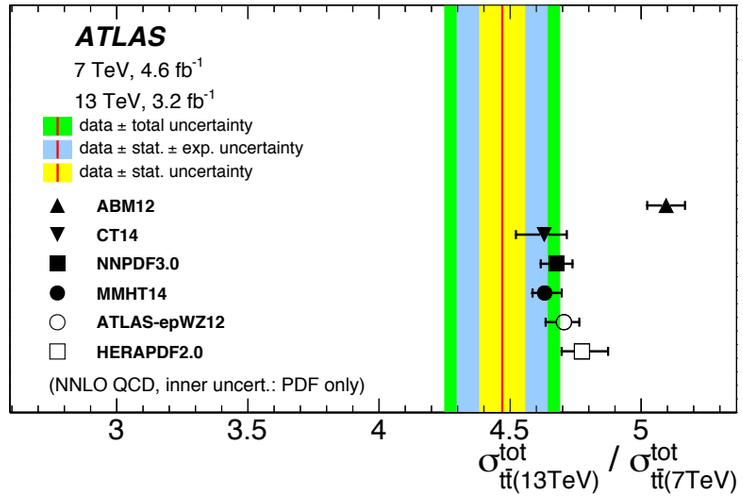
Source / $\sqrt{s}$ [TeV]	$\delta\ \sigma_Z^{\mathrm{fid}}$ 13	8	7	$\delta\ \sigma_{t\bar{t}}^{\mathrm{tot}}$ 13	8	7
Luminosity	A	B	C	A	B	C
Beam energy	A	A	A	A	A	A
Muon (lepton) trigger	A	A*	A	A	B	B
Muon reconstruction/ID	A	B	C	A	D	D
Muon isolation	A	A	A	B	C	D
Muon momentum scale	A	A	A	A	A	A
Electron trigger	A	A	A	A	—	—
Electron reconstruction/ID	A	B	C	A	D	D
Electron isolation	A	A	—	B	C	D
Electron energy scale	A	A	A	A	A	A
Jet energy scale	—	—	—	A	B	B
b-tagging	—	—	—	A	B	B
Background	A	A	A	B	B	B
Signal modelling (incl. PDF)	A	A	A	B*	B	B

Exploit uncertainty correlations in ratios, to reduce the effects

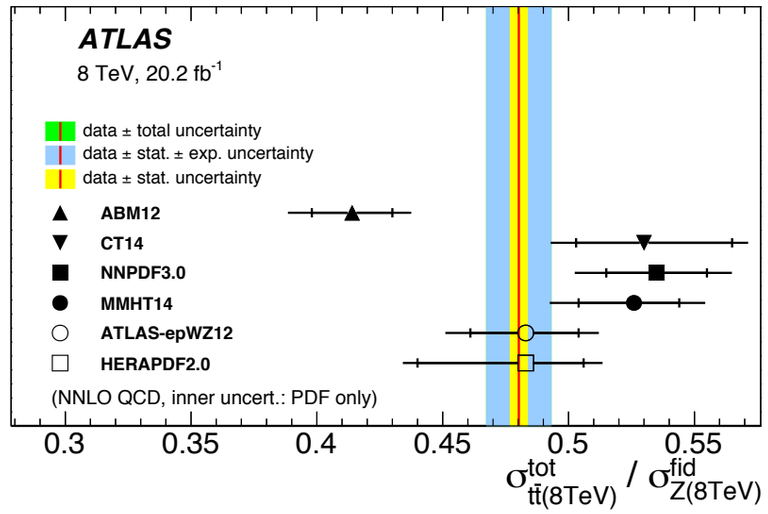
➡ *Same letter implies correlation between uncertainties in the same row*

Ratio results

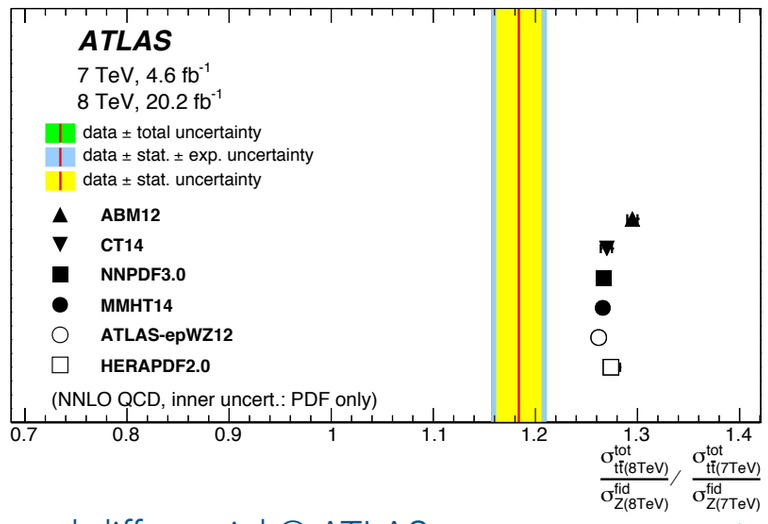
- tt cross section ratios @ different √s show ***differences*** due to ***different g distributions as a function of x***



- tt/Z ratio at same com energy shows ***higher precision of measurements than theory***, showing spread of results, due to different gluon densities and α_S

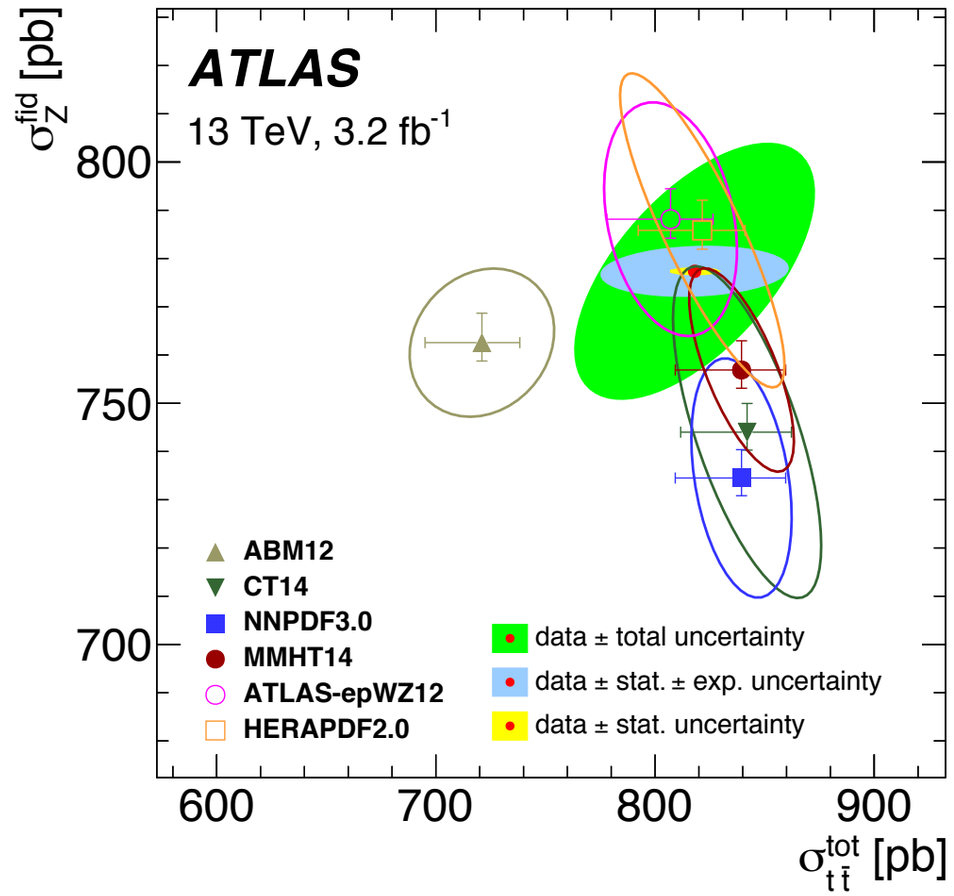


- ***Large deviations*** in tt double ratio at 8 and 7 TeV, not fully described by PDF effects



All other predictions in good agreement with the data

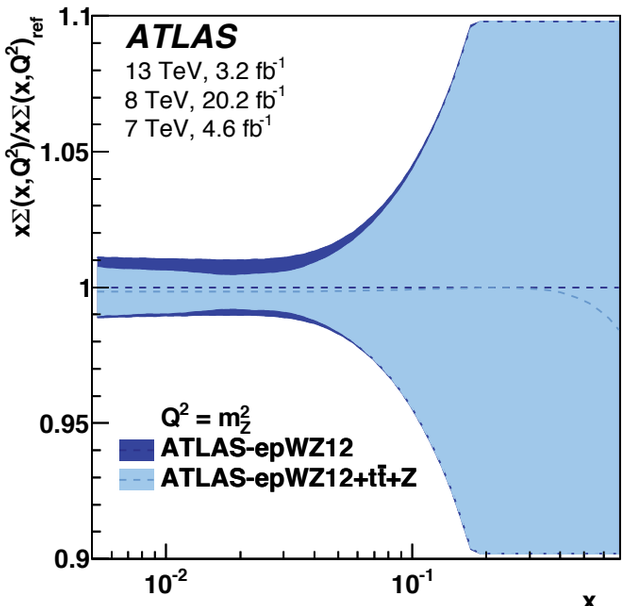
Pdf studies

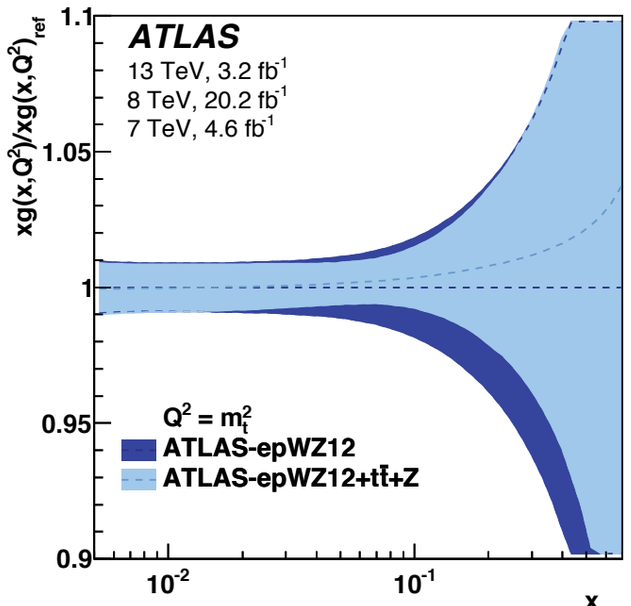


Best compatibility when profiling obtained with ATLAS-epWZ12 (χ^2=8.3/6), and HERAPDF2.0 (χ^2=10/6)

Profile ATLAS-epWZ12

- constrain light-quark sea distribution function at x<0.02
- constrain gluon distribution function at x~0.1





Conclusions

- ***Very precise DY measurements*** were performed by ATLAS, providing not only a good test of the available higher order predictions, but also valuable information on the proton structure
  - ***enhanced strangeness*** is hinted by the data
  - ***constraints of light and gluon fractions*** are found thanks to tt/Z ratios
  - $|V_{cs}|$ has been measured with a very competitive uncertainty
  - ***differential*** studies in W and Z rapidity have been compared to predictions

- Results available for both in ***HEP data*** (W,Z and tt/Z)
  - if used, need to treat ***correlations*** properly, for information, feel free to contact the ATLAS SM conveners (atlas-phys-sm-conveners@cern.ch)

- ***Caveat:*** reaching this precision is a great challenge requiring a lot of work (and time) - ***stay tuned*** for even more precise and more differential DY measurement in the future!!

Thank you for your attention!

Backup

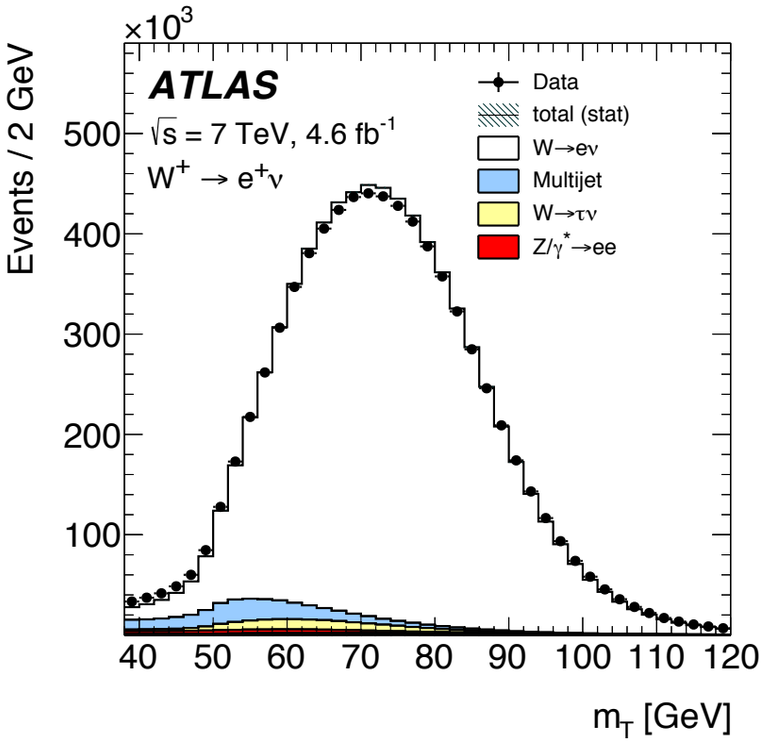
Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector

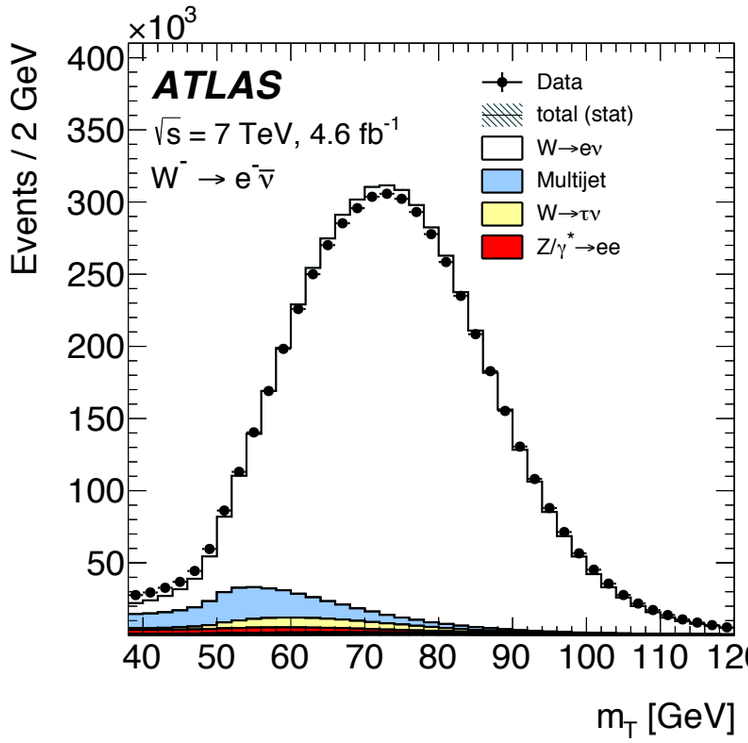
$\sqrt{s}$=7 TeV, 4.6 fb^{-1}

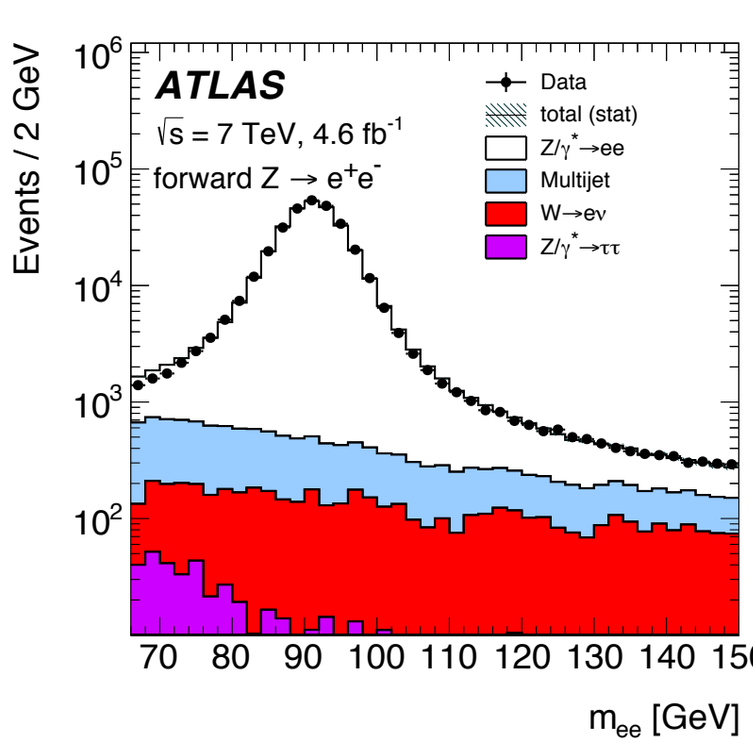
http://inspirehep.net/record/1502620

submitted to EPJC

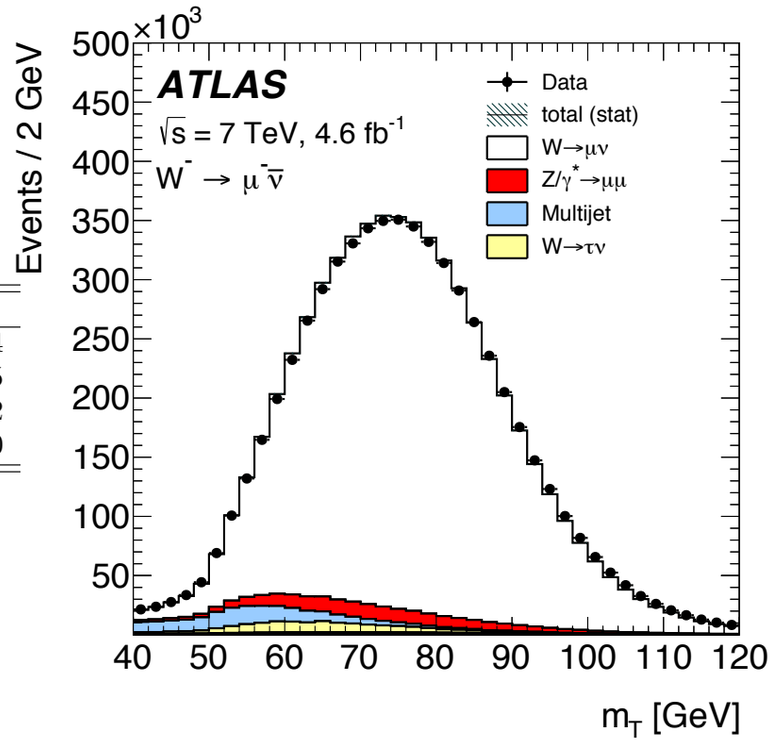
Reco-level analysis

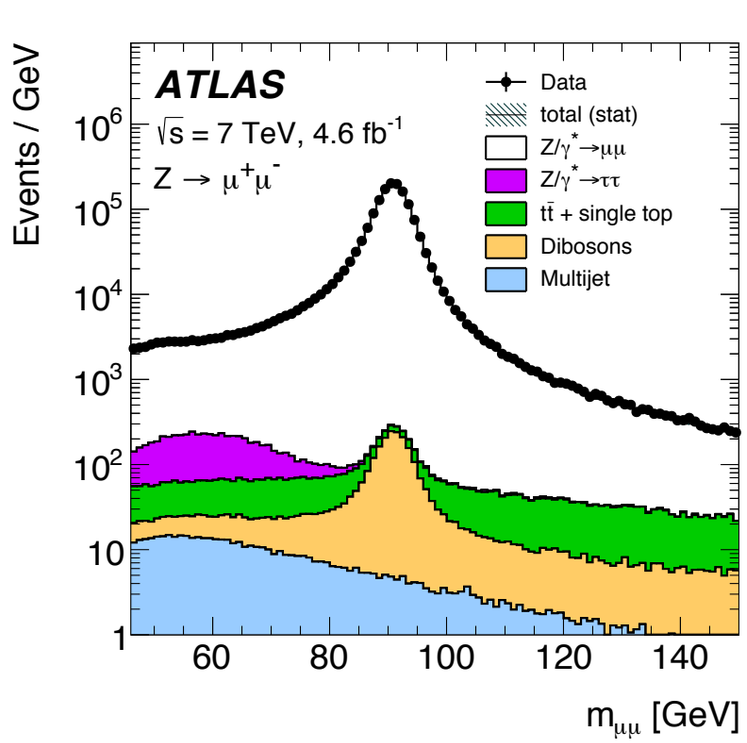




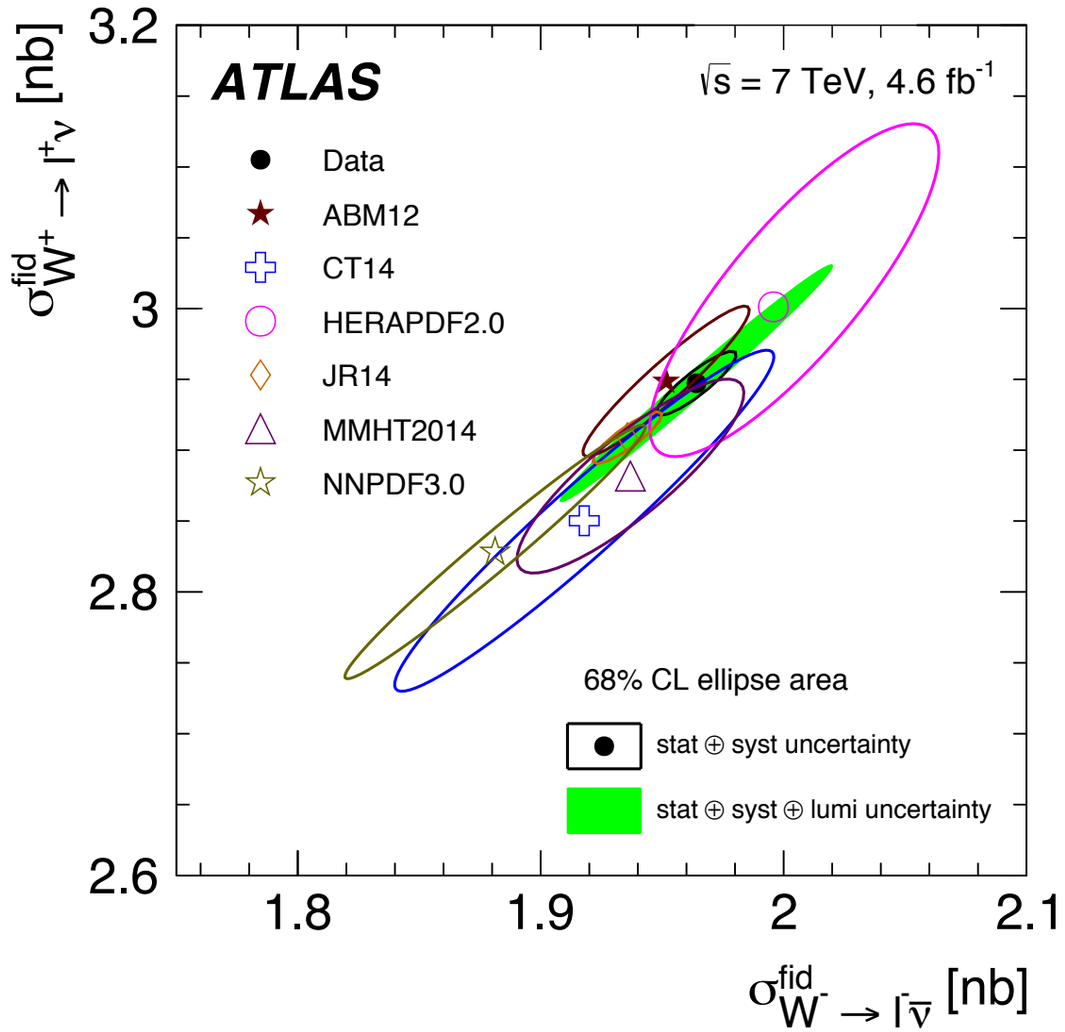


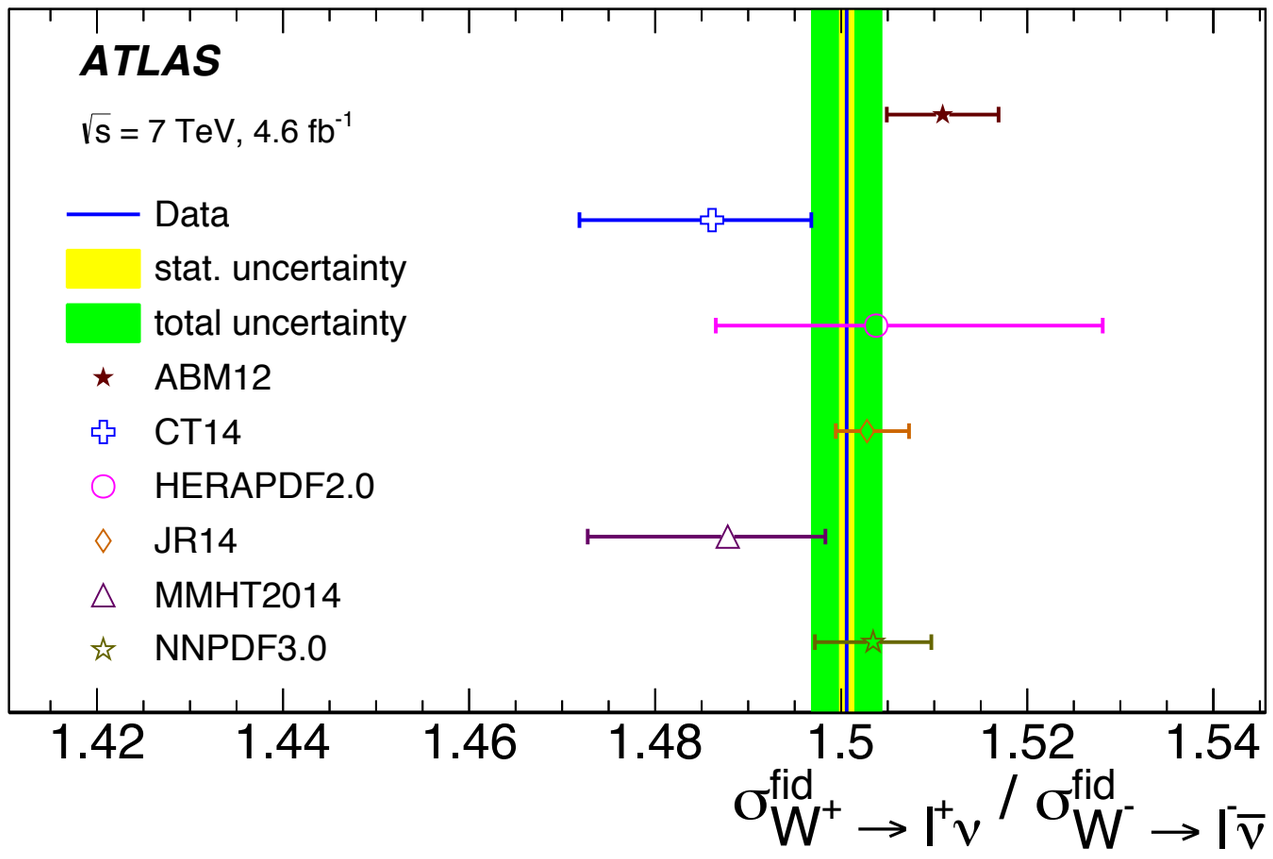
	N	B	C
$W^+ \to e^+\nu$	7552884	515000 ± 48000	0.572 ± 0.004
$W^- \to e^-\bar{\nu}$	5286997	468000 ± 40000	0.586 ± 0.005
Central $Z/\gamma^* \to e^+e^-$	1011940	4750 ± 350	0.500 ± 0.002
Forward $Z/\gamma^* \to e^+e^-$	321575	9170 ± 460	0.425 ± 0.010



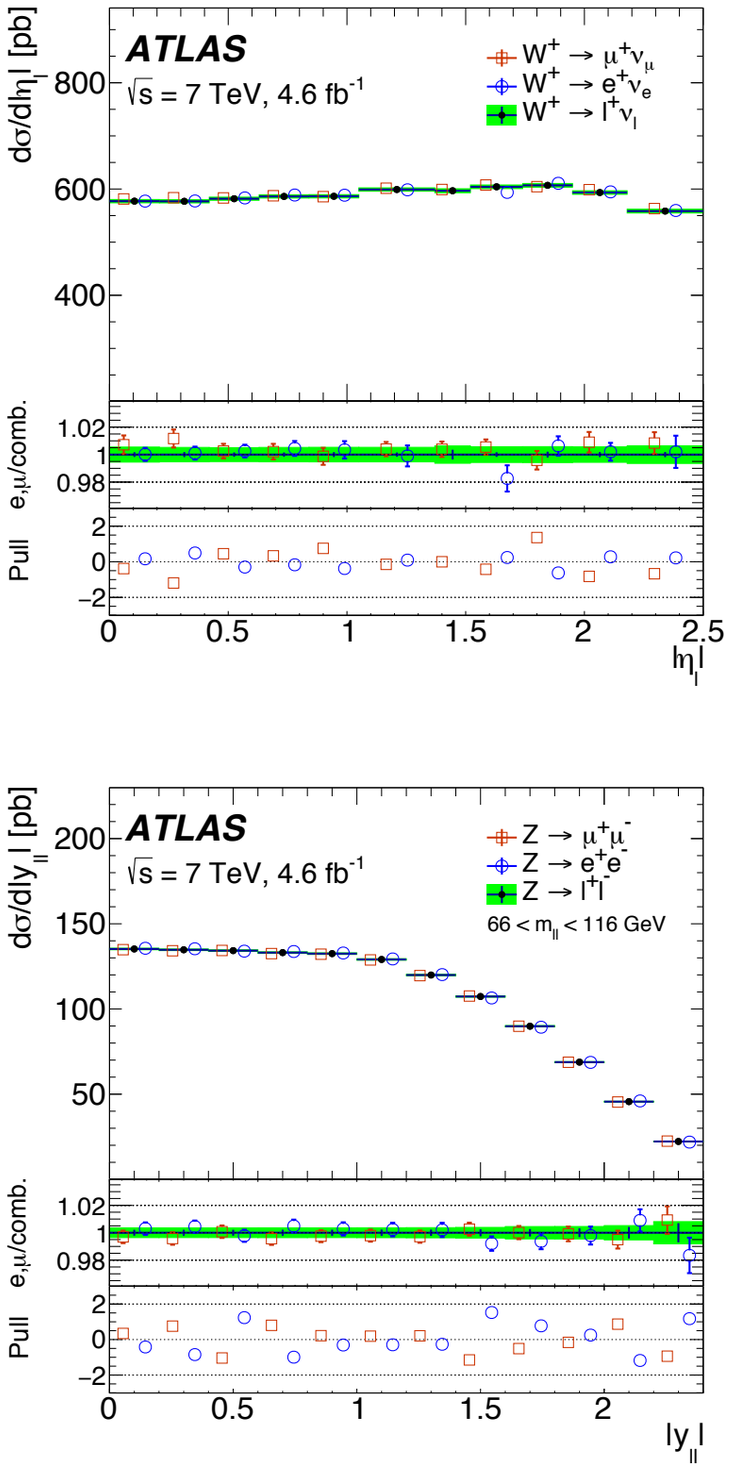


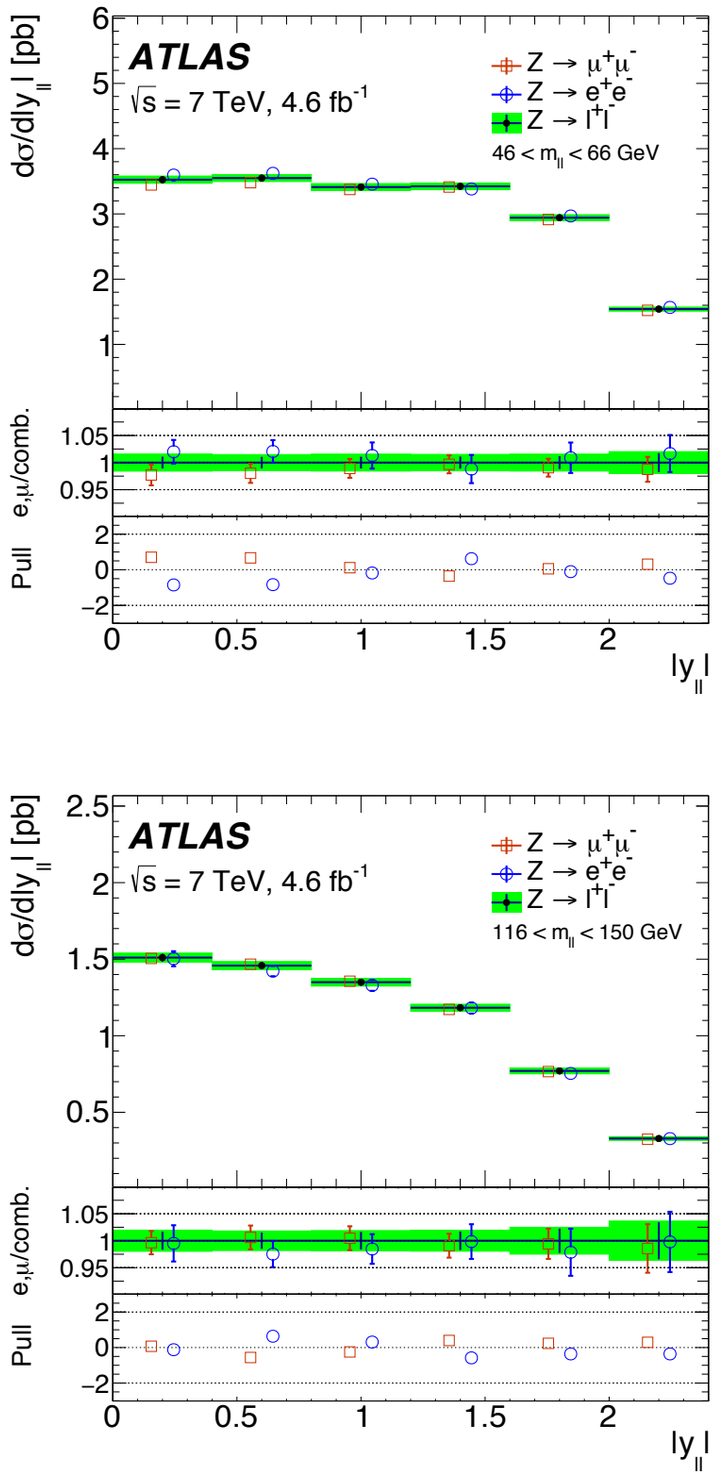
Cross sections: measurement vs theory



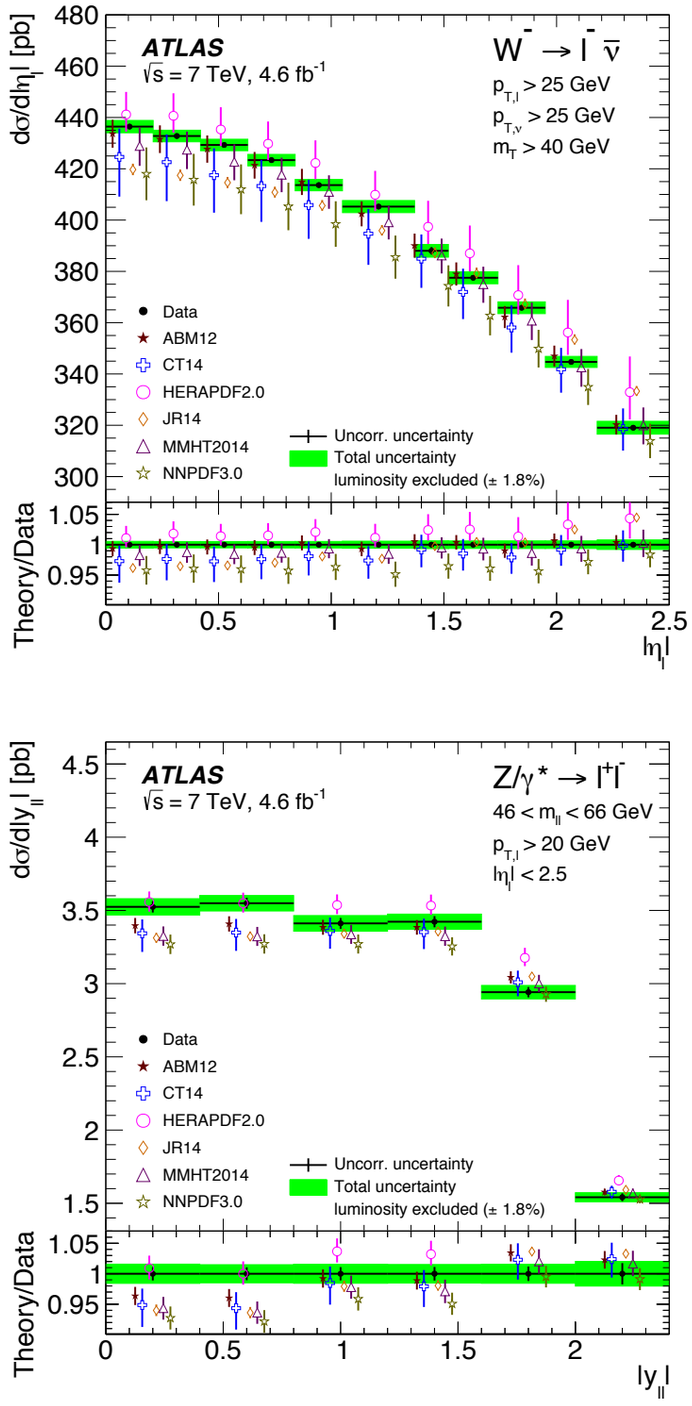


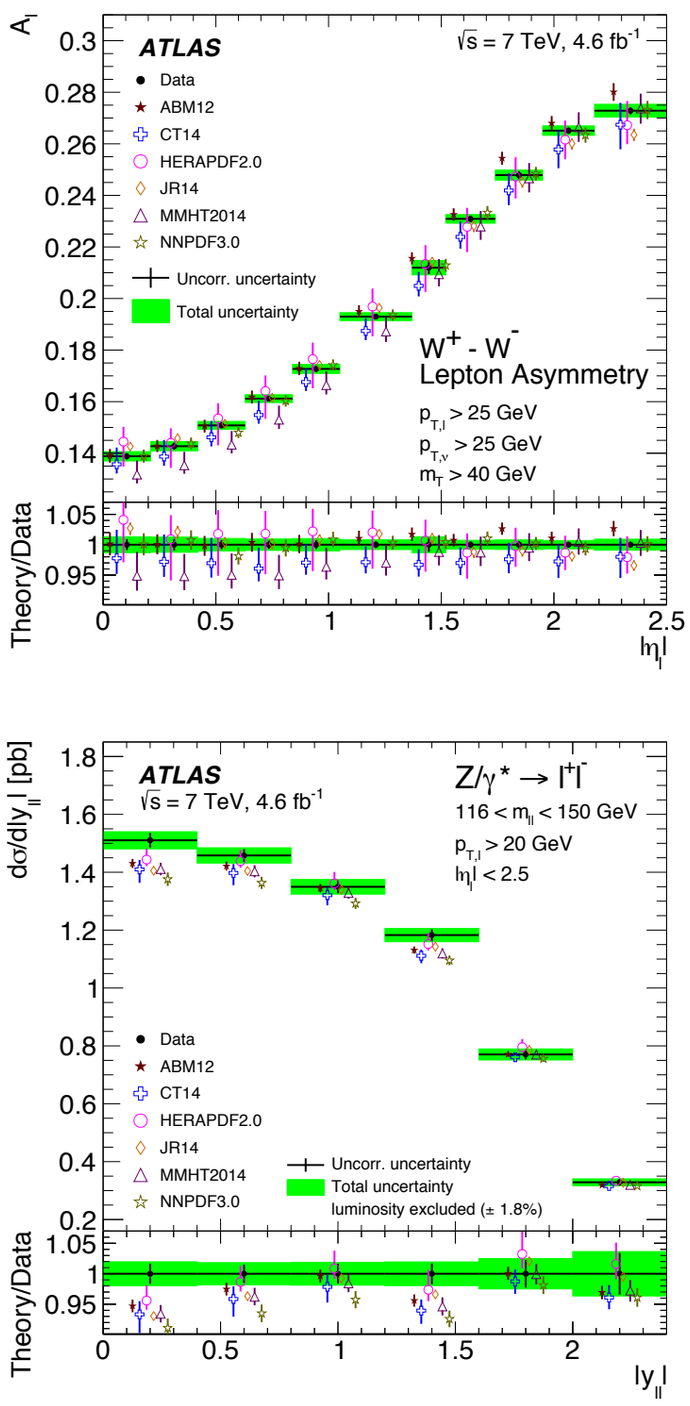
Combining with χ^2 fit

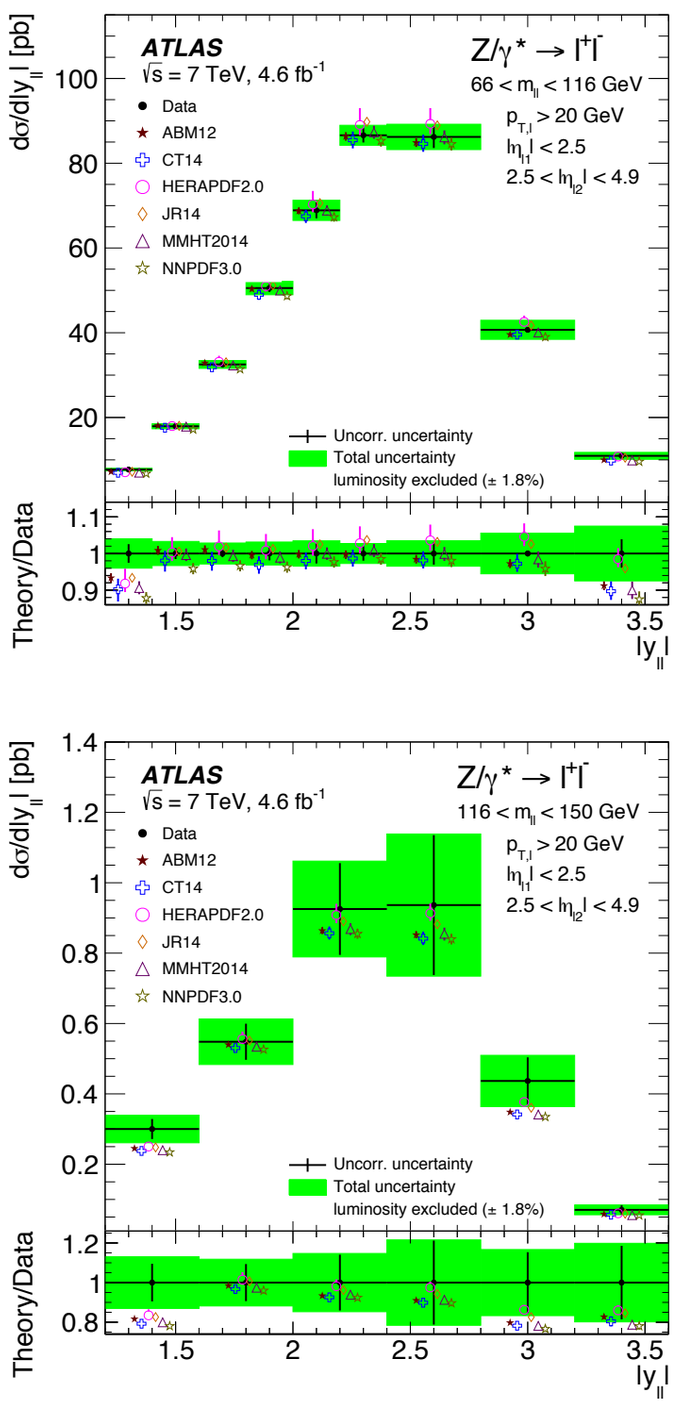




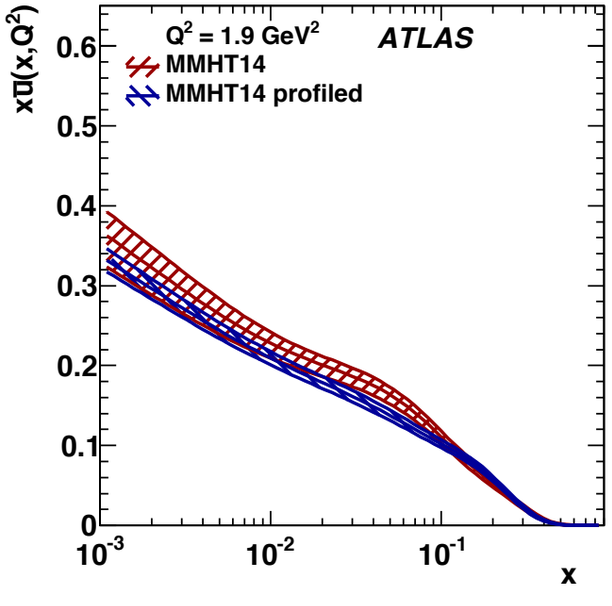
Differential rapidity distributions

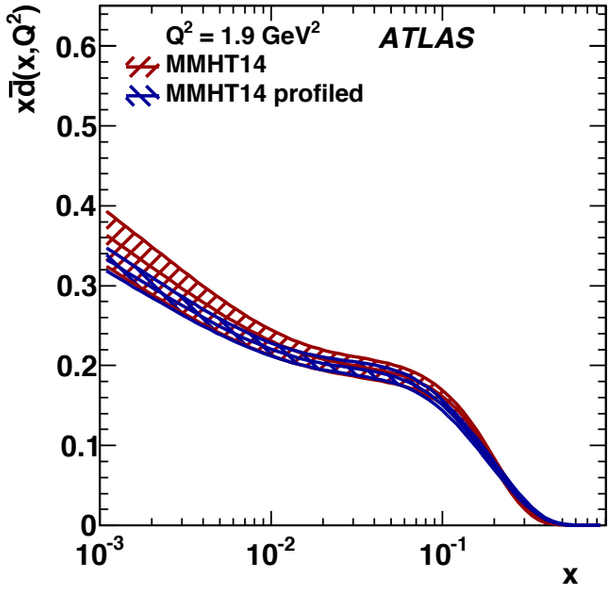


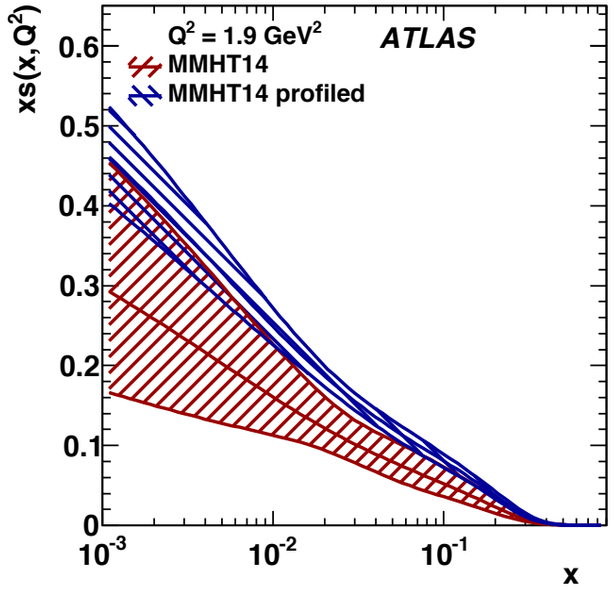


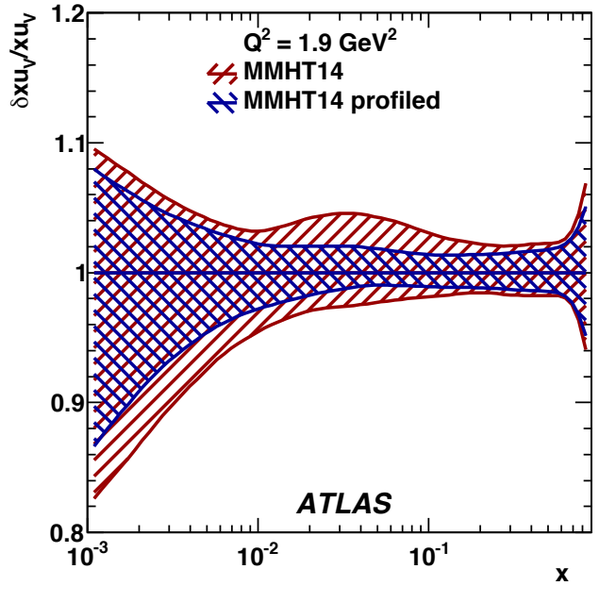


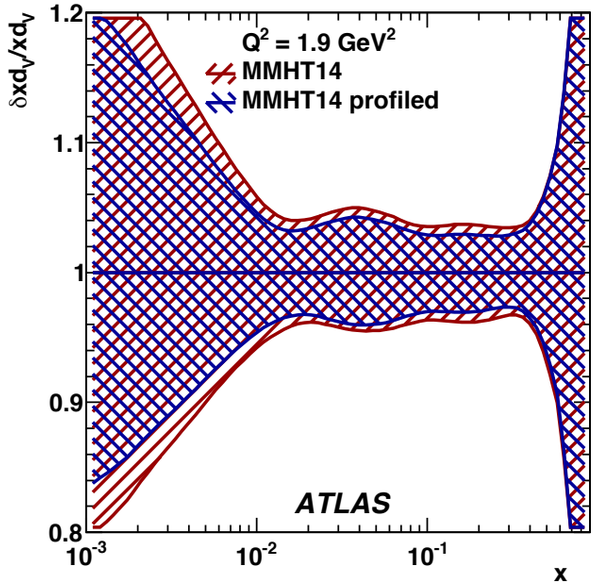
Pdf profiling results

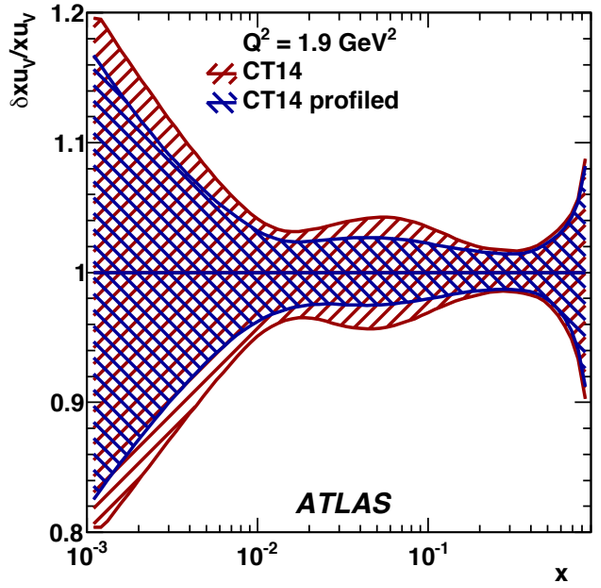


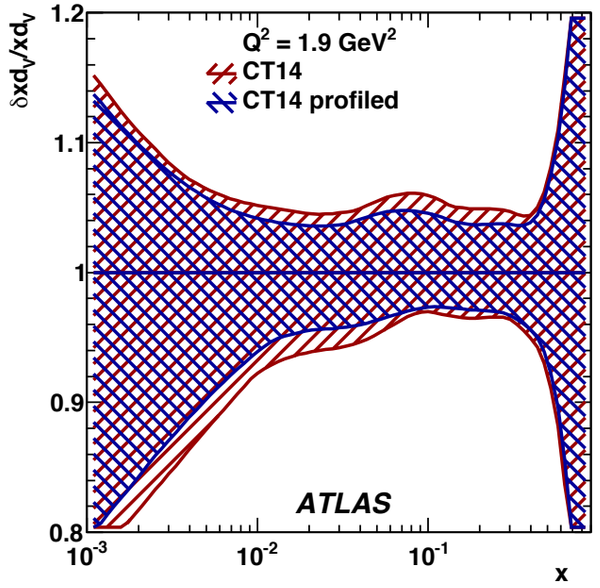








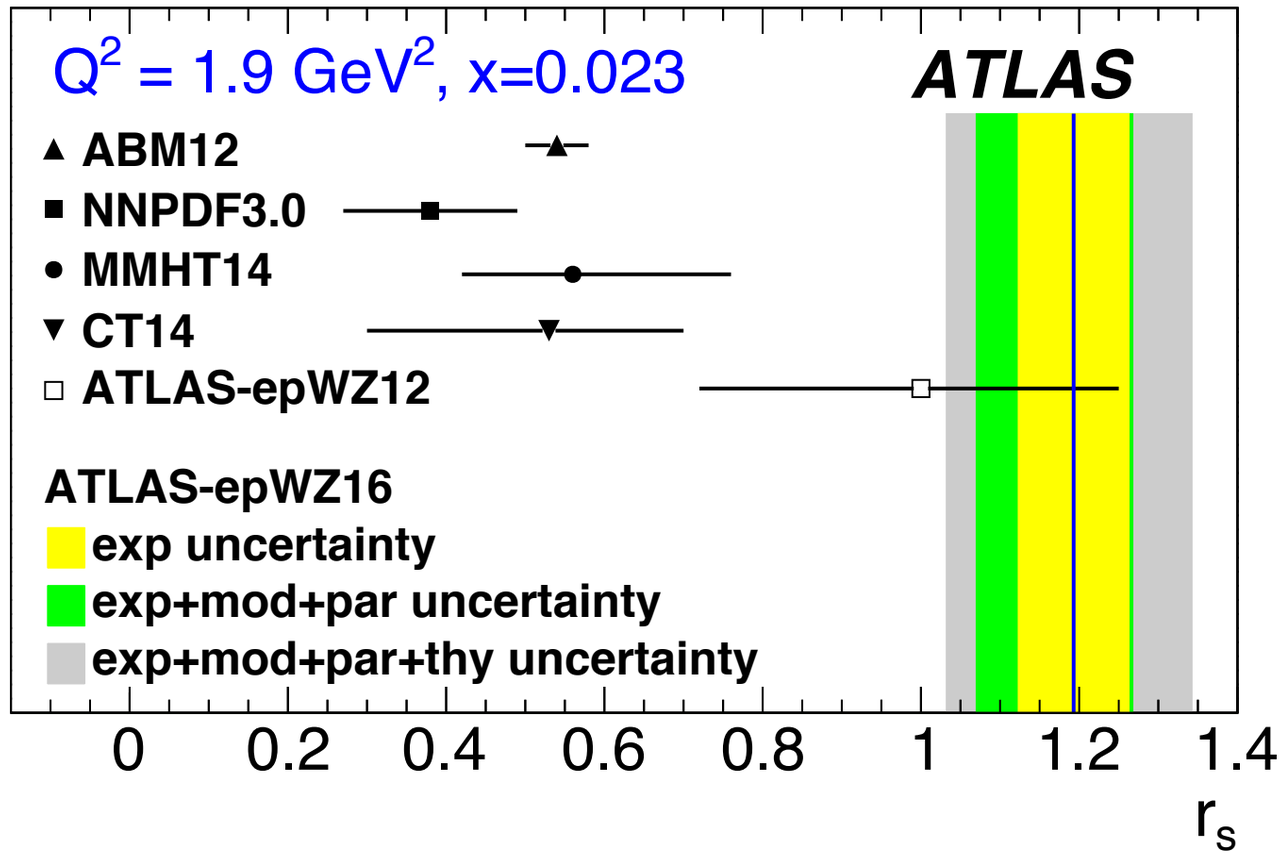




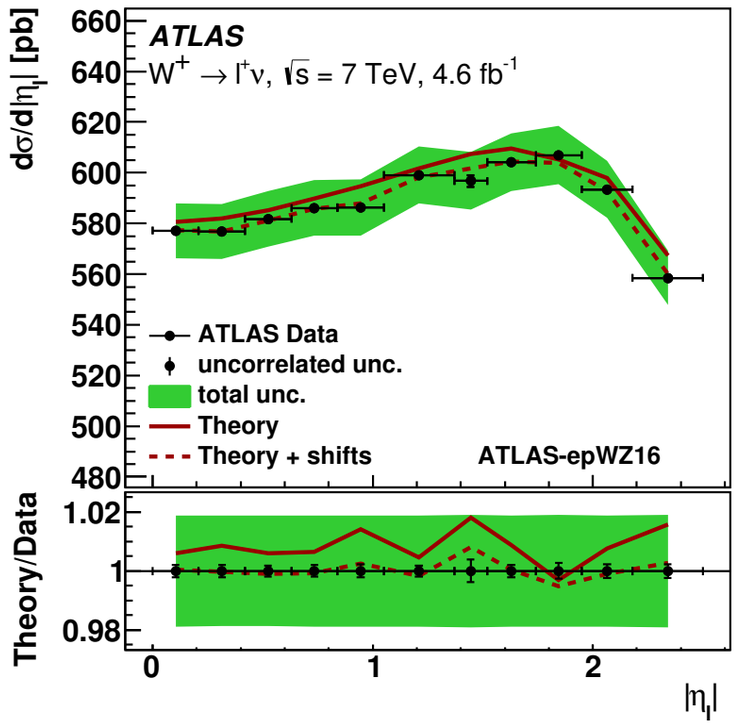
Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+\nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^-\bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46 - 66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ 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

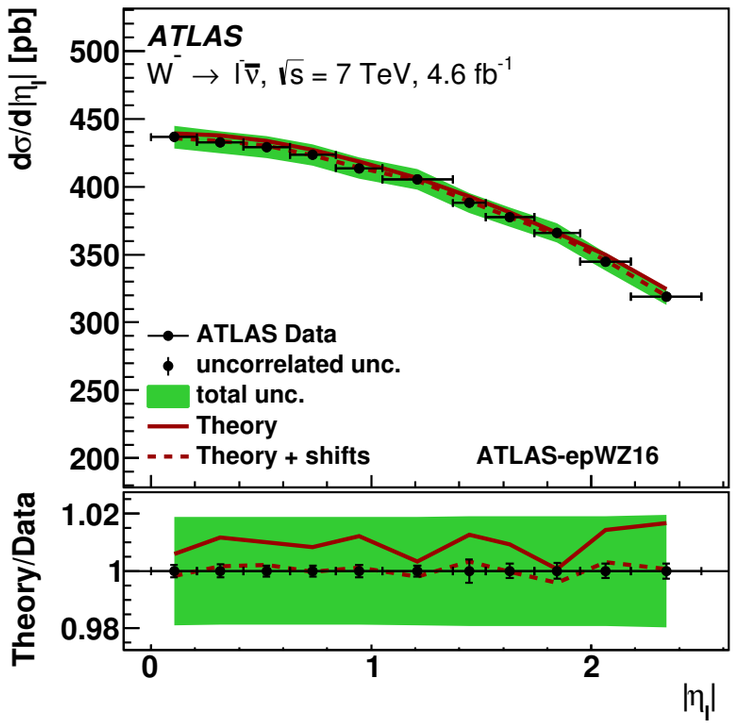
Evaluating strange fraction

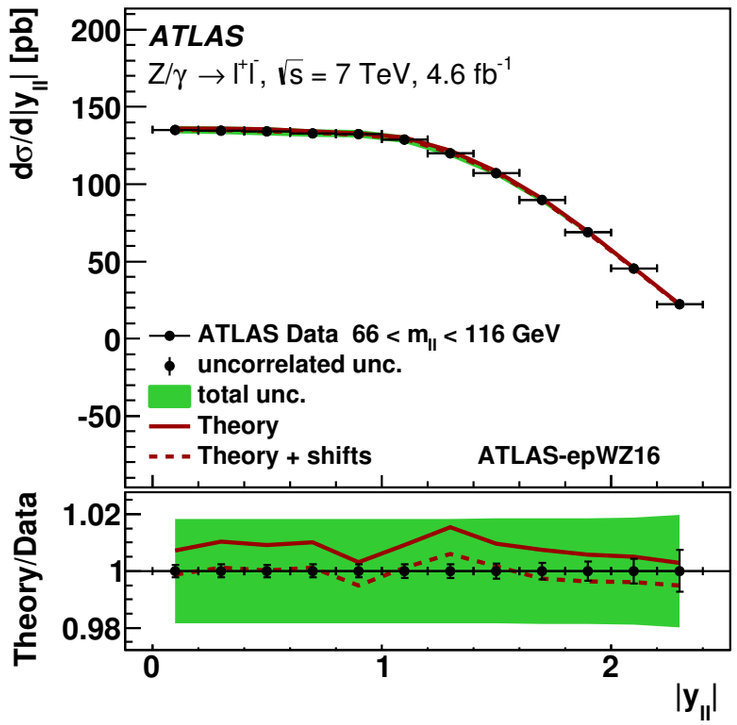
	$r_s = \frac{s+\bar{s}}{2\bar{d}}$	$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$
Central value	1.19	1.13
Experimental data	± 0.07	± 0.05
Model (m_b, $Q^2_{\min}$, Q^2_0 & m_c)	± 0.02	± 0.02
Parameterization	$^{+0.02}_{-0.10}$	$^{+0.01}_{-0.06}$
α_S	$^{+0.00}_{-0.01}$	± 0.01
Beam energy E_p	± 0.03	$^{+0.01}_{-0.02}$
EW corrections	± 0.01	± 0.00
QCD scales	$^{+0.08}_{-0.10}$	$^{+0.06}_{-0.07}$
FEWZ 3.1b2	$+0.10$	$+0.08$
Total uncertainty	$^{+0.15}_{-0.16}$	± 0.11

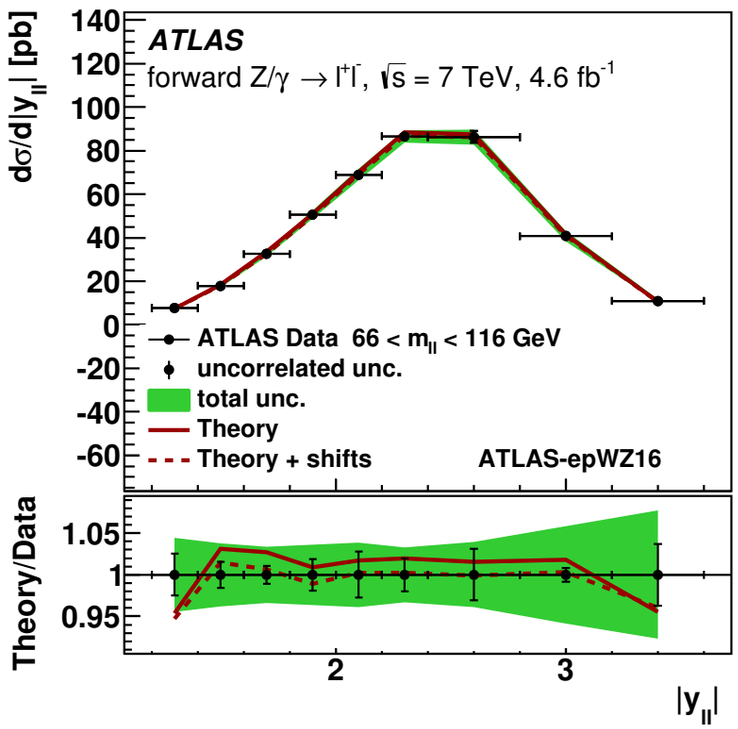


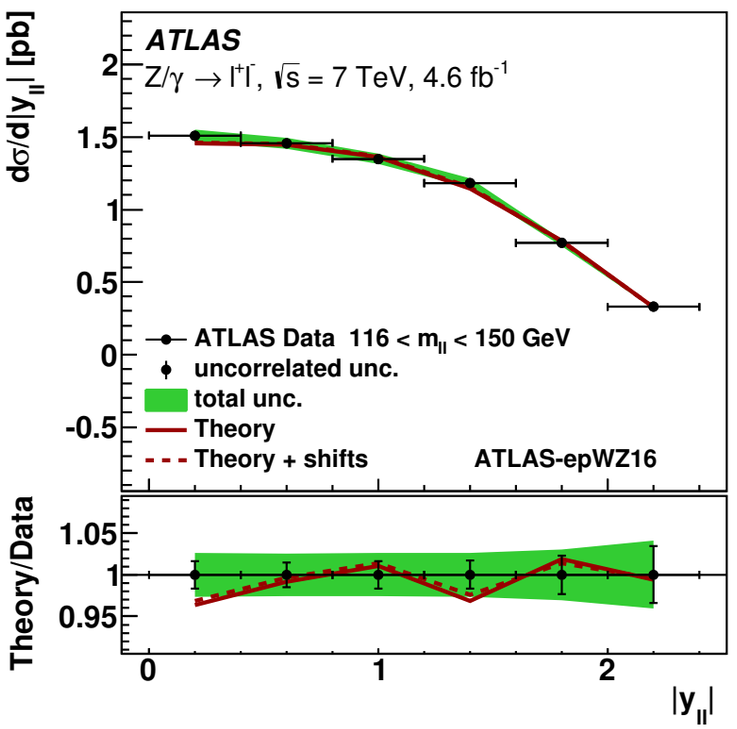
ATLAS-epWZ16 (i)



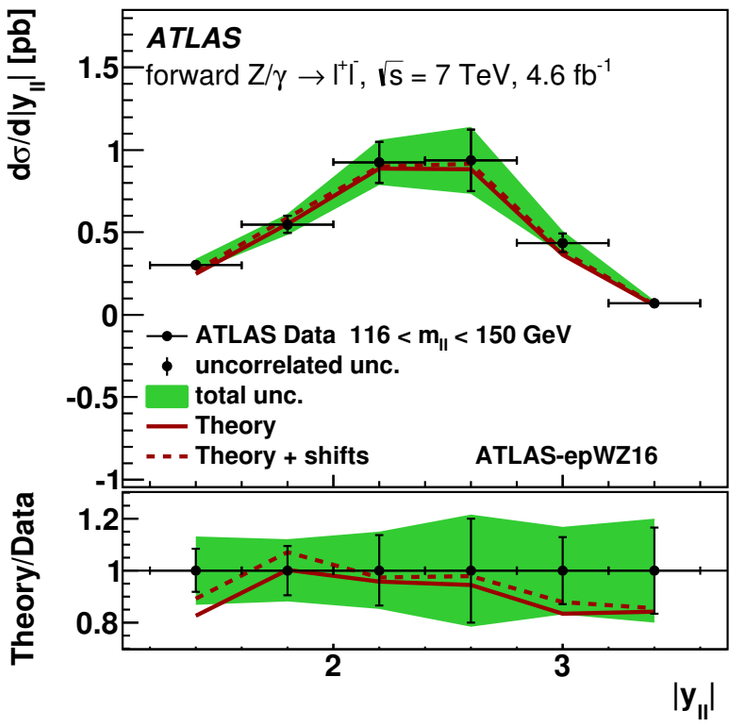


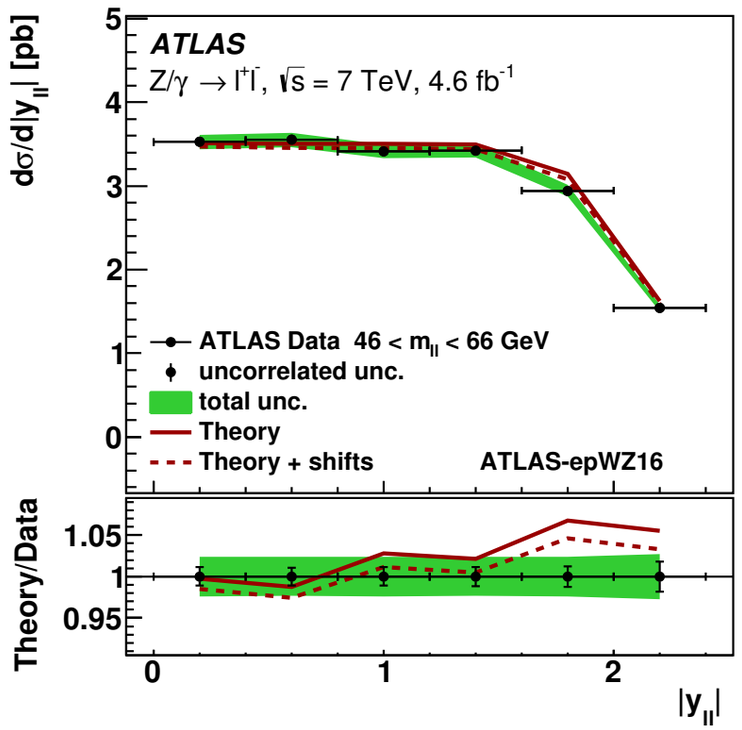


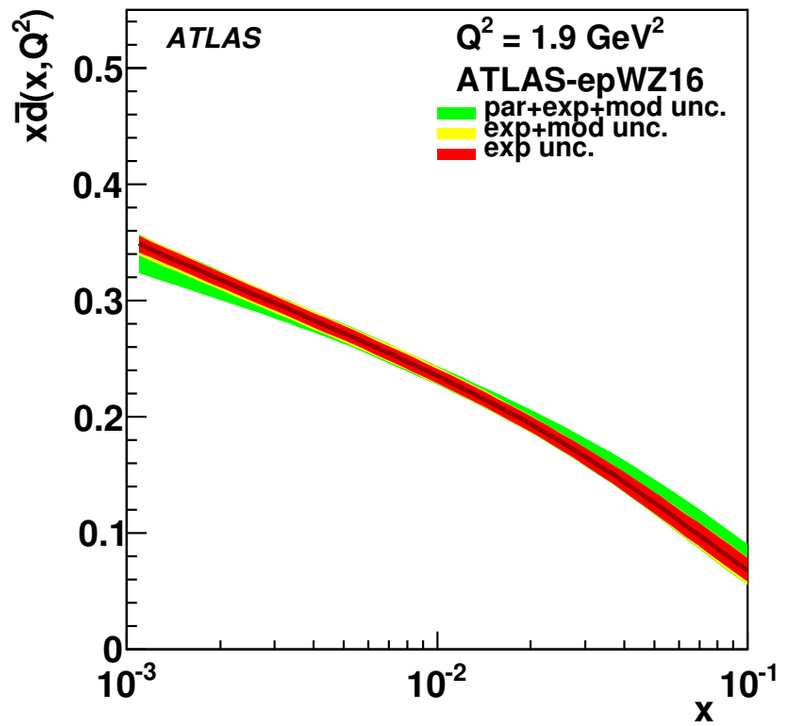


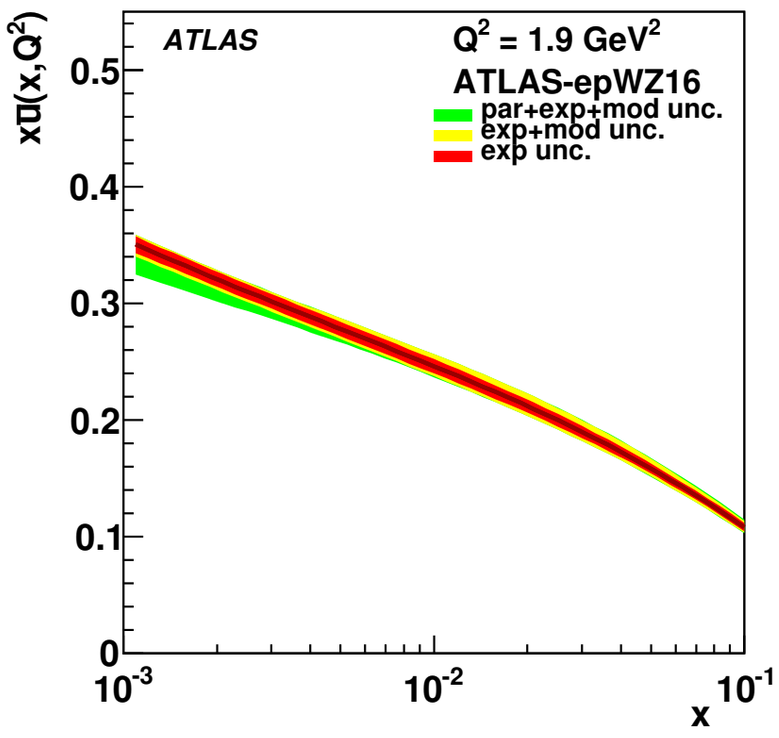


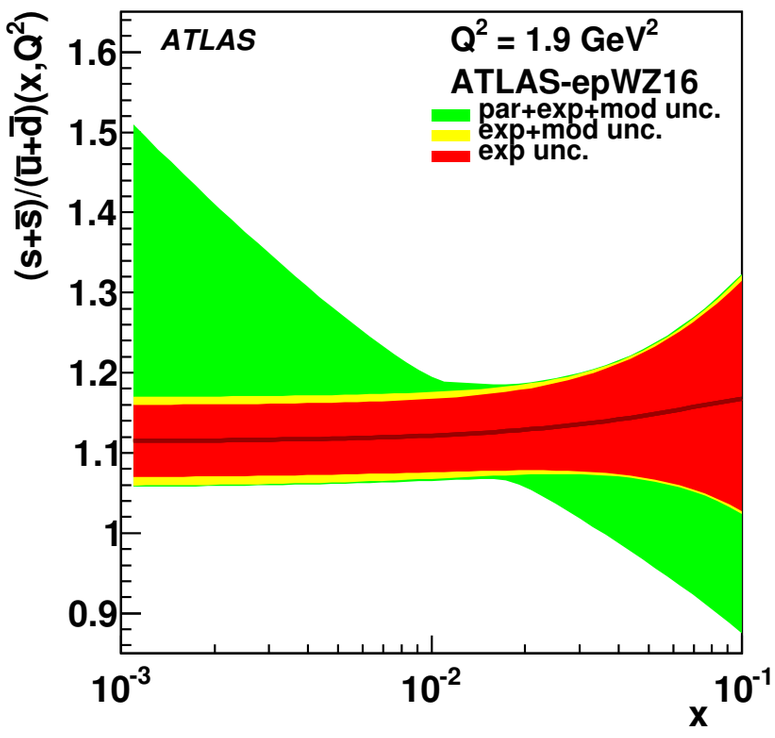
ATLAS-epWZ16 (ii)











Measurements of top-quark pair to Z-boson cross-section ratios at $\sqrt{s}$=13,8,7 TeV with the ATLAS detector

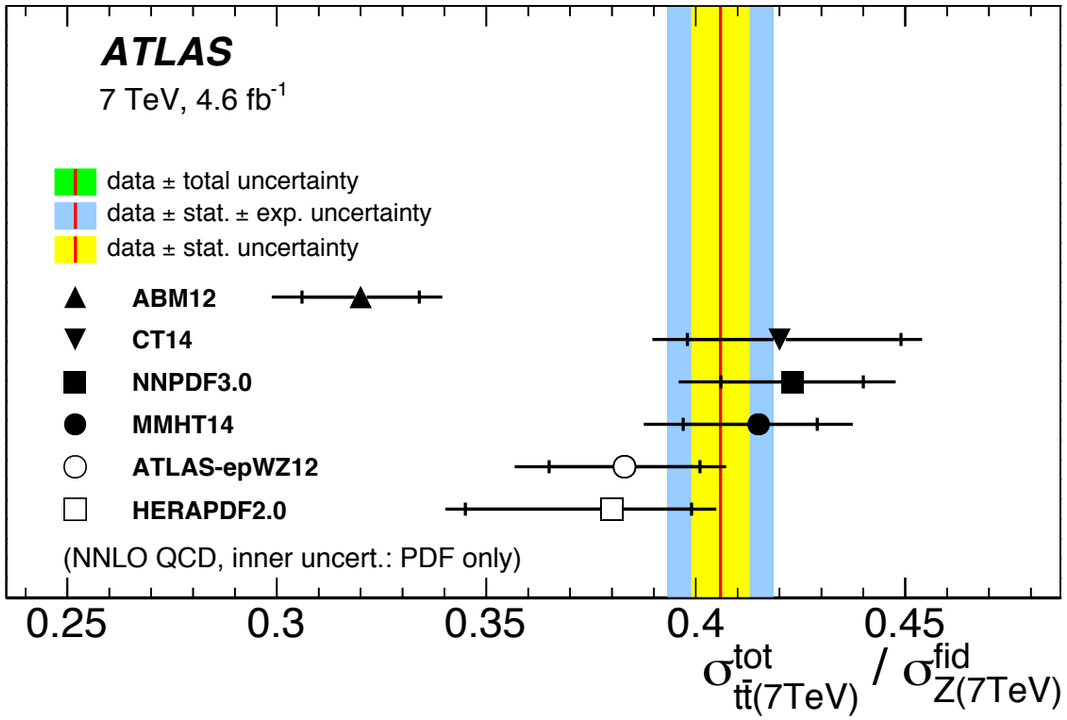
JHEP 1702 (2017) 117

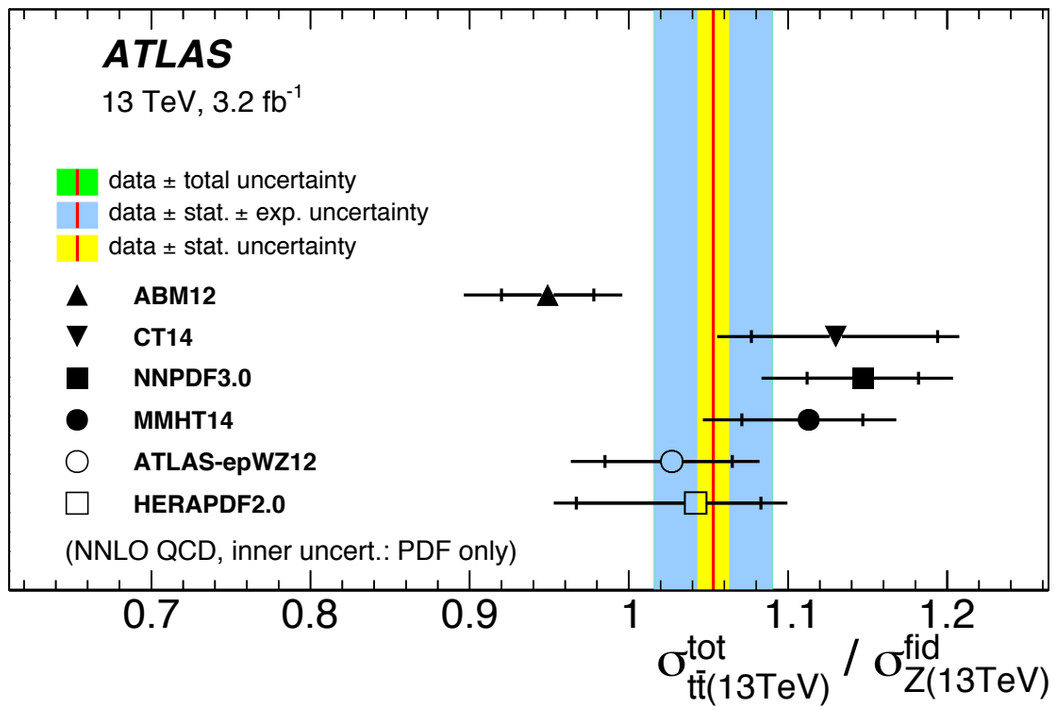
Predictions

	$R^{\text{fid}}_{Z_i/Z_j}$			$R^{\text{tot}}_{t\bar{t}_i/t\bar{t}_j}$		
i/j	13/7	13/8	8/7	13/7	13/8	8/7
Central value	1.722	1.531	1.125	4.634	3.251	1.425
Uncertainties [%]						
PDF	$^{+1.0}_{-0.9}$	$^{+0.8}_{-0.7}$	$^{+0.22}_{-0.21}$	$^{+1.9}_{-2.3}$	$^{+1.4}_{-1.8}$	$^{+0.5}_{-0.6}$
α_S	$^{-0.1}_{-0.4}$	$^{-0.1}_{-0.3}$	$^{-0.1}_{-0.1}$	$^{-0.32}_{+0.29}$	$^{-0.25}_{+0.22}$	$^{-0.08}_{+0.07}$
Scale	$^{+0.03}_{-0.60}$	$^{+0.02}_{-0.29}$	$^{+0.02}_{-0.31}$	$^{+0.19}_{-0.26}$	$^{+0.13}_{-0.19}$	$^{+0.05}_{-0.07}$
m_t	N/A	N/A	N/A	$^{+0.29}_{-0.29}$	$^{+0.22}_{-0.22}$	$^{+0.07}_{-0.07}$
Total	$^{+1.0}_{-1.2}$	$^{+0.8}_{-0.8}$	$^{+0.22}_{-0.40}$	$^{+1.9}_{-2.4}$	$^{+1.4}_{-1.8}$	$^{+0.5}_{-0.6}$

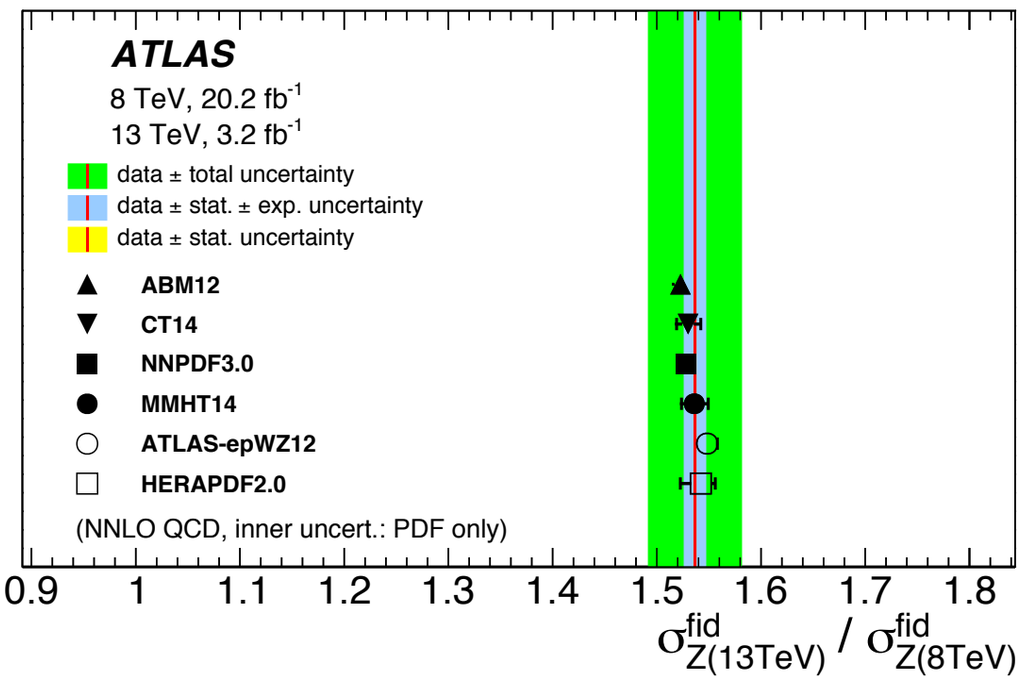
	$R^{\text{tot/fid}}_{t\bar{t}/Z}(i \text{ TeV})$			$R^{\text{tot/fid}}_{t\bar{t}/Z}(i/j)$		
i or i/j	13	8	7	13/7	13/8	8/7
Central value	1.132	0.533	0.421	2.691	2.124	1.267
Uncertainties [%]						
PDF	$^{+6}_{-5}$	$^{+7}_{-5}$	$^{+7}_{-5}$	$^{+1.5}_{-2.0}$	$^{+1.1}_{-1.6}$	$^{+0.4}_{-0.5}$
α_S	$^{+0.9}_{-0.8}$	$^{+1.1}_{-1.3}$	$^{+1.1}_{-1.5}$	$^{-0.22}_{+0.70}$	$^{-0.22}_{+0.50}$	$^{-0.00}_{+0.20}$
Scale	$^{+2.6}_{-3.6}$	$^{+2.6}_{-3.5}$	$^{+2.7}_{-3.6}$	$^{+0.62}_{-0.27}$	$^{+0.32}_{-0.20}$	$^{+0.31}_{-0.07}$
Intrinsic Z	$^{+0.7}_{-0.7}$	$^{+0.7}_{-0.7}$	$^{+0.7}_{-0.7}$	$^{+0.00}_{-0.00}$	$^{+0.00}_{-0.00}$	$^{+0.00}_{-0.00}$
m_t	$^{+2.8}_{-2.7}$	$^{+3.0}_{-2.9}$	$^{+3.1}_{-3.0}$	$^{+0.29}_{-0.29}$	$^{+0.22}_{-0.22}$	$^{+0.07}_{-0.07}$
Total	$^{+7}_{-7}$	$^{+8}_{-7}$	$^{+8}_{-7}$	$^{+1.8}_{-2.1}$	$^{+1.3}_{-1.6}$	$^{+0.5}_{-0.5}$

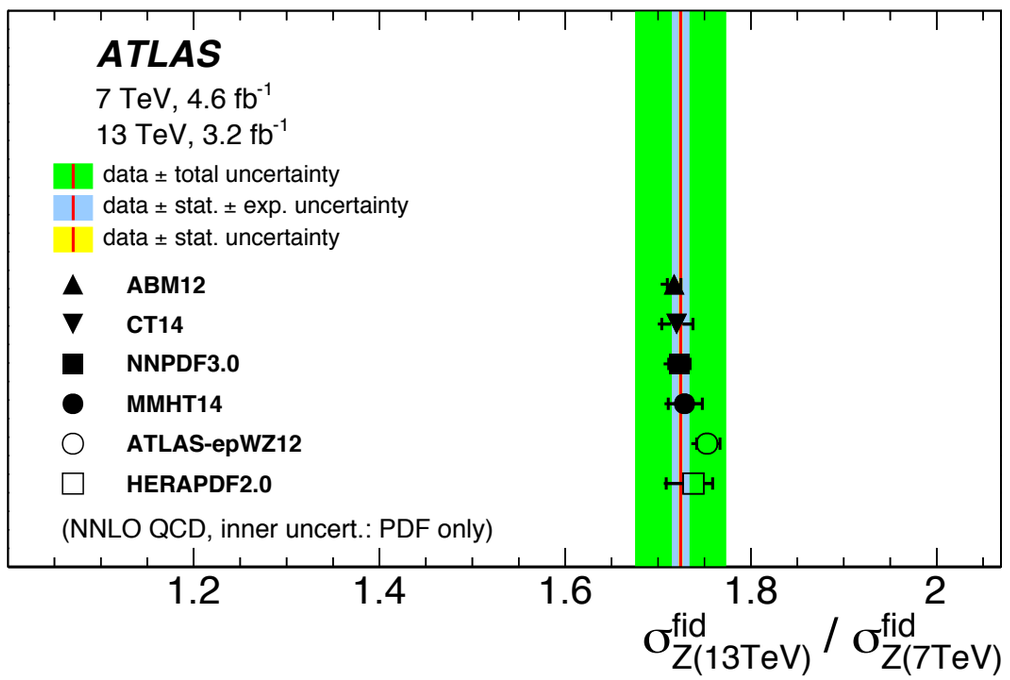
Ratios: tt(Ei)/Z(Ei)

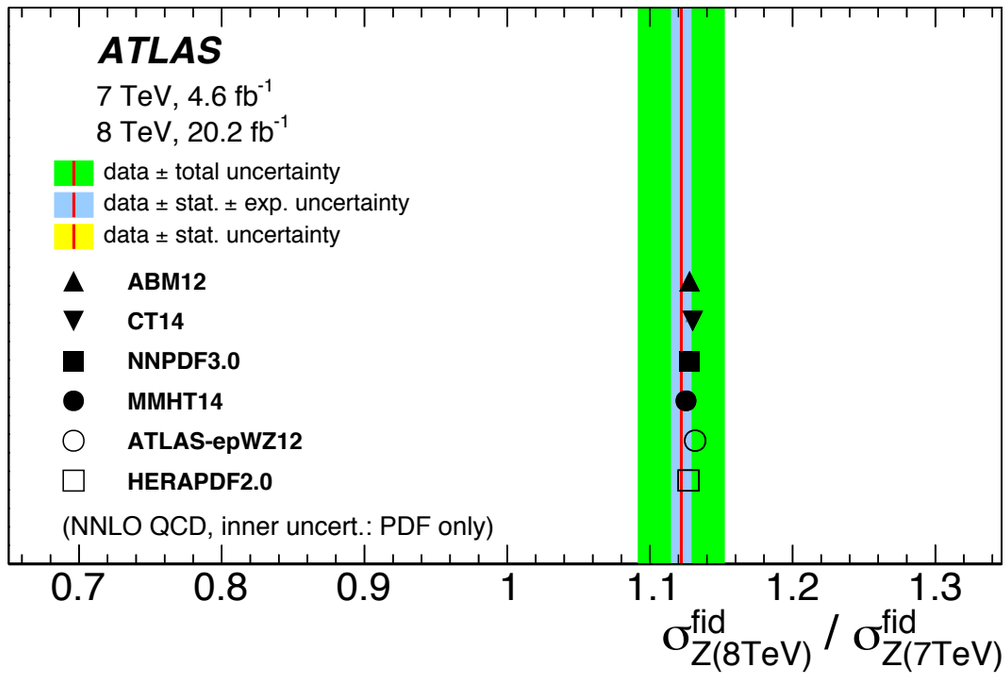




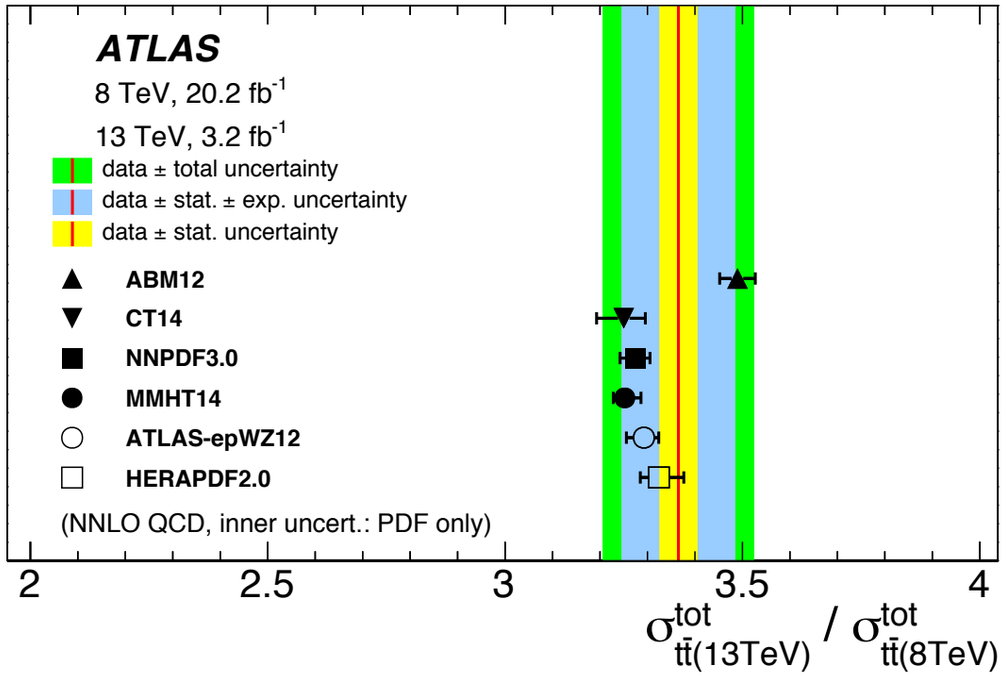
Ratios: Z(Ei)/Z(Ej)

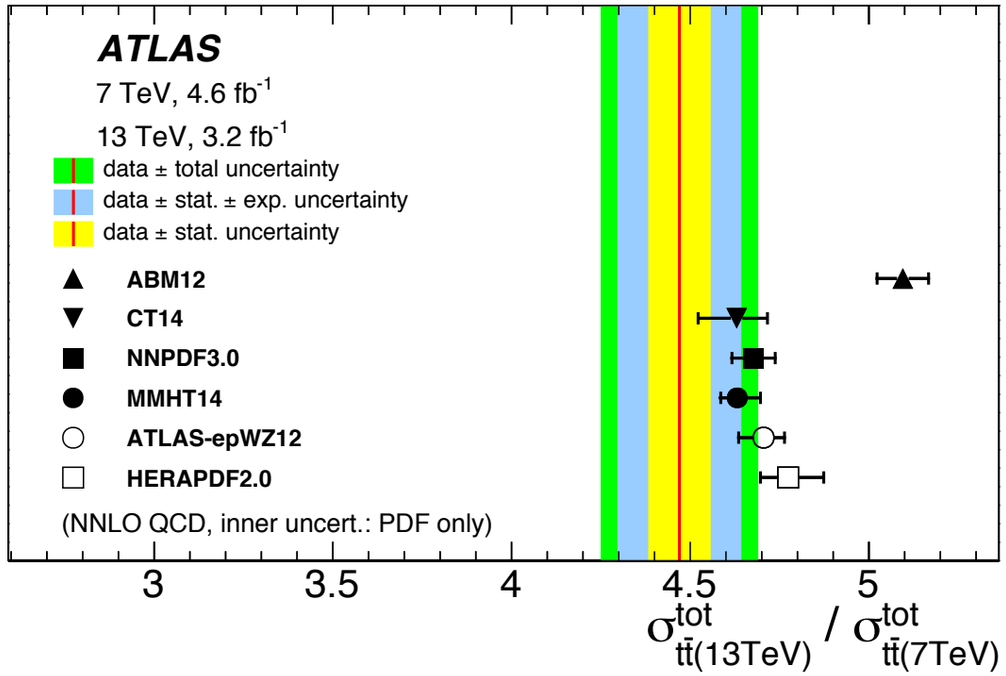


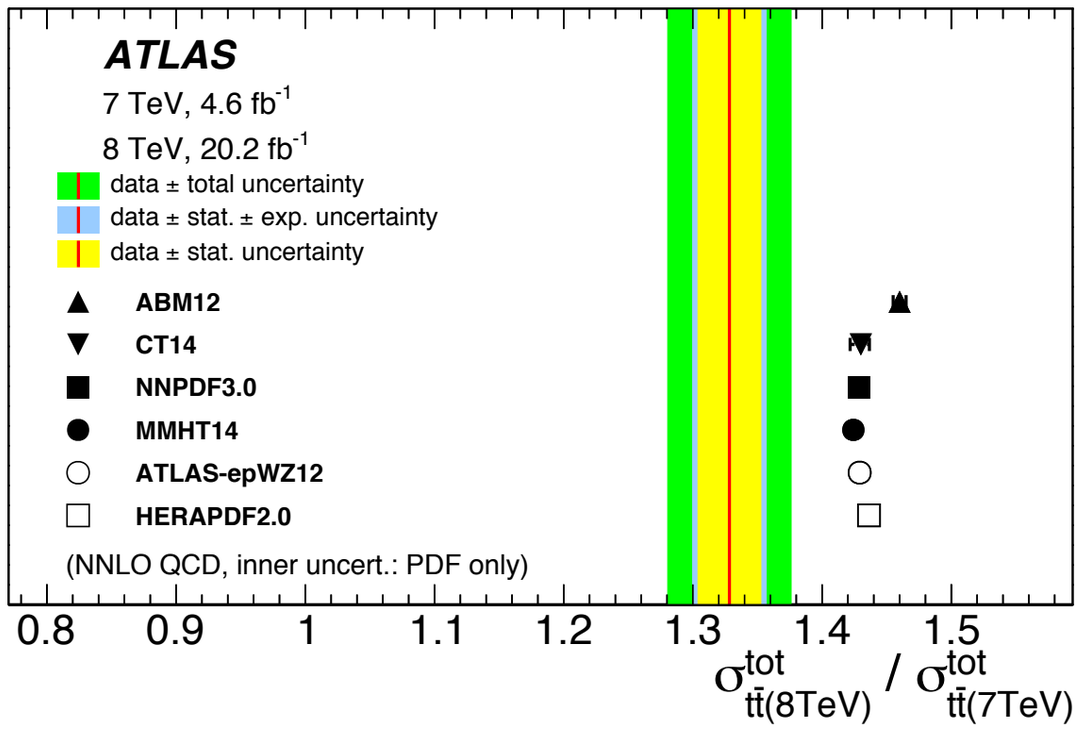




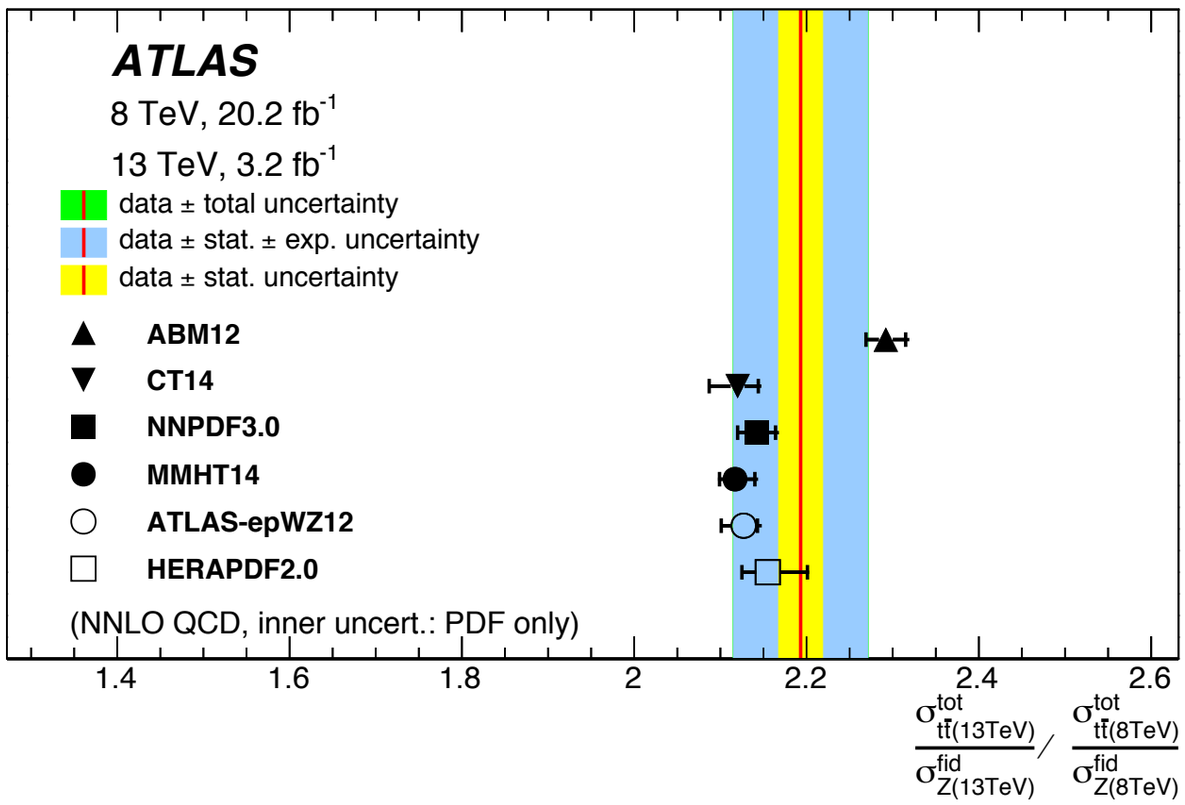
Ratios: tt(Ei)/tt(Ej)

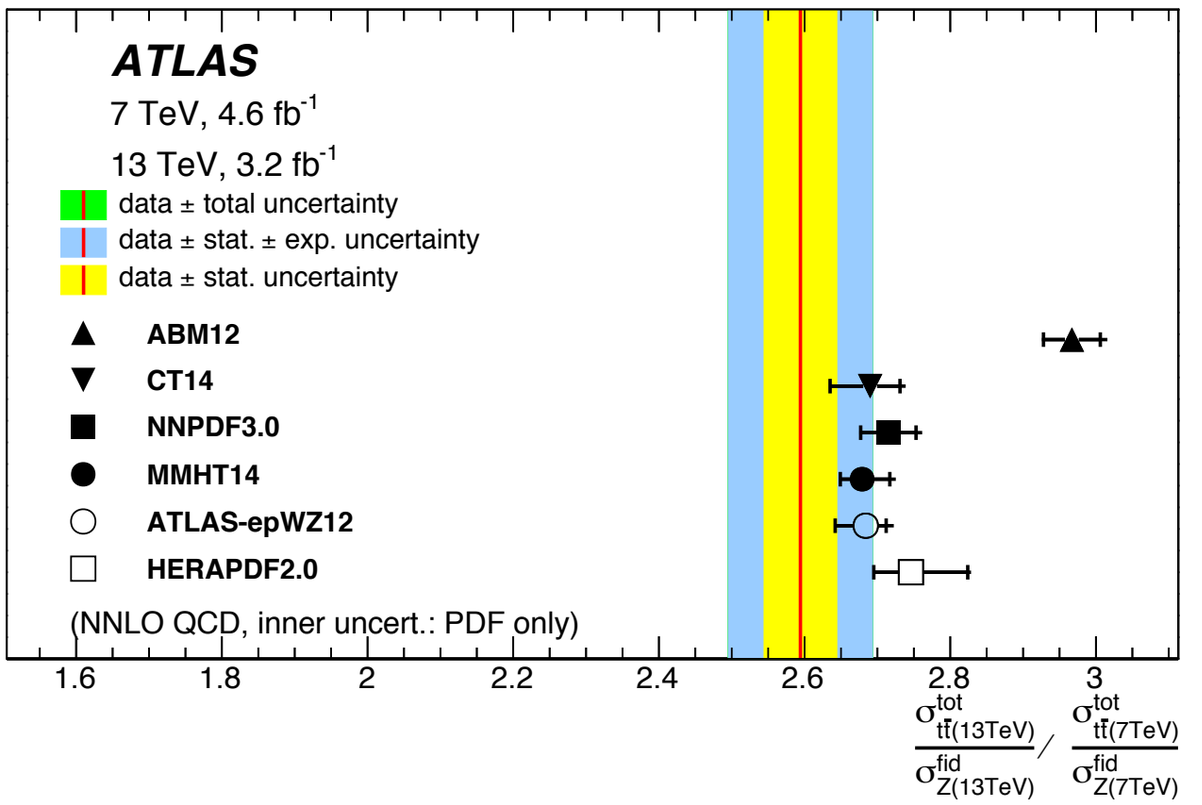






Double ratios: [tt(Ei)/Z(Ei)]/[tt(Ej)/Z(Ej)]

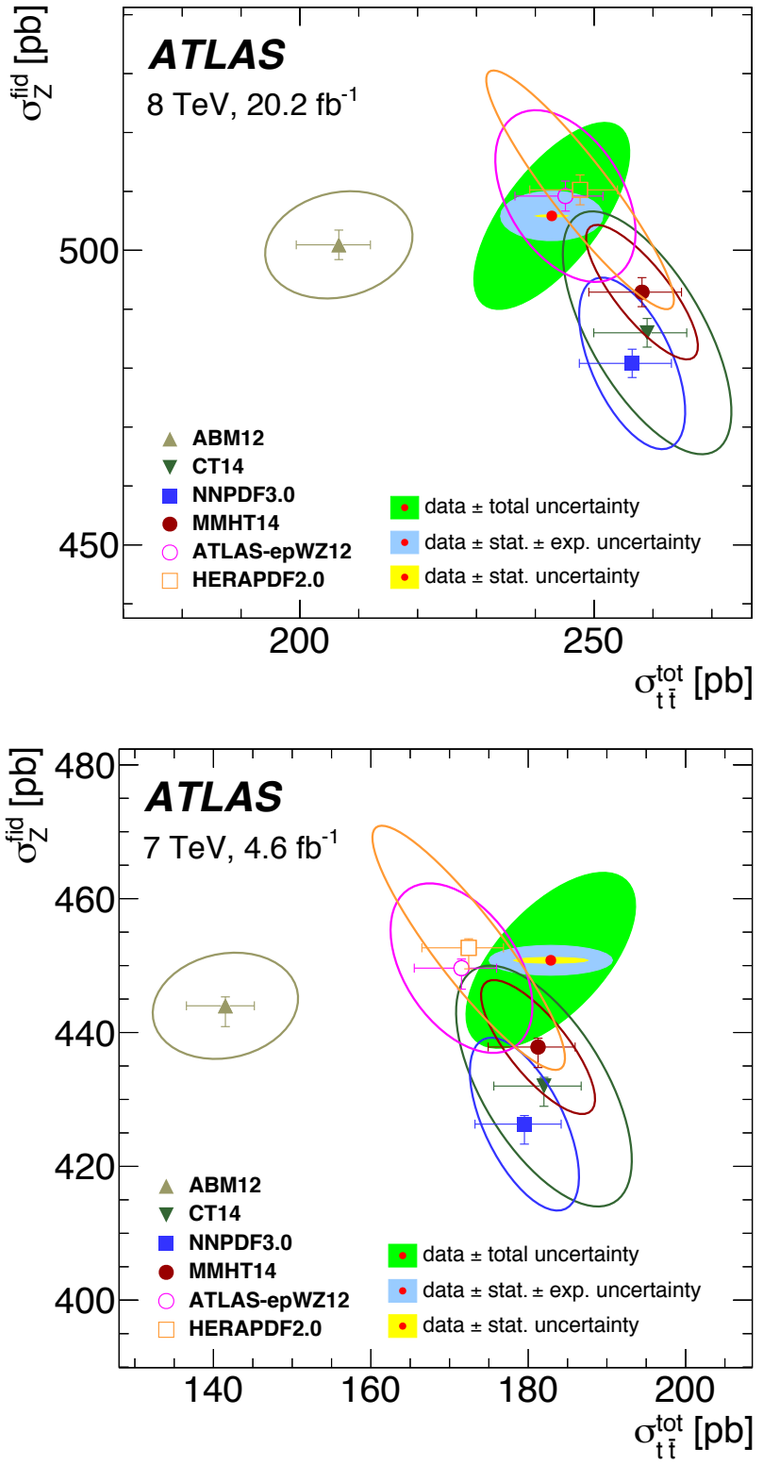




Correlation coefficients

	Z 13 TeV	$t\bar{t}$ 13 TeV	Z 8 TeV	$t\bar{t}$ 8 TeV	Z 7 TeV	$t\bar{t}$ 7 TeV
Z 13 TeV	1.00	0.61	0.10	0.16	0.10	0.15
$t\bar{t}$ 13 TeV	-	1.00	0.11	0.32	0.11	0.31
Z 8 TeV	-	-	1.00	0.68	0.10	0.14
$t\bar{t}$ 8 TeV	-	-	-	1.00	0.15	0.54
Z 7 TeV	-	-	-	-	1.00	0.62
$t\bar{t}$ 7 TeV	-	-	-	-	-	1.00

Pdf studies



	ATLAS-epWZ12	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12
χ^2/NDF	8.3 / 6	15 / 6	13 / 6	17 / 6	10 / 6	25 / 6
p-value	0.22	0.02	0.05	0.01	0.11	< 0.001