Measurement of W, Z boson production and $t\bar{t}$ / Z cross-section ratios by ATLAS

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DESY

LHC discussion 12.06.2017

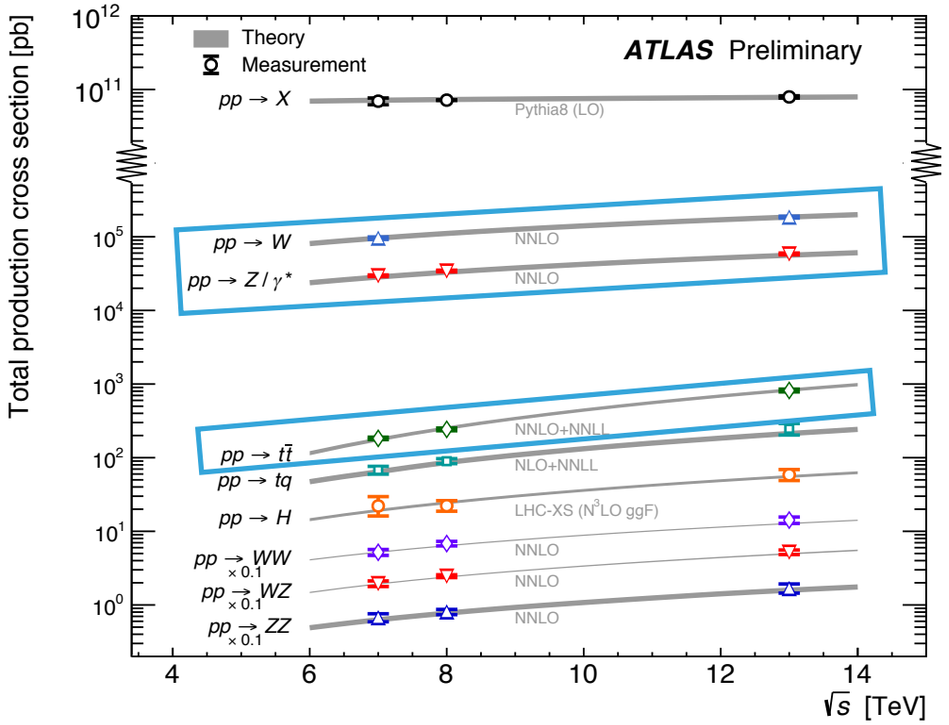
Introduction

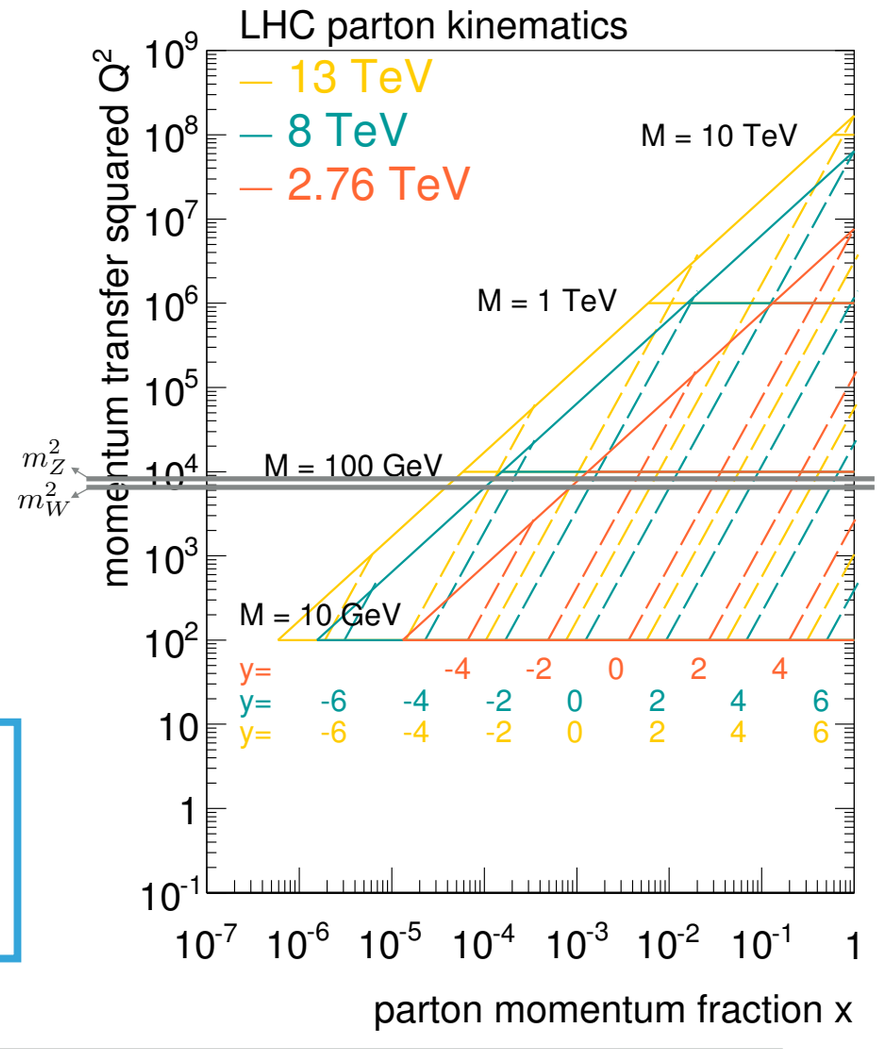
- Drell-Yan is the **largest source** of isolated leptons at LHC
- Theory calculations at **NNLO QCD** and **NLO EW**
- Use Drell-Yan data to extract information on calculation inputs

  → To **constrain calculation uncertainties**

- Measurements in **rapidity bins** provide information for parton flavour parametrisation as a **fiction of *x***

  → $y = \frac{1}{2}\ln(\frac{x_1}{x_2})$





This talk focuses on

- W, Z precision measurements at $\sqrt{s} = 7$ TeV
- tt / Z ratios at $\sqrt{s} = 7, 8, 13$ TeV

Part I

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

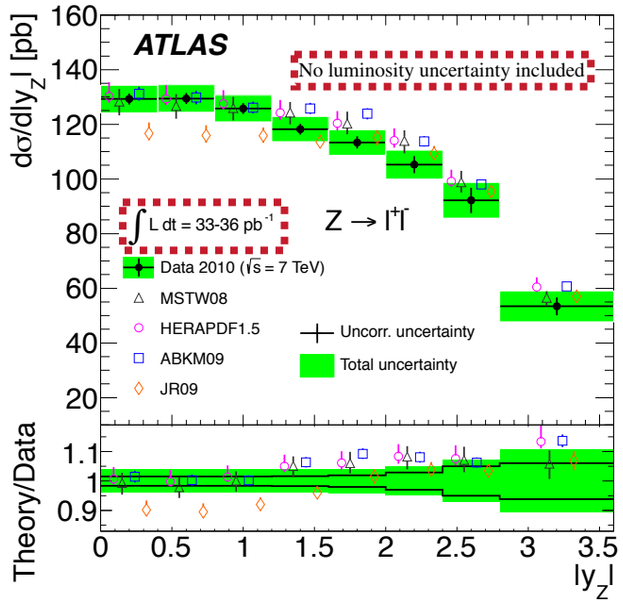
Precision measurement and interpretation of inclusive $W^+ W^-$ and Z/γ^* production cross sections with the ATLAS detector

Eur. Phys. J. C 77 (2017) 367

Motivation

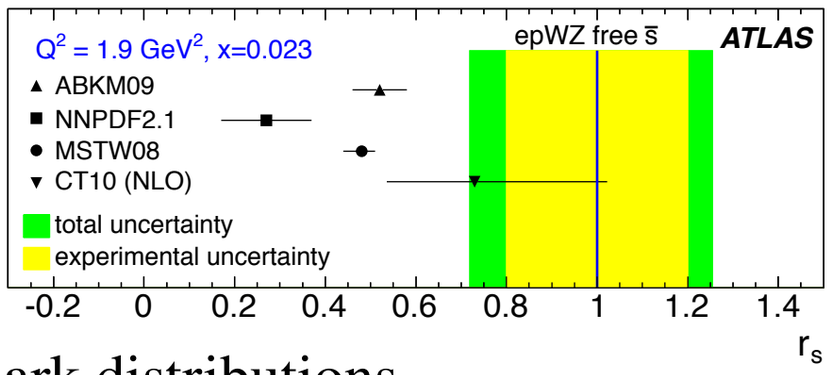
- **Increasing the precision** comparing to previous ATLAS measurements ($\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 33\text{-}36\ \text{pb}^{-1}$: Phys.Rev. D85)
- Test of **electron-muon universality** in the weak interaction sector:

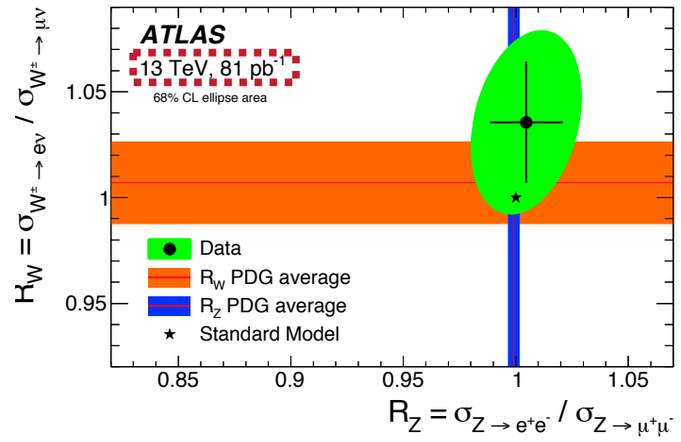
  → ATLAS results at 13 TeV with 50ns data: Phys. Lett. B 759



- **Strangness density** at lox x
- Cross-section **ratios:**

  → **Cancellation** of many experimental uncertainties

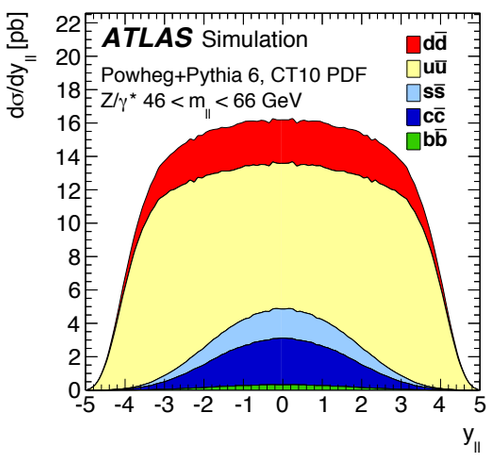


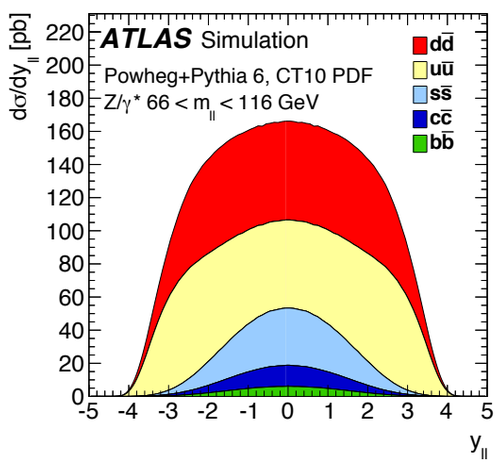


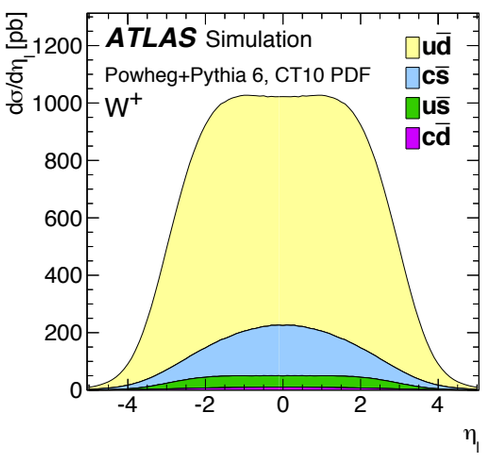
→ W^+/W^-: ratio sensitive to $\mathbf{u_v\text{-}d_v}$ quark distributions

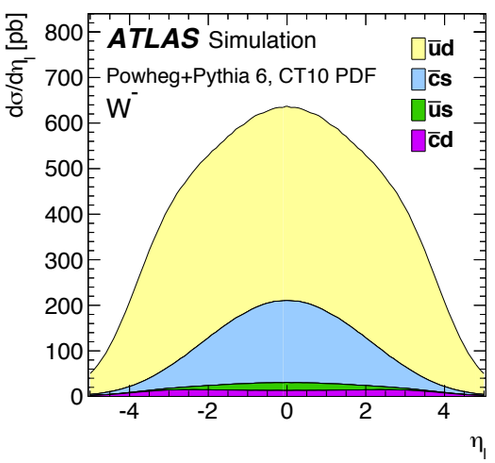
→ $W^{\pm}/Z$ ratio: sensitive to **s-quark** distribution

- Sensitivity to PDF by performing measurements in bins of y_{ll} and η_l :



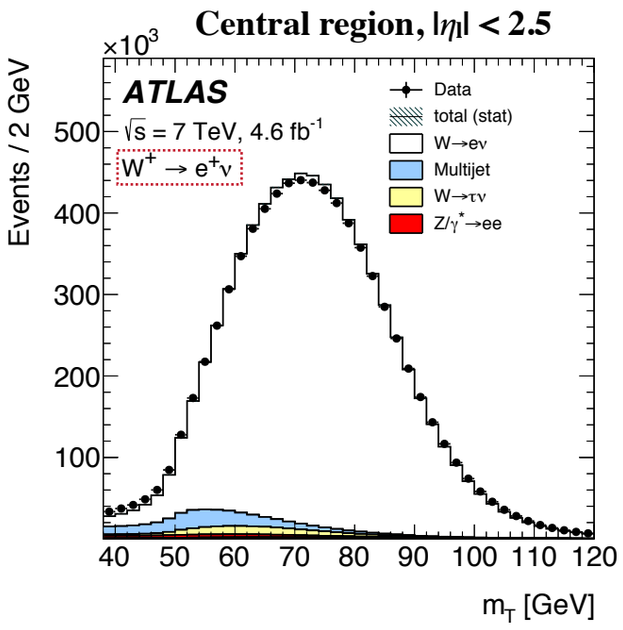


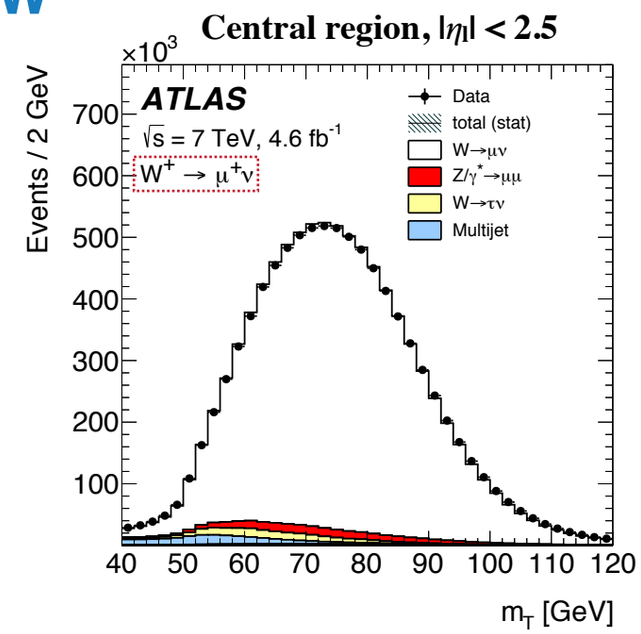




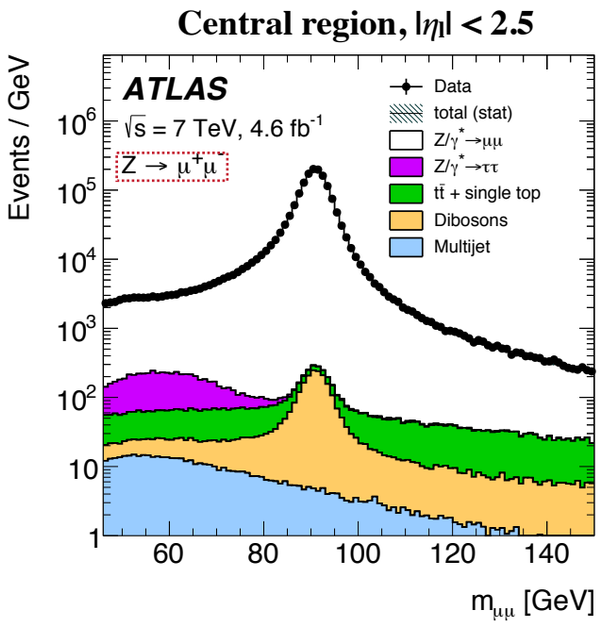
W, Z kinematics and integrated cross sections

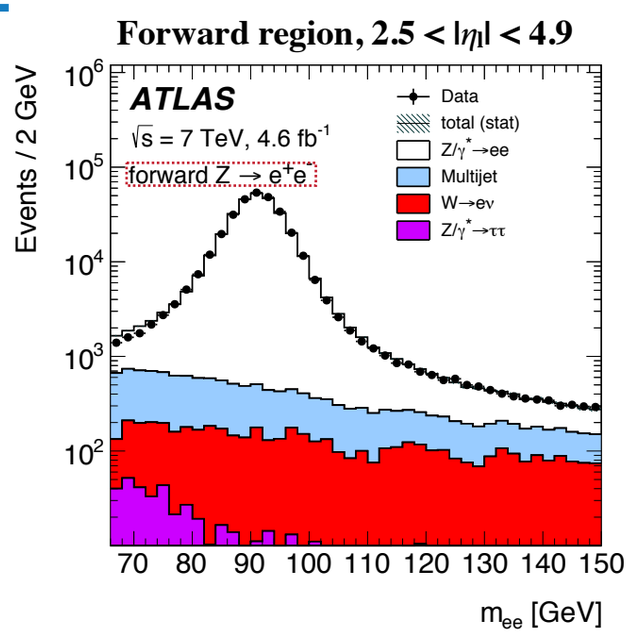
W





Z





	N	Bkg (%)
$W \to e\nu$	12.8 M	8.3
$W \to \mu\nu$	15.4 M	7.7
CC: $Z/\gamma^* \to e^+e^-$	1.0 M	0.47
CF: $Z/\gamma^* \to e^+e^-$	0.3 M	2.8
$Z/\gamma^* \to \mu^+\mu^-$	1.6 M	0.41

- **EW and Top bkg:** MC simulation
- **MJ bkg:** data-driven method

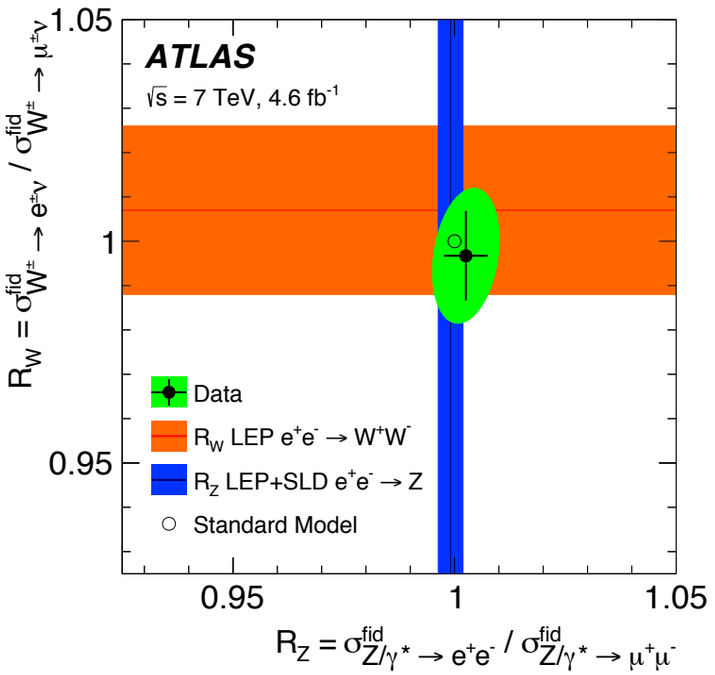
	$\sigma^{fid} \pm$ stat $\pm$ syst $\pm$ lumi [pb]
$W^+ \to e^+\nu$	2939 ± 1 ± 28 ± 53
$W^+ \to \mu^+\nu$	2948 ± 1 ± 21 ± 53
$W^- \to e^-\bar{\nu}$	1957 ± 1 ± 21 ± 35
$W^- \to \mu^-\bar{\nu}$	1964 ± 1 ± 13 ± 35
$Z/\gamma^* \to e^+e^-$	502.7 ± 0.5 ± 2.0 ± 9.0
$Z/\gamma^* \to \mu^+\mu^-$	501.4 ± 0.4 ± 2.3 ± 9.0

- **W sys:** Hadronic recoil response (E_T^{miss}, JES, JER), MJ bkg, Reco eff.
- **Z sys:** lepton Reco, ID, Iso eff.

Significant uncertainty reduction comparing to the previous measurement: Phys.Rev. D85 (2012)

Lepton universality and combination

Lepton universality



- **R_W and R_Z** represent ratios of corresponding branching fractions
- Due to cancellation of correlated uncertainties reach a precision of **1% and 0.5%** for W and Z branching fractions, respectively
- Precision improvement comparing to previously published 7 TeV and 13 TeV (50 ns) results: Phys.Rev. D85 (2012), Phys. Lett. B 759 (2016)
- The measurements **confirm lepton (e-μ) universality** (SM: unity) in the weak vector-boson decays

Combination of *e* and μ channels

- Combination is based on χ^2 minimisation and uses individual sources of systematic uncertainties
- Correlation model:

	Z	W^+	W^-
Z	1	0.349(0.964)	0.314(0.958)
W^+		1	0.890(0.991)
W^-			1

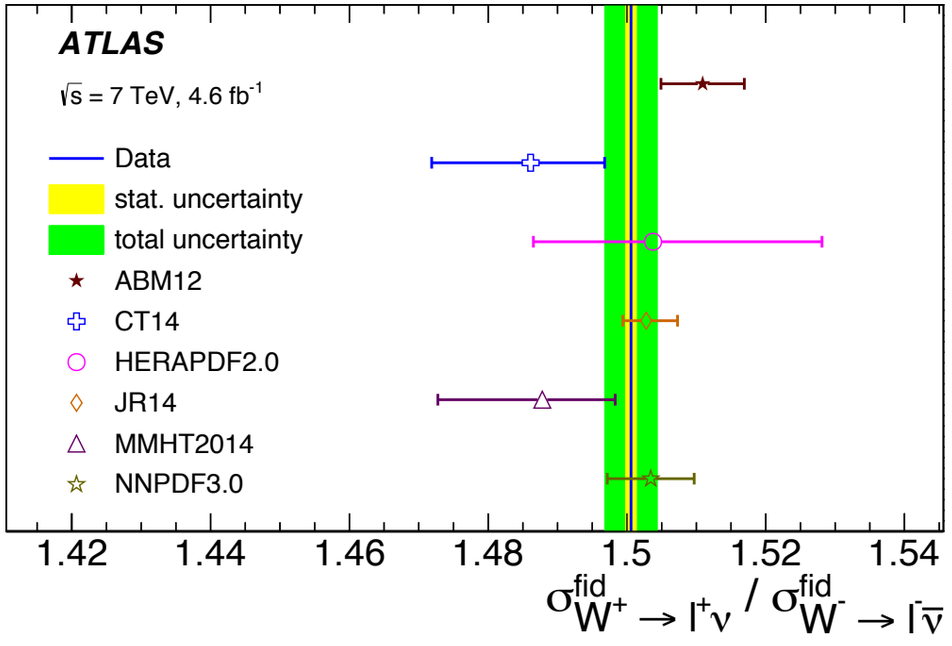
- Combined cross sections:

	σ^{fid} ± stat ± syst ± lumi [pb]
W→eν	4896 ± 2 ± 49 ± 88
W→μν	4912 ± 1 ± 32 ± 88
W→lν	4911 ± 1 ± 26 ± 88
Z/γ*→ll	502.2 ± 0.3 ± 1.7 ± 9.0

* Numbers in brackets are calculated taking into account luminosity uncertainty

- Main **correlated** experimental syst. **sources**: ***e*** and μ momentum scale and resolution, hadronic recoil response, signal modelling, bkg. estimation with MC simulation

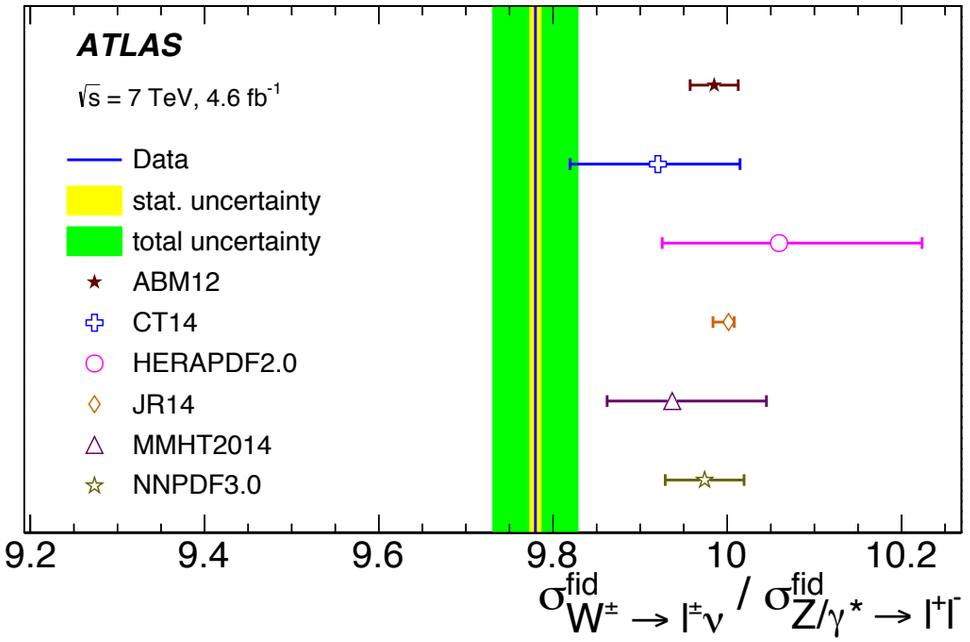
Cross-section ratios

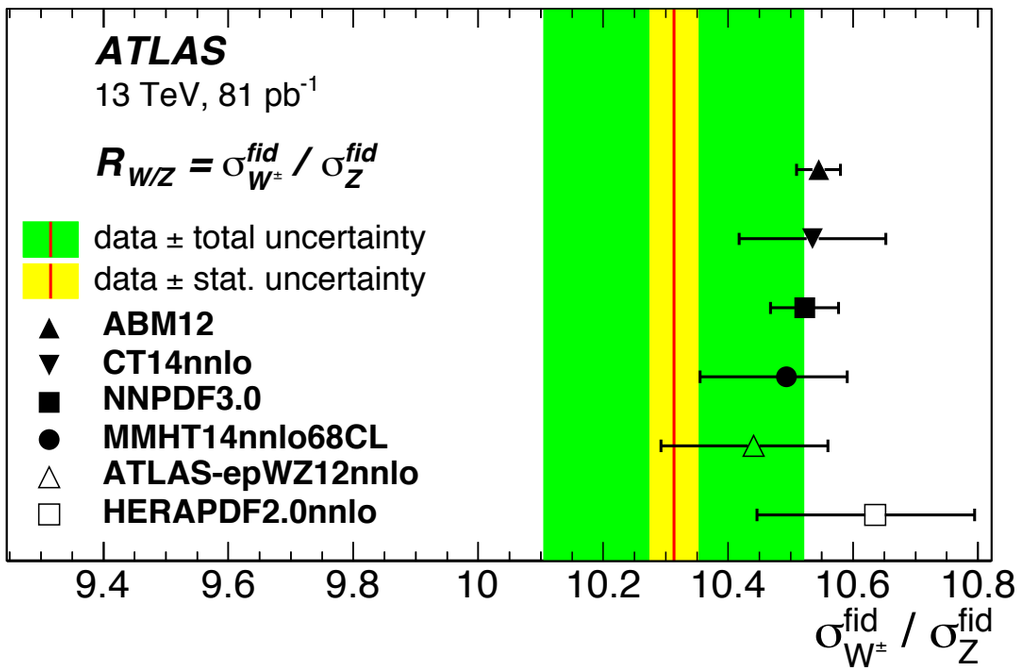


- Complete cancellation of luminosity uncertainty
- High precision of data comparing to some theory predictions indicates their potential constraining power
- W^+/W^- ratio is generally well reproduced
- Predictions for $W^{\pm}/Z$ are systematically higher than measured in data

→ compatible with results based on 13 TeV data (50 ns):

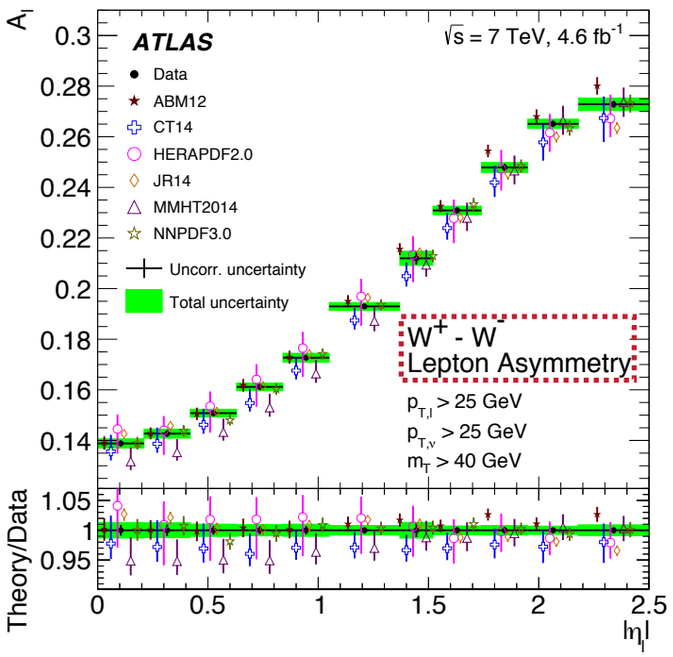
Phys. Lett. B 759 (2016)

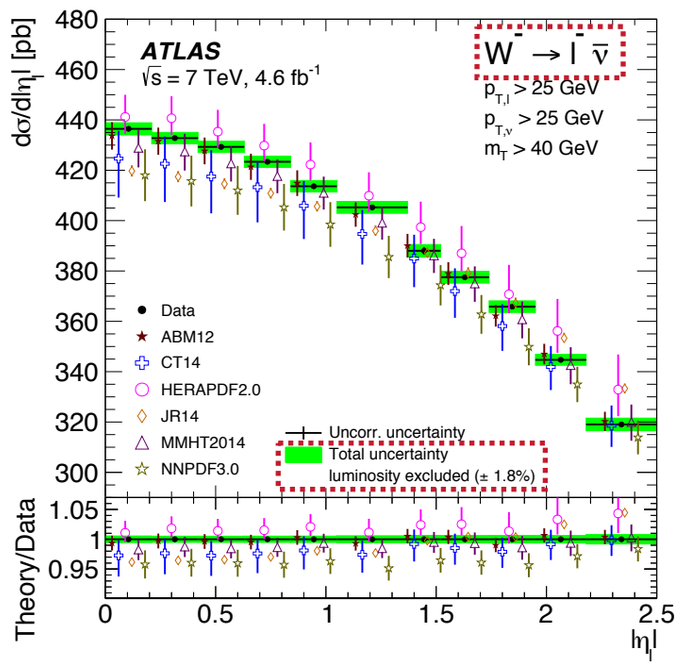




Differential cross sections

W





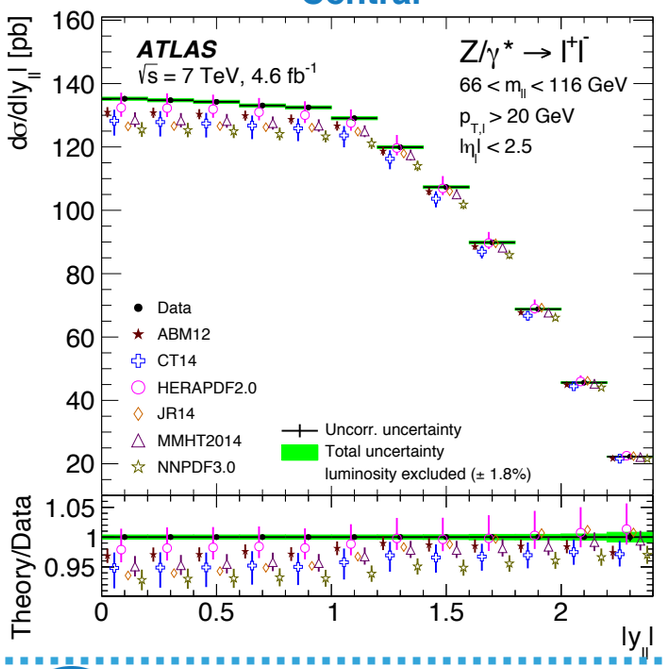
- Lepton charge asymmetry:

$$A_\ell = \frac{d\sigma_{W+}/d|\eta_\ell| - d\sigma_{W-}/d|\eta_\ell|}{d\sigma_{W+}/d|\eta_\ell| + d\sigma_{W-}/d|\eta_\ell|}$$

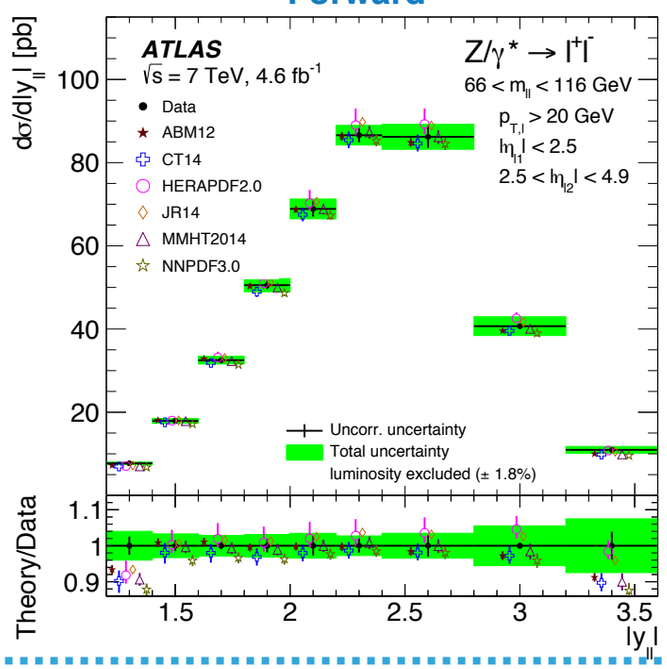
- Good agreement for A_ℓ
- Shape of W differential cross section well described with predictions
- Experimental uncertainty: **from 0.5% to 1%**

Z

Central



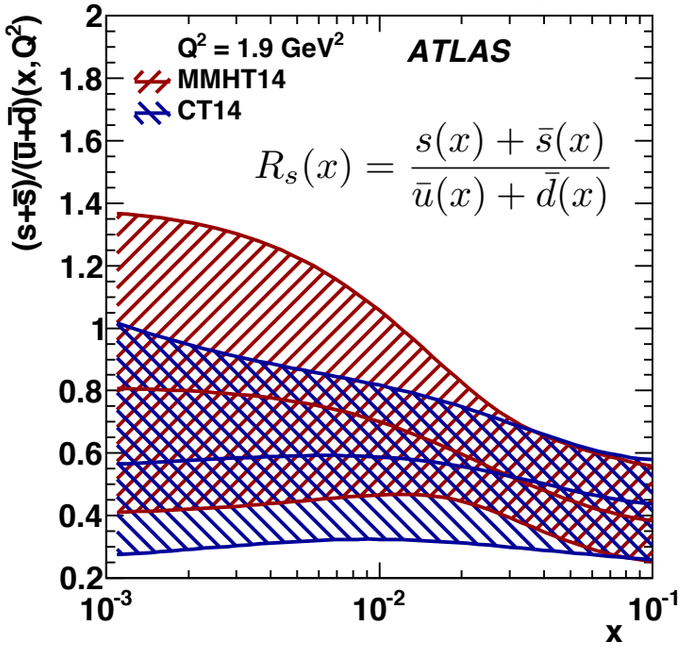
Forward



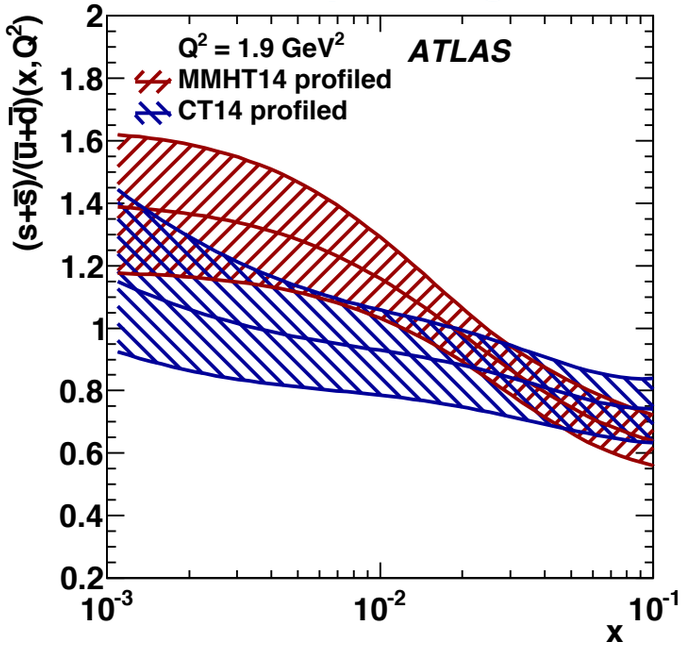
- At central rapidity ($|y_{\ell\ell}| < 1$) most of theoretical predictions are lower than data
  - ➡ Potential indication of strangeness unsuppression in the data
- At forward region measurement is not very sensitive to differences between PDFs

PDF profiling

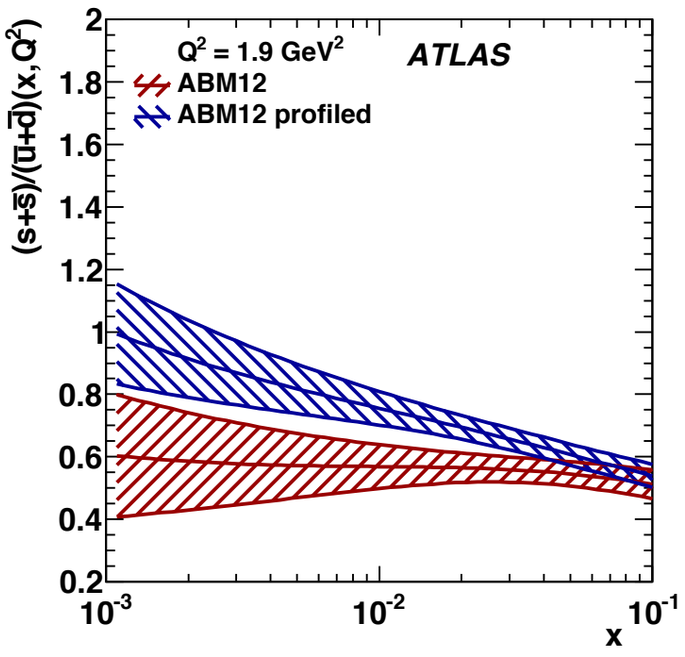
Before profiling

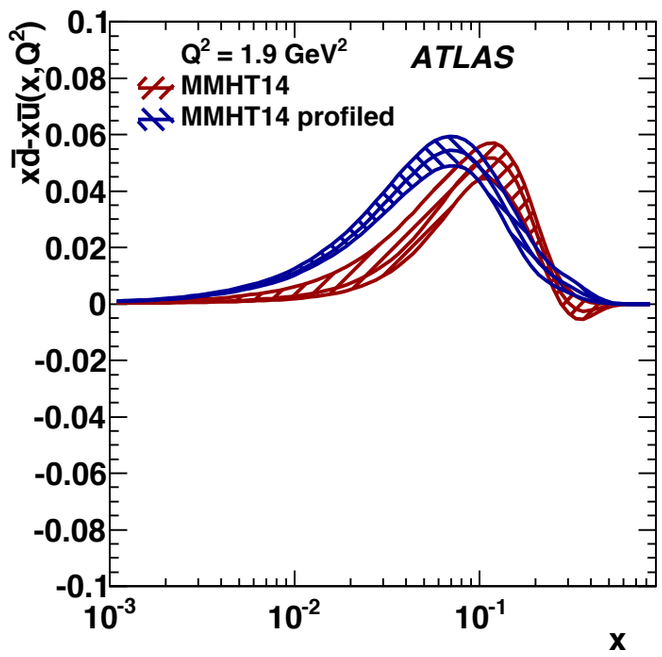


After profiling



- **Quantitive estimation** of data and predictions agreement
- Provides a **shifted set** of parton distributions with **reduced uncertainties**
- Quark density ratio $\mathbf{R_S}$ (for MMHT14 and CT14) at $\mathbf{x \simeq 0.023}$ shows significant **reduction of uncertainties** and **increasing of central values** towards unity
  - → Supports the hypothesis of **unsuppressed s-quark density** at low x

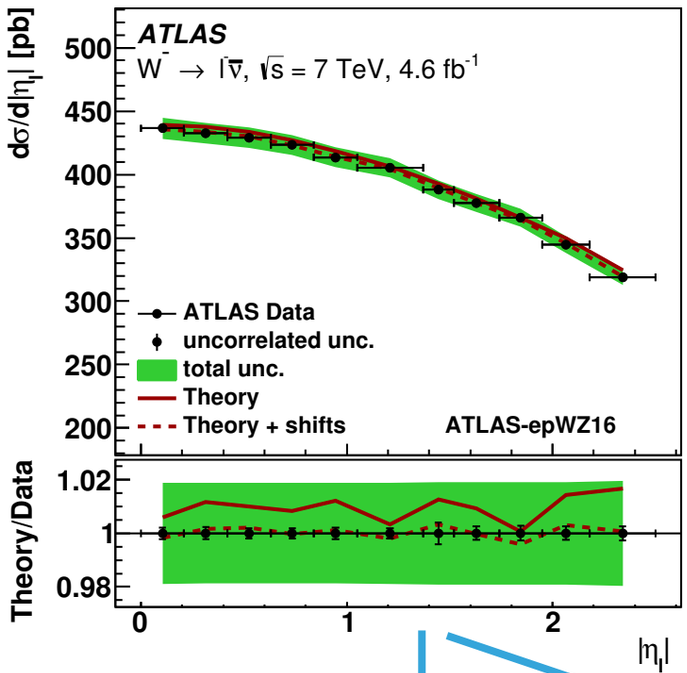




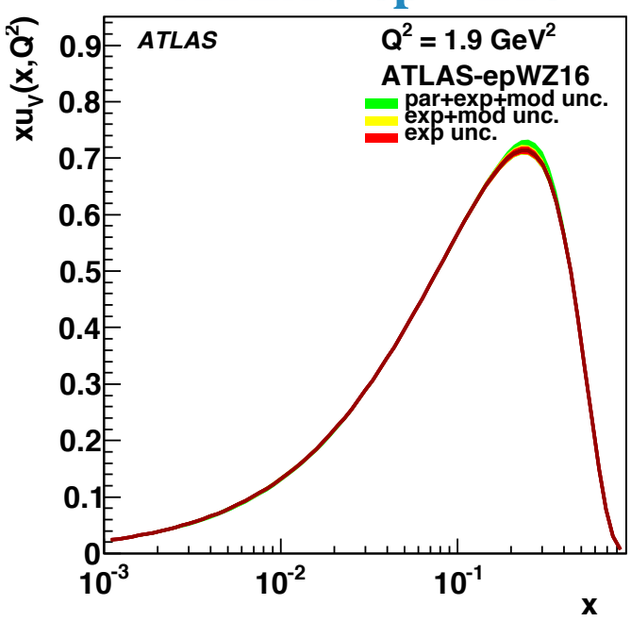
- ABM12 demonstrates tension between profiled and original R_S
  - → Profiled set has increased central value
  - → Uncertainty stays at the same high level of precision
- $x\bar{d} - x\bar{u}$ profiled result is shifted towards smaller x values

QCD analysis

QCD fit

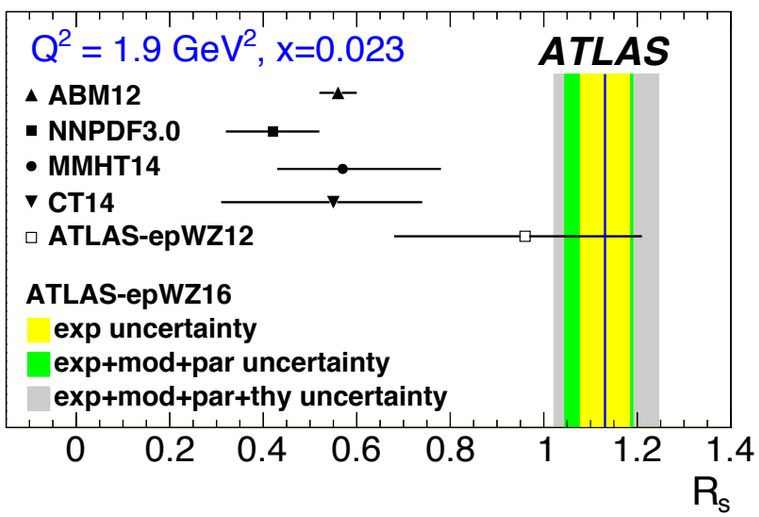


ATLAS-epWZ16

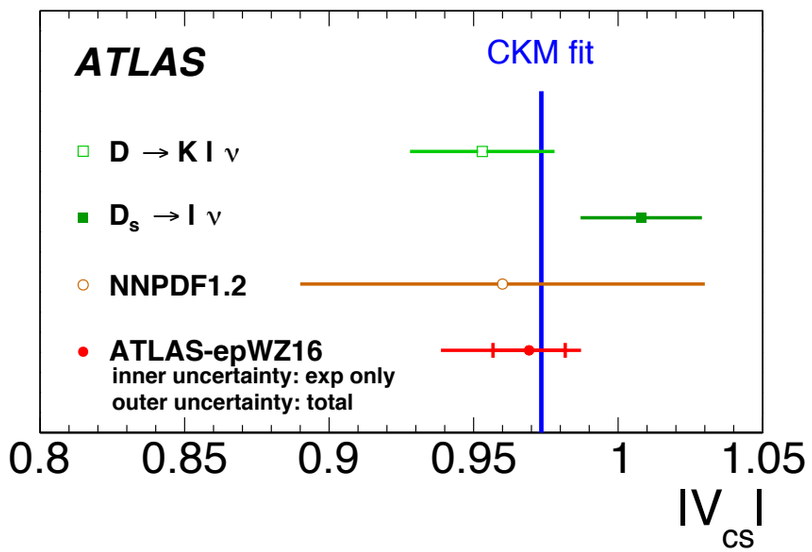


- QCD fit is performed using **DIS HERA I+II and ATLAS DY** data
  - → **ATLAS data** provide more **sensitivity** to quark sea and valence-quark distributions **at lower *x***
- Data are all **described** by the fit (ATLAS: $\chi^2/npts = 108/61$, total: $\chi^2/n.d.f. = 1321/1102$)
- Fit determines a **new set of PDFs**, termed **ATLAS-epWZ16**
- **ATLAS-epWZ16** has **smaller experimental uncertainties** than the ATLAS-epWZ12 set

Strange density (R_S)



Magnitude of CKM matrix element



- Measured R_S confirms that the **strangeness is unsuppressed at low x~0.023 and low Q^2 = 1.9 GeV^2**
- **$|V_{cs}|$ obtained** from the fit where it was varied, while rest CKM elements were fixed

Part II

$\sqrt{s} = 13$ TeV, $\int \mathcal{L} = 3.2$ fb^{-1}

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

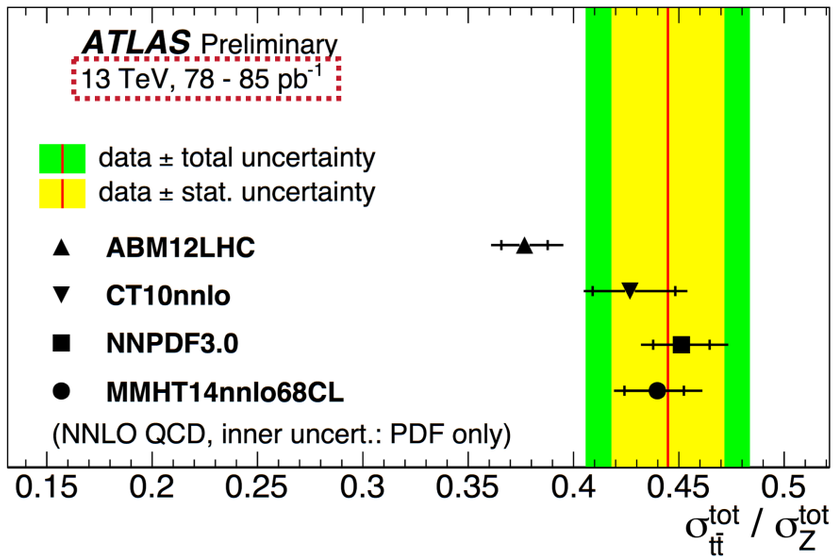
JHEP 02 (2017) 117

Motivation

Single $\sigma_{t\bar{t}}/\sigma_Z$ ratios at given √s

- Sensitive to the gluon-to-quark PDF ratio
- Luminosity uncertainty cancelation
- Lepton-related systematic cancelation

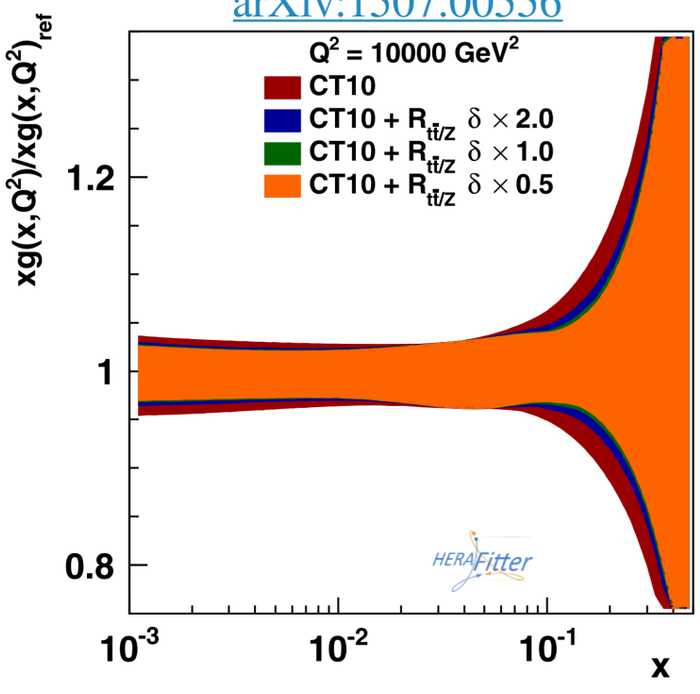
atlas-conf-2015-049



Single $R_Z^{i/j\ \mathrm{TeV}}$, $R_{t\bar{t}}^{i/j\ \mathrm{TeV}}$ ratios at different √s

- Systematic uncertainties cancelation
- σ_Z at different $\sqrt{s}$ have similar PDF sensitivity → Z boson data can be used to cross-normalise measurements at different $\sqrt{s}$

arXiv:1507.00556



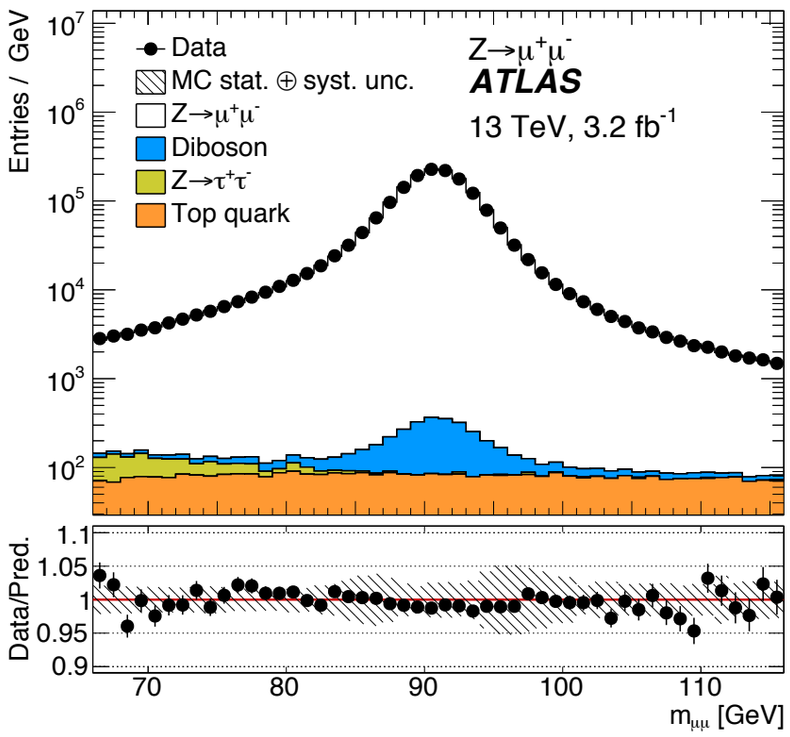
Double ratios

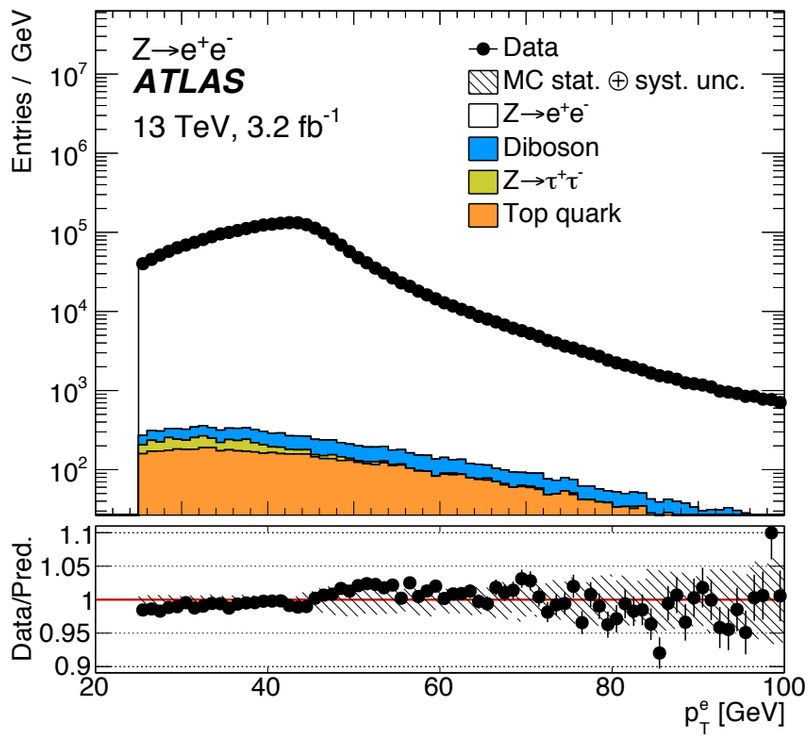
- Luminosity-uncertainty-independent checks of SM

Public results used in ratios:

- $t\bar{t}$ at 7, 8, 13 TeV: Eur. Phys. J. C74 and C76 , Phys. Lett. B 761
- Z at 7, 8, TeV: arXiv:1612.03016 , Eur. Phys. J. C76(5) 1-61

Z analysis at 13 TeV





Systematic sources

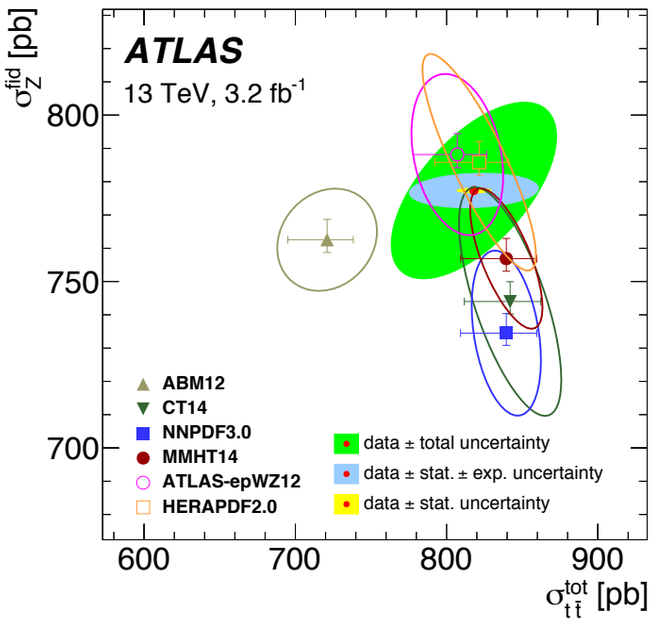
Source	$Z \to e^+e^-$ [%]	$Z \to \mu^+\mu^-$ [%]
Lepton trigger	< 0.1	0.1
Lepton reconstruction, ID	0.4	0.7
Lepton isolation	0.1	0.4
Lepton scale and resolution	0.2	0.1
Charge identification	0.1	–
Pile-up modelling	< 0.1	< 0.1
PDF	0.1	< 0.1
$p_T^{\ell\ell}$ mismodelling	0.1	< 0.1
Total	0.5	0.8

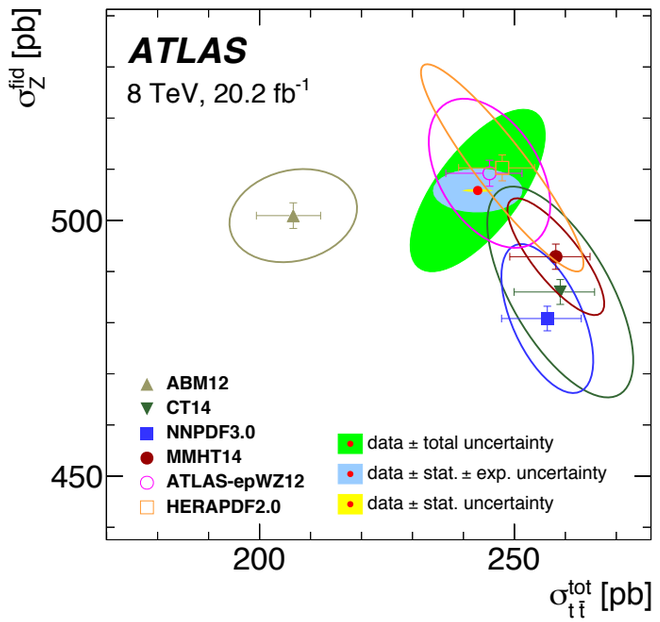
Background contributions

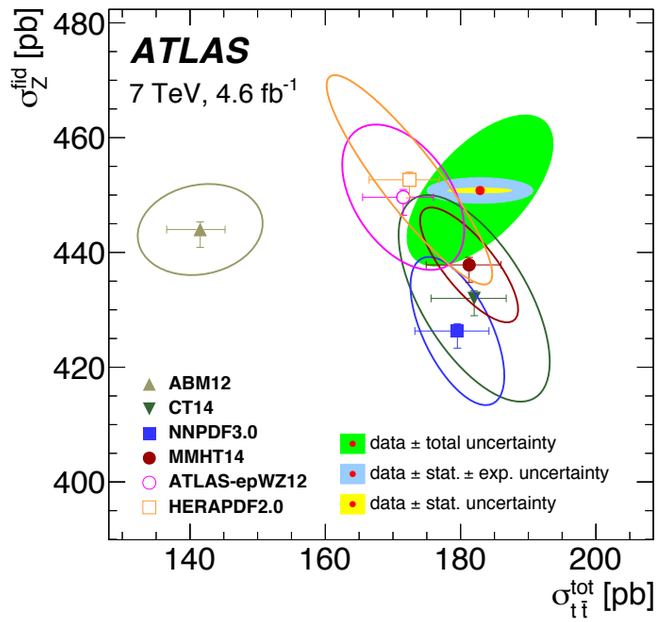
- estimated from MC simulations
- total background event: ~0.5%
- main contribution: top-quark pair production
- sum of all electroweak backgrounds: ~0.2%
- multijet events: < 0.1%

Correlation model

Correlation ellipses







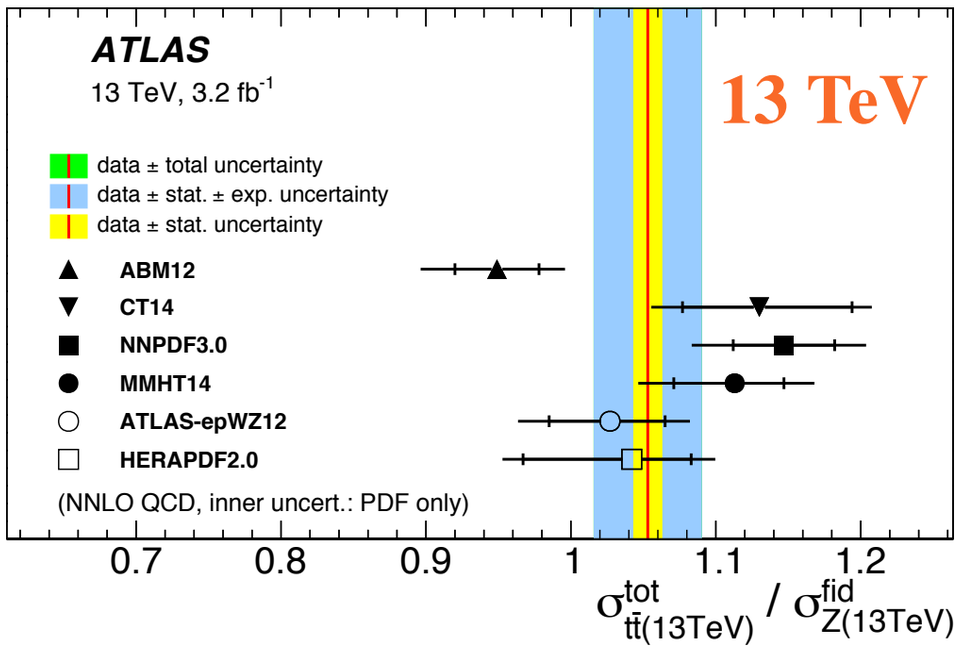
- Opposite sign of correlation in **data provides discriminative input to PDFs** determination

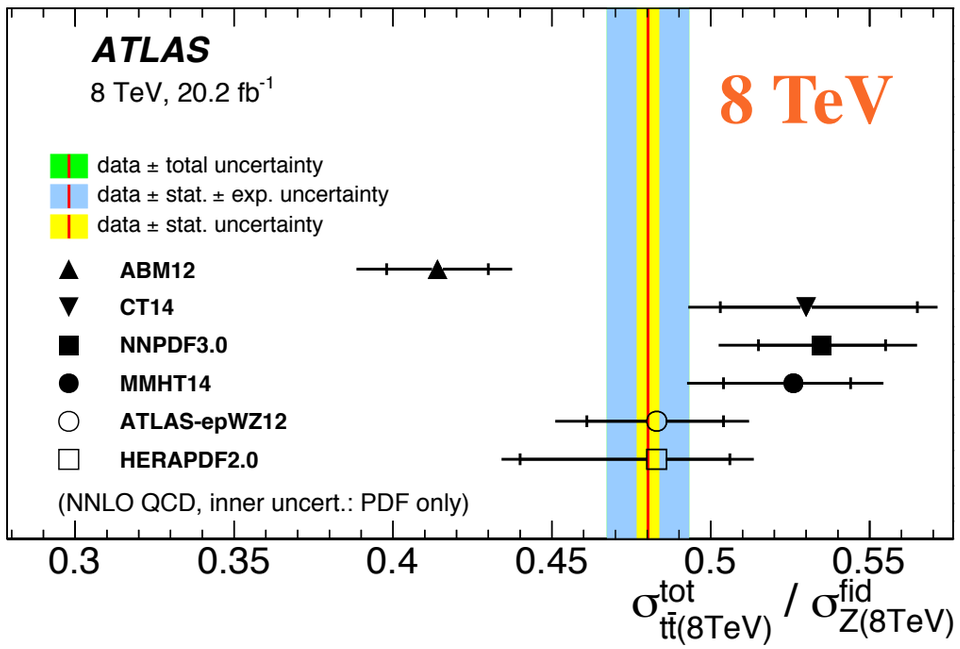
Correlation of grouped systematic sources

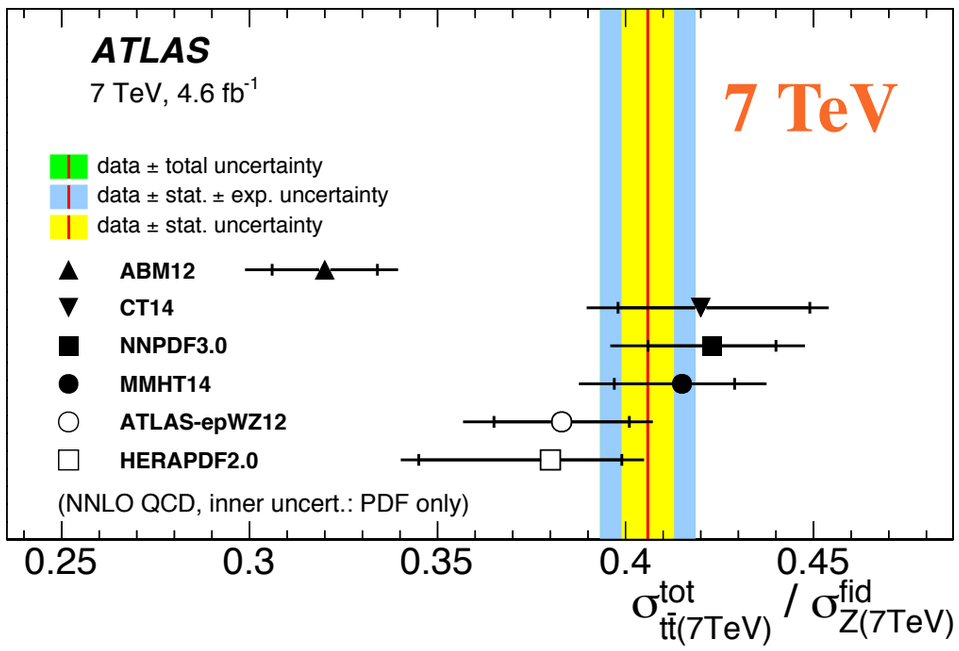
Source / $\sqrt{s}$ [TeV]	$\delta\,\sigma_Z^{\mathrm{fid}}$ 13	8	7	$\delta\,\sigma_{t\bar{t}}^{\mathrm{tot}}$ 13	8	7
Luminosity	A	B	C	A	B	C
Beam energy	A	A	A	A	A	A
Muon (lepton) trigger	A	A*	A	A	B	B
Muon reconstruction/ID	A	B	C	A	D	D
Muon isolation	A	A	A	B	C	D
Muon momentum scale	A	A	A	A	A	A
Electron 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

- Main source of correlation is the **luminosity uncertainty**
- **Table entries:** → in different rows are uncorrelated
  → within a row with the same letter are fully correlated
  → with starred letter are mostly correlated
- box - dominant uncertainty sources

$t\bar{t}$ to Z ratios at a given $\sqrt{s}$

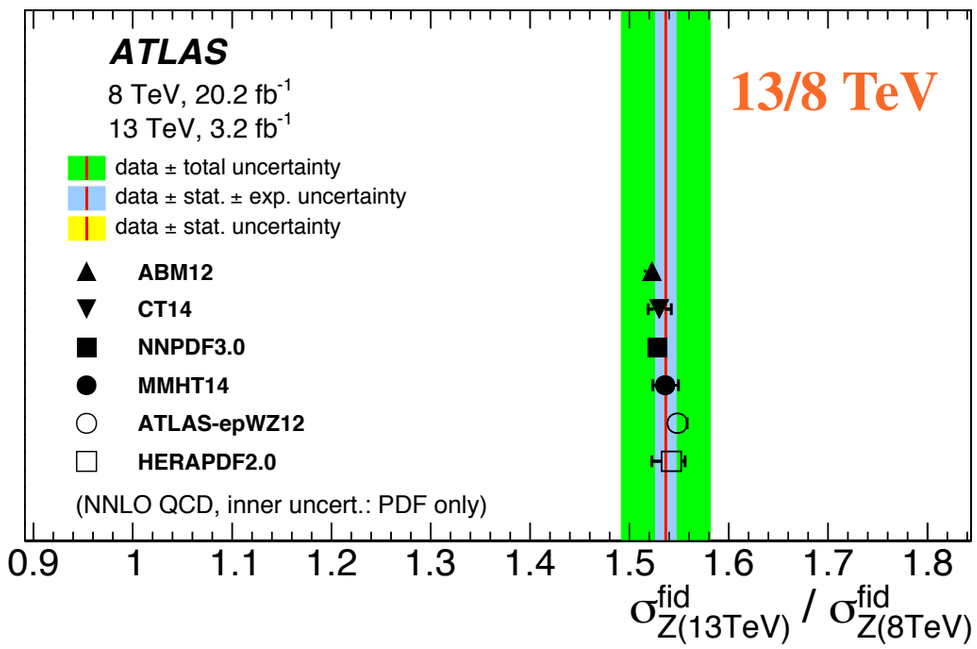


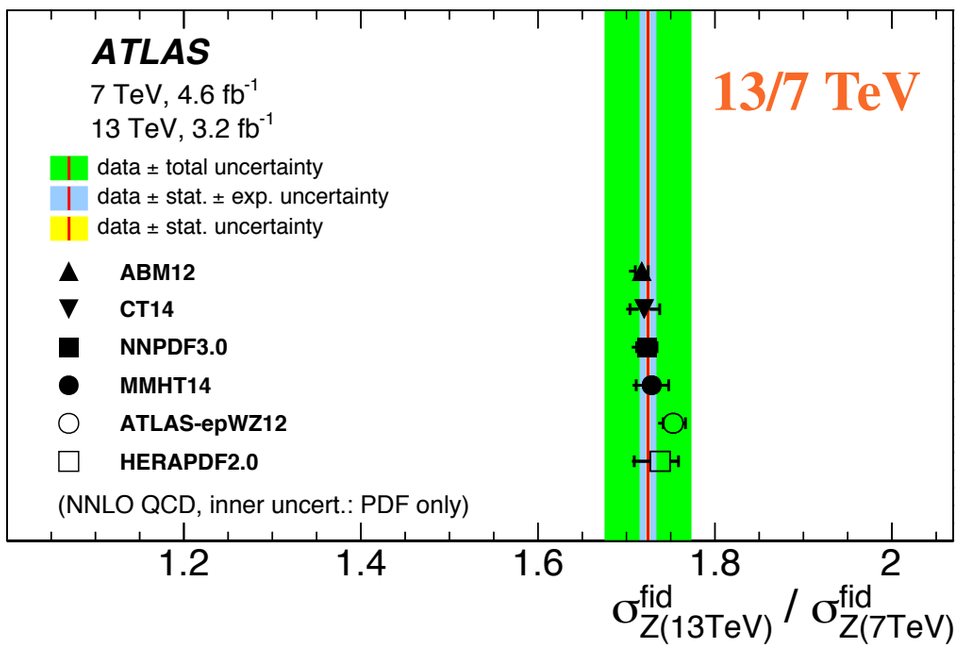


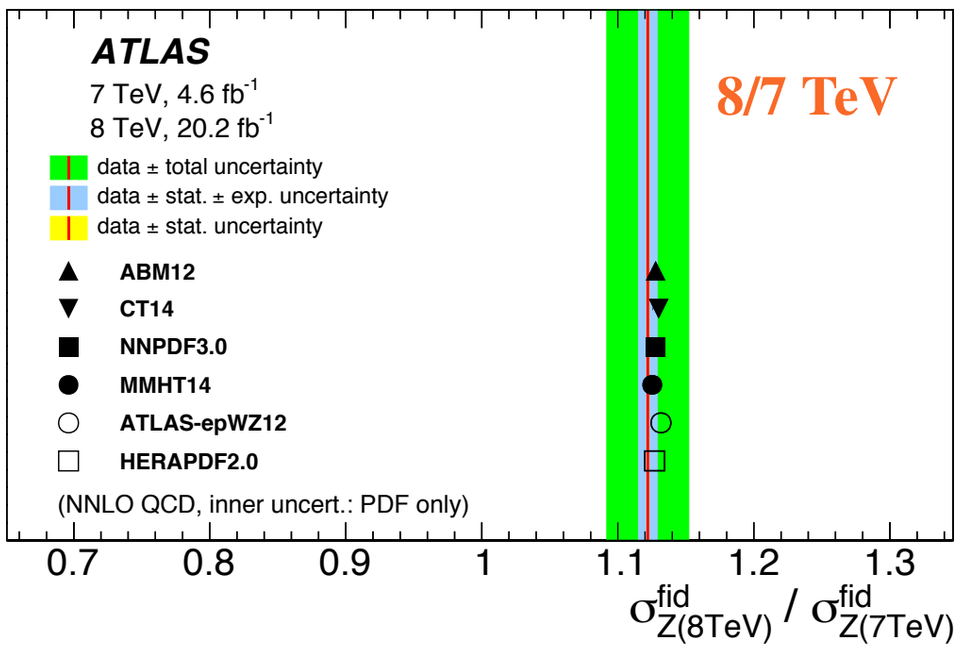


- **Luminosity** uncertainties almost entirely **cancel**
- ATLAS **data are more precise** than most of the theory predictions → indication of **strong constraining power**
- **Similar pattern** of predictions for all $\sqrt{s}$:
  - → ABM12 yields the lowest values
  - → PDF4LHC sets predict the largest ratios
  - → HERA-based sets are in the middle

Z ratios at different √s

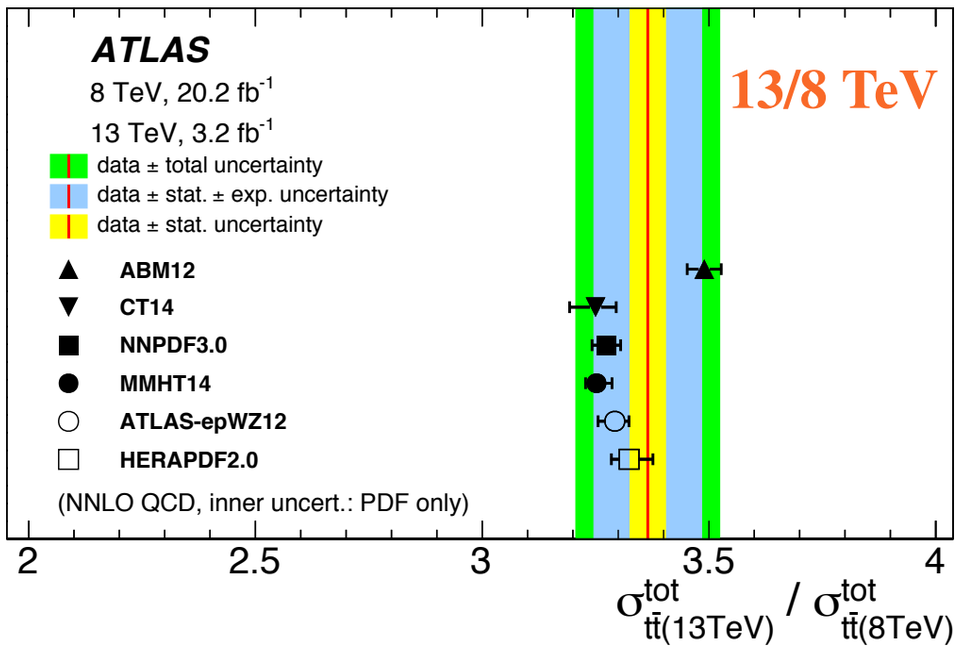


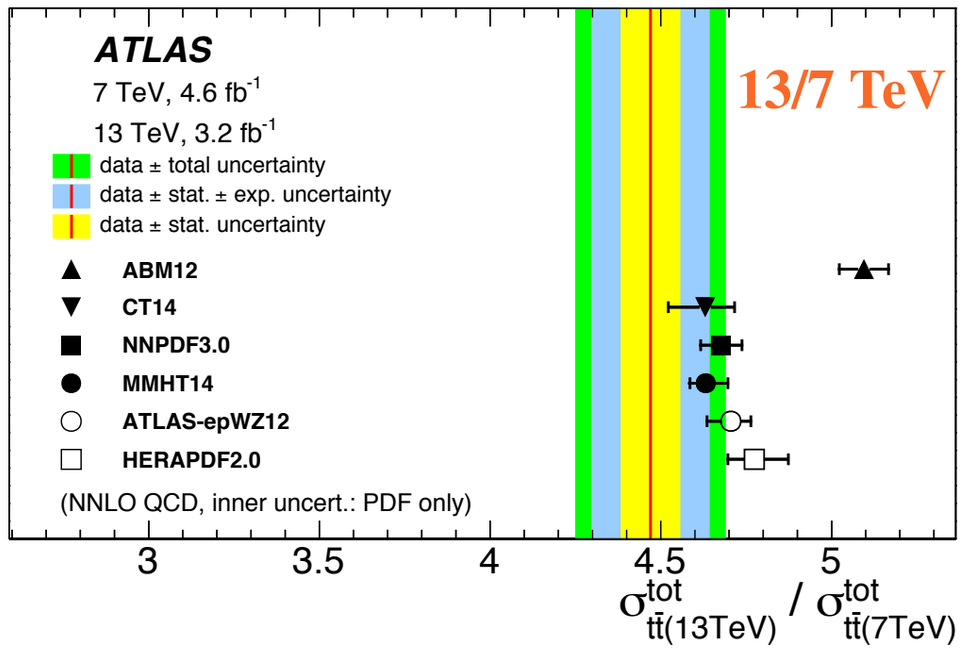


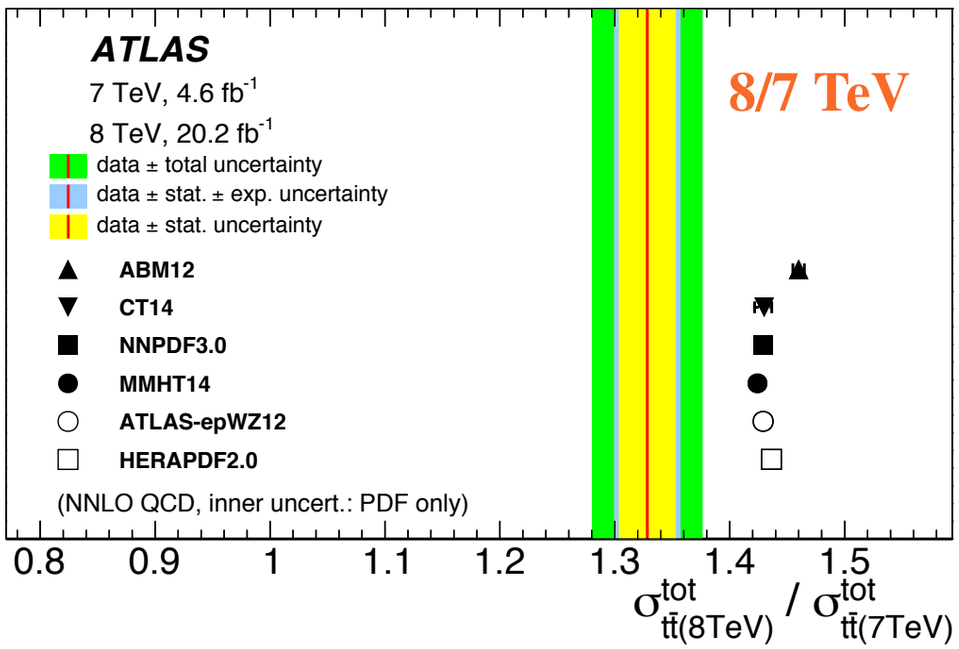


- Uncertainties **dominated** by the **luminosity uncertainty**
- Most of predictions **agree** with data **within exp. uncertainty**
  - → May indicate that the **luminosity-determination** uncertainty in ratio is **conservative**
  - → *Z*-boson data could be used to cross-normalise the measurements at the different centre-of-mass energies

$t\bar{t}$ ratios at different $\sqrt{s}$

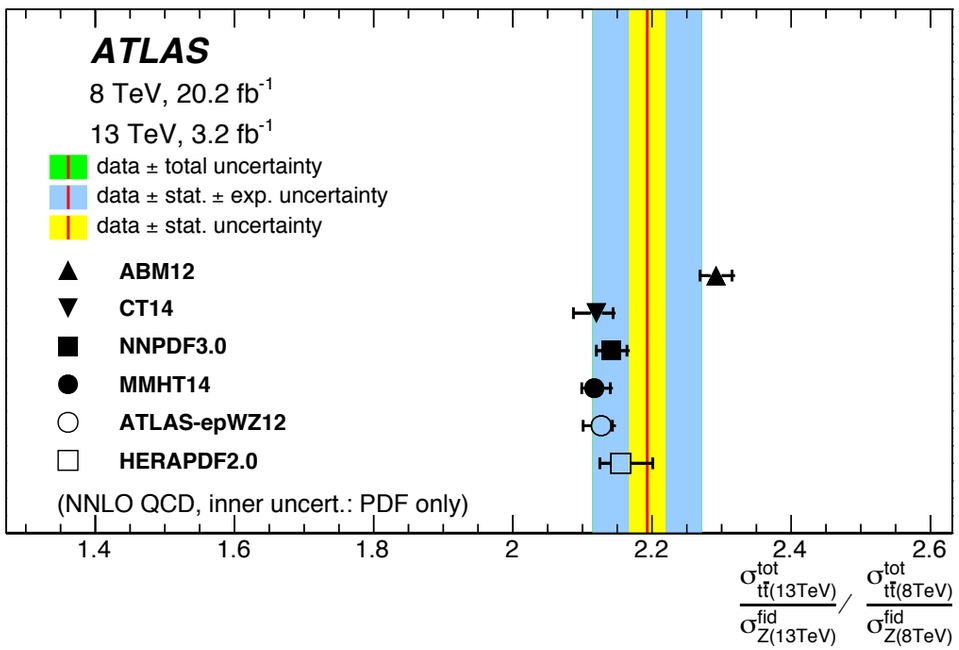


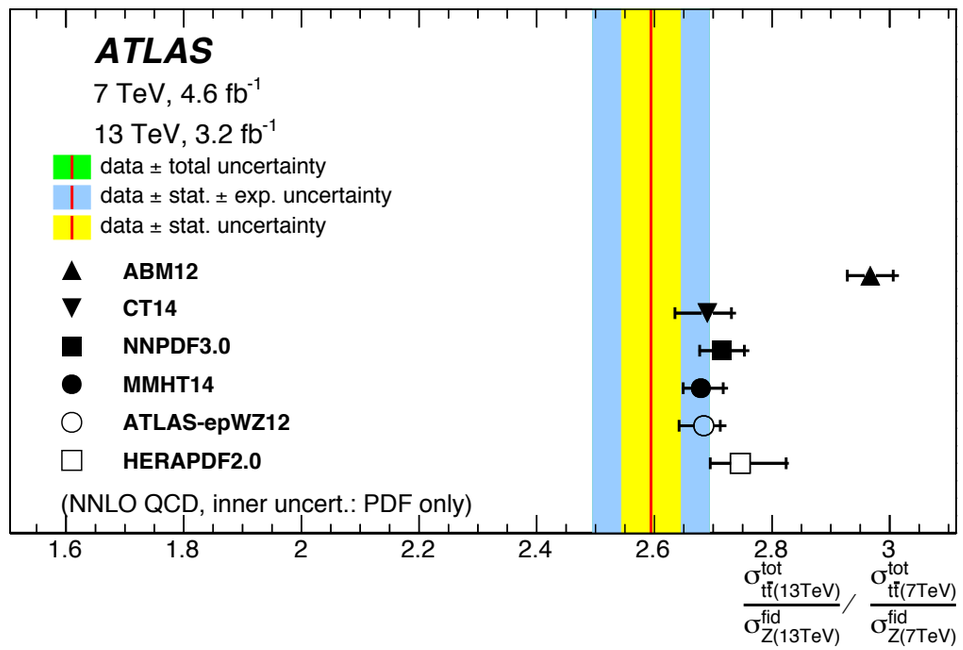


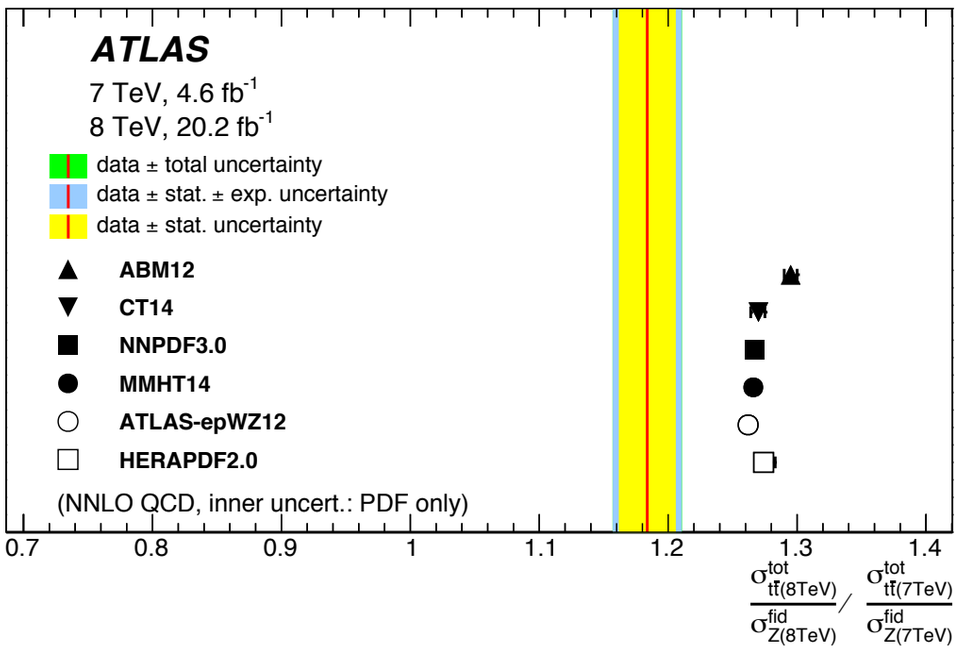


- Predictions follow **the same pattern** for all ratios
- **Deviation** of 8 TeV to 7 TeV measured ratio, at the level of **~2σ** from PDF4LHC, **was observed** in previously published results: **Eur. Phys. J. C74**
  - → Motivation to test with double ratio where luminosity uncertainty should cancel

$t\bar{t}$ to Z double ratios at different $\sqrt{s}$



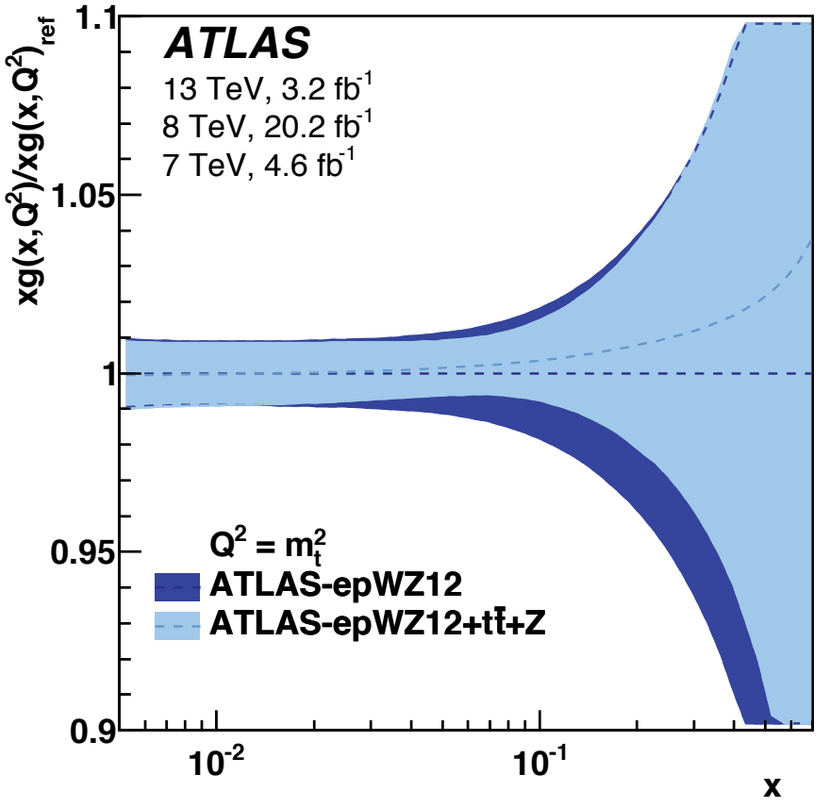


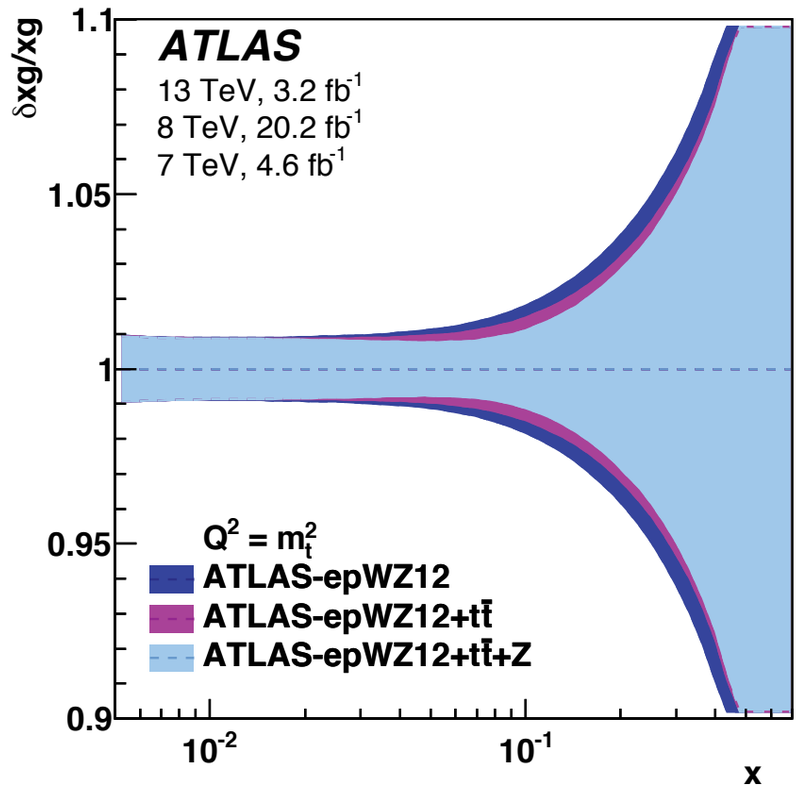


- Almost complete **cancellation of the luminosity** uncertainty
  - → More than compensates for the uncertainties which Z boson measurement bring to the ratios
- Trends are similar to those observed for the $t\bar{t}$ single ratios
- Data - theory **tension** in 8 to 7 TeV ratio is **increased**:
  - → Most of predictions deviate from data at the level of **~3**σ, where σ is the total exp.+lumi. uncertainty

PDF Constraint

Gluon distributions





- The impact of the ATLAS data on the PDF uncertainties is quantified using PDF profiling
- Central values of the profiled distribution agree very well with the original ATLAS-epWZ12 set
- $t\bar{t}$ and Z cross section data impose visible constraints on the gluon distribution at $x \sim 0.1$
- Profiling was also performed excluding 7 TeV $t\bar{t}$ data yielding similar results

Summary

WZ precision measurements

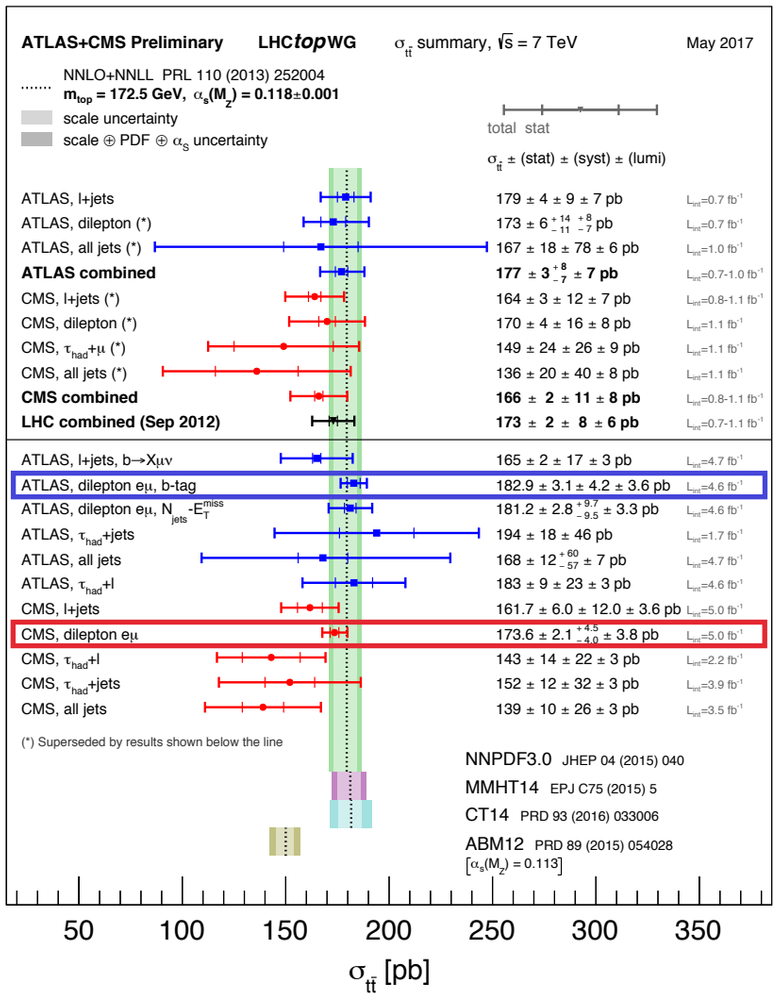
- A measurement **precision at sub-percent level**, higher than of predictions
- Quantitive comparison of differential x-sections showed deviations of predictions, **hinting** the data **impact on the determination of s-quark distribution**
- Measurement used to derive new set of parton distribution functions **ATLAS-epWZ16**
- QCD fit analysis supported the previous atlas observations of a **large ratio of s-quark distribution to the lighter sea-quark distributions at low x**
- Determination of CKM **matrix element** $|V_{cs}|$ is performed

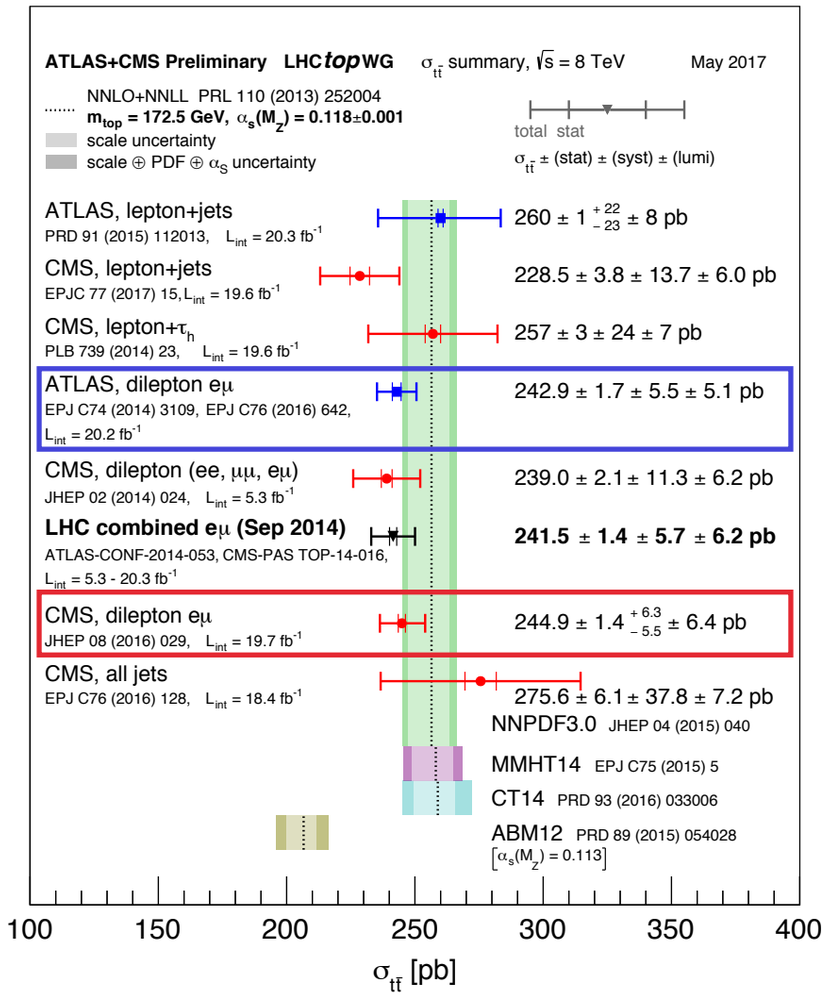
$t\bar{t}$ / Z cross-section ratios

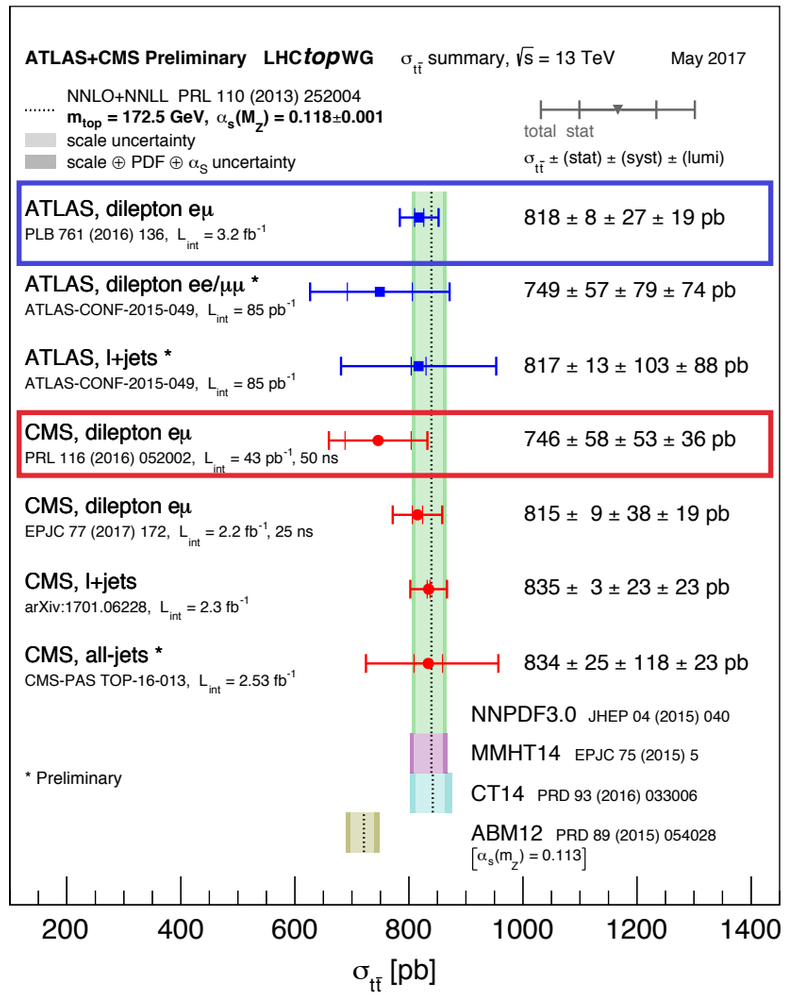
- $t\bar{t}$ **to Z experimental precision is higher then theoretical** (indicates **constraining power**) due to luminosity and lepton-related systematic cancellation
- **Z to Z** ratios demonstrate **very good agreement between data and predictions**
- $t\bar{t}$ **to** $t\bar{t}$ measured ratios show different compatibility with the predictions for different $\sqrt{s}$
- Double ratios provide **complete cancellation of the luminosity uncertainty**
- PDF constraint: presented data have significant power to **constrain** the **gluon distribution function at Bjorken-x ~ 0.1**

Backup slides

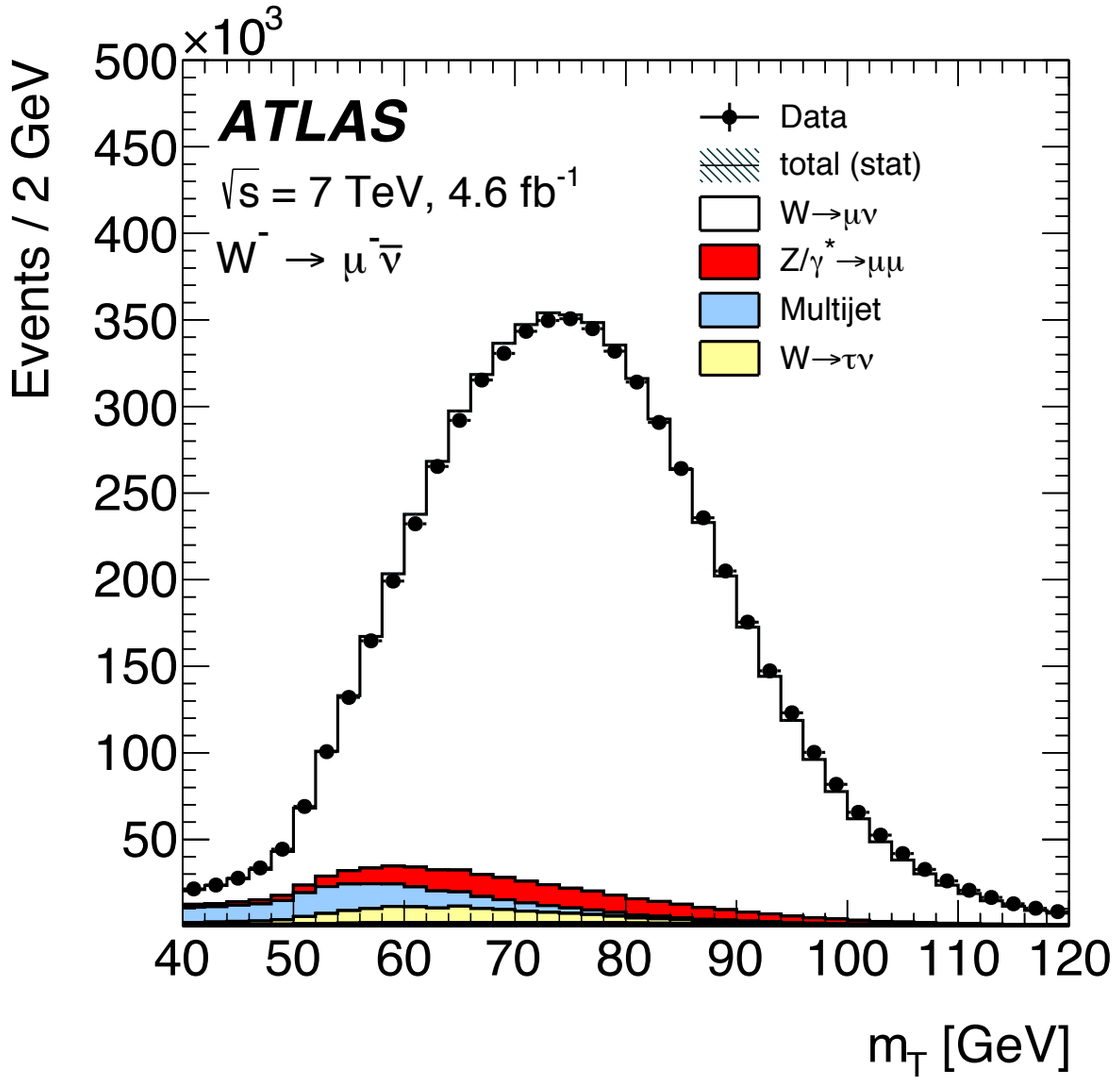
Summary of results from ATLAS and CMS

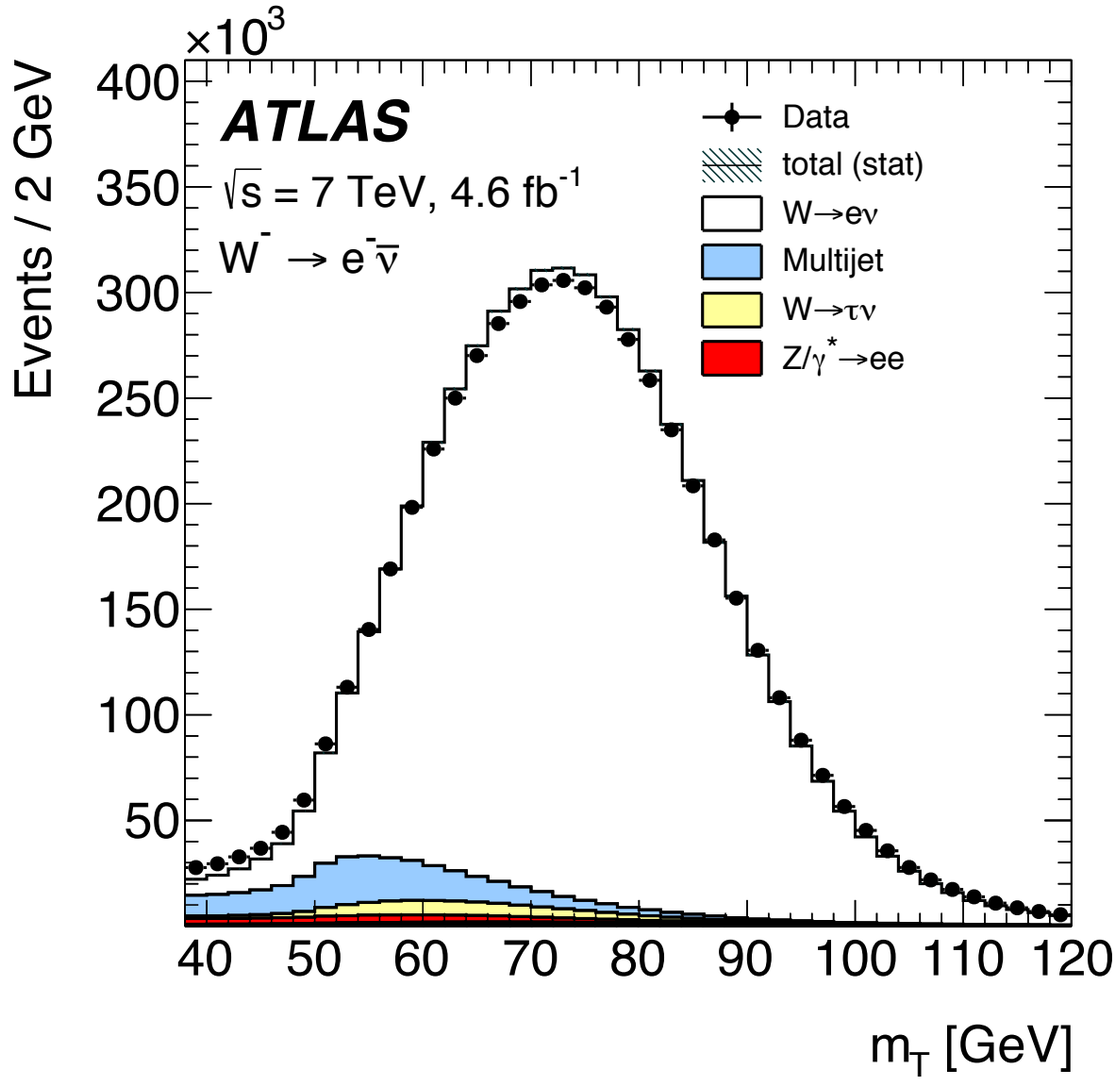






W kinematics





Precision comparison (lepton systematics)

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
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.8	0.7	1.0	—
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity	3.4			

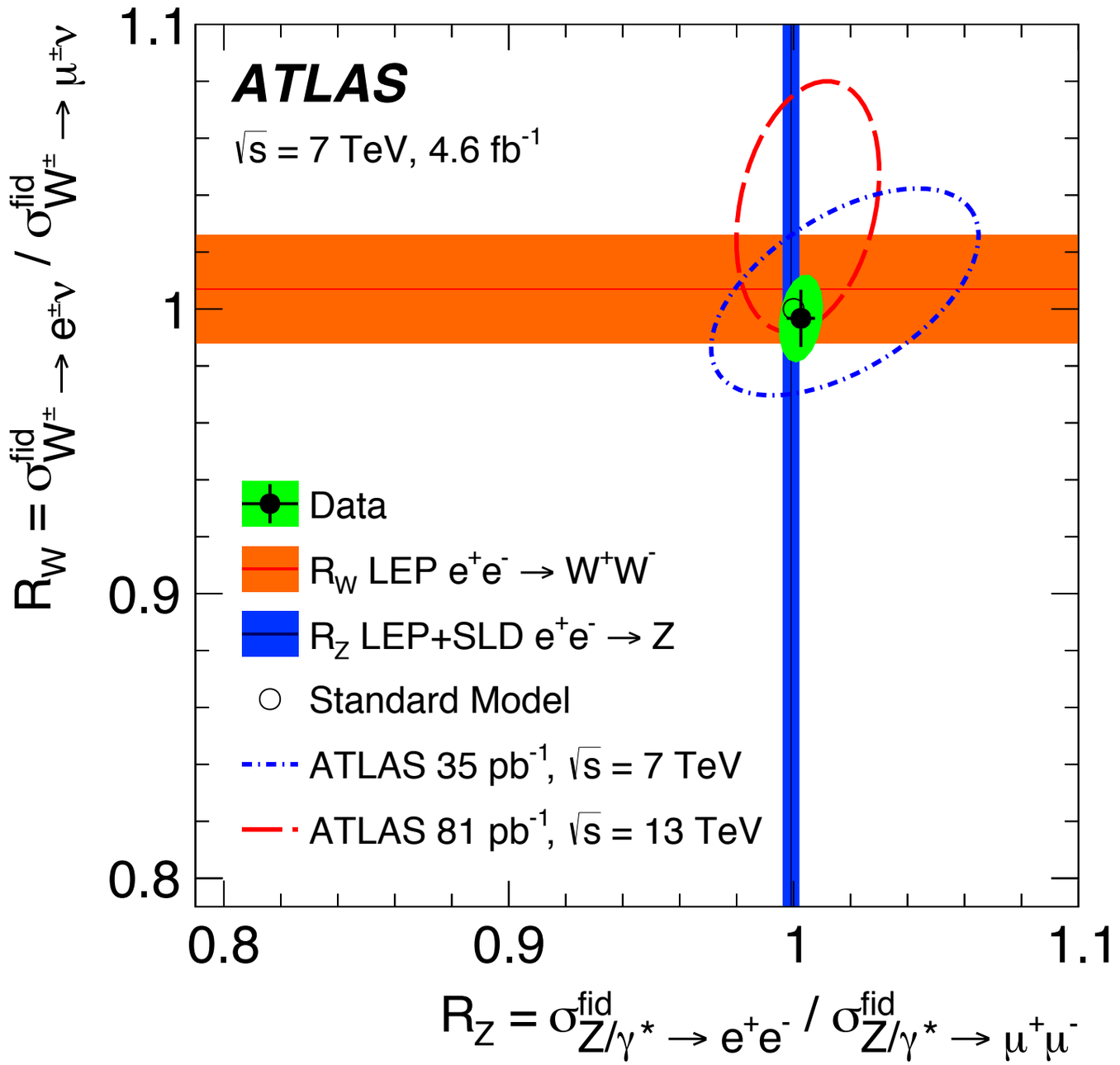
2011 data, 4.6 fb^{-1}	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$	$\delta\sigma_{\text{forward}\,Z}$
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.14	0.13	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

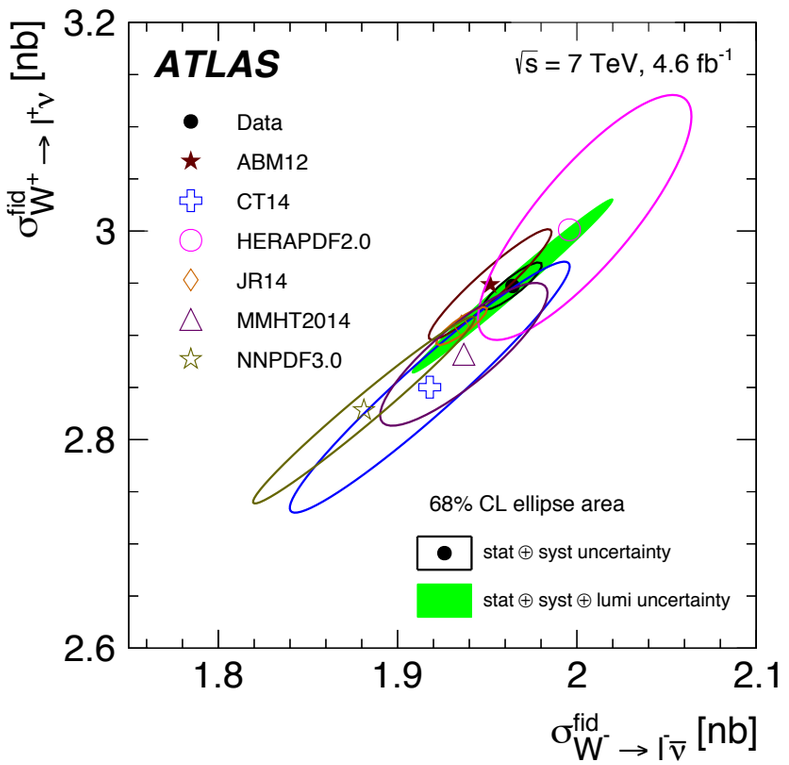
2010 data, 36 pb^{-1}	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_{T} resolution	0.04	0.03	0.05	0.02
Muon p_{T} scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Total excluding luminosity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

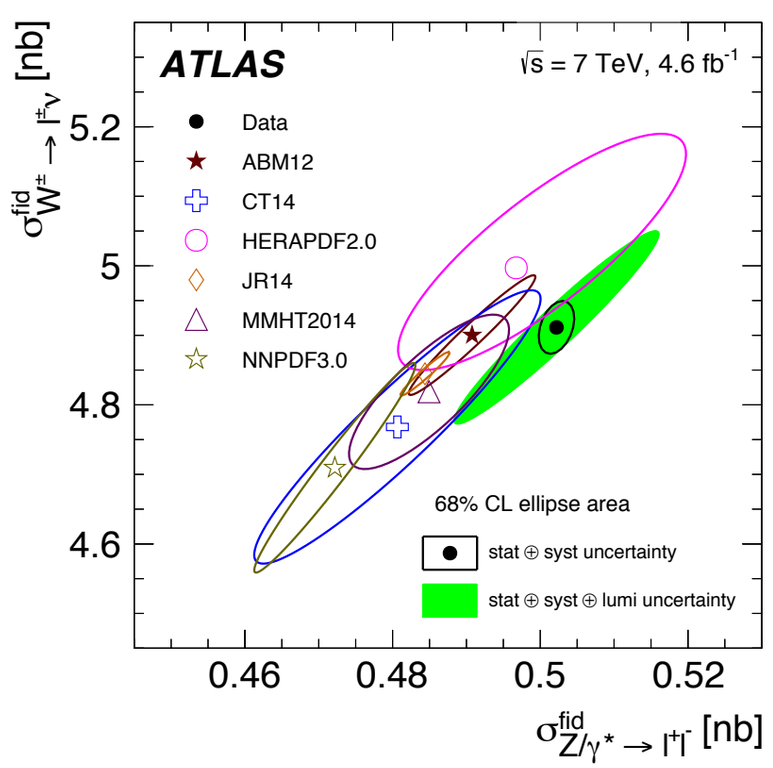
2011 data, 4.6 fb^{-1}	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
Multijet background	0.33	0.27	0.07
Total experimental uncertainty	0.61	0.59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

Lepton universality comparison



Comparison with theory



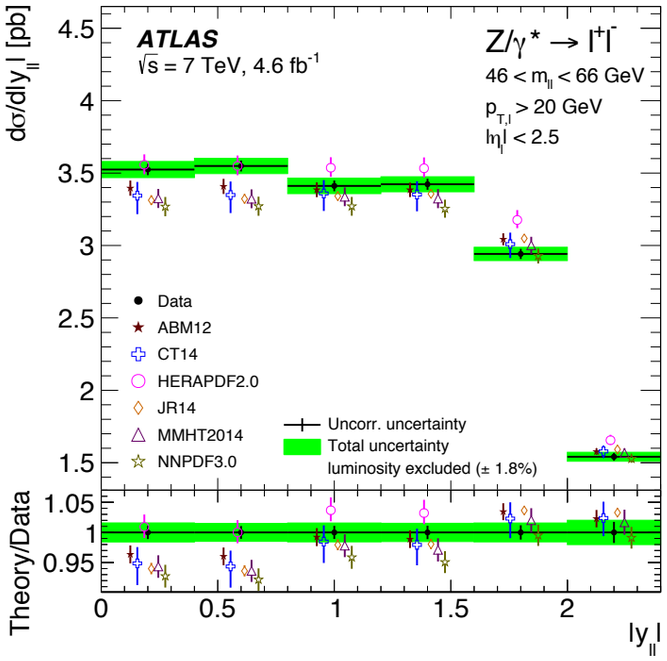


- 2-d presentation conveys both values and correlations of measurement and predictions
- Spread of predictions is larger than uncert. of data
- The measurements are seen to discriminate between different PDF sets and to provide info to reduce PDF uncertainties

Differential cross sections

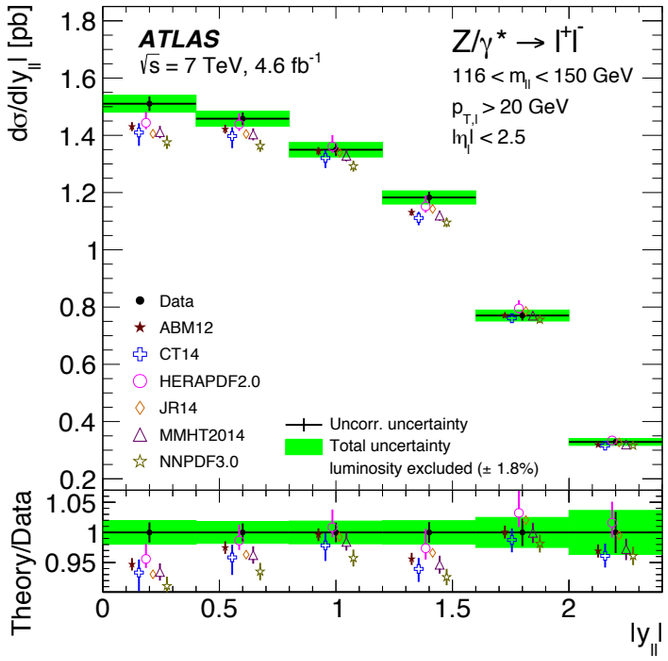
Low mass

Central

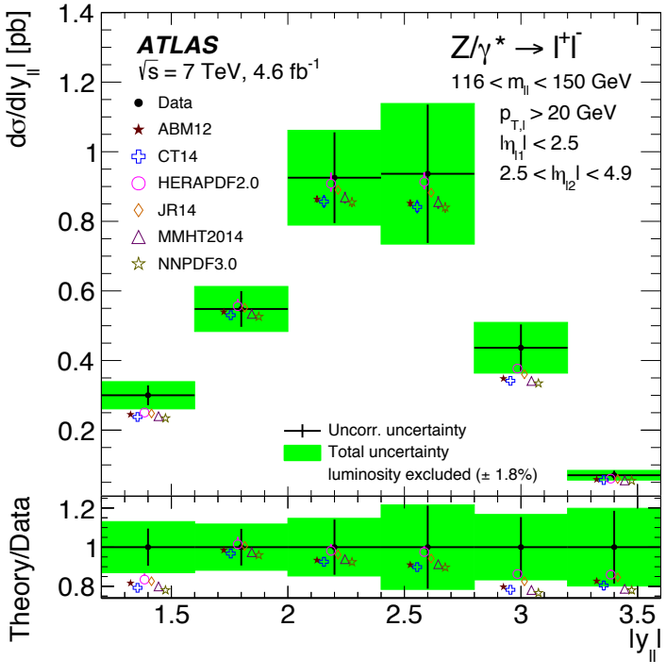


High mass

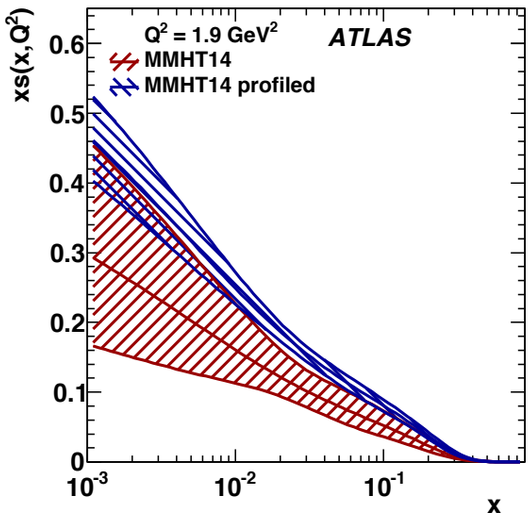
Central

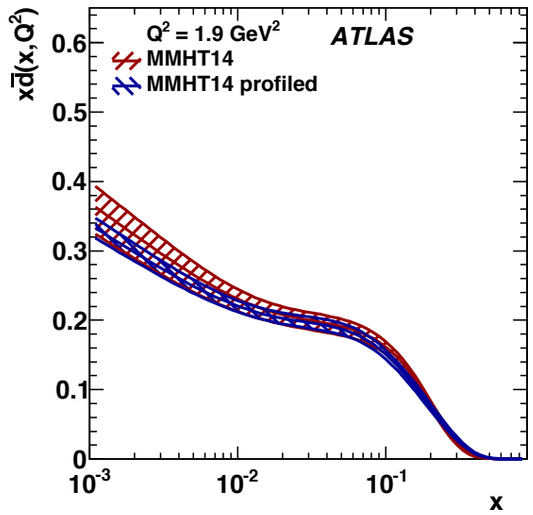


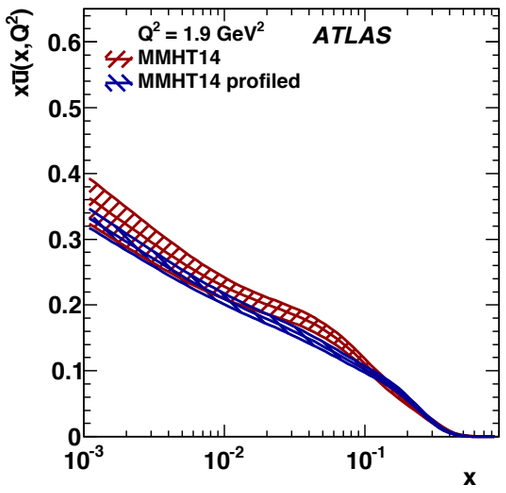
Forward

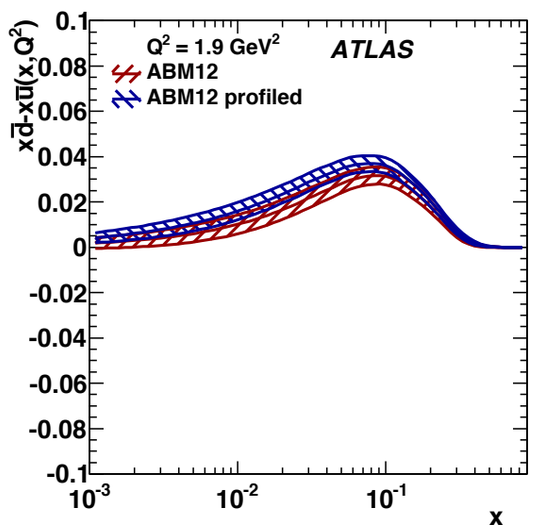


PDF profiling

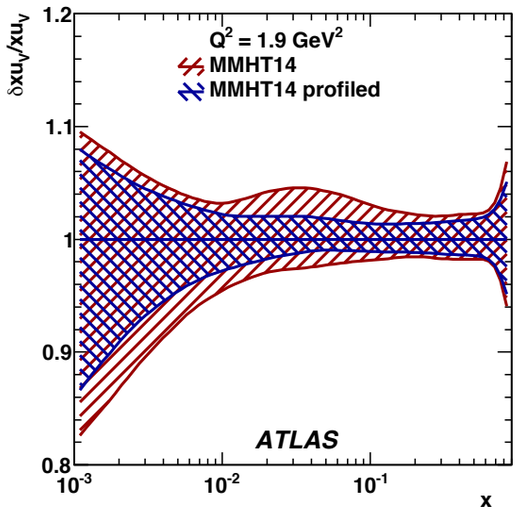


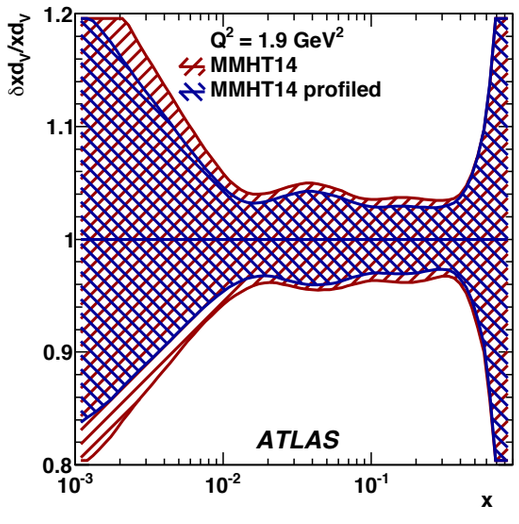


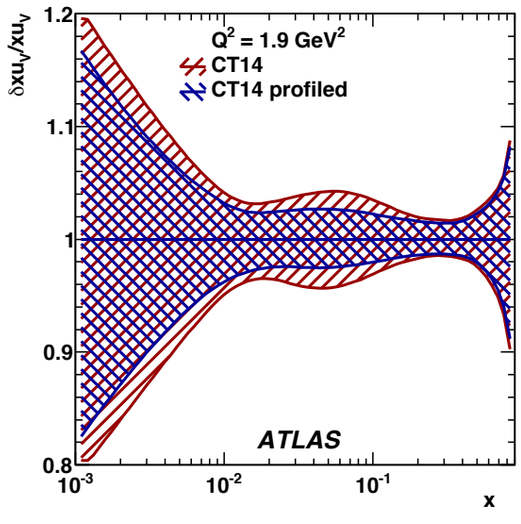


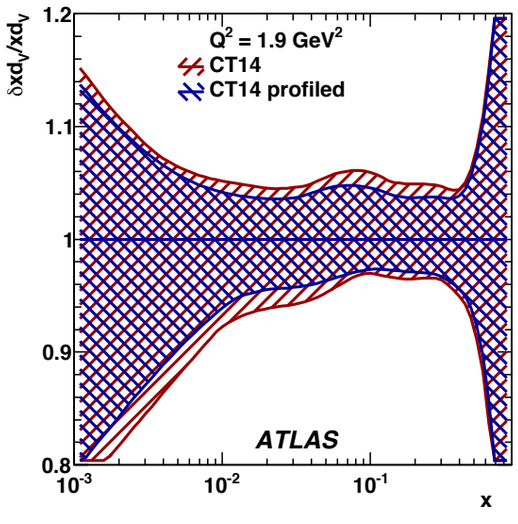


- s-quark distribution significantly increased and the uncertainties are reduced
- Reduction of light sea at low x



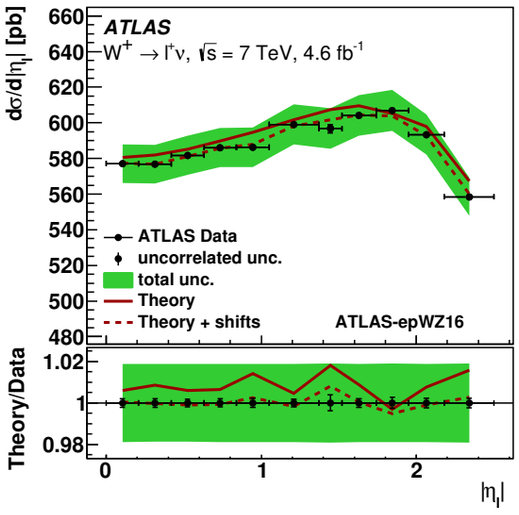


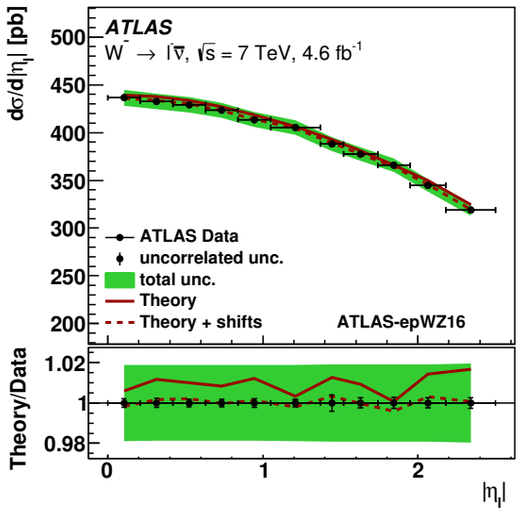




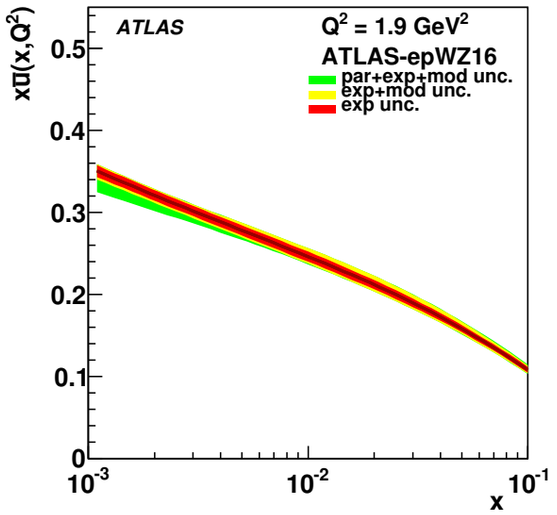
QCD analysis

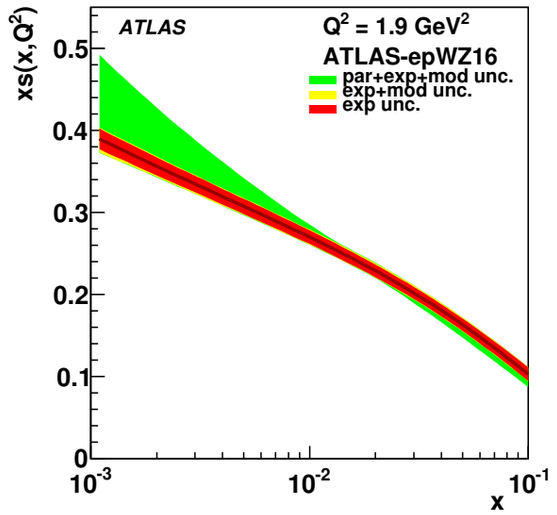
QCD fit

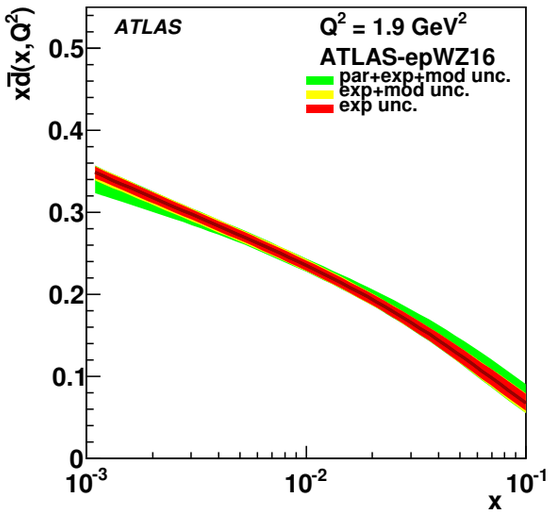


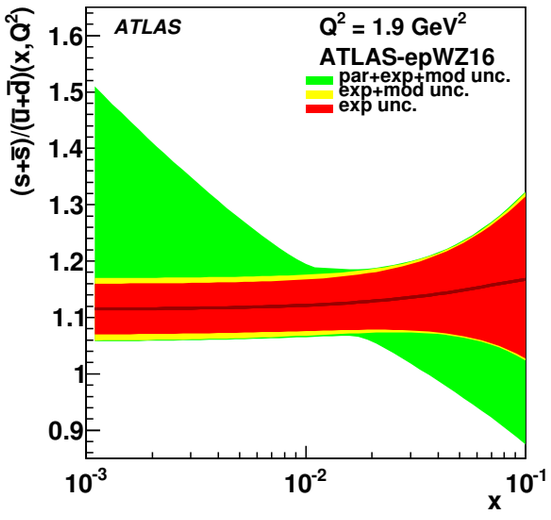


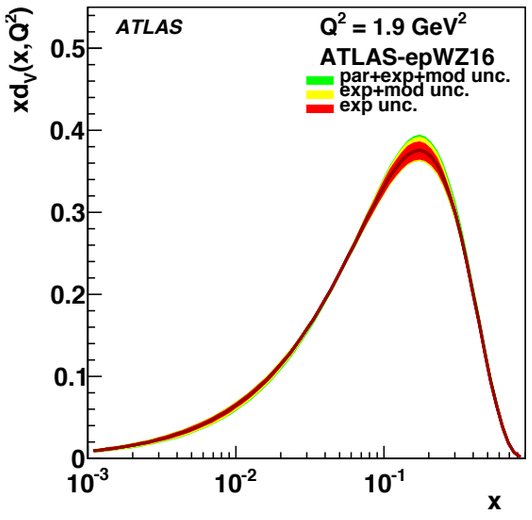
ATLAS-epWZ16

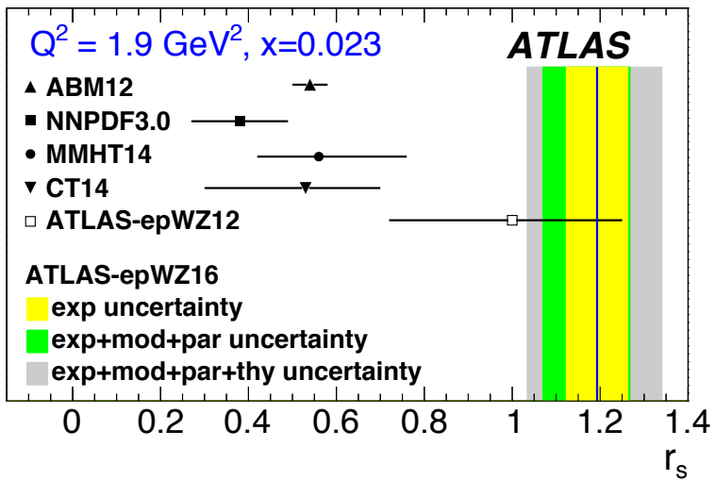












Theoretical predictions

- **Cross-section predictions**

	σ_Z^{fid}			$\sigma_{t\bar{t}}^{tot}$		
$\sqrt{s}$ $[TeV]$	13	8	7	13	8	7
Central value [pb]	744	486	432	842	259	182
Total Unc. [%]	$^{+3.0}_{-3.7}$	$^{+2.8}_{-3.3}$	$^{+2.9}_{-3.2}$	$^{+5}_{-6}$	$^{+6}_{-6}$	$^{+6}_{-6}$

- σ_Z **NNLO** calculations with **DYTURBO** (fast ver. of DYNNLO)
- **NLO EW** corrections with **FEWZ 3.1**
- $\sigma_{t\bar{t}}$ **NNLO+NNLL** calculations with **Top++**
- **CT14 PDF** set is used as a **baseline**

- **Fiducial definition**

	7 TeV	8 TeV	13 TeV
FSR treatment	Born	Born	Born
$p_{T,\ell}$ >	20 GeV	20 GeV	25 GeV
$\lvert\eta_\ell\rvert$ <	2.5	2.4	2.5
$\lvert y_{\ell\ell}\rvert$ <	-	2.4	-
$m_{\ell\ell}$	66-116 GeV	66-116 GeV	66-116 GeV

- **Extrapolation factors**

	13 TeV	8 TeV	7 TeV
A_Z	0.395 ± 0.007	0.466 ± 0.008	0.505 ± 0.009
E_Z	-	0.941 ± 0.001	0.898 ± 0.001

- **13 TeV fiducial** phase space is used as **common**
- **Az factor** is computed for extrapolation from fiducial to total phase space
- **Ez factors** are estimated for extrapolation to 13TeV fiducial phase space

Uncertainties of the grouped systematic sources

Source	σ_Z $\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 7 TeV	$\sigma_{t\bar{t}}$ $\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 7 TeV
Luminosity	2.10	1.90	1.80	2.31	2.10	1.98
Beam energy	0.69	0.62	0.60	1.50	1.72	1.79
Muon (lepton) trigger	0.12	0.55	0.05	0.05	0.17	0.19
Muon reco and ID	0.68	0.45	0.30	0.44	0.42	0.31
Muon isolation	0.41	0.04	0.15	0.27	0.22	0.44
Muom momentum scale	0.06	0.03	0.03	0.04	0.01	0.14
Electron trigger	0.01	0.19	0.04	0.14	—	—
Electron reco and ID	0.41	0.80	0.26	0.34	0.41	0.13
Electron isolation	0.14	0.00	—	0.39	0.30	0.59
Electron energy scale	0.25	0.07	0.08	0.20	0.51	0.21
Jet energy scale	—	—	—	0.38	0.72	0.40
Flavour tagging	—	—	—	0.53	0.40	0.46
Background	0.08	0.15	0.08	1.09	1.04	1.04
Signal modelling (incl PDF)	0.12	0.08	0.27	2.98	1.70	1.81

The correlation coefficients

- **With luminosity and bee energy uncertainties**

	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

- **Without luminosity and bee energy uncertainties**

	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.	0.13	0.09	0.08	0.12	0.03
$t\bar{t}$ 13 TeV	—	1.	0.01	0.32	0.00	0.27
Z 8 TeV	—	—	1.	0.01	0.09	0.00
$t\bar{t}$ 8 TeV	—	—	—	1.	0.00	0.67
Z 7 TeV	—	—	—	—	1.	0.00
$t\bar{t}$ 7 TeV	—	—	—	—	—	1.

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Measured and predicts cross-sections

- **Measured cross-sections (Z - combined channels)**

$\sqrt{s}$ [TeV]	Value ± stat ± syst ± beam ± lumi [pb]
	σ_Z^{fid}
13	777 ± 1 (0.1%) ± 3 (0.4%) ± 5 (0.7%) ± 16 (2.1%)
8	506 ± < 1 (< 0.1%) ± 3 (0.6%) ± 3 (0.6%) ± 10 (1.9%)
7	451 ± < 1 (0.1%) ± 1 (0.3%) ± 3 (0.6%) ± 8 (1.8%)
	$\sigma_{t\bar{t}}^{\text{tot}}$
13	818 ± 8 (0.9%) ± 27 (3.3%) ± 12 (1.5%) ± 19 (2.3%)
8	243 ± 2 (0.7%) ± 5 (2.3%) ± 4 (1.7%) ± 5 (2.1%)
7	183 ± 3 (1.7%) ± 4 (2.3%) ± 3 (1.8%) ± 4 (2.0%)

- **Predicted cross-sections (Z - combined channels)**

	σ± stat ± syst [pb]		
$\sqrt{s}$ [TeV]	13	8	7
$\sigma_{Z\to ee}^{\text{fid}}$	778.3 ± 0.7 ± 17.7	507.0 ± 0.2 ± 11.0	451.2 ± 0.5 ± 8.7
$\sigma_{Z\to \mu\mu}^{\text{fid}}$	774.4 ± 0.6 ± 18.2	504.7 ± 0.2 ± 10.8	450.0 ± 0.3 ± 8.8
$\sigma_{t\bar{t}\to e\mu+X}^{\text{fid}}$	9.94 ± 0.09 ± 0.37	3.04 ± 0.02 ± 0.10	2.30 ± 0.04 ± 0.08
$\sigma_{t\bar{t}}^{\text{tot}}$	818 ± 8 ± 35	243 ± 2 ± 9	183 ± 3 ± 6

- **Z-boson measured cross-sections (electron end muon channels separate)**

	25 ns	
	Electron channel	**Muon channel**
	value ± stat ± syst ± lumi	value ± stat ± syst ± lumi
Correction C_Z	$0.5536 \pm 0.0002\ ^{+0.0028}_{-0.0029}$	$0.7064 \pm 0.0003\ ^{+0.0057}_{-0.0057}$
Fiducial cross section (pb)	778.3 ± 0.7 ± 4.0 ± 16.3	774.4 ± 0.6 ± 6.2 ± 16.3
Total cross section (pb)	1970.3 ± 1.7 ± 36.5 ± 41.4	1960.6 ± 1.5 ± 38.3 ± 41.2

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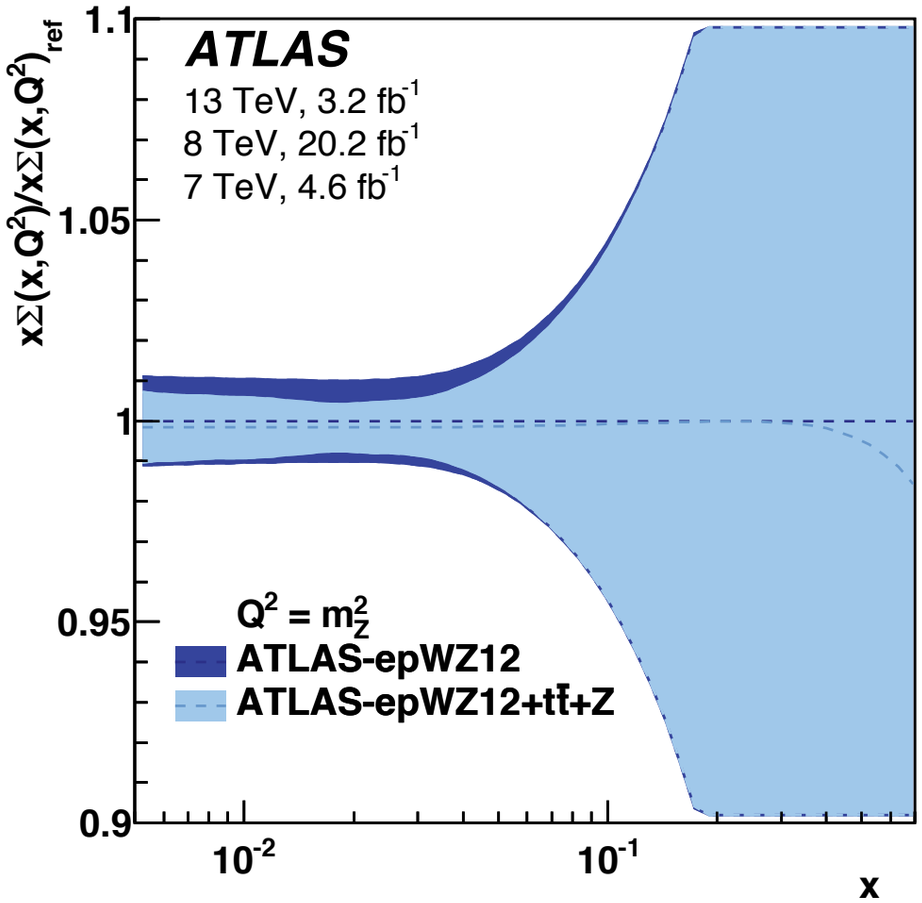
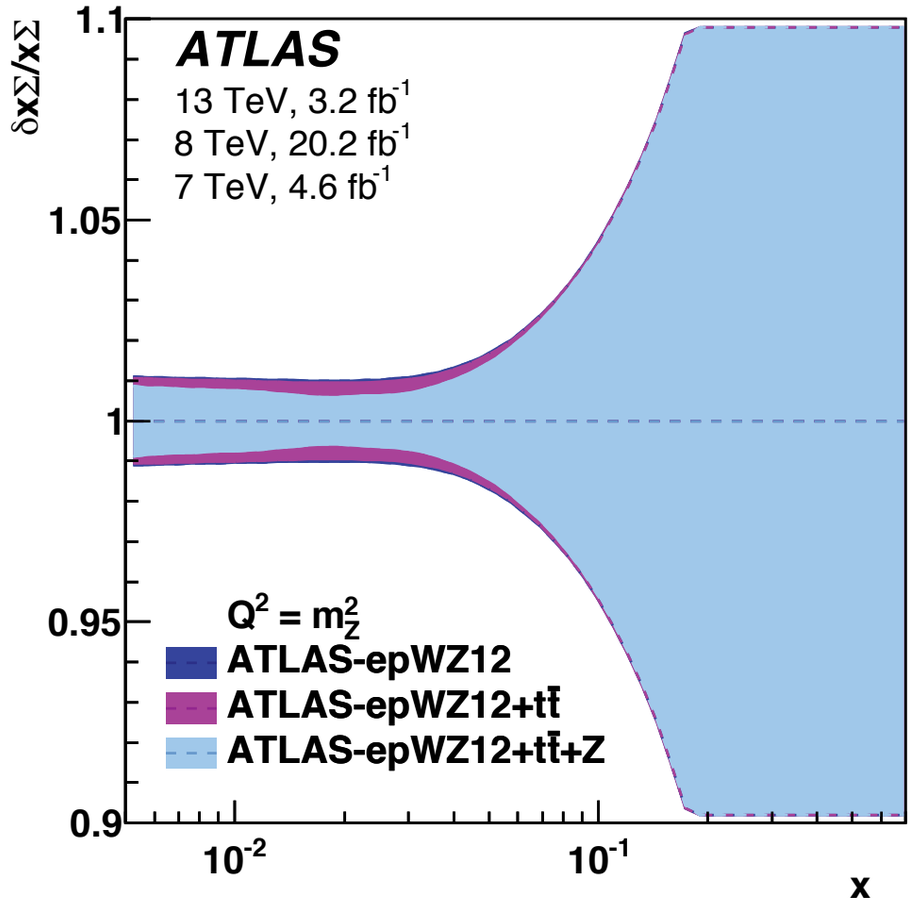
PDF Constraint

Light-quark sea distributions





- $t\bar{t}$ and Z cross-section data impose visible constraints on the light-quark sea distribution at $x < 0.02$ and on the gluon distribution at $x \sim 0.1$

All single and double ratios

	$\sigma^{tot}/\sigma^{tot}$	$\sigma^{tot}/\sigma^{fid}$	$\sigma^{fid}/\sigma^{fid}$
	value ± stat ± syst ± lumi	value ± stat ± syst ± lumi	value ± stat ± syst ± lumi
$\sigma^{13\,TeV}_{t\bar{t}}/\sigma^{13\,TeV}_{Z}$	0.414 ± 0.004(0.92%) ± 0.016(3.84%) ± 0.001(0.21%)	1.053 ± 0.010(0.92%) ± 0.036(3.40%) ± 0.002(0.21%)	0.01281 ± 0.00012(0.92%) ± 0.00044(3.40%) ± 0.00003(0.21%)
$\sigma^{8\,TeV}_{t\bar{t}}/\sigma^{8\,TeV}_{Z}$	0.211 ± 0.001(0.71%) ± 0.006(2.73%) ± 0.000(0.20%)	0.480 ± 0.003(0.71%) ± 0.012(2.57%) ± 0.001(0.20%)	0.00602 ± 0.00004(0.72%) ± 0.00014(2.35%) ± 0.00001(0.20%)
$\sigma^{7\,TeV}_{t\bar{t}}/\sigma^{7\,TeV}_{Z}$	0.184 ± 0.003(1.69%) ± 0.005(2.71%) ± 0.000(0.18%)	0.406 ± 0.007(1.69%) ± 0.011(2.59%)± 0.001(0.18%)	0.00511 ± 0.00009(1.68%) ± 0.00013(2.46%) ± 0.00001(0.18%)
$\sigma^{13\,TeV}_{Z}/\sigma^{8\,TeV}_{Z}$	1.714 ± 0.001(0.06%) ± 0.013(0.77%) ± 0.049(2.83%)	-	1.537 ± 0.001(0.06%) ± 0.010(0.67%) ± 0.044(2.83%)
$\sigma^{13\,TeV}_{Z}/\sigma^{7\,TeV}_{Z}$	1.988 ± 0.002(0.09%) ± 0.014(0.71%) ± 0.055(2.77%)	-	1.724 ± 0.001(0.09%) ± 0.009(0.52%) ± 0.048(2.77%)
$\sigma^{8\,TeV}_{Z}/\sigma^{7\,TeV}_{Z}$	1.160 ± 0.001(0.07%) ± 0.007(0.63%) ± 0.030(2.62%)	-	1.122 ± 0.001(0.07%) ± 0.007(0.61%) ± 0.029(2.62%)
$\sigma^{13\,TeV}_{t\bar{t}}/\sigma^{8\,TeV}_{t\bar{t}}$	3.365 ± 0.039(1.16%) ± 0.113(3.35%) ± 0.105(3.12%)	-	3.270 ± 0.038(1.17%) ± 0.107(3.28%) ± 0.102(3.12%)
$\sigma^{13\,TeV}_{t\bar{t}}/\sigma^{7\,TeV}_{t\bar{t}}$	4.470 ± 0.086(1.92%) ± 0.149(3.33%) ± 0.136(3.04%)	-	4.322 ± 0.083(1.92%) ± 0.143(3.31%) ± 0.131(3.04%)
$\sigma^{8\,TeV}_{t\bar{t}}/\sigma^{7\,TeV}_{t\bar{t}}$	1.328 ± 0.024(1.83%) ± 0.015(1.11%) ± 0.038(2.89%)	-	1.322 ± 0.024(1.83%) ± 0.015(1.12%) ± 0.038(2.89%)

	R^{tot}/R^{tot}	R^{tot}/R^{fid}	R^{fid}/R^{fid}
	value ± stat ± syst	value ± stat ± syst	value ± stat ± syst
$\frac{\sigma^{13\,TeV}_{t\bar{t}}}{\sigma^{13\,TeV}_{Z}}/\frac{\sigma^{8\,TeV}_{t\bar{t}}}{\sigma^{8\,TeV}_{Z}}$	1.966 ± 0.023(1.16%) ± 0.067(3.40%)	2.193 ± 0.026(1.16%) ± 0.074(3.39%)	2.131 ± 0.025(1.17%) ± 0.071(3.34%)
$\frac{\sigma^{13\,TeV}_{t\bar{t}}}{\sigma^{13\,TeV}_{Z}}/\frac{\sigma^{7\,TeV}_{t\bar{t}}}{\sigma^{7\,TeV}_{Z}}$	2.250 ± 0.043(1.93%) ± 0.076(3.38%)	2.594 ± 0.050(1.93%) ± 0.086(3.32%)	2.508 ± 0.048(1.92%) ± 0.082(3.27%)
$\frac{\sigma^{8\,TeV}_{t\bar{t}}}{\sigma^{8\,TeV}_{Z}}/\frac{\sigma^{7\,TeV}_{t\bar{t}}}{\sigma^{7\,TeV}_{Z}}$	1.145 ± 0.021(1.83%) ± 0.015(1.31%)	1.184 ± 0.022(1.83%) ± 0.015(1.29%)	1.178 ± 0.022(1.83%) ± 0.015(1.31%)

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