High precision measurements of the differential W and Z/γ^* boson cross sections and $t\bar{t}$/Z cross-section ratios in ATLAS

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on behalf of the ATLAS collaboration

Low x 2017
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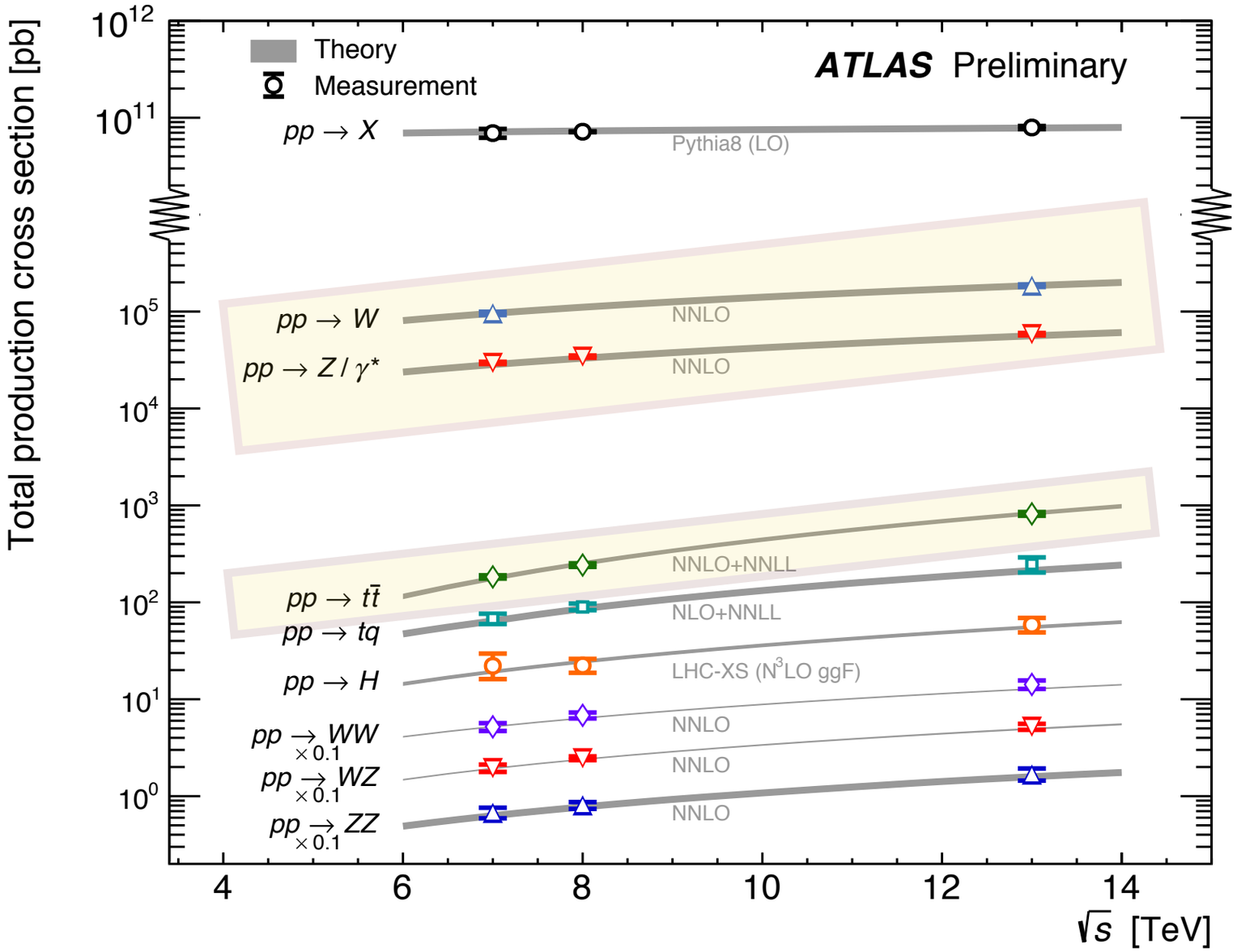
Analyses overview



➡ Status on May 2017

Today in the talk:

➡ **Single vector boson and top production:**

✓ W and Z: 7 TeV

✓ $t\bar{t}$ and Z: 7, 8, 13 TeV

- Measurements for different √s sample different x values:

$$x = e^{\pm y}\frac{M}{\sqrt{s}}$$

- Good agreement between theory and data
- High precision of experimental and theoretical measurements:
  - current level of understanding up to NNLO
  - test of SM model, understanding of pQCD and electroweak (EW) processes
- Probe the proton at different average x values → PDF constraints

4.6 fb^{-1}, **7 TeV**

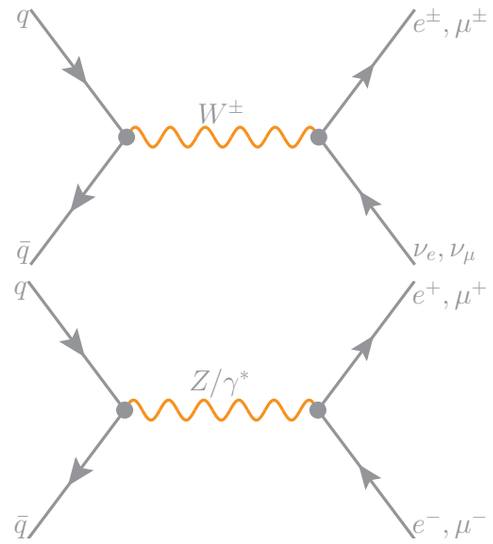
Inclusive W^+, W^- and Z/γ^* production cross sections

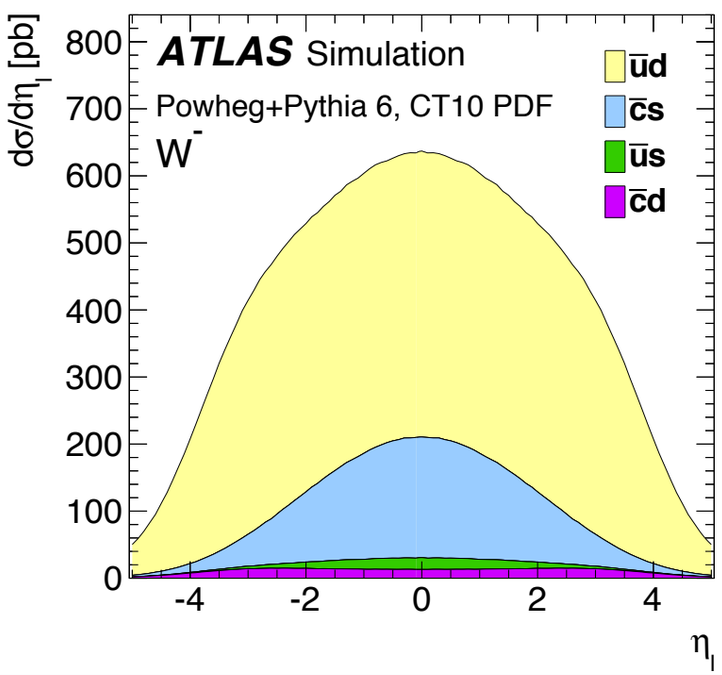
Eur. Phys. J. C 77 (2017) 367

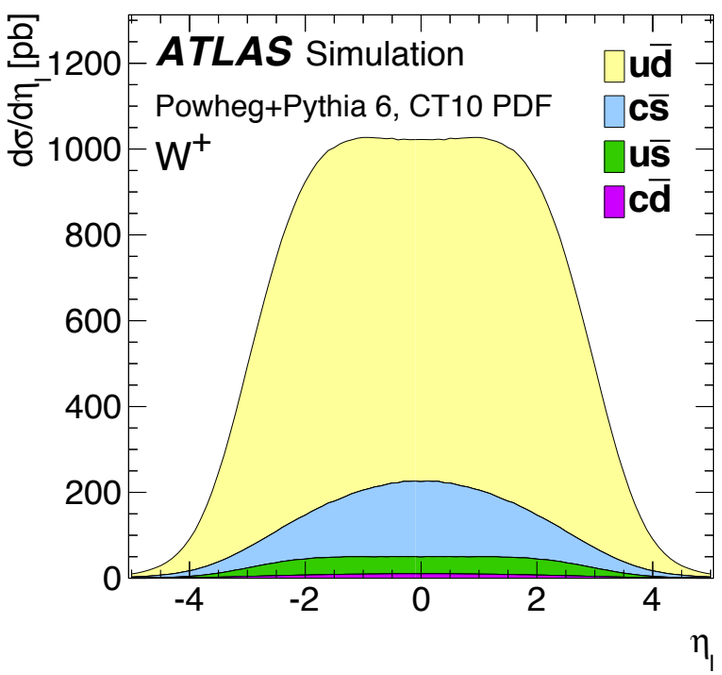
- Integrated and differential cross sections
- Ratios of W/Z boson cross sections
- Comparison with theoretical predictions
- Lepton universality
- New PDF set
- Strange-quark density determination

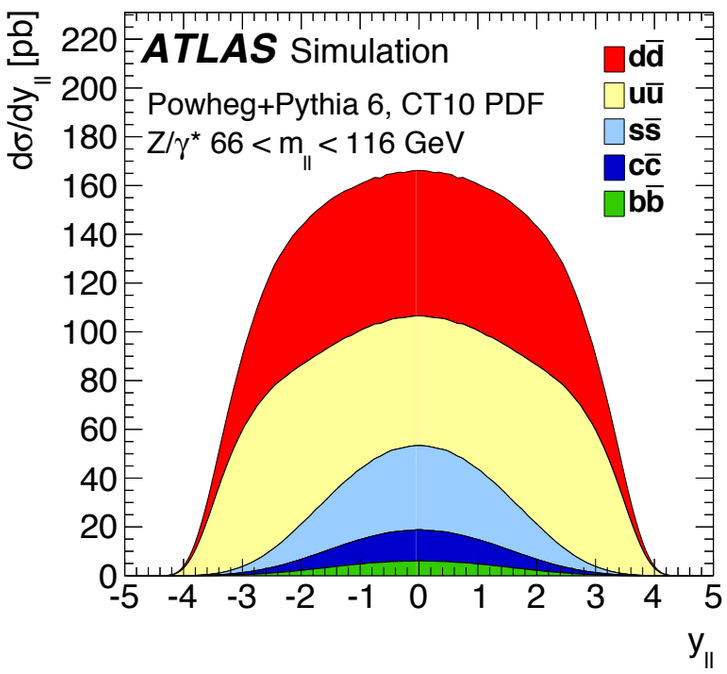
W and Z production and ratios

- Drell-Yan dilepton production of W and Z bosons is a clear signature:
  - large statistics
  - small background contamination
- Different quark combinations contribute to Z and W processes
  - Sensitivity to **u** and **d** quarks: $\bar{u}d \rightarrow \mathbf{W^-}$ $u\bar{d} \rightarrow \mathbf{W^+}$ $d\bar{d} \rightarrow \mathbf{Z}$
- Ratios:
  - **W^+/W^-:** sensitive to difference of u_v and d_v valence-quark distributions
  - **W/Z:** sensitive to strange-quark distribution
    - offer cancelation of systematics uncertainties
    - potential to improve quark PDFs









W and Z cross-section definitions

- **Fiducial and total cross sections:**

measured candidate events — background events — acceptance factor

$$\sigma^{fid} = \frac{N_{W[Z]} - B_{W[Z]}}{L_{\text{int}} \cdot C_{W[Z]}}; \qquad \sigma^{tot} = \frac{\sigma^{fid}}{A_{W[Z]}}$$

integrated luminosity — correction factor for detector efficiency

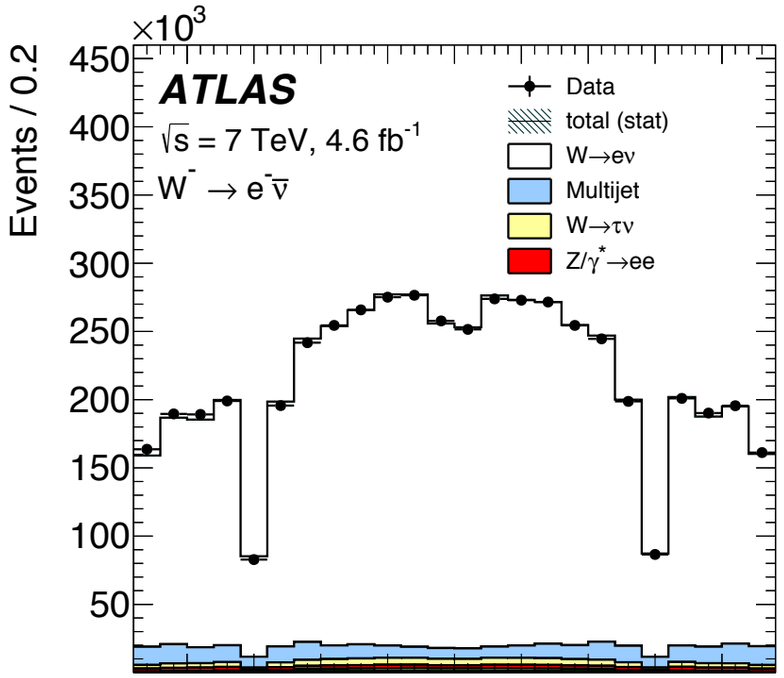
  - *Fiducial phase space:*

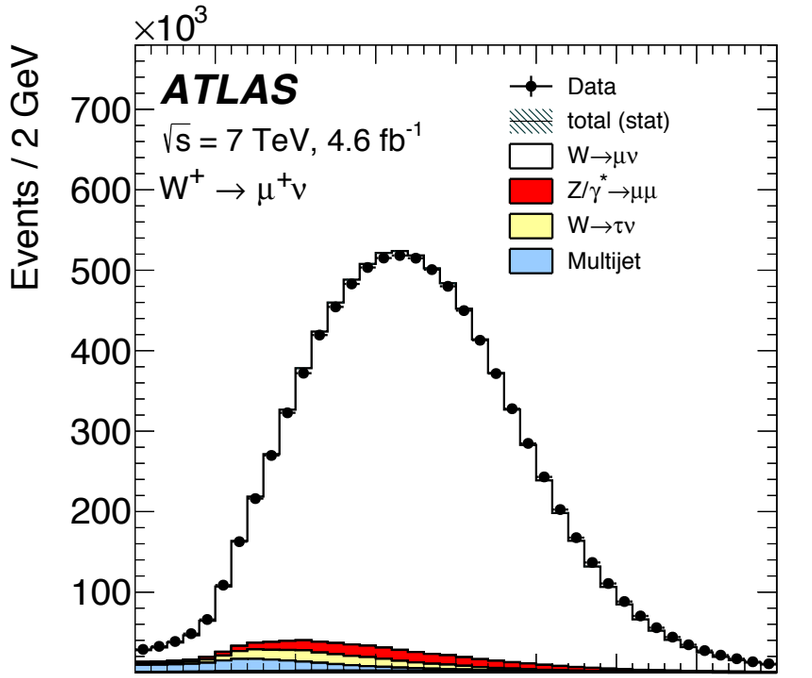
	W	Z	
		central (CC)	*forward (electrons) (CF)*
$p_{T,\ell,\nu}$	>25 GeV	>20 GeV	>20 GeV
$\lvert\eta_\ell\rvert$	2.5	2.5	2.5 (ℓ_1) or 2.5-4.9 (ℓ_2)
$m_T(m_{\ell\ell})$	>40 GeV	46-150GeV	66-150 GeV

- **Differential cross sections**
  - **$W^{\pm}\to\ell\nu$:** pseudorapidity bins, $\lvert\eta_\ell\rvert$
  - **$Z/\gamma^*\to\ell\ell$:** rapidity bins, $\lvert y_{\ell\ell}\rvert$, in three mass regions $m_{\ell\ell}$ = [46, 66,116,150] GeV

W and Z kinematic distributions

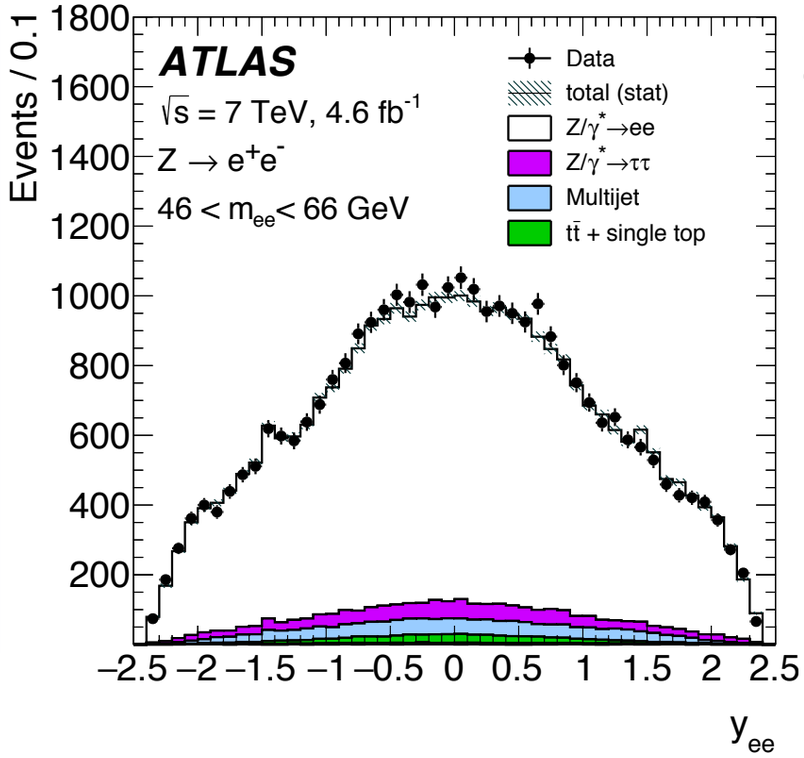
W boson

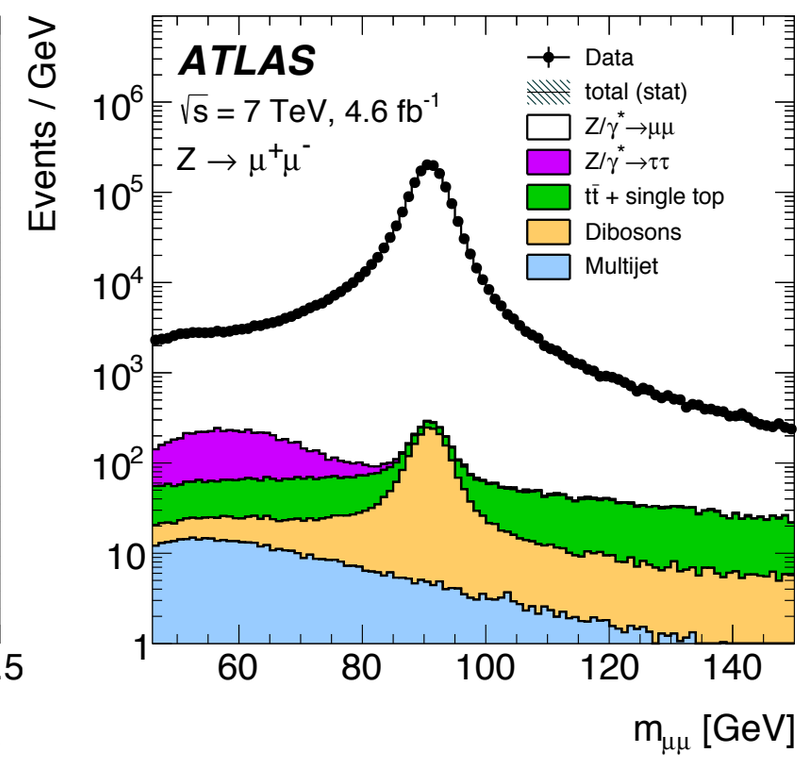




- **Selected candidates**
  - ***W→eν*:** ~13M
  - ***W→μν*:** ~16M
  - ***Z→ee*:** 1M (CC), 320k (CF)
  - ***Z→μμ*:** 1.6M
- **Signal MC:** Powheg+Pythia

Z boson





- Background estimation:
  - EW & $t\bar{t}$ from MC
  - QCD multi-jet: data-driven
- Background contamination:
  - ***W→ℓν*:** ~7-9%
  - ***Z→ℓℓ*:** <1%(CC), ~3%(CF)

W and Z integrated cross sections

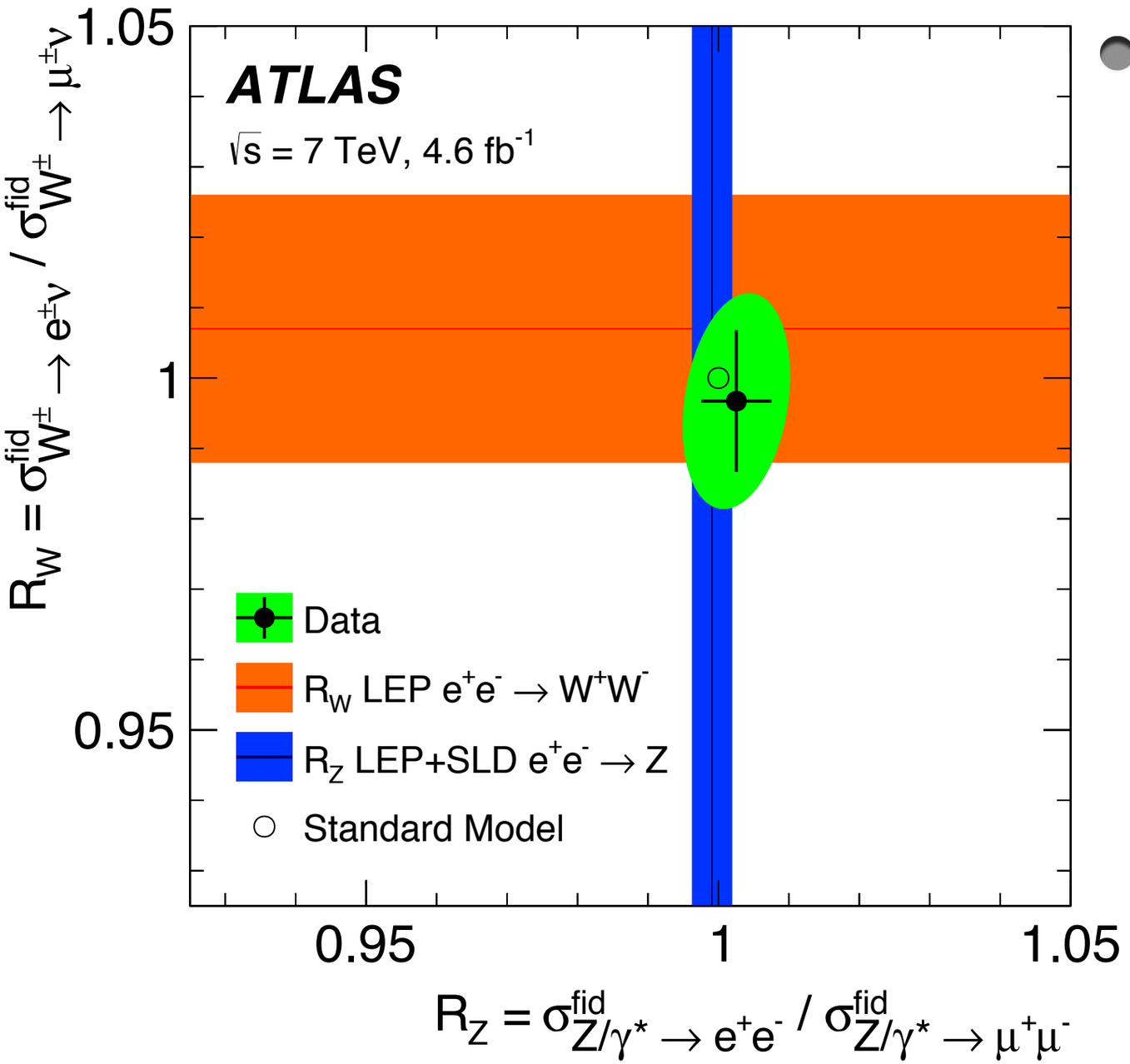
- Fiducial integrated cross sections of W and Z production in electron and muon channels were **combined**
- Most **precise** vector boson measurements:
  - ➡ Z (W) cross section is 10 (3.5) times precise then previous results (arXiv:1109.5141)
  - ✓ 0.32% for **Z** boson
  - ✓ 0.5% (0.6%) for **W^+(W^-)** bosons

  \+ **1.8 %** luminosity uncertainty

- Main **systematics contributions** to the measurements:
  - Reconstruction efficiencies of the leptons (<0.3% for Z <0.2% for W)
  - W signal modelling (<0.64%)
  - Background estimation (<0.72 for W and 0.14% for Z)

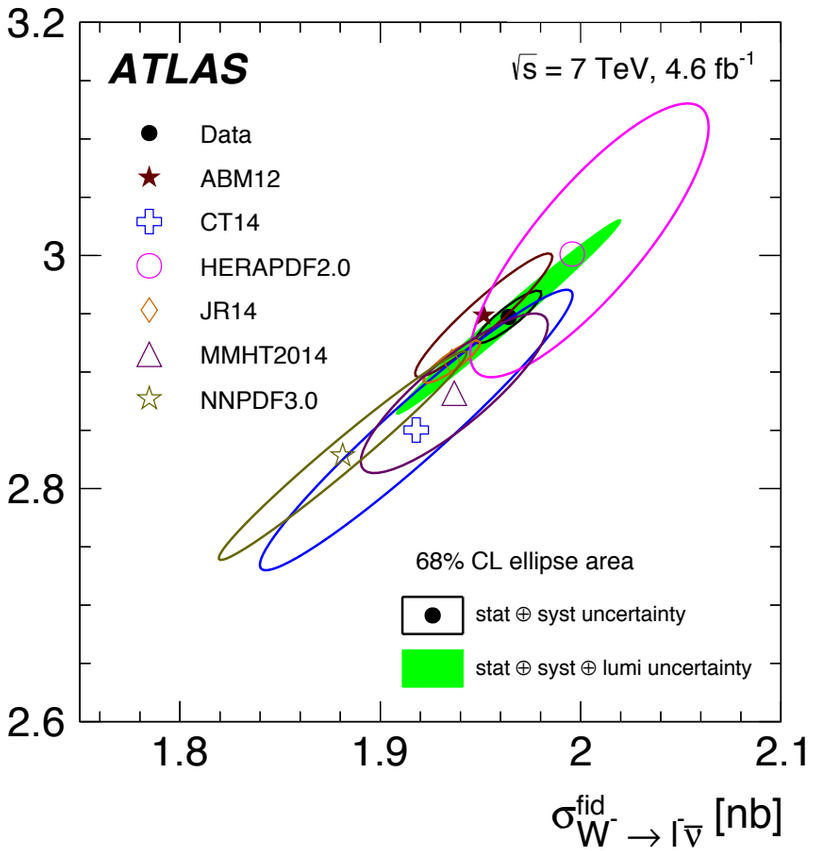
	$\sigma^{\text{fid}}_{W\to\ell\nu}$ [pb]
$W^+ \to e^+\nu$	$2939 \pm 1\,(\text{stat}) \pm 28\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \mu^+\nu$	$2948 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \ell^+\nu$	$2947 \pm 1\,(\text{stat}) \pm 15\,(\text{syst}) \pm 53\,(\text{lumi})$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

Lepton universality



- Ratio of the electron-to-muon ratios for W and Z bosons
  - Good agreement with Standard Model
    - $\mathbf{R_W}$: more precise measurement than the combination of LEP results from $e^+e^- \to W^+W^-$ data
    - $\mathbf{R_Z}$: good agreement with $e^+e^- \to Z$ LEP and SLC data
- ✓ R_W and R_Z measurements confirm lepton universality in the weak vector-boson decays

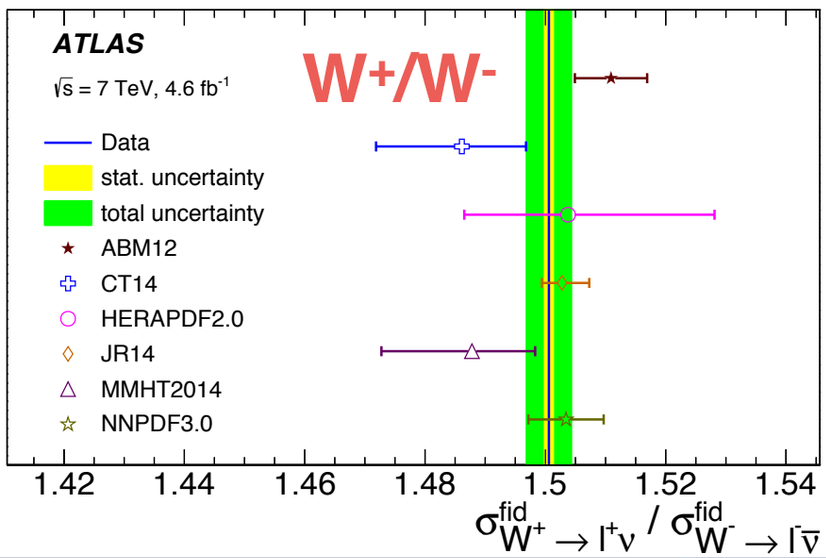
Comparison with the predictions

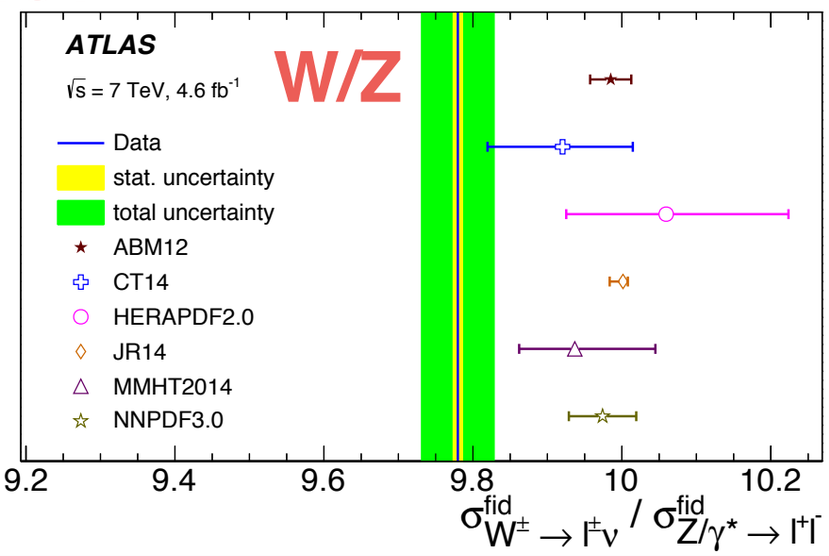


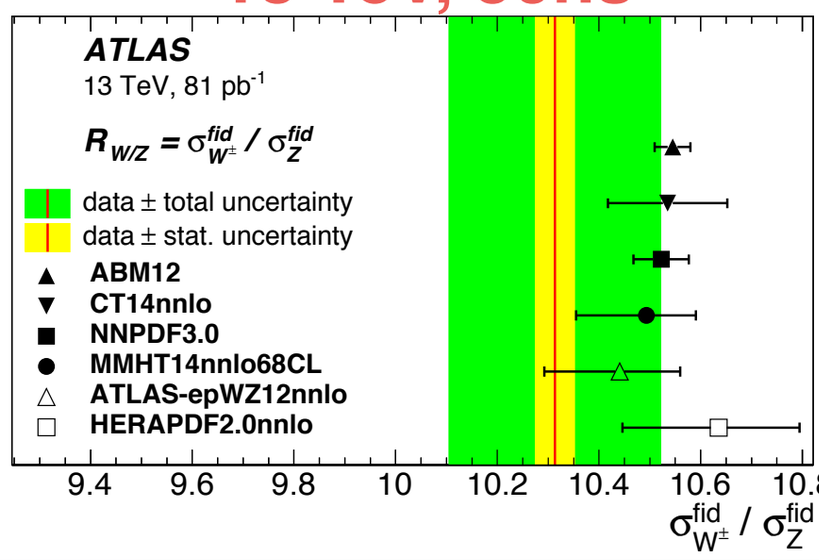
- **Predictions**:
  - **NNLO pQCD**: DYNNLO1.5 and FEWZ3.1b2
  - **NLO EWK** corrections: MCSANC1.2 (ISR photon, EW loop correction and etc.)
- Data measurements are more precise then predictions → constrain power
- Predictions for different PDF sets are lower then data

- **Ratios**
- **W^+/W^-:** described by predictions
- **W/Z:** predictions are higher than data
  - ✓ Comparable with W/Z ratio at 13 TeV (Phys.Lett. B759 (2016))

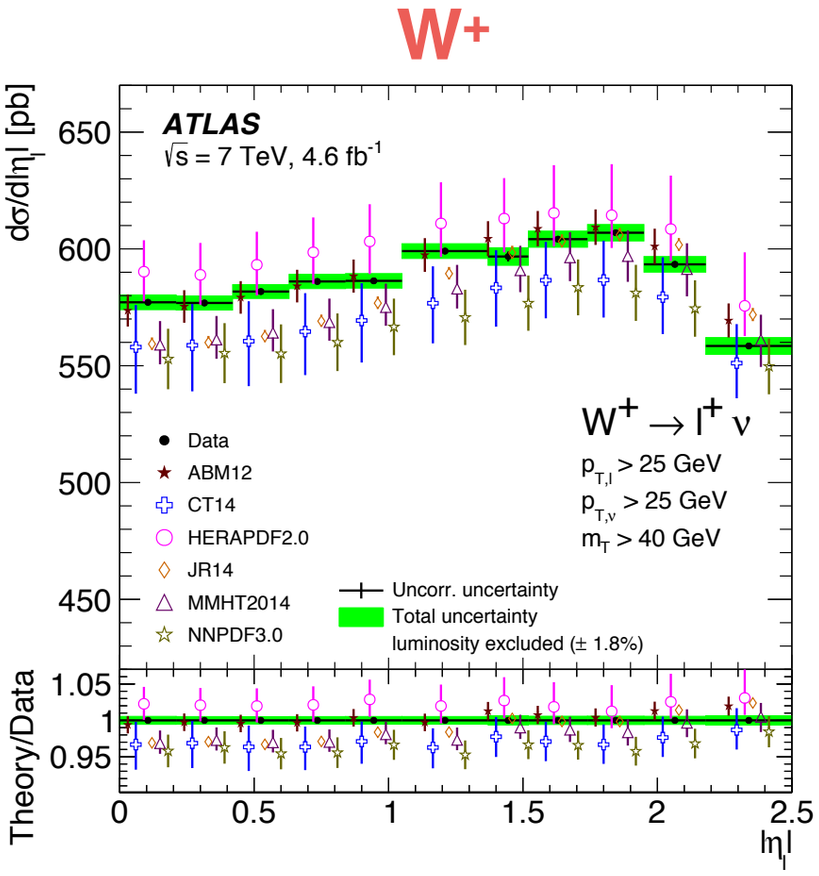
7 TeV **13 TeV, 50ns**

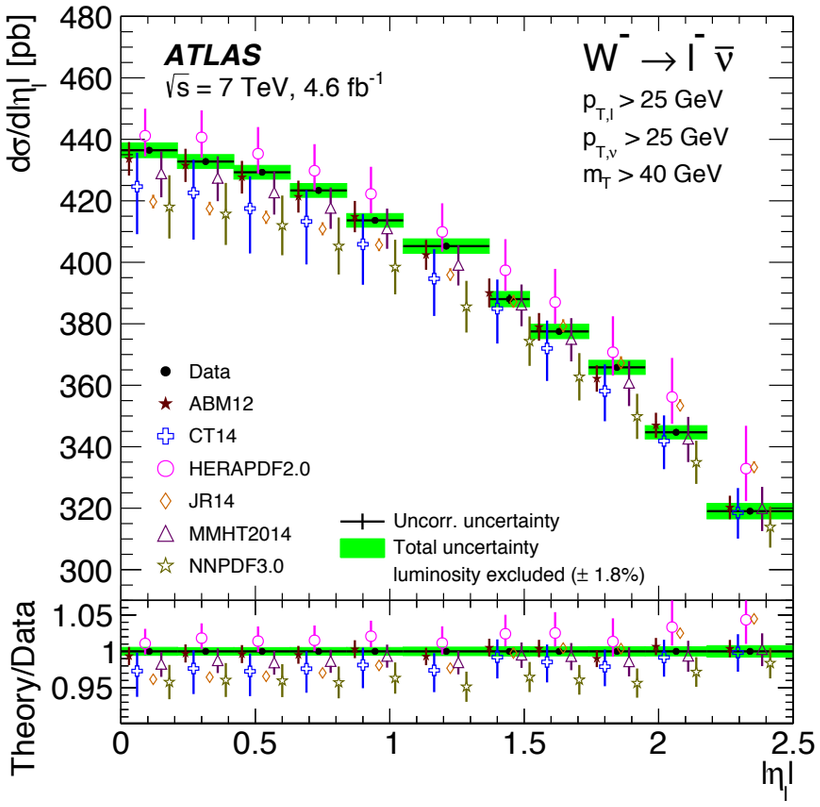


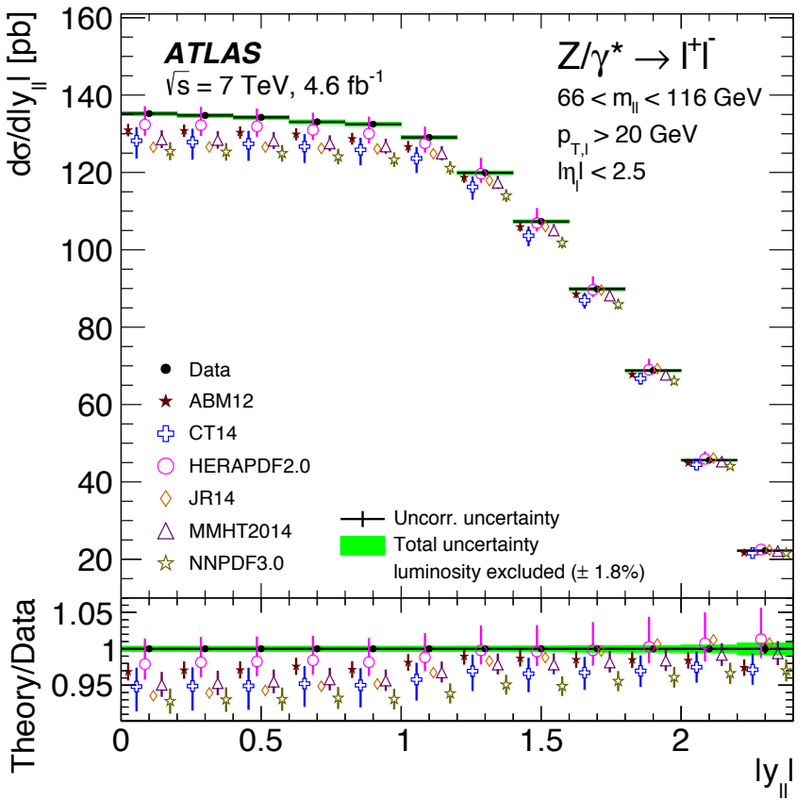




W and Z differential cross sections



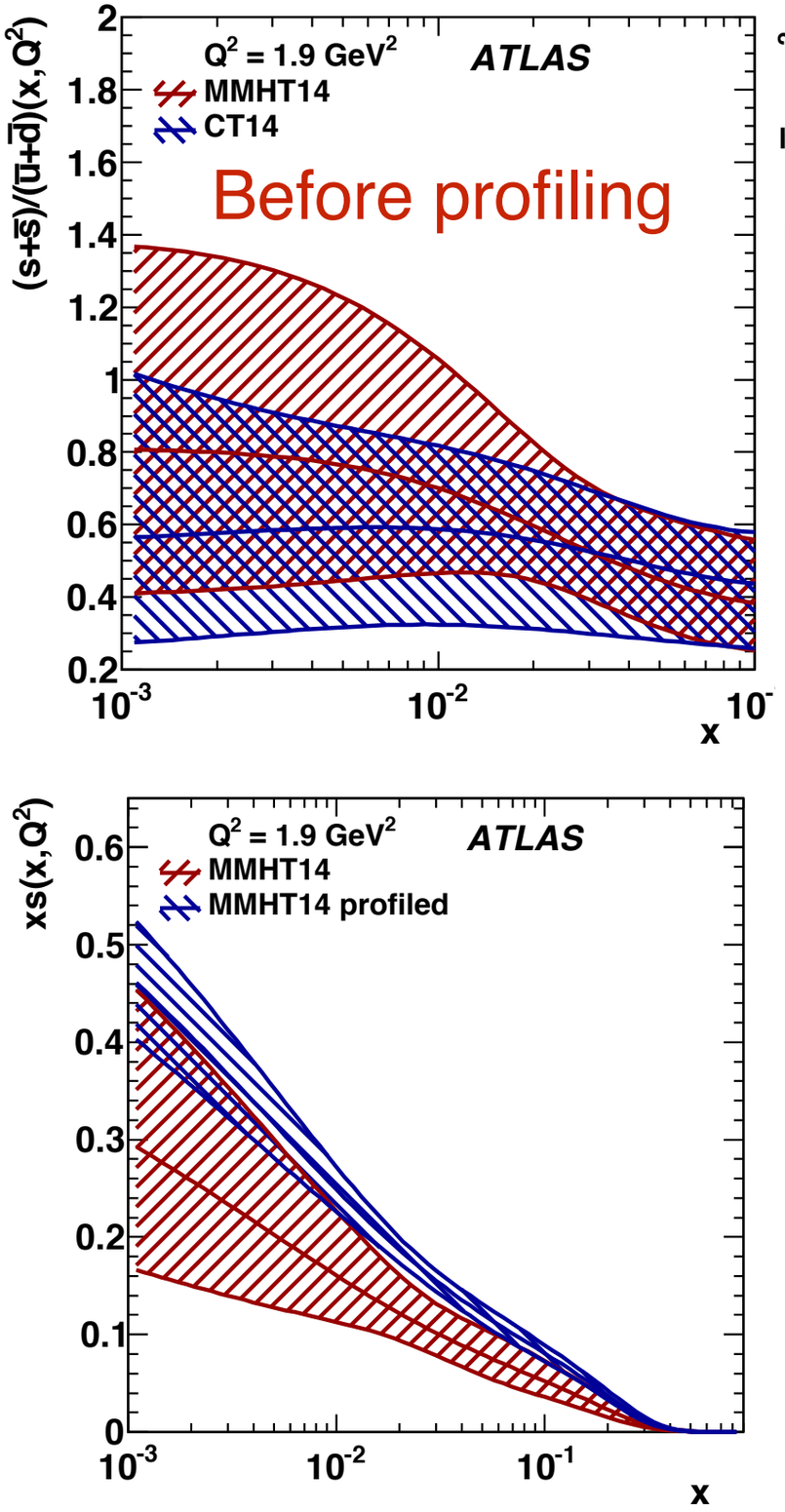


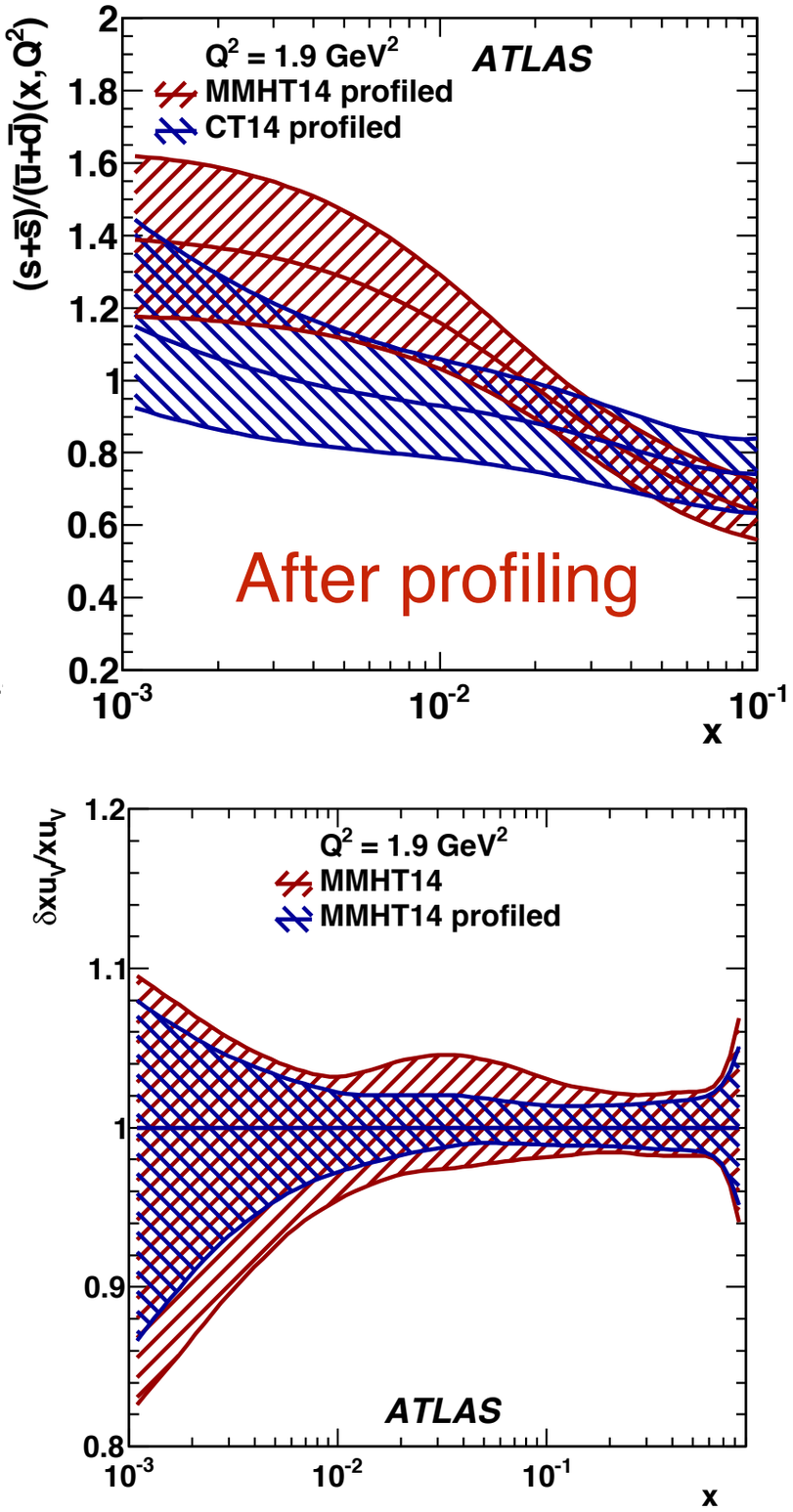


- The electron and muon channels were combined: χ^2/n.d.f = 59.5/53
  - **Precision** of combined differential cross sections:
    - ✓ 0.4-0.6% for the W+ and W- and central Z peak measurements
- Cross sections are compared to NNLO pQCD predictions
  - **W**: good description by ABM12 and other predictions are below data
    - the difference for many PDF do not exceed luminosity uncertainty
  - **Z:** all predictions are below the data

Interpretation of results

PDF constrains

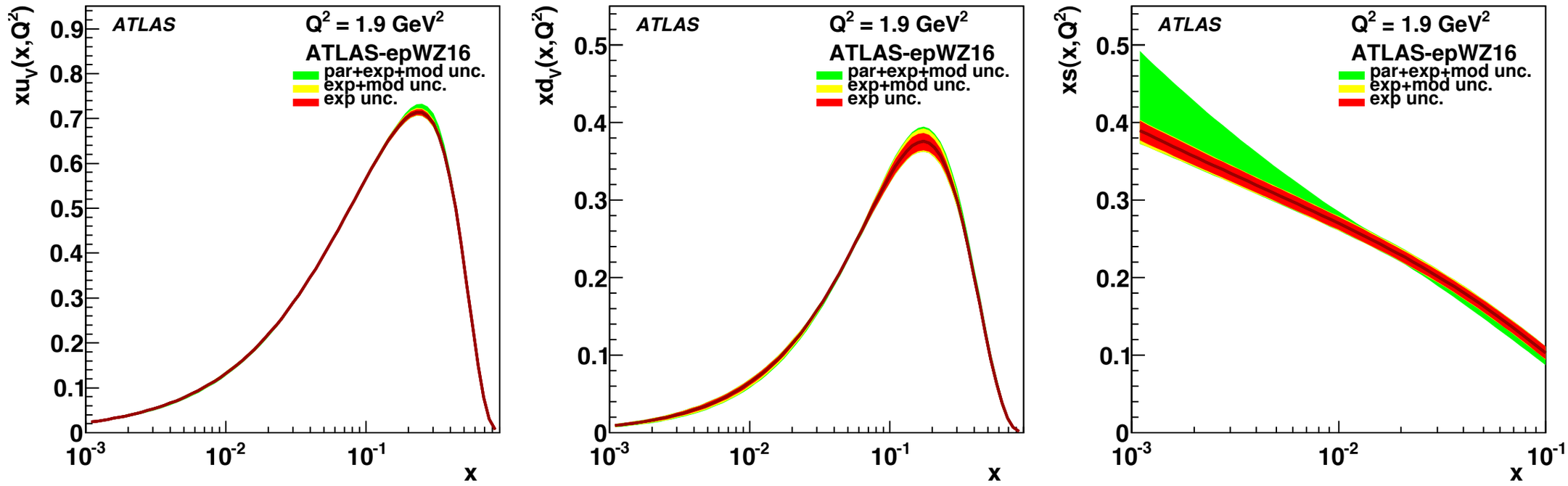




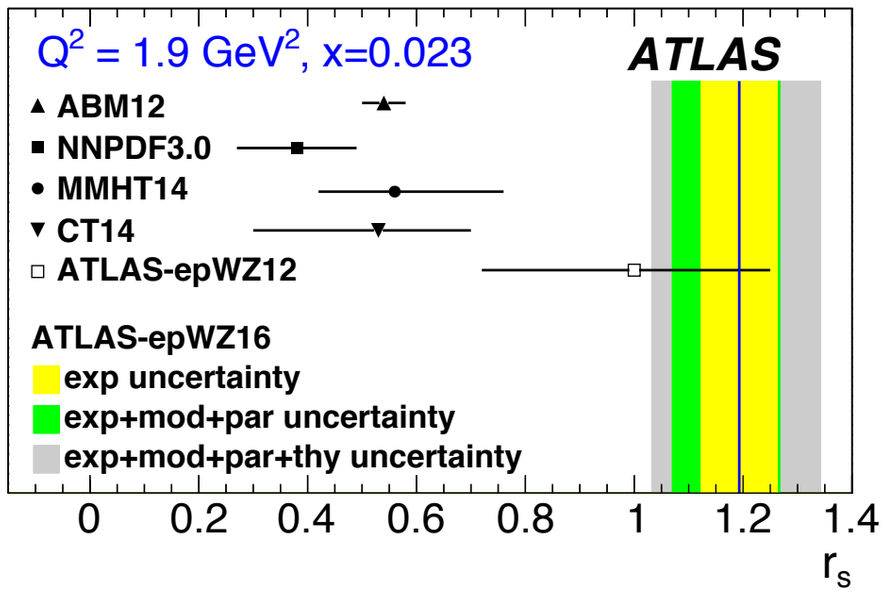
- Impact of measurements on given PDF is estimated using profiling:
  - significantly reduced uncertainties
  - central value increased towards unity at x~0.023
  - strange quark is significantly increased with reduced uncertainties
  - significant reduction on the relative uncertainty of xu_v distribution

QCD analysis

- Measurements are combined with final (DIS) HERA I+II data: **ATLAS-epWZ16**
  - more sensitivity light-quark composition at low x
  - reduced uncertainties



Estimation of strange quark density



- Fraction of strange quark density in the proton

$$r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.19 \pm 0.07(\text{exp}) \pm 0.02(\text{mod})^{+0.02}_{-0.10}(\text{par})$$

✓ data confirm **unsuppressed strange quark density** with improved precision

3.2, 20.3, 4.6 fb^{-1} - **13, 8, 7 TeV**

Top-quark pair to Z-boson cross-section ratios

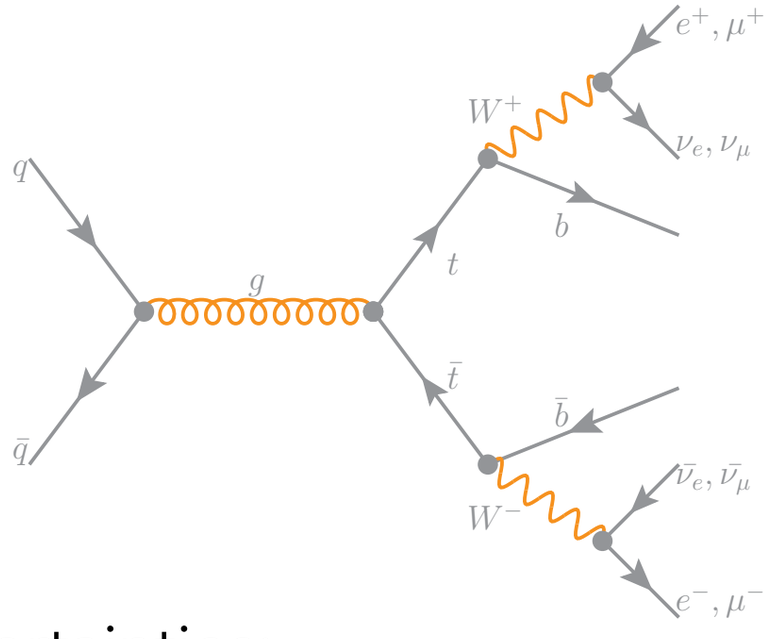
JHEP 1702 (2017) 117
arXiv:1612.03636

- New Z boson cross section at 13 TeV
- Fiducial and total cross sections
- Comparison with theoretical predictions
- Correlation model of all measurements
- Various ratios at $\sqrt{s}$ = 13, 8, 7 TeV
- PDF contraints

Top-quark pair to Z-boson cross-section ratios

- **Single ratio:** $t\bar{t}$ to Z cross-section ratio:

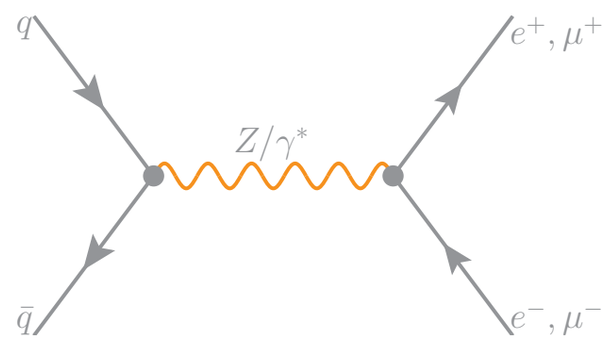
$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu})}$$



- $t\bar{t}$ production is dominated by ***gg*** process
- *Z* production is more sensitive to ***qq̄***
  - *sensitive* to gluon-to-quark PDF ratio
  - *cancellations* in experimental and theoretical uncertainties: (luminosity and lepton-related systematic uncertainties)

➡ $R_{t\bar{t}/Z}^{tot/fid}(\text{i TeV})$ - at the same √s

➡ $R_{Z_i/Z_j}^{fid}, R_{t\bar{t}_i/t\bar{t}_j}^{tot}$ - given process at the different √s



- **Double ratio:** at different center-of-mass energies √s:

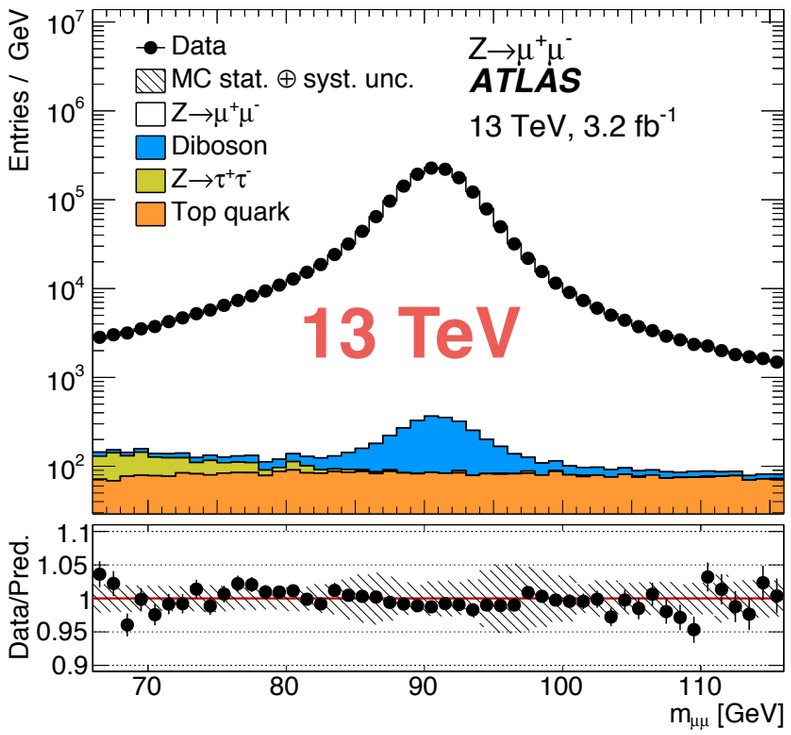
$$R_{t\bar{t}/Z}^{tot/fid}(\text{i})/R_{t\bar{t}/Z}^{tot/fid}(\text{j}), \quad \text{where i,j} = 13,8,7 \text{ TeV}$$

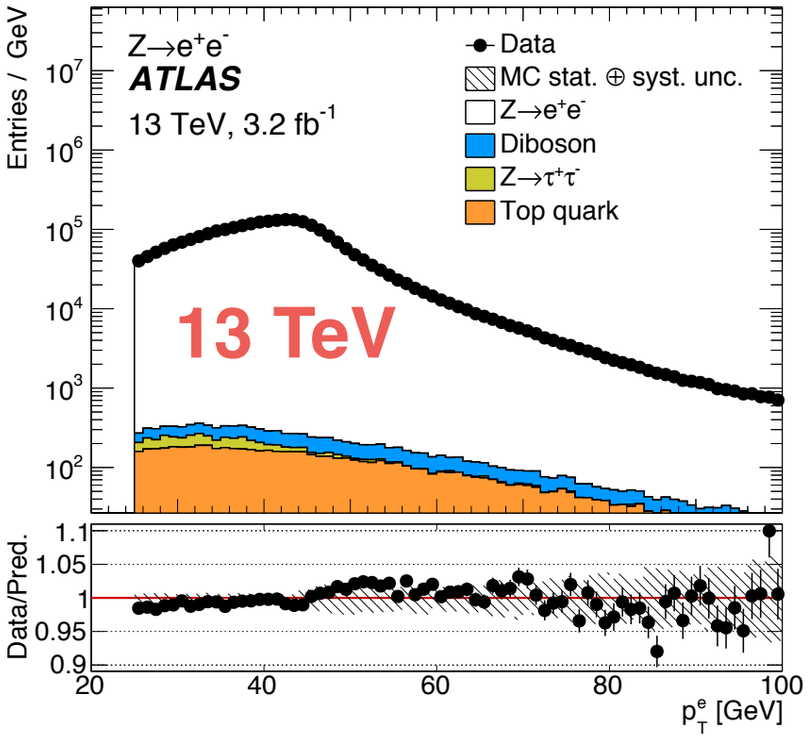
  - comparison of the data and theory predictions
  - double ratios serve as precision tests of the SM predictions
    - ✓ luminosity independent cross-check

Analysis measurements

- Use **previous published results:**
  - Z boson cross sections at $\sqrt{s}$ = 7, 8 TeV (*Eur. Phys. J. C 77 (2017) 367, Eur. Phys. J. C 76(5), 1-61 (2016)*) and top quark pair cross sections at $\sqrt{s}$ = 7, 8 and 13 TeV (*Eur. Phys. J. C74 (2014) 3109; Eur. Phys. J. C76 (2016) 642, Phys. Lett. B761 (2016) 136*)
  - new measurement: Z boson cross section at $\sqrt{s}$ = 13 TeV
- ✓ Event and lepton selection for Z analysis was fully consistent with $t\bar{t}$
- **Common fiducial phase space** for all Z

$$p_T > 25 \text{ GeV} ; \ |\eta| < 2.4$$
$$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$$





- **Signal MC:** Powheg+Pythia
- Background estimation:
  - EW & $t\bar{t}$ from MC
  - QCD multi-jet: data-driven
    - total: ~0.5%
    - sum of all EW: ~0.2%
    - multijet: < 0.1%
    - main contribution: $t\bar{t}$

Input to ratios

Theoretical predictions

	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	$^{+3.0}_{-3.7}$	$^{+2.8}_{-3.3}$	$^{+2.9}_{-3.2}$	$^{+5}_{-6}$	$^{+6}_{-6}$	$^{+6}_{-6}$

- **Z cross sections calculations:**
  - NNLO QCD with DYNNLO 1.5
  - NLO EW corrections with Fewz 3.1
- **$t\bar{t}$ cross sections calculations:**
  - NNLO+NNLL QCD with Top++v2.0
  - only total cross section available

✓ CT14 PDF set is used as the baseline

➡ main contribution on uncertainty: PDF (for both) + Scale ($t\bar{t}$)

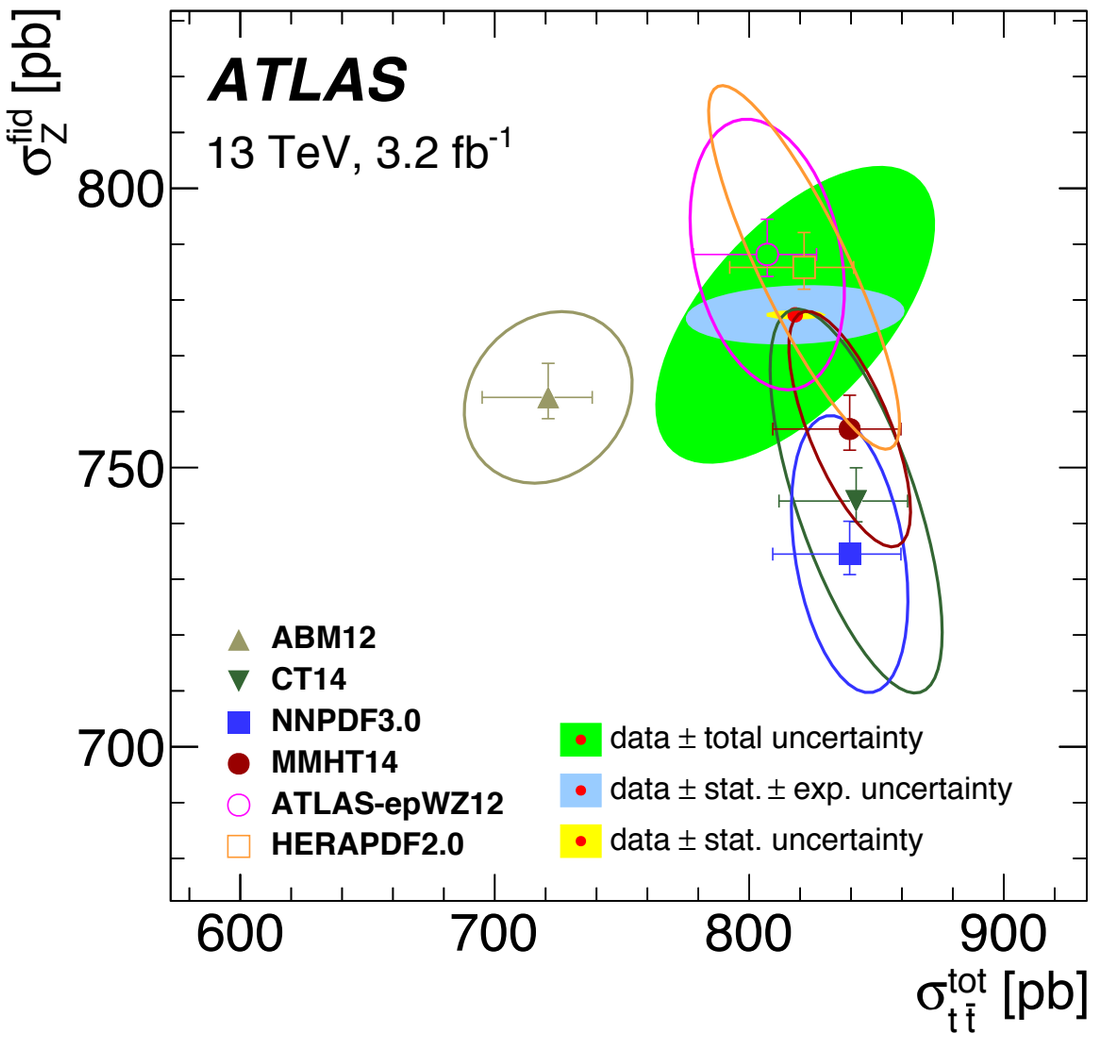
Data

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

- Combined cross sections
  - all data is dominated by systematic uncertainty
- Largest sources of uncertainty:
  - ➡ luminosity, beam energy, signal modelling ($t\bar{t}$)

Correlation model

Comparison with the predictions using correlation model



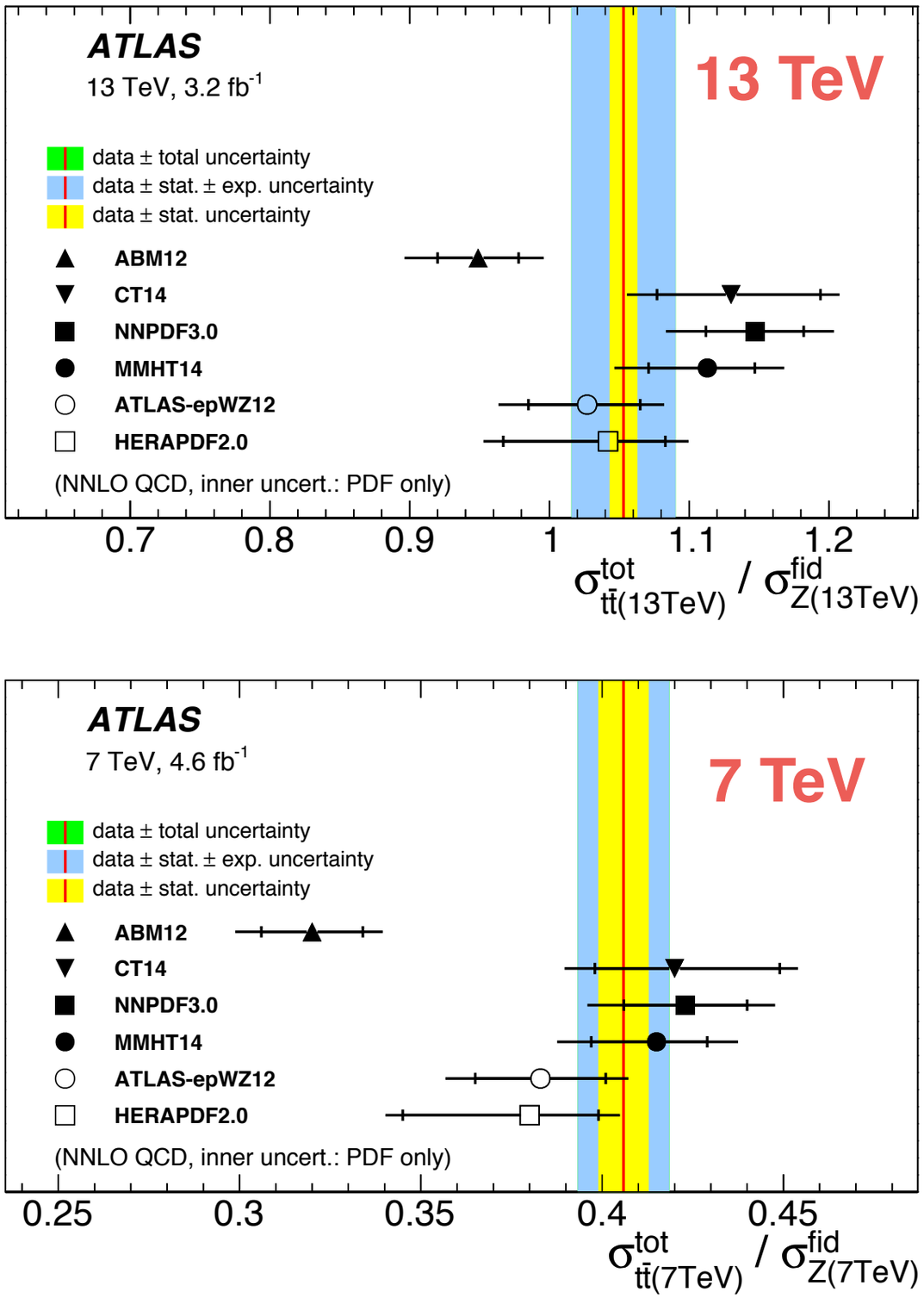
- The correlation of measured cross section is opposite sign to predicted (the same for 7 and 8 TeV)
  - discriminative input to determination of PDF

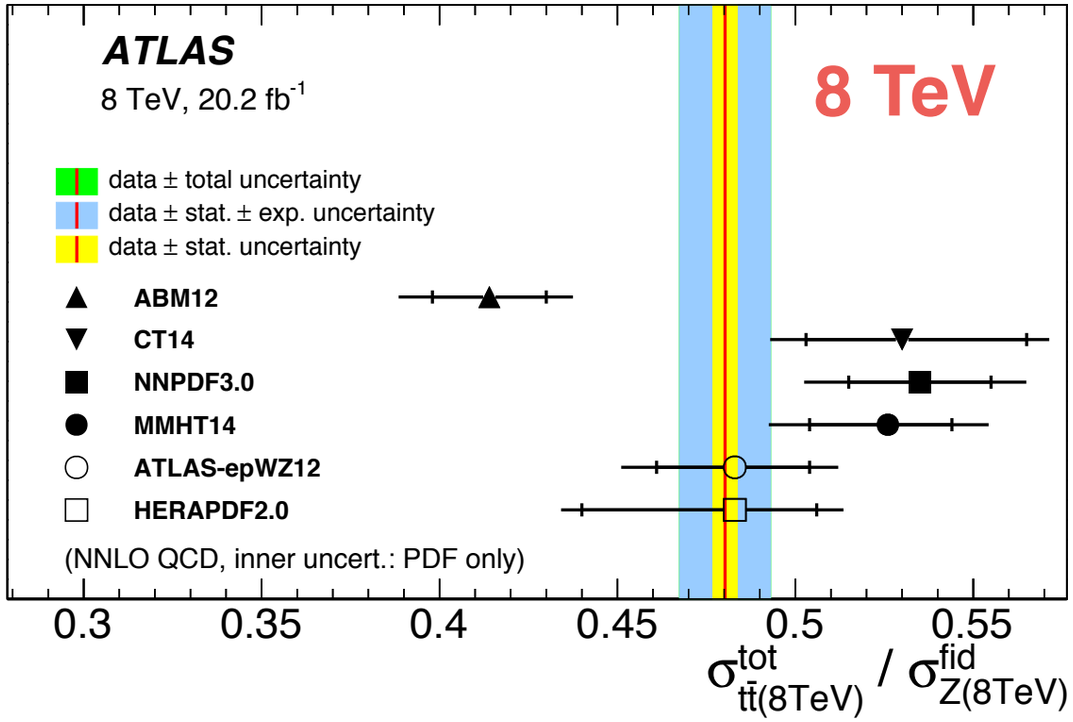
Source / $\sqrt{s}$ [TeV]	$\delta\,\sigma_Z^{\rm fid}$ 13	8	7	$\delta\,\sigma_{t\bar{t}}^{\rm tot}$ 13	8	7
Luminosity	A	B	C	A	B	C
Beam energy	A	A	A	A	A	A
Muon (lepton) trigger	A	A*	A	A	B	B
Muon reconstruction/ID	A	B	C	A	D	D
Muon isolation	A	A	A	B	C	D
Muon momentum scale	A	A	A	A	A	A
Electron trigger	A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

- the same row and letter: fully correlated
- with started letter: mostly correlated
- different rows: uncorrelated

Top-quark pair to Z cross-section ratios

Single ratios at given √s

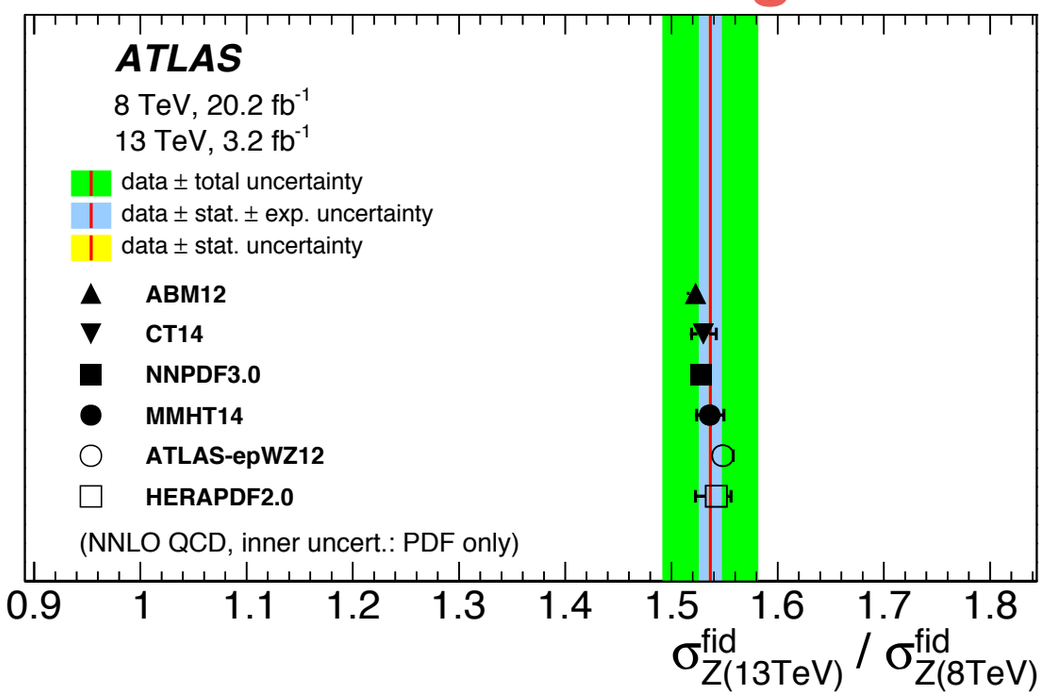


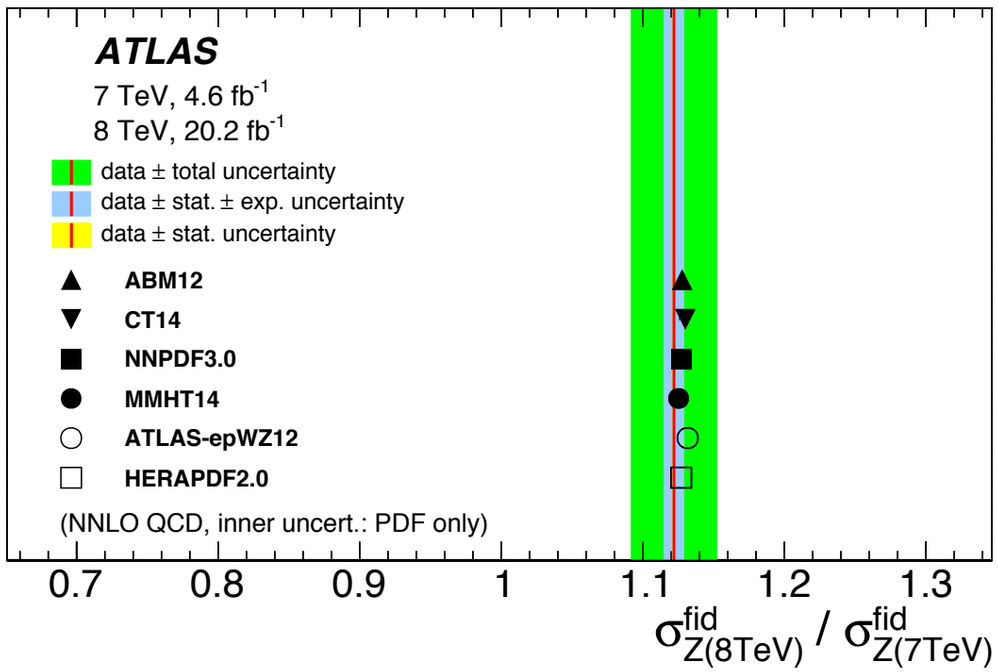


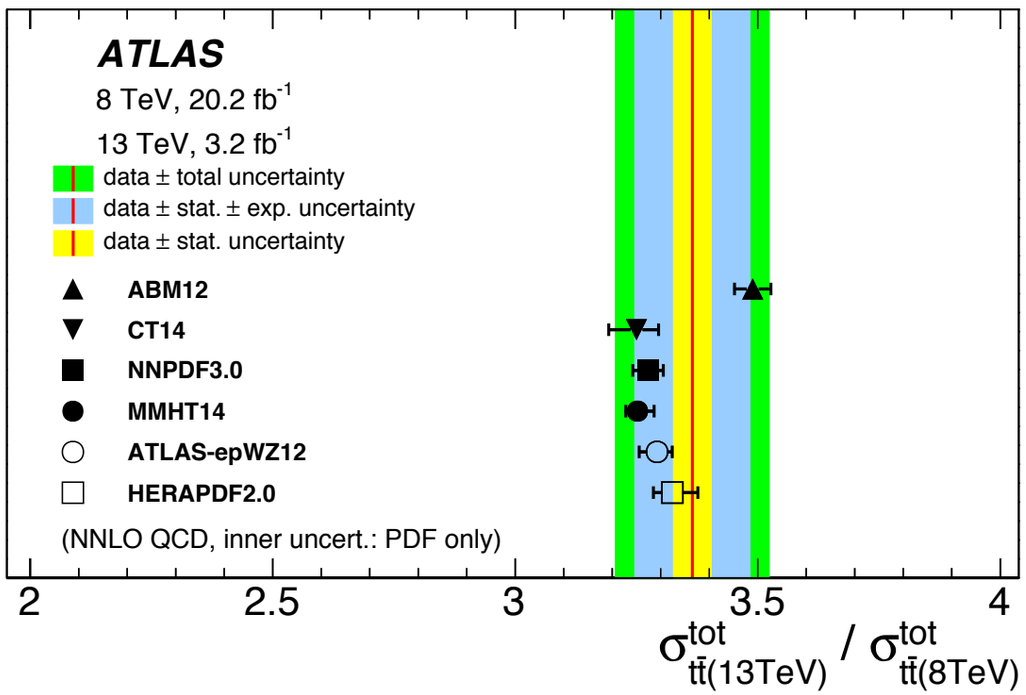
- ATLAS data are more precise than most of the theory predictions
- luminosity uncertainty almost cancels
- smallest data uncertainty: 8 TeV ratio
- **13 TeV** and **8 TeV** data are most consistent with ATLAS-epWZ12 and HERAPDF2.0
- **7 TeV** most consistent with MMHT14

Cross-section ratios for given process

Single ratios at different √s



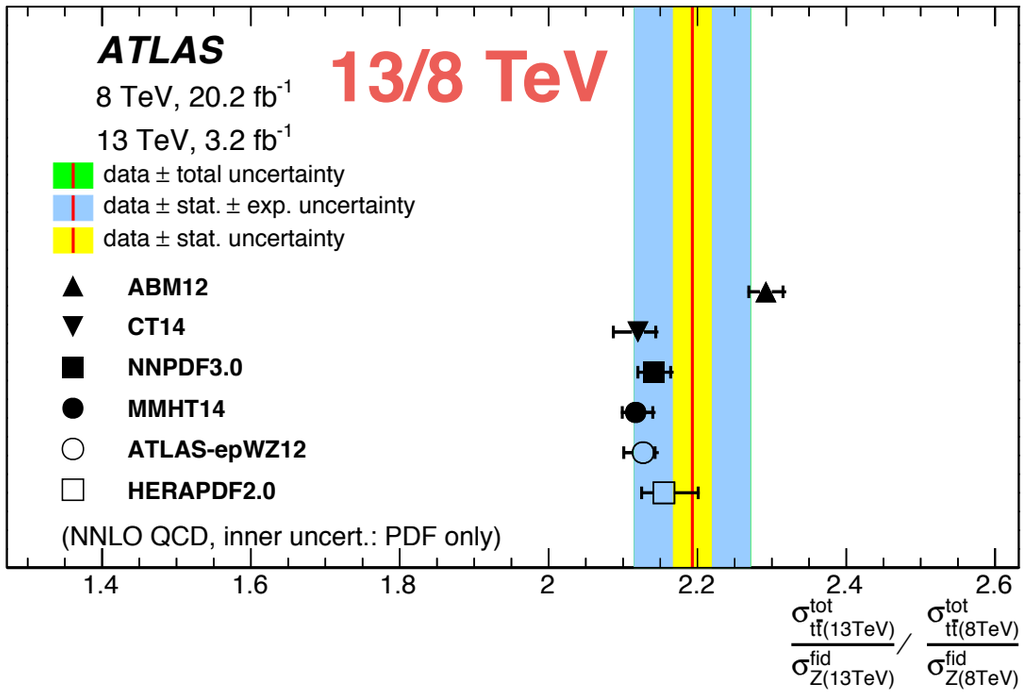


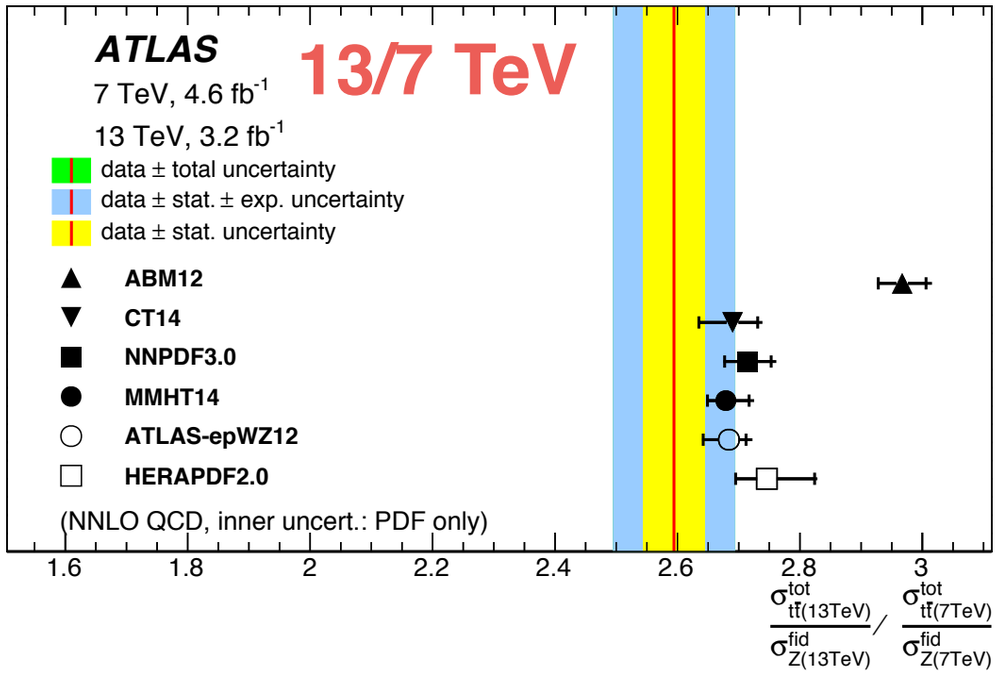


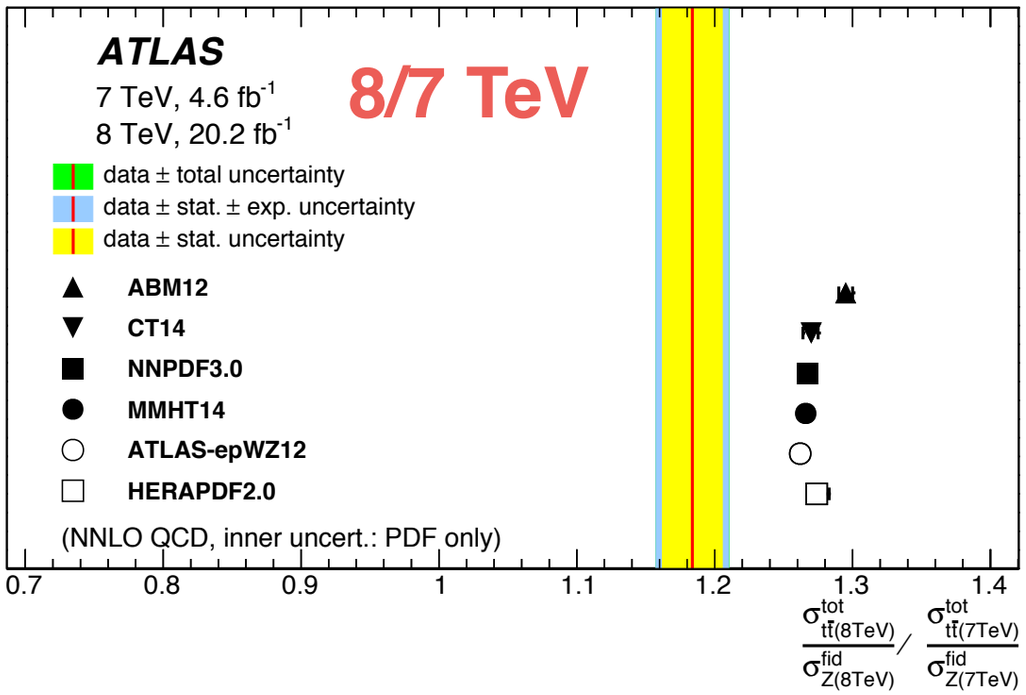
- **Z:** - uncertainty is dominated by luminosity
  - measurements are consistent with the predictions for all PDF sets within experimental uncertainties
  - ➡ luminosity-determination uncertainty in the measured ratio is <u>conservative</u>
- **$t\bar{t}$:** - ABM12 prediction is largest
  - PDF4LHC PDFs are smallest
  - agree with the prediction within experimental uncertainties

Double ratios

Double ratios at different √s

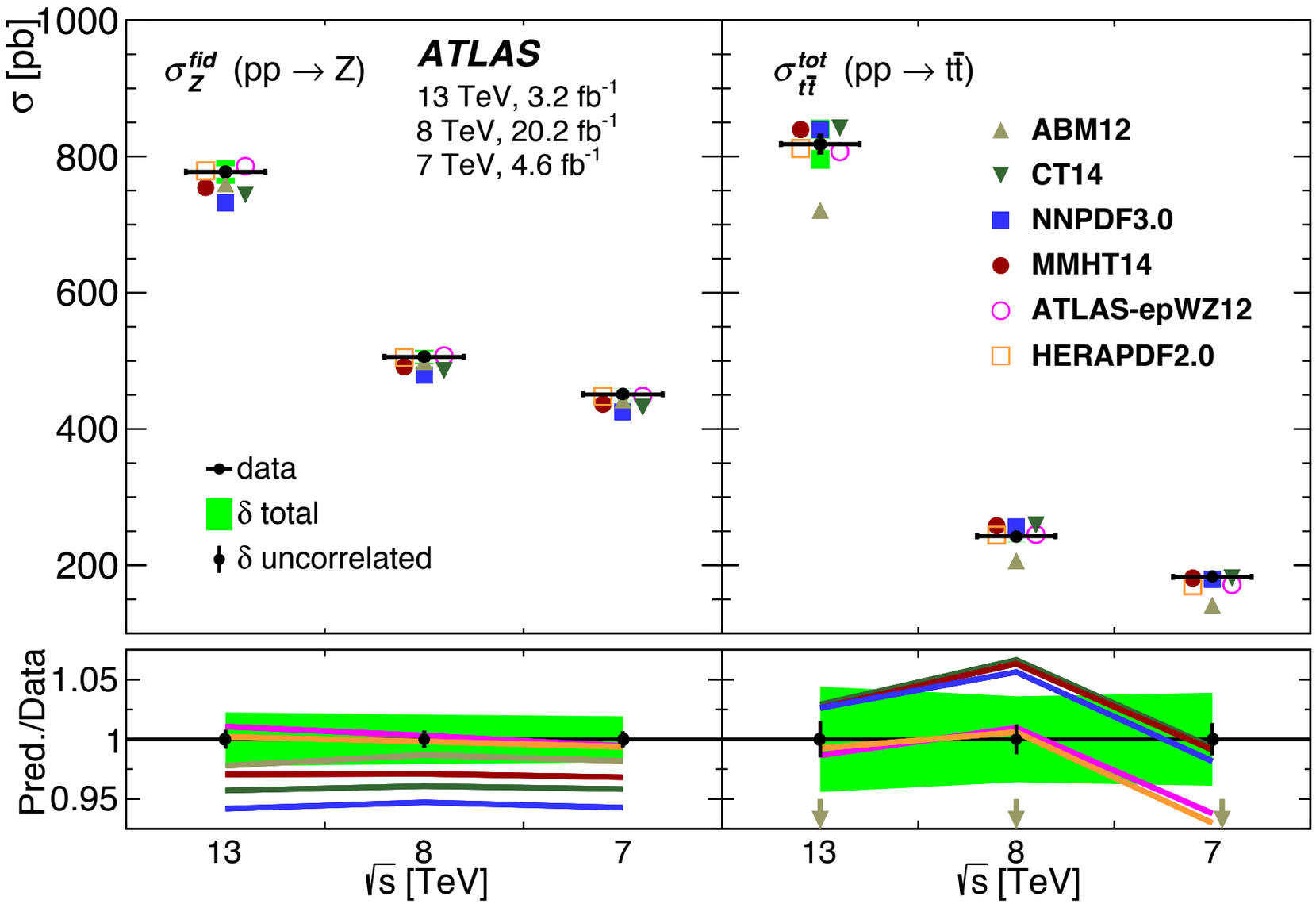






- Almost complete cancelation of the luminosity uncertainty
- **13/8 TeV**: within 1σ, most predictions below the data
- **13/7 TeV**: within 1σ, most predictions above the data
- **8/7 TeV**: 3-4 σ deviation vs predictions. Dominant experimental uncertainty: statistical error of 7 TeV sample.
  - not described by PDFs
  - difficult to ascribe to x-dependence of gluon distribution

Quantitive comparison with predictions



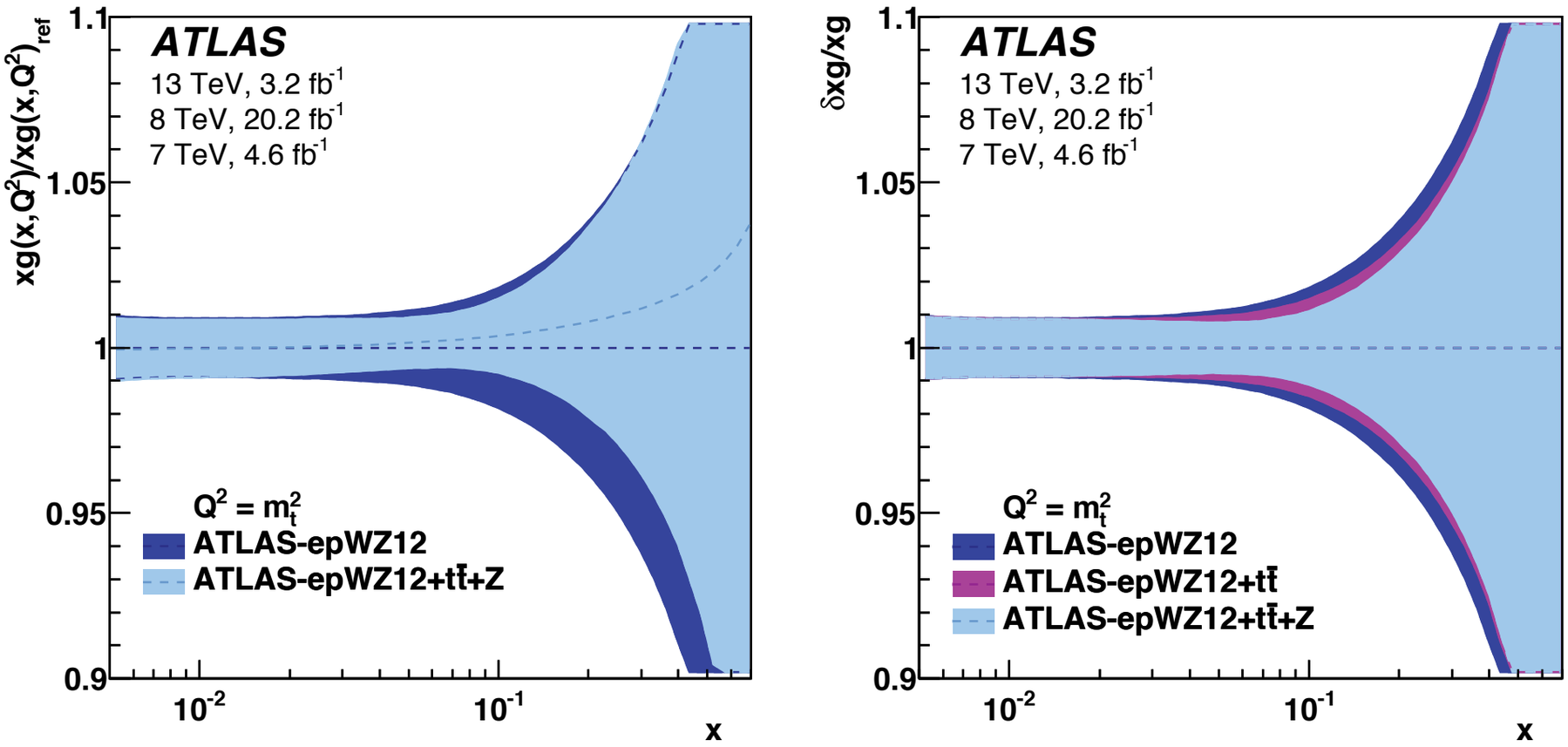
➡ Predictions based on HERAPDF2.0 and ATLAS-epWZ12 PDF sets have good compatibility with the ATLAS data

	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

PDF constraints

- The impact of the ATLAS data on the PDF uncertainties is quantified by using PDF profiling for ATLAS-epWZ12 PDF

Gluon distributions



- ✓ $t\bar{t}$ and Z data constrain gluon distribution at x ~ 0.1
- ✓ central values agree very well
- ✓ profiling was also performed with excluded $t\bar{t}$ data 7 TeV and yielded similar results

Summary

- Inclusive Drell-Yan production measurements performed by ATLAS has reached a sub-percent level of uncertainty
  - opportunity to understand the structure of proton and to test SM model predictions
  - impact of new data on the determination of the strange-quark distribution
  - confirmed unsuppressed strangeness
  - new test of elector-muon universality
- Benefits from the ratios: provide the cancelation of the experimental and theoretical systematics uncertainties
  - excellent agreement between Z-boson cross-section ratios and predictions at various $\sqrt{s}$ (omitting luminosity)
  - significant power to constrain gluon PDF from top-quark pair to Z-boson ratio

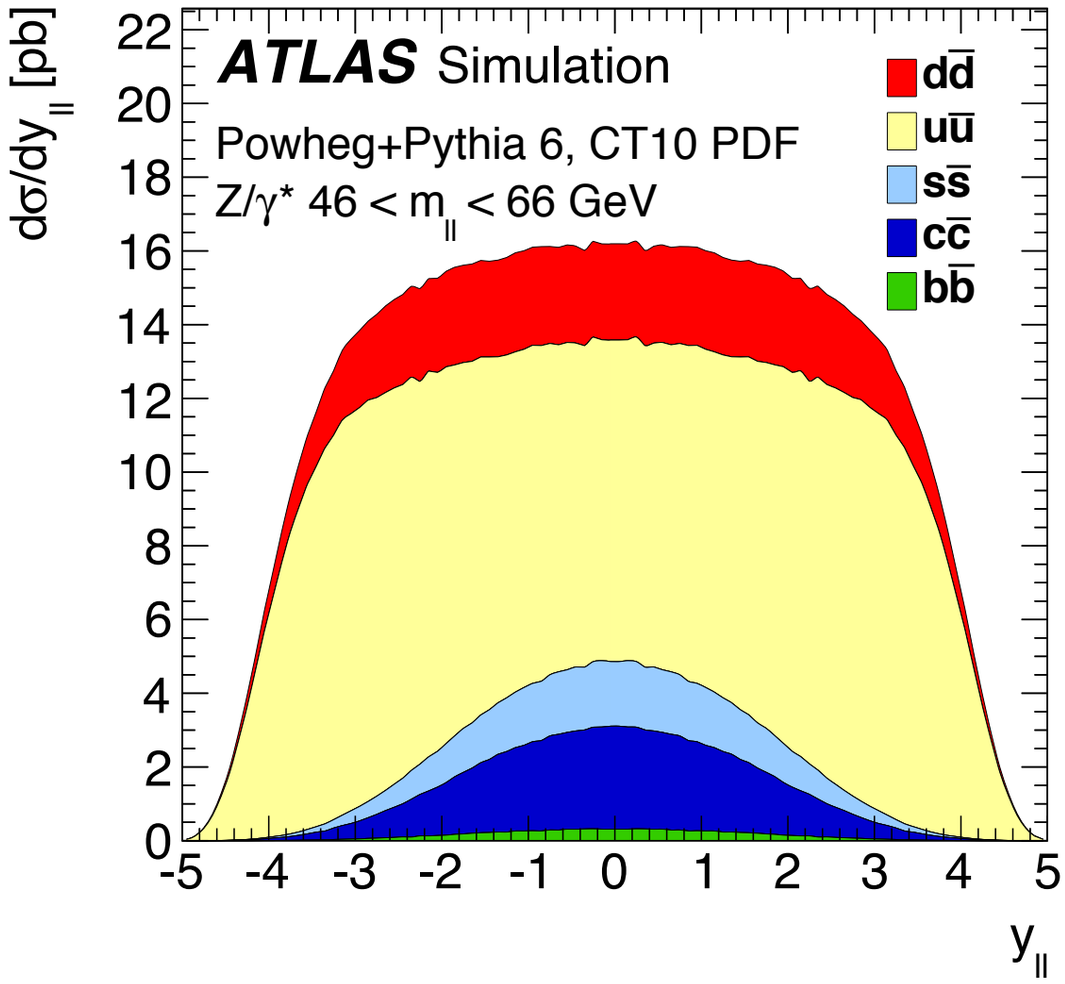
✓ A few 13 TeV vector boson production measurements have already been performed (W,Z inclusive cross sections, Z+jet at $\sqrt{s}$ = 13 TeV (Eur. Phys. J. C77 (2017) 361)), and more will follow. Stay tuned!

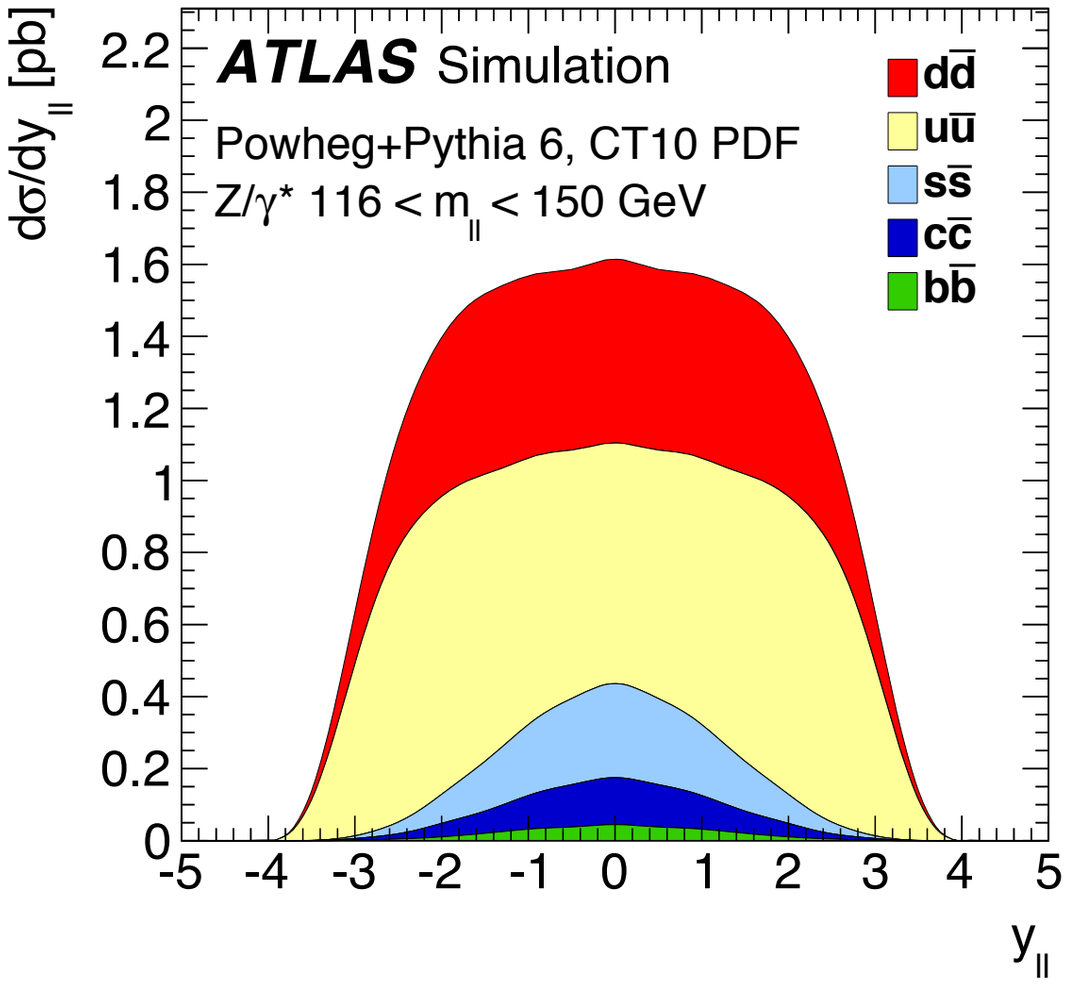
Thank you for your attention!

Backup slides

Z boson

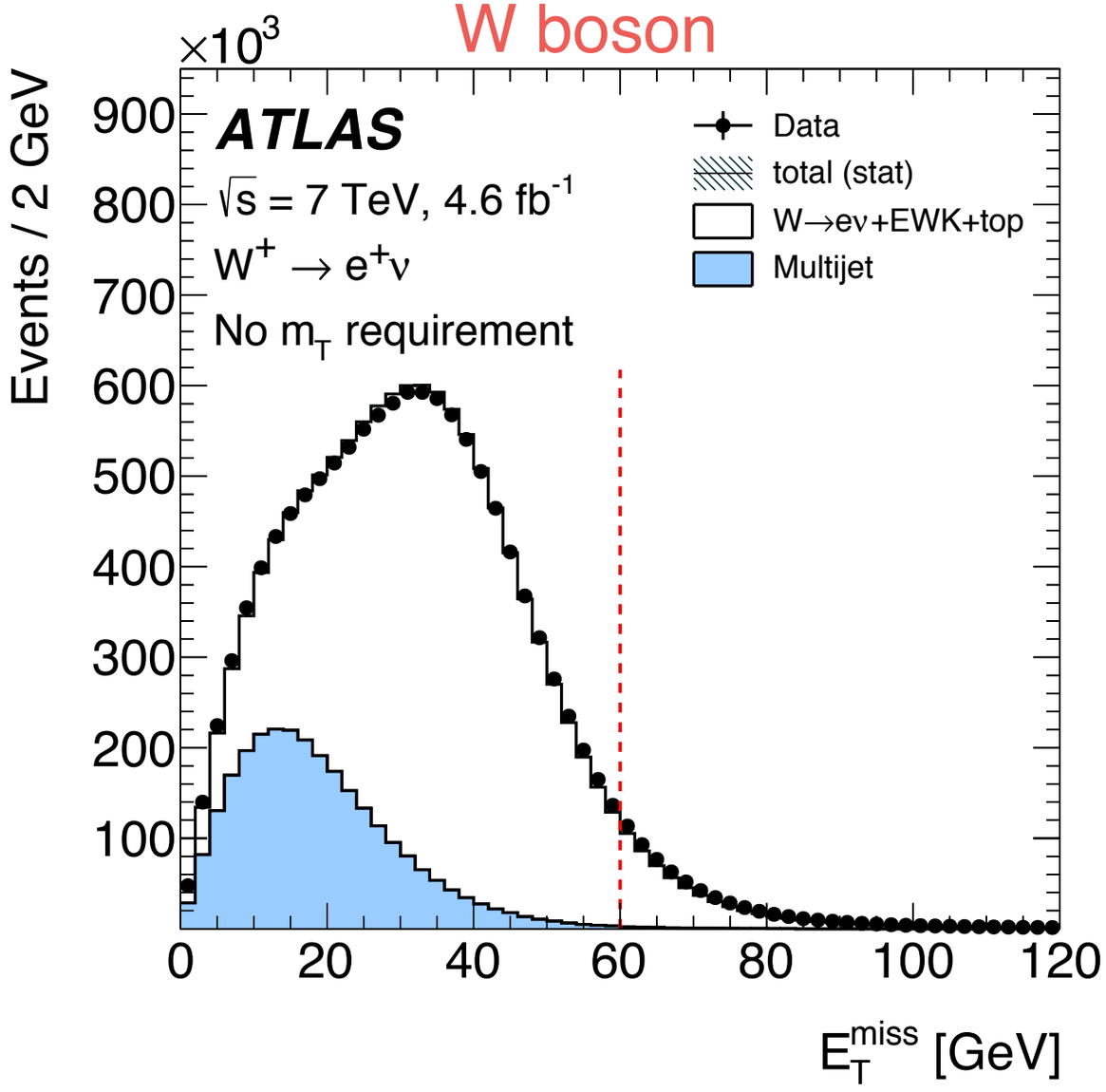
- Illustration of different $q\bar{q}$ contributing at LO QCD to the measured differential $Z/\gamma^* \to \ell\ell$ cross sections in the different mass regions
- The prediction is obtained from the Powheg+Pythia
- No event selection is performed



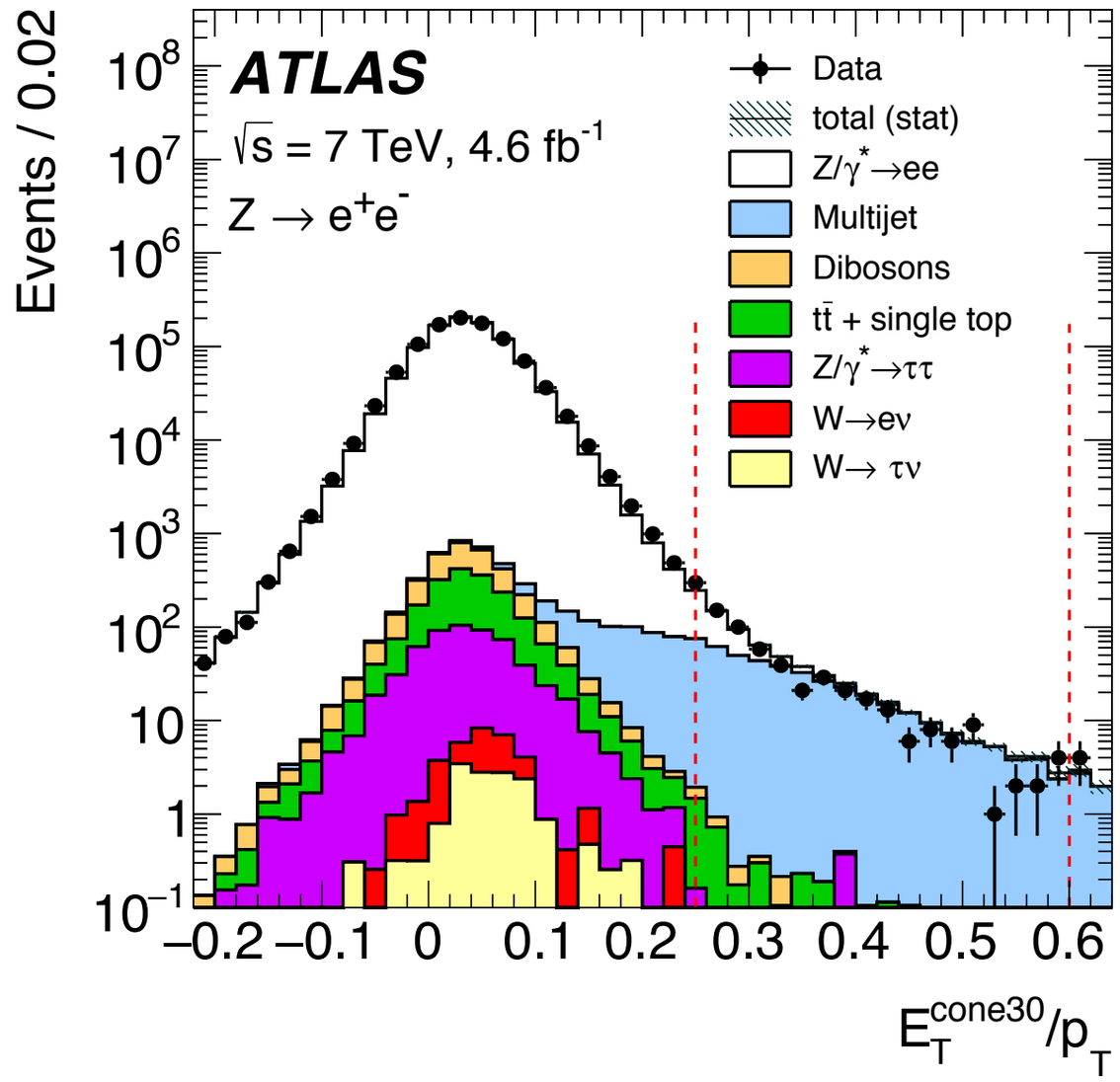


W/Z: Multi-jet background (electrons)

W boson



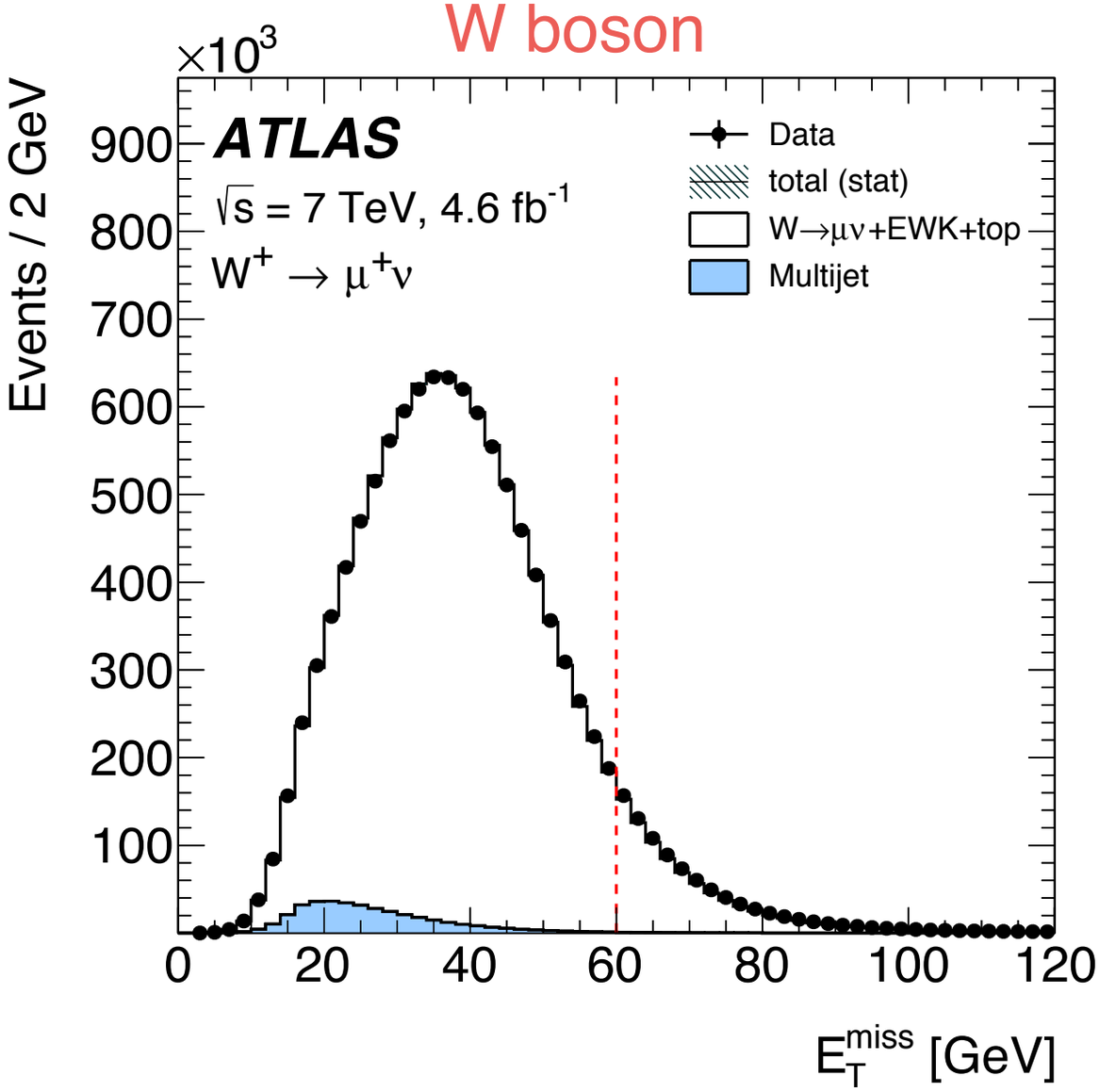
Z boson



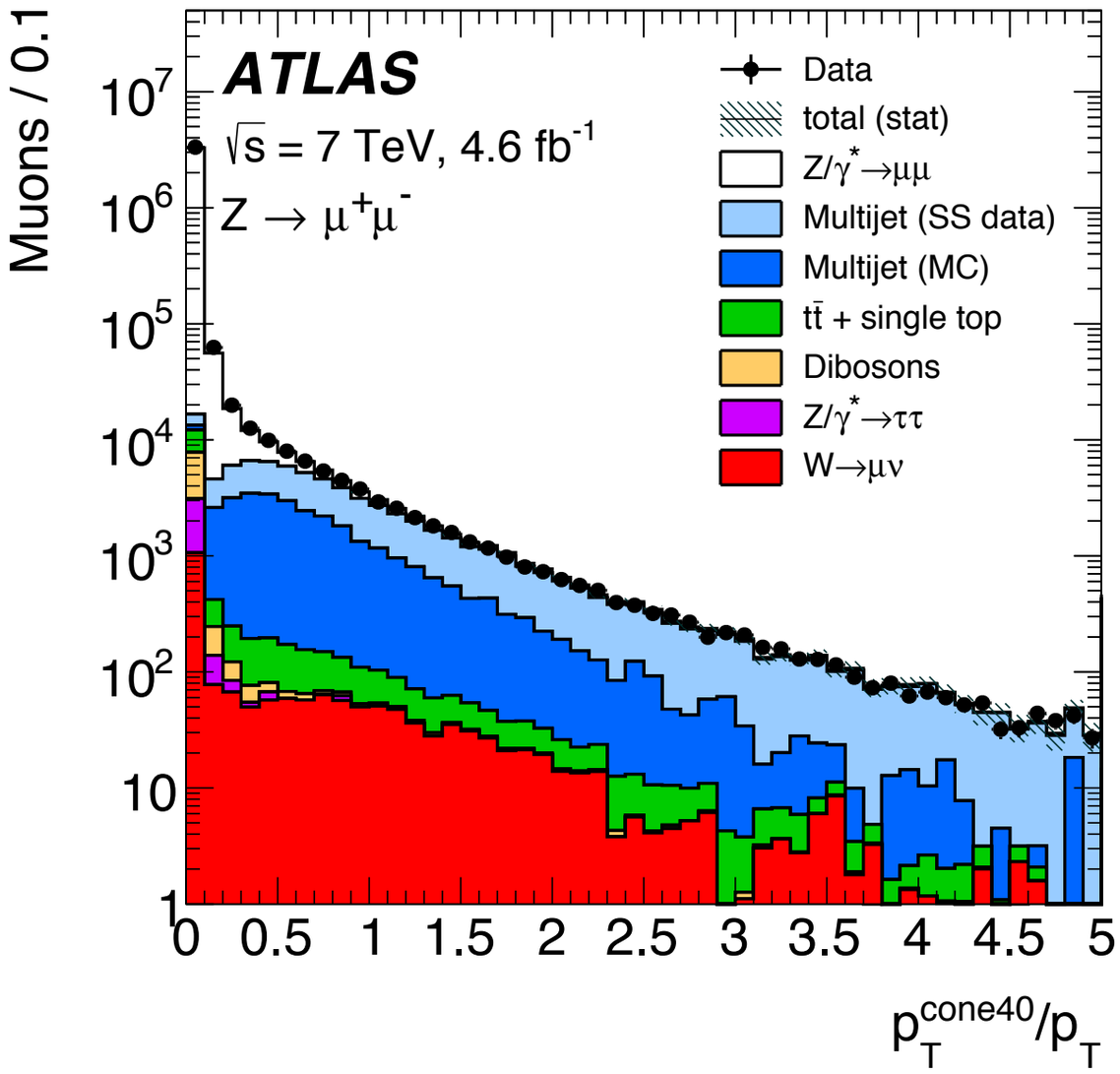
- Template fit using discriminative variable: E_T^{miss} (E_T^{cone}/p_T) for W(Z) boson
  - control region: relaxed E_T and m_T requirements
  - template: inverted identification requirement and requirement to have not isolated electron

W/Z: Multi-jet background (muons)

W boson

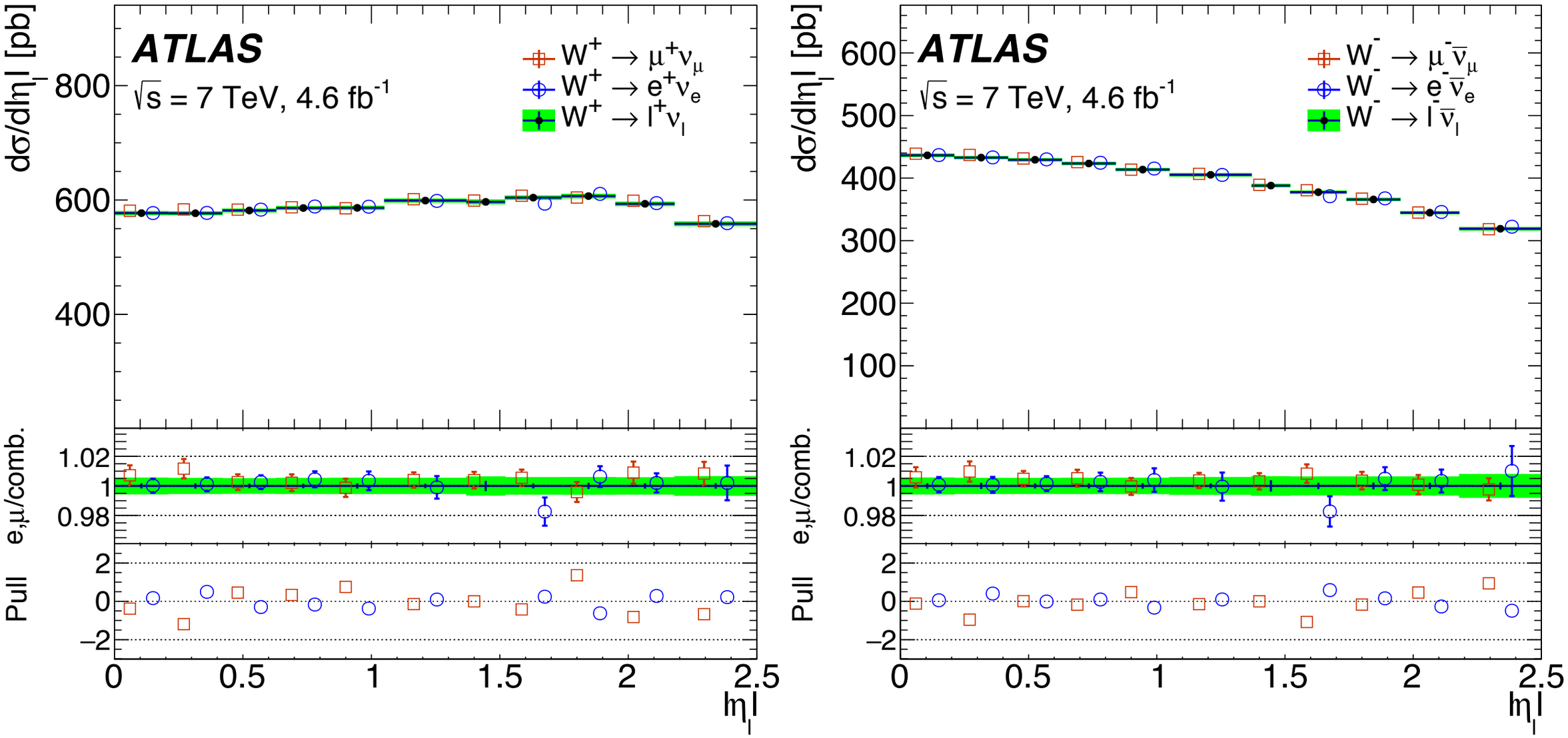


Z boson



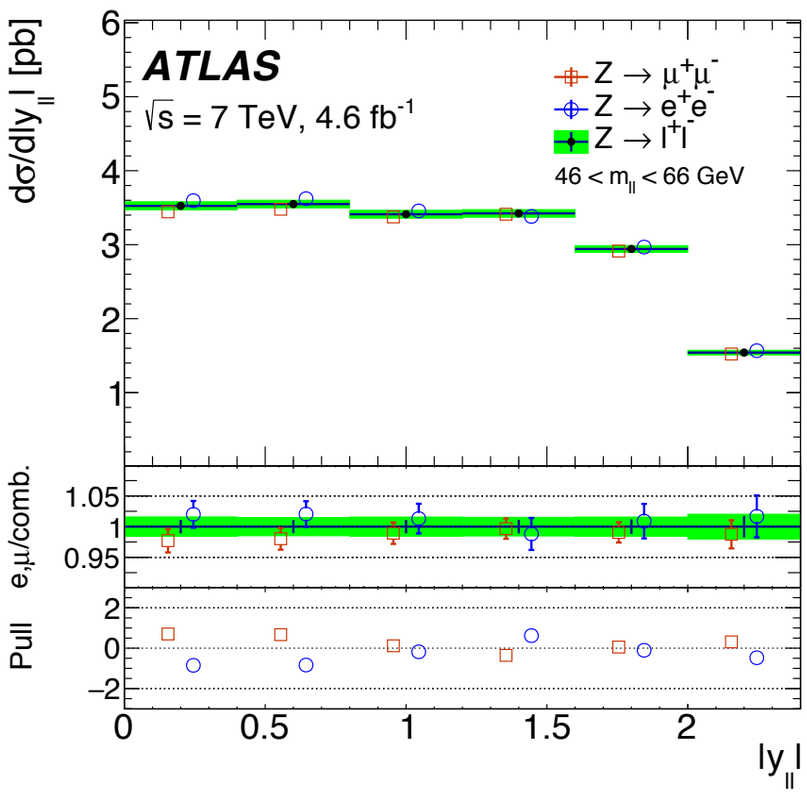
- W template: inverted isolation requirement, no requirement on E_T^{miss}
- Z template: combined same-charge data events and simulated heavy-flavour events (with subtracted same-charge fraction)

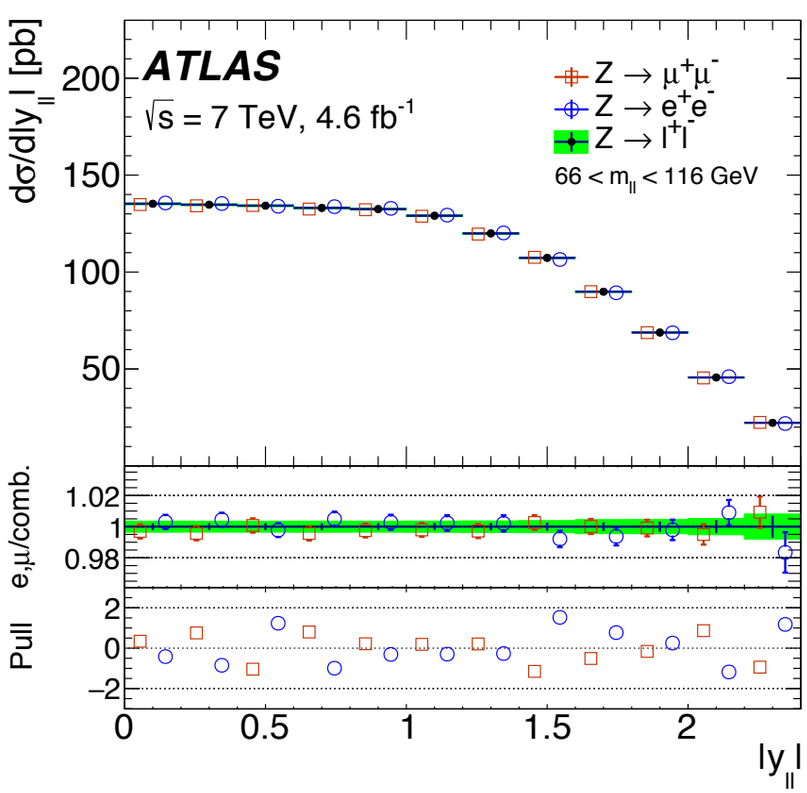
W/Z: Combined differential cross sections

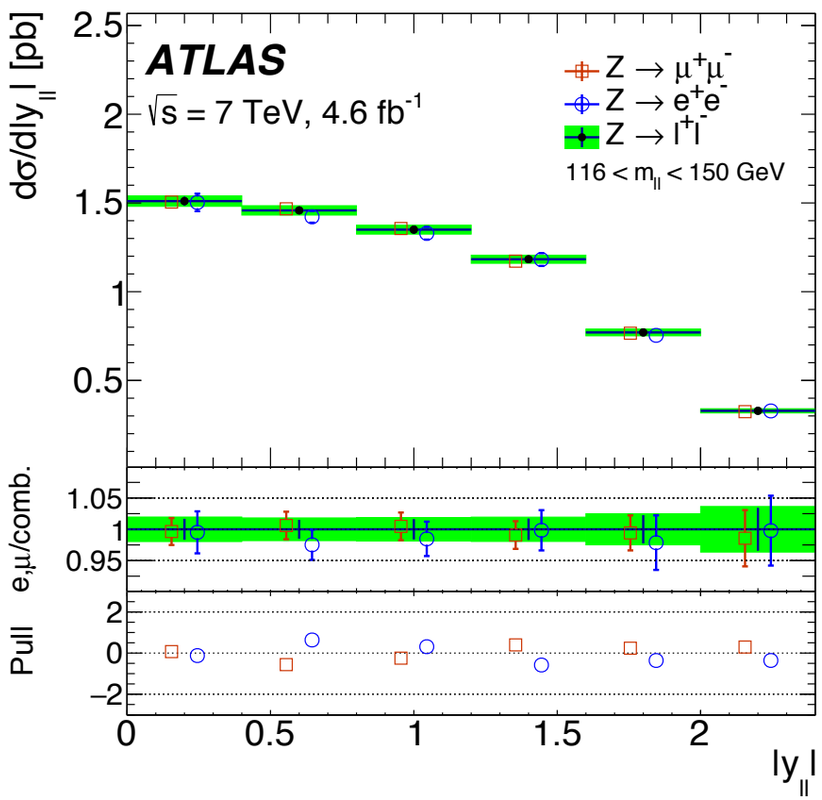


- Precision of the combined cross sections: 0.4 - 0.6% for W^+ and W^-

W/Z Combined differential cross sections







- Precision of the combined cross sections: 0.4 - 0.6% for Z peak measurements
- Off-peak: few percent of uncertainty

W/Z: Systematic uncertainties and ratio

Electron channel

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

Muon channel

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

Ratio values

$R_{W^+/W^-}^{\mathrm{tot}}$	$1.450 \pm 0.001\,(\mathrm{stat}) \pm 0.004\,(\mathrm{syst}) \pm 0.029\,(\mathrm{acc})$
$R_{W/Z}^{\mathrm{tot}}$	$10.83 \pm 0.01\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}) \pm 0.09\,(\mathrm{acc})$
$R_{W^+/Z}^{\mathrm{tot}}$	$6.407 \pm 0.004\,(\mathrm{stat}) \pm 0.032\,(\mathrm{syst}) \pm 0.062\,(\mathrm{acc})$
$R_{W^-/Z}^{\mathrm{tot}}$	$4.419 \pm 0.003\,(\mathrm{stat}) \pm 0.024\,(\mathrm{syst}) \pm 0.082\,(\mathrm{acc})$

QCD fit

- Basic settings of the central NNLO QCD fit

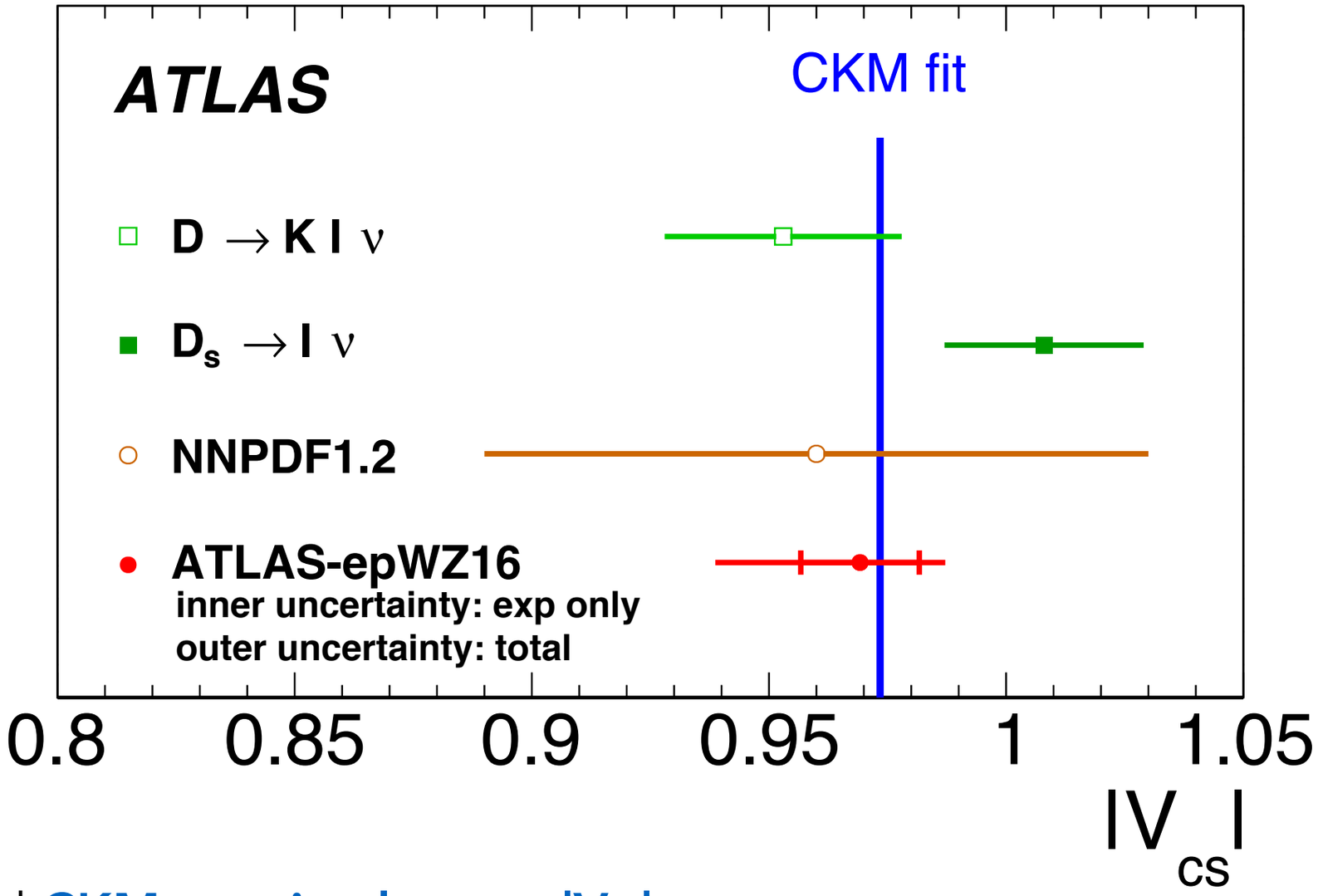
Parameter	Value
Starting scale, Q_0^2	1.9 GeV^2
$\mathbf{m_c}$	1.43 GeV
$\mathbf{m_b}$	4.5 GeV
$\alpha_s(m_Z)$	0.118

- Parametrization used to describe Parton distributions

$$
\begin{aligned}
xu_v(x) &= A_{u_v}x^{B_{uv}}(1-x)^{C_{uv}}(1+E_{u_v}x^2)\\
xd_v(x) &= A_{d_v}x^{B_{dv}}(1-x)^{C_{dv}}\\
x\bar{u}(x) &= A_{\bar{u}}x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}\\
x\bar{d}(x) &= A_{\bar{d}}x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}\\
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}\\
x\bar{s}(x) &= A_{\bar{s}}x^{B_{\bar{s}}}(1-x)^{C_{\bar{s}}}.
\end{aligned}
$$

where $A_{\bar{u}} = A_{\bar{d}}$ and $B_{\bar{s}} = B_{\bar{d}} = B_{\bar{u}}$

W/Z CKM matrix element

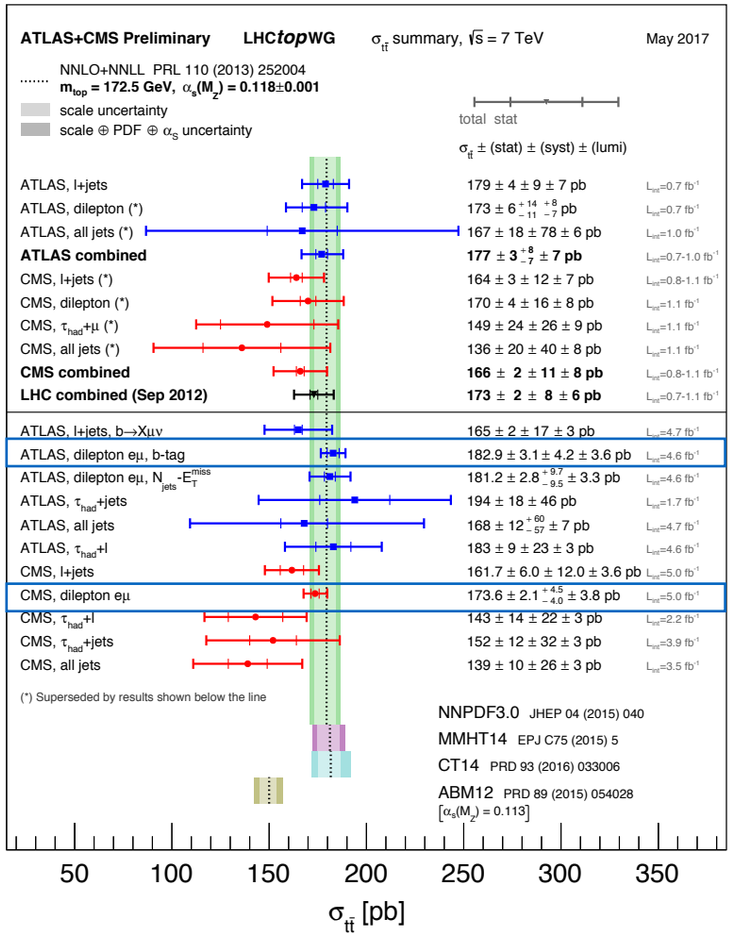


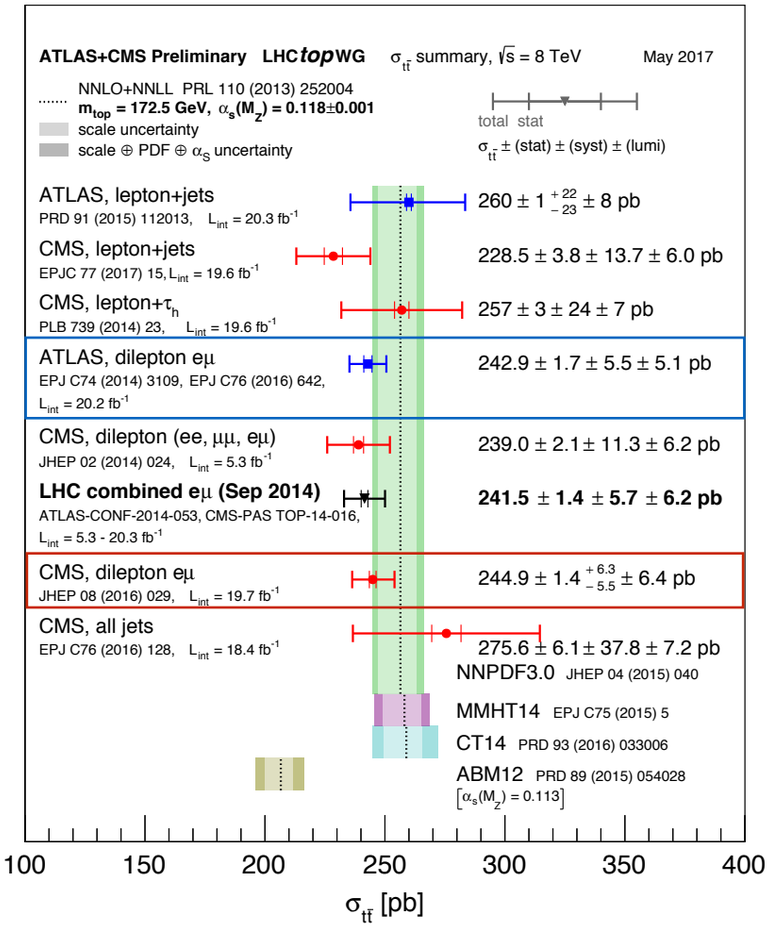
✓ Determined **CKM matrix element $|V_{cs}|$**

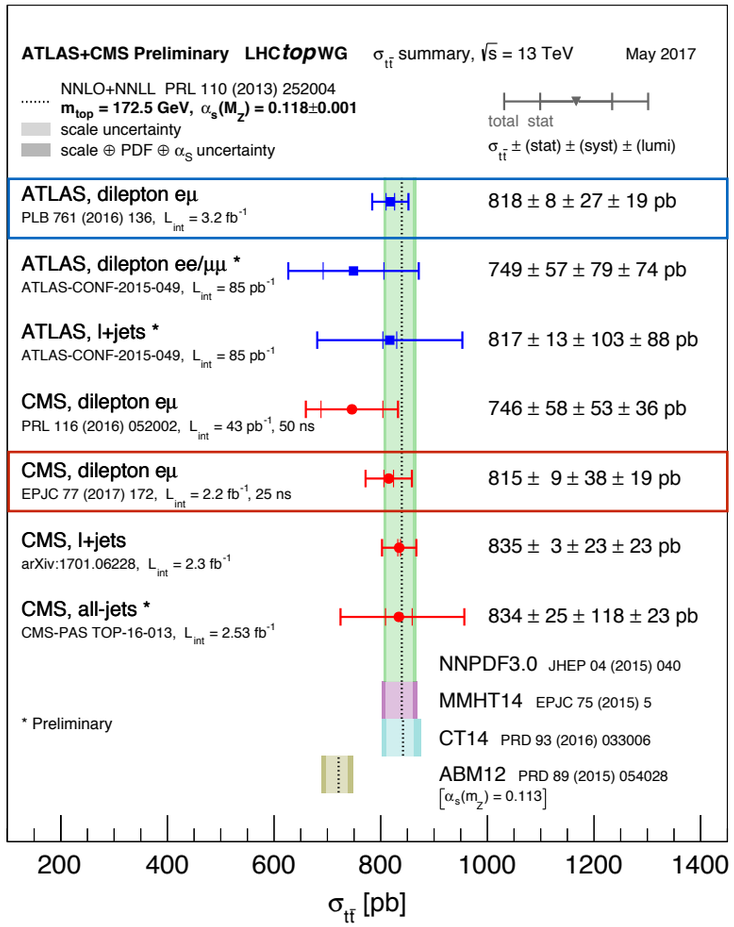
- Precision is comparable with results from charm meson decays

Summary of measurements of ATLAS+CMS

- Summary of measurements of the top-pair production cross-section at 7, 8 and 13 TeV

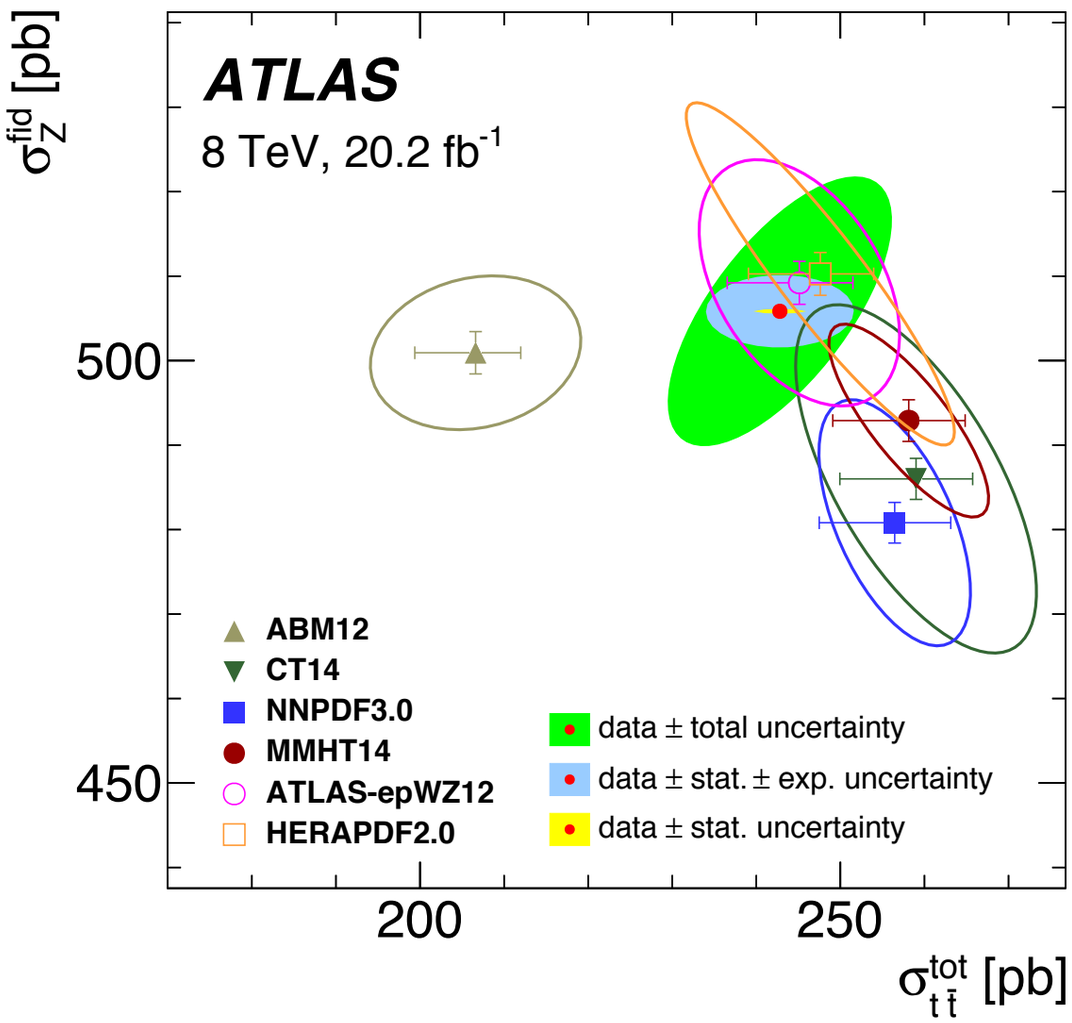


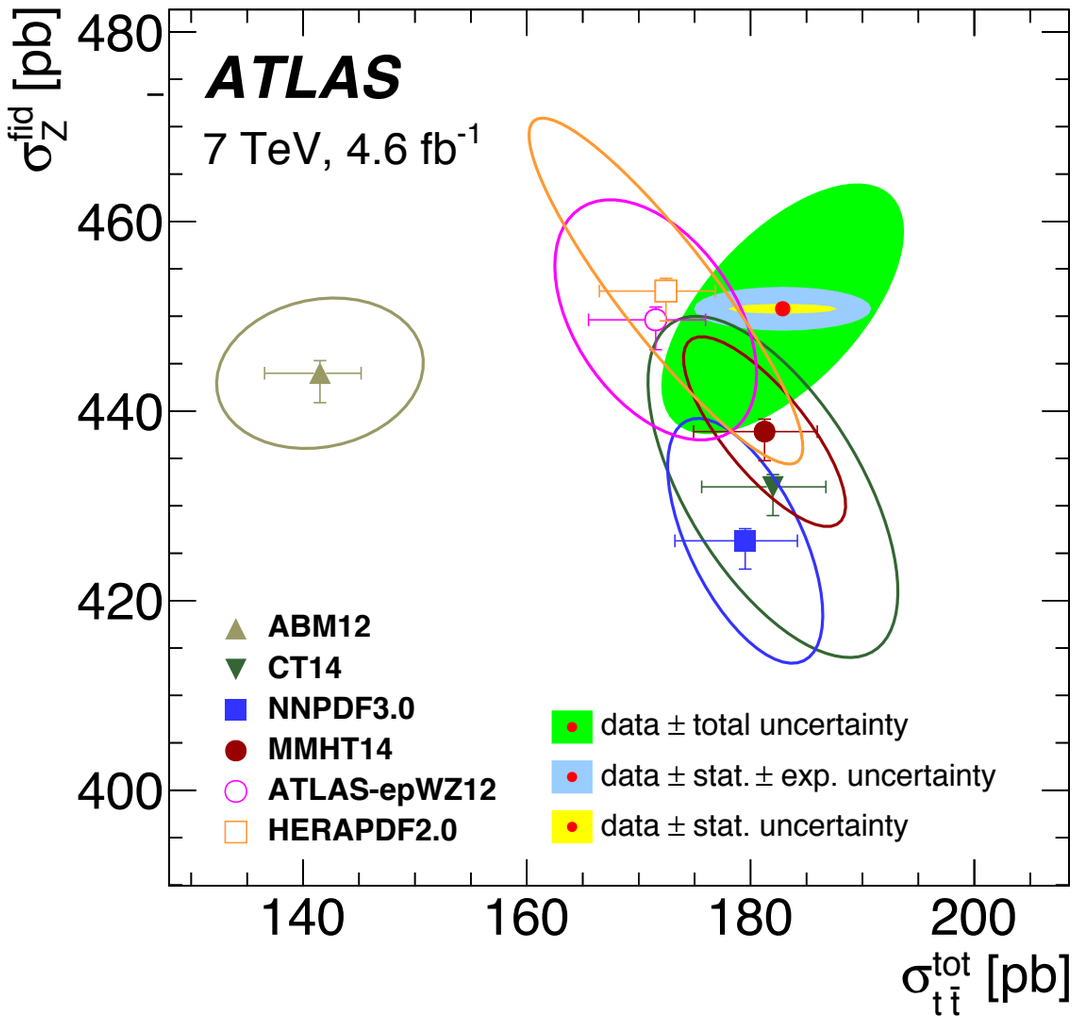




2D 68% CL contours of σ_Z^{fid} vs σ_{tt}^{tot}

- Two-dimensional 68% CL contours of σ_Z^{fid} vs σ_{tt}^{tot} for 8 and 7 TeV

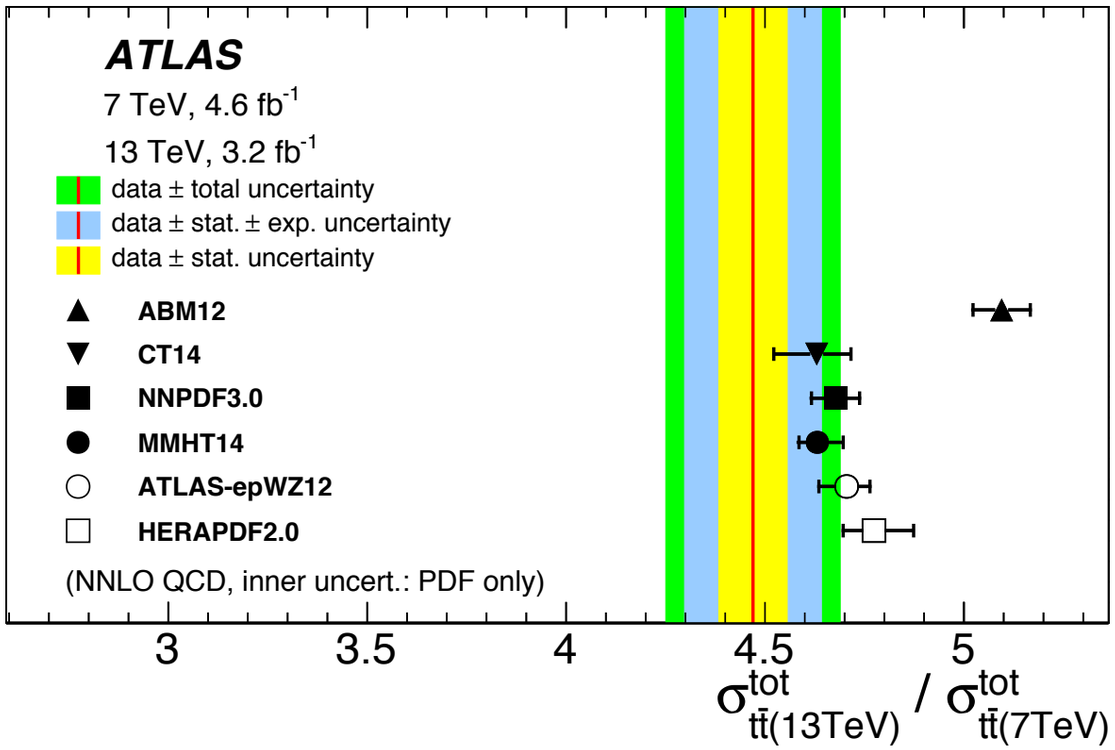


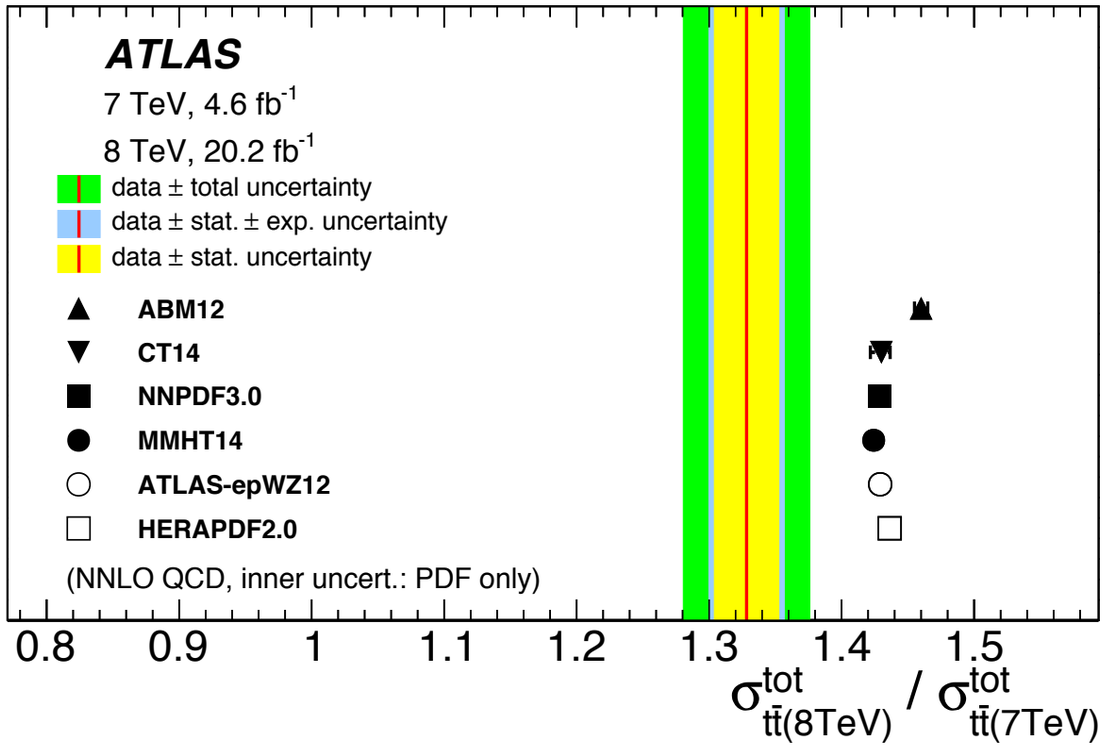


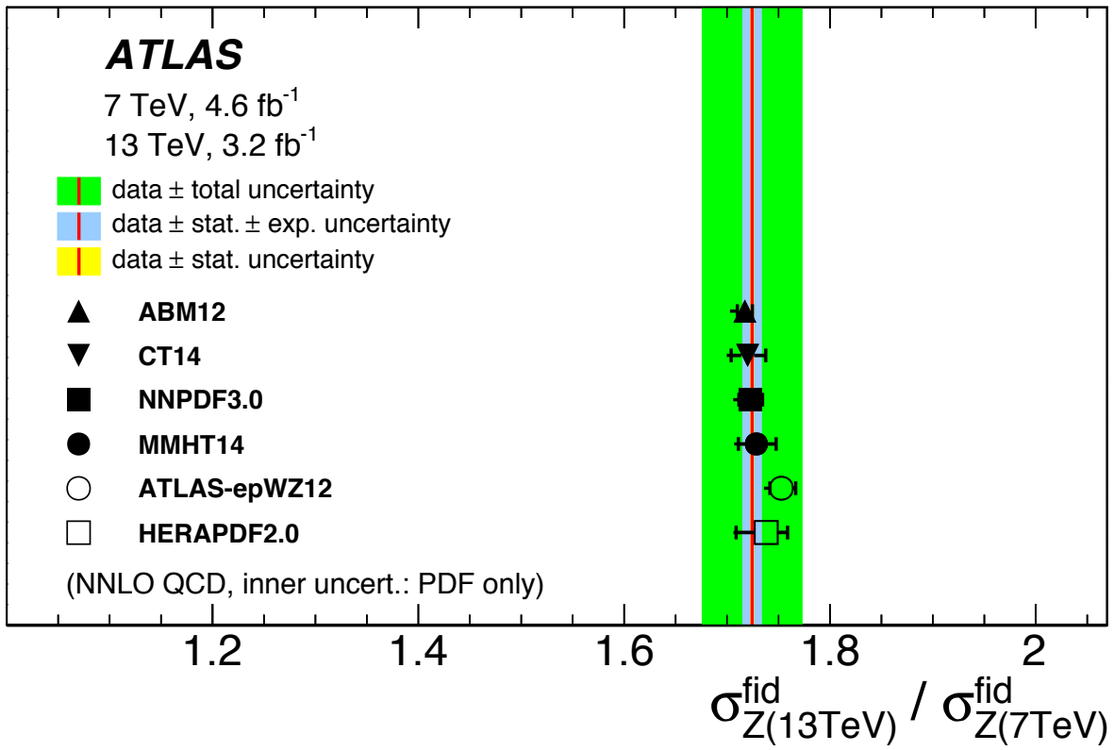
- Correlation coefficients

	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

Single ratios







PDF profiling

- Using the **xFitter** tool
- χ^2 function is defined:

$$\chi^2(\beta_{\text{exp}}, \beta_{\text{th}}) = \sum_{i=1}^{N_{\text{data}}} \frac{\left(\sigma_i^{\text{exp}} + \sum_j \Gamma_{ij}^{\text{exp}} \beta_{j,\text{exp}} - \sigma_i^{\text{th}} - \sum_k \Gamma_{ik}^{\text{th}} \beta_{k,\text{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\text{exp}}^2 + \sum_k \beta_{k,\text{th}}^2 .$$

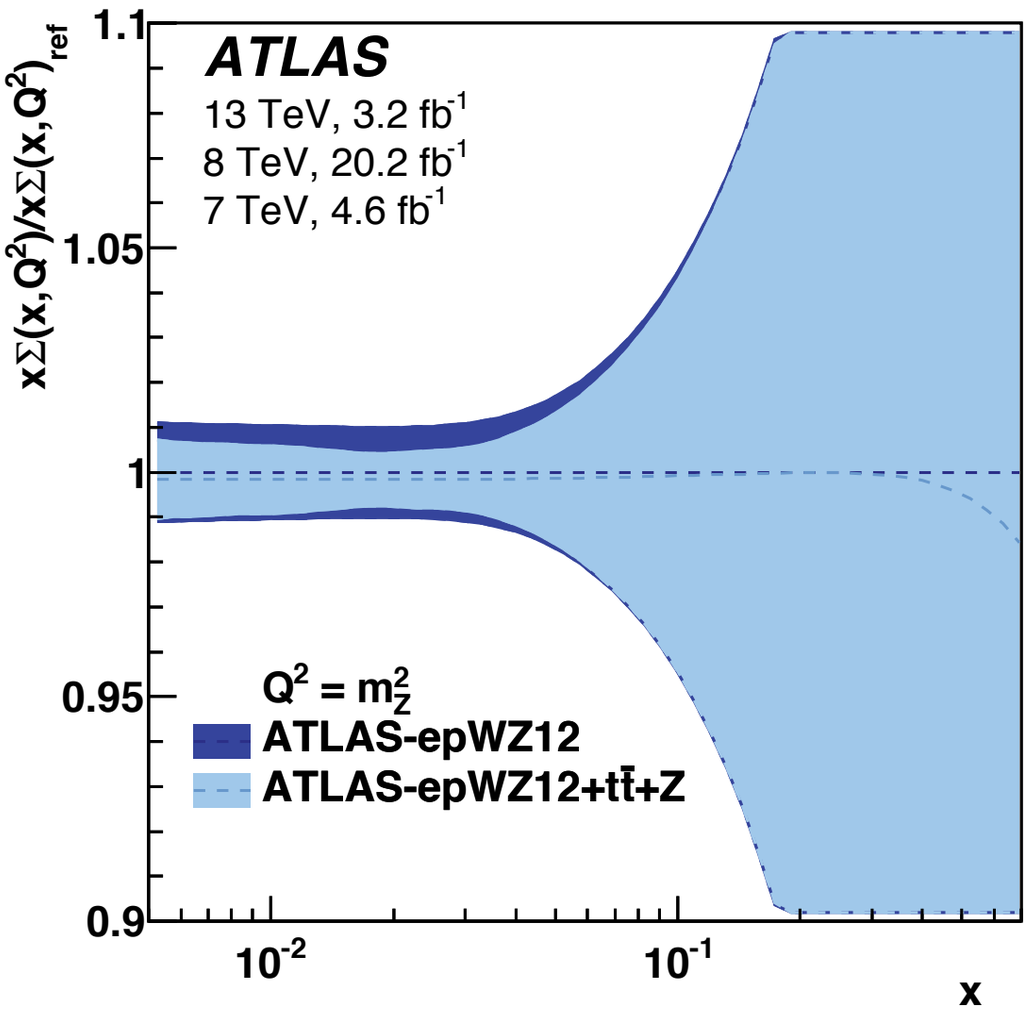
$\sigma_i^{\text{exp}}, \sigma_i^{th}$ – measurements and theoretical predictions

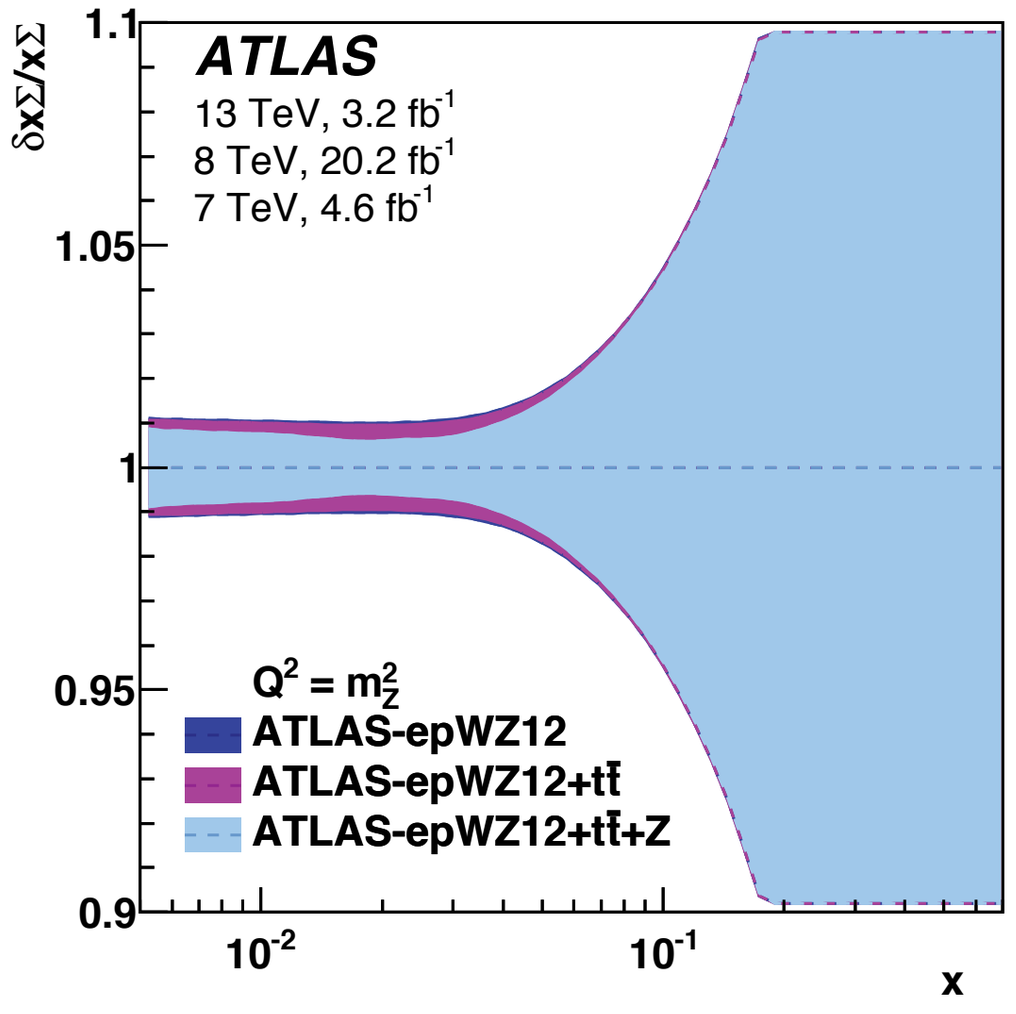
$\vec{\beta}_{\text{exp}}, \vec{\beta}_{th}$ – nuisance parameters vectors including correlated experimental and theoretical uncertainties

$\Gamma_{ij}^{\text{exp}}, \Gamma_{ik}^{th}$ – influnce of $\vec{\beta}_{\text{exp}}$ and $\vec{\beta}_{th}$ on data and theory predictions

- The χ^2 minimisation yields the optimal values of the $\beta_{k,th}$ shifts and the relative reduction of the PDF uncertainties

PDF constraints





- The total light-quark-sea distribution:
  - the profiled PDF set is divided by the central value of ATLAS-epWZ12 PDF set
  - relative uncertainty

Systematic uncertainties and correlations

- **Relative systematics uncertainties** for Z-boson and $t\bar{t}$ production at 13, 8 and 7 TeV

Systematic [%] / $\sqrt{s}$ [TeV]	$\delta\ \sigma_Z^{\text{fid}}$ 13	8	7	$\delta\ \sigma_{t\bar{t}}^{\text{tot}}$ 13	8	7
Luminosity	2.1	1.9	1.8	2.3	2.1	2.0
Beam energy	0.7	0.6	0.6	1.5	1.7	1.8
Muon (lepton) trigger	0.1	0.6	0.1	0.1	0.2	0.2
Muon reconstruction/ID	0.7	0.5	0.3	0.4	0.4	0.3
Muon isolation	0.4	0.0	0.2	0.3	0.2	0.4
Muon momentum scale	0.1	0.0	0.0	0.0	0.0	0.1
Electron trigger	0.0	0.2	0.0	0.1	—	—
Electron reconstruction/ID	0.4	0.8	0.3	0.3	0.4	0.1
Electron isolation	0.1	0.0	—	0.4	0.3	0.6
Electron energy scale	0.3	0.1	0.1	0.2	0.5	0.2
Jet energy scale	—	—	—	0.4	0.7	0.4
b-tagging	—	—	—	0.5	0.4	0.5
Background	0.1	0.2	0.1	1.1	1.0	1.0
Signal modelling (incl. PDF)	0.1	0.1	0.3	3.0	1.7	1.8

- The **correlation coefficients** amongst the combined Z-boson and $t\bar{t}$ fiducial and total cross-section measurements

	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

Ratios at 13, 8 and 7 TeV

Single ratios

	$\sigma^{\text{tot}}/\sigma^{\text{tot}}$	$\sigma^{\text{tot}}/\sigma^{\text{fid}}$	$\sigma^{\text{fid}}/\sigma^{\text{fid}}$
	Value ± stat ± syst ± lumi	Value ± stat ± syst ± lumi	Value ± stat ± syst ± lumi
$t\bar{t}/Z(13)$	0.416 ± 0.004 (0.9%) ± 0.016 (3.8%) ± 0.001 (0.2%)	1.053 ± 0.010 (0.9%) ± 0.036 (3.4%) ± 0.002 (0.2%)	0.012 80 ± 0.000 12 (0.9%) ± 0.000 33 (2.6%) ± 0.000 03 (0.2%)
$t\bar{t}/Z(8)$	0.211 ± 0.001 (0.7%) ± 0.007 (3.1%) ± 0.000 (0.2%)	0.480 ± 0.003 (0.7%) ± 0.012 (2.6%) ± 0.001 (0.2%)	0.006 02 ± 0.000 04 (0.7%) ± 0.000 14 (2.4%) ± 0.000 01 (0.2%)
$t\bar{t}/Z(7)$	0.184 ± 0.003 (1.7%) ± 0.006 (3.1%) ± 0.000 (0.2%)	0.406 ± 0.007 (1.7%) ± 0.011 (2.6%)± 0.001 (0.2%)	0.005 11 ± 0.000 09 (1.7%) ± 0.000 13 (2.5%) ± 0.000 01 (0.2%)
$Z(13)/Z(8)$	1.707 ± 0.001 (0.1%) ± 0.013 (0.8%) ± 0.048 (2.8%)	-	1.537 ± 0.001 (0.1%) ± 0.010 (0.7%) ± 0.044 (2.8%)
$Z(13)/Z(7)$	1.979 ± 0.002 (0.1%) ± 0.014 (0.7%) ± 0.055 (2.8%)	-	1.724 ± 0.001 (0.1%) ± 0.009 (0.5%) ± 0.048 (2.8%)
$Z(8)/Z(7)$	1.160 ± 0.001 (0.1%) ± 0.007 (0.6%) ± 0.030 (2.6%)	-	1.122 ± 0.001 (0.1%) ± 0.007 (0.6%) ± 0.029 (2.6%)
$t\bar{t}(13)/t\bar{t}(8)$	3.365 ± 0.039 (1.2%) ± 0.112 (3.3%) ± 0.105 (3.1%)	-	3.270 ± 0.038 (1.2%) ± 0.086 (2.6%) ± 0.102 (3.1%)
$t\bar{t}(13)/t\bar{t}(7)$	4.470 ± 0.086 (1.9%) ± 0.149 (3.3%) ± 0.136 (3.0%)	-	4.322 ± 0.083 (1.9%) ± 0.116 (2.7%) ± 0.131 (3.0%)
$t\bar{t}(8)/t\bar{t}(7)$	1.328 ± 0.024 (1.8%) ± 0.015 (1.1%) ± 0.038 (2.9%)	-	1.322 ± 0.024 (1.8%) ± 0.015 (1.1%) ± 0.038 (2.9%)

Double ratios

	$\left[\sigma^{\text{tot}}/\sigma^{\text{tot}}\right] / \left[\sigma^{\text{tot}}/\sigma^{\text{tot}}\right]$	$\left[\sigma^{\text{tot}}/\sigma^{\text{tot}}\right] / \left[\sigma^{\text{fid}}/\sigma^{\text{fid}}\right]$	$\left[\sigma^{\text{fid}}/\sigma^{\text{fid}}\right] / \left[\sigma^{\text{fid}}/\sigma^{\text{fid}}\right]$
	Value ± stat ± syst ± lumi	Value ± stat ± syst ± lumi	Value ± stat ± syst ± lumi
$t\bar{t}/Z(13/8)$	1.975 ± 0.023 (1.2%) ± 0.067 (3.4%) ± 0.006 (0.3%)	2.193 ± 0.026 (1.2%) ± 0.074 (3.4%) ± 0.008 (0.4%)	2.131 ± 0.025 (1.2%) ± 0.057 (2.7%) ± 0.006 (0.3%)
$t\bar{t}/Z(13/7)$	2.260 ± 0.044 (1.9%) ± 0.075 (3.3%) ± 0.007 (0.3%)	2.594 ± 0.050 (1.9%) ± 0.086 (3.3%) ± 0.008 (0.3%)	2.508 ± 0.048 (1.9%) ± 0.067 (2.7%) ± 0.008 (0.3%)
$t\bar{t}/Z(8/7)$	1.145 ± 0.021 (1.8%) ± 0.015 (1.3%) ± 0.003 (0.3%)	1.184 ± 0.022 (1.8%) ± 0.015 (1.3%) ± 0.003 (0.3%)	1.178 ± 0.022 (1.8%) ± 0.015 (1.3%) ± 0.003 (0.3%)