



Differential Drell-Yan measurements and Z/top-pair cross section ratios

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On behalf of the
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GEFÖRDERT VOM

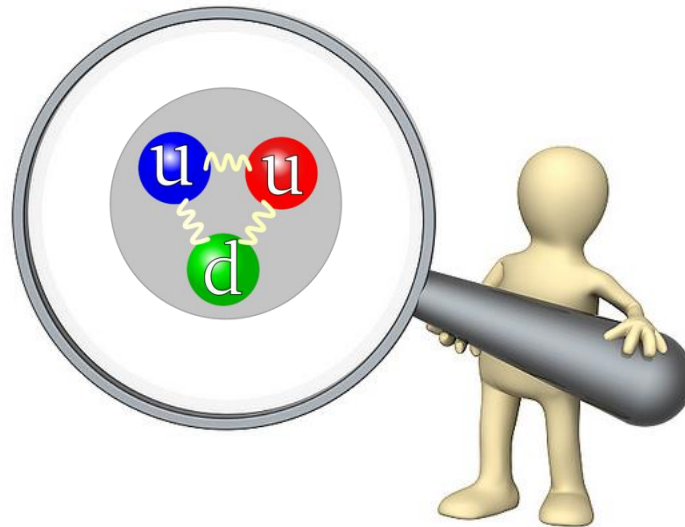


Bundesministerium
für Bildung
und Forschung





- Understanding of proton structure essential for search for new physics @ LHC



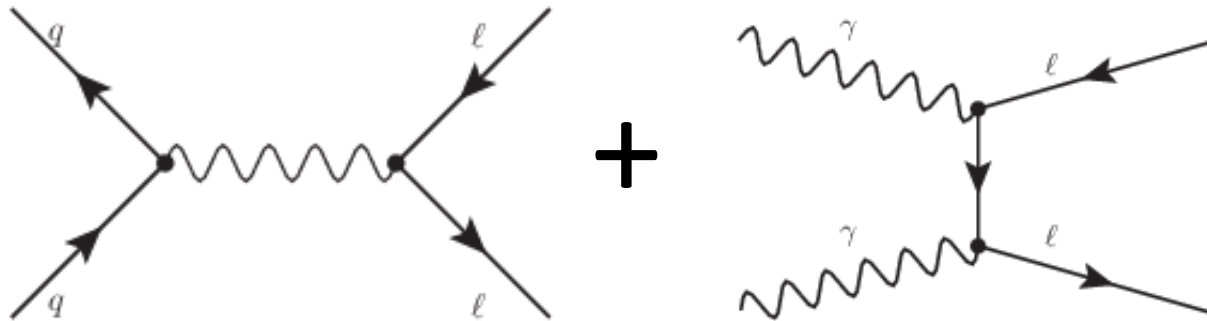
- Measurement of Drell-Yan (Z) cross sections
 - Contains important information about PDFs
 - Ratios to top-pair cross sections help to further reduce uncertainties



High-mass Drell-Yan

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<https://arxiv.org/abs/1606.01736>

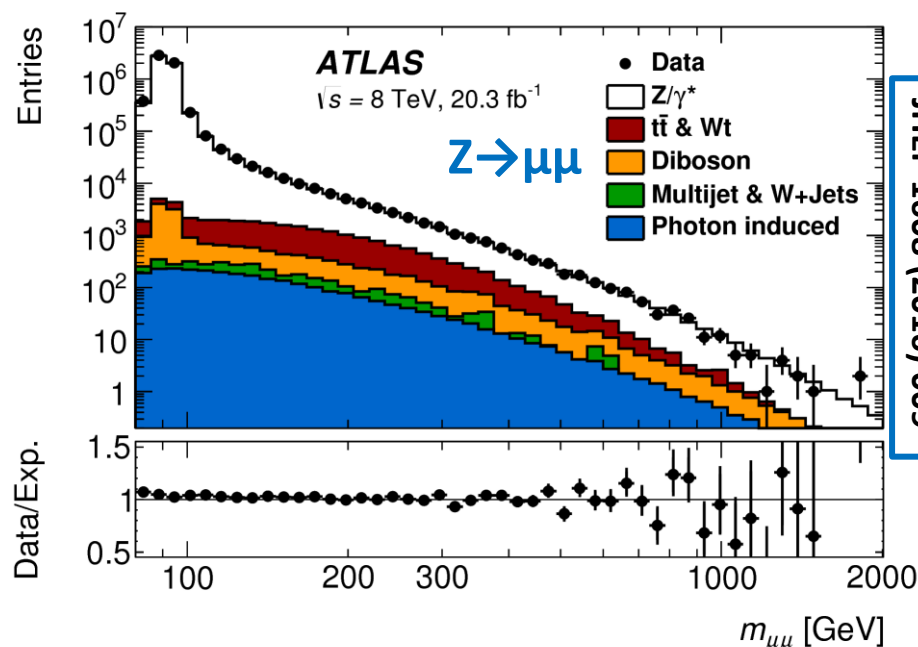
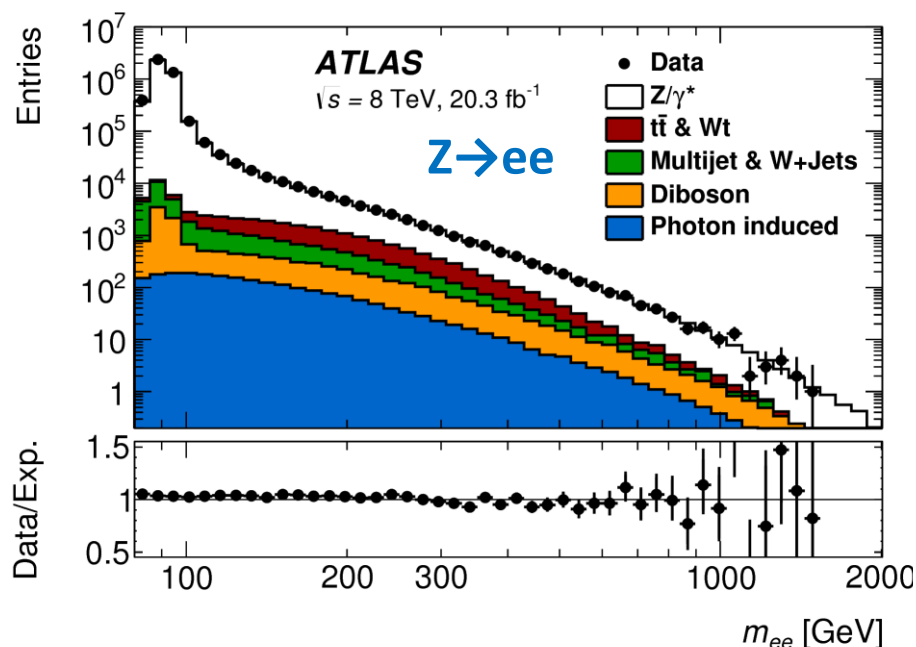




- Measurement of the Drell-Yan production at high invariant mass ($m_{ll} > 116 \text{ GeV}$)
 - Sensitivity to PDFs at large x
 - Sensitivity to photon PDF due to contribution from photon induced production
 - Sensitivity to electroweak corrections
- Measurement of double differential cross-section as function...
 - m_{ll} vs $|y_{ll}|$
 - m_{ll} vs $|\Delta\eta_{ll}|$

- Selection of two isolated electrons/muons
- Common fiducial volume
 - $p_T > 40 \text{ GeV}$ (leading), $p_T > 30 \text{ GeV}$ (subleading)
 - $|\eta_1| < 2.5$
- Backgrounds
 - $t\bar{t}$ & Wt – determined from MC
 - Main background in both channels ($\approx 9\%$)
 - Diboson – determined from MC
 - Multijet & W +Jets – determined from data
 - Very small in muon channel ($< 1\%$)
 - Large in electron channel for certain regions of phase space ($\approx 3\% - \approx 50\%$)

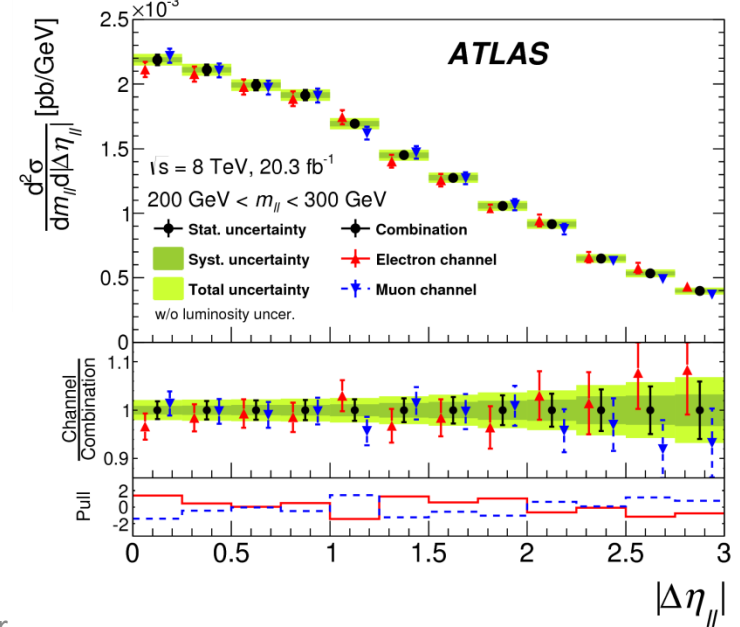
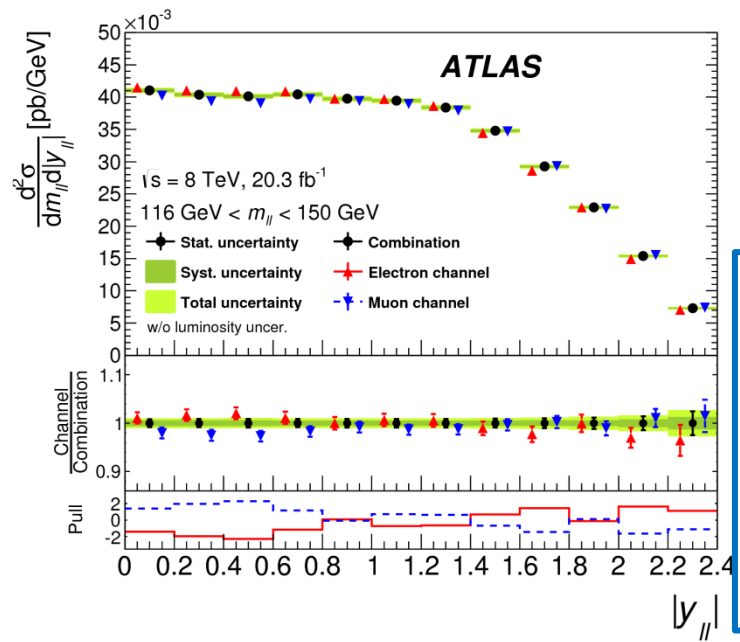
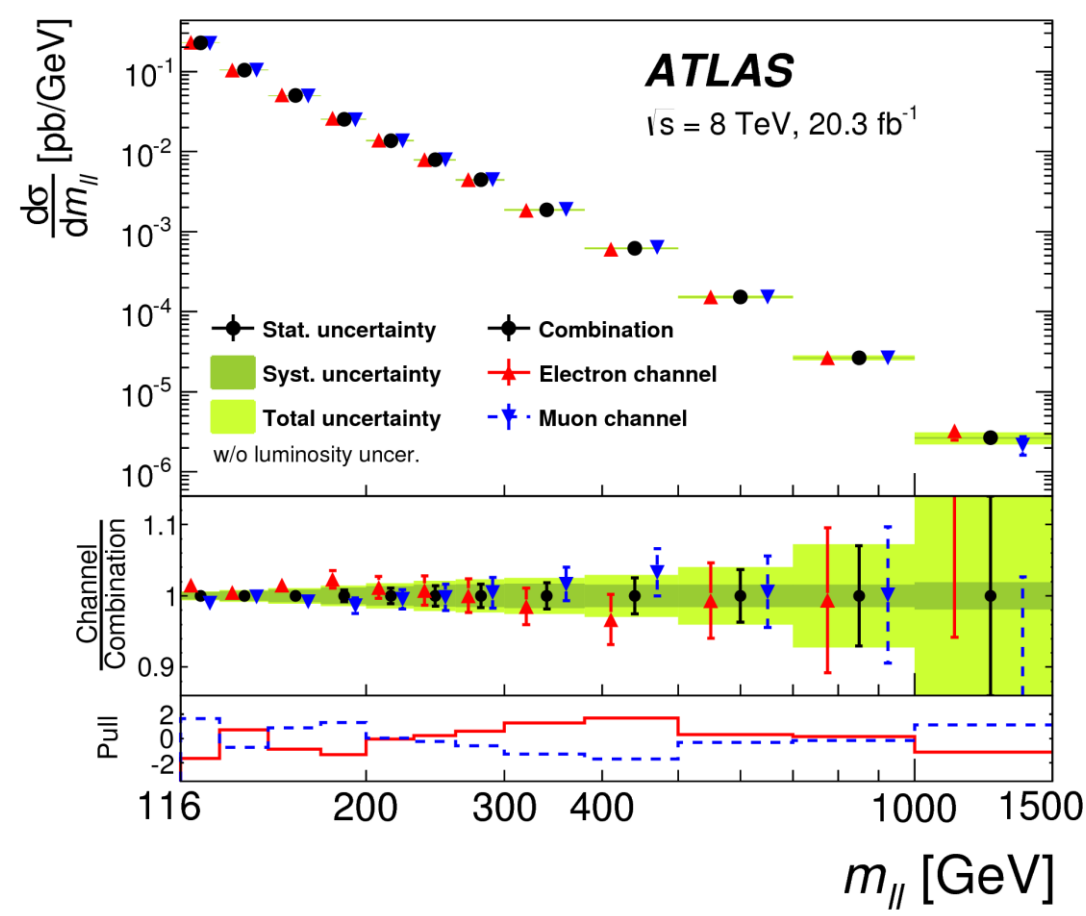
Data MC agreement



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- Good agreement between data and expectations
 - Simple bin-by-bin unfolding to obtain cross-section
- Very high purity, simple approach possible

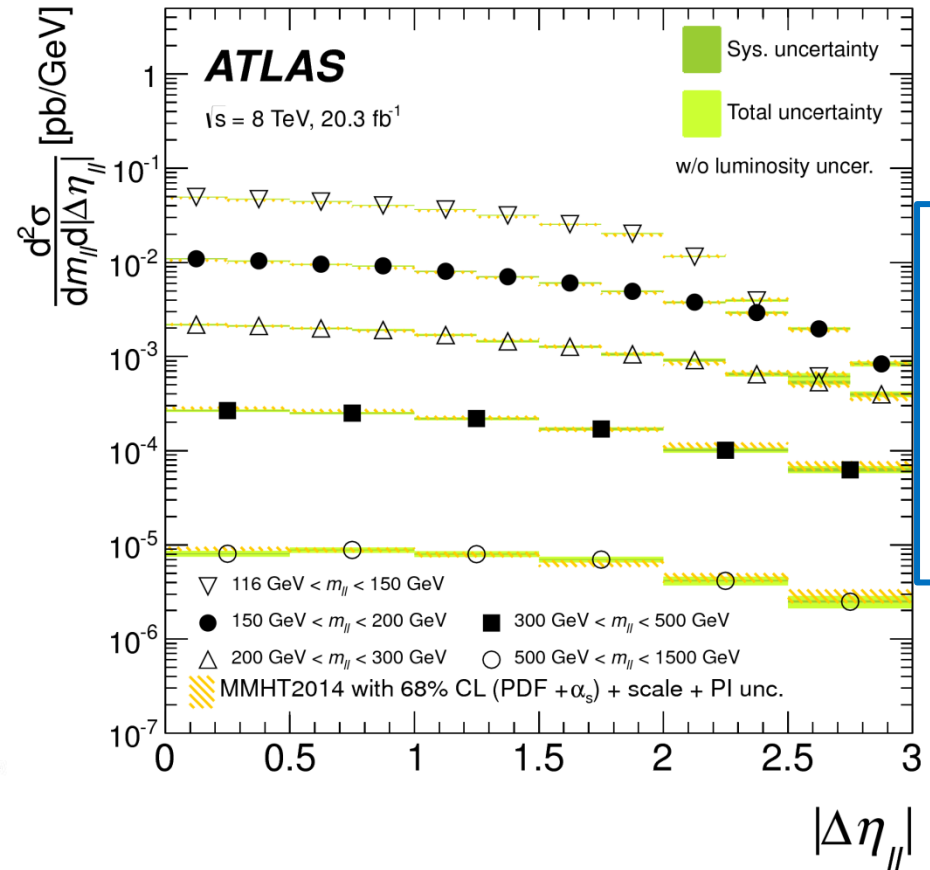
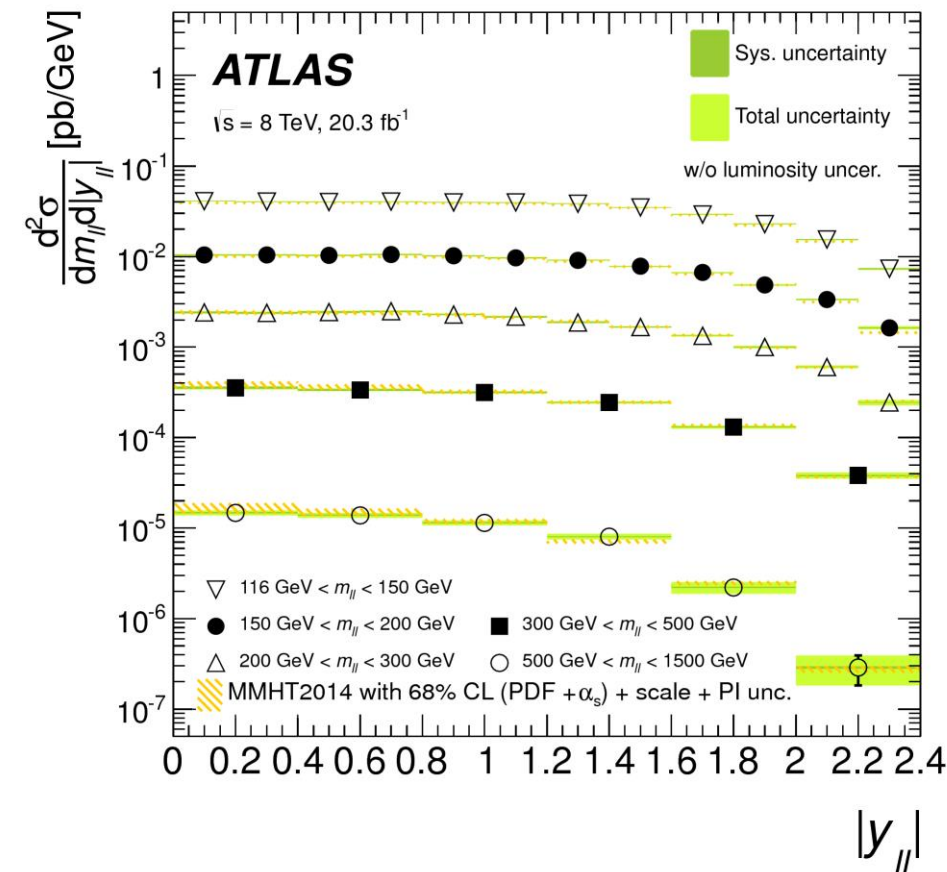
Cross section combination



	$m_{ }$	$ y_{ } $	$ \Delta\eta_{ } $
χ^2/dof	14.2/12	53.1/48	59.3/47

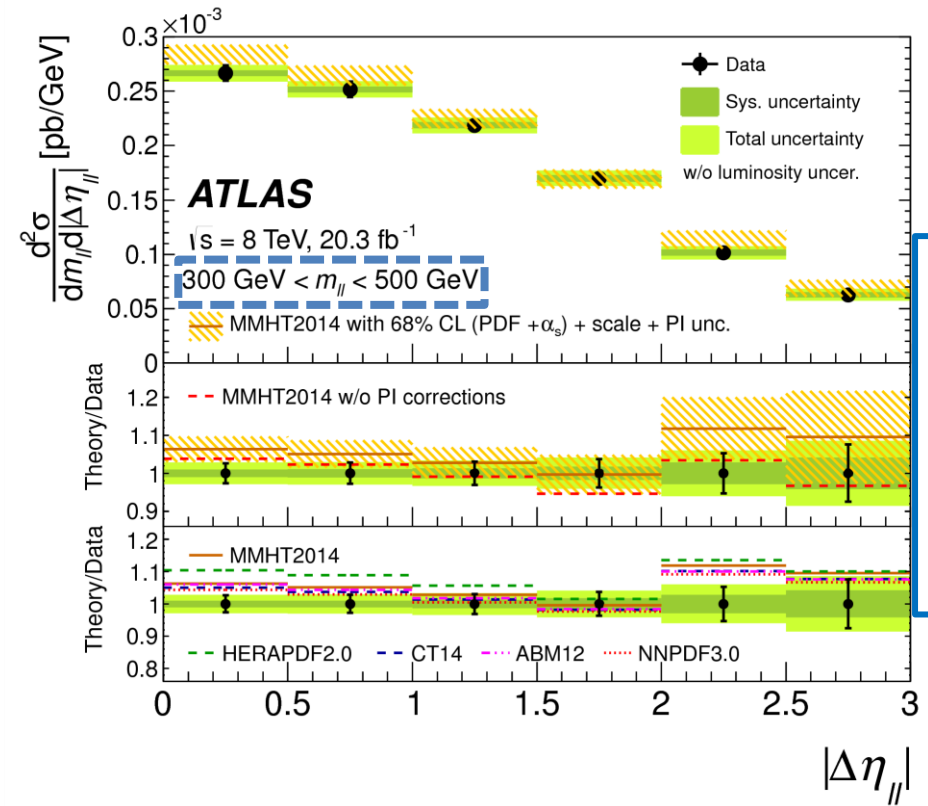
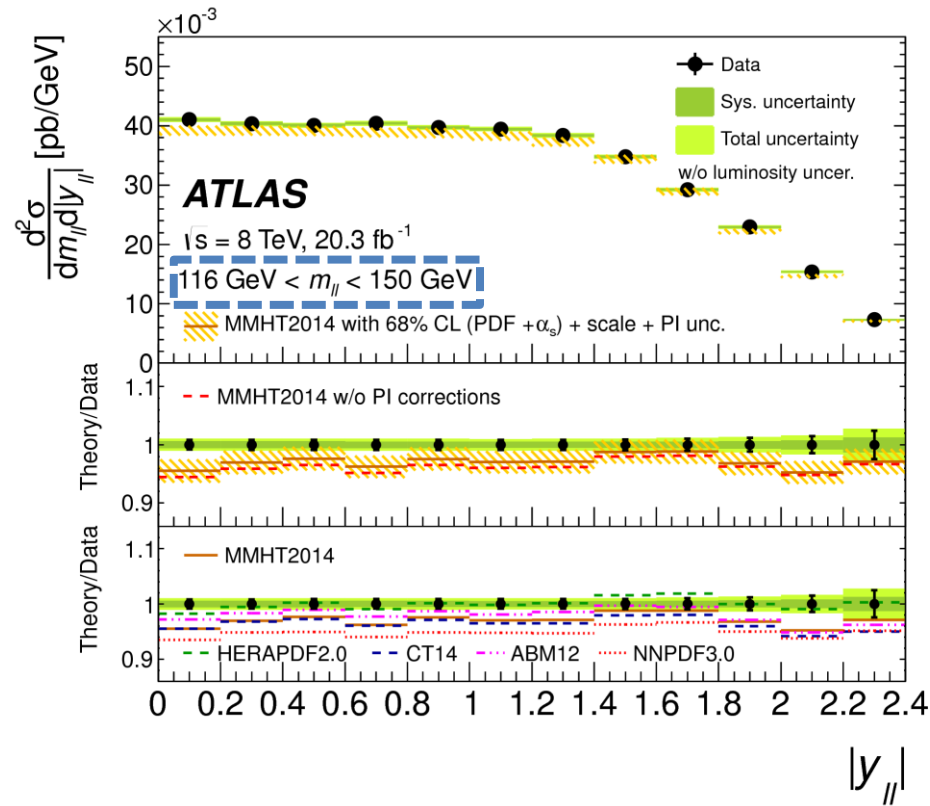
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Cross section result



- Total uncertainty (excl. luminosity) at low mass below 1%
- Comparison to theory calculations (FEWZ)
 - NNLO in QCD, NLO in EW
- Table with full statistical correlations on [HepData](https://hepdata.net)

Cross section result



- Comparison to different PDFs
- Except at high mass: Measurement more precise than theory
- Photon PDF uncertainty (NNPDF2.3qed) often dominates theory uncertainty



$\chi^2/\text{d.o.f}$

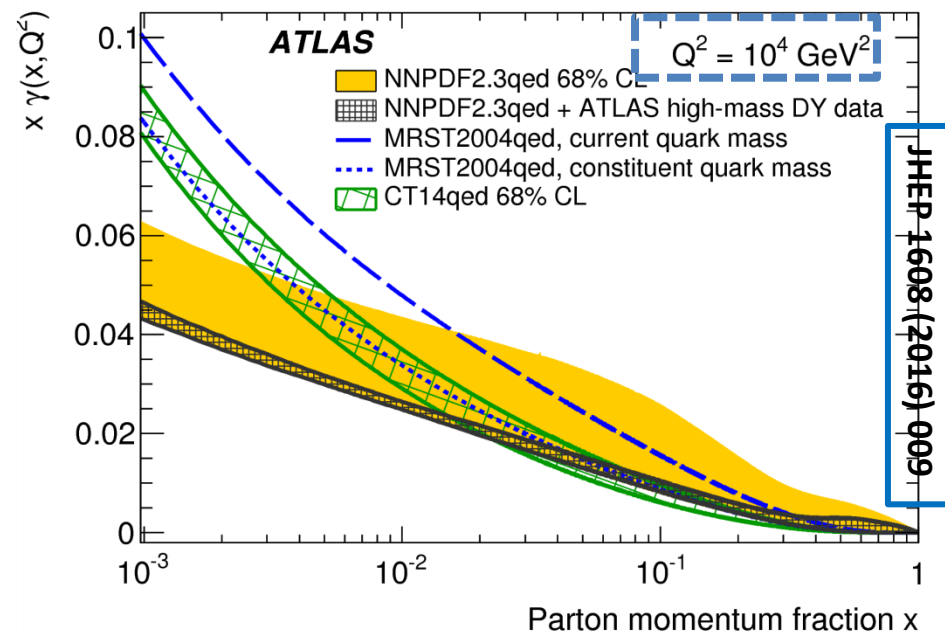
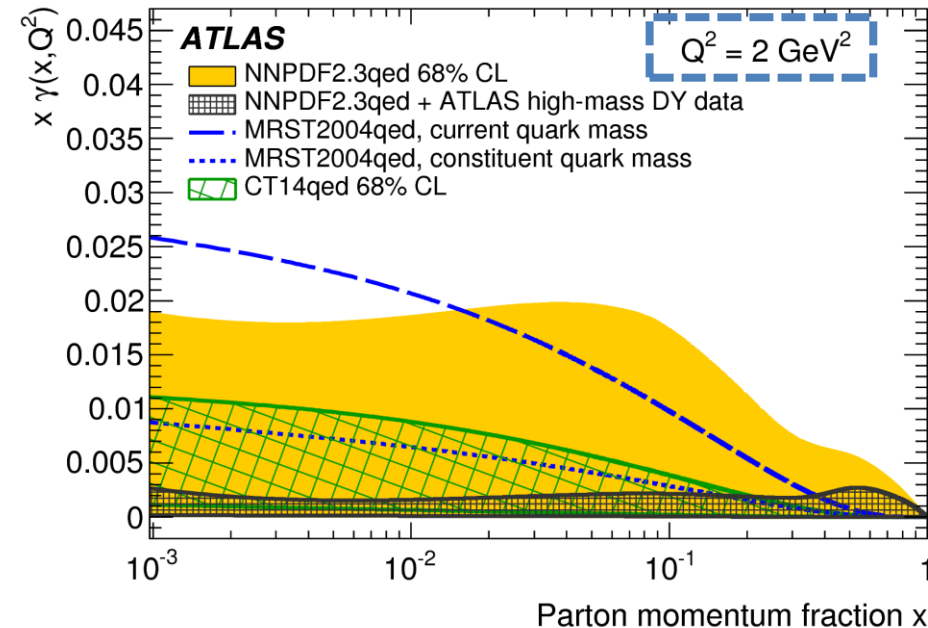
	$m_{\ell\ell}$	$ y_{\ell\ell} $	$ \Delta\eta_{\ell\ell} $	JHEP 1608 (2016) 009
MMHT2014	18.2/12	59.3/48	62.8/47	
CT14	16.0/12	51.0/48	61.3/47	
NNPDF3.0	20.0/12	57.6/48	62.1/47	
HERAPDF2.0	15.1/12	55.5/48	60.8/47	
ABM12	14.1/12	57.9/48	53.5/47	

- Quantitative comparison to different measurements with xFitter
 - General compatibility between data and theory
 - Best agreement found with ABM12, especially when considering the PDF uncertainty

Photon PDF reweighting



- Bayesian reweighting of photon PDF to simulate impact of the measurement

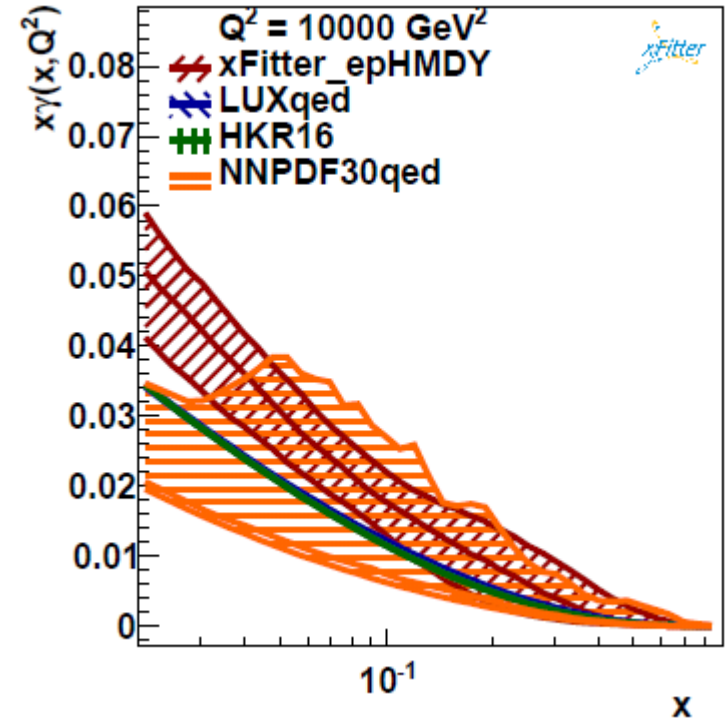


- Large reduction of the photon PDF uncertainty
→ Indicating large sensitivity of the data
- Fit needed to fully explore measurement

New photon PDF results



- Measurement has been used in a full PDF fit by F. Giuli et al. (arXiv:1701.08553)
 - Clear reduction of the photon PDF uncertainty
 - Although smaller than in the Bayesian reweighting approach
- LUXqed PDF has been released shortly after the measurement
 - New ansatz, much smaller uncertainty



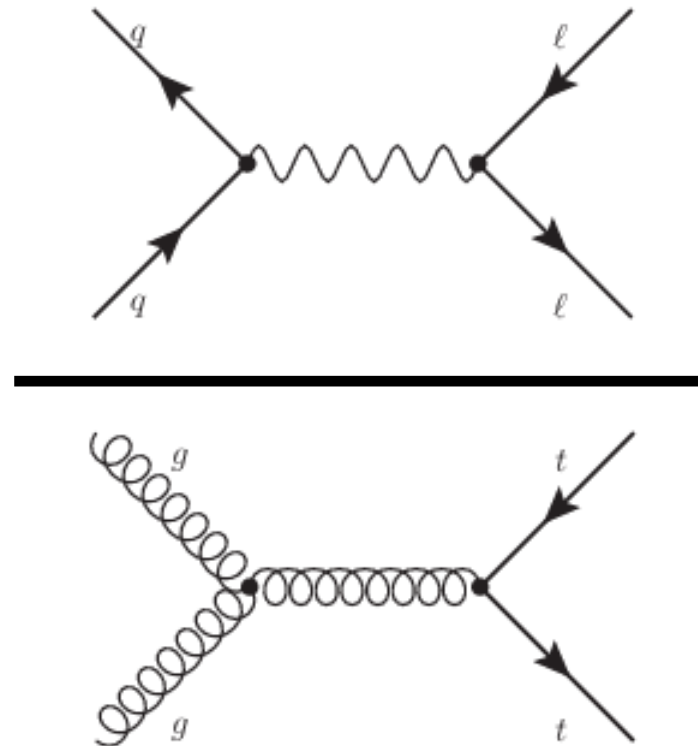
arXiv:1701.08553



Z/top-pair cross section ratios

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<https://arxiv.org/abs/1612.03636>



- Measurement of the ratios of σ_Z^{fid} and $\sigma_{t\bar{t}}^{tot}$ at different \sqrt{s}
 - $R_{Z_i/Z_j}^{fid} = \sigma_{Z(iTeV)}^{fid} / \sigma_{Z(jTeV)}^{fid}$, $R_{t\bar{t}_i/t\bar{t}_j}^{tot} = \sigma_{t\bar{t}(iTeV)}^{tot} / \sigma_{t\bar{t}(jTeV)}^{tot}$
 - $R_{t\bar{t}/Z}^{tot/fid}(iTeV) = \sigma_{t\bar{t}(iTeV)}^{tot} / \sigma_{Z(iTeV)}^{fid}$
 - $R_{t\bar{t}/Z}^{tot/fid}(i/j) = [\sigma_{t\bar{t}(iTeV)}^{tot} / \sigma_{Z(iTeV)}^{fid}] / [\sigma_{t\bar{t}(jTeV)}^{tot} / \sigma_{Z(jTeV)}^{fid}]$
- Significant cancellation of some systematic uncertainties in the ratios
 - Luminosity, beam energy...
- Ratios sensitive to PDFs, α_s , m_t ...
 - Z-boson and $t\bar{t}$ production driven to large extent by different PDFs
 - Sensitivity to gluon-to-quark ratio



- Analysis uses previously published cross sections measurements at $\sqrt{s} = 7, 8, 13$ TeV
 - σ_Z^{fid} at $\sqrt{s} = 13$ TeV measured within the paper to have fully synchronized selection
- Fiducial volume for Z-boson measurement defined by
 - $p_T^l > 25$ GeV, $|\eta_l| < 2.5$, $66 < m_{ll} < 116$ GeV
- Predictions of top-quark-pair fiducial cross sections not yet available at NNLO
 - Measurements extrapolated to total cross section



Total cross sections						
	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

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- Fiducial Z cross sections calculated at NNLO QCD (DYNNLO1.5) and NLO EW (FEWZ3.1)
- Total top-pair cross section calculated at NNLO+NNLL (Top++v2.0)

Correlation Model (Theory)

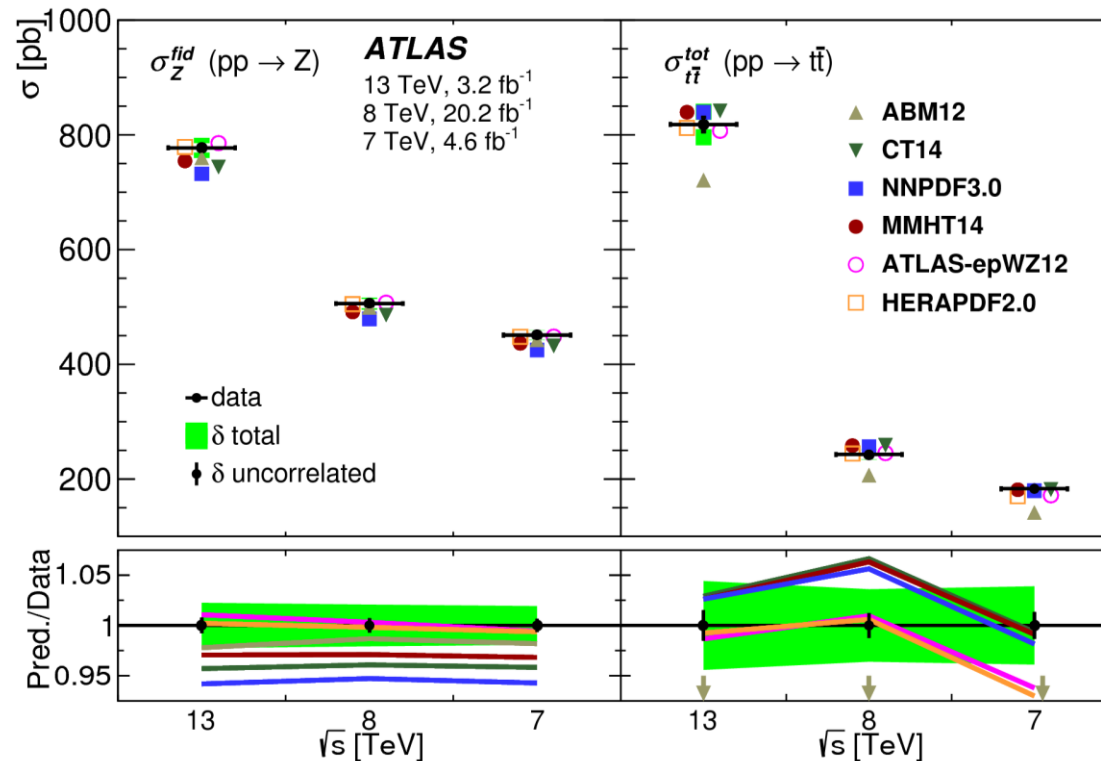


	Ratios					
	R_{Z_i/Z_j}^{fid}			$R_{t\bar{t}_i/t\bar{t}_j}^{\text{tot}}$		
i/j	13/7	13/8	8/7	13/7	13/8	8/7
Central value	1.722	1.531	1.125	4.634	3.251	1.425
Uncertainties [%]						
PDF	+1.0 -0.9	+0.8 -0.7	+0.22 -0.21	+1.9 -2.3	+1.4 -1.8	+0.5 -0.6
α_s	-0.1 -0.4	-0.1 -0.3	-0.1 -0.1	-0.32 +0.29	-0.25 +0.22	-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

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- PDF uncertainty: Correlated eigenvector by eigenvector
- QCD scale uncertainty: Uncorrelated between processes but correlated at different \sqrt{s}
- α_s uncertainty: Correlated between predictions
- Z-boson intrinsic & m_t uncertainty: Correlated within process

Measured Cross sections



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- Measurements dominated by systematic uncertainty
- Largest sources of systematic uncertainty
 - Luminosity, beam energy, signal modelling (ttbar)

Correlation Model (Meas.)

Systematic uncertainties

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Correlations

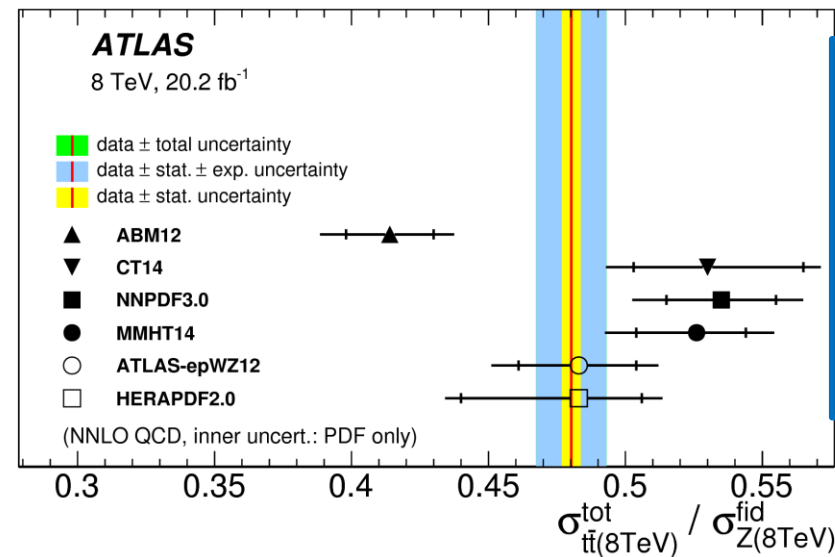
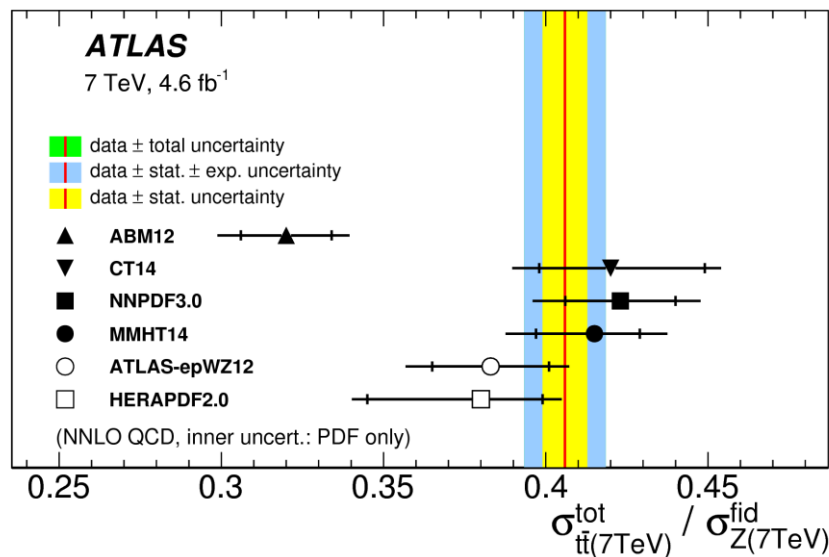
Systematic [%] / \sqrt{s} [TeV]	$\delta \sigma_Z^{\text{fid}}$			$\delta \sigma_{t\bar{t}}^{\text{tot}}$		
	13	8	7	13	8	7
Luminosity	2.1	1.9	1.8	2.3	2.1	2.0
Beam energy	0.7	0.6	0.6	1.5	1.7	1.8
Muon (lepton) trigger	0.1	0.6	0.1	0.1	0.2	0.2
Muon reconstruction/ID	0.7	0.5	0.3	0.4	0.4	0.3
Muon isolation	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

Source / \sqrt{s} [TeV]	$\delta \sigma_Z^{\text{fid}}$			$\delta \sigma_{t\bar{t}}^{\text{tot}}$		
	13	8	7	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

same letter = correlated

- Luminosity fully correlated at same \sqrt{s}
- Beam energy fully correlated
- Signal modelling (almost) fully correlated across \sqrt{s}

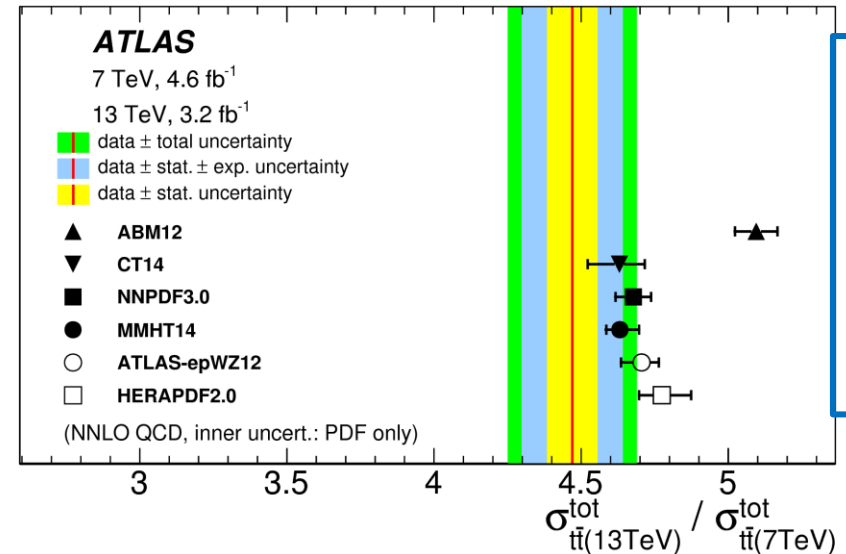
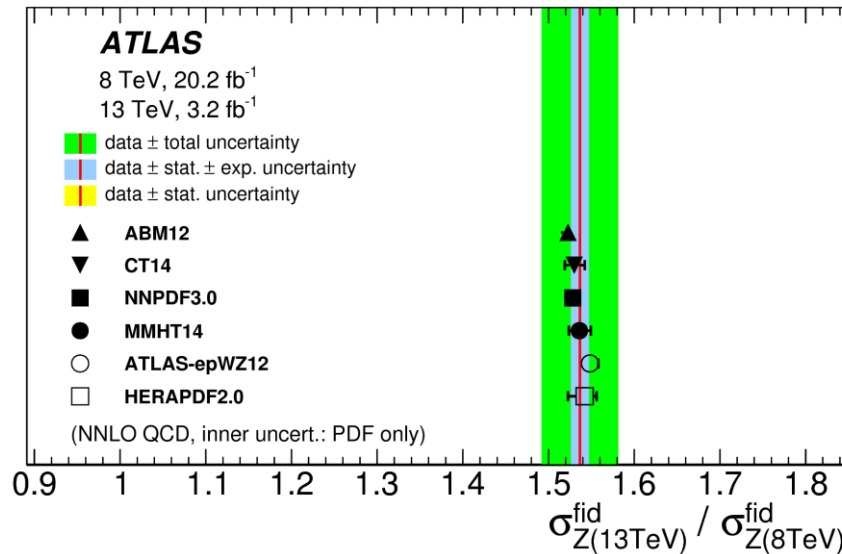
Single ratios at given \sqrt{s}



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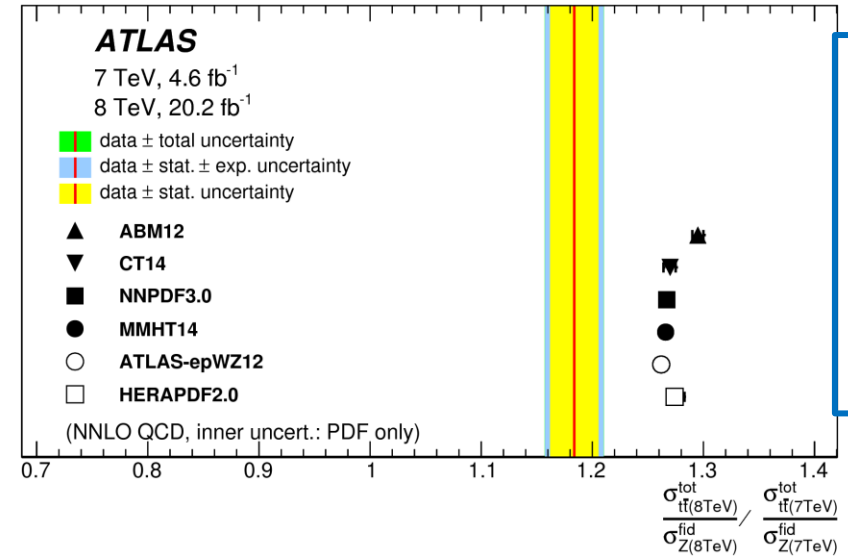
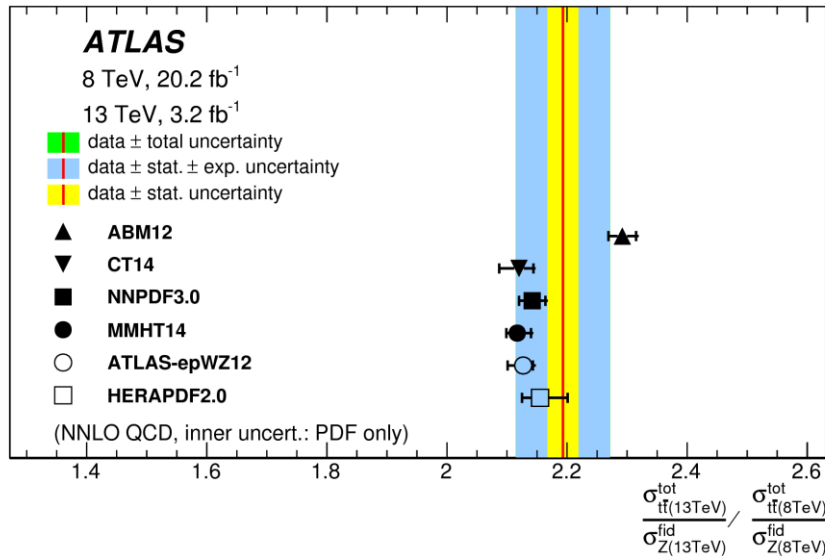
- Luminosity uncertainty cancels
- Measurement more precise than theory predictions
- Spread of predictions explained by difference in gluon density and α_s
- Data agree best with HERAPDF2.0 and ATLAS-epWZ12
- ABM12 deviates up to 2.6σ (8 TeV)

Single ratios at different \sqrt{s}



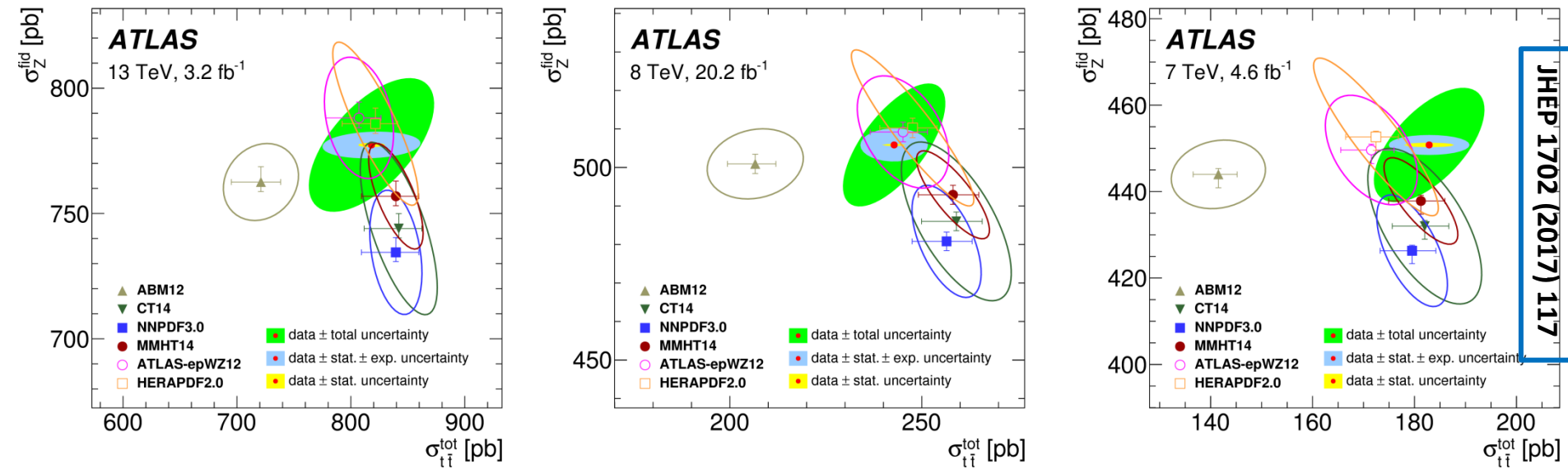
- Ratios of σ_Z^{fid} consistent with all predictions
 - Measurement dominated by luminosity uncertainty
 - Good agreement may indicate that assuming uncorrelated luminosity uncertainties is very conservative
- Differences in ratios of $\sigma_{t\bar{t}}^{\text{tot}}$ due to different gluon distributions as a function of x

Double ratios



- Total uncertainty becomes much smaller in the double ratios
- Ratio 13 TeV/8 TeV consistent with all predictions (1σ level)
- Ratio 8 TeV/7 TeV deviates at the 3σ level
 - Difficult to describe this with PDF effects
 - 13 TeV / 7 TeV agrees with most PDFs within 1σ

2D & Quantitative Comparison



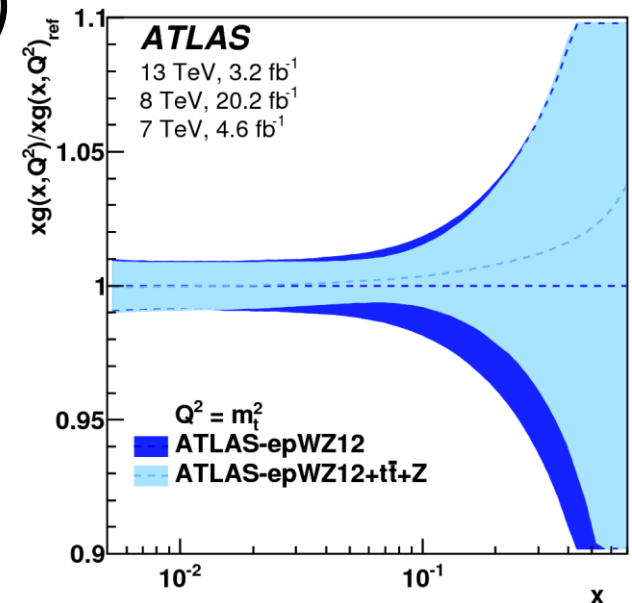
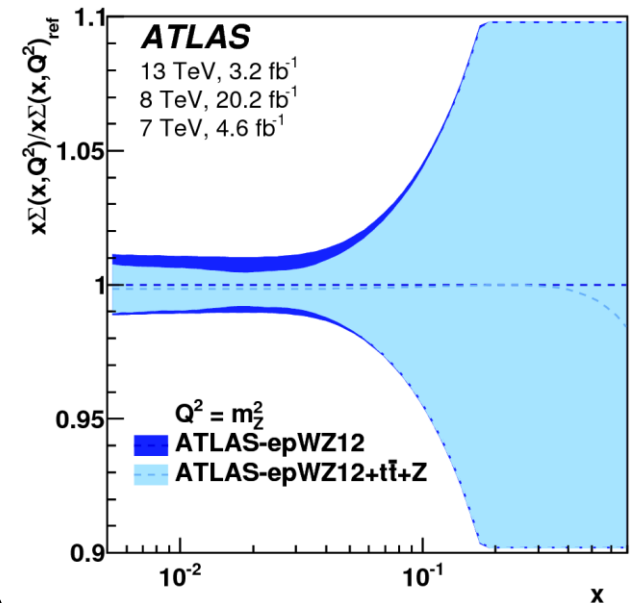
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- Cross sections can also be directly compared to theory predictions
- Quantitative comparison to different PDFs can be made with xFitter

	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



- Impact of measurement on PDF uncertainties can be quantified by using PDF profiling
 - ATLAS-epWZ12 is chosen
- Light-quark sea distribution $x\Sigma(x, Q^2)$ constrained at $x < 0.02$
 - Mainly strange-quark distribution
- Gluon distribution $xg(x, Q^2)$ constrained at $x > 0.1$



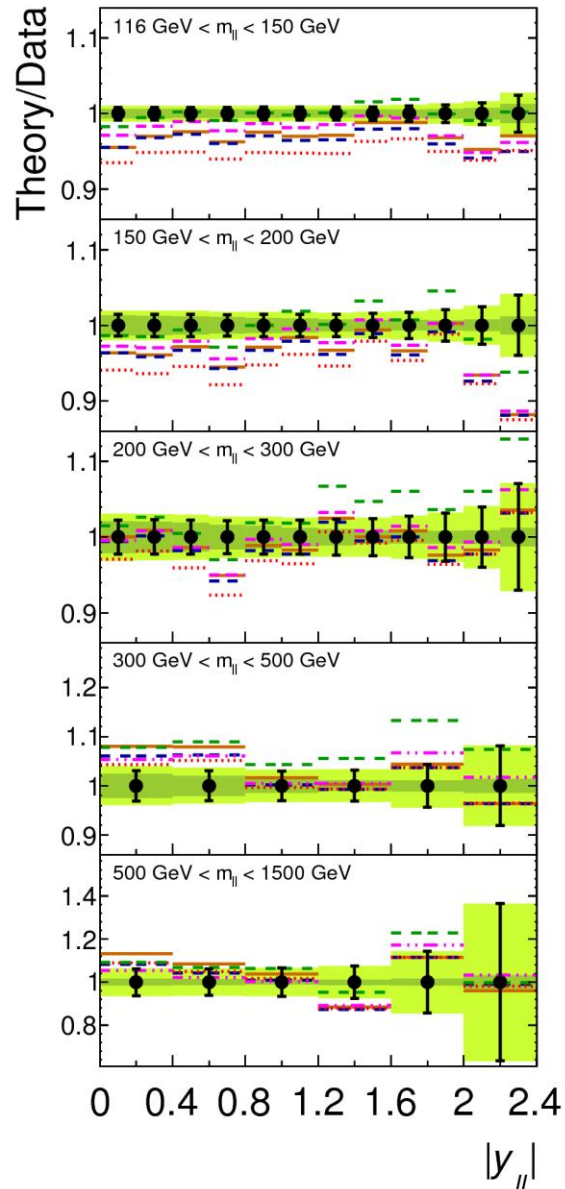
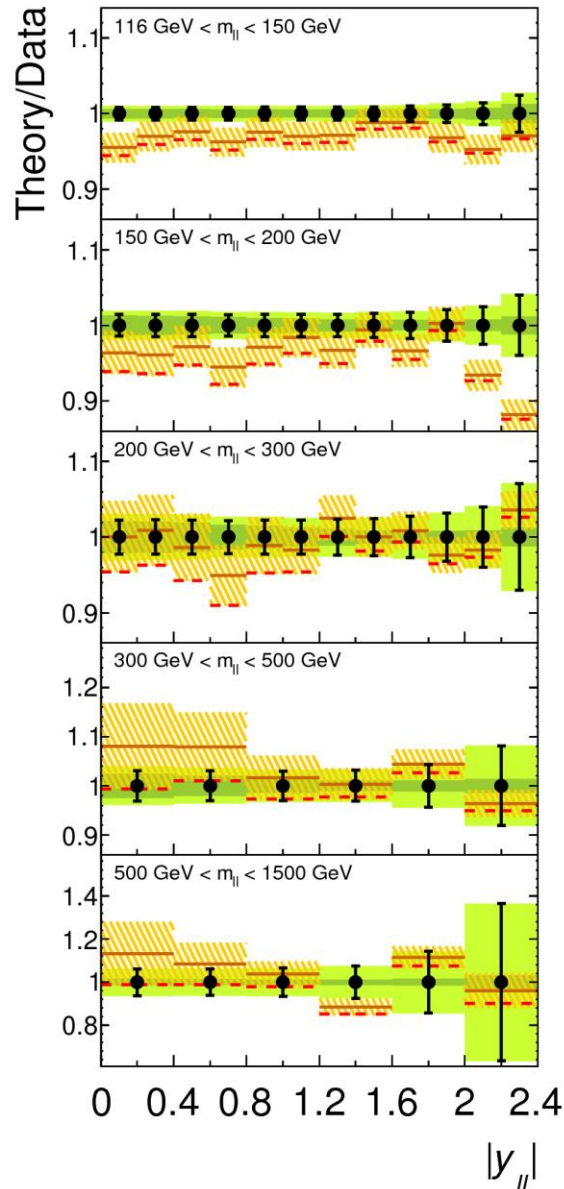
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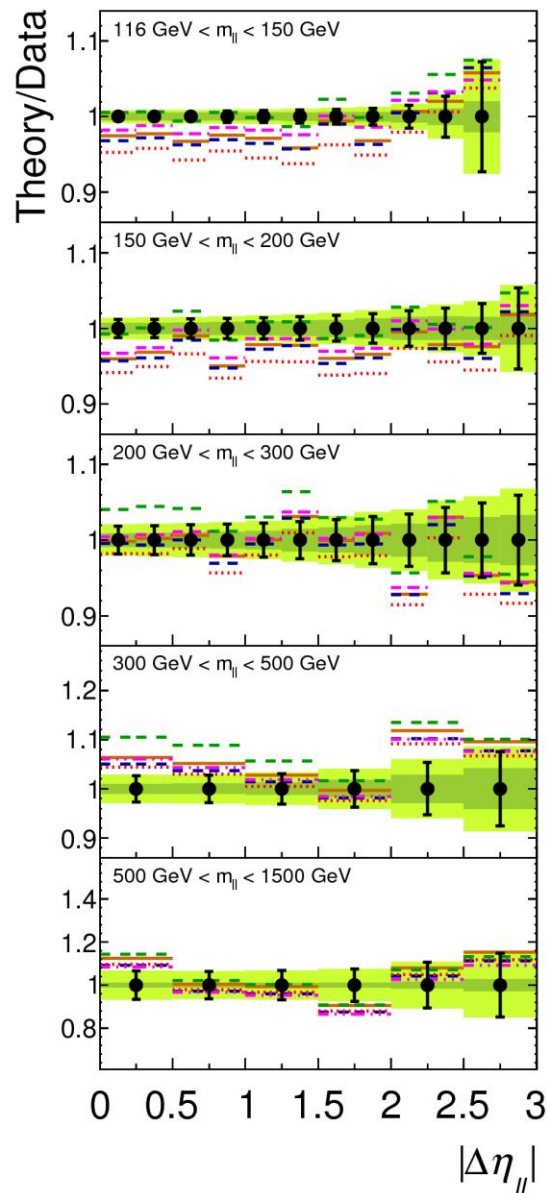
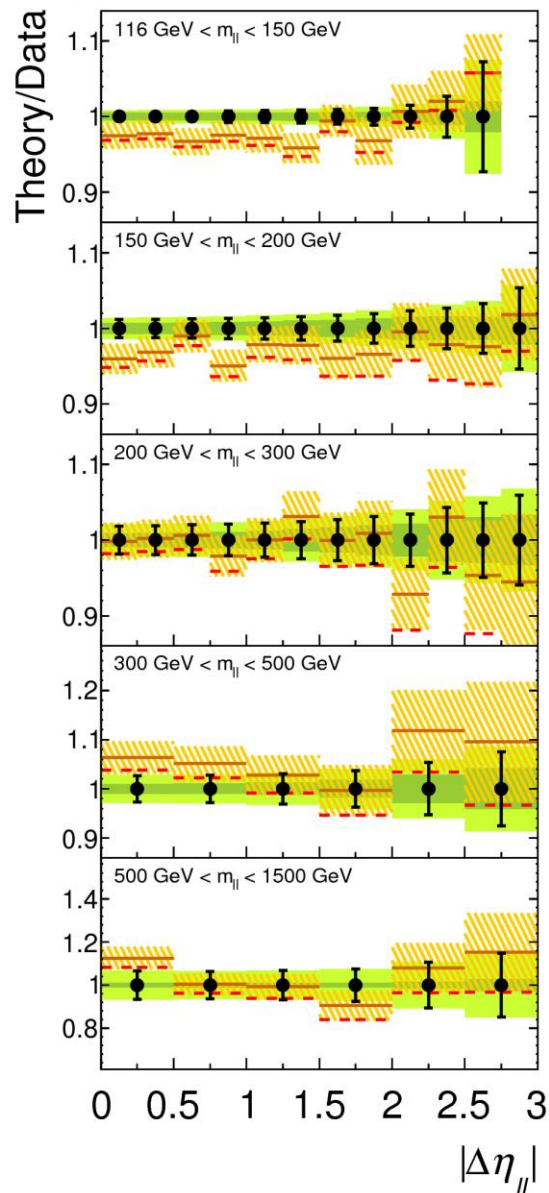


- Measurement of high-mass DY spectra and $Z/t\bar{t}$ ratios help to improve understanding of proton structure in several places
 - Photon PDF
 - Strange-quark PDF
 - Gluon PDF
- Looking forward to see these measurements with increased data-sets



Backup







	$R_{t\bar{t}/Z}^{\text{tot/fid}}(i \text{ TeV})$			$R_{t\bar{t}/Z}^{\text{tot/fid}}(i/j)$		
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

Measured Cross sections

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

Systematic [%] / \sqrt{s} [TeV]	$\delta \sigma_Z^{\text{fid}}$			$\delta \sigma_{t\bar{t}}^{\text{tot}}$		
	13	8	7	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

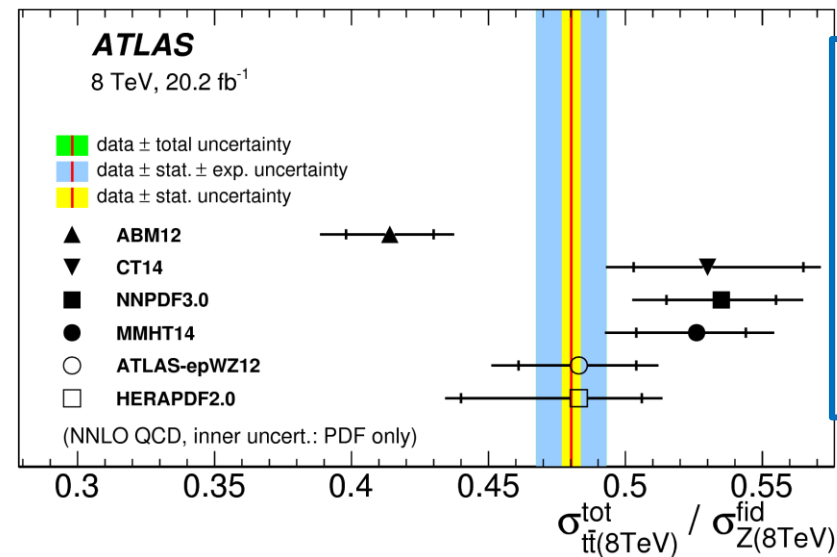
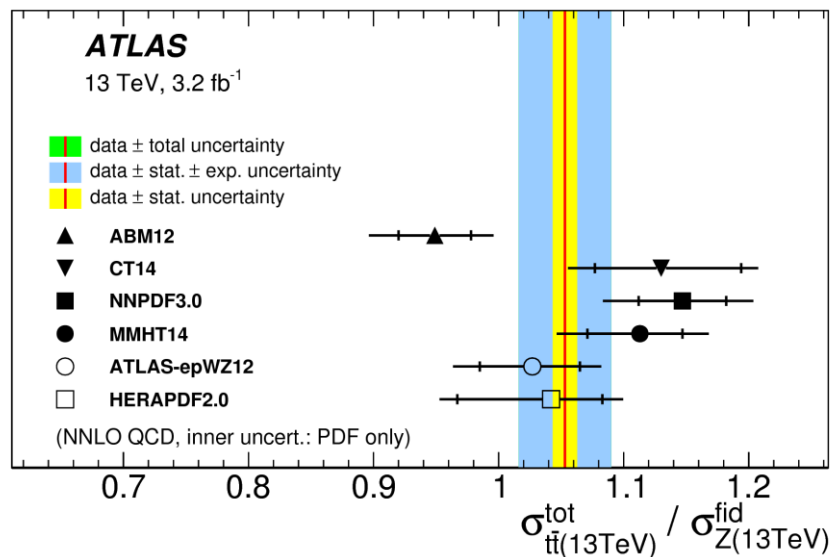
Measured Cross sections

	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
Events	$1,360,680 \pm 1170 \text{ (stat)} \pm 760 \text{ (syst)} \pm 130 \text{ (lumi)}$	$1,727,700 \pm 1320 \text{ (stat)} \pm 950 \text{ (syst)} \pm 160 \text{ (lumi)}$
C	$0.554 \pm 0.003 \text{ (tot)}$	$0.706 \pm 0.006 \text{ (tot)}$
σ_Z^{fid} [pb]	$778 \pm 1 \text{ (stat)} \pm 4 \text{ (syst)} \pm 5 \text{ (beam)} \pm 16 \text{ (lumi)}$	$774 \pm 1 \text{ (stat)} \pm 6 \text{ (syst)} \pm 5 \text{ (beam)} \pm 16 \text{ (lumi)}$

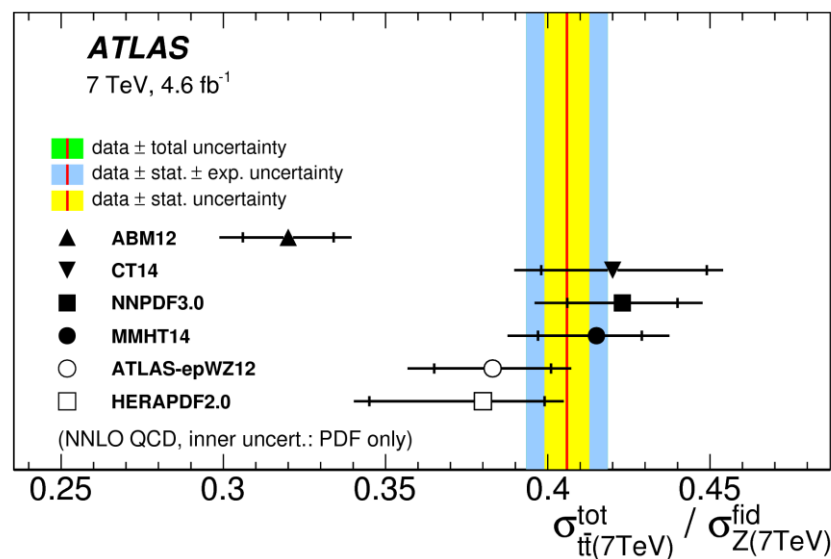
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\sqrt{s} [TeV]	13	8	7
$p_T^\ell >$	25 GeV	20 GeV	20 GeV
$ \eta_\ell <$	2.5	2.4	2.5
$ y_{\ell\ell} <$	-	2.4	-
$m_{\ell\ell}$	66–116 GeV	66–116 GeV	66–116 GeV
Extrapolation E	-	$0.941 \pm 0.001 \text{ (PDF)}$	$0.898 \pm 0.001 \text{ (PDF)}$

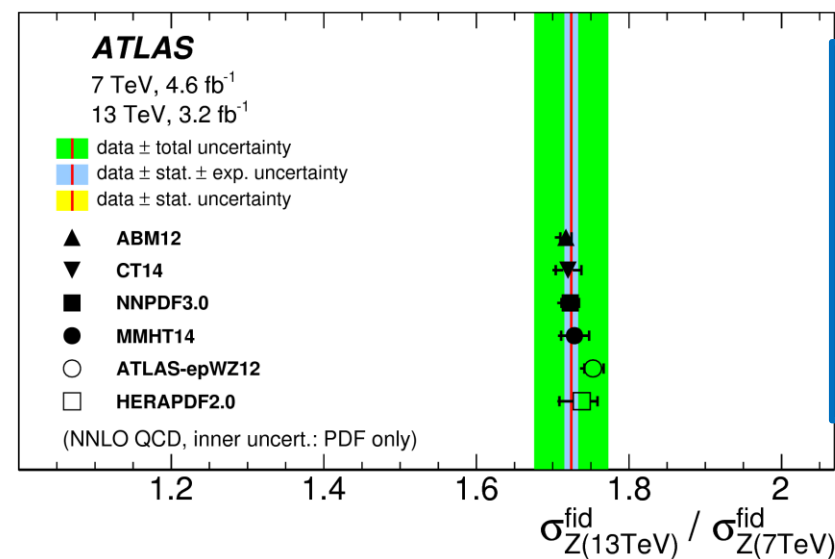
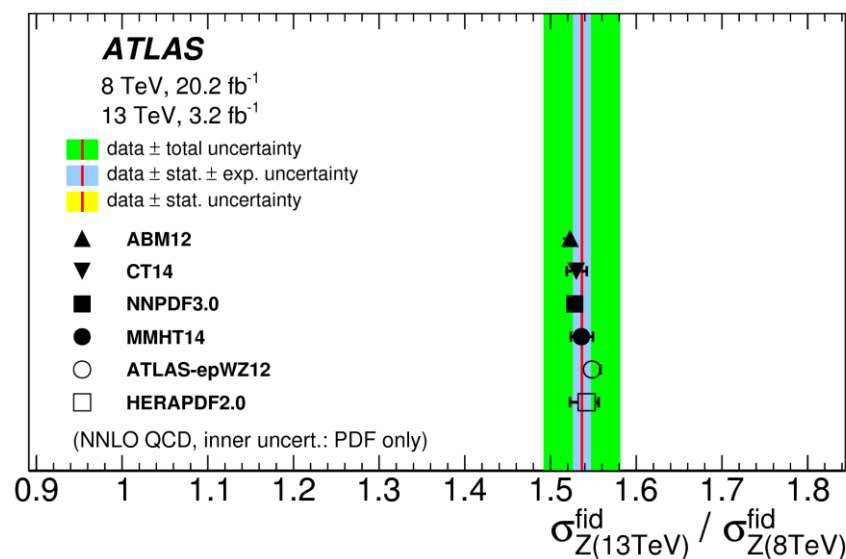
Single ratios at given \sqrt{s}



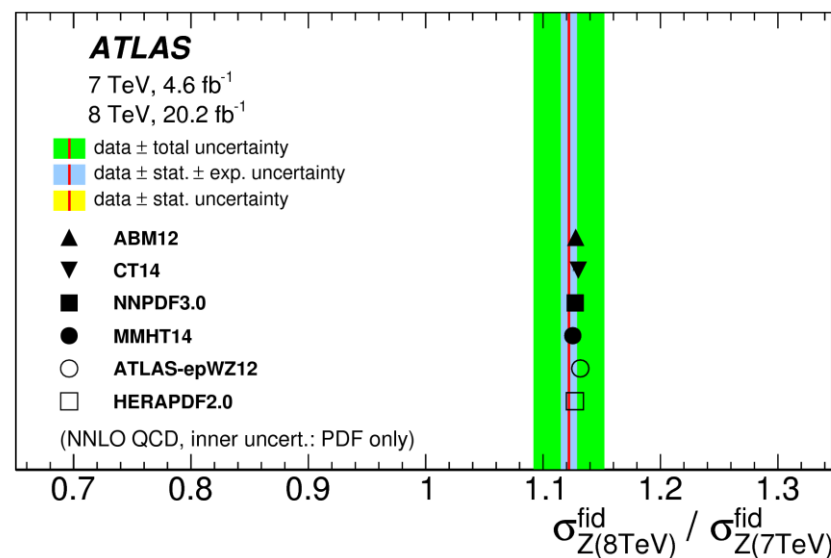
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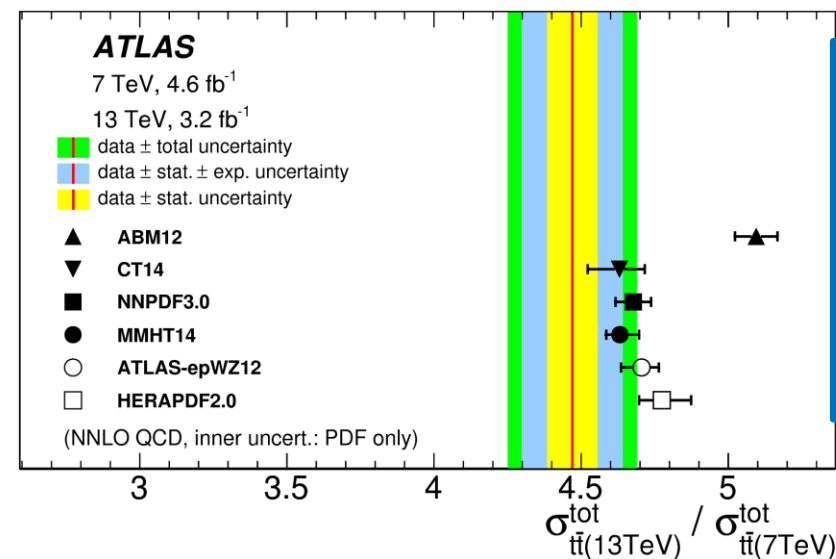
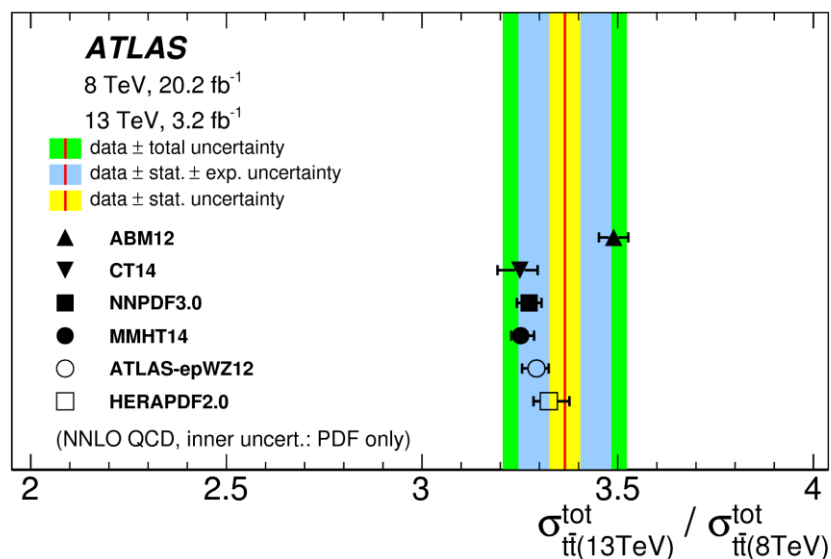
Single ratios at different \sqrt{s}



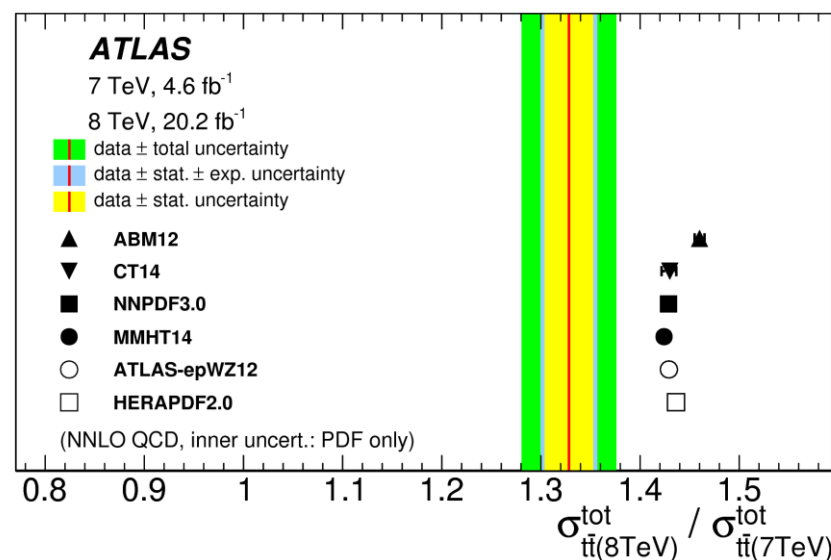
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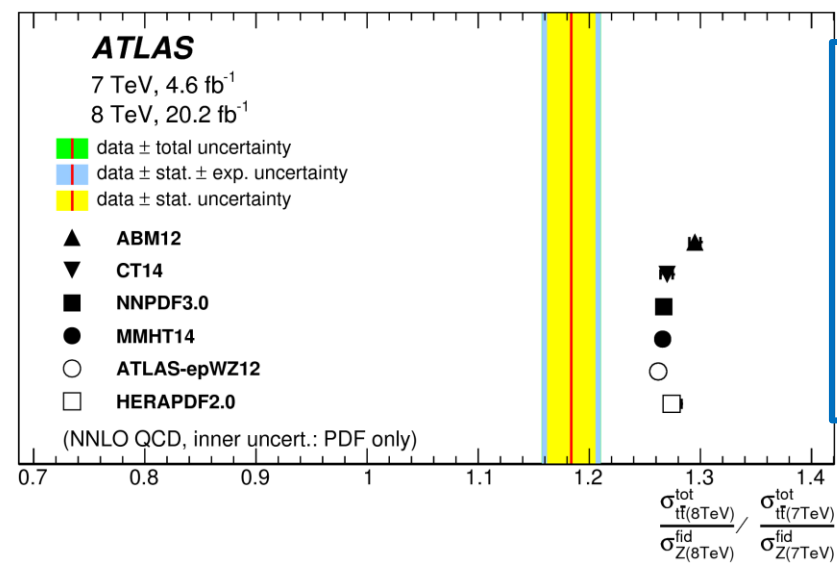
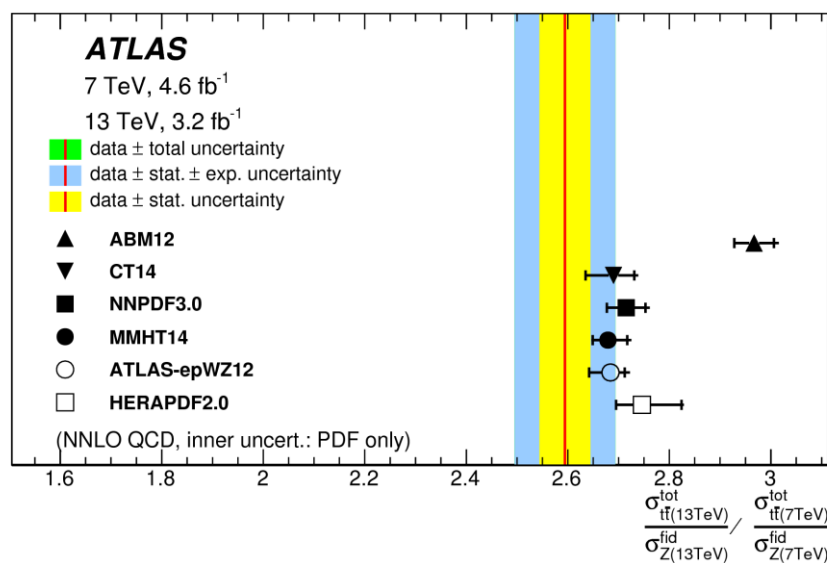
Single ratios at different \sqrt{s}



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Double ratios



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