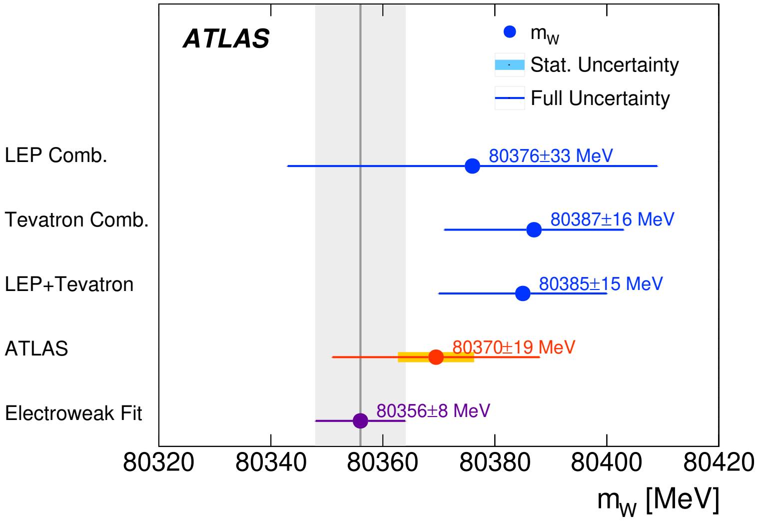
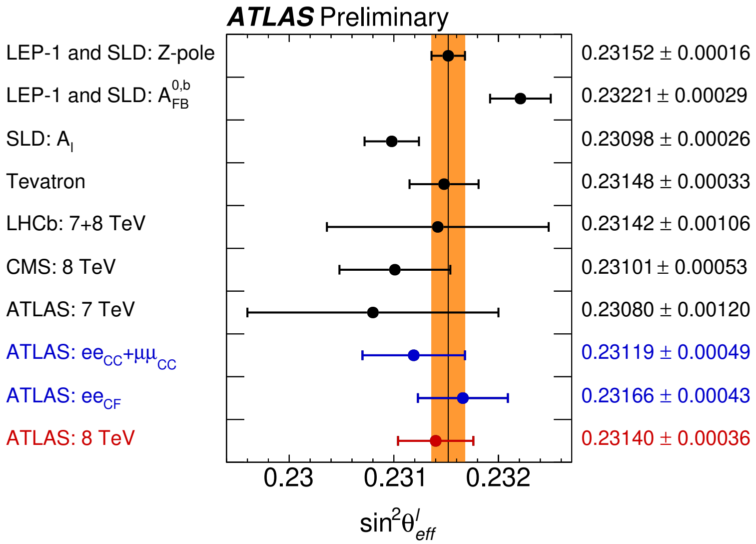
Precision Drell-Yan measurements at ATLAS

S. Glazov, CERN, 13 Nov 2018

ATLAS measurements of the M_W and $\sin^2\theta_W$



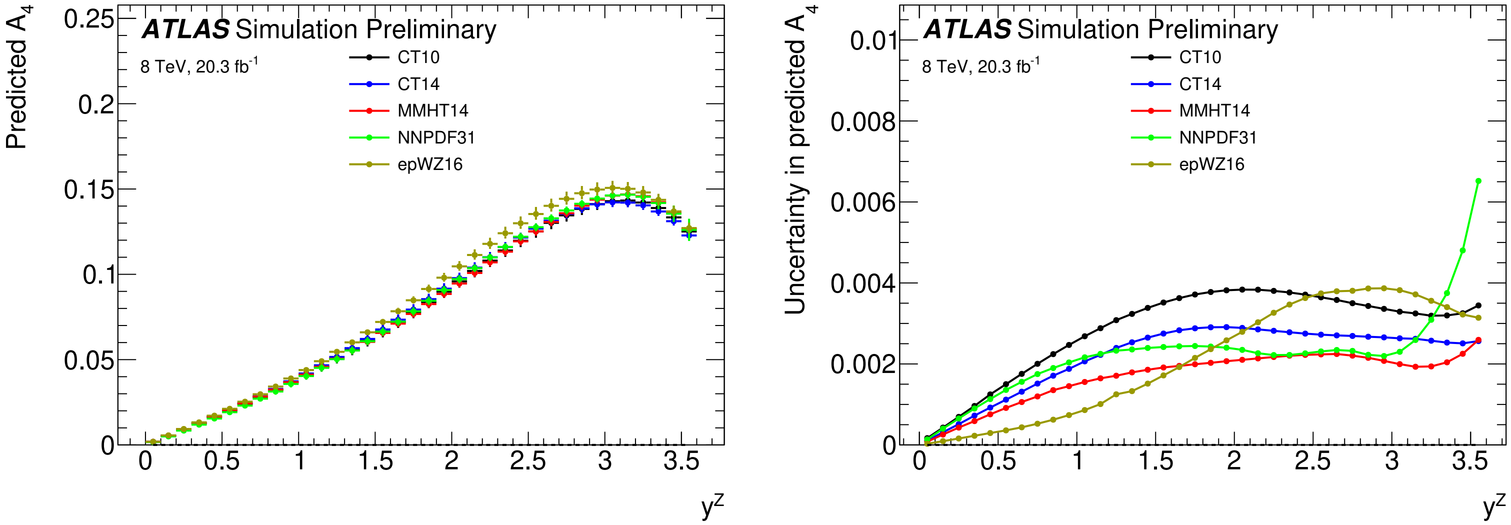


- LHC officially entered the precision electroweak race, with ATLAS measurements of m_W and $\sin^2\theta_W$ using run-I data comparable to most accurate determinations from LEP/Tevatron.
- Leading uncertainties are from PDFs, this will become worse for 13/14 TeV as the data start to probe lower x.

→ PDFs and their uncertainties can not any longer be treated as a black box, need similar or even bigger scrutiny, in terms of uncertainty decomposition and correlations, as experimental uncertainties.

EPJC 78 (2018) 110, ATLAS-CONF-2018-037

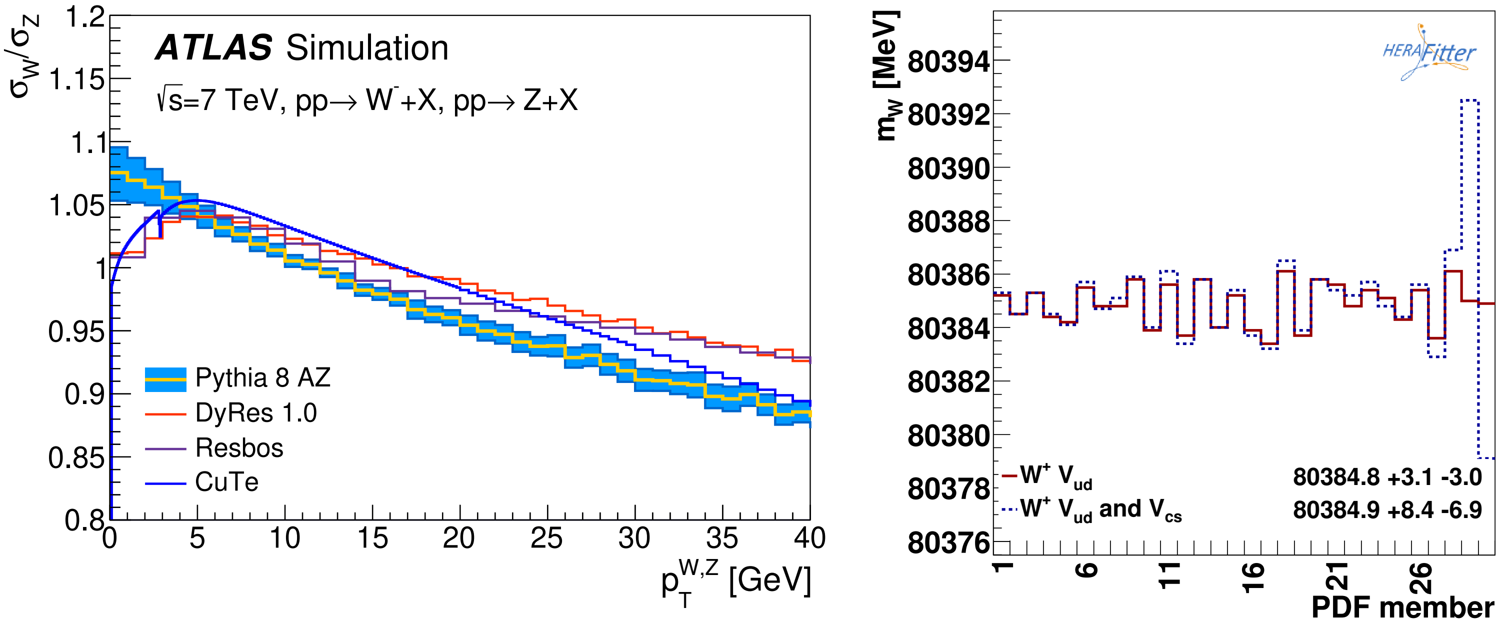
A_4 PDF uncertainties



- $\sin^2\theta_W$ is most sensitive to forward-backward asymmetry ("A_4") for the Z pole region.
- Asymmetry is generated by difference in quark- vs anti-quark PDF, different coupling to up- vs down-type quarks.
- Need accurate u_v, d_v for $x \sim 0.01$. Dilution from valence/sea needs to be under control.
- Exotic QCD effects such as $s - \bar{s}$ asymmetry, intrinsic c and b may also contribute.

ATL-PHYS-PUB-2018-004

m_W PDF sensitivity



- m_W measurement is sensitive to the modeling of W_{p_T} for which understanding of heavy quark contributions to W ($c\bar{s}$) and Z ($b\bar{b}$, $c\bar{c}$) production is important
- Decay lepton distribution is affected by the W polarization (A_4). Sensitive to valence quark distributions, valence/sea dilution at low x.

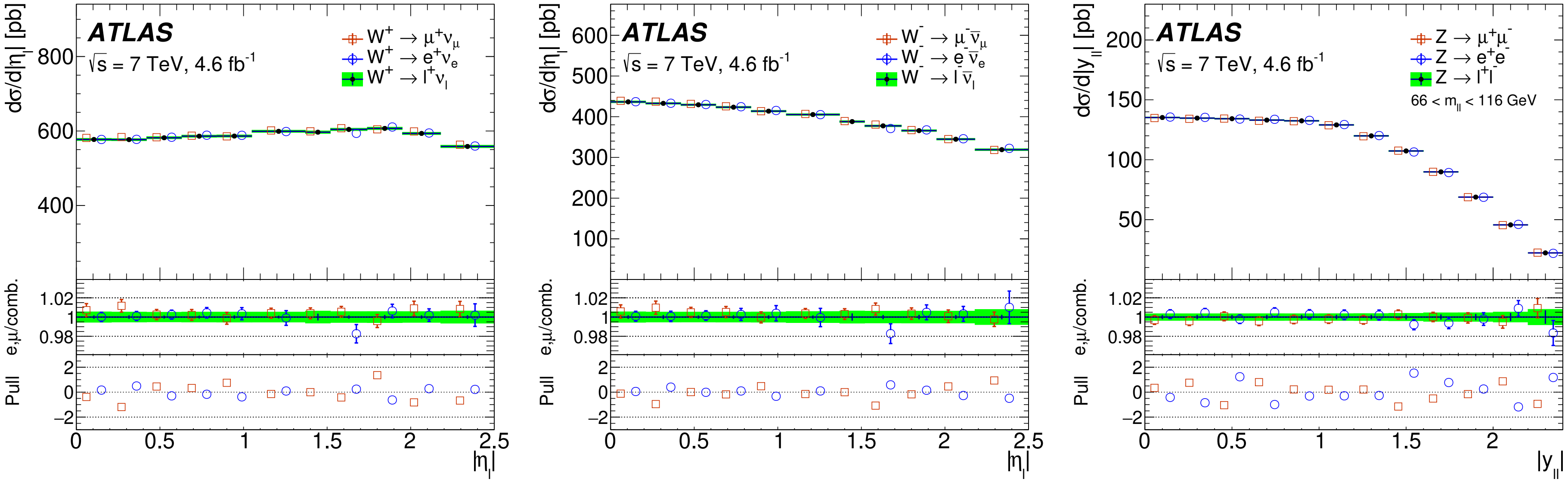
→ similar PDF effects influencing both $\sin^2\theta_W$ and m_W measurements. Potentially important correlations for EWK tests of the SM.

ATL-PHYS-PUB-2014-015

ATLAS data for precision PDFs

- Measurement of differential W, Z cross sections at $\sqrt{s} = 7$ TeV ("WZ2011").
- Measurement of the triple differential Z cross section at $\sqrt{s} = 8$ TeV ("Z3D").
- Measurements of σ_Z and $\sigma_{t\bar{t}}$ and their ratios at different CME.
- Measurements of Z_{p_T} and A_i
- Measurement of $W + c$
- Off-peak DY measurements

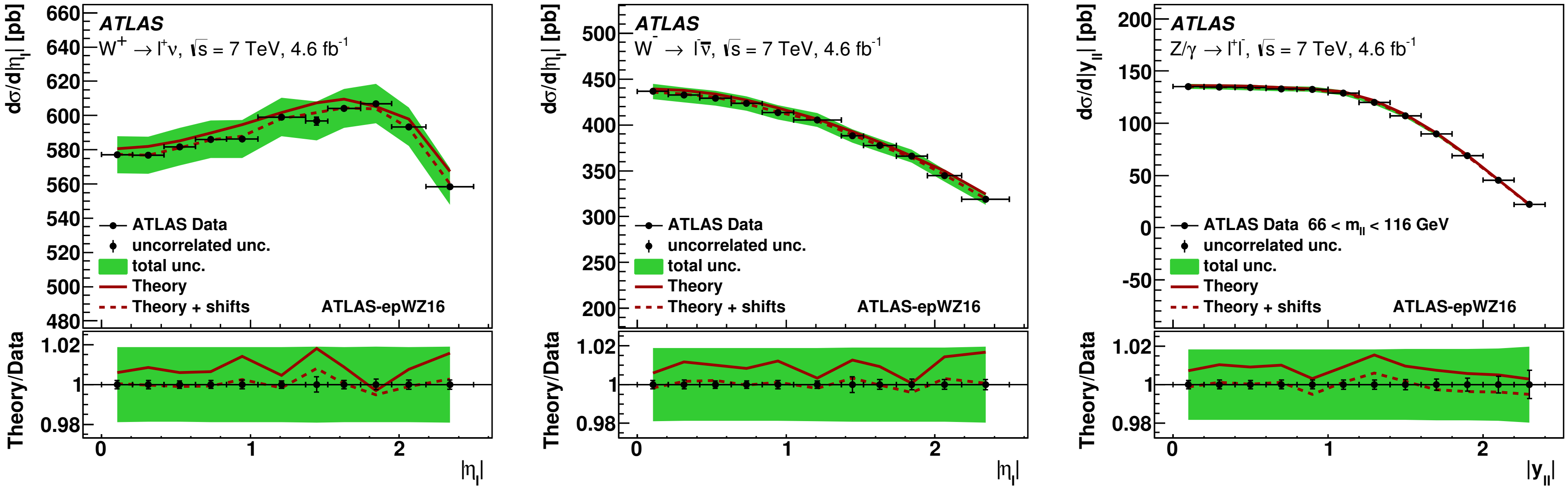
W and Z cross sections at $\sqrt{s} = 7$ TeV



- Differential measurements of $W^{\pm}$, Z/γ^{*} production (including off-peak) using electron and muon decays, with sub-percent accuracy, and full correlated errors treatment.
- Good compatibility of the two channels, $\chi^2/\mathrm{dof} = 59.5/53$, combined result has better than 0.5% accuracy.

ATLAS EPJ C77 (2017) 367.

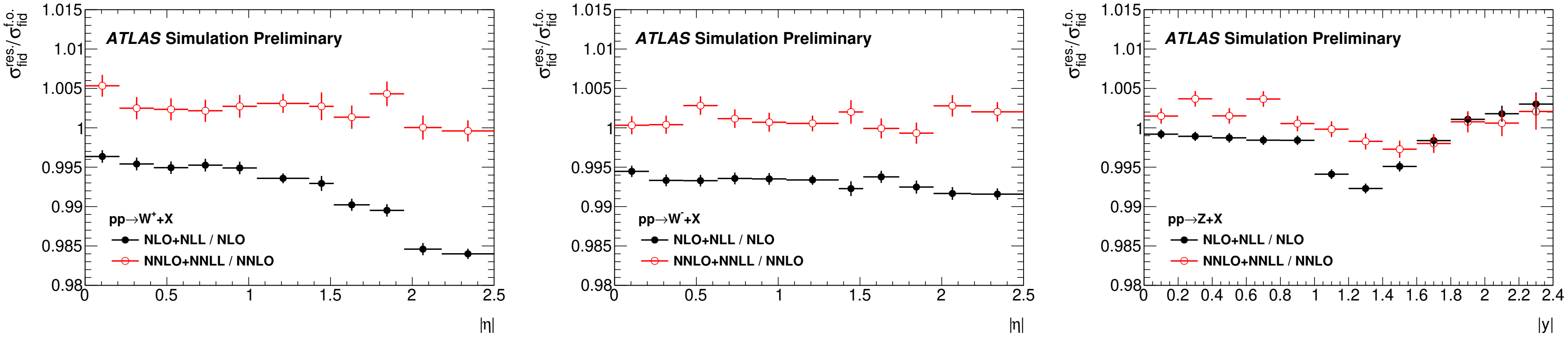
W and Z cross sections at $\sqrt{s} = 7$ TeV



- ATLAS $W, Z/\gamma^*$ data together with the inclusive HERA-II data included in a QCD analysis at NNLO QCD + NLO EWK using xFitter program.

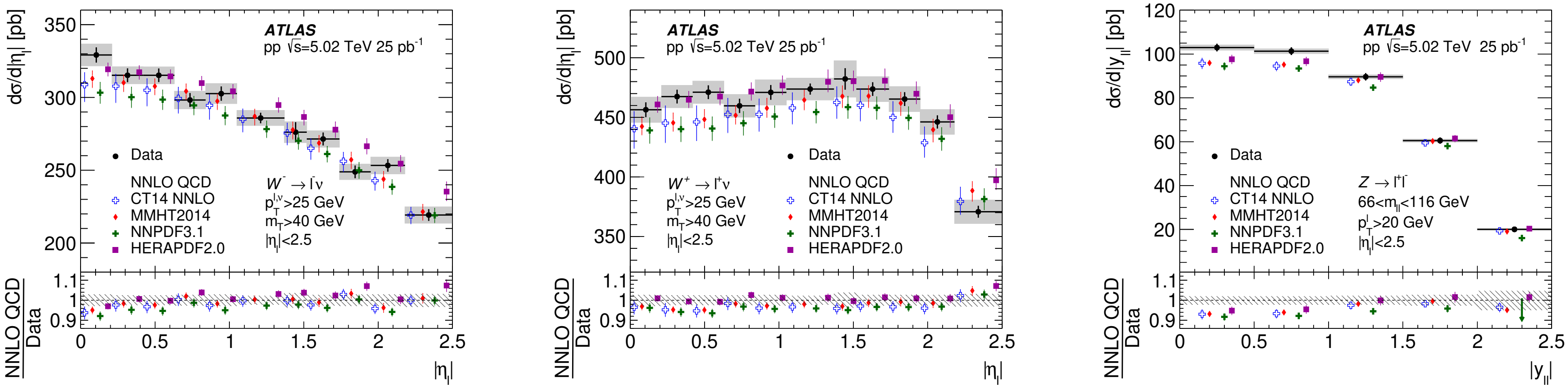
- Challenge for the theory to match the data accuracy, $\chi^2/\mathrm{N_{data}} = 108/61$ (ATLAS only) for the nominal scale settings $\mu_F = \mu_R = M_{\ell\ell}(M_W)$, improving to $\chi^2/\mathrm{N_{data}} = 85/61$ for $\mu_F = \mu_R = 1/2 M_{\ell\ell}(M_W)$

Effect of resummation



- 2011 W, Z differential cross section measurements are performed within fiducial volume, with $p_T^{\ell} > 20$ GeV and $E_T^{miss} > 25$ GeV cuts.
- Fiducial cuts shape $p_T^{W,Z}$ distribution, make pure fixed order predictions inaccurate.
- Difference observed between FEWZ and DYNNLO predictions for symmetric cuts (at $\sim 1\%$ level), however using asymmetric cuts does not solve the problem of p_T distribution shaping.
- Differences between NNLO and NNLO+NNLL calculations are comparable to data accuracy (but much better vs NLO - NLO+NLL).
- Differences for W^+ vs W^- – building asymmetry does not solve the problem completely.

New measurement at $\sqrt{s} = 5$ TeV

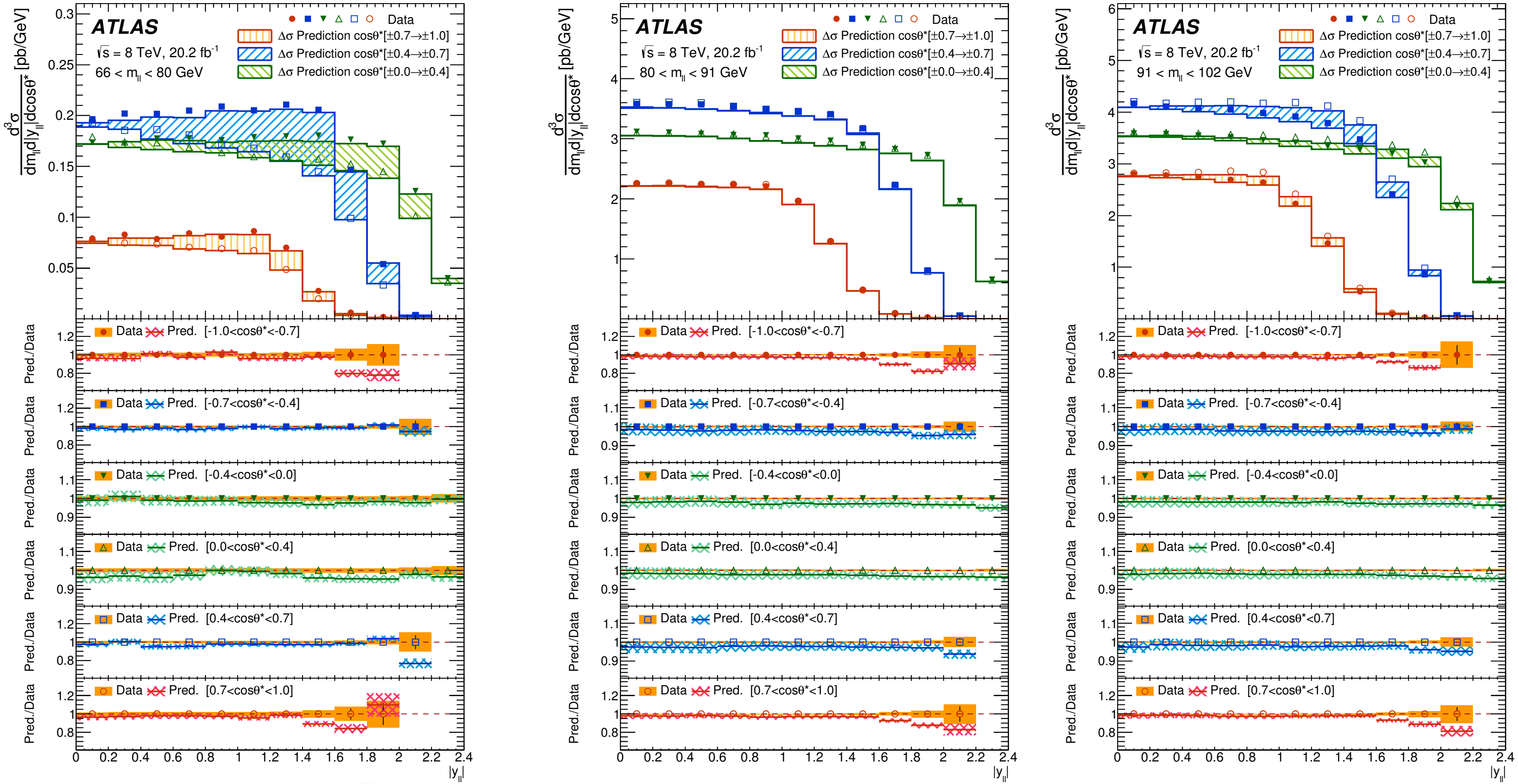


- New first measurement of $W^{\pm}, Z$ differential cross section using $\sqrt{s} = 5$ TeV data with $L = 25$ pb^{-1}.
- Luminosity uncertainty of 1.9%, statistics at 1% for fiducial Z and systematics is at 1.5% for W
- Similar trends as $\sqrt{s} = 7$ TeV data: e.g. most of PDFs underestimate data for central y_Z.

→ interesting data for additional constraints at higher x.

ATLAS, arXiv:1810.08424

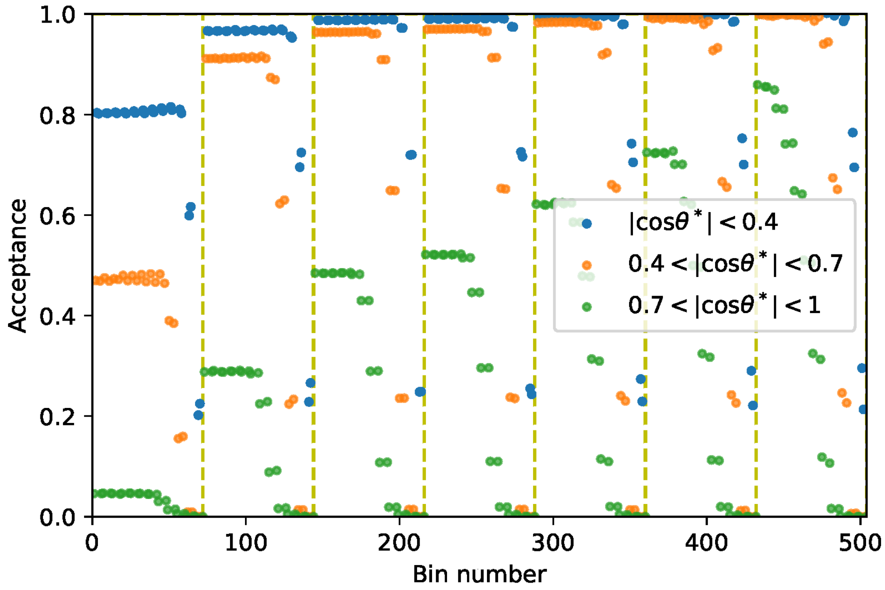
Triple differential cross section $d^3\sigma/dM_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*$



- Triple differential cross section, measured for $46 < M_{\ell\ell} < 200$ GeV range, for CC and CF topology.
- Simultaneous sensitivity to PDFs and $\sin^2\theta_W$, care needed for pure PDF interpretation.

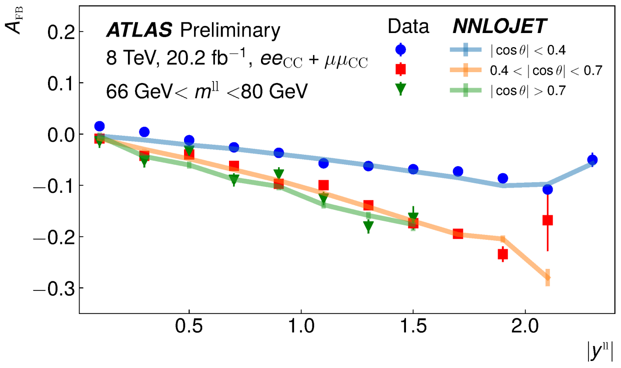
JHEP 12 (2017) 059

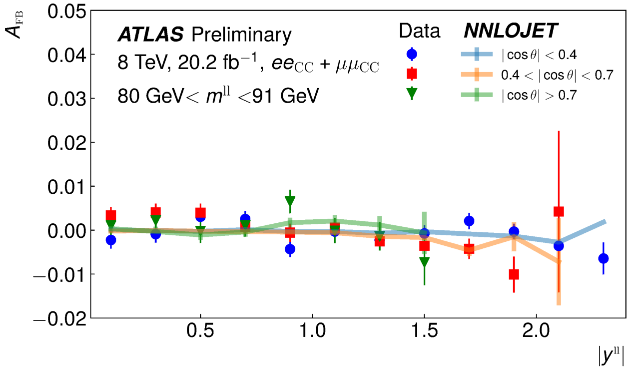
Acceptance for Z3D

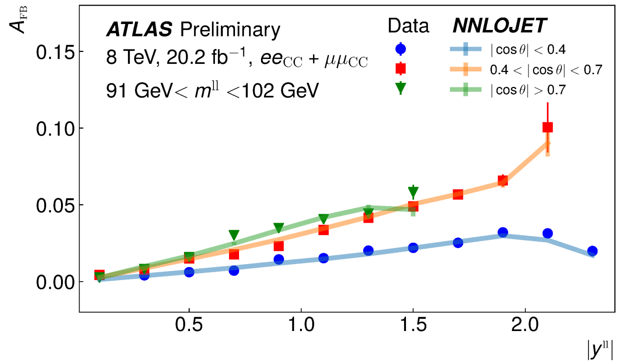


- Acceptance, $A = \sigma_{fid}/\sigma_{tot}$ calculated using NNLOjet program at NNLO ($n_{jet} = 0$) shows strong variation vs $|\cos\theta_{CS}|$, $|y_{\ell\ell}|$ and $M_{\ell\ell}$ ("bin number $= 72i_M + 12i_y + i_{\cos\theta^*}$).
- More than 50% of bins at low $|\cos\theta^*|$ and $M_{\ell\ell} > 66$ GeV have $A > 95\%$.
- Restricting cross section data to these bins (which are also more accurate experimentally) allows to mitigate effect of fiducial cuts.
- Other bins can be converted to FBA.

FBA derived from Z3D



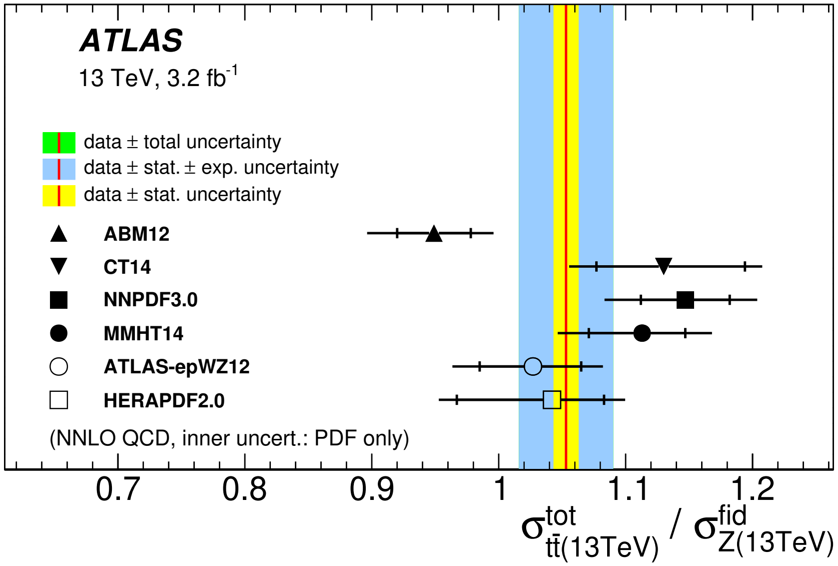


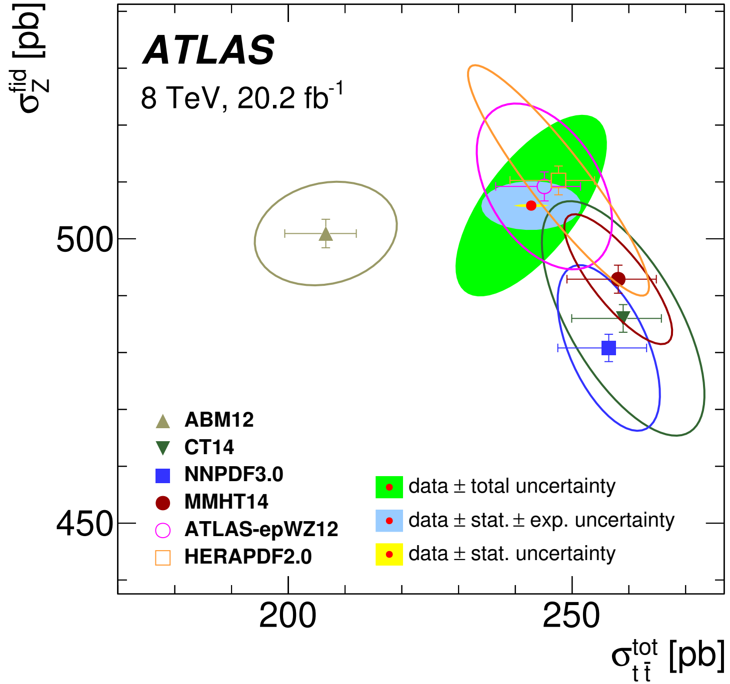


- Binned in $\cos\theta^*_{CS}$ asymmetry provides additional information vs integrated (e.g. info on A_0).
- Asymmetry reduces impact of fiducial cuts; good agreement between data and NNLO predictions based on NNLOJET.

→ pure NNLO fits are possible to Z3D data, however extreme care is needed about EWK effects and treatment of $\sin^2\theta_W$.

$\sigma_{t\bar{t}}/\sigma_Z$ ratio measurement





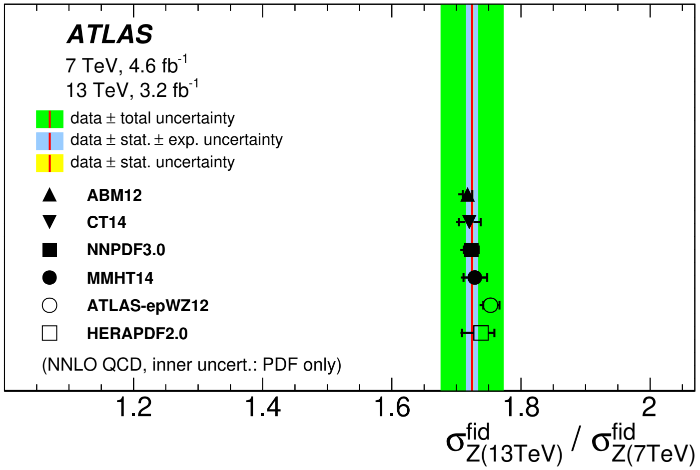
- Production of $t\bar{t}$ and Z dominated by gg and $q\bar{q}$, respectively: ratio of cross sections is sensitive to gluon/sea at $x \sim 0.1$.
- Dedicated measurement of σ^{fid}_{Z} at $\sqrt{s} = 13$ GeV for

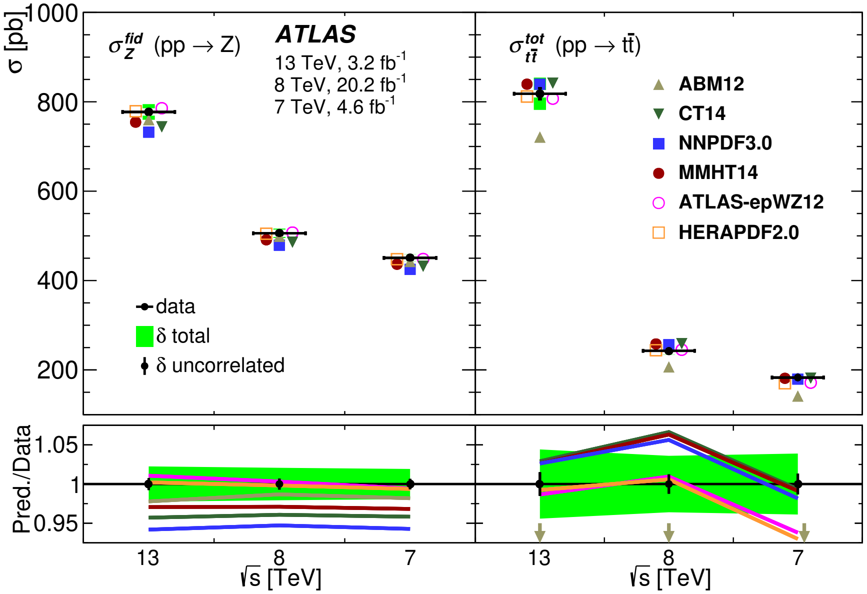
$$\frac{\sigma^{\text{tot}}_{t\bar{t}}}{\sigma^{\text{fid}}_{Z}} = \frac{2\sigma^{\text{tot}}_{t\bar{t}\to X+e\mu}}{\sigma^{\text{fid}}_{Z\to ee} + \sigma^{\text{fid}}_{Z\to\mu\mu}}$$

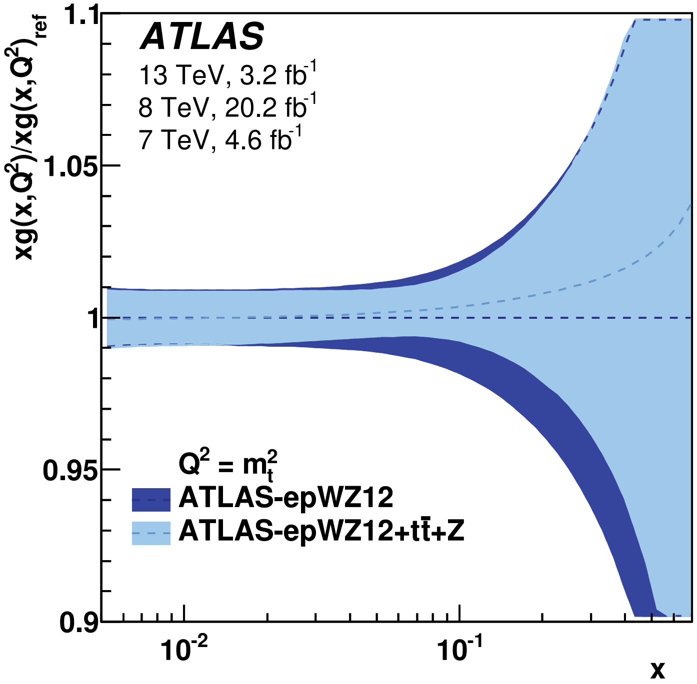
- Evaluation of correlations for existing 7, 8 TeV measurements.

ATLAS, JHEP 02 (2017), 117

Correlated Z and $t\bar{t}$ cross sections

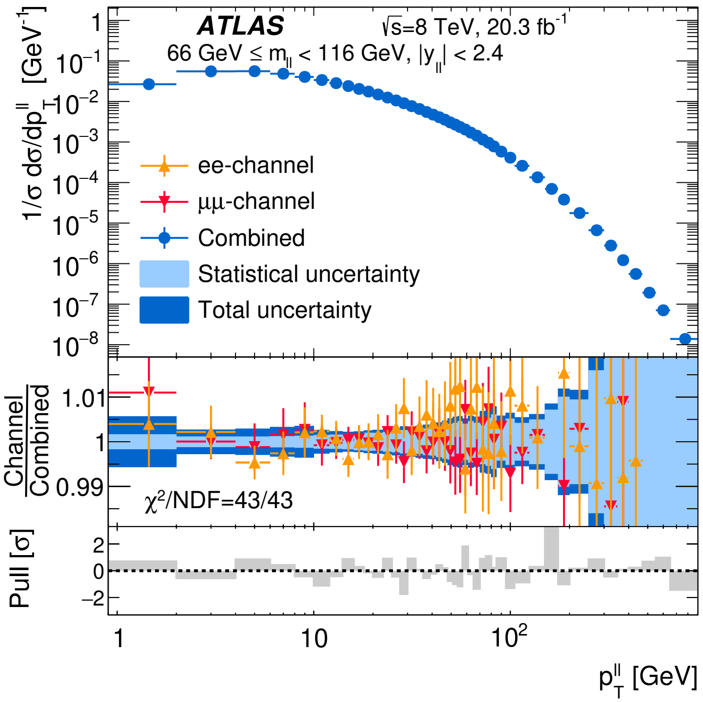


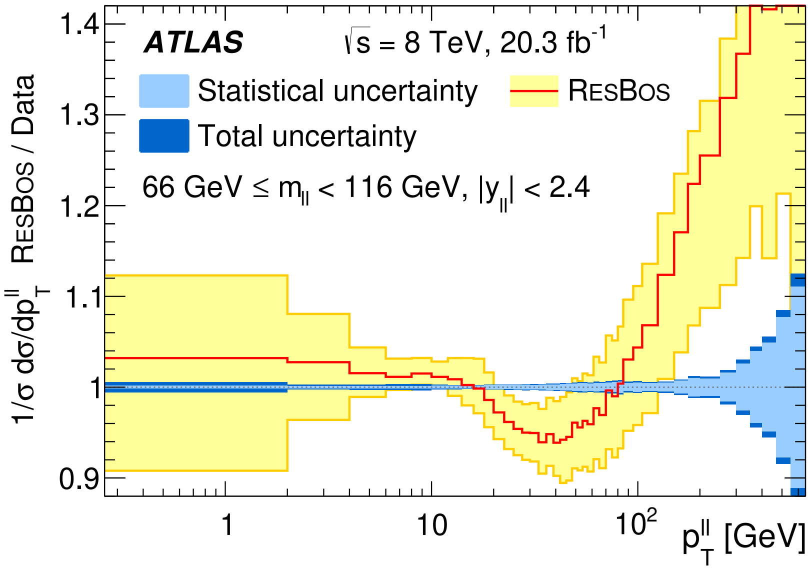




- Ratio of σ_Z^{fid} at different $\sqrt{s}$ has small PDF uncertainty, smaller vs lumi error.
- ATLAS data agree best with HERAPDF2.0 and ATLAS-epWZ12 PDFs.
- Profile ATLAS-epWZ12 PDF using correlated fiducial cross sections; sizable impact on the gluon uncertainty (and almost no pull on central value).

Measurement of Z_{p_T}

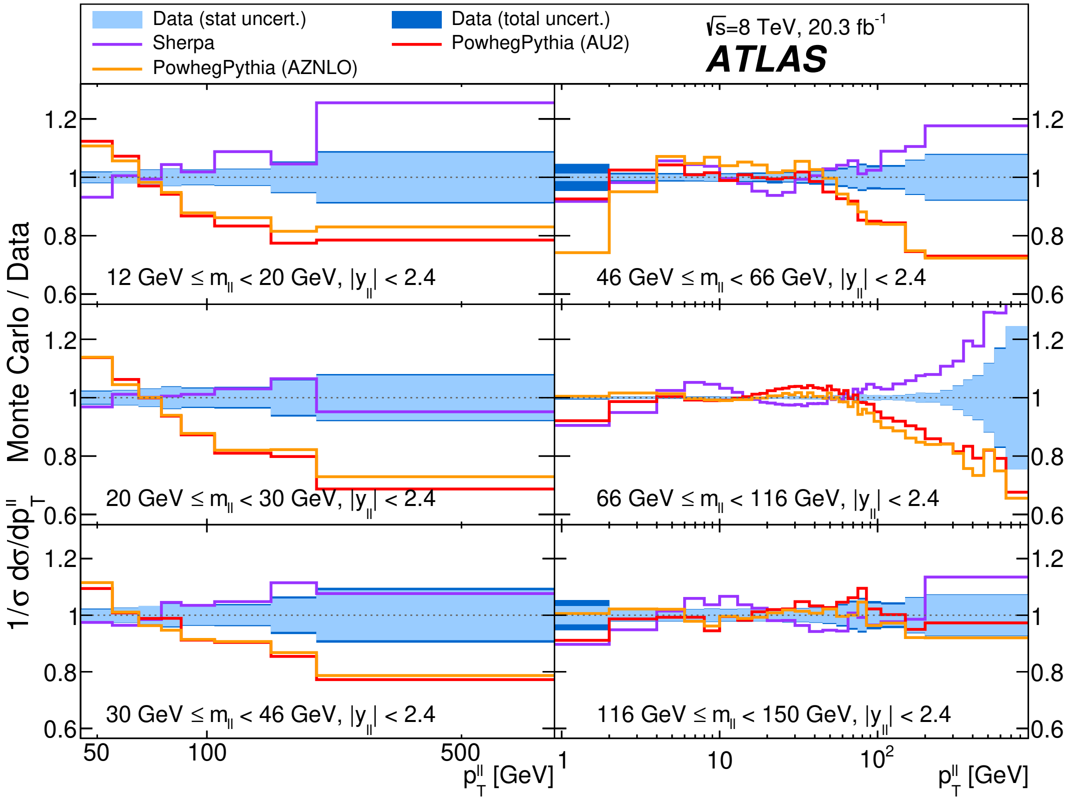




- Measurements of Z_{p_T} at $\sqrt{s} = 7$ and 8 TeV.
- ATLAS measurements use both $Z \to ee$ and $Z \to \mu\mu$ channels, which have comparable accuracy. The combined result is accurate to better than 0.5% for $P_T < 100$ GeV range.

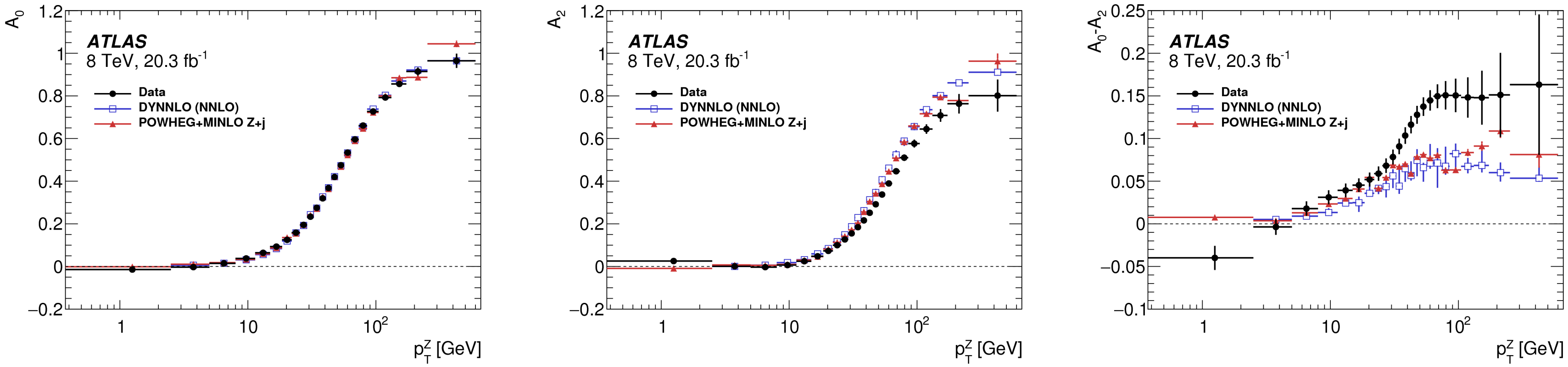
ATLAS, EPJ C76 (2016) 12

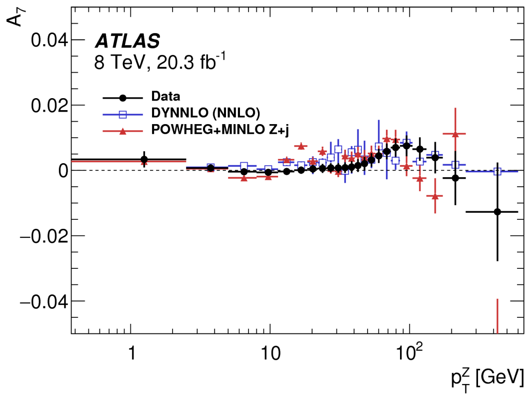
Off-peak p_T measurements



- Large $\sqrt{s} = 8$ TeV samples can be used to probe distributions double differentially. Studying dependence in mass can probe different PDF decomposition, scale dependence, electroweak effects.
- Dedicated Powheg+Pythia tune AZNLO, developed using Z_{p_T} $\sqrt{s} = 7$ TeV data, works very well for the peak range but deviates at low masses.

Z angular coefficients



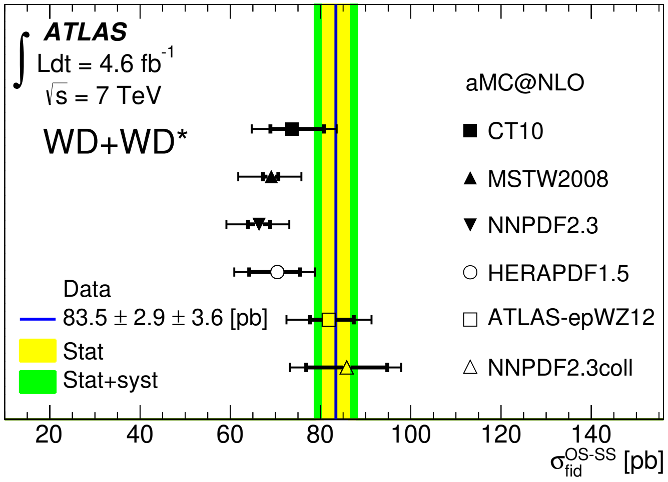


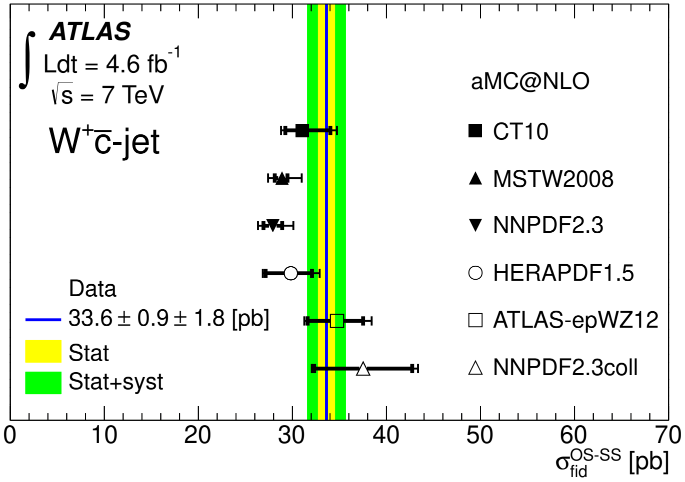
- $A_0 - A_0$ is expected to become non-zero at NLO($n_{jet} = 1$), data confirms that
- Data deviates from NLO($n_{jet} = 1$) expectations for A_2 (and $A_0 - A_2$) at high p_T.
- Higher order coefficients appear from NLO($n_{jet} = 1$), evidence of them in data.

→ essential check of HO calculations, required to pass for accurate PDF interpretations.

ATLAS JHEP 08 (2016) 159.

Measurements of $W+c$

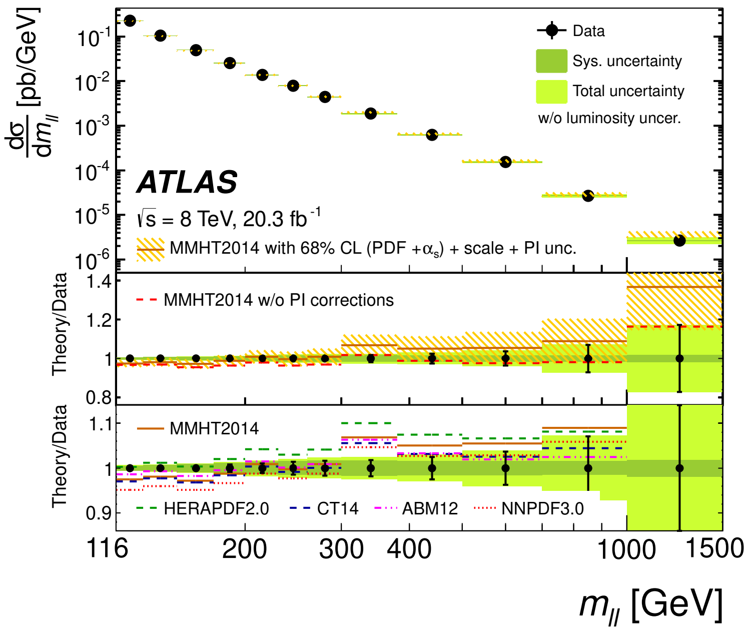


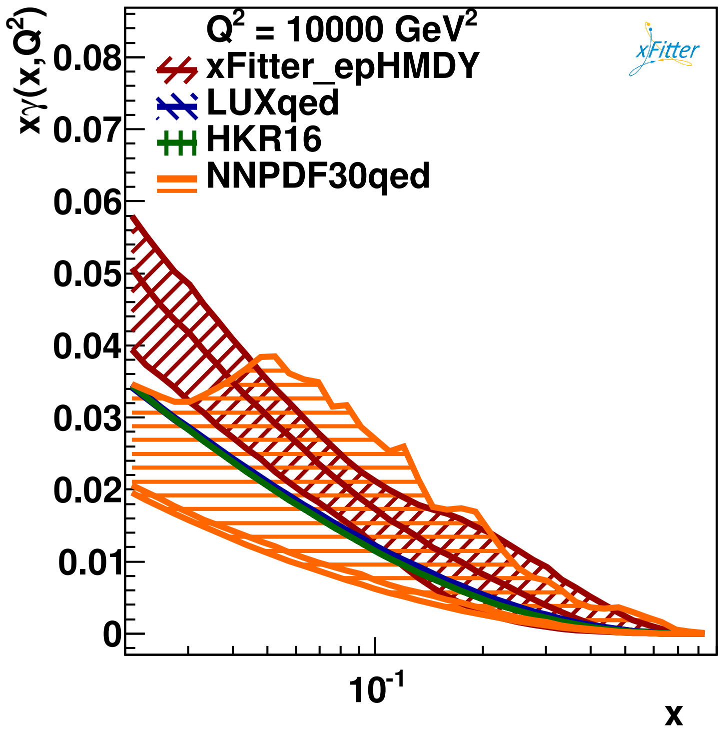


- Measurements of $\sigma(W^\pm c^\mp) - \sigma(W^\pm c^\pm)$ from ATLAS using c-jets tagged by soft muons and $D^{(*)}$ mesons, to probe strange-sea PDF using $gs \to Wc$ process.
- Reported at particle level, still not used in PDF fits.
- NLO scale uncertainties are larger than data uncertainties even for this $\sqrt{s} = 7$ TeV result: need for NNLO corrections.

JHEP 02 (2014) 013

High mass DY measurement at $\sqrt{s} = 8$ TeV



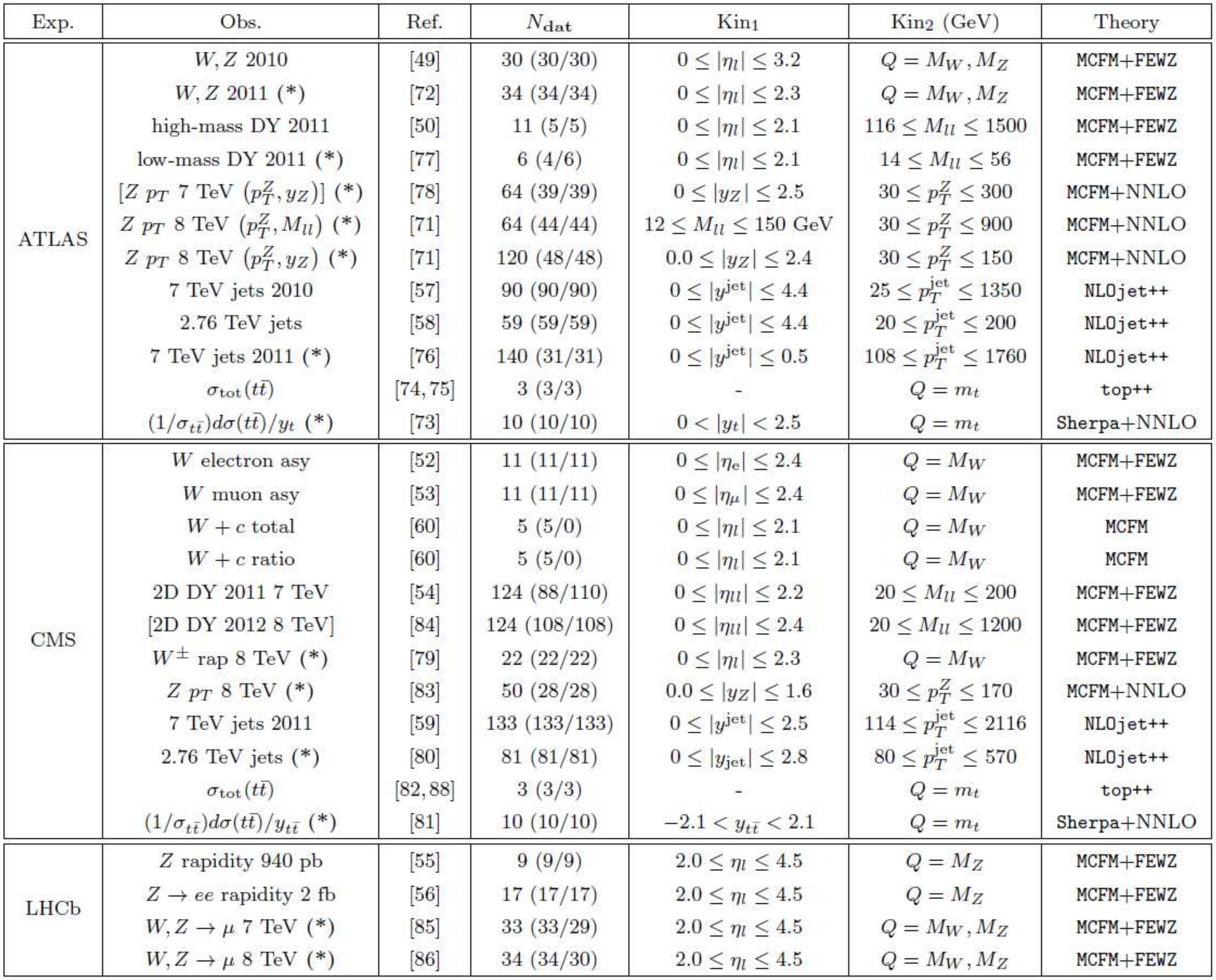


- Measurement in e and μ channels with combined experimental precision better than 1% for low $M_{\ell\ell}$ (plus 1.9% lumi), double differential in $M_{\ell\ell}$ and $y_{\ell\ell}$ and $\delta\eta_{\ell\ell}$.
- Sensitive to $\gamma\gamma \to \ell\ell$ with significant constraining power vs NNPDF3.0, as shown by xFitter-team analysis
  ATLAS, JHEP 08 (2016) 009; xFitter, EPJC 77 (2017) 400

Summary

- Precision measurements of $\sin^2 \theta_W$ and m_W have significant PDF uncertainties, demand accurate PDF analyses with detailed decomposition of uncertainties.
- A number of accurate measurements from ATLAS to constrain relevant PDFs.
- However care is needed when using these data in PDF analyses:
  - Impact of fiducial cuts;
  - Interplay between PDF and EWK effects: PDFs with varied EWK parameters;
  - NNLO corrections for $W + c$.

NNPDF3.1 LHC data



Exp.	Obs.	Ref.	N_{dat}	Kin$_1$	Kin$_2$ (GeV)	Theory
ATLAS	W,Z 2010	[49]	30 (30/30)	$0 \le \lvert\eta_l\rvert \le 3.2$	$Q = M_W, M_Z$	MCFM+FEWZ
	W,Z 2011 (*)	[72]	34 (34/34)	$0 \le \lvert\eta_l\rvert \le 2.3$	$Q = M_W, M_Z$	MCFM+FEWZ
	high-mass DY 2011	[50]	11 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$	$116 \le M_{ll} \le 1500$	MCFM+FEWZ
	low-mass DY 2011 (*)	[77]	6 (4/6)	$0 \le \lvert\eta_l\rvert \le 2.1$	$14 \le M_{ll} \le 56$	MCFM+FEWZ
	$[Z\ p_T$ 7 TeV $(p_T^Z, y_Z)]$ (*)	[78]	64 (39/39)	$0 \le \lvert y_Z\rvert \le 2.5$	$30 \le p_T^Z \le 300$	MCFM+NNLO
	$Z\ p_T$ 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)	$12 \le M_{ll} \le 150$ GeV	$30 \le p_T^Z \le 900$	MCFM+NNLO
	$Z\ p_T$ 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)	$0.0 \le \lvert y_Z\rvert \le 2.4$	$30 \le p_T^Z \le 150$	MCFM+NNLO
	7 TeV jets 2010	[57]	90 (90/90)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 4.4$	$25 \le p_T^{\mathrm{jet}} \le 1350$	NLOjet++
	2.76 TeV jets	[58]	59 (59/59)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 4.4$	$20 \le p_T^{\mathrm{jet}} \le 200$	NLOjet++
	7 TeV jets 2011 (*)	[76]	140 (31/31)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 0.5$	$108 \le p_T^{\mathrm{jet}} \le 1760$	NLOjet++
	$\sigma_{\mathrm{tot}}(t\bar{t})$	[74, 75]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_t$ (*)	[73]	10 (10/10)	$0 < \lvert y_t\rvert < 2.5$	$Q = m_t$	Sherpa+NNLO
CMS	W electron asy	[52]	11 (11/11)	$0 \le \lvert\eta_e\rvert \le 2.4$	$Q = M_W$	MCFM+FEWZ
	W muon asy	[53]	11 (11/11)	$0 \le \lvert\eta_\mu\rvert \le 2.4$	$Q = M_W$	MCFM+FEWZ
	$W + c$ total	[60]	5 (5/0)	$0 \le \lvert\eta_l\rvert \le 2.1$	$Q = M_W$	MCFM
	$W + c$ ratio	[60]	5 (5/0)	$0 \le \lvert\eta_l\rvert \le 2.1$	$Q = M_W$	MCFM
	2D DY 2011 7 TeV	[54]	124 (88/110)	$0 \le \lvert\eta_{ll}\rvert \le 2.2$	$20 \le M_{ll} \le 200$	MCFM+FEWZ
	[2D DY 2012 8 TeV]	[84]	124 (108/108)	$0 \le \lvert\eta_{ll}\rvert \le 2.4$	$20 \le M_{ll} \le 1200$	MCFM+FEWZ
	$W^\pm$ rap 8 TeV (*)	[79]	22 (22/22)	$0 \le \lvert\eta_l\rvert \le 2.3$	$Q = M_W$	MCFM+FEWZ
	$Z\ p_T$ 8 TeV (*)	[83]	50 (28/28)	$0.0 \le \lvert y_Z\rvert \le 1.6$	$30 \le p_T^Z \le 170$	MCFM+NNLO
	7 TeV jets 2011	[59]	133 (133/133)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 2.5$	$114 \le p_T^{\mathrm{jet}} \le 2116$	NLOjet++
	2.76 TeV jets (*)	[80]	81 (81/81)	$0 \le \lvert y_{\mathrm{jet}}\rvert \le 2.8$	$80 \le p_T^{\mathrm{jet}} \le 570$	NLOjet++
	$\sigma_{\mathrm{tot}}(t\bar{t})$	[82, 88]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_{t\bar{t}}$ (*)	[81]	10 (10/10)	$-2.1 < y_{t\bar{t}} < 2.1$	$Q = m_t$	Sherpa+NNLO
LHCb	Z rapidity 940 pb	[55]	9 (9/9)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ