Diffraction and Low-x 2018

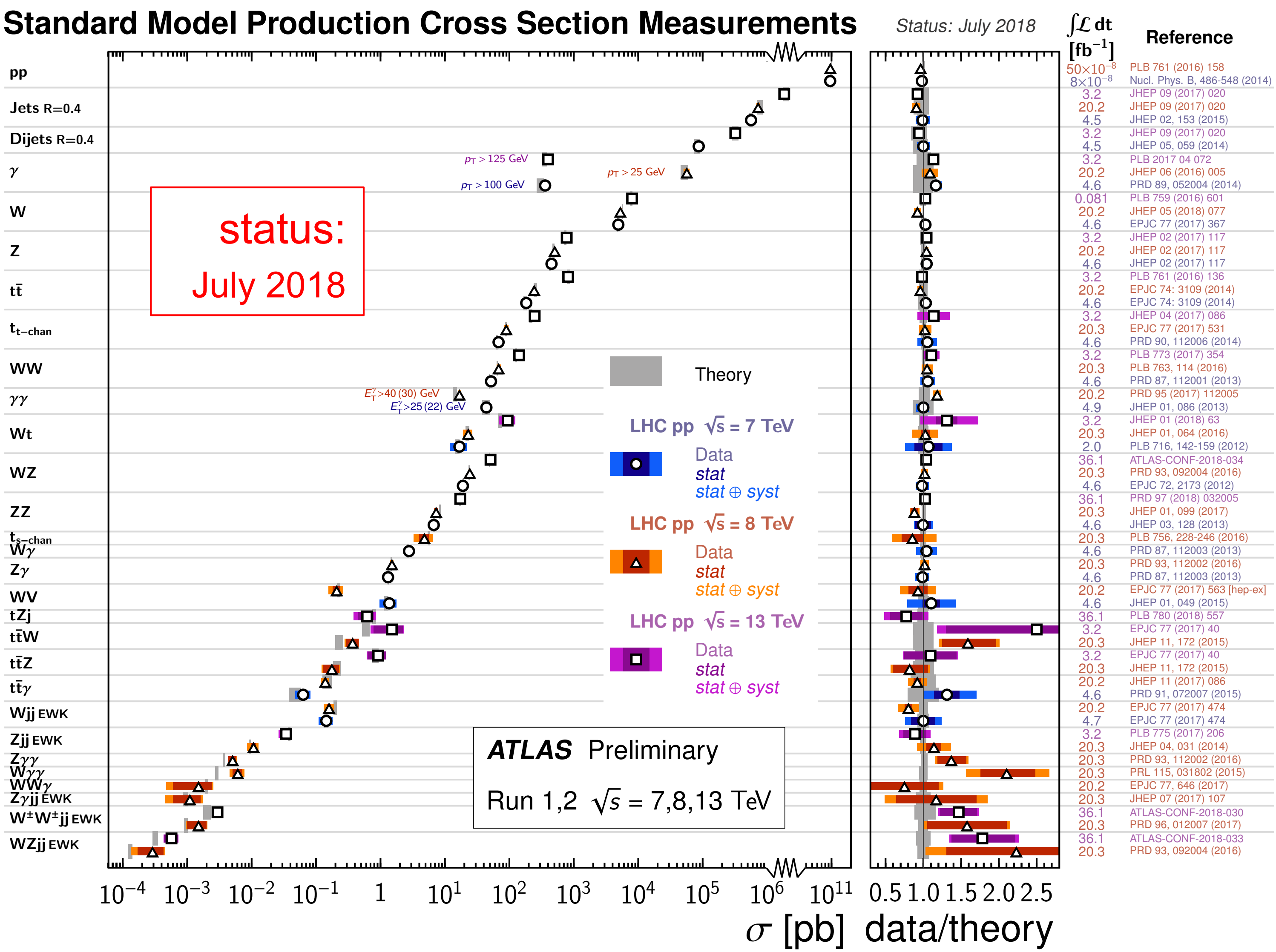
Constraints on proton PDFs by measurements with the ATLAS Detector

Claire Gwenlan, Oxford

on behalf of the ATLAS collaboration

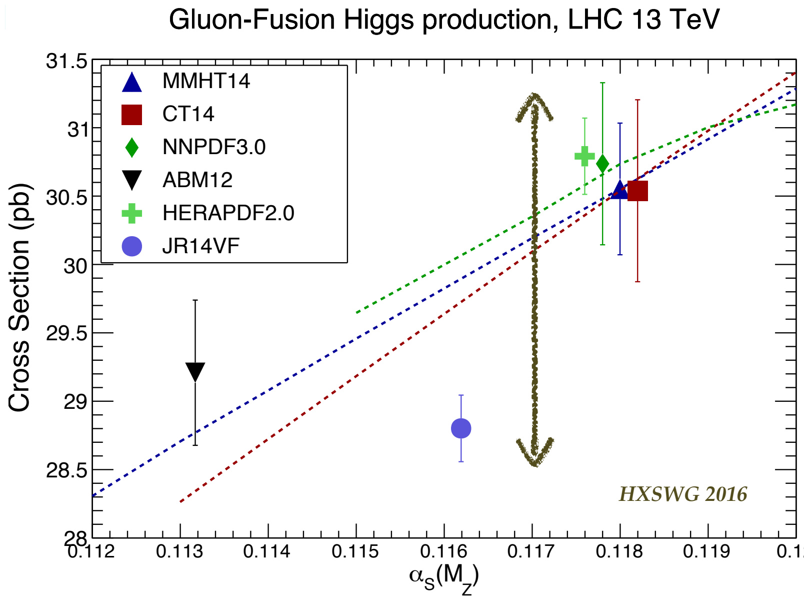
ATLAS SM measurements

… providing insight into pQCD, **proton structure (pdfs)**, non-pert. effects, and other SM parameters



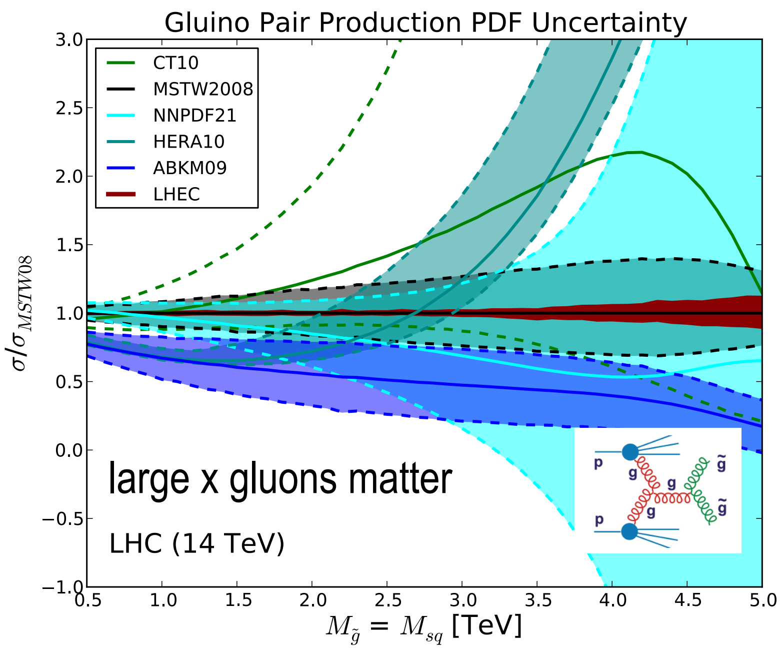
extraordinary agreement between **measurements** and **SM predictions**

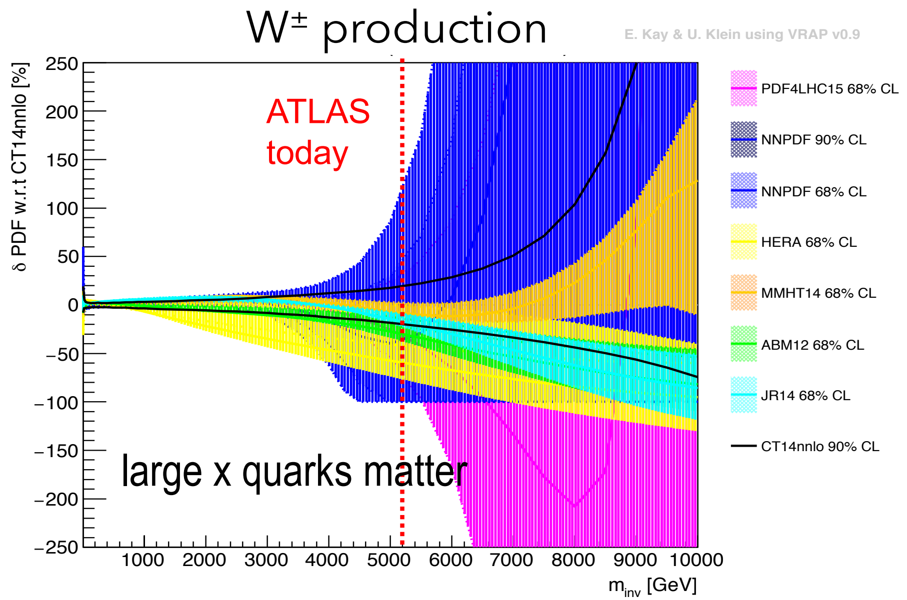
proton pdfs – why do they matter?



ATLAS 2017

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0





Mw

Higgs

BSM

…

crucial for **SM** and **BSM** physics at hadron colliders

(**other questions:** validity of factorisation in pp, intrinsic charm/beauty in proton, small x dynamics, …)

LHC measurements sensitive to pdfs

- wealth of SM measurements from ATLAS, sensitive to **pdfs**, provide:

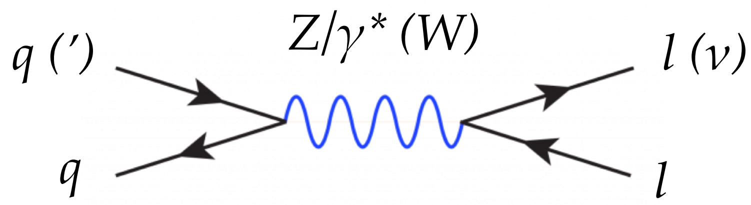
1. **pdf discrimination**, by confronting theoretical predictions with data
2. **pdf improvements**, by including LHC data in QCD fits

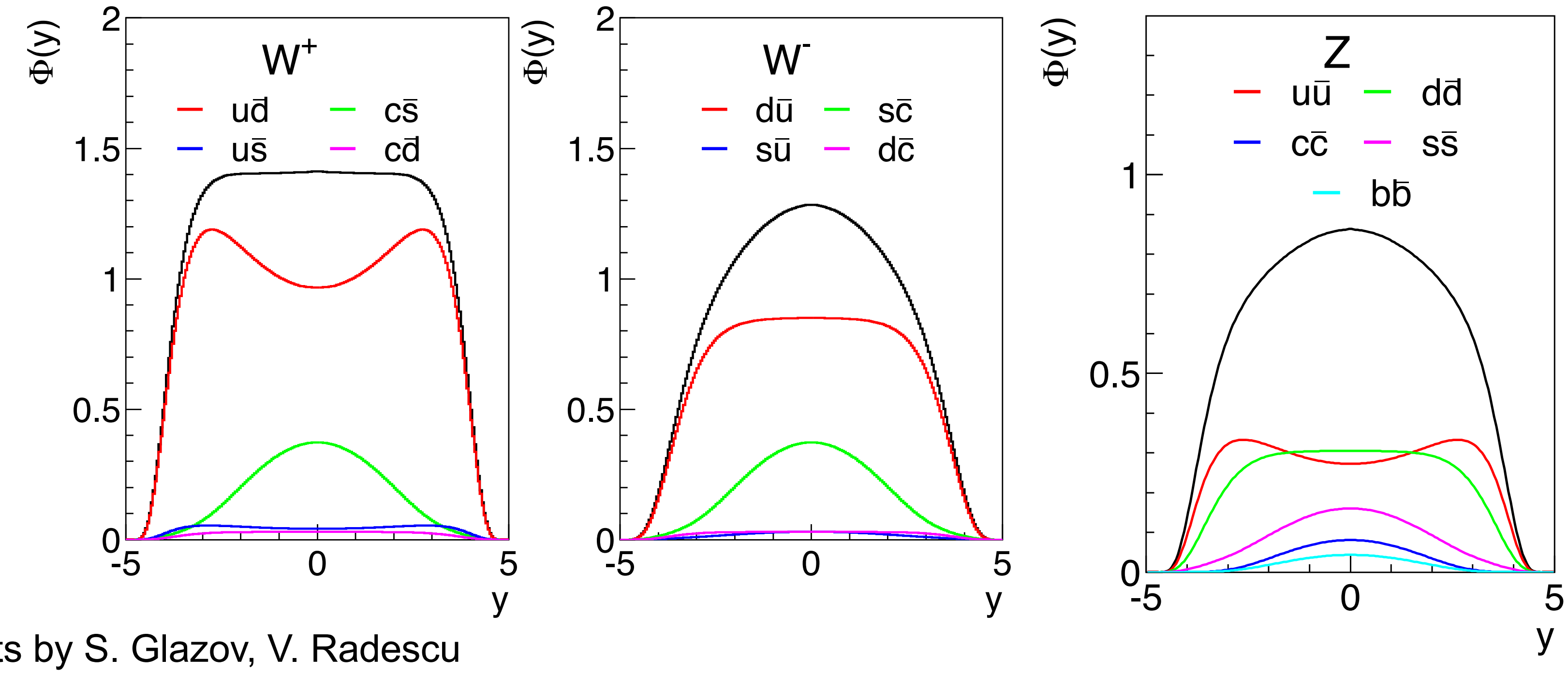
Measurement	pdf sensitivity
Inclusive W, Z and asymmetries	Quark flavor separation (u,d,s)
W with charm quarks	Direct sensitivity to s-quark
Off peak Drell-Yan at low and high mass	Quarks at low and high x (u,d), photon pdf
Inclusive jet, dijets, trijets	High x quarks and gluon (alphas)
ttbar production (total, differential)	Gluon (alphas)
Zpt	Gluon sensitivity
W,Z, W/Z production with jets	Medium x gluon
Isolated photons	Medium and high x gluon
γ or Z+c,b production	c, b quarks, intrinsic charm
Single top production	Gluon and b quark

extraction of precision **pdfs** requires both precise data, and precise theory calculations

ATLAS inclusive W, Z

- sensitivity to light quarks (u, d, s)
- different quark combinations contribute to each process; **flavour separation**





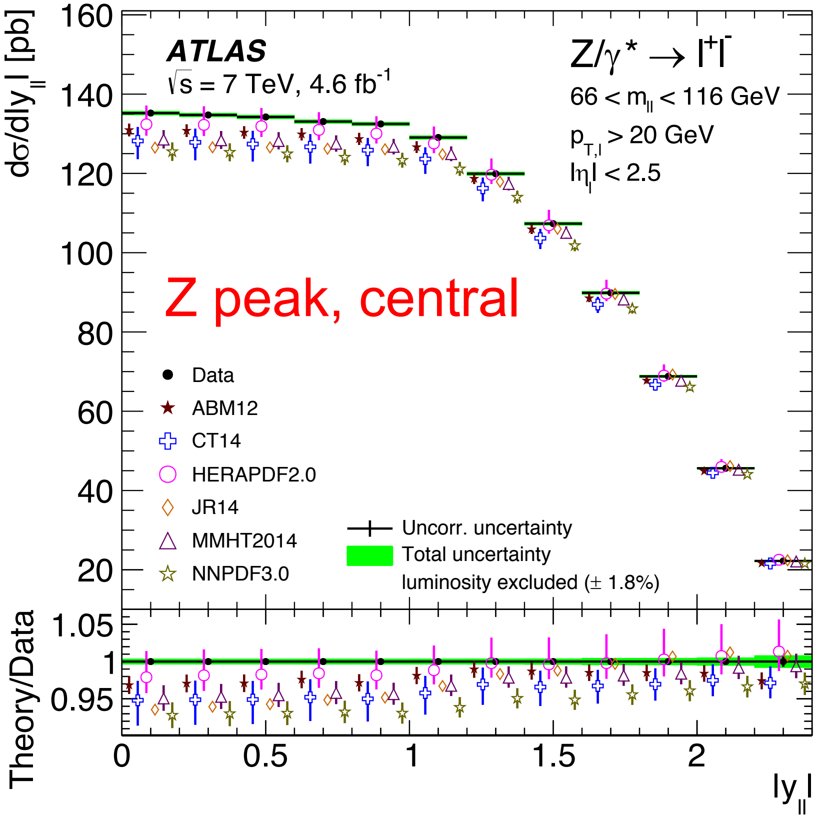
plots by S. Glazov, V. Radescu

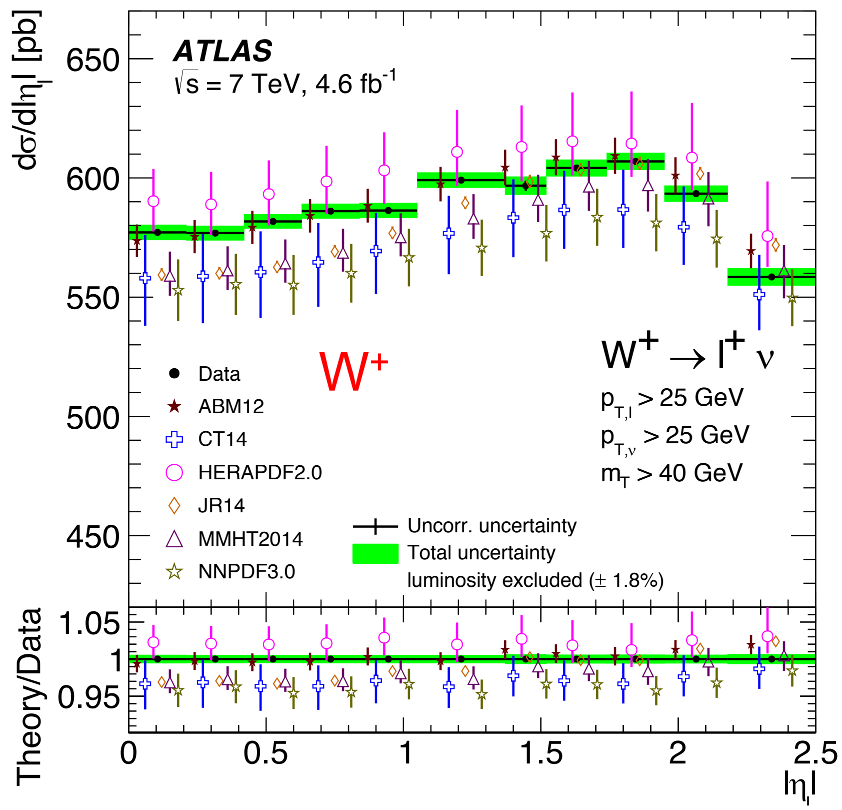
experimentally very precise; state-of-the-art theory available (NNLO QCD + NLO EW)

(accurate modelling of contribution from second-generation quarks essential for precision physics)

ultimate precision W,Z differential cross sections

ATLAS incl. W,Z differential cross sections: $W^{\pm}$ $|\eta_l|$, Z $|y_{ll}|$ (3 m_{ll} central, 2 m_{ll} forward)





EPJ C77 (2017) 367

4.6 fb^{-1}; extraordinary total experimental precision (**< 1% uncertainty)**

light quark pdf constraints; enhanced from provision of both W,Z with full syst. correlations

a strange story

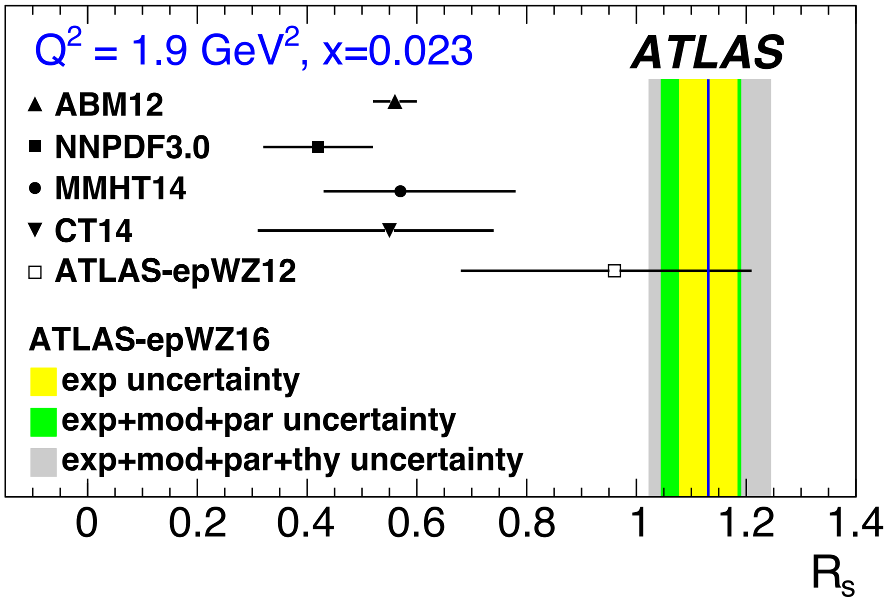
NNLO QCD analysis (following HERAPDF ansatz; xFitter framework) EPJ C77 (2017) 367

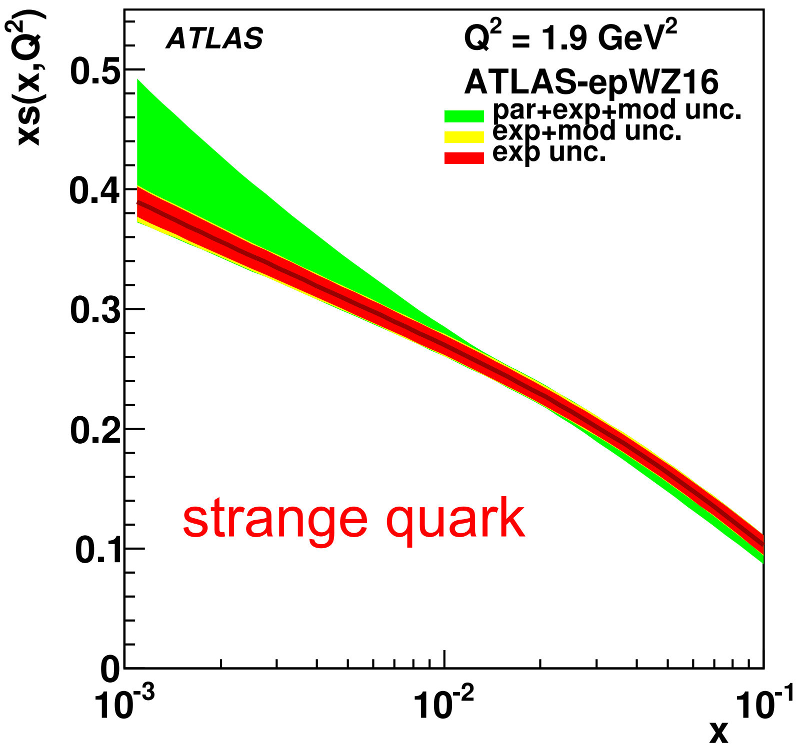
HERA I+II plus ATLAS (4.6 pb^{-1}) $W^{\pm}$ $|\eta_l|$, Z $|y_{ll}|$
(3 m_{ll} central, 2 m_{ll} forward)

NLO (MCFM interfaced to APPLGRID) plus k-factors, NNLO QCD (DYNNLO) + NLO EW (MCSANC)

→ ATLAS-epWZ16 pdf (available on lhapdf)

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$





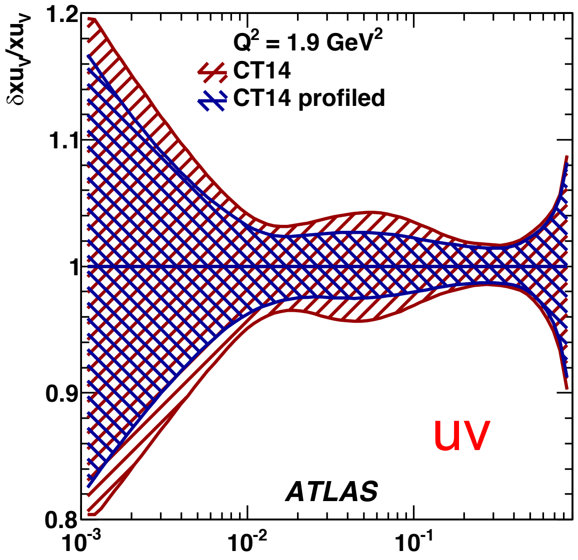
consistent with previous ATLAS results

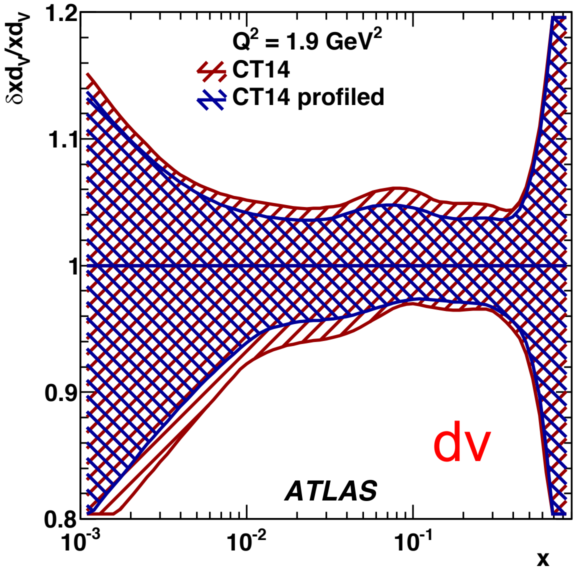
PRL 109 (2012) 012001 (W,Z inclusive, 36 pb^{-1})

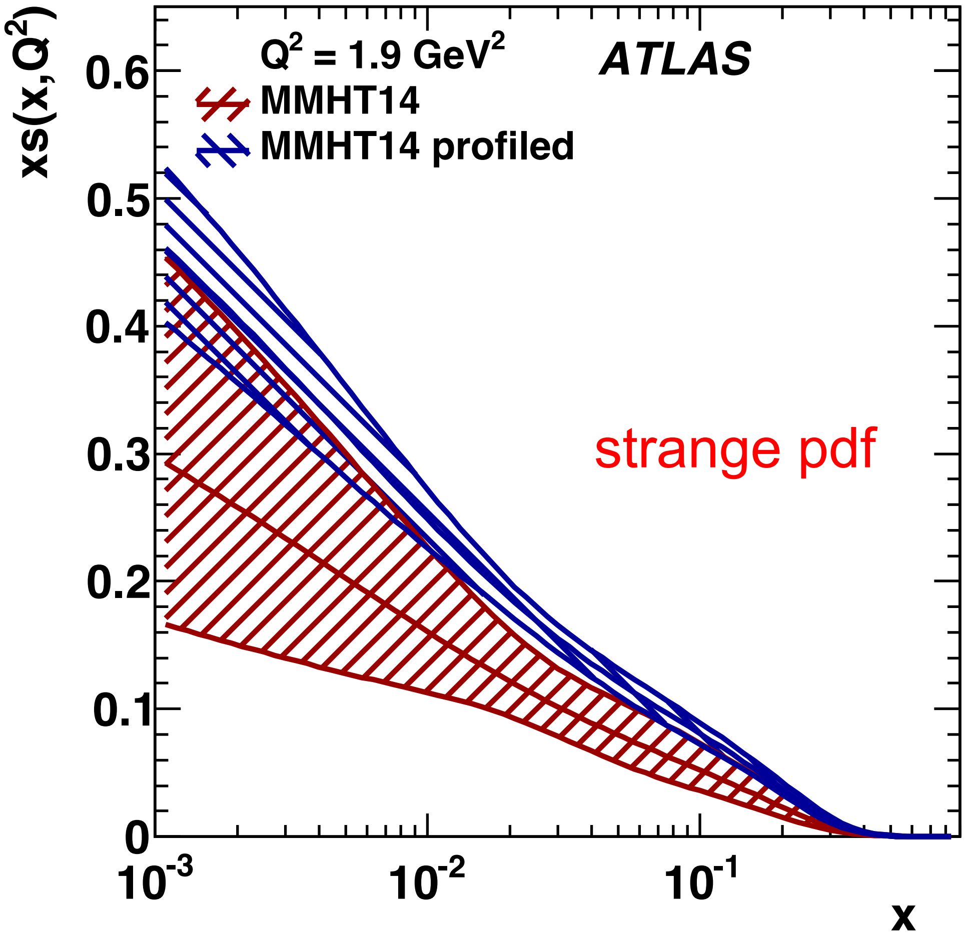
JHEP05 (2014) 068 (W+c analysis)

impact on modern global pdfs

EPJ C77 (2017) 367





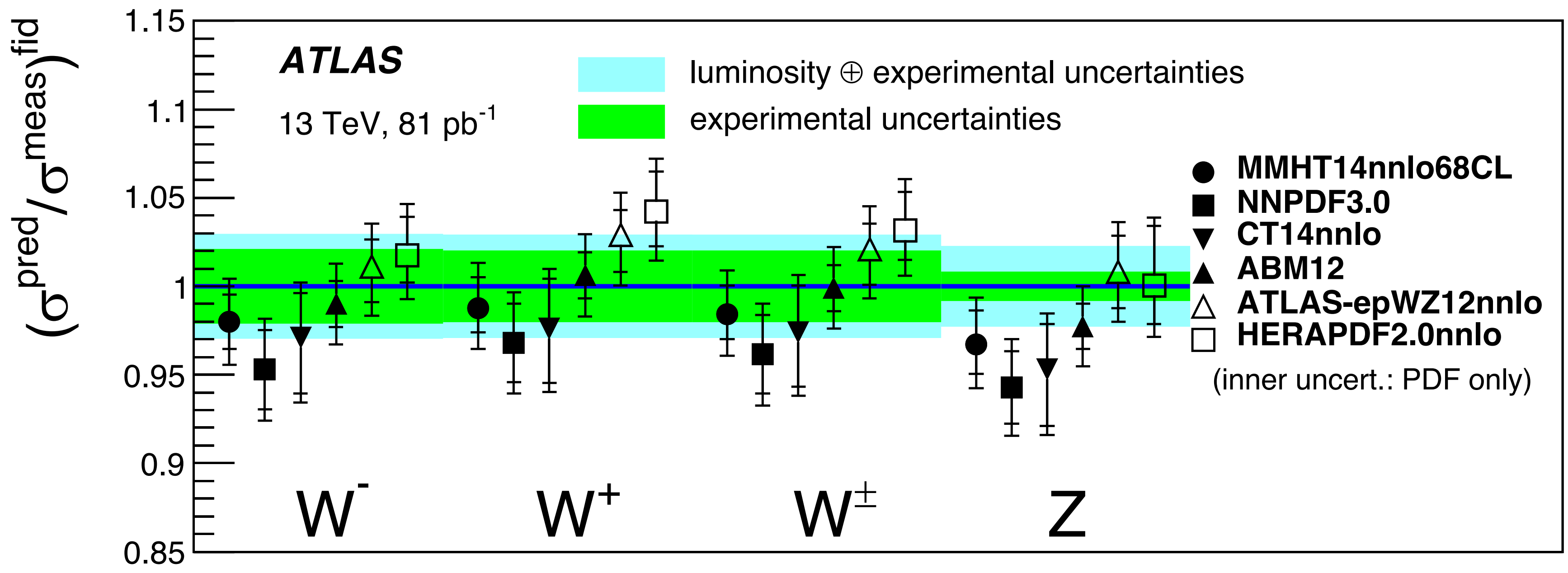


- profiling exercise to study impact of ATLAS inclusive W,Z (4.6 pb^{-1}) differential cross sections on global pdf fits

improved valence; enhanced strange, consistent with ATLAS QCD fit

ATLAS inclusive W,Z @ 13 TeV

(syst uncerts: 2% (W), 1% (Z); lumi uncert: 2.1%)   PLB 759 (2016) 601



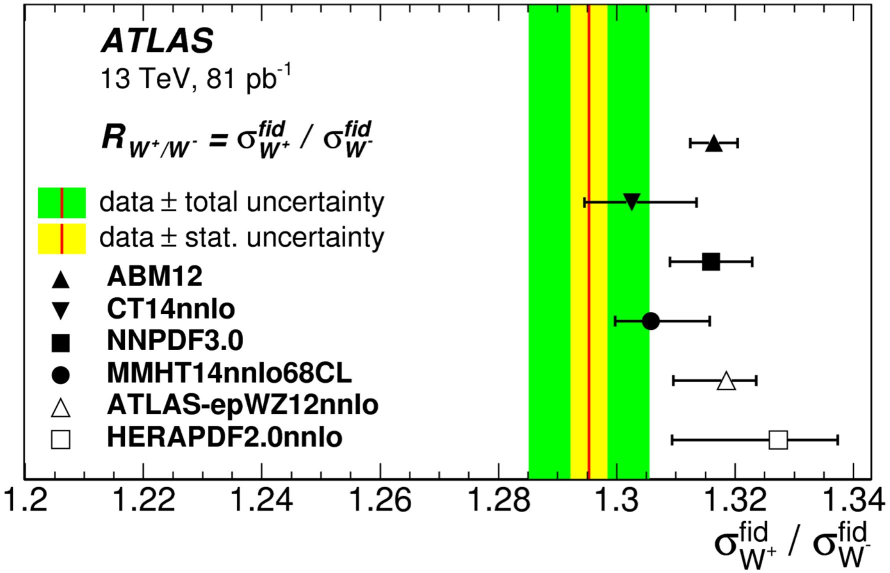
(pdfs shown use different combinations of HERA, Tevatron and LHC data)

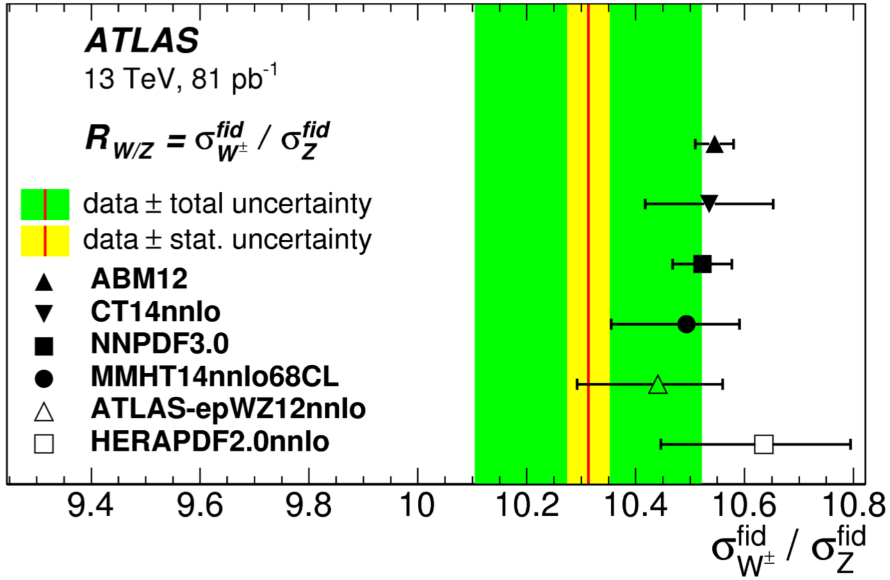
- measurements at higher CM energy give access to different kinematic region in x, providing new and complementary **pdf sensitivity**

consistent with LHC Run 1 results and provides extra handle to constrain **pdfs**

ATLAS W and Z cross section ratios @ 13 TeV

PLB 759 (2016) 601





W+/W–:

sensitive to valence quarks at low x

W/Z:

constrains strange quark density

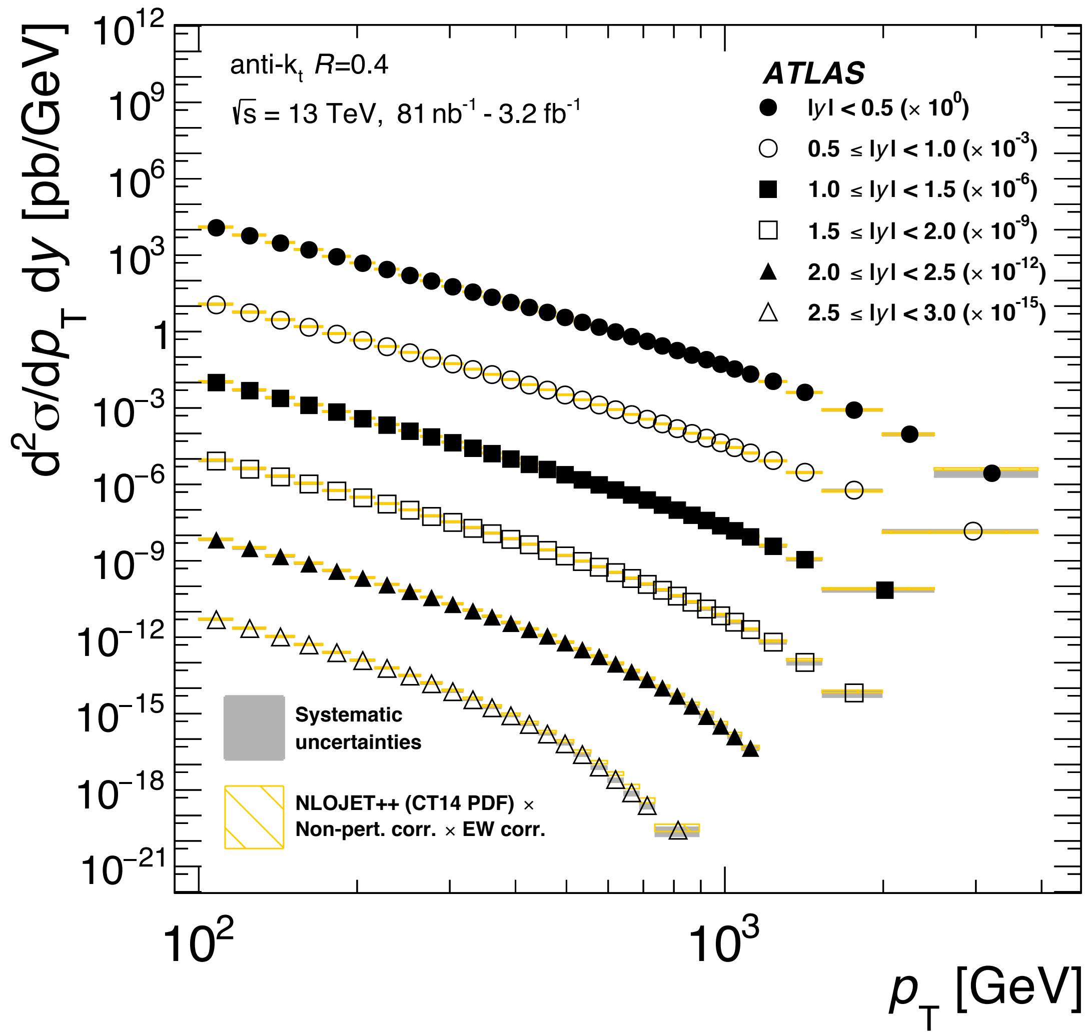
cross section ratio measurements: partial cancellation of systematics

sensitivity to pdf differences; W/Z ratio consistent with enhanced strange

ATLAS inclusive jet and dijets

JHEP05 (2018) 195

gluon at high x very poorly known – direct impact on BSM searches

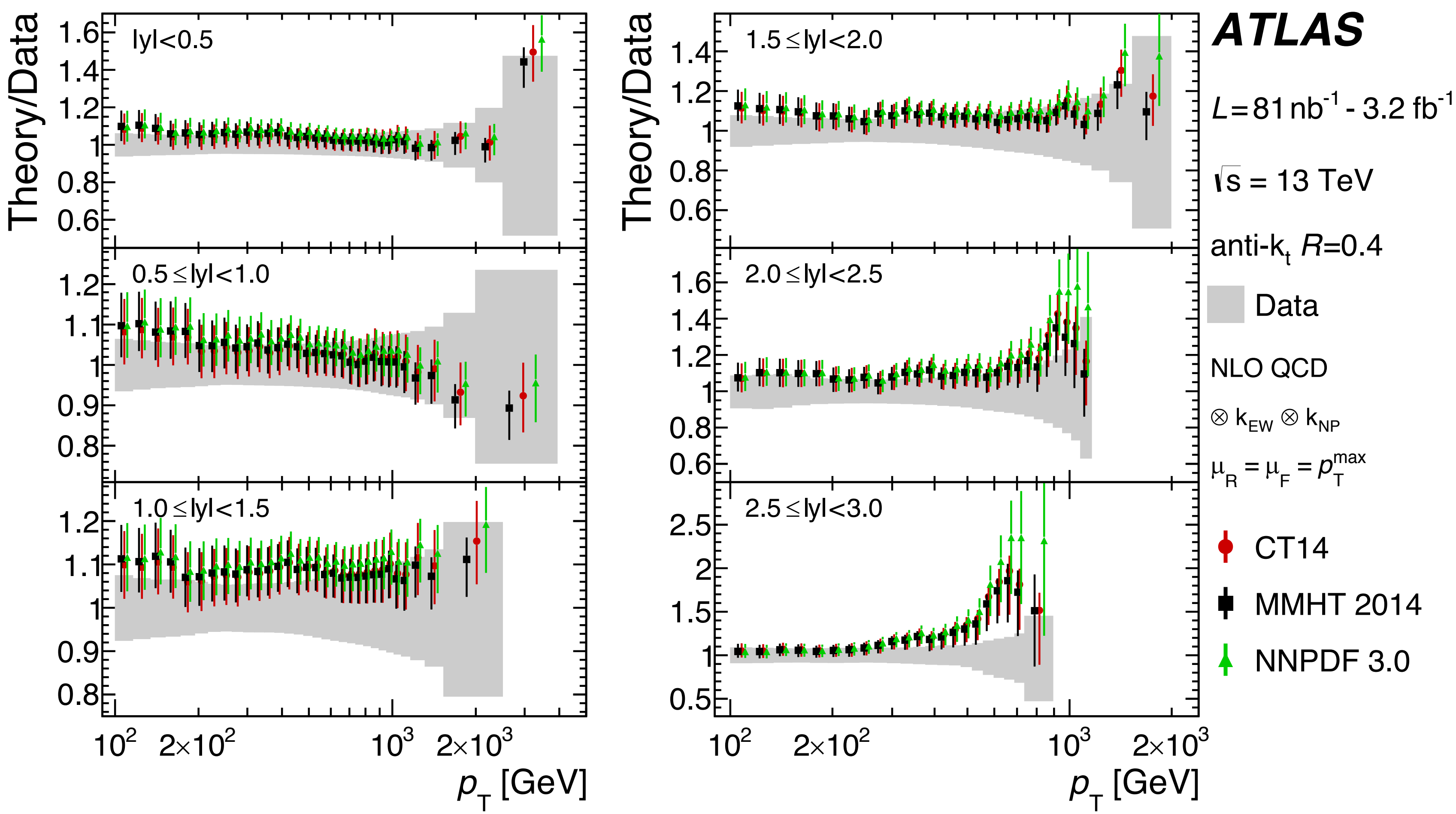


- **jet production** in pp sensitive to **gluon** and **quarks** at high x
- new ATLAS 13 TeV measurements of **inclusive jets** (dijets) reach to pt=3.5 TeV (mjj = 9 TeV)

(see, also, talk by: G. Callea)

ATLAS inclusive jets in detail

JHEP05 (2018) 195



cf. **NLO QCD** – quantitative comparisons performed for CT14, MMHT14, NNPDF3.0, ABMP16, HERAPDF2.0

tension when considering all rapidity bins together; also seen previously with 7,8 TeV measurements;

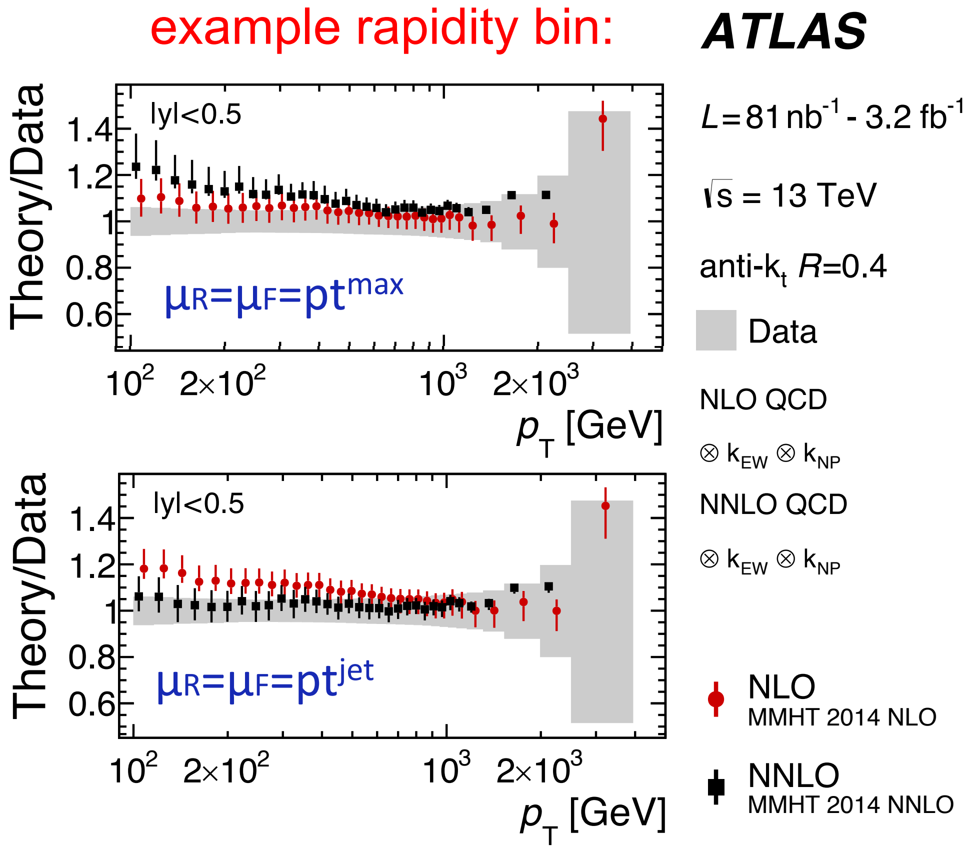
sensitive to exact assumptions on corrs. for two-point systs. ie. those evaluated from difference between two model choices; see EG. JHEP09 (2017) 020

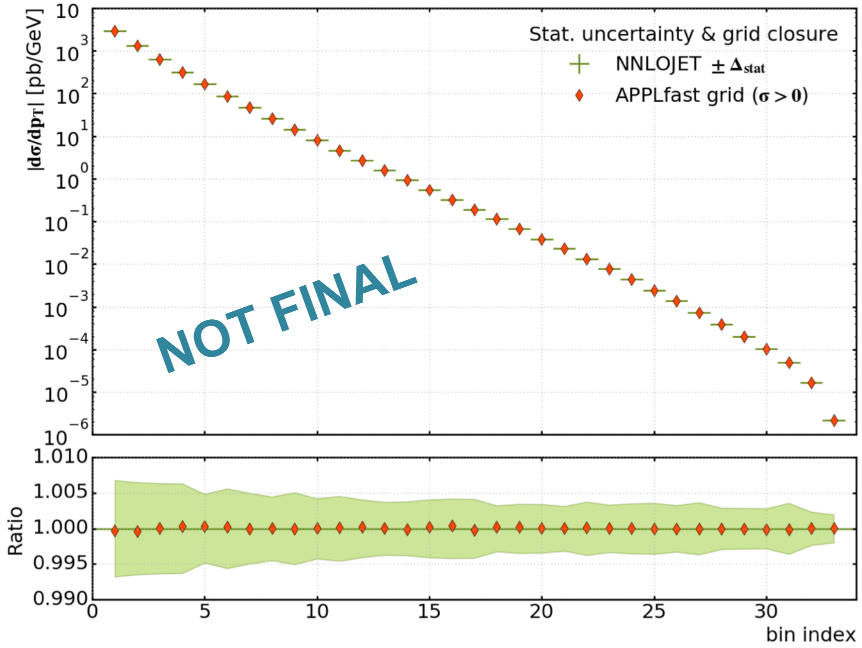
ATLAS inclusive jets cf. NNLO QCD

JHEP05 (2018) 195

APPLfast coll., status report, DIS18

example rapidity bin:





APPLfast reproduction of NNLOJet incl. jet cross section

- **NNLO QCD** calcs. for inclusive and dijets available (PRL 118 (2017) 072002, 119 (2017) 152001)
- **inclusive jets:** NNLO improves description for scale choice of pt^{jet}

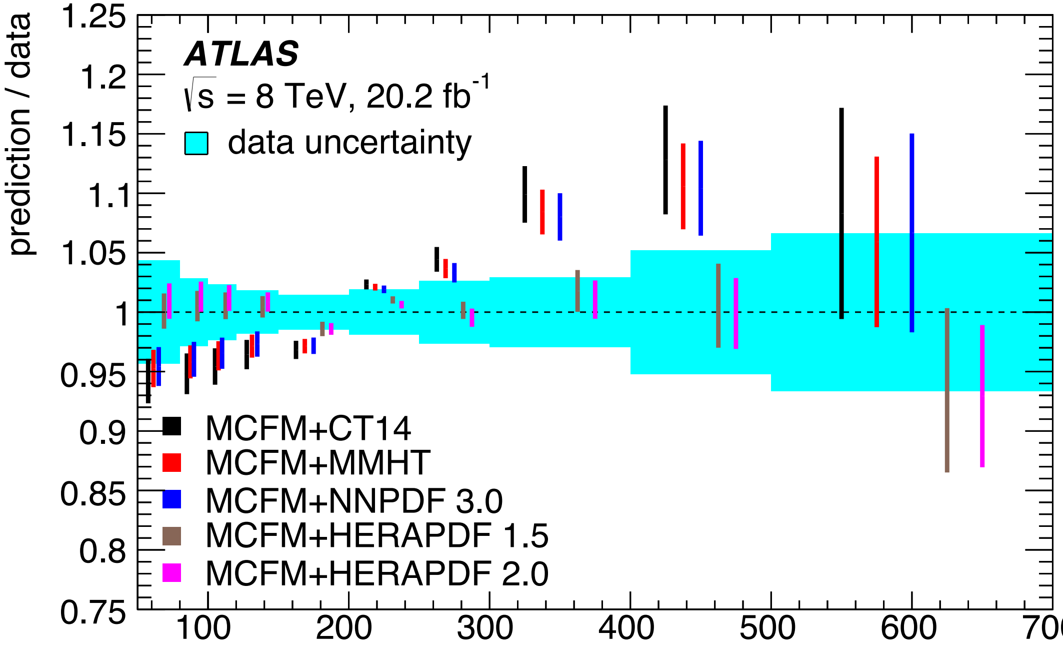
  (NB, recent review by J. Currie et al., arXiv:1807.06057, favours choice of $2\times pt^{jet}$)
- APPLfast grid technology on the way to allow rigorous inclusion in pdf fits at NNLO

ATLAS top quark pair differential cross sections (1)

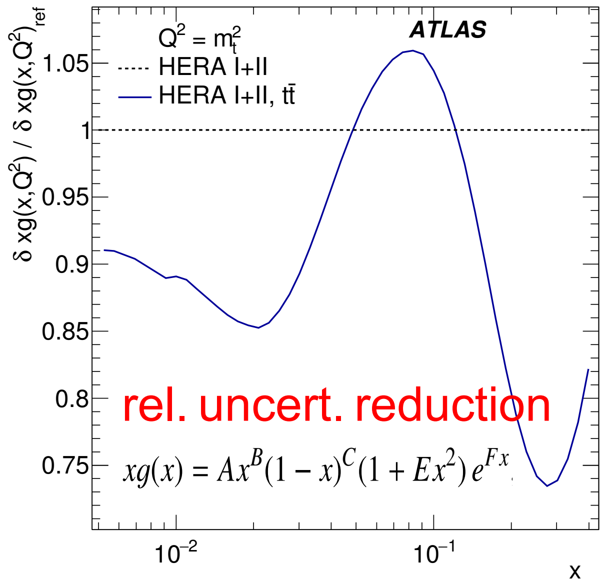
mainly via gg channel – constraints on **gluon**

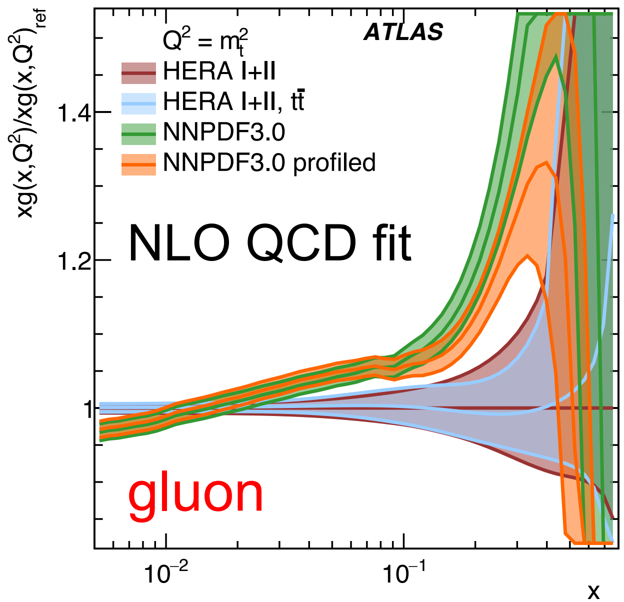
wealth of useful top measurements from ATLAS

EG. dilepton channel ttbar measurement (8TeV, 20.2 fb^{-1}) of **leptonic variables**; comparison of normalised cross sections to NLO QCD, corrected for QED FSR ↓



EPJ C77 (2017) 804





also extracted: $m_t^{\text{pole}} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\,\text{GeV}$

ATLAS top quark pair differential cross sections (2)

NNLO QCD calcs. for differential distributions with **stable top quarks** also now available, and implemented in fastNLO (PRL 116 (2016), 082003; JHEP04 (2017) 071)

NEW for this conference:

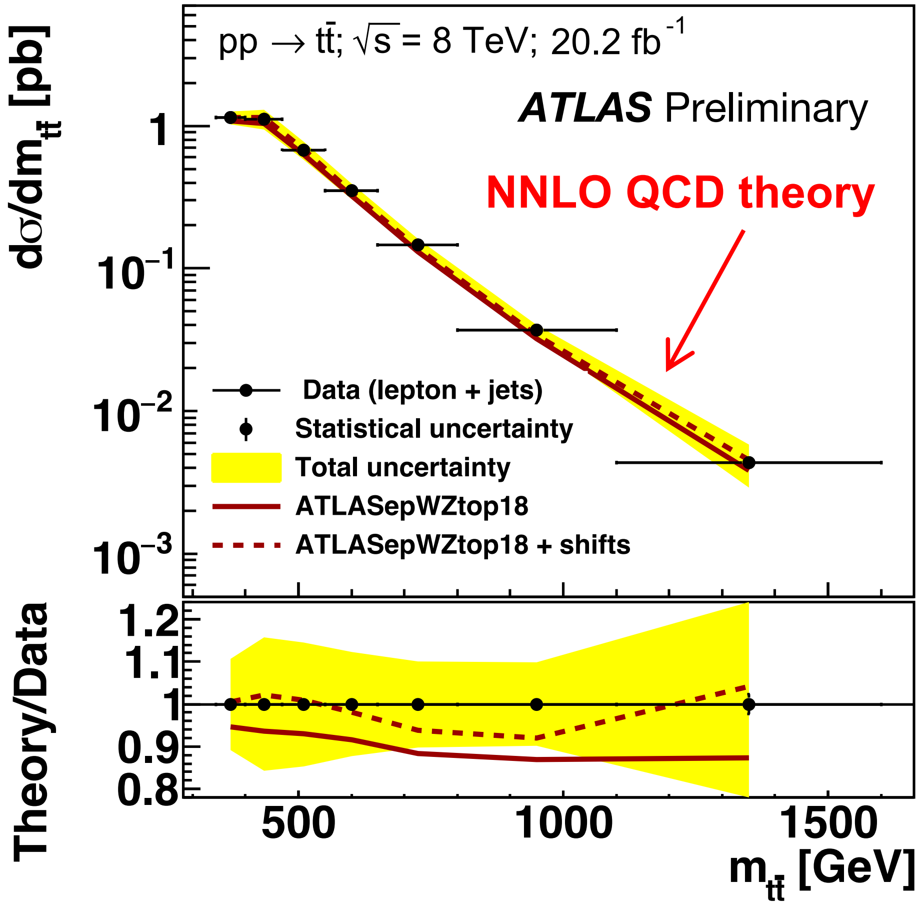
ATLAS NNLO QCD analysis:

HERA I+II + ATLAS W,Z +
ATLAS ttbar cross sections in lepton+jet and di-lepton FS †

multiple spectra considered simult., taking into account stat+syst corrs

NB, **statistical correlations for lj**, within and between spectra, **newly available**; in addition to syst corrs for all lj+ll spectra

ATLAS-PHYS-PUB-2018-017



† ATLAS top quark pair data: EPJ C76 (2016) 538 (lj) and Phys Rev D94 (2016) 092003 (ll)

ATLAS top quark pair differential cross sections (2)

fit quality dependent on choice of spectra (**lj**: mtt, pTt, yt, ytt; **ll**: mtt, ytt), and treatment of two-point† systematic correlations (impact of stat corrs small, but non-negligible)

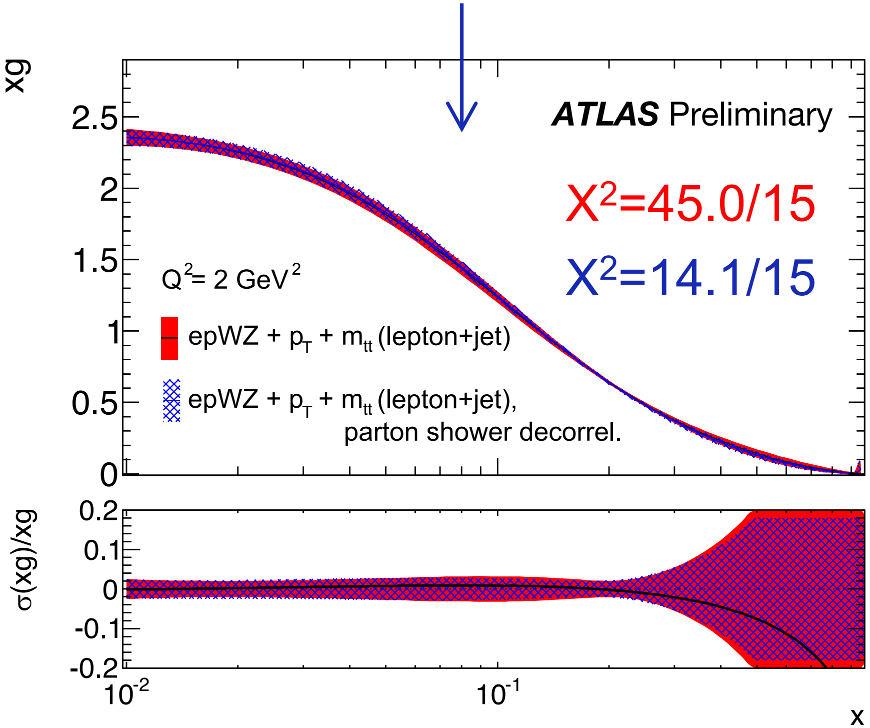
tension observed with lepton+jet yt, ytt distributions

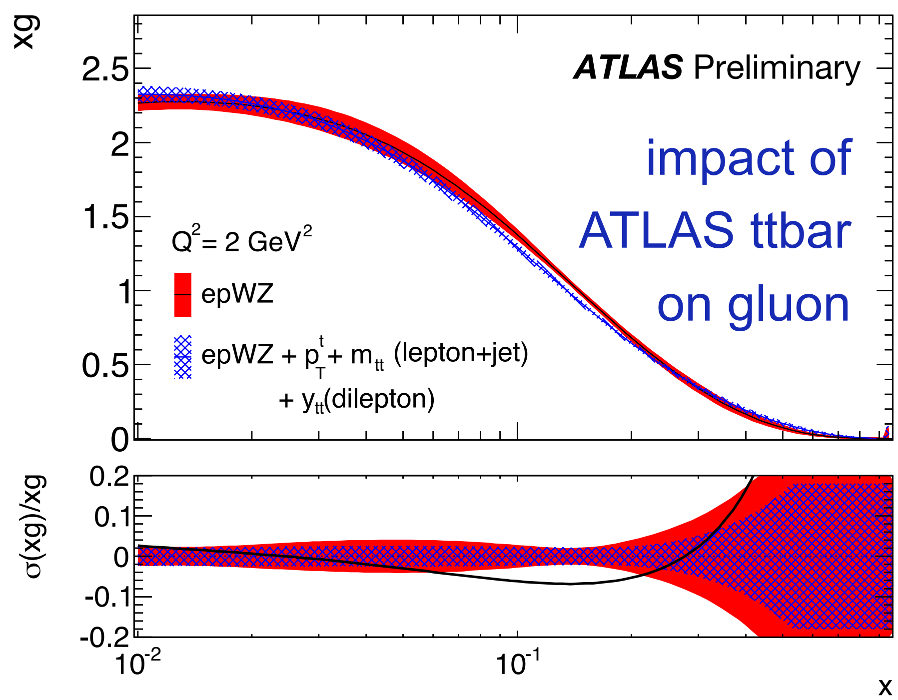
ATLAS-PHYS-PUB-2018-017

other spectra fit well individually;

in combination, quality sensitive to treatment of two-point systematics, especially parton shower uncertainty

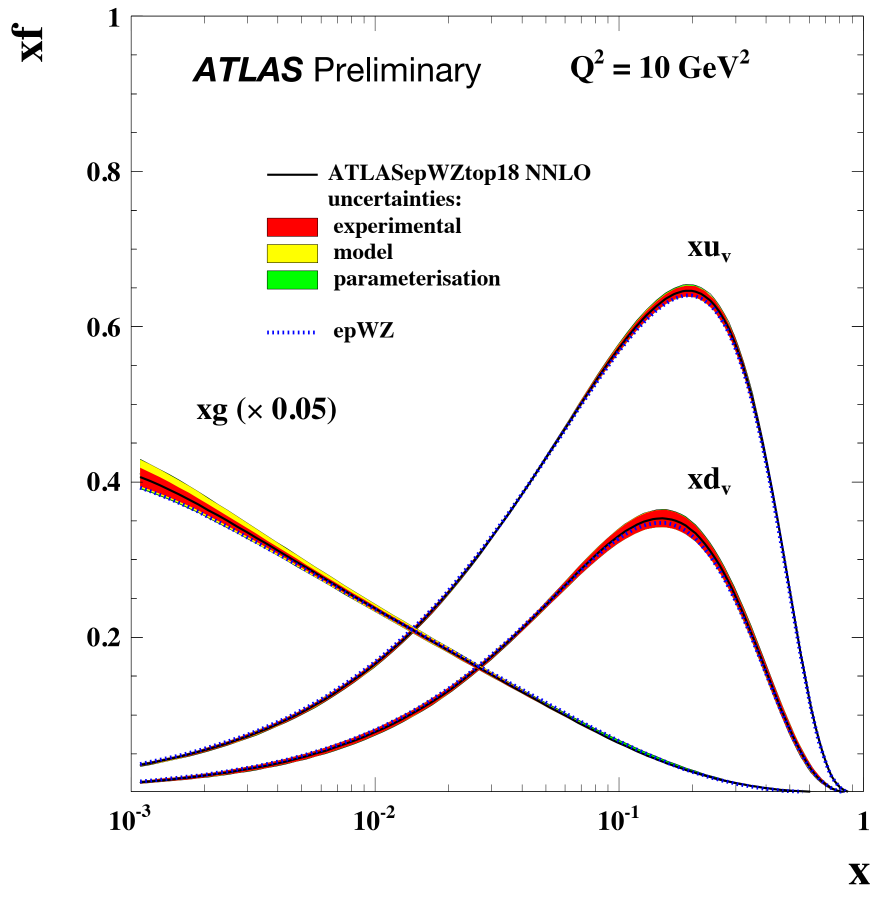
final choice of spectra: mtt+pTt (lj) + ytt (ll)

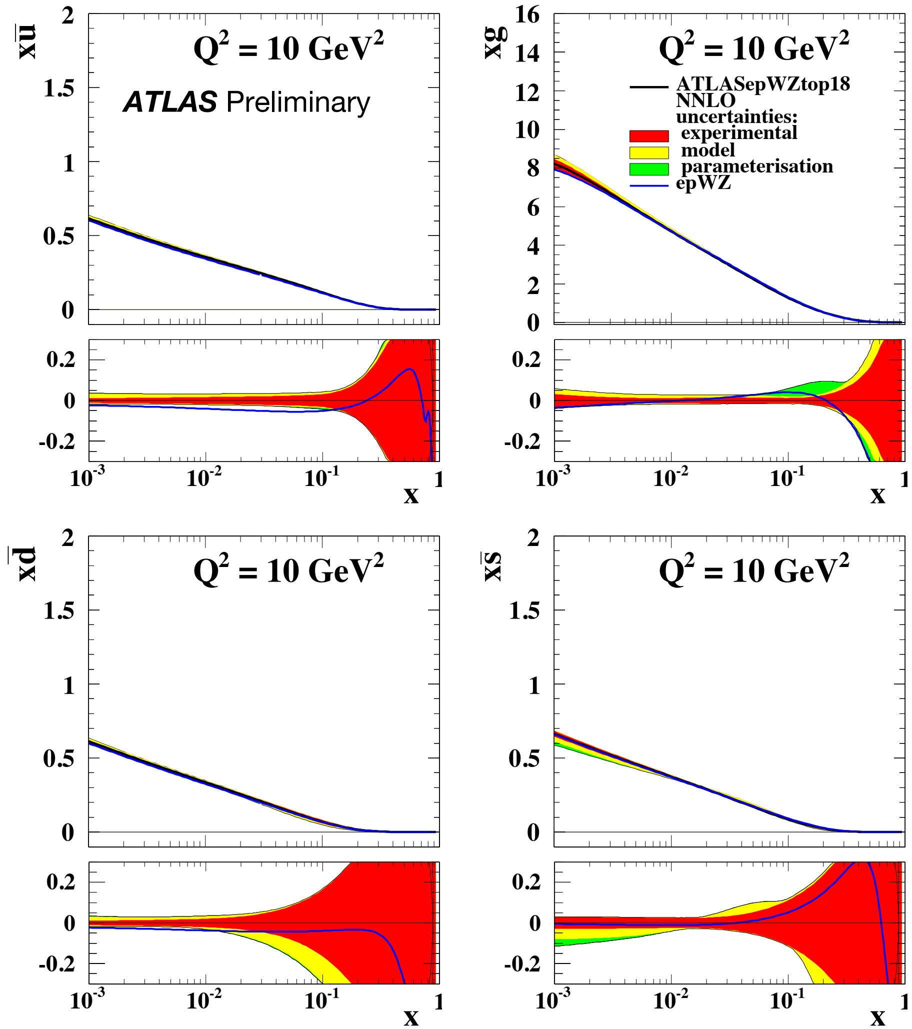




ATLAS top quark pair differential cross sections (2)

NEW ATLASepWZtop18 pdf: HERA I+II + ATLAS W,Z + ATLAS ttbar (mtt+pTt (lj) + ytt (ll))

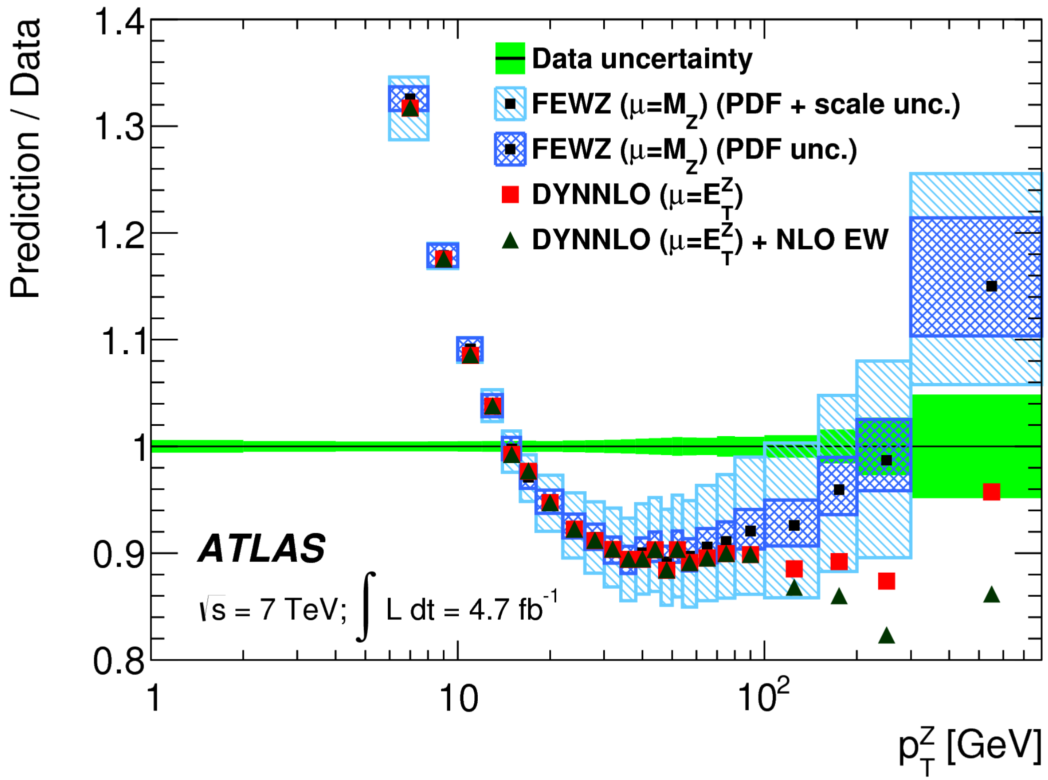


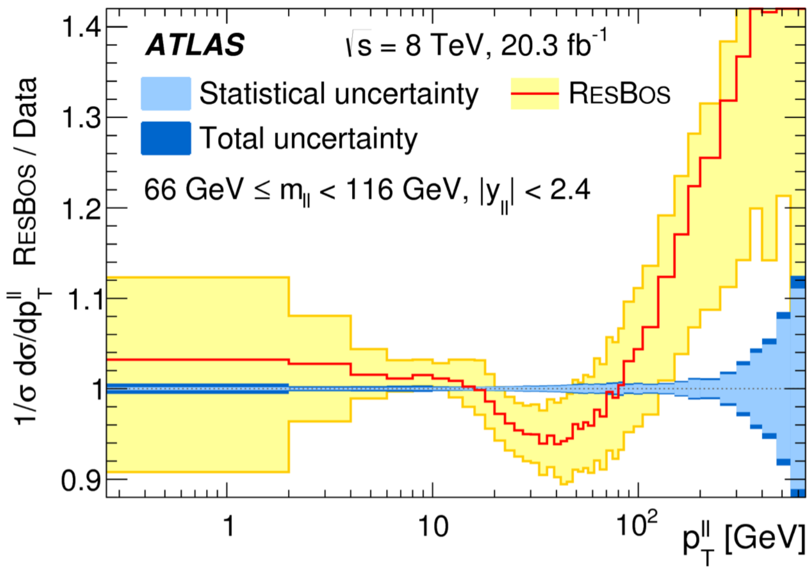


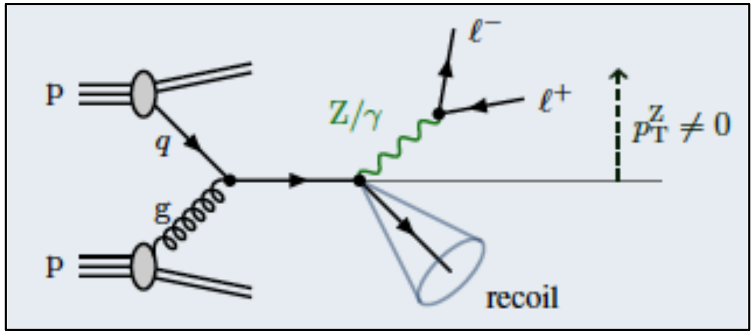
ATLAS-PHYS-PUB-2018-017

ATLAS ptZ

JHEP09 (2014) 145
EPJ C76 (2016) 291







sensitive to **pdfs**, especially gluon

experimentally, very precise

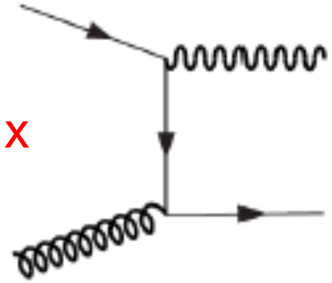
ATLAS: ee, μμ channels; combined precision better than 0.5% precision for pt < 100 GeV

theoretically challenging – low pt region dominated by soft particle emission (resummation, shower models); high pt region dominated by emission of hard partons (pdfs)

(NNLO available; APPLfast grids on the way)

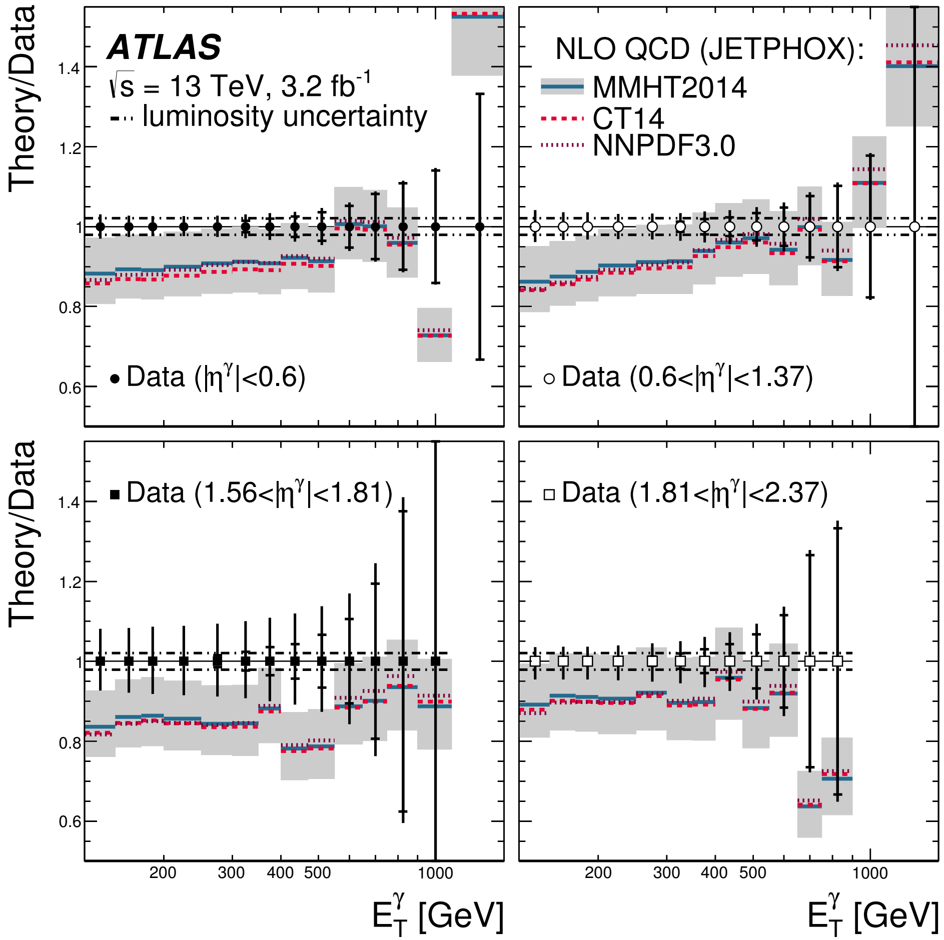
ATLAS prompt photon

PLB 770 (2017) 473



isolated photons: mainly sensitive to gluon at medium to high x

(syst uncerts. 5 – 19% at highest E_t^γ; lumi uncert: 2.1%)

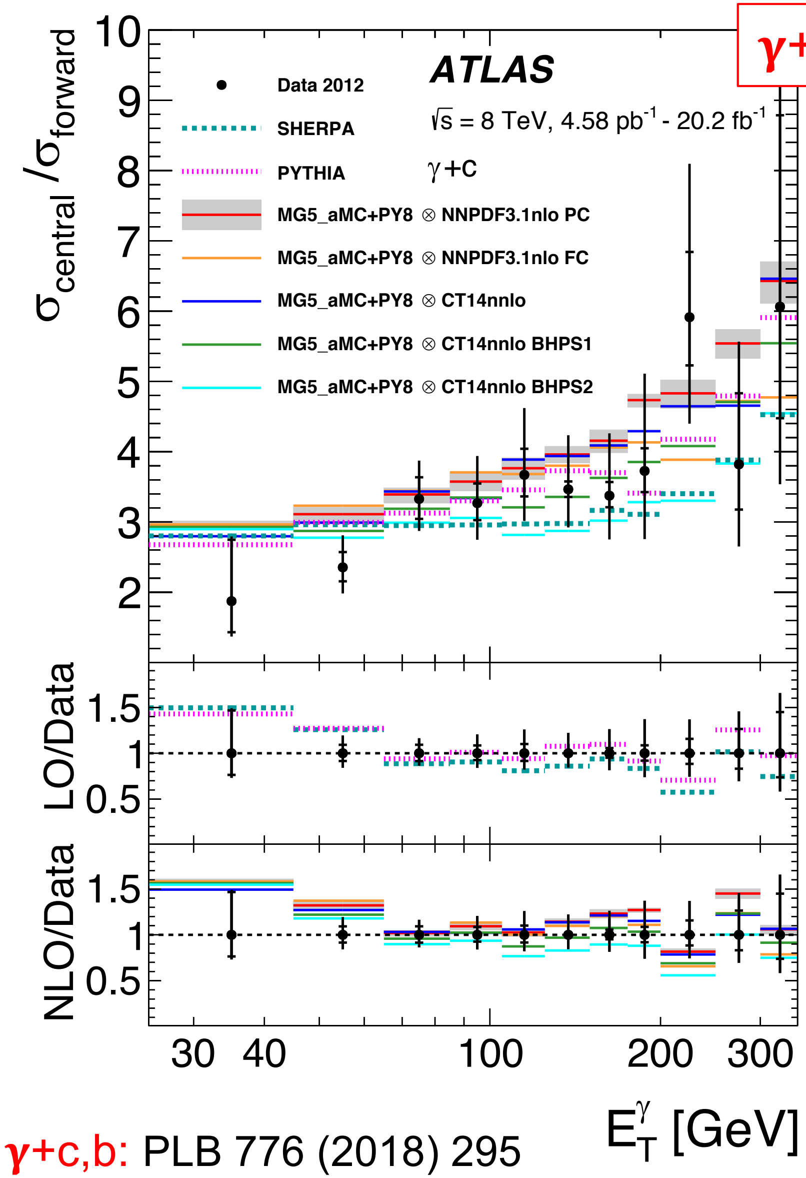


- clean experimental environment
- cf. JETPHOX (NLO QCD)
  theory uncertainties dominate across most of phase space
- measurements available at different CM energies – similar Et, Q^2 regions sample different x
- NNLO corrections available
  PRL 118 (2017) 222001

(see, also, talk by: G. Callea)

examples of c,b from ATLAS

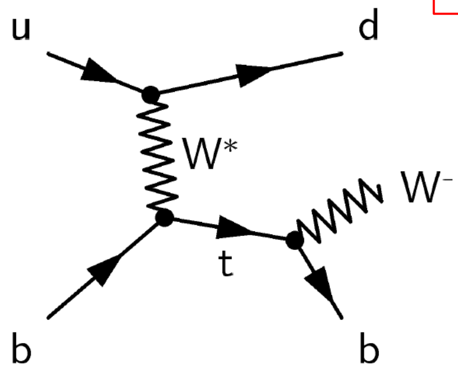
γ+c



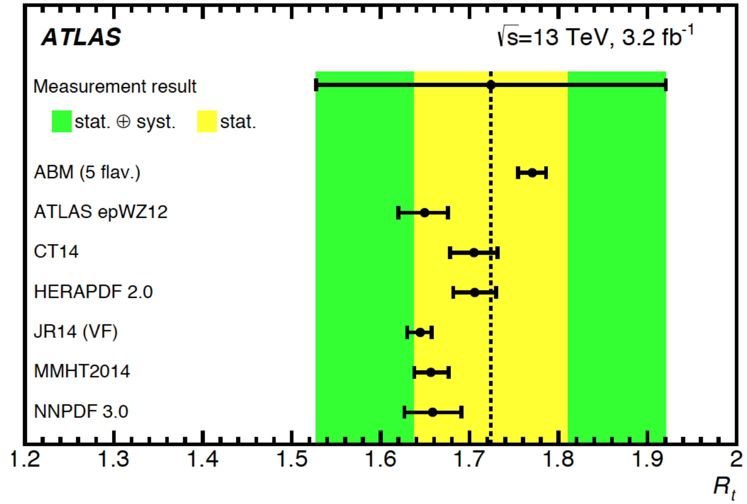
γ+c,b: PLB 776 (2018) 295

Z+b: JHEP10 (2014) 141

single top

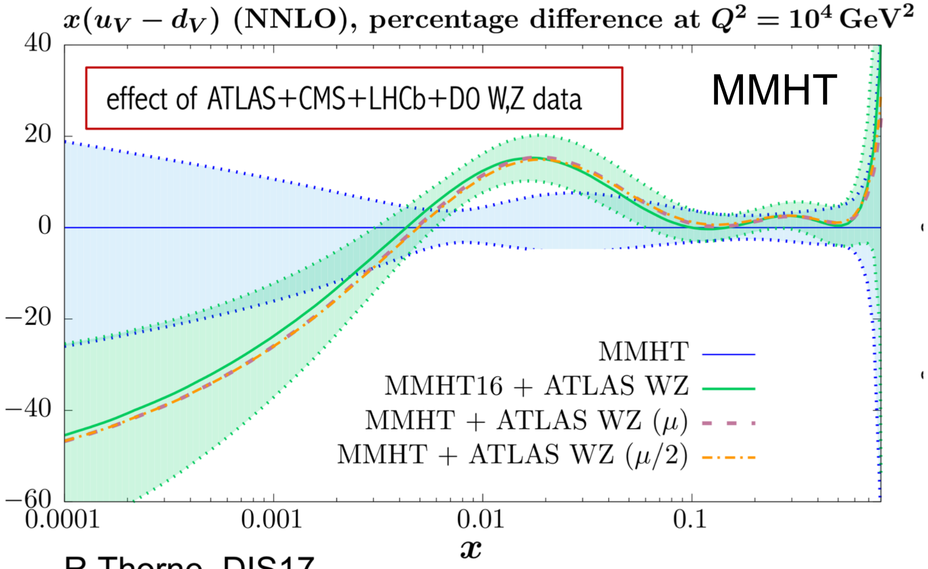


Rt = σ(tq)/σ(tbarq)

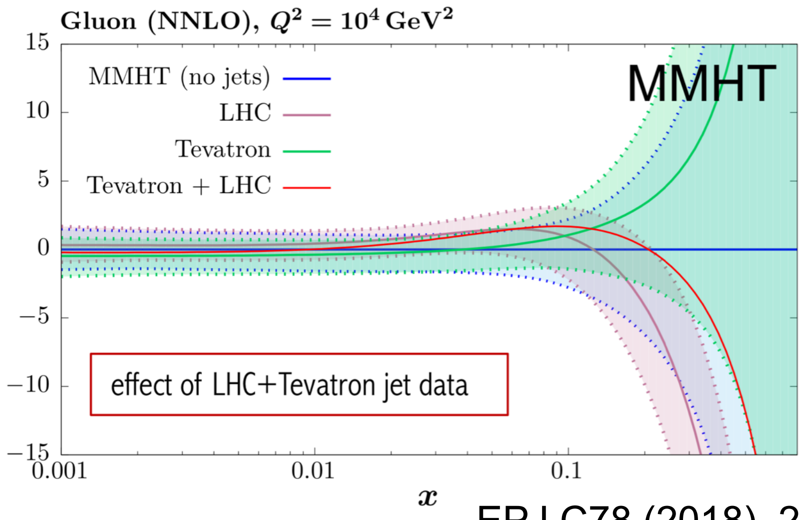


JHEP04 (2017) 086

impact of LHC data on modern global pdf fits



R.Thorne, DIS17

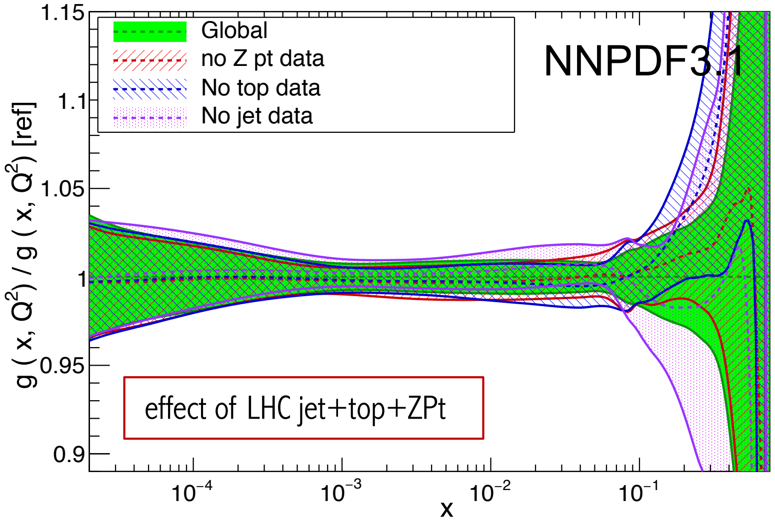


EPJ C78 (2018), 248

global pdf fitters actively including LHC data from **ATLAS**, CMS and LHCb

many measurements shown in this talk are yet to be included

much more still to come…



EPJ C77 (2017), 663

summary

ATLAS has extensive and growing portfolio of **pdf-sensitive** measurements

only a tiny subset presented here – others not discussed here include:
LM/HM DY; W+c; QCD jets at 2.76,7,8 TeV; many more top measurements; W,Z+Jets; …

measurements of same process at **different CM energies**, and **ratio measurements** (EG. of different processes, or same process at different energies) with partially cancelling systematics can provide significant **pdf constraints**

new **ATLAS NNLO QCD pdf**, incl. **top quark pair differential cross sections**

NNLO QCD calculations available for other important physics processes –
developments in grid technology (APPLfast) mean these data should be useable in rigorous NNLO pdf fits in the near future

still much to come from ATLAS from both Run 1 and Run 2 SM analyses

extras

ultimate precision W, Z differential cross sections

Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+ \nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^- \bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 46 – 66 GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 66 – 116 GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 66 – 116 GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 116 – 150 GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 116 – 150 GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

EPJ C77 (2017) 367

ultimate precision W,Z differential cross sections

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

e 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	

μ channel

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ATLASepWZ16 QCD fit parameterisation

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

total of 15 free parameters

with constraints:

$A_{\bar{u}} = A_{\bar{d}}$

$B_{\bar{s}} = B_{\bar{d}} = B_{\bar{u}}$

ensuring ubar=dbar as x→0:

A_g (momentum sum) A_{u_v} A_{d_v} (number sum)

impact on modern global pdfs

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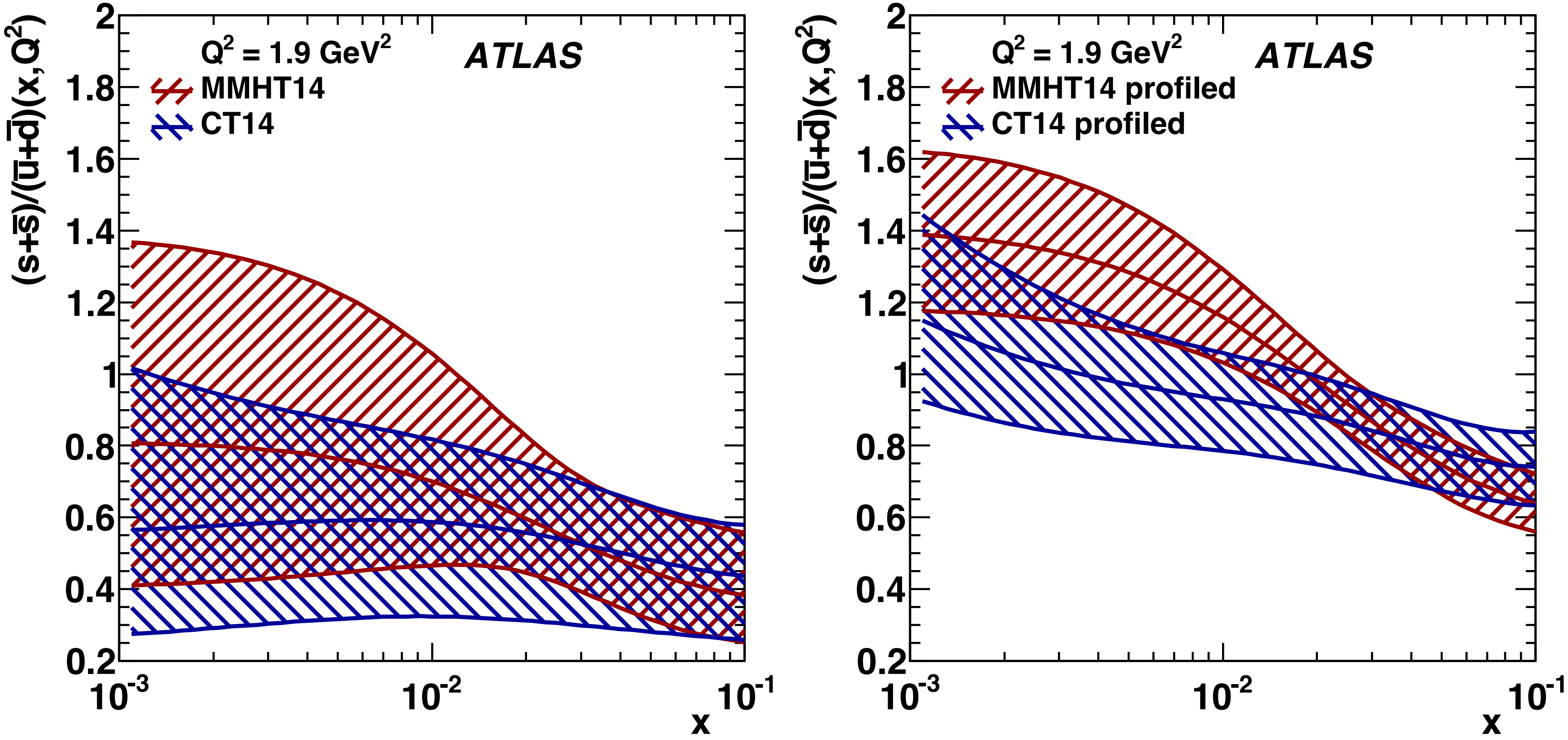
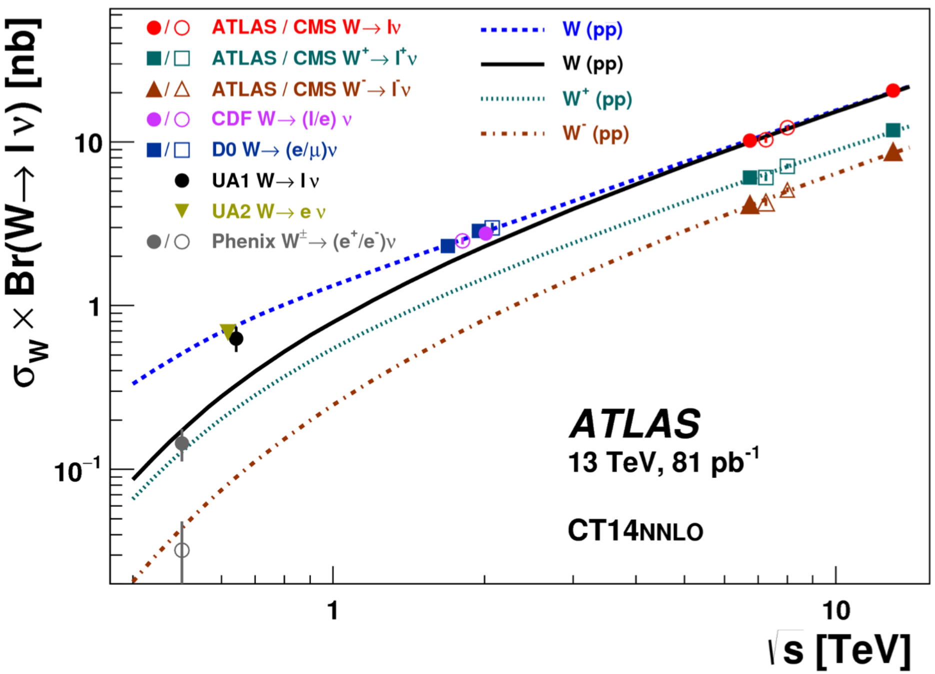
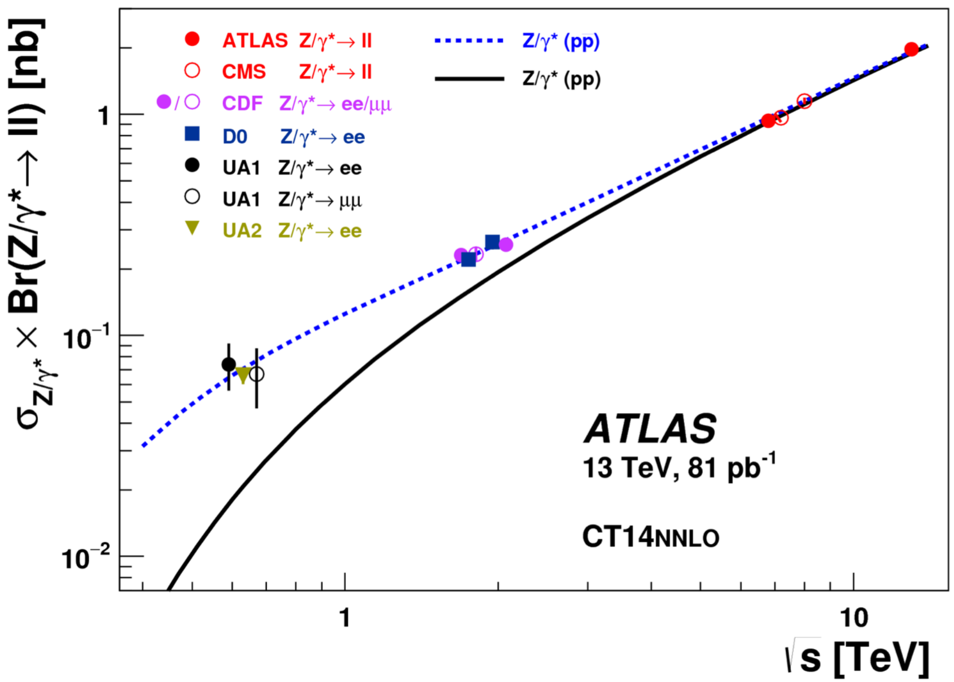


- profiling exercise to study impact of ATLAS W, Z (4.6 pb^{-1}) differential cross sections on proton pdfs from global fitters

ATLAS inclusive W, Z

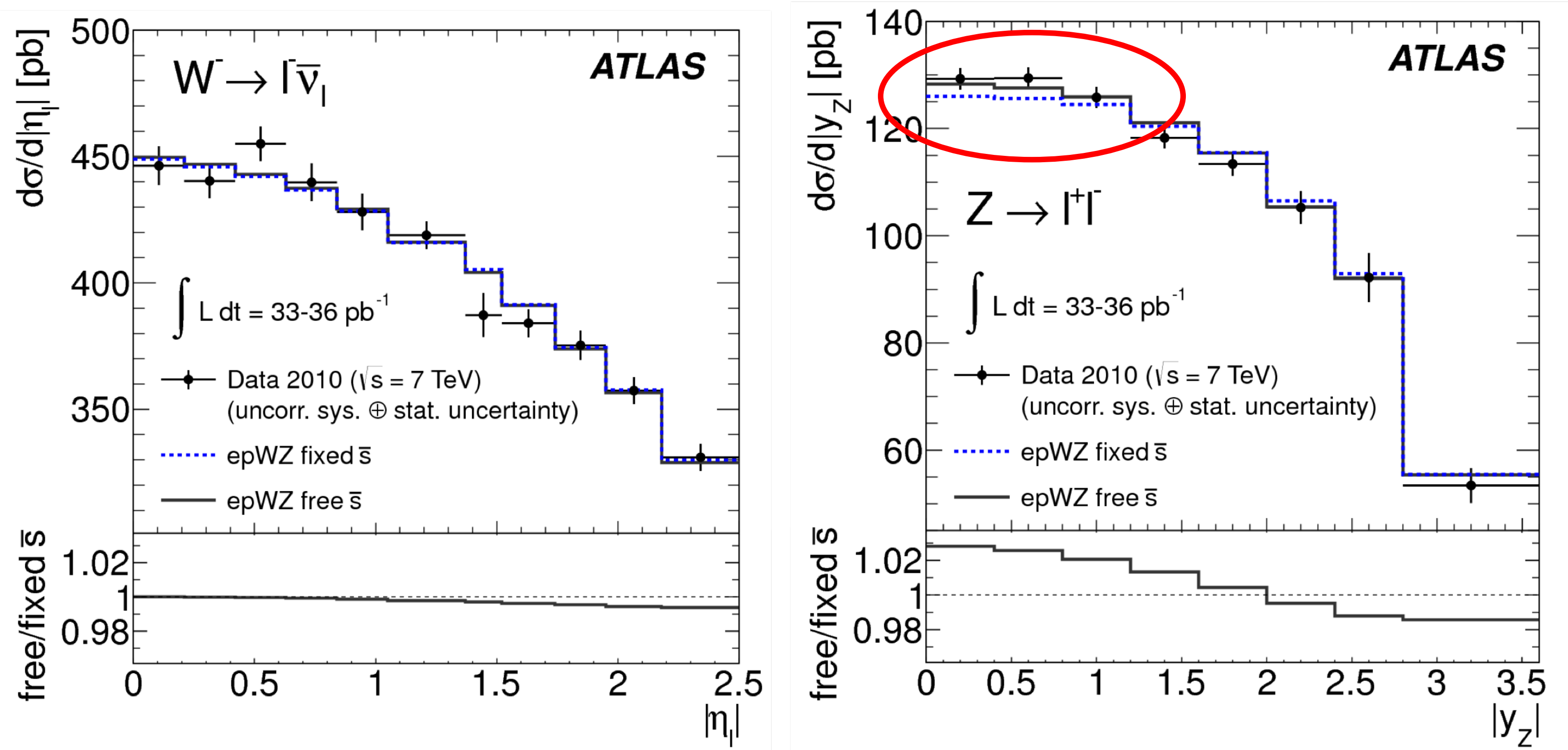
PLB 759 (2016) 601





energy dependence well described

ATLAS inclusive W, Z



- impact of unsuppressed strange on W,Z inclusive cross sections

Phys Rev Lett 109 (2012) 012001

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ATLAS inclusive jets

Rapidity ranges	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
	P_{obs}				
$p_{\text{T}}^{\text{max}}$					
$\|y\| < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq \|y\| < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq \|y\| < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq \|y\| < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq \|y\| < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq \|y\| < 3.0$	62%	71%	69%	25%	55%
$p_{\text{T}}^{\text{jet}}$					
$\|y\| < 0.5$	69%	67%	66%	30%	46%
$0.5 \leq \|y\| < 1.0$	7.4%	8.9%	8.6%	3.4%	2.0%
$1.0 \leq \|y\| < 1.5$	69%	62%	68%	45%	54%
$1.5 \leq \|y\| < 2.0$	1.3%	1.6%	1.4%	0.1%	0.5%
$2.0 \leq \|y\| < 2.5$	8.7%	6.6%	7.4%	1.0%	3.6%
$2.5 \leq \|y\| < 3.0$	65%	72%	72%	28%	59%

Table 2: Summary of observed P_{obs} values from the comparison of the inclusive jet cross-section and the NLO pQCD prediction corrected for non-perturbative and electroweak effects for various PDF sets, for the two scale choices and for each rapidity bin of the measurement.

χ^2/dof all $\|y\|$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$p_{\text{T}}^{\text{max}}$	419/177	431/177	404/177	432/177	475/177
$p_{\text{T}}^{\text{jet}}$	399/177	405/177	384/177	428/177	455/177

Table 3: Summary of χ^2/dof values obtained from a global fit using all p_{T} and rapidity bins, comparing the inclusive jet cross-section and the NLO pQCD prediction corrected for non-perturbative and electroweak effects for several PDF sets and for the two scale choices. All the corresponding p-values are $\ll 10^{-3}$.

ATLAS inclusive jets cf. NLO QCD

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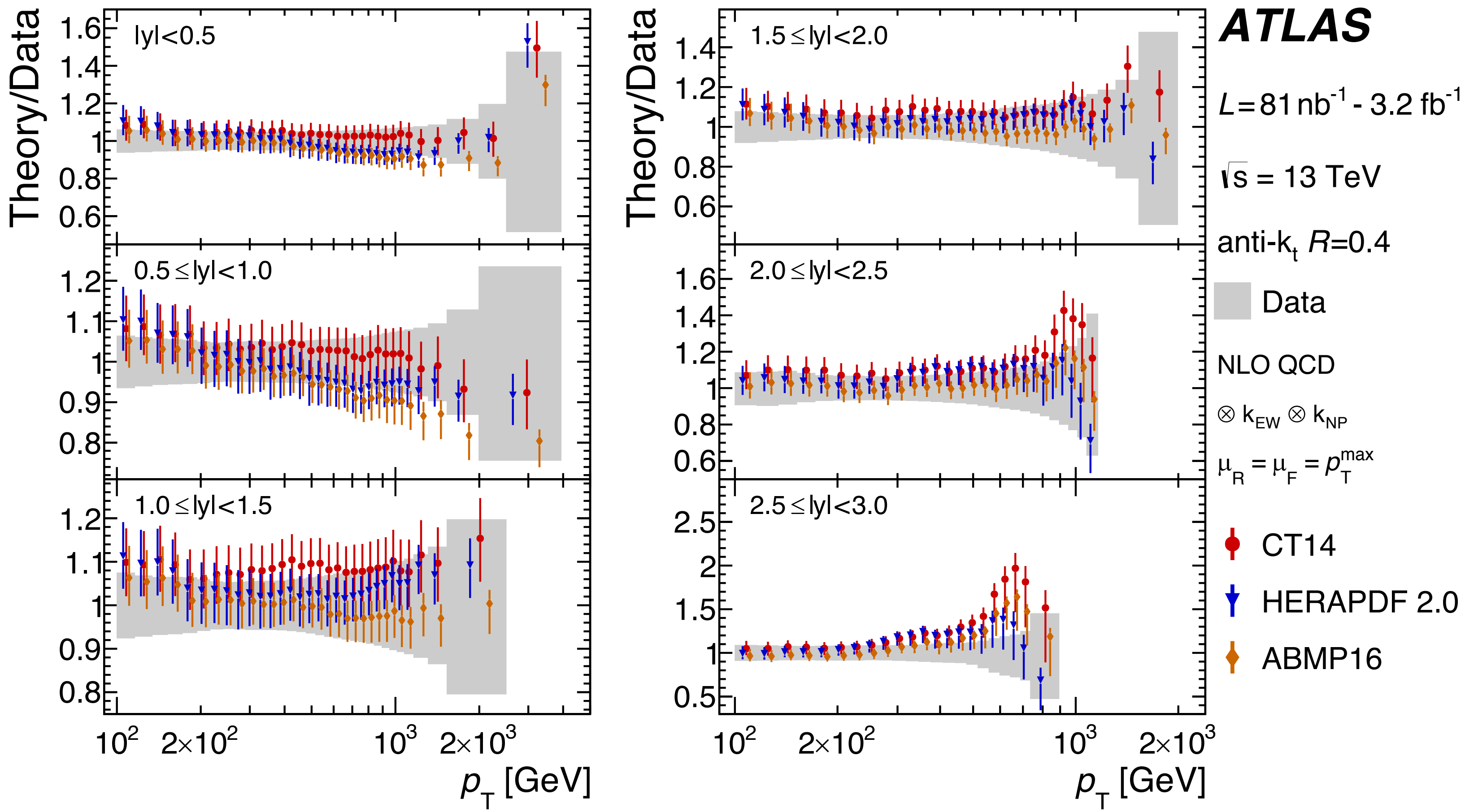

ATLAS inclusive jets cf. NNLO QCD

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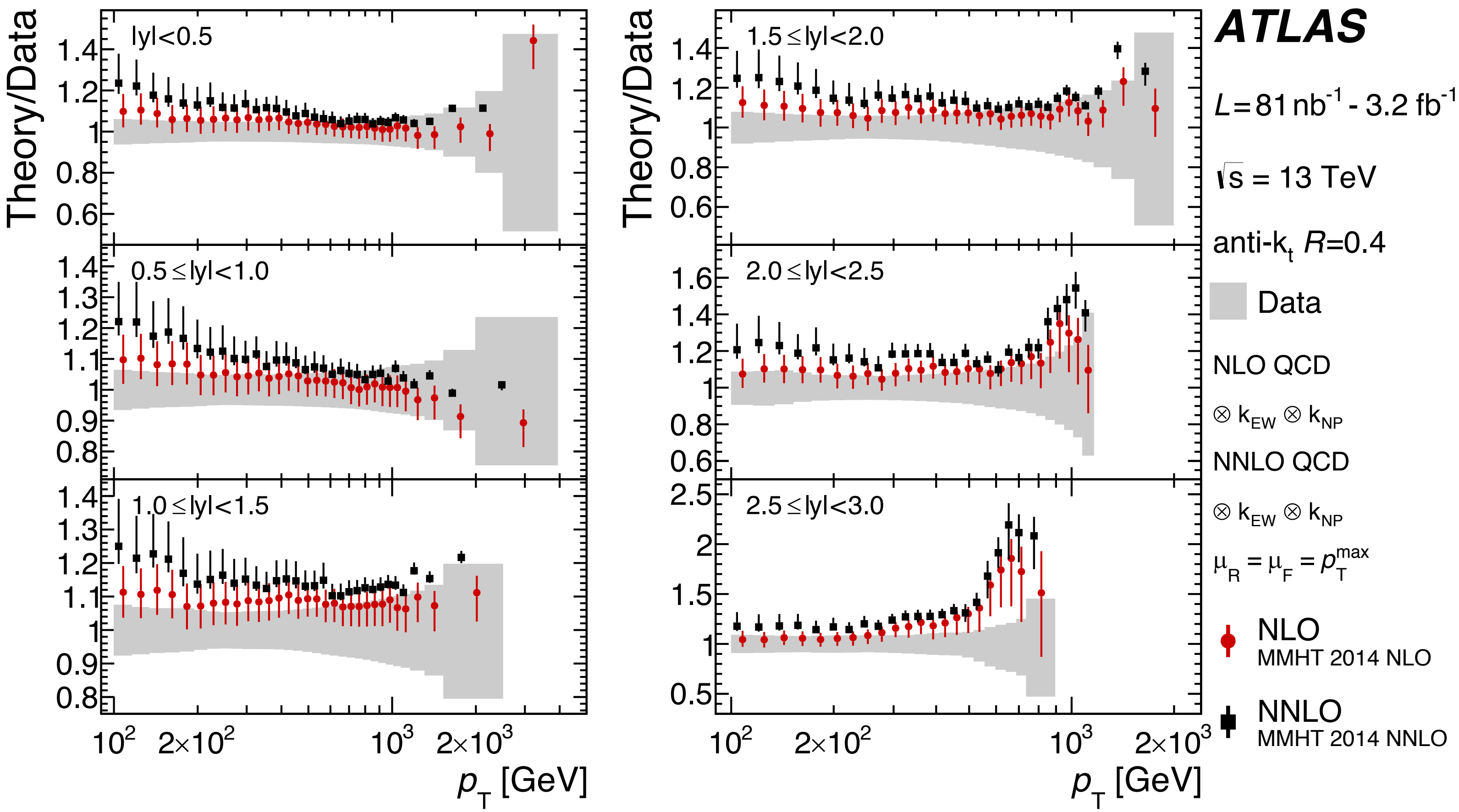

scale: pt^{max}

ATLAS inclusive jets at NNLO QCD

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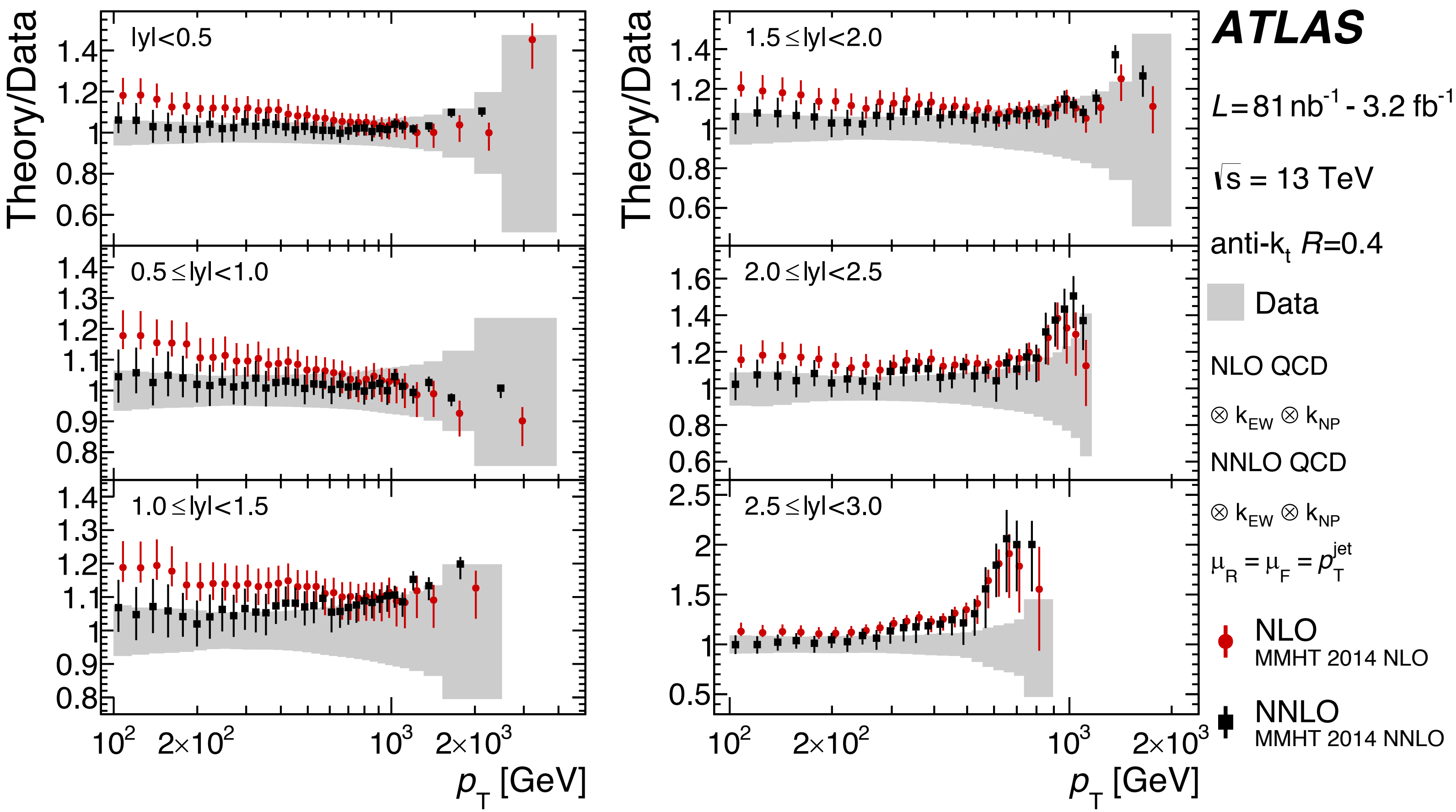

scale: pt^{jet}

ATLAS dijets at NLO QCD

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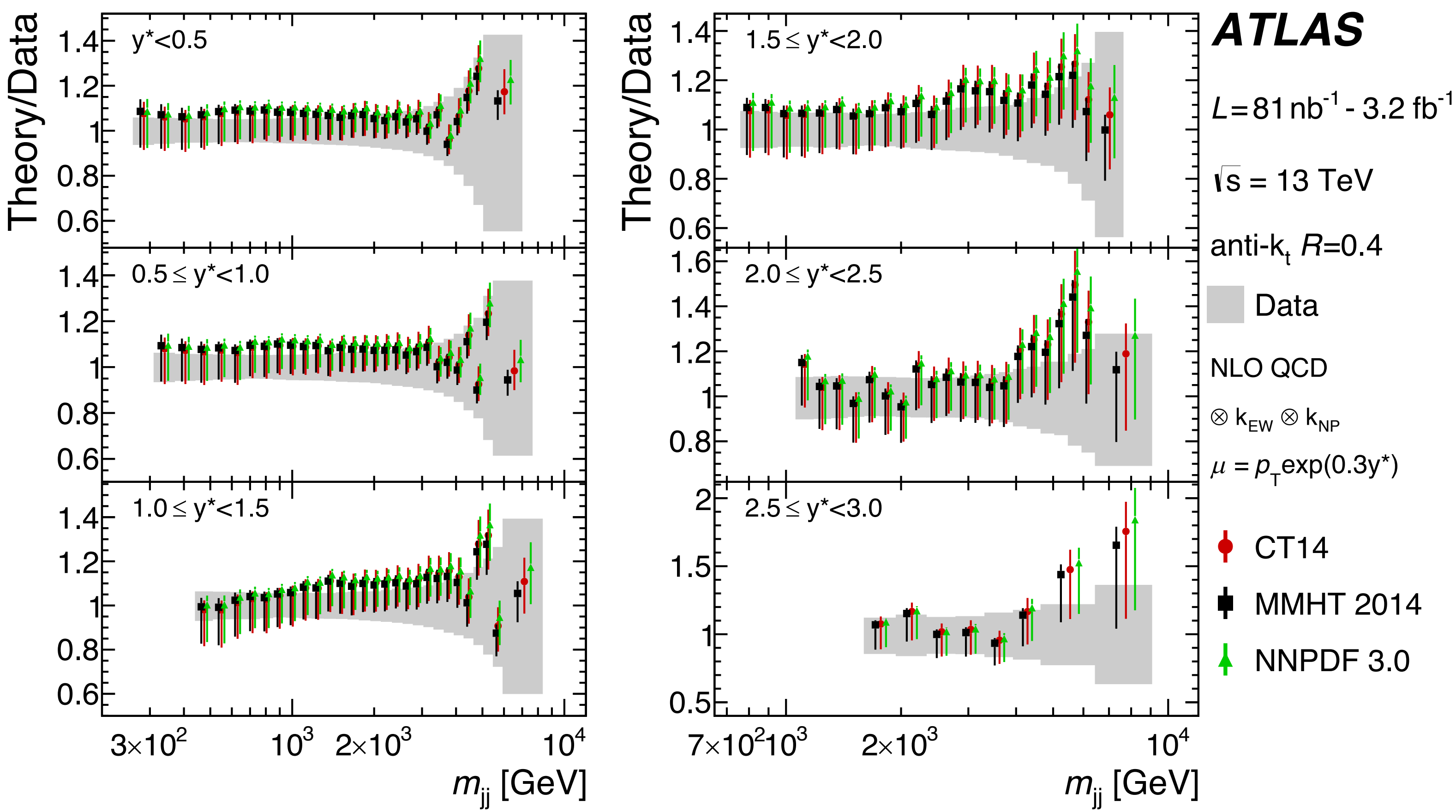

ATLAS dijets at NLO QCD

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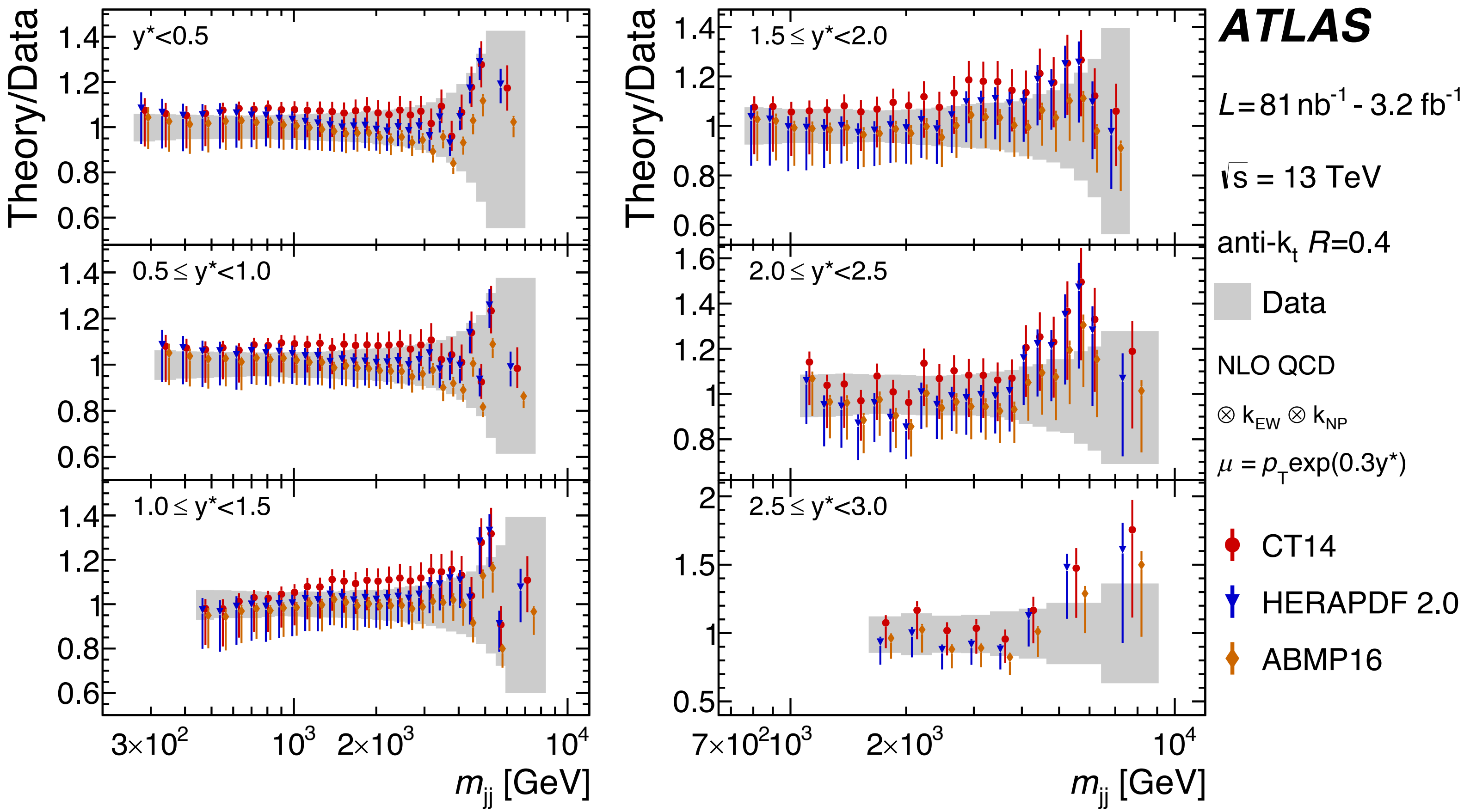
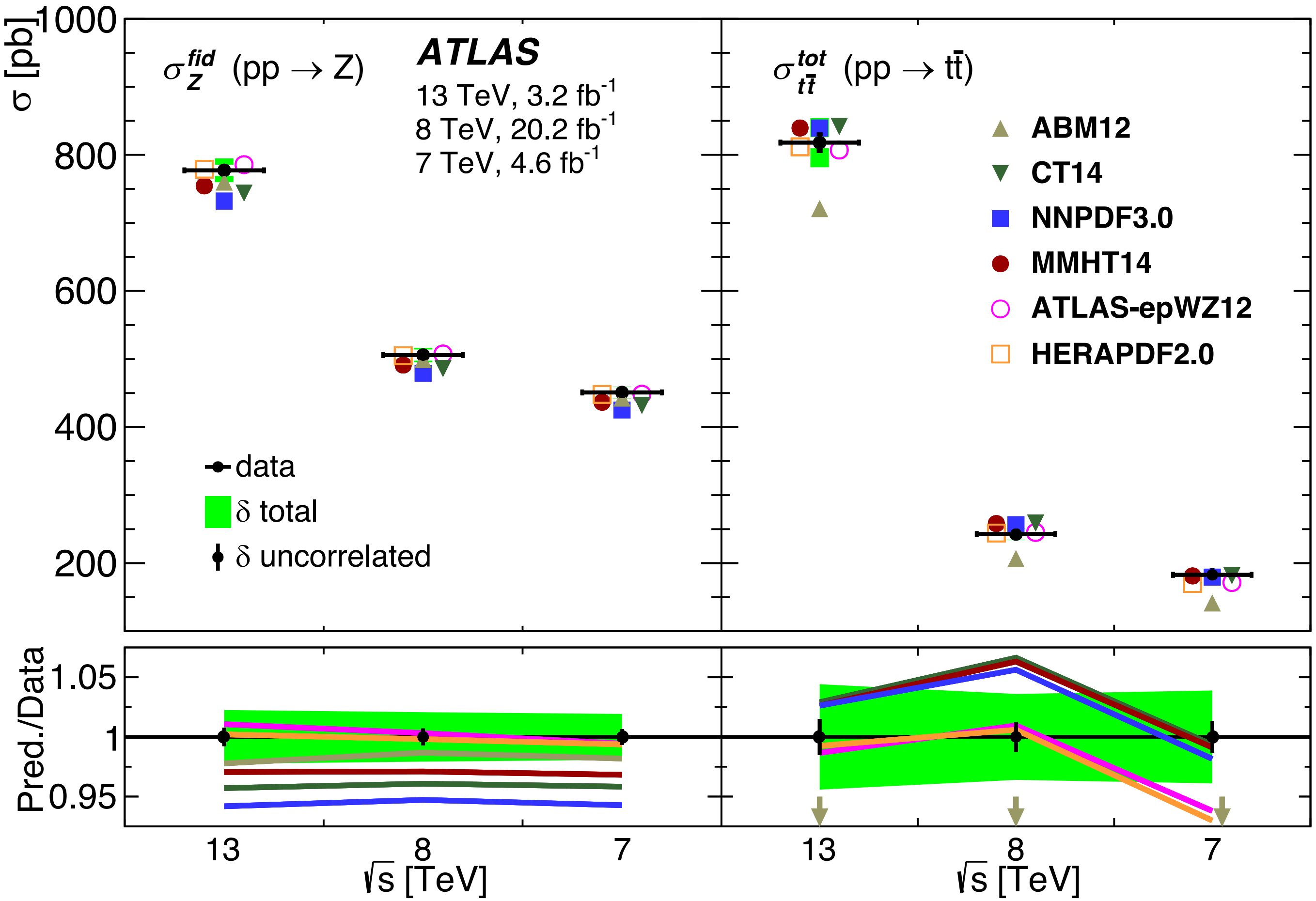


top quark pair and Z cross sections and ratios

ttbar and Z inclusive cross sections and their ratios, plus ratios at different CM (7,8,13 TeV)

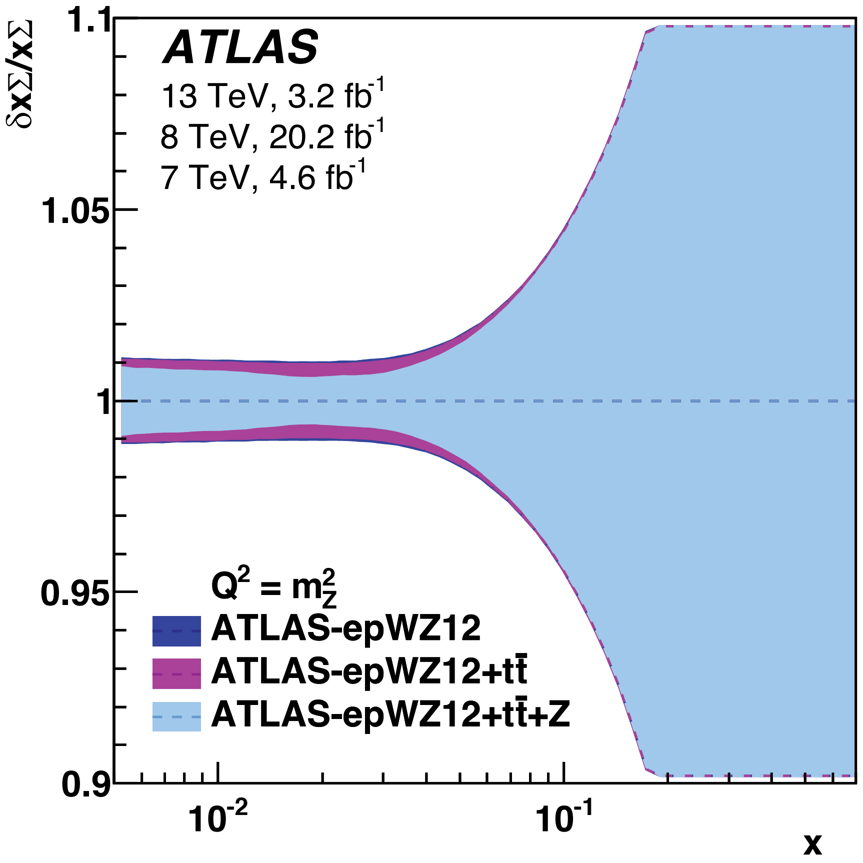
JHEP02 (2017) 117

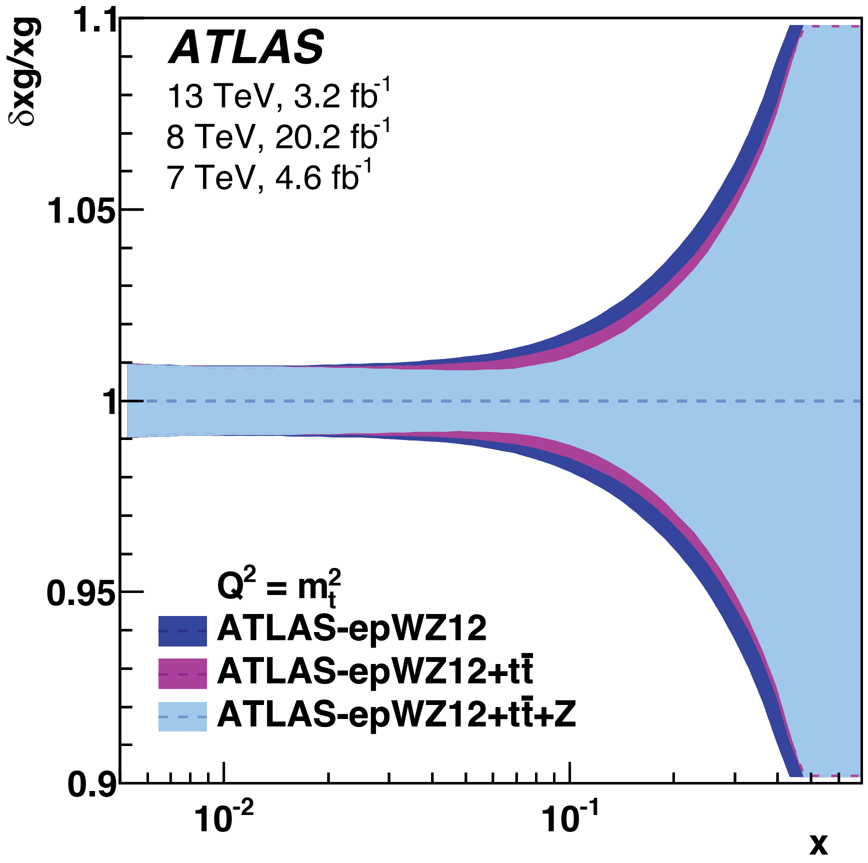


state-of-the-art theory: **Z**: NLO QCD (DYNNLO) + NLO EW (FEWZ); **ttbar**: NNLO+NNLL (Top++)

top quark pair and Z cross sections and ratios

JHEP02 (2017) 117

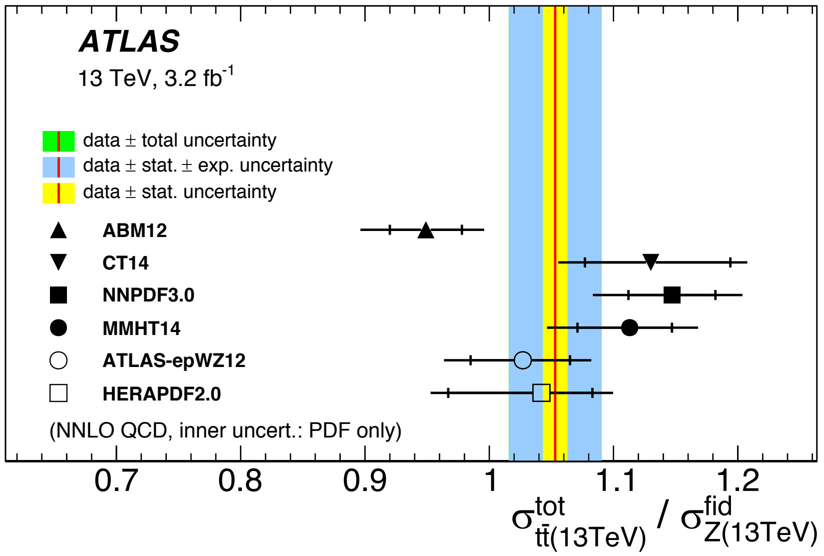


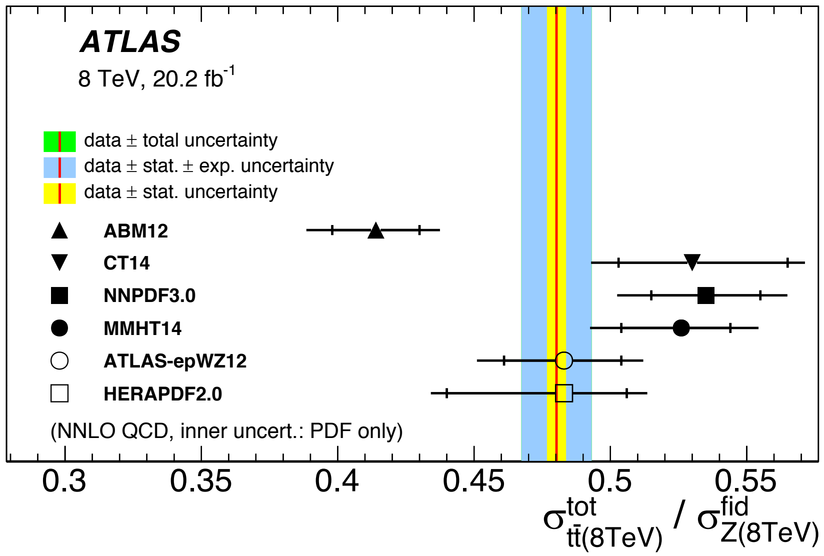


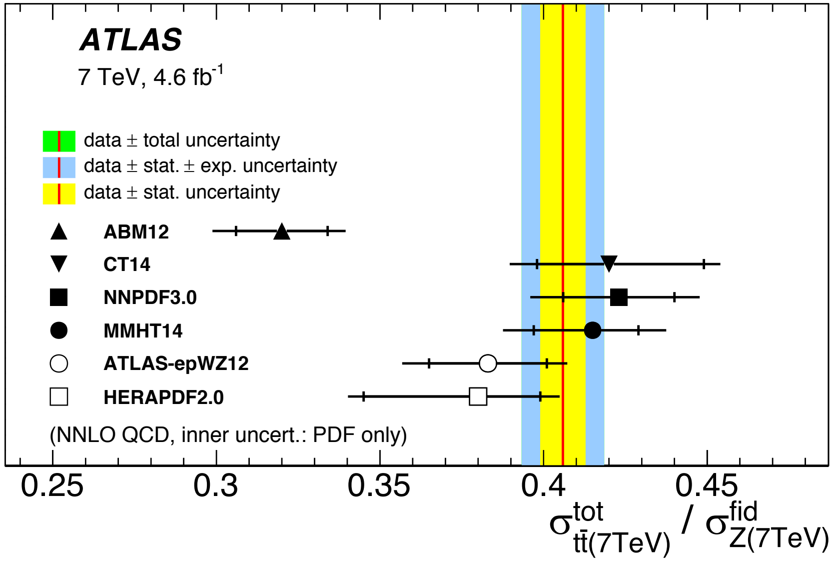
constraints on medium-to-high-x sea quark and gluon pdfs

top quark pair and Z cross sections and ratios

JHEP02 (2017) 117







top quark pair and Z cross sections and ratios

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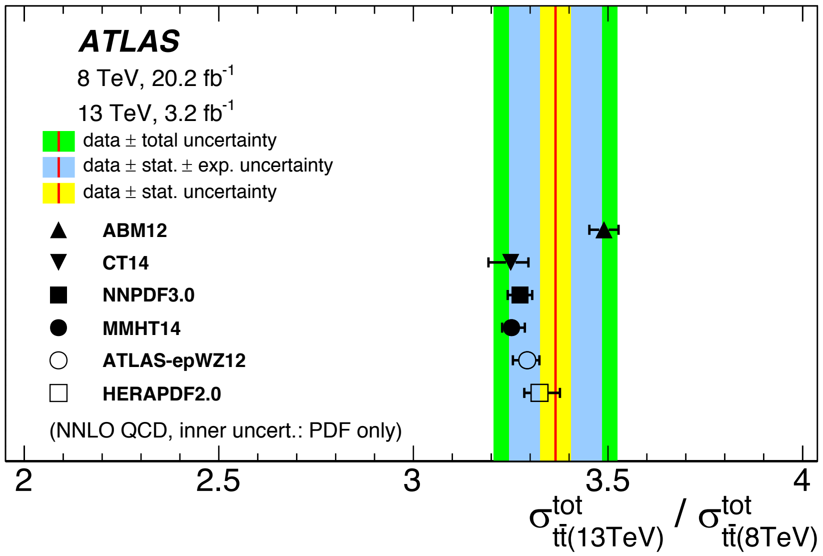
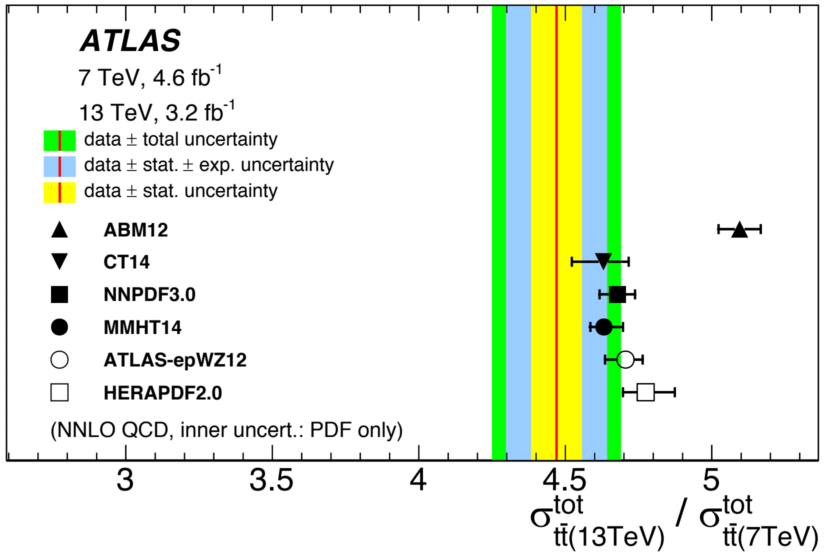
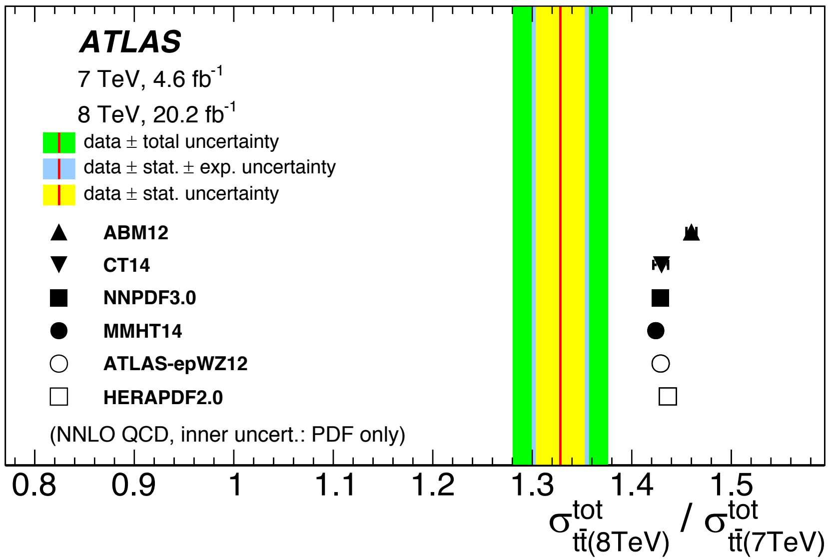
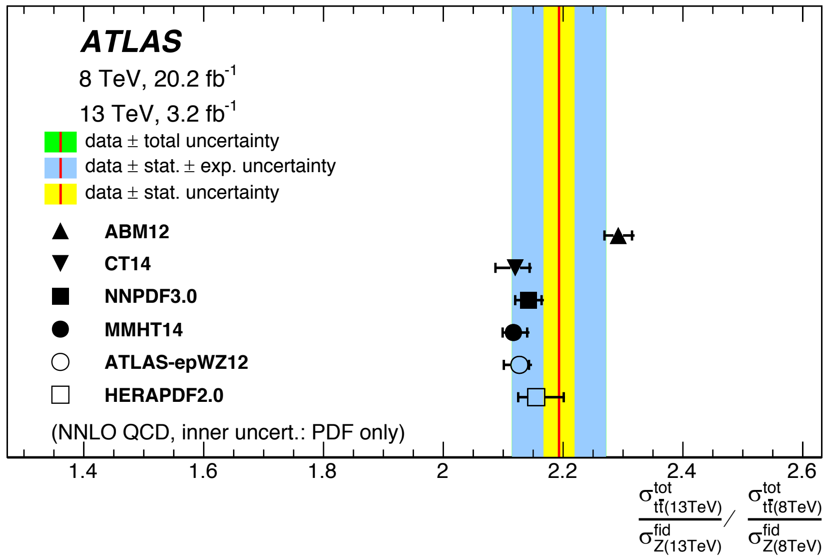


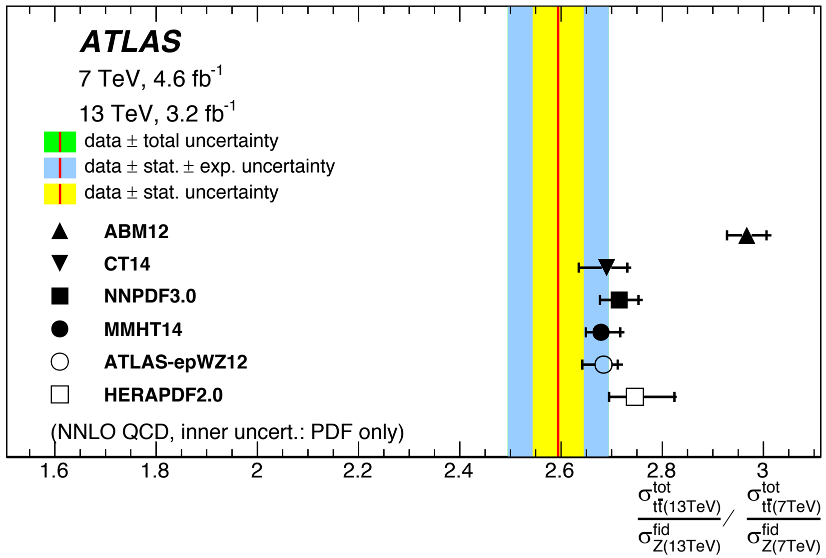


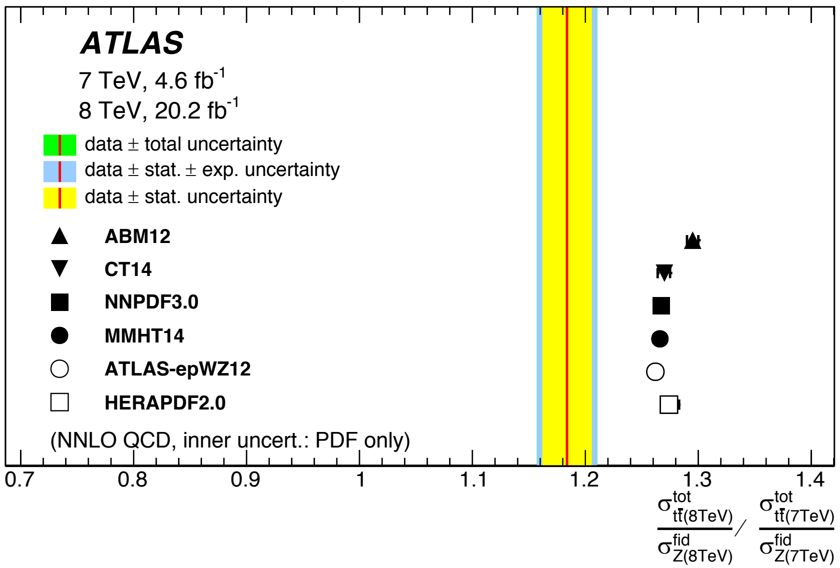


top quark pair and Z cross sections and ratios

JHEP02 (2017) 117







ATLAS top quark pair differential cross sections

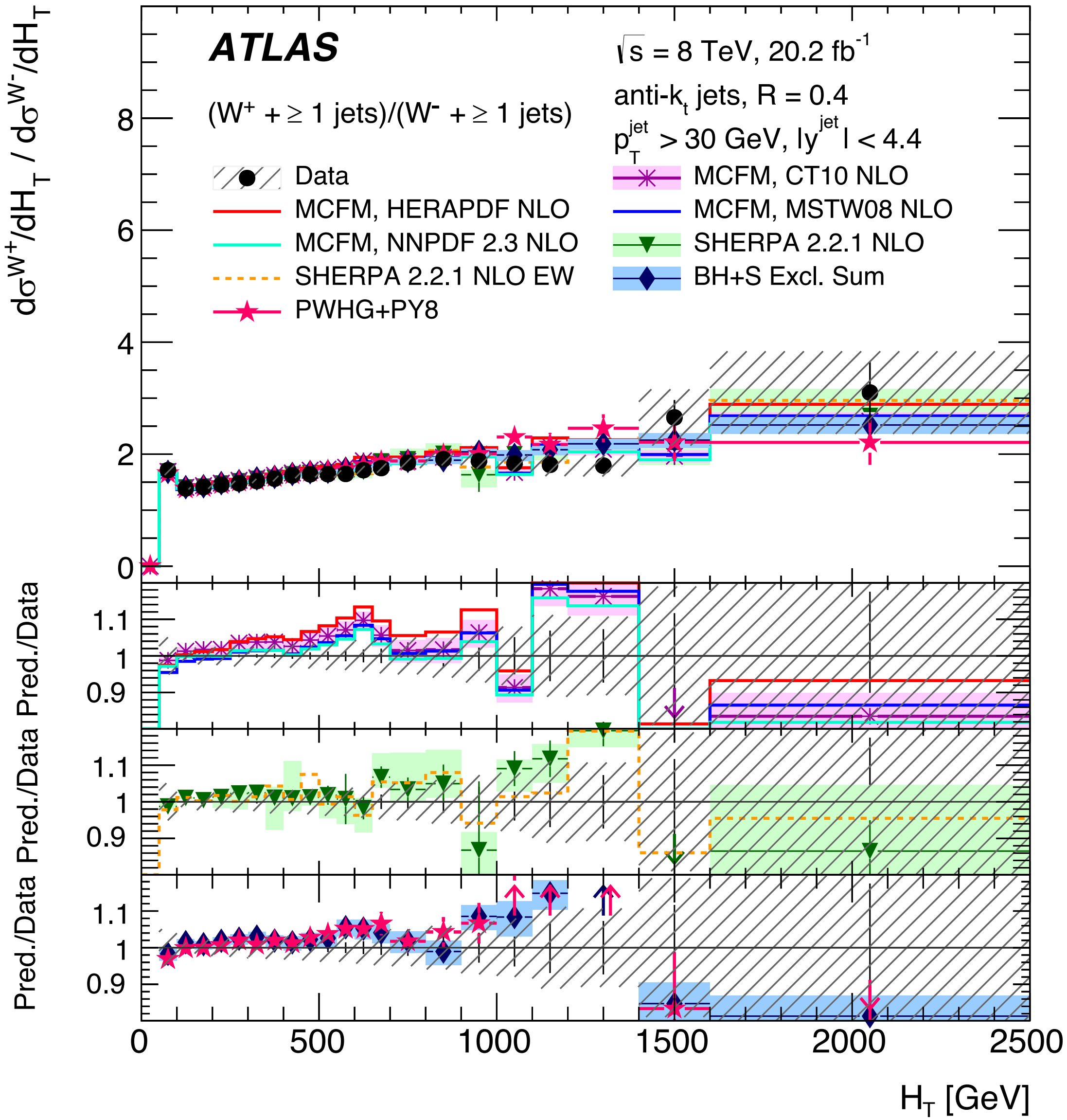
		lepton+jets spectra			
		p_T^t and y_t with statistical correlations	p_T^t and y_t without statistical correlations	p_T^t and m_{tt} with statistical correlations	p_T^t and m_{tt} without statistical correlations
Total χ^2/NDF		1264 / 1068	1260 / 1068	1290 / 1070	1287 / 1070
Partial χ^2/NDP	HERA	1148 / 1016	1147 / 1016	1162 / 1016	1162 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	82.7 / 55	83.5 / 55	83.2 / 55	83.1 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	33 / 13	30 / 13	45 / 15	42 / 15

		lepton+jets spectra		
		p_T^t and y_t decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate parton-shower model uncertainty
Total χ^2/NDF		1259 / 1068	1247 / 1070	1248 / 1070
Partial χ^2/NDP	HERA	1147 / 1016	1154 / 1016	1153 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	83.9 / 55	81.9 / 55	81.6 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	27.8 / 13	11.5 / 15	14.1 / 15

NEW ATLAS-PHYS-PUB-2018-017

ATLAS W+Jets

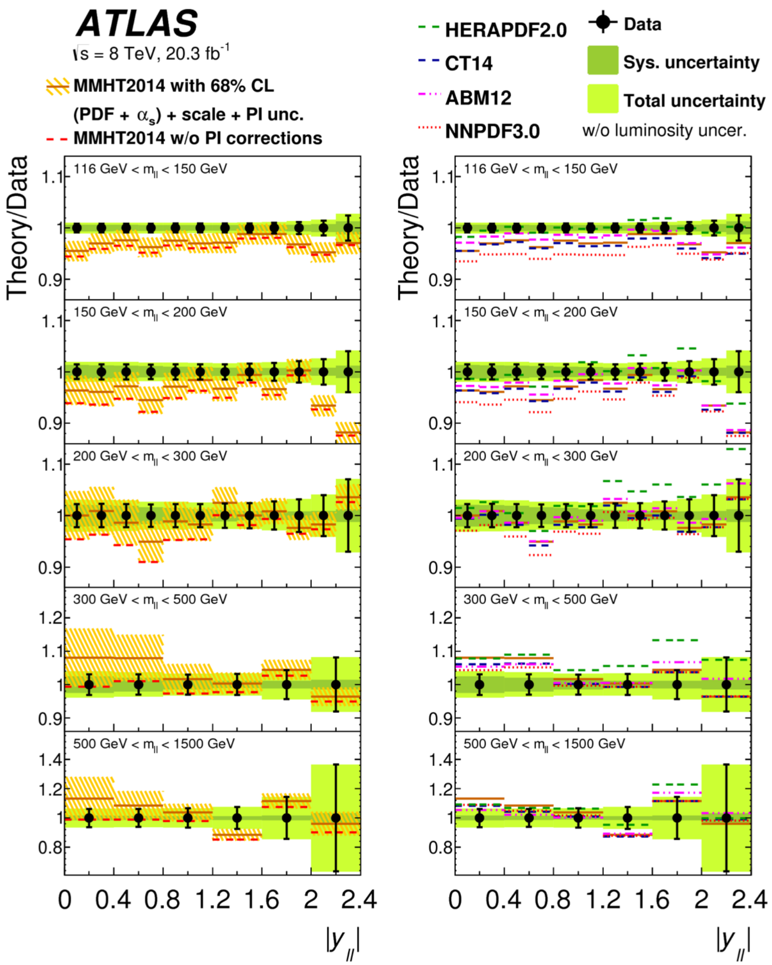
JHEP05 (2018) 077



W+Jets: mainly sensitive to gluon at medium x

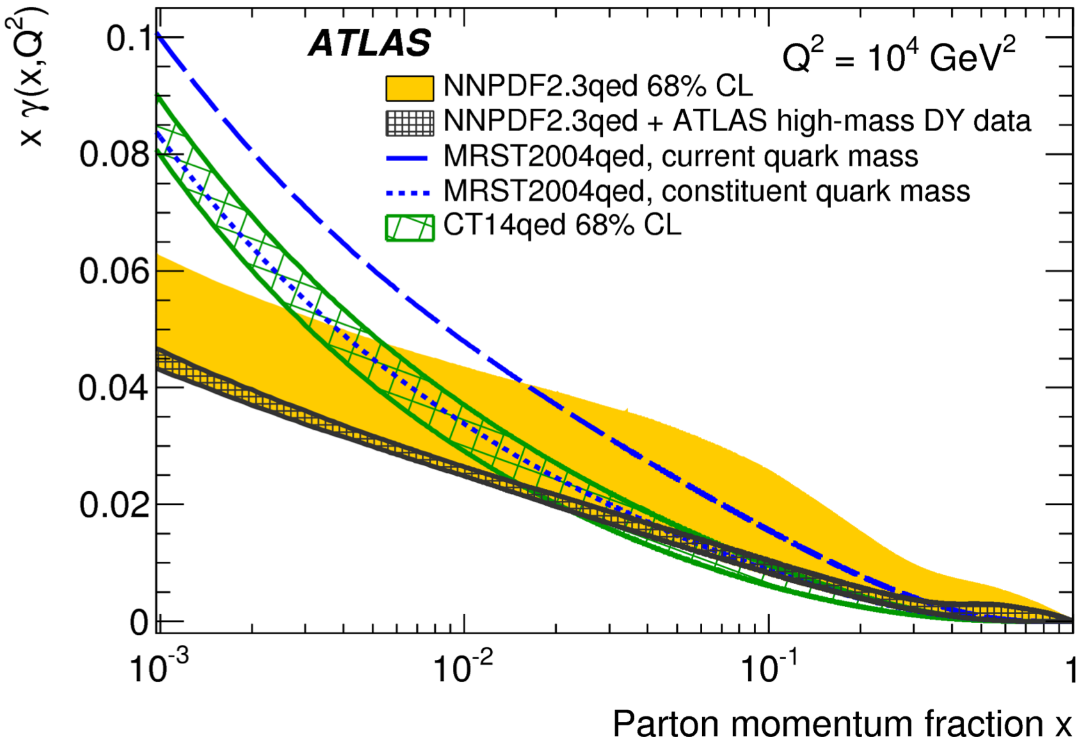
ATLAS High Mass Drell Yan

- sensitive to quarks, quark flavour at high x (complementary to Z peak measurements)
- **important contribution from irreducible photon induced (PI) contribution:**



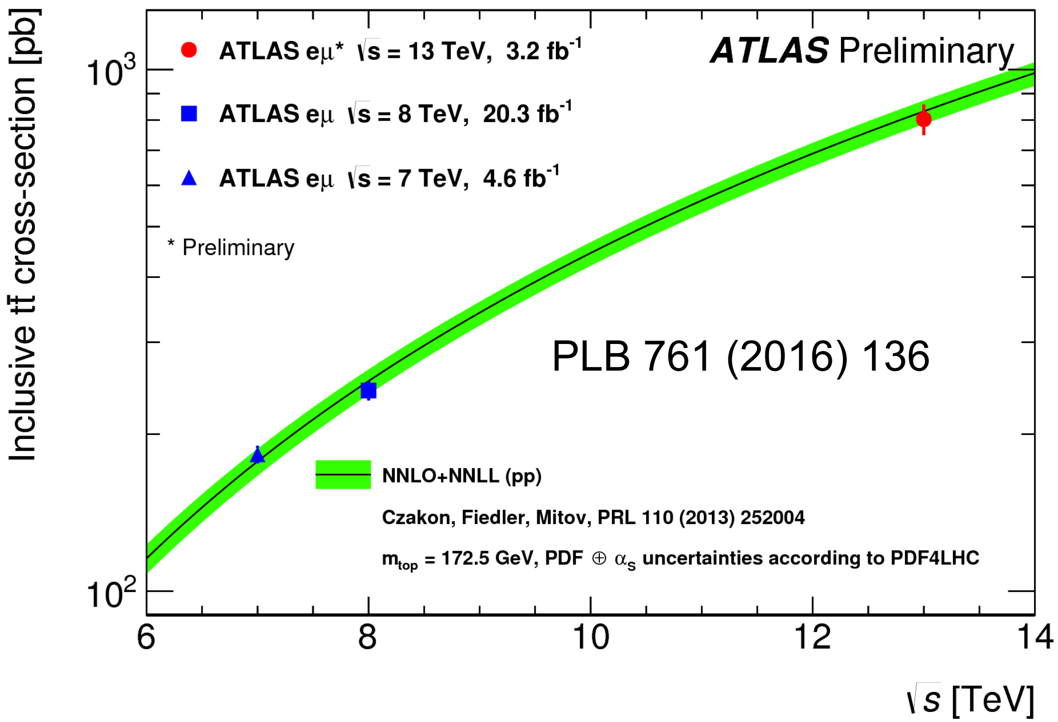
High Mass: 116 < mll < 1500 GeV

JHEP08 (2016) 009

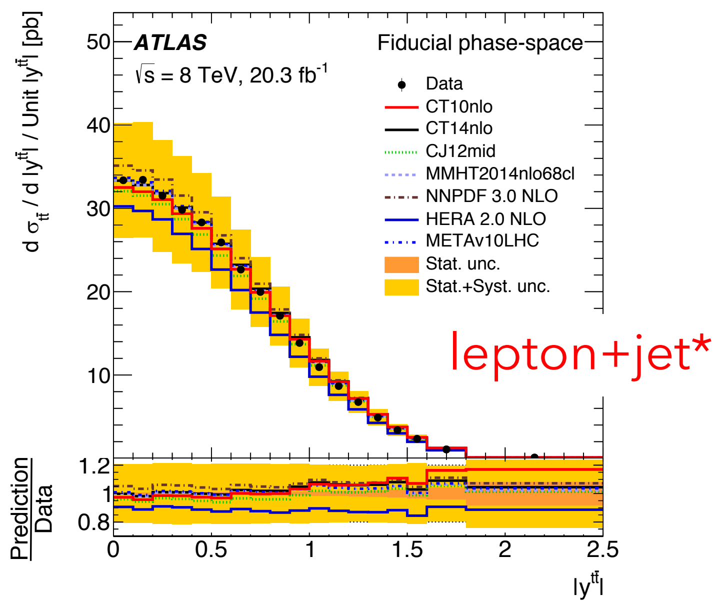


ATLAS HM DY yields information on photon content of proton

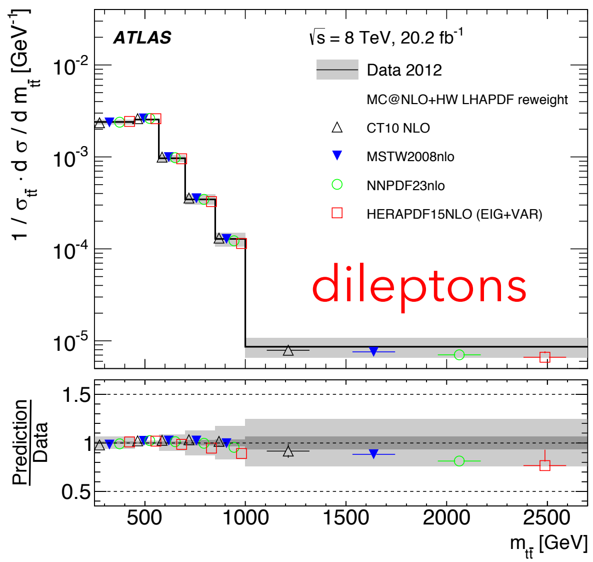
top quark pair @ 7,8,13 TeV



EPJ C76 (2016) 538



Phys Rev D94 (2016) 092003



- **wealth of top quark pair total and differential cross section measurements**
- mainly constrains high x gluon; also sensitive to quarks at large top-pt and mtt
- **yet more measurements to come**

*NNLO calcs. available in fastNLO format, arXiv:1704.08551, and refs. therein