Determination of proton parton distribution functions using ATLAS data

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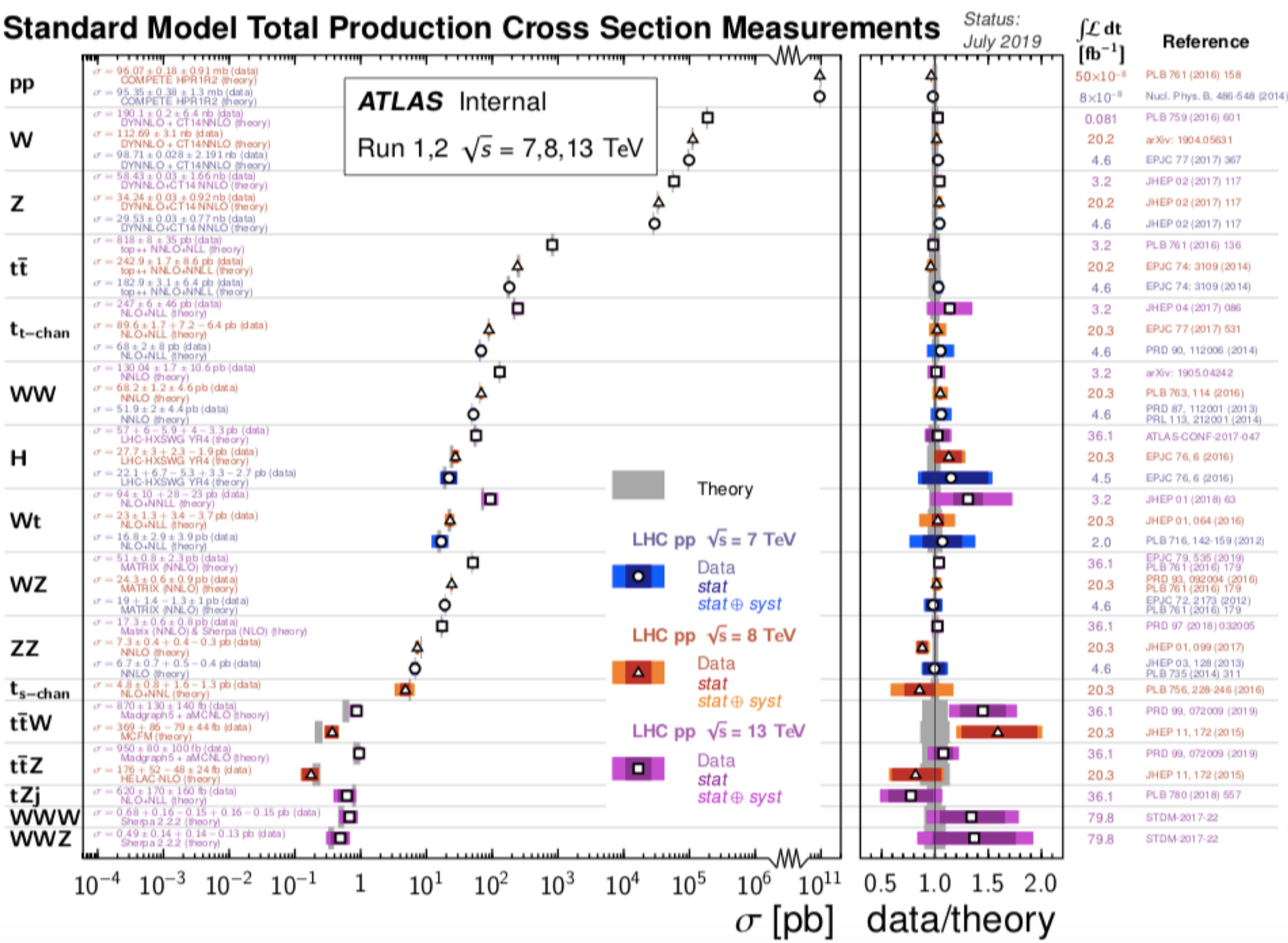
The LHC SM measurements

- Hadron colliders can give us more insight into hard QCD, Parton Distribution Functions (PDFs), non-perturbative effects, and other SM parameters



Remarkable agreement with SM predictions! Much of theory uncertainty from PDFs

- **PDFs discrimination** (by confronting theory with data)

- **PDFs improvement** (by adding the LHC data)

<u>Status: July 2019</u>

The LHC measurements for PDFs

- Crucial for cross section measurements and searches beyond the SM, as PDFs are often one of the dominant uncertainties
- Below, some measurements which can constrain PDFs:

Process	Sensitivity to PDFs
W asymmetry, Z3D	Valence quarks
W and Z production (differential)	Quark flavour separation
W+c production, W and Z (differential)	Strange quark
Drell-Yan (DY): high invariant mass	Sea quarks, high-x, photon PDF
Drell-Yan (DY): low invariant mass	Low-x, resummation effects
W,Z + jets	High-x flavor separation
Inclusive jet and di-jet production	Gluon and $\alpha_s(M_Z)$
Direct photon	Gluon medium-, high-x
$\boldsymbol{t\bar{t}}$, single top production	Gluon and $\alpha_s(M_Z)$

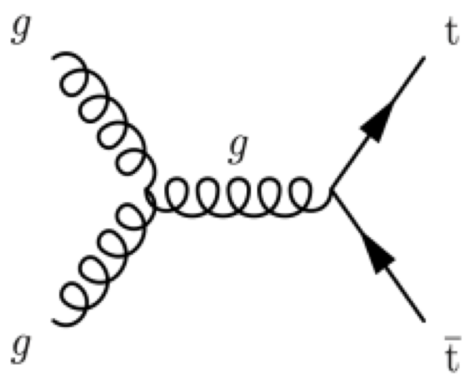
In **BOLD** the topics covered in this talk…

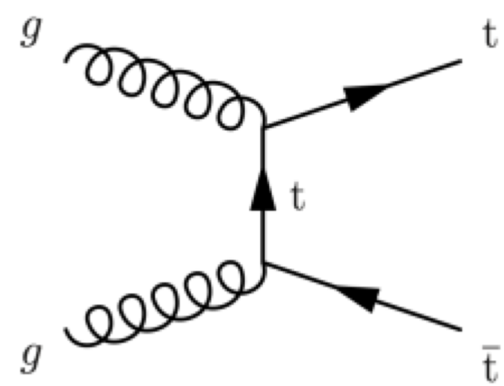
- Other interesting observables for posing PDFs constraints: Z p_T, angular coefficients A_i, etc.

To extract precise PDFs, we need both precise data and precise calculations

$t\bar{t}$ data at 8 TeV

- To access the impact of including ATLAS $t\bar{t}$ production data in fits to extract the proton PDF
- QCD fit to DIS data from HERA and W,Z at 7 TeV (**Eur. Phys. J. C 77 (2017) 367**) and $t\bar{t}$ at 8 TeV
- $t\bar{t}$ data are complementary to the $W, Z/\gamma^*$ data
- Expected to be **sensitive to gluon distribution in the medium- and high-x regime** ($x \gtrsim 5\cdot10^{-2}$)
- Important to perform this fit now since the **NNLO predictions of pQCD** for $t\bar{t}$ production data have recently become available and usable in PDF fits (1704.08551)
- $t\bar{t}$ production input datasets:
  - lepton+jets channel at 8 TeV (**Eur. Phys. J. C 76 (2016) 538**)
  - dilepton channel at 8 TeV (**Phys. Rev. D 94 (2016) 092003**)





- Results publicly available: **ATL-PHYS-PUB-2018-017**

Theoretical framework

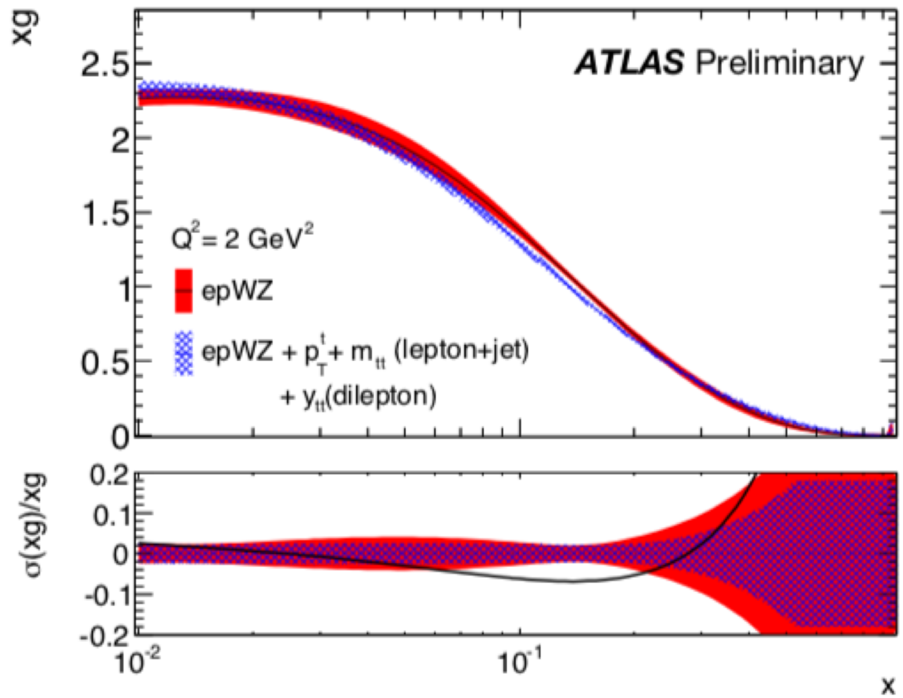
- Fit performed using **xFitter** (open-source fitting framework)
- NNLO predictions for the lepton+jets channel are supplied in the form of FastNLO grids
- NLO predictions for dilepton channel produced by using APPLgrid interfaced to MCFM - corrected using k-factor to match higher-order predictions
- Available spectra for the fit:
  - Lepton+jets channel ($m_{t\bar{t}}$, p_T^t, $y_{t\bar{t}}$, y_t)
  - Dilepton channel ($m_{t\bar{t}}$, $y_{t\bar{t}}$)
- Bin-to-bin statistical correlations **within each spectrum** and **between the spectra** (lepton+jets channel) available and included in the fit → effect is small but not negligible
- The largest systematic uncertainties are due to:
  - Initial state/final state radiation (ISR/FSR) ~8%
  - Parton shower model (PS) ~5%
  - Hard-scattering model ~4%

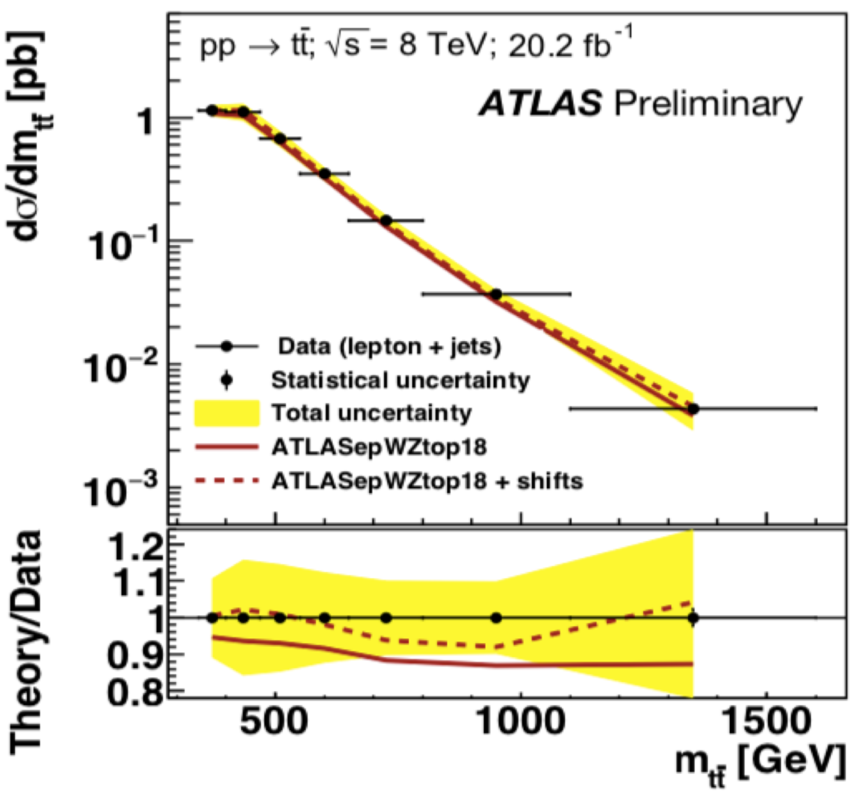
Most significant effect from decorrelating PS uncertainty

- Effect of decorrelating these sources of uncertainty investigated

Fits to dilepton and lepton+jets spectra

Total χ^2/NDF		1253.8/1061
Partial χ^2/NDF	HERA	1149/1061
Partial χ^2/NDF	ATLAS $W, Z/\gamma^*$	78.9/55
Partial χ^2/NDF	ATLAS $m_{t\bar{t}}$ and p_T^t	16.0/15
Partial χ^2/NDF	ATLAS $y_{t\bar{t}}$	5.4/5

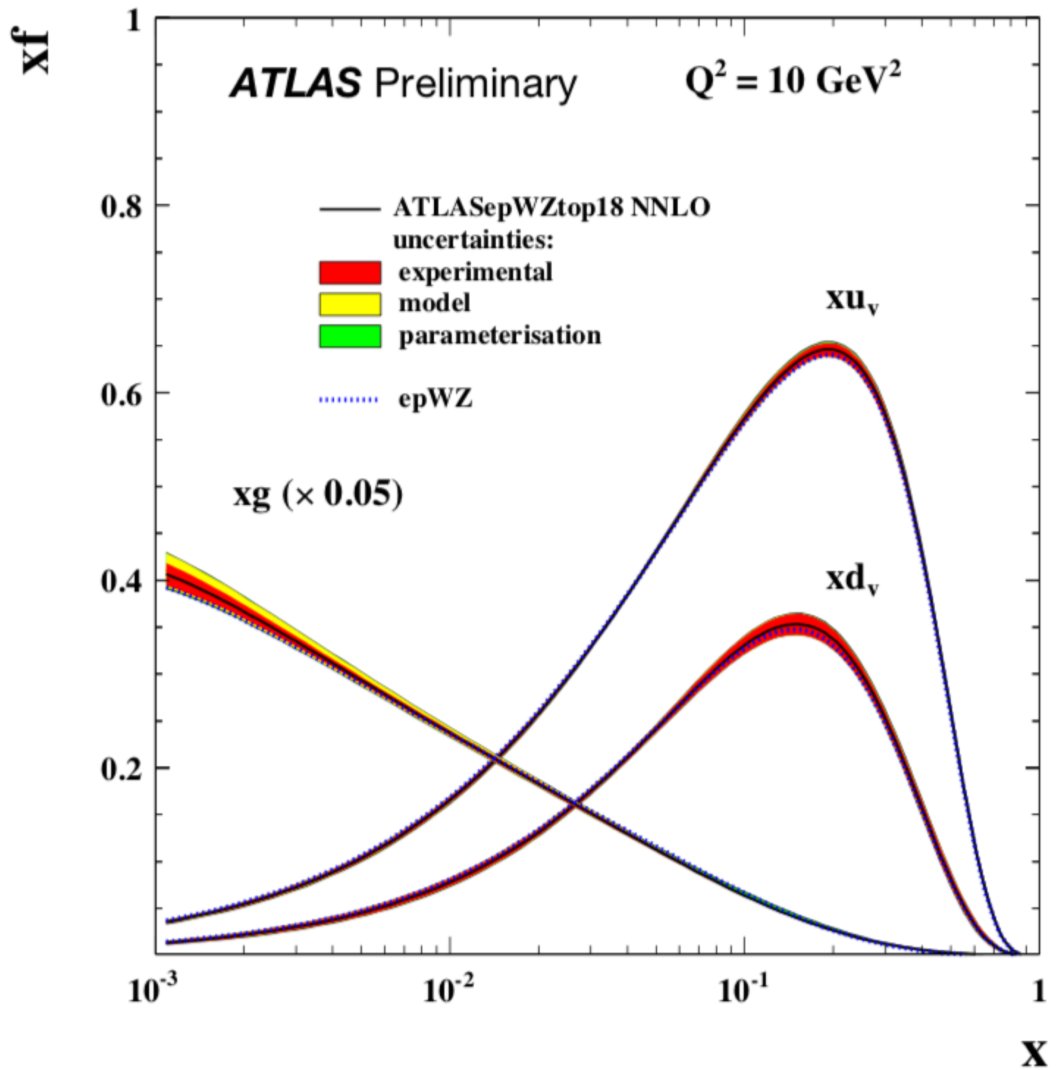




- ATLAS epWZtop18 PDF fit released:
  - $m_{t\bar{t}}$ and p_T^t spectra from lepton+jets data
  - $y_{t\bar{t}}$ spectrum from dilepton data
- **Harder gluon** and a **significantly reduced high-*x* uncertainty** on the gluon PDF

Resulting PDFs

- The model uncertainties include variations of the charm/beauty masses, the minimum Q^2 cut value and the Q_0^2 starting scale
- The parametrisation uncertainties correspond to an envelope of results obtained with extra parameters
- The shapes of the extracted PDFs are not sensitive on the top quark mass, but the χ^2 of the fit is sensitive to it
- The strong coupling constant α_S was set to the PDG value and investigating its impact was beyond the scope of the study



W+jets data at 8 TeV

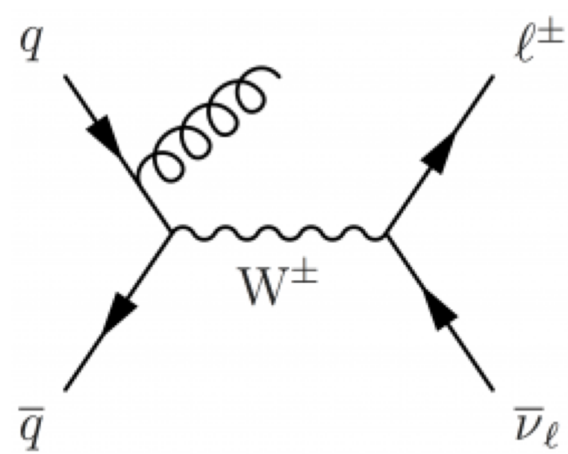
- QCD fit to DIS data from HERA and the ATLAS Electroweak boson data: W,Z at 7 TeV (**Eur. Phys. J. C 77 (2017) 367**) and W+jets at 8 TeV (**JHEP 05 (2018) 077**)

- Some differences and improvements wrt the ATLAS epWZ16 fit to accommodate or exploit the new data:
  - More parameter variations and extended central parametrisation, consistent with recent ATLAS epWZtop18 fit
  - The new fit uses the W,Z data at 7 TeV before the combination (electron and muon decay channel **uncombined**) in order to correlate common sources of systematic uncertainties to those of the W+jets data
  - Variation of the minimum Q^2 selection of 10 GeV^2 (rather than 7.5 Gev^2) to exclude the low-Q^2, low-x HERA data which may be more adversely affected by large-logs, higher twist effects etc. (in line with recent ATLAS epWZtop18 fit)

- The **xFitter** package is use for performing the fit

- NNLO corrections included as k-factors

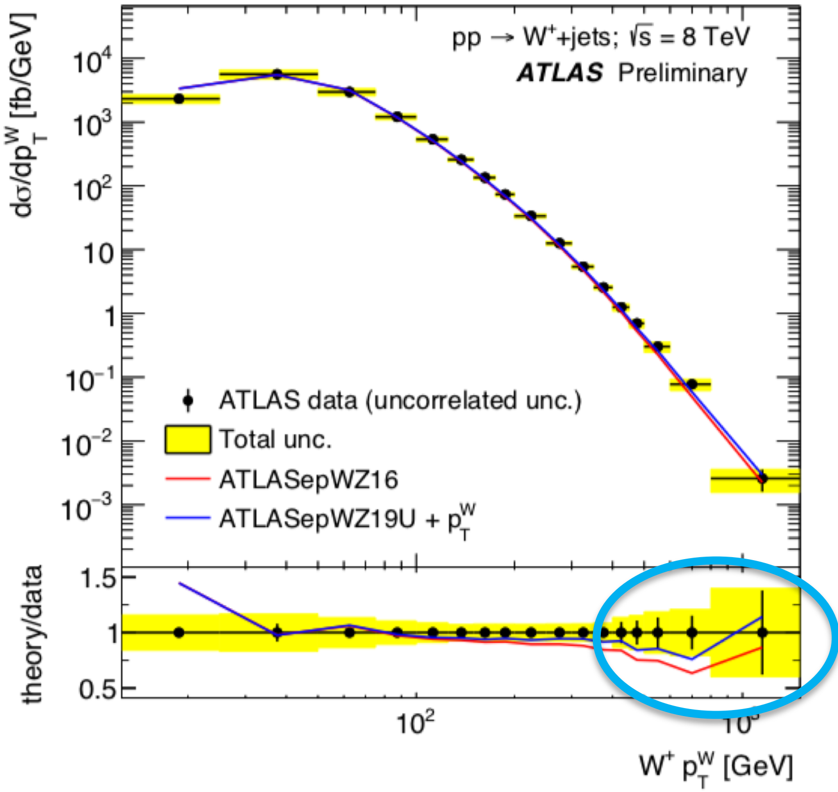
- Results publicly available here: [ATL-PHYS-PUB-2019-016]



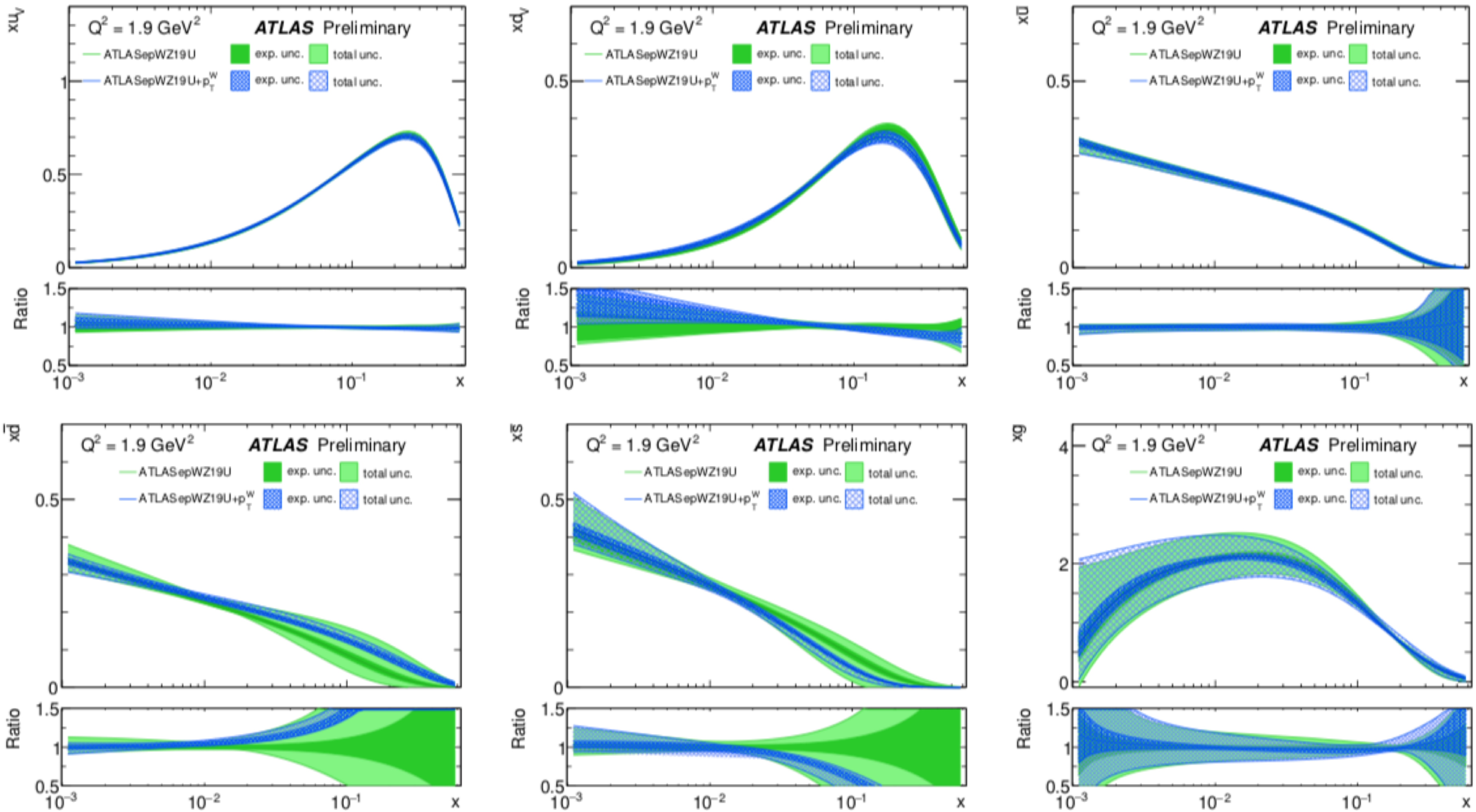
Fit quality

Fit	ATLASepWZ19U	ATLASepWZ19U + p_T^W	ATLASepWZ19U + p_T^{leading}
Total χ^2/NDF	1310 / 1106	1354 / 1140	1365 / 1152
HERA partial χ^2/NDF	1123 / 1016	1132 / 1016	1141 / 1016
HERA correlated χ^2	48	49	50
HERA log penalty χ^2	-18.38	-22.4	-24.72
ATLAS W, Z partial χ^2/NDF	117 / 106	116 / 106	109 / 106
ATLAS W + jets partial χ^2/NDF	-	18 / 34	43 / 46
ATLAS correlated χ^2	40	62	47

- Fits including the W+jets data showing no tension with the HERA data or inclusive W,Z data
- Slightly better χ^2 when including the p_T^W spectrum
- New PDF fit released: **ATLAS epWZ-Wjets19**
- Clear improvements in the description of the data in the large-p_T region with the new fits



New fit results



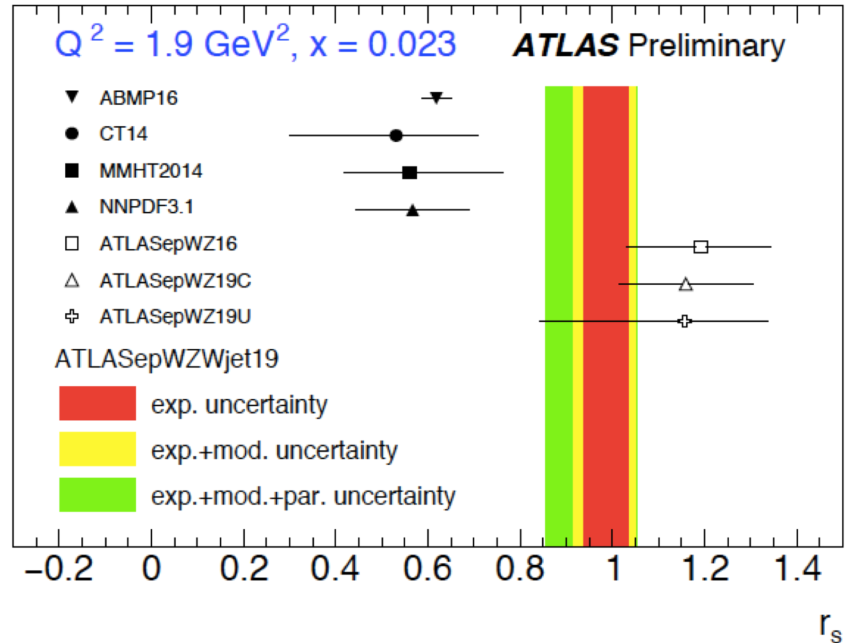
Compared to previous ATLAS epWZ16 fit:

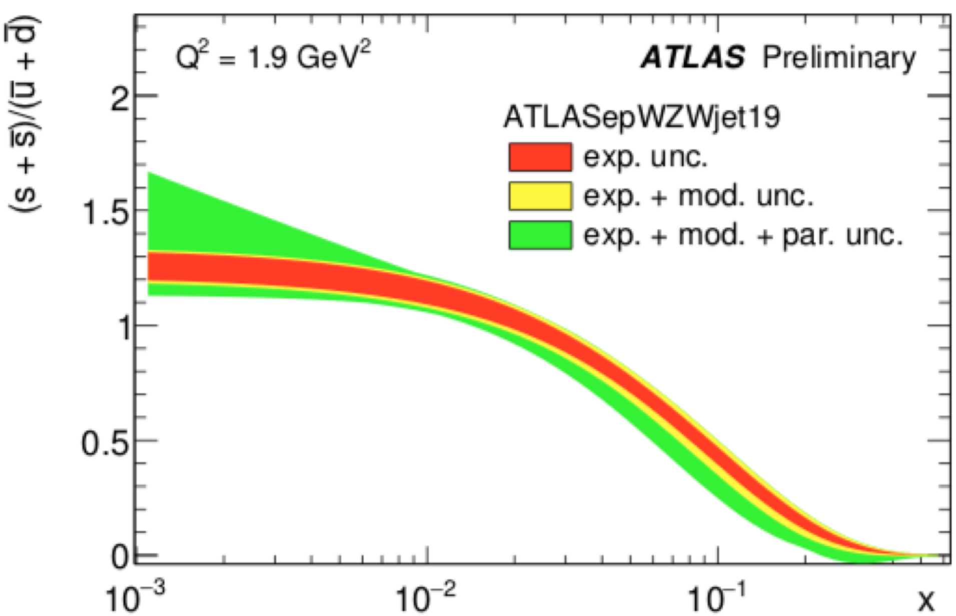
- Softer d_v at medium-x
- Harder $\bar{d}$
- Softer strange PDF at high-x

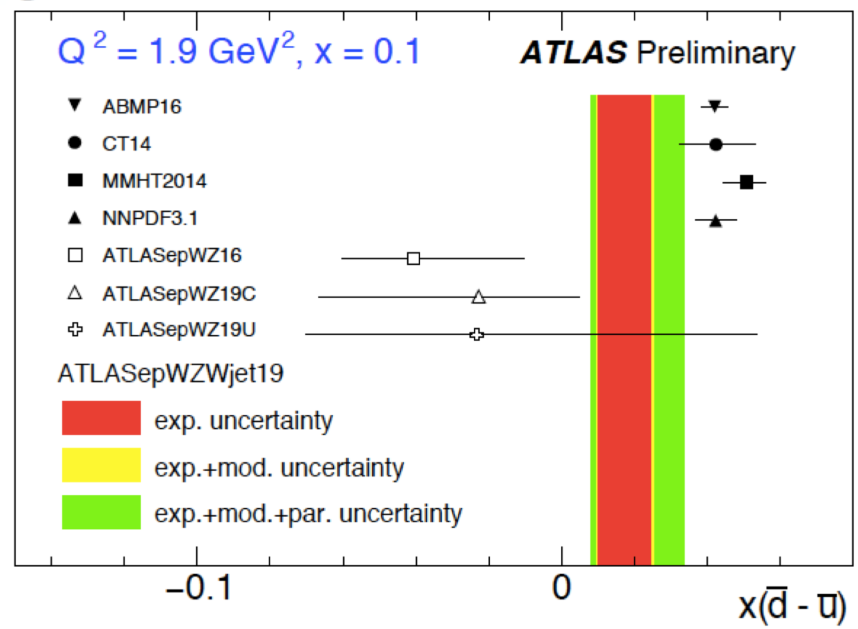
- u-quark and gluon distributions essentially unchanged

Main outcome of the fit

- Including the W + jet data reduces the strange density at higher-x… But still consistent with **enhanced strange at low-x!**
- New fit with the W + jet data results in the new **$x(\bar{d}-\bar{u})$ to be positive**
- Much more consistent with the fits from the global fitters (previous ATLASepWZ16 fit showed a negative $x(\bar{d}-\bar{u})$)





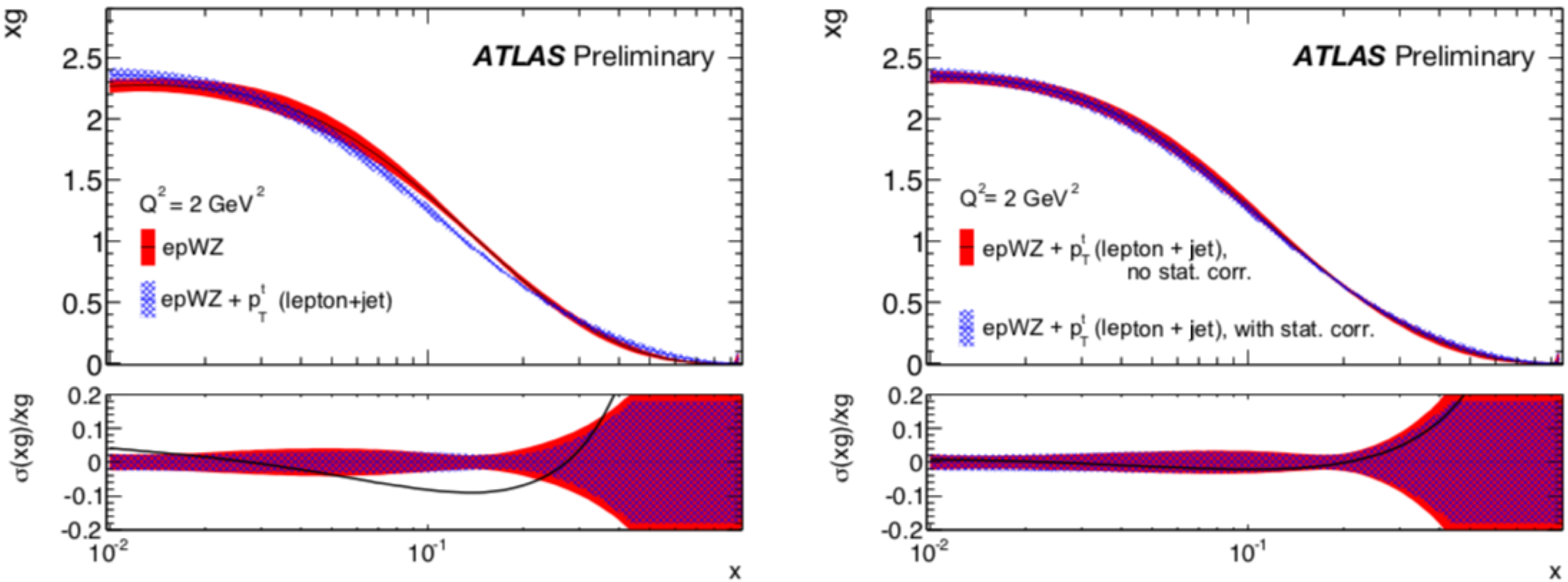


Conclusion

- I've reported a summary of the latest ATLAS measurements regarding PDFs
- QCD fit to DIS data from HERA and W,Z at 7 TeV and $t\bar{t}$ at 8 TeV (lepton+jets and dilepton spectra)
- **Harder gluon** and a **significantly reduced high-*x* uncertainty** on the gluon PDF
- QCD fit to DIS data from HERA and W,Z at 7 TeV and W+jets at 8 TeV (p_T^W spectrum)
- New fit confirms **enhancement** of the **strange** contribution at **low-x**, also with a **positive** $\left(\bar{d} - \bar{u}\right)$ distribution at higher x
- To look forward:
  - Including more published data is possible e.g. top, direct photon production etc.
  - New data samples are hoped to be available soon
  - Data from different beam energies: similar systematic uncertainties but different x-region accessible - can lead to improved sensitivity
  - NNLO calculations available for important physics processes due to recent developments in grid technology (APPLfast, APPLgrid, FastNLO, NNLOJet)
- It looks like a very interesting time is coming ahead!

Backup Slides

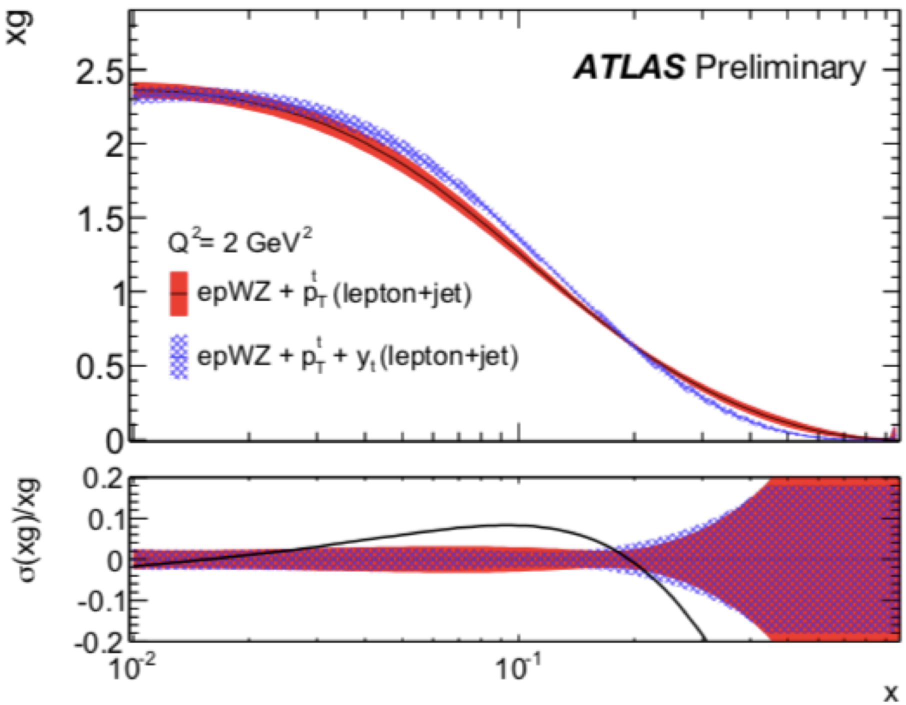
Fits to individual $t\bar{t}$ lepton+jets spectra

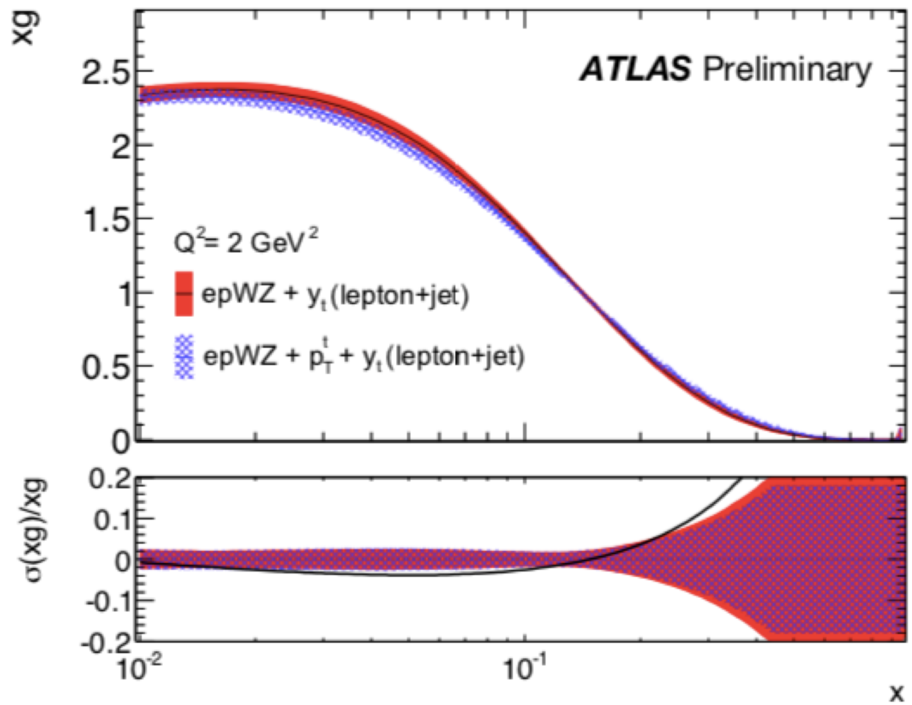


		lepton+jets spectrum			
		m_{tt}	p_T^t	y_{tt}	y_t
Total χ^2/NDF		1238.4 / 1062	1239.4 / 1063	1257.5 / 1060	1246.5 / 1060
Partial χ^2/NDP	HERA	1153 / 1016	1151 / 1016	1149 / 1016	1146 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	82.0 / 55	82.1 / 55	86.4 / 55	85.0 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	3.4 / 7	7.9 / 8	19.7 / 5	18.3 / 5

- Partial χ^2 good for $m_{t\bar{t}}$ and p_T^t but fits to $y_{t\bar{t}}$ and y_t are poor

Fits to more than one $t\bar{t}$ lepton+jets spectrum

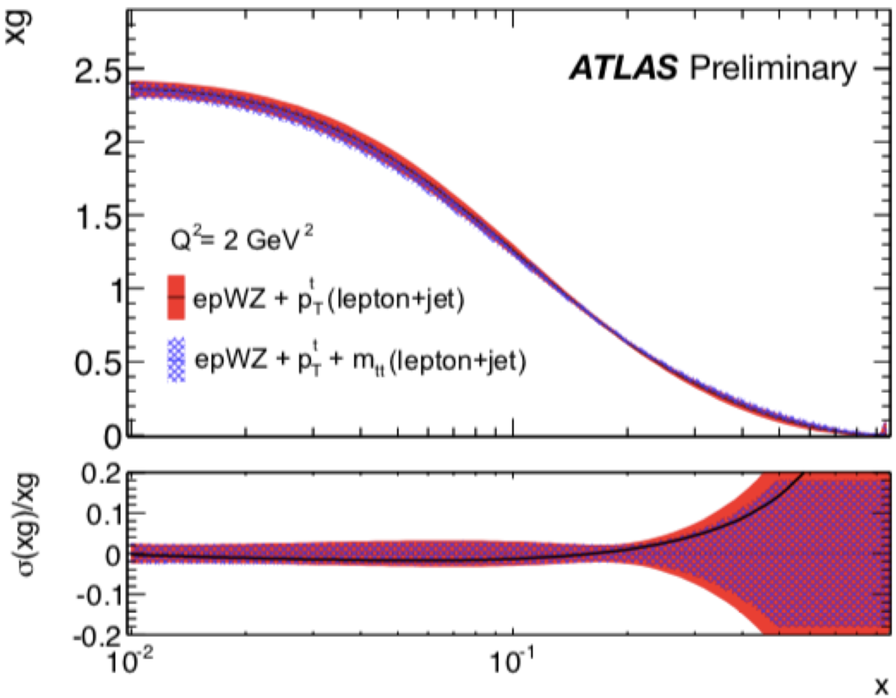


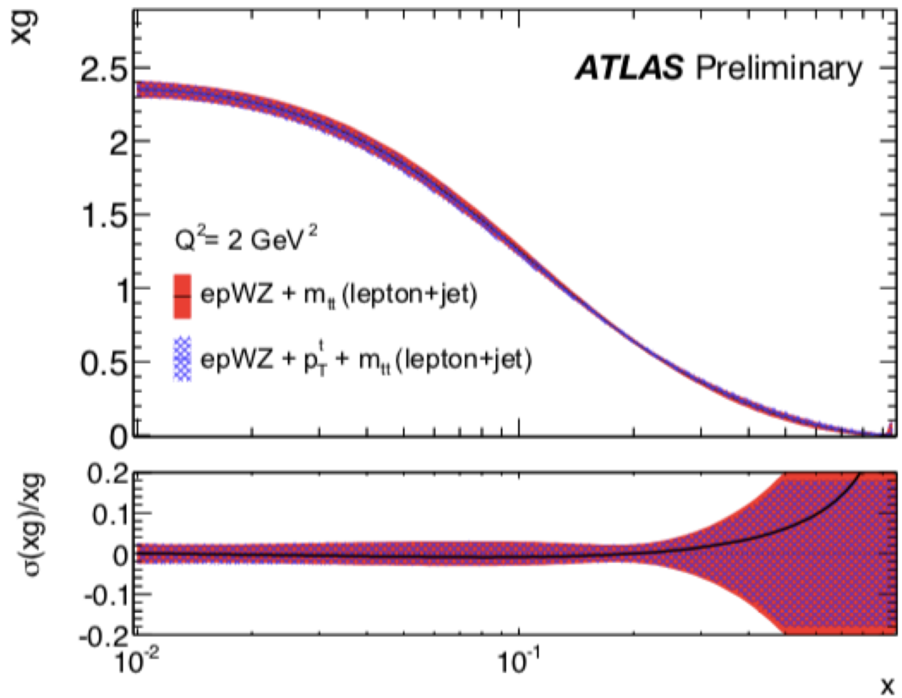


		lepton+jets spectra			
		p_T^t and y_t with statistical correlations	p_T^t and y_t without statistical correlations	p_T^t and m_{tt} with statistical correlations	p_T^t and m_{tt} without statistical correlations
Total χ^2/NDF		1264 / 1068	1260 / 1068	1290 / 1070	1287 / 1070
Partial χ^2/NDP	HERA	1148 / 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

- Using both p_T^t and y_t spectra softens the high-x gluon obtained from p_T^t alone whereas it hardens the high-x gluon obtained from y_t alone

Fits to more than one $t\bar{t}$ lepton+jets spectrum

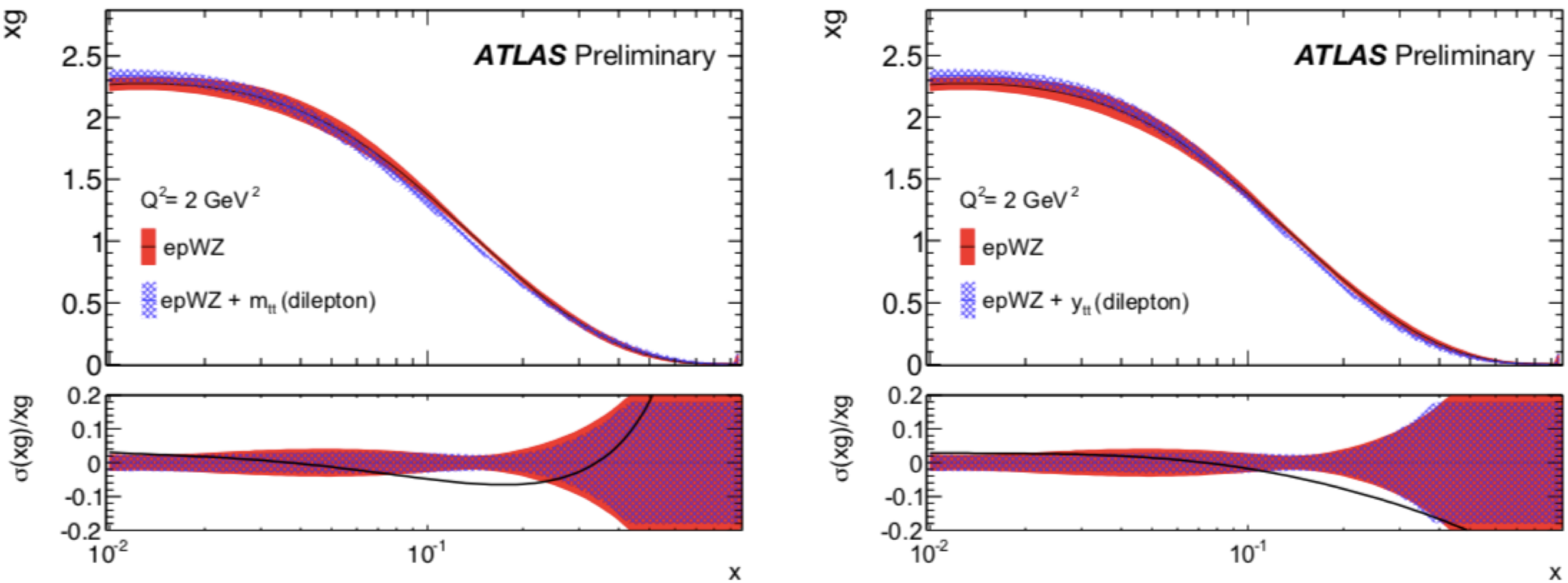




		lepton+jets spectra			
		p_T^t and y_t with statistical correlations	p_T^t and y_t without statistical correlations	p_T^t and m_{tt} with statistical correlations	p_T^t and m_{tt} without statistical correlations
Total χ^2/NDF		1264 / 1068	1260 / 1068	1290 / 1070	1287 / 1070
Partial χ^2/NDP	HERA	1148 / 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

- **Very surprising:** effect of fitting the two spectra separately is compatible

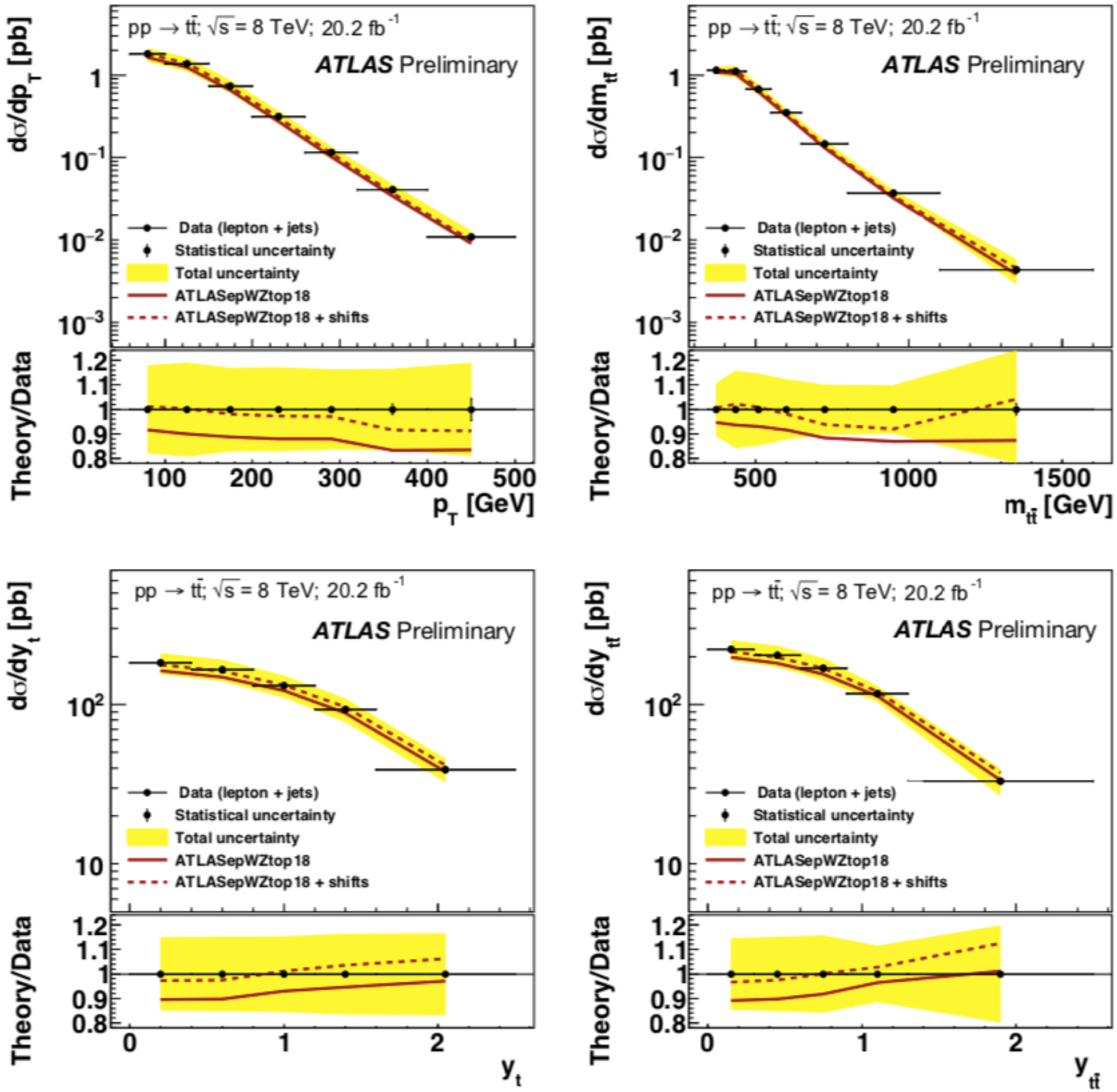
Fits to the $t\bar{t}$ dilepton spectra



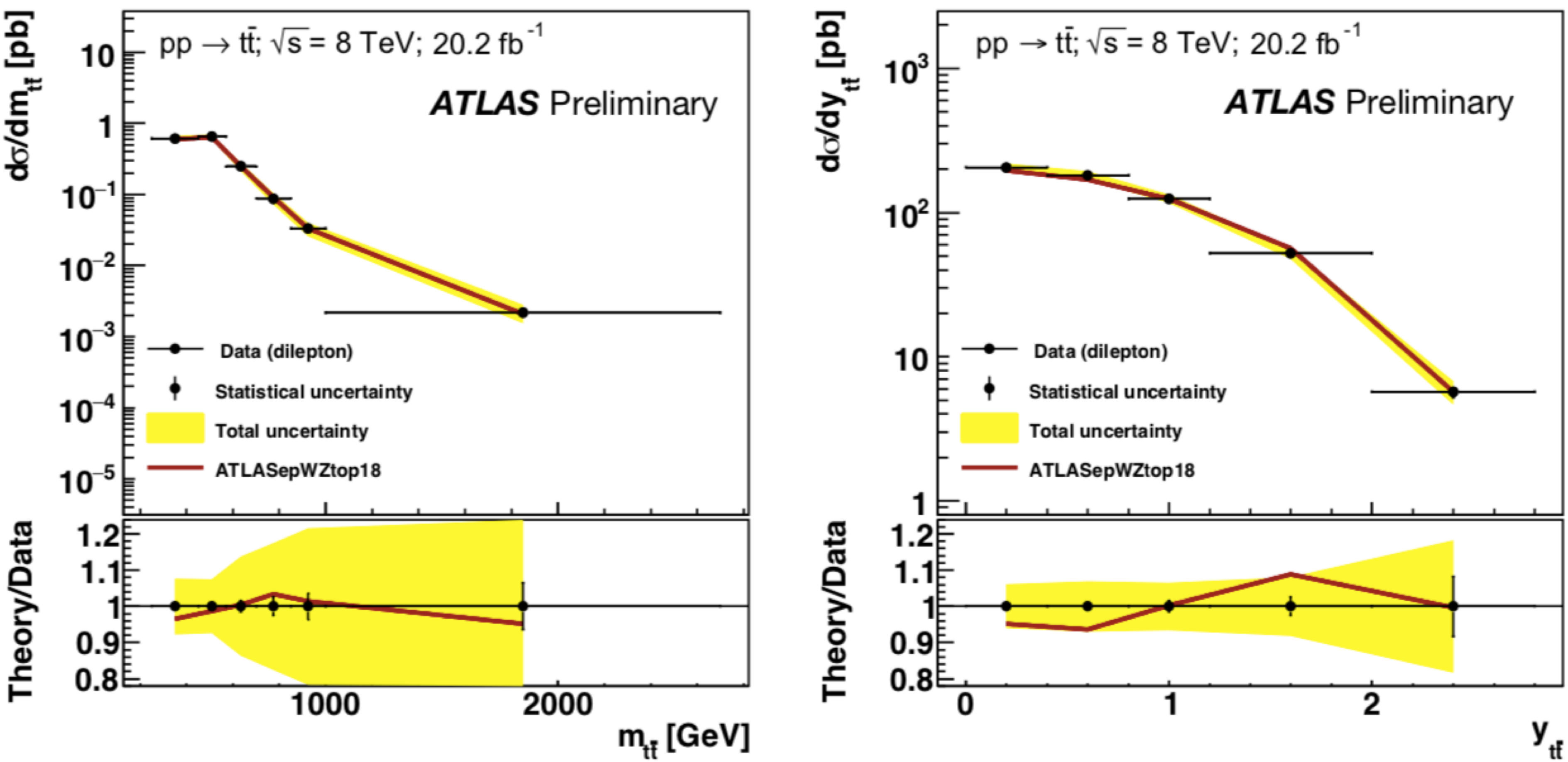
		dilepton spectrum	
		m_{tt}	y_{tt}
Total χ^2/NDF		1233.8 / 1061	1233.8 / 1060
Partial χ^2/NDP	HERA	1152 / 1016	1147 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	79.3 / 55	82.8 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	2.6 / 6	4.5 / 5

- As for the lepton+jets spectra, the $m_{t\bar{t}}$ data support a harder gluon while the $y_{t\bar{t}}$ data prefer a softer gluon – anyway both fits show good χ^2

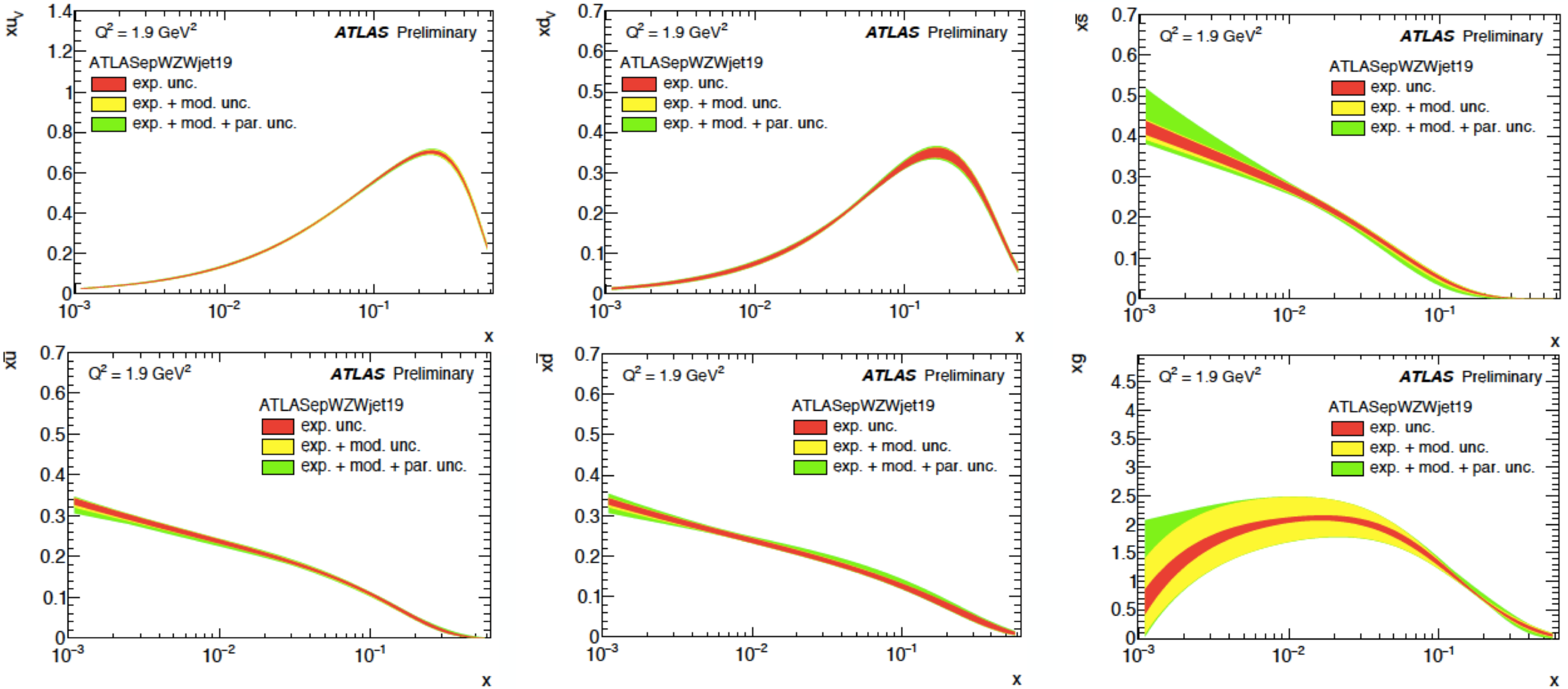
Comparison to $t\bar{t}$ lepton+jets spectra



Comparison to $t\bar{t}$ dilepton spectra



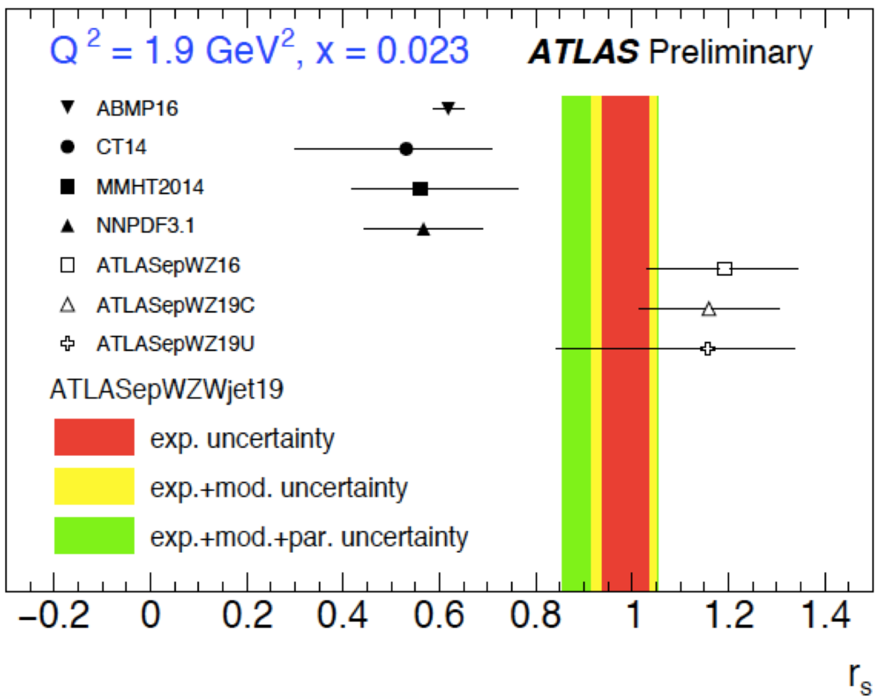
Fits including the W+jets data

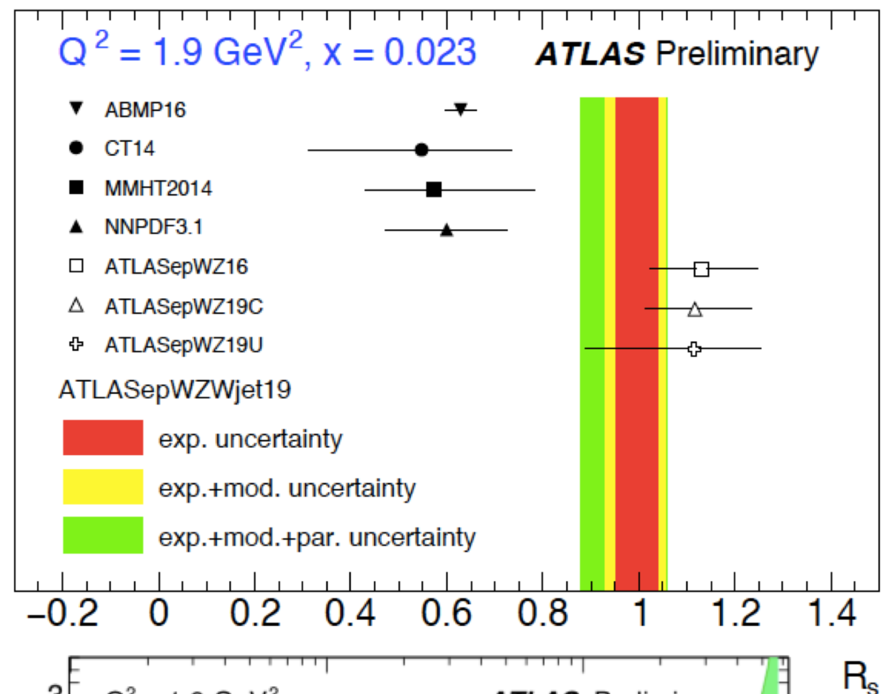


Compared to previous ATLAS epWZ16 fit:

- Softer d_v
- Harder $\bar{d}$
- u-quark distributions unchanged
- Softer strange PDF at low-x

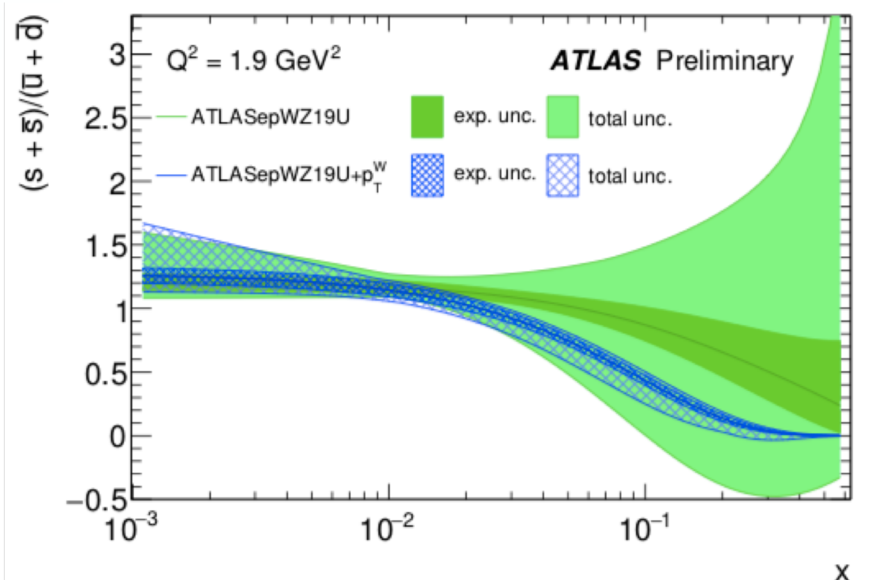
How strange is the proton?



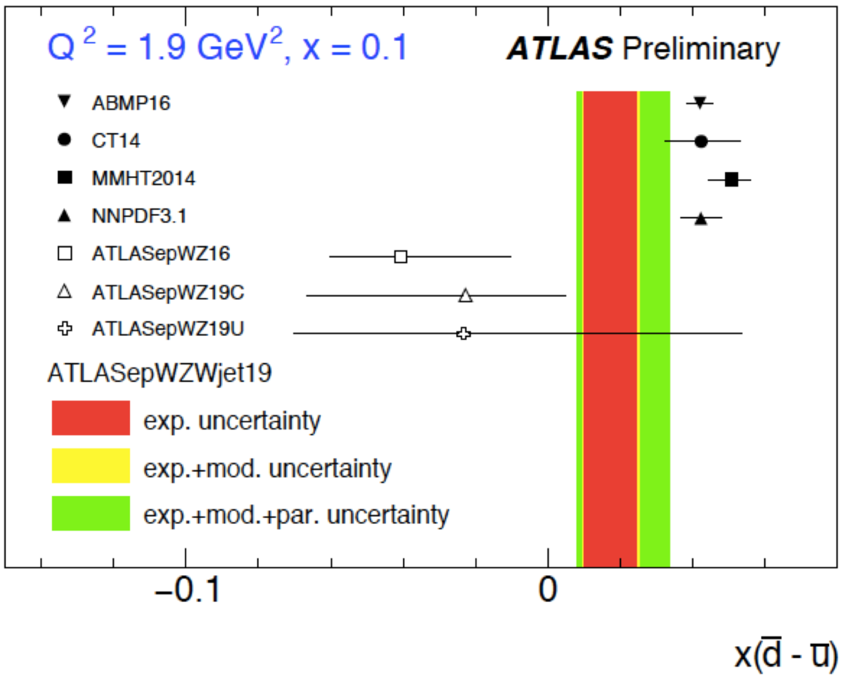


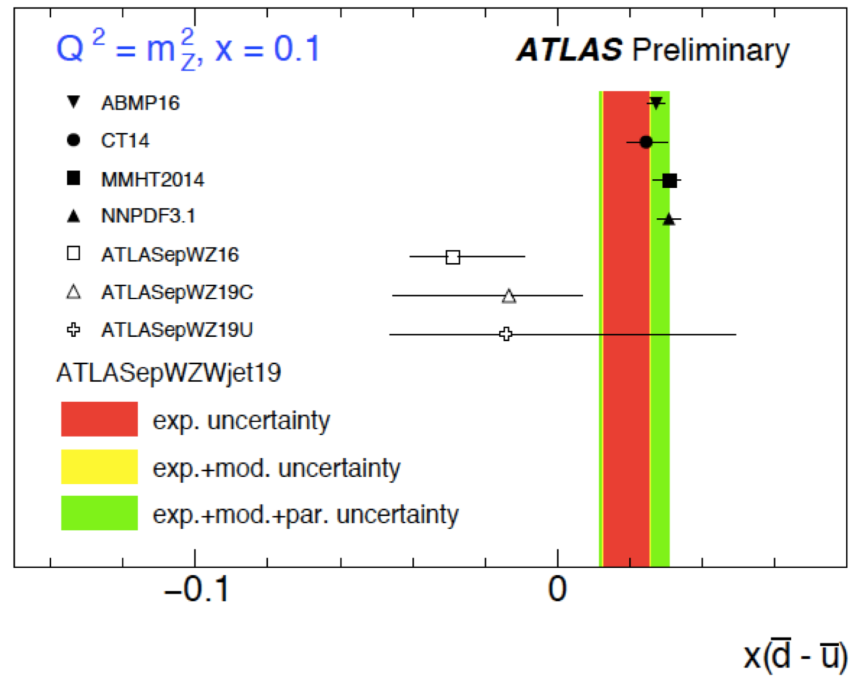
$$r_s = \frac{1}{2}(s+\bar{s})/\bar{d} \quad R_s = \frac{s(x)+\bar{s}(x)}{\bar{u}(x)+\bar{d}(x)}$$

- Consistent with earlier ATLAS fits
- Slightly higher than PDF from the global fitters

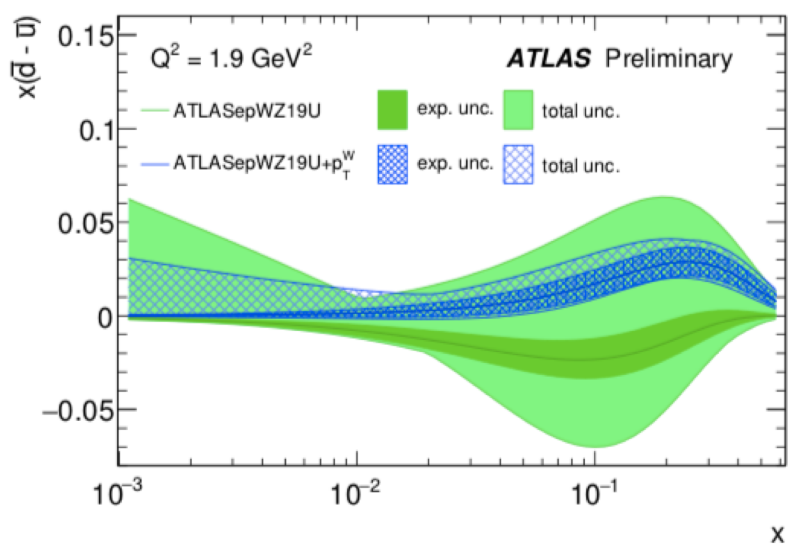


Light quark asymmetry





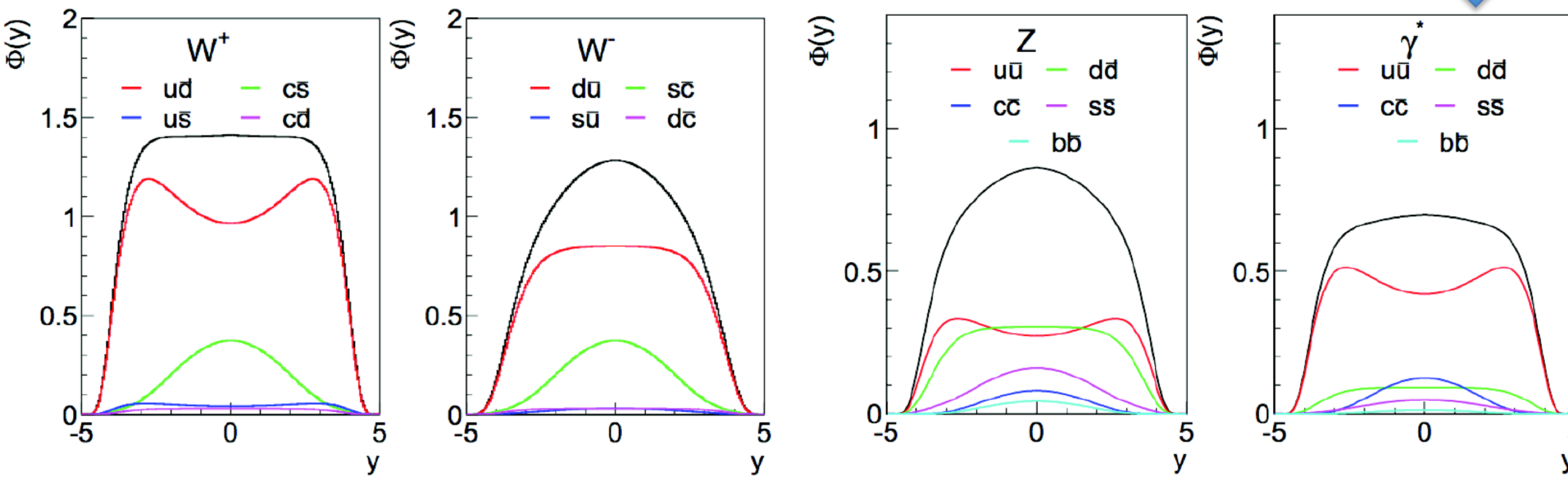
- Comparison with global fitters shown here
- New fit more in line with global fitters predictions



Flavour decomposition of W,Z at the LHC

- W and Z bosons produced in abundance at LHC with clear experimental signatures
- Inclusive cross sections of W and Z well understood at NNLO
- Composition of incoming flavours different for W and Z production
- u and d quark dominate for W production; all flavours contribute for Z production

S. Glazov
V. Radescu



$$W^+ \approx 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \approx 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

$$Z \approx 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \approx 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$

- Ratio measurements: W^+/W^- ratio, $W^\pm/Z$ ratio, $t\bar{t}/Z$ ratio @13 TeV
- **Why are these ratio measurements so important?**
  Taking the ratio offer the chance to cancel out some systematics and to enhance sensitivity to some parton flavours

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

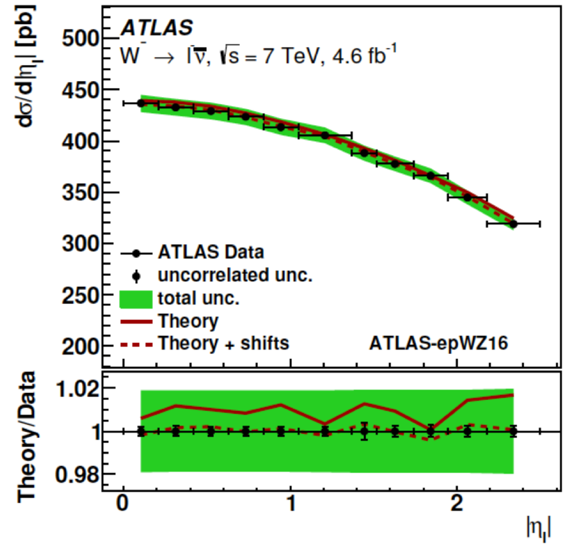
W/Z cross section measurement @7 TeV

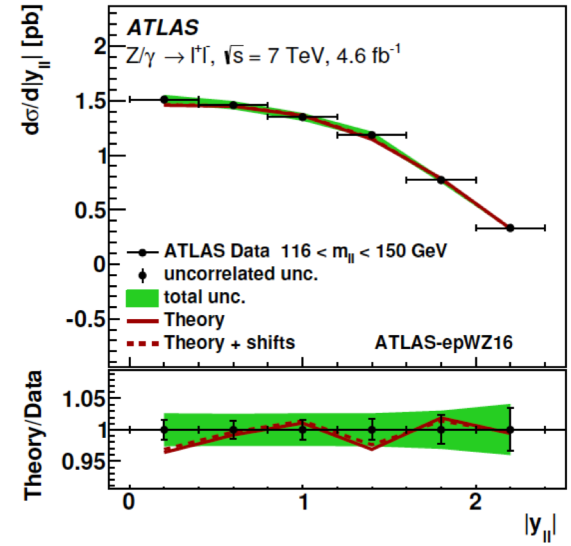
- W/Z ATLAS data at 7 TeV (4.6 fb^{-1})
- Data: HERAI+II plus $W^{\pm}$ $|\eta_l|$, Z $|y_{ll}|$ (3 m_{ll} central, 2 m_{ll} forward)
- MCFM interfaced to APPLgrid (NLO predictions)
- k_F from NLO QCD + LO EW to NNLO QCD + NLO EW (DYNNLO and MCSANC)

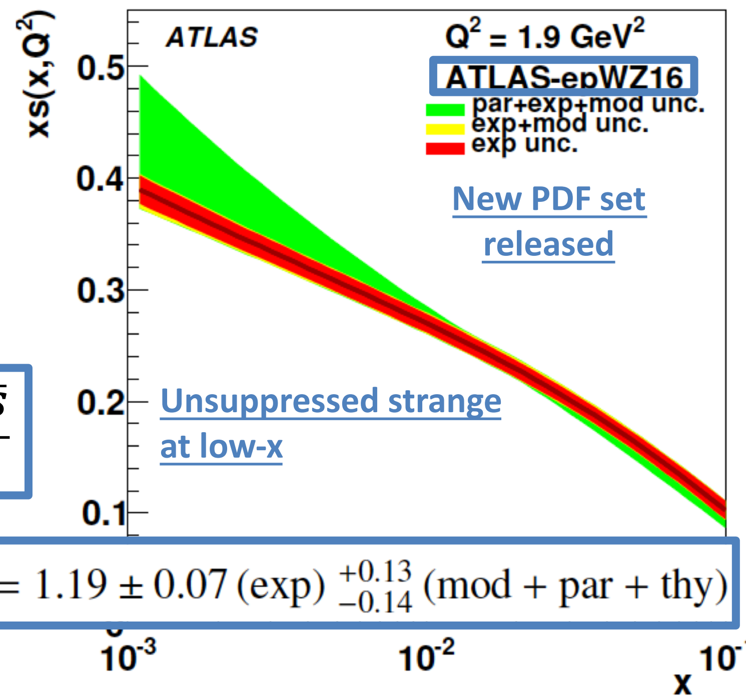
$$K_f = \frac{\sigma^{\text{NLO EW}}_{\text{NNLO QCD}}(\text{DYNNLO})}{\sigma^{\text{LO EW}}_{\text{NLO QCD}}(\text{APPLGRID})}$$

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

$$r_s = \frac{s + \bar{s}}{2d}$$







New PDF set released

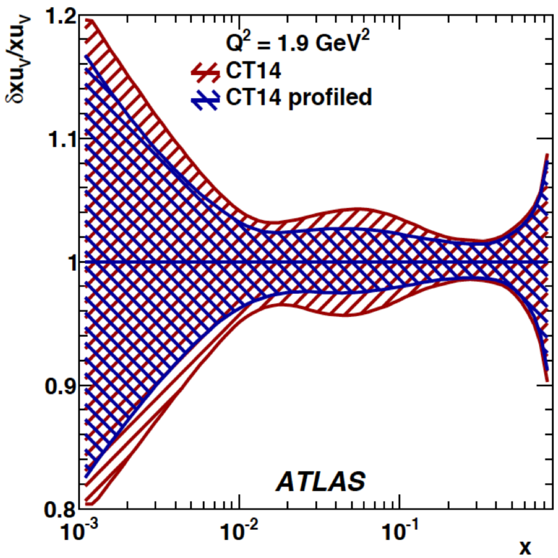
Unsuppressed strange at low-x

$$r_s = 1.19 \pm 0.07\,(\text{exp})\;^{+0.13}_{-0.14}\,(\text{mod} + \text{par} + \text{thy})$$

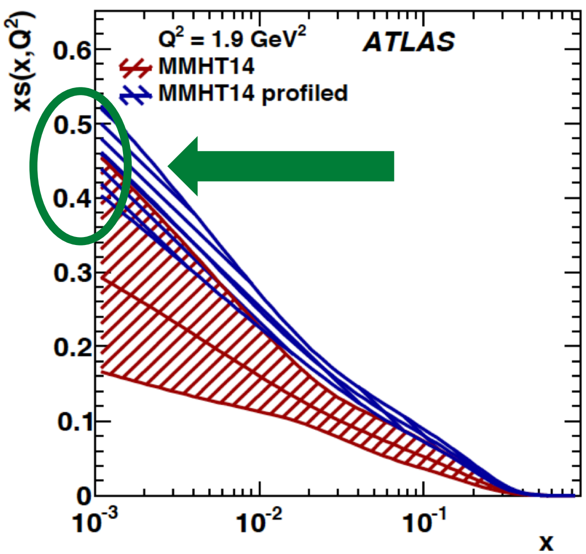
W/Z cross section measurement @7 TeV

- W/Z ATLAS data at 7 TeV (4.6 fb^{-1})
- Profiling exercise with 5 PDF sets: ABM12, CT14, MMHT14, NNPDF3.0, ATLAS-epWZ12
- No change in valence quarks PDFs
- Enhanced r_s wrt predictions by other PDF sets

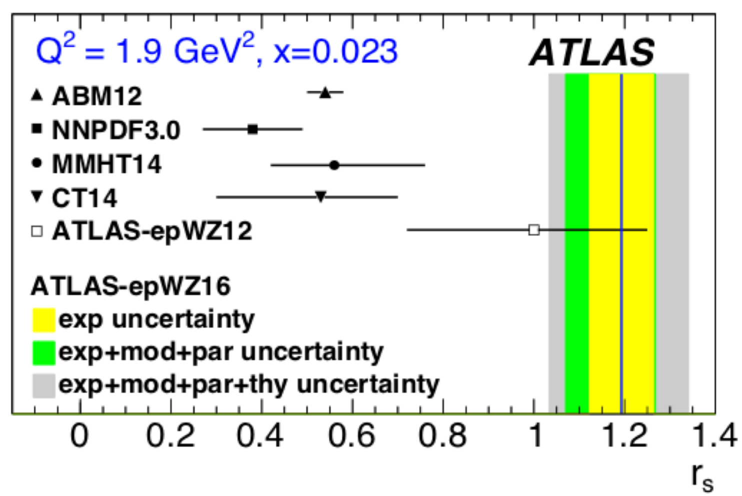
Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+ \nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^- \bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 46 – 66 GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell}$ = 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



Valence quarks PDFs



Strange quark PDF



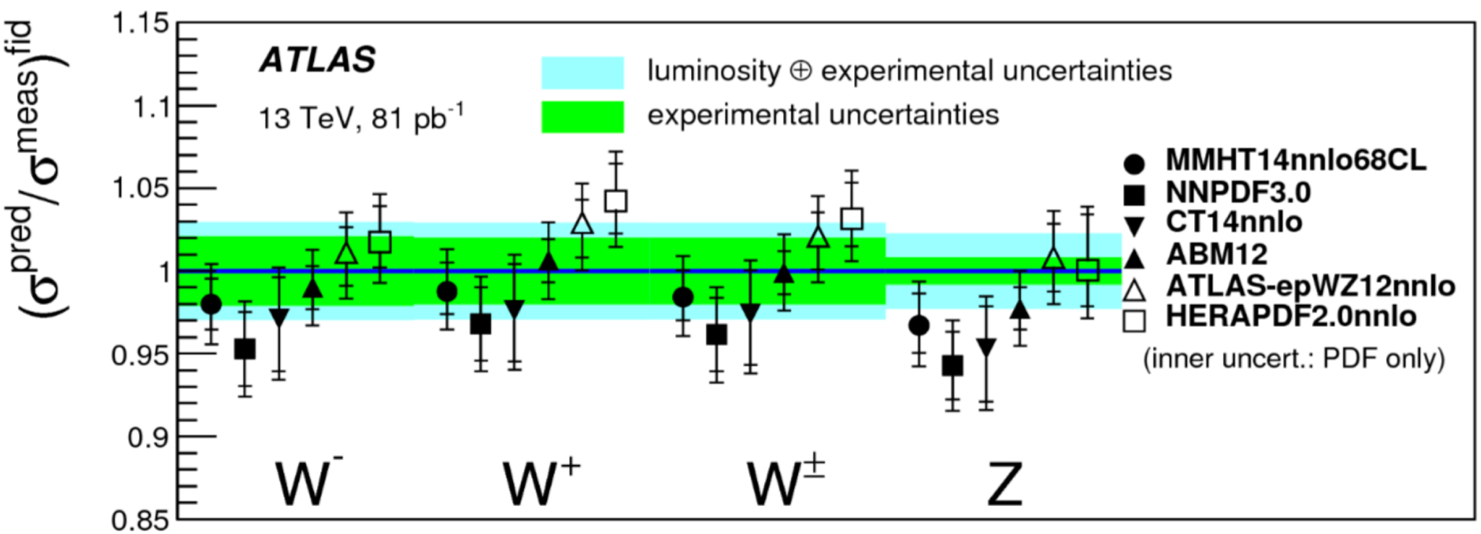
Eur. Phys. J. C 77 (2017) 367

W,Z @13 TeV

Phys. Lett. B 759 (2016) 601

- Motivation for measuring W, Z inclusive cross sections with Run-2 LHC data:
  - Access a different kinematic region in x which provides different PDFs sensitivity

- Luminosity uncertainty: 2.1%; systematic uncertainties: 2% (W), 1% (Z)

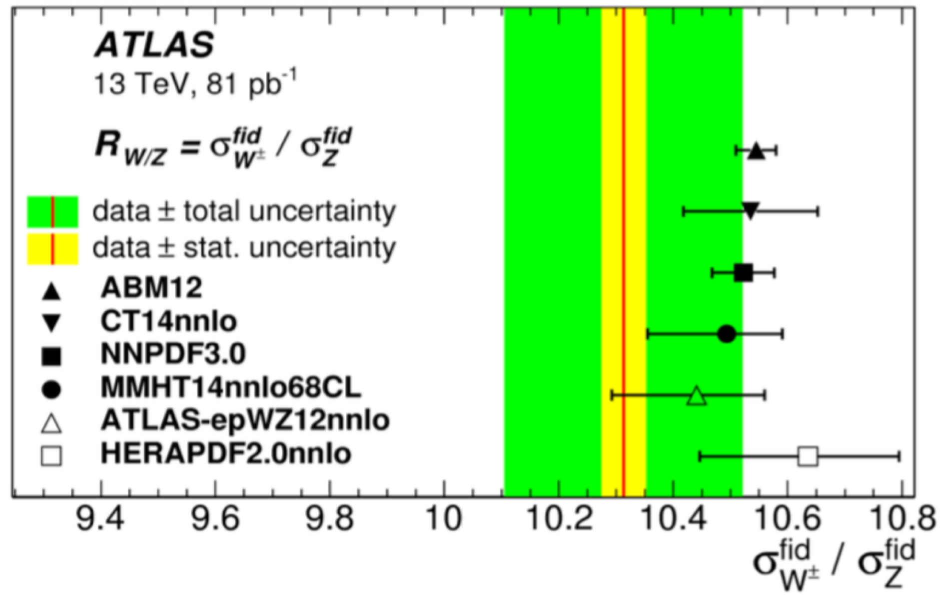


Results confirm the findings in Run1 and provide extra handle to better constrain PDFs

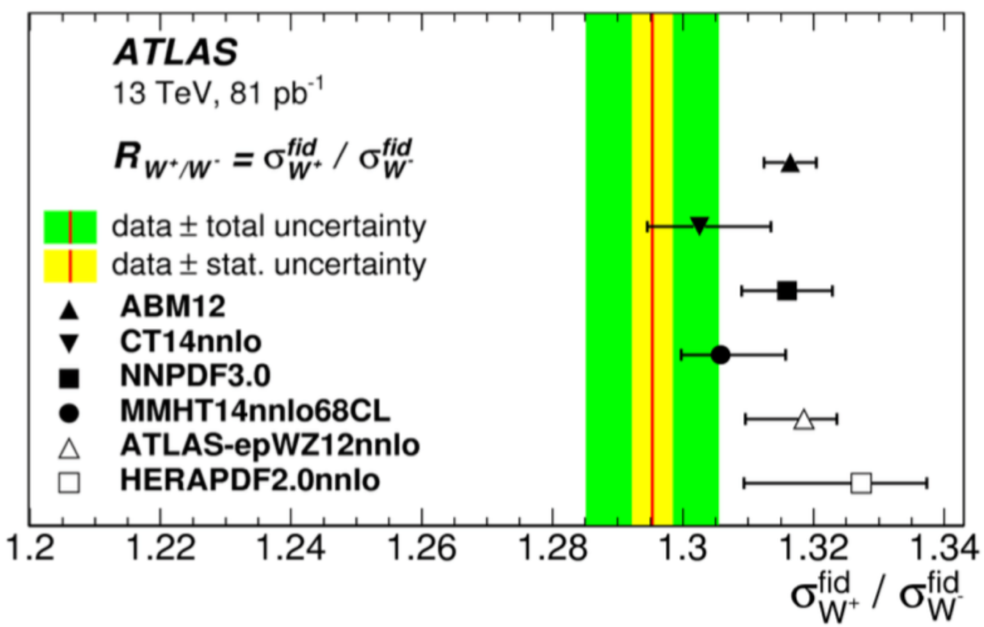
- **Most PDF sets describe the data well**
  - ABM12 has the best agreement with the data: no Tevatron data, but LHC W,Z and top
  - NNPDF3.0, MMHT14nnlo68CL and CT14nnlo generally a little bit low: Tevatron as well as most LHC data (except top and W + c for CT14, except W + c for MMHT)
  - HERAPDF2.0nnlo a little bit high in W^+ (different u,d content from other PDFs): only HERA data

W and Z cross section ratio @13 TeV

- **W/Z ratio**
  - Sensitive to valence to strange ratio
  - W/Z ATLAS analysis (2010 data, 36 pb[-1]): $r_s = (s + \bar{s})/2\bar{d} = 1.00 \pm 0.25$ (**Phys Rev Lett 109 (2012) 012001**)
  - ATLAS W+c paper (**JHEP 05 (2014) 068**) confirm the result: $r_s = 0.96^{+0.24}_{-0.31}$
  - Consistent with previous results: preference for an enhanced r_s



Phys. Lett. B 759 (2016) 601



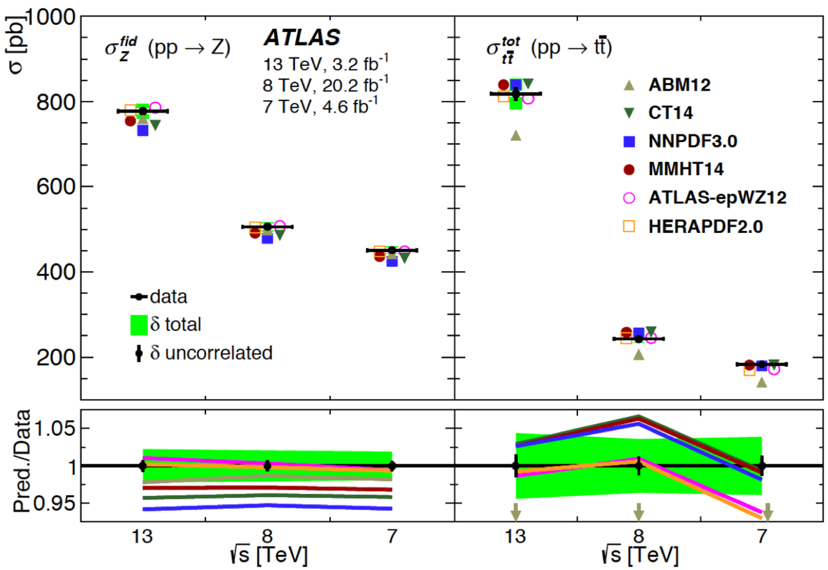
- **W^+/W^- ratio**
  - Sensitive to u_V and d_V in the low-x regime
  - Smaller ratio than predicted by most PDFs

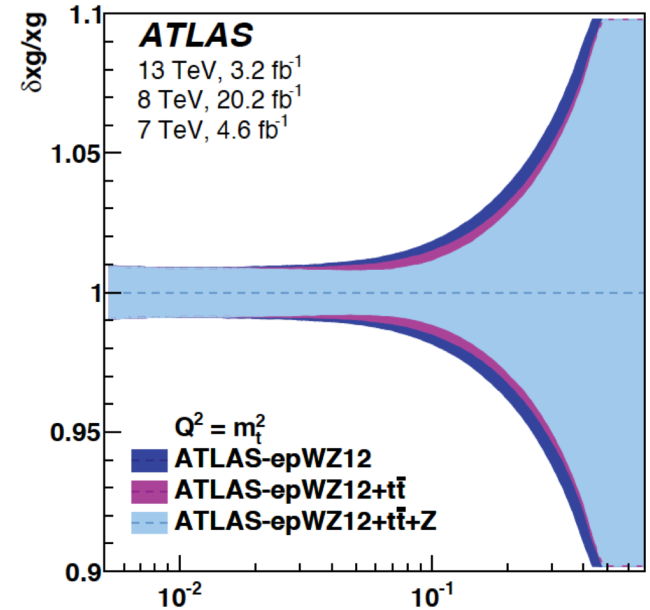
$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

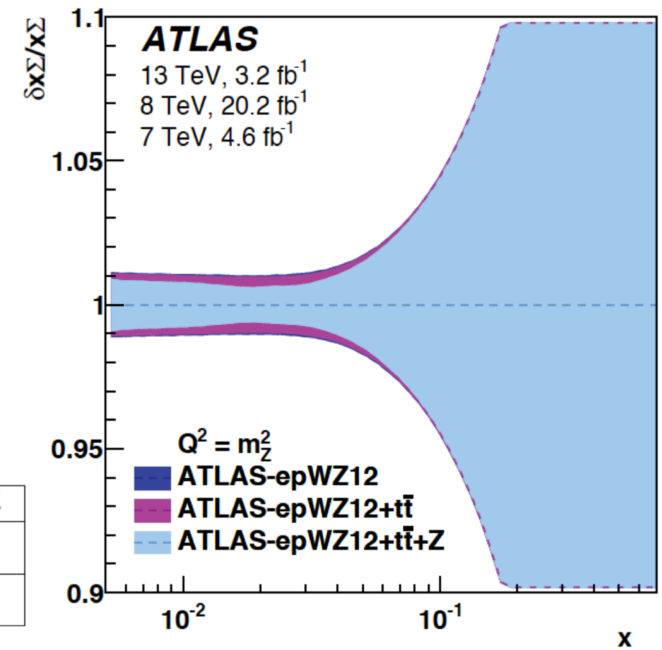
$t\bar{t}$/Z ratio @7, 8 and 13 TeV

JHEP 02 (2017) 117

- 2015 data only at 13 TeV (3.2 fb^{-1})
- Profiling of the ATLAS-epWZ12
- Z: NNLO QCD (DYNNLO) with CT14 + NLO EW (FEWZ)
- $t\bar{t}$: NNLO+NNLL from Top++
- Z data help to constrain both the light-quark-sea and gluon distributions
- $t\bar{t}$ data contribute to constrain $xg(x, Q^2)$





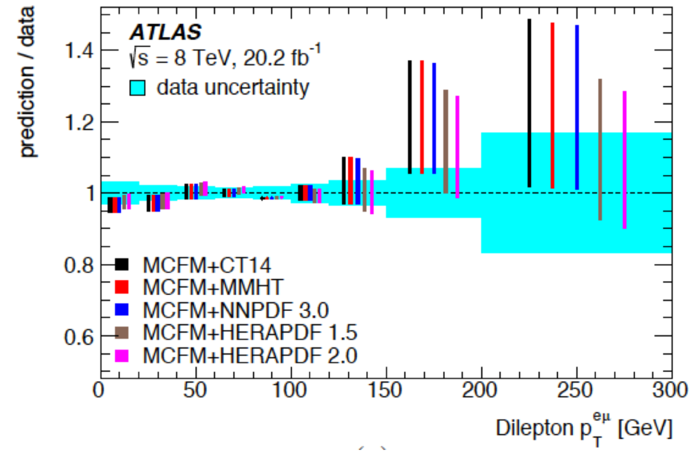


	ATLAS-epWZ12	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12
χ^2/NDF	8.3 / 6	15 / 6	13 / 6	17 / 6	10 / 6	25 / 6
p-value	0.22	0.02	0.05	0.01	0.11	< 0.001

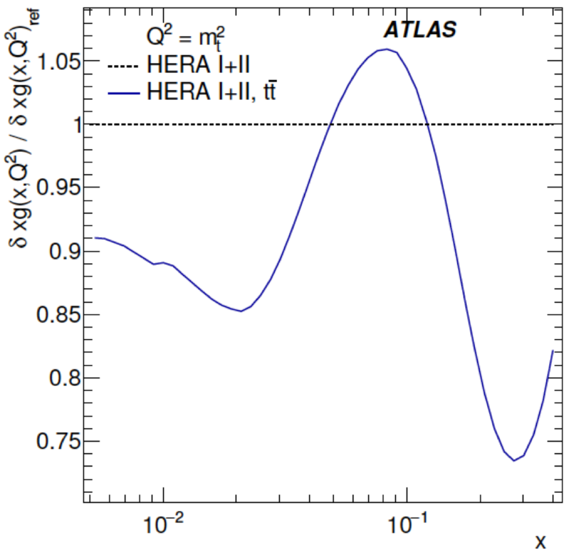
Eur. Phys. J. C 77 (2017) 191

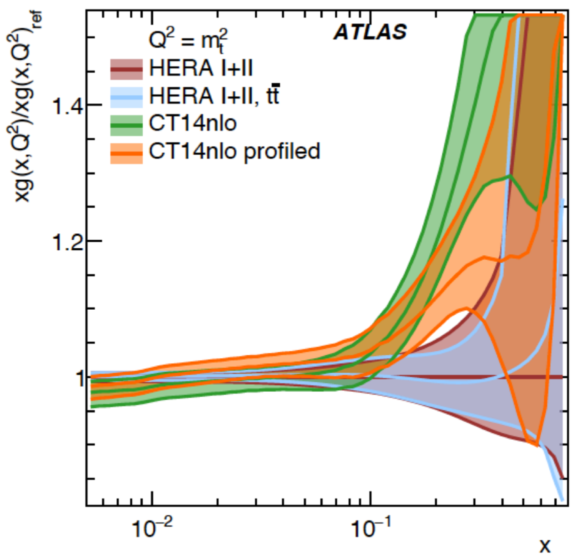
Dilepton differential and top mass - $t\bar{t}$ @8 TeV

- ATLAS data at 8 TeV (20.2 fb^{-1})
- Comparison with FO QCD predictions (different PDFs)
- Constraints on the gluon PDF



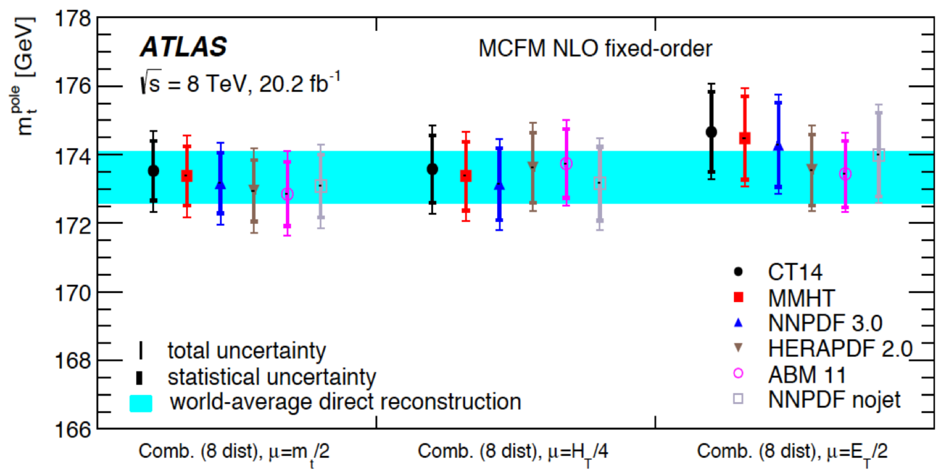
$$xg(x) = Ax^B(1-x)^C(1+Ex^2)\,e^{Fx}$$





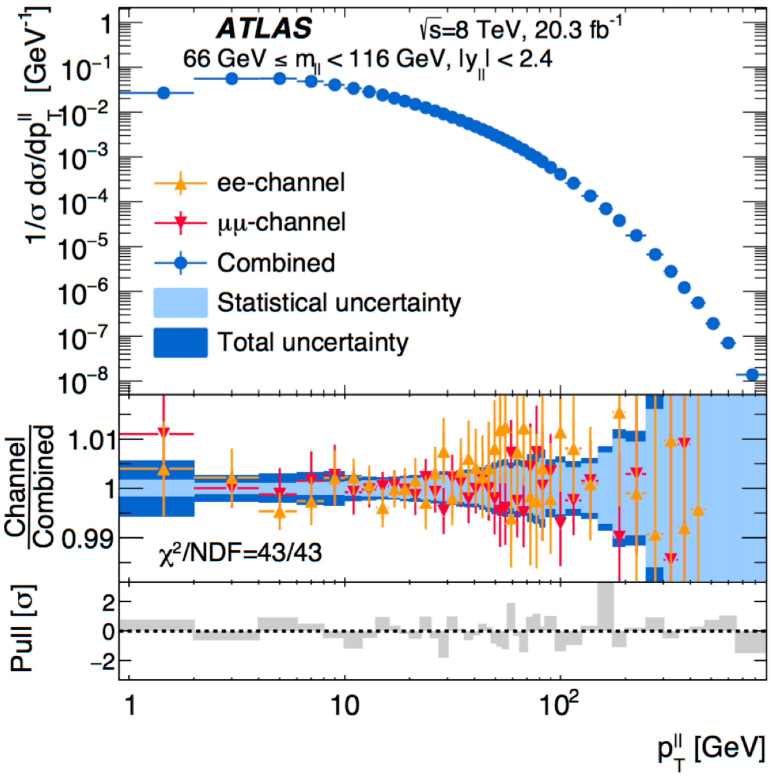
$$m_t^{pole} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\ \text{GeV}$$

- Inclusion of $t\bar{t}$ data reduces the unc. by over most of the x-range
- Profiling with NLO NNPDF3.0 and CT14: **softer gluon in the high-x region**
- **Extraction of m_t^{pole}** (8 sensitive distributions)
- FO NLO predictions compatible with world average within uncertainties

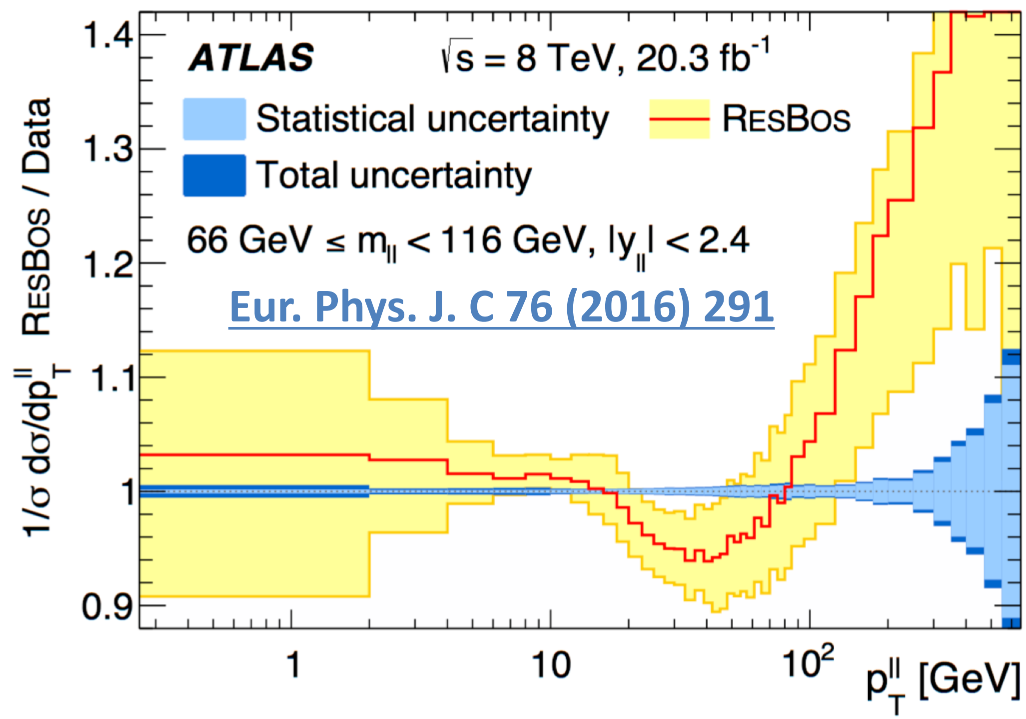


Z p_T measurement

- From the experimental point of view, very precise measurement, ideal for probing QCD
- **Low p_T region**: dominated by the emission of soft partons (resummation and shower models)
- **High p_T region**: dominated by the emission of hard partons (PDFs)



ATLAS measurements use both ee,μμ channels (compatible accuracy). The combined result is accurate to better than 0.5% for p_T < 100 GeV range



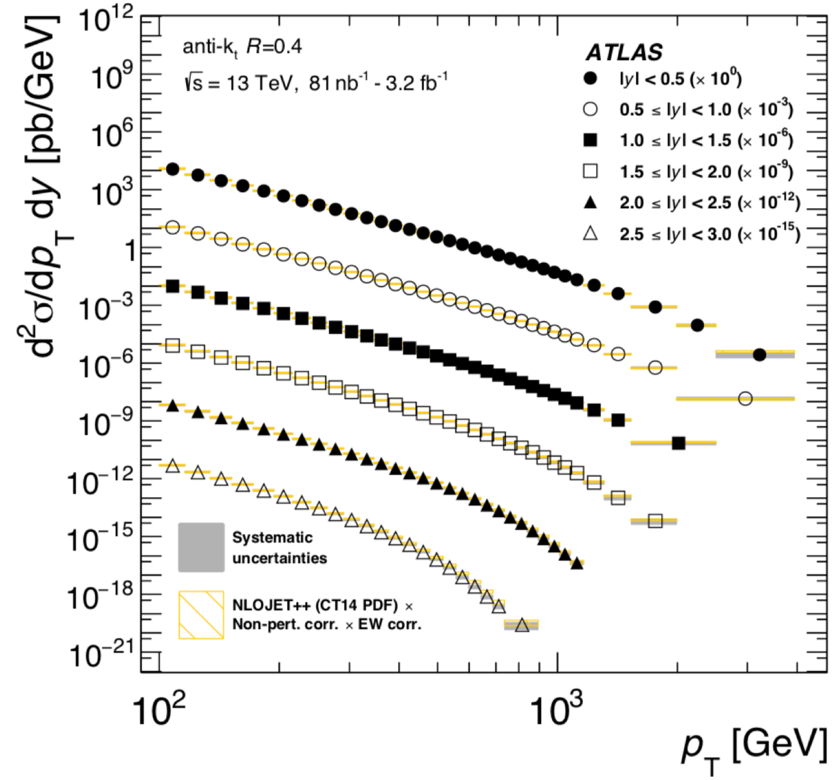
Eur. Phys. J. C 76 (2016) 291

Ongoing efforts in extracting PDFs using resummed calculations

Inclusive jet production at Run II

JHEP 05 (2018) 195

- Jet measurements of 2015 bring a new kinematic reach (reaching up to p_T = 4 TeV), interesting to observe if it will help to further constrain PDFs
- New results at 13TeV: **good agreement** with SM predictions
- Inclusive jet data: tension observed in the data/theory comparisons, when using the full phase-space

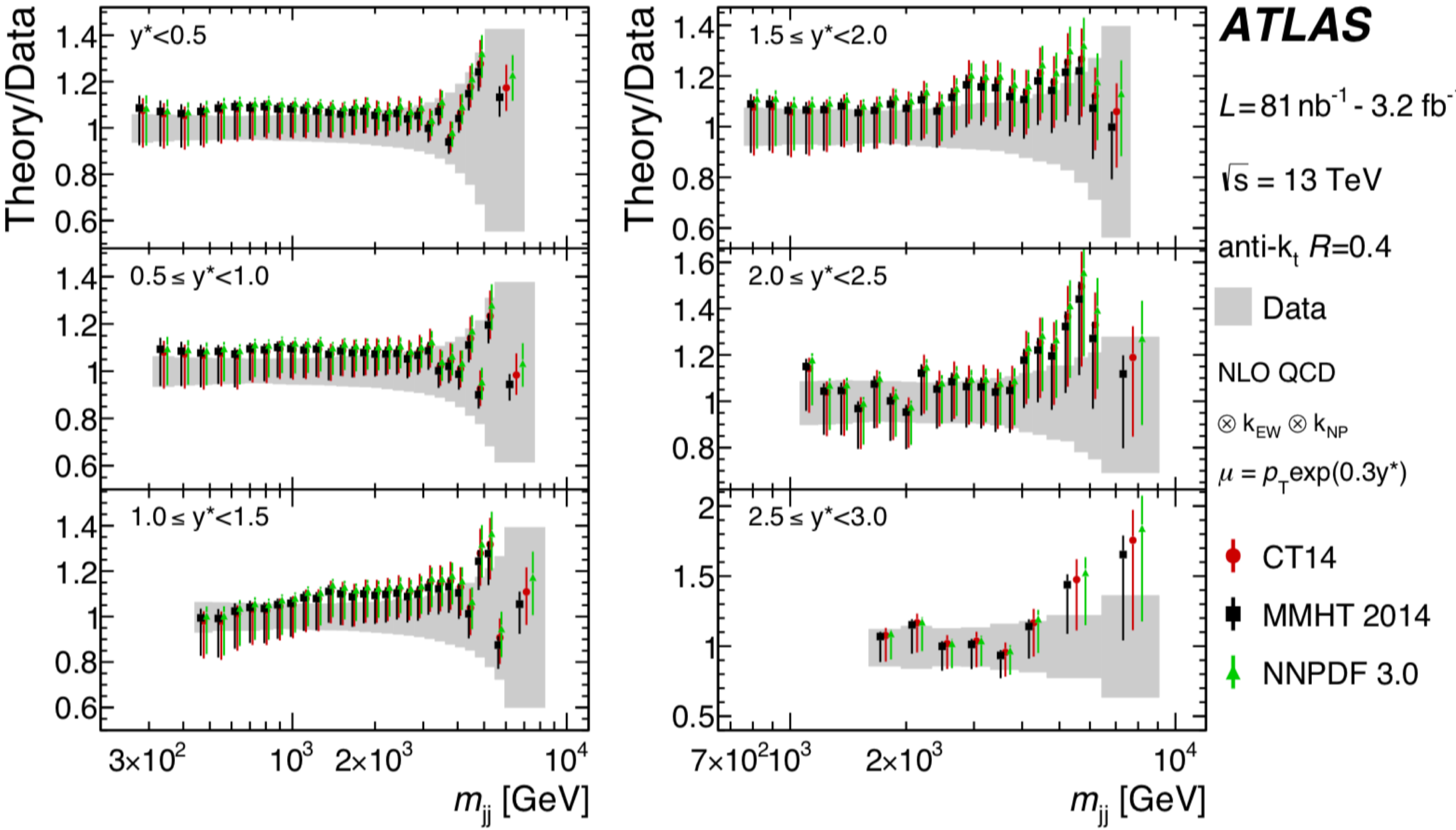


NNLO calculations for jets: more lever arm to the test of SM

- In the following slides, **double-differential inclusive jet cross section with 2015 data**
  - Integrated luminosity of 3.2 fb^{-1}
  - Following the procedure already outlined for 2.76 and 7 TeV analysis
  - PDF sensitivity at high p_T and in the forward region

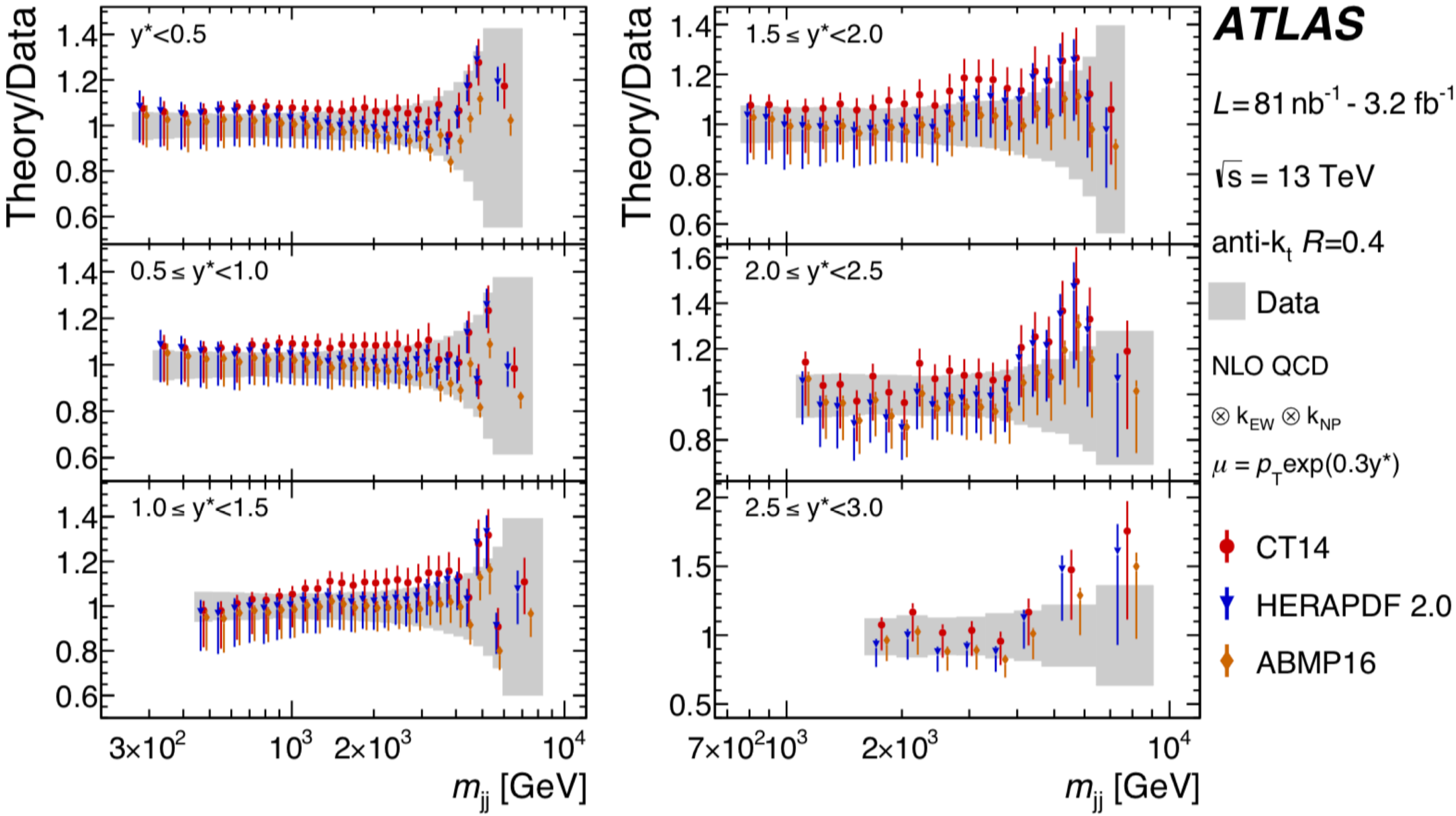
Double differential inclusive jet cross section

- **Data are generally lower than the theory for CT14, MMHT2014, NNPDF3.0**
  (general feature seen comparing anti-kT R = 0.4 and R = 0.6 for Run 1 already)



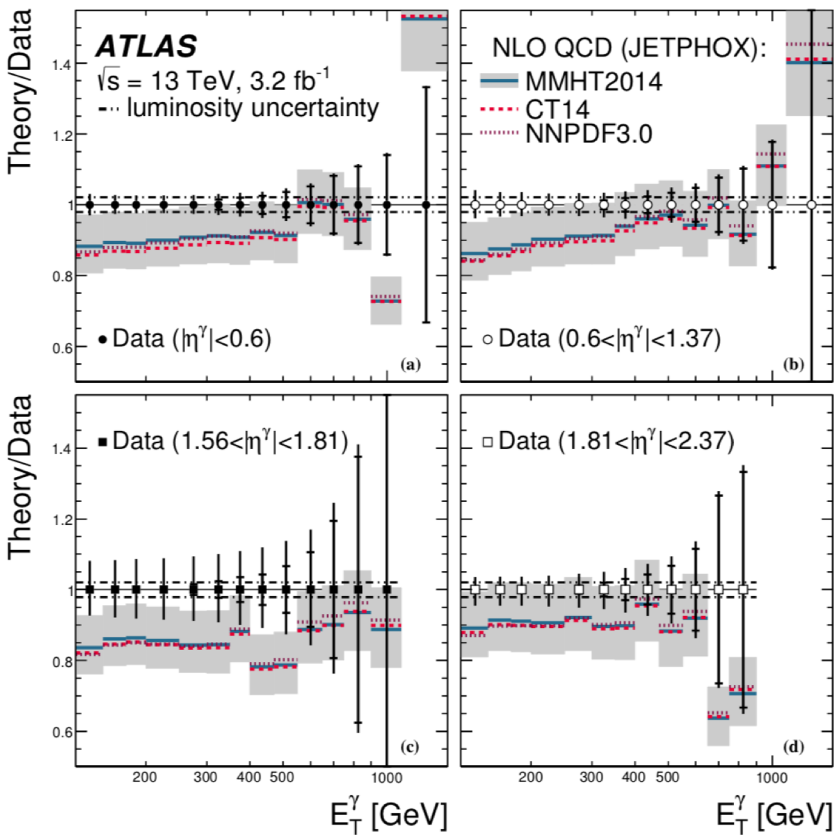
Double differential inclusive jet cross section

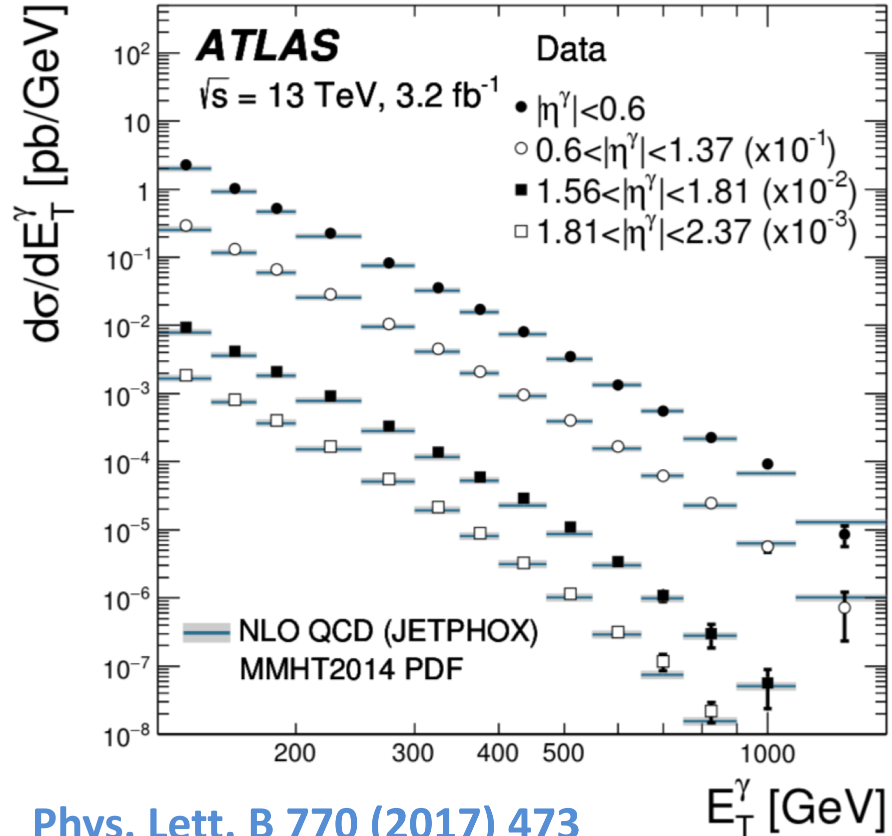
- **CT14 prediction larger than data, while ABMP16 is a bit lower; HERAPDF2.0 is ok**
- Quantitative data/theory comparisons studies for all these PDF sets available



Isolated photons @ 13 TeV

- Dominant production: $gq \to q\gamma$
- Constraint on gluon at medium x e.g. $x \simeq 0.1$
- Range: 125 GeV < $E_T \lesssim$ 2 TeV
- Dominant systematic uncertainties:
  - Energy scale
  - Background correlations



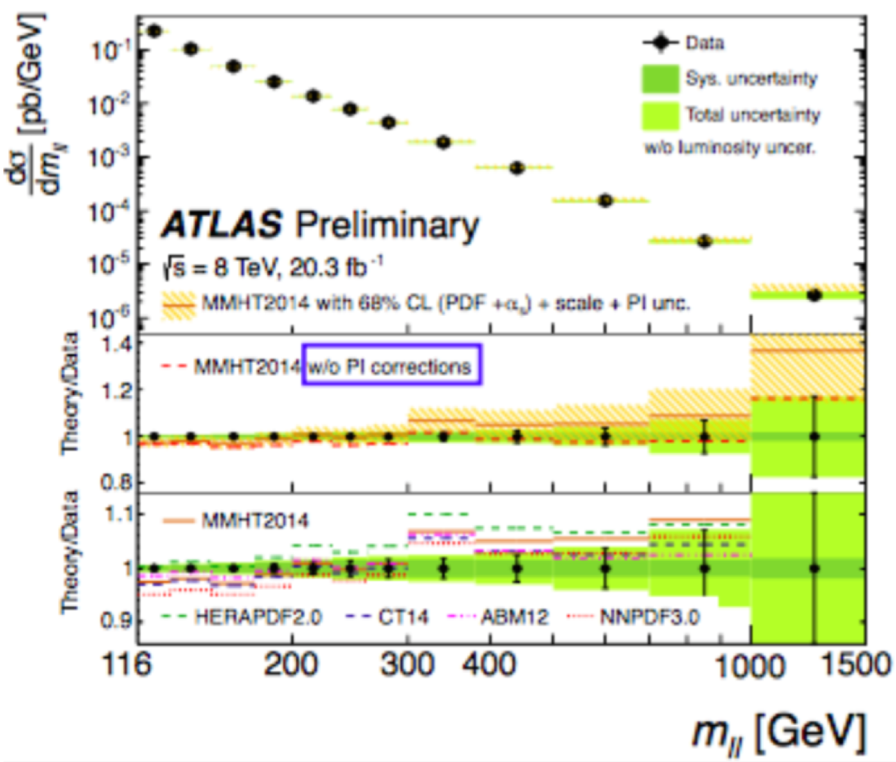


[Phys. Lett. B 770 (2017) 473]

- JetPhox: low in normalisation (~20% lower than data)
- Result independent from the PDF set in use
- NLO predictions: large scale uncertainties

High mass Drell Yan @8 TeV: comparison to theory

- ATLAS high mass Drell Yan at 8 TeV (published now) [JHEP 08 (2016) 009]
- The measured cross sections are compared to theoretical predictions using a selection of recent PDF sets
- Theory = NNLO pQCD $\otimes$ NLO EW + LO photon-induced (PI); pQCD uses MMHT14 NNLO PDF
- PI uses NNPDF23qed for photon PDF ± 68% of replicas; $\alpha_s = 0.118 \pm 0.001$
- Scale error: envelope of μ_F and μ_R varied by factors of 2



- Theory uncertainties are larger than data uncertainties → potential for PDF constraints
- Theory generally in agreement with data
- Comparison with other NNLO PDF sets (HERAPDF2.0, CT14, ABM12, NNPDF30)
- Photon induced contribution reaches 15% at large m_{ll}
- Where PI contribution is large, theory uncertainty dominated by the PI piece
- Else PDF uncertainty dominates theory precision

High mass Drell Yan @8 TeV: comparison to theory

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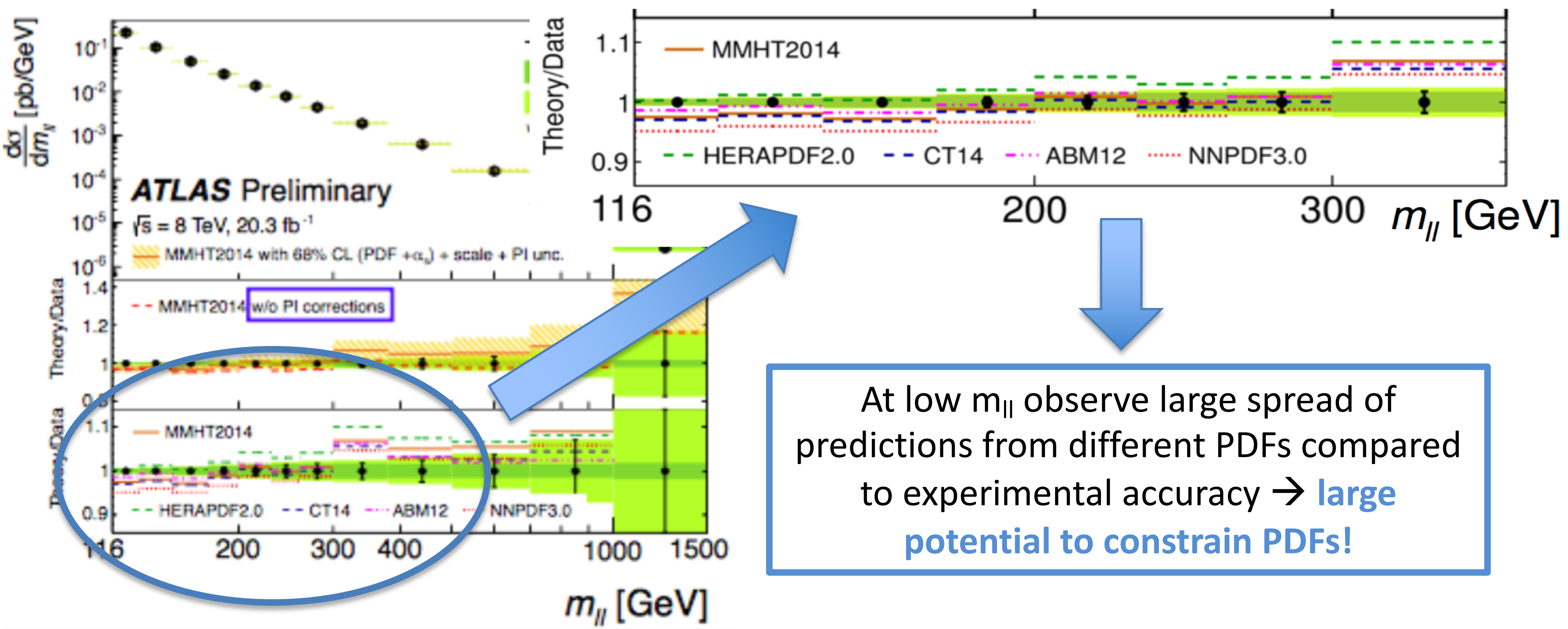
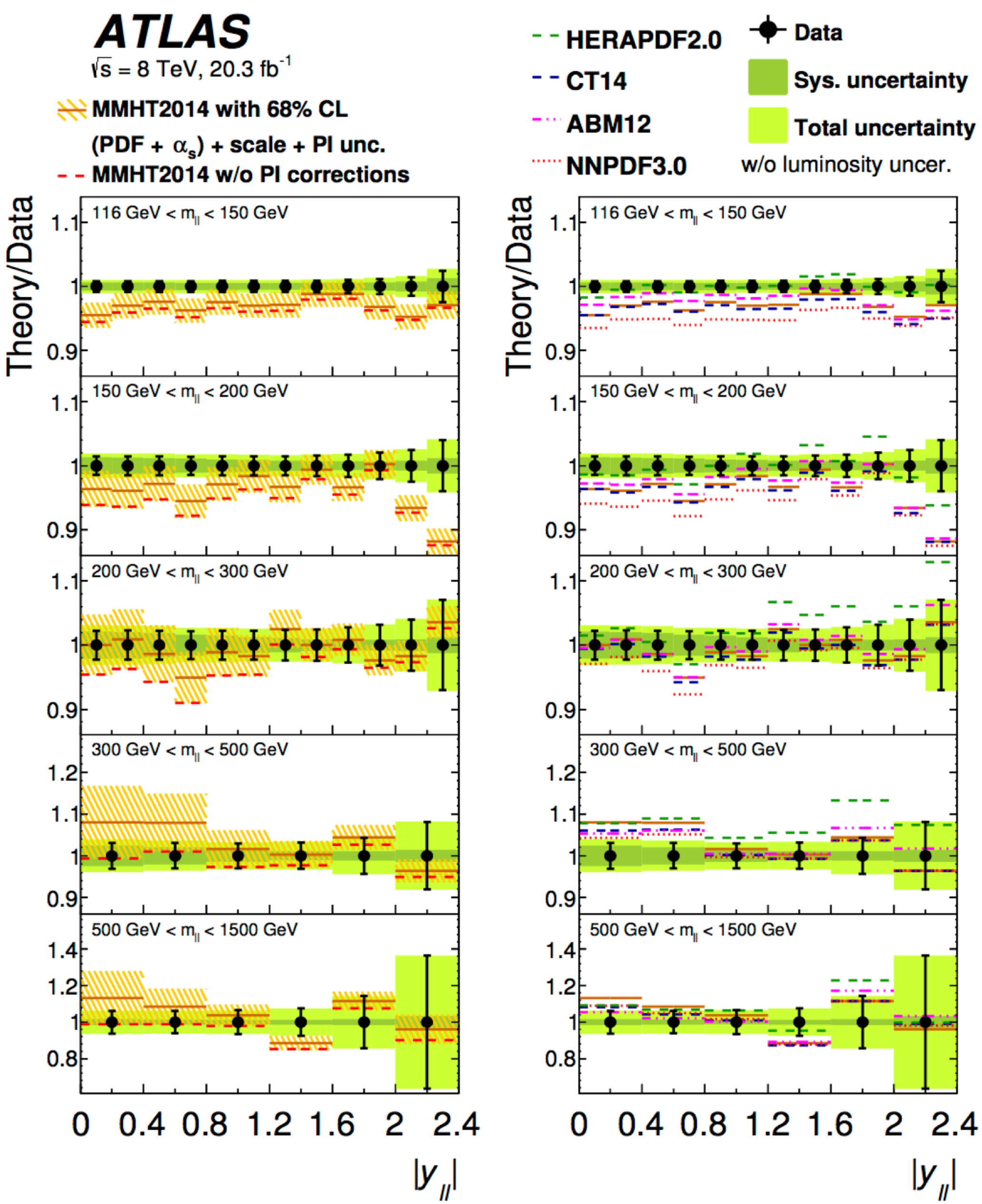


At low m_{ll} observe large spread of predictions from different PDFs compared to experimental accuracy → **large potential to constrain PDFs!**

High mass Drell Yan @8 TeV: comparison to theory



$$\frac{d^2\sigma}{dm_{ll}d|y_{ll}|}$$ **data/theory ratio**

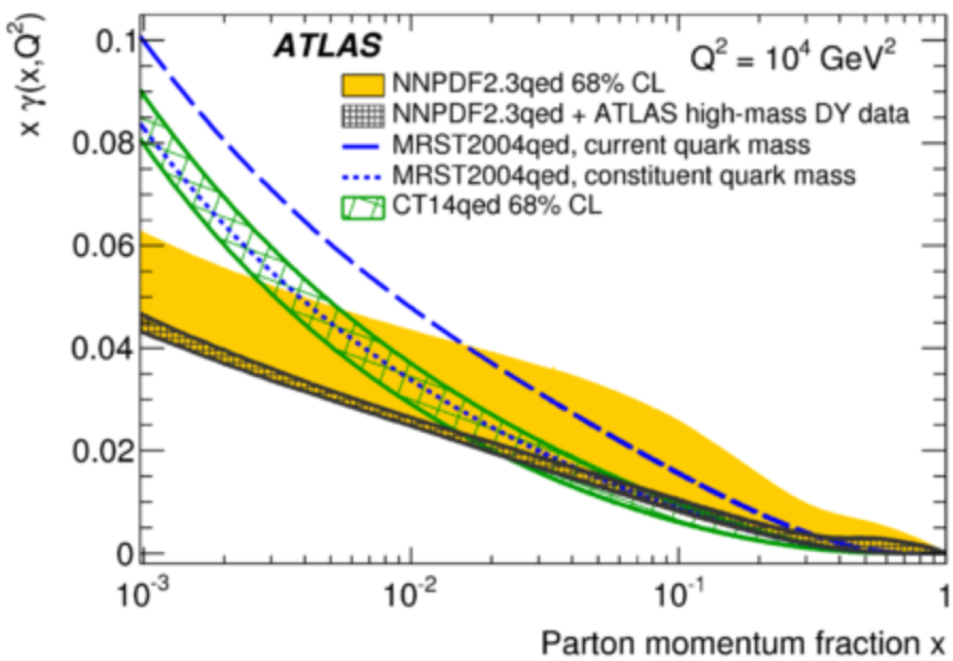
- Photon-induced (PI) contribution increases with m and decreasing $|y_{ll}|$
- PDF uncertainties calculated for each PDF scaled to 68% CL
- Compatibility of data to predictions with other PDFs test with χ^2 function

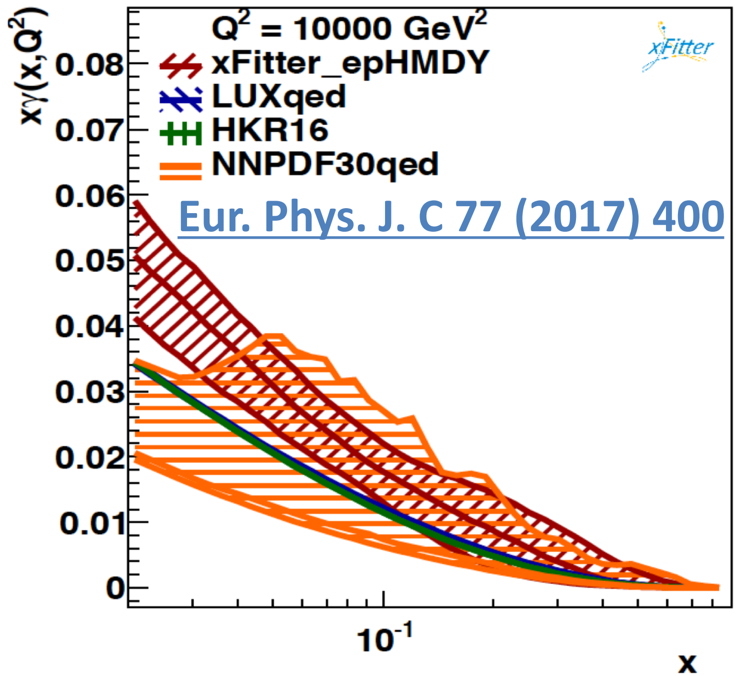
	$m_{\ell\ell}$	$\lvert y_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$
MMHT2014	18.2/12	59.3/48	62.8/47
CT14	16.0/12	51.0/48	61.3/47
NNPDF3.0	20.0/12	57.6/48	62.1/47
HERAPDF2.0	15.1/12	55.5/48	60.8/47
ABM12	14.1/12	57.9/48	53.5/47

Data in agreement with predictions

(χ^2 probability at worst ~6%)

Photon PDF





Eur. Phys. J. C 77 (2017) 400

- Assess impact of new data on photon PDF → use Bayesian reweighting of NNPDF replicas
- Each replica receives a weight according to χ^2 function
- Poorly fitting replicas receive a small weight; replicas fitting the data well receive a large weight
- New PDF central value is estimated from mean of weighted replicas
- New PDF uncertainty determined from 68% CL
- **Original NNPDF uncertainty dramatically reduced in reweighting**

Profiling PDFs

- To estimate the impact of a new data set on a given PDF set quantitatively
- Profiling performed using a χ^2 function with both experimental and theoretical uncertainties arising from PDF variations:

$$\chi^2(\boldsymbol{b}_{\text{exp}}, \boldsymbol{b}_{\text{th}}) = \sum_{i=1}^{N_{\text{data}}} \frac{\left(\sigma_i^{\text{exp}} + \sum_\alpha \Gamma_{i\alpha}^{\text{exp}} b_{\alpha,\text{exp}} - \sigma_i^{\text{th}} - \sum_\beta \Gamma_{i\beta}^{\text{th}} b_{\beta,\text{th}}\right)^2}{\Delta_i^2} + \sum_\alpha b_{\alpha,\text{exp}}^2 + \sum_\beta b_{\beta,\text{th}}^2$$

- Correlated experimental and theoretical uncertainties are included using nuisance parameter vectors $\boldsymbol{b_{exp}}$ and $\boldsymbol{b_{th}}$
- Their influence on the data and the theory predictions is described by $\boldsymbol{\Gamma_{i\alpha}^{exp}}$ and $\boldsymbol{\Gamma_{i\beta}^{th}}$ matrices
- Index $\boldsymbol{\alpha}$ ($\boldsymbol{\beta}$) corresponds to the experimental (theoretical) uncertainty nuisance parameters
- The measurements and the uncorrelated experimental uncertainties are $\boldsymbol{\sigma_i^{exp}}$ and Δ_i
- $\boldsymbol{\sigma_i^{th}}$ represents the theory predictions

Profiling PDFs

- The minimisation of the χ^2 equation shown in the slides and **its original form** leads to a system of linear equations

$$\chi^2 = \sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i} + \sum_j b_j^2 + \sum_i \ln \frac{\delta_{i,\mathrm{unc}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i}{\delta_{i,\mathrm{unc}}^2 D_i^2 + \delta_{i,\mathrm{stat}}^2 D_i^2}$$

- The generalised function, with asymmetric PDF uncertainties, is minimised iteratively
- The values at the minimum of the χ^2 function provides a compatibility test of the data and theory
- The values at the minimum of the nuisance parameters $\boldsymbol{b_{\beta,th}^{min}}$ can be interpreted as optimization ("profiling") of PDFs to describe the data
- Explicitly, the profiled central PDF set $f_0{}'$ is given by

$$f_0' = f_0 + \sum_\beta b_{\beta,\mathrm{th}}^{\mathrm{min}}\left(\frac{f_\beta^+ - f_\beta^-}{2} - b_{\beta,\mathrm{th}}^{\mathrm{min}}\frac{f_\beta^+ + f_\beta^- - 2f_0}{2}\right)$$

- f_0 is the original PDF set and $f_\beta^\pm$ represents the eigenvectors corresponding to up and down variations
- **The resulting PDFs have reduced uncertainties**