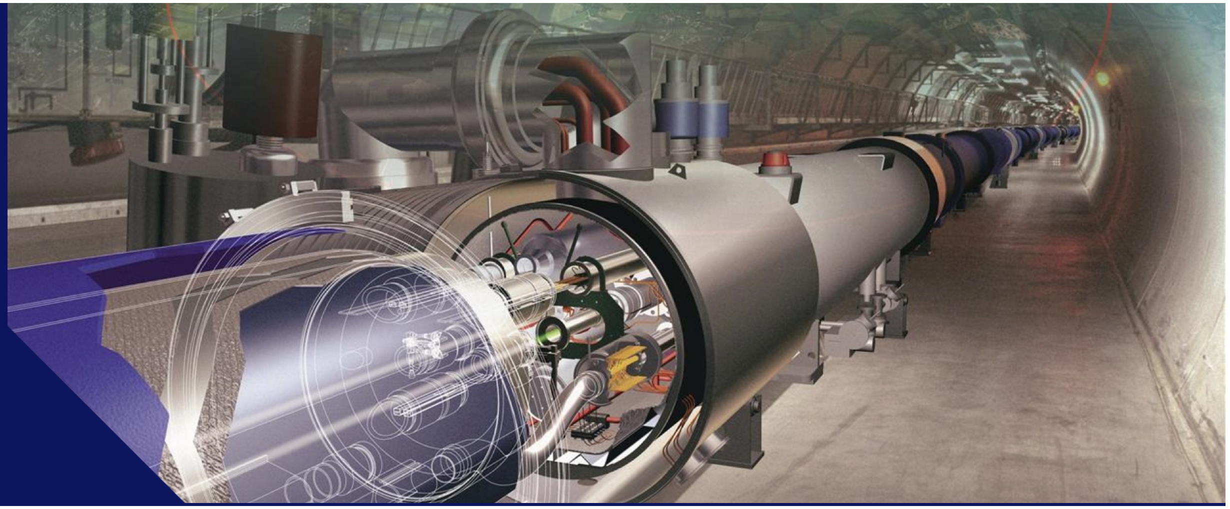
PDF4LHC

CERN

22 November 2022



Highlights from ATLAS: ATLASpdf21 fit

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on behalf of the ATLAS collaboration

ATLASpdf21 overview

- **NEW** from ATLAS: EPJC82 (2022) 5,438 (arXiv:2112.11266)

- **ATLASpdf21** is a PDF fit to a **diverse set of ATLAS datasets** for which full information on **correlated systematic uncertainties** is provided, and **NNLO QCD+NLO EW** calculations are available

- ***Key Highlights or Advancements with respect to previous ATLAS fits:***

- **multiple ATLAS datasets (7, 8 and 13 TeV)** from LHC Runs 1 and 2
- careful study and application of **experimental systematic correlations** both within and between datasets – ***and information made public to the community***
- consideration of theoretical **scale uncertainties**
- more flexible **PDF parameterisation** – resulting PDFs achieve good description of data routinely included in global fits but **NOT** in **ATLASpdf21**
- use of **enhanced tolerance ($T=\sqrt{\Delta\chi^2}=3$)** for realistic uncertainty estimates
- generally **good agreement with other modern PDF sets**, while achieving a better fit to the ATLAS measurements

ATLASpdf21 fit details

- **ATLASpdf21**: uses a diverse set of ATLAS measurements with PDF sensitivity
- **NNLO QCD + NLO EW fit**, performed using xFitter and either NNLO grids or NLO grids + K-factors

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_l (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta$ in bins of $y_{\ell\ell}$,$M_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [23]	8	20.2	e	p_{T}^{W}
Z + jets [24]	8	20.2	e	$p_{\mathrm{T}}^{\mathrm{jets}}$ in bins of $\lvert y_{\mathrm{jets}}\rvert$
$t\bar{t}$ [25, 26]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}$, p_{T}^{t}, $y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}$, p_{T}^{t}, y_t, $y_{t\bar{t}}$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_{T}^{γ} in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	p_{T} in bins of $\lvert y_{\mathrm{jets}}\rvert$

- **HERA I+II** NC and CC DIS data remain the backbone of the fit, providing information across wide range of Q^2 and x ($10^{-4} \leq x \leq 0.4$)
- **LHC** measurements provide valuable additional information:
- ***quark flavour separation***
- ***gluon at high-x***
- *extra constraints on all PDFs at medium and high x*

ATLASpdf21 fit parameterisation

- valence quark (***xuv***, ***xdv***) and light anti-quark distributions (***xubar***, ***xdbar***, ***xsbar***):

$$xf(x) = Ax^{B}(1-x)^{C}P(x) = Ax^{B}(1-x)^{C}(1 + Dx + Ex^{2} + Fx^{3})$$

- gluon ***xg*** has extra negative term, giving extra flexibility $-A'_{g}x^{B'_{g}}(1-x)^{C'_{g}}$ at small x (mostly affects fit quality to HERA data)
- PDFs parameterised at Q_0^2 = 1.9 GeV^2
- constraints from number and momentum sum rules fix normalisation (A) parameters for **valence quarks** and **gluon**
- all other A, B, C (except C'g=25) are free – notably, **no constraints** on A or B of **sea quarks**, so NO **normalisation** or **shape** constraints on $x\bar{d} - x\bar{u}$ or $x\bar{s}/(x\bar{d} + x\bar{u})$ as ***x* ⟶ 0**
- D, E, F added until no further significant improvement in X^2 – adds 4 parameters (Dg, Euv, Duv, Ddv)
- ***–➤ results in 21 free parameter fit (with $\alpha_s(M_Z)$ = 0.118)***
- (other parameters Fuv, Ddbar, are considered as part of the parameterisation uncertainty – these are the only further D,E,F that give visible change in PDFs, though no significant improvement in X^2)
- *check using Chebyshev polynomials also performed – 21 parameter fit showed no improvement in X^2 and PDF shapes compatible within uncertainties of normal polynomial fit*

correlation of systematic uncertainties

- ***correlation between different ATLAS datasets carefully studied***

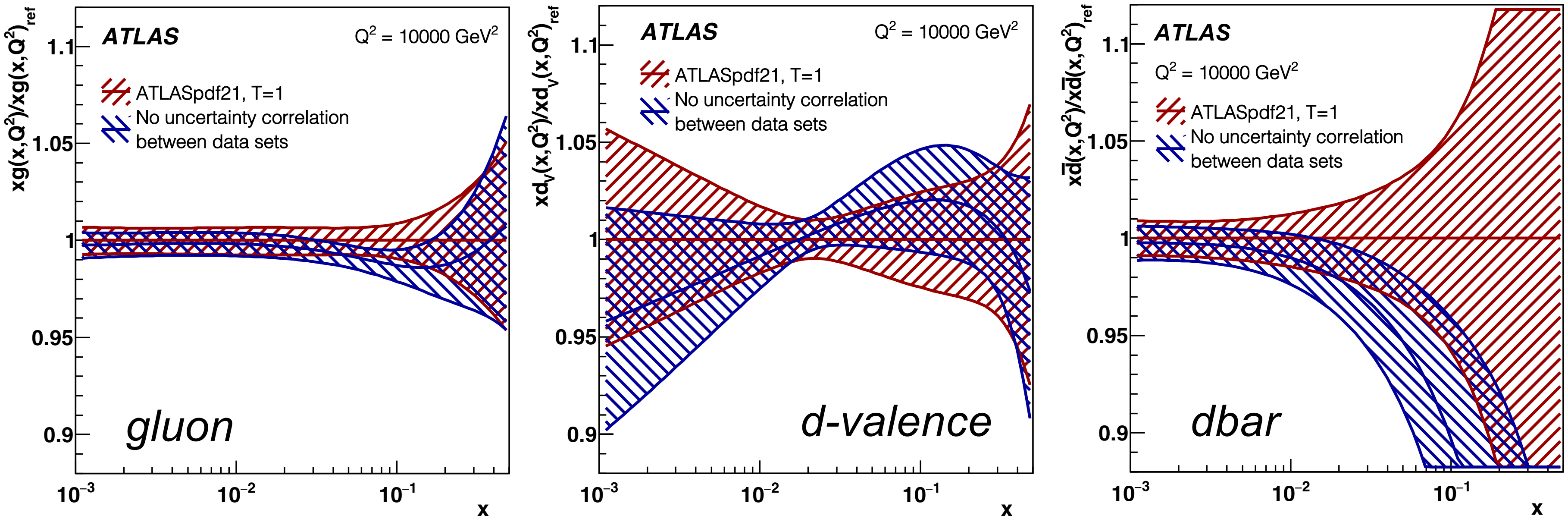
Systematic uncertainty	8 TeV $W+$jets	8 TeV $Z+$jets	8 TeV $t\bar{t}$ lepton+jets	13 TeV $t\bar{t}$ lepton+jets	8 TeV inclusive jets
Jet flavour response	JetScaleFlav2	Flavor Response	flavres-jes	JET29NP JET Flavour Response	syst JES Flavour Response*
Jet flavour composition	JetScaleFlav1Known	Flavor Comp	flavcomp-jes	JET29NP JET Flavour Composition	syst JES Flavour Comp
Jet punchthrough	JetScalepunchT	Punch Through	punch-jes	-	syst JES PunchThrough MC15
Jet scale	JetScalePileup2	PU OffsetMu	pileoffmu-jes	-	syst JES Pileup MuOffset
	-	PU Rho	pileoffrho-jes	JET29NP JET Pileup RhoTopology	syst JES Pileup Rho topology*
	JetScalePileup1	PU OffsetNPV	pileoffnpv-jes	JET29NP JET Pileup OffsetNPV	syst JES Pileup NPVOffset
	-	PU PtTerm	pileoffpt-jes	JET29NP JET Pileup PtTerm	syst JES Pileup Pt term
Jet JVF selection	JetJVFcut	JVF	jetvxfrac	-	syst JES Zjets JVF
B-tagged jet scale	-	btag-jes	JET29NP JET BJES Response	-	-
Jet resolution	-	jeten-res	JET JER SINGLE NP	-	-
Muon scale	-	-	mup-scale	MUON SCALE	-
Muon resolution	-	-	muonms-res	MUON MS	-
Muon identification	-	-	muid-res	MUON ID	-
Diboson cross section	-	-	dibos-xsec	Diboson xsec	-
$Z+$jets cross section	-	-	zjet-xsec	Zjets xsec	-
Single-t cross section	-	-	singletop-xsec	st xsec	-

- entries in same row are considered **100% correlated for central fit**
- additionally, **different degrees of correlation** are studied for **inclusive jet data**, since different choice of jet radius (R=0.6) cf. V+Jet and ttbar (R=0.4)
- ***exact degree of correlation for inclusive jet data does not change resulting PDFs***

impact of correlations between datasets

- ***focus on LHC scales and medium-x relevant for Higgs, W, Z***

(*exp. only* ***ΔΧ²=1)***

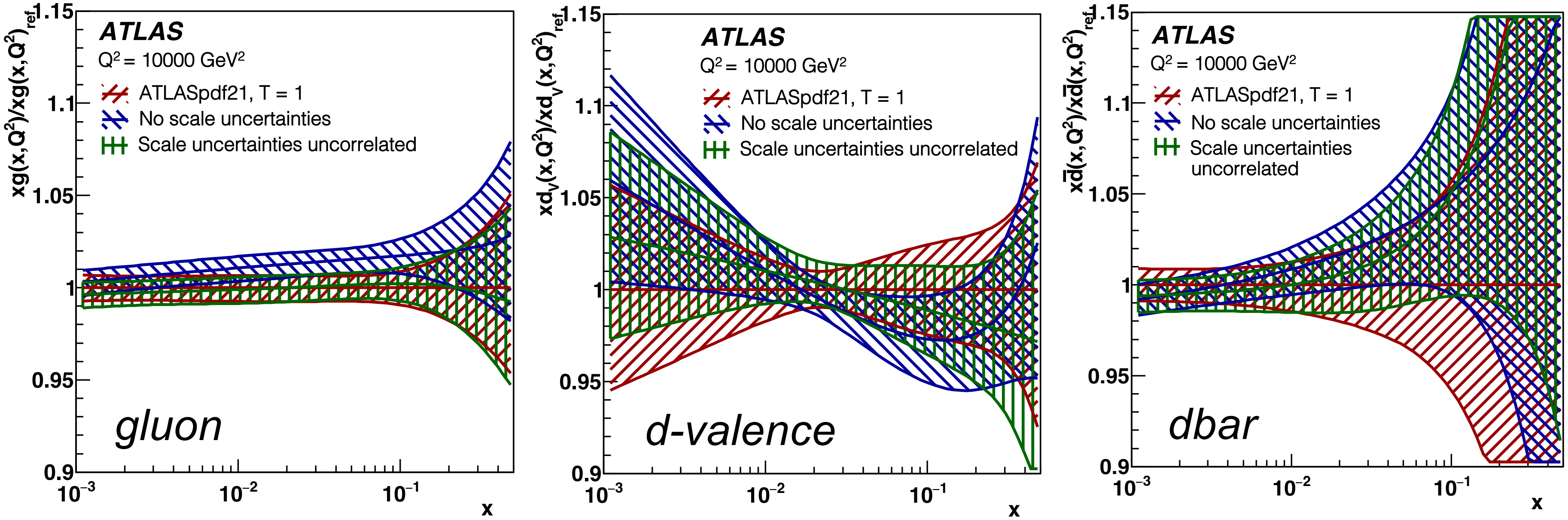


- impact on PDFs *generally* small, but can be large in **d-type quark** sector
- goal is $\mathcal{O}$(1%) PDF precision to detect subtle BSM effects in SM precision measurements, EG. M_W, $\sin^2\theta_W$ –➤ **properly accounting for correlations can be important**

♀ **BLUE**: systematic correlations between V+jets, ttbar (l+j) and inclusive jets not applied, with exception of luminosity

scale uncertainties

- ***impact of including scale uncertainties for inclusive W, Z*** *(exp. only* ***$\Delta X^2=1$)***

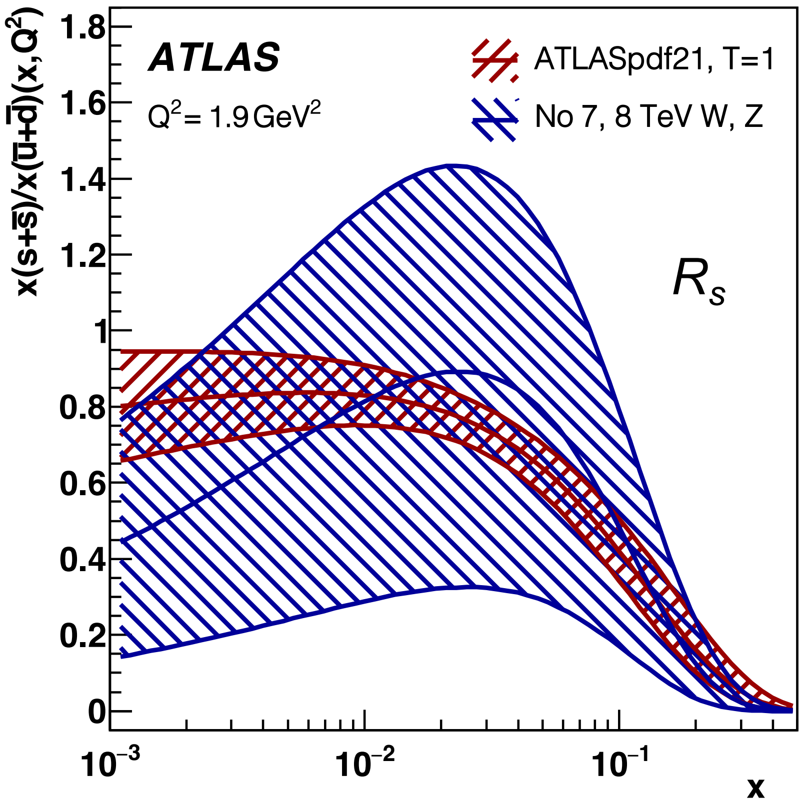


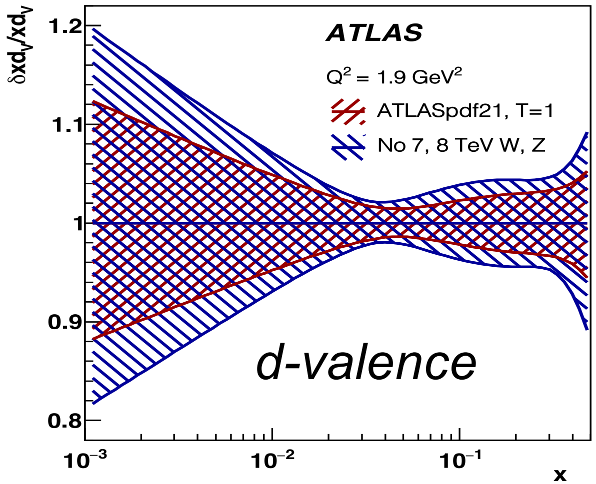
- experimental uncertainties are comparable to scale uncertainties for inclusive W, Z at √s=7 and 8 TeV → include as theoretical uncertainties in **ATLASpdf21** fit
- PDF shape differences generally small, but can matter for $\mathcal{O}(1\%)$ precision
- –➤ **scale uncertainties can be important**

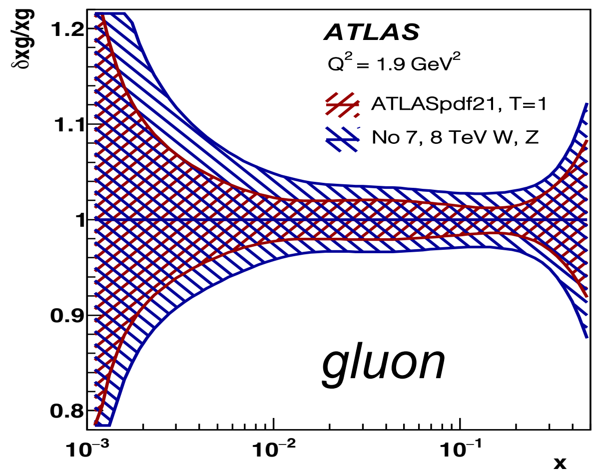
GREEN: scale uncertainties included but not correlated between √s=7 and 8 TeV

impact of various datasets: vector boson

- *impact of ATLAS inclusive W and Z:* (*exp. only, $\Delta X^2=1$*)



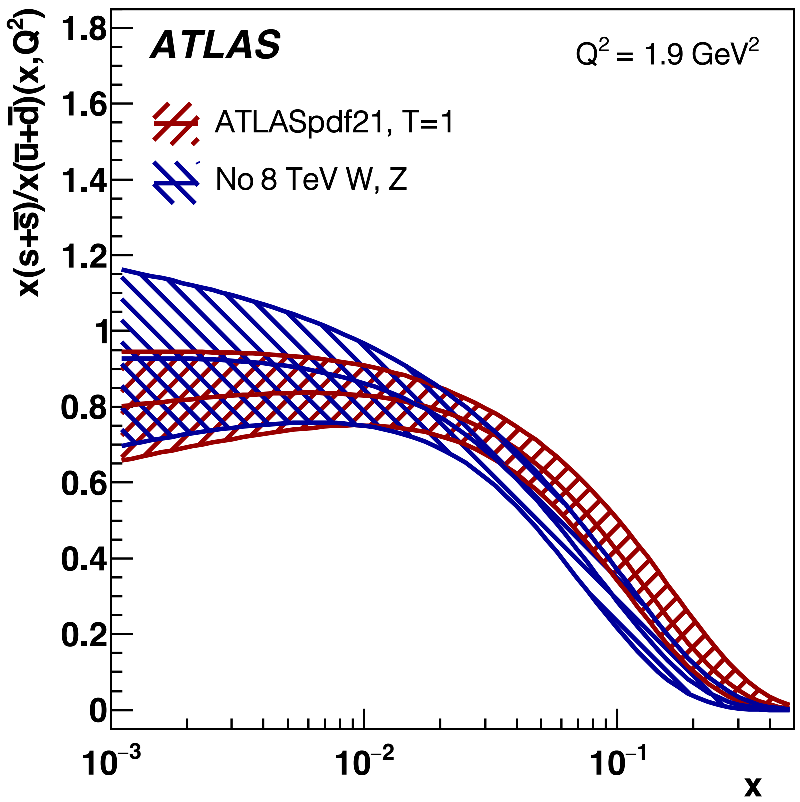


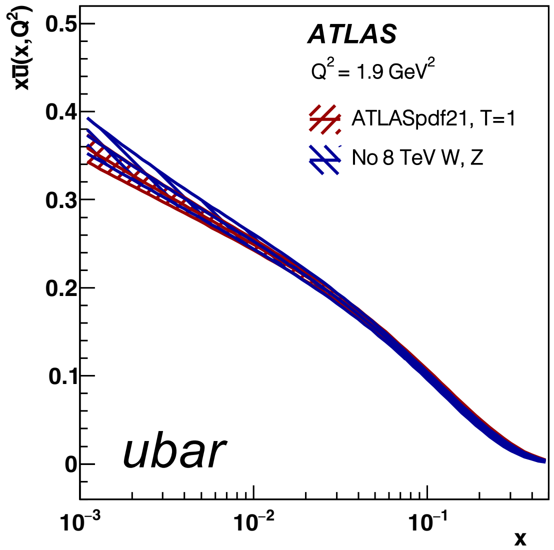


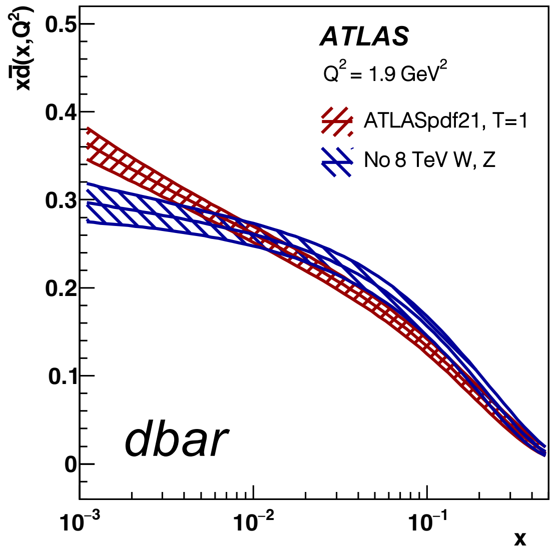
- without ATLAS **inclusive vector boson**, ratio of **strange to light quarks**, **Rs**, is poorly determined
- substantial impact also on **valence quark** and **gluon uncertainties** ↑

impact of various datasets: vector boson

- ***impact of ATLAS inclusive W and Z:*** *(exp. only, **ΔX^2=1**)*





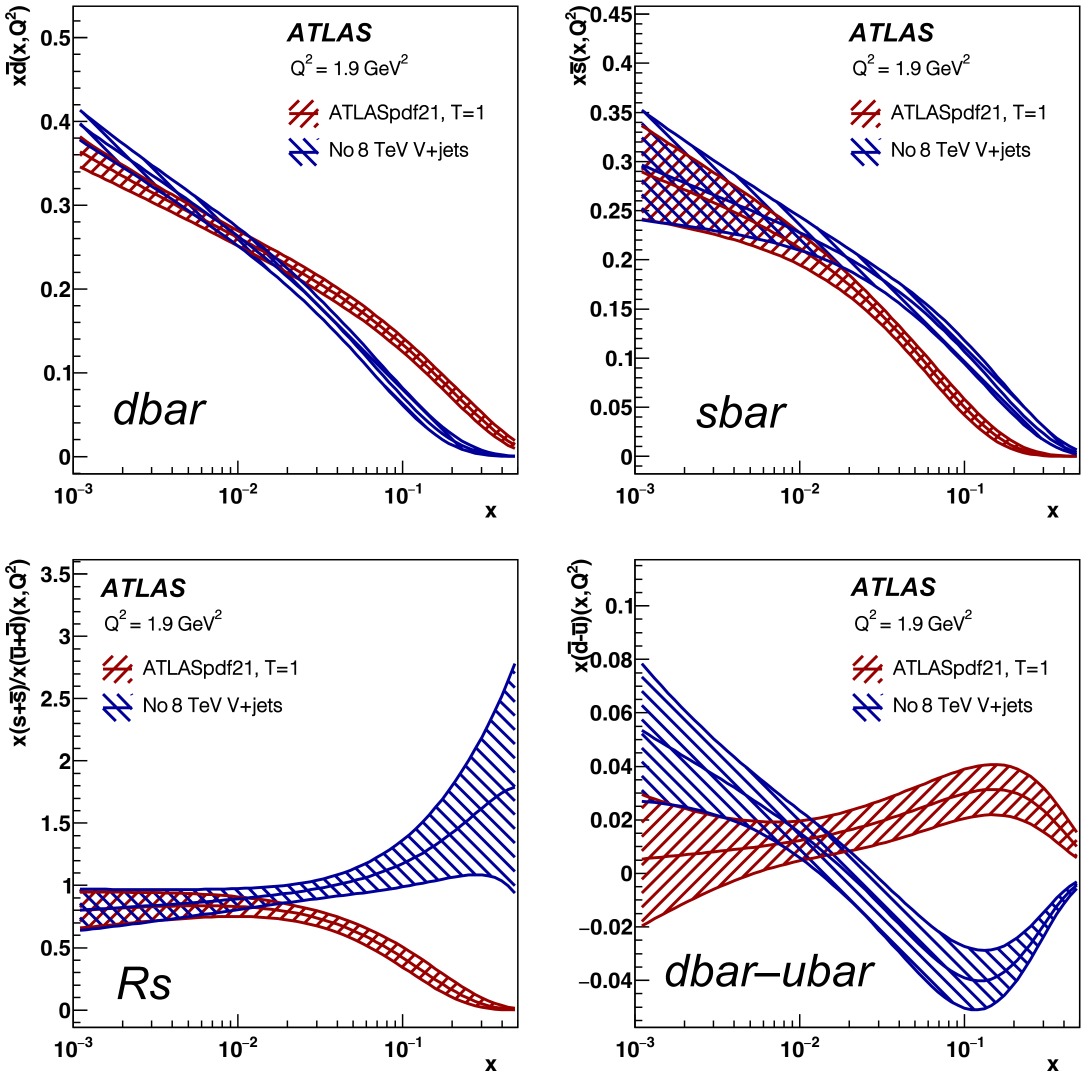


- while √s=7 TeV have the larger impact on uncertainties, √s= 8 TeV also have influence:
- … they prefer slightly **lower Rs at small x** ↑
- and also play a role in **dbar ~ ubar** at small x →

impact of various datasets: V+Jets

- ***impact of ATLAS V+Jets data:***

(*exp. only, **$\Delta X^2=1$***)

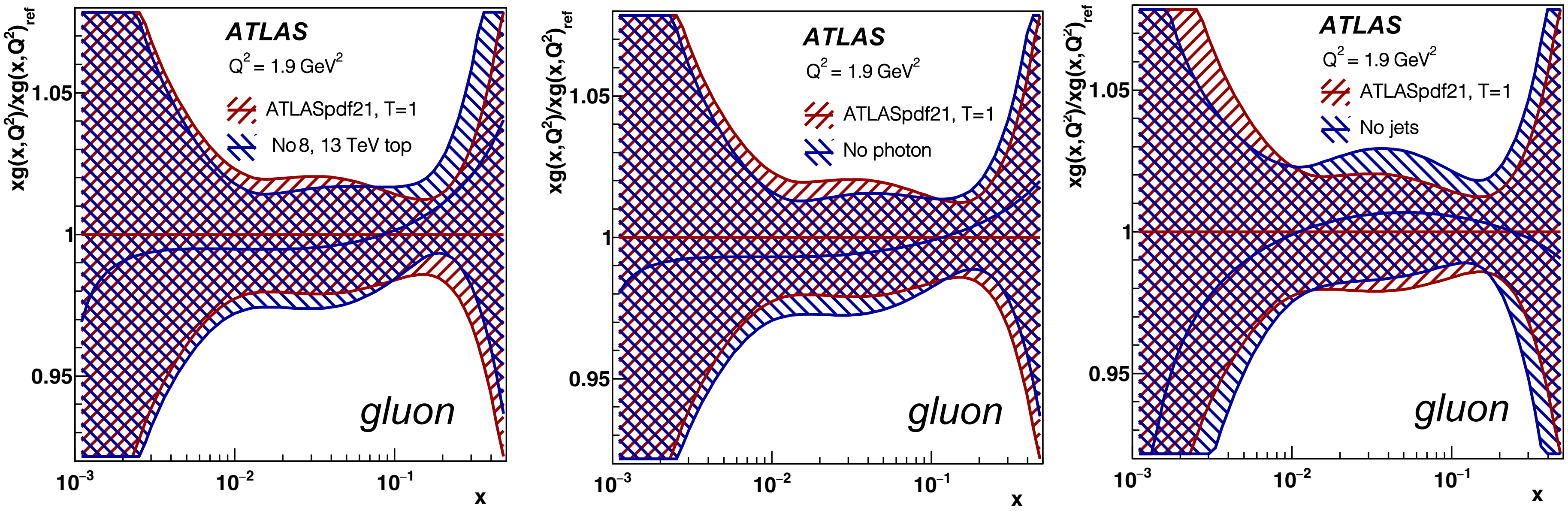


- ATLAS **V+jet** data leads to increase in **dbar** and decrease in **sbar** at medium to high x (sum constrained by HERA)
- … with consequent impact on **Rs** and **(dbar–ubar)**
- change looks large since V+Jets resolves a **double minimum**; rest of the data are almost equally happy with **BLUE** or **RED** PDFs

(NB, only *experimental uncertainties* are shown here; with total uncertainties included, **BLUE** is compatible with **RED**, since some parameterisation variations for **BLUE** fall into SAME MINIMUM as **RED**)

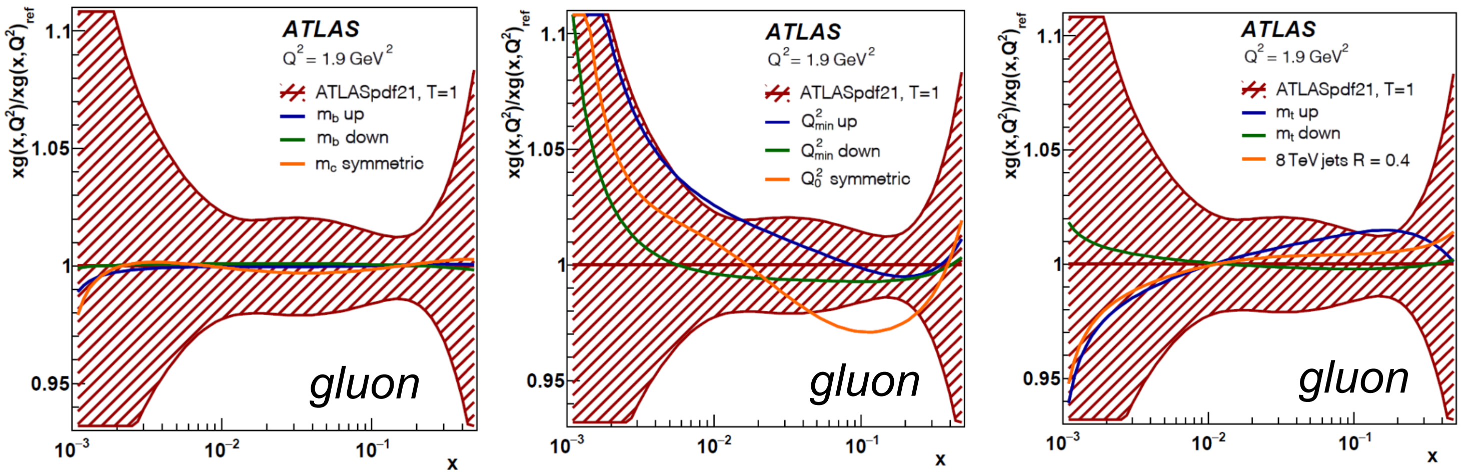
impact of various datasets: ttbar, γ , jet

- ***impact of ATLAS ttbar, direct-γ and inclusive jet data:*** *(exp. only, **$\Delta X^2=1$**)*



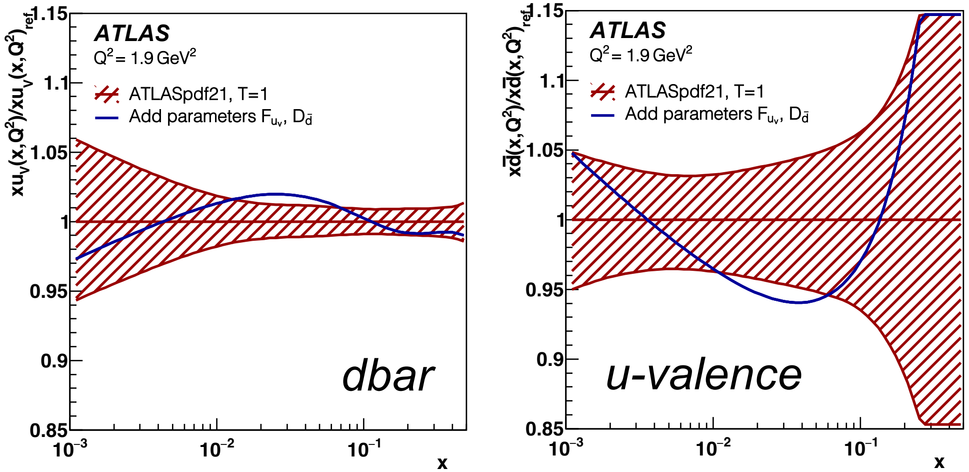
- impact primarily on **high x gluon** – note slight pulls on shape (**BLUE** to **RED**)
- visible decrease in uncertainties from **inclusive jet cross section data**

model and parameterisation uncertainties



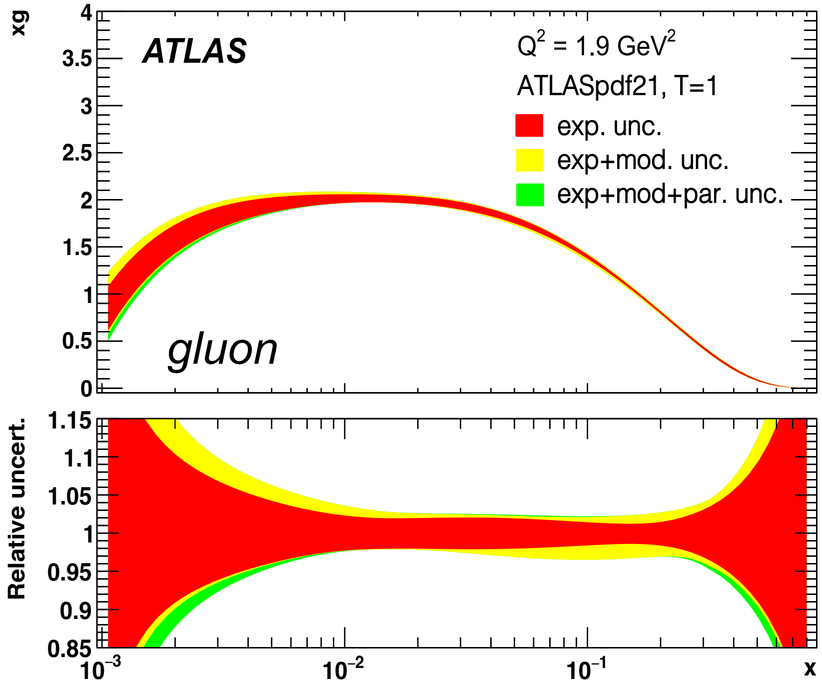
model
(gluon most sensitive)

Central χ^2/NDF	2010/1620
Model variations	
$Q^2_{\rm min} = 12.5$ GeV^2	1947/1571
$Q^2_{\rm min} = 7.5$ GeV^2	2076/1660
$m_c = 1.45$ GeV (sym)	2025/1620
$Q^2_0 = 1.6$ GeV^2 (sym)	2018/1620
$m_b = 4.3$ GeV	2016/1620
$m_b = 4.1$ GeV	2014/1620
$m_t = 175.0$ GeV	2063/1620
$m_t = 172.5$ GeV	2018/1620
$R = 0.4$	2080/1620
Parameter variations	
$F_{u_v}, D_{\bar{d}}$	2007/1620



parameterisation

ATLASpdf21 results



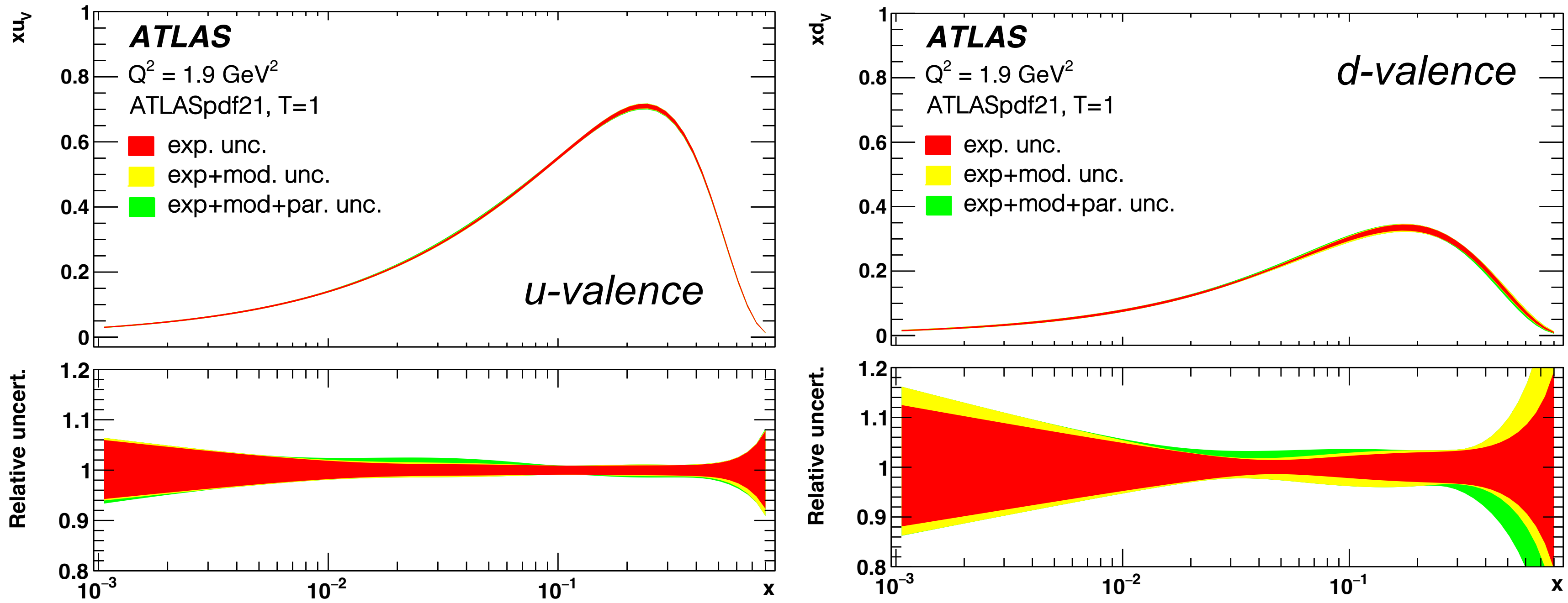
- ***combining uncertainties:***
- model uncertainties added together in quadrature and parameterisation taken as envelope of deviation from central fit – both are then added in **quadrature** with experimental uncertainties

- NB, **scale uncertainties** are treated as additional **correlated uncertainties**, on same footing as other systematics ⟶ appear as part of the **experimental uncertainty**

- … **gluon** is the most sensitive PDF to model uncertainties
- parameterisation uncertainties enter through momentum sum rule

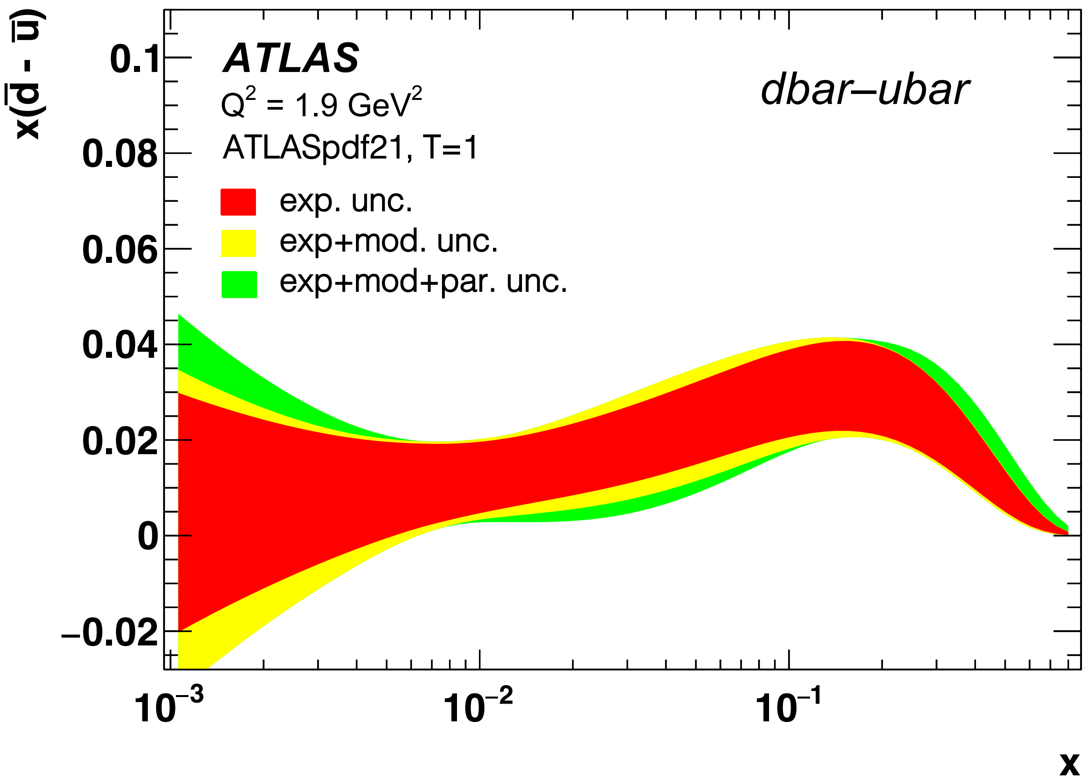
- as expected, **gluon** well-determined for 0.01 **< x <** 0.3, but not at low or high x

ATLASpdf21 results



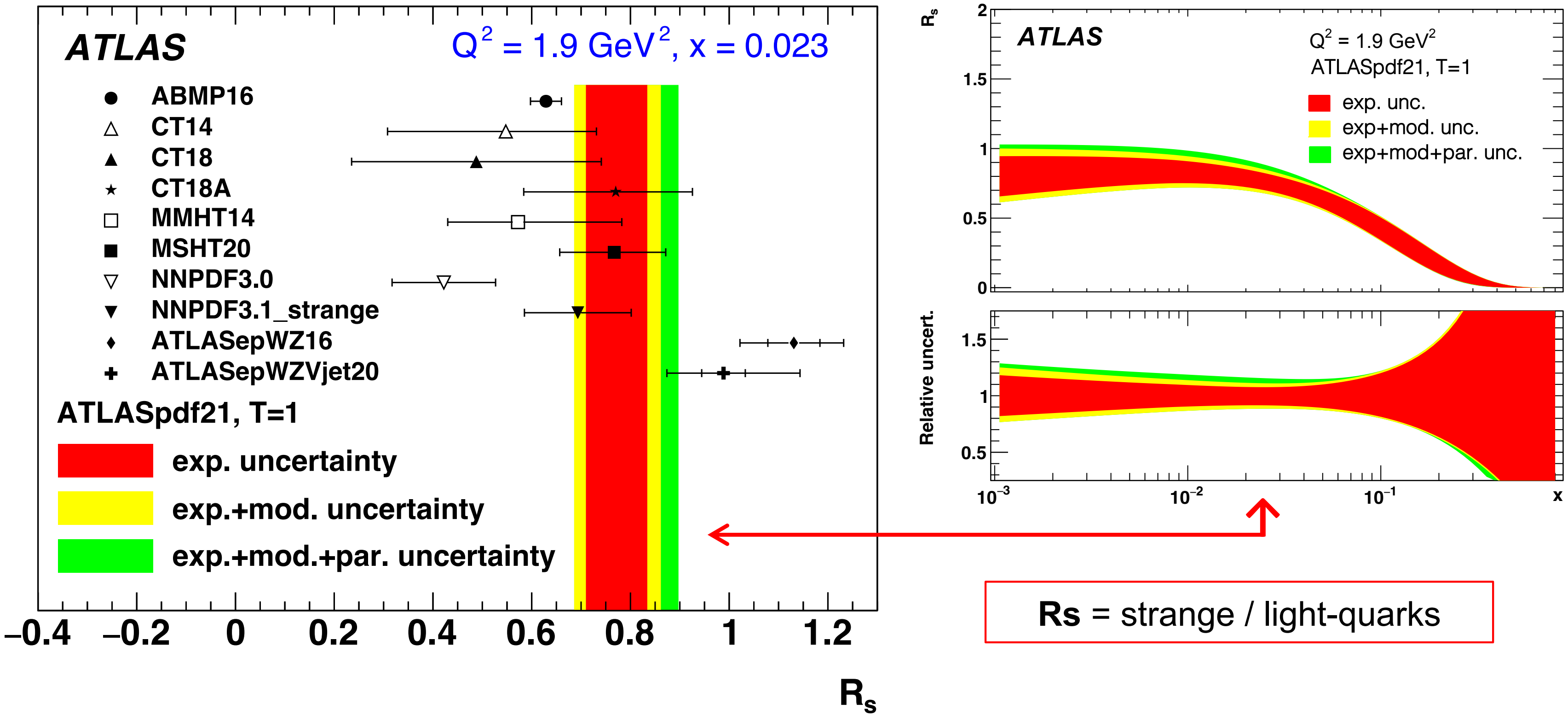
- as expected, **u-quarks** more precisely determined than **d-quarks**

ATLASpdf21 results



- … at small x, **dbar ~ ubar**, though this constraint is NOT imposed by the fit
- **dbar–ubar** positive at large x, consistent with E866 and E906 / Seaquest

ATLASpdf21: not quite so strange?

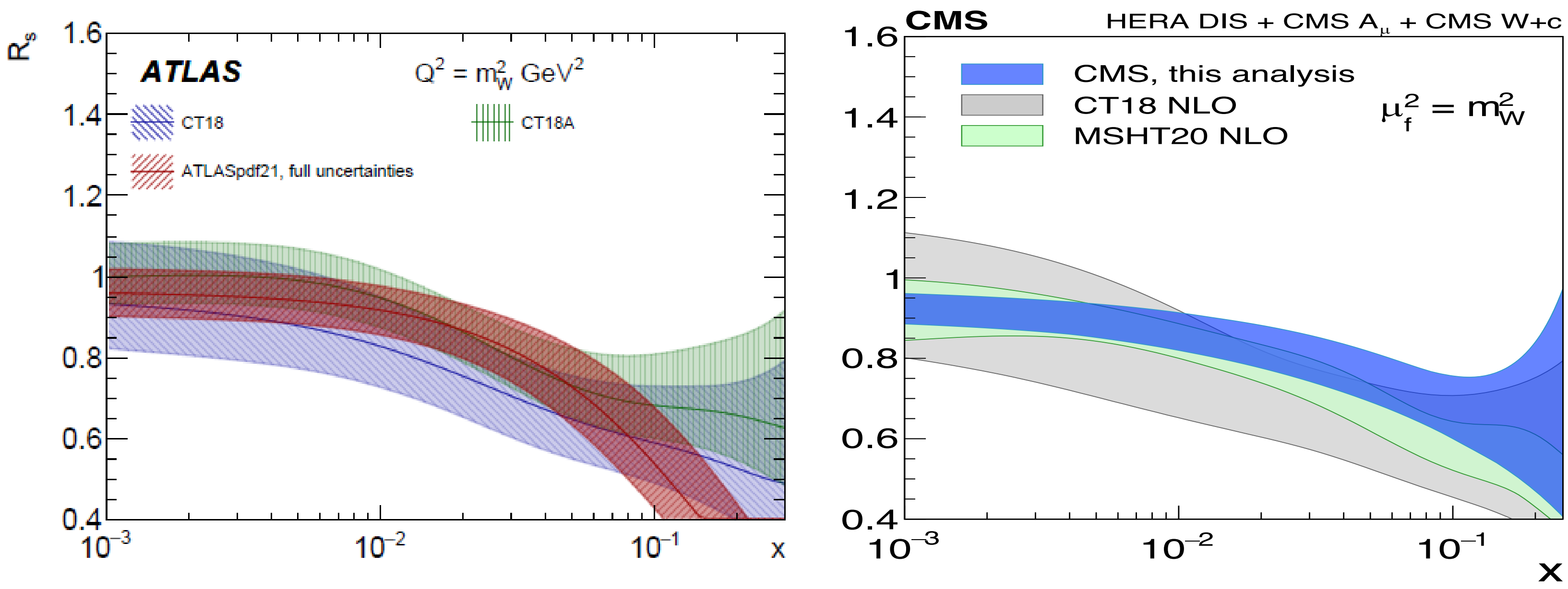


Rs = strange / light-quarks

- **ATLAS**: **Rs**, at low scale and small x, moves from **≈ 1** in previous fits → **0.8** in **ATLASpdf21**
- arises from ATLAS V+Jets and √s=8 TeV W, Z, and increased flexibility of small-x parameterisation
- **MSHT**, **CT** and **NNPDF** **Rs** increases from **0.5 → 0.8**, when including ATLAS √s=7 TeV inclusive W, Z

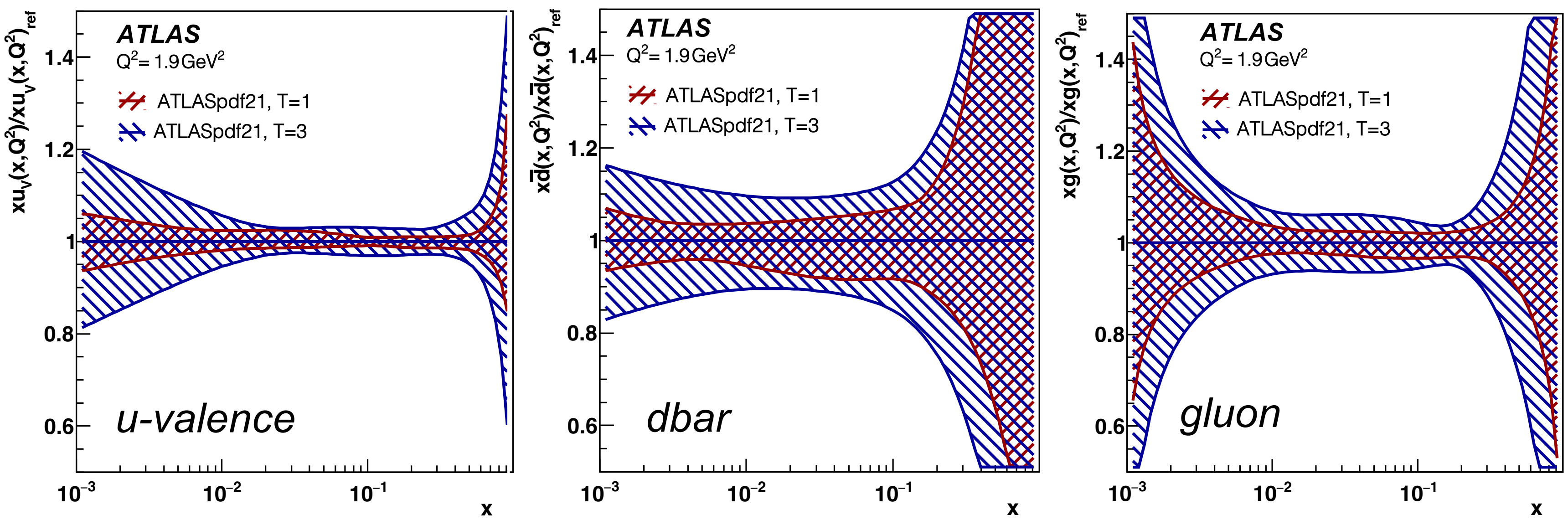
strangeness content of proton

- ***comparison of Rs at scale Mw with CMS, CT18 and MSHT20:***



Rs = strange / light-quarks

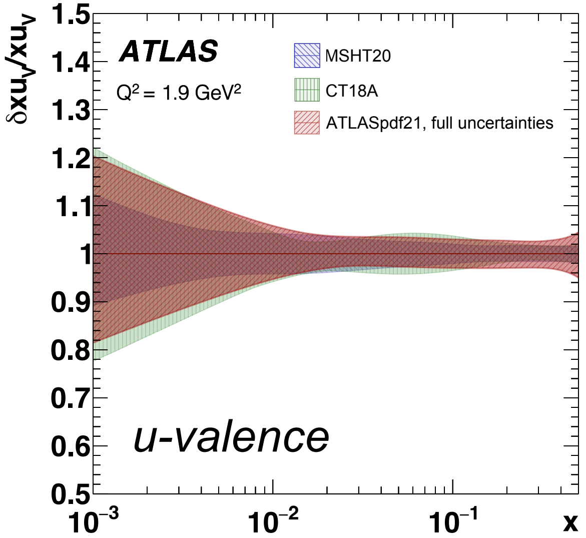
X^2 tolerance

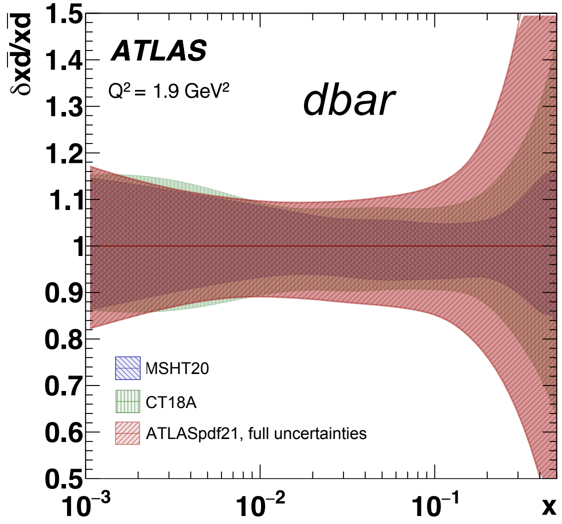


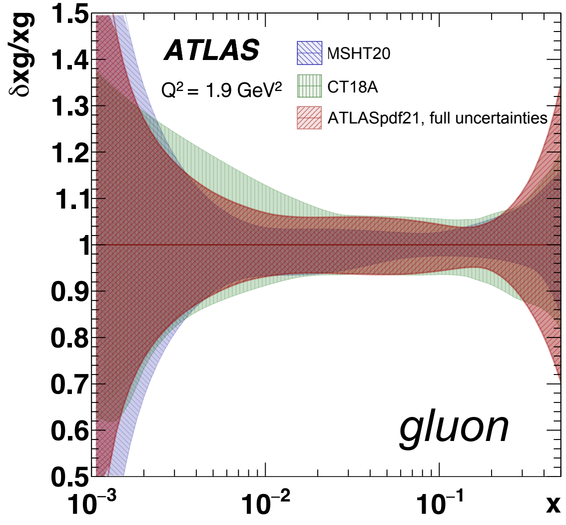
- traditionally, ATLAS have considered only conventional ***$T^2=\Delta X^2=1$*** for 68% CL
- with multiple datasets now included, we consider **enhanced tolerances**, following MSHT dynamic tolerance procedure, first introduced in MSTW

→ *choice of $T=\sqrt{\Delta X^2}=3$ such that all datasets fitted within their 68% CL for all eigenvectors*

X^2 tolerance and cf. global PDFs



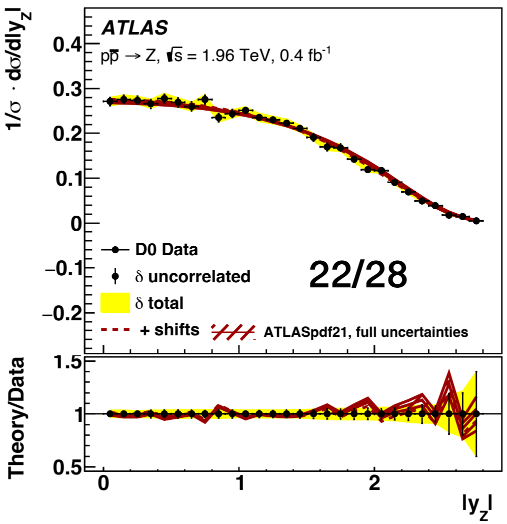


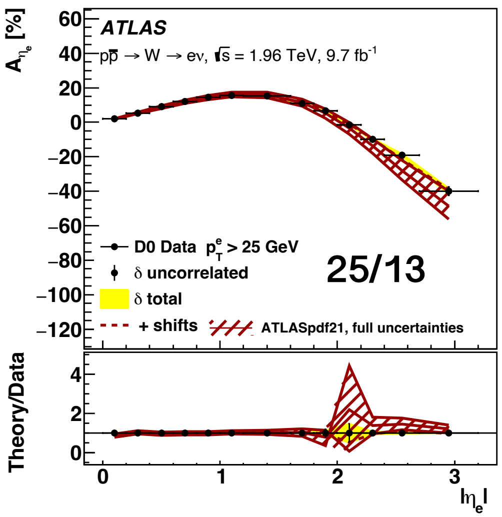


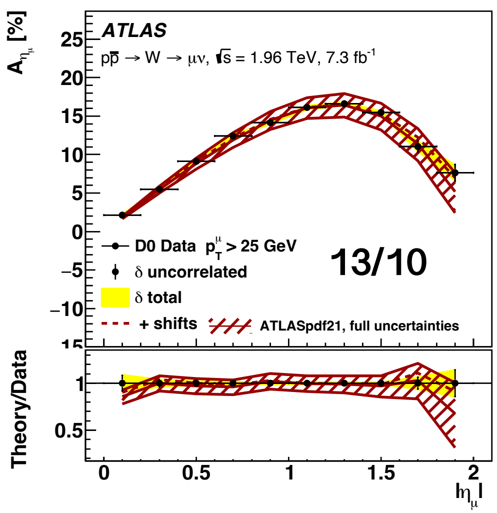
- **ATLASpdf21** uncertainties competitive with **global PDFs** for small and medium x
- ATLAS PDF uncertainties expected to be **larger than global PDFs at large x**, since fewer constraining datasets – global PDFs use older fixed target DIS and Drell-Yan, plus Tevatron
- ***ATLAS data able to replicate many features of those other datasets, but with more understanding and control over systematic uncertainties and their correlations –➤***

ATLASpdf21 vs. Tevatron and E866

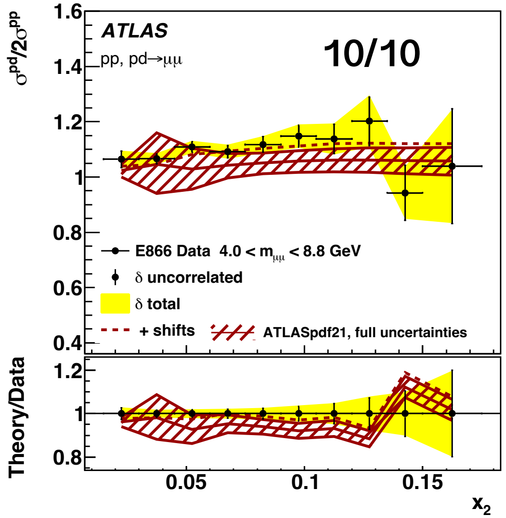
- ***Tevatron inclusive W, Z:*** *(T=3 bands shown)*

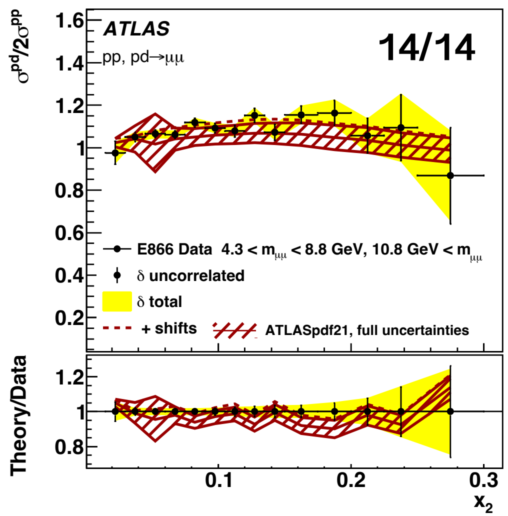


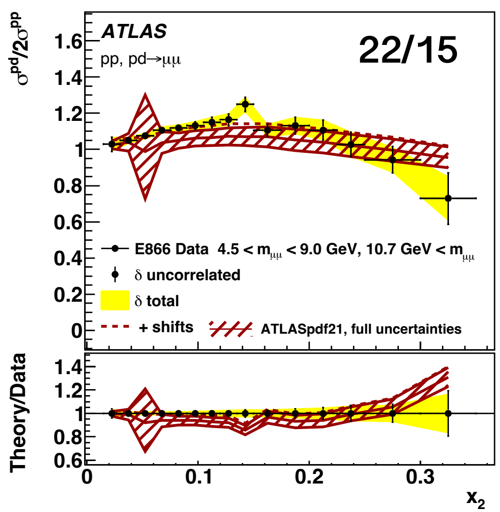




- ***E866 pp, pD Drell-Yan:***

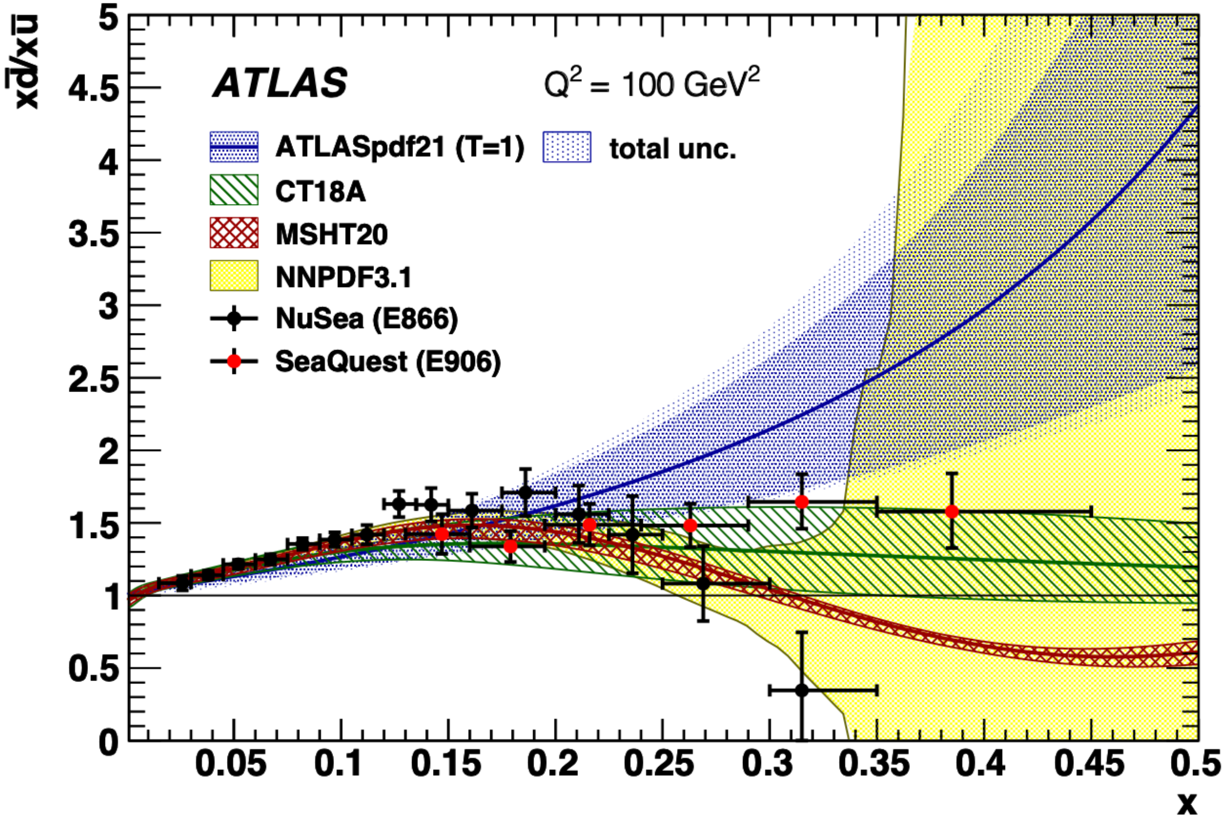






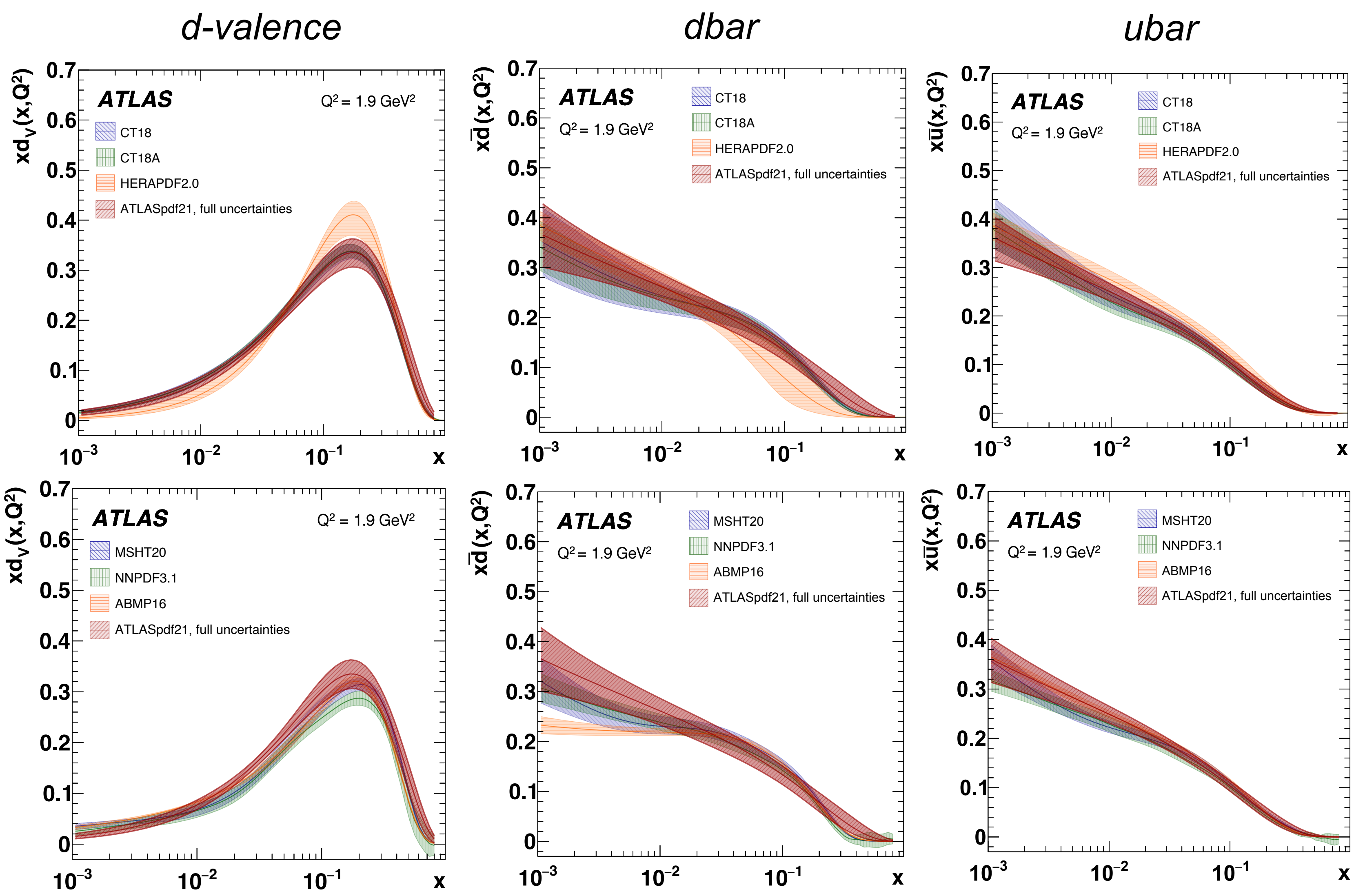
ATLASpdf21 description of E906

- ***SeaQuest/E906 dbar/ubar ratio:***



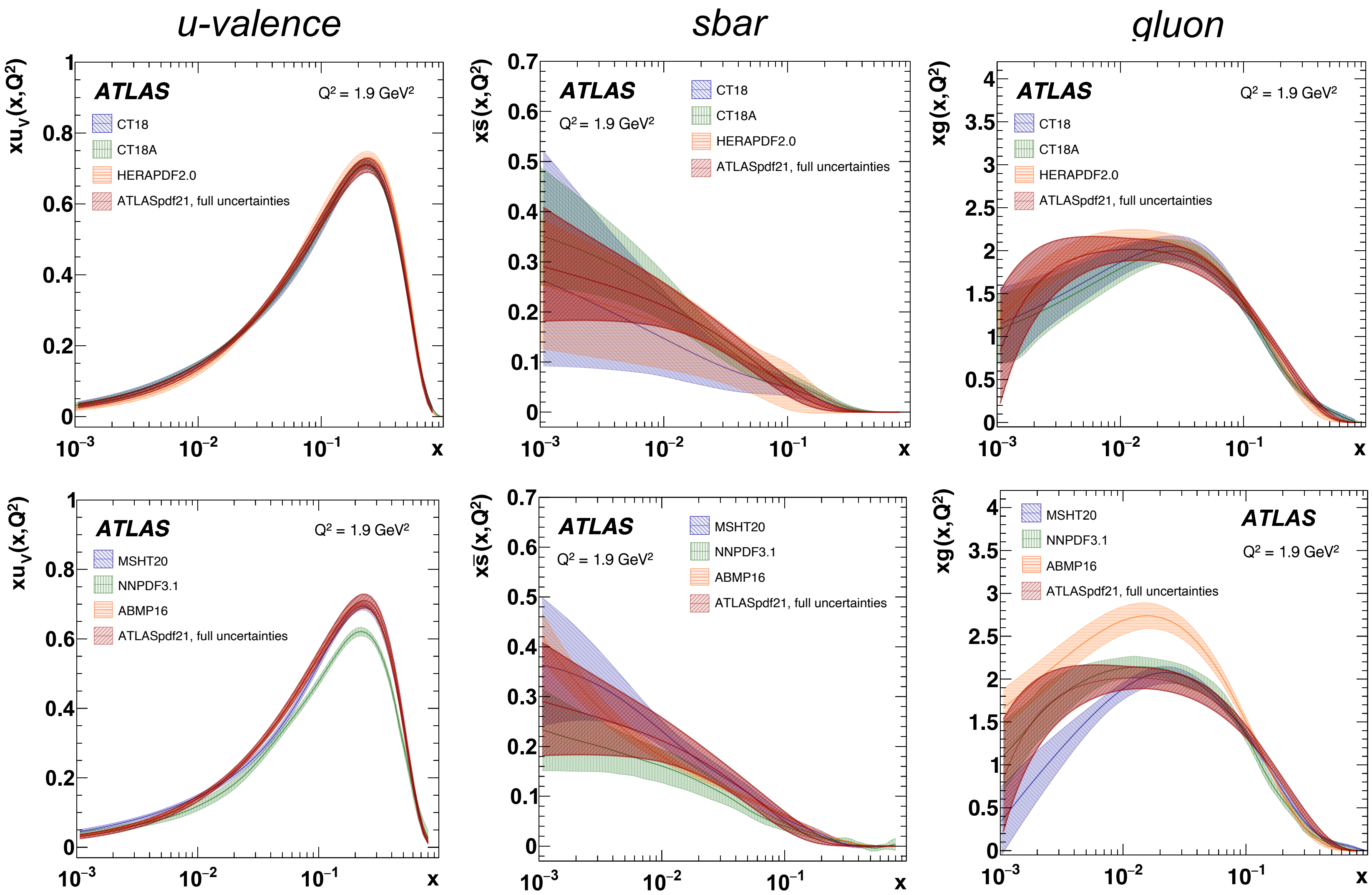
- … **ATLASpdf21** in good agreement with the recent SeaQuest/E906 result ***(ΔX²=1 shown)***

comparison with global PDFs



- **ATLASpdf21** agrees with other PDFs as well as they agree with each other!

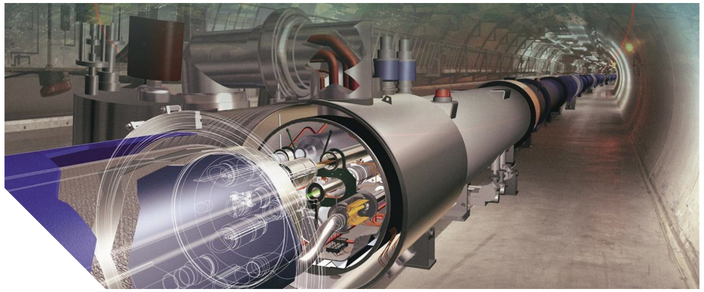
comparison with global PDFs



- **ATLASpdf21** agrees with other PDFs as well as they agree with each other!

summary

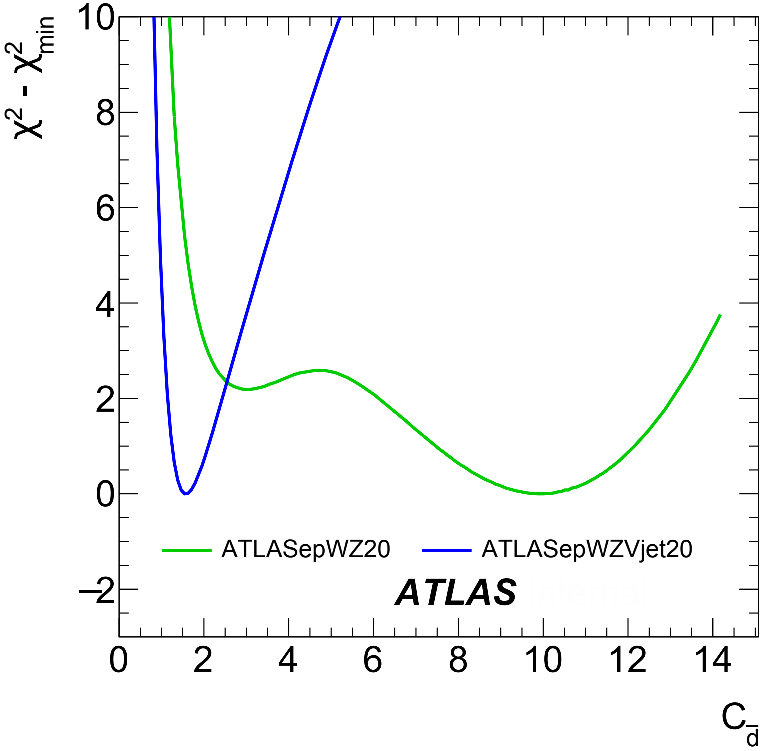
- **ATLASpdf21** (EPJC82 (2022) 5,438) demonstrates the ability to fit, simultaneously and with small uncertainties, a **wide portfolio of ATLAS measurements**
- –➤ uses all available **PDF-sensitive** measurements which also have information on **correlated systematics** and **NNLO QCD + NLO EW** predictions

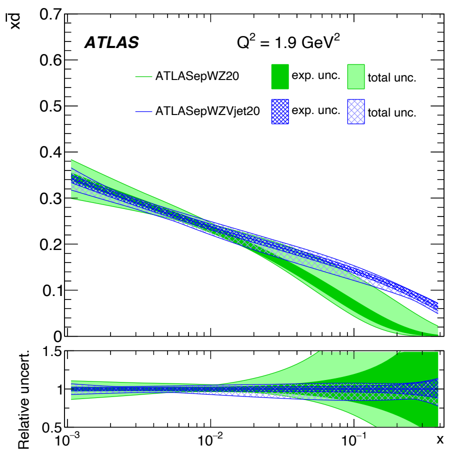


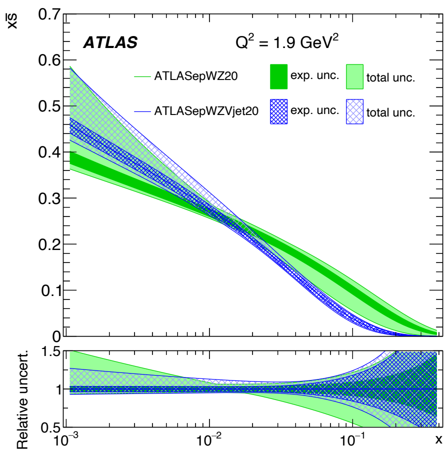
- *systematic correlations **within** and **between** datasets are included and information on recommended treatment **made public to the community***
- ***scale uncertainties** considered and included when comparable to experimental uncertainties*
- ***ATLAS data able to replicate many features of fixed target DIS and Drell-Yan and Tevatron data, but with more understanding and control over systematic uncertainties and their correlations***
- *enhanced tolerance used for **realistic PDF uncertainty estimation***
- ***generally good agreement** with modern PDF sets (CT, MSHT, NNDPF), and a better fit to the ATLAS data*

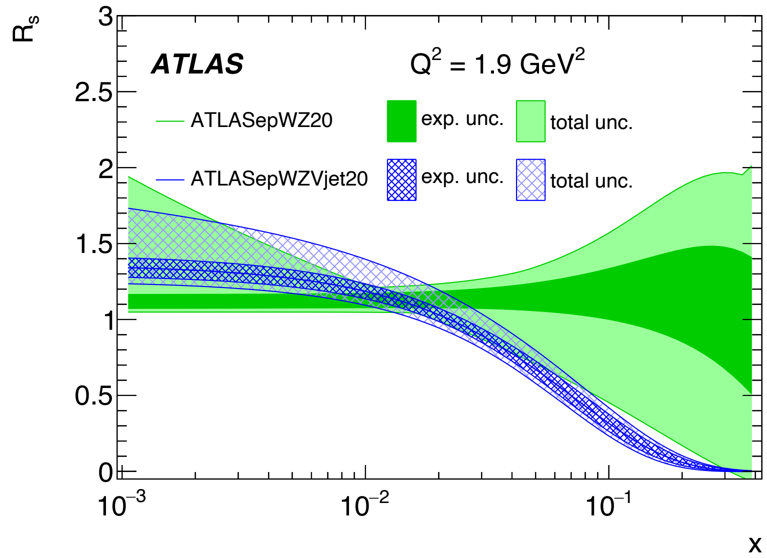
extras

more on the previous double minimum









- ATLASepWZVjet20, arXiv:2101.05095
- **V+Jets** data resolves a previous double minimum – only happy with **low** C_{dbar}

➔ **dbar** harder at high-x (consequently sbar softer)

- some model/parameterisation variations for **GREEN** fall into alternative ⇡ low-C_{dbar} minimum such that, with full uncertainties, no large tension

summary of theoretical framework

Data set	NLO QCD code	LO EW code	NNLO QCD code	NLO EW code
Inclusive $W, Z/\gamma^*$ [9]	MCFM	MCFM	DYNNLO 1.5, FEWZ 3.1.b2	DYNNLO 1.5, FEWZ 3.1.b2
Inclusive Z/γ^* [13]	MCFM	MCFM	NNLOJET	NNLOJET
Inclusive W [12]	MG5_aMC@NLO 2.6.4	MG5_aMC@NLO 2.6.4	DYNNLO 1.5	DYNNLO 1.5
$W^\pm$ + jets [24]	N_{jetti}	N_{jetti}	N_{jetti}	SHERPA
Z + jets [25]	Ref. [52]	Ref. [52]	Ref. [52]	SHERPA
$t\bar{t}$ (lepton + jets) [26]	-	Ref. [53]	Ref. [53]	Ref. [56]
$t\bar{t}$ (dilepton) [27]	MCFM	MCFM	Ref. [28]	Ref. [56]
$t\bar{t}$ [15]	-	Ref. [53]	Ref. [53]	Ref. [56]
Inclusive isolated γ [14]	MCFM	MCFM	Ref. [58]	Ref. [59]
Inclusive jets [16–18]	NLOJET++	NLOJET++	NNLOJET	Ref. [64]

- all fits performed using **xFitter**, and cross-checked with independent code
- LHC cross sections calculated using codes above, interfaced to **APPLGRID** or **fastNLO**

X^2 definition

partial

$$\chi^2 = \sum_{i,k} \left(D_i - T_i(1 - \sum_j \gamma_{ij} b_j) \right) C^{-1}_{\mathrm{stat,uncor},ik}(D_i, D_k) \left(D_k - T_k(1 - \sum_j \gamma_{kj} b_j) \right)$$

$$+ \sum_i \log \frac{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{uncor}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2}$$

↫ *log penalty term*

$$+ \sum_j b_j^2$$

↫ *correlated term*

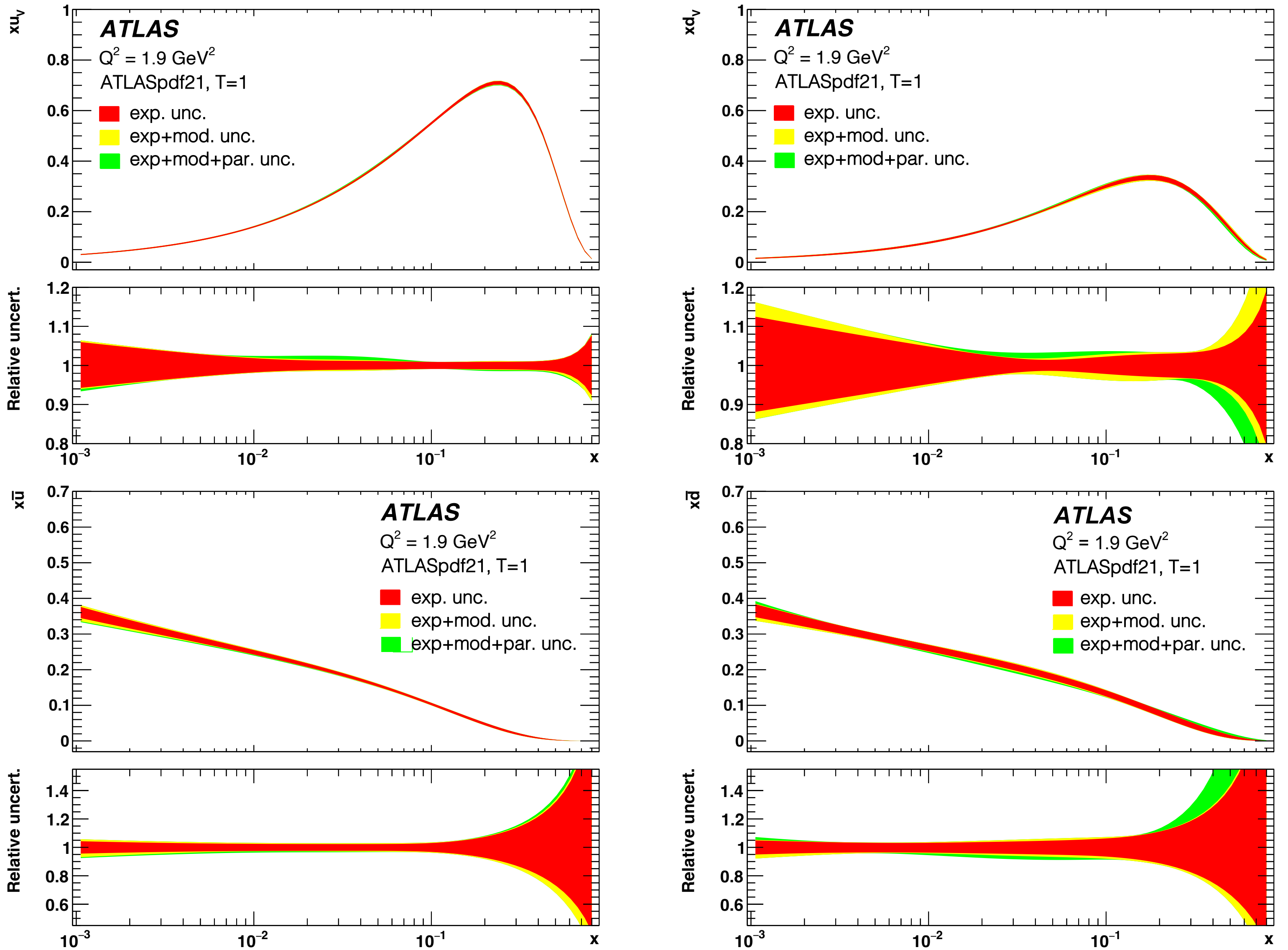
where D_i represent the measured data, T_i the corresponding theoretical prediction, $\delta_{i,\mathrm{uncor}}$ and $\delta_{i,\mathrm{stat}}$ are the uncorrelated systematic uncertainties and the statistical uncertainties of D_i, and the correlated systematic uncertainties, described by γ_{ij}, are accounted for using the nuisance parameters b_j. The quantity $C_{\mathrm{stat,uncor},ik}$ is a covariance matrix for both the statistical and uncorrelated systematic uncertainties. Summations over i and k run over all data points and summation over j runs over all sources of correlated systematic uncertainty.

ATLASpdf21 fit quality

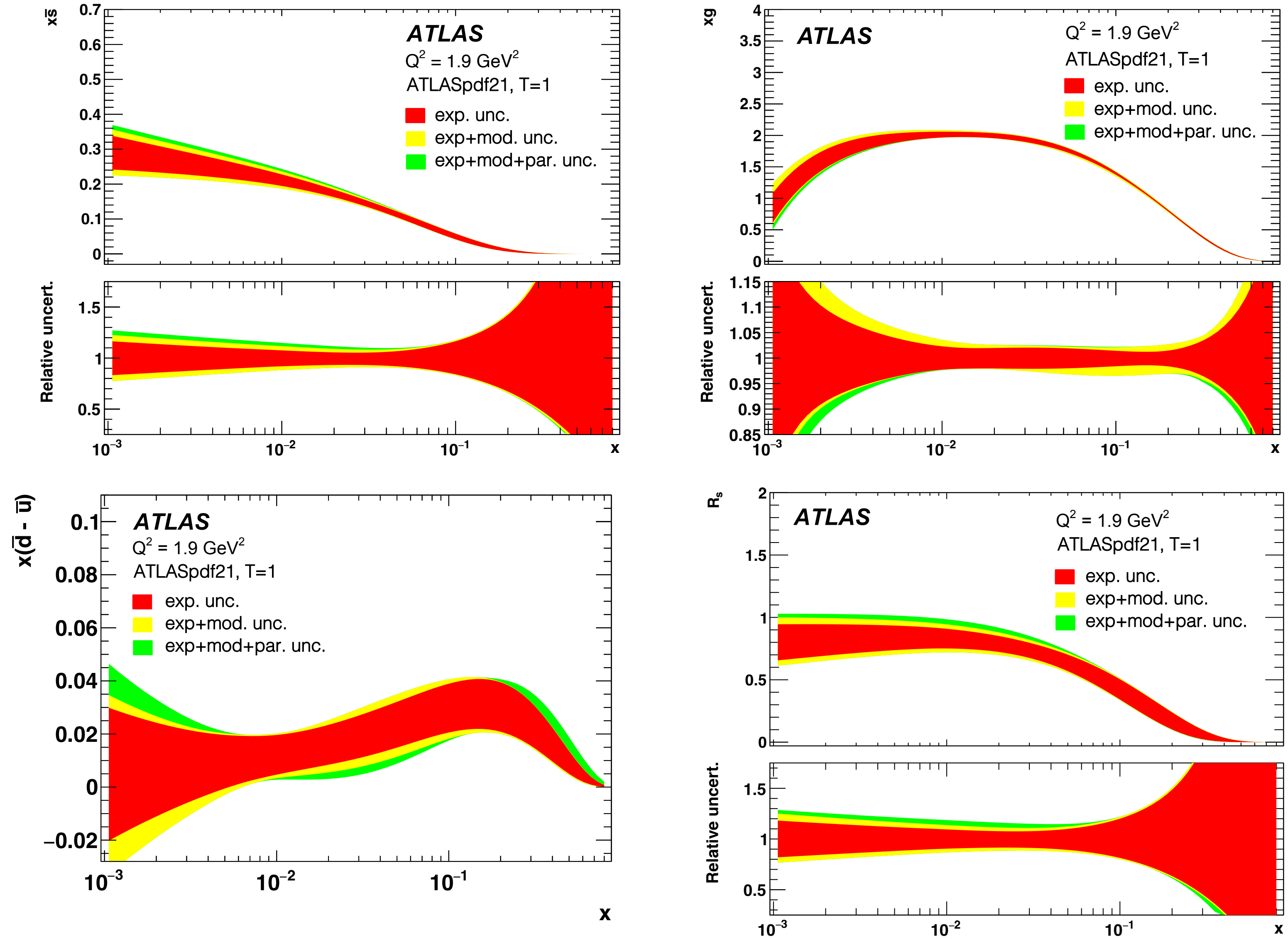
Total χ^2/NDF	2010/1620
HERA χ^2/NDP	1112/1016
HERA correlated term	50
ATLAS W, Z 7 TeVχ^2/NDP	68/55
ATLAS Z/γ^* 8 TeVχ^2/NDP	208/184
ATLAS W 8 TeVχ^2/NDP	31/22
ATLAS W and Z/γ^* 7 and 8 TeV correlated term	$71 = (38 + 33)$
ATLAS direct γ 13/8 TeVχ^2/NDP	27/47
ATLAS direct γ 13/8 TeV correlated term	6
ATLAS V+jets 8 TeVχ^2/NDP	105/93
ATLAS $t\bar{t}$ 8 TeVχ^2/NDP	13/20
ATLAS $t\bar{t}$ 13 TeVχ^2/NDP	25/29
ATLAS inclusive jets 8 TeVχ^2/NDF	207/171
ATLAS V+jets 8 TeV and $t\bar{t}$ + jets 8,13 TeV and $R = 0.6$ inclusive jets 8 TeV correlated term	$87 = (16 + 9 + 21 + 41)$

- … this is a **better fit quality** than achieved by **global PDF** fits to these data

ATLASpdf21 results

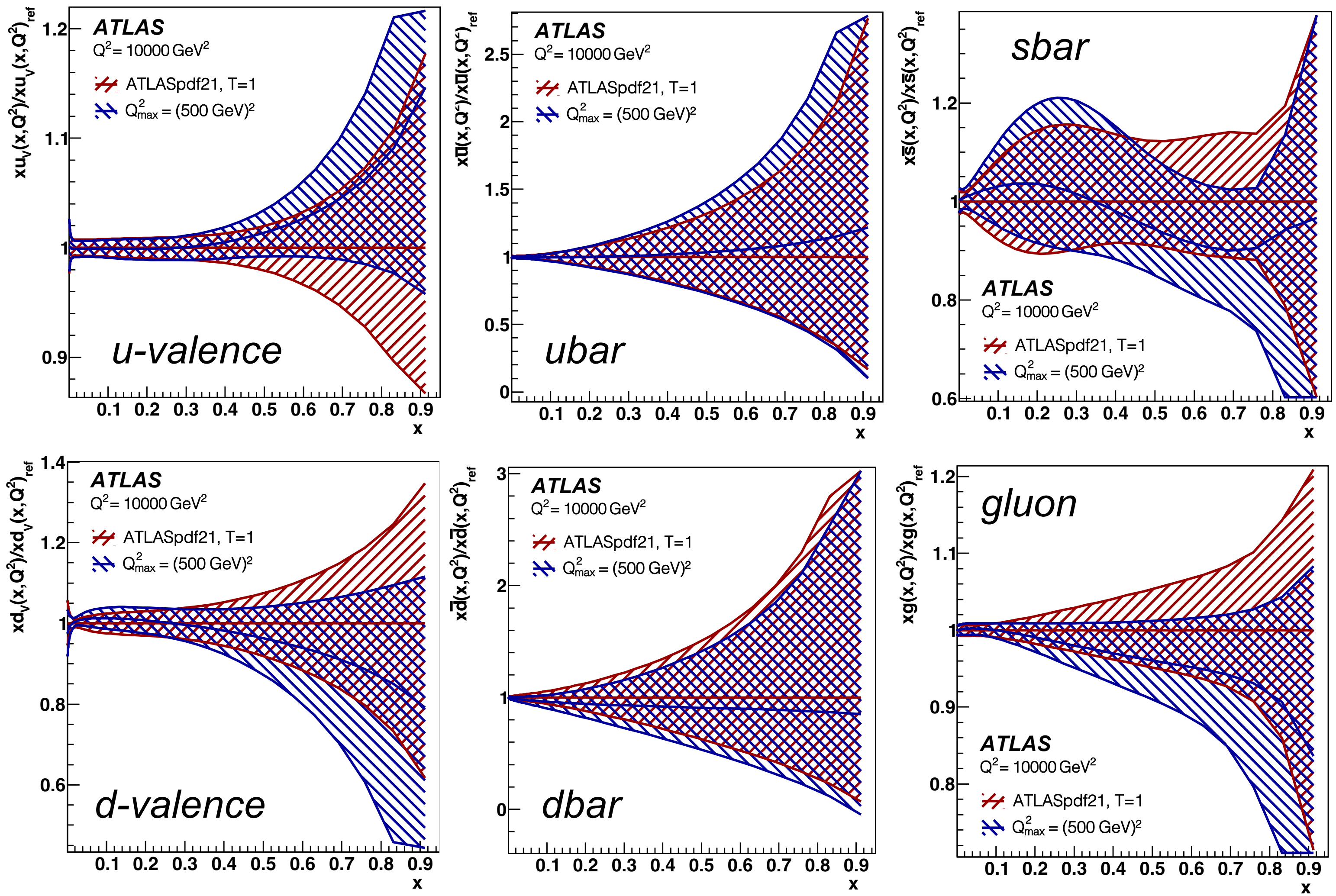


ATLASpdf21 results



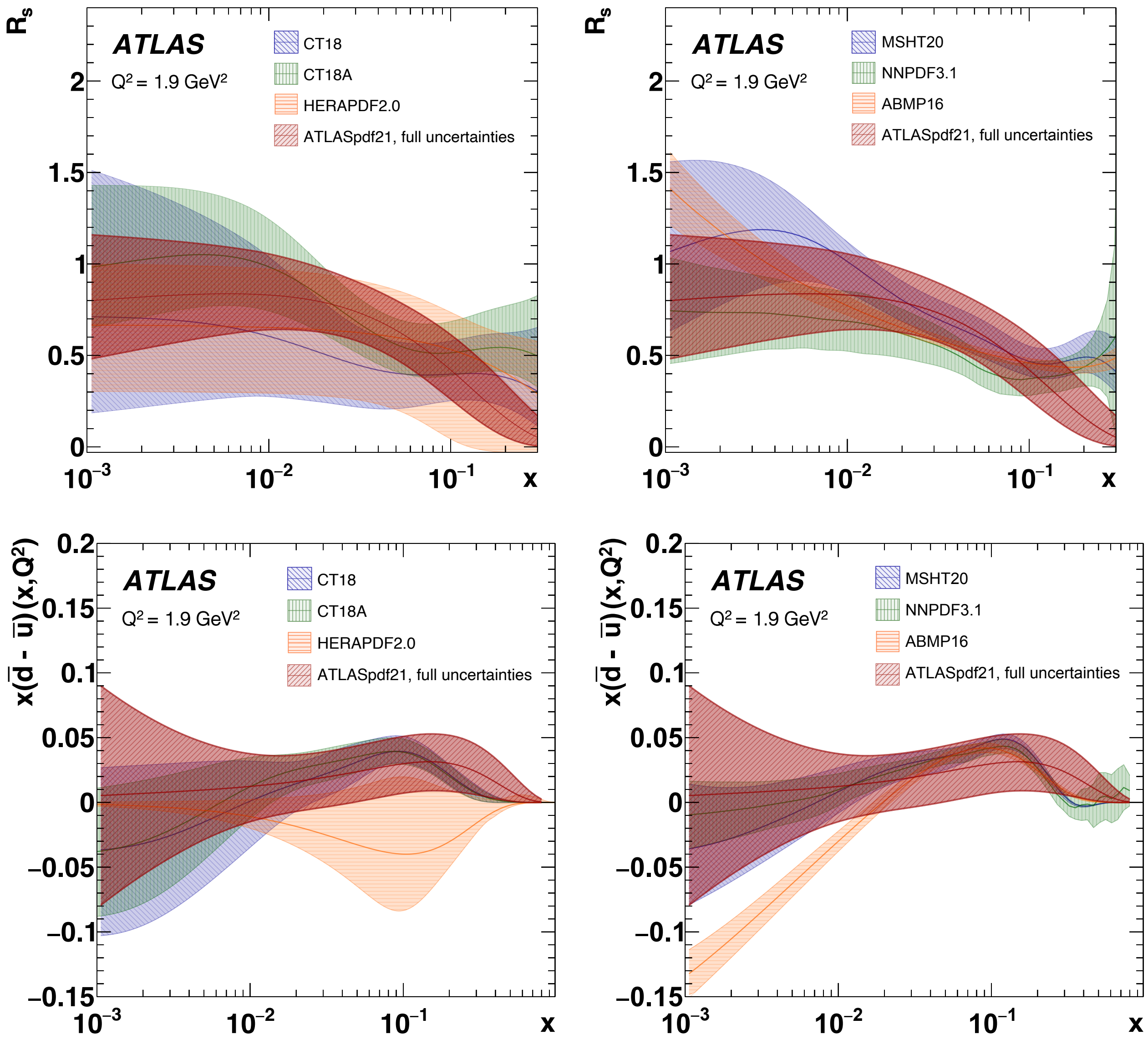
sensitivity to BSM effects?

(ΔX²=1)



- cross-check fit performed, removing data with scale > 500 GeV, to search for subtle effects of any possible hidden new physics at high scales **–➤ PDFs not significantly changed**

comparison with global PDFs

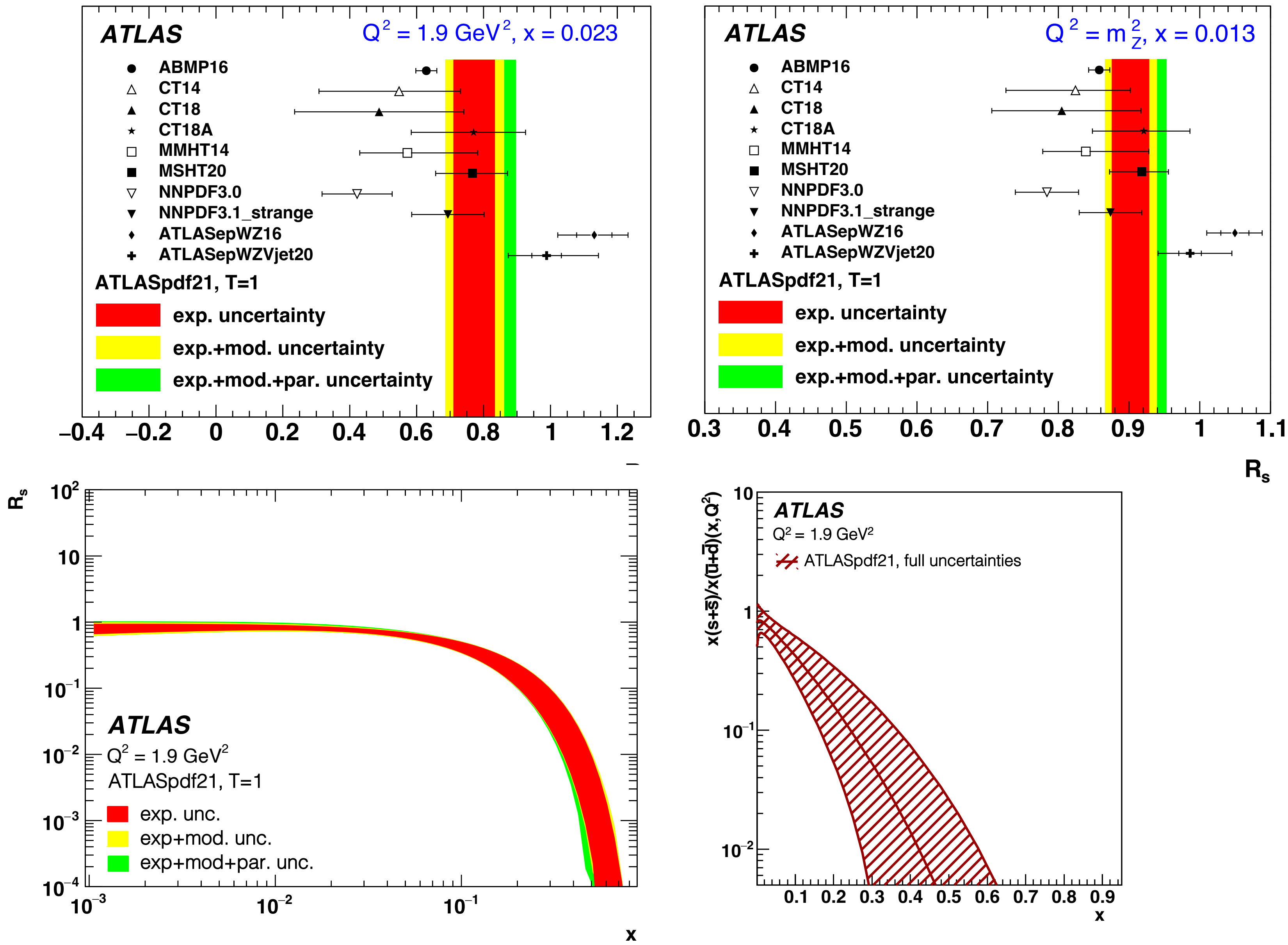


Rs

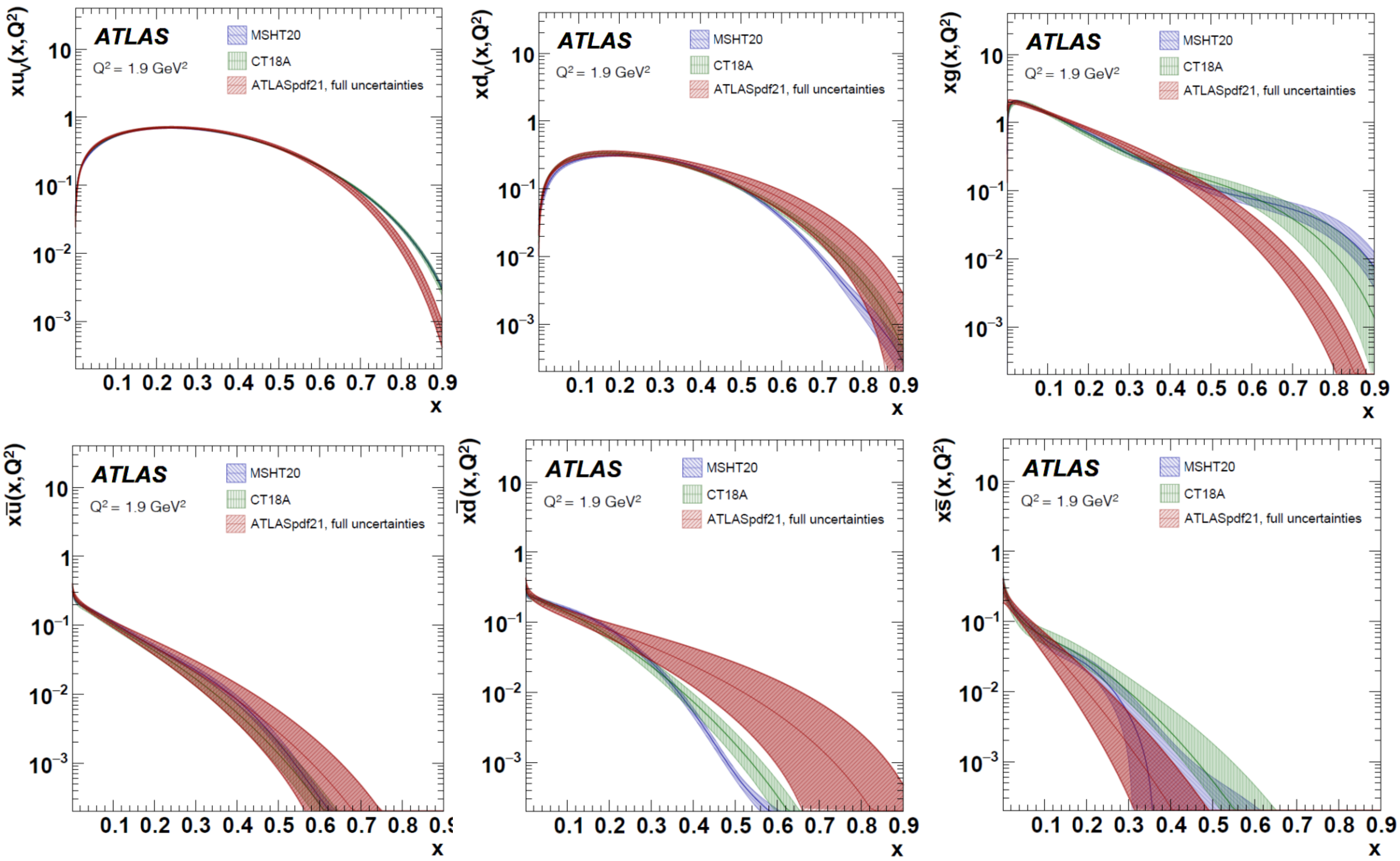
dbar–ubar

PDF (free pars)	χ^2/NDP
ATLASpdf21 (21)	**2010/1641**
CT18 (29)	2135/1641
CT18A (29)	2133/1641
MSHT20 (52)	2218/1641
HERAPDF2.0 (14)	2262/1641
NNPDF3.1	2109/1641

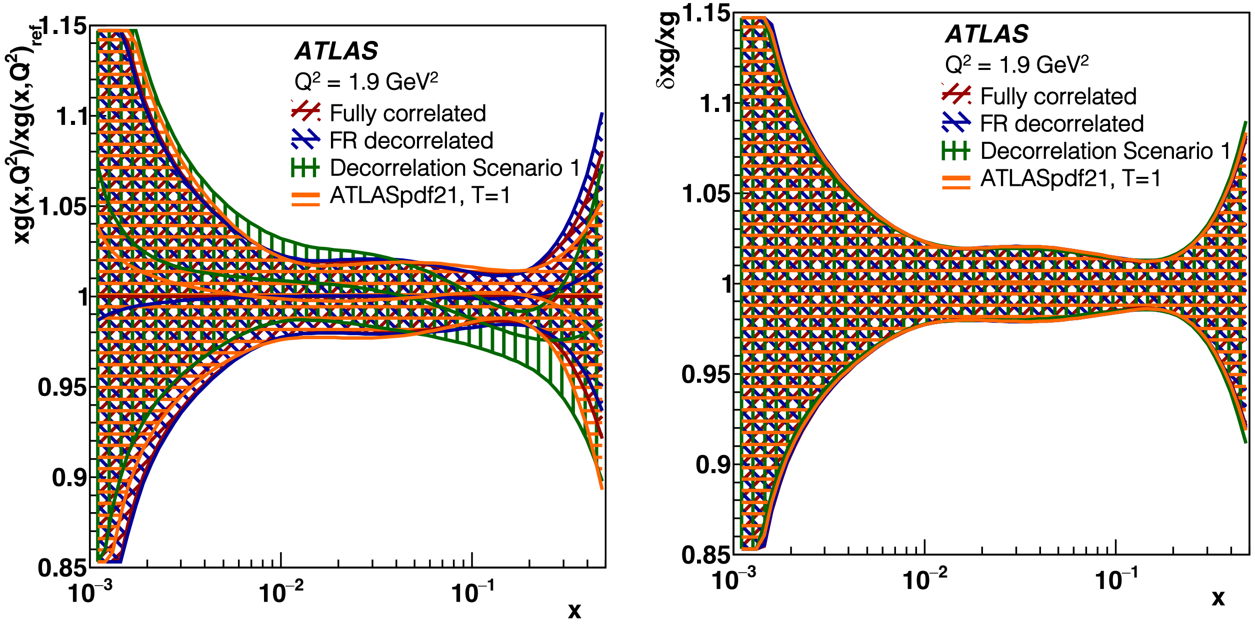
ATLASpdf21 strangeness ratio



comparison with global PDFs at high x



inclusive jet correlation model



ATLASpdf21 ⇣

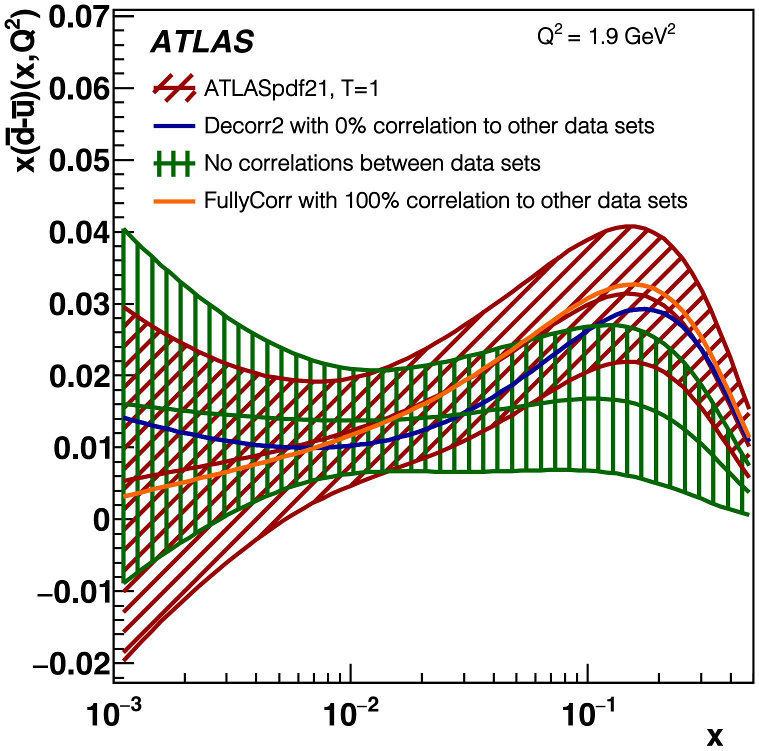
Jets 8 TeV $R = 0.6$	Fully correlated	FR decorrelated	Decorrelation scenario 1	Decorrelation scenario 2 (default)
χ^2/NDP	289/171	227/171	250/171	248/171

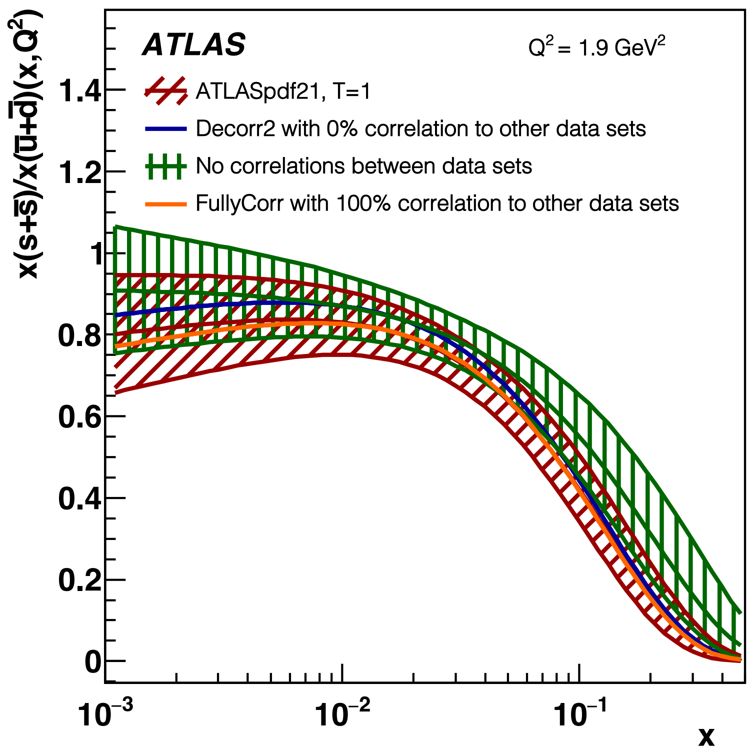
- alternative models to treat **correlated systematics** for inclusive jets were considered

1. fully correlated
2. decorrelating jet flavour response (FR) between rapidity bins
3. two decorrelation scenarios (recommended in the √s= 8TeV inclusive jet measurement publication)

–➤ impacts X^2, but little effect on extracted PDFs

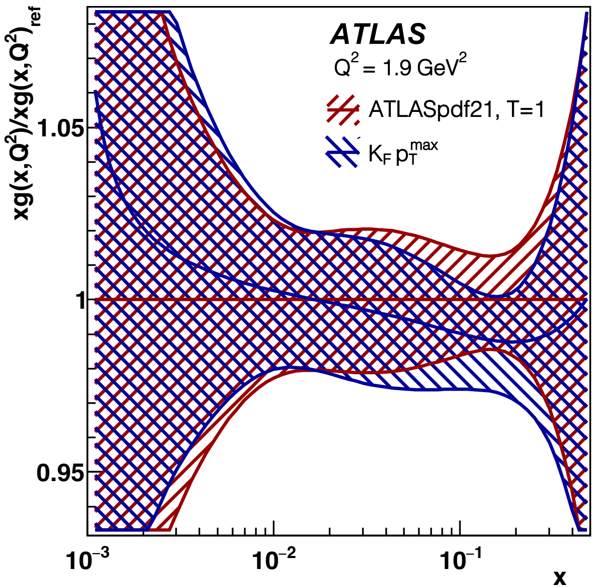
correlation between various datasets

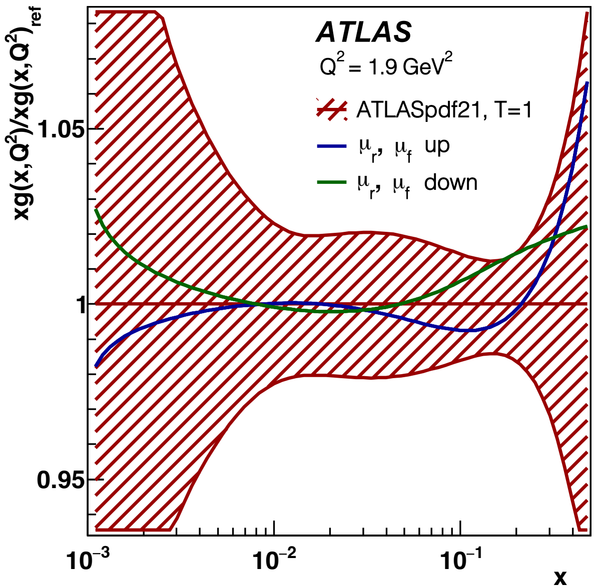




- main impact from **systematic correlations** comes from those between **V+Jets** and **ttbar**
- exact degree of correlation to inclusive jet data does not change the PDFs significantly (**RED** vs **BLUE**)
- choice of correlating all inclusive jet systematics also not important (**RED** vs **ORANGE**)

inclusive jet sensitivity to scale choice

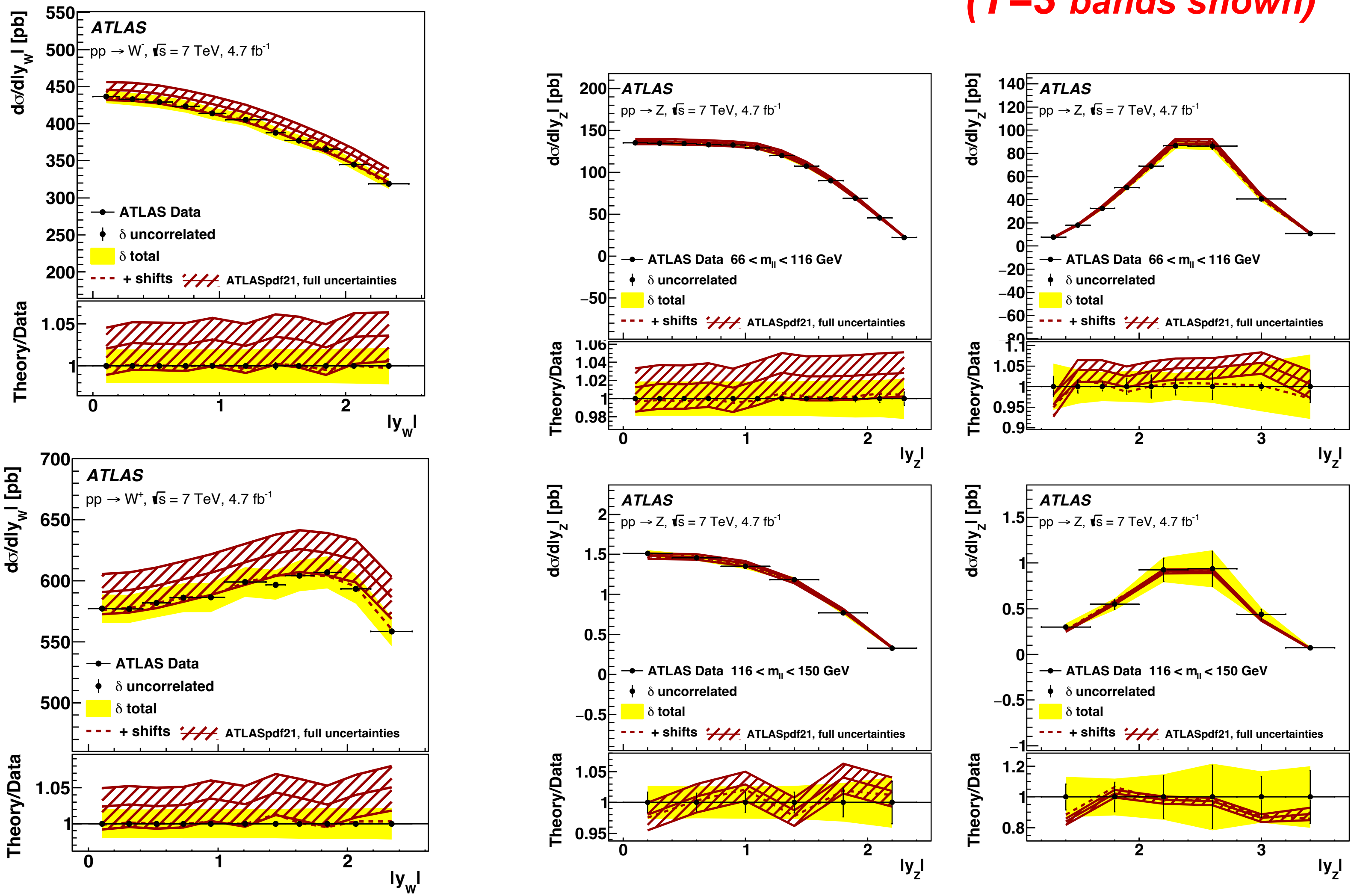




Total χ^2/NDF	χ^2/NDP for jets	Treatment of K-factors	Scale choice
2010/1620	248/171	smoothed	p_T^{jet} scale
2019/1620	257/171	smoothed	p_T^{max} scale
2032/1620	272/171	smoothed	$2p_T^{jet}$ scale
1991/1620	228/171	smoothed	$p_T^{jet}/2$ scale
1983/1620	223/171	unsmoothed	p_T^{jet} scale

ATLASpdf21 vs. $\sqrt{s}$=7 TeV W, Z

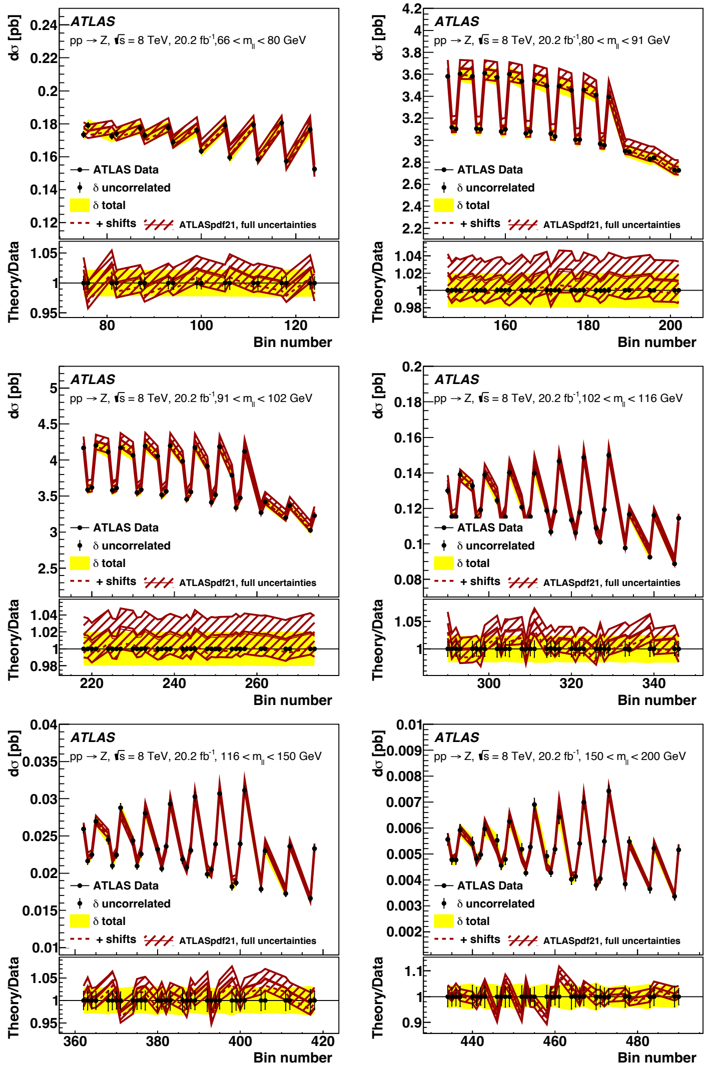
(T=3 bands shown)

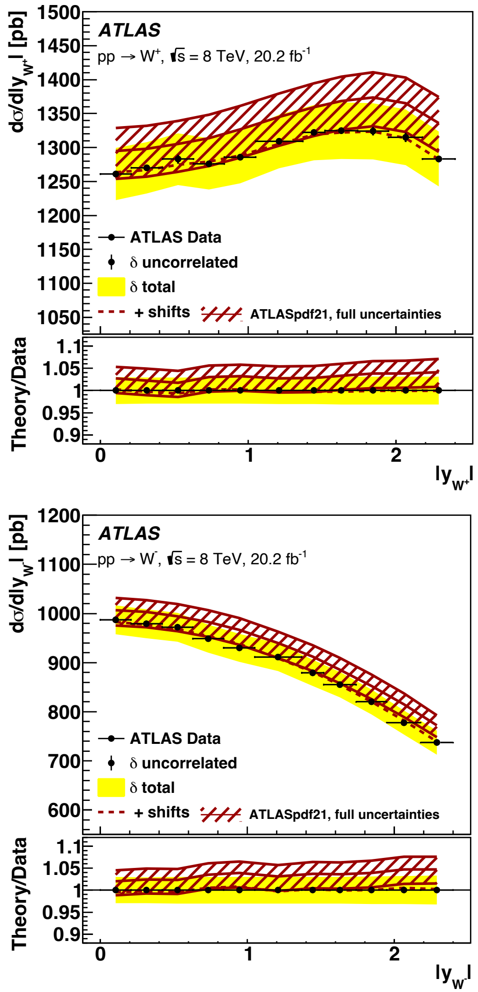


- NB, N^{3}LO cross section for Z expected to be 2% lower than NNLO, bringing **theory into agreement with data** without need for systematic uncertainty shifts

ATLASpdf21 vs. √s=8 TeV W, Z

(T=3 bands shown)

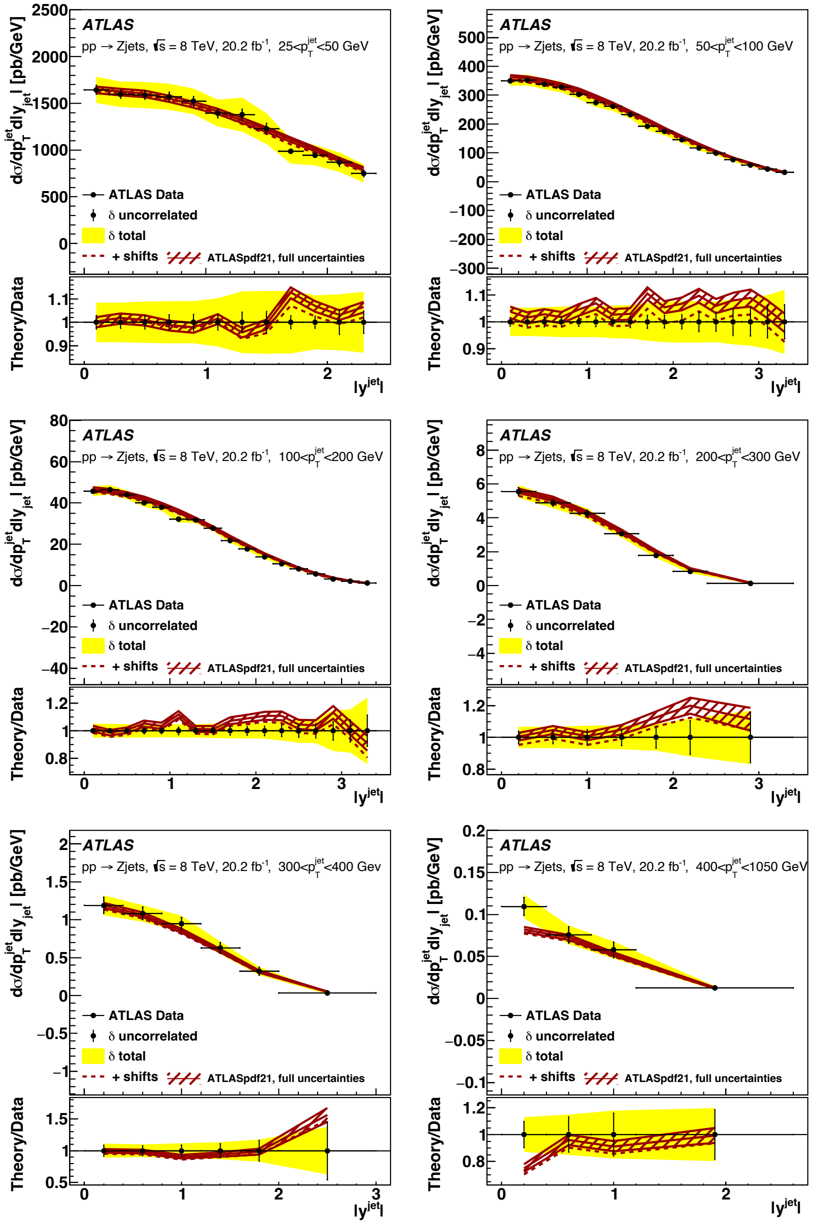


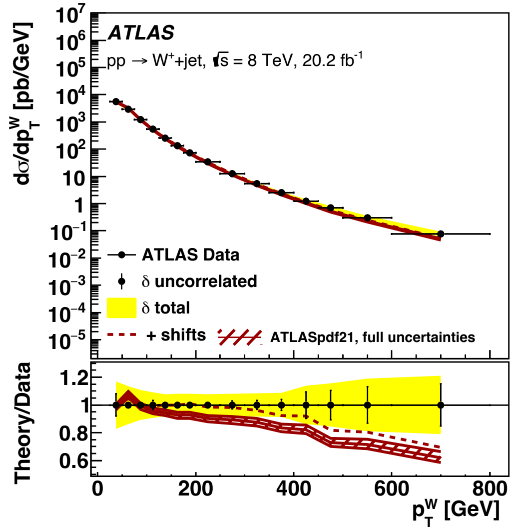


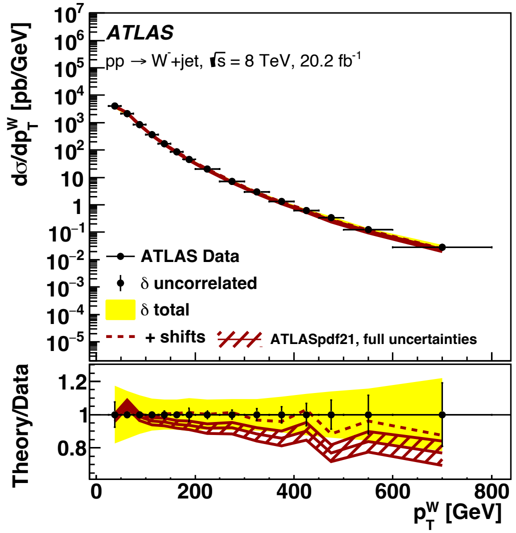
- NB, N^{3}LO cross section for Z expected to be 2% lower than NNLO, bringing **theory into agreement with data** without need for systematic uncertainty shifts

ATLASpdf21 vs. V+Jets

(T=3 bands shown)

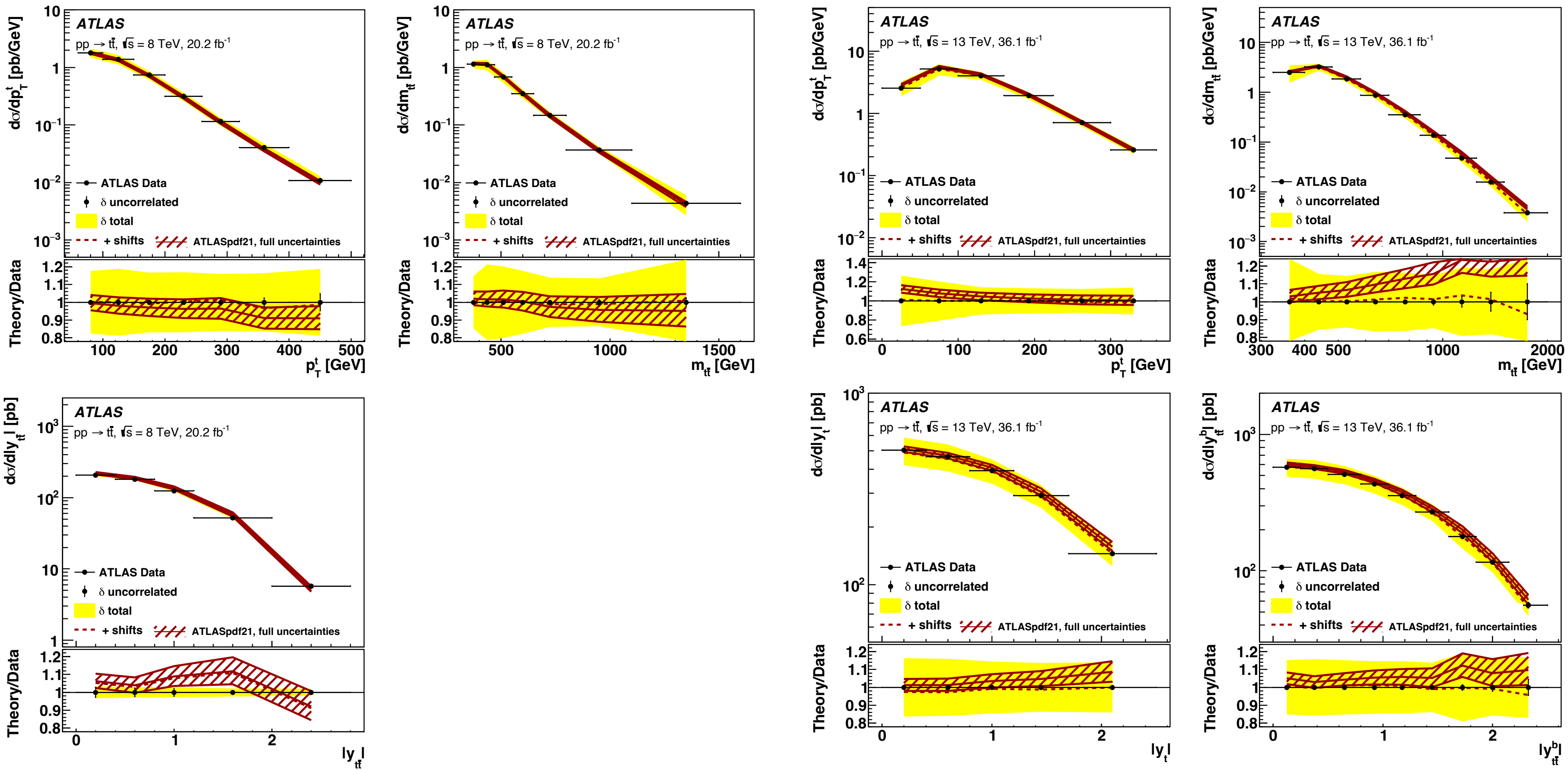






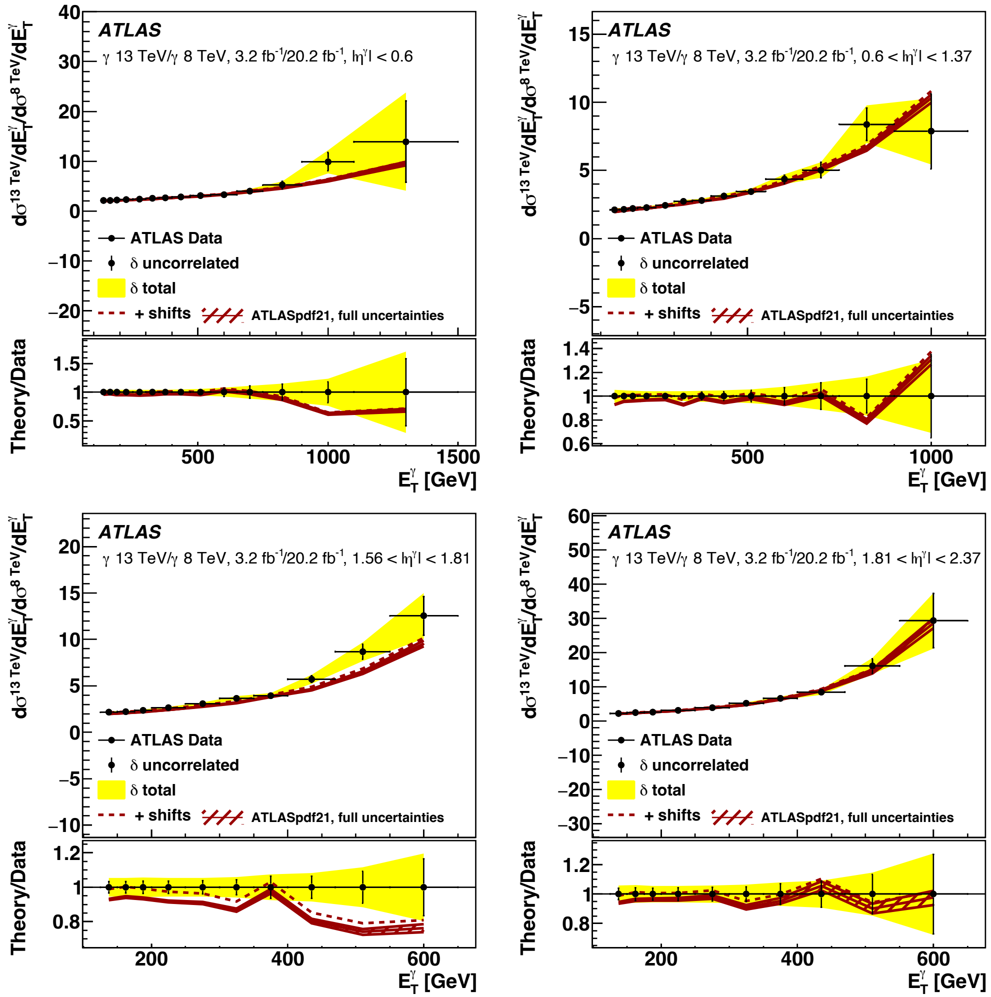
ATLASpdf21 vs. ttbar

(T=3 bands shown)



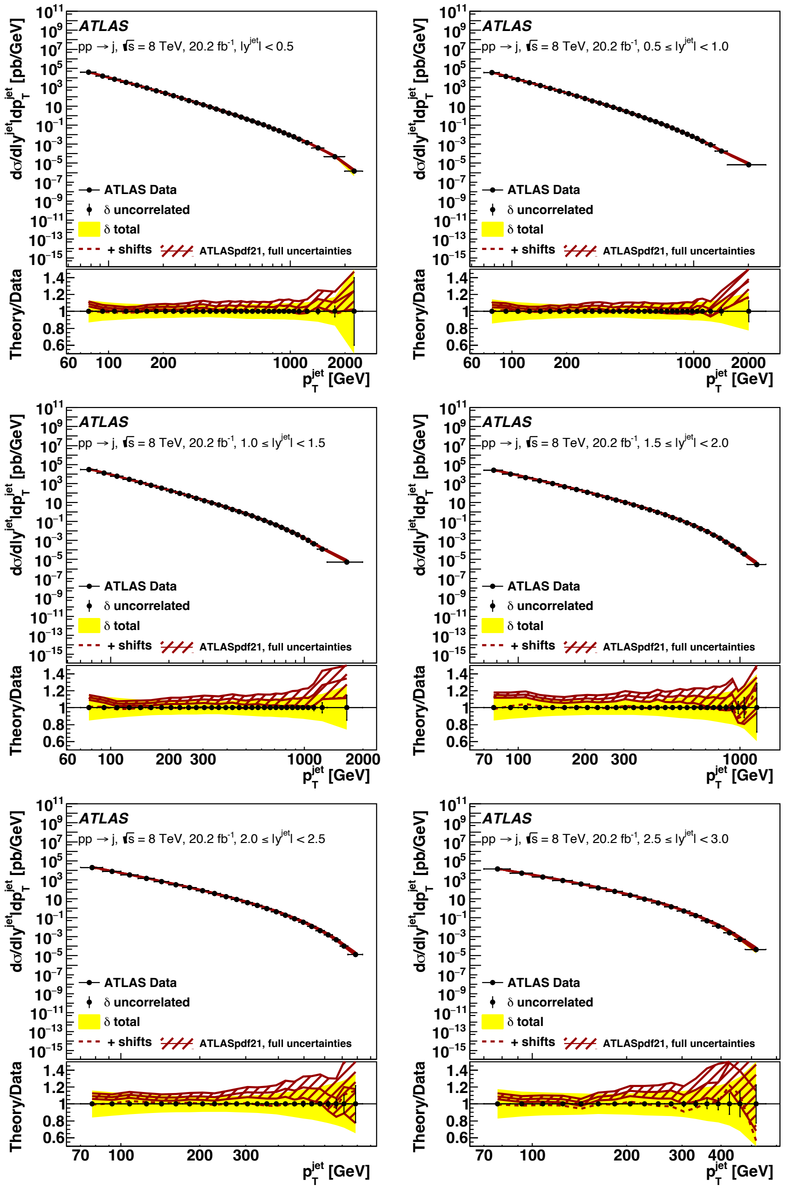
ATLASpdf21 vs. direct-γ

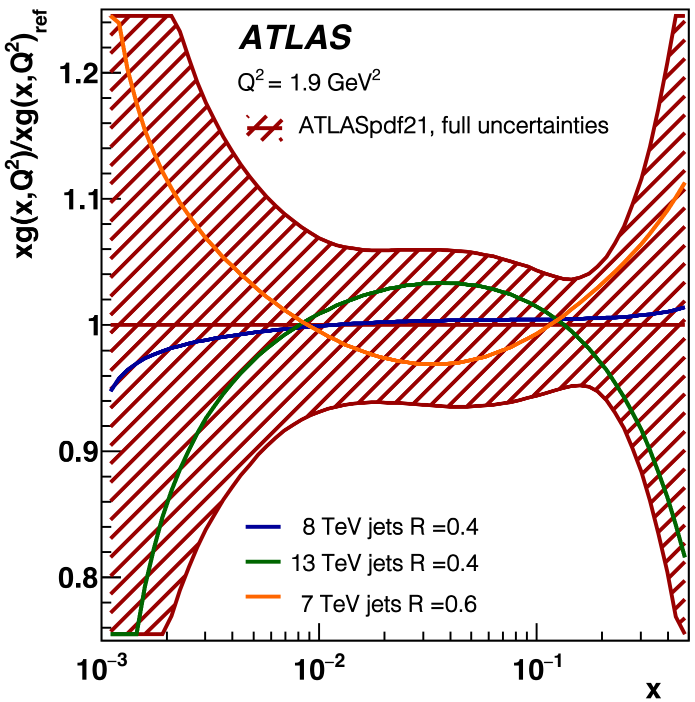
(T=3 bands shown)



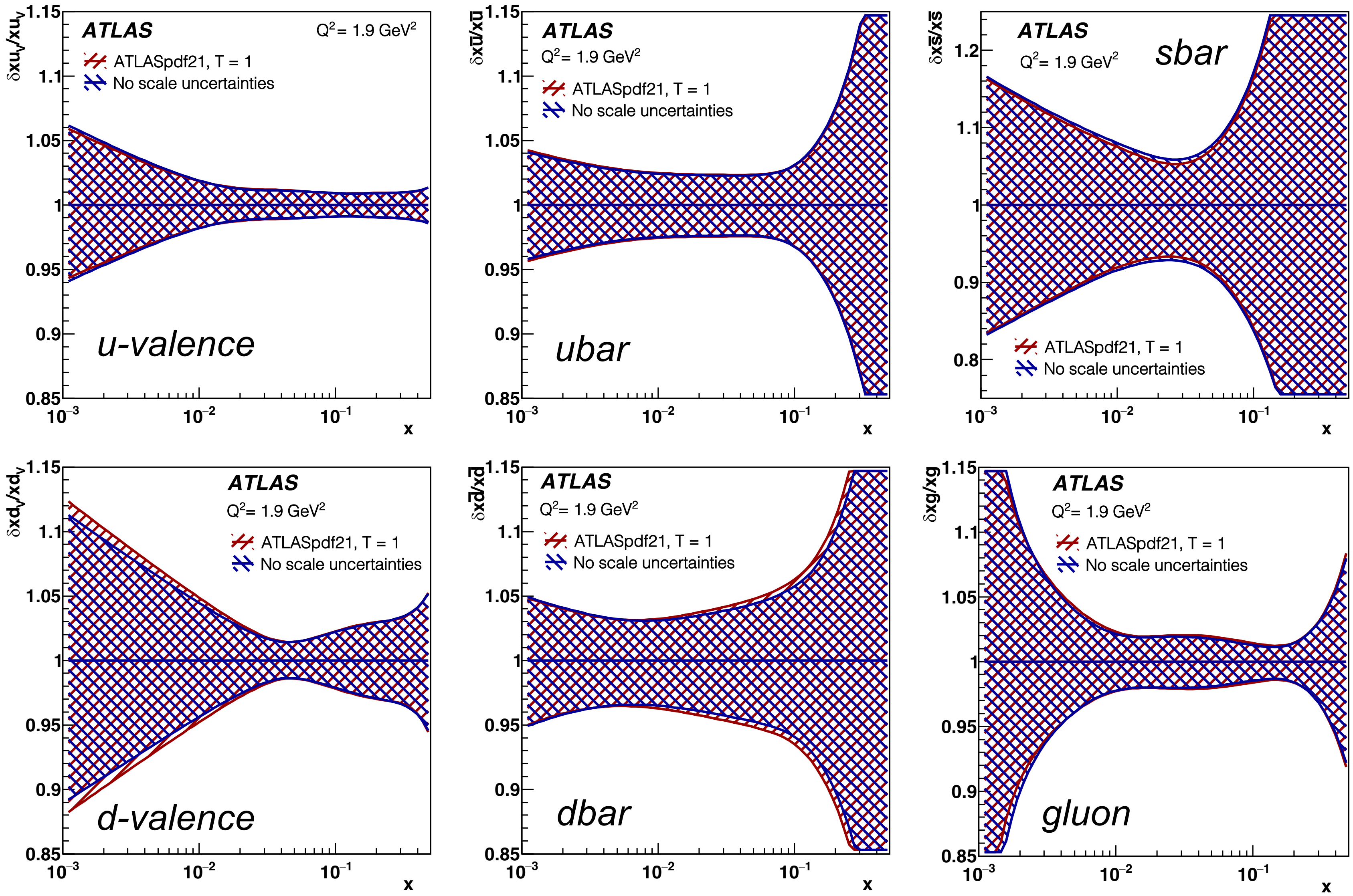
ATLASpdf21 vs. inclusive jet data

(T=3 bands shown)





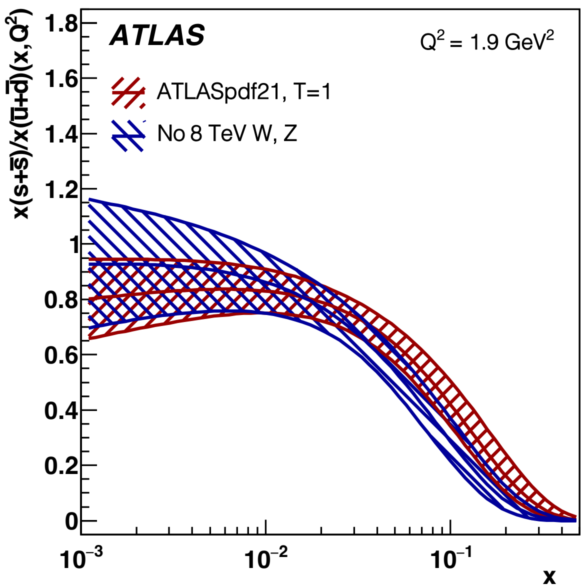
scale uncertainties



- addition of scale uncertainties has minimal impact on overall PDF uncertainty

a word on tension between √s= 7 and 8 TeV W, Z

There is mild tension between the W, Z data at 8 TeV and the W, Z data at 7 TeV. The *partial* χ^2/NDP for the W, Z data at 7 TeV decreases from 68/55 to 50/55 if the W, Z data at 8 TeV are excluded from the fit, and the *partial* χ^2/NDP for the W, Z data at 8 TeV decreases from 239/206 to 222/206 if the W, Z data at 7 TeV are excluded from the fit. These increases in χ^2 are most pronounced for the 7 TeV c-c data around the Z mass-peak (66–116 GeV) and for the mass bins around the Z peak in 8 TeV data. As already remarked, theoretical scale uncertainties for W, Z data at both 7 and 8 TeV are added to the fit uncertainties. If these uncertainties are not added the tension between W, Z data at 7 and 8 TeV increases. The *partial* χ^2/NDP for W, Z data at 7 TeV increases to 80/55 and the *partial* χ^2/NDP for W, Z data at 8 TeV increases to 268/206 if both data sets are included in the fit and scale uncertainties are not applied.



partial X^2/NDP for √s=7 TeV inclusive W, Z:

68/55 vs. 50/55