Determination of Proton PDFs Using ATLAS Data

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

université PARIS-SACLAY

ATLAS EXPERIMENT

Outline

- Introduction
- Inputs and PDF fits
- Results:
  - Cross section measurements
  - PDF analyses
- Summary

Introduction

Parton Distribution Functions (PDFs) of the proton cannot be predicted from first principle

They are determined using relevant cross section measurements from collisions as ℓp, pp, …

They are universal (relying on the factorisation theorem), the determination from one process can be used as prediction for others

At hadron colliders, they are

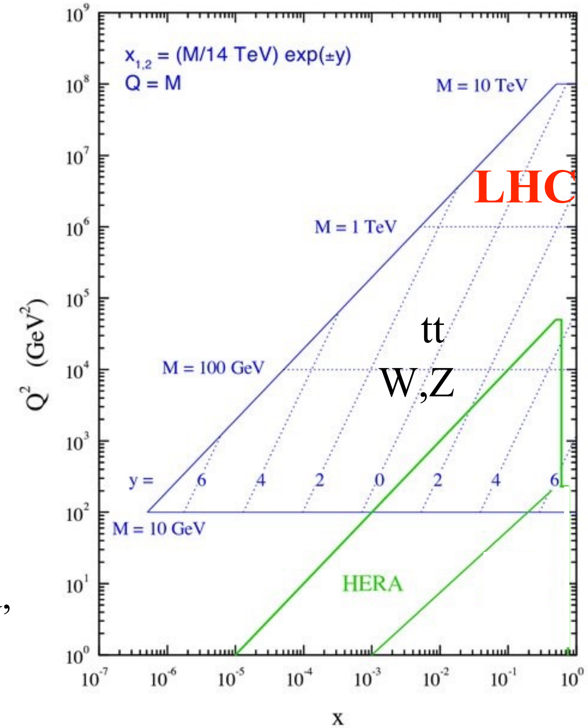
- dominant uncertainty source for precision measurements
- becoming limiting factors for BSM searches

Important to improve our knowledge on PDFs by using relevant data at the LHC

Inputs and ATLAS PDF Fits

Inputs \ Fits	epWZ12[1]	epWZ16 [2]	epWZtop18 [3]	**epWZVjet20 [4]**
HERA NC, CC [5]	✓	✓	✓	✓
ATLAS W, Z 7 TeV 35 pb^{-1} [6]	✓			
ATLAS W, Z 7 TeV 4.6 fb^{-1} [2]		✓	✓	✓
ATLAS tt (l+jets, dilepton) 8 TeV [7]			✓	
ATLAS W/Z+jets 8 TeV [8]				✓

[1] PRL 109 (2012) 012001
[2] EPJC 77 (2017) 367
[3] ATL-PHY-PUB-2018-017
[4] JHEP 07 (2021) 223
[5] EPJC 75 (2015) 580
[6] PRD 85 (2012) 072004
[7] EPJC 76 (2016) 538; PRD 94 (2016) 092003
[8] JHEP 05 (2018) 077; EPJC 79 (2019) 847



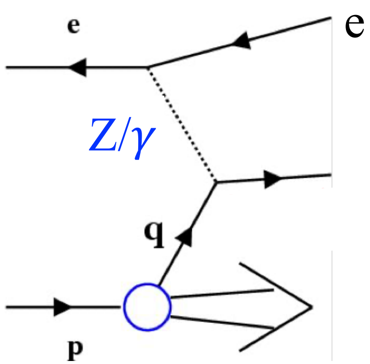
Q^2: four moment transfer squared, Bjorken *x*: proton's momentum fraction carried by struck parton

Why HERA Electron/Positron-Proton DIS Input?

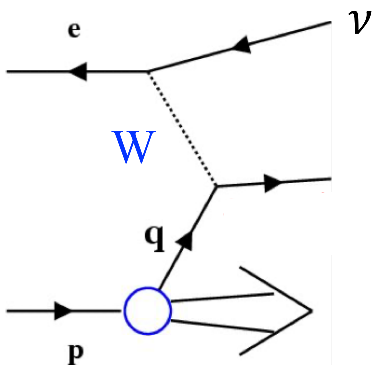
HERA provides two dominant neutral/charged current (NC/CC) Deep Inelastic Scattering (DIS) processes

NC/CC cross section data have been the primary inputs for constraining the PDFs of the proton

NC



CC

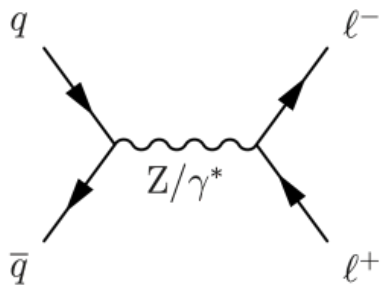


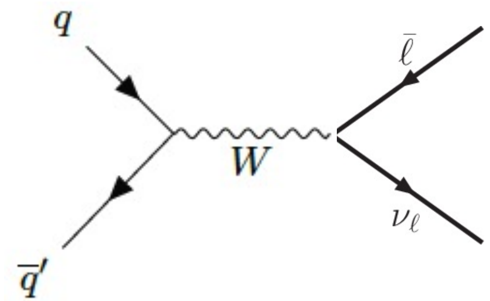
$$\sigma_{\rm NC} \sim F_2 + F_3$$
$$F_2 \sim x\,(q+\bar{q})$$
$$F_3 \sim x\,(q-\bar{q})$$

$$\sigma_{\rm CC} \sim W_2 + W_3$$
$$W_2 \sim xU + x\bar{D}$$
$$W_3 \sim xU - x\bar{D}$$
$$U = u + c$$
$$\bar{D} = \bar{d} + \bar{s}$$

➜ However HERA NC/CC data alone do not allow to distinguish sea quarks *d* and *s*
Also, the data precision at high *x* (and high Q^2) are statistically limited

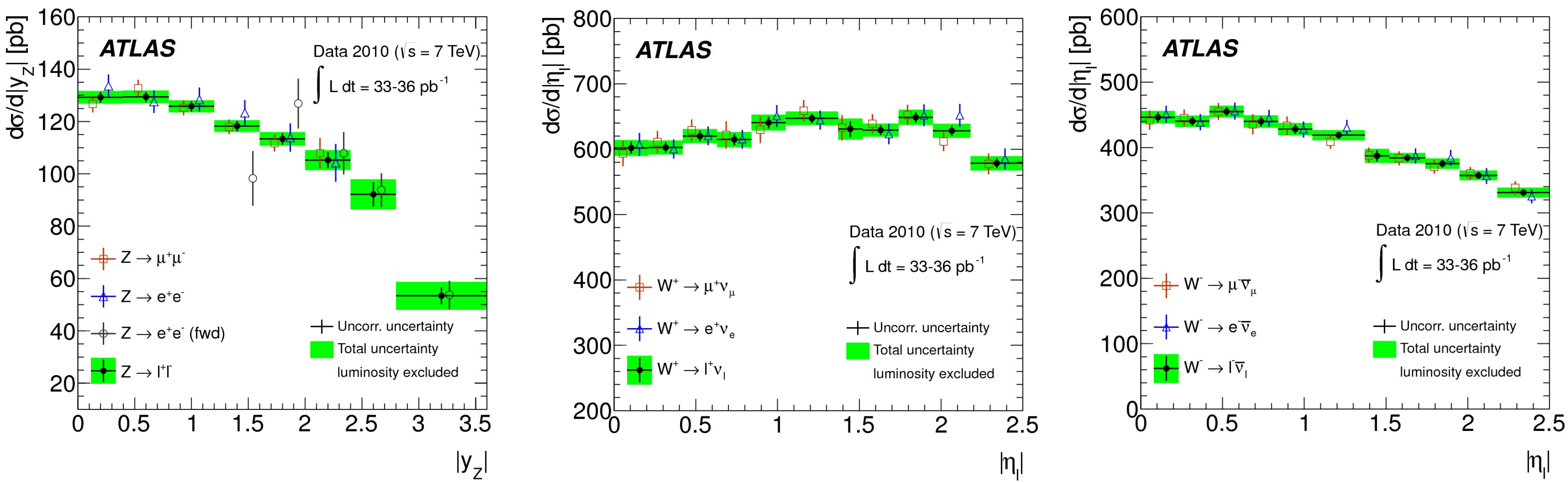
Inclusive Z and W Production at the LHC





The Z and W production at the LHC is sensitive to quark flavor separation
First ATLAS differential cross sections measured with ~35 pb^{-1} at 7 TeV

Phys. Rev. D 85 (2012) 072004



PDF Parameterisations

PDF parameterisations for gluon PDF:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} P_g(x) - A'_g x^{B'_g} (1-x)^{C'_g}$$

and for quark PDFs $(xu_{\mathrm{v}}, xd_{\mathrm{v}}, x\bar{u}, x\bar{d}, x\bar{s})$:

$$xq_i(x) = A_i x^{B_i} (1-x)^{C_i} P_i(x)$$

with $$P_i(x) = \left(1 + D_i x + E_i x^2\right) e^{F_i x}$$

with constraints:

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

which ensure *u* and *d* sea PDFs are the same at low *x*

A_g is fixed by momentum sum rule, and A for *u* and *d* valence PDFs are fixed by quark number sum rules.

$C'_g = 25 \gg C_g$ suppresses negative contribution at high *x*

We also assume the s and anti-s PDFs are the same

PDF Analyses

Use HERAFitter (developed/used for HERAPDF sets) and now xFitter
[Cross-checked with an independent fitting code]

Predictions are calculated with NNLO (QCD) and NLO (EW) accuracy using
either analytic formulae for NC/CC DIS processes
or *K*-factor techniques for other processes

PDF parameters are determined by adjusting agreement between predictions *T* and data *D*:

$$\chi^2 = \sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma_{ij} b_j\right)\right]^2}{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i} + \sum_j b_j^2 + \sum_i \log \frac{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{uncor}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2}$$

(partial χ^2) (correlated χ^2) (log penalty)

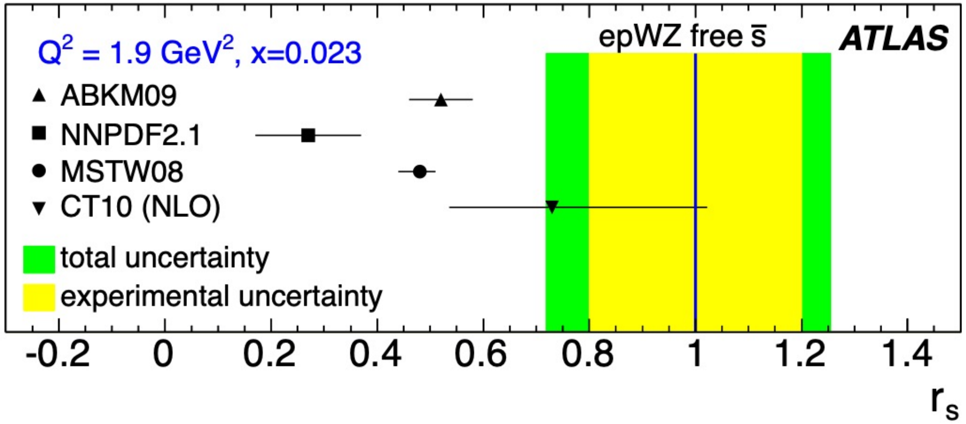
In addition to uncorrelated and statistical uncertainties, the correlated one γ is taken into account using nuisance parameters b

ATLAS epWZ12

In the early PDF analyses, the strange PDF is generally assumed to be suppressed with respect to other light sea quarks due to its larger mass value

The analysis @NNLO of the first ATLAS differential cross section data showed no such suppression

PRL 109 (2012) 012001



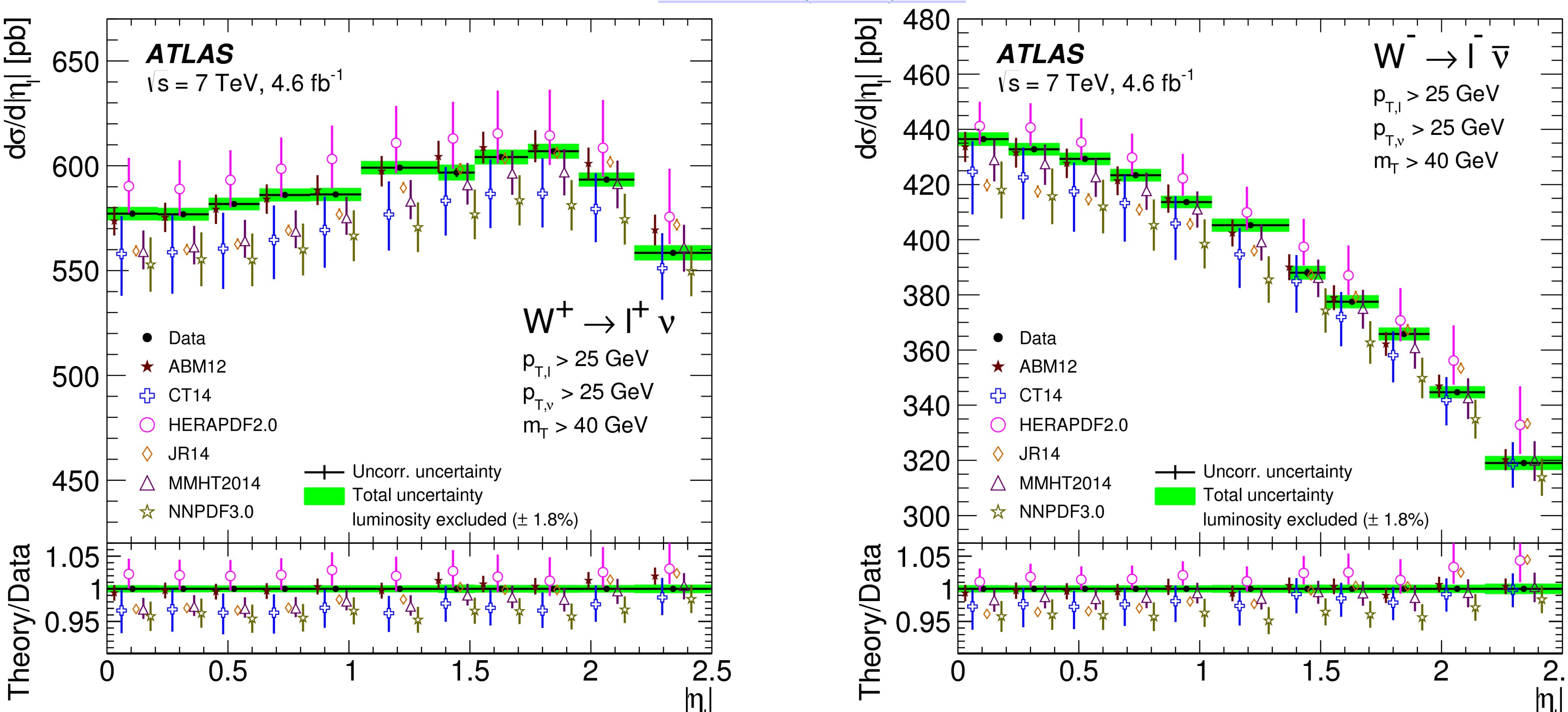
$$r_s \equiv \frac{s+\bar{s}}{2\bar{d}} = 1.00 \pm 0.20(\text{exp}) \pm 0.07(\text{mod})^{+0.10}_{-0.15}(\text{par})^{+0.06}_{-0.07}(\alpha_s) \pm 0.08(\text{th})$$

W Measurement with Full 7 TeV Data

ATLAS updated W cross section measurement in the e and μ channels using full 7 TeV data of 4.6 fb^{-1} corresponding to a factor of ~130 increase in statistics wrt the early measurement

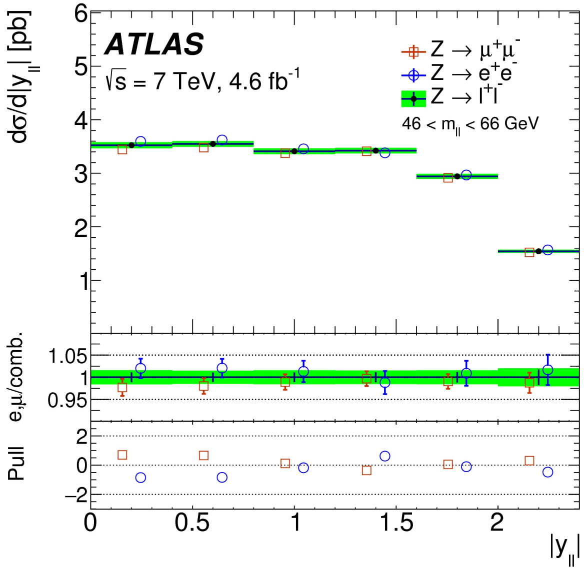
The combined measurements are compared with predictions using different PDF sets
➜ showing large PDF constraining power

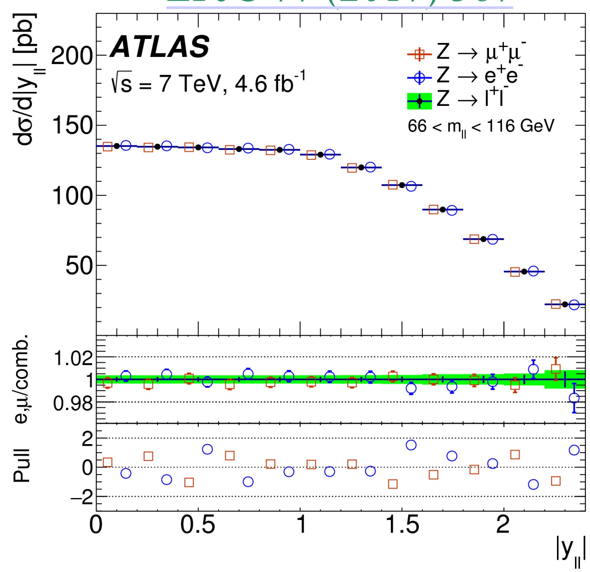
EPJC 77 (2017) 367

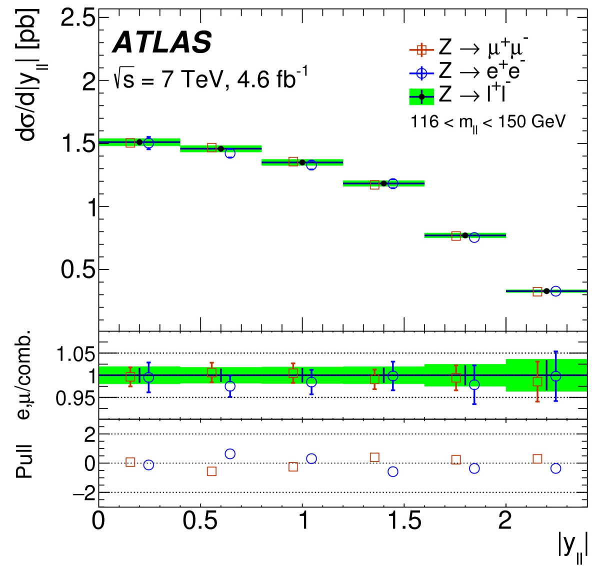


Z Measurement with Full 7 TeV Data

EPJC 77 (2017) 367

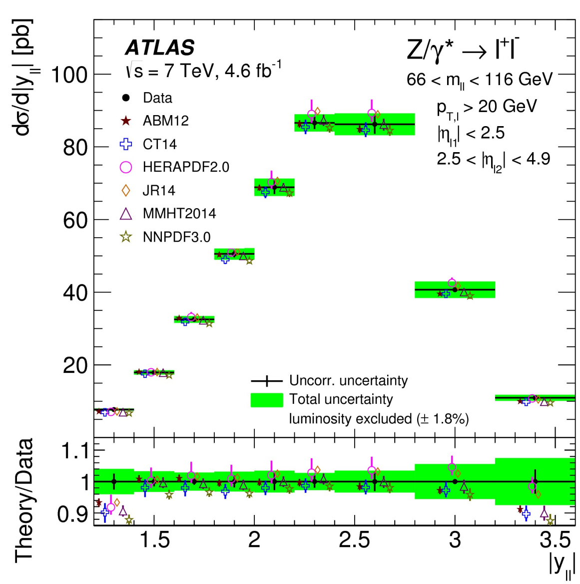


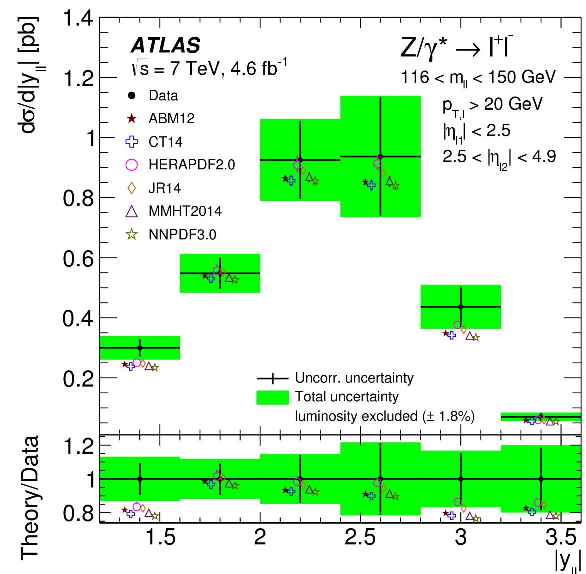




Z cross sections are measured in central rapidity region in three mass regions

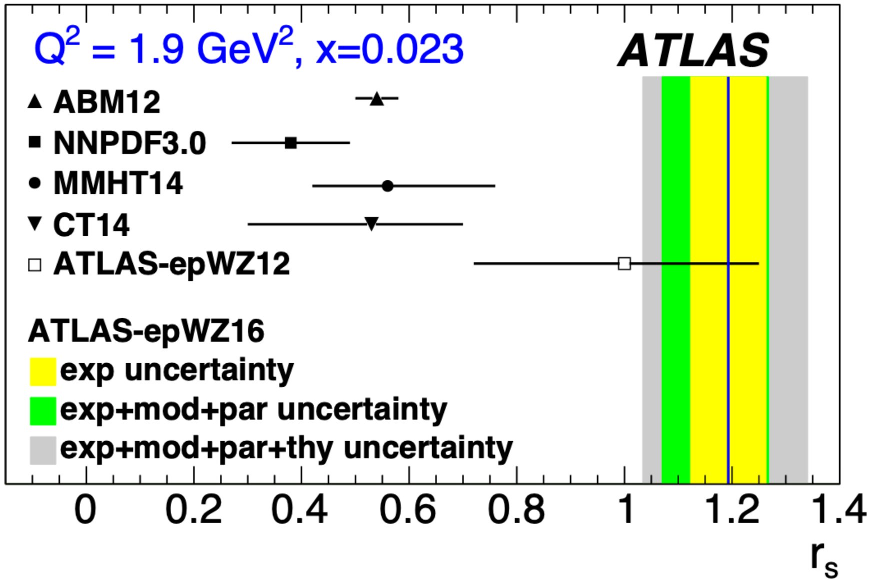
and extended to forward region in two mass regions

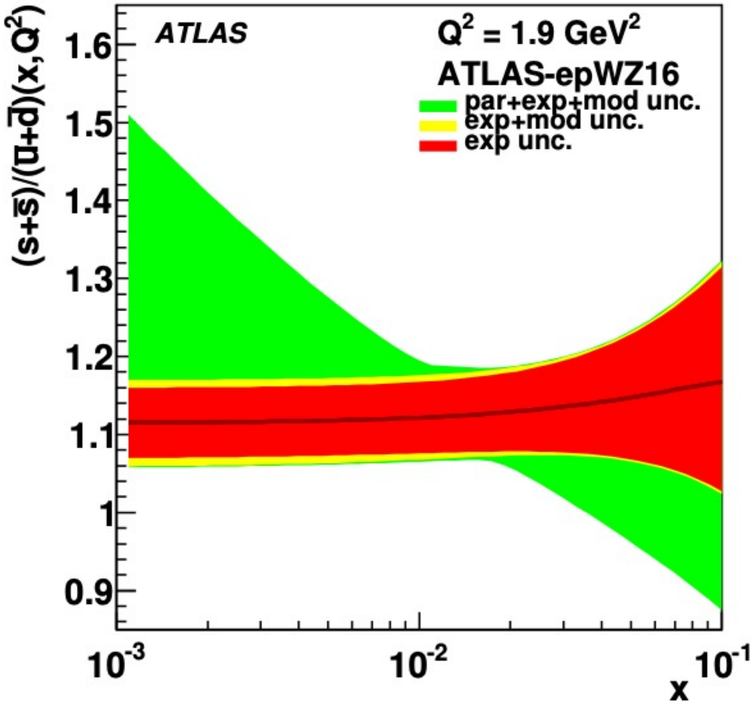




ATLAS epWZ16

A QCD analysis performed using these W, Z data of 4.6 fb^{-1} at 7 TeV EPJC 77 (2017) 367





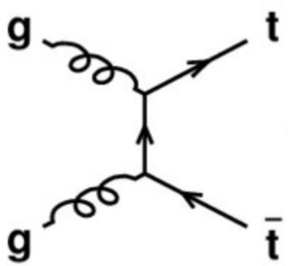
$$r_s \equiv \frac{s+\bar{s}}{2\bar{d}} = 1.19 \pm 0.07(\mathrm{exp})^{+0.13}_{-0.14}(\mathrm{mod}+\mathrm{par}+\mathrm{th})$$

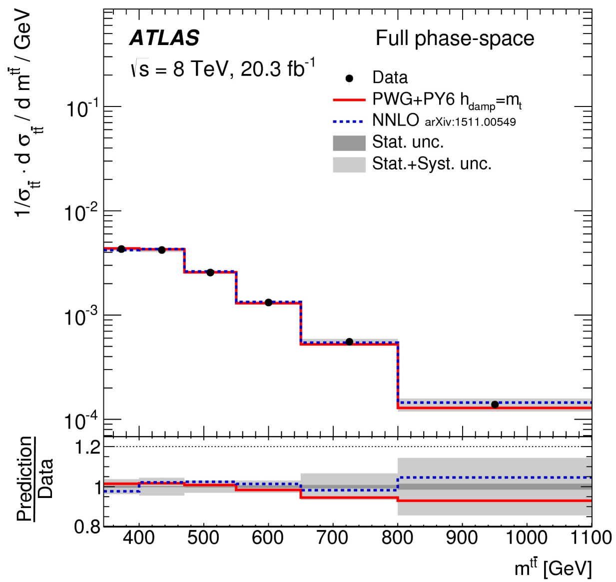
The conclusion of unsuppressed strange PDF remains with improved precision

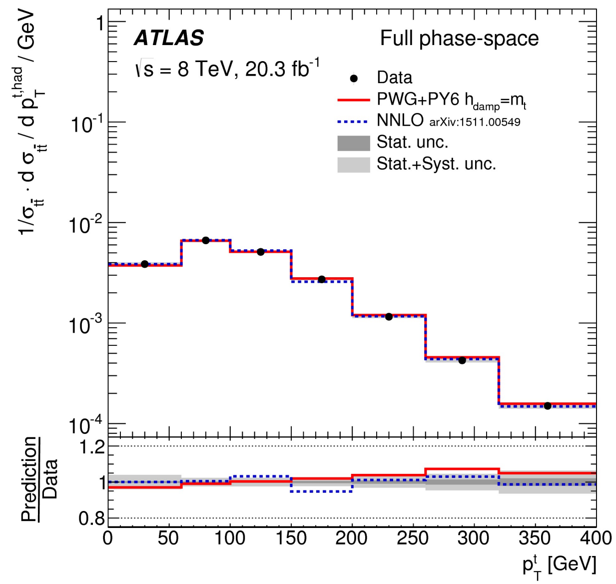
Its shape in *x* has also been determined thought with large uncertainty, raising considerable discussion in the community (see later slides)

ATLAS ttbar Cross-Section Measurements

Top-quark production at the LHC is sensitive to gluon PDF

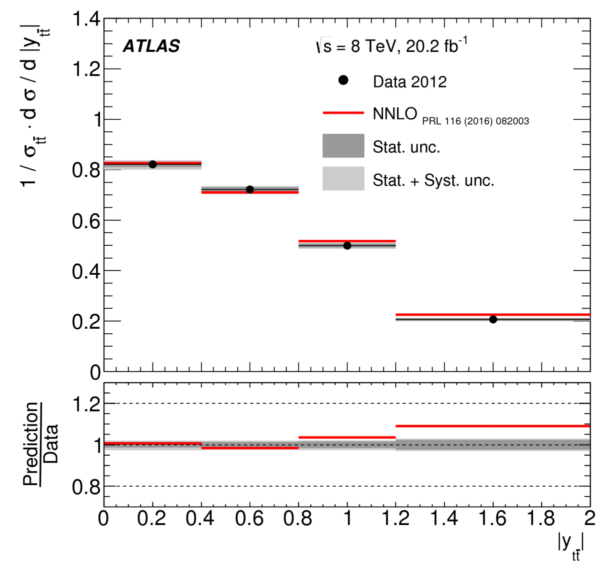






Two sets of measurements using full 8 TeV data of 20.3 fb^{-1}

Upper figures: differential cross sections in lepton+jets channel: EPJC 76 (2016) 538

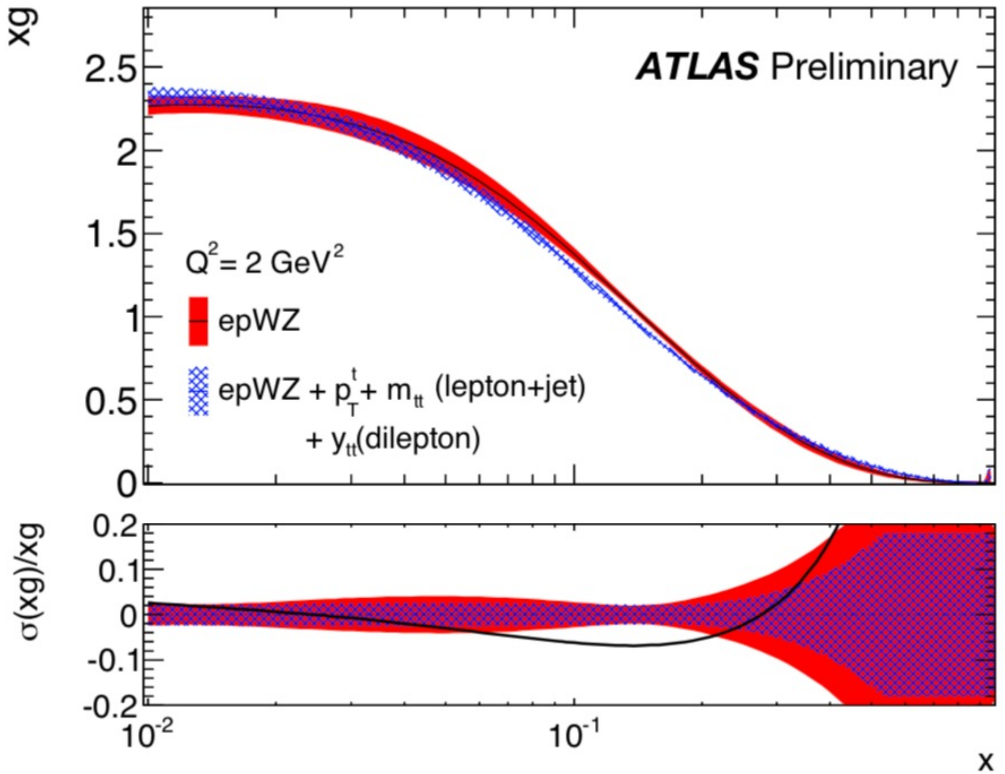


Right figure: differential cross sections in dilepton channel: PRD 94 (2016) 092003

ATLAS epWZtop18

Another QCD analysis was performed by including these top-quark cross section data

ATL-PHY-PUB-2018-017

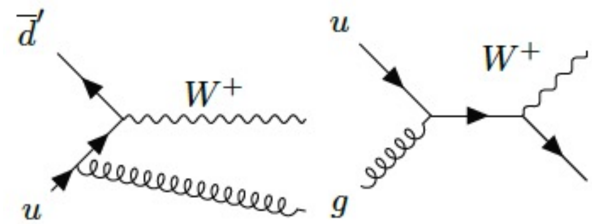


As expected, the top cross section data are useful to constrain the gluon PDF at medium and high-*x*.

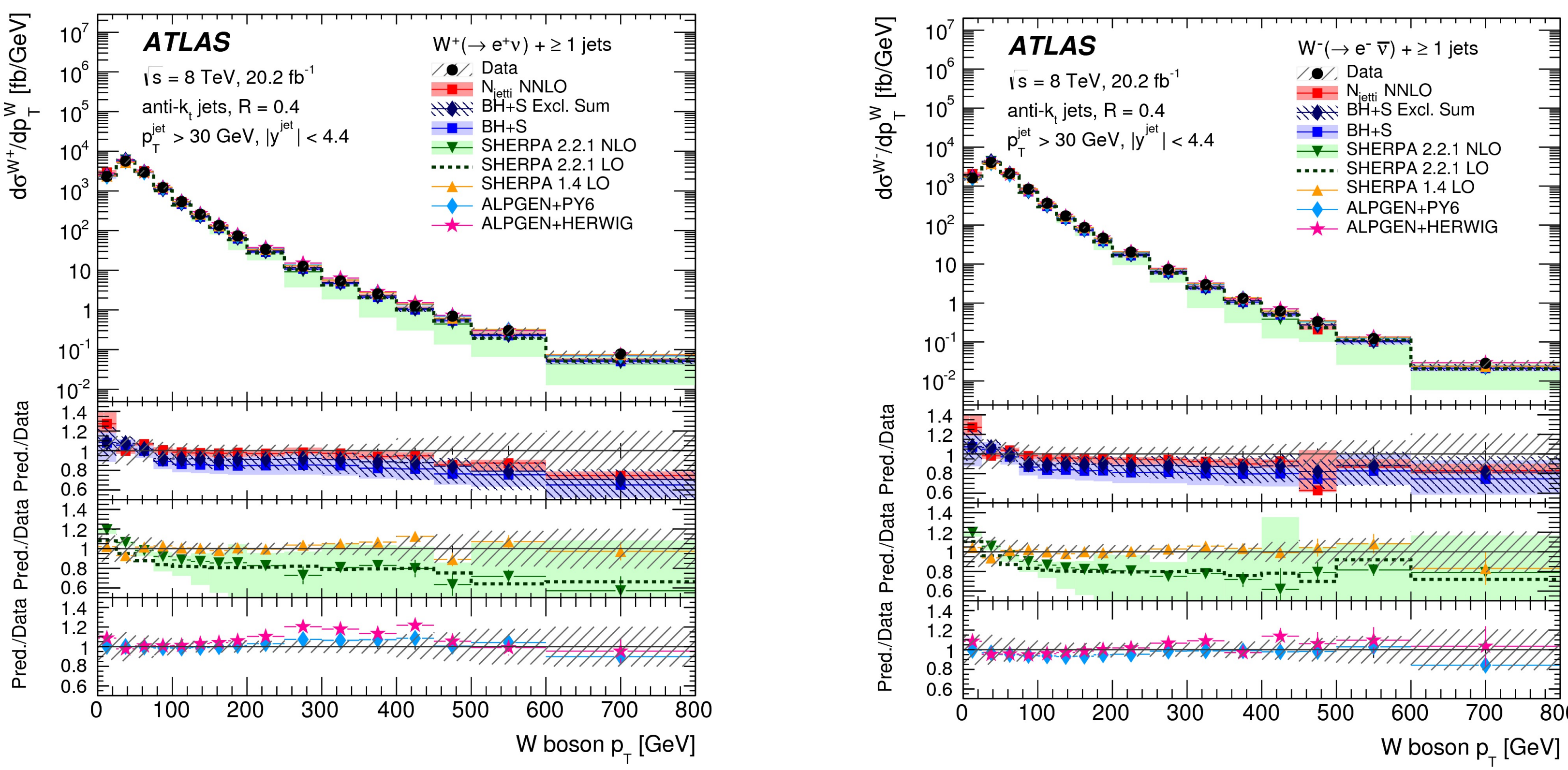
W+jets Measurements 8 TeV

Based on data sample: 20.2 fb^{-1} @ 8 TeV.

These measurements provide new testing ground for pQCD and probe quark and gluon PDFs at leading order



JHEP 05 (2018) 077



Z+jets Measurements 8 TeV

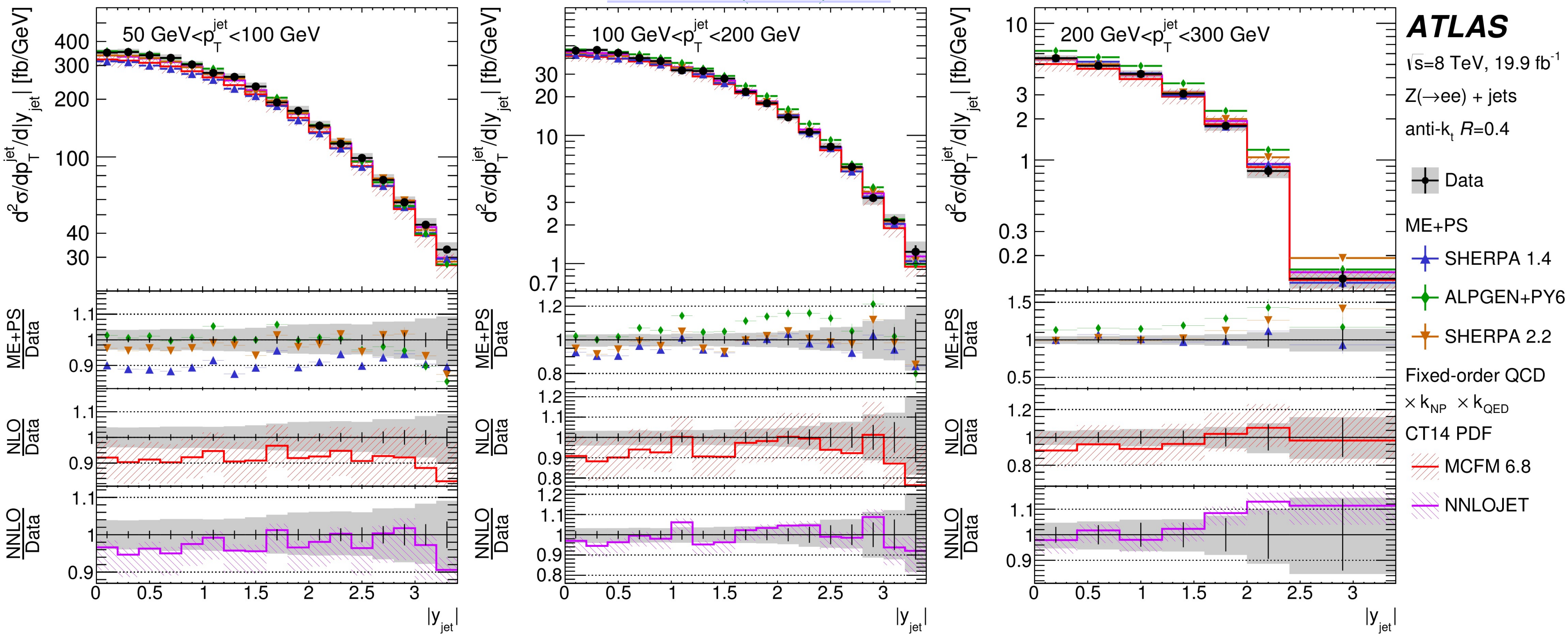
Based on data sample: 19.9 fb^{-1} @ 8 TeV.

The measurements are sensitive to gluon and sea-quark PDFs, probing low-*x* with the central $|y_{jet}|$ and intermediate and high-*x* with the forward $|y_{jet}|$.

Z+jets production is dominated by qg scattering.

Shown here are some of the measurements.

EPJC 79 (2019) 847



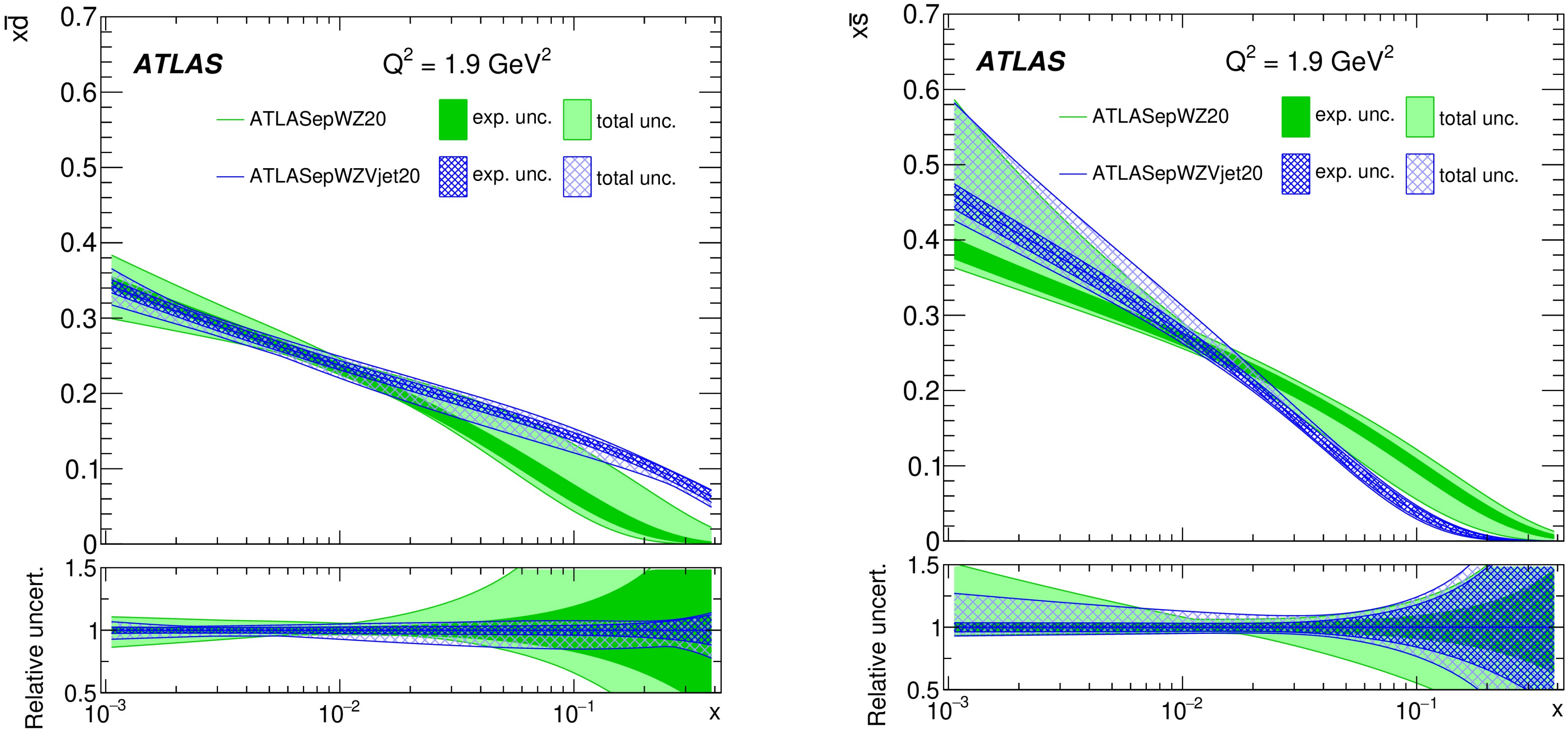
ATLAS epWZVjet20

A QCD analysis showed V+jets data have a big PDF constraining power

The biggest impact is on *d* and *s* sea quarks at $0.02 < x < 0.3$ as expected

epWZ20 (similar to epWZ16) differs from epWZVjet20 in that V+jets are not included in the fit

EPJC 79 (2019) 847



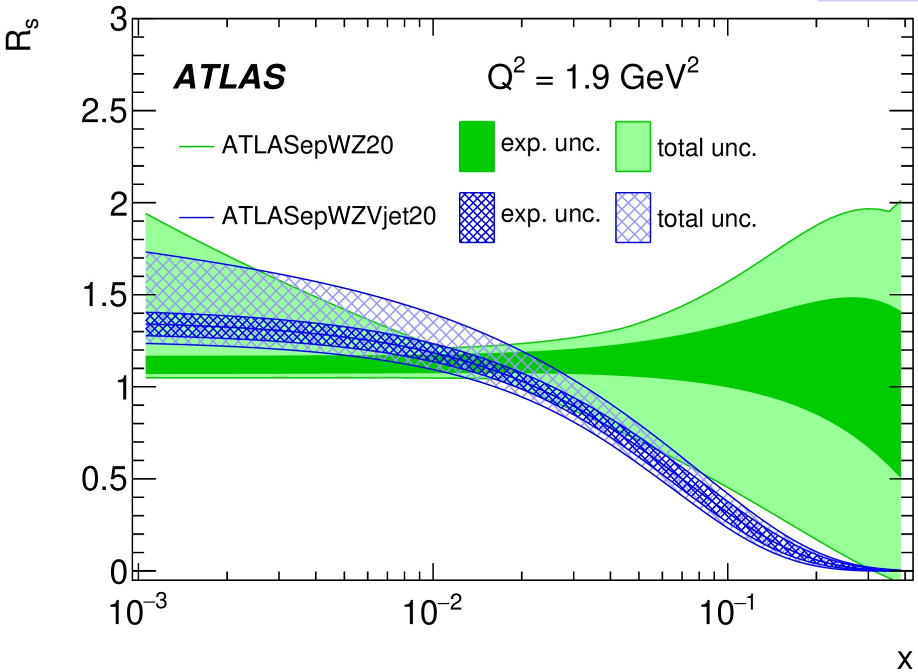
ATLAS epWZVjet20

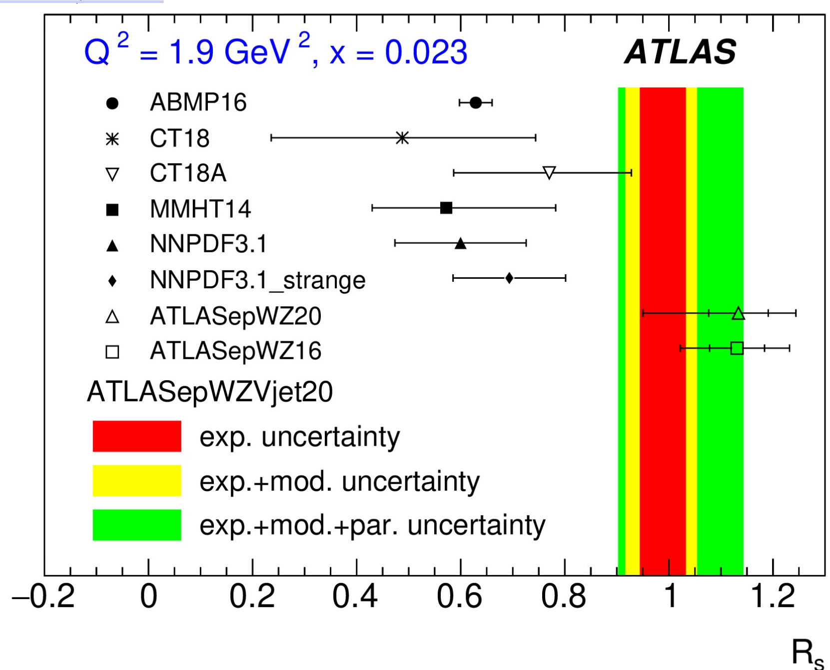
In terms of R_s

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

the strange PDF remains unsuppressed at low x but becomes softer at high x due to the inclusion of the V+jet data

EPJC 79 (2019) 847





ATLAS epWZVjet20

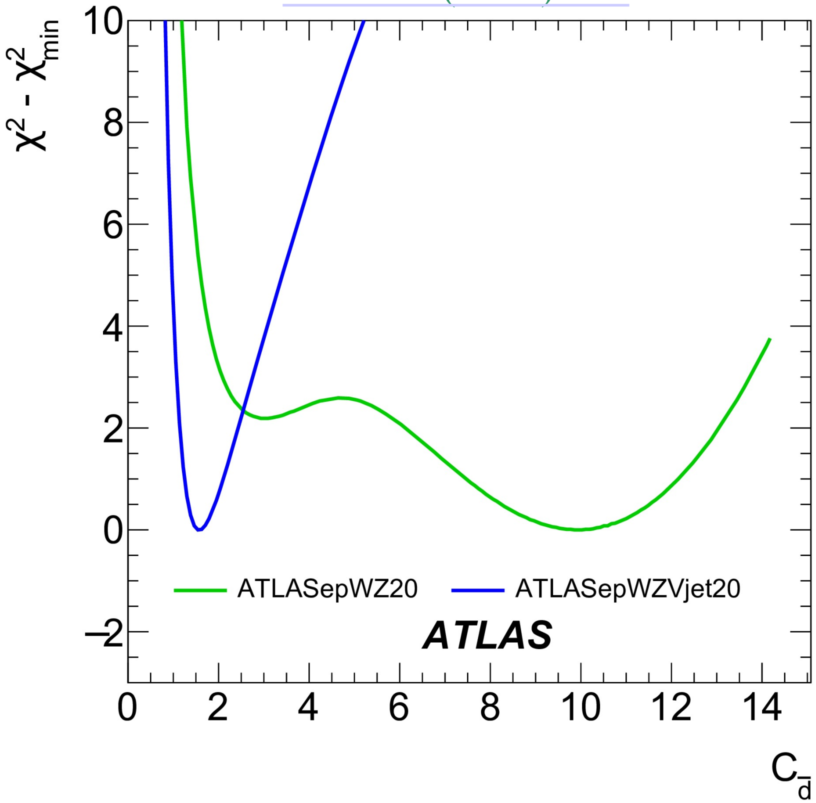
A scan of χ^2 along C for $\bar{d}$ sea PDF performed $x\bar{d} \sim (1-x)^{C_{\bar{d}}}$

→ Double minimum observed in ATLAS epWZ20

→ V+jets breaks degeneracy

→ V+jets favours low C and thus higher $\bar{d}$ sea PDF at high x

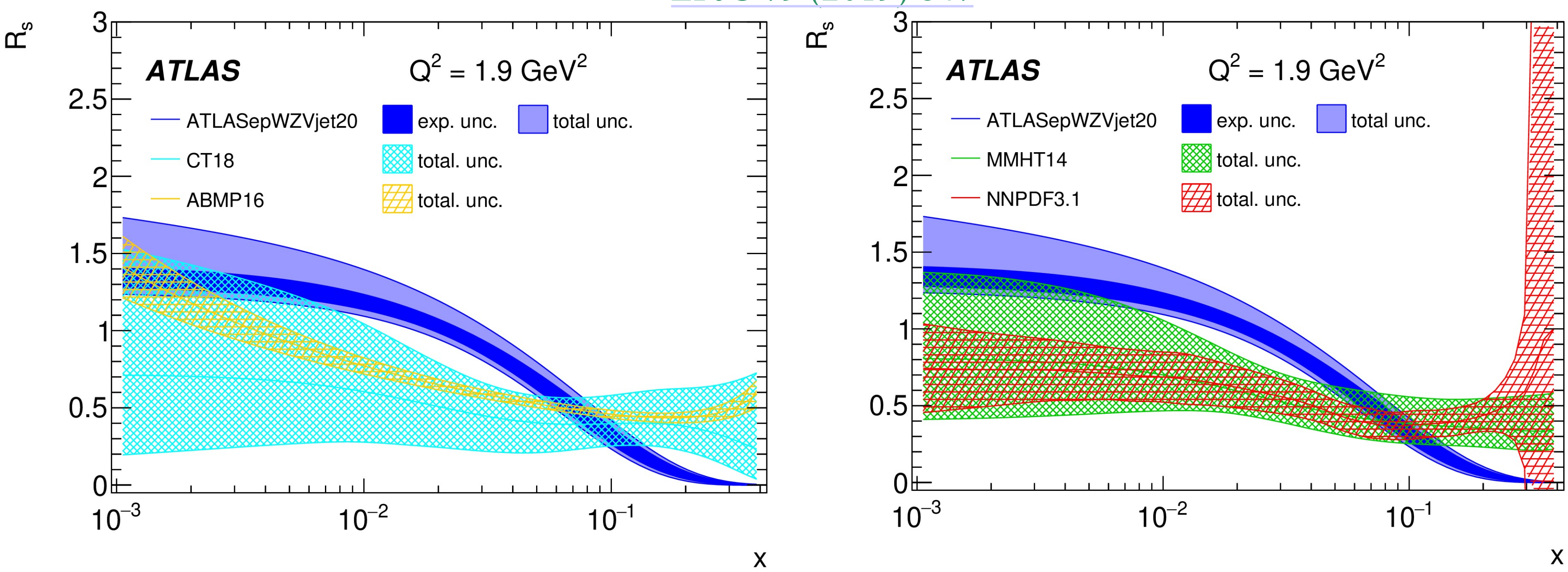
EPJC 79 (2019) 847



Comparison with Other PDF Sets

Clear difference in shape with other Global PDF sets which do not include ATLAS data

EPJC 79 (2019) 847



The difference needs to be reduced, which will impact other PDFs due to their correlation

MMHT14 and MSHT20 comparison is available at EPJC 81 (2021) 341
A recent independent study on the subject is available at arXiv:2109.06854

Summary

Differential cross sections of inclusive W/Z, W/Z+jets production and top-quark pairs have been measured by ATLAS with full 7 or 8 TeV data

Several NNLO QCD analyses have been performed showing their PDF constraining power, complementary to inclusive NC/CC DIS data at HERA

In particular, the strange PDF is found unsuppressed at low x and the different shape at high x has been better understood

W+c production has been measured at the LHC and were used to constrain the s PDF with NLO predictions; good prospect with recently available NNLO prediction [JHEP 06 (2021) 100]

Much efforts still needed if we aim for PDF uncertainties of $\mathcal{O}(\sim 1\%)$