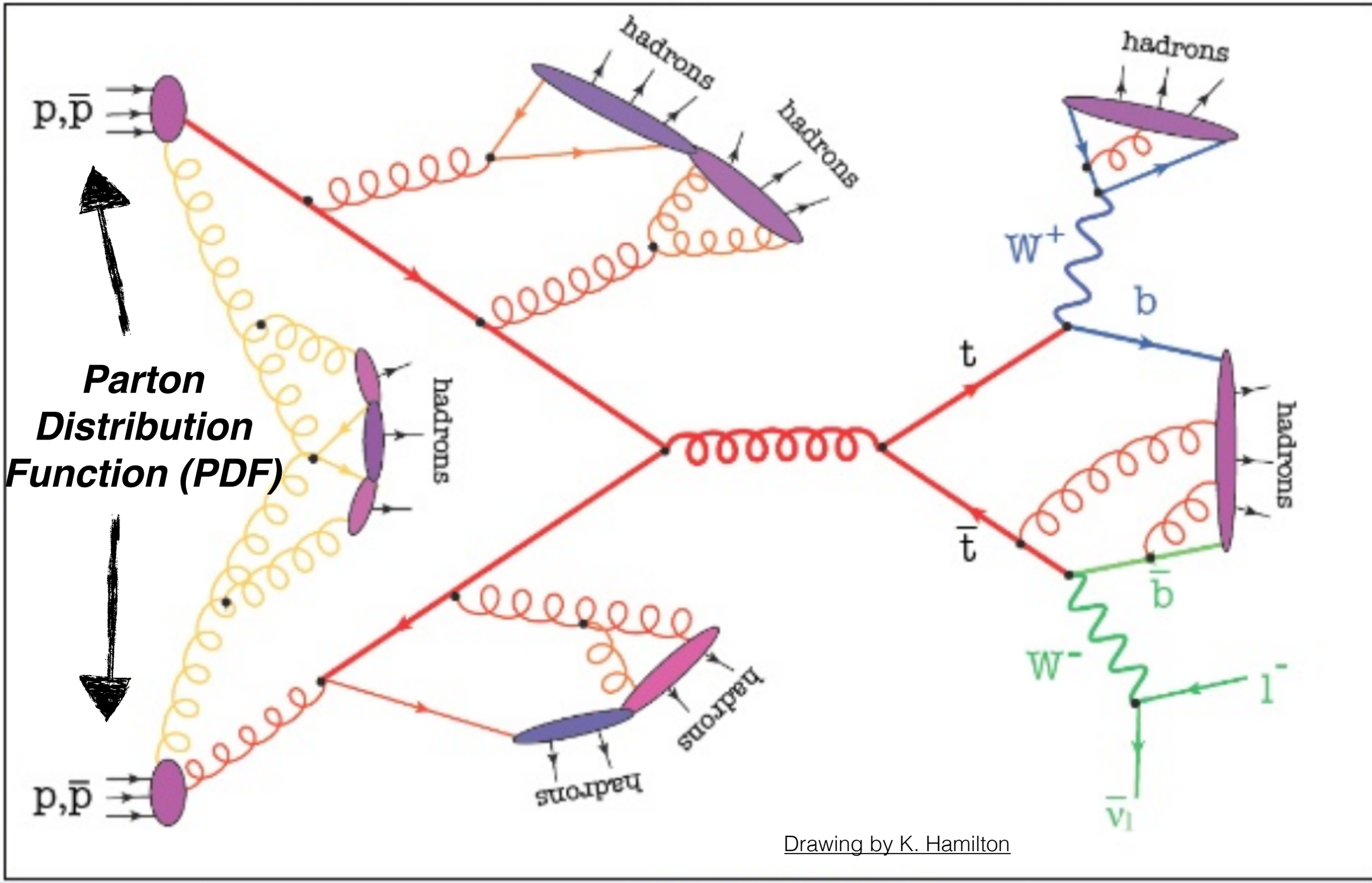
Probing perturbative QCD using electroweak bosons

Vasiliki Kouskoura
on behalf of the ATLAS Collaboration

BROOKHAVEN NATIONAL LABORATORY

ICNFP 2019

Perturbative QCD at the LHC



Drawing by K. Hamilton

Results at four centre-of-mass energies

- Measurement of inclusive isolated photon cross-section in pp collisions at **13 TeV** using 36 fb^{-1} of ATLAS data
- Measurement of the ratio of cross sections for inclusive isolated photon production in pp collisions at **13 TeV** and **8 TeV** with the ATLAS detector
- Measurement of the cross section and charge asymmetry of W bosons produced in pp collisions at **8 TeV** with the ATLAS detector
- Measurement of $W^{\pm}$ boson and Z boson production cross sections in pp collisions at **2.76 TeV** with the ATLAS detector
- Measurement of W and Z boson production in pp collisions at **5.02 TeV** with the ATLAS detector
- Measurement of the inclusive cross section for the production of jets in association with a Z boson in pp collisions at **8 TeV** with the ATLAS detector

Motivation

Why bother with perturbative QCD?

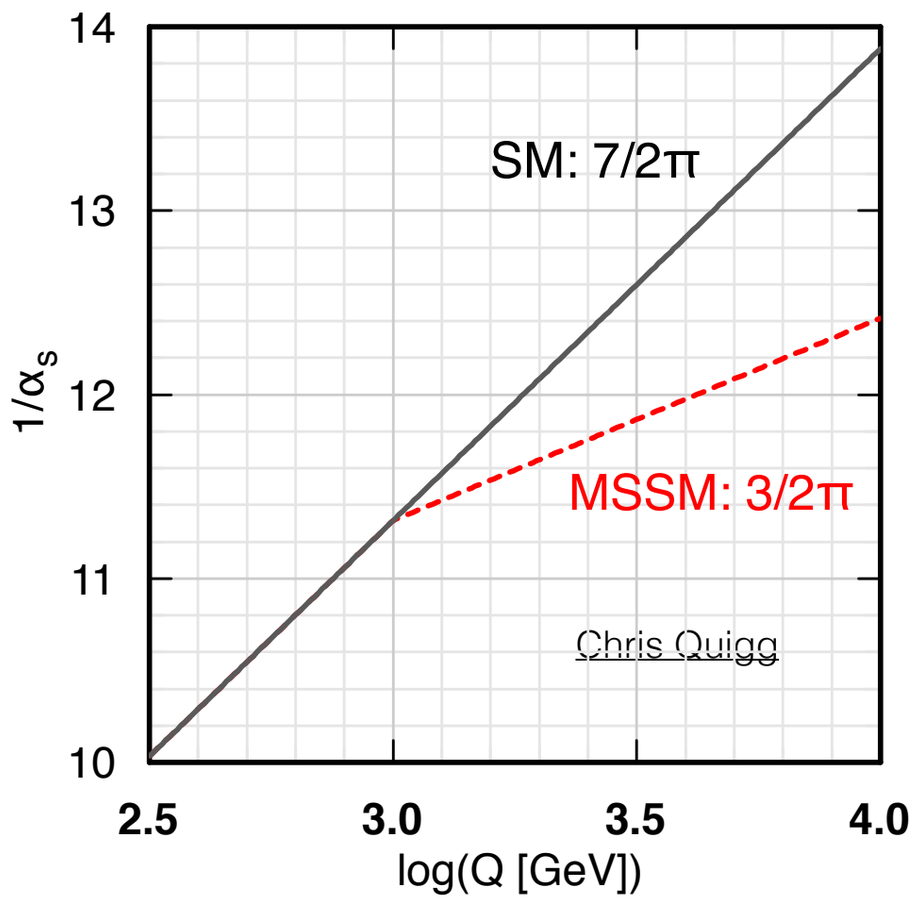
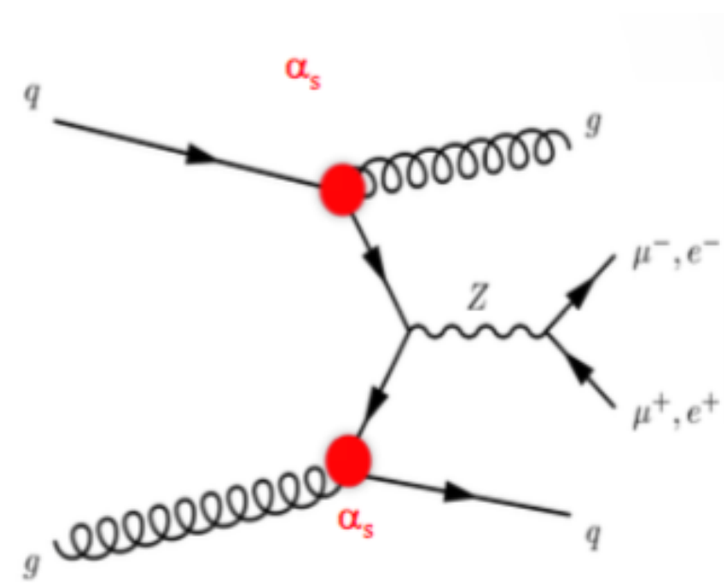


Fig. 1. Evolution of the strong coupling constant (displayed as $1/\alpha_s$) in the standard and supersymmetric versions of the SU(5) unified theory, for superpartners that become active at $Q = 1$ TeV.

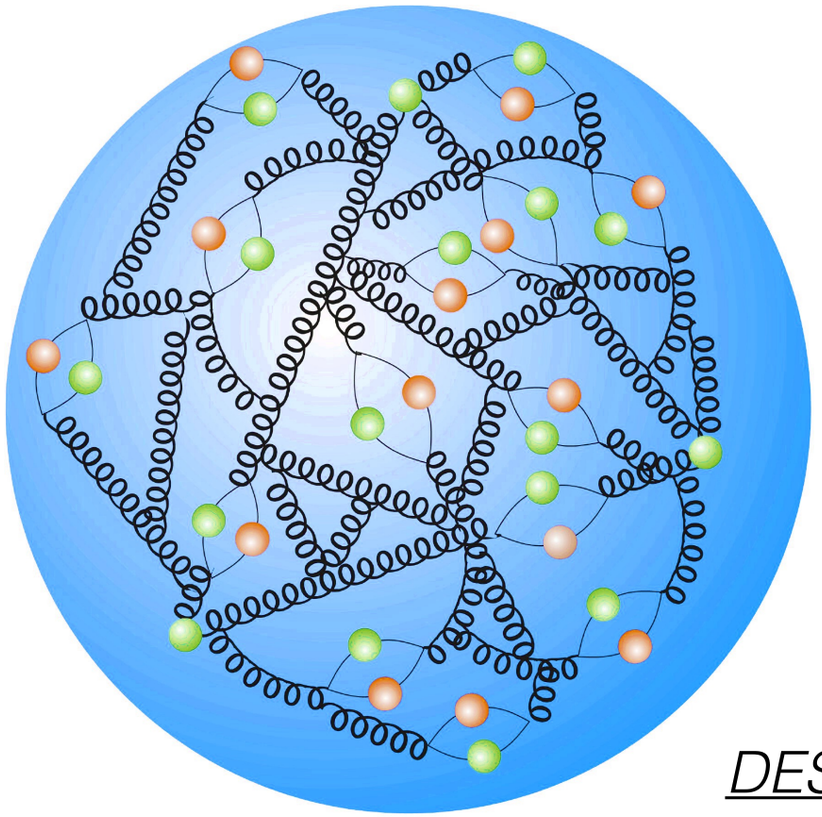
- Test the Renormalization Group Equation
  - New Physics contributions in the loops (not produced with on-shell particles) could cause deviations from the QCD prediction of the RGE

- Determination of strong coupling constant α_s



Motivation

Why bother with perturbative QCD?



DESY

valence and sea quarks inside a proton

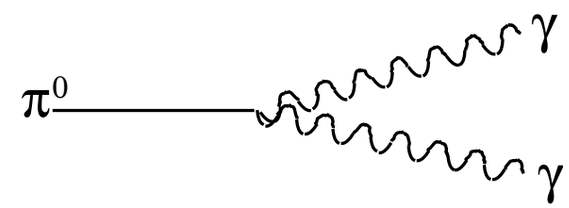
- Constraints on the parton distribution functions (PDFs) of the content of the proton
- Inclusive W/Z boson production is highly sensitive to valence quarks PDFs
- Inclusive photon production is more sensitive to gluon PDF

- Test of perturbative QCD predictions
  - Colorless photon used as a probe of the hard partonic interaction

- Description of background event kinematics for Monte Carlo validation that are used in several measurements (eg. Higgs production) and different searches for New Physics

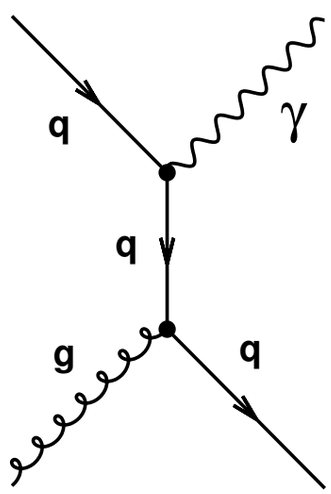
Inclusive isolated-photon cross section in pp collisions

- Prompt photon production provides a testing ground for pQCD
- Abundant photon production in hadron colliders, mostly from hadron decays



$$pp \to \gamma + \mathrm{X}$$

"direct" photon

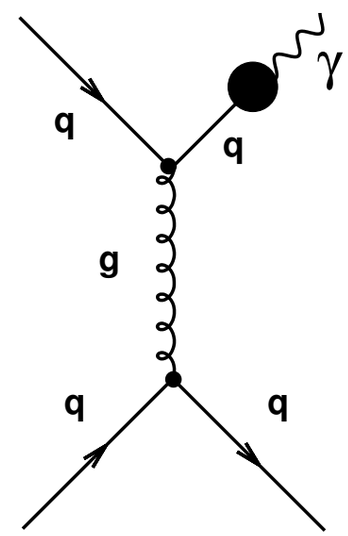


$qg \to q\gamma$

Matrix Element (ME)

non-distinguishable processes

"fragmentation" photon from high pT parton

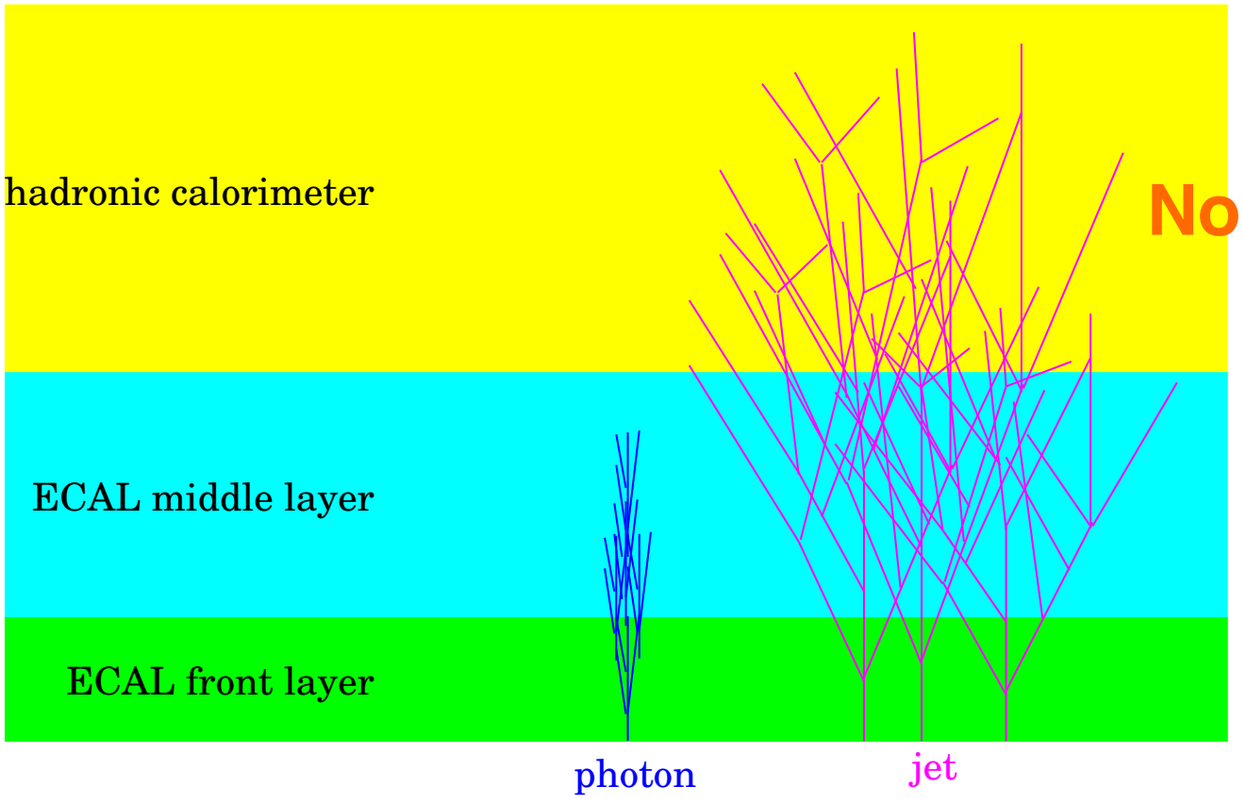


fragmentation/parton shower (PS)

sensitive to the gluon density in the proton at LO

Photon identification in the ATLAS detector

Jets vs photons

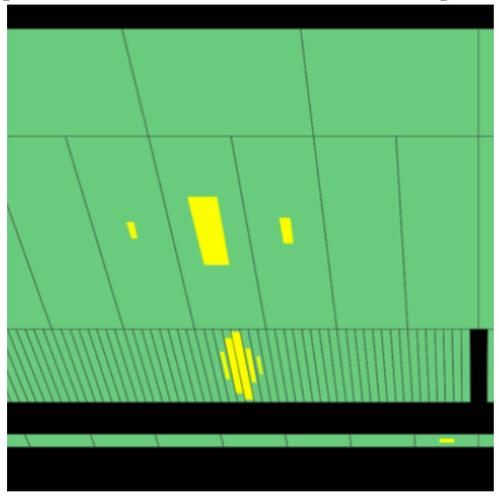


No energy leakage in Hadron Calorimeter

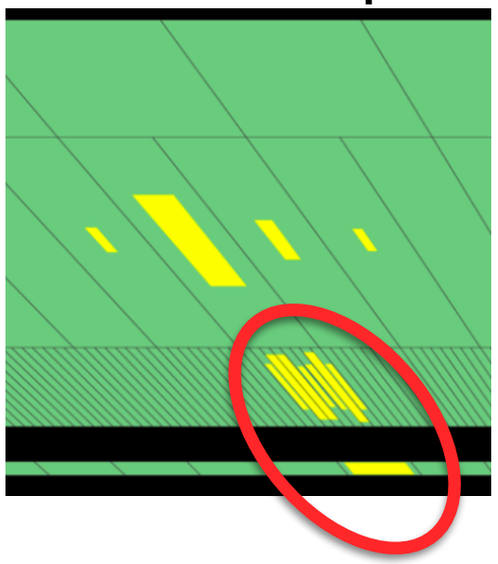
Narrow shower in ECAL 2nd layer

$\pi^0 \to \gamma\gamma$ vs photons

photon in strips



π^0 in strips

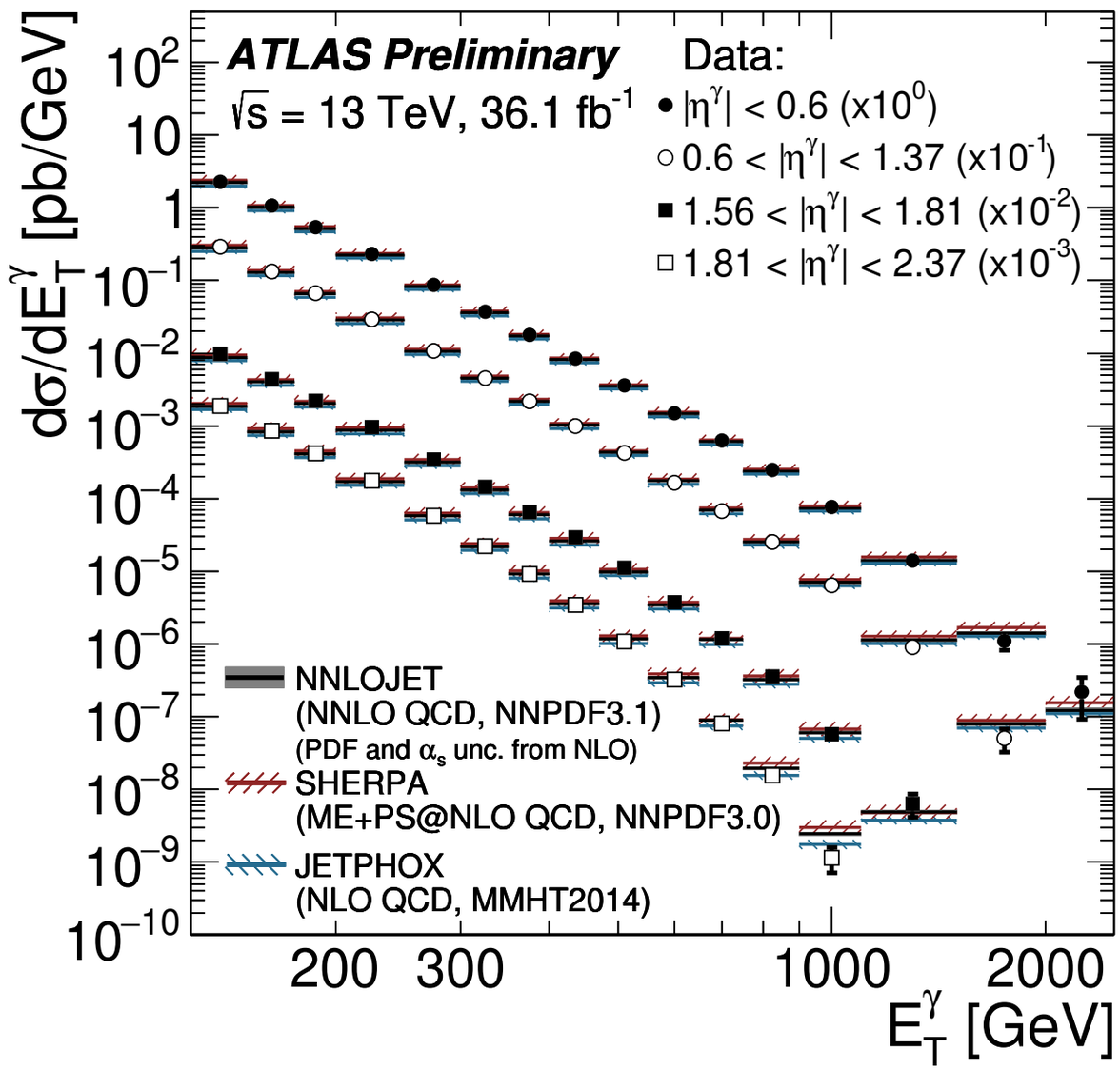


Narrow shower in 1st layer

Inclusive isolated-photon cross section in pp collisions

13 TeV, 36.1 fb^{-1}

arXiv:1908.02746

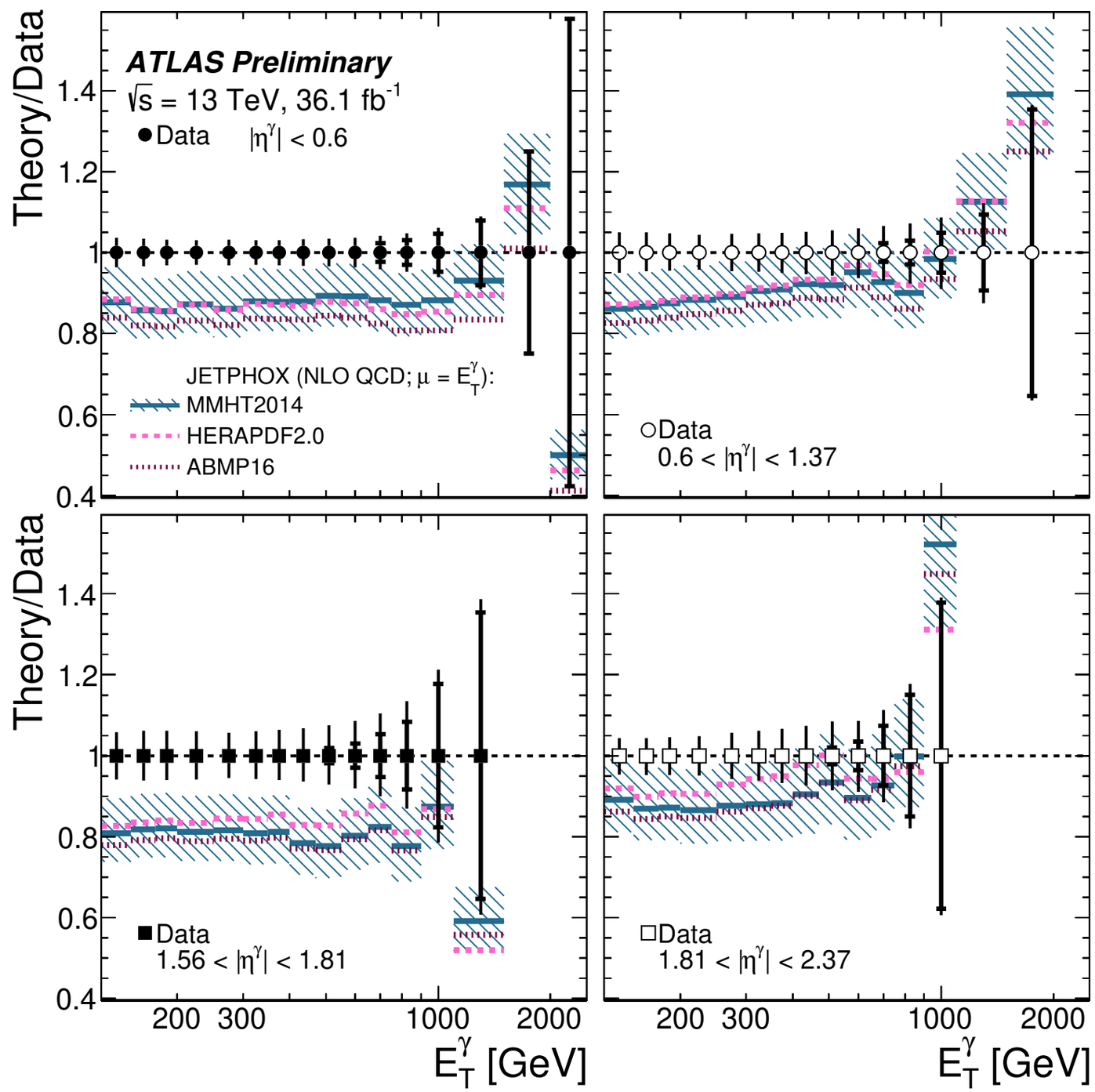


- Observed $d\sigma/dE_T^\gamma$ in 4 η regions
- Several theory models (hard process and PDFs)
  - JetPhox+MMHT2014
  - Sherpa NLO + NNPDF3.0
  - NNLOJet + NNPDF3.1
- scales $\mu_R=\mu_F=\mu_f=E_T^\gamma$

The inclusion of the ATLAS data leads to a reduction in the gluon density uncertainties

Inclusive isolated-photon cross section in pp collisions

13 TeV, 36.1 fb^{-1}



Ratio of NLO pQCD prediction of Jetphox with $\mu_R=\mu_F=\mu_f=E_T^\gamma$ using the MMHT2014 PDF set to the measured differential cross section for isolated-photon production as a function of E_T^γ in different regions of $|\eta^\gamma|$

Cross section ratios

JHEP 04 (2019) 093

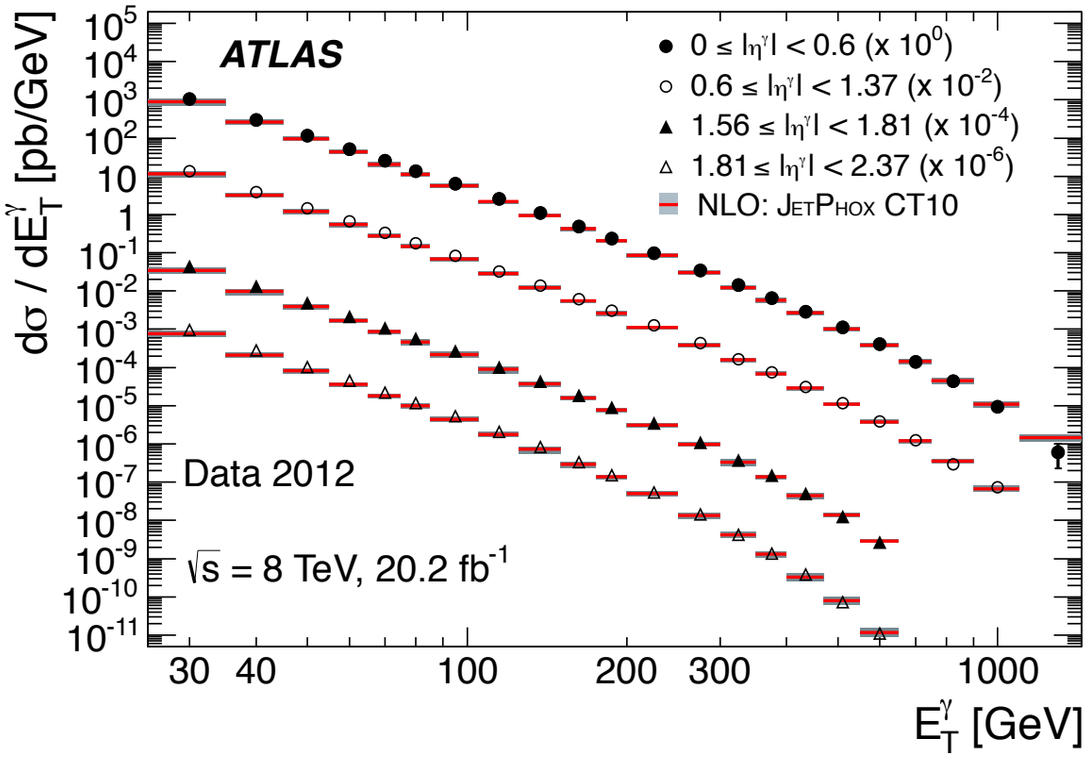
$$R^{\gamma} \equiv \frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}$$

and

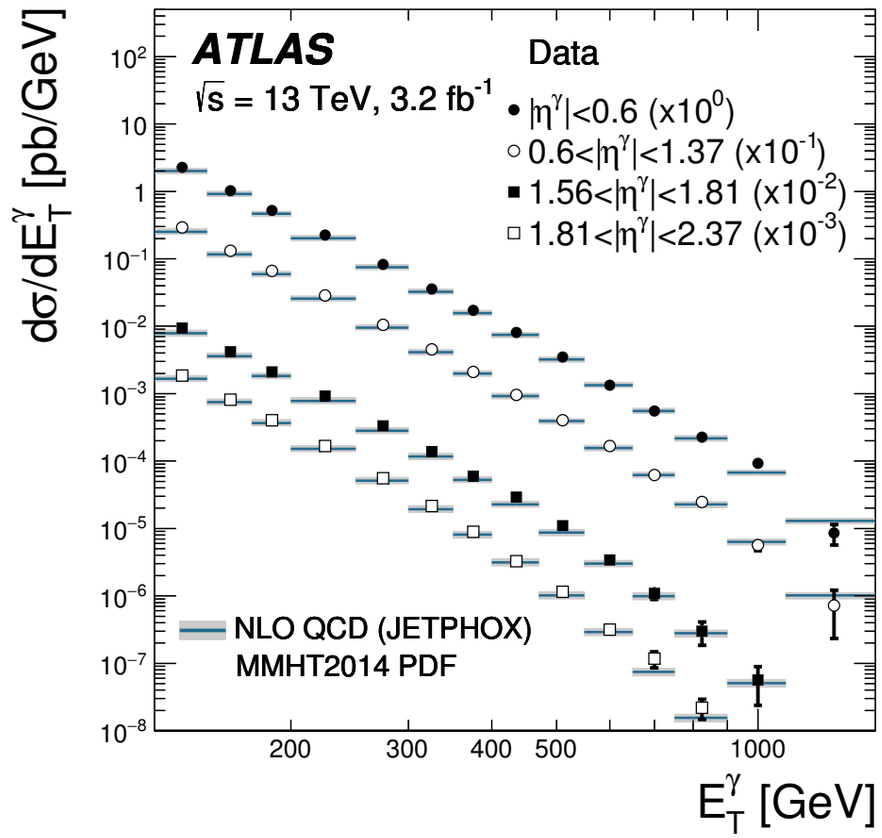
$$D^{\gamma/Z} \equiv \left(\frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}\right) \Big/ \left(\frac{\sigma_{Z,fid}^{13\,TeV}}{\sigma_{Z,fid}^{8\,TeV}}\right)$$

Inclusive cross section ratios between 13 and 8 TeV

JHEP 06 (2016) 005



Phys. Lett. B 770 (2017) 473

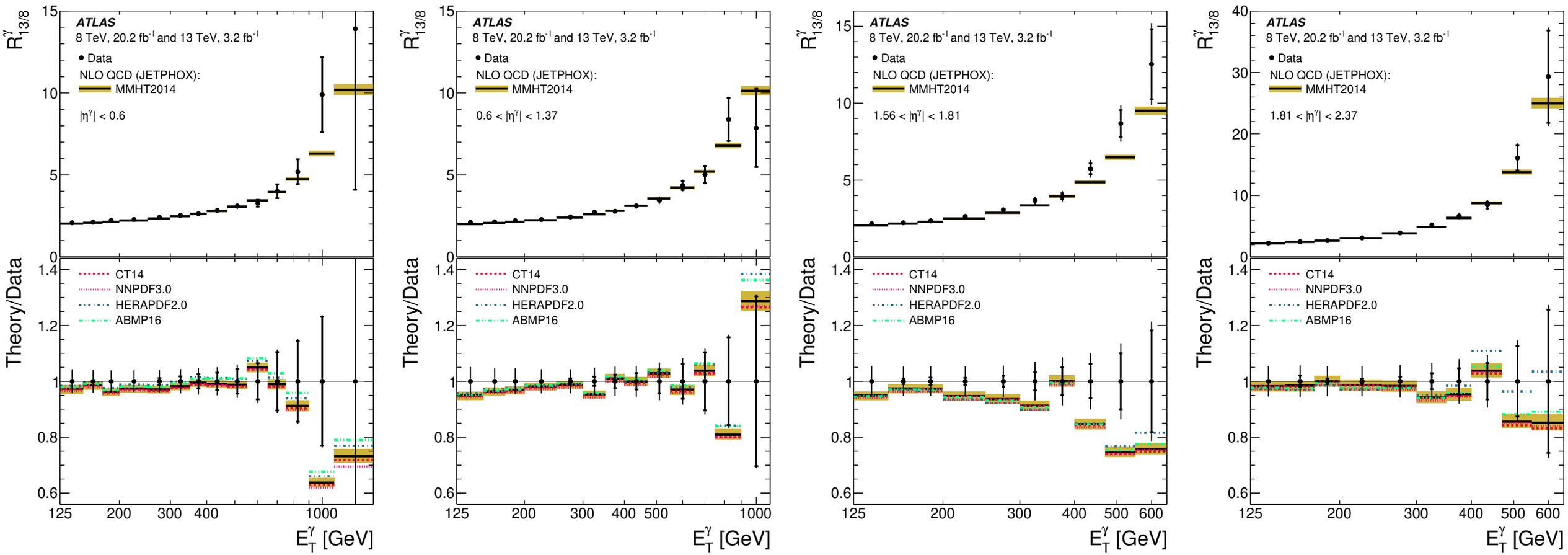


- Comparisons to NLO QCD limited by the size of the theoretical uncertainties (typically larger than the experimental uncertainties)
- More stringent test of theory through cross section ratios at different √s
  - ☑ Test the evolution as a function of √s
- Systematic uncertainties are correlated and would reduce in the ratio
- Luminosity uncertainty - uncorrelated between √s plays an important role

Results on R^γ

JHEP 04 (2019) 093

Top plots: $R^\gamma \equiv \frac{d\sigma_\gamma^{13\,TeV}}{d\sigma_\gamma^{8\,TeV}}$ — measurements and theory predictions *compared to NLO QCD calculations*



Bottom plots: $\frac{(R^\gamma)^{theory}}{(R^\gamma)^{meas}}$ for different PDF sets

CT14
NNPDF3.0
HERAPDF2.0
ABMP16

NLO predictions agree with the measured within the reduced theoretical uncertainties (2-4%)

Results on double ratios $D^{\gamma/Z}$

- Reduce further the uncertainty by performing measurement of double ratios

$$D^{\gamma/Z}_{13/8} = \frac{R^{\gamma}_{13/8}(\mathrm{E}^{\gamma}_{\mathrm{T}})}{\sigma^{\mathrm{fid}}_{Z}(13\ \mathrm{TeV})/\sigma^{\mathrm{fid}}_{Z}(8\ \mathrm{TeV})}$$

- Double ratios with another final state benefit from the cancelation of the luminosity uncertainty … ***but…***

Note: $R^{\gamma} \equiv \frac{d\sigma^{13\,TeV}_{\gamma}}{d\sigma^{8\,TeV}_{\gamma}}$ is a function of E^{γ}_{T} in several regions of $|\eta^{\gamma}|$

$R^{Z} \equiv \frac{\sigma^{13\,TeV}_{Z,fid}}{\sigma^{8\,TeV}_{Z,fid}}$ is a single number, measured as $R^{Z} = 1.537 \pm 0.001(\mathrm{stat}) \pm 0.010(\mathrm{syst}) \pm 0.044(\mathrm{lumi})$

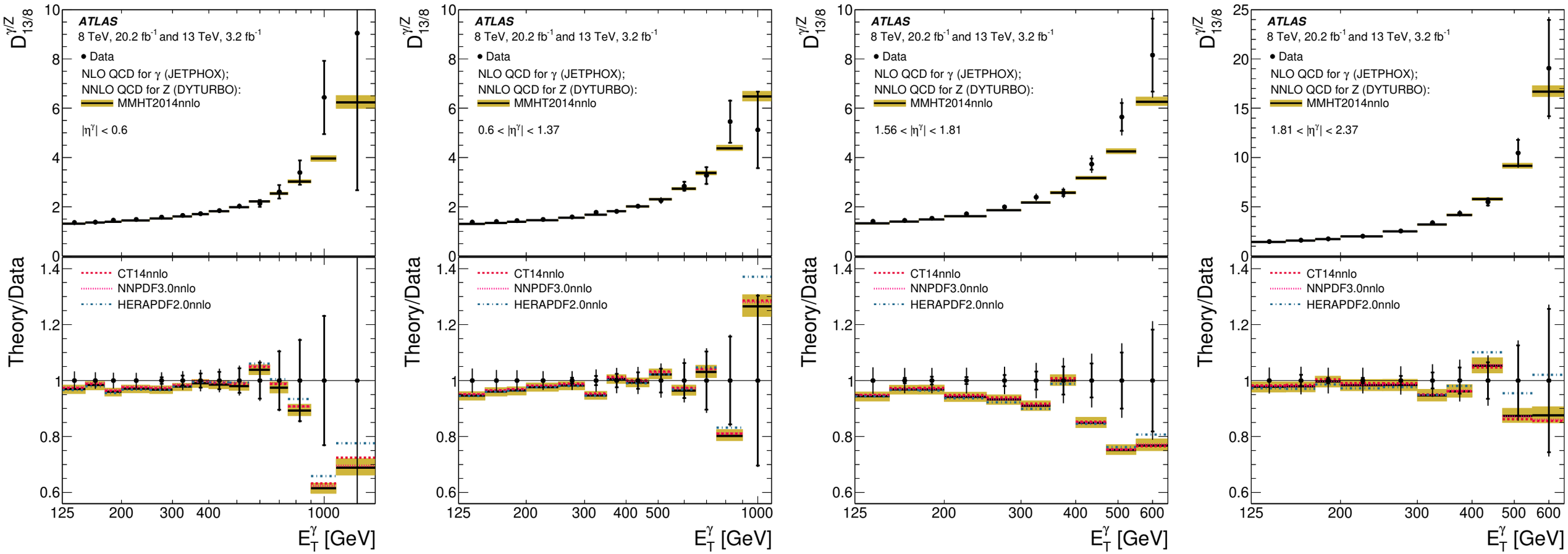
ATLAS measurement ***JHEP 02 (2017) 117***

Results on double ratios $D^{\gamma/Z}$

JHEP 04 (2019) 093

Top plots: $D^{\gamma/Z} \equiv \frac{R^{\gamma}}{R^{Z}}$ — measurements and theory predictions

compared to NLO QCD calculations



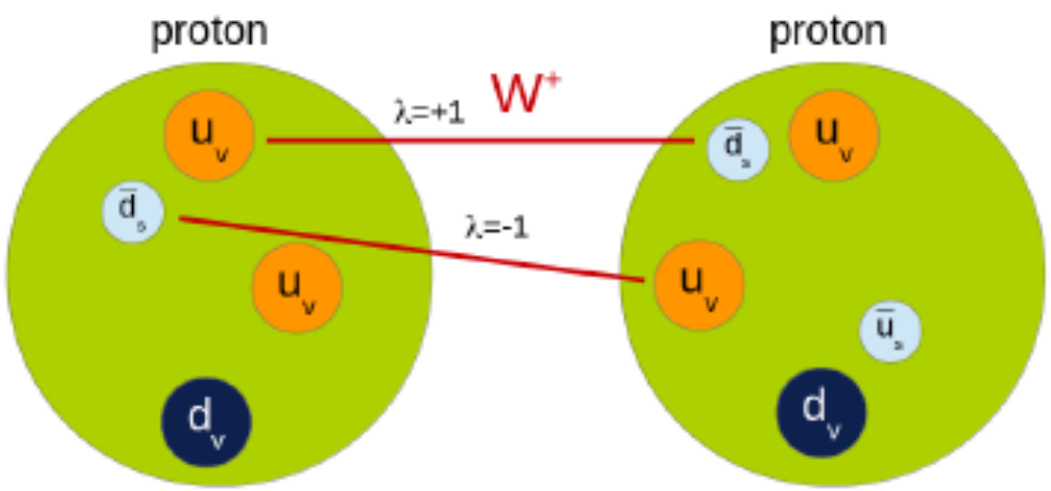
Bottom plots: $\frac{(D^{\gamma/Z})^{theory}}{(D^{\gamma/Z})^{meas}}$ for different PDF sets

CT14nnlo
NNPDF3.0nnlo
HERAPDF2.0nnlo

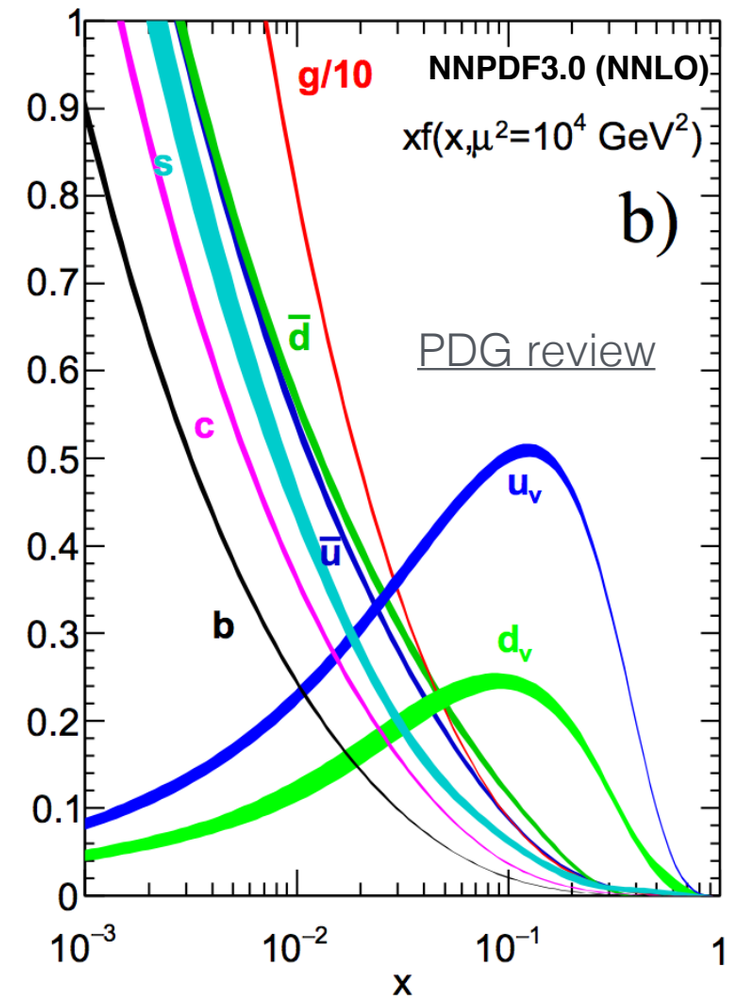
NLO predictions agree with the measured within the reduced theoretical uncertainties (2-4%)

W boson cross section and charge asymmetry

- W-boson production at LHC is highly sensitive to valence quarks PDFs



main production mechanism at the LHC



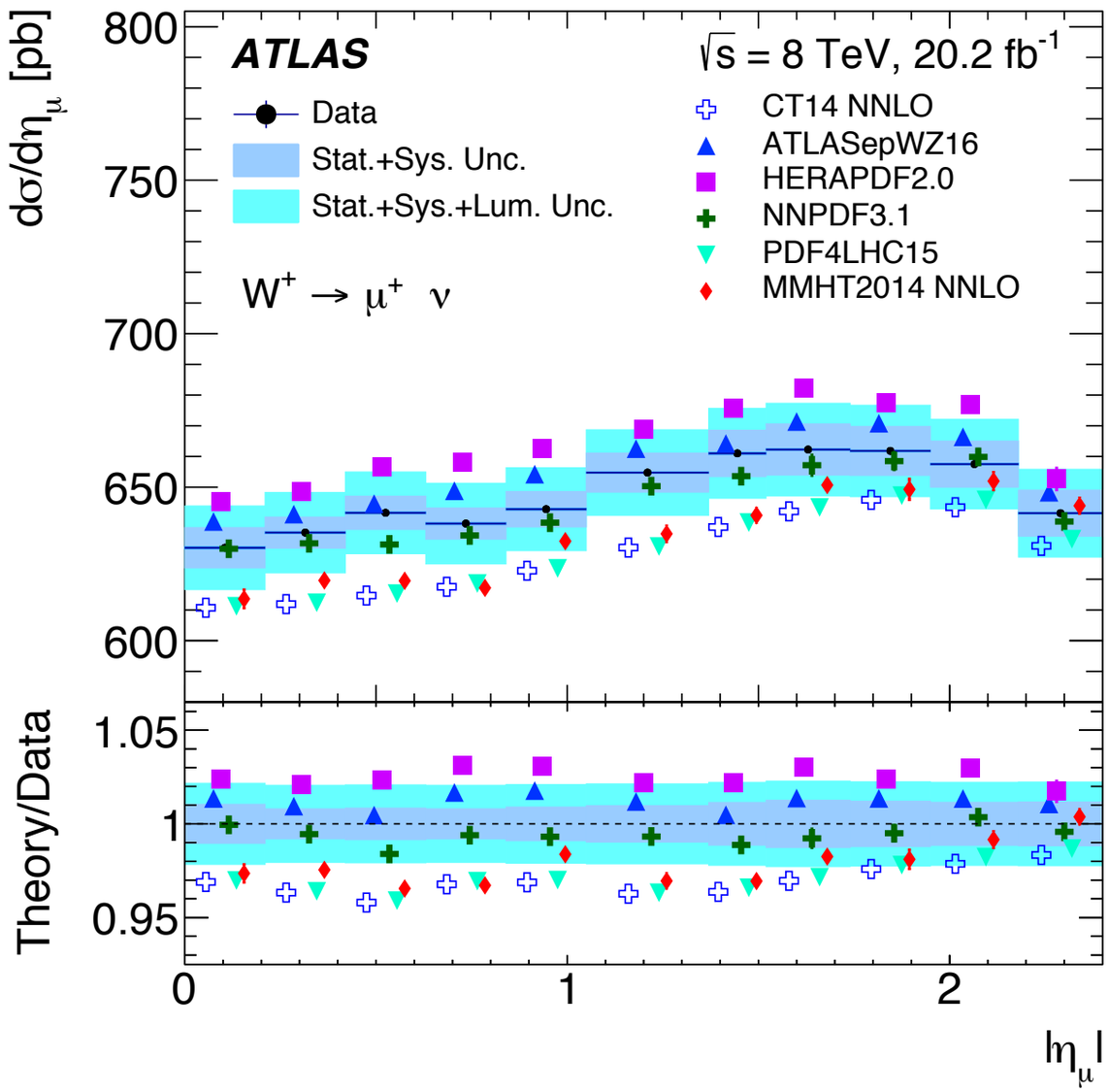
W bosons are preferentially produced with a boost in the direction of the incoming valence quark

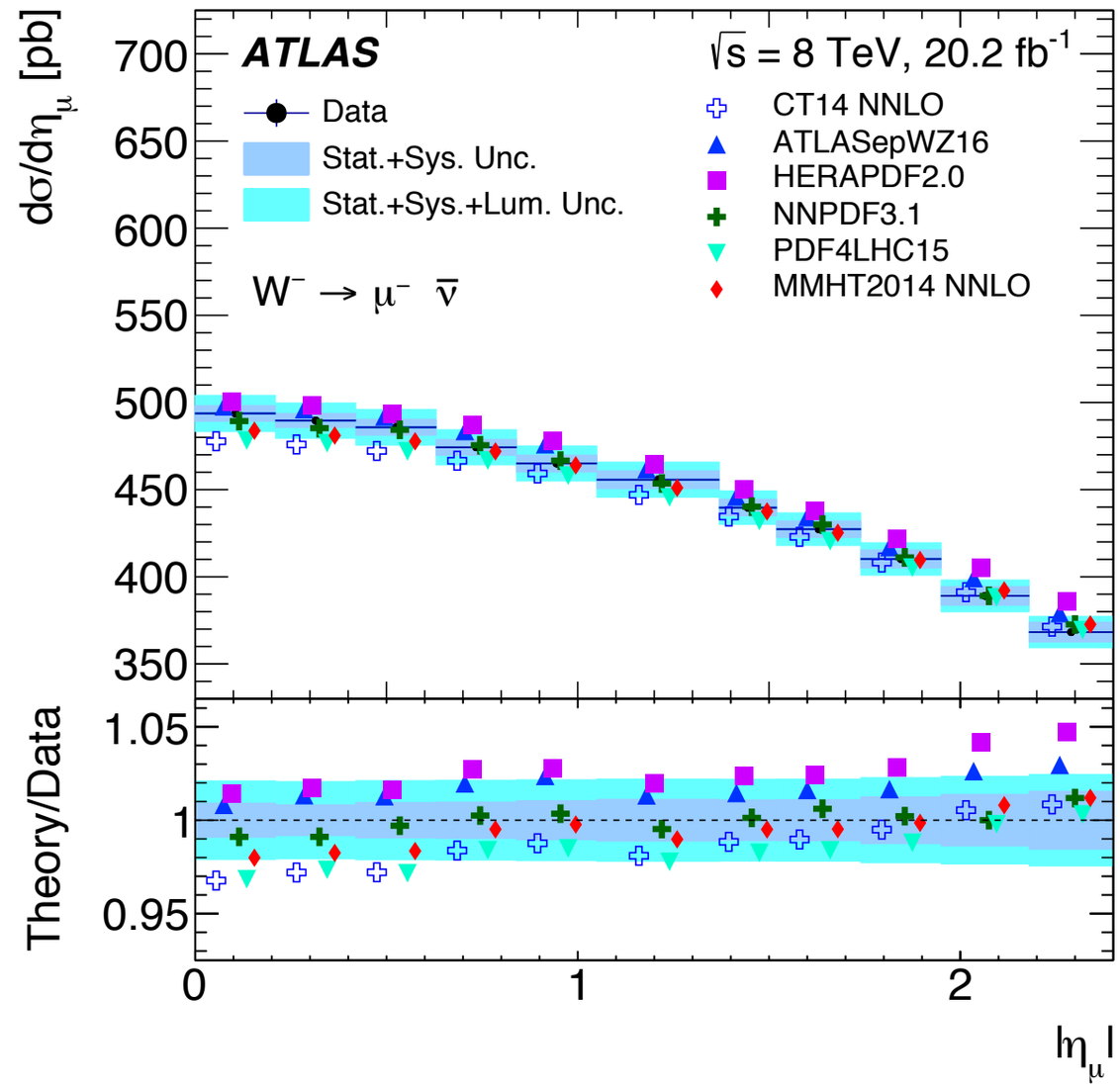
- The difference between u_v and d_v yields an asymmetry between W^+ and W^- production which is a function of rapidity y
- ATLAS provides measurements of differential cross sections as a function of y and for various $\sqrt{s}$ pp collisions to illuminate further our understanding on PDFs

W boson cross section and charge asymmetry

8 TeV, 20 fb^{-1}

arXiv:1904.05631

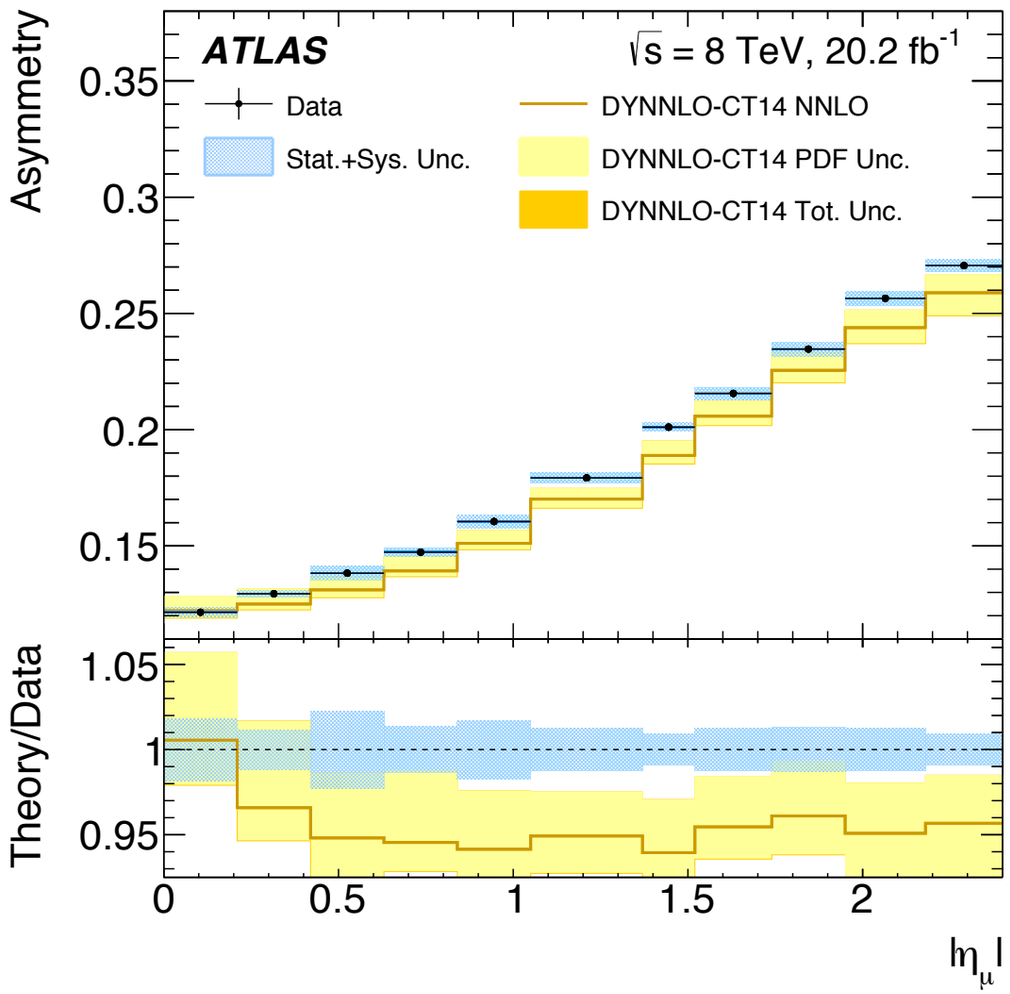


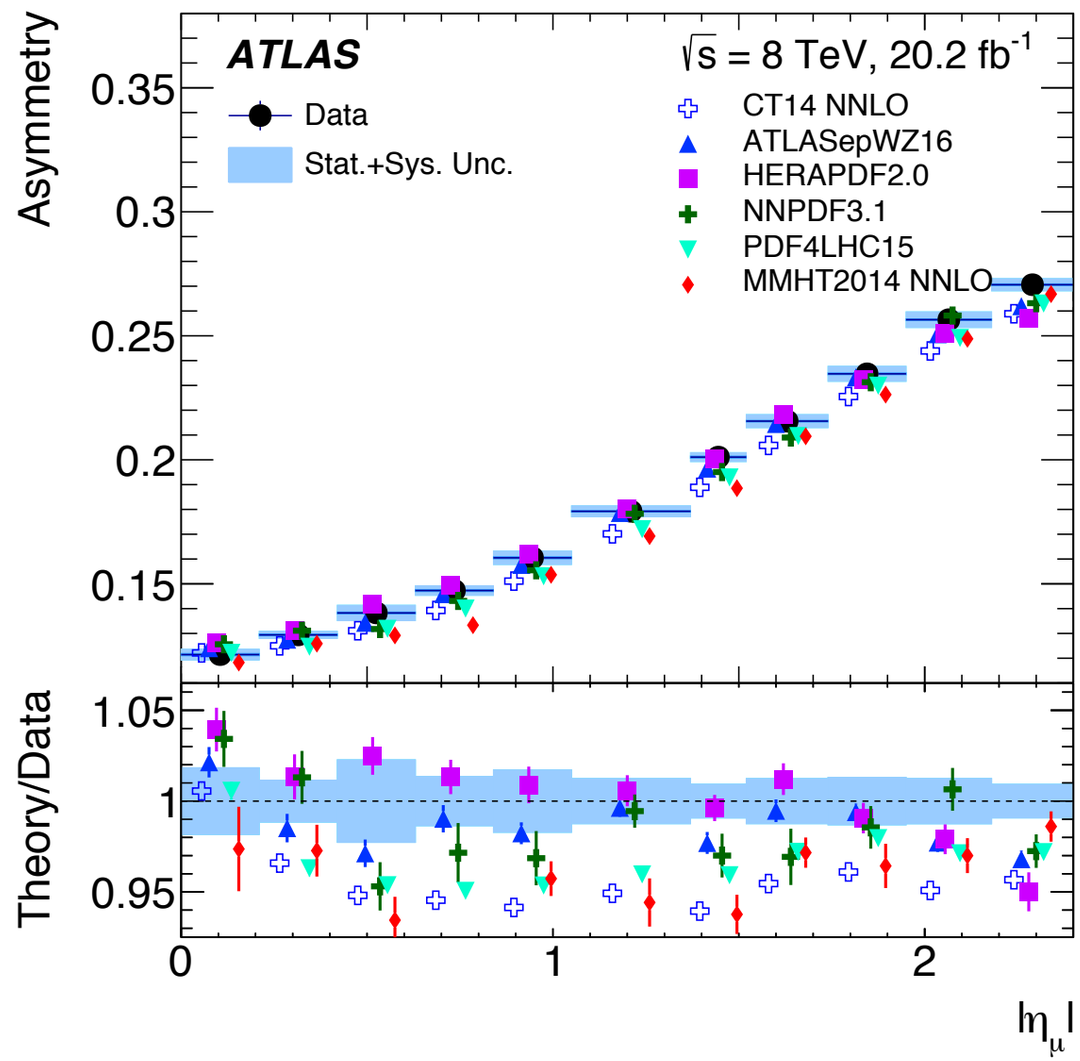


- W^+ and W^- fiducial cross sections, differential in muon pseudorapidity
- Data compared with the nominal predictions based on six different PDF sets. The statistical uncertainties of the DYNNLO predictions are indicated by error bars

W boson cross section and charge asymmetry

8 TeV, 20 fb^{-1}





$$A_\ell = \frac{\mathrm{d}N_{W^+\to\ell^+\nu_\ell}/\mathrm{d}\eta_\ell \;-\; \mathrm{d}N_{W^-\to\ell^-\bar{\nu}_\ell}/\mathrm{d}\eta_\ell}{\mathrm{d}N_{W^+\to\ell^+\nu_\ell}/\mathrm{d}\eta_\ell \;+\; \mathrm{d}N_{W^-\to\ell^-\bar{\nu}_\ell}/\mathrm{d}\eta_\ell}$$

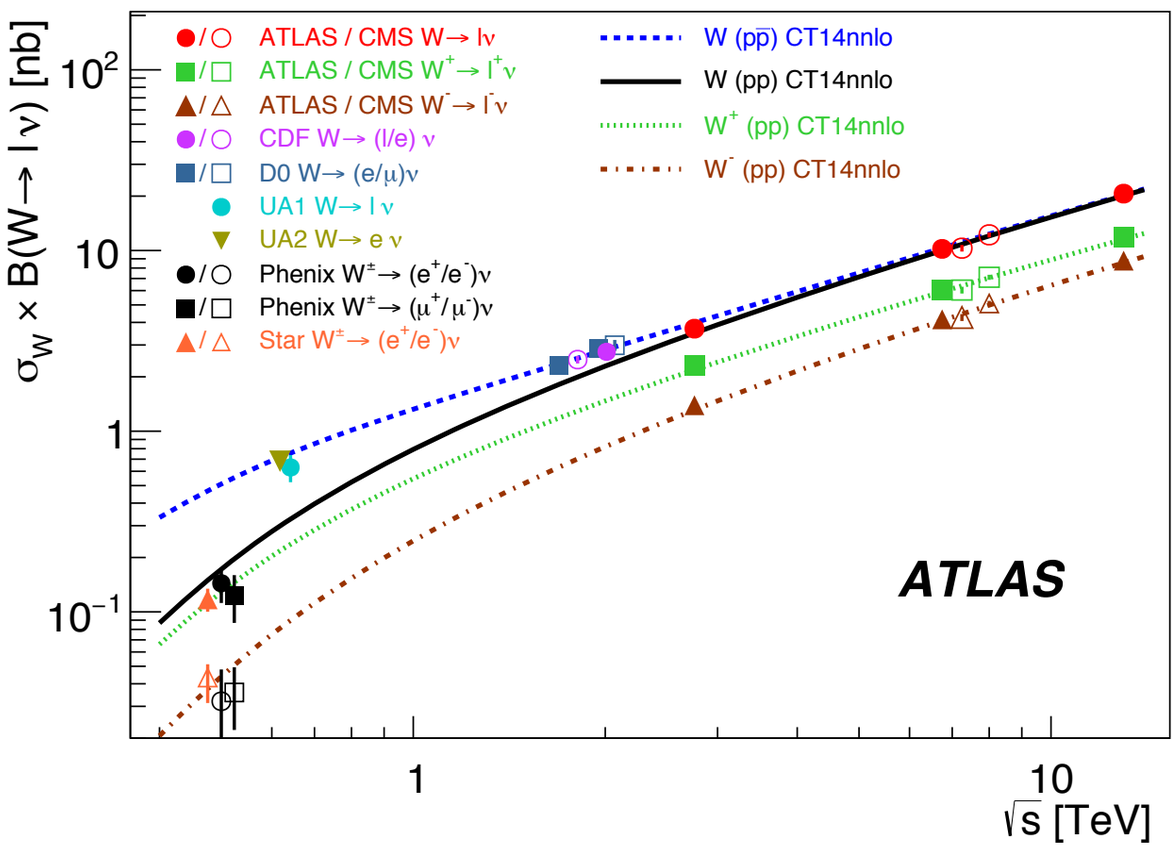
- W boson charge asymmetry as a function of absolute muon pseudo-rapidity. Data are compared with the prediction from DYNNLO in which the CT14 NNLO PDF set is used and with a selection of PDFs
- Result gives stronger support of ATLASepWZ16, consistent discrepancy between W^+ and W^- for HERAPDF

W/Z boson cross section and W charge asymmetry

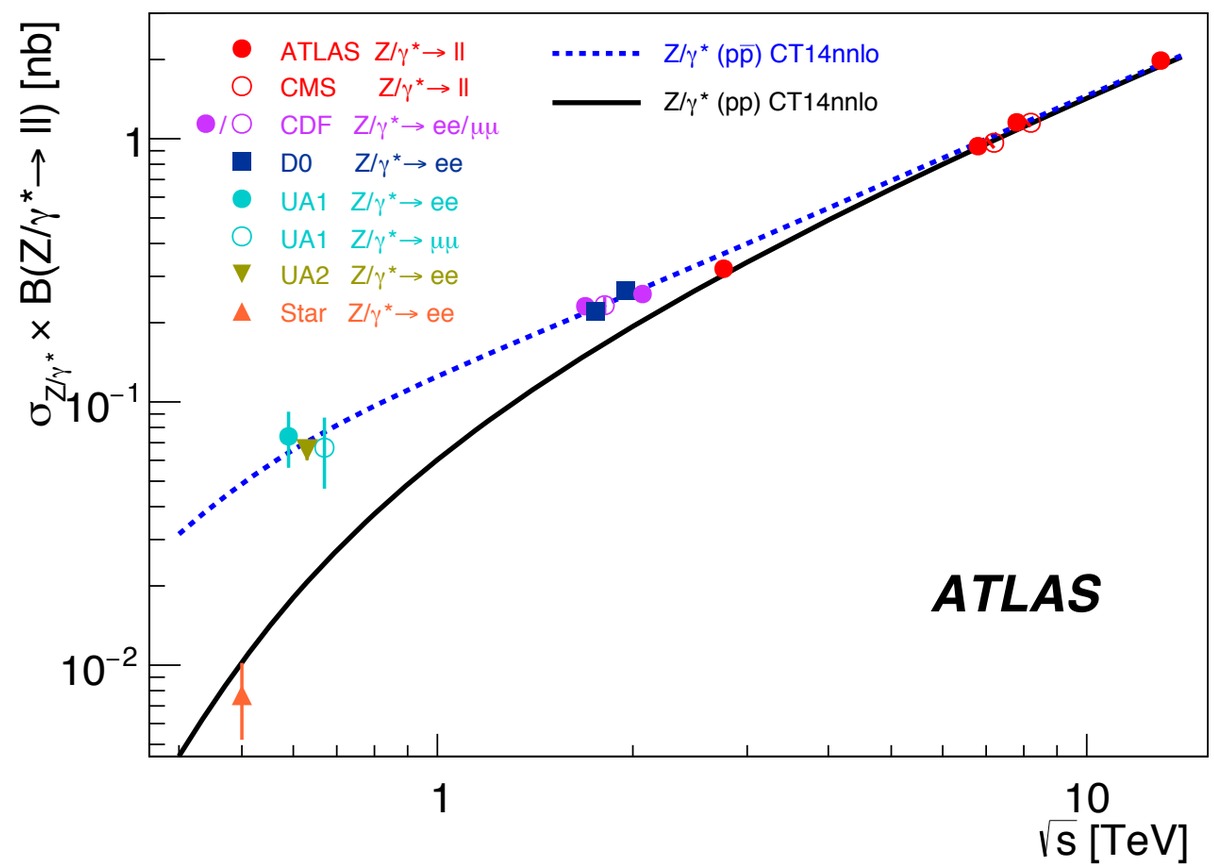
arXiv:1907.03567

2.76 TeV, 4 pb^{-1}

- σW × B (W → ℓ ν) for W+ bosons, W- bosons and their sum



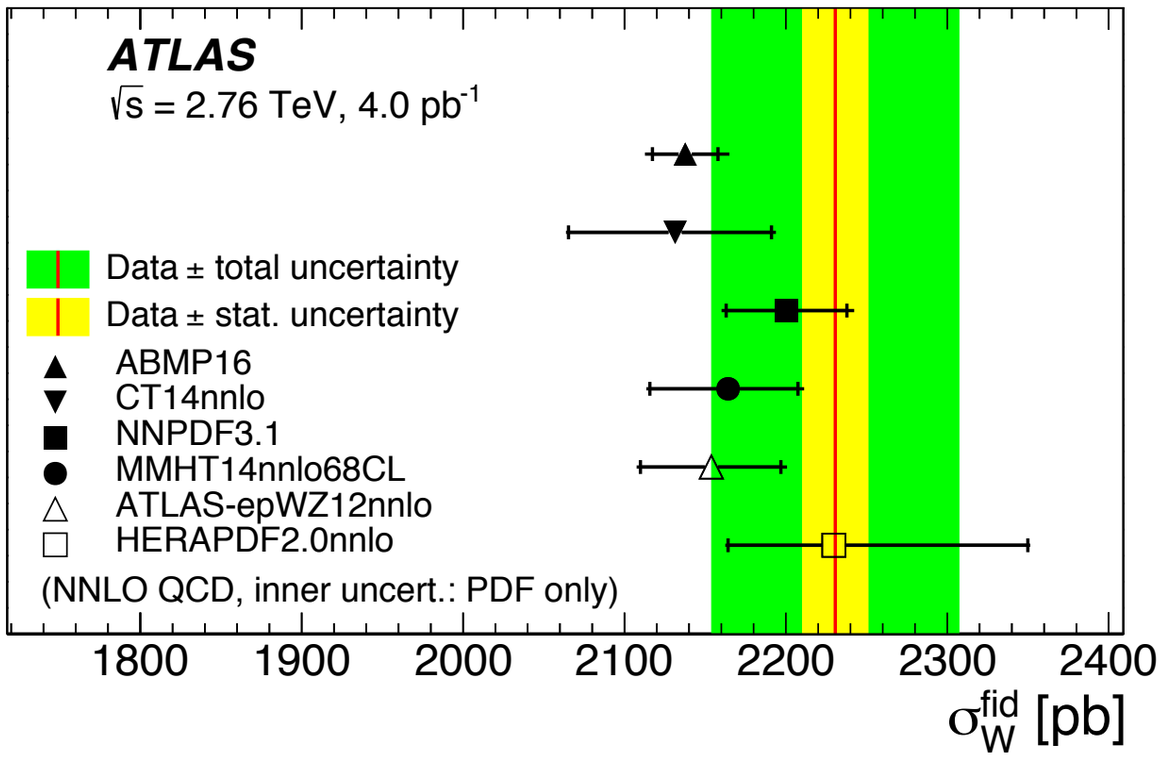
- σZ/γ* × B(Z/γ* → ℓ ℓ)



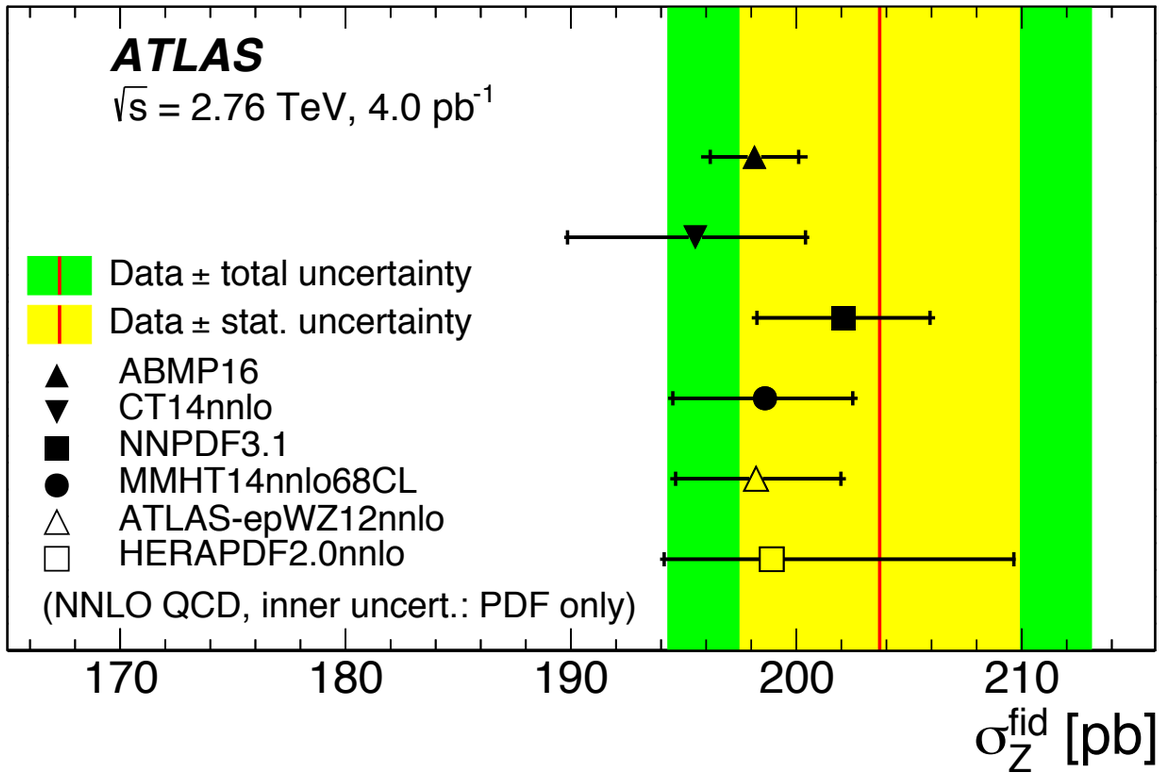
- Theoretical calculations are performed at NNLO in QCD using DYNNLO 1.5 and FEWZ 3.1. The theoretical uncertainties are not shown.

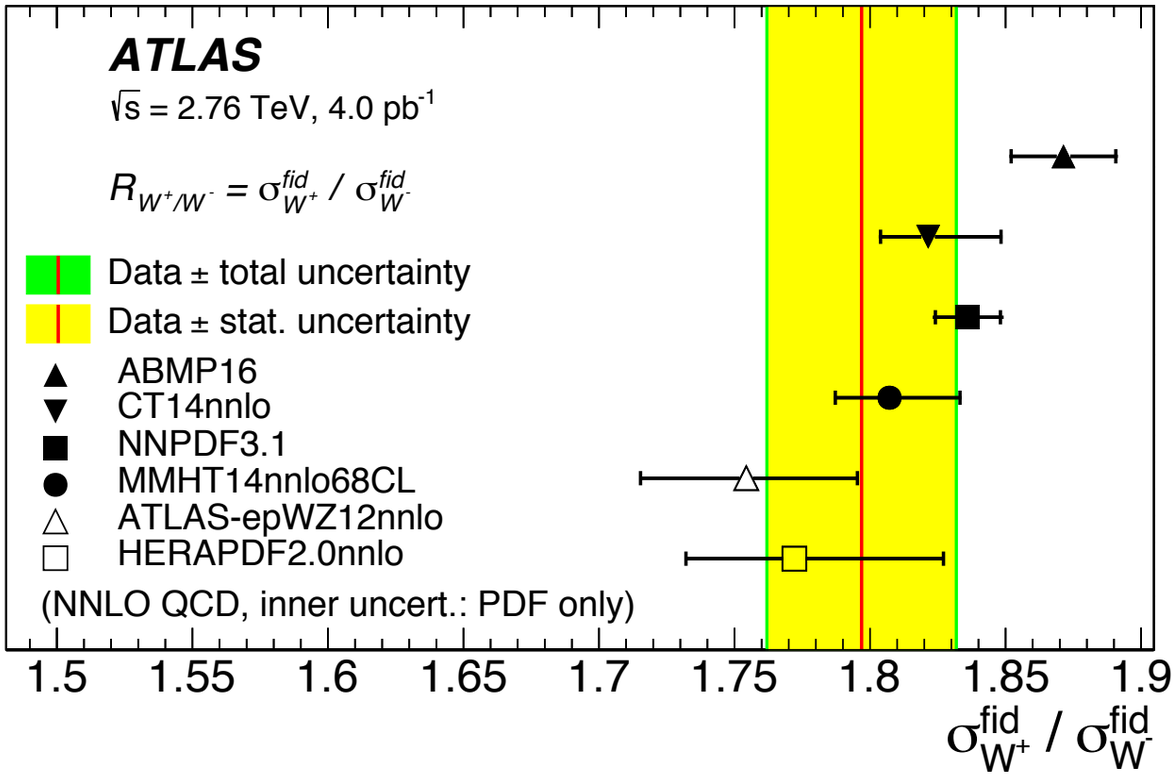
W/Z boson cross section and W charge asymmetry

2.76 TeV, 4 pb^{-1}



- Theoretical calculations are performed at NNLO in QCD with different PDFs
- Systematic uncertainties are reduced with the ratios

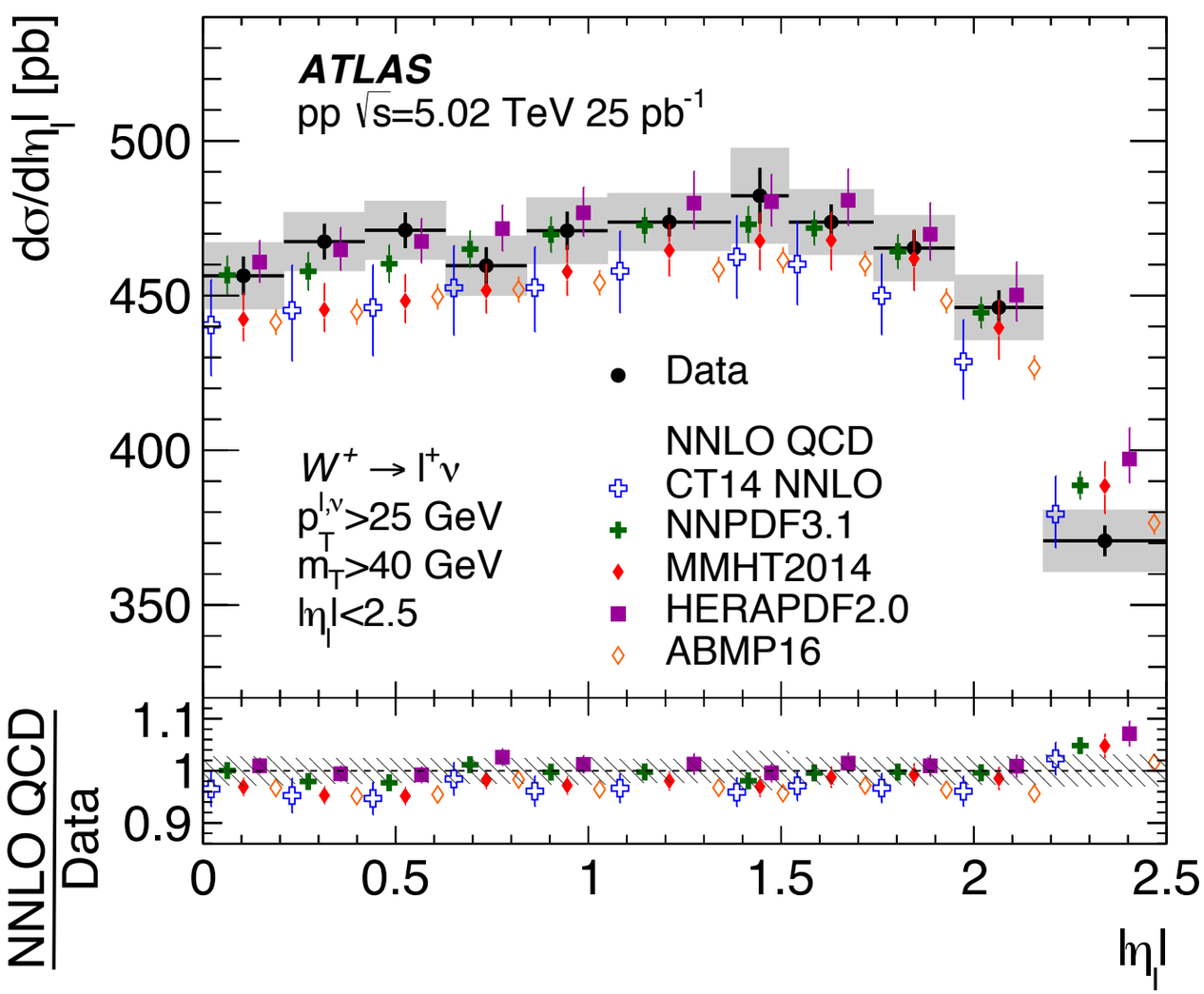


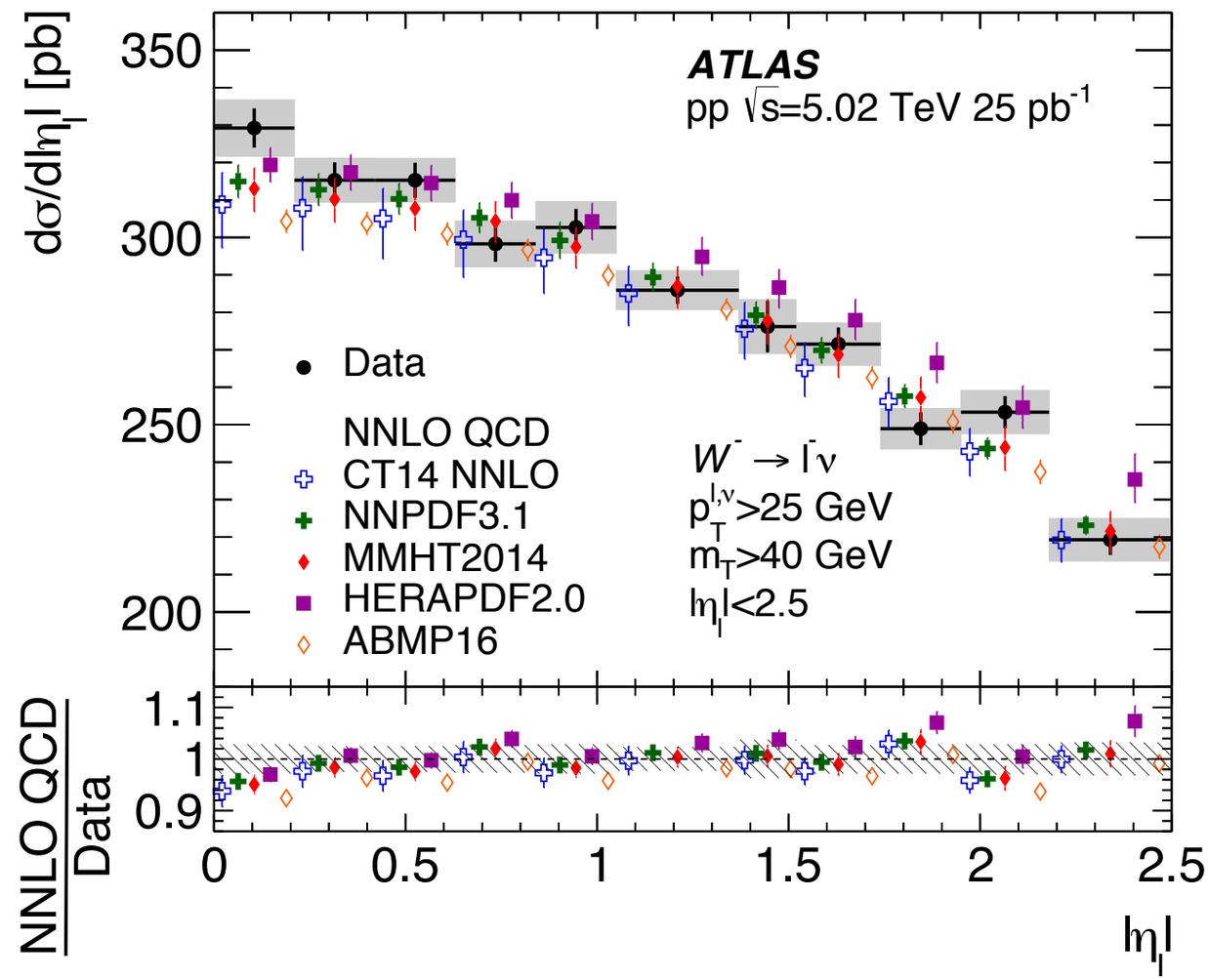


W/Z boson cross section and W charge asymmetry

Eur. Phys. J. C 79 (2019) 128

5.02 TeV, 25 pb^{-1}





Fiducial integrated and differential cross sections measured in *pp* collisions serve as a reference for Pb+Pb interactions.

Combined integrated fiducial cross sections:

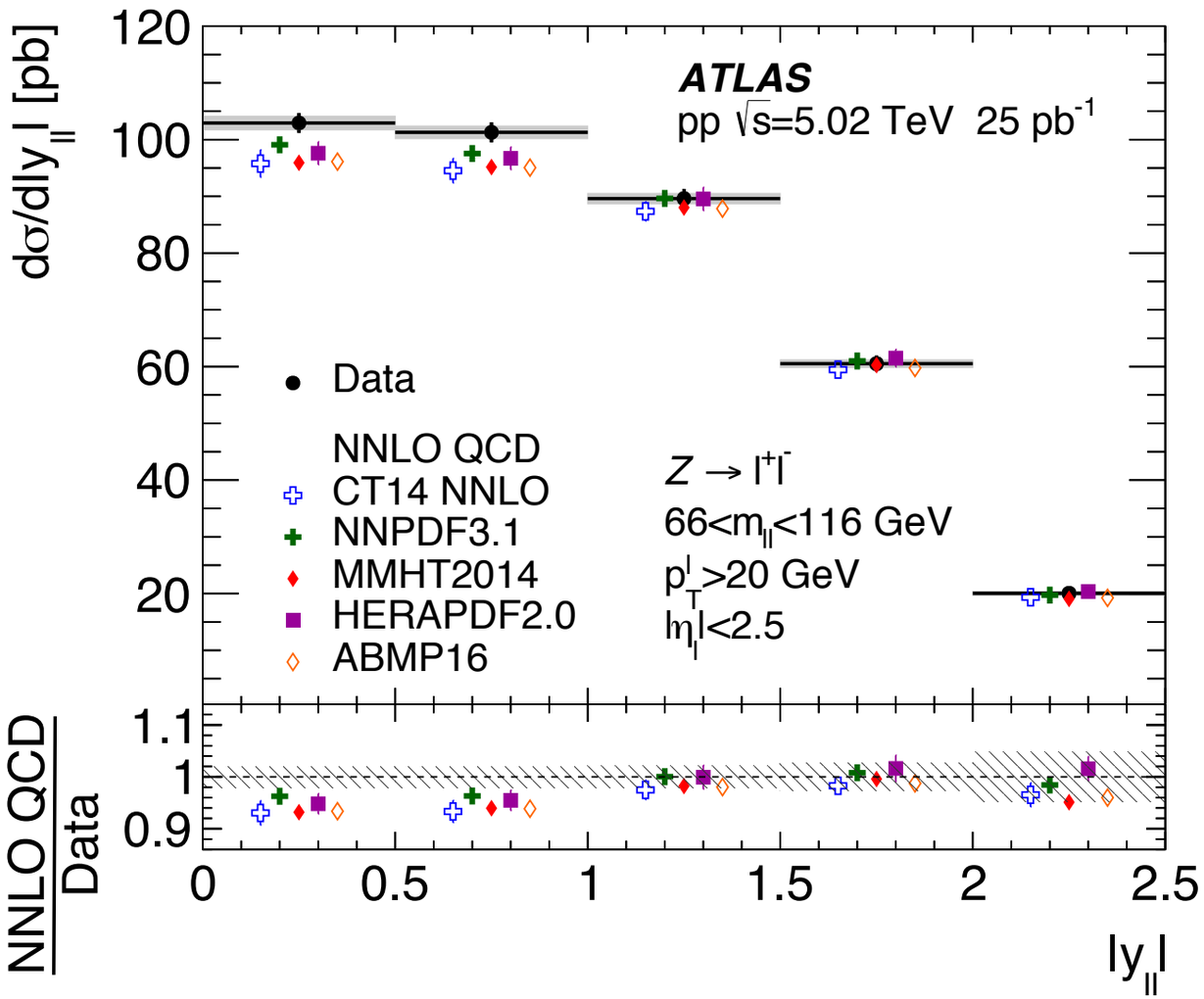
W^+ : 2266 ± 9 (stat) ± 29 (sys) ± 43 (lumi) pb

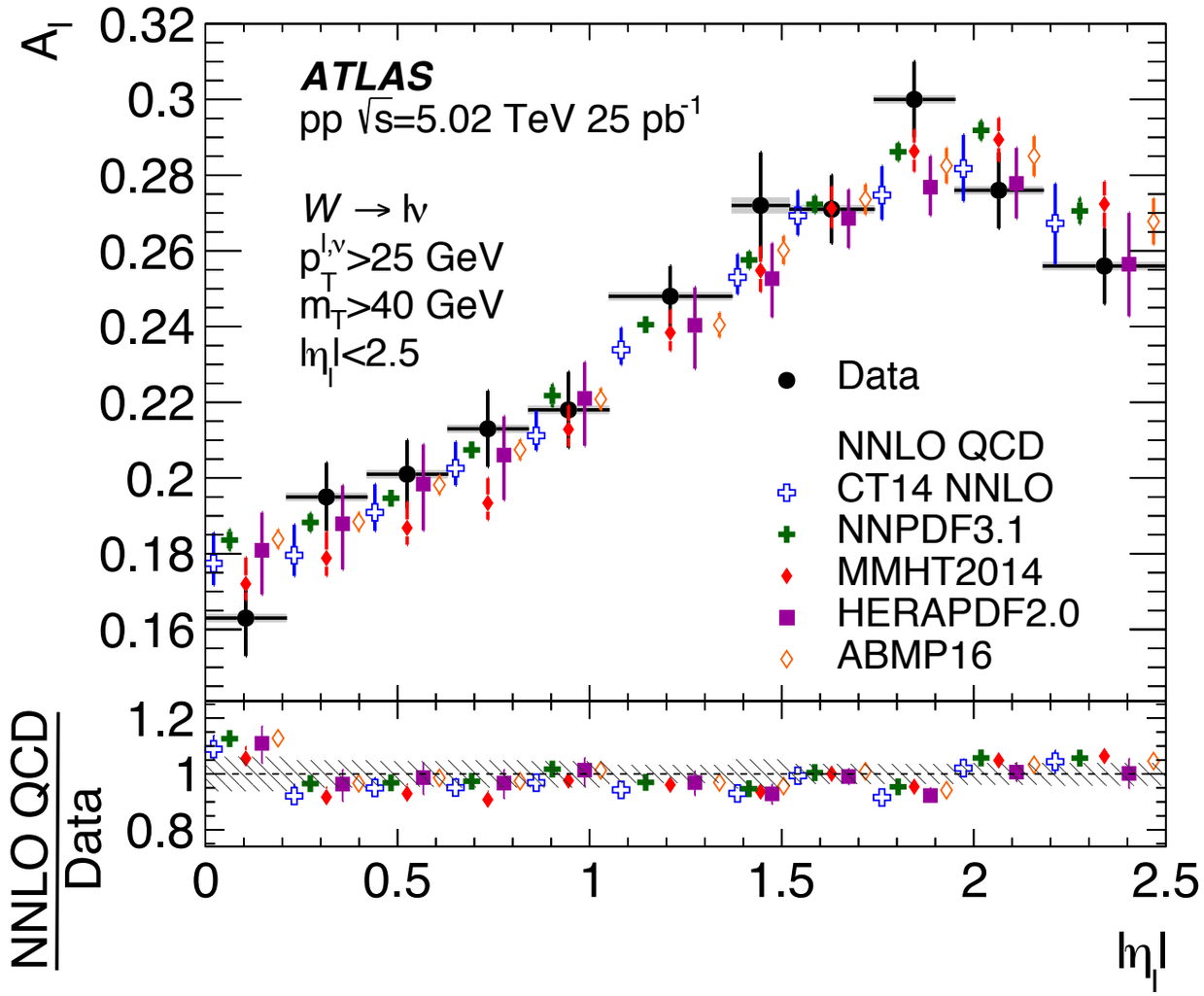
W^- : 1401 ± 7 (stat) ± 18 (sys) ± 27 (lumi) pb

Z : 374.5 ± 3.4 (stat) ± 3.6 (sys) ± 7.0 (lumi) pb

W/Z boson cross section and W charge asymmetry

5.02 TeV, 25 pb^{-1}





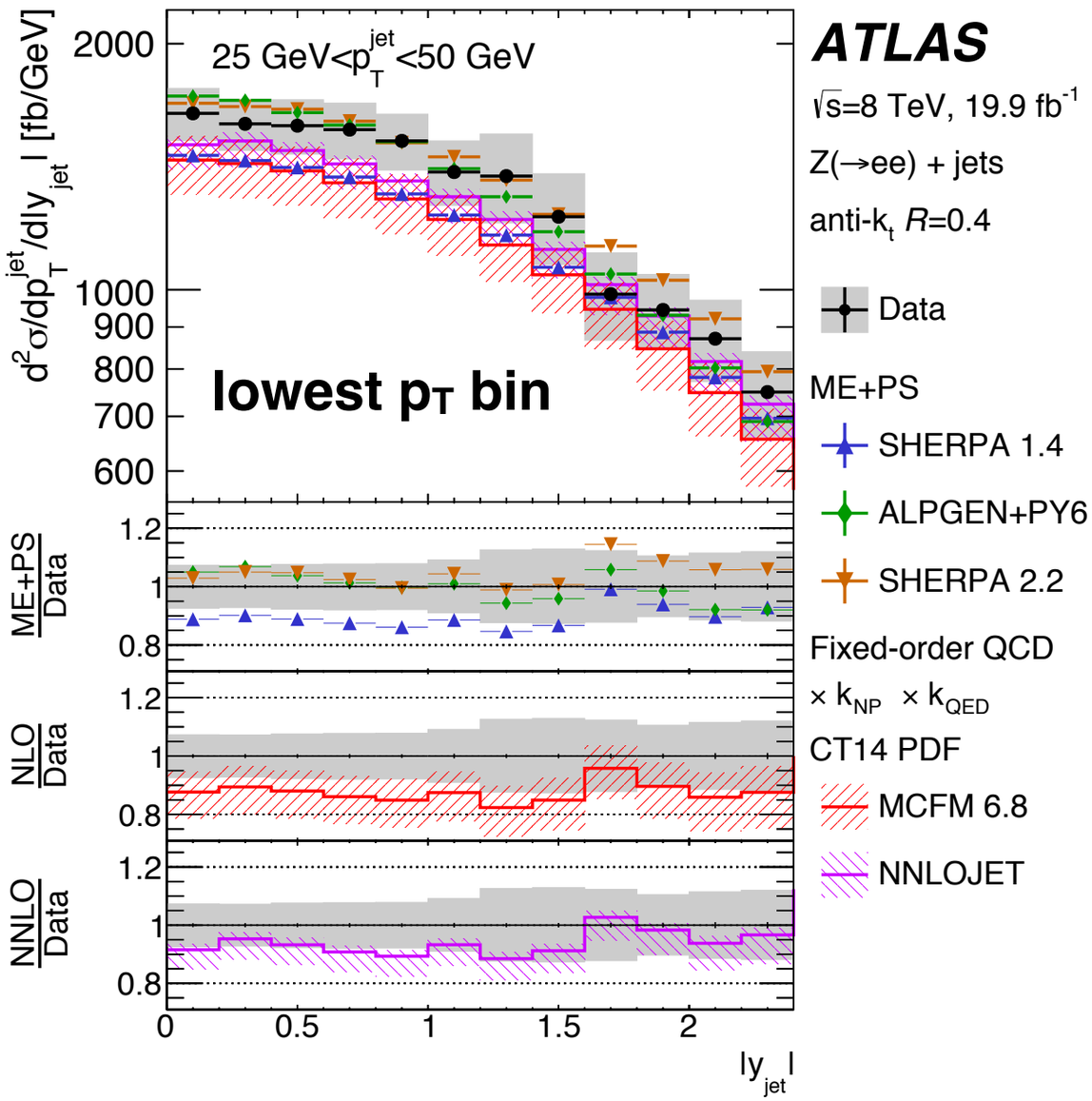
- Overall good agreement with NNLO pQCD calculations and with each PDF set
- Significant tension with all sets at very low ***η*** (low x) for W^- and Z. Good agreement for different PDF sets except ABMP and CT14 in W^+

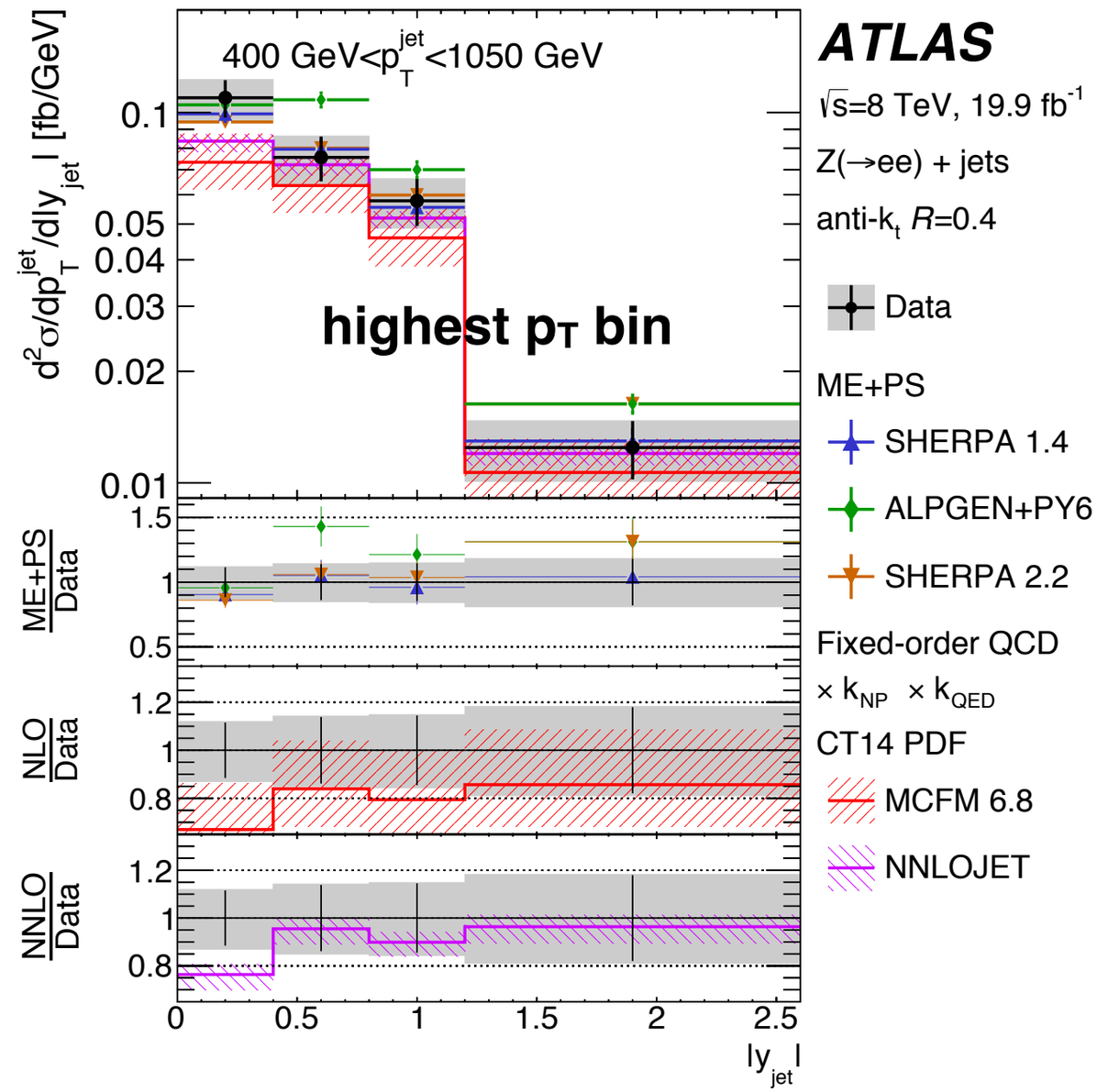
Z plus jets inclusive cross section measurement

8 TeV, 20 fb^{-1}

arXiv:1907.06728

Double-differential cross-section measurement as a function of inclusive jet y and p_T

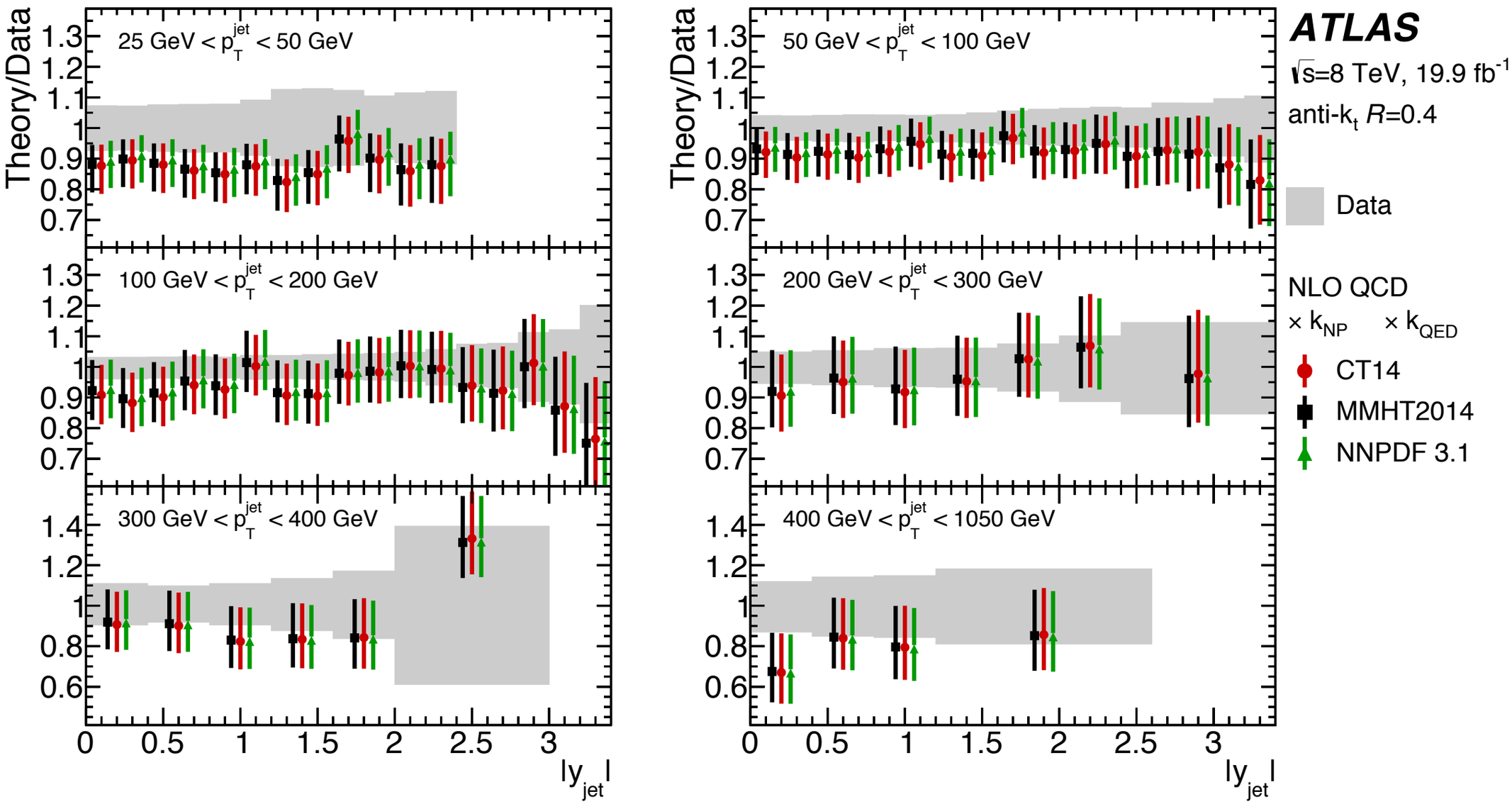




LO Alpgen+Pythia describes well low p_T, but exceeds data by 20% at high p_T; **LO Sherpa 1.4** lower than data by 10% at low p_T, describes data well at high p_T; **NLO Sherpa 2.2** agrees well with data; **NLO MCFM** 5-10% lower than data, differences covered by uncertainties; **NNLO** shows best agreement with data in all bins of the measurement.

Z plus jets inclusive cross section measurement

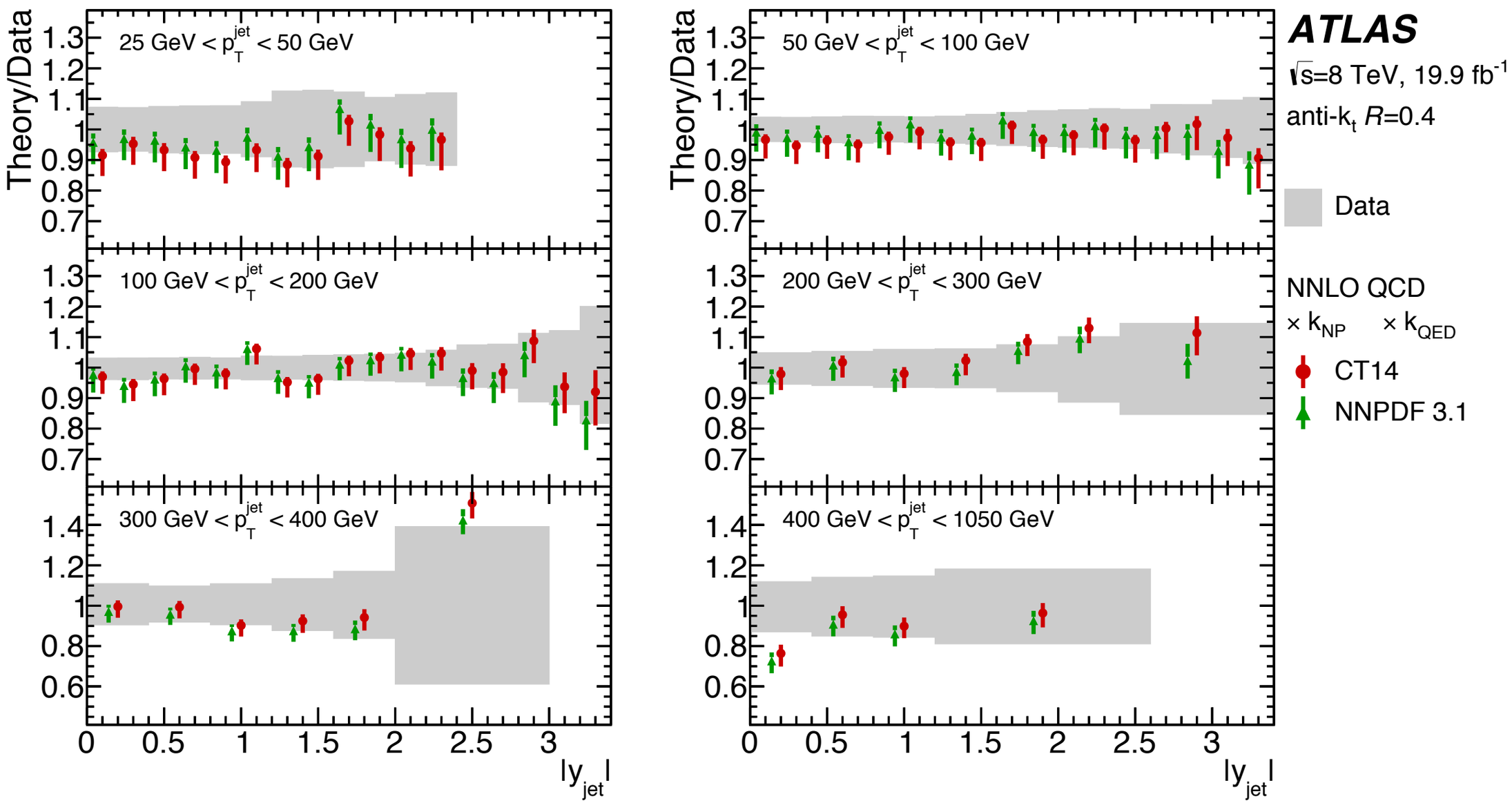
8 TeV, 20 fb^{-1}



- Data compared to **NLO predictions with different PDFs**
- Differences among NLO predictions with different PDFs covered by the theoretical uncertainties
- Data uncertainty smaller than theory uncertainty in most of the bins $\Longrightarrow$ we need to go to NNLO corrections

Z plus jets inclusive cross section measurement

8 TeV, 20 fb^{-1}



- Data compared to **NNLO predictions with different PDFs**
- Difference between CT14 and NNPDF3.1 is 2-5%, comparable in some region with the size of theoretical uncertainties

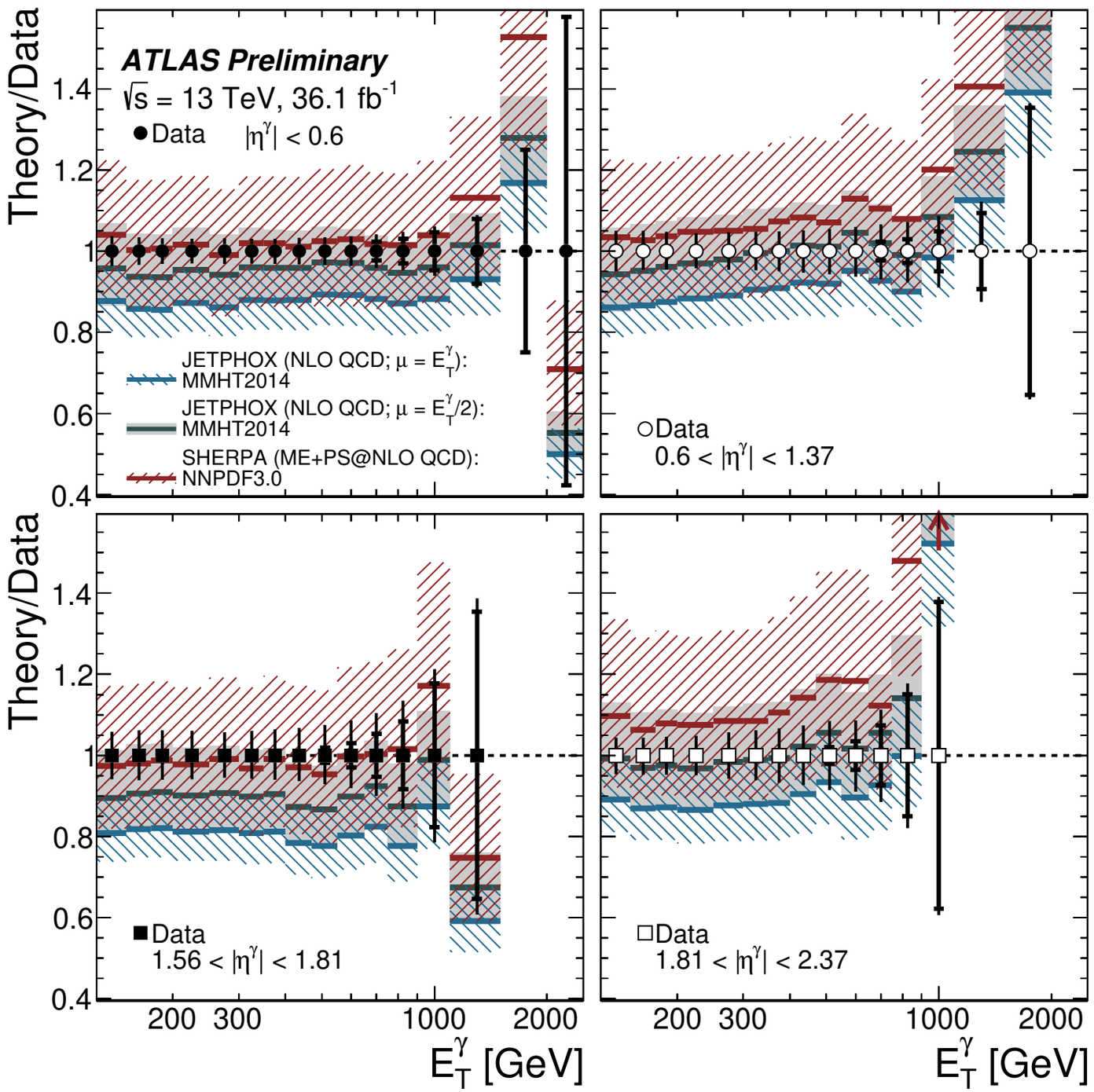
Conclusions

- ATLAS performed comprehensive studies of PDF and other pQCD effects in inclusive electroweak boson production
- Measurements sensitive to various NNLO PDF predictions
- More results with the full Run 2 dataset are expected

Thank you

Inclusive isolated-photon cross section in pp collisions

13 TeV, 36.1 fb^{-1}



Inclusive isolated-photon cross section in pp collisions

13 TeV, 36.1 fb^{-1}