Wishlist for PDFs from Experimentalists

S. Glazov, Vietnam 27/09/2016

Topic of the talk

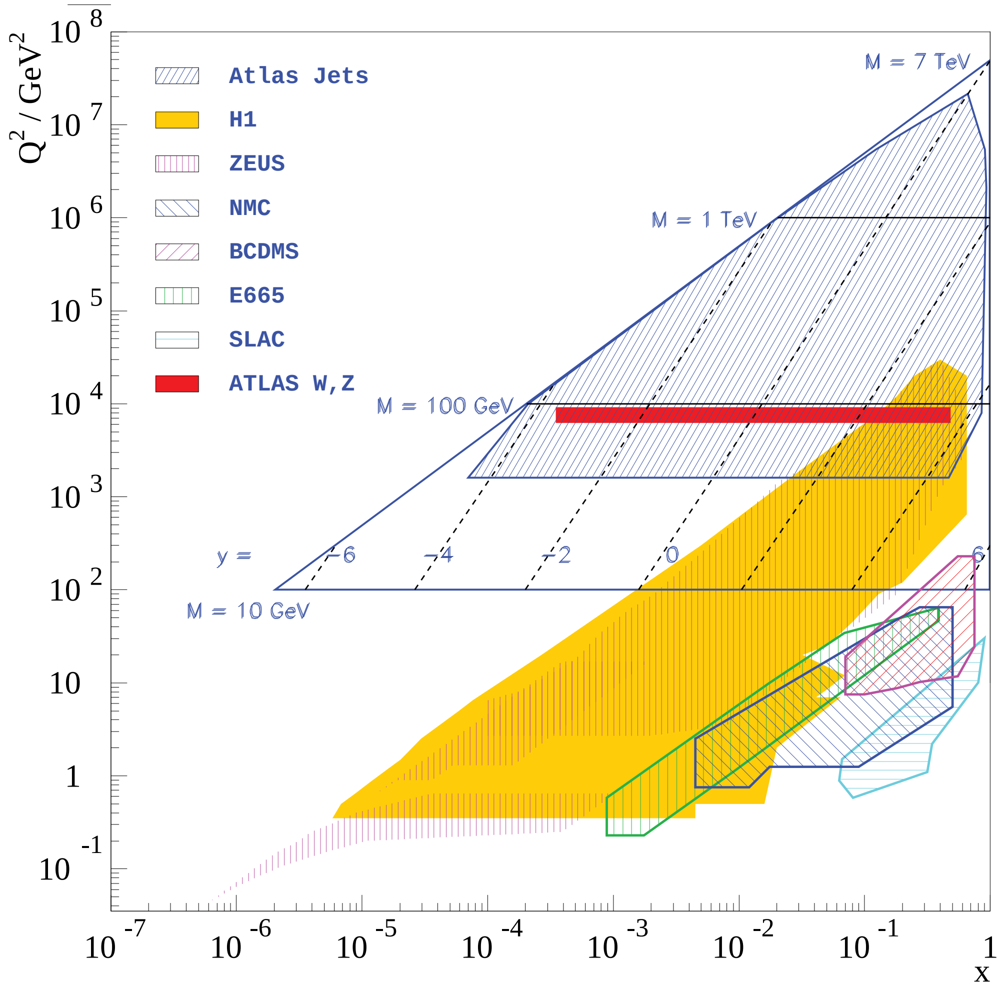
The talk will address two questions to phenomenological/theoretical community:

- Experimental needs for precise PDFs, with robust central values and reliable uncertainties.
- Experimental data, sensitive to PDFs which require further theory developments.

Specific topics on which the following discussion will focus:

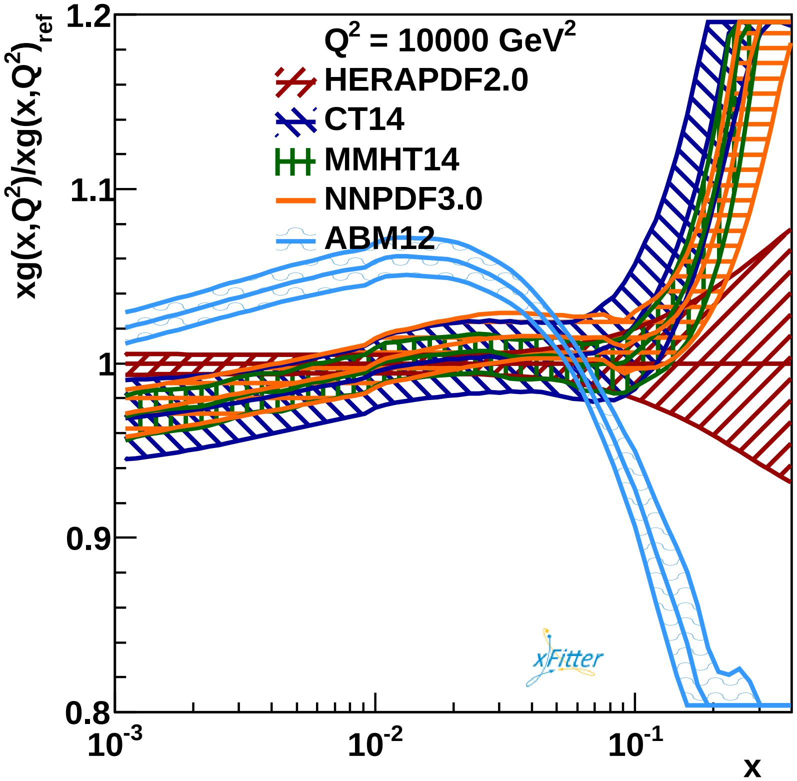
- the Gluon distribution;
- the Strange-quark distribution.

Cross sections at the LHC



The cross sections are given by a convolution of the parton densities and coefficient functions, $\sim x_1 f_1(x_1, \mu)\, x_2 f_2(x_2, \mu)\, \hat{\sigma}(x_1, x_2, \mu)$.
Leading order relation between rapidity y and x_1, x_2: $x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{S}} e^{\pm y_{\ell\ell}}$.

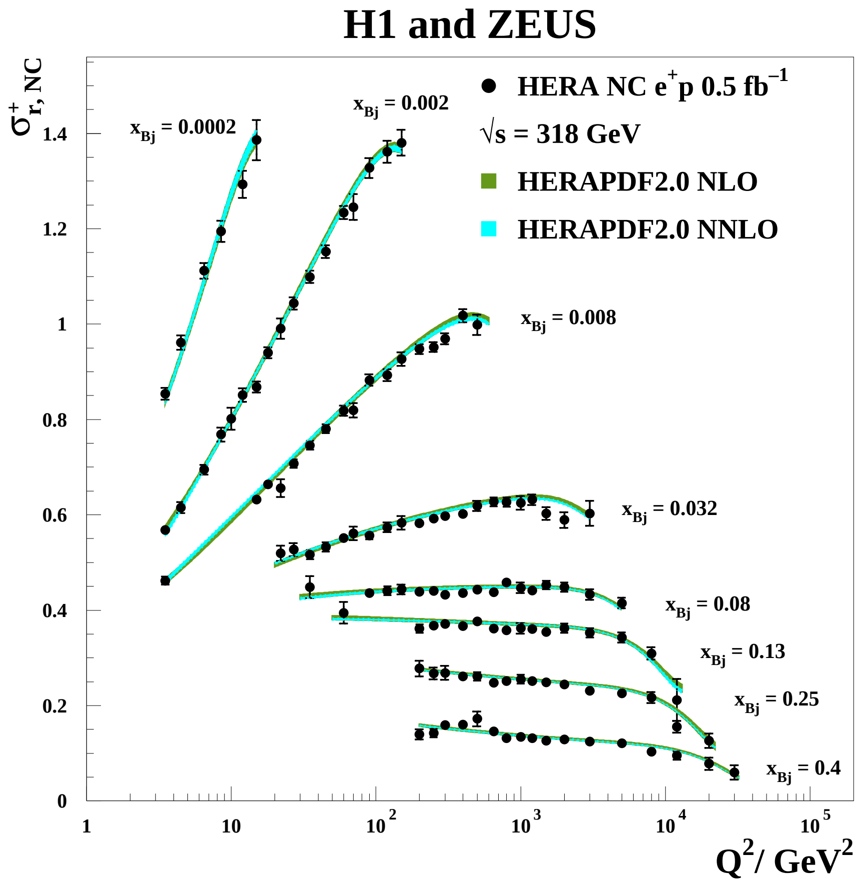
The gluon distribution from the 5 PDF sets



- Gluon at $x \sim 0.01$ important for Higgs production
- Gluon at $x > 0.3$ important for searches
- Gluon at $x \sim 0.1$ important for $t\bar{t}$ production.

- Good agreement of the three PDF4LHC sets (MMHT14, CT14 and NNPDF3.0)
- ABM12 set has different (low) α_S, differs the most.
- HERAPDF agrees with PDF4LHC for $0.01 < x < 0.1$, lower at high x and higher at low x.

HERA data for the gluon distribution

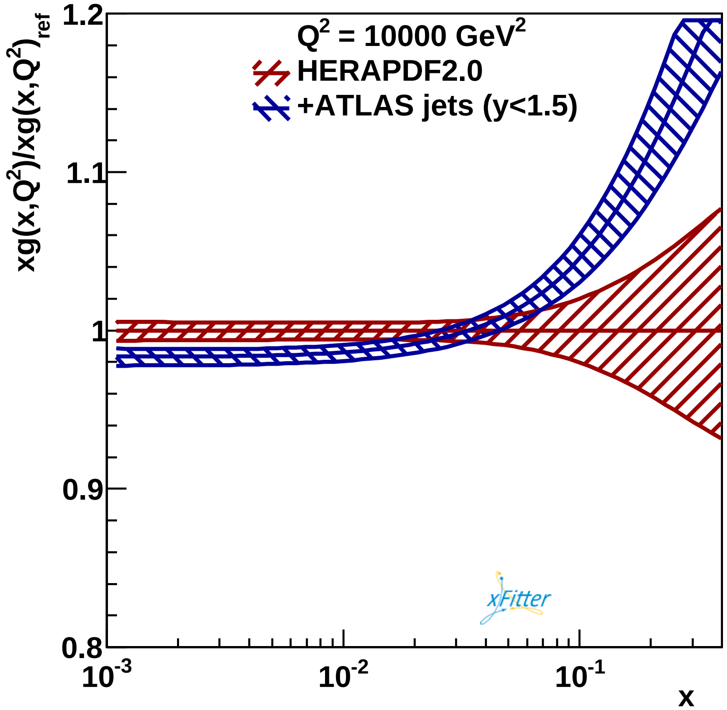


- Observable:
  $\sigma_r \approx F_2 - \frac{y^2}{1+(1-y)^2} F_L$
  where $0 < y \leq 1$ and
  $S\,xy = Q^2$.
- Constraints on $xg(x, Q^2)$ from scaling violation of the SF F_2:

$$\frac{dF_2}{d \log Q^2} \sim \alpha_S\, g$$

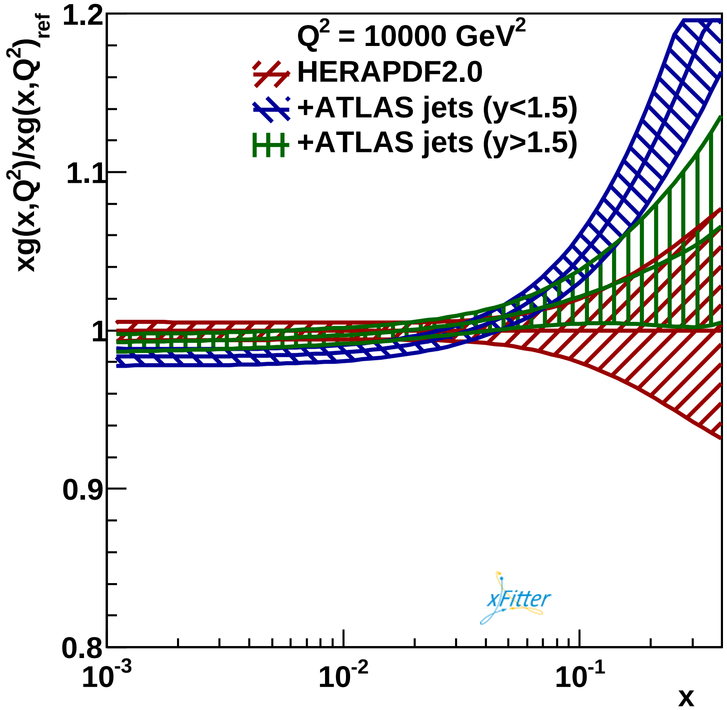
- The Q^2 dependence of F_2 is well constraint by the data, leading to experimentally precise determination
- Some tensions between data and theory with NLO (NNLO) fit $\chi^2/N_{\rm DF}$ = 1357/1131 (1363/1131). → N^3LO ?

Adding jet data ...



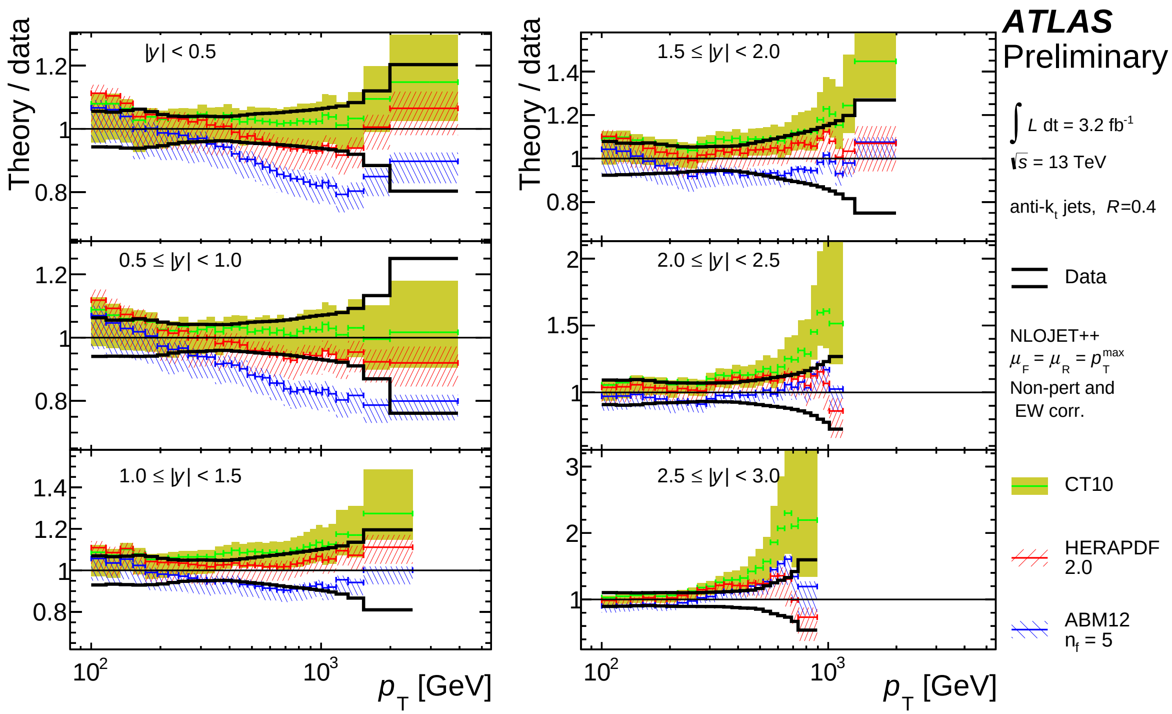
- Estimate impact data on the gluon distribution by employing PDF profiling of the HERAPDF2.0 set
- Use ATLAS jet $\sqrt{s} = 7$ TeV data ($R = 0.4$, JHEP02(2015)153)
- Predictions based on NLOJET++ plus NP and EWK corrections
- Use data for $y < 1.5$. Poor $\chi^2/N_{\mathrm{DF}} = 209/85$
- Strong pull towards PDF4LHC pdfs.

Adding jet data ...



- Estimate impact data on the gluon distribution by employing PDF profiling of the HERAPDF2.0 set
- Use ATLAS jet $\sqrt{s} = 7$ TeV data (JHEP02(2015)153)
- Predictions based on NLOJET++ plus NP and EWK corrections
- Use data for $y < 1.5$ ($1.5 < y < 3.0$). Poor $\chi^2/N_{\rm DF} = 209/85$ ($97/51$)
- Strong (moderate) pull towards PDF4LHC pdfs.

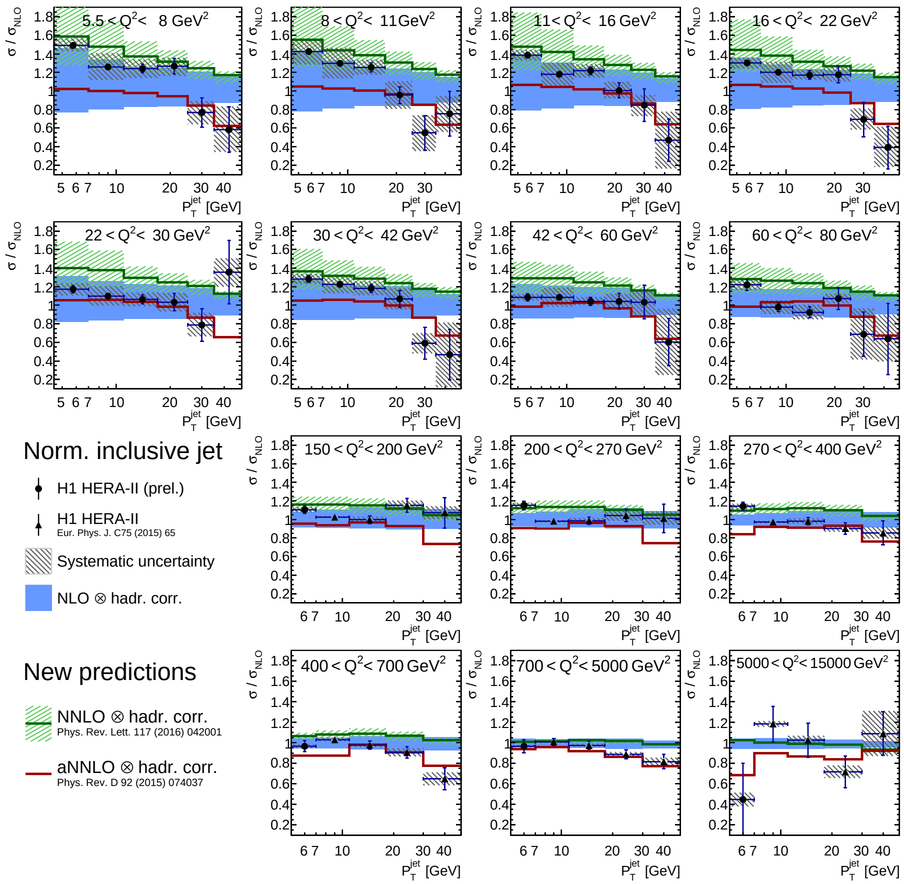
Inclusive jets at $\sqrt{s} = 13$ TeV



- New (ATLAS-CONF-2016-092) measurement of inclusive jets using $\sqrt{s} = 13$ TeV data
- JES uncertainty is at 5% level for $|y| < 0.5$ and $p_T < 1$ TeV.
- CT10 (similar to PDF4LHC group) agrees best for $y < 1$, for high y HERAPDF fits perhaps better.

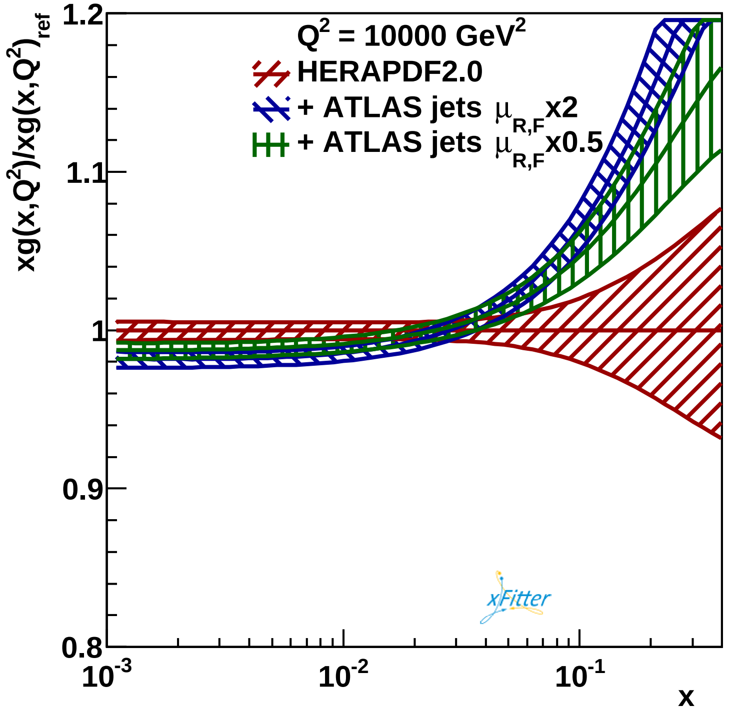
→ NNLO for jets

NNLO predictions vs DIS jet data



- Normalized to inclusive DIS, inclusive-jet and dijet measurements using H1 HERA Run-II data compared to approximate NNLO prediction from JetViP and NNLO from NNLOJET (H1prelim-16-062).
- NNLO improves description of the data.

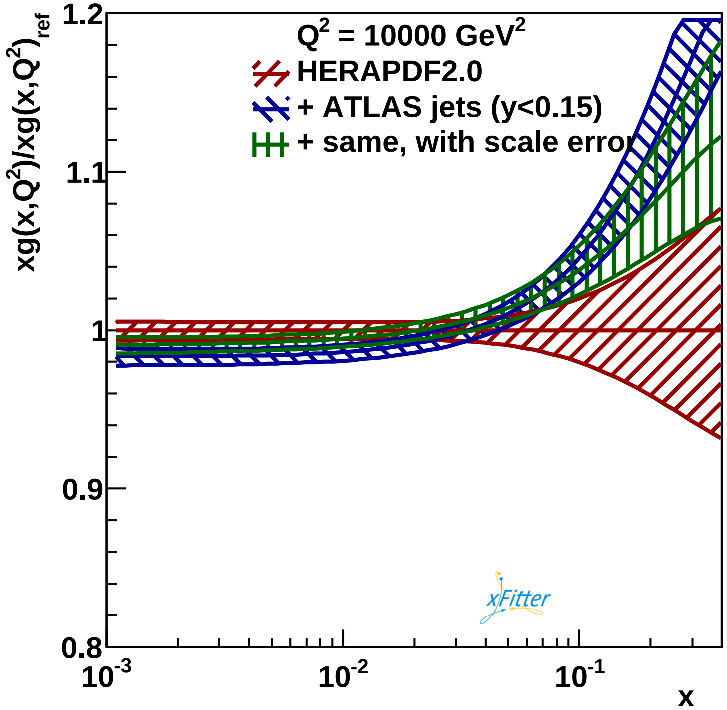
Effect of scale uncertainties on the jet data



- NLO predictions have substantial uncertainties, which can be estimated by varying μ_R and μ_F scale factors.
- Variation of $\mu_F = \mu_R = 0.5, 2$ vs default choice of inclusive p_T for the ATLAS data leads to substantial variation of the central value of the profiled gluon density.

$\rightarrow$ PDFs with theoretical uncertainties.

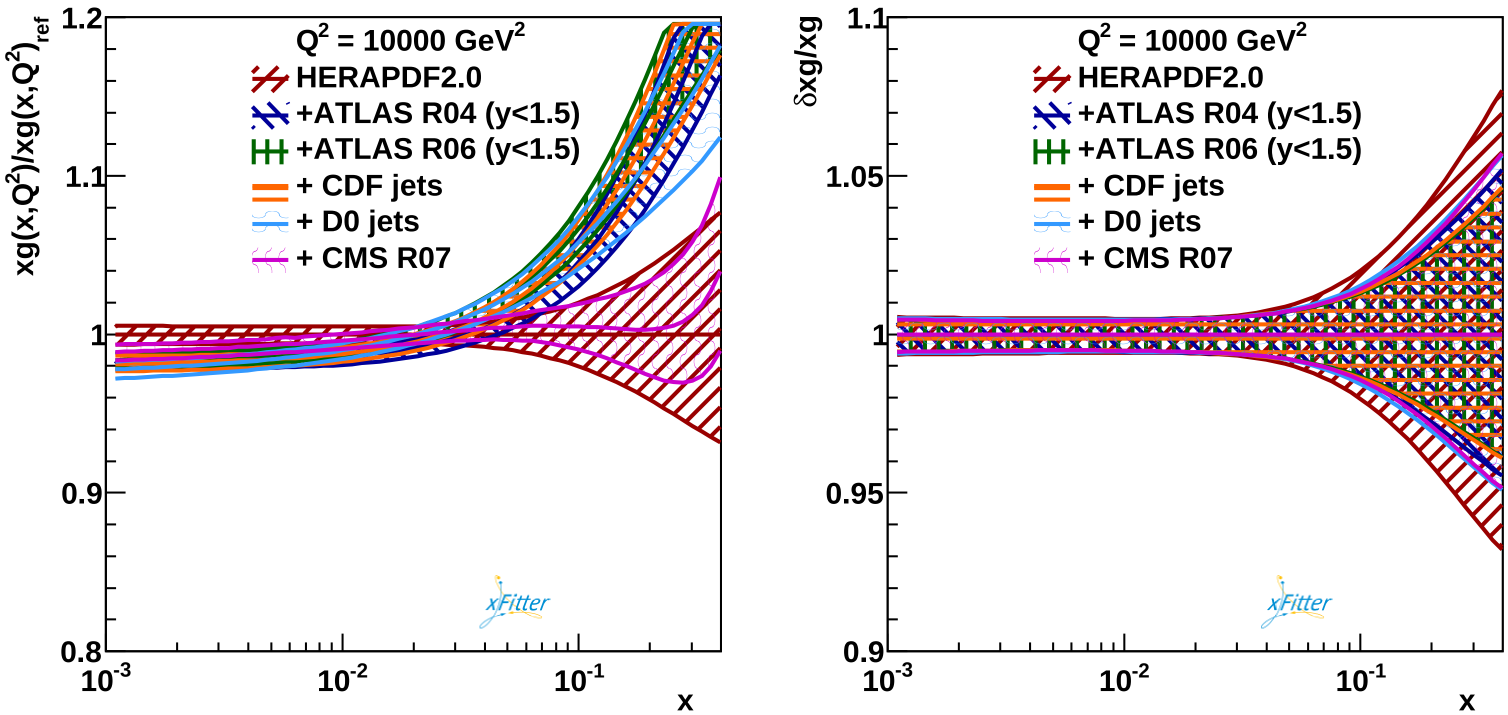
Effect of scale uncertainties on the jet data



- NLO predictions have substantial uncertainties, which can be estimated by varying μ_R and μ_F scale factors.
- Extra error due to variation of $\mu_F = \mu_R = 0.5, 2$ vs default choice of inclusive p_T for the ATLAS data leads to substantial change of the central value of the profiled gluon density.

$\rightarrow$ PDFs with theoretical uncertainties, proper weights for data samples.

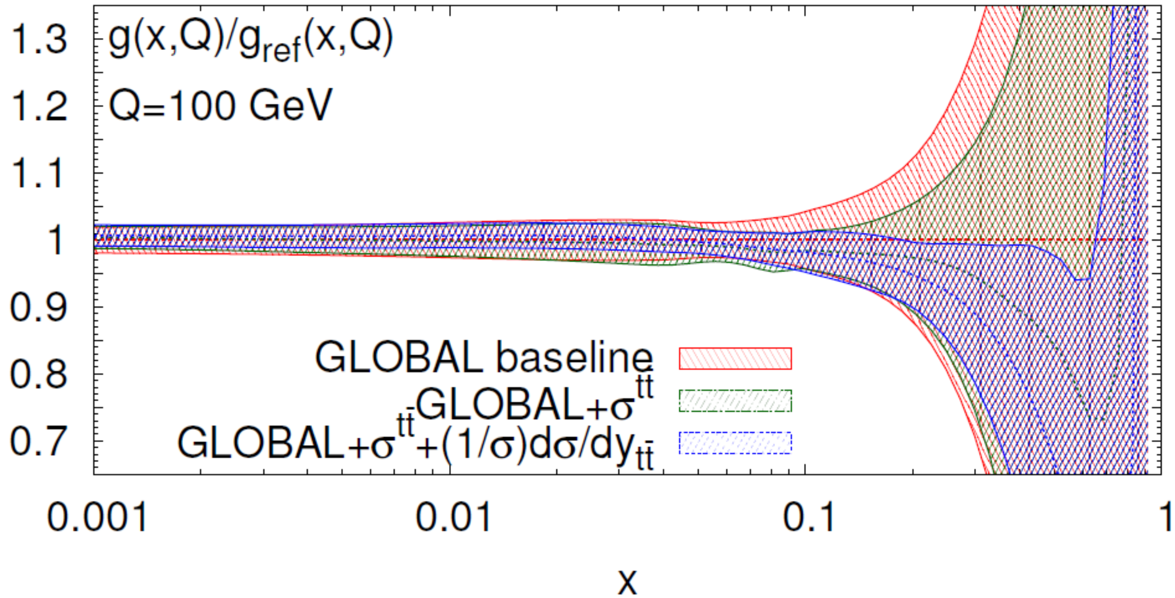
Other jet measurements



- Try different jet data: run-II DO PRL101:062001, CDF PRD78:052006, CMS at $\sqrt{s} = 7$ TeV ($R = 0.7$), Phys. Rev. D87 112002.
- All jet samples have comparable constraining power on gluon.
- D0,CDF and ATLAS $R = 0.4, 0.6$ jet measurements lead to harder gluon, CMS data do not change the shape significantly.

→ direct comparison of ATLAS and CMS data

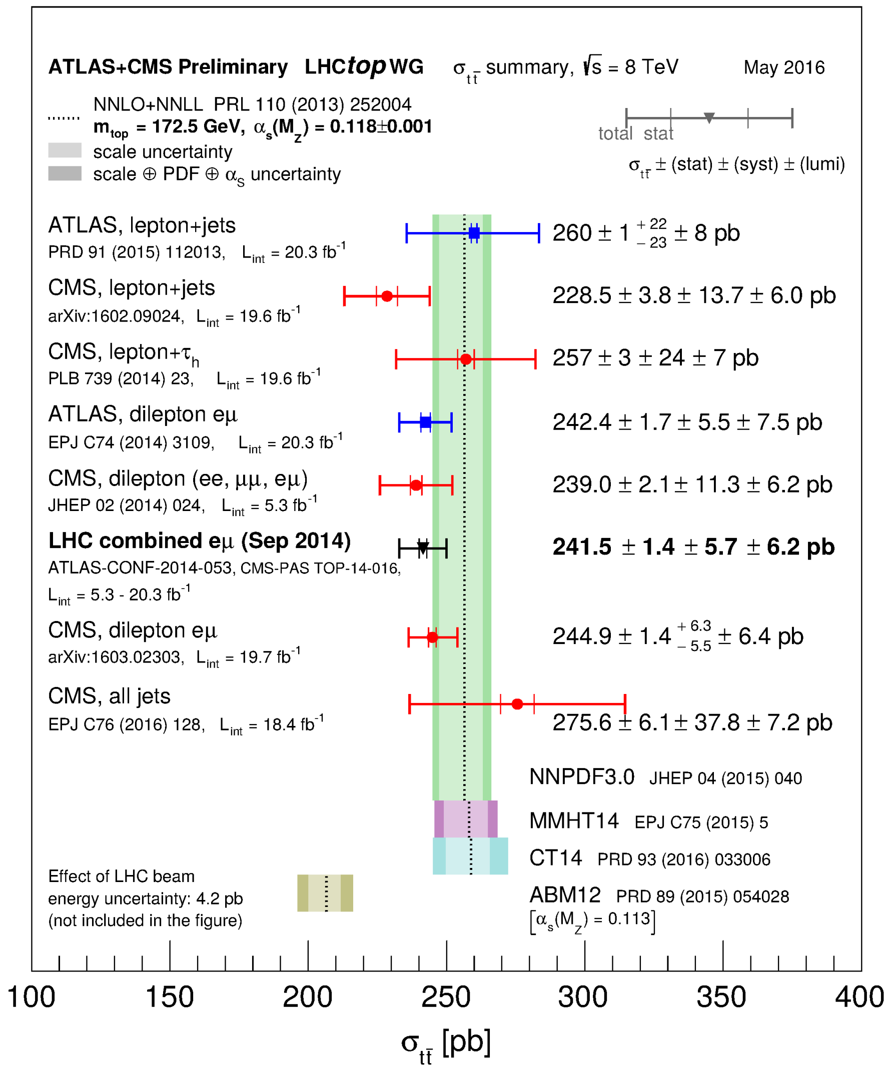
Other observables: $t\bar{t}$ total and differential



- Both total and differential cross sections for $t\bar{t}$ production are highly sensitive to the gluon distribution at $x \sim 0.1$.
- Study from Emanuele Nocera, shown at QCD@LHC2016, uses as a baseline global data sample (which excludes jets) as well as pure HERA. The two references agree.
- $t\bar{t}$ data seem to pull gluon down at high x.

$\rightarrow$ (fast) NNLO for differential cross sections

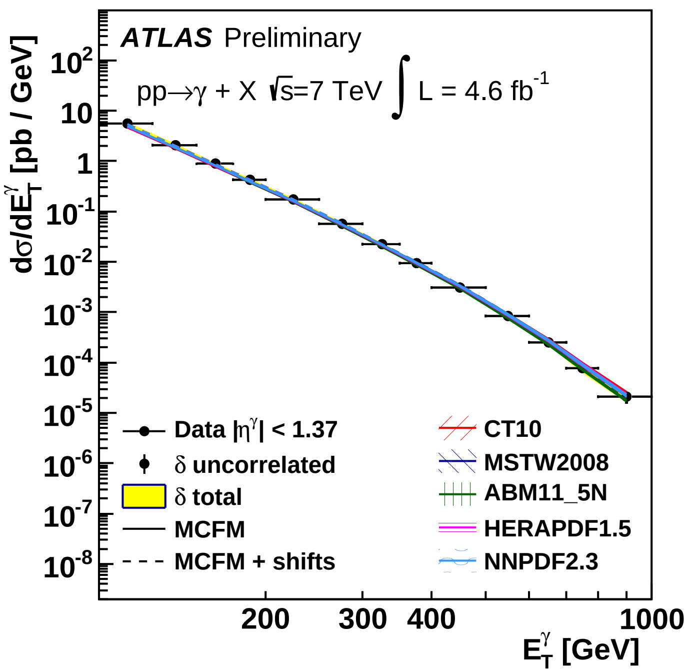
Measurements of $\sigma_{t\bar{t}}$

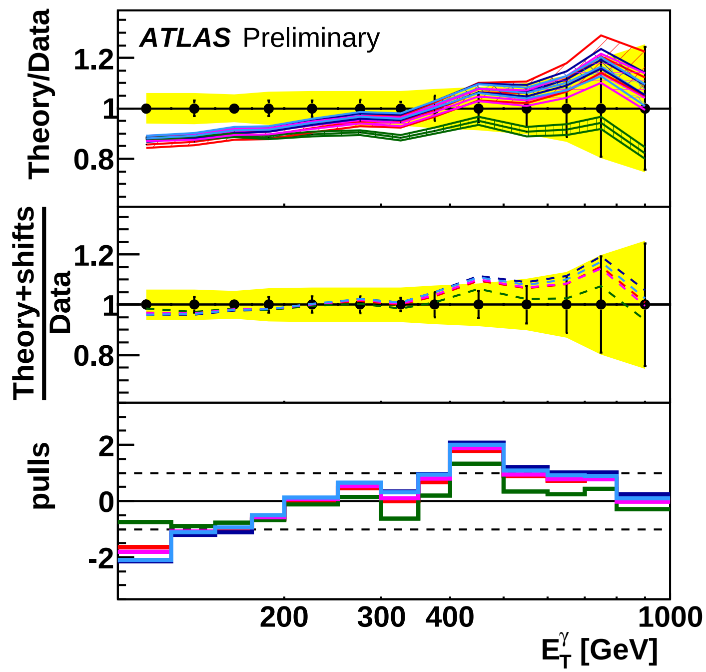


- Most accurate measurements use dilepton $e\mu$ channel. Very good consistency between ATLAS and CMS for $\sqrt{s} = 8$ TeV data.
- Luminosity uncertainty can be reduced by measuring $\sigma_{t\bar{t}}/\sigma_Z$ ratio
- The systematic uncertainties have significant component from the signal modelling, which is reduced for fiducial cross-section measurement. This becomes larger effect for run-II data, since extrapolation is larger.

$\rightarrow$ NNLO for differential cross sections with cuts on FS leptons.

PDF sensitivity of the inclusive photon data



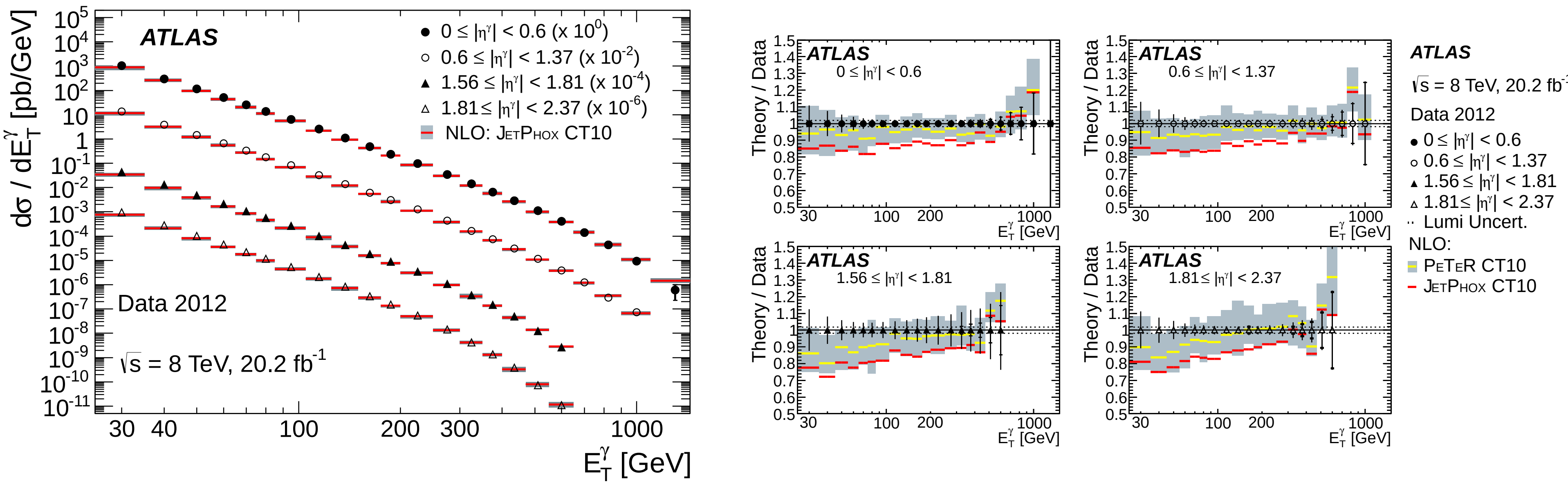


Direct photon production is sensitive to the gluon density mostly via Compton scattering $gq \to q\gamma$.

ATLAS data compared to predictions using MCFM (ATL-PHYS-PUB-2013-018)

Better shape agreement for ABM11 PDF, which has soft gluon density at high x.

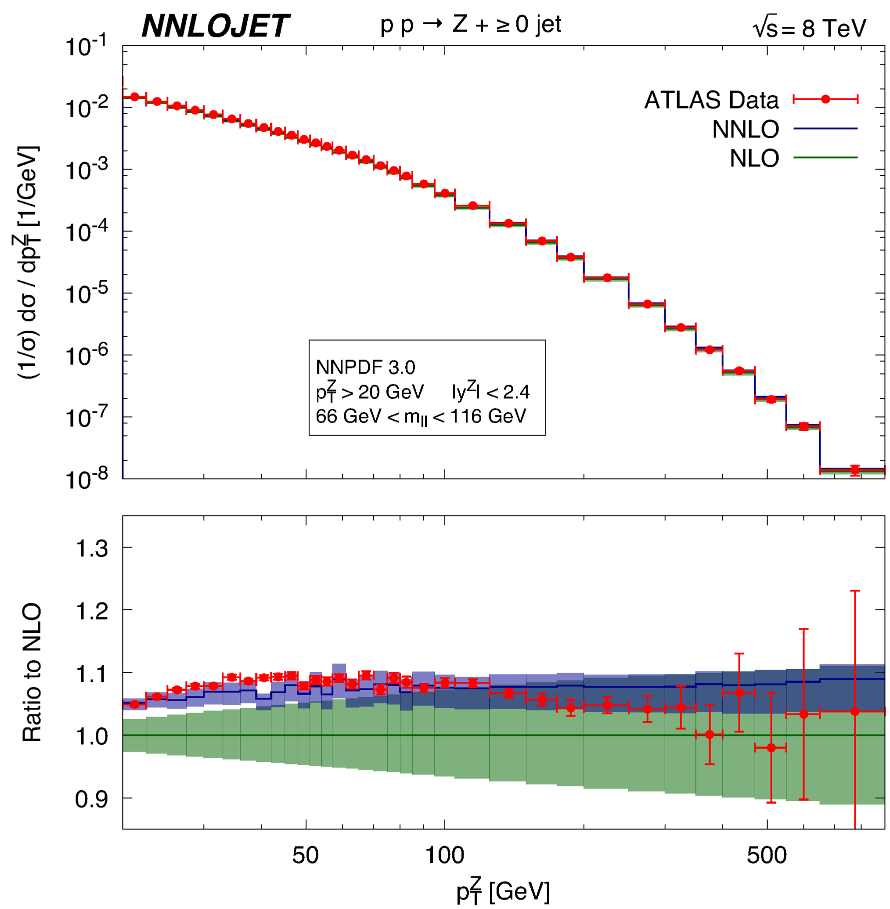
Inclusive photons at $\sqrt{s} = 8$ TeV



- Inclusive γ production measurement by ATLAS (JHEP 06 (2016) 005), for $25 < E_{\mathrm{T}} < 1500$ GeV, double differential in E_T and η
- Measurements compared to NLO JetPhox and NLO+threshold resummation + EWK Sudakov logs PeTeR predictions.
- PeTeR matches data better, theory errors are larger vs experimental uncertainties.

→ NNLO, include back to PDF fits

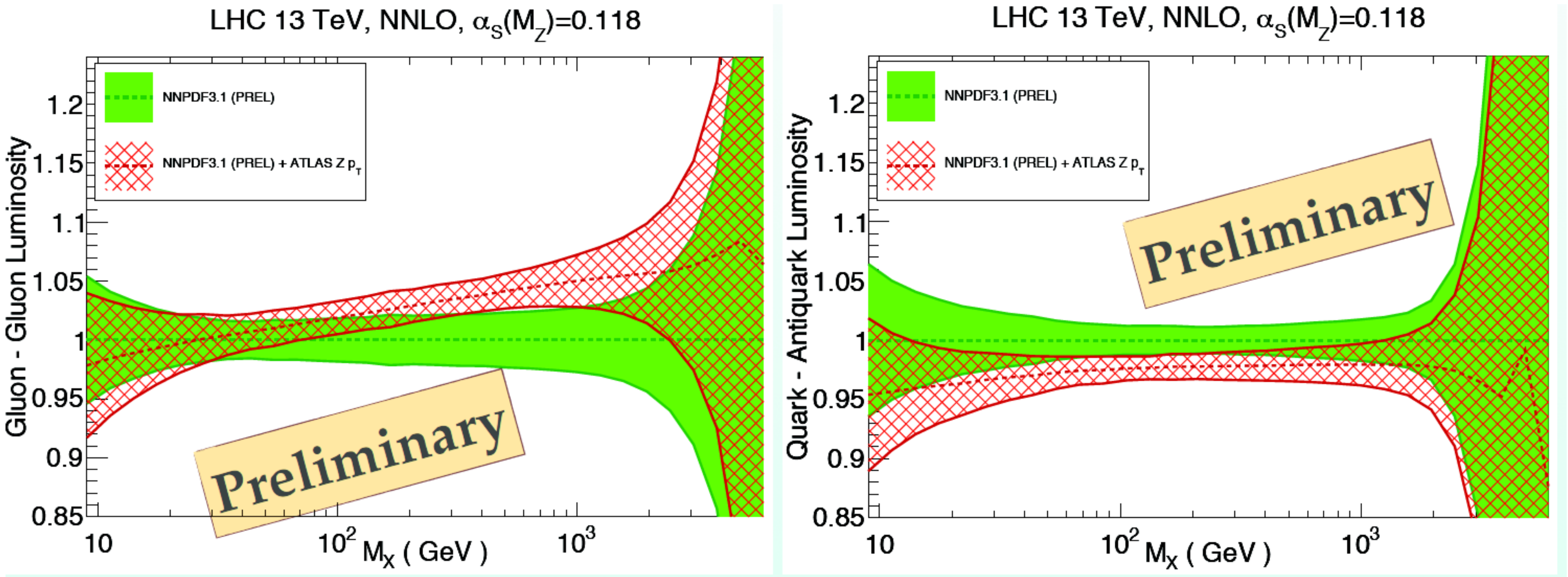
Inclusive $\gamma^*/Z \to \ell\ell$ data



- Another process sensitive to qg Compton scattering is the $\gamma^*/Z \to \ell\ell$ DY process at high p_T.
- Here we have very precise data (e.g. ATLAS Eur. Phys. J. C 76(5), 1-61 (2016)) and NNLO calculations (plot from arXiv:1605.04295v1).

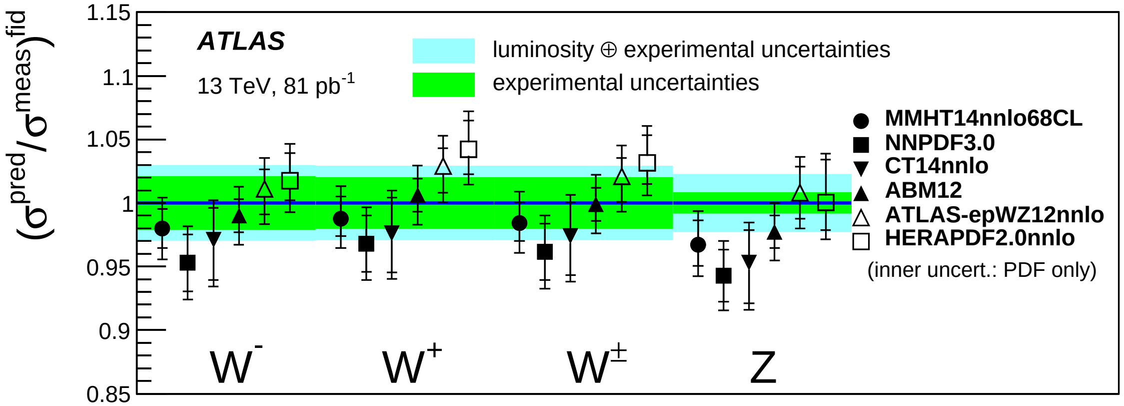
$\longrightarrow$ NNLO helps, but there are remaining differences. Could this be a PDF effect ?

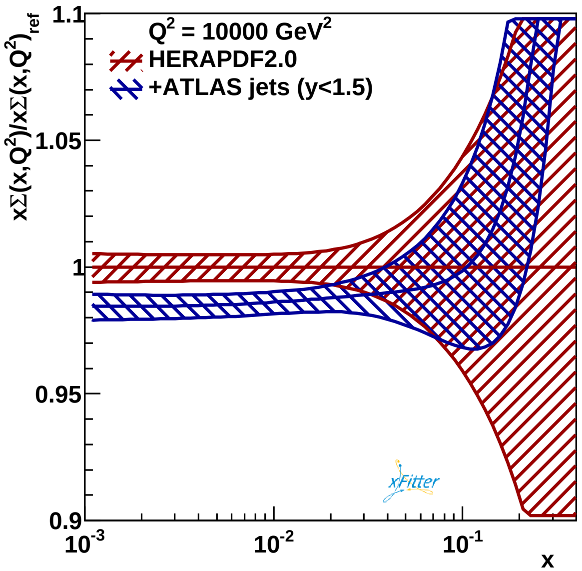
Inclusion of Z_{P_T} data in PDF fit (NNPDF)



- Study presented by J. Rojo at the latest PDF4LHC meeting
- Implies further significant hardening of the gluon distribution.

W, Z production at $\sqrt{s} = 13$ TeV

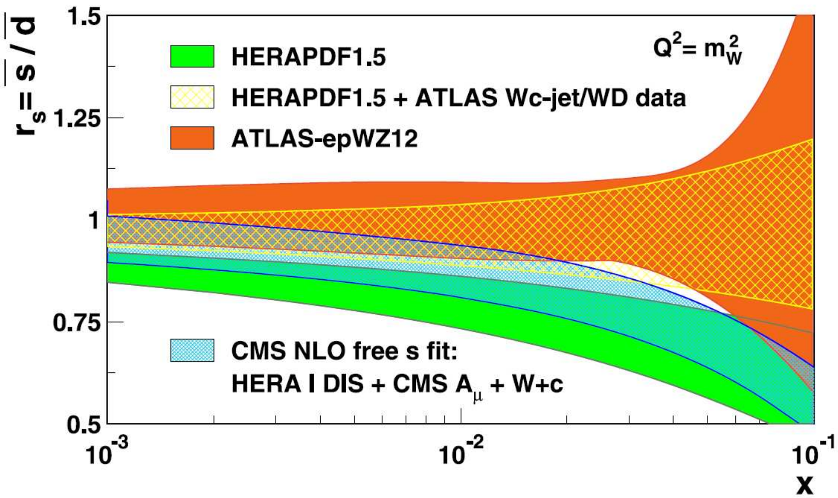




- Even for early $\sqrt{s} = 13$ TeV data the dominant uncertainty on the fiducial Z-boson production cross section comes from the luminosity.
- The luminosity uncertainty is improved for $\sqrt{s} = 8$ TeV data to 1.9%. For $\sqrt{s} = 13$ TeV data it is now at 2.1% and 1.8% for $\sqrt{s} = 7$ TeV data.
- The difference between HERA vs PDF4LHC pdfs may be explained by the pull of the jet data.

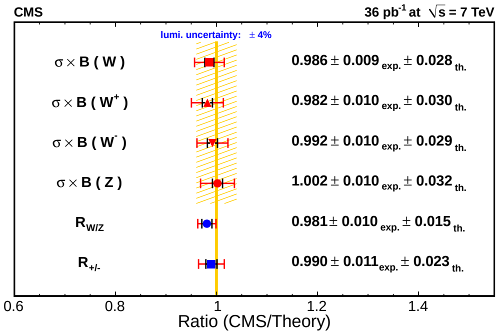
→ need for even better luminosity measurement

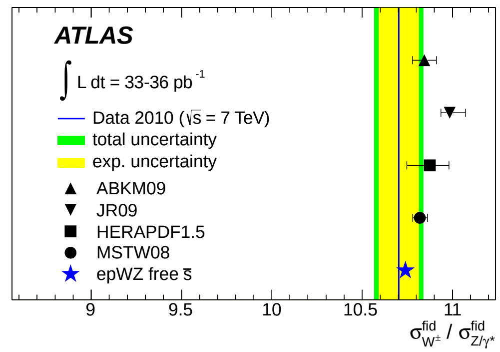
Strange-quark distribution

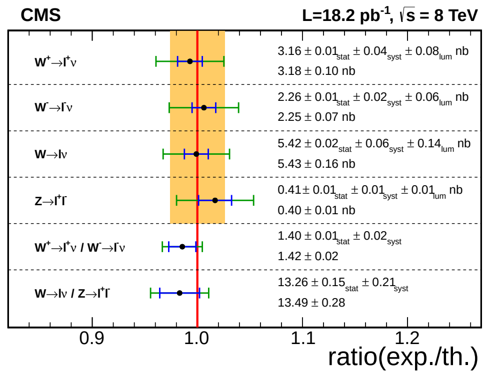


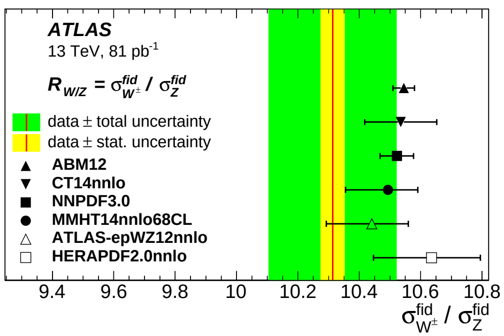
- Light-quark sea is likely to be symmetric for *u*- and *d*-quarks for small *x*. For the strange-quark distribution it might be different.
- Fixed-target neutrino data on $\nu_\mu s \to \mu^\pm c^\mp \to \mu^- \mu^x X$ scattering suggests suppression.
- LHC data are sensitive to the strange-quark distribution via:
  - *Z*-boson rapidity distribution (more central for $s\bar{s}$)
  - σ_W/σ_Z cross section ration (affects more *Z* vs *W*)
  - $gs \to W^\pm c^\mp \to \ell^\pm \nu c^\mp$ production of *W*-boson with tagged charm.

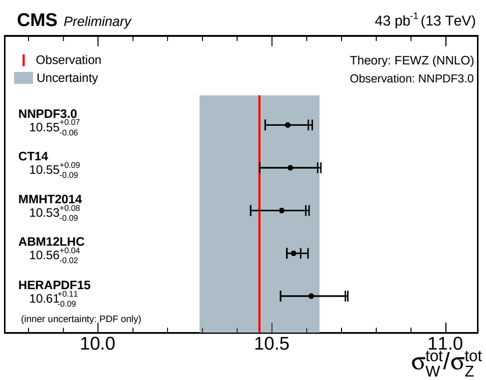
W/Z cross section ratios









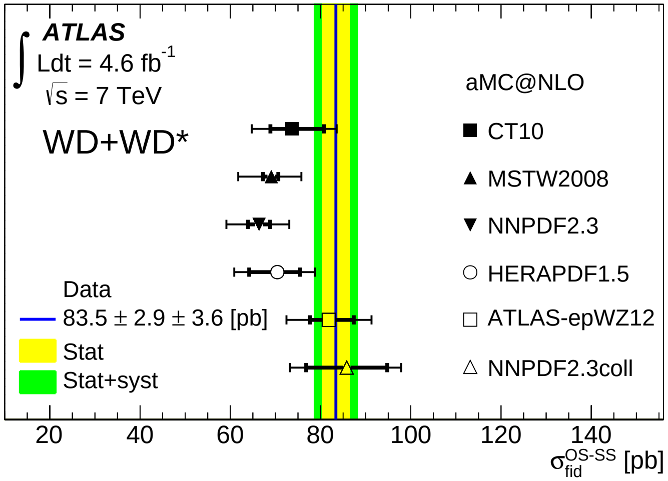


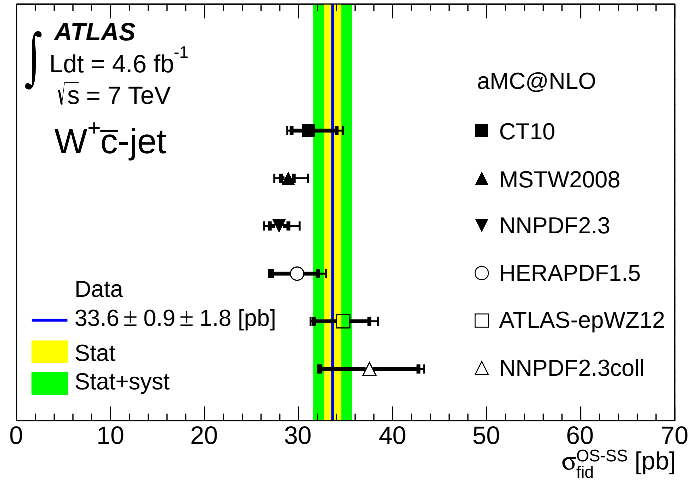
- All measured ratios σ_W/σ_Z tend to be below predictions for PDFs with suppressed strangeness.
- Further more accurate measurements required; best exp. accuracy is for fiducial cross sections.
- Additional uncertainty for fiducial predictions: difference between FEWZ vs DYNNLO NNLO predictions for the ratio (at 0.5% level).

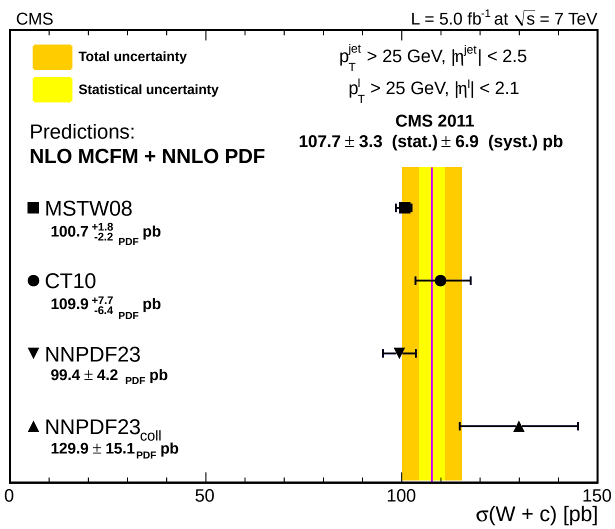
→ N3LO ?

CMS JHEP 10 (2011) 132, PRL 112 (2014) 191802, CMS-PAS-SMP-15-004, ATLAS PRL 109 (2012) 012001, PLB 759 (2016) 601

Measurements of W+c from ATLAS and CMS







- Measurements of $\sigma(W^\pm c^\mp) - \sigma(W^\pm c^\pm)$ from ATLAS and CMS (JHEP 02 (2014) 013, arXiv:1402.6263), using c-jets tagged by soft muons and $D^{(*)}$ mesons, to probe strange-sea PDF using $gs \to Wc$ process.
- Large NLO scale uncertainties. For $W + c$-jet ($p_T > 20$ GeV), can use NNLO for W+jet.

$\to$ NNLO for $W + D$

Summary

- A number of experimental measurements reach high accuracy, start to challenge theoretical uncertainties.
- Most urgent are transitions NLO $\rightarrow$ NNLO for jets, direct photon, $W + c$, $t\bar{t}$ differential cross sections.
- Precision DY measurements approach the limitations of NNLO calculations, N^3LO would be highly desirable.
- Experiments have many results which should be more systematically compared to each other.
- PDF fits which include theoretical uncertainties in systematic way are highly desirable.