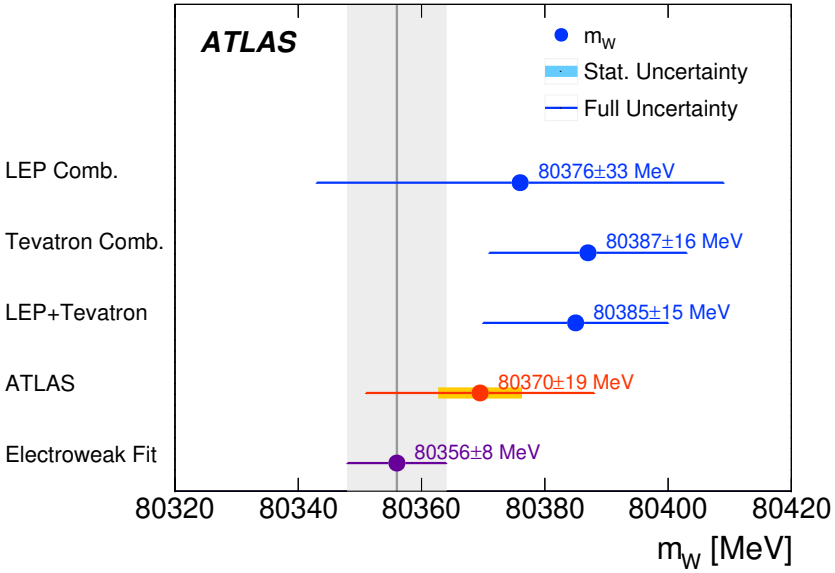
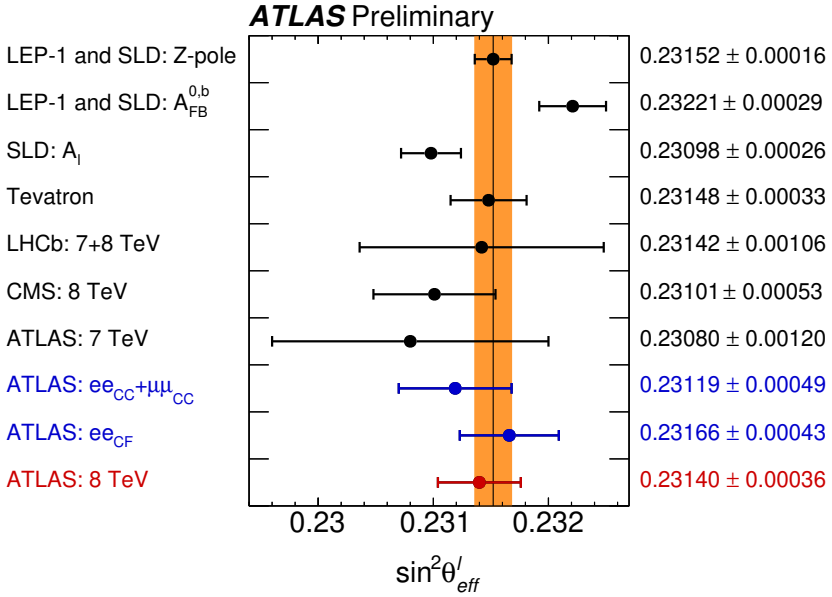
Towards high-precision PDFs : Experimental perspectives

S. Glazov, 11 Dec 2020

Measurements of the M_W and $\sin^2\theta_W$

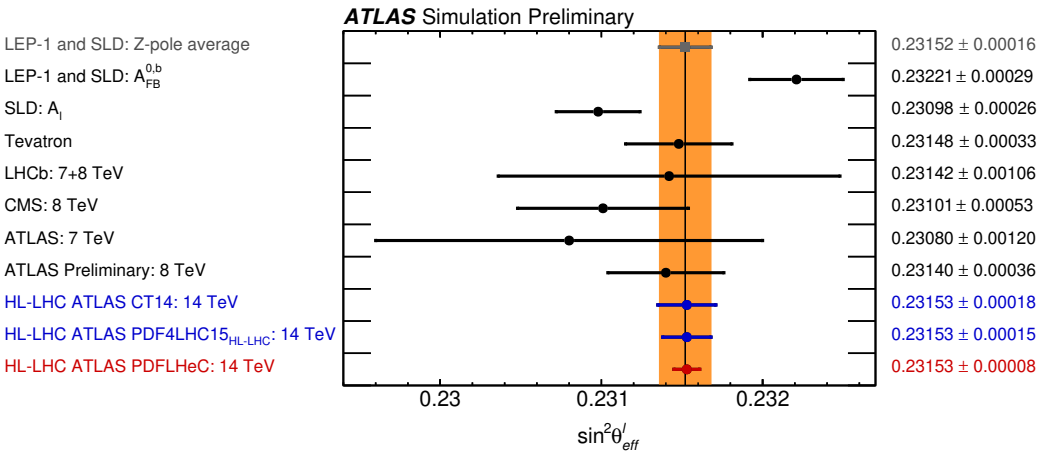


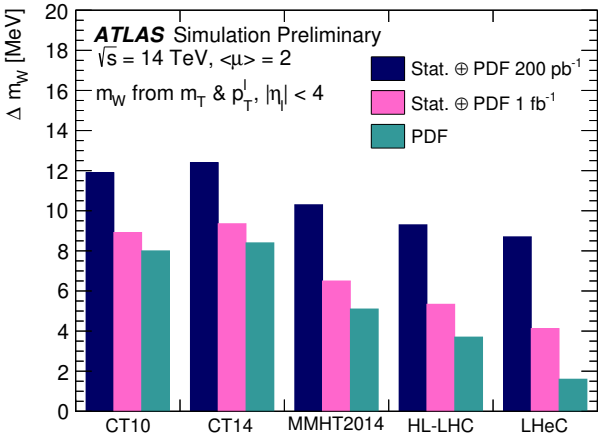


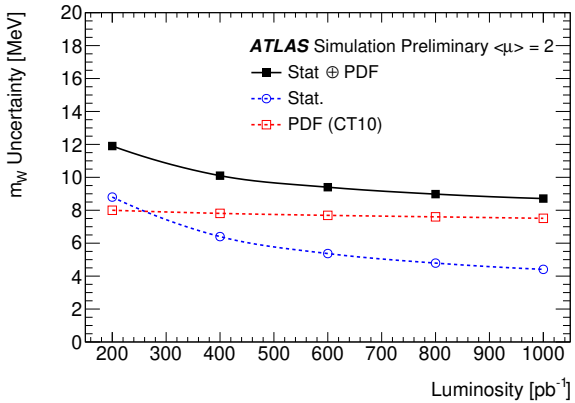
- LHC officially entered the precision electroweak race, with ATLAS measurements of m_W and CMS of $\sin^2\theta_W$ using run-I data comparable to most accurate determinations from LEP/Tevatron.
- Leading uncertainties are from PDFs, this will become worse for 13/14 TeV as the data start to probe lower x.

ATLAS: EPJC 78 (2018) 110, CMS: EPJC 78 (2018) 701
ATLAS-CONF-2018-037

m_W, $\sin^2\theta_W$ expectations for HL-LHC







→ Projections to full luminosity show that PDF uncertainties will remain large

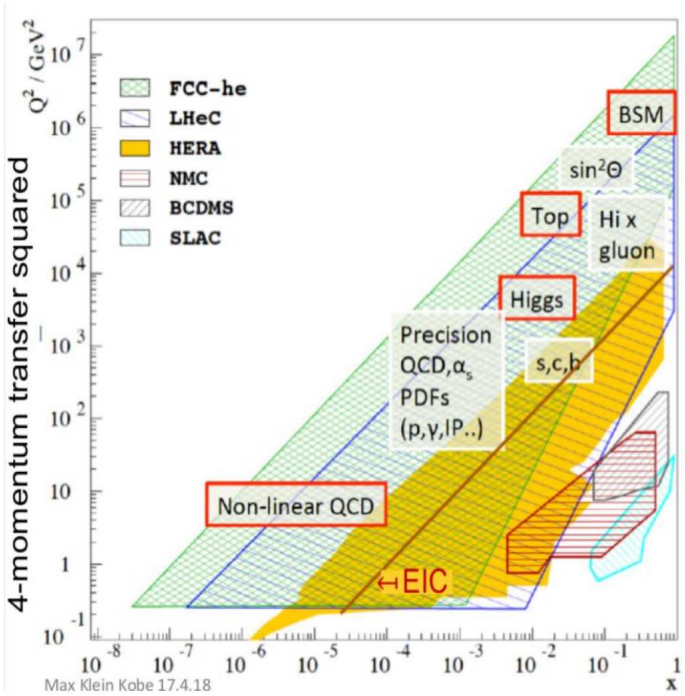
→ PDFs and their uncertainties can not any longer be treated as a black box, need similar or even bigger scrutiny, in terms of uncertainty decomposition and correlations, as experimental uncertainties.

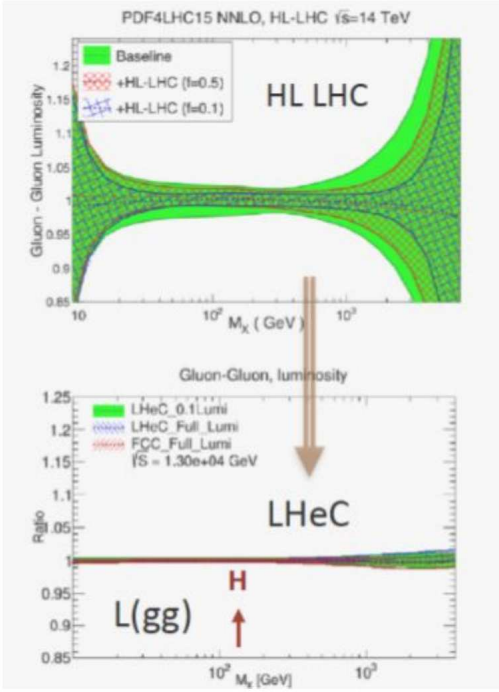
ATL-PHYS-PUB-2018-037, ATL-PHYS-PUB-2018-026

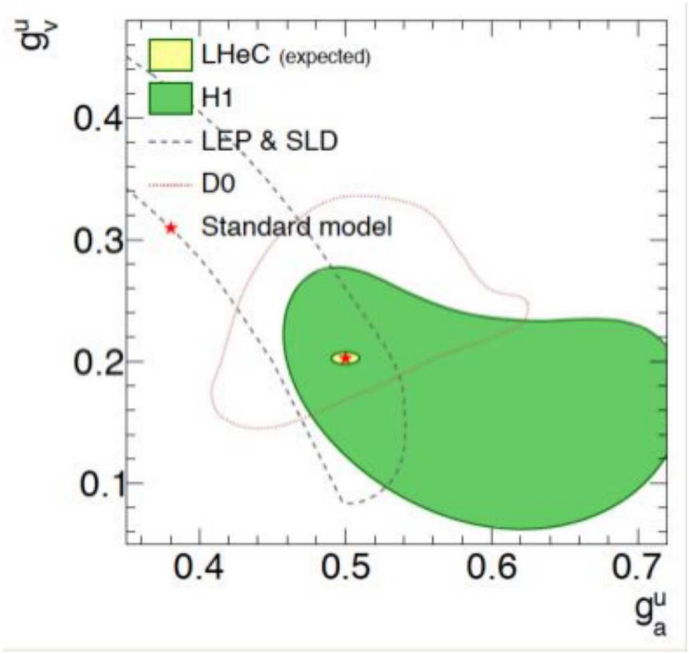
Ways to make progress

- Provide more accurate measurements for PDF determination
  - Perform measurements with small explerimental and theoretical uncertainties + large PDF sensitivity
  - Make sure that experimental and theoretical correlations are understood
- Design EWK parameter measurements to control PDFs
  - Using validated PDF profiling/reweighting
  - Monitoring residual dependence of PDFs on EWK parameters
- Full fit of PDFs and EWK parameters
  - Coherent EWK treatment of all observables.
  - May determine correlation of the measured EWK parameter and low-level unterlying uncertainty, e.g. impact of HERA luminosity on $\sin^2\theta_W$ at the LHC.

LHeC



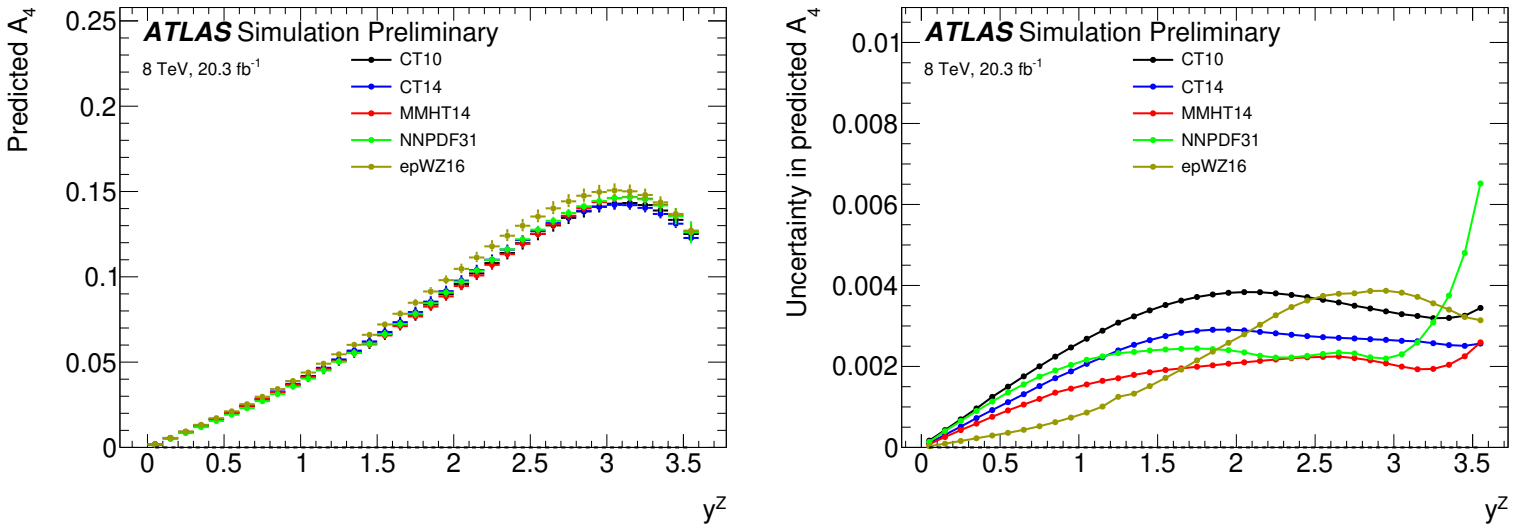




CERN-ACC-Note-2018-084

- High luminosity, high energy ep collider LHeC would allow to improve accuracy and extend kinematic range of the measurements
- Large improvement in PDFs and flavour decomposition, potential to use single self-consistent set of measurements to determine them
- Not only complementary to HL LHC but very competitive EWK precision measurements program
- PERLE facility at Orsay → 500 MeV energy recovery linac, first step towards 50-60 GeV.

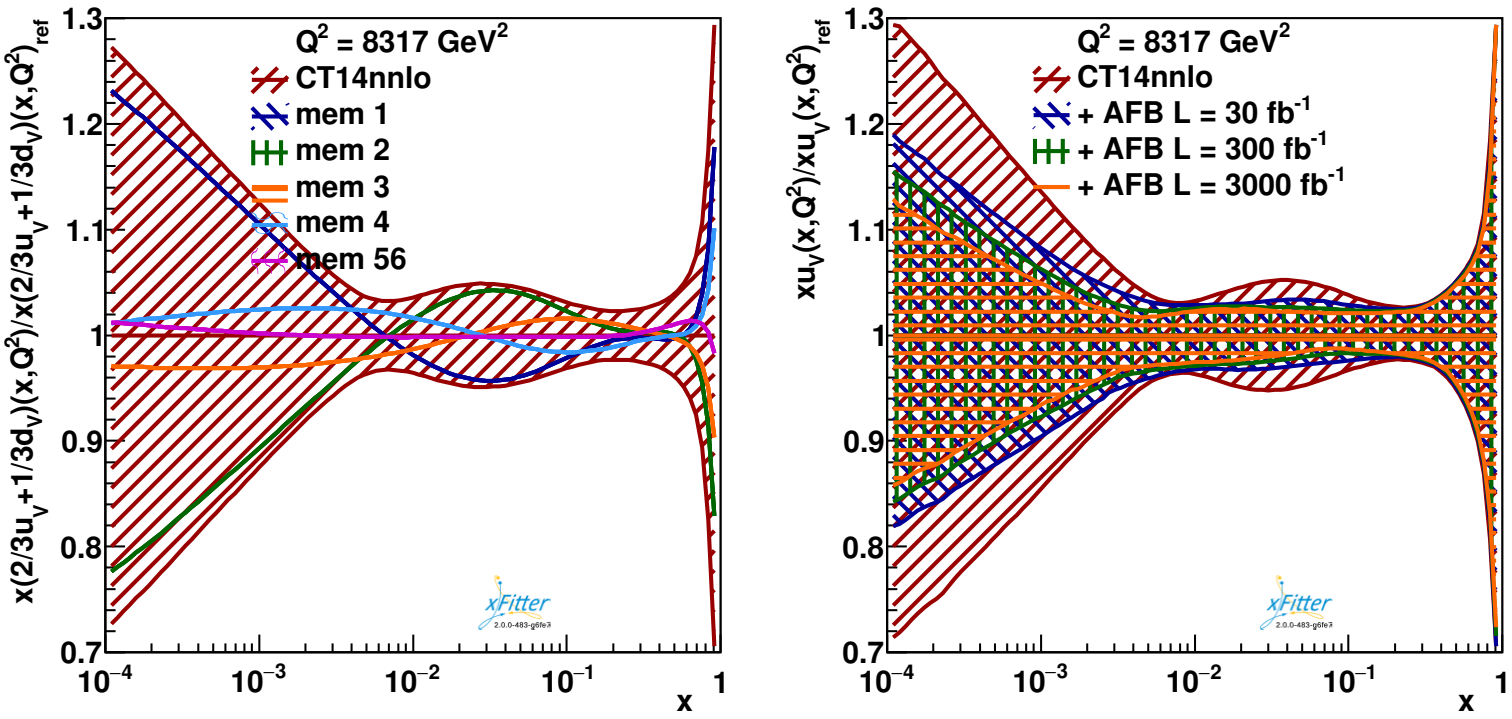
A_4 PDF uncertainties



- $\sin^2\theta_W$ is most sensitive to forward-backward asymmetry ("A_4") for the Z pole region.
- Asymmetry is generated by difference in quark- vs anti-quark PDF, different coupling to up- vs down-type quarks.
- Need accurate u_v, d_v for $x \sim 0.01$. Dilution from valence/sea needs to be under control.
- Exotic QCD effects such as $s - \bar{s}$ asymmetry, intrinsic c and b may also contribute.

ATL-PHYS-PUB-2018-004

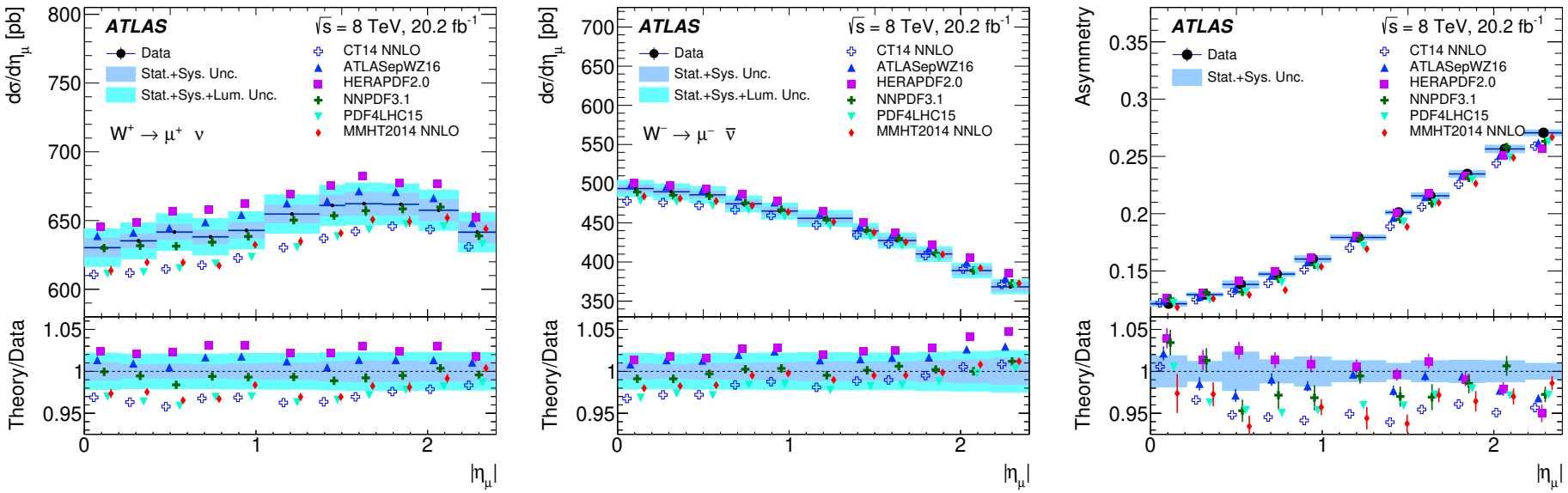
$\gamma - Z$ interference measurement and PDF contraints



- Off-resonance FB asymmetry is sensitive to $\gamma^* Z$ interference, proportional to $\frac{2}{3}u_V(x, Q^2) + \frac{1}{3}d_V(x, Q^2)$
- Can be used to constrain this linear combination of PDFs, however other observables are needed to decompose separate u_V and d_V contributions.

xFitter, JHEP 1910 (2019) 176

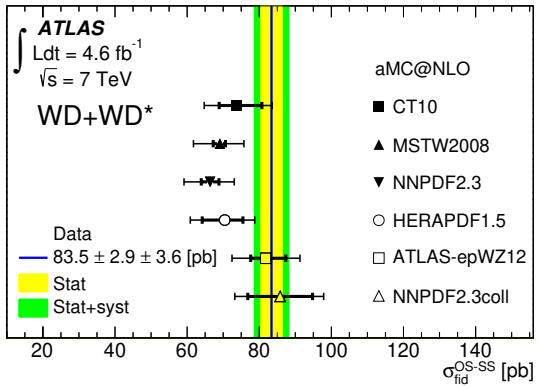
$W^{\pm} \to \ell^{\pm}\nu$ charge asymmetry measurement

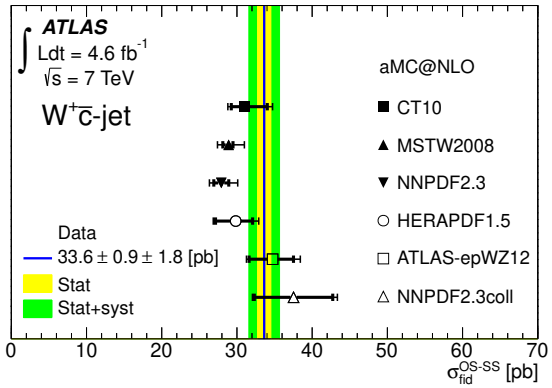


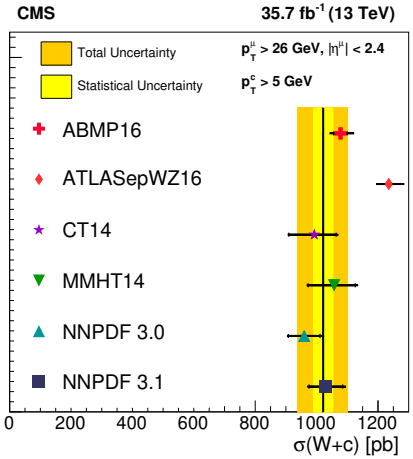
- W lepton charge asymmetry is at leading order proportional to $u_V - d_V$, can provide the missing constraint.
- Data accuracy is limited by systematic uncertainties, driven by pileup (lepton fakes, E_T^{miss} reconstruction). Could be measured better in dedicated low pileup samples.
- Data agree better with PDFs including ATLAS 7 TeV measurement (and HERAPDF2.0).

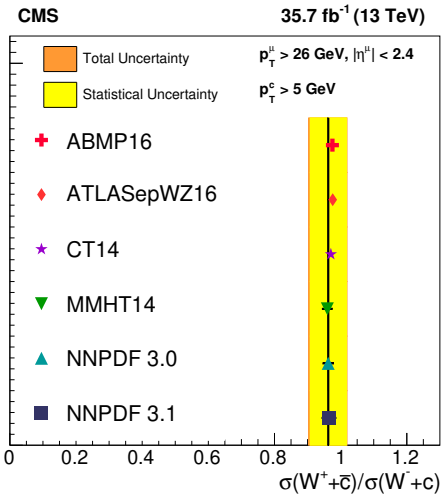
ATLAS, EPJC 79 (2019) 760

Measurements of $W+c$





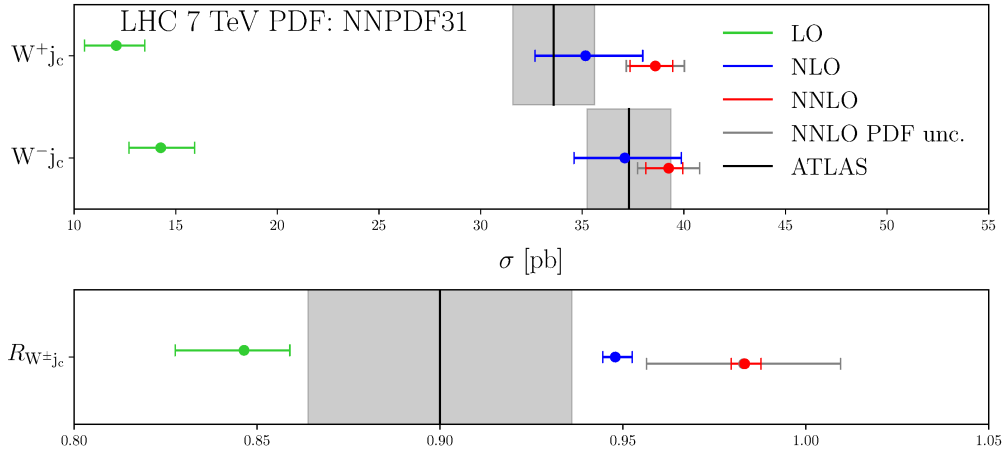




- Measurements of $\sigma(W^{\pm}c^{\mp}) - \sigma(W^{\pm}c^{\pm})$ from ATLAS using c-jets tagged by soft muons and $D^{(*)}$ mesons, to probe strange-sea PDF using $gs \rightarrow Wc$ process.
- W^+ vs W^- data can be used to constrain $s/\bar{s}$
- NLO scale uncertainties are larger than data uncertainties even for this $\sqrt{s} = 7$ TeV result: need for NNLO analysis.

ATLAS: JHEP 02 (2014) 013, CMS: EPJC 79 (2019) 269

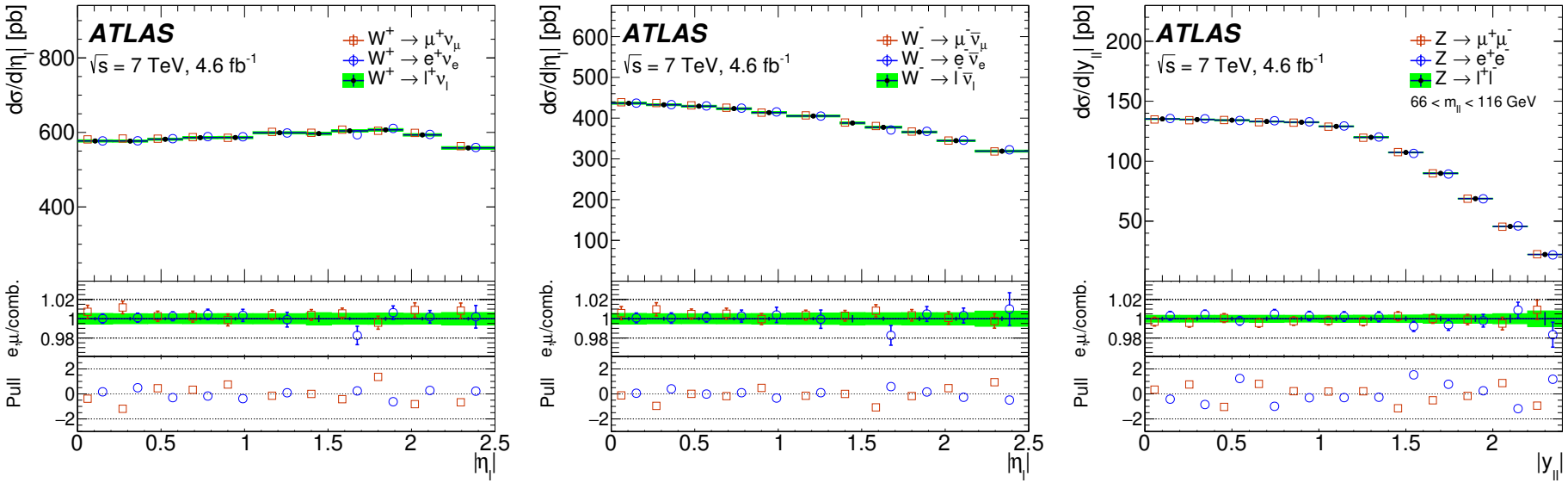
NNLO corrections for $W + c$



- Recent calculations of NNLO corrections for $W + c$ jet process.
- Corrections are significant, uncertainties are reduced singificantly too.
- However mis-match between flavour k_T and anti-k_T algoritms used for reconstruction
- Measurements of $W + D^{(*)}$ production are more accurate vs $W + c$ jet: predictions incuding charm fragmentation would be highly welcome.

arXiv:2011.01011

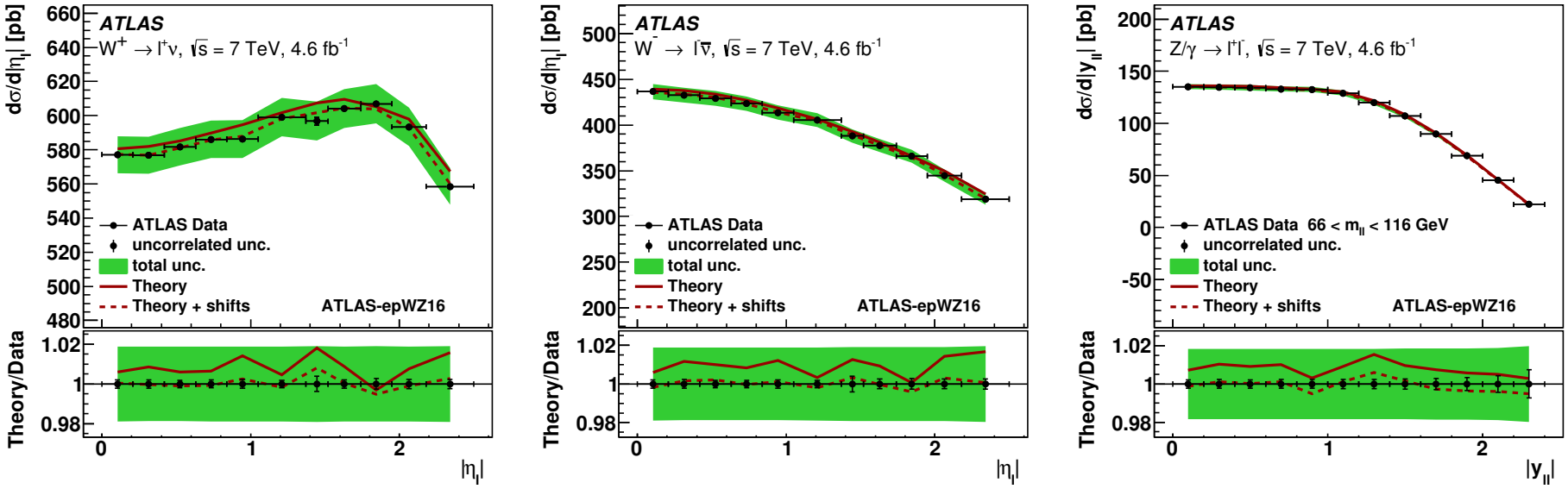
W and Z cross sections at $\sqrt{s} = 7$ TeV



- Differential measurements of $W^{\pm}$, Z/γ^* production (including off-peak) using electron and muon decays, with sub-percent accuracy, and full correlated errors treatment.
- Good compatibility of the two channels, $\chi^2/\text{dof} = 47.2/44$, combined result has better than 0.5% accuracy.

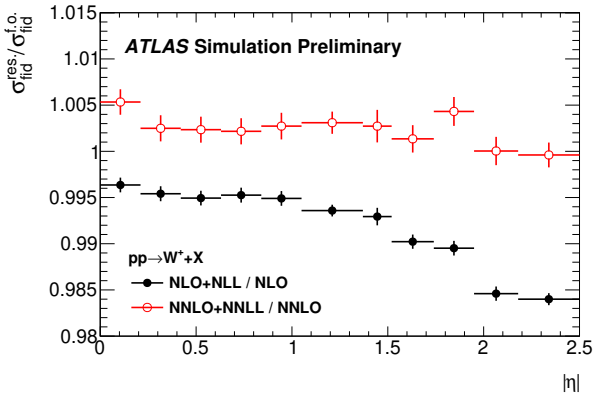
ATLAS EPJ C77 (2017) 367.

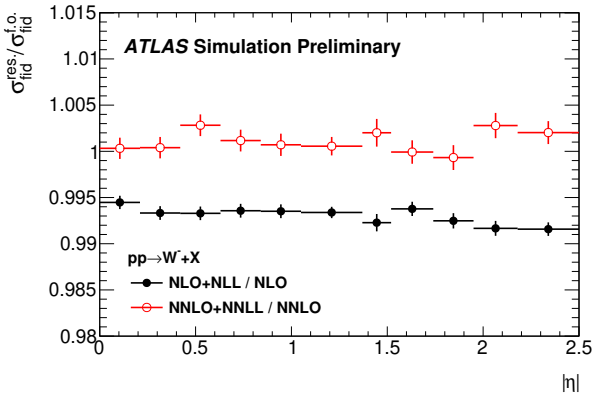
W and Z cross sections at $\sqrt{s} = 7$ TeV

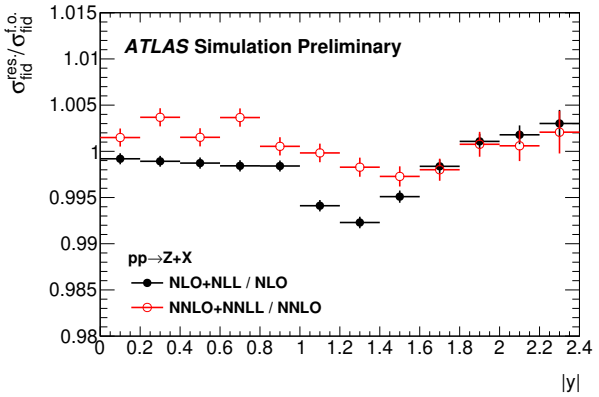


- ATLAS $W, Z/\gamma^*$ data together with the inclusive HERA-II data included in a QCD analysis at NNLO QCD + NLO EWK using xFitter program.
- Challenge for the theory to match the data accuracy,
  $\chi^2/\mathrm{N_{data}} = 108/61$ (ATLAS only) for the nominal scale settings
  $\mu_F = \mu_R = M_{\ell\ell}(M_W)$, improving to
  $\chi^2/\mathrm{N_{data}} = 85/61$ for $\mu_F = \mu_R = 1/2 M_{\ell\ell}(M_W)$

Effect of resummation



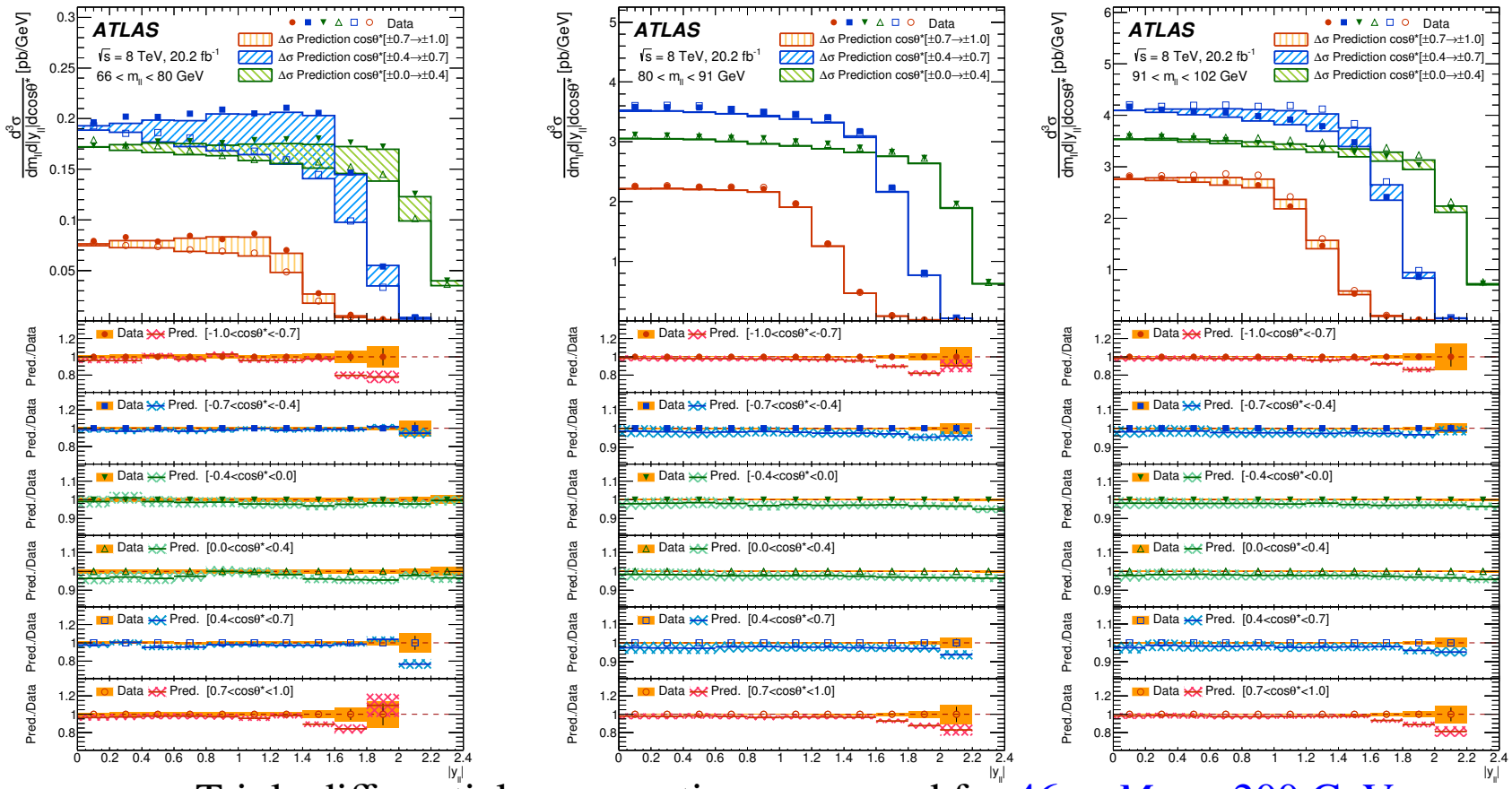




- 2011 W, Z differential cross section measurements are performed within fiducial volume, with $p_T^{\ell} > 20$ GeV and $E_T^{miss} > 25$ GeV cuts.
- Fiducial cuts shape $p_T^{W,Z}$ distribution, make fixed order predictions inaccurate.
- Difference observed between FEWZ and DYNNLO predictions for symmetric cuts (at $\sim 1\%$ level), however using asymmetric cuts does not solve the problem of p_T distribution shaping.
- Differences between NNLO and NNLO+NNLL calculations are comparable to data accuracy (but much better vs NLO - NLO+NLL).
- Differences for W^+ vs W^- – building asymmetry does not solve the problem completely.

ATL-PHYS-PUB-2018-004

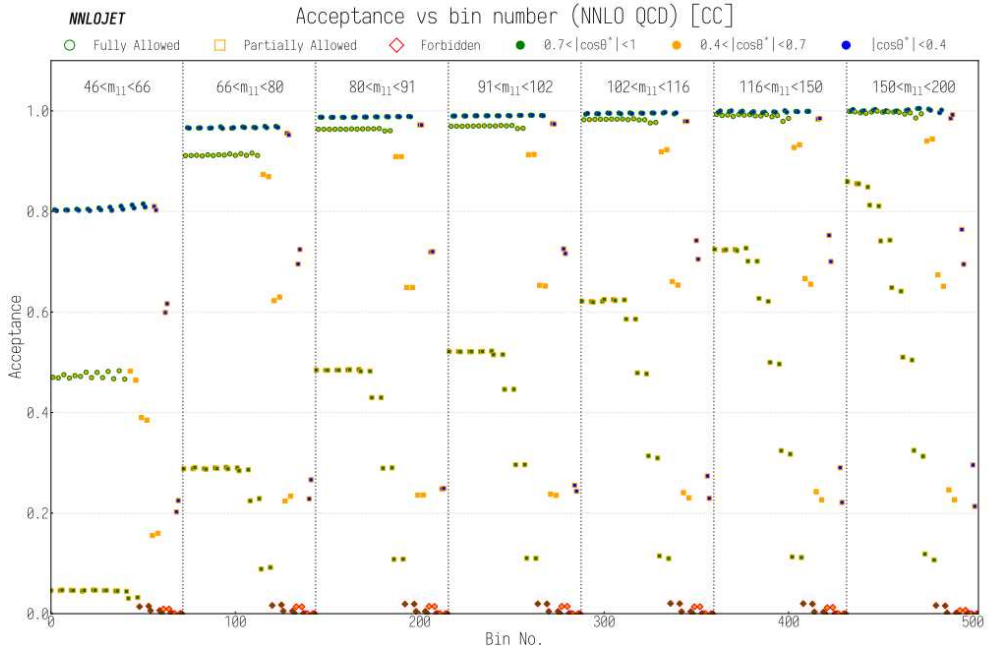
Triple differential cross section $d^3\sigma/dM_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*$



- Triple differential cross section, measured for $46 < M_{\ell\ell} < 200$ GeV range, for CC and CF topology.
- Simultaneous sensitivity to PDFs and $\sin^2\theta_W$, care needed for pure PDF interpretation.

JHEP 12 (2017) 059

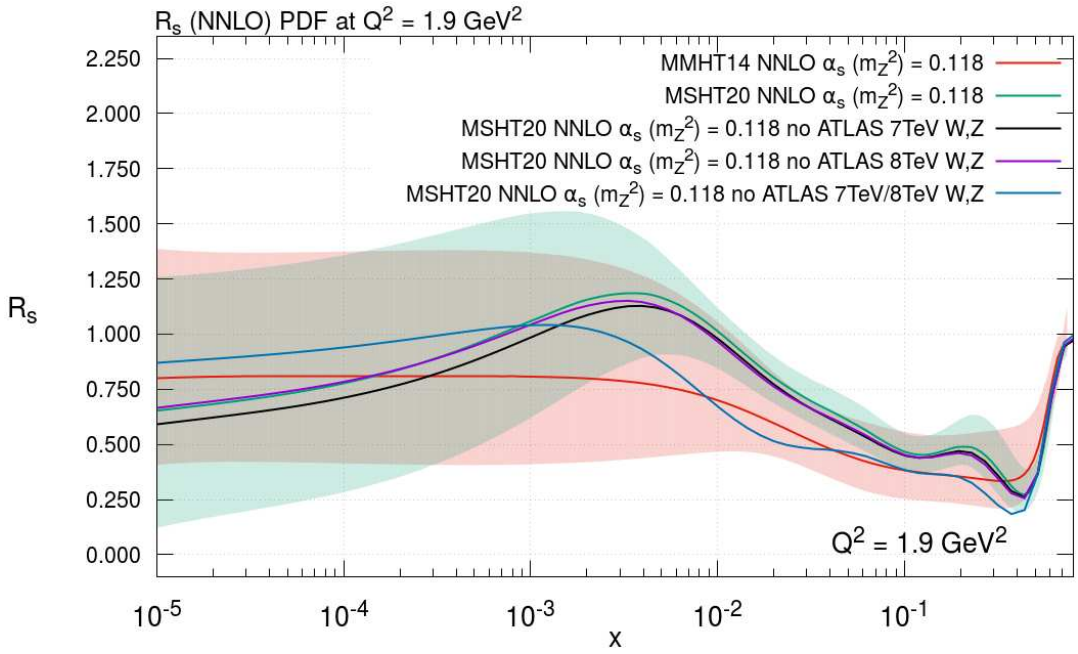
Acceptance for Z3D



- Acceptance, $A = \sigma_{fid}/\sigma_{tot}$ calculated using NNLOjet program at NNLO ($n_{jet} = 0$) shows strong variation vs $|\cos\theta_{CS}|$, $|y_{\ell\ell}|$ and $M_{\ell\ell}$ ("bin number $= 72i_M + 12i_y + i_{\cos\theta^*}$).
- More than 50% of bins at low $|\cos\theta^*|$ and $M_{\ell\ell} > 66$ GeV have $A > 95\%$.
- Restricting cross section data to these bins (which are also more accurate experimentally) allows to mitigate effect of fiducial cuts.
- Other bins can be converted to FBA.

D. Walker, PhD thesis

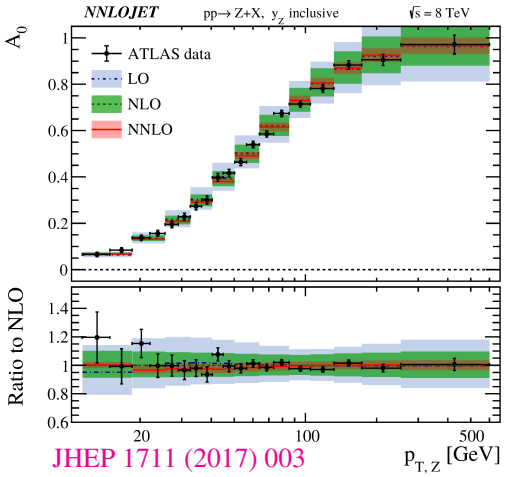
MSHT20 fit to ATLAS 8 TeV Z data



- Default fit is restricted to bins with acceptance $> 95\%$, integrates in $\cos\theta$ to remove $\sin^2\theta_W$ sensitivity.
- Acceptable $\chi^2/dof = 85.6/59$. When the low acceptance bins are included, fit quality is reduced significantly with $\chi^2/dof = 2.1$ without improvement in PDFs (data errors are large for the low acceptance bins).
- The value of $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ for $x \sim 0.02$ is driven in the fit by the ATLAS data, keeping 7 or 8 TeV yields similar value, removing both sets lowers R_S to the central result of MMHT14 fit.

arXiv:2012.04684

De-fiducializing for NC DY measurements



JHEP 1711 (2017) 003

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}p_T\,\mathrm{d}y_{\ell\ell}\mathrm{d}m_{\ell\ell}\mathrm{d}\cos\theta\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\,\mathrm{d}y_{\ell\ell}\mathrm{d}m_{\ell\ell}}\sum_{i=0}^{8} P_i(\cos\theta,\phi)$$

Fiducial cuts for leptons $p_T > 25$ GeV, $|\eta| < 2.4$, most relevant coefficient is A_0 which is $\sim \cos^2\theta$.

For a measurement differential in p_T and $y_{\ell\ell}$, one can first perform correction to the full phase space and then integrate in p_T, compare

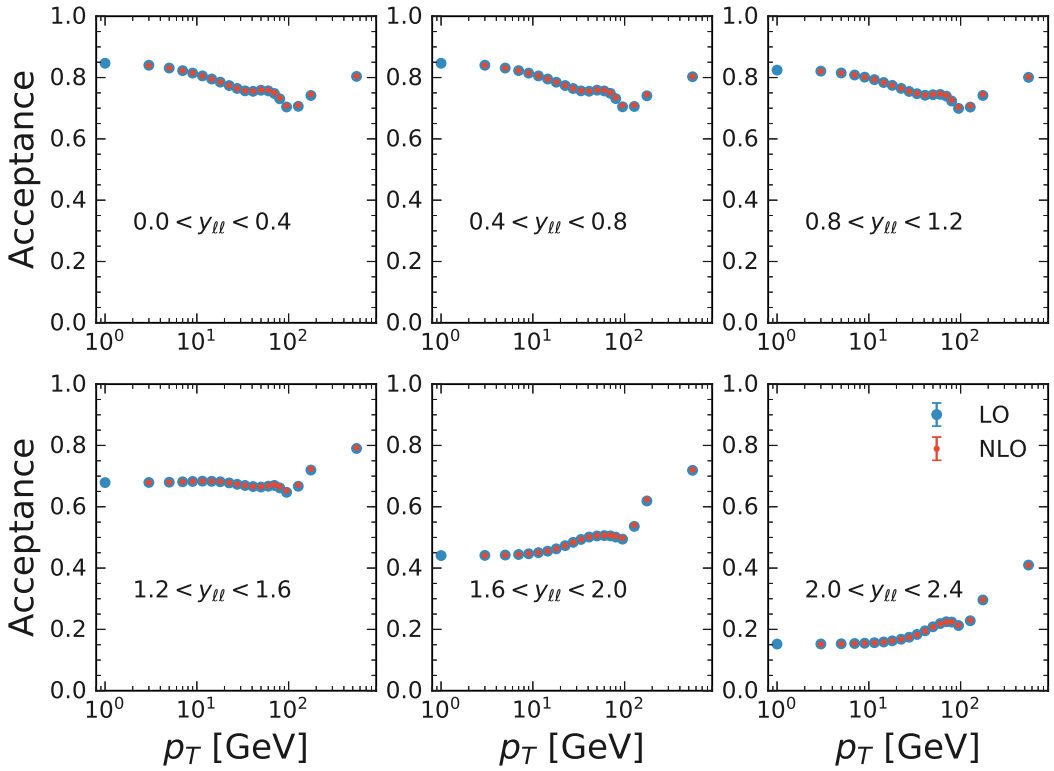
$$\sigma_{\text{full,theory}} = \int \frac{\mathrm{d}\sigma_{\text{theory}}}{\mathrm{d}p_T}\mathrm{d}p_T \quad \text{vs} \quad \sigma_{\text{full,data}} = \int \frac{\mathrm{d}\sigma_{\text{data}}}{\mathrm{d}p_T}\frac{1}{A(p_T)}\mathrm{d}p_T\,,$$

instead of fiducial cross sections

$$\sigma_{\text{fidu,theory}} = \int \frac{\mathrm{d}\sigma_{\text{theory}}}{\mathrm{d}p_T}A(p_T)\mathrm{d}p_T \quad \text{vs} \quad \sigma_{\text{fidu,data}} = \int \frac{\mathrm{d}\sigma_{\text{data}}}{\mathrm{d}p_T}\mathrm{d}p_T\,.$$

Acceptance $A(p_T)$ depends on kinematics and Z polarisation.

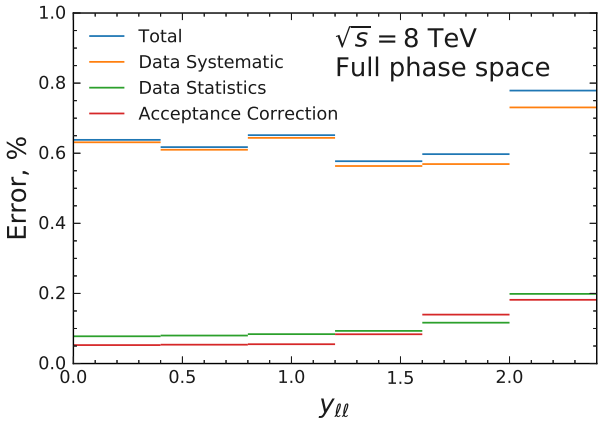
Acceptance vs p_T for Z boson production

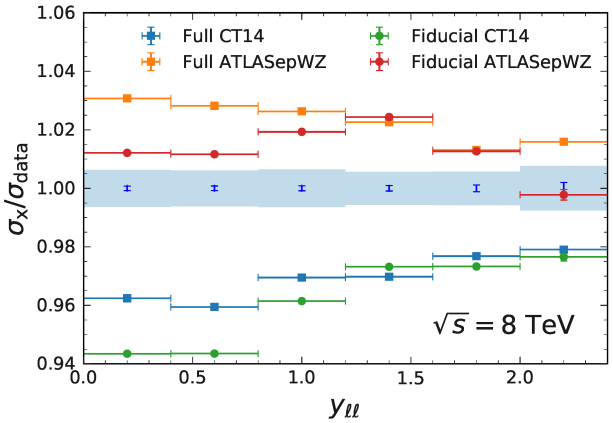


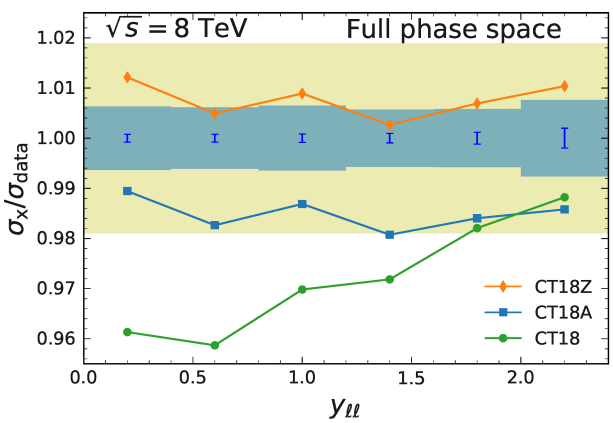
- ATLAS measurement of $d^2\sigma_Z/dp_T dy_{\ell\ell}$ using 8 TeV data
- MCFM predictions for Z+jet for acceptance, computed at LO and NLO agree to better than 0.2% for most of the bins.

EPJC 80, 875 (2020)

Full phase space ATLAS y_Z vs NNLO predictions

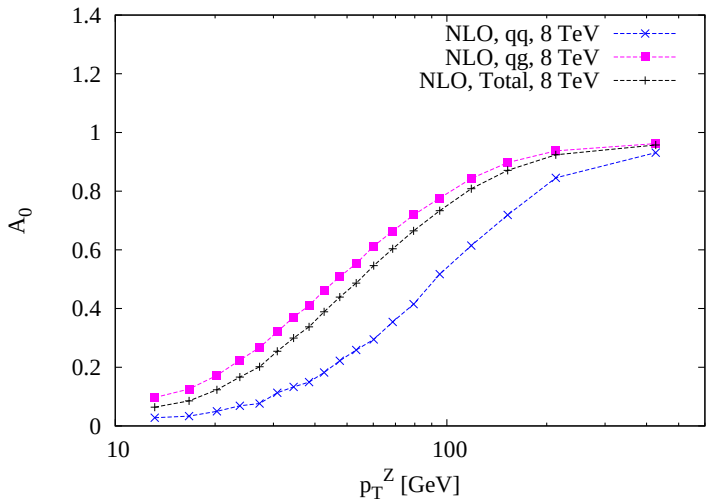


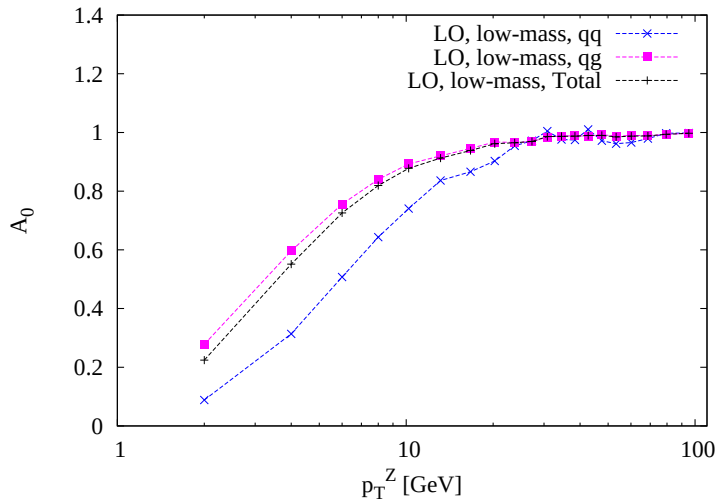




- Integrate the corrected data in p_T to obtain $d\sigma/dy_{\ell\ell}$ distribution. The extrapolation uncertainties are subleading.
- Compare with NNLO predictions computed using MCFM. Perform comparison using full and fiducial measurements, different PDFs. Agreement between data and theory is improved for full phase space, CT14 PDF.
- Compare data to theory using CT18 sets. Best agreement with CT18A and CT18Z, which have increased R_s.

Measurements of Z/γ^* polarisation (A_0)

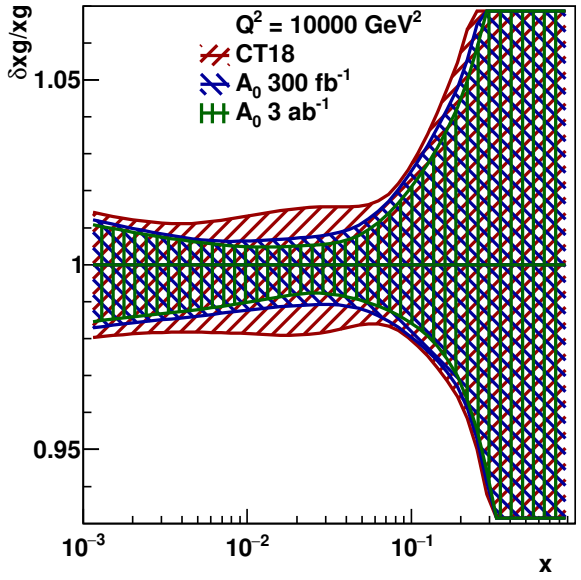


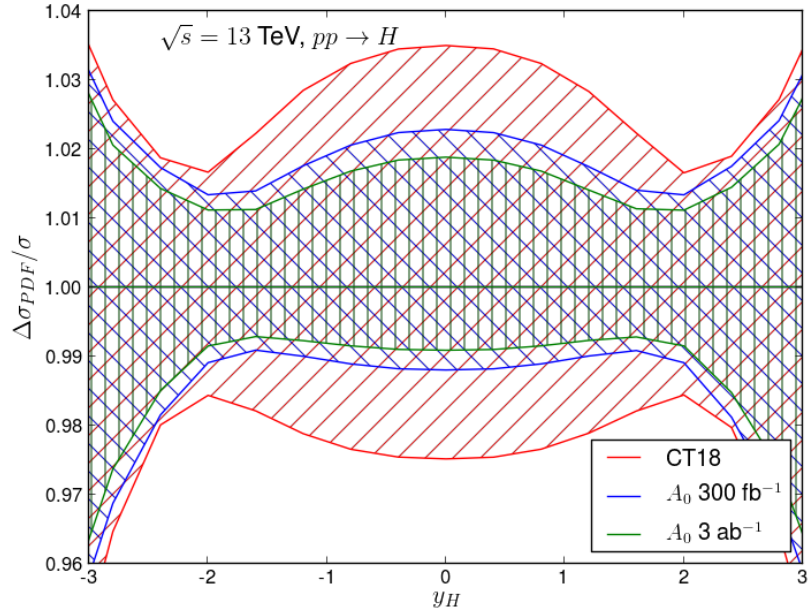


- The two diagrams contributing to Z+jet process at LO, $q\bar{q}$ and qg yield $A_0 = 0$ for $p_T = 0$ and $A_0 = 1$ for $p_T \gg M_{\ell\ell}$.
- The maximum sensitivity to g and $\bar{q}$ PDFs is reached at $p_T \sim 0.5 m_{\ell\ell}$.
- Measurements at the Z peak are senstive to the gluon at $0.001 < x < 0.01$ while measurements at $m_{J/\psi} < m_{\ell\ell} < m_\Upsilon$ can be used to probe $x < 0.001$.

DESY-20-216, in preparation

A_0 pseudodata profiling and Higgs cross section.





- Studies of A_0 coeffient measured by ATLAS using $\sqrt{s} = 8$ TeV data sample show good compatibility with modern PDF sets for NLO predictions, with $\chi^2/dof = 59/53$ for CT18NNLO set.
- Considering statistical uncertainty plus simplified systematics, pseudodata for $\mathcal{L}$= 300, 3000 fb^{-1} are profilied using `xFitter`.
- $\rightarrow$ significant reduction of gluon uncertainty, leading to visible reduction in PDF uncertainty for $gg \rightarrow H$ process, computed using MCFM.

Summary

- LHC measurements entering precision era require precise PDFs
- New ideas how to construct measurements with reduced theoretical uncertainties but large sensitivity to PDFs.
- A lot of work ahead:
  - Understanding of correlations among data within each experiment, across experiments, resolution of tensions
  - PDFs with explicit theory uncertainties, correlation among them