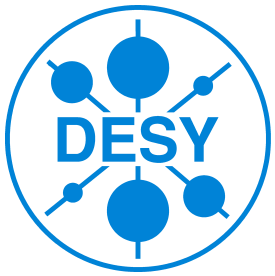
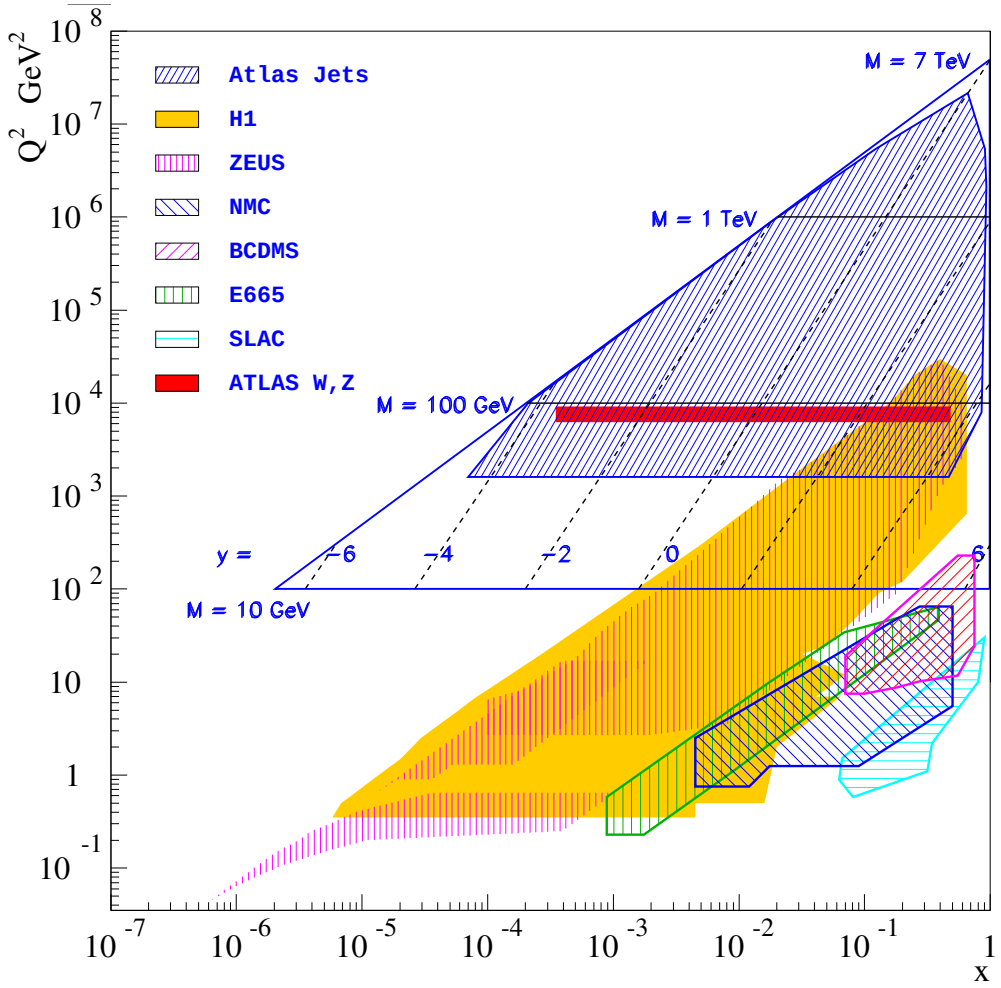


The HERAFitter project and results using HERAFitter

S. Glazov (DESY), for the HERAFitter developers' team

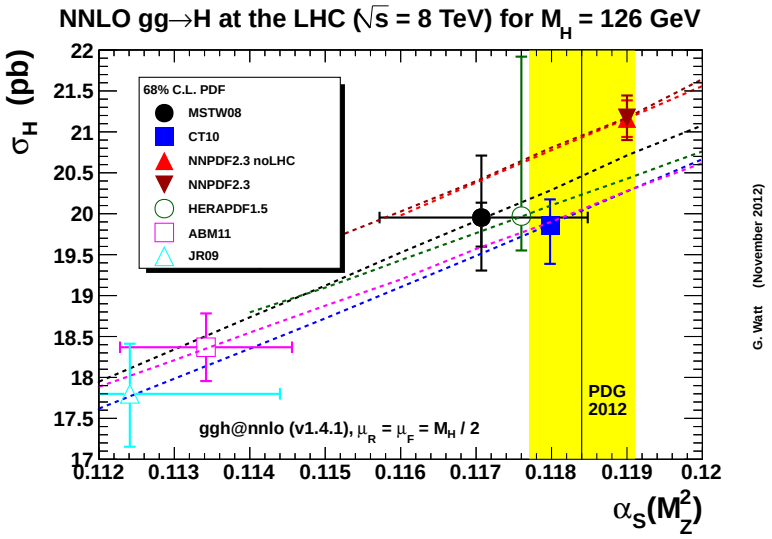
SM@LHC 2015, Florence.

Cross sections at LHC and PDFs



The cross sections are given by a convolution of the **parton distribution** and coefficient **functions**, $\sim x_1 f_1(x_1,\mu)\, x_2 f_2(x_2,\mu)\, \hat{\sigma}(x_1,x_2,\mu)$. PDFs are essential for predictions at the LHC.

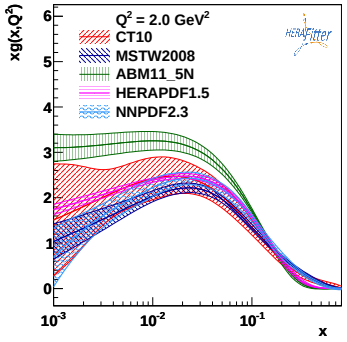
PDFs from different groups



- Many groups, ABM, MSTW (→MMHT), CTEQ (→CT and CJ), HERAPDF, NNPDF, JR, provide PDFs based on QCD analysis of DIS and pp data.
- In some cases, results of these groups do not agree with each other within quoted uncertainties.

→ HERAFitter is an open source platform to include coefficient function codes from different groups, common ground for benchmarking.
→ HERAFitter is a tool to optimize experimental measurements to maximize their PDF sensitivity.

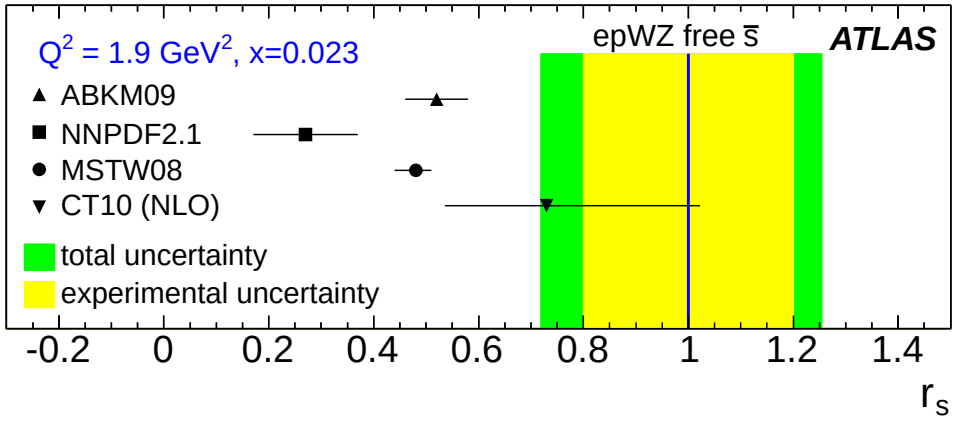
HERAFitter in an nutshell

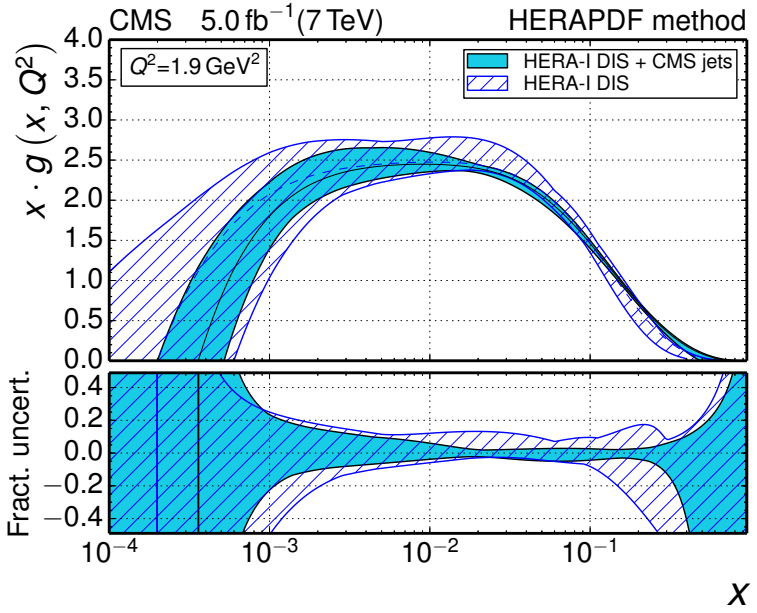


- Open-source program for development of QCD analyses herafitter.org
- Fast LO,NLO and NNLO evolution code using the QCDNUM and APFEL programs.
- Coefficient functions for deep inelastic scattering processes using the fast convolution engine of QCDNUM and codes from ACOT, RT, ABM, FONLL. Coefficient functions for pp and $p\bar{p}$ processes using APPLGRID and FastNLO programs.
- Alternative evolution: dipole model and TMD gluons.
- Flexible interface to include new data with correlated uncertainties.
- Fast analytic minimization vs nuisance parameters, MINUIT for PDFs.

arXiv:1410.4412

Usage by LHC experiments





HERAFitter is used for a number of LHC publications and theory papers, e.g.

- Determination of the strange-sea distribution function suppression using ATLAS W, Z boson measurements (PRL 109(2012) 012001).
- PDF constraints and α_S from the inclusive jet measurement by CMS (arXiv:1410.6765).

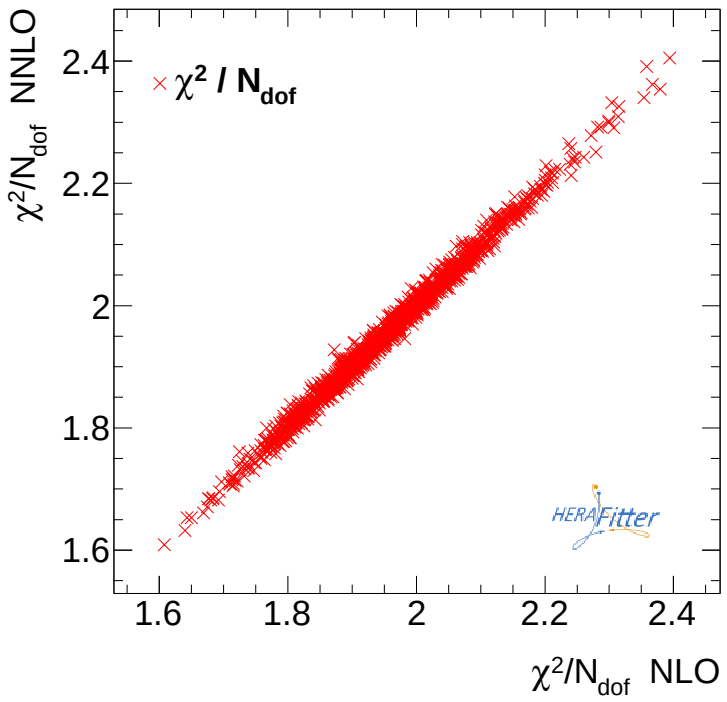
LO, NLO, NNLO PDFs with correlated uncertainties

Consider two processes, for process 1 there are NLO and NNLO calculations, for process 2 only NLO calculations exist. How to minimize theory errors for the prediction of the cross-section ratio ?

- $\frac{\sigma_1^{\rm NLO}(PDF^{\rm NLO})}{\sigma_2^{\rm NLO}(PDF^{\rm NLO})}$ — use NLO coefficient functions and PDFs for both processes. Good if scale dependence is identical (e.g. W charge asymmetry). Large scale uncertainties otherwise.
- $\frac{\sigma_1^{\rm NNLO}(PDF^{\rm NNLO})}{\sigma_2^{\rm NLO}(PDF^{\rm NLO})}$ — use NNLO (NLO) coefficient functions and different PDFs for the first (second) process. Reduces scale uncertainties, however PDF uncertainties are not treated correctly (correlation information lost).
- $\frac{\sigma_1^{\rm NNLO}(PDF^{\rm NNLO})}{\sigma_2^{\rm NLO}(PDF^{\rm NNLO})}$ — use NNLO (NLO) coefficient functions for the first (second) process and common NNLO PDF. Reduces scale uncertainties, however PDFs are treated inconsistently for process 2 calculation.

→ need for PDF sets with correlated uncertainties between different orders.

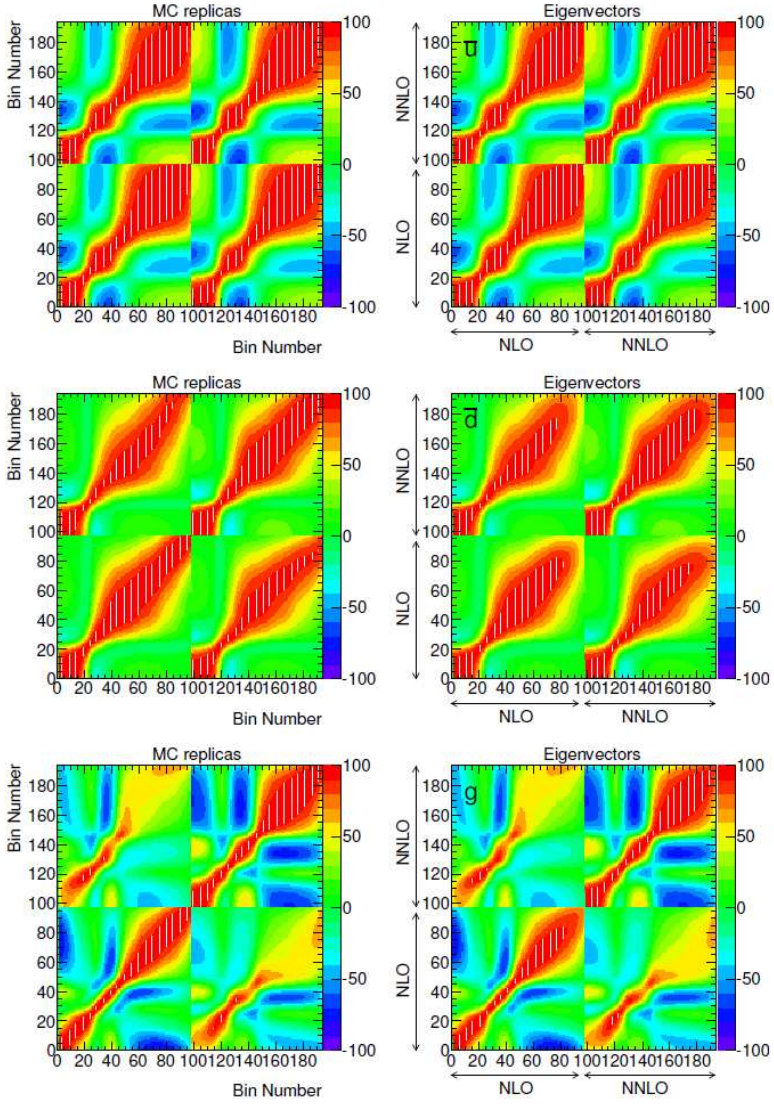
Correlated analysis methodology



- Fit using HERA data only, similar to HERAPDF1.0.
- Synchronize QCD fit settings for fits at different orders (parameterisation, starting scale, data cuts)
- Use MC method for uncertainties, synchronize seeds for fits at different orders.

arXiv:1404.4234

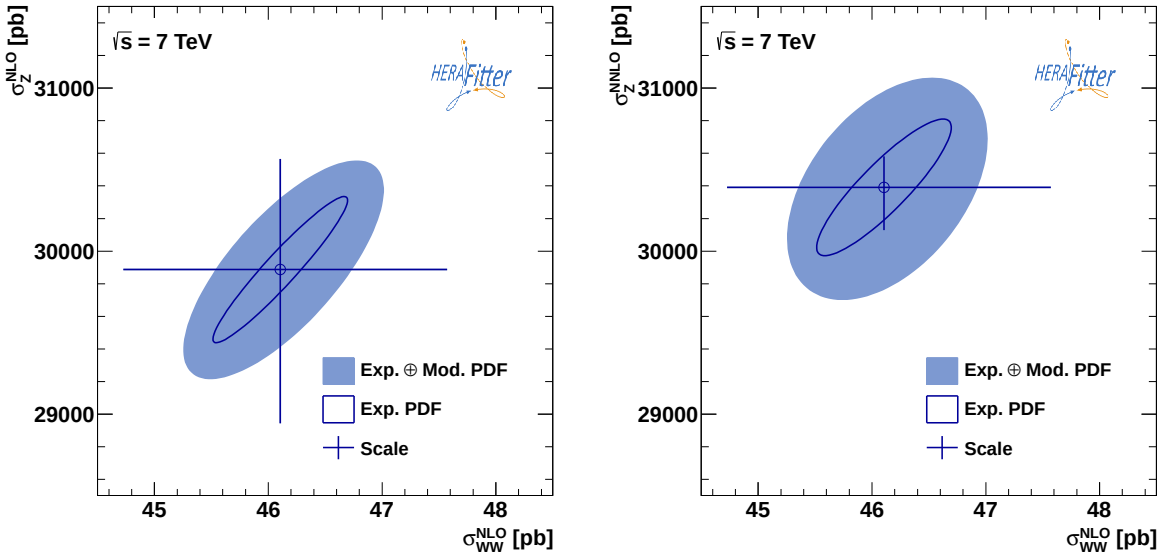
Correlated PDFs



(Bin number: ~ x)

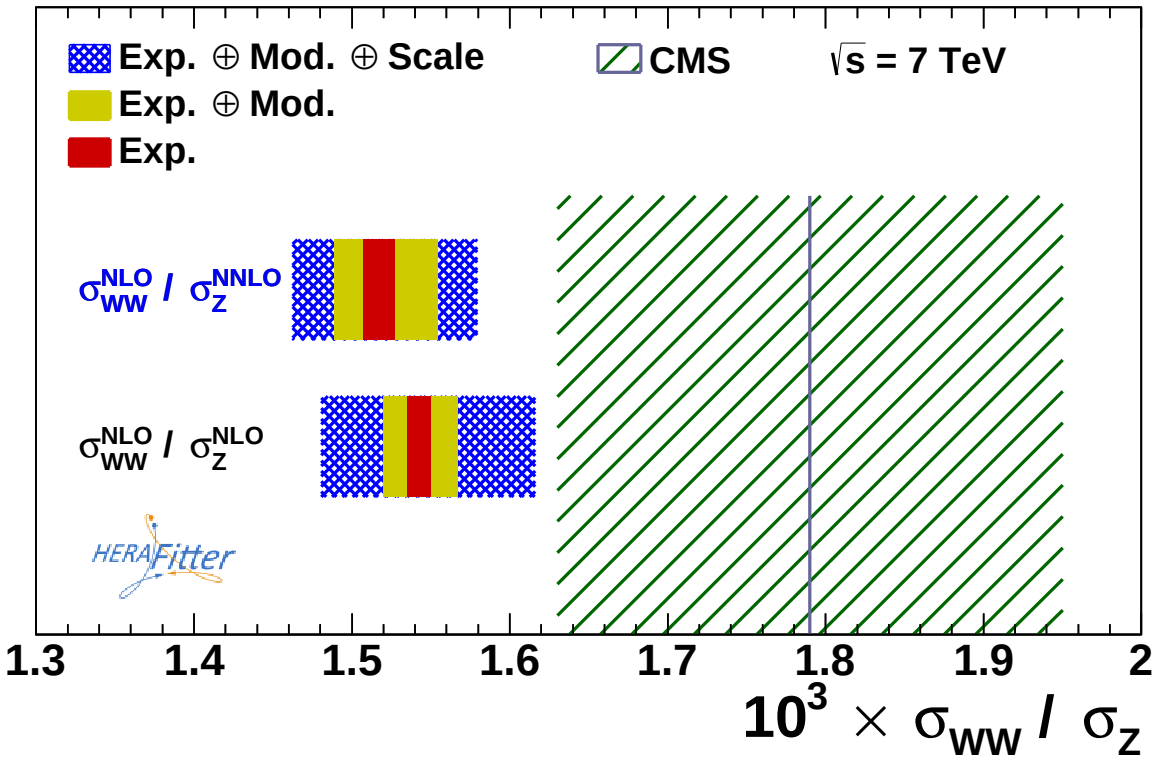
- PDF uncertainties determined by MC method are also transformed to eigenvector representation. This is achieved by diagonalization NLO-NNLO covariance matrix of PDF values at the QCDNUM x-grid points at the evolution starting scale $Q^2 = 1.7\ \mathrm{GeV}^2$ (fragments of the correlation matrix are shown here).
- High correlations for PDFs at similar x values. Very good description of the correlations using eigenvector representation. All PDFs except gluon at high x show high correlations between NLO and NNLO.

Z and WW production at LHC



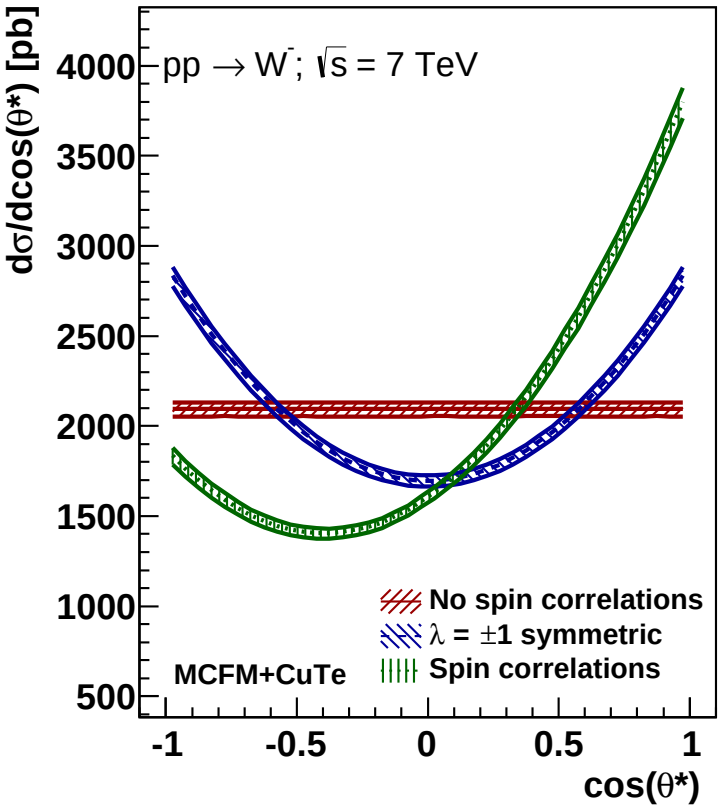
- Use case: Z boson and WW diboson production at the LHC.
- Z boson cross section calculated using FEWZ at NLO and NNLO; WW diboson cross section calculated using MCFM at NLO.
- Similar PDF dependence leads to high correlation of PDF uncertainties. The correlation is reduced when using NNLO calculation for σ_Z.
- Scale uncertainty is reduced when using σ_Z^{NNLO}.

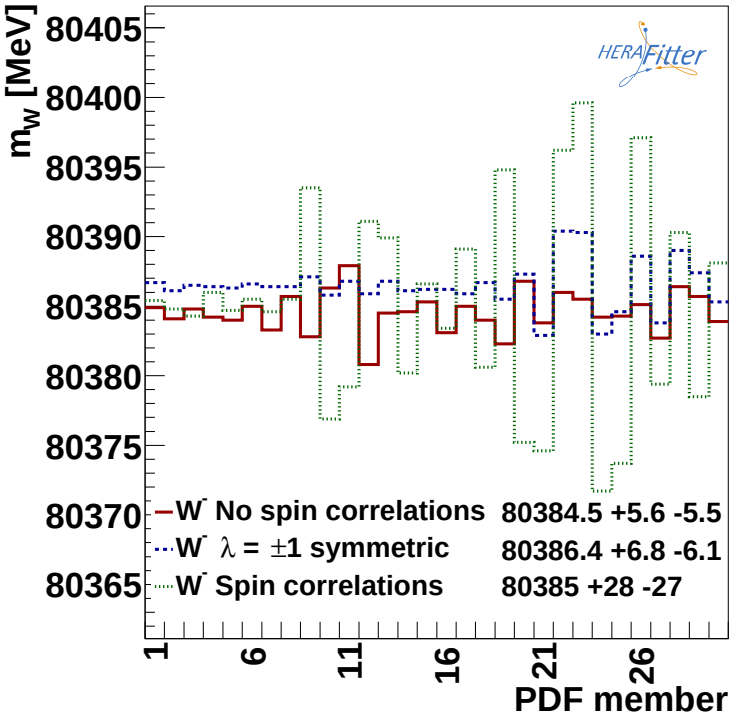
WW/Z cross-section ratio



- Compare the ratio of WW to Z production cross sections to the measurement by the CMS collaboration (EPJC73 (2013) 2610)
- While PDF uncertainty increases when using mixed NNLO-NLO predictions, the total uncertainty is reduced due to reduction of the scale uncertainty for the σ_Z prediction.

W mass measurement and PDF uncertainties

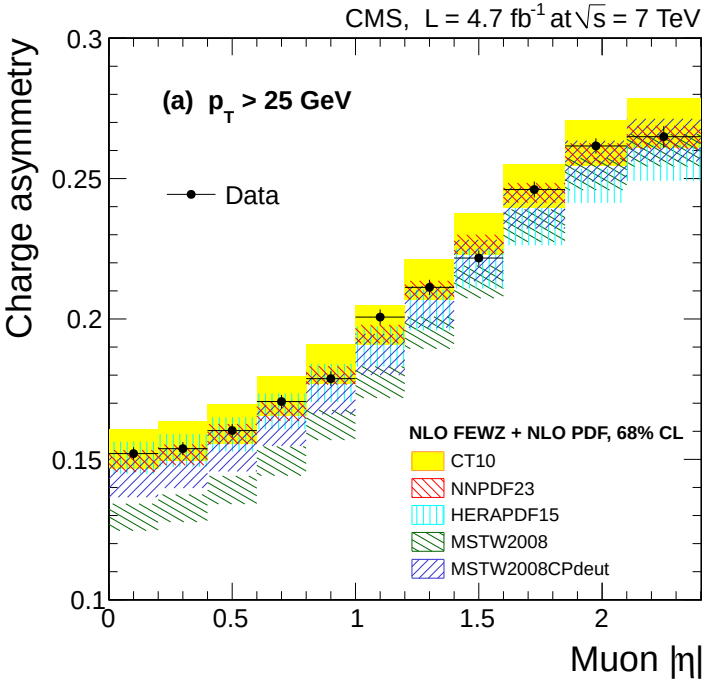


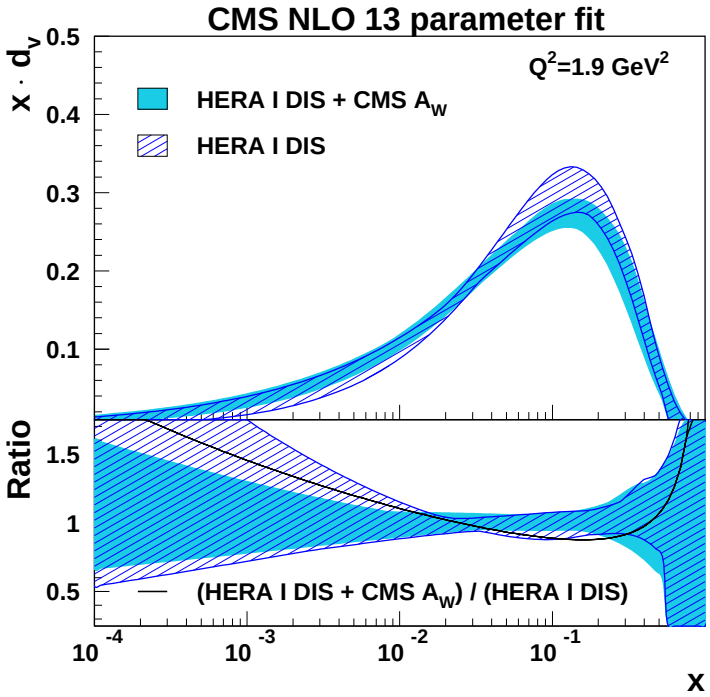


- At the LHC, the W boson mass can be measured using lepton p_T.
- W boson is produced polarised; polarisation affects lepton kinematics.
- Effect of the polarisation can be studied by turning it off, completely or transverse polarisation only. Uncertainty in transverse polarisation, arising from valence quarks, has siginficant impact on the W mass.

ATL-PHYS-PUB-2014-015

W asymmetry at the LHC





- Lepton charge asymmetry measurements from $W^{\pm} \to \ell^{\pm}\nu$ decays,

$$A_\ell = \frac{\sigma_{W^+\to\ell^+\nu} - \sigma_{W^-\to\ell^-\nu}}{\sigma_{W^+\to\ell^+\nu} + \sigma_{W^-\to\ell^-\nu}},$$

  at the LHC are sensitive to $u_v - d_v$ densities.

- QCD analysis of the HERA+CMS asymmetry data illustrates reduction of the d_v uncertainty in the range where data contributes.

arXiv:1312.6283

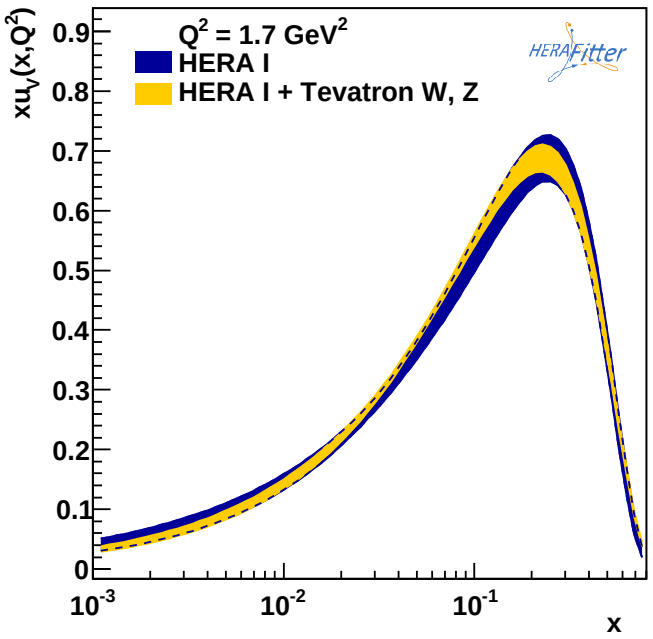
Tevatron W, Z production data

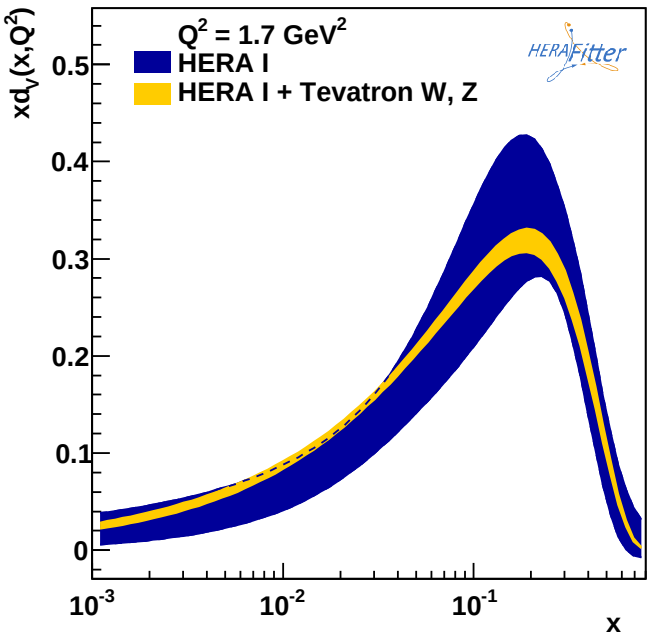
Observable	Experiment	Integrated luminosity	Kinematic requirements	Used in the nominal fit
$d\sigma(Z)/dy$	D0	0.4 fb^{-1}	$71 < m_{ee} < 111$ GeV	yes
$d\sigma(Z)/dy$	CDF	2.1 fb^{-1}	$66 < m_{ee} < 116$ GeV	yes
A_μ	D0	7.3 fb^{-1}	$p_T^\mu > 25$ GeV, $p_T^\nu > 25$ GeV	yes
$A_{W\to e\nu}$	CDF	1.0 fb^{-1}	none	yes
$A_{W\to e\nu}$	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	yes
A_e	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	no

- CDF and D0 experiments at Tevatron report measurements of $d\sigma(Z)/dy$, lepton (A_ℓ) and W ($A_{W\to\ell\nu}$) charge asymmetry.
- At $p\bar{p}$, $d\sigma(Z)/dy$ is more sensitive to d-quark vs DIS, W and lepton charge asymmetries are sensitive to d_v and u_v-quark distributions.

Tevatron: arXiv:0702025, arXiv:0908.3914, arXiv:1309.2591, arXiv:0901.2169, arXiv:1312.2895, arXiv:1412.2862 HERAFitter: arXiv:1503.05221

Impact of Tevatron data on d_v





- Study impact of Tevatron data by comparing fits to HERA-I data alone vs HERA-I plus Tevatron data.
- Perform parameterisation scan, starting form basic form and adding exponential or polynomial terms:

$$xf(x) = Ax^B(1-x)^C\left(1 + Dx + Ex^2\right)\exp Fx$$

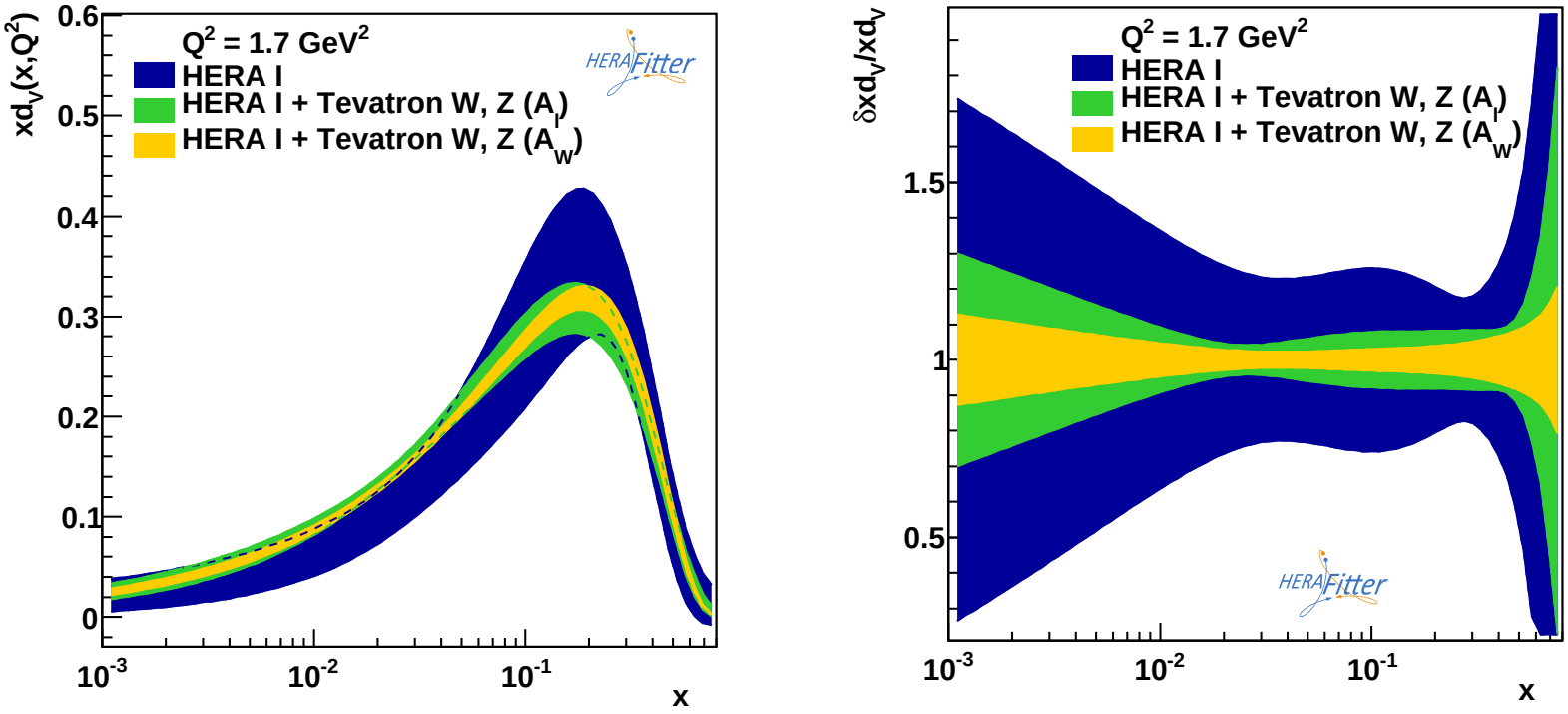
- Tevatron data have large impact on d_v uncertainty. After inclusion, relative uncertainties on d_v and u_v are about equal.

Fit quality

Data set	(partial) χ^2/dof	partial χ^2/dof vs PDF set		
		CT10	MMHT14	NNPDF3.0
D0 $d\sigma(Z)/dy$	23 / 28	—	—	—
CDF $d\sigma(Z)/dy$	32 / 28	—	—	—
D0 A_μ	12 / 10	13/10	—-	12/10
CDF $A_{W\to e\nu}$	14 / 13	14/13	—	15/13
D0 $A_{W\to e\nu}$	8 / 14	8/14	5/14	2/14
Total $\chi^2_{\rm min}$ (incl. HERA) / dof	606 / 628	—	—	—

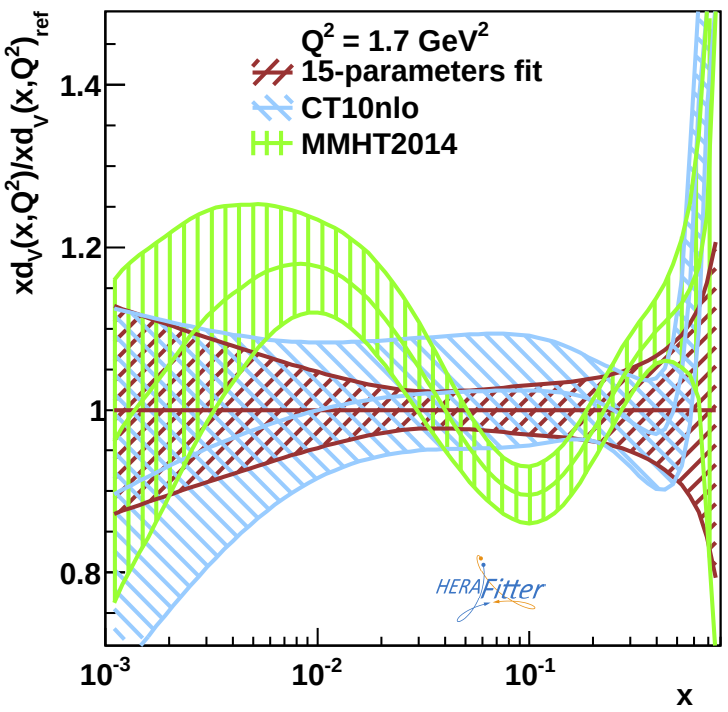
- All data sets can be described by the fit and predictions based on CT10, MMHT14 and NNPDF3.0 PDF sets with good quality.
- Both D0 and CDF data sets have comparable description: no tensions among Tevatron data.

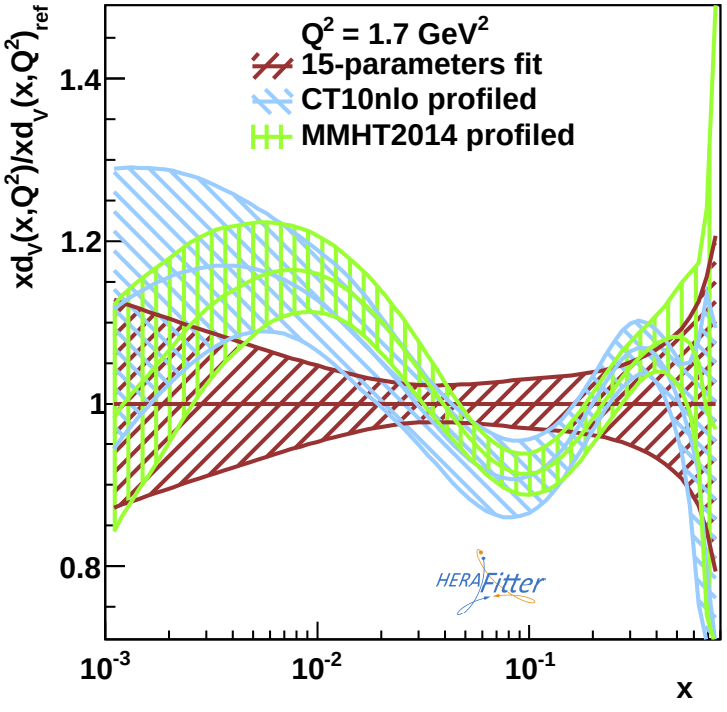
Fits to *W* vs lepton asymmetry



- D0 provides asymmetry measurement in terms of lepton and *W* asymmetry. The later requires assumptions on the neutrino longitudinal direction.
- Fits to either data type are compatible, *W*-asymmetry data lead to more accurate PDFs.

Impact on global PDFs





- Imapct on PDFs can be studied by minimizing data to theory χ^2 vs nuisance parameters corresponding to PDF eigenvectors ("profiling"):

$$\chi^2(\beta_j^{\mathrm{PDF}}) = C^T \left(D - T(\beta_j^{\mathrm{PDF}})\right) C + \sum_j (\beta_j^{\mathrm{PDF}})^2$$

- Uncertainties on d_v are reduced, CT10 and MMHT14 agree better.

Summary

- HERAFitter is an open-source platform for QCD analyses.
- HERAFitter provides state-of-the-art calculations for LO,NLO,NNLO predictions and fast minimization tools.
- HERAFitter is actively used by the LHC experiments and theory community.
- Studies by HERAFitter developers of the correlated PDFs for different orders allows to reduce theoretical uncertainties for cross-section ratios, calculated at different order.
- Fits and profiling studies of the recent Tevatron W, Z data show importance of them to constrain d_v distribution, which is essential for the W-boson mass measurement at the LHC.

PDF uncertainties for Z and WW production

Variation	$\sigma_{WW}^{\mathrm{NLO}}$ %	$\sigma_{Z}^{\mathrm{NLO}}$ %	$\sigma_{Z}^{\mathrm{NNLO}}$ %
$r_s(-0.3)$	1.00	-0.29	-0.33
$r_s(+0.3)$	-0.81	0.39	0.42
$M_c(-0.06\ \mathrm{GeV})$	-0.81	-0.89	-0.76
$M_c(+0.06\ \mathrm{GeV})$	0.55	0.66	0.61
$M_b(-0.45\ \mathrm{GeV})$	0.13	0.11	-0.02
$M_b(+0.25\ \mathrm{GeV})$	-0.07	-0.07	0.00
$\alpha_S(M_Z)(-0.002)$	-0.54	-1.27	-1.17
$\alpha_S(M_Z)(+0.002)$	0.52	1.23	1.17
$Q^2_{\mathrm{min}}(-2.5\ \mathrm{GeV}^2)$	-0.25	-0.35	0.23
$Q^2_{\mathrm{min}}(+2.5\ \mathrm{GeV}^2)$	0.75	0.73	-1.06
$Q_0^2(-0.2\ \mathrm{GeV}^2)$	-0.21	-0.19	-0.14
$+D_{u_v}$	-0.03	-0.32	0.97
$+D_{\bar{U}}$	-0.04	-0.02	-0.01
$+E_{\bar{U}}$	0.01	0.00	0.00

Table 2 Shifts of the WW di-boson and Z boson production cross sections due to the model and parameterisation variations in the PDF fit.

While experimental PDF uncertainties are all very highly correlated, uncertainties releated to model and parameterisation assumptions show anticorrelation for some sources:

- Charm- (M_C), bottom- (M_B) quark mass parameters, strong coupling ($\alpha_S(M_Z)$) and evolution starting scale (Q_0^2) variations cause correlated variations of the cross sections.
- $r_s = \bar{s}/\bar{d}$ variation is anticorrelated between Z and WW.
- Requirement on input data scale (Q^2_{min}) is anticorrelated between NLO and NNLO.