



OPEN SOURCE QCD FIT FRAMEWORK AND ITS RELATED STUDIES

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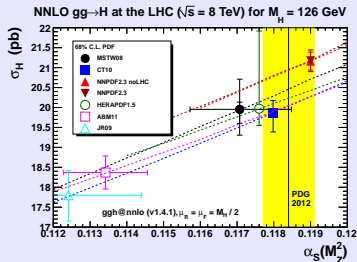
MOTIVATION

Parton Distribution Functions are essential for precision physics at the LHC:

- one of the main theory uncertainties in M_W measurement,
- uncertainties in Higgs production,
- PDFs uncertainties also affect substantially theory predictions for BSM high mass production.

There are two main sources for PDF uncertainties:

- the data precision is limited,
- different PDF groups use different methodologies and input datasets for analysis: MSTW, CT, NNPDF, HERAPDF, ABM, JR



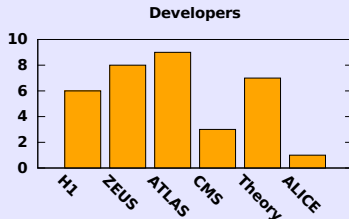
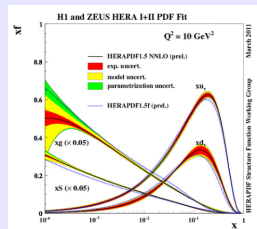
G. Watt (November 2012)

HERAFITTER PROJECT

HERAFitter is an open source QCD fit platform with a continuing rapid development

<http://www.herafitter.org>

- is a unique framework to address the theoretical differences
- provides means to the experimentalists to estimate impact of new data
- new developments of the HERAFitter and dedicated studies made by developers and interested users



PDF EXTRACTION IN HERAFITTER

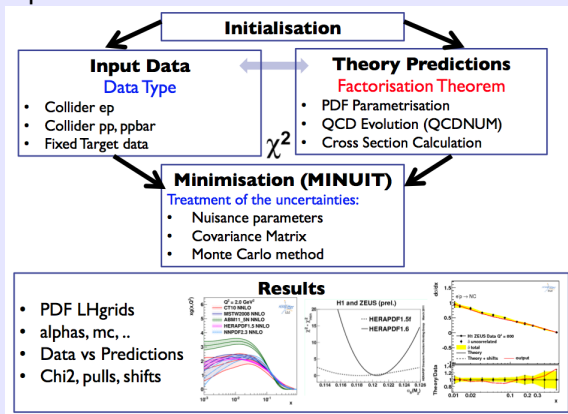
■ On data side

Important to provide correlation information

■ On theory side

Important to have fast tools to perform PDF fits i.e. APPLGRID, FASTNLO - grid techniques rely on factorisation theorem

Operation scheme:

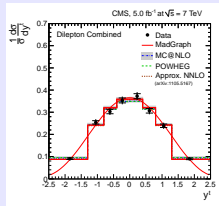


EXPERIMENTAL INPUT

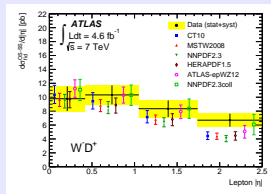
A number of datasets from ep , pp and $p\bar{p}$ colliders can be used in the HERAFitter to constrain proton PDFs in various kinematic domains

Examples:

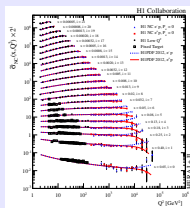
- Top pair at LHC – CMS
- W+c production – ATLAS
- HERA inclusive DIS
- Tevatron incl. jets



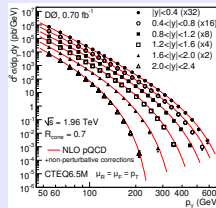
Eur.Phys.J. C73 (2013) 2339.



JHEP 1405 (2014) 068.



JHEP 1209 (2012) 061.



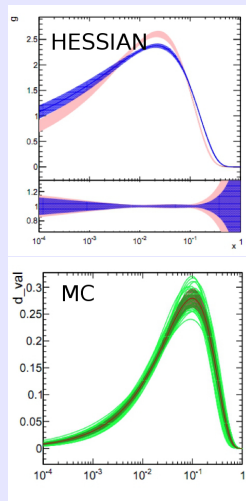
Phys.Rev. D85 (2012) 052006.

EXPERIMENTAL UNCERTAINTIES

HERAFitter provides various methods for the treatment of experimental uncertainties

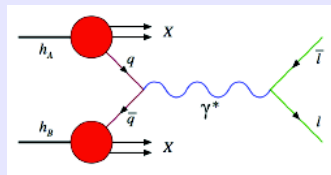
- Symmetric/Asymmetric Hessian : error inflation by a tolerance parameter to accommodate
- Monte Carlo method : MC replicas shifting data point randomly according to their uncertainties
- Offset method : correlated errors accommodated in uncertainties

Monte Carlo Method for error estimation compared to Hessian error propagation:
Benchmarking exercise with NNPDF group
[[arXiv:0901.2504](https://arxiv.org/abs/0901.2504)]



THEORY PREDICTIONS

The prediction of a particular process cross section is obtained by a convolution of the evolved PDFs and the partonic cross section, calculated at a certain order in QCD with an appropriate theory calculation



PROCESSES

- Drell-Yan
- top pair
- single top
- jets
- DIS NC, CC
- DIS jets
- DIS heavy quarks

CALCULATIONS

- QCDNUM [arXiv:1005.1481](#)
- MCFM(ApplGrid) [arXiv:1007.3492](#),
[arXiv:0911.2985](#)
- fastNLO [arXiv:1208.3641](#)
- HATHOR [arXiv:1007.1327](#)
- uPDFevolv [arXiv:1407.5935](#)
- OPENQCDRAD

www-zeuthen.desy.de/alekhin/OPENQCDRAD

The PDFs are parametrised at a starting input scale Q_0^2 by a chosen functional form with a set of free parameters. These PDFs are evolved to the scale of the measurement Q^2 , $Q^2 > Q_0^2$.

HERAFitter supports several approaches to QCD evolution:

- DGLAP via QCDNUM
- Dipole models(GBW, IIM, BGK) [Phys.Rev. D86 \(2012\) 074017](#)
 - an alternative approach to the low-x region
- Unintegrated PDFs [arXiv:1206.1796](#)
 - based on CCFM evolution

Also user can use External PDFs via LHAPDF interface to construct theoretical predictions.

HEAVY FLAVOUR SCHEMES IN DIS

Heavy quarks introduce additional scales which complicates the calculations. HERAFitter supports a variety of flavour schemes:

■ VFNS (Variable Flavour Number Schemes):

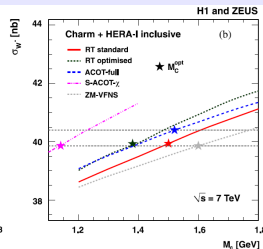
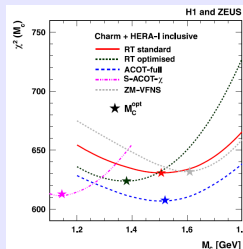
- Zero Mass VFNS
- R. Thorne's RT-VFNS schemes, used by MSTW group
- ACOT schemes as used by CT(CTEQ) group

■ FFNS (Fixed Flavour Number Scheme)

- via QCDNUM
- via OPENQCDRAD, as used by ABM

Some schemes were tested by H1/ZEUS collaborations in F_2^{charm} analysis [Eur. Phys. J. C73 \(2013\) 2311](#)

Spread in predictions for W and Z @LHC is reduced significantly when predictions are evaluated at the optimal m_{charm} determined from F_2^{charm}



FUNCTIONAL FORMS FOR PDF PARAMETRISATION

Several forms of PDF parametrisation allowed in HERAFitter:

- standard polynomials

$$xf_j(x) = A_j x^{B_j} (1-x)^{C_j} P_i(x),$$

- Bi-Log-Normal Distributions

$$xf_j(x) = a_j x^{p_j - b_j \log(x)} (1-x)^{q_j - d_j \log(1-x)},$$

- Chebyshev polynomials

$$xg(x) = A_g (1-x) \sum_{i=0}^{N_g-1} A_{g_i} T_i \left(-\frac{2 \log x - \log x_{\min}}{\log x_{\min}} \right),$$

$$xS(x) = (1-x) \sum_{i=0}^{N_S-1} A_{S_i} T_i \left(-\frac{2 \log x - \log x_{\min}}{\log x_{\min}} \right)$$

The HERAFitter package allows for various types of data uncertainty treatment

- Covariance Matrix Representation

$$\chi_{exp}^2(m, b) = \sum_{i,j} (m_i - \mu_i) C_{ij}^{-1} (m_j - \mu_j) ,$$

$$C_{ij} = C_{ij}^{stat} + C_{ij}^{uncor} + C_{ij}^{sys}$$

- Nuisance Parameters Representation

$$\chi_{exp}^2(m, b) = \sum_i \frac{[m^i - \sum_j \gamma_j^i m^j b_j - \mu^i]^2}{\delta_{i,stat}^2 \mu^i (m^i - \sum_j \gamma_j^i m^j b_j) + (\delta_{i,uncor} \mu^i)^2} + \sum_j b_j^2$$

- mixed form (covariance and nuisance parameter)

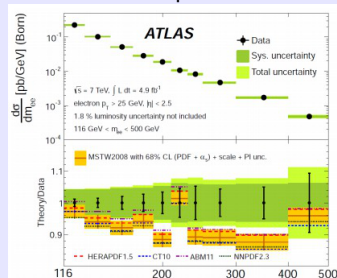
HERAFitter offers the possibility to include form of treating statistical, uncorrelated and correlated systematic uncertainties given in different forms.

COMPARISON BETWEEN DATA AND THEORY

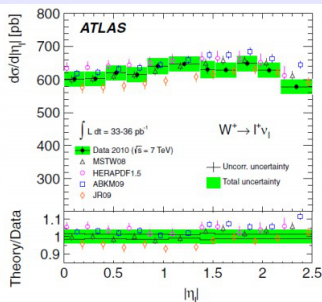
HERAFitter provides a quantitative assessment of level of agreement between data and theory by taking into account theoretical and experimental uncertainties

$$\chi^2 = \sum_i \left(\frac{\mu_i - m_i \left[1 + \sum_j b_j^{\text{exp}} \gamma_{ji}^{\text{exp}} + \sum_j b_j^{\text{theo}} \gamma_{ji}^{\text{theo}} \right]}{\Delta_i} \right)^2 + \sum_j \left(b_j^{\text{exp}} \right)^2 + \sum_j \left(b_j^{\text{theo}} \right)^2$$

Used in ATLAS publications



Phys. Lett. B 725 (2013) 223



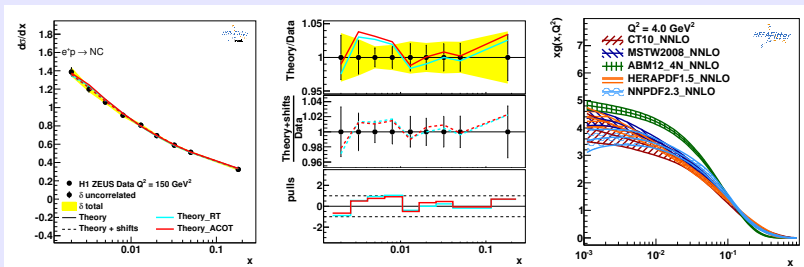
Phys. Rev. D 85 (2012) 072004

FUNCTIONALITY

The resulting PDFs are provided in a format ready to be used by the **LHAPDF** library (both **V5** and **V6**).

HERAFitter **drawing tools** can be used to display the PDFs with their uncertainties at a chosen scale.

- Plot and compare PDFs (via LHAPDF)
- Compare different PDF sets to data
- Estimate agreement using χ^2 criteria

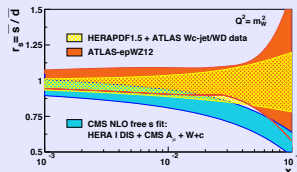
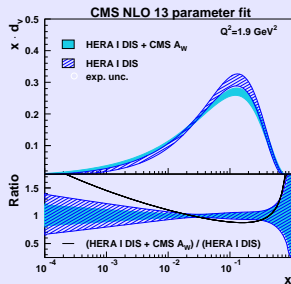


RESULTS

HERAFitter framework has been successfully used in many analyses (by experiments and theory groups)

<http://www.herafitter.org/HERAFitter/HERAFitter/results>

- ATLAS Drell-Yan measurements,
JHEP 1406 (2014) 112, Phys.Lett. B725 (2013) 223242
- PDF determination using CMS and ATLAS inclusive jet data
CMS PAS SMP-12-028 (2014), Eur.Phys.J. 73 (2013) 2509
- Strange quark density measurements in ATLAS and CMS
ATL-PHYS-PUB-2013-018, PRD 90 (2014) 032004
- Sensitivity of proton PDF to the inclusive photon production at ATLAS
ATL-PHYS-PUB-2013-018



PDFs at LO, NLO, NNLO with correlated uncertainties between orders

Motivation: most of the Standard Model processes at the LHC are calculated to NLO accuracy often with large theoretical uncertainty

- Factorisation theorem: $\sigma = \hat{\sigma} \otimes PDF$
- uncertainties rise from PDFs and coefficient functions
- missing higher order uncertainties often determined by the scale variation

to reduce theoretical uncertainties ratios of cross sections are used.

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}^{corr}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}^{corr}} \quad \begin{array}{l} \text{PDF uncertainties cancel} \\ \text{improved scale uncertainty} \end{array}$$

Requires preserved correlations in PDF uncertainties at different orders

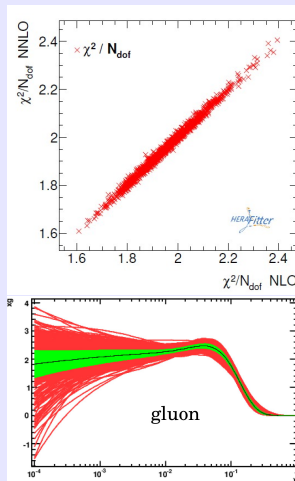
A QCD fit to HERA I data (JHEP 1001, 2010, 109) using HERAFitter

MC replica method used to preserve the correlations:

- 1337 MC replicas of the data fluctuating the inputs within uncertainties using Gaussian prob densities
- perform a consistent fit of PDFs at different orders to each replica

central PDF = average over replicas,
PDF uncertainty = RMS over replicas

- eigenvector representation was also obtained



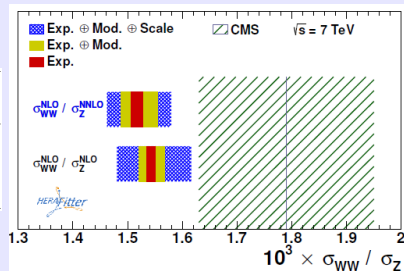
COMPARISON TO DATA: WW/Z RATIO

[ARXIV:1404.4234]

WW/Z ratio measurement from CMS [arXiv:1306.1126](#)

The cross section ratio using the correlated PDFs was build

Ratio	Value	Exp. PDF	Mod. PDF	Scale
	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
$\frac{\sigma_{WW}^{\text{NLO}}}{\sigma_Z^{\text{NLO}}}$	1.543	± 0.008	$+0.023$ -0.021	$+0.069$ -0.058
$\frac{\sigma_{WW}^{\text{NLO}}}{\sigma_Z^{\text{NNLO}}}$	1.517	± 0.010	$+0.036$ -0.027	$+0.050$ -0.046

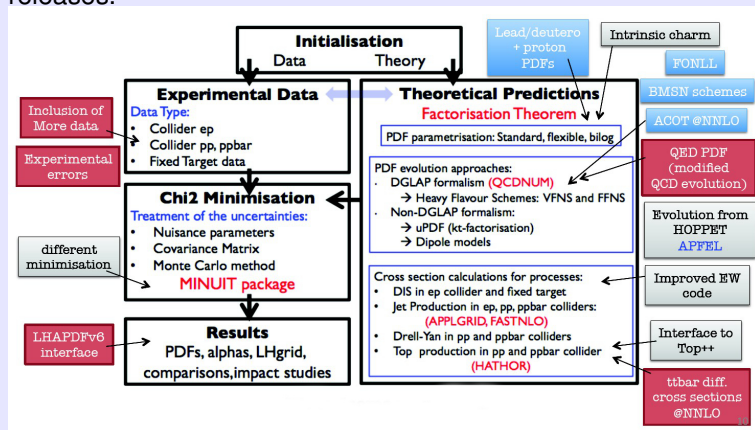


- predictions agree with the data within $1-2\sigma$
- the total theoretical uncertainty is **reduced by 30-40%**
- mixed-order calculations with correlated PDFs help to reduce PDF and scale uncertainties

PDFs are planned to be released in LHAPDF6: [HF14cor*](#)

PROSPECTS

Many new developments are planned to be implemented in future releases.



Join us on User's meetings every month.

<http://wiki-zeuthen.desy.de/HERAFitter/HERAFitter/HERAFitterMeetings>

We welcome more ideas.

The HERAFitter project is a unique open source platform for QCD analyses to study the structure of the proton.



The project successfully encapsulates a wide variety of QCD tools to facilitate analyses of the experimental data and theoretical calculations:

- various treatments for heavy flavours,
- various options for data uncertainties treatment
- various parametrisation techniques
- various physics cases

Stable release: herafitter-1.0.0

<http://www.herafitter.org>
herafitter-help@desy.de

PDF school and workshop
Proton Structure in the LHC Era
29 Sep - 3d Oct, DESY, Hamburg
www.terascale.de/pdf2014
HERAFitter tutorials