HERAFitter - an open source QCD fit framework and related studies

Ringailė Plačakytė

on behalf of the HERAFitter team

Content:

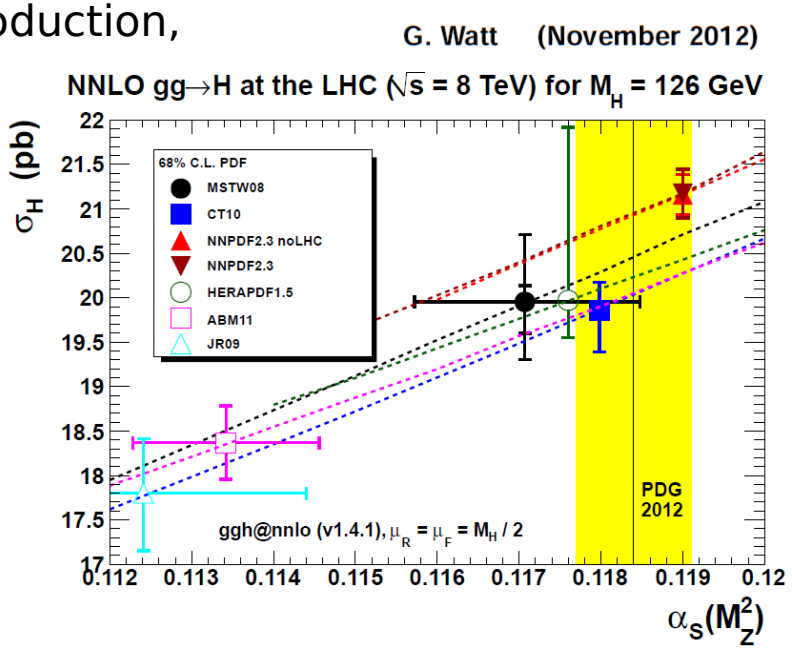
- Motivation
- HERAFitter project overview
- First HERAFitter Developers publication: PDFs with correlated uncertainties between orders
- Summary

Low-x, 17-21 June, Kyoto, Japan

Motivation

PDFs are essential for precision physics at LHC

PDFs are one of main uncertainties in Higgs production, M_W measurement, BSM searches, etc.



Different PDF fitting groups (CT, MSTW, NNPDF, HERAPDF, ABM, JR) use different data and methodology to extract PDFs

→ lead to differences in predicted cross sections

HERAFitter is an open source QCD fit framework ready to extract PDFs

→ can be used to benchmarking and understanding differences in PDFs

→ provides tools to assess impact of new data

www.herafitter.org

HERAFitter Project

www.herafitter.org

HERAFitter is extensively used by different **experiments** and **theory** groups

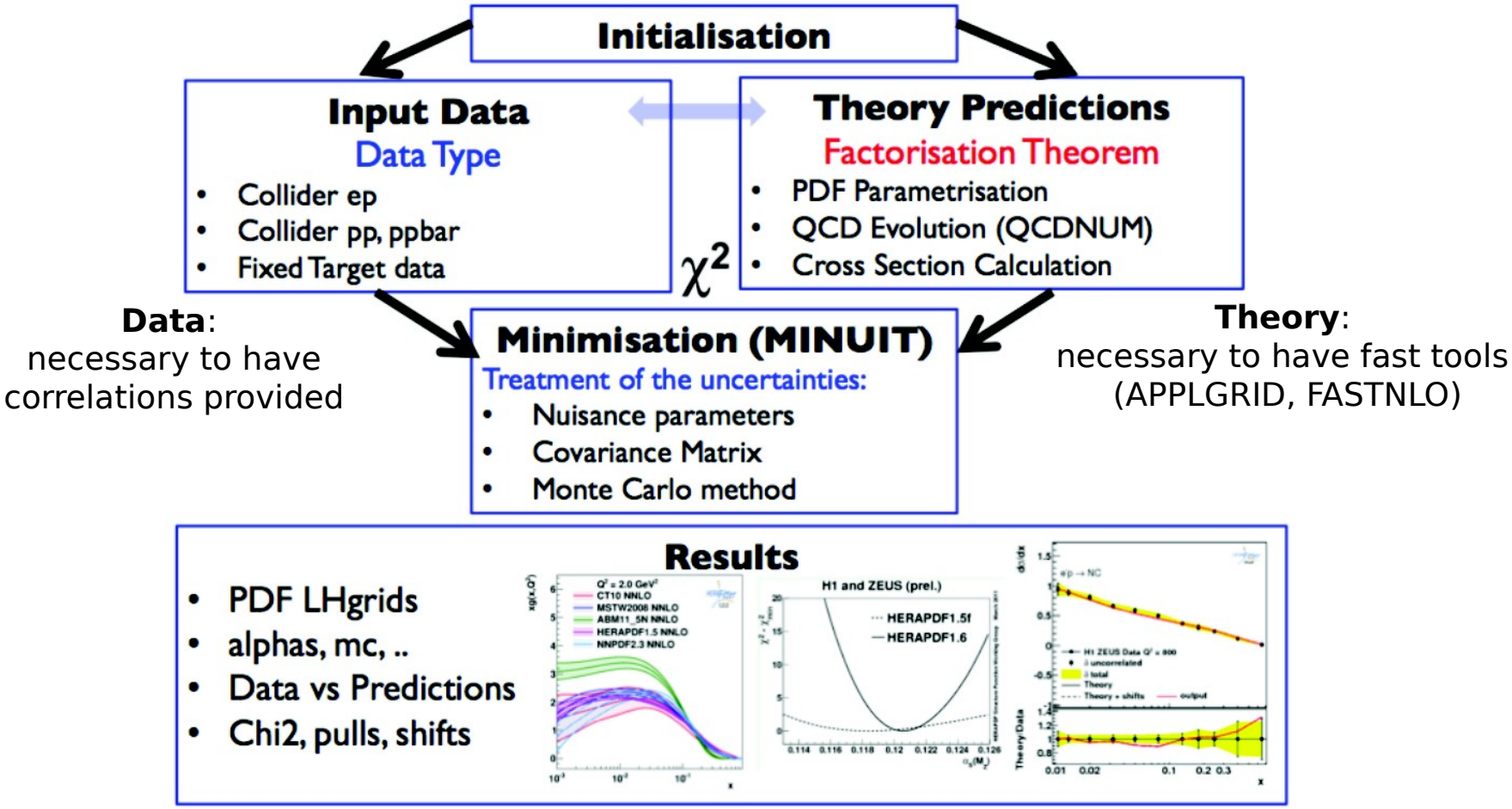
https://www.herafitter.org/HERAFitter/HERAFitter/results

Date	Group	Reference	Title
NEW 05.2014	ggH benchmark HERAPDF, CT, NNPDF, MSTW	arxiv:1405.1067	Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report
NEW 04.2014	LHC/ATLAS	arXiv:1404.1212	Measurement of the low-mass Drell-Yan differential cross section at sqrt(s)=7 TeV using the ATLAS detector
NEW 02.2014	LHC/ATLAS	arXiv:1402.6263	Measurement of the production of a W boson in association with a charm quark in pp collisions at sqrt(s)=7 TeV with the ATLAS detector
01.2014	R. Sadykov Theory	arXiv:1401.1133	Impact of QED radiative corrections on Parton Distribution Functions
01.2014	F. Hautmann and H. Jung Theory	arXiv:1312.7875	Transverse momentum dependent gluon density from DIS precision data
12.2013	M. Klein, V. Radescu (LHeC studies)	arXiv:1310.5189	Report of the Snowmass 2013 energy frontier QCD working group
12.2013	A. Luszczak and H. Kowalski Theory	arXiv:1312.4060	Dipole model analysis of high precision HERA data
12.2013	LHC/ATLAS	ATL-PHYS-PUB-2013-018	A study of the sensitivity to the proton parton distributions of the inclusive photon production cross section in pp collisions at 7 TeV measured by the ATLAS experiment at the LHC
12.2013	LHC/CMS	CMS-SMP-12-021 / arXiv:1312.6283	Measurement of the muon charge asymmetry in pp W production at 7 TeV
12.2013	LHC/CMS	CMS-SMP-12-028	PDF constraints and extraction of the strong coupling constant from the inclusive jet cross section at 7 TeV
2013	LHC/ATLAS	Phys. Lett. B 725 (2013) pp. 223	Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at sqrt(s)=7 TeV
2013	LHC/ATLAS	EPJC (2013) 73 2509	Measurement of the inclusive jet cross section in pp collisions at sqrt(s) = 2.76 TeV and comparison to the inclusive jet cross section at sqrt(s) = 7 TeV using the ATLAS detector
2013	LHC/ATLAS	Phys.Rev.Lett. 109 (2012) 012001	Determination of the strange quark density of the proton from ATLAS measurements of the W -> l nu and Z -> ll cross sections
2013	HERA/H1 and Z	Eur. Phys. J. C73 (2013) 2311	Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep-Inelastic ep Scattering at HERA
2012	HERA/H1	JHEP 09 (2012) 061	Inclusive Deep Inelastic Scattering at High Q2 with Longitudinally Polarised Lepton Beams at HERA
2012	LHeC	J.Phys. G39 (2012) 075001	A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector

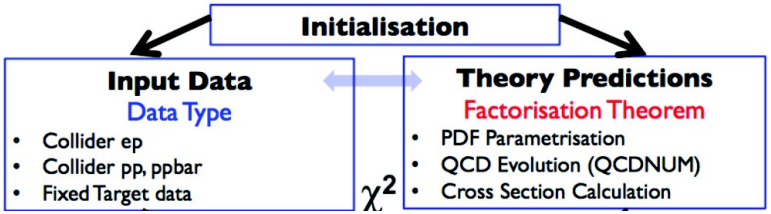
HERAFitter Structure

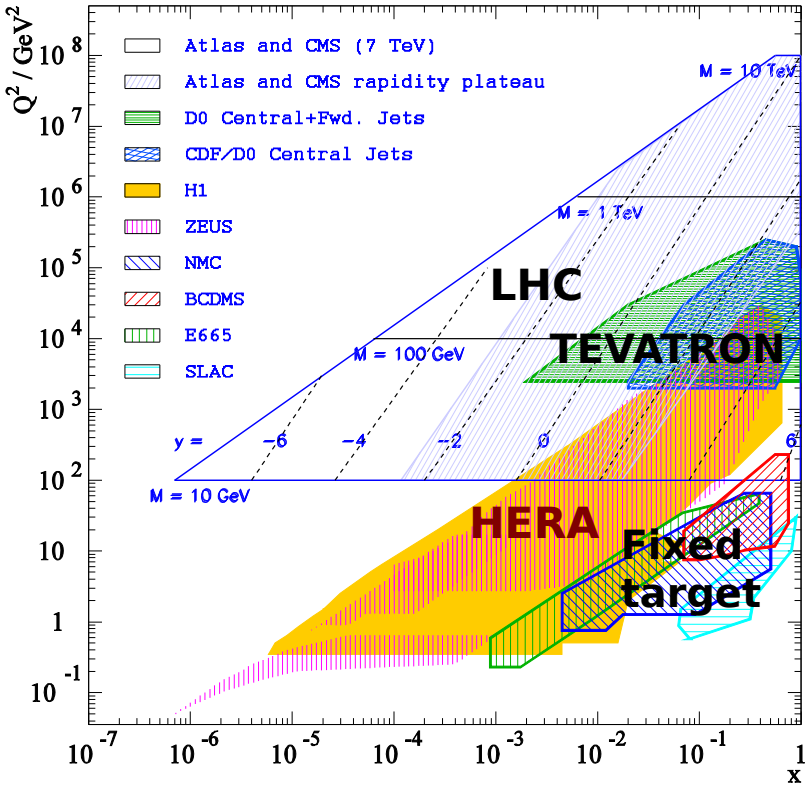
The first HERAFitter stable release (HERAFitter-1.0.0) available since Dec 2013

A flow diagram of the PDF extraction:



HERAFitter Structure





Theory processes available in HERAFitter:

DIS inclusive processes in *ep* and fixed target

DGLAP formalism:

different schemes of heavy quark treatment
VFNS: RT (MSTW), ACOT (CTEQ)
FFNS (pole and running mass)

Diffractive PDFs

non-DGLAP formalism:

Dipole Models (GBW, IIM, BGK)
– an alternative approach for the low x region

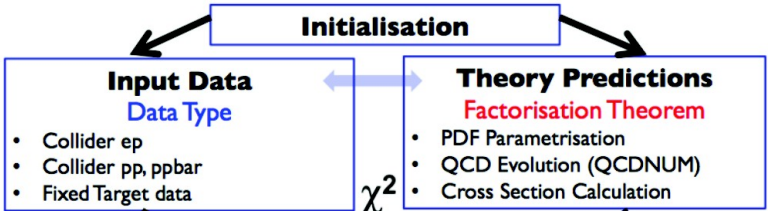
Unintegrated PDFs
– based on CCFM evolution

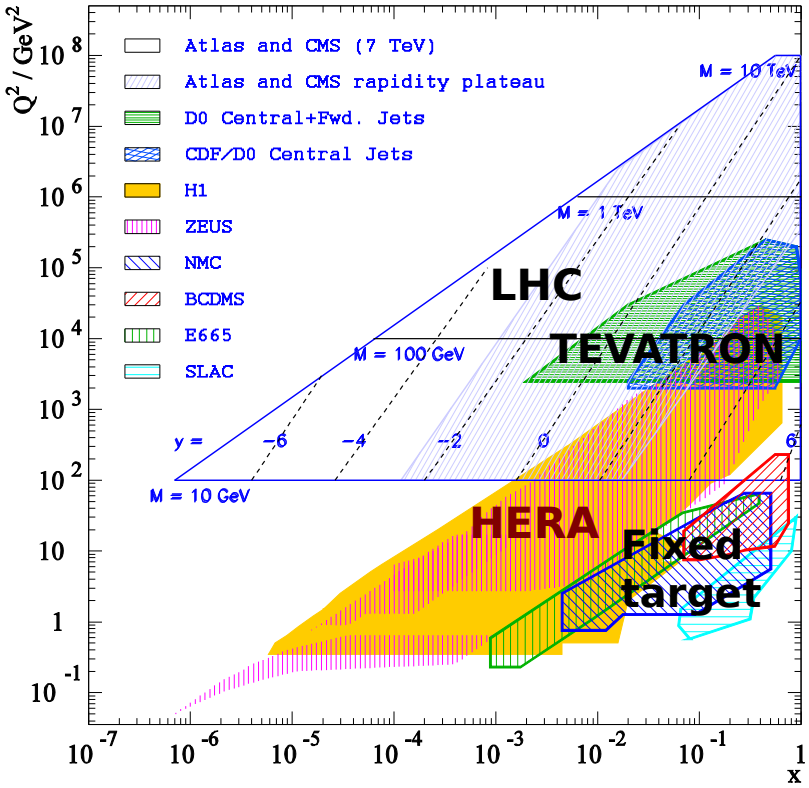
Jet production (*ep, pp, ppbar*)
FastNLO and APPLGRID techniques
- decoupled hard scattering coefficients from PDFs stored on grids

Drell-Yan processes (*pp, ppbar*)
LO calculation x NLO k-factors
APPLGRID technique

Top pair production
total ttbar cross sections (differential soon)

HERAFitter Structure





Theory processes available in HERAFitter:

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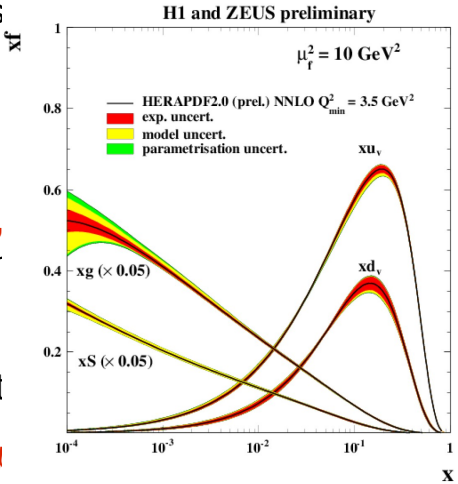
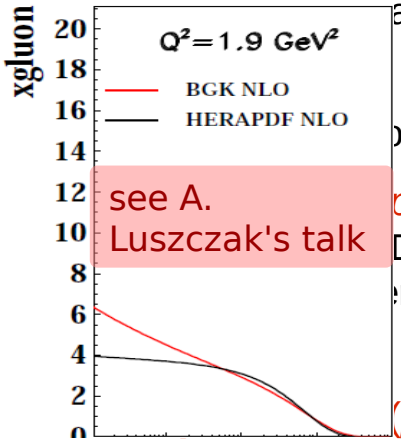
see V. Myronenko's talk



Diffractive PDFs

non-DGLAP formalism:

Dipole Models (GBW, IIM,



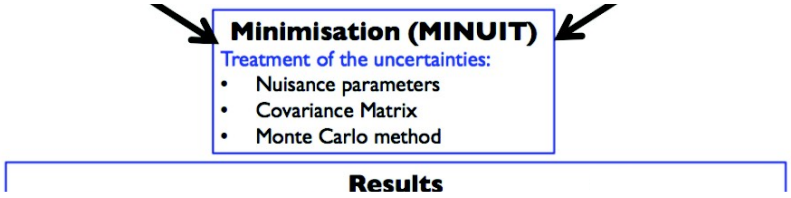
see A. Luszczak's talk

LO calculation x NLO k-factors
APPLGRID technique

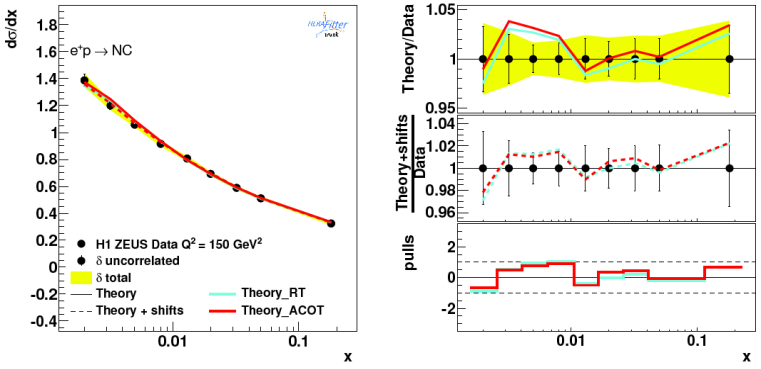
Top pair production

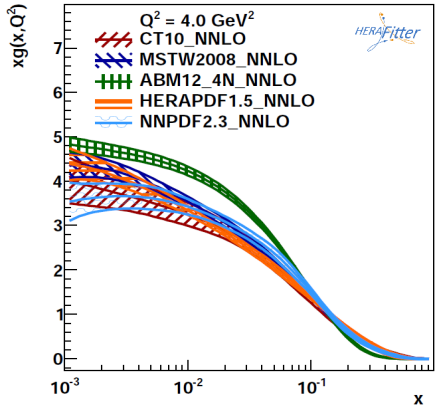
total ttbar cross sections (differential soon)

HERAFitter: Functionality and Tools



Examples of plots created with drawing tools:





PDFs sets available in LHAPDF (v5 and v6):
HERAPDF1.0, HERAPDF1.5, ATLAS-epWZ12, LHECNLO(v5)

χ^2 function

→ nuisance parameters
→ covariance matrix
→ mixed

Various types of uncertainty treatment for data:

Hessian - error inflation by a tolerance parameter (nuisance) to accommodate inconsistencies between data sets

Monte Carlo - MC replica method shifting data cross section points randomly within their uncertainties

Offset – correlated sources accommodated in uncertainties

Various forms of parametrisation ansatz

→ HERAPDF, CTEQ style, Chebyshev, bi-log normal

Bayesian Reweighting technique

→ a method to study data sensitivity on PDFs without fitting the data

Regularisation methods

→ constrain PDFs in a flexible parametrisation style

Tools

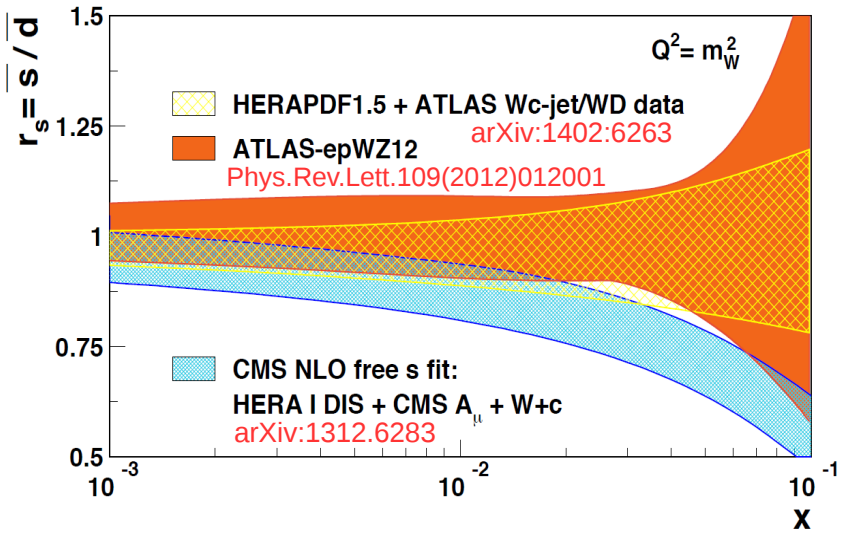
→ PDFs in LHAPDF format, drawing tools

Generic minima finding solution tool

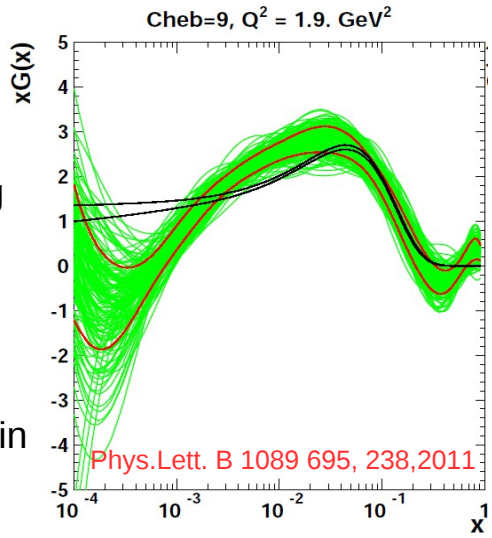
Lead PDFs

Functionality and Tools: Examples

Both, nuisance (Atlas) and covariance (CMS) χ^2 methods were used in the s quark density determination at LHC:



PDF parametrisation uncertainty study at low x≤ 0.1 using Chebyshev pol



Similar recent ggH benchmark studies in arXiv:1405.1067

χ^2 function

→ nuisance parameters:

$$\chi^2 = \sum_i \frac{\left(D_i - T_i^*\right)^2}{\left(\delta_i^{unc}\right)^2} \qquad T_i = T_i + \sum_i r_j \beta_{ij}$$

Correlated error

Nuisance parameter

→ covariance matrix:

$$\chi^2 = \sum_{i,j} \left(D_i - T_i\right) Cov_{i,j}^{-1} \left(D_j - T_j\right)$$

→ mixed:

$$\chi^2 = \sum_{ij}^{N} \left(D_i - T_i - \sum_k^K r_k \beta_{ik} \right) C_{ij}^{-1} \left(D_j - T_j - \sum_k^K r_k \beta_{jk} \right)$$

Various forms of parametrisation ansatz

→ HERAPDF, CTEQ style, Chebyshev, bi-log normal

Bayesian Reweighting technique

→ a method to study data sensitivity on PDFs without fitting the data

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Tools

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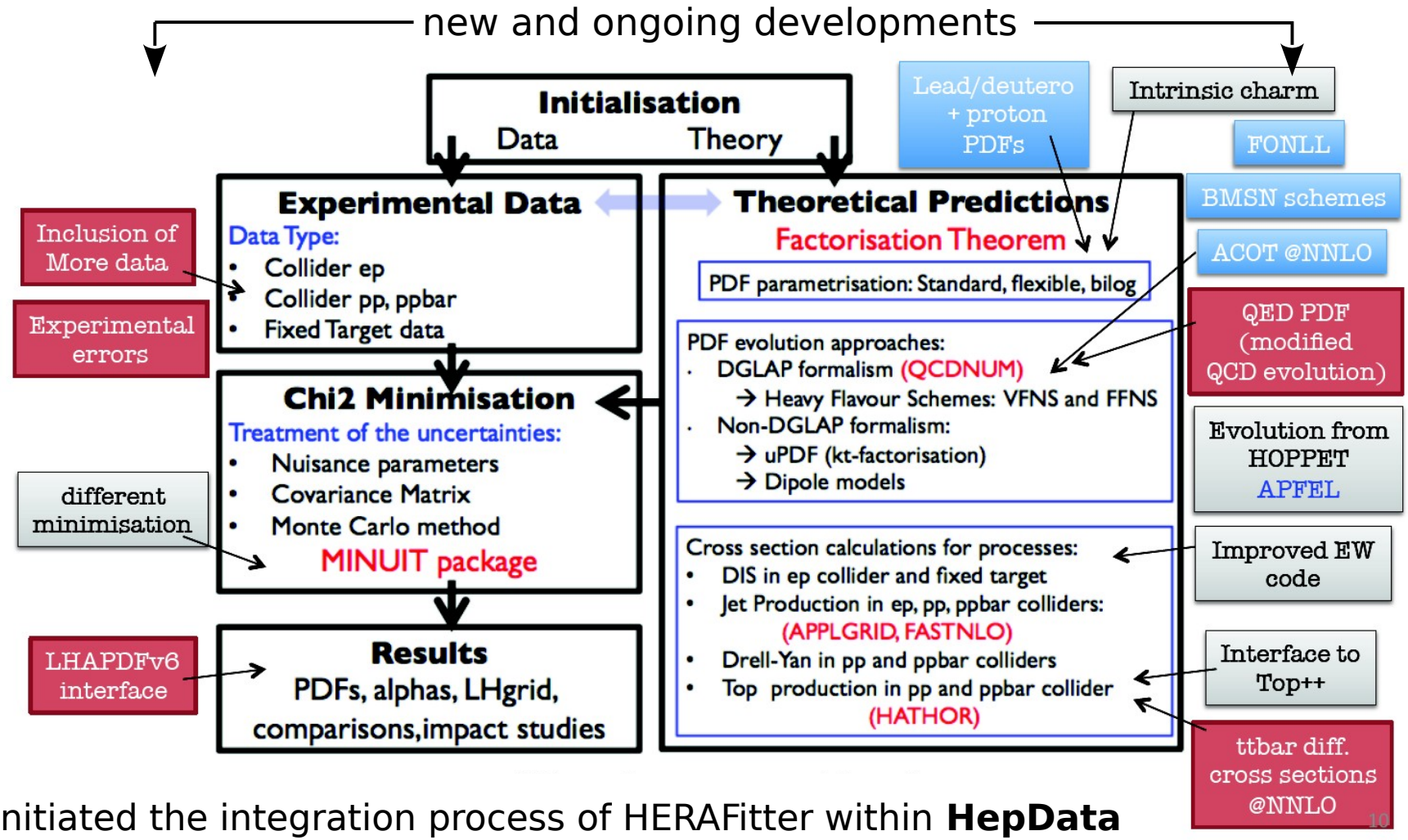
Lead PDFs

Future Developments

The first HERAFitter stable release (HERAFitter-1.0.0) available since Dec 2013

→ many new developments ongoing since then



Initiated the integration process of HERAFitter within **HepData**

The first HERAFitter Developers Team publication:

arXiv:1404.4234

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

NEW

DESY Report 2014-054

Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders

HERAFitter developers' team ·
P. Belov[1,12] · D. Britzger[1] · S. Camarda[1] · A.M. Cooper-Sarkar[2] ·
C. Diaconu[3] · J. Feltesse[13] · A. Gizhko[1] · A. Glazov[1] · V. Kolesnikov[4] ·
K. Lohwasser[14] · A. Luszczak[5] · V. Myronenko[1] · H. Pirumov[1] ·
R. Plačakytė[1] · K. Rabbertz[6] · V. Radescu[1] · A. Sapronov[4] ·
A. Schöning[10] · S. Shushkevich[1] · W. Slominski[7] · P. Starovoitov[1] ·
M. Sutton[8] · J. Tomaszewska[9] · O. Turkot[1] · G. Watt[11] · K. Wichmann[1]
and M. Lisovyi[1]

Abstract Sets of parton distribution functions (PDFs) of the proton are reported for the leading (LO), next-to-leading (NLO) and next-to-next-to leading order (NNLO) QCD calculations. The parton distribution functions are determined with the HERAFitter program using the data from the HERA experiments and preserving correlations between uncertainties for the LO, NLO and NNLO PDF sets. The sets are used to study cross-section ratios and their uncertainties when calculated at different orders in QCD. A reduction of the overall theoretical uncertainty is observed if correlations between the PDF sets are taken into account for the ratio of WW di-boson to Z boson production cross sections at the LHC.

[1] DESY, Hamburg, Germany
[2] Department of Physics, University of Oxford, Oxford, United Kingdom
[3] CPPM, IN2P3-CNRS, Univ. Mediterranee, Marseille, France
[4] Joint Institute for Nuclear Research (JINR),Joliot-Curie 6, 141980, Dubna, Moscow Region, Russia
[5] T. Kosciuszko Cracow University of Technology
[6] Institut für Experimentelle Kernphysik, Karlsruhe, Germany
[7] Jagiellonian University, Institute of Physics, Ul. Reymonta 4, PL-30-059 Cracow, Poland
[8] University of Sussex, Department of Physics and Astronomy, Sussex House, Brighton BN1 9RH, United Kingdom
[9] Warsaw University of Technology, Faculty of Physics, Koszykowa 75, 00-662 Warsaw, Poland
[10] Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany
[11] Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, United Kingdom
[12] Current address: Department of Physics, St. Petersburg State University, Ulyanovskaya 1, 198504 St. Petersburg, Russia
[13] CEA, DSM/Irfu, CE-Saclay, Gif-sur-Yvette, France
[14] DESY, Platanenallee 6, D15738 Zeuthen, Germany

1 Introduction

Accurate knowledge of the parton distribution functions (PDFs) of the proton is required for precision physics at the LHC. PDF sets are now available as determined by several groups [1,2,3,4,5,6] at leading-order (LO), next-to-leading-order (NLO) and next-to-next-to-leading-order (NNLO) accuracy in QCD. To obtain the cross-section predictions, the PDF sets should be paired with calculations of the coefficient functions at the matching order of the accuracy. Theoretical uncertainties for the predictions arise from both the PDF and coefficient-function uncertainties.

Most of the Standard Model processes at the LHC are calculated to NLO accuracy. The uncertainties due to missing higher orders for the coefficient functions are typically determined by varying factorisation and renormalisation scales. This leads to large uncertainties often as large as 10% of predicted cross sections, which usually exceed uncertainties due to the PDFs determination. For a handful of processes known at NNLO, the PDF uncertainties often exceed uncertainties due to missing higher orders in coefficient-function calculations.

The experimental precision achieved by the LHC experiments often exceeds the precision of theoretical calculations. Ultimately a more complete set of NNLO calculations should remedy the situation in future. At present, special methods are employed to reduce theoretical uncertainties. One such method is to measure

Motivation

Predictions for various processes at LHC are available at different orders in pQCD

→ PDFs and coefficient functions ideally should be paired at the same order

→ Factorisation theorem: $\sigma \approx \hat{\hat{\sigma}} \otimes \mathrm{PDF}$

uncertainties rise from PDFs and coefficient functions

missing higher order uncertainties often determined by the scale variation

Ratios of cross sections are used to reduce theoretical uncertainties:

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}}{\hat{\sigma}_Y^{NLO} \otimes PDF_{NLO}}$$

PDF uncertainties cancel
large scale uncertainty

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}}$$

improved scale uncertainty
No cancellation of PDF uncertainty

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PDF uncertainties cancel
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not clear definition in pQCD

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}^{corr}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}^{corr}}$$

PDF uncertainties cancel
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No cancellation of PDF uncertainty

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PDF uncertainties cancel
improved scale uncertainty
not clear definition in pQCD

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}^{corr}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}^{corr}}$$

PDF uncertainties cancel
improved scale uncertainty

Requires preserved correlations in PDF uncertainties at different orders

QCD Analysis Settings

arXiv:1404.4234

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

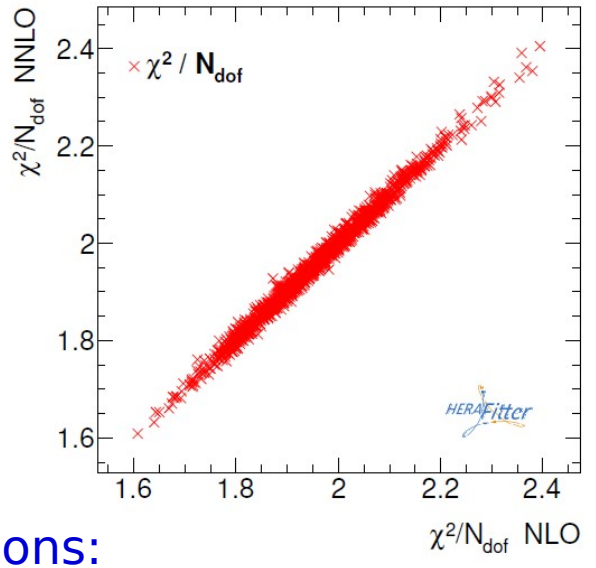
Parametrisation: $xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$

+ additional constraints and assumptions

Settings	LO	NLO	NNLO
HF scheme	TR' opt	TR' opt	TR' opt
r_s (s fraction)	1.0	1.0	1.0
m_c (GeV)	1.38	1.38	1.32
m_b (GeV)	4.75	4.75	4.75
α_s	0.13	0.1184	0.1184
Q^2_0 (GeV^2)	1.7	1.7	1.7
Q^2_{min} (GeV^2)	7.5	7.5	7.5

→ vary model parameters and parametrisation following HERAPDF prescription (JHEP 1001, 2010, 109)

correlation of χ^2 between orders



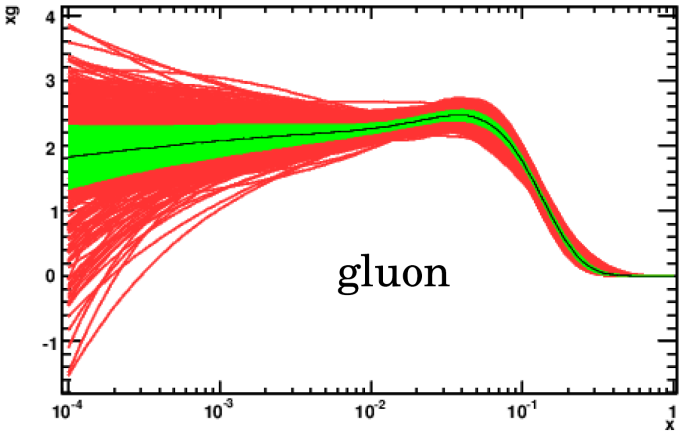
MC replica method used to preserve the correlations:

→ 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

model and param uncertainties treated correlated between orders



Eigenvector Representation

arXiv:1404.4234

Eigenvector representation is often more convenient than MC replica

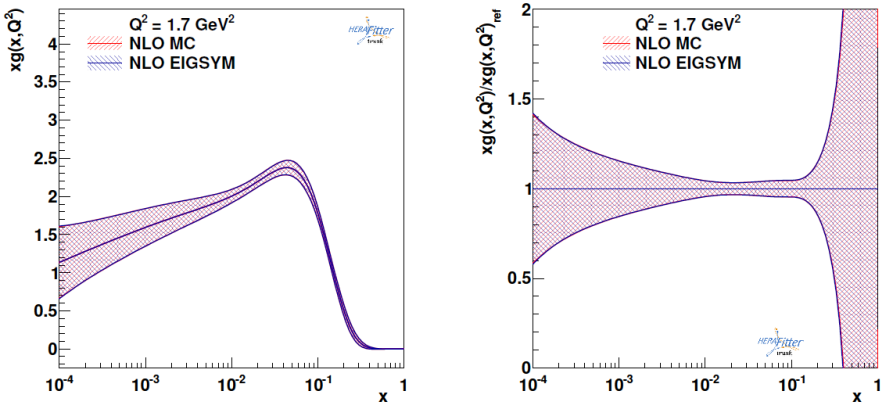
employ the method suggested for extraction of META PDFs (arXiv:1401.0013)

→ build the covariance matrix

→ diagonalise matrix and keep only leading eigenvectors

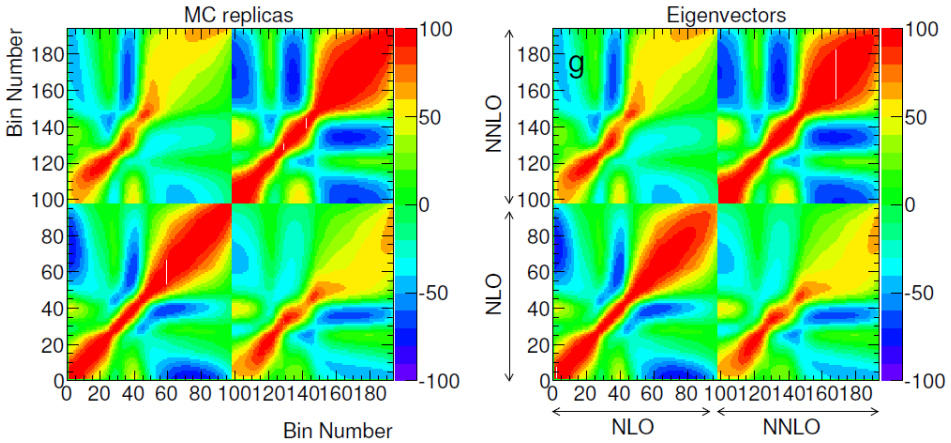
→ evolve tabulated values (central and eigenvectors) using DGLAP evolution

Comparison of PDFs determined with MC method and its eigenvector representation



→ very good agreement between PDFs

Correlation coefficients among PDFs:



→ PDFs show high degree of correlation at neighboring x bins (smoothness of parametrisation)

→ strong correlation between NLO and NNLO PDFs

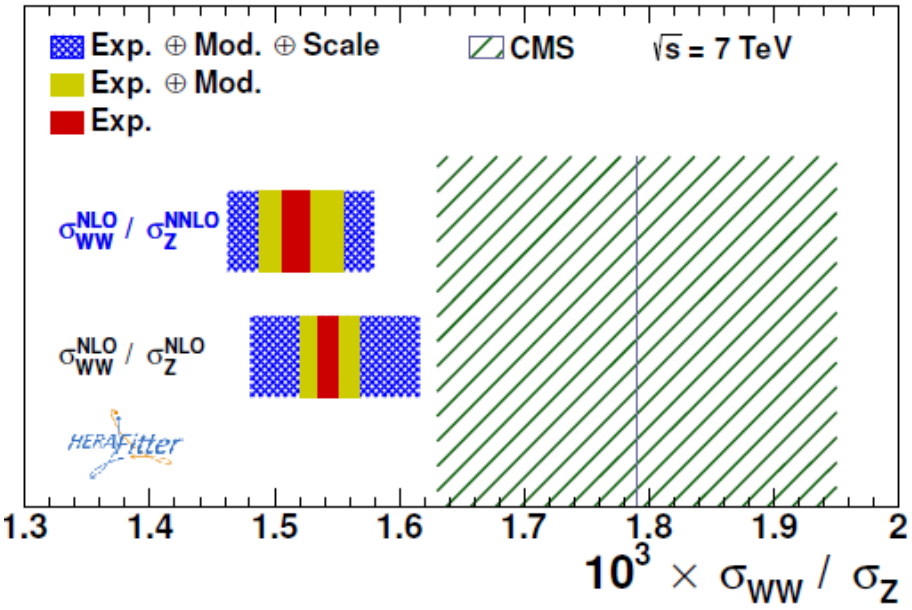
Comparison to Data: WW/Z ratio

arXiv:1404.4234

Used case example: WW/Z ratio measurement from CMS (arXiv:1306.1126)

→ build the cross section ratio using the correlated PDFs

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



→ predictions agree with the data within 1-2σ

→ 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**

Summary

HERAFitter project - a multi-functional QCD framework well integrated into the high energy community (both, experimental and theory)

→ open to everyone and everyone can contribute

→ first **stable release** HERAPDF-1.0.0 (Dec 2013)

herafitter-help@desy.de

Sets of **LO, NLO and NNLO PDFs with correlated uncertainties at different orders** were extracted using HERAFitter arXiv:1404.4234

→ a high degree of correlation was observed for PDFs at different orders and similar x

→ the total theoretical uncertainty is reduced for the mixed-order calculation by 30-40% due to reduced scale uncertainties

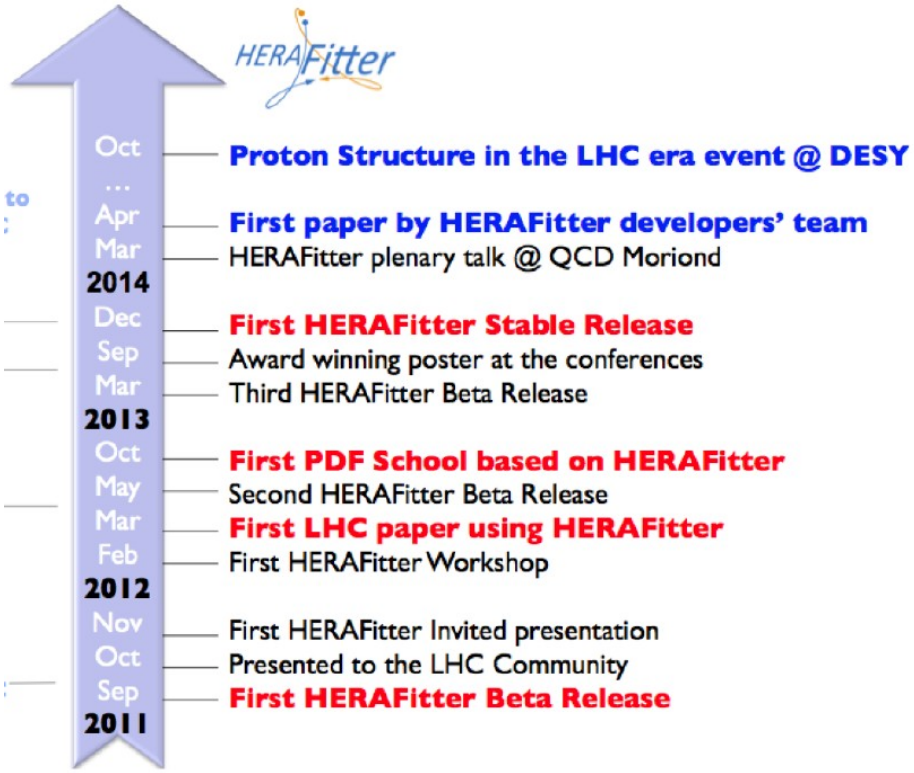
Back-up slides

HERAFitter Project

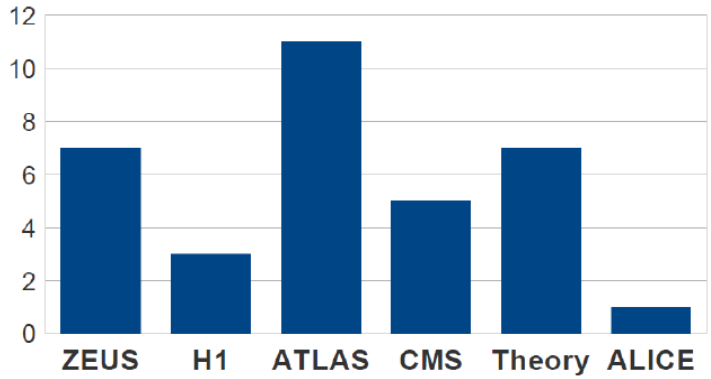
HERAFitter project is a QCD fit framework ready to extract PDFs and assess the impact of new data

www.herafitter.org

→ everyone is welcome to download it and use it



Developers:



Experimental Data

DIS inclusive processes in *ep* and fixed target

DGLAP formalism:

different schemes of heavy quark treatment
VFNS: RT (MSTW), ACOT (CTEQ)
FFNS (pole and running mass)

Combination and QCD Analysis of Charm Production in DIS at HERA

- various heavy flavour schemes and an impact on DY cross sections at LHC studied

  → possible only with HERAFitter

- running mass of charm quark determined

Eur. Phys. J. C73 (2013) 2311