

# 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

Diffraction14, September 10-16 2014,  
Primošten (Croatia)



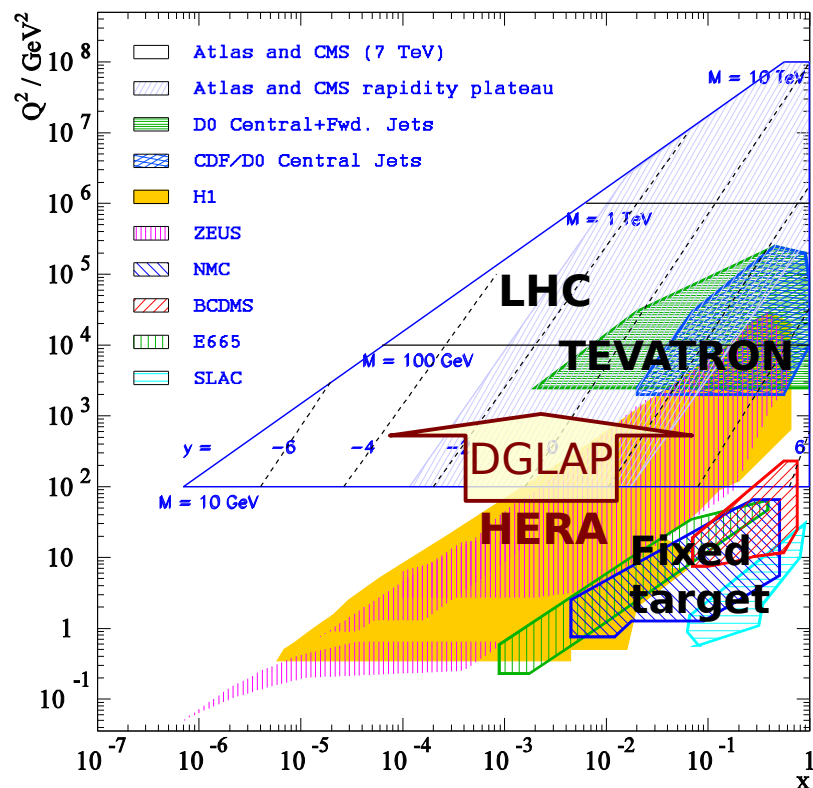
# Motivation

PDFs are crucial for precision physics at hadron colliders

- PDFs are one of main uncertainties in Higgs production,  $M_W$  measurement, BSM searches, etc
- DPDFs are essential ingredient in predicting many diffractive processes at the LHC

QCD factorisation:

$$\sigma = \text{hard scattering ME} \otimes (\text{D})\text{PDF}$$



evolution in  $Q^2$  via DGLAP

**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

# HERAFitter Project

www.herafitter.org

→ open access

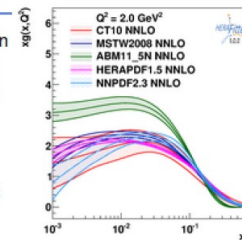
→ no registration required (subscription optional)



## Welcome to HERAFitter

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.

The HERAFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data which we would like to present here. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.



## Downloads of HERAFitter software package

**HERAFitter-1.0.0 stable release is publicly available.**

All the HERAFitter releases can be accessed [HERE](#).

## HERAFitter Meetings

- **User's Meetings:** monthly meetings to enhance communication between users and developers (open access)
- **Developer's Meeting:** technical weekly meetings to ensure communication among developers (restricted access)
- **Steering Group's Meeting** (restricted access @)

## HERAFitter representation

- [List of results](#)
- [List of collected talks](#)

## Developers Info (restricted to developers)

- [Internal Developments](#)

## Organisation

Steering Group is composed of:

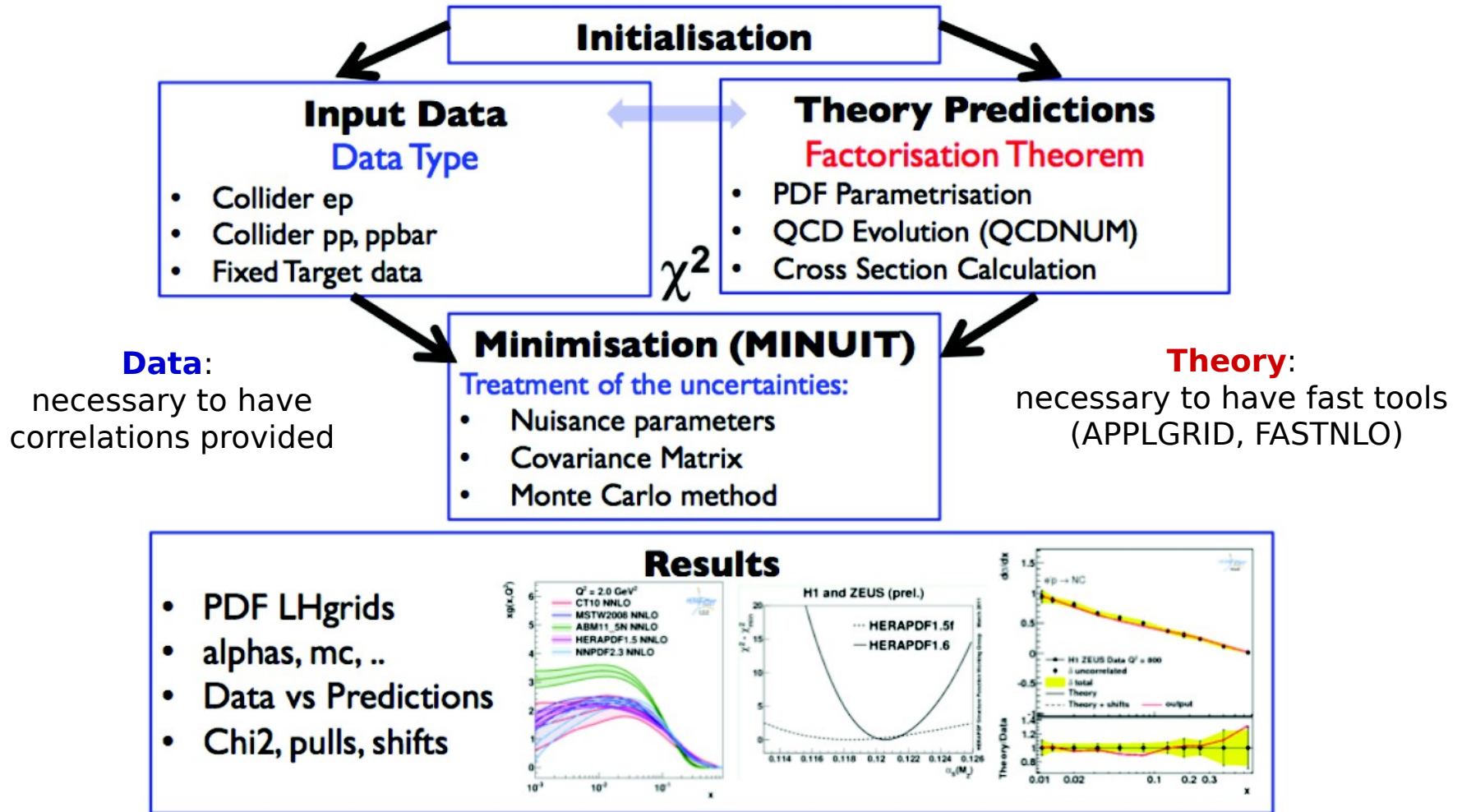
- **Conveners:** Voica Radescu, Ringailė Placakyte, Amanda Cooper-Sarkar
- **Release coordinator** (revision of the release candidates): Sasha Glazov
- **Librarian** (continuous revision/development of the main code and doxygen): Hayk Pirumov
- **Contact Persons:** Cristi Diaconu (H1), Klaus Rabbertz (CMS), Bogdan Malaescu (ATLAS), Olaf Behnke (ZEUS), Ronan McNulty (LHCb), Gavin Salam (theory)
- **DESY IT Contact:** Yves Kemp, Bogdan Lobodzinsky

## Getting help

Send email to [herafitter-help@desy.de](mailto:herafitter-help@desy.de)

# HERAFitter Structure

A flow diagram of the PDF extraction in the HERAFitter package:



# HERAFitter: Functionality and Tools

## $\chi^2$ function

→ nuisance parameters:

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

↑ Nuisance parameter
 ← Correlated error

→ covariance matrix:

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

→ 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 types of the uncertainty treatment for data:

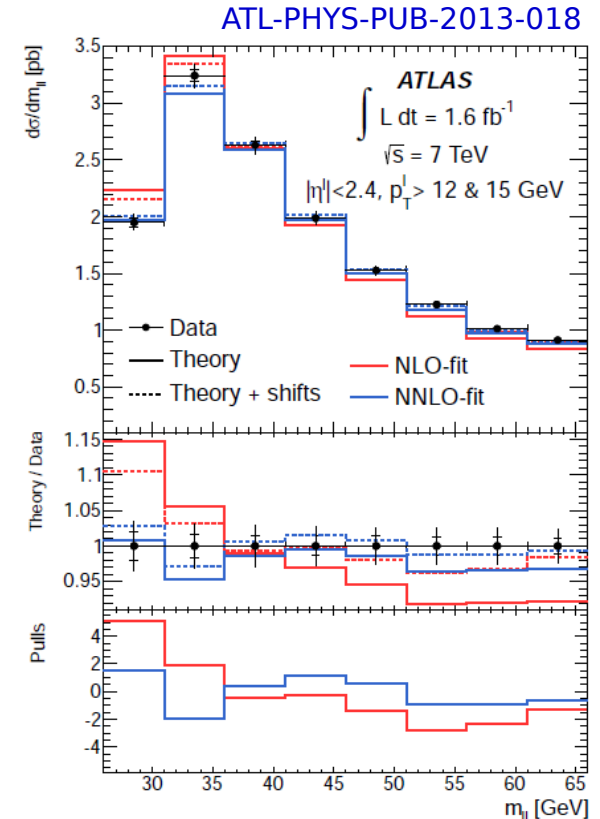
**Hessian** - error inflation by a tolerance (nuisance) parameter

**Monte Carlo** - MC replica method shifting data cross sections randomly within their uncertainties

**Offset** – correlated sources accommodated in uncertainties

## Various forms of ansatz

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





# HERAFitter: Functionality and Tools

## Interface to LHAPDF (v5 and v6):

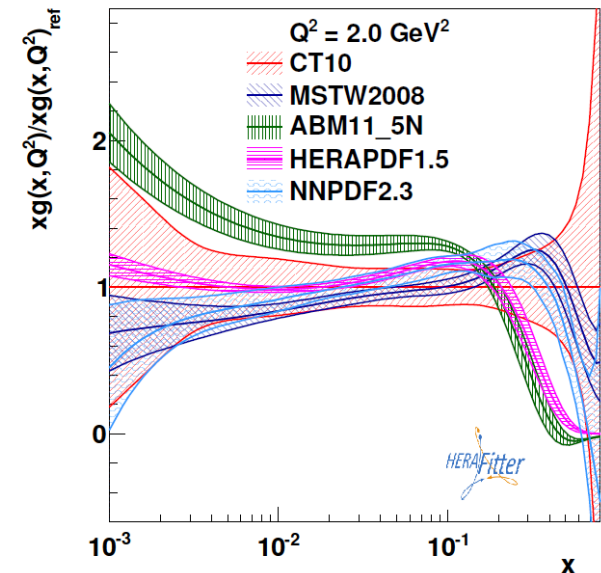
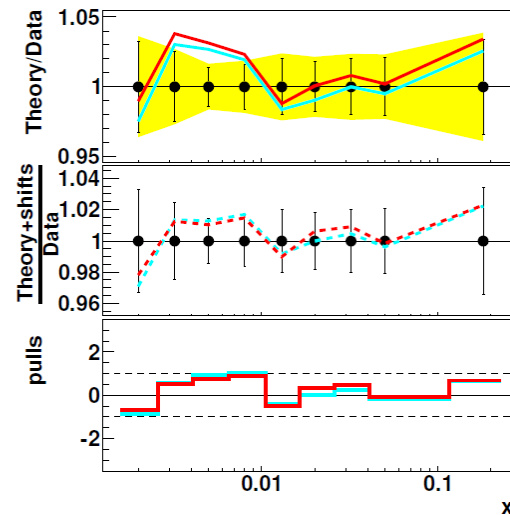
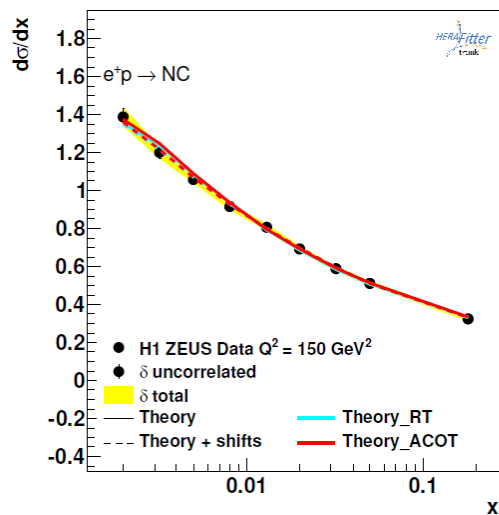
Available PDFs in LHAPDF: HERAPDF1.0, HERAPDF1.5, ATLAS-epWZ12, LHECNLO(v5)

## Drawing tools:

- comparison of different PDFs
- data to theory (or vs) ratio, shifts
- printing of  $\chi^2$ s and pulls, parameter values
- drawing uncertainty bands (data and theory)
- different options for result saving formats (root, pdf, eps, ...)

used in publications:

ATL-PHYS-PUB-2013-018



# Physics Cases in HERAFitter: DIS

## DIS inclusive processes in $ep$ and fixed target

### DGLAP formalism

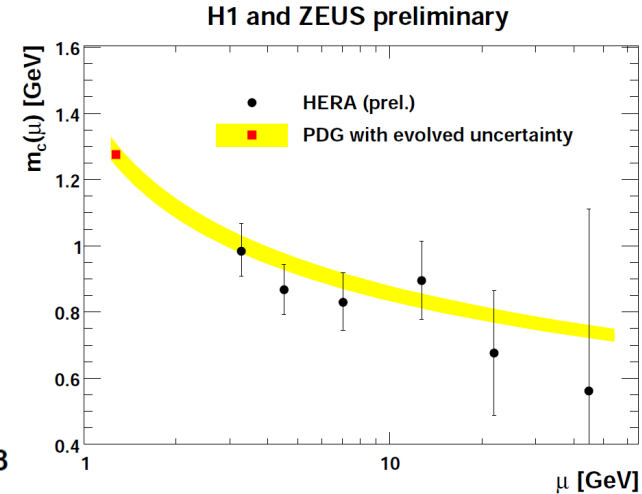
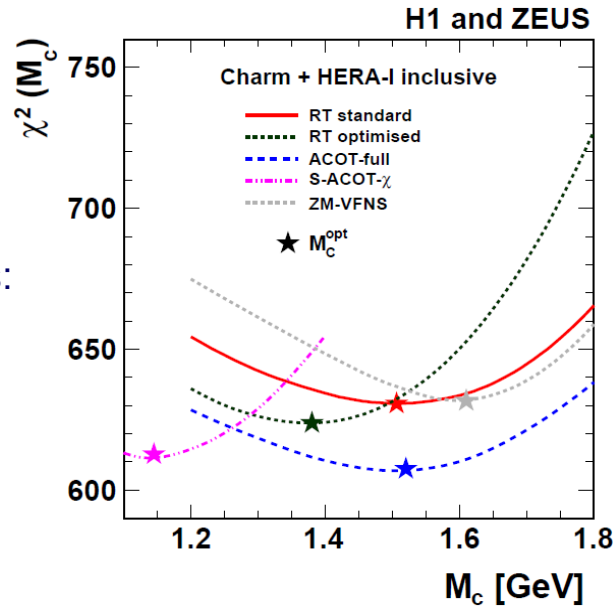
different schemes of heavy quark treatment:

Variable Flavour Number Schemes:  
RT (MSTW), ACOT (CTEQ)

Fixed Flavour Number Scheme  
(pole and running mass)

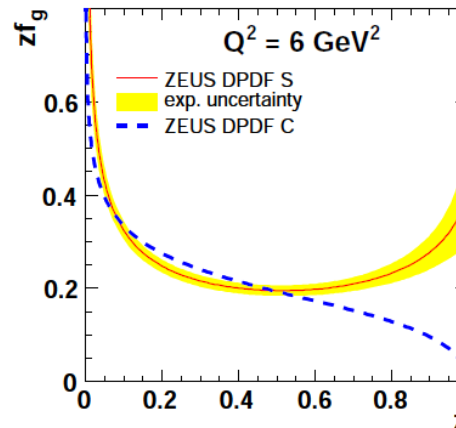
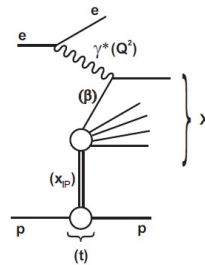
Eur.Phys. J. C73  
(2012), 2311

H1-prelim-14-071  
ZEUS-prel-14-006  
and S. Moch

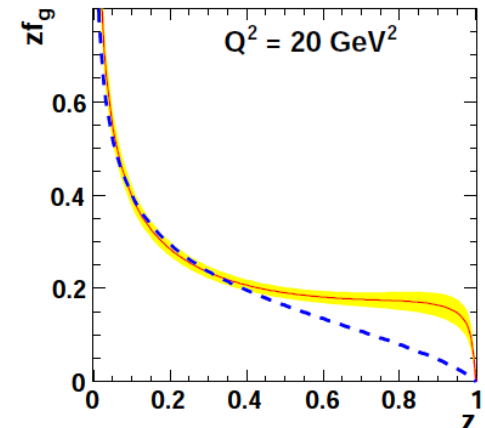


## Diffractive PDFs (DPDFs)

DPDFs parametrisation and setting follow the style used in the ZEUS Collaboration



Nucl.Phys. B 831 (2010) 1-25



# Physics Cases in HERAFitter: DIS

## DIS inclusive processes in $ep$ and fixed target

### Alternative to DGLAP formalism

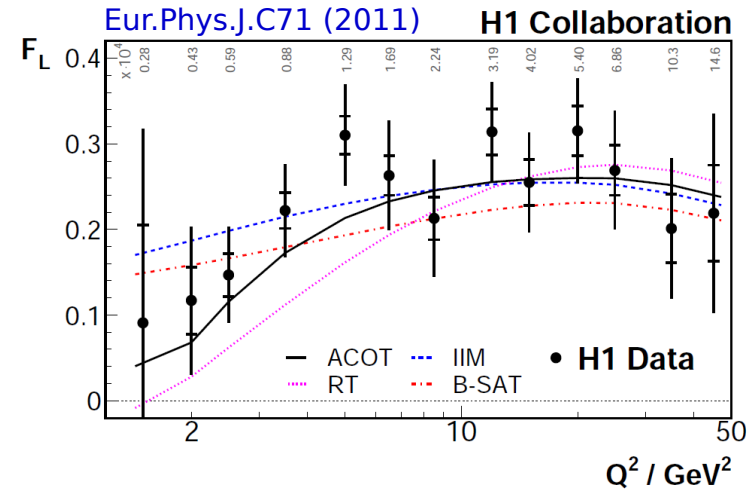
→ at small- $x$  and small- $Q^2$  DGLAP dynamics may be modified by non-perturbative QCD effects

## Dipole Models

→ provides an alternative approach to  $p\text{-}\gamma$  scattering at low  $x$  (valid for inclusive and diffractive processes)

### in HERAFitter:

- GBW dipole saturation model [Phys. Rev. D 59 014017](#)
- Modified with DGLAP effects GBW model: BGK [Phys. Lett. B590, 199 \(2004\)](#)
- colour glass condensate approach IIM model [Rev. D 66 , 014001 \(2002\)](#)

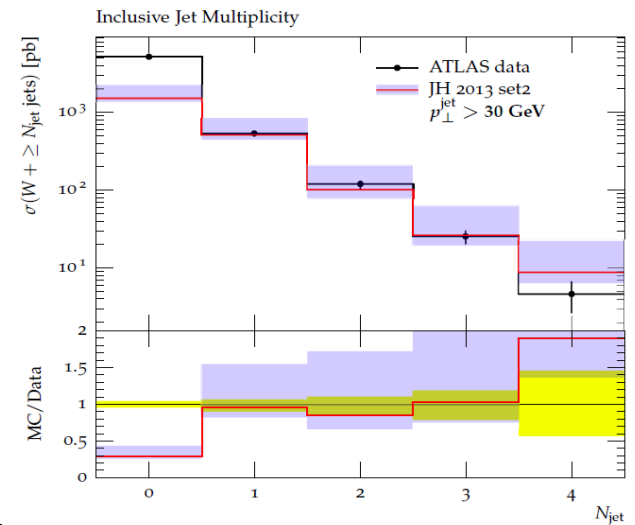


## Transverse Momentum Dependent PDFs (uPDFs)

→ based on the  $k_T$ -factorisation (CCFM) evolution

→ valid for inclusive DIS and for particular hadron-hadron scattering processes (heavy flavor, VB, Higgs production)

Withing HERAFitter used to determine unintegrated TMD gluon density [arXiv:1312.7875](#)





# Physics Cases in HERAFitter: Jets

## Jet production ( $ep, pp, ppbar$ )

using fast techniques (FastNLO and APPLGRID)

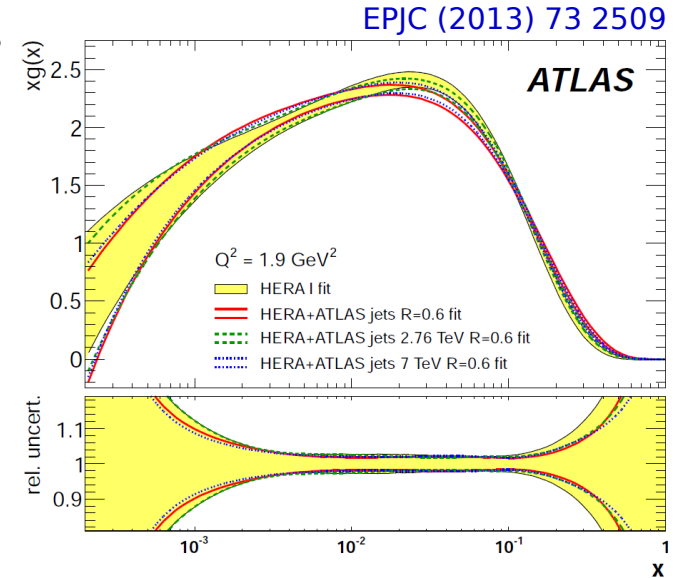
→ decoupled hard scattering coefficients from PDFs stored on grids

→ allow to study sensitivity to the gluon PDF

## ATLAS: using ratio of jets at different beam energies

→ benefits from cancellation of common sys. uncertainties

→ compare the gluon for PDF fit using just HERA I and a fit using HERA I + ATLAS 2.76, 7 TeV jet data (2010)

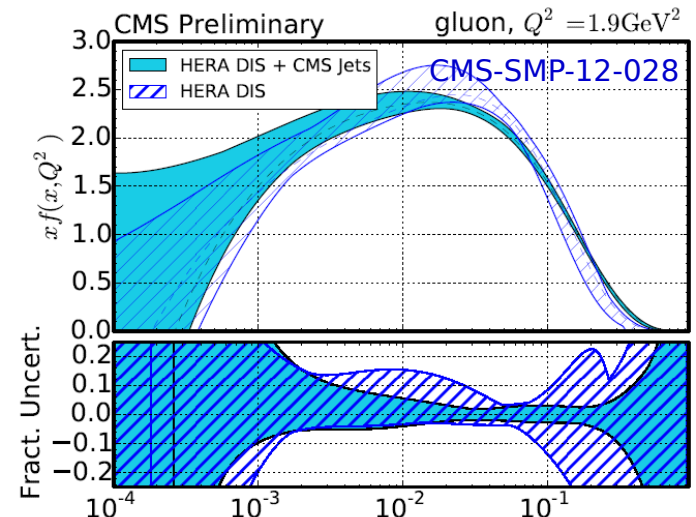


## CMS: using inclusive jets at 7 TeV (2011 data)

→ PDFs are extracted and compared to fits using HERA I and fits using HERA I + CMS 7 TeV jet data

→ extracted strong coupling constant

$$\alpha_S(M_Z) = 0.1192^{+0.0017}_{-0.0015}$$



# Physics Cases in HERAFitter: Drell-Yan

## Drell-Yan processes ( $pp, ppbar$ )

LO calculation x NLO k-factors and APPLGRID technique

→ strange quark density determination

ATLAS: using  $W^\pm$  and Z inclusive cross sections ( $35 \text{ pb}^{-1}$ ) and  $W+$  charm data ( $4.6 \text{ fb}^{-1}$ )

→ data suggest that light quark sea at low  $x$  is flavor symmetric

$$r_s = 0.5(s + \bar{s})/\bar{d}$$

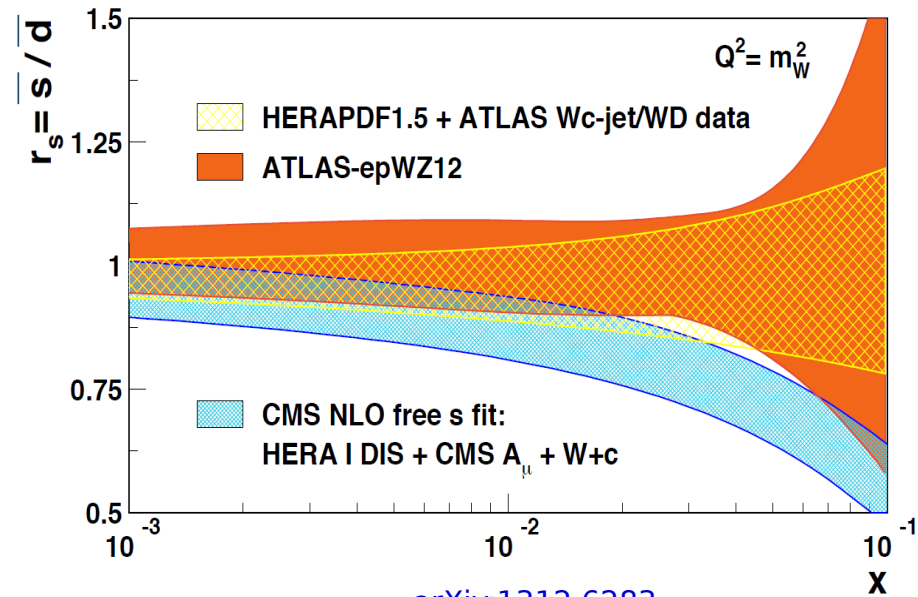
$$= 1.00 \pm 0.07_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.04_{\text{par}} \pm 0.02_{\alpha_S} \pm 0.03_{\text{th}}$$

CMS: using  $W^\pm \mu$  charge asymmetry ( $4.7 \text{ fb}^{-1}$ ) and  $W+$  charm data ( $5 \text{ fb}^{-1}$ )

→ determined strange fraction is consistent with fixed target (NOMAD) results

$$\kappa_S = \frac{\int_0^1 x [\bar{s}(x, Q^2) + s(x, Q^2)] dx}{\int_0^1 x [\bar{u}(x, Q^2) + \bar{d}(x, Q^2)] dx} = 0.52^{+0.12}_{-0.10} (\text{exp.})^{+0.05}_{-0.06} (\text{model})^{+0.13}_{-0.10} (\text{parametrization})$$

arXiv:1402:6263  
Phys.Rev.Lett.109(2012)012001



# Benchmarking and Future Colliders

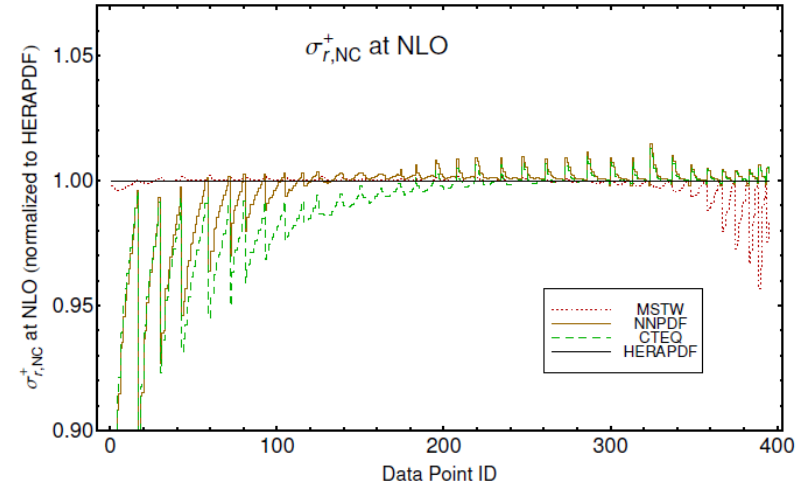
## Various benchmarking studies

→ HERAFitter provided unique possibility to preform PDF related studies under the same conditions

“Les Houches 2013: Physics at TeV Colliders Standard Model Working Group Report”:

→ benchmark studies provide comparison of cross sections with LHC data from Run 1 and projections for future measurements in Run 2

arXiv:1405.1067



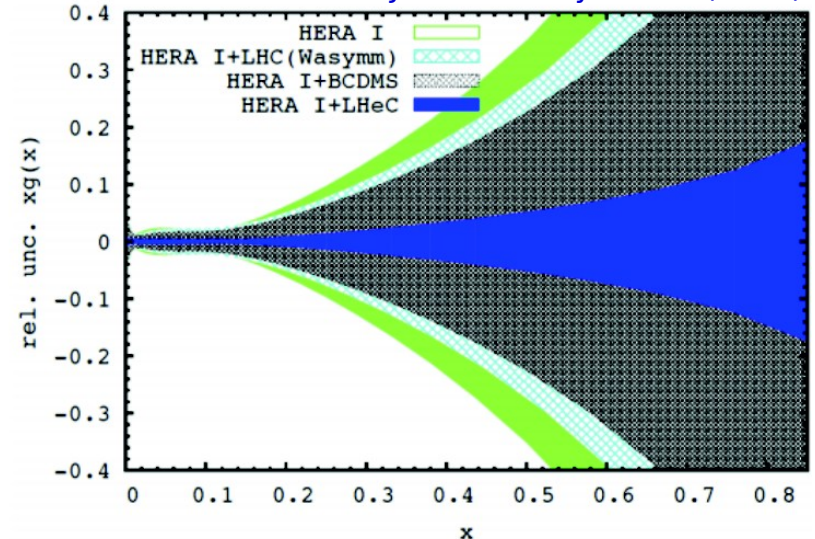
## Impact on PDF studies at LHeC

→ possibility to perform impact studies using simulated data

per-mille accuracy on alphas:

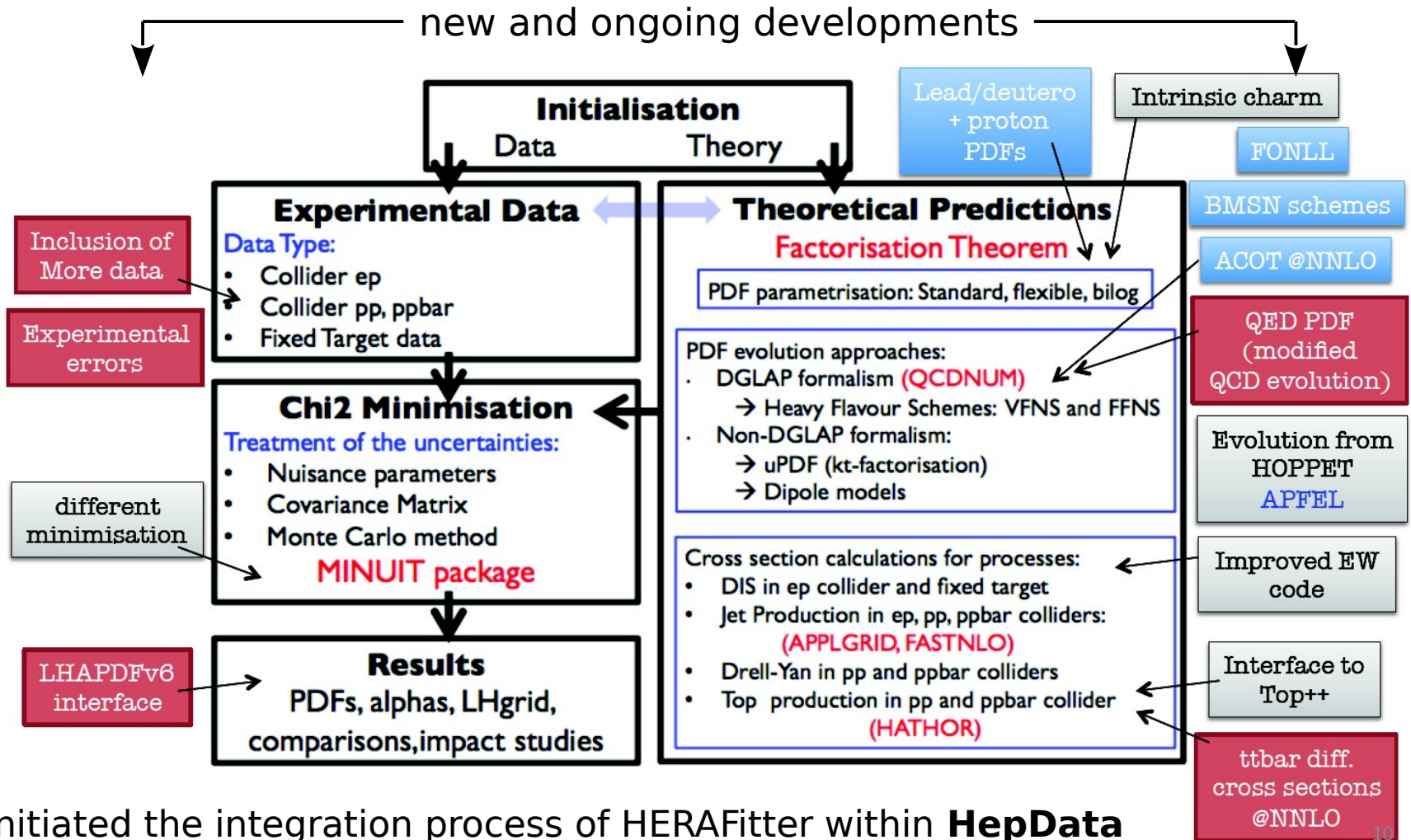
case	cut [ $Q^2$ in GeV]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Journal of Phys. G 39 (2012)



# 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**



## List of analyses by HERAFitter

<b>NEW</b> 04.2014	<b>HERAFitter team</b>	arXiv:1404.4234	Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders	Material	
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## List of analyses using HERAFitter

Date	Group	Reference	Title
<b>NEW</b> 05.2014	HERA/ZEUS 	arxiv:1405.6915	Measurement of beauty and charm production in deep inelastic scattering at HERA and measurement of the beauty-quark mass
<b>NEW</b> 05.2014	ggH benchmark HERAPDF, CT, NNPDF, MSTW	arxiv:1405.1067	Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report
<b>NEW</b> 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
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 <b>Theory</b>	arXiv:1401.1133	Impact of QED radiative corrections on Parton Distribution Functions
01.2014	F. Hautmann and H. Szeferly <b>Theory</b>	arXiv:1312.7875	Tr
12.2013	M. Klein, V. Radescu (LHeC studies)	arXiv:1310.5189	Re
12.2013	A. Luszczak and H. Szeferly <b>Theory</b>	arXiv:1312.4060	Dij
12.2013	LHC/ATLAS 	ATL-PHYS-PUB-2013-018	A : sectic
12.2013	LHC/CMS 	PRD 90 (2014) 032004 / arXiv:1312.6283	Me
12.2013	LHC/CMS 	CMS-SMP-12-028	PC TeV
2013	LHC/ATLAS 	Phys. Lett. B 725 (2013) pp. 223	Me
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 $W \rightarrow l \nu$ and $Z \rightarrow ll$ cross sections
2013	HERA/H1 and ZEUS  	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

20 publications and preliminary results obtained using HERAFitter

- 8 LHC (ATLAS and CMS)
- 3 HERA (H1 and ZEUS)
- 4 theory/phenomenology
- 2 LHeC
- 1 HERAFitter Developers Team

# HERAFitter Developer's Publication

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2013	HERA/H1 and ZEUS	Eur. Phys. J. C 73 (2013) 2311	Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep-Inelastic ep Scattering at HERA
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**1 HERAFitter Developers Team**



# 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:  $\sigma \approx \hat{\sigma} \otimes \text{PDF}$

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:

$$\frac{\hat{\sigma}_X^{NLO} \otimes \text{PDF}_{NLO}}{\hat{\sigma}_Y^{NLO} \otimes \text{PDF}_{NLO}} \quad \begin{array}{l} \text{PDF uncertainties cancel} \\ \text{large scale uncertainty} \end{array}$$

$$\frac{\hat{\sigma}_X^{NLO} \otimes \text{PDF}_{NLO}}{\hat{\sigma}_Y^{NNLO} \otimes \text{PDF}_{NNLO}} \quad \begin{array}{l} \text{improved scale uncertainty} \\ \text{No cancellation of PDF uncertainty} \end{array}$$

$$\frac{\hat{\sigma}_X^{NLO} \otimes \text{PDF}_{NNLO}}{\hat{\sigma}_Y^{NNLO} \otimes \text{PDF}_{NNLO}} \quad \begin{array}{l} \text{PDF uncertainties cancel} \\ \text{improved scale uncertainty} \\ \text{not clear definition in pQCD} \end{array}$$

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

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Requires preserved correlations in PDF uncertainties at different orders

# QCD Analysis Settings

arXiv:1404.4234

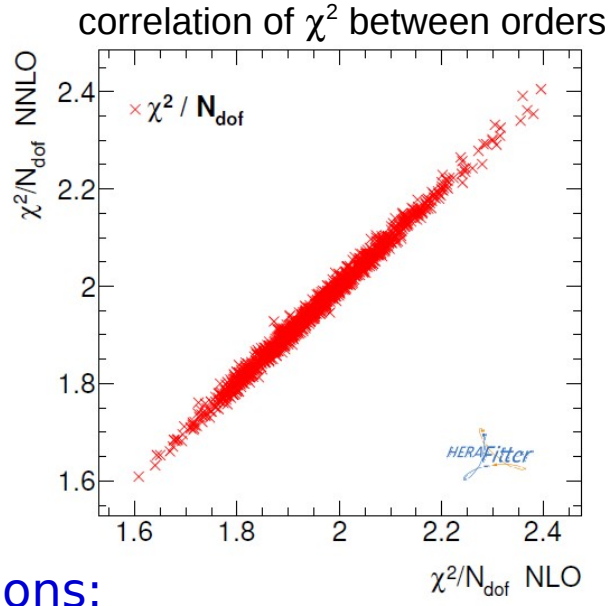
A QCD fit to HERA I data (JHEP 1001, 2010, 109) using HERAFitter

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
$\alpha_s$	0.13	0.1184	0.1184
$Q_0^2$ (GeV <sup>2</sup> )	1.7	1.7	1.7
$Q_{min}^2$ (GeV <sup>2</sup> )	7.5	7.5	7.5

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



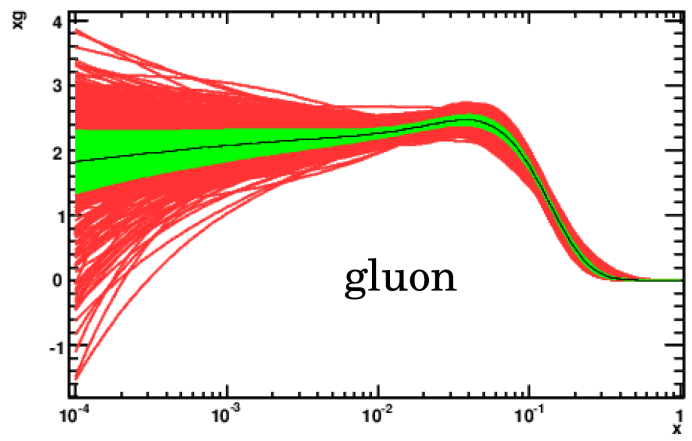
## MC replica method used to preserve the correlations:

→ 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

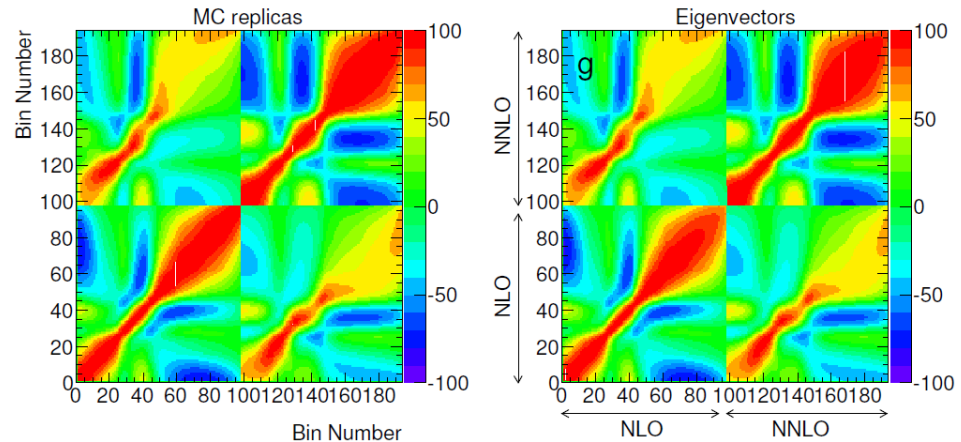
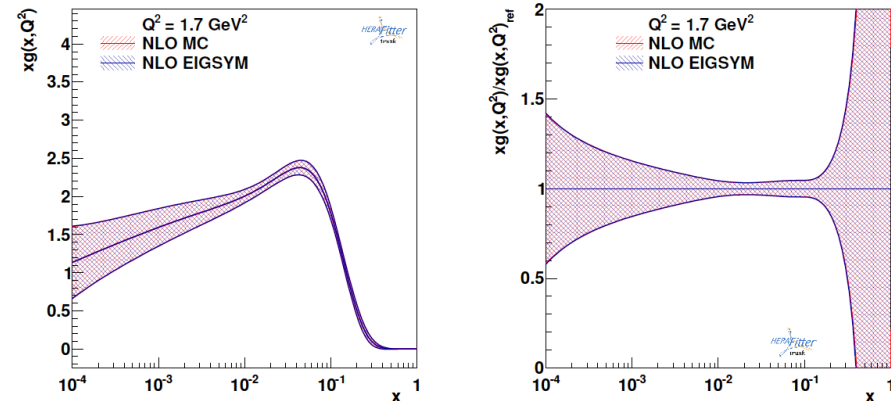
Eigenvector representation is often more convenient than MC replica

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

Correlation coefficients among PDFs:



→ very good agreement between PDFs

- PDFs show high degree of correlation at neighboring  $x$  bins (smoothness of parametrisation)
- strong correlation between NLO and NNLO PDFs

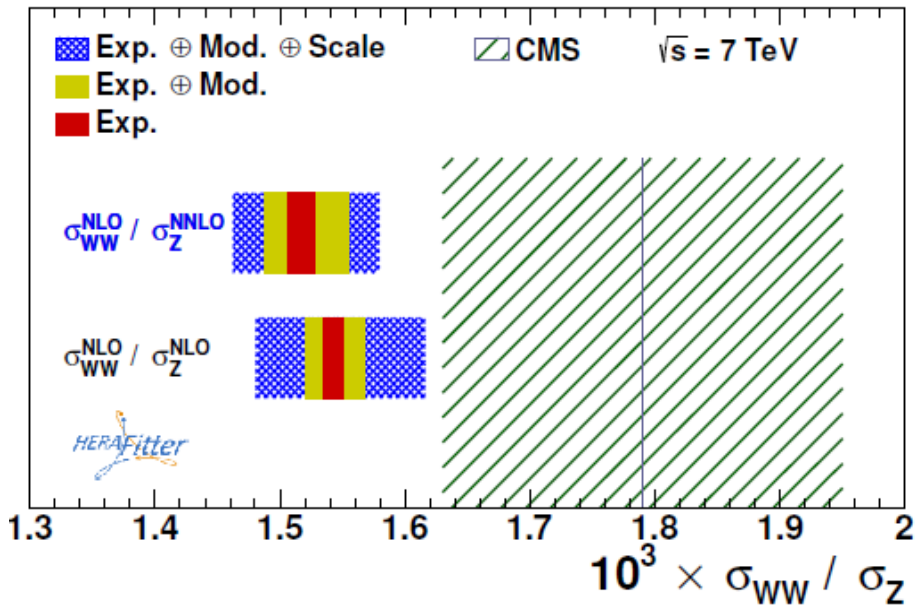
# Comparison to Data: WW/Z ratio

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 $\times 10^{-3}$
$\frac{\sigma_{WW}^{NLO}}{\sigma_Z^{NLO}}$	1.543	$\pm 0.008$	$+0.023$ $-0.021$	$+0.069$ $-0.058$
$\frac{\sigma_{WW}^{NLO}}{\sigma_Z^{NNLO}}$	1.517	$\pm 0.010$	$+0.036$ $-0.027$	$+0.050$ $-0.046$



→ 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)

- various physics cases
- various options for data uncertainty treatment
- different parametrisation styles

The first **HERAFitter stable release (HERAFitter-1.0.0)**

Project is open to everyone and everyone can contribute

[www.herafitter.org](http://www.herafitter.org)

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

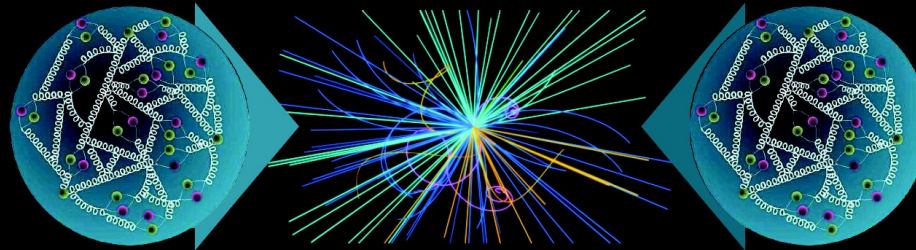
- a high degree of correlation was observed for PDFs at different orders and similar  $x$
- the total theoretical uncertainty is reduced for the mixed-order calculation by 30-40% due to reduced scale uncertainties



29 September - 02 October 2014

DESY Hamburg

# Proton Structure in the LHC Era



## School on phenomenology of proton-proton interactions

### Lectures

Enhancing discovery potential: QCD precision measurements at the LHC	A. Cooper-Sarkar
The tricky part of the factorization: Parton Distribution Functions	D. Soper
Determination of strong coupling constant and PDFs	G. Dissertori
The precise part of the factorization: theory calculations at NLO and NNLO	M. Schulze
Jets in hadron collider at highest order	Z. Nagy
The number of flavors and the quark masses	S.-O. Moch

Tutorials in HERAFitter, fastNLO, Applgrid, Difftop, NNPDF reweighting:

D. Britzger, S. Camarda, A. Glazov, A. Guffanti, M. Guzzi, K. Lohwasser,  
H. Pirumov, R. Plačákytė, K. Rabbertz, V. Radescu, P. Starovoitov

## Workshop 01-02 October 2014

on theory and experimental issues in determination of PDFs and QCD parameters

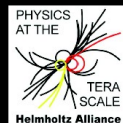
Registration deadline: 15th September 2014

Registration fee: 40 €

Contact: [anacen@desy.de](mailto:anacen@desy.de)



CTEQ



[www.terascale.de/pdf2014](http://www.terascale.de/pdf2014)

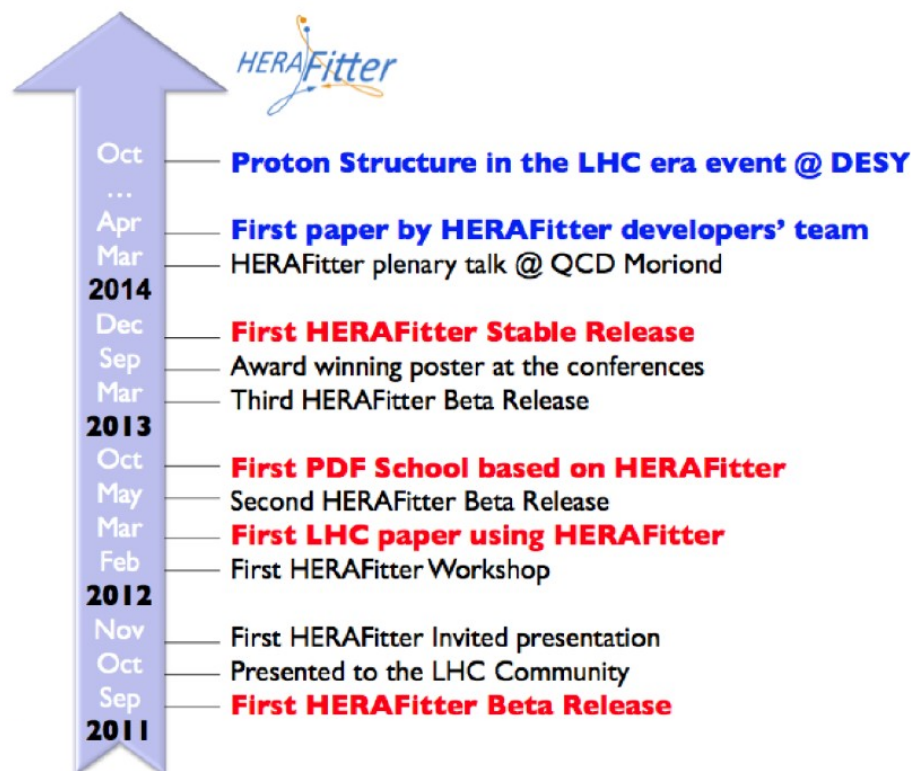
# Back-up slides

# Motivation

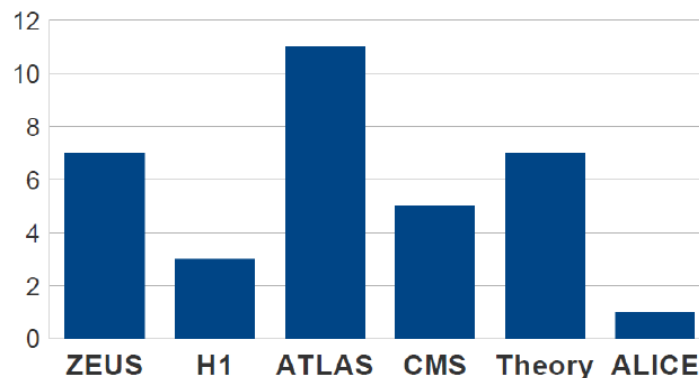
**HERAFitter** project is a QCD fit framework ready to extract PDFs and assess the impact of new data

[www.herafitter.org](http://www.herafitter.org)

→ everyone is welcome to download it and use it



Developers:



# HERAFitter Download

## HERAFitter / DownloadPage

### Releases of the HERAFitter QCD analysis package

- Versioning convention: **I.J.k** with
  - **I** - stable release
  - **J** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: @HERAFitter\_release\_notes.pdf.
- Description paper in preparation.

Date	Version	Files	Remarks
12/2013	1.0.0	<a href="#">@herafitter-1.0.0.tgz</a>	stable released with decoupled <a href="#">@theoryfiles.tgz</a>
06/2013	0.3.1	<a href="#">@herafitter-0.3.1.tgz</a>	fix release includes <a href="#">@manual-0.3.1.pdf</a> and decoupled <a href="#">@theoryfiles.tgz</a>
03/2013	0.3.0	<a href="#">@herafitter-0.3.0.tgz</a>	release includes <a href="#">@manual-0.3.1.pdf</a> and decoupled <a href="#">@theoryfiles.tgz</a>
07/2012	0.2.1	<a href="#">@herafitter-0.2.1.tgz</a>	fix release for 0.2.0
05/2012	0.2.0	<a href="#">@herafitter-0.2.0.tgz</a>	added functionality for LHC users
09/2011	0.1.0	<a href="#">@herafitter-0.1.0.tgz</a>	first release

Releases  
(publicly accessible)

### Documentation

- Data set Index used in HERAFitter to identify each data set is stored for logging purposes in [@here](#).
- From 0.3.0 on a manual is provided together with an example directory.
- The **README** file (accessible via the package) gives an explanation for a quick start.

#### Web access to SVN

- For users with a valid DESY account, the SVN repository is accessible on the web at <https://svnsrv.desy.de/k5viewvc/h1fitter>.
- For users without DESY account, the SVN repository is accessible on the web at <https://svnsrv.desy.de/basviewvc/h1fitter/> with [herafitter-user@desy.de](mailto:herafitter-user@desy.de) account.

#### Doxygen Documentation

- The doxygen documentation is located [@here](#)

Documentation:  
manual,  
release notes,  
README,  
DOXYGEN

### Links to external packages

External packages that could be run with HERAFitter via configuration flags can be accessed for convenience [HERE](#).

External packages

### HERAverager data combination package

Information can be accessed here <https://wiki-zeuthen.desy.de/HERAverager>.

### Subscription