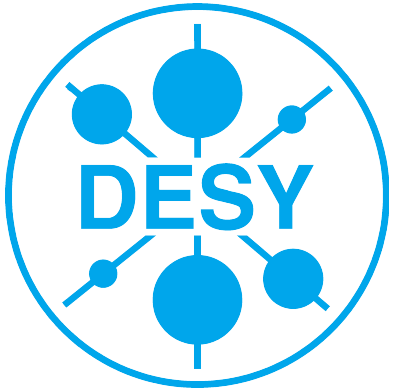


HERAFitter – an Open Source QCD Fit Platform

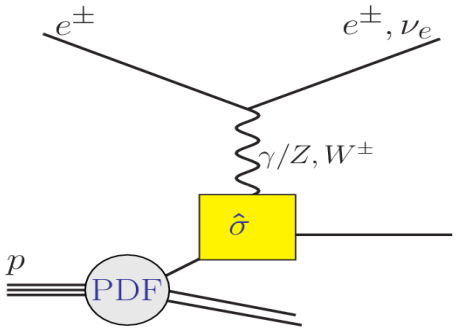
See also talks by M. Ubiali and I. Brock

Oleg Kuprash (DESY)
for the HERAFitter team

May 21, 2014

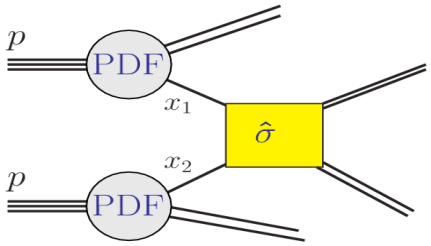
26th Rencontres de Blois
Particle Physics and Cosmology

Motivation



Extraction of the PDFs relies on **Factorisation:** hadronic cross section is a convolution of the PDFs and hard-scattering coefficients:

$$\sigma = \hat{\sigma} * \mathrm{PDF}$$



- main information on PDFs comes from DIS data at HERA which probes linear combination of quarks
- LHC provides new observables and precise measurements to better constraint gluon and flavour decomposition of the sea

→ **PDFs are essential for precision physics at the LHC:**

- uncertainties due to PDFs are one of the main uncertainties in Higgs production, Mw measurements etc
- affect theoretical predictions for BSM high mass production

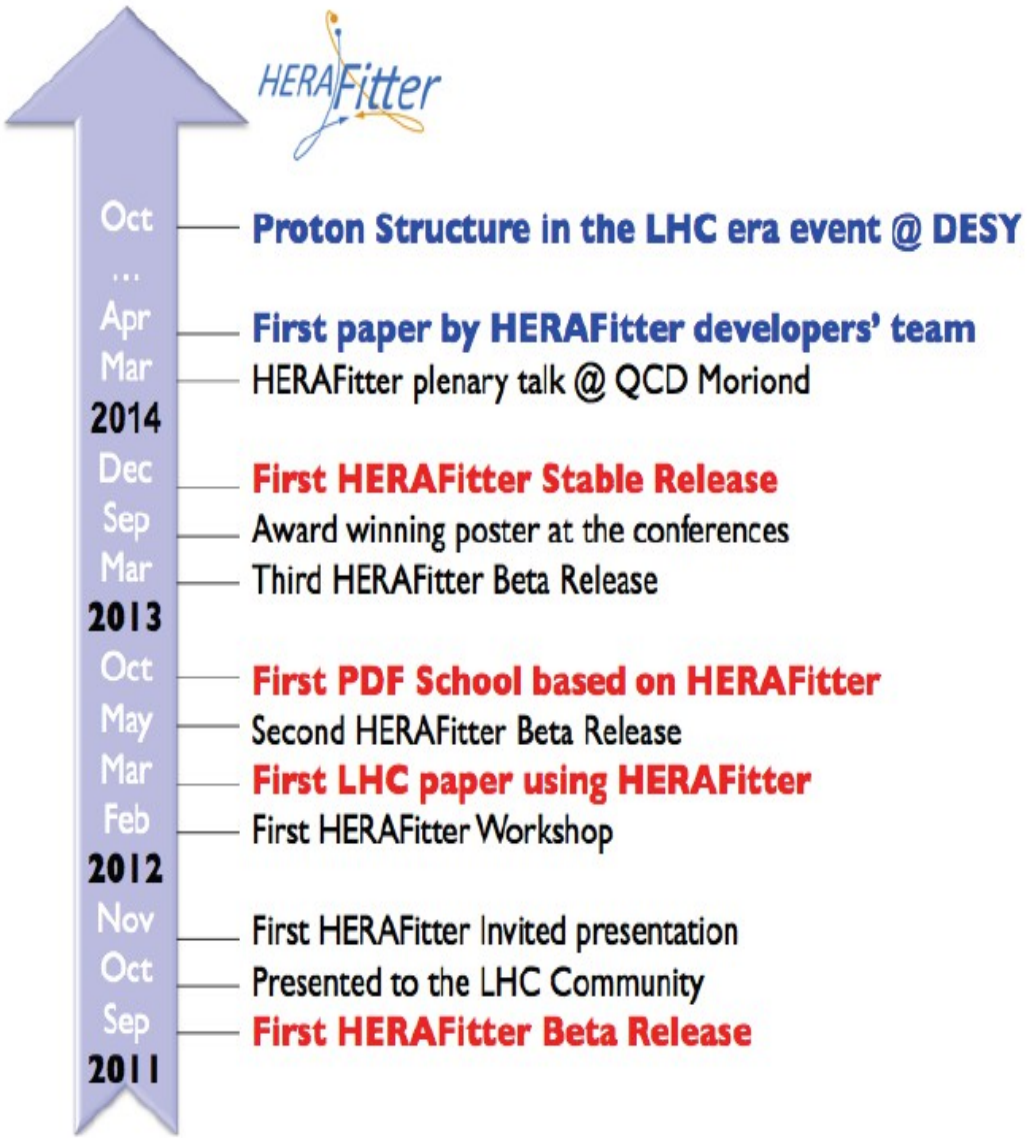
Different global PDF groups (CT, MSTW, NNPDF, HERAPDF, ABM, JR) use different data and methodology to extract PDFs

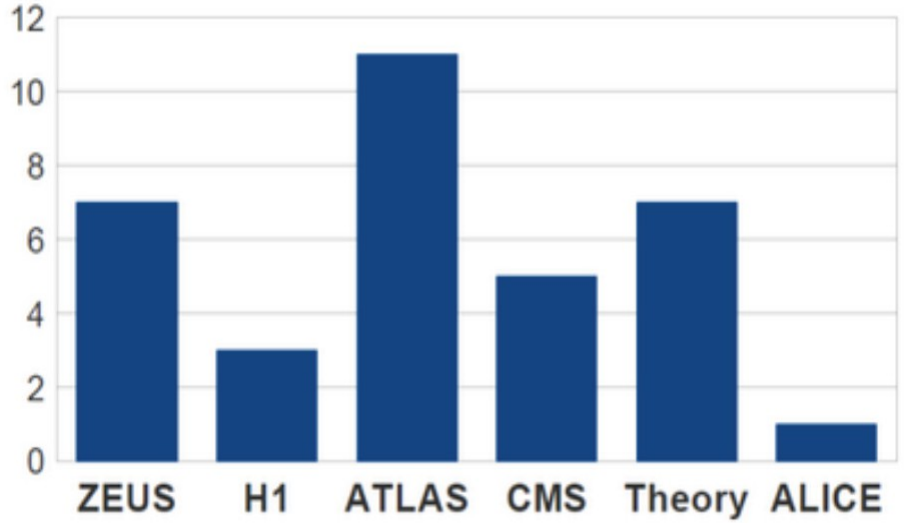
- Leads to differences in the cross section predictions

→ **Crucial to understand theoretical differences**

HERAFitter project

- Tool to fit PDFs (and not only)





HERAFitter:

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

Extraction of PDFs in HERAFitter

Input Data[(i)]:
cross sections, their uncertainties & correlations
Data type:
- ♦ collider ep, pp, ppbar
- ♦ fixed target

Theory Predictions[(ii)]

Factorisation theorem:
- ♦ PDF parametrisation
- ♦ QCD evolution
- ♦ cross section calculation

(i) On data side:
important to provide correlation information

Minimisation (MINUIT):
Treatment of the uncertainties:
- ♦ nuisance parameters
- ♦ covariance matrix
- ♦ Monte Carlo Method

(ii) On theory side:
important to have fast tools to perform PDF fits, i.e. APPLGRID, FASTNLO

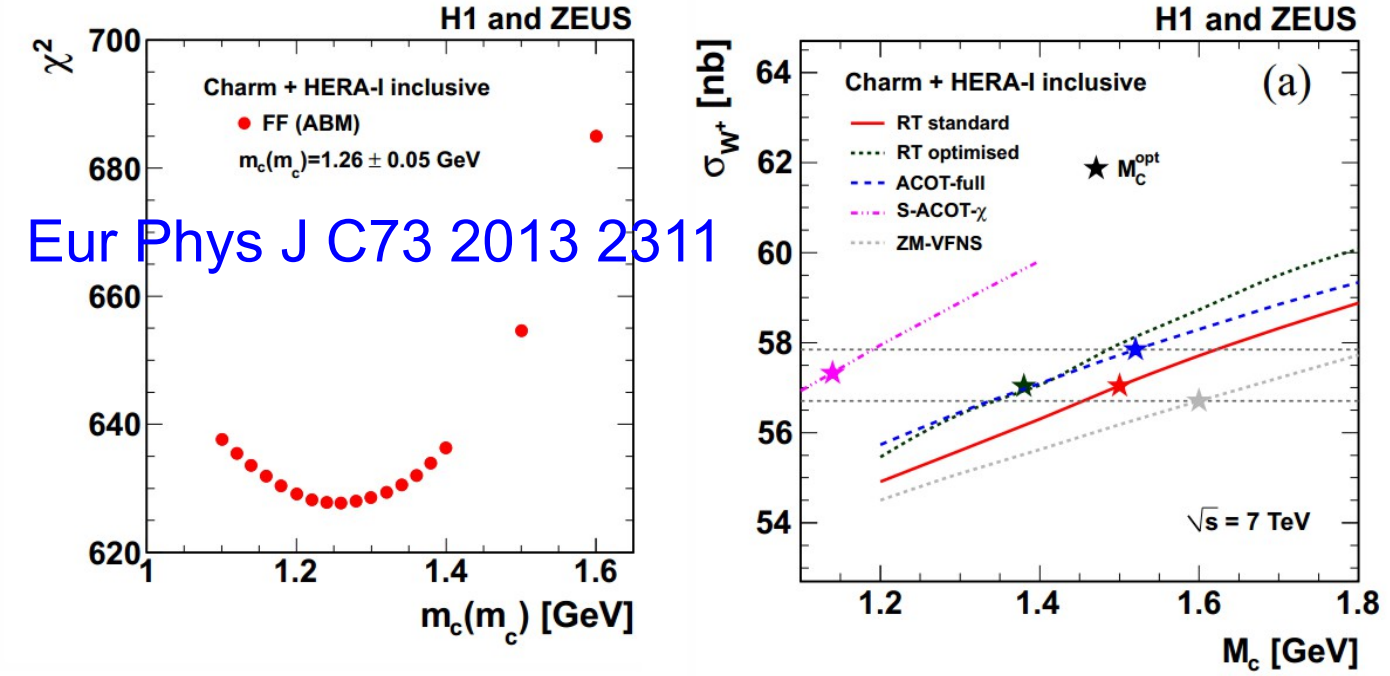
Results
- ♦ PDF Lhgrids
- ♦ Alphas, mc, mb
- ♦ Data vs Predictions
- ♦ Chi2, systematics shifts

Heavy Flavour Schemes in DIS

Heavy quarks introduce additional scales which complicates the calculations:

- VFNS (Variable Flavour Number Scheme)
  - 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 OPENQCDRAD, as used by ABM
  - via QCDNUM

Variety of scheme options was studied by HERA in F2 charm HERA combination paper

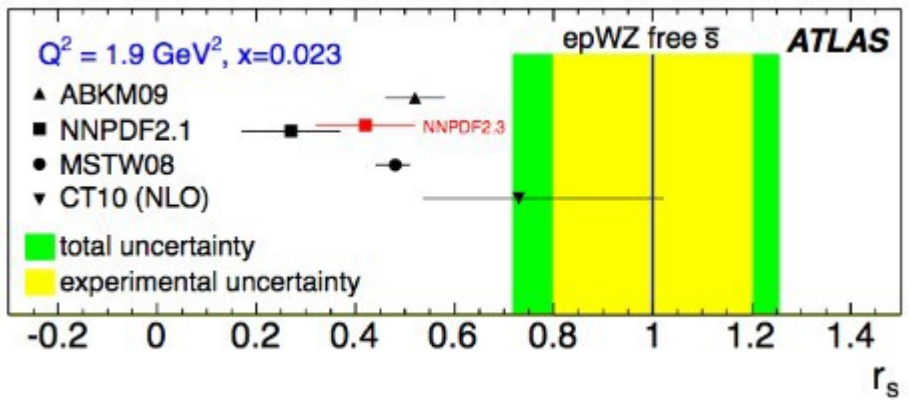


Spread in predictions for W and Z is reduced significantly when predictions are evaluated at the optimal mc determined from F2 charm data

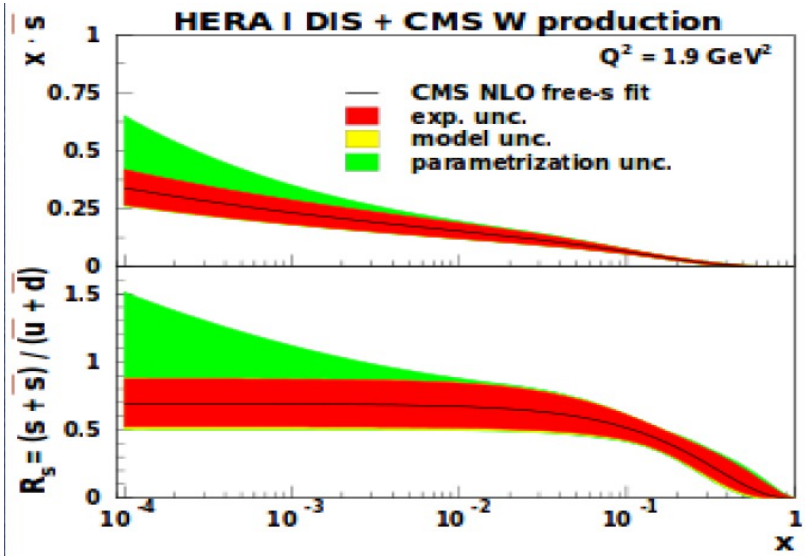
Strange Quark at LHC

◆ W± and Z inclusive cross section were used by ATLAS to determine strange quark fraction in the sea

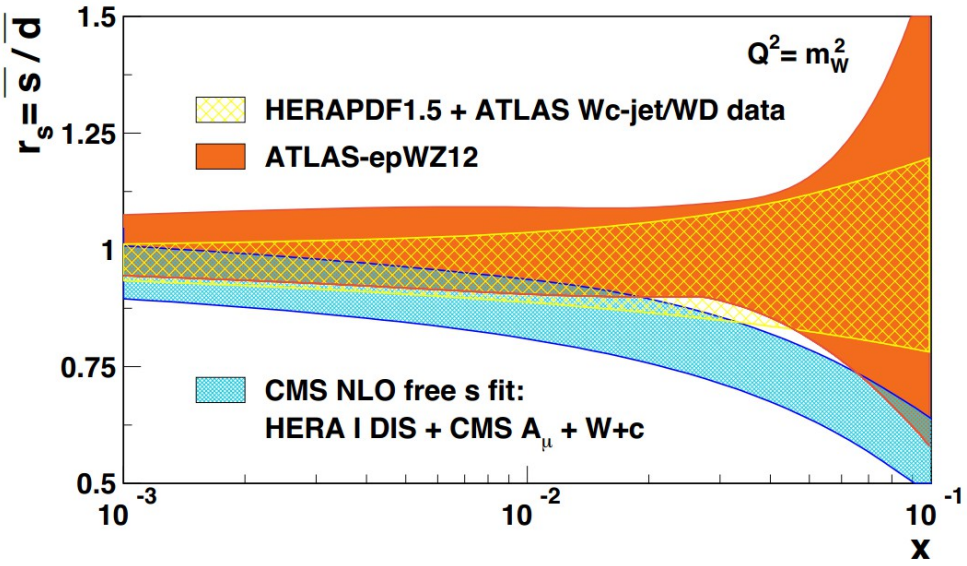
[Phys. Rev. Lett. 109 (2012) 012001]



◆ W+charm data including W asymmetry were used by CMS to probe strange quark distribution [CMSSMP12021]



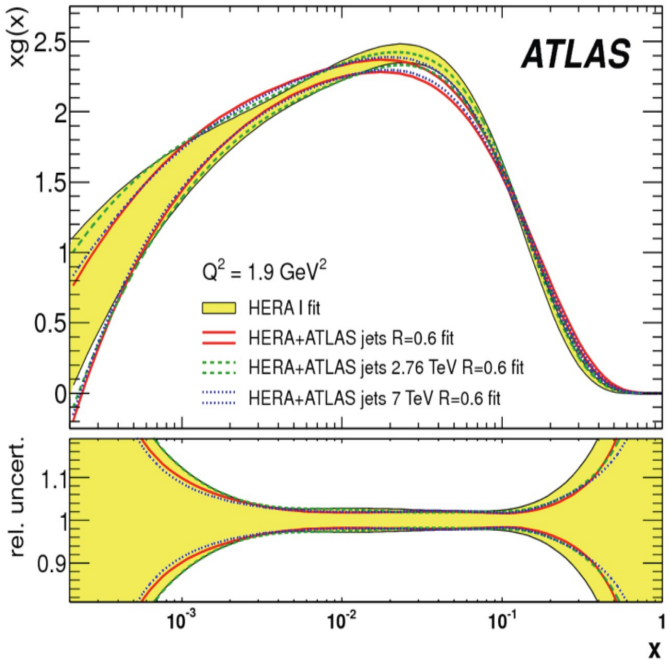
◆ W+charm data were used by ATLAS to determine the ratio of the strange-to-down sea-quark distributions [arXiv:1402.6263]



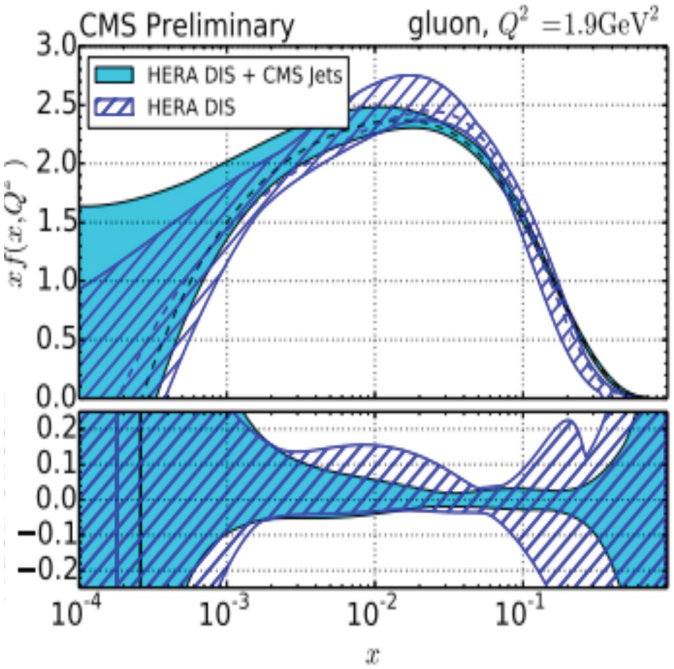
Sensitivity to Gluon and Strong Coupling

Study sensitivity to the gluon PDF:

- using ratio of jets at different beam energies – ATLAS [EPJC (2013) 732509]
  - benefits from cancellation of common sys. unc.
  - compare the gluon for PDF fit using just HERAI and a fit using HERAI + ATLAS 2.76, 7 TeV jet data (2010)



- using inclusive jet cross section at 7 TeV CMS data from 2011 (5 fb^{-1}) [SMP-12-028]
  - PDFs are extracted and compared to fits using just HERAI and fits using HERAI + CMS 7 TeV jet data



Extraction of the strong coupling [SMP-12-028]:

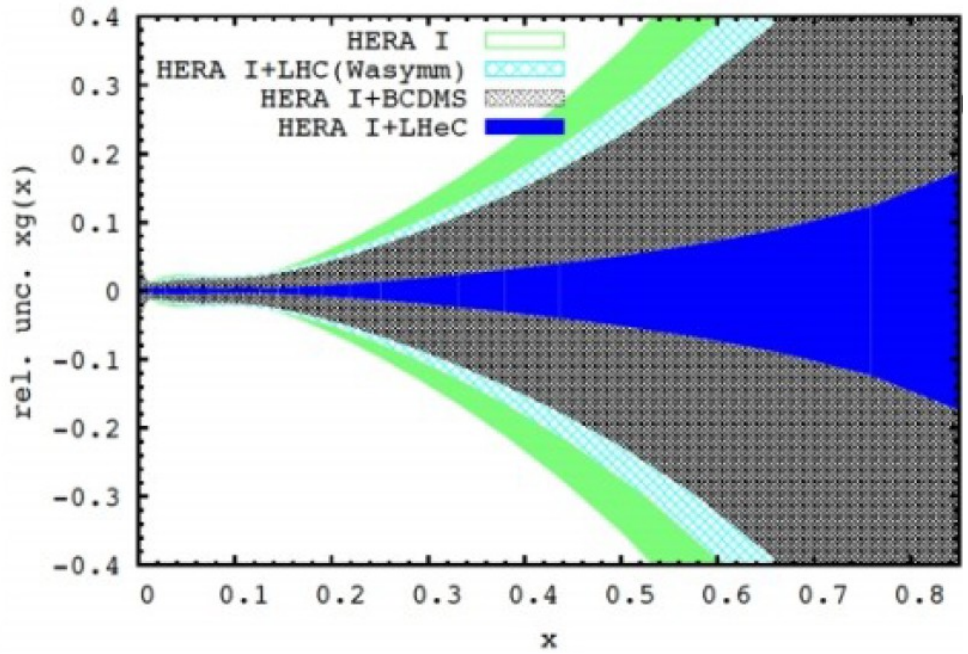
- From PDF and alphas simultaneous fit

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

Sensitivity studies

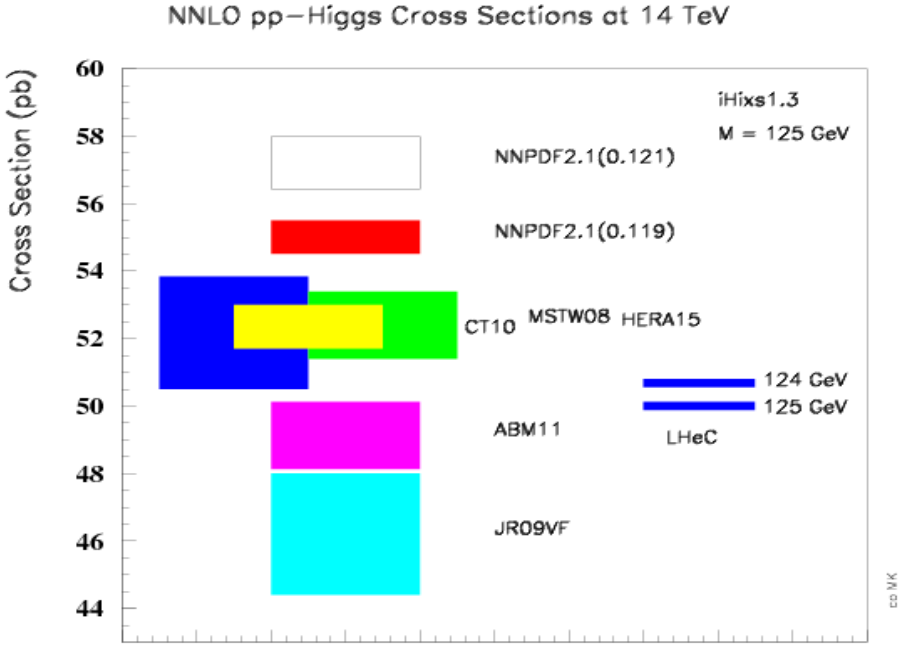
Platform can be used for sensitivity studies of the potential of future colliders:

LHeC ep simulated data were used to study sensitivity to PDFs:



[Journal of Physics G 39 (2012) Number 7]

The output in LHAPDF format can be used for Higgs predictions



[Mod.Phys.Lett. A28 (2013) 16, 1330011]

Results using HERAFitter

List of analyses by HERAFitter

NEW 04.2014	**HERAFitter team**	arXiv:1404.4234	Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders

→ next page

List of analyses using HERAFitter

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	arXiv:1401.1133	Impact of QED radiative corrections on Parton Distribution Functions
01.2014	F. Hautmann and H. Jung	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	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 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

PDFs with correlated uncertainties between orders

LO, NLO and NNLO PDF sets with correlated uncertainties allow reduction of theoretical uncertainties in ratios

- various processes at LHC are calculated at LO, NLO, NNLO accuracy in QCD
- theoretical uncertainties on predicted cross sections arise from PDFs and from missing higher orders (estimated by varying factorisation and renormalisation scales)
- to reduce uncertainties, ratios of two processes cross sections can be used. Assume that for the first process both NLO and NNLO calculations exist, while for the second process only NLO. Theoretical predictions can be constructed in several ways:

$$\frac{\sigma_1^{NLO}\left(PDF^{NLO}\right)}{\sigma_2^{NLO}\left(PDF^{NLO}\right)}$$

✔ cancellation of PDF unc.
✗ large scale unc.

$$\frac{\sigma_1^{NNLO}\left(PDF^{NNLO}\right)}{\sigma_2^{NLO}\left(PDF^{NLO}\right)}$$

✗ PDF unc. do not cancel
✔ scale unc. reduced

$$\frac{\sigma_1^{NNLO}\left(PDF^{NNLO}\right)}{\sigma_2^{NLO}\left(PDF^{NNLO}\right)}$$

✔ PDF unc. cancel
✔ improved scale unc.
✗ unclear definition in pQCD

$$\frac{\sigma_1^{NNLO}\left(PDF_{corr}^{NNLO}\right)}{\sigma_2^{NLO}\left(PDF_{corr}^{NLO}\right)}$$

✔ PDF unc. cancel
✔ scale unc. reduced

- Monte Carlo replica method is used to determine experimental uncertainties of PDFs and to preserve correlation between LO, NLO, and NNLO

Predictions vs Data

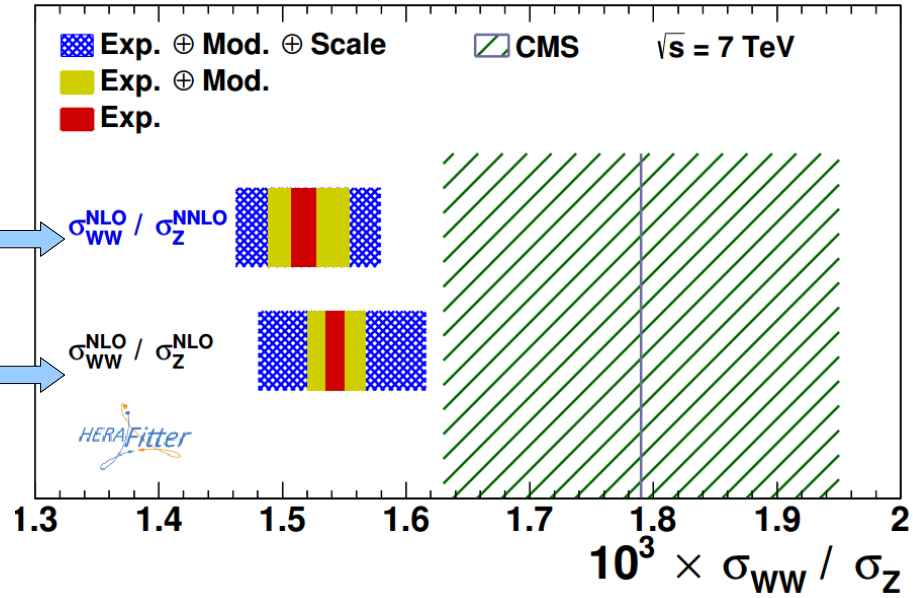
arXiv:1404.4234 [hep-ph]

±0.066 total uncertainty for NLO/NNLO assuming uncorrelated total PDF unc

$$\sigma_{WW}^{\mathrm{NLO}}/\sigma_{Z}^{\mathrm{NNLO}} = [1.517^{+0.051}_{-0.047}] \times 10^{-3}$$

$$\sigma_{WW}^{\mathrm{NLO}}/\sigma_{Z}^{\mathrm{NLO}} = [1.543^{+0.073}_{-0.062}] \times 10^{-3}$$

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 of the ratio WW to Z production cross sections are compared to the CMS measurement [E.P.J. C73 (2013) 2610]
- usage of the mixed-order NLO – NNLO predictions, allows reduction of the total uncertainty due to the reduction of the scale uncertainty for Z production prediction
- usage of the correlated PDFs allows sizable reduction of the ratio uncertainty

Summary

- HERAFitter is an open source QCD framework and it has proved to be a successful platform that is well integrated in the high energy physics community

- HERAFitter infrastructure has increased the scientific output of the HERA and LHC data, provides a flexible environment for theory benchmarking

- Stable release: herafitter-1.0.0, can be found at http://www.herafitter.org

- HERAFitter developers team: correlations of the PDFs at LO, NLO, NNLO

→ we welcome new developments!

Backup

PDFs extraction from LHC data

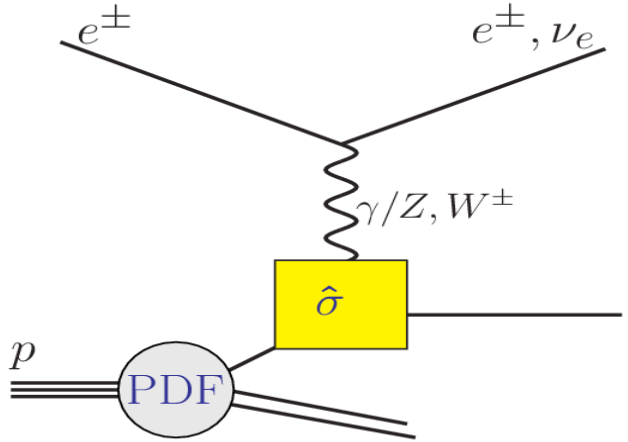
LHC introduces new observables and abundant data to help provide flavour separation and a better understood gluon:

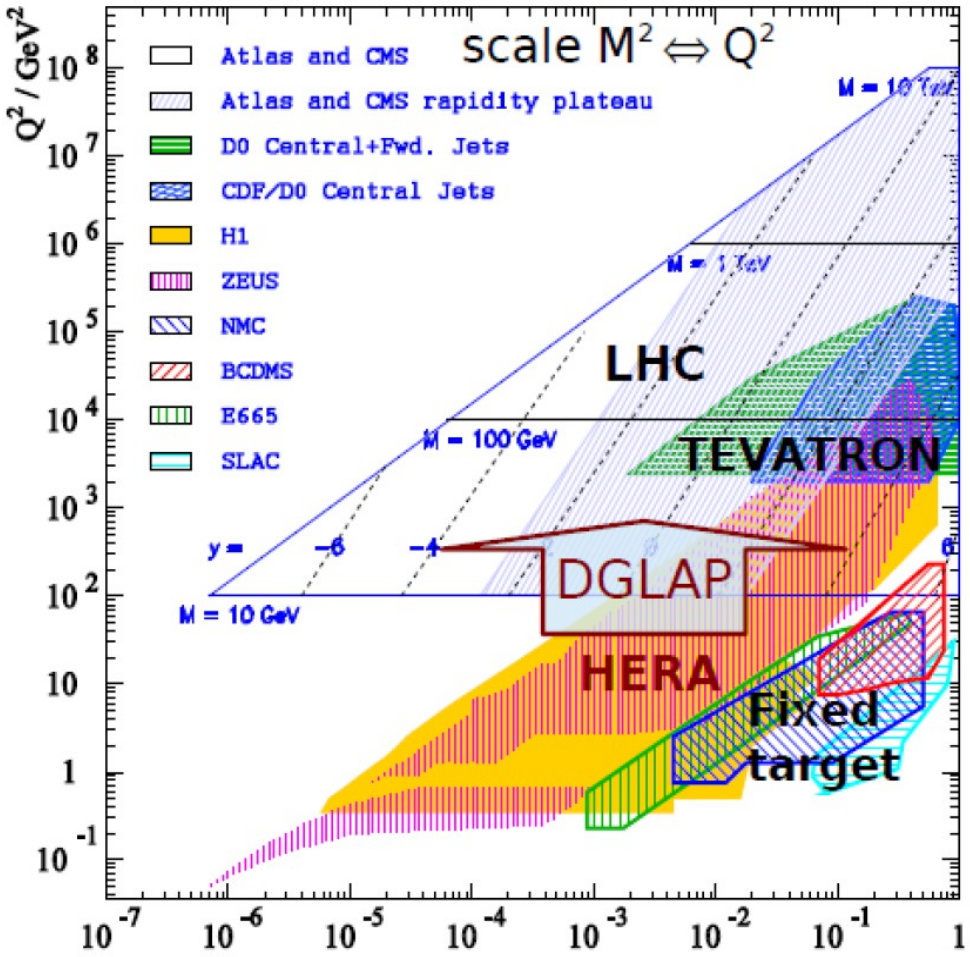
- Inclusive jets and dijets → gluon and alphas
- W, Z production, asymmetries → quark flavour separation
- W+charm → direct sensitivity to s-quark
- Isolated photons → gluon at medium and high x
- W,Z production with jets → gluon at medium x
- ttbar, single top → gluon and u, d

Proton Structure

Factorisation: hadronic cross section is a convolution of the PDFs and hard-scattering coefficients:

$$\sigma = \hat{\sigma} * \mathrm{PDF}$$





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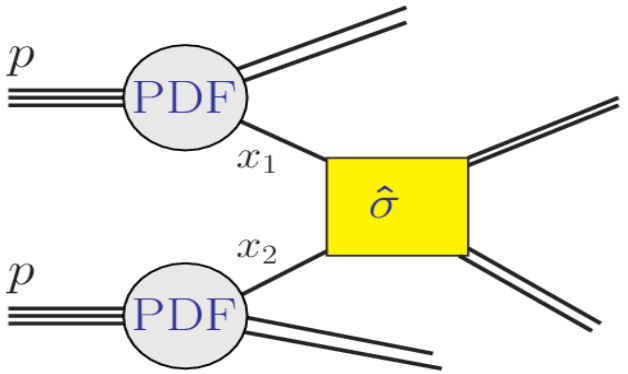
- LHC provides new observables and precise measurements to better constraint gluon and flavour decomposition of the sea



Chi2 definitions and Fit Uncertainties

HERAFitter package allows for various types of data uncertainty treatment

Chi2 representation using:

- nuisance parameters b_j

$$\chi^2(m,b) = \sum_i \frac{\left[m^i - \sum_j \gamma_j^i m^i b_j - \mu^i\right]^2}{\delta_{i,\text{stat}}^2 \mu^i \left(m^i - \sum_j \gamma_j^i m^i b_j\right) + \left(\delta_{i,\text{uncor}} m^i\right)^2} + \sum_j b_j^2$$

μ^i – measured value
m^i – theory prediction
b_j – systematic shifts
γ_j^i – correlations
δ_i – uncertainties

- covariance matrix

$$\chi^2(m) = \sum_{i,j}(m_i - \mu_i)C_{ij}^{-1}(m_j - \mu_j) \qquad C_{ij} = C_{ij}^{stat} + C_{ij}^{uncor} + C_{ij}^{sys}$$

- mixed (covariance and nuisance)

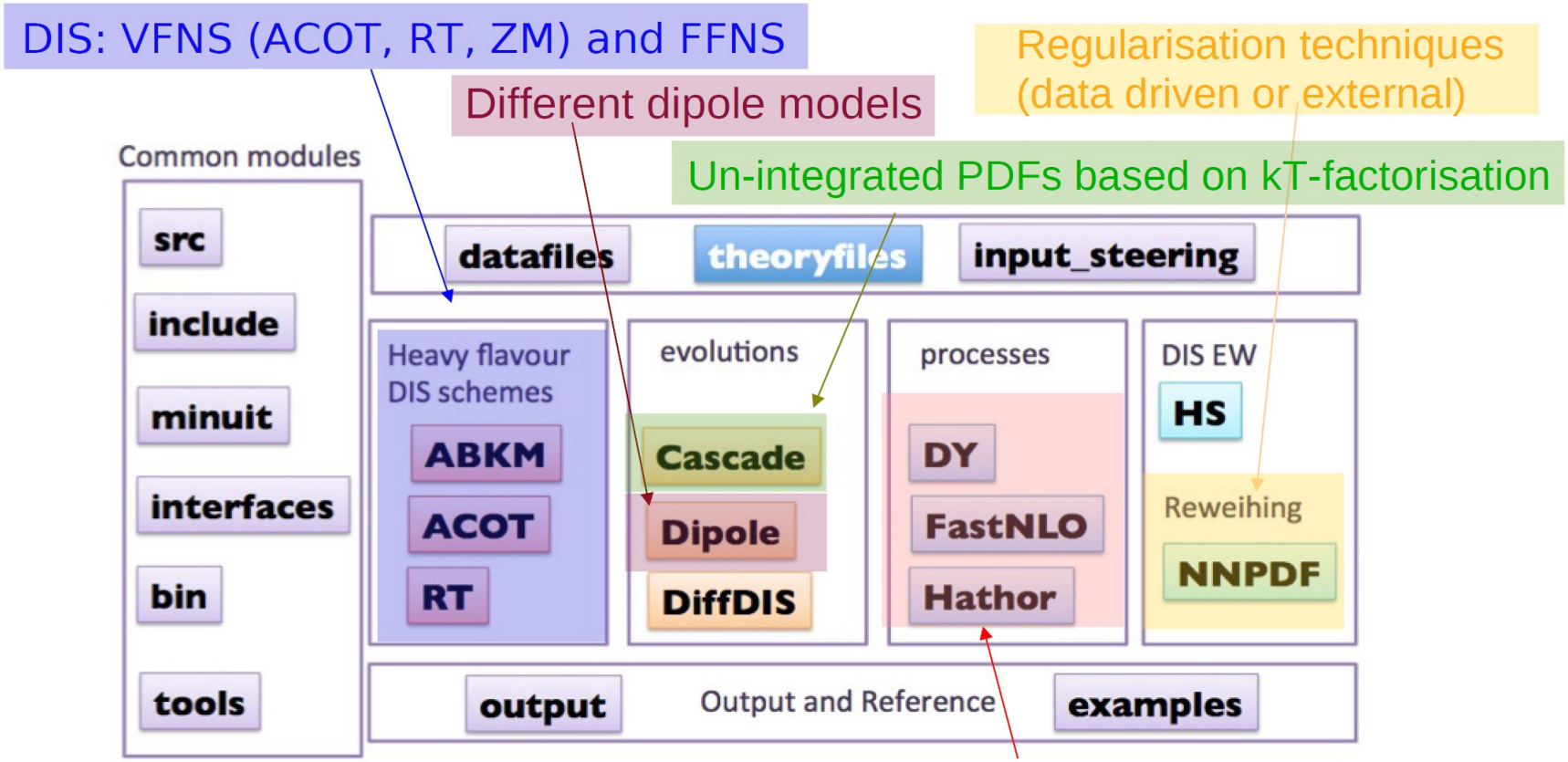
Various types of uncertainty treatment:

- Hessian – error inflation by nuisance parameters to accommodate inconsistencies between data sets
- Monte Carlo – MC replicas by shifting data points randomly within their uncertainties (taking into account correlations)
- Offset – correlated sources accommodated in uncertainties

The platform is used in various benchmark exercises

HERAFitter: Overview

- HERAFitter has a modular structure → facilitating fast development
- new developments of the HERAFitter are dedicated studies made by developers and interested users



Various χ^2 representations,
Hessian and MC replica methods,
various data uncertainty treatments,
etc...

Interfaces to:
APPLGRID
FastNLO
HATHOR

Scheme made by
Ringailė Plačakytė

Data, that are already included in HERAFitter

```
! H1 and ZEUS combined:
        'datafiles/hera/H1ZEUS_NC_e-p_HERA1.0.dat',
        'datafiles/hera/H1ZEUS_NC_e+p_HERA1.0.dat',
        'datafiles/hera/H1ZEUS_CC_e-p_HERA1.0.dat',
        'datafiles/hera/H1ZEUS_CC_e+p_HERA1.0.dat',
! H1 jets:
        'datafiles/hera/H1_NormInclJets_HighQ2_99-07.dat',
        'datafiles/hera/H1_InclJets_HighQ2_99-00.dat',
        'datafiles/hera/H1_InclJets_LowQ2_99-00.dat',
! ZEUS jets:
        'datafiles/hera/ZEUS_InclJets_HighQ2_96-97.dat',
        'datafiles/hera/ZEUS_InclJets_HighQ2_98-00.dat',
        'datafiles/hera/ZEUS_dijet_98-07.dat',
! H1 low Ep inclusive:
        'datafiles/hera/H1_LowEp_460_575.dat',
! HERA combined charm data:
        'datafiles/hera/H1ZEUS_Charm_combined.dat',
! BCDMS:
        'datafiles/bcdms/BCDMS_F2p.100gev.dat',
        'datafiles/bcdms/BCDMS_F2p.120gev.dat',
        'datafiles/bcdms/BCDMS_F2p.200gev.dat',
```

```
        'datafiles/bcdms/BCDMS_F2p.280gev.dat',
! Tevatron:
        'datafiles/tevatron/D0_Z_Boson_Rapidity.dat',
        'datafiles/tevatron/CDF_Z_Boson_Rapidity.dat',
        'datafiles/tevatron/CDF_JETS2008.dat',
        'datafiles/tevatron/CDF-TOP-CONF-NOTE-9913_prelim.dat',
        'datafiles/tevatron/D0_JETS.dat',
! LHC
        'datafiles/lhc/cms/CMS-TOP-11-024_prelim.dat',
        'datafiles/lhc/cms/CMS_Z_boson_Rapidity.dat',
        'datafiles/lhc/cms/CMS_eAsymmetry_SPM_12_001.dat',
! For atals jets, use R06 or R04 data, but never both at the same time !
        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_00_03.dat'
        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_03_08.dat'
        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_08_12.dat'
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        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_21_28.dat'
        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_28_36.dat'
        'datafiles/lhc/atlas/Jets2010/inclusivejets_R06_36_44.dat'
!  W/Z cross sections are given at NNLO !
        'datafiles/lhc/atlas/WZ2010/WP_applgrid_nnlo.dat'
        'datafiles/lhc/atlas/WZ2010/WM_applgrid_nnlo.dat'
        'datafiles/lhc/atlas/WZ2010/Z0_applgrid_nnlo.dat'
```
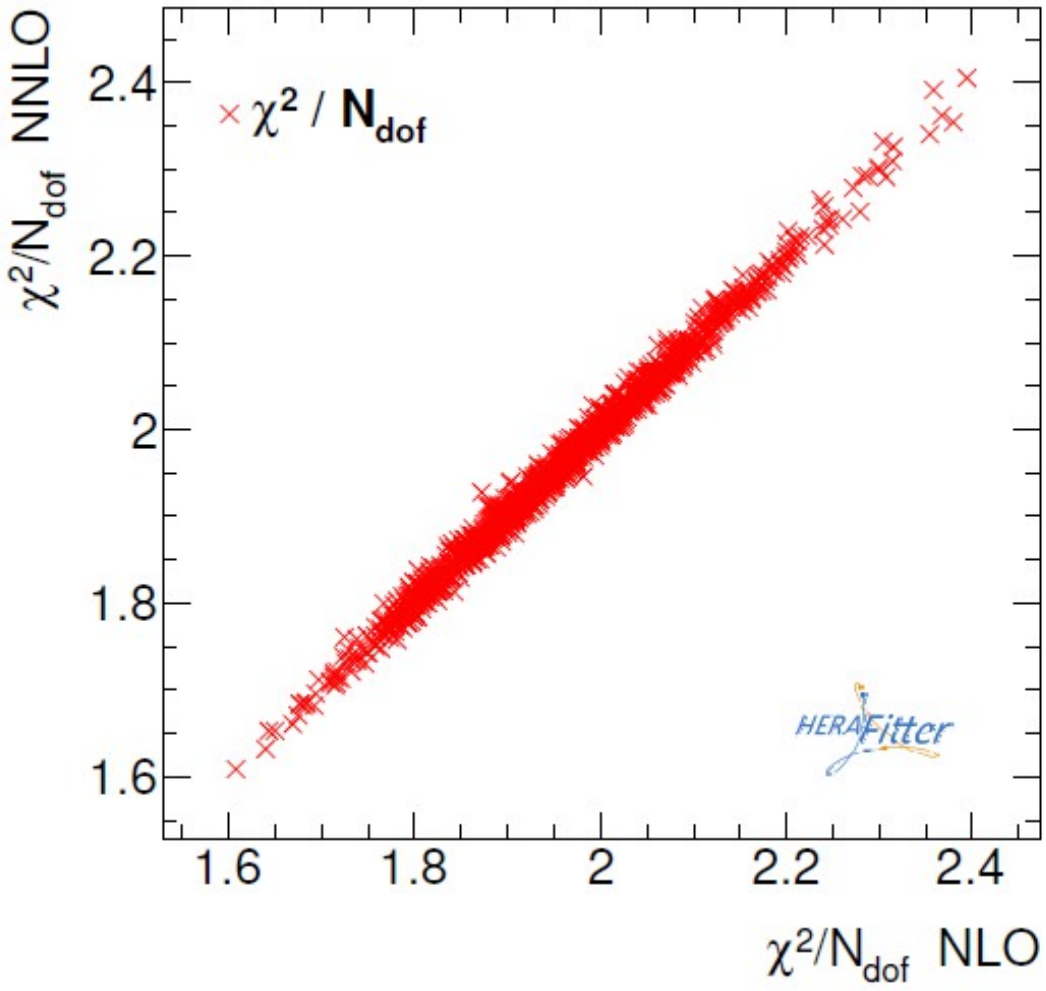

Correlation of Chi2/dof between NLO and NNLO PDF fits



- high level of correlation
- 1337 sets of fits to data replicas (only 39 sets needed for the eigenvector representation, more details at arXiv:1404.4234)