HERAFitter

Open Source QCD Fit Platform to determine PDFs

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for

the HERAFitter Team

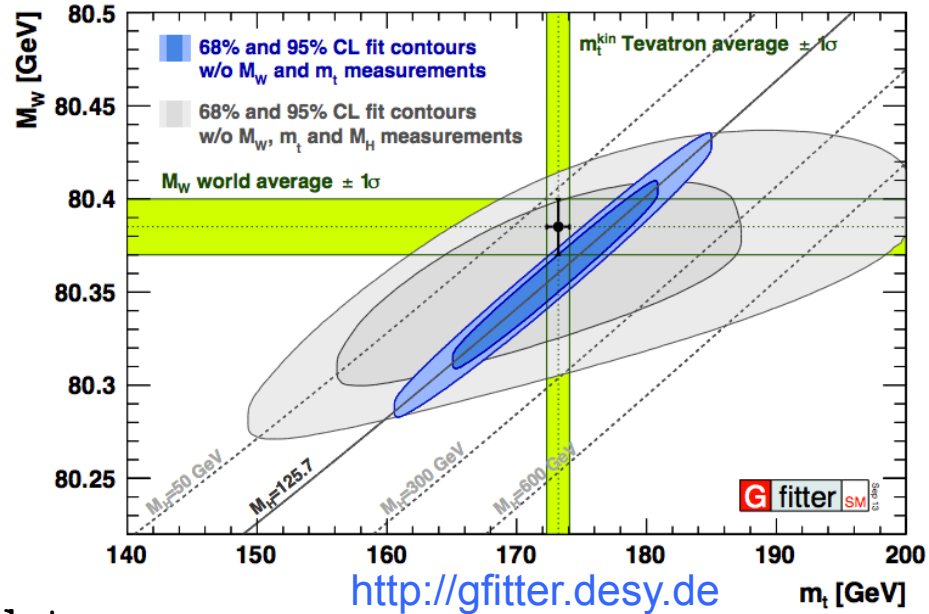
Outline:

- Motivation
- Project Overview
- Application and Results

Motivation

- Parton Distribution Functions are essential for precision physics at the LHC:
  - PDF uncertainties affect substantially theory predictions for BSM high mass production
  - PDFs are one of the main theory uncertainties in Higgs production
  - PDFs are one of the main theory uncertainties in Mw measurement

Uncertainty due to PDFs:
~10 MeV for Tevatron
[arxiv:1307.7627v2]
>10 MeV for LHC



http://gfitter.desy.de

- PDF uncertainties arise from:
  - Uncertainties of experimental data
  - Differences among several groups: MSTW, CT, NNPDF, HERAPDF, ABM, JR

→ **it is crucial to understand the theoretical differences**

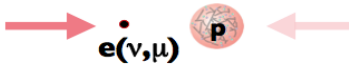
→ **it is important to provide accurate data (with correlation information) for better PDF discrimination**

Proton Structure

PDF extraction relies on the factorisation theorem:

- cross sections: PDFs ⊗ hard scattering coeff.

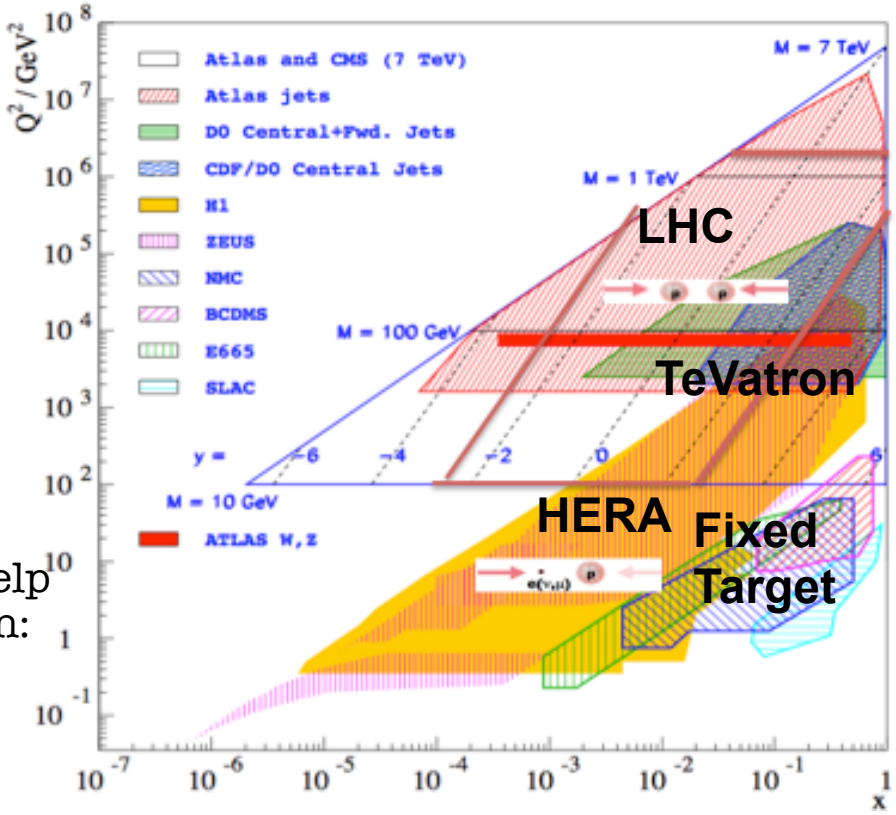
Main information on PDFs comes from DIS data at HERA which probes linear combination of quarks:



However, no flavour decomposition of the sea quarks

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

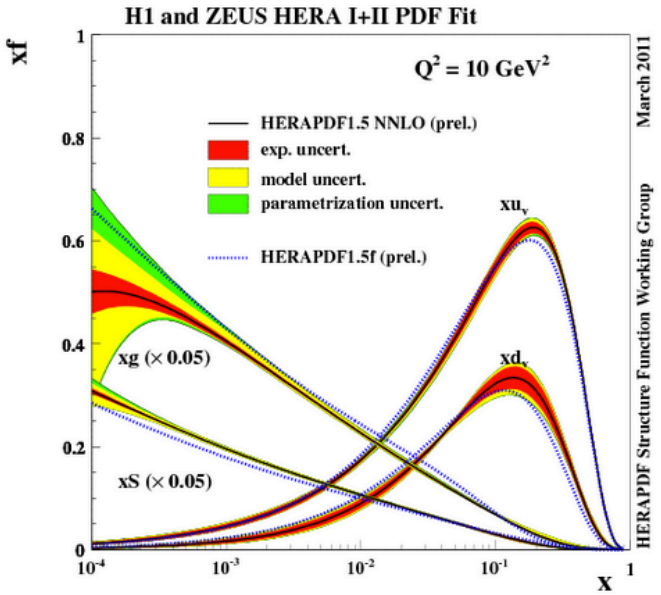
- Inclusive jets and dijets → gluon and alphas
- W, Z production, asymmetries → quark flavour separation
- W+charm → direct sensitivity to s-quark
- Isolated photons → gluon at medium and high x
- W,Z production with jets → gluon at medium x
- ttbar, single top → gluon and u, d



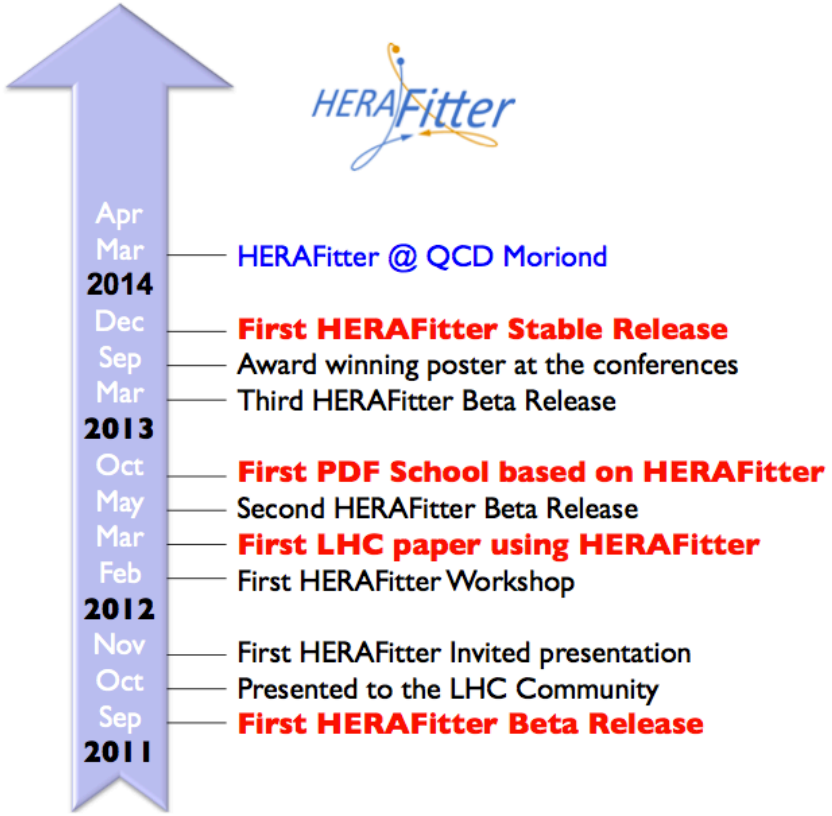
Coverage in x is essential
QCD evolution is in Q2

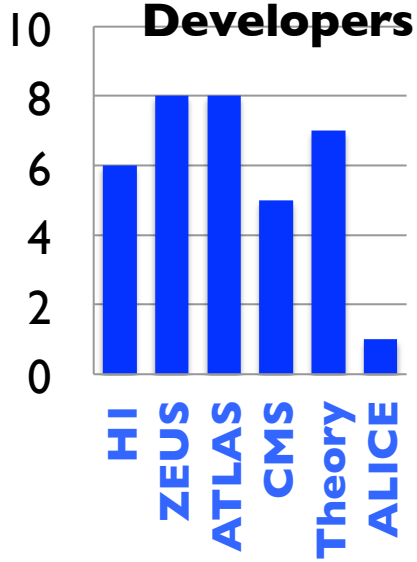
HERAFitter Project

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



H1prelim-11-042
ZEUSprelim-11-002



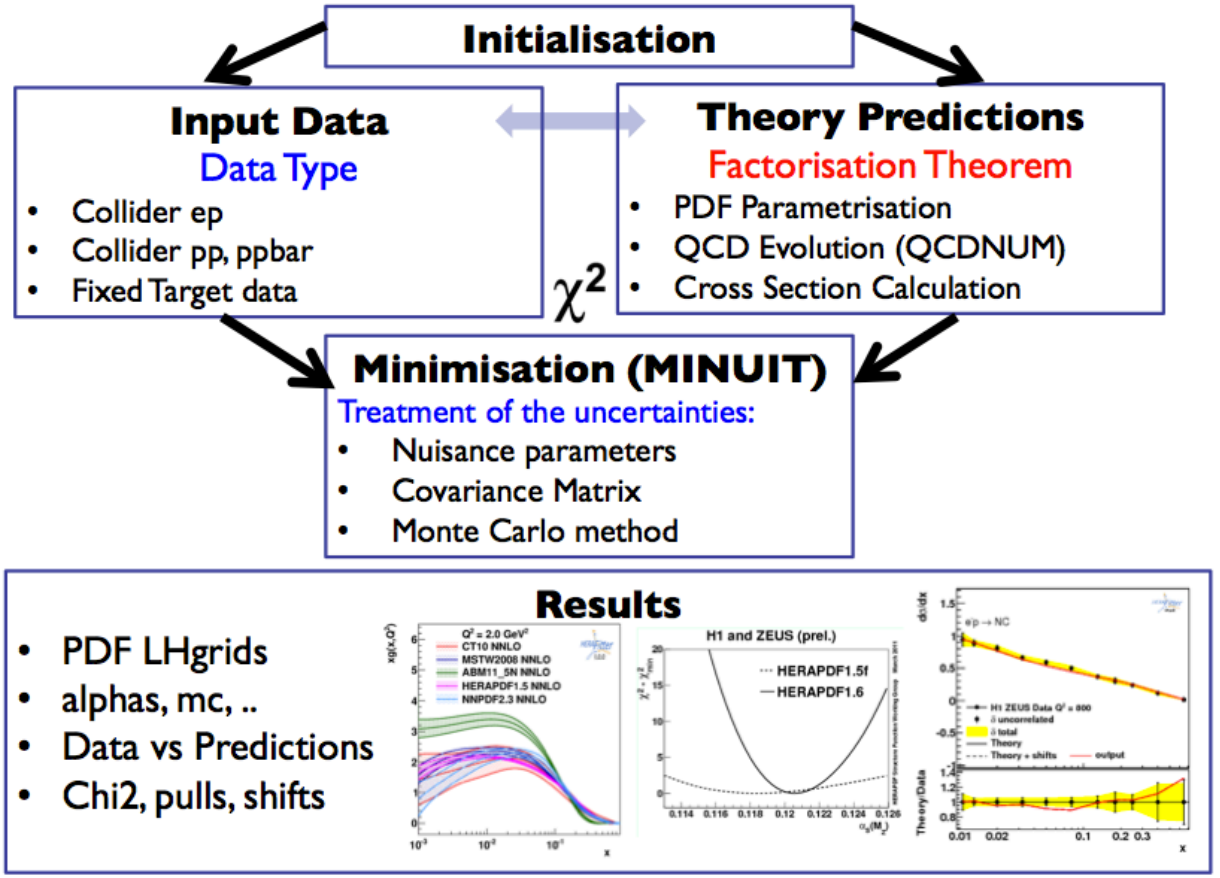


HERAFitter:

- **is a unique framework to address the theoretical differences**
- **provides means to the experimentalists to assess impact of new data**

Schematics of PDF extraction in HERAFitter

A flow diagram of a PDF extraction in a QCD fit machinery:



~2000 iterations

Performance: 15min – 2h

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

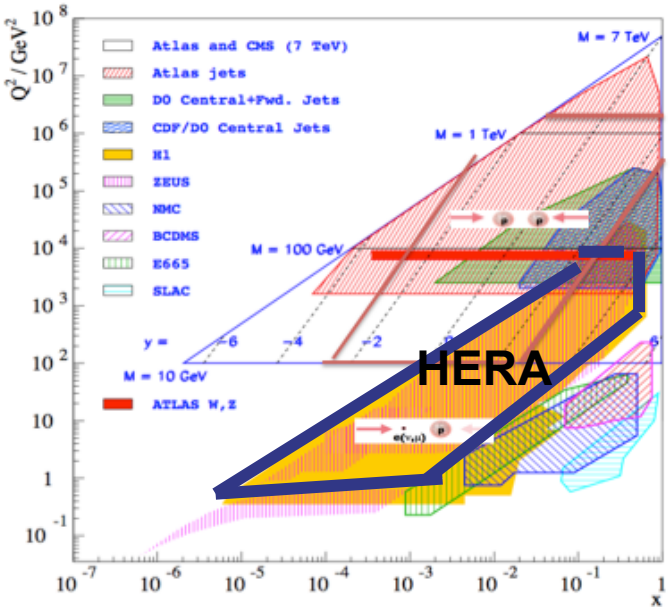
Heavy Flavour Schemes in DIS

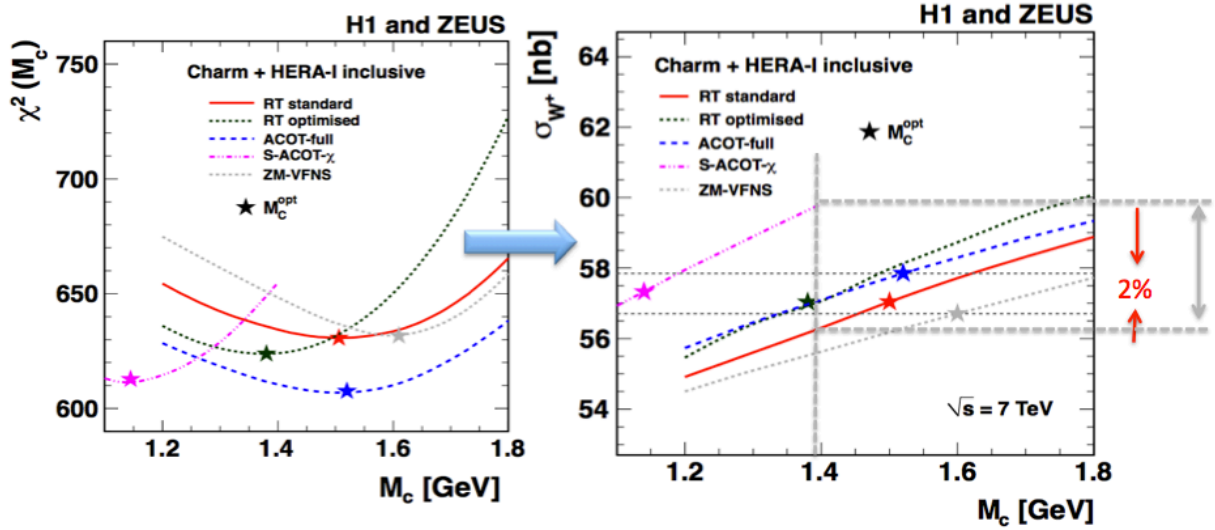
Heavy quarks introduce additional scales which complicates the calculations:

- **VFNS (Variable Flavour Number Schemes):**
  - RT-VFNS schemes → as used by MSTW group
  - Zero Mass VFNS
  - ACOT schemes → as used by CT(CTEQ) group
- **FFNS (Fixed Flavour Number Scheme)**
  - via QCDNUM
  - Via Openqcdrad-1.6 → as used by ABM

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

[Eur. Phys. J. C73 (2013) 2311]





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

Quantitative Comparison between data and theory

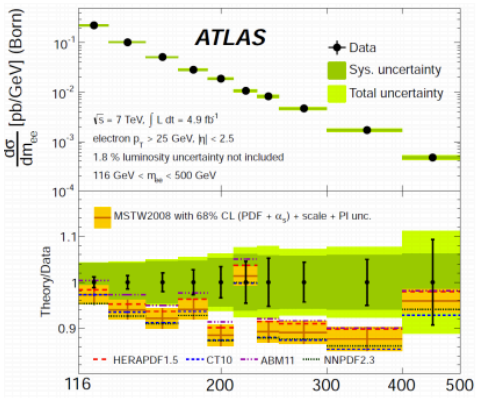
HERAFitter provides a quantitative assessment of level of agreement between data and theory by taking into account theoretical and experimental uncertainties

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

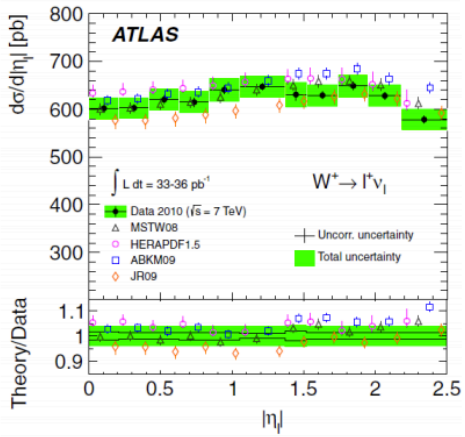
ATL-PHYS-PUB-2013-018

	Excluding PDF uncertainties			Including PDF uncertainties		
	$\mu_r = \mu_f = E_T^\gamma$	Envelope		$\mu_r = \mu_f = E_T^\gamma$	Envelope	
CT10	49.1	34.7	- 63.1	29.8	20.0	- 38.4
MSTW2008	39.9	27.2	- 52.7	32.0	21.3	- 42.3
ABM11_5N	16.2	9.2	- 25.5	15.7	8.9	- 24.9
HERAPDF1.5	28.7	19.0	- 38.9	23.6	15.7	- 32.0
NNPDF2.3	33.5	22.6	- 44.7	27.6	18.7	- 36.9

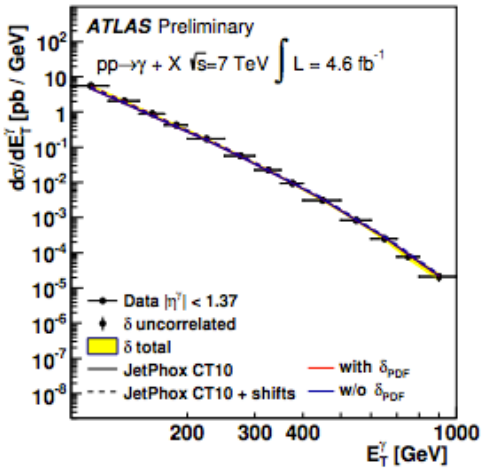
Used in ATLAS publications:

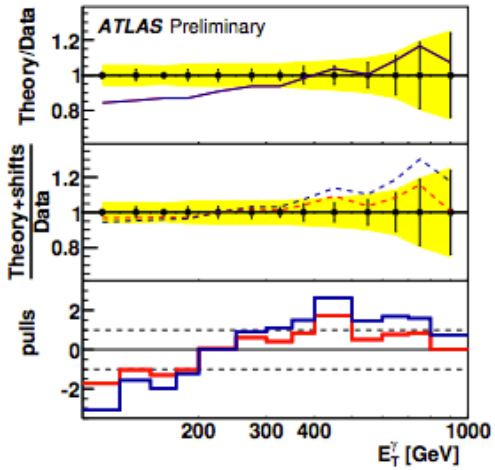


Phys. Lett. B 725 (2013) 223



Phys. Rev. D 85 (2012) 072004



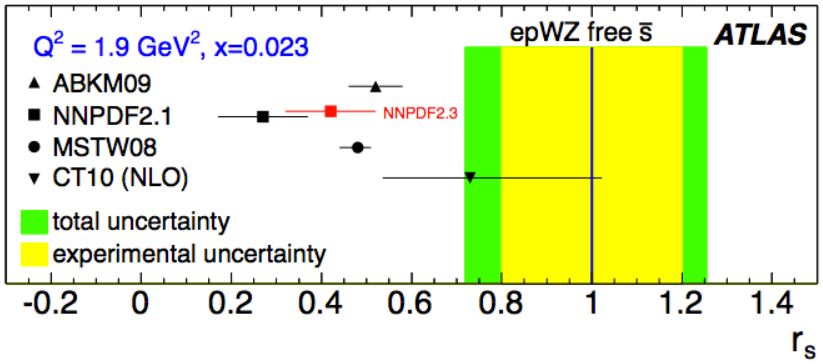


Determination of the strange quark at the LHC

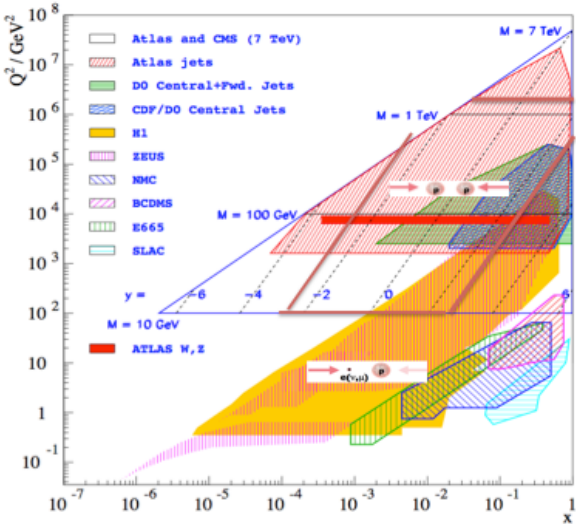
- **Using W+, W-, Z (35/pb) inclusive cross sections** – ATLAS

[PRL 109 (2012) 012001] → kinematic region probed is at x~0.01

  - NNLO QCD Analysis (NLO is in agreement):



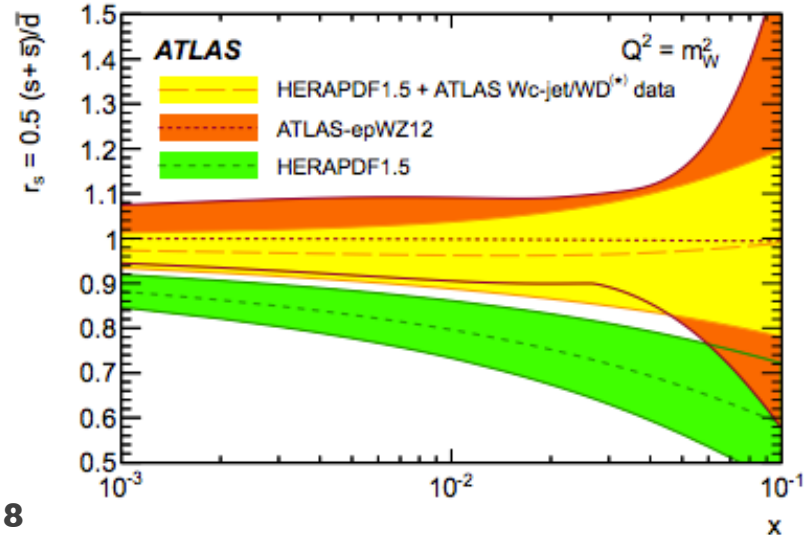
→ Result supports an SU(3) symmetric light sea



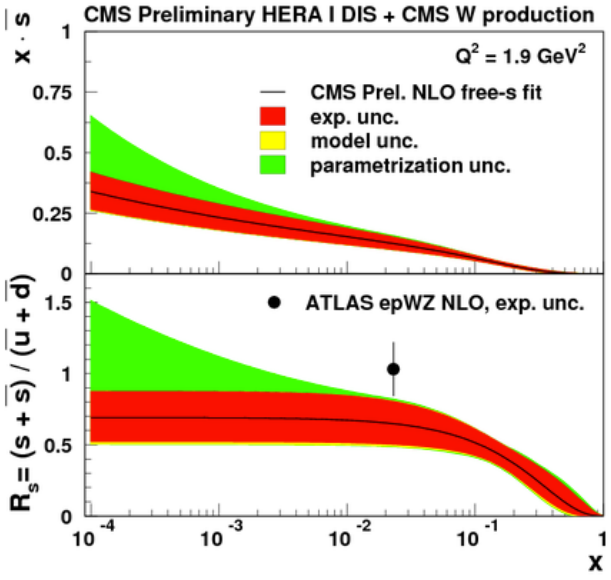
- **Using W+charm production at 7 TeV (4.6/fb):**

ATLAS [arxiv:1402.6263]:

- In good agreement with above:



CMS (includes W asymmetry) [SMP-12-021]



NLO analyses

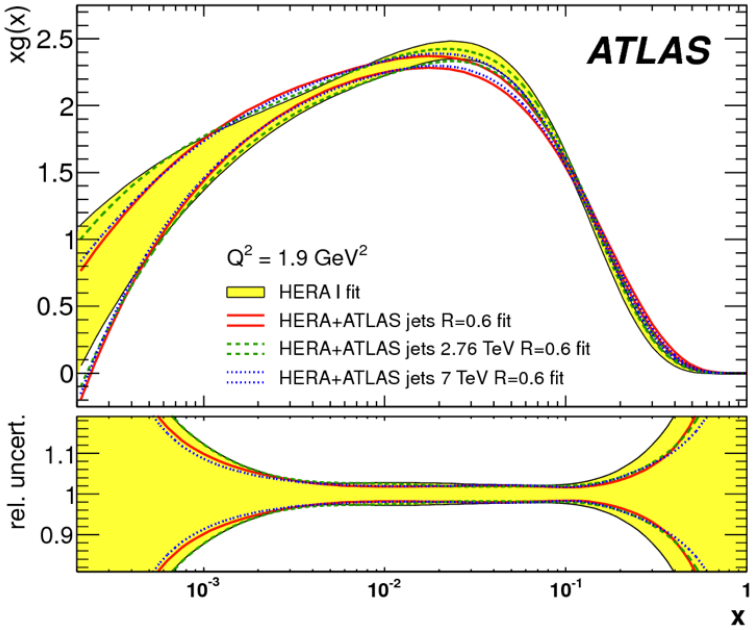
ATLAS: Rs=(s+sbar)/2dbar

CMS: Rs=(s+sbar)/ubar+dbar

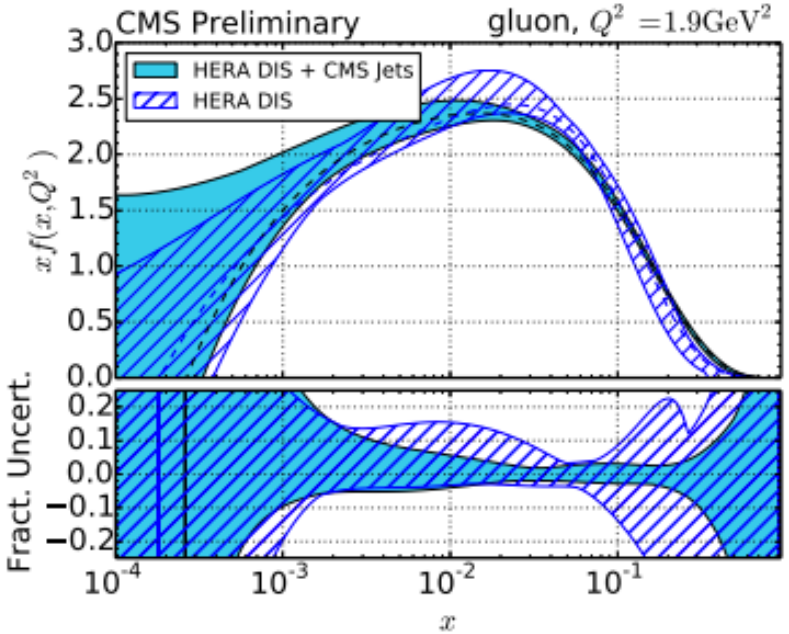
Sensitivity to gluon and strong coupling:

Study sensitivity to the gluon PDF:

- Using ratio of jets at different beam energies – ATLAS [EPJC (2013) 73 2509]
  - Benefits from cancellation of common sys. unc.
  - Compare the gluon for PDF fit using just HERA I and a fit using HERA I + ATLAS 2.76, 7 TeV jet data (2010)



- Using inclusive jet cross section at 7 TeV CMS data from 2011 (5/fb) [SMP-12-028]:
  - PDFs are extracted and compared to fits using just HERA I and fits using HERA I + CMS 7 TeV jet data



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

- From PDF and alphas simultaneous fit:

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

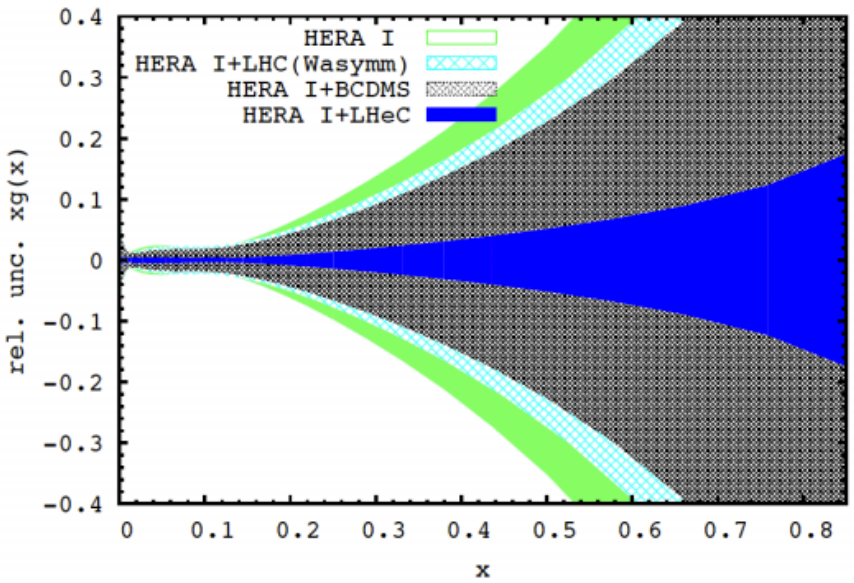
Impact studies of LHeC on PDFs

[Journal of Phys. G 39 (2012)]

HERAFitter provides the possibility to perform impact studies using simulated data:

- LHeC can provide a complete PDF set with precise gluon, valence, and strong coupling:

LHeC promises per mille accuracy on alphas – using HERAFitter

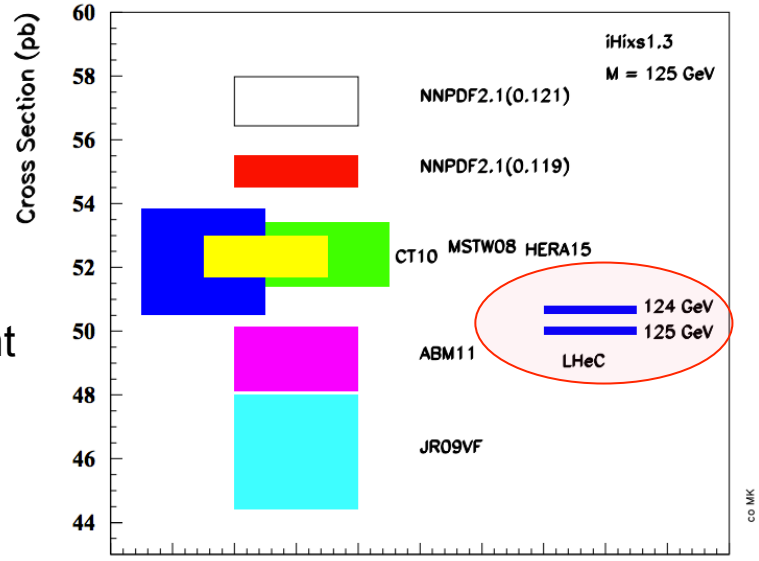


case	cut [Q^2 in GeV	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$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

HERAFitter provides LHAPDF grids:

14 TeV gg → H total cross section at the LHC calculated for a variety of PDFs at 68% CL

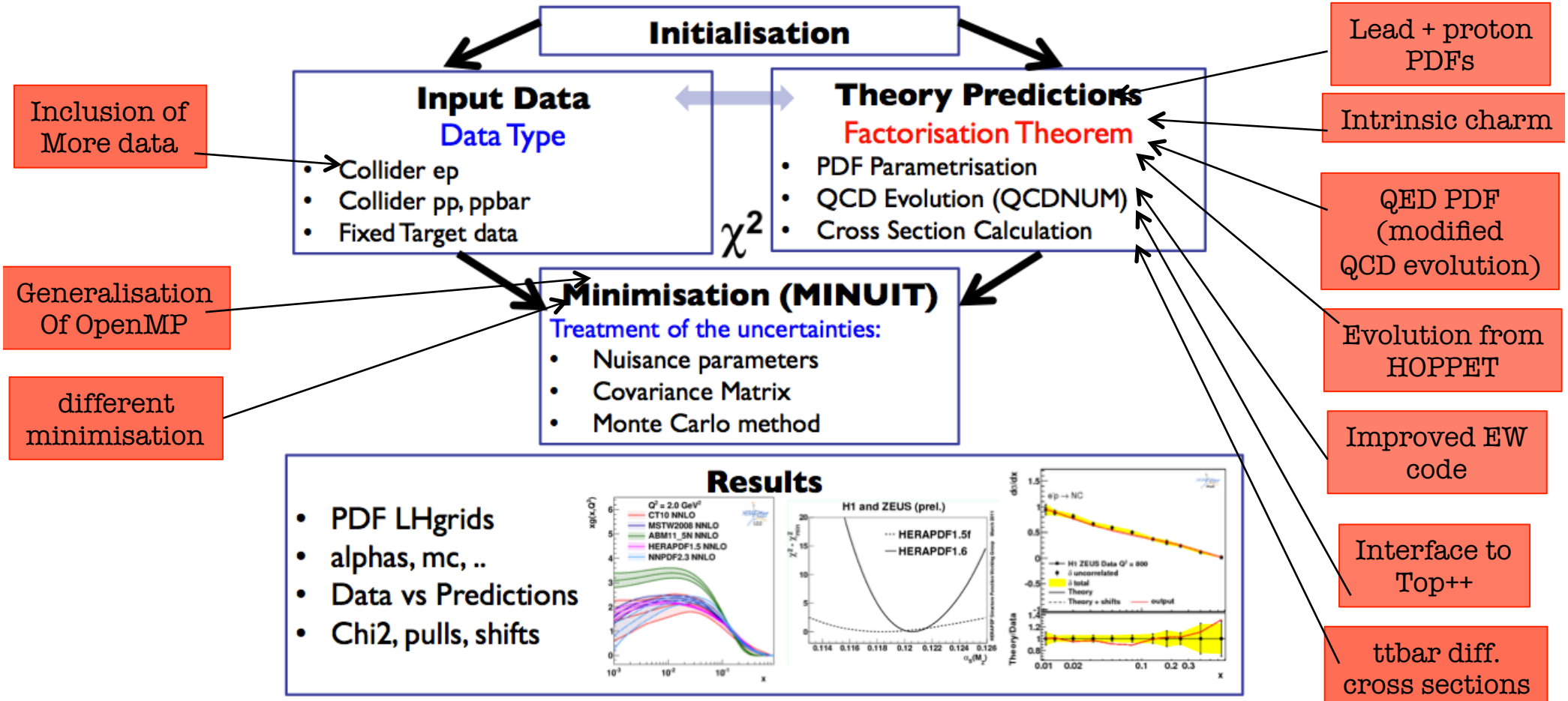
- precision from LHeC can add a very significant constraint on the mass of the Higgs
- **LHeC-NLO. LHgrid available in lhapdf v5.9.1**



HERAFitter Prospects

HERAFitter has a modular structure facilitating fast developments

- Many new developments are planed to be implemented in future releases:



We welcome more ideas!

HERAFitter Summary and Prospects

- 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:
  - → driven by the abundant data in need for a careful QCD investigation

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

  - Various treatments for heavy flavours;
  - Various options for data uncertainties treatment;
  - Various parametrisation techniques;
  - Various physics cases.

  - **theory:** include new state of the art developments (i.e. ttbar differential cross-section)
  - **experiment:** include new observables/measurements to improve PDFs

Stable release: herafitter-1.0.0

- www.herafitter.org

We welcome new developments!

Results using HERAFitter

- Following PDF grids have been generated since the start of the project:
  - **HERAPDF1.0, HERAPDF1.5, ATLAS-epWZ12, LHeC-NLO**
- HERAFitter has been used in the following publications:

" Determination of the strange quark density of the proton from ATLAS measurements of the W and Z cross sections" [PRL 109 (2012) 012001]

" Measurements of the inclusive jet cross section in pp collisions at 2.76 TeV and comparison to the inclusive jet cross section at 7 TeV using the ATLAS detector" [EPJC (2013) 73 2509]

" Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at 7 TeV with the ATLAS detector" [PLB 725 (2013) 223]

"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"[]

"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"

" Measurement of the muon charge asymmetry in pp W production at 7 TeV" [SMP-12-021]

" PDF constraints and extraction of the strong coupling constant from the inclusive jet cross section at 7 TeV" [SMP-12-08]

" Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep Inelastic ep Scattering at HERA" [EPJC (2013) 73 2311]

"Inclusive Deep Inelastic Scattering at High Q2 with Longitudinally Polarised" [JHEP 1209 (2012) 061]

LHeC impact studies [Journal of Phys. G 39 (2012)]

Theory

"Parton Distribution Uncertainties using Smoothness Prior" [PLB 695 (2011) 238]

Extra Slides

Functional Forms for PDF parametrisation

- PDFs are parametrised at a starting scale as function of x, QCD evolves them in Q2
- Various functional forms can be tested within HERAFitter platform:
  - Standard Polynomials:

$$xf(x) = Ax^B(1-x)^C P_i(x),$$

  - Log-Normal Distributions:

$$xf(x) = x^{p-b\log(x)}(1-x)^{q-\log(1-x)}$$

  - Chebyshev Polynomials:

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

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

  - Use of External PDFs via LHAPDF interface to construct theoretical predictions.

Chi square definitions

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties below 10%, so they follow normal distribution which allows use of chi square minimization for determining optimal PDF parameters.

- The HERAFitter package allows for various types of data uncertainty treatment:
  - Various chi square representations:
    - **Covariance Matrix Representation**:

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

    - **Nuisance Parameters Representation:**

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

μ^i is the measured central value

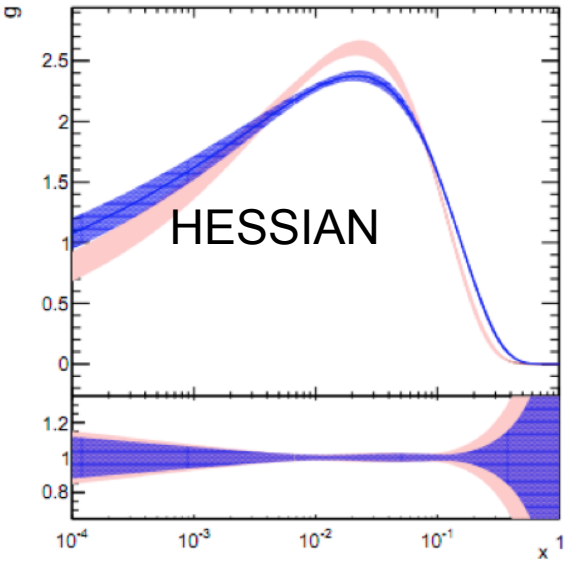
    - **Mixed form (covariance and nuisance parameter):**

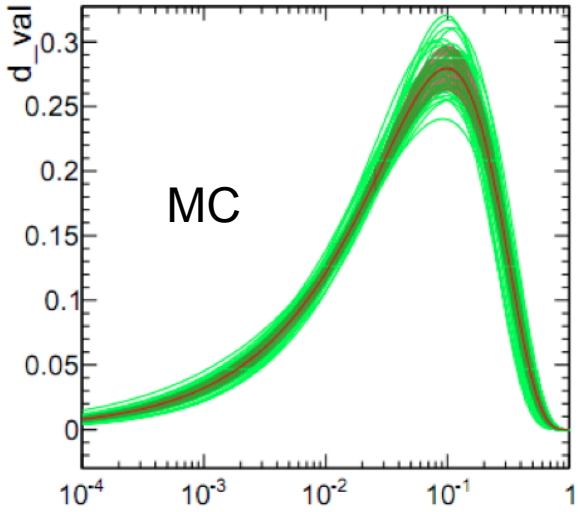
      HERAFitter offers the possibility to include form of treating statistical, uncorrelated and correlated systematic uncertainties given in different forms.

Experimental Uncertainties

HERAFitter allows for various types of data uncertainty treatment:

- Hessian and toy Monte Carlo error propagation





→ Monte Carlo Method for error estimation compared to Hessian error propagation:

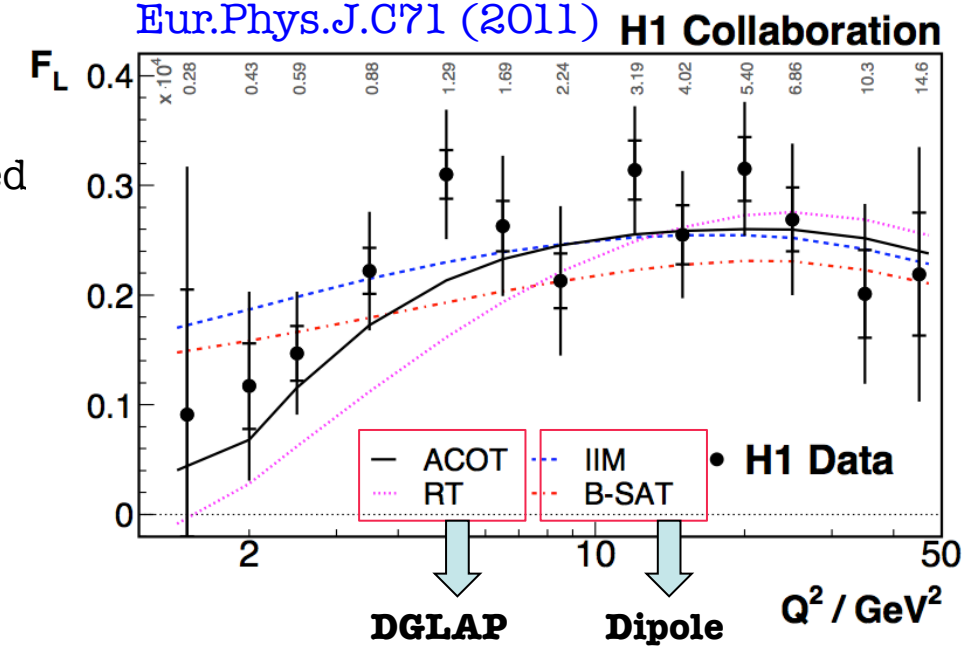
- Benchmarking exercise with NNPDF group [arXiv:0901.2504]

- Regularisation methods: to constrain PDFs in a flexible parametrisation style:
  - Data Driven Regularisation (as used by NNPDF): fit and control samples
  - External Regularisation based on a penalty term in chisquare
- Possibility to include asymmetric unceratinties.

Low x Physics

As an alternative to DGLAP, HERAFitter includes also Dipole models:

- Studied by the H1 collaboration in comparing different models on FL:
  - Dipole Models implemented in HERAFitter:
    - GBW model: first model
    - IIM (based on BK-equation)
    - BGK (based on GBW, but gluon evolved using DLGAP)
  - DGLAP Models:
    - RT as used by MSTW group
    - ACOT as used by CTEQ group



Unintegrated PDFs based on the kT-factorisation (CCFM) evolution.

- applicable only to NC ep scattering:
  https://www.herafitter.org/HERAFitter/HERAFitter/HERAFitterMeetings/Meeting2012-Oct-29?action=AttachFile&do=get&target=updf.pdf

Diffractive DIS PDF fits.

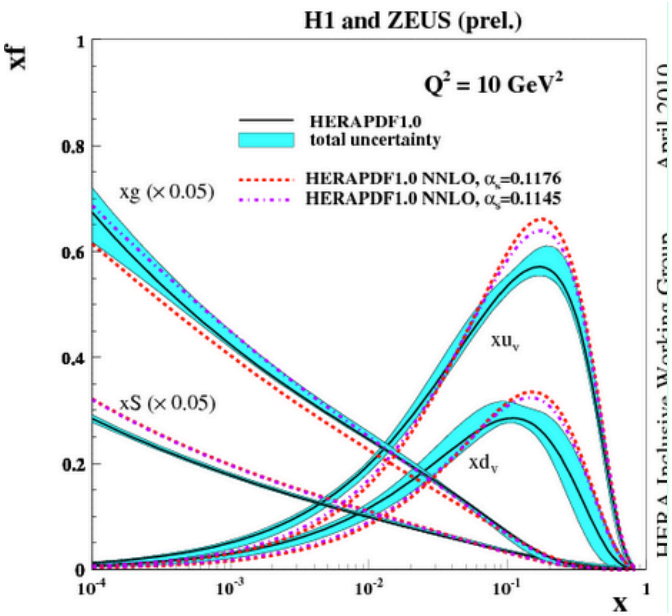
Results

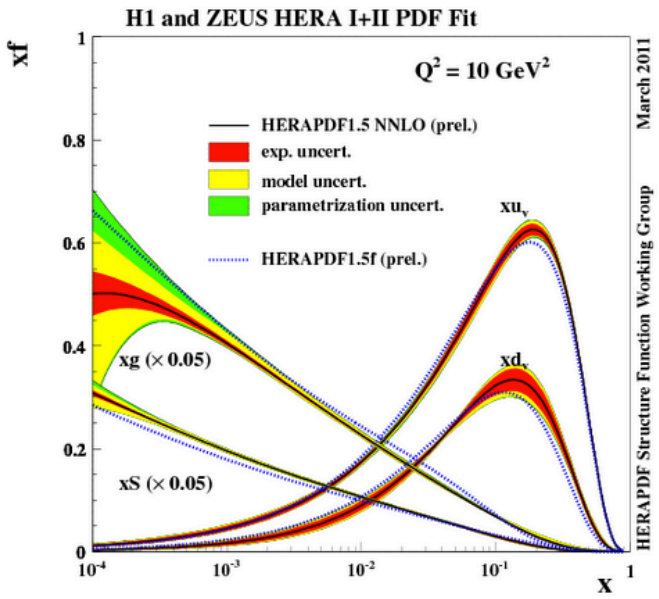
List of analyses using HERAFitter

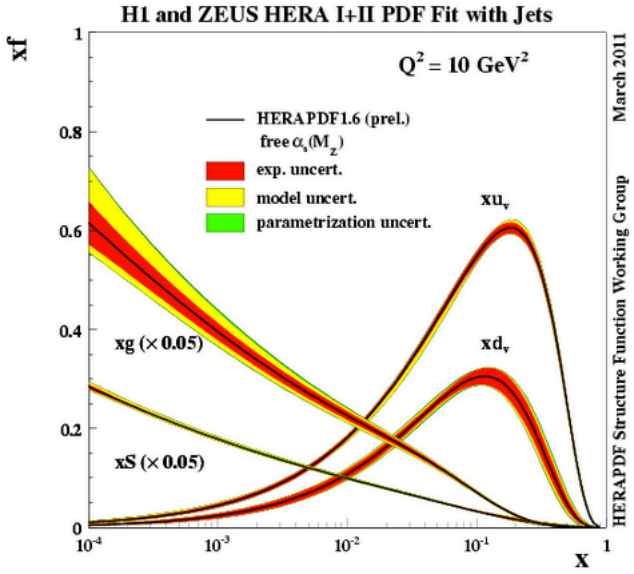
Date	Group	Reference	Title
NEW 02.2014	LHC/ATLAS	arXiv:1402.6263	Measurement of the production of a W boson in association with a charm quark in pp collisions at sqrt(s)=7 TeV with the ATLAS detector
NEW 01.2014	R. Sadykov	arXiv:1401.1133	Impact of QED radiative corrections on Parton Distribution Functions
NEW 01.2014	F. Hautmann and H. Jung	arXiv:1312.7875	Transverse momentum dependent gluon density from DIS precision data
NEW 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

HERAFitter @ HERA

- HERAFitter roots to the PDF analyses performed by H1 and ZEUS:
  - HERAPDF1.0 HERAPDF1.5 (LO/NLO/NNLO) HERAPDF1.6





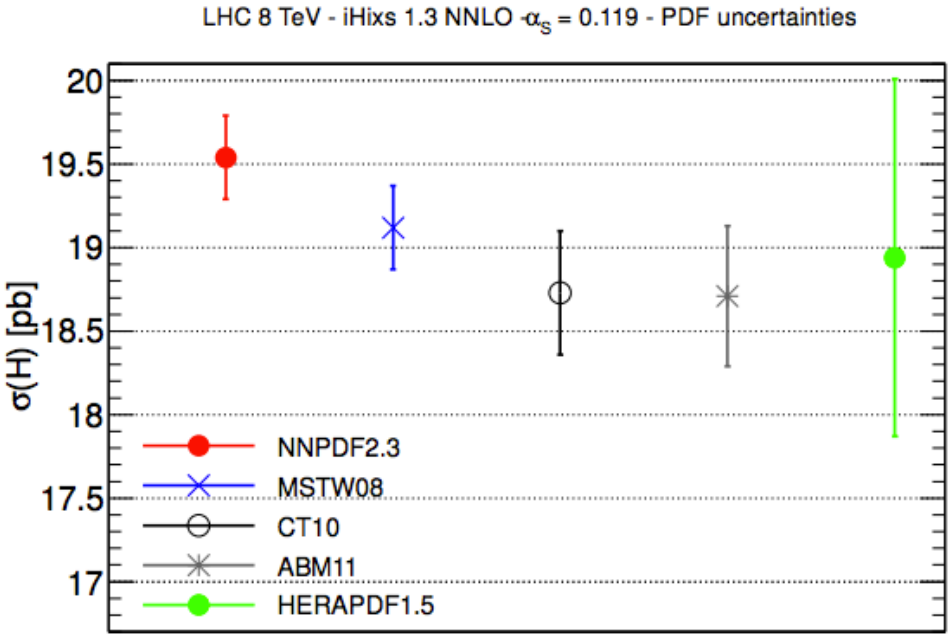


  - To come soon: HERAPDF2.0

Motivation

- Parton Distribution Functions are essential for precision physics at the LHC:
  - PDFs are one of the main theory uncertainties in Mw measurement
  - PDF uncertainties also affect substantially theory predictions for BSM high mass production

- PDF uncertainties arise from:
  - Precision of experimental data
  - Differences among several groups:
    - MSTW, CT, NNPDF, HERAPDF, ABM, JR
    - Current benchmarking of PDFs → 10% differences among PDF groups for predictions for the Higgs cross section



http://nnpdf.hepforge.org/html/pdfbench/catalog/pdfbenchcatalog.pdf

→ **it is crucial to understand the theoretical differences**

→ **it is important to provide accurate data for better PDF discrimination**