HERAFitter

Open Source QCD Fit Platform to determine PDFs

Paul Laycock

For the HERAFitter team

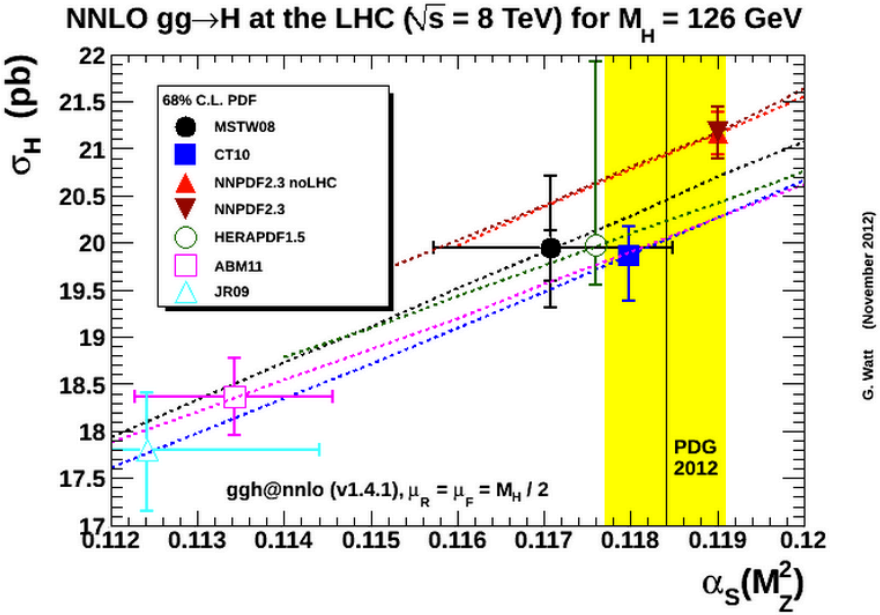
Outline:

- Motivation
- Project Overview
- Functionality
- Application and Results

Motivation

- Parton Distribution Functions are essential for precision physics at the LHC:
  - PDFs are one of the main theory uncertainties in Higgs production
  - 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



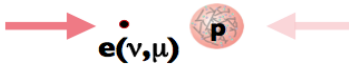
[G. Watt, Nov 2012]

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

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

Proton Structure

- **PDF extraction relies on the factorisation theorem:**
  - **cross sections: PDFs ⊗ hard scattering coefficients**
- Main information on PDFs comes from DIS data at HERA which probes linear combination of quarks:

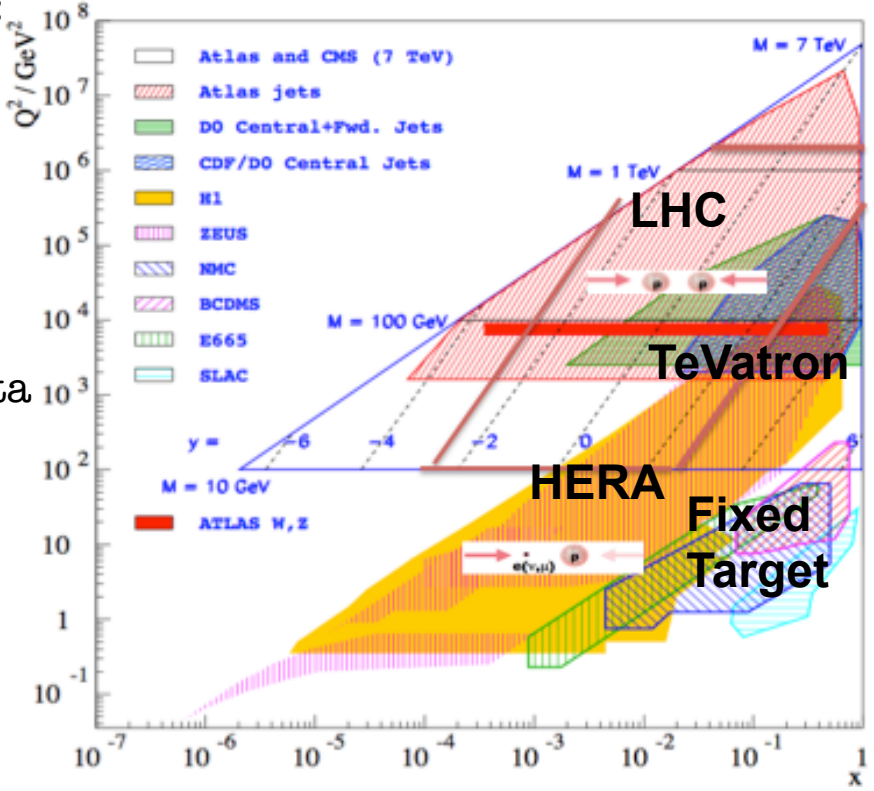


$$F_2 \sim 0.44x(u+\bar{u}+c+\bar{c}) + 0.11x(d+\bar{d}+s+\bar{s}+b+\bar{b})$$

No flavour decomposition of the sea

- LHC is introducing new observables and abundant data to help provide flavour decomposition and better understood gluon:

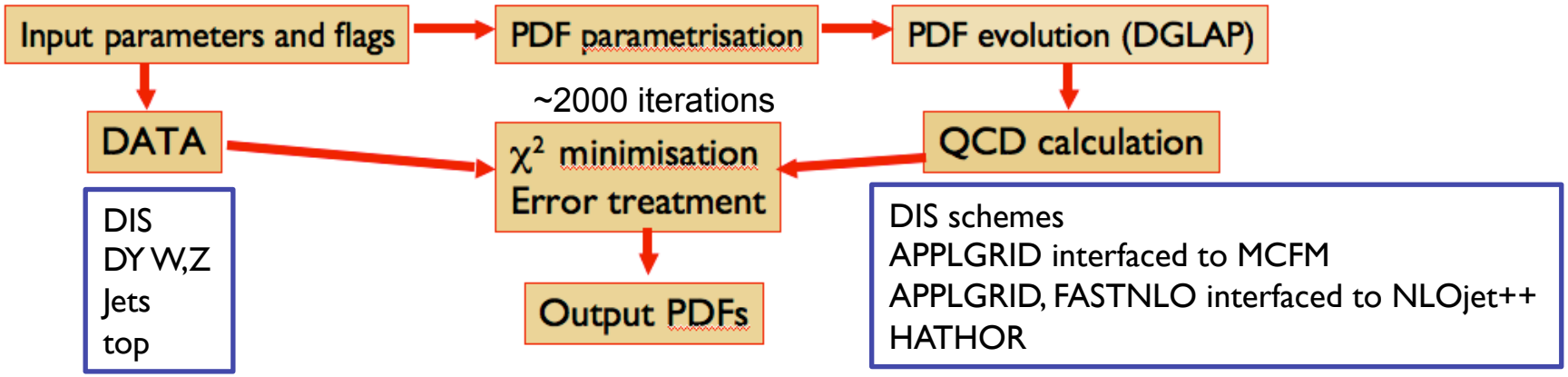
Measurement at LHC	PDF sensitivity
Inclusive jets and dijets	high x quarks and gluons (alphas)
Inclusive W, Z and asymmetries	quark flavour separation (u,d,s)
Off peak Drell-Yan at low and high mass	quarks at low and high x (u,d)
W with charm quarks	Direct sensitivity to s-quark
Isolated photons	medium - x gluons
Single top productoon	u,d and b quark
ttbar production (total, differential)	Medium-x gluon (alphas)
W,Z production with jets	Medium-x gluon
Z+b production	sensitive to b-quark



Coverage in x is essential
QCD evolution is in Q2

Schematics of extraction PDFs

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

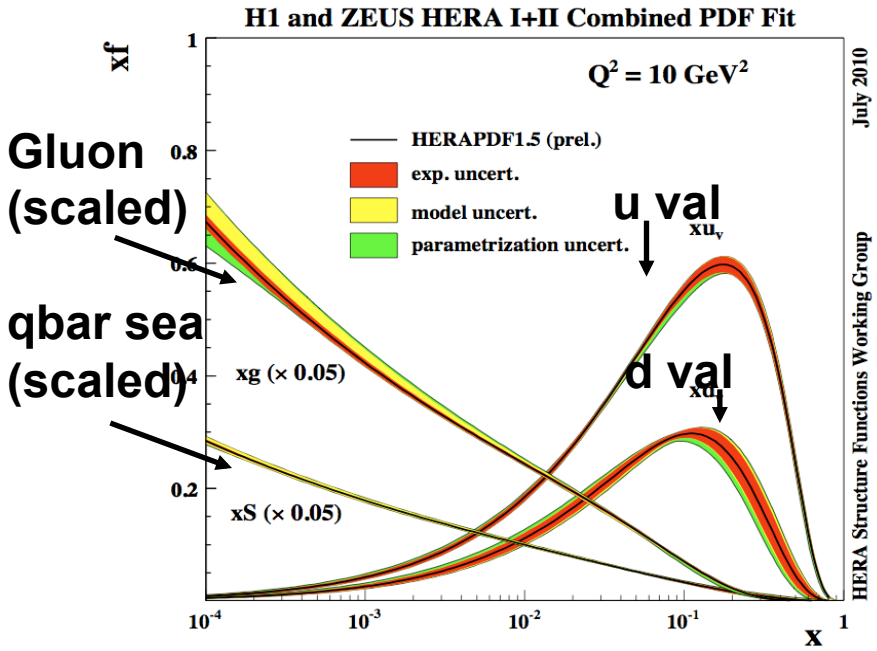


On data side:

- Important to provide correlation information

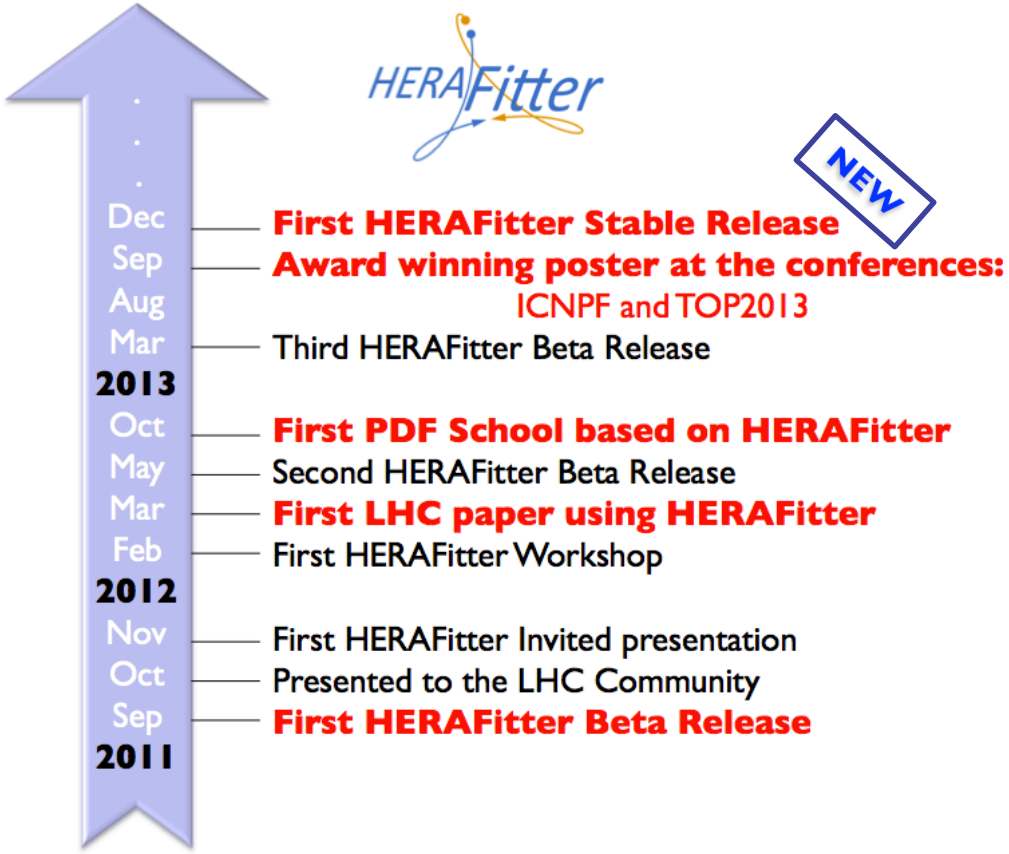
On theory side:

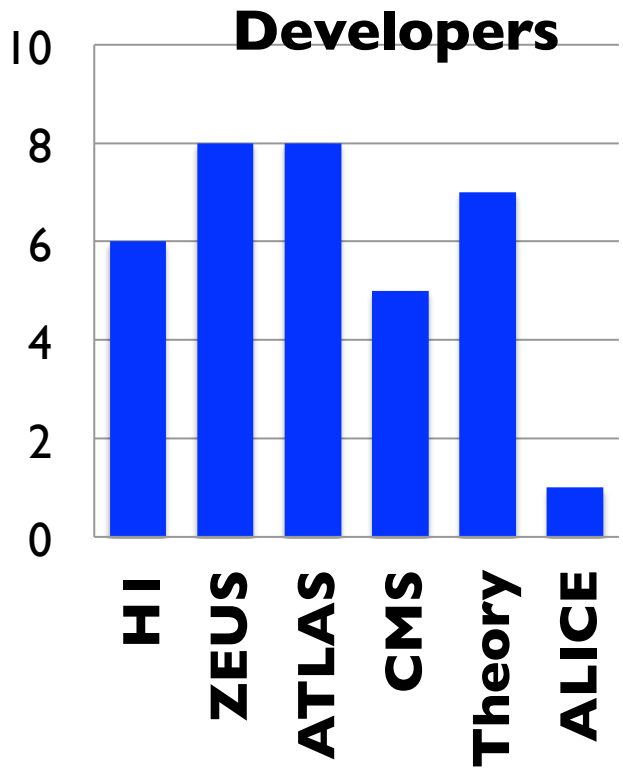
- Important to have fast tools to perform PDF fits i.e. APPLGRID, FASTNLO
  - → grid techniques rely on factorisation theorem



HERAFitter Project

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



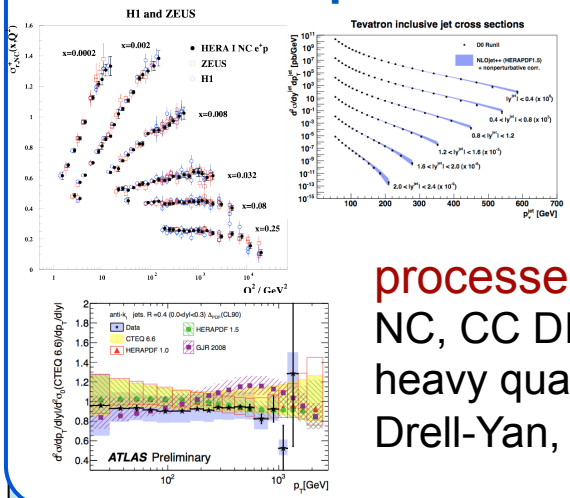


HERAFitter:

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

HERAFitter in a glance

experimental input



experiments:
HERA, Tevatron, LHC, fixed target

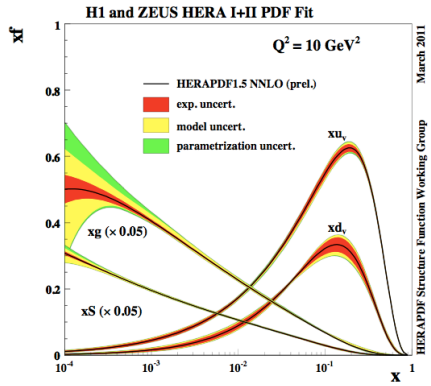
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

Benchmarking

Comparison of schemes

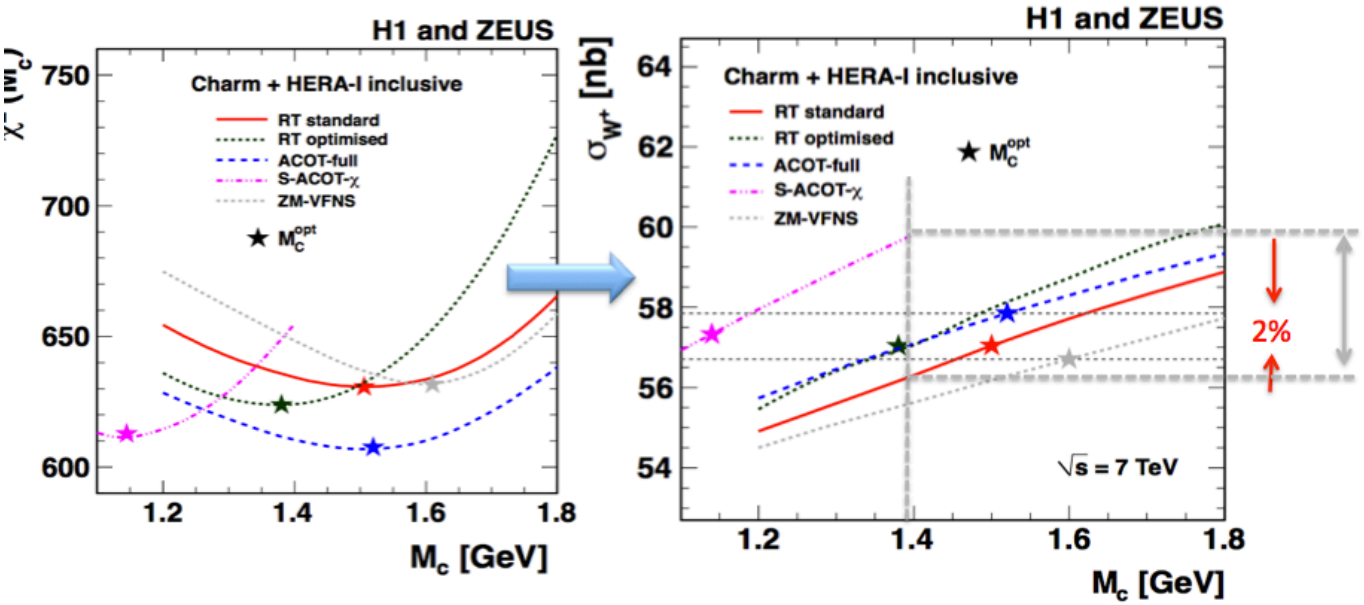
Heavy Flavour Schemes in DIS

For the DIS process, several schemes are available for heavy quark treatments:

- **VFNS (Variable Flavour Number Schemes):**
  - RT-VFNS schemes (RT STandard, RT Optimal) – as used by MSTW group

    (as well as variants based on k-factors RT FAST, RT OPT FAST - runs 15min)
  - Zero Mass VFNS [qcdnum, ACOT variant]
  - ACOT Full, ACOT Chi, ACOT ZM, they are all based on k-factors – as used by CT 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

Low x Physics

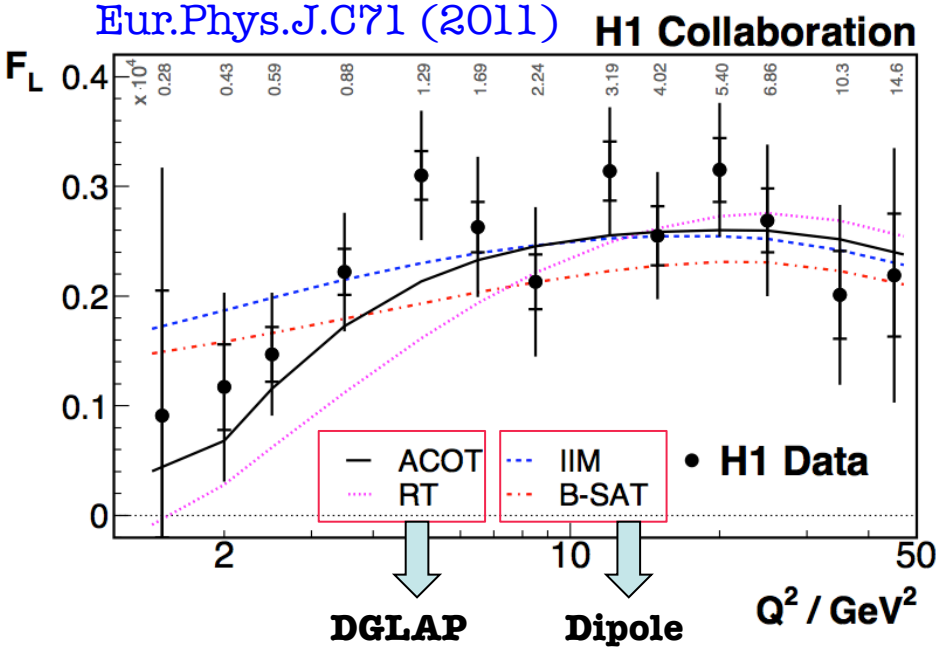
- As an alternative to DGLAP, HERAFitter includes also Dipole models:
  - Studied by the H1 collaboration in comparing different models on FL:

▽ 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.

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:
    - **Simple form**:

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

    - **Scaled form:**

$$\chi^2_{\text{exp}}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\text{stat}}\mu^i\left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\text{uncor}}\,m^i\right)^2} + \sum_j b_j^2 + \text{log penalty}$$

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

$$\chi^2_{\text{exp}}(\boldsymbol{m},\boldsymbol{b}) = \sum_{ij}\left(m^i - \sum_l \Gamma^i_l(m^i)b_l - \mu^i\right) C^{-1}_{\text{stat. }ij}(m^i,m^j)\left(m^j - \sum_l \Gamma^j_l(m^j)b_l - \mu^j\right) + \sum_l b_l^2\,.$$

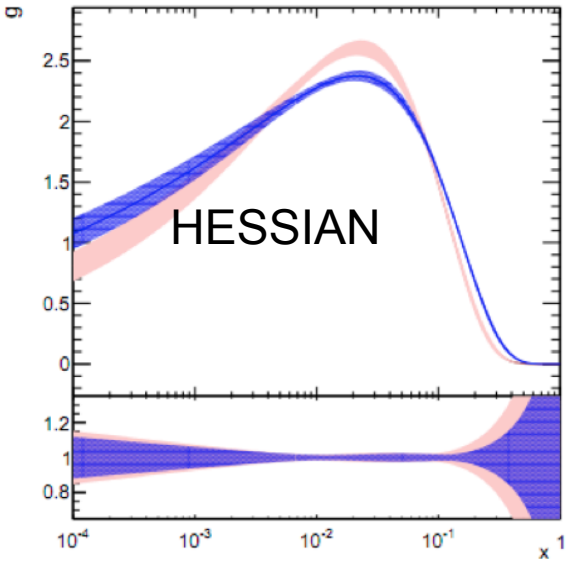
Experimental Uncertainties

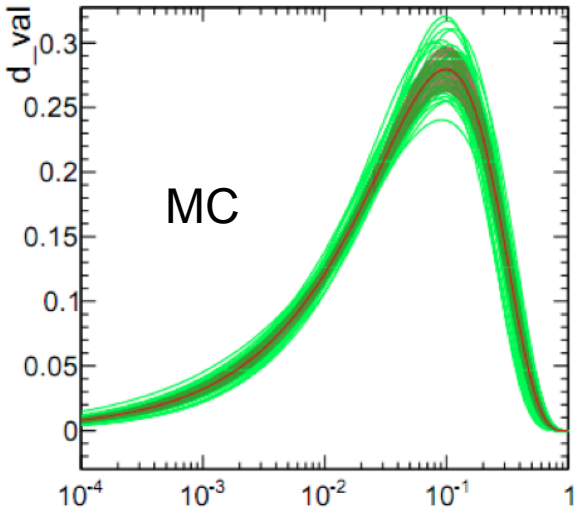
HERAFitter allows for various types of data uncertainty treatment:

- Hessian and toy Monte Carlo error propagation

```
&MCErrors

  lRAND    = False
  lRANDDATA = True
  ISeedMC = 123456
  ! --- Choose what distribution for the
  ! STATYPE (SYS_TYPE)  =   1  gauss
  ! STATYPE (SYS_TYPE)  =   2  uniform
  ! STATYPE (SYS_TYPE)  =   3  lognormal
  ! STATYPE (SYS_TYPE)  =   4  poisson (
  STATYPE =  1
  SYSTYPE =  1
&End
```





- 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 chisq

Quantitative Comparison between data and theory

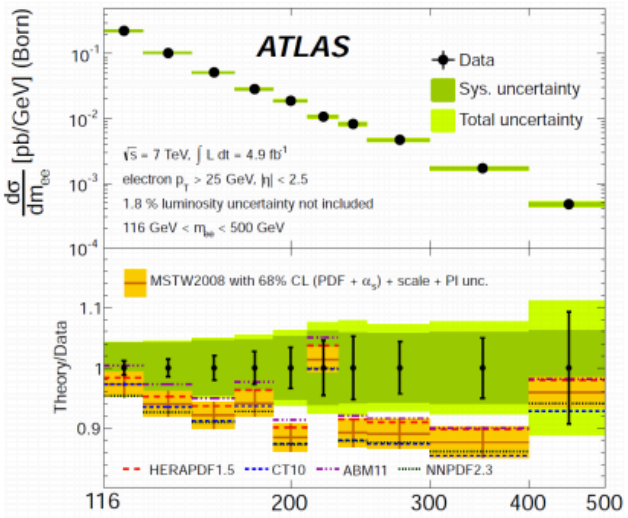
HERAFitter provides a quantitative assessment of level of agreement between data and theory by taking into account theoretical and experimental uncertainties

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

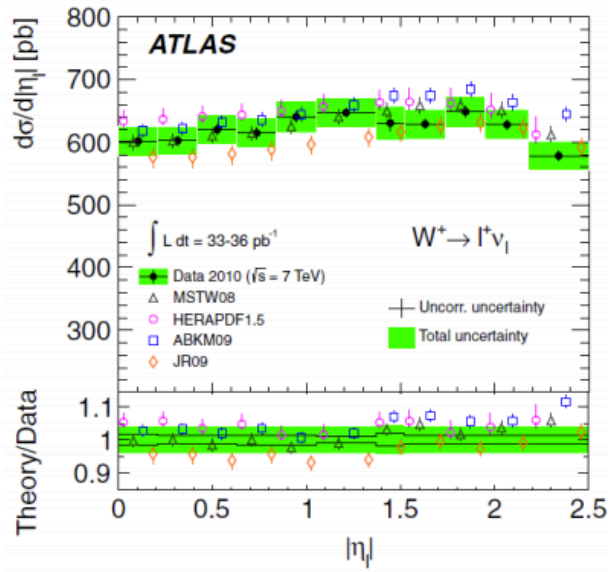
Ex: 30 points from ATLAS WZ 2010 vs NNLO predictions

PDF set	Central PDF	With PDF uncertainties
CT10	34.1	32.0
MSTW08	72.0	49.7
HERAPDF1.5eig	43.1	39.2

Used in ATLAS publications:



Phys. Lett. B 725 (2013) 223



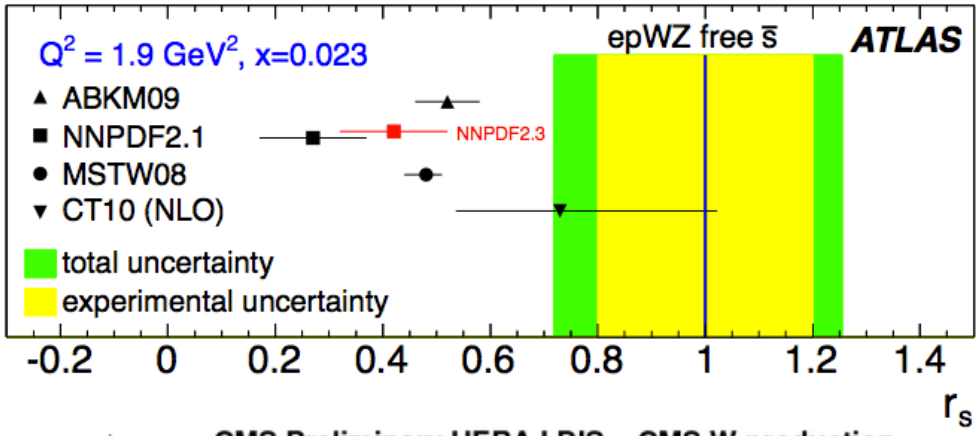
Phys. Rev. D 85 (2012) 072004

Determination of the strange quark in the proton:

- 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:

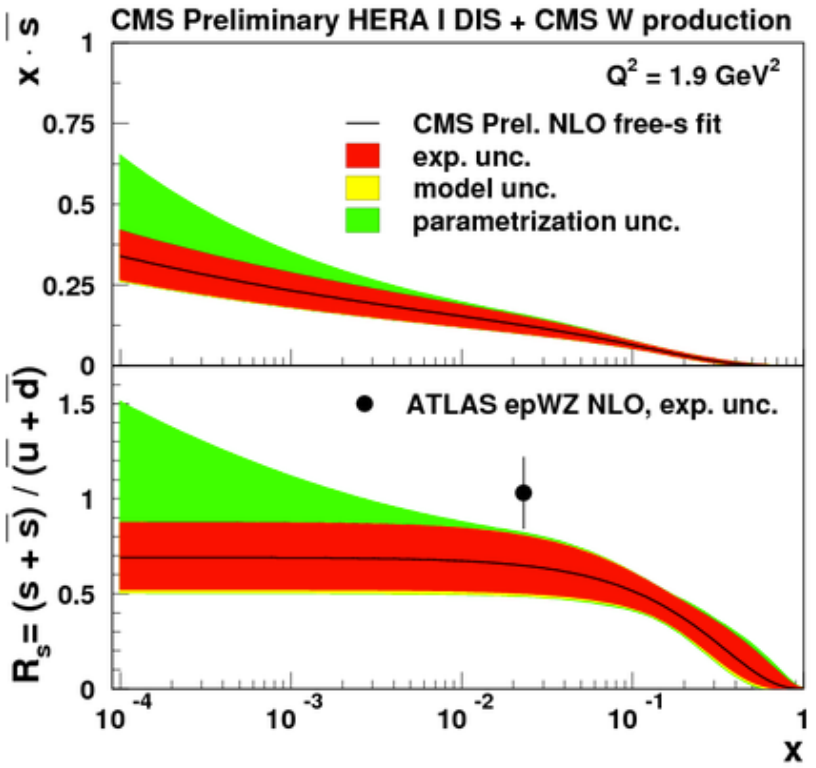
$$r_s = 1.00 \pm 0.20_{\text{exp}} \pm 0.07_{\text{mod}}{}^{+0.10}_{-0.15}{}_{\text{par}}{}^{+0.06}_{-0.07}\alpha_S \pm 0.08_{\text{th.}}$$

  - NLO result is in agreement with NNLO
  - **ATLAS-epWZ-EIG.LHgrid available since lhapdf v5.9.1**



NEW

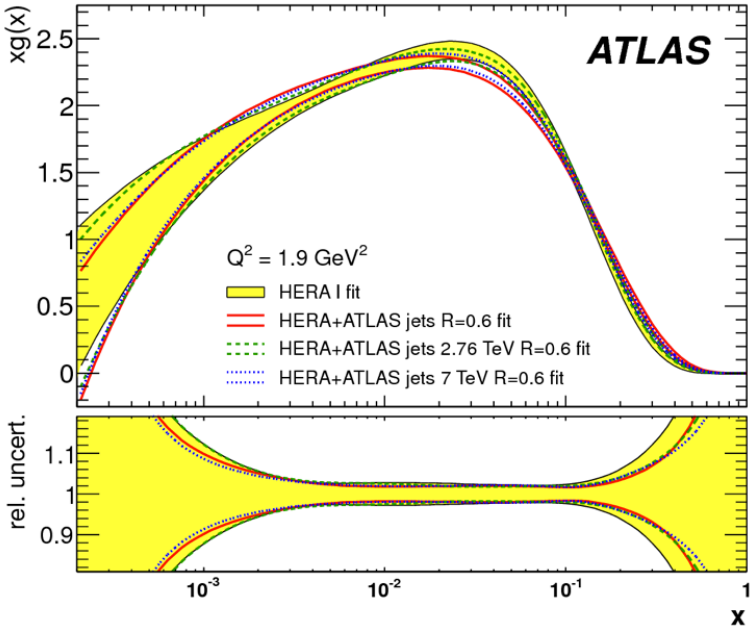
- Using W+charm (5/fb) and W muon asymmetry (4.7/fb) – CMS [SMP-12-021]
- NLO QCD Analysis: Rs(x) is determined



Sensitivity to gluon and strong coupling:

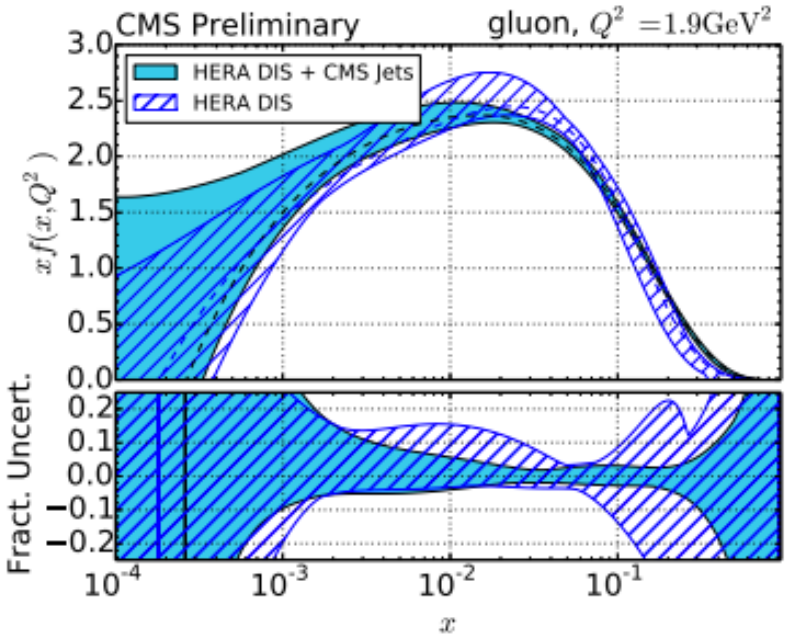
Study sensitivity to the gluon PDF:

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



NEW

- 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:

- From PDF and alphas simultaneous fit:

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

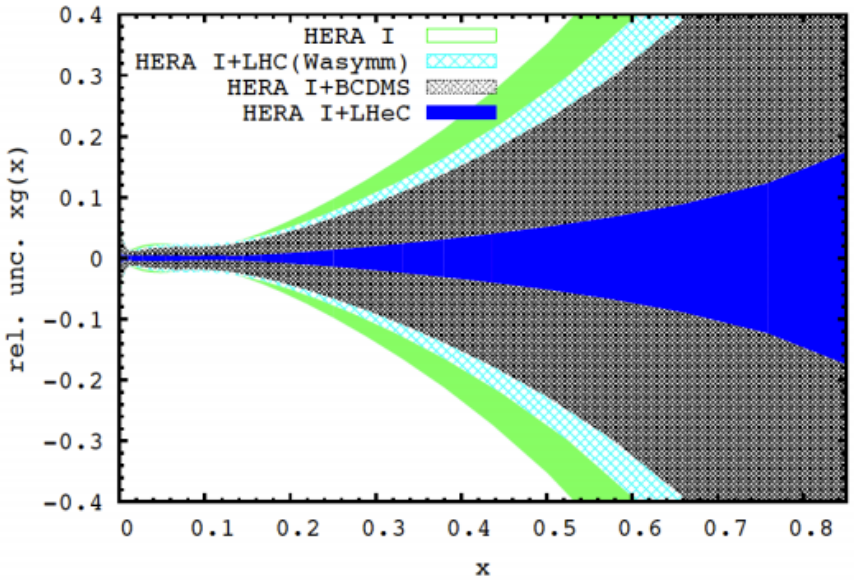
Impact studies of LHeC on PDFs

[Journal of Phys. G 39 (2012)]

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

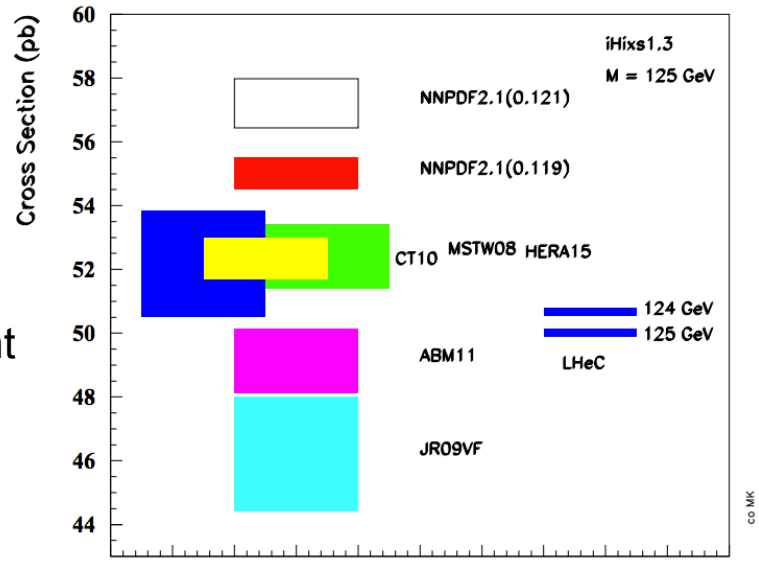
- LHeC can provide a complete PDF set with precise gluon, valence, and strong coupling:

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

NNLO pp−Higgs Cross Sections at 14 TeV



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 since lhapdf v5.9.1**

Summary

- Successful releases of the HERAFitter package – an open source QCD Framework designed to help address the theoretical differences, but mostly provides means for various tests within experimental data analysis
  - HERAFitter platform has grown into a multi-functional QCD platform:
    - Various treatments for heavy flavours;
    - Various options for data uncertainties treatment;
    - Various parametrisation techniques;
    - Various physics cases.

NEW

Stable release available: herafitter-1.0.0

- www.herafitter.org
- herafitter-help@desy.de

We welcome new developments!

HERAFitter perspectives

A list of planned developments:

- **Theory (short and long terms):**
  - QED PDFs
  - Nuclear + proton PDFs.
  - Heavy Flavour scheme in QCDNUM, using fast convolution engine.
  - Improvements in Hathor cross-section calculation for fits, other ttbar codes
  - Addition of DiffTop – program to calculate differential cross sections
  - EW corrections.
  - DYNNLO in APPLGRID.
  - Photon‘s PDF.
  - Different evolution schemes:
    - e.g. matched to MC showering, mixed Dipole-DGLAP fits.
- **Data treatments:**
  - Alternative to MINUIT minimization package

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 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)]

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

EXTRA

HERAFitter perspectives in a list

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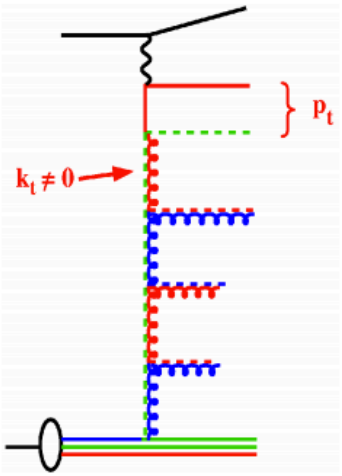
uPDFs in HERAFitter



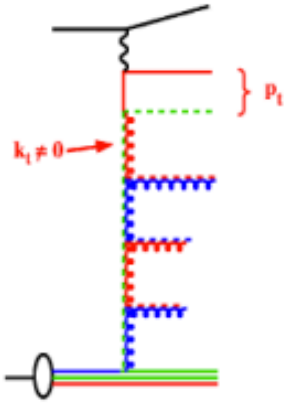
- $\frac{d\sigma}{dxdQ^2} = \int dx_g \left[dk_\perp^2 x_g \mathcal{A}_i(x_g, k_\perp^2, p) \right] \hat{\sigma}(x_g, k_\perp^2, x, Q^2)$
- $\hat{\sigma}(x_g, k_\perp^2, x, Q^2)$ is (off-shell, k_t dependent) hard scattering cross section
- uPDFs for gluons and quarks needed:
  - Until now: only gluon uPDF determined
- valence quarks: use starting distribution CTEQ6
- method:

$$\sigma_r(x, Q^2) = \int_x^1 dx_g \mathcal{A}(x_g, k_\perp, p) \hat{\sigma}(x, x_g, Q^2)$$

- calculate $\int_{x/x'}^1 dx'' \tilde{A}(x'', k_\perp, p) \cdot \hat{\sigma}(x, x' x'', Q^2)$ in a grid of x",Q^2
- starting distribution: $\mathcal{A}_0(x) = N_g x^{-B_g} (1-x)^{C_g} (1 - D_g x)$
- calculate $\sigma_r(x, Q^2)$ by 1-dim Gauss integration (fast!)
  - external input:
    - kernel evolution grid for gluon
    - evolved valence quark distribution (as uPDF)
  - convolution of kernel with off-shell ME done in `herafitter`

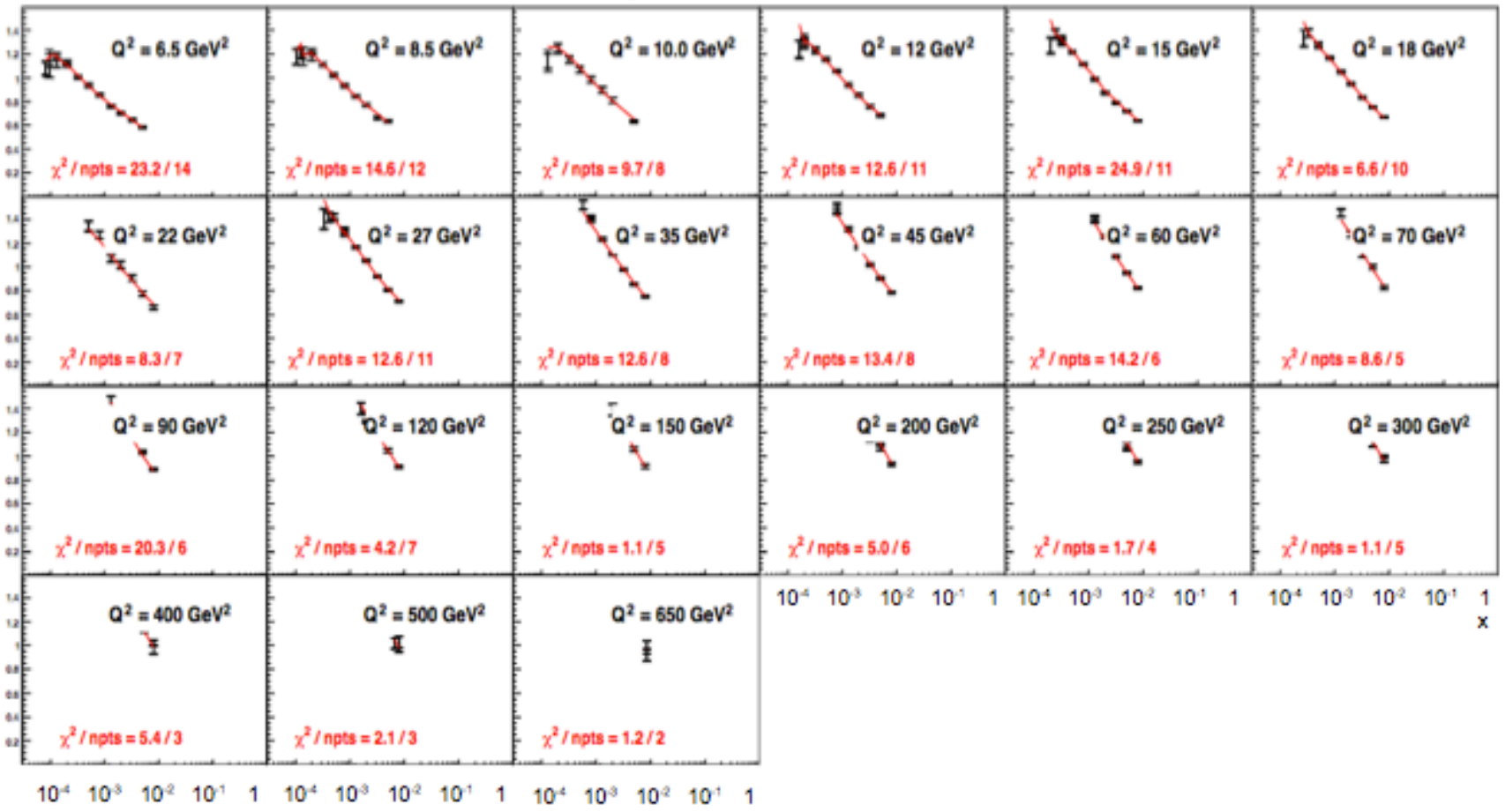
uPDFs in HERAFitter

- unintegra



Low Q^2 F_2

from herafitter output



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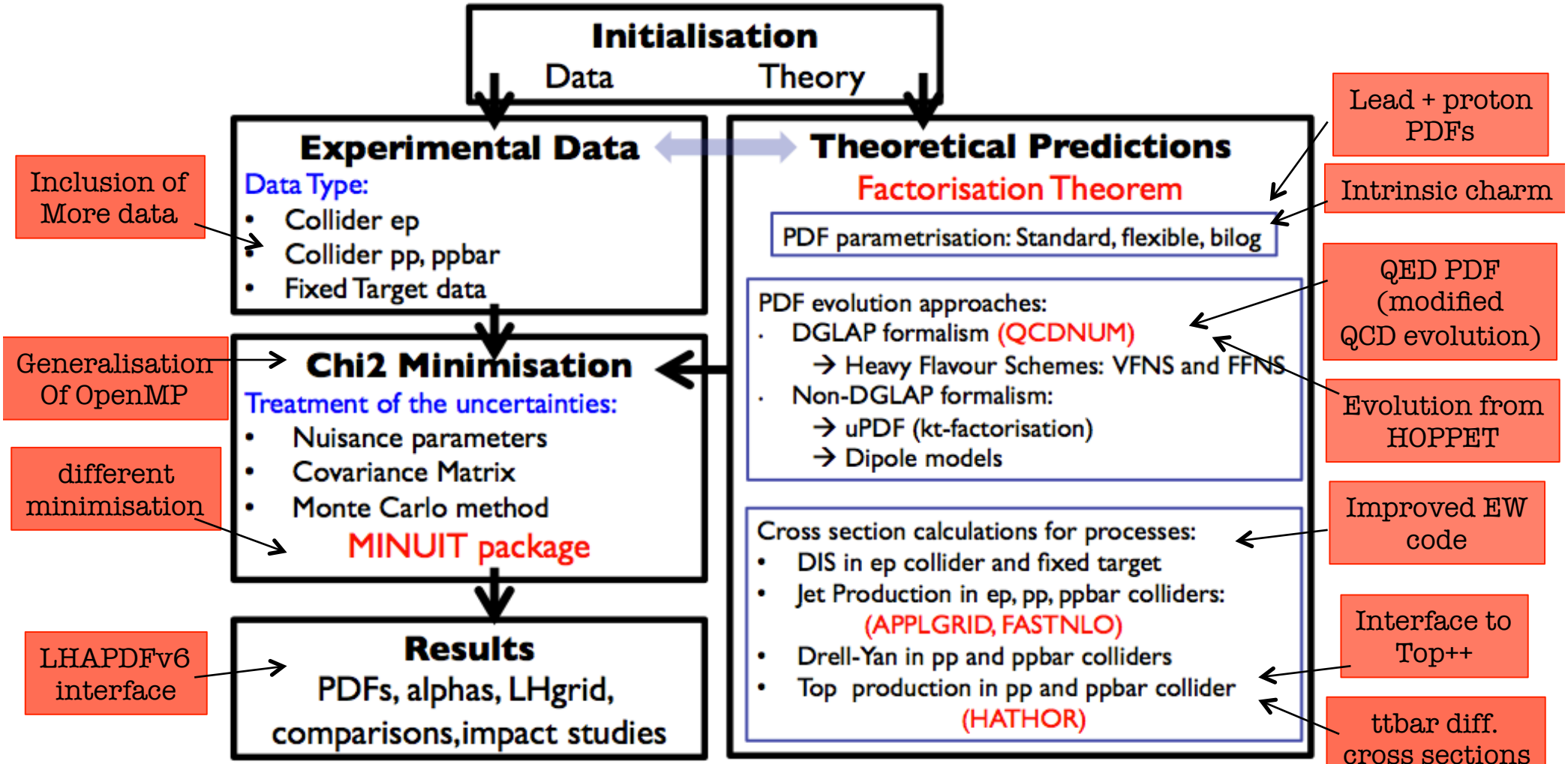
meeting Oct

- Fit performed in $Q^2 > 5$ GeV, $x < 0.01$

HERAFitter Perspectives

HERAFitter has a modular structure facilitating fast developments

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



We welcome more ideas!