First stable release HERAFitter 1.0.0

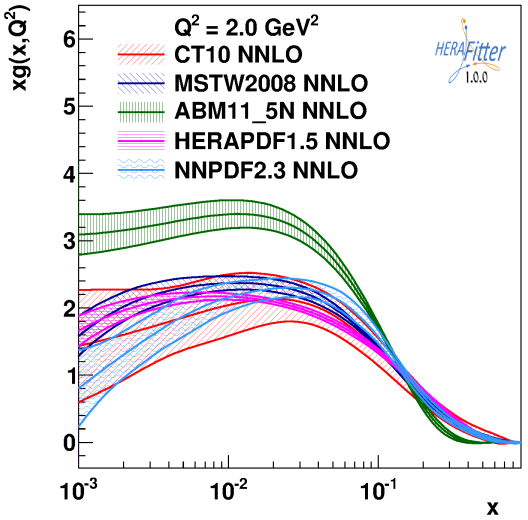
HERAFitter

Open Source QCD Fit Platform to determine PDFs

Stefano Camarda
For the
HERAFitter team

Outline:

- Motivation
- Project Overview
- Functionality
- Application and Results



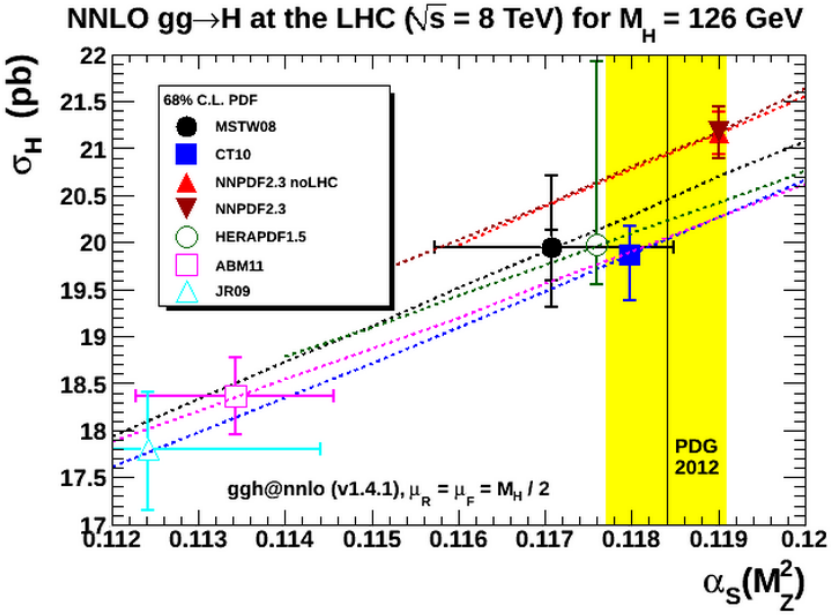
PDF4LHC Meeting – December 13th 2013

DESY

Motivation

- PDFs are essential for precision physics at the LHC:
  - PDFs are one of the main theory uncertainties in Higgs production
  - PDF uncertainties also affect 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]

→ **crucial to understand the theoretical differences**

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

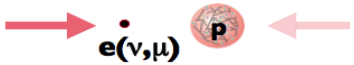
HERAFitter provides an ideal framework for

- Investigation of different methodologies in PDF fits
- Assess the impact of data on PDF → improve the sensitivity of new measurements to PDF

Proton Structure

- **PDF determination relies on factorisation theorem:**
  cross sections: PDFs ⊗ hard scattering coefficients

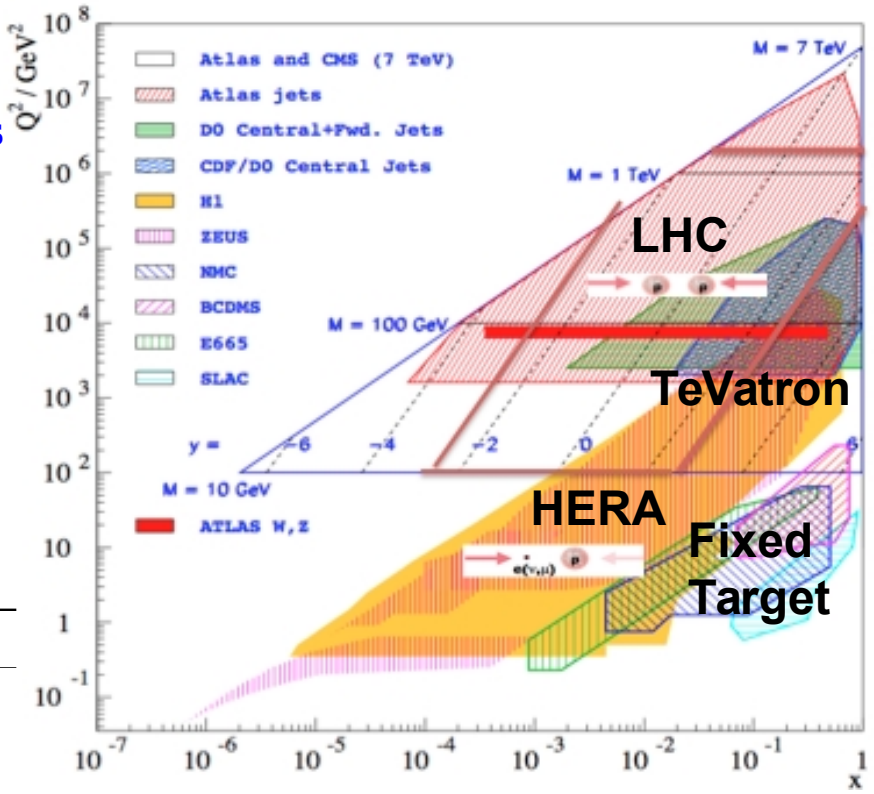
- Main constraint on PDFs comes from DIS data at HERA which probes linear combination of quarks:



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

No flavour decomposition of the sea

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



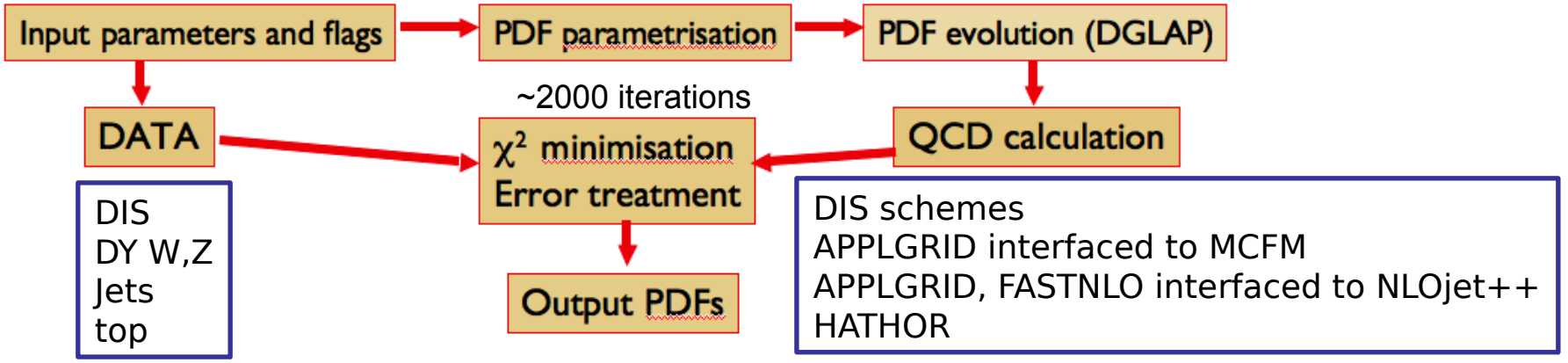
Coverage in x is essential
QCD evolution is in Q2

LHC provides new observables and precise measurements to better constraint

- Flavour decomposition of the sea
- Gluon PDF

Schematics of PDFs determination

Flow diagram of PDF determination in QCD fit

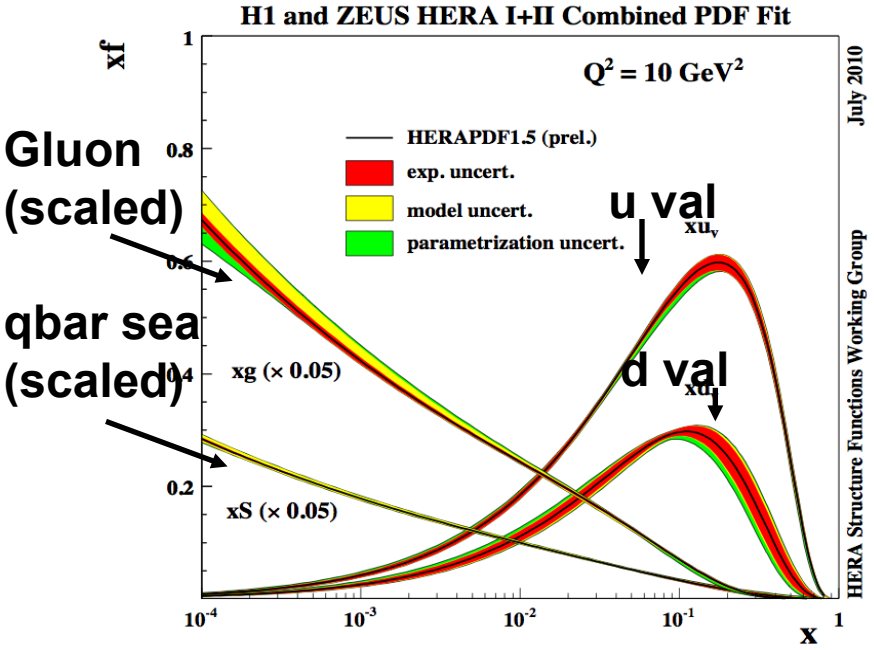


Data

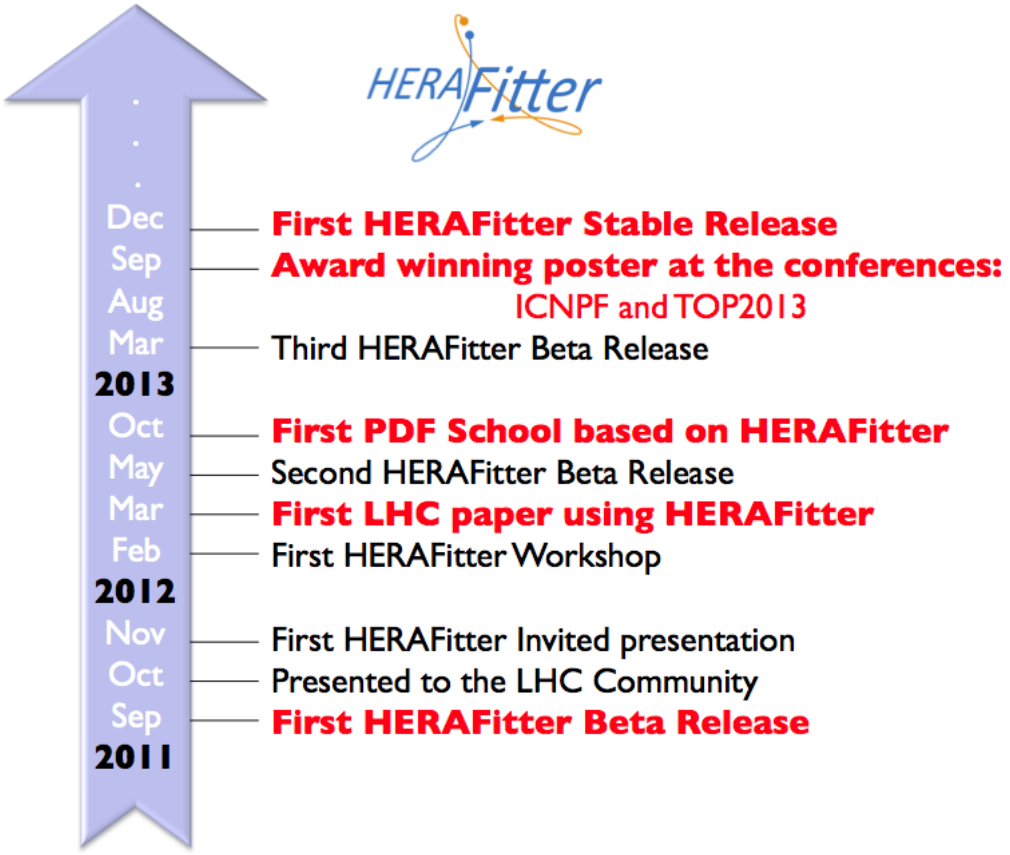
- Important to provide uncertainties correlation

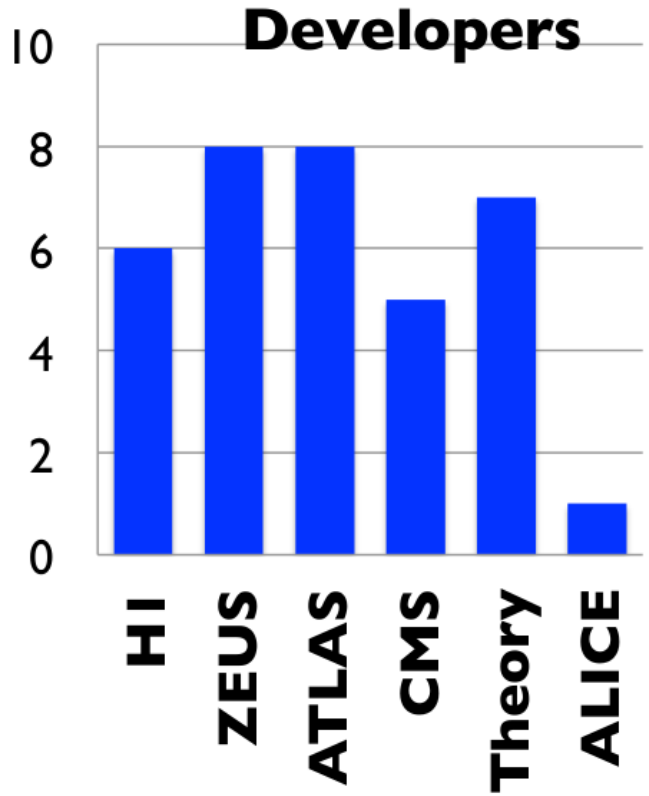
Theory

- Need fast tools to perform PDF fits:
  APPLGRID, FASTNLO
  → grid techniques relying on factorisation theorem



Dec 2013 → First Stable Release HERAFitter 1.0.0

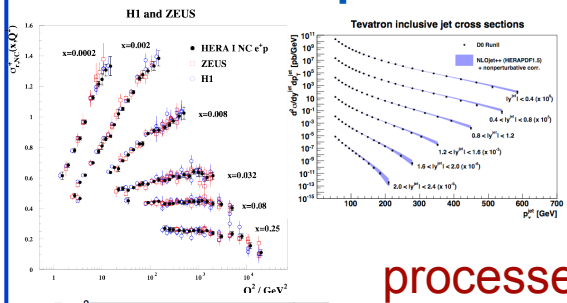




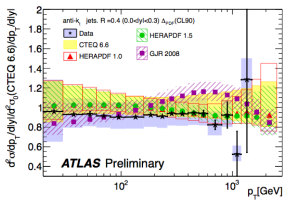
- **Unique framework to address PDF theoretical differences**
- **Provides means to the experimentalists to assess impact of new data**

HERAFitter 1.0.0 in a glance

experimental input



experiments:
HERA, Tevatron,
LHC, fixed target



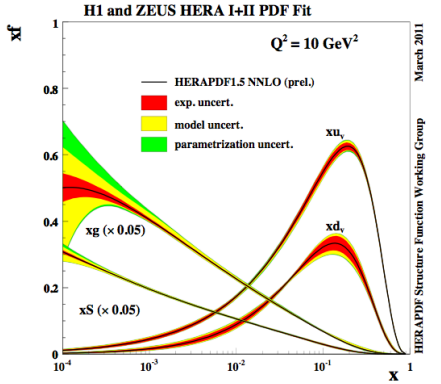
processes:
NC, CC DIS, jets, diffraction,
heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

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

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

HERAFitter



PDF or uPDF or DPDF

αS (MZ),mc,mb,mt,
fs,..

Theory predictions

Benchmarking

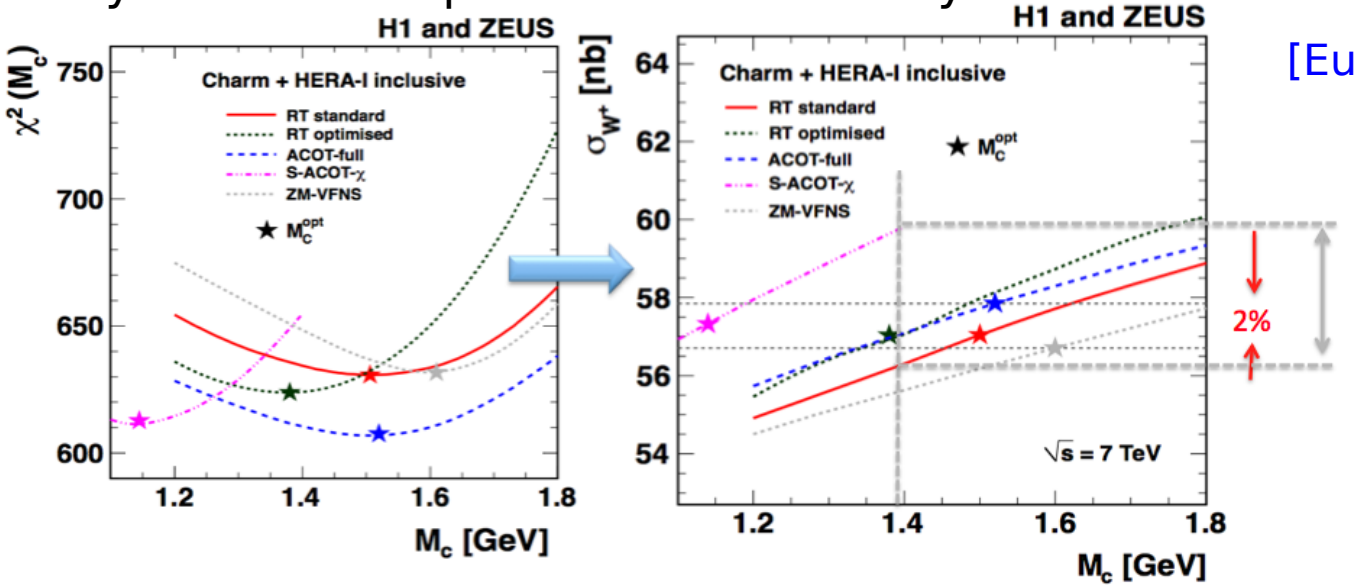
Comparison of schemes

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)
  - 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

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**:

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

    - **Scaled form:**

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

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

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

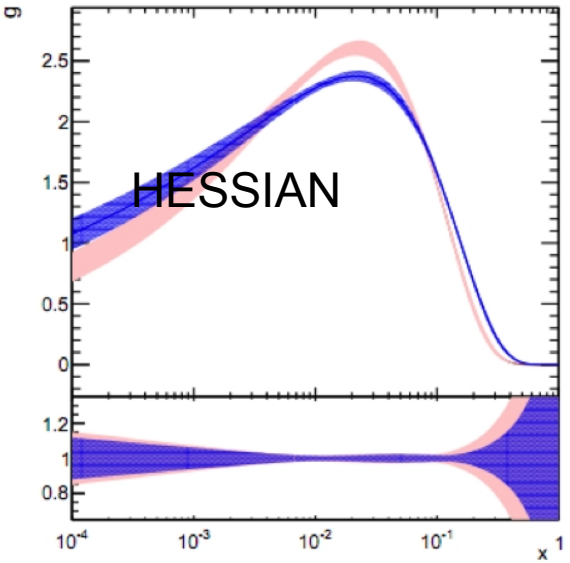
Experimental Uncertainties

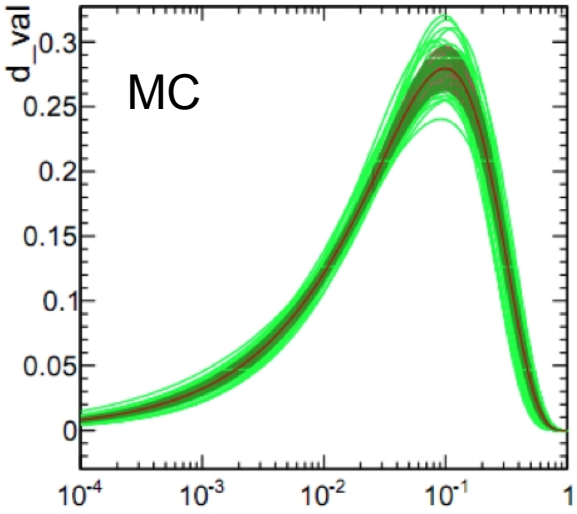
HERAFitter provides various methods for the treatment of experimental uncertainties

- Asymmetric Hessian errors
- Monte Carlo errors

```
&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 (o
  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: constrain PDFs with 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

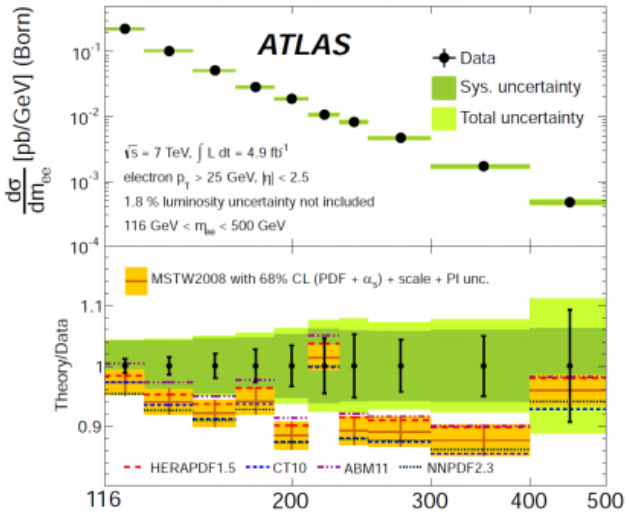
HERAFitter provides a quantitative assessment of level of agreement between data and theory by taking into account theoretical and experimental uncertainties

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

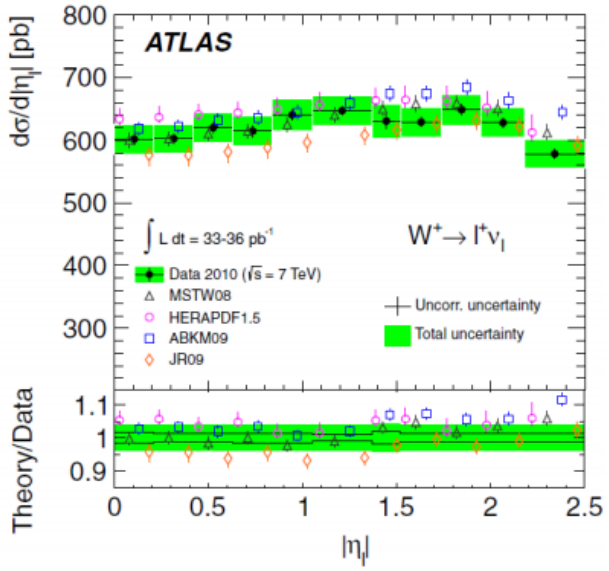
Ex: 30 points from ATLAS
WZ 2010 vs NNLO predictions

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

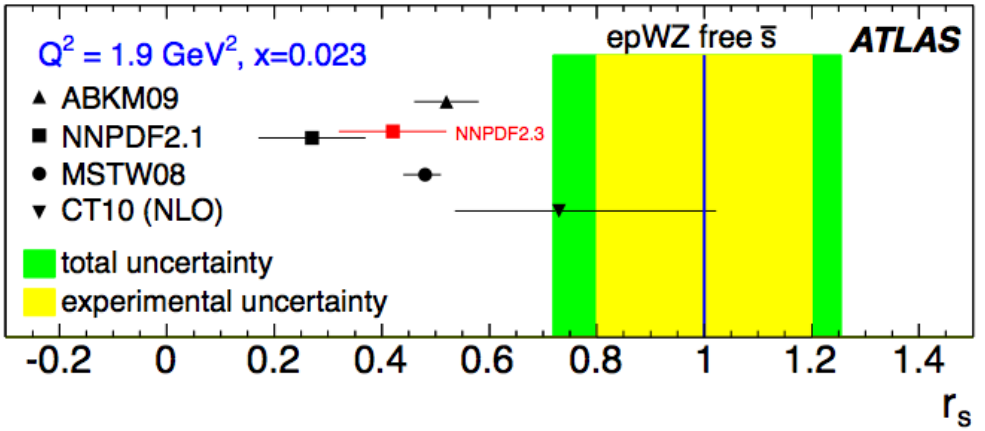


Phys. Rev. D 85 (2012) 072004

Determination of the strange quark in the proton

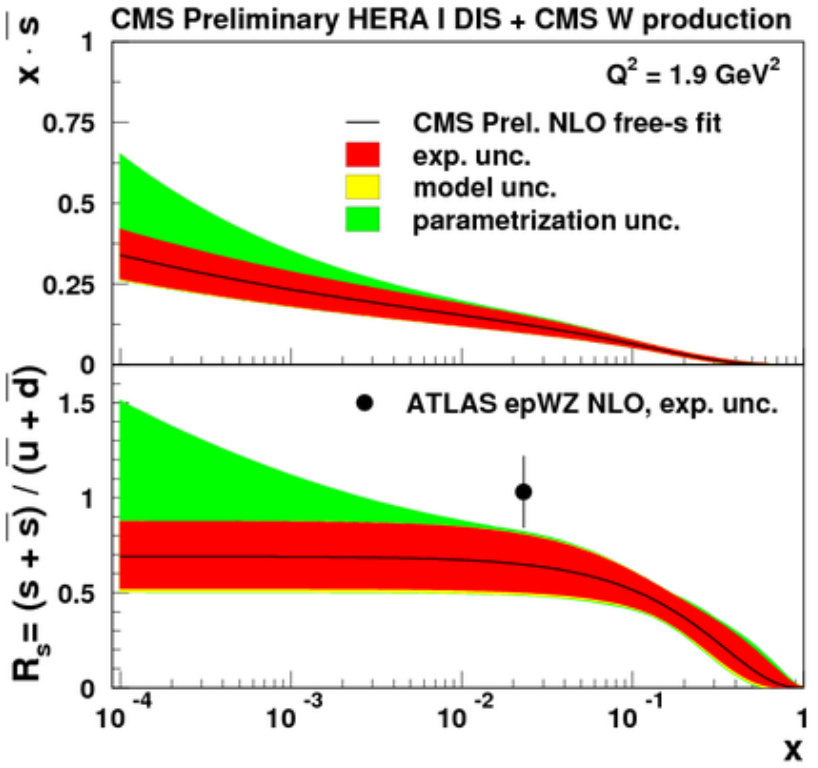
- Using W+, W-, Z (35/pb) inclusive cross sections – ATLAS [PRL 109 (2012) 012001]
  (kinematic region probed is at x~0.01)
  - NNLO QCD Analysis
  - **ATLAS-epWZ-EIG.LHgrid available in lhapdf**

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



NEW

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

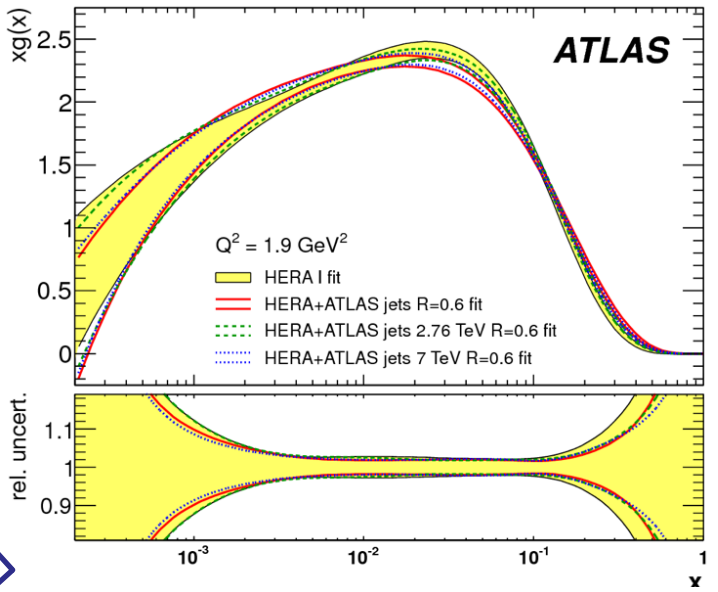


More details in Mark and Georg's talks

Sensitivity to gluon and strong coupling:

Study sensitivity to the gluon PDF:

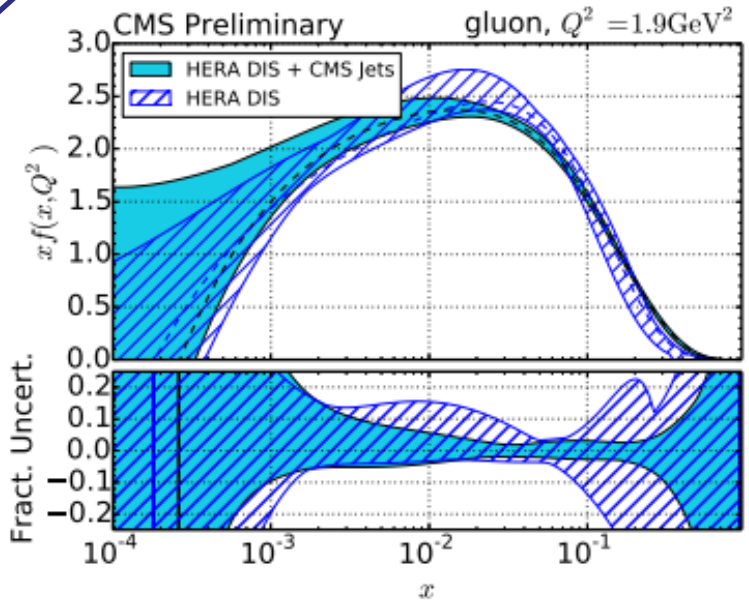
- Using ratio of jets at different beam energies – ATLAS [EPJC (2013) 73 2509]
  - Compare the gluon for PDF fit using just HERA I and a fit using HERA I + ATLAS 2.76, 7 TeV jet data (2010)



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



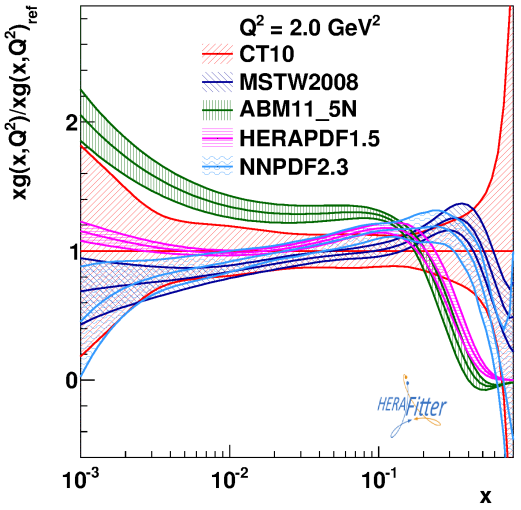
Extraction of the strong coupling:

- From PDF and alphas simultaneous fit:

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

More details in Mark and Georg's talks

PDF Sensitivity study on prompt photon



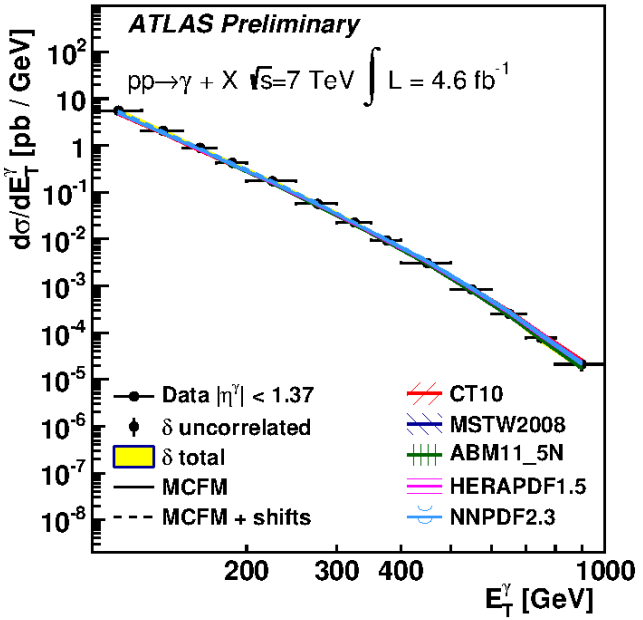
First result with stable release HERAFitter 1.0.0

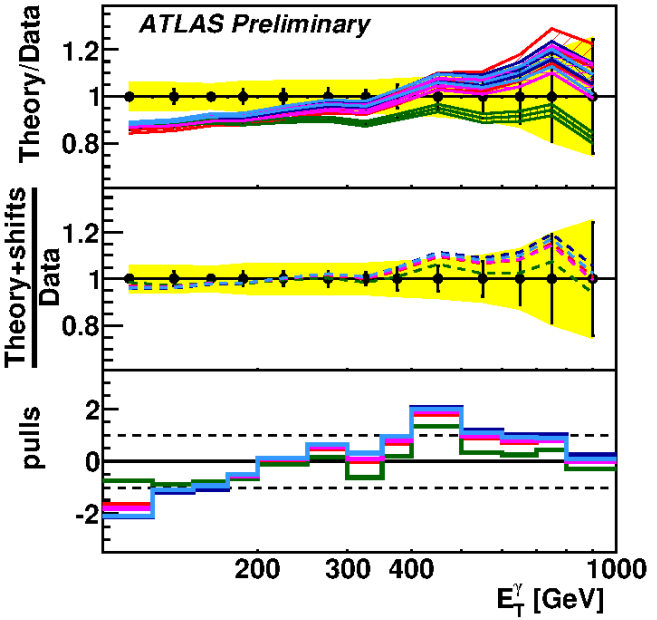
Assess:

- **Compatibility** between data and NLO predictions
- **Sensitivity** to the gluon PDF

HERAFitter 1.0.0 stable release provides automatic tools for:

- χ^2 comparison with and without PDF uncertainties
- PDF plots
- Data plots





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.

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 Theory

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

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

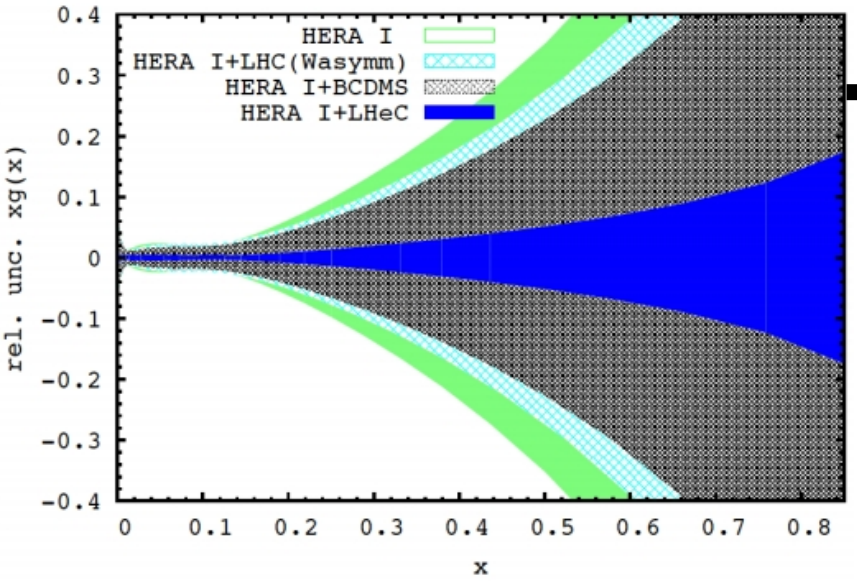
Backup

Impact studies of LHeC on PDFs

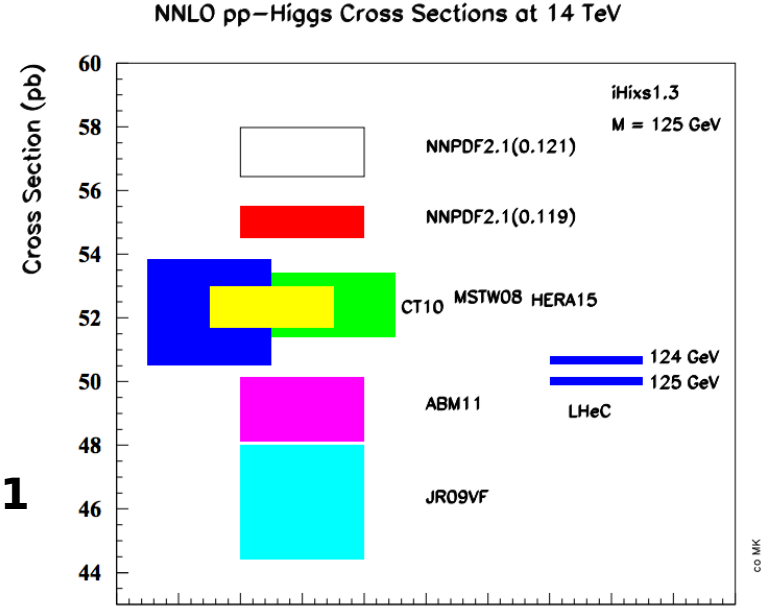
HERAFitter provides the possibility to perform impact studies using simulated data:

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

LHeC promises per mille accuracy on alphas – using HERAFitter [Journal of Phys. G 39 (2012)]



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



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**

Low x Physics

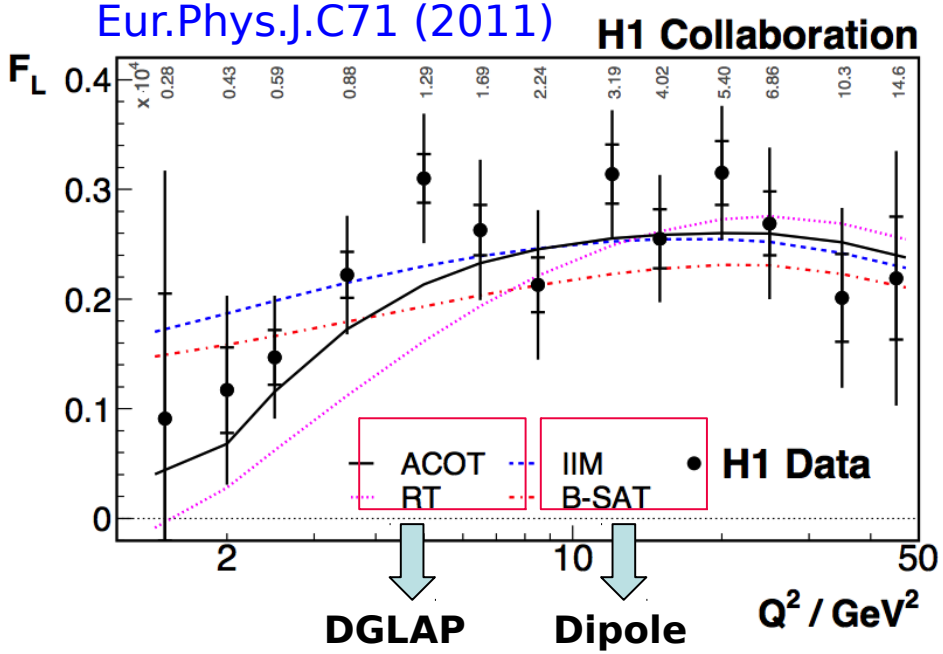
- As an alternative to DGLAP, HERAFitter includes also Dipole models:
  - Studied by the H1 collaboration in comparing different models on FL:

▿ 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

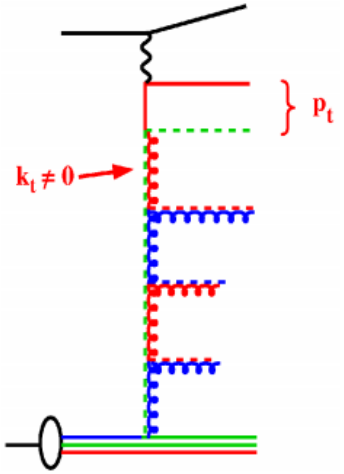


- Unintegrated PDFs based on the kT-factorisation (CCFM) evolution.
  - applicable only to NC ep scattering

https://www.herafitter.org/HERAFitter/HERAFitter/HERAFitterMeetings/Meeting2012-Oct-29?action=AttachFile&do=get&target=updf.pdf

- Diffractive DIS PDF fits.

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:

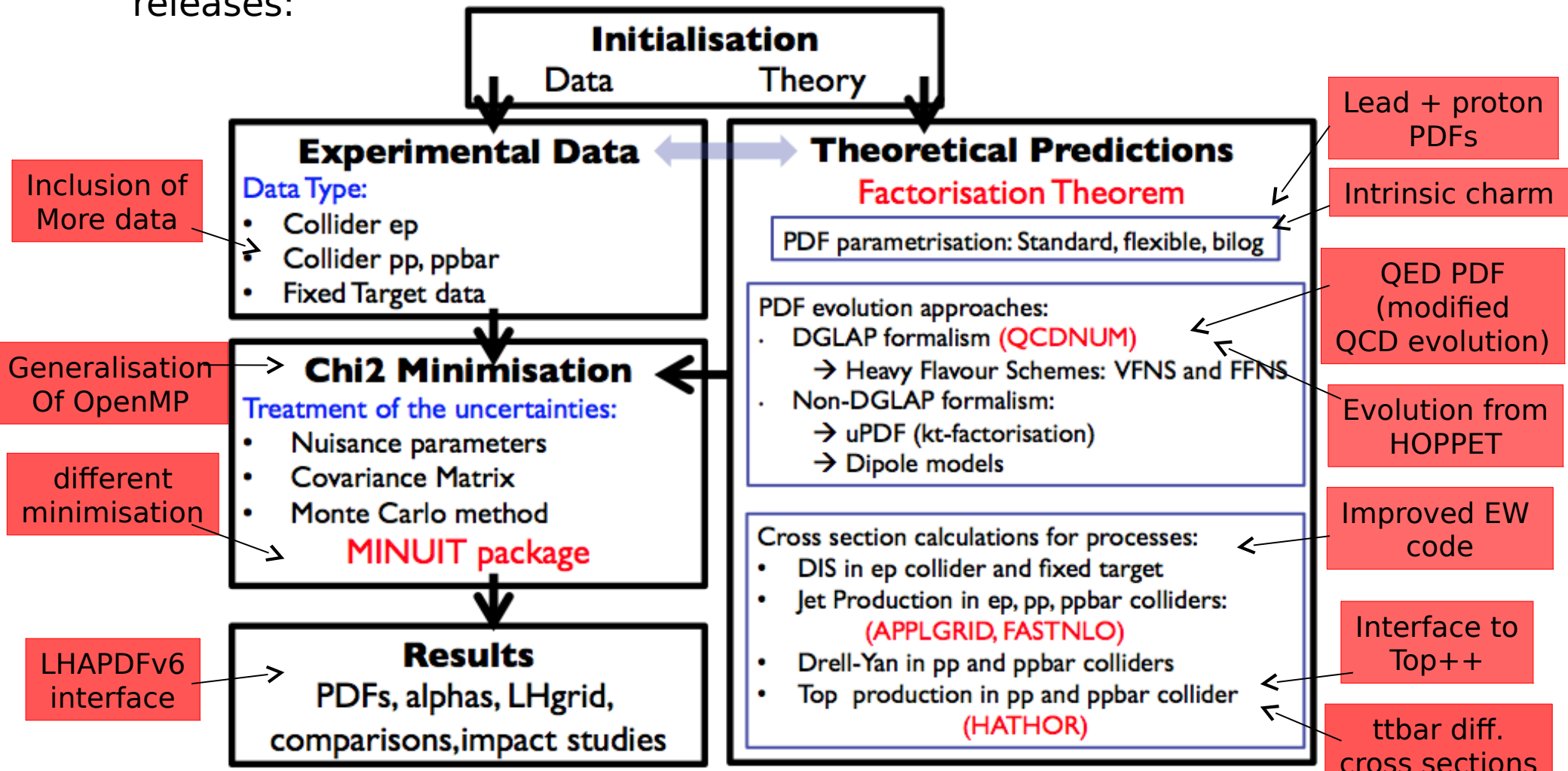
$$\sigma_r(x, Q^2) = \int^1 dx_g \mathcal{A}(x_g, k_\perp, p) \hat{\sigma}(x, x_g, Q^2)$$

- calculate $\int_{x/x'}^1 dx'' \tilde{\mathcal{A}}(x'', k_\perp, p) \cdot \hat{\sigma}(x, x'\, x'', Q^2)$ 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`

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!