HERAFitter - open source QCD Fit framework and its related studies

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on behalf of the HERAFitter's developers team

Outline:

- Motivation
- Project overview
- Applications and results

ICNFP2014, Crete, 06.08.2014

Motivation

PDFs are essential for precision physics at the LHC:

- PDFs are one of the main uncertainties in Higgs production, Mw measurements etc
- Affect theory predictions for BSM searches

Different 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.**

➔ **Important to provide accurate data together with correlation information for better PDF discrimination.**

Proton Structure

According to the factorisation theorem:

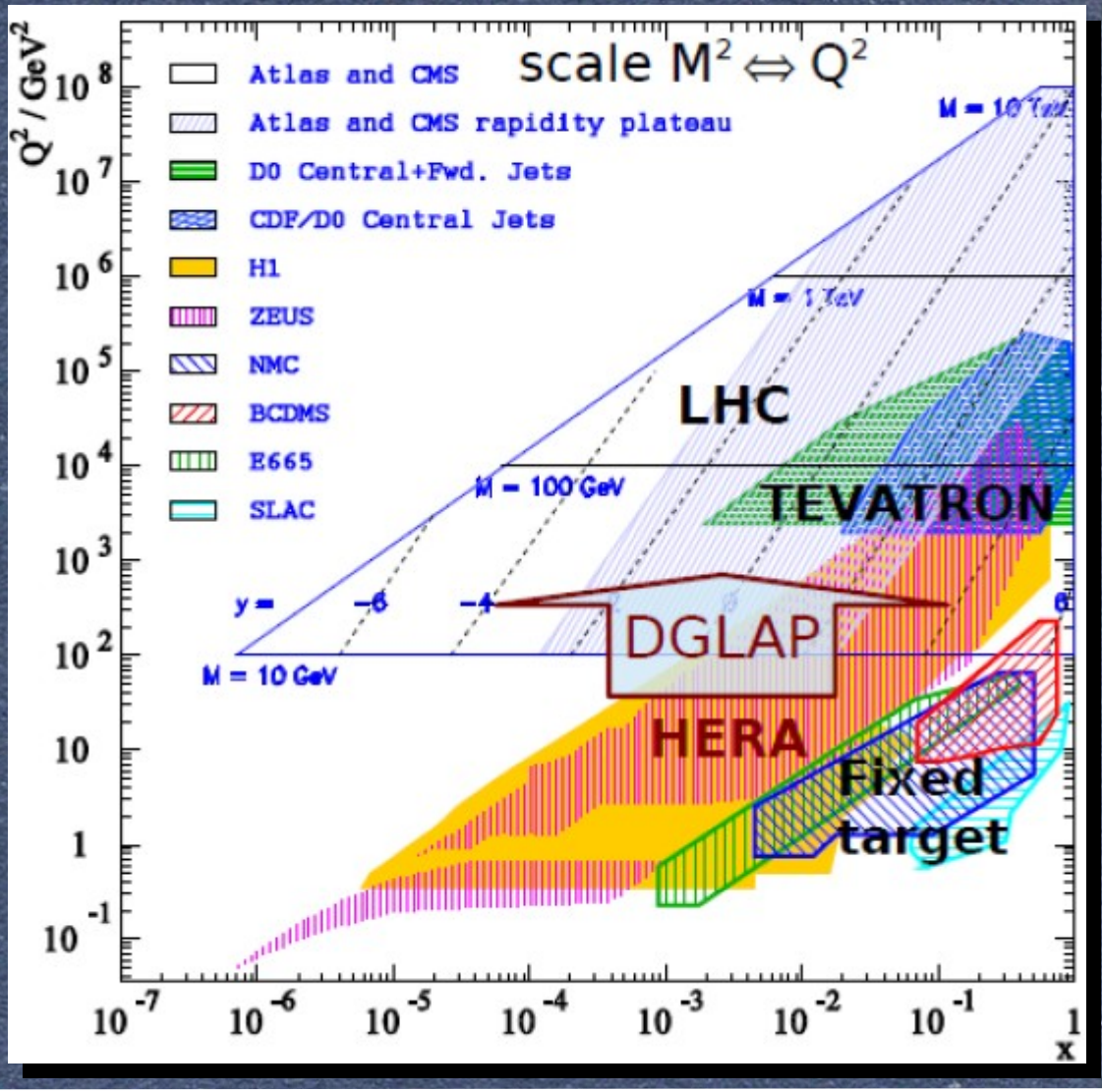
cross section: PDFs ⊗ hard-scattering coefficients

Main information on PDFs comes from DIS data at HERA

- Sensitive to light quarks and gluons
- No information on flavour decomposition of the sea

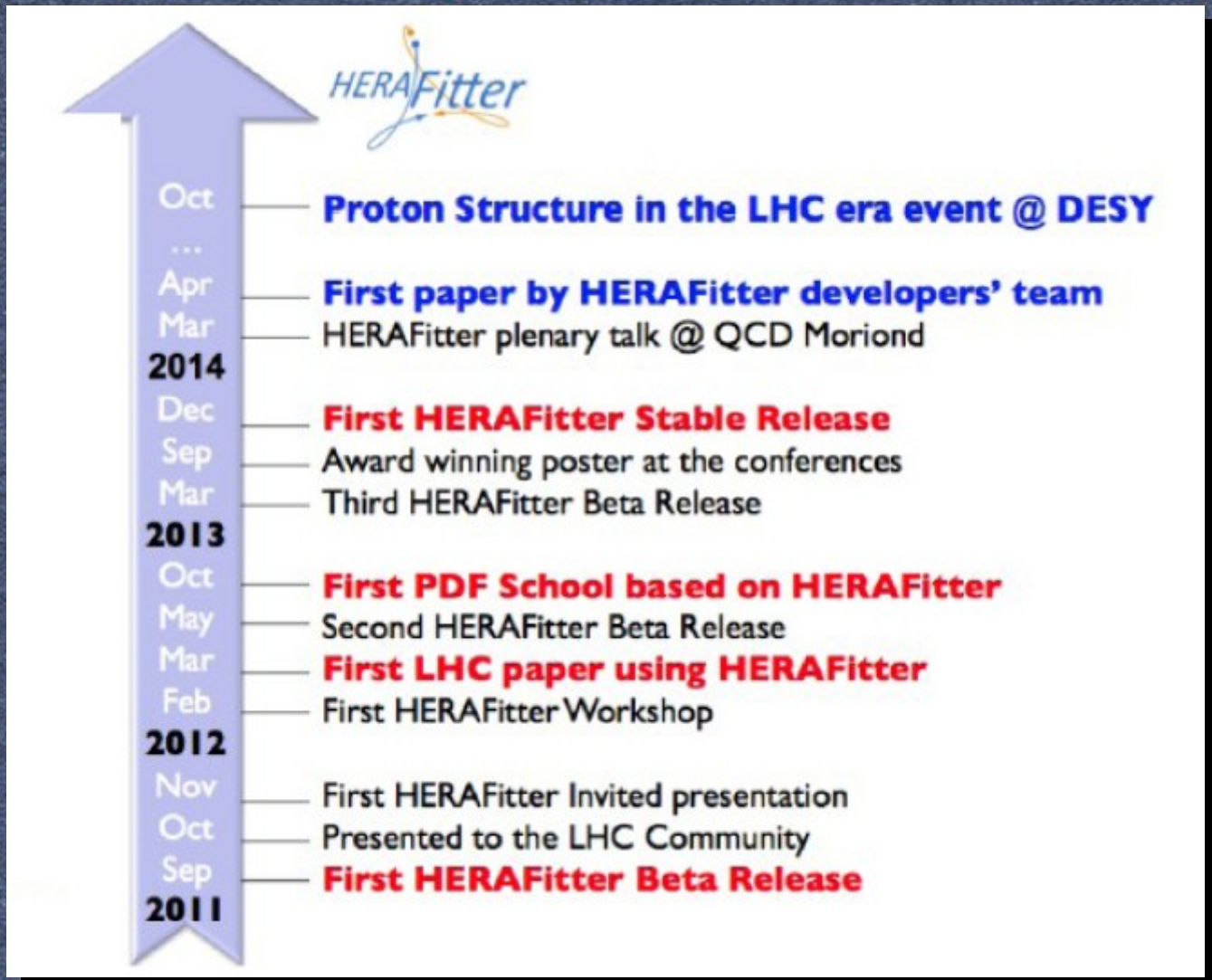
LHC data provide flavour separation and better understanding of gluon:

- Inclusive jets/dijets/trijets → gluon and α_s
- W/Z production, asymmetry → q anti-q, flavour separation
- W+charm → direct sensitivity to s-quark
- Isolated photons → gluon at medium and high x
- W/Z+jet production → gluon at medium x
- Top production → gluon, u and d



HERAFitter Project

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



HERAFitter provides a framework for:

- Addressing theoretical differences and benchmarking
- Studying impact of new data on PDFs

HERAFitter Structure

Modular structure of HERAFitter:

Initialization

Input Data

Data Type:
- collider ep
- collider pp, ppbar
- fixed target

Theory Predictions

Factorisation Theorem:
- PDF parametrisation
- QCD evalution
- cross section calculation

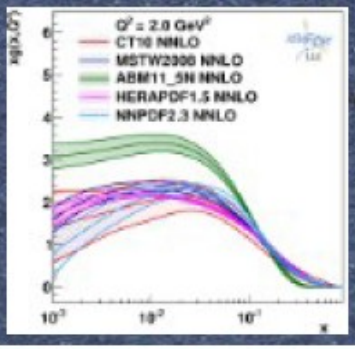
Minimisation

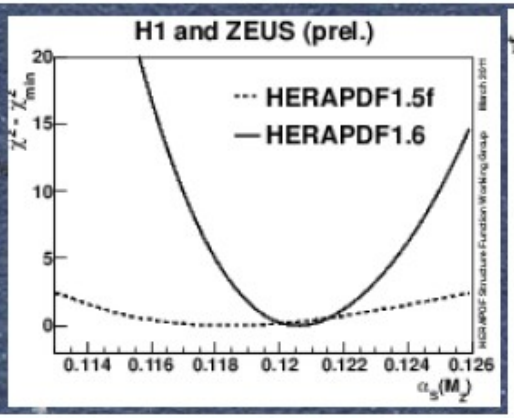
Treatment of uncertainties:
- Nuisance parameters
- Covariance matrix
- Monte Carlo method

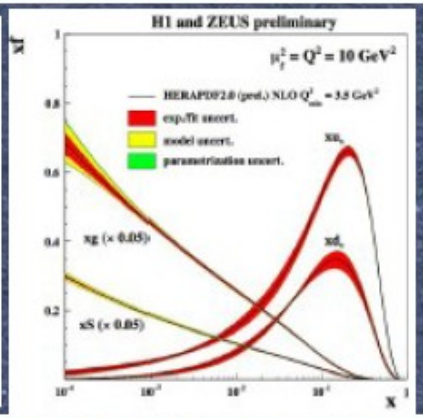
- Performance: 15min – 2h
- Fast tools needed to perform PDF fits: APPLGRID, FASTNLO

Results

- LHAPDF grids
- alphas, mc, …
- data to theory comparison
- χ^2, shifts, pulls







χ^2 Definition and Experimental Uncertainties

HERAFitter package allows for various types of data uncertainty treatment

- χ^2 representation using:
  - Nuisance parameters

$$\chi^2(m,b) = \sum_i \frac{\left[\mu_i - m_i\left(1-\sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i\left(1-\sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2$$

  - 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 estimation:
  - *Hessian:* uncertainties estimated by examining behavior of χ^2 in the neighborhood of the minima
  - *Monte Carlo:* MC replicas by shifting data points randomly within their uncertainties.
  - *Offset:* correlated sources accommodated in uncertainties

The platform is used in various benchmark exercises.

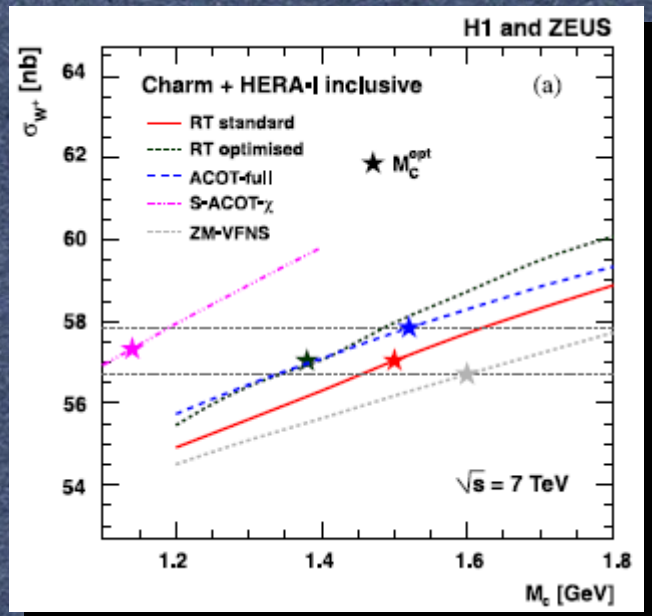
Heavy Flavour Schemes

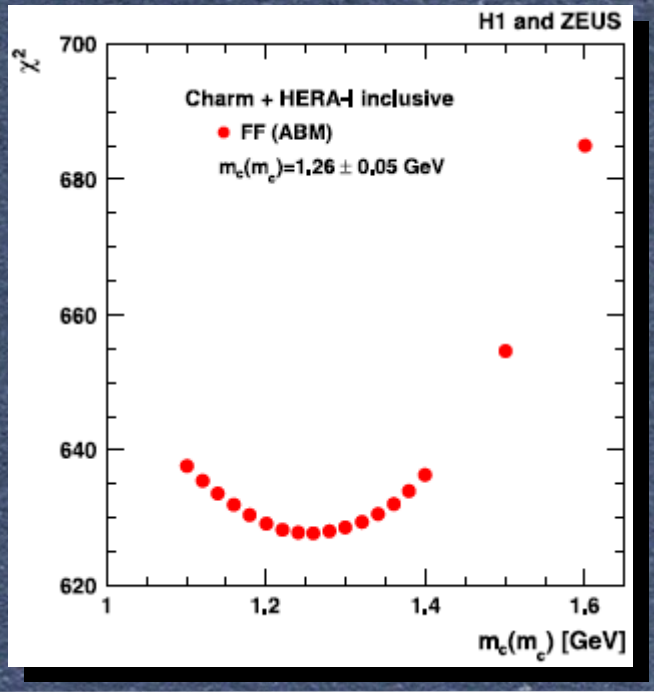
Several schemes for heavy quark treatment in DIS processes:

- Variable Flavour Number Schemes (VFNS)
  - RTVFNS (Standard, Optimal) as used by MSTW group
  - Zero Mass VFNS
  - Various ACOT (Full, Chi, ZM) schemes, based on kfactors as used by CT group.

- Fixed Flavour Number Scheme (FFNS)
  - via QCDNUM
  - via OPENQCDRAD (ABM)

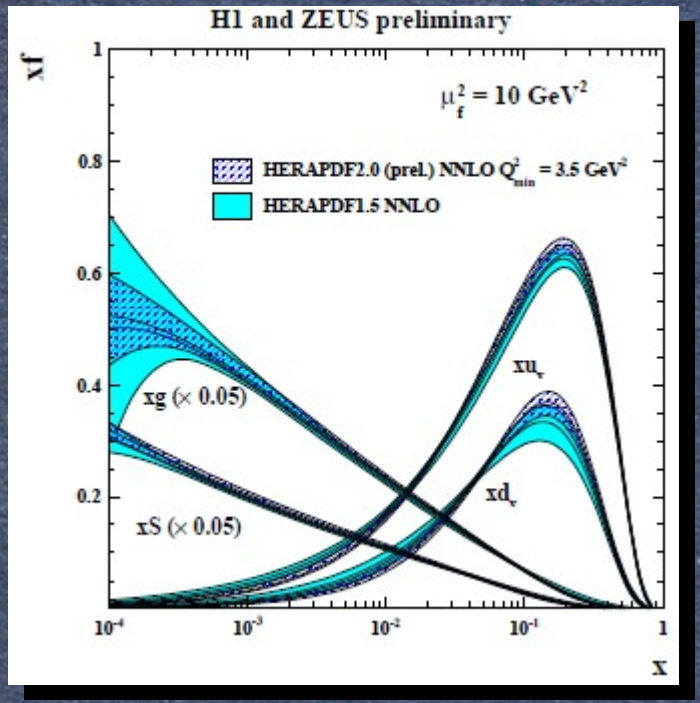
Variety of scheme options was studied in F2 charm HERA combined paper *(Eur. Phys. J. C73 (2013) 2311)*





Other recent results from HERA

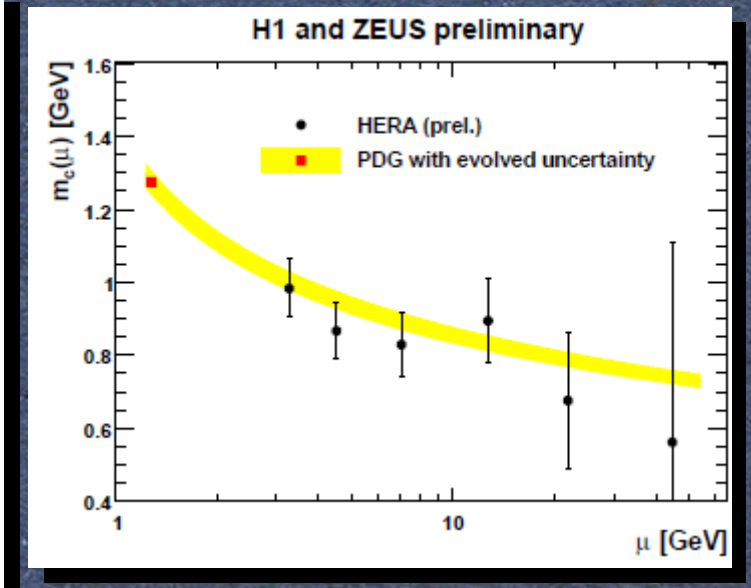
- *H1prelim-14-042, ZEUS-prel-14-007*



Combined HERA data are used as input to QCD analysis to determine sets of PDFs HERAPDF2.0

Talk by H. Abramowicz

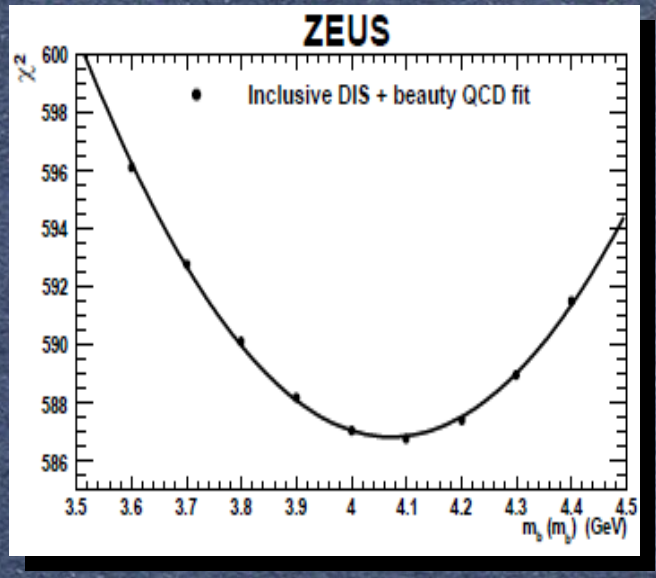
- *H1-prelim-14-071, ZEUS-prel-14-006 and S. Moch*



Combined HERA charm data used to determine charm quark running mass

Talk by V. Radescu

- *DESY-14-083 arXiv:1405.6915*



Beauty data measured by ZEUS used to determine beauty quark mass

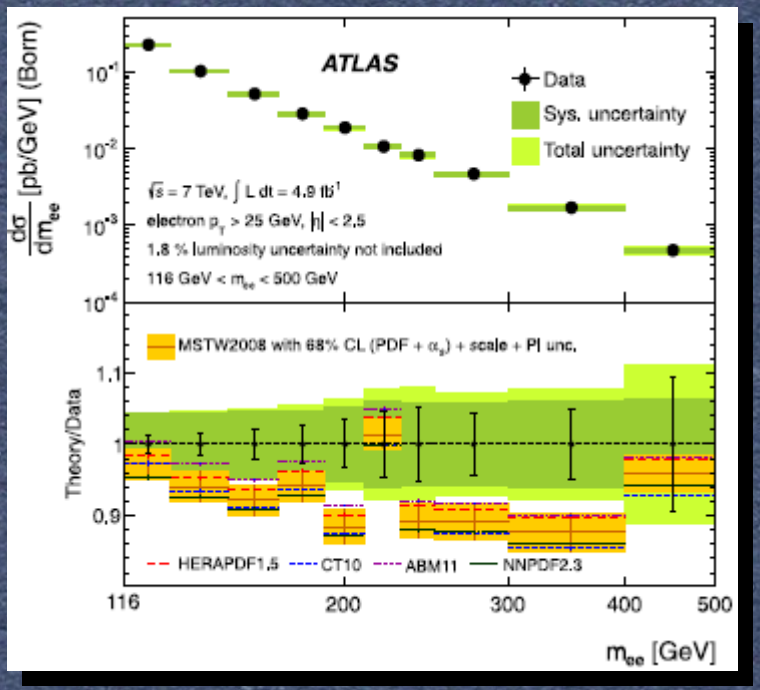
Talk by V. Radescu

HERAFitter Application at LHC: Data vs Theory

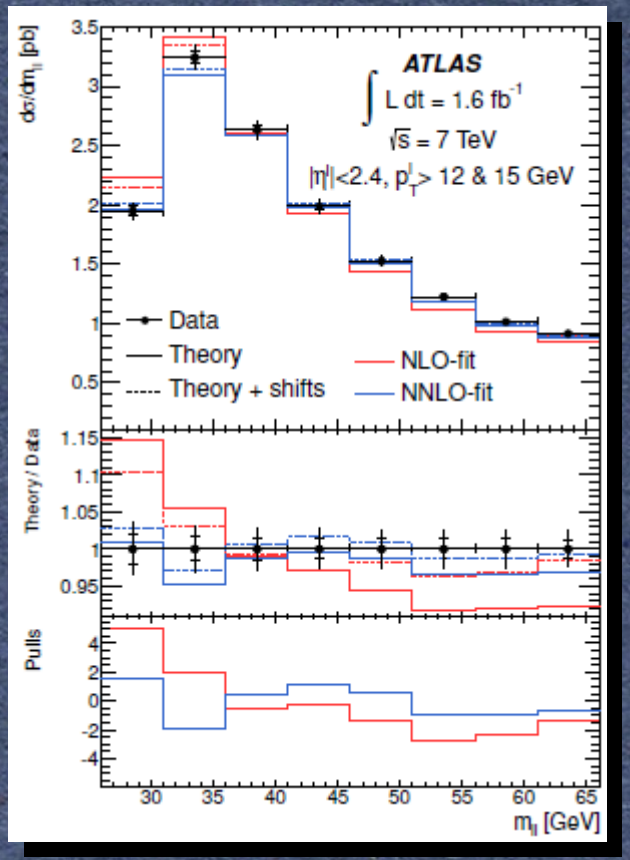
HERAFitter provides a quantitative assessment of level of agreement between data and theory by taking into account theoretical and experimental uncertainties.

Used in ATLAS publications:

Phys. Lett. B 725 (2013) 223

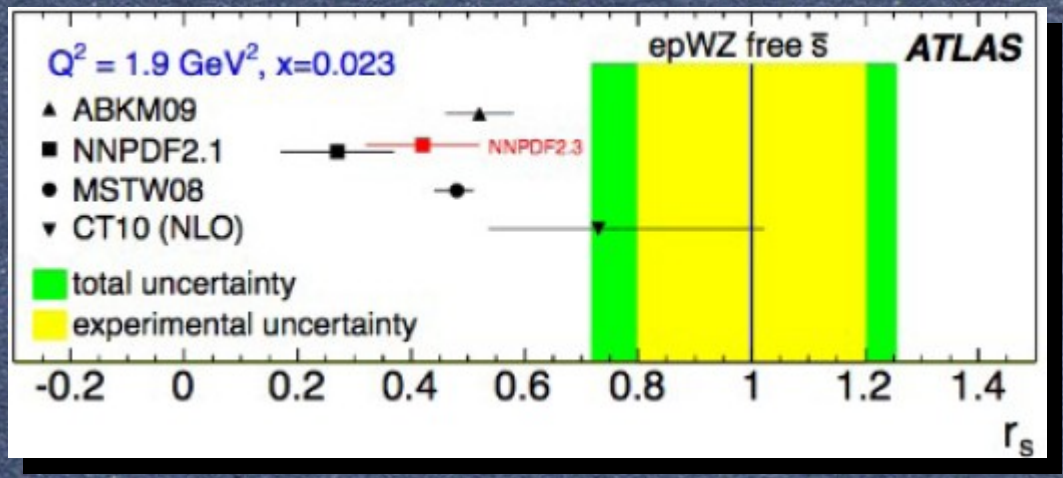


JHEP 06 (2014) 112

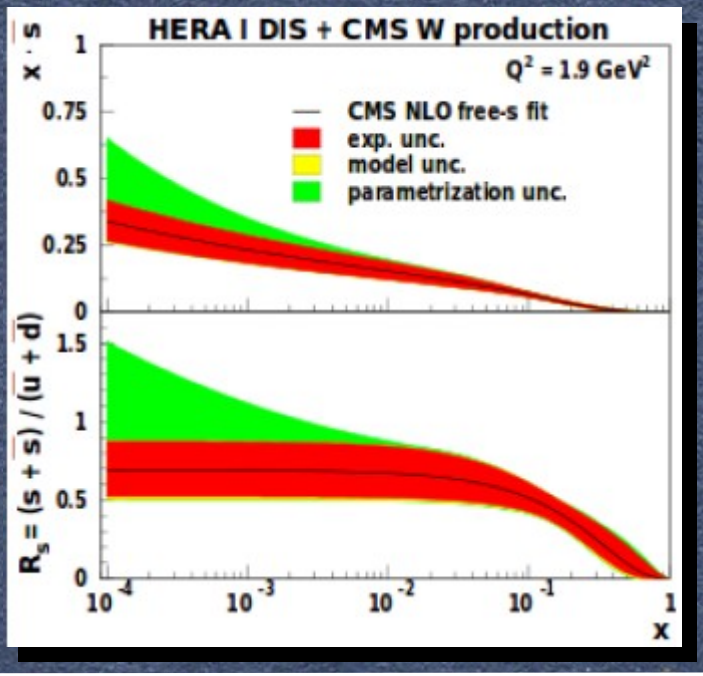


Strange Quark at LHC

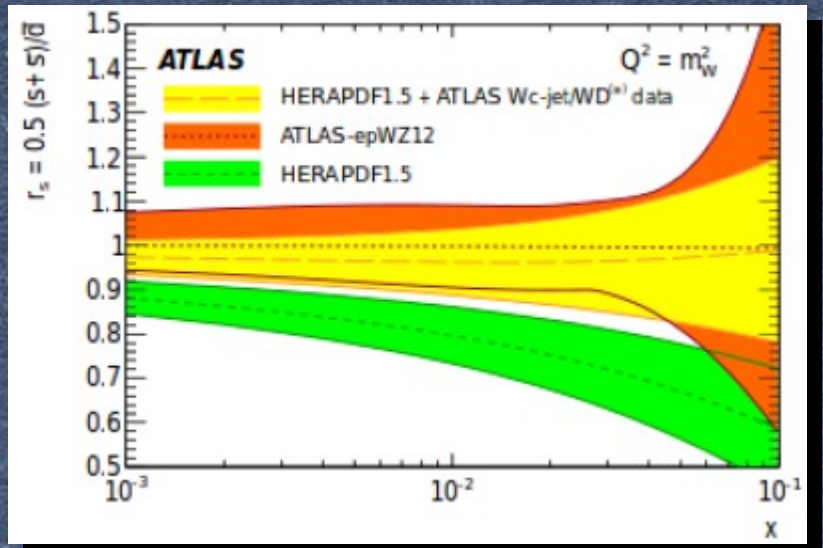
- W± and Z inclusive cross section was used by ATLAS to determine strange quark fraction in the sea *(Phys. Rev. Lett. 109 (2012) 012001).*



- W+charm data including W asymmetry was used to probe strange quark distribution *(arXiv:1312.6283).*

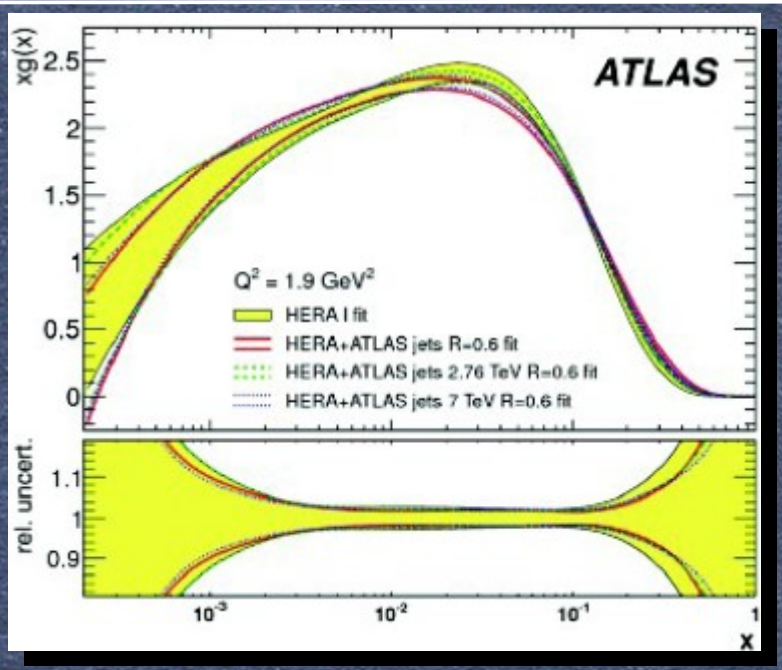


- W+charm data was used by ATLAS to determine the ratio of the strange to down sea quark distributions *(JHEP 05 (2014) 068).*

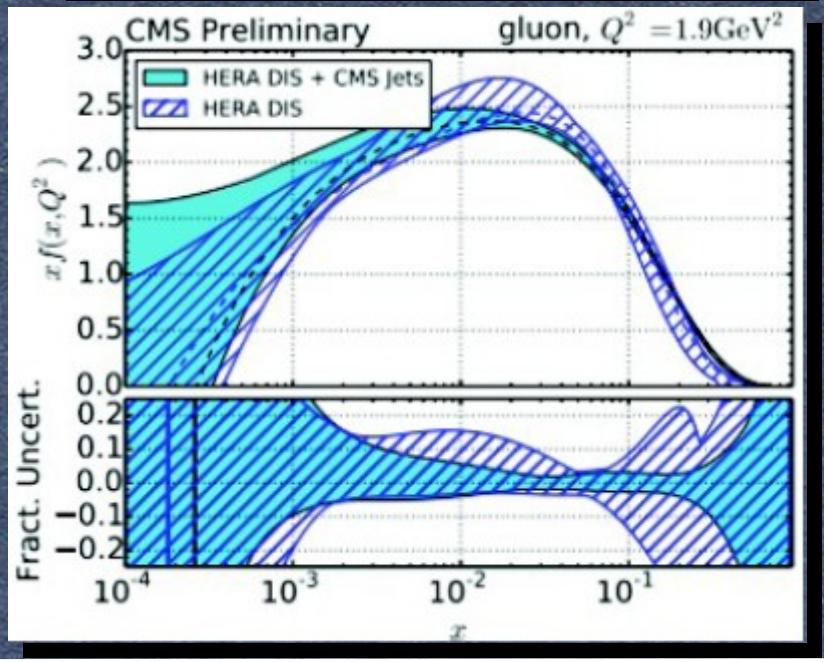


Sensitivity to Gluon and Strong Coupling

- Inclusive jet cross sections at different center-of-mass energies was used to study sensitivity of gluon density at low and high x regions. *(Eur. Phys. J. C 73 (2013) 2509).*



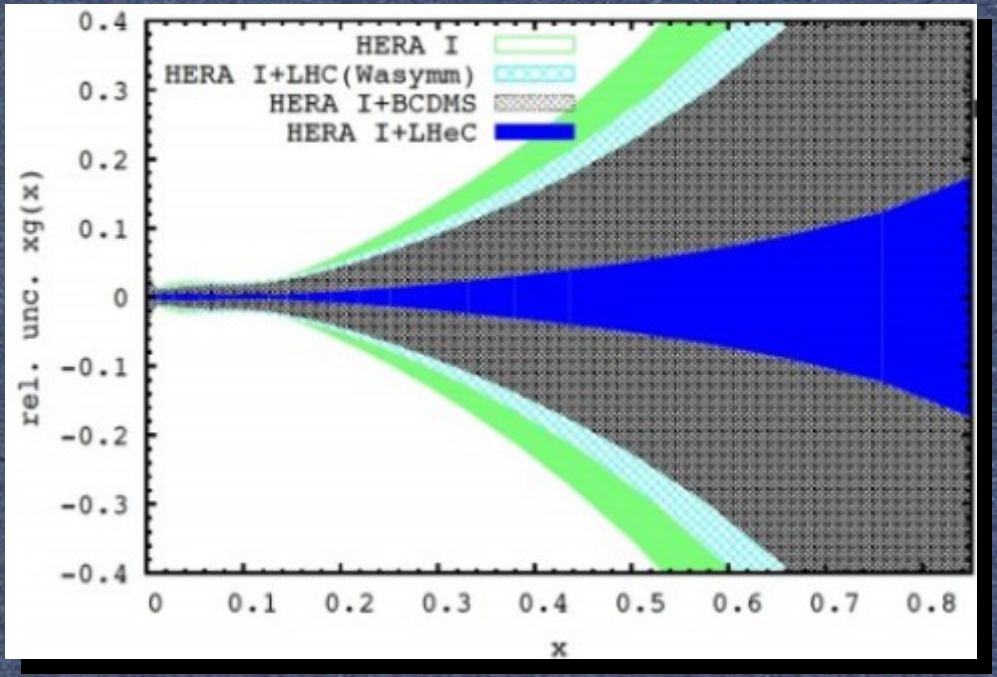
- PDF are extracted and compared to fits using HERA I data only and fits using HERA I + CMS jet data.
- The same inclusive jet cross section is also used to extract the strong coupling constant *(CMS-PAS-SMP-12-028).*



Sensitivity Studies

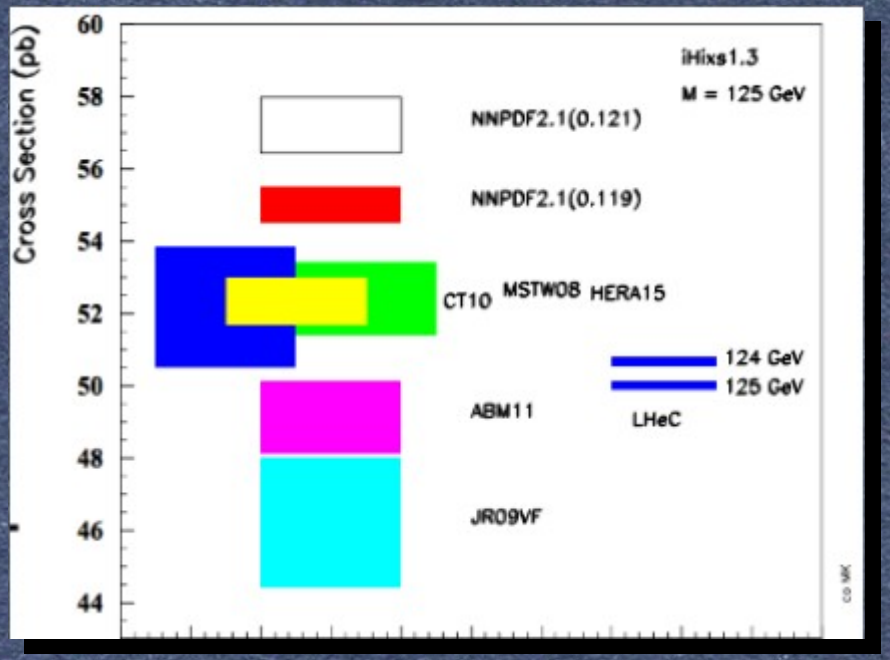
Platform can be used for sensitivities studies of the potential of future colliders:

- LHeC ep simulated data was used for to study sensitivity to PDFs:



(Journal of Phys. G 39 (2012))

- The output in LHAPDF format can be used for Higgs predictions:



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

List of Results Using HERAFitter

https://www.herafitter.org/HERAFitter/HERAFitter/results

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	Material

List of analyses using HERAFitter

Date	Group	Reference	Title
NEW 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
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
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

Motivation

- Various processes at LHC are calculated at different QCD orders
  - LO → used in parton showers MC
  - NLO → bulk of predictions
  - NNLO → available only for few processes
- Uncertainties rise from PDFs themselves and from missing higher orders usually determined 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:

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

✔ Cancelation 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
✔ Scale unc. improves
✗ Large scale unc.

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

✔ PDF unc. cancel
✔ Scale unc. reduces

Sets of PDFs with correlated uncertainties between different orders required

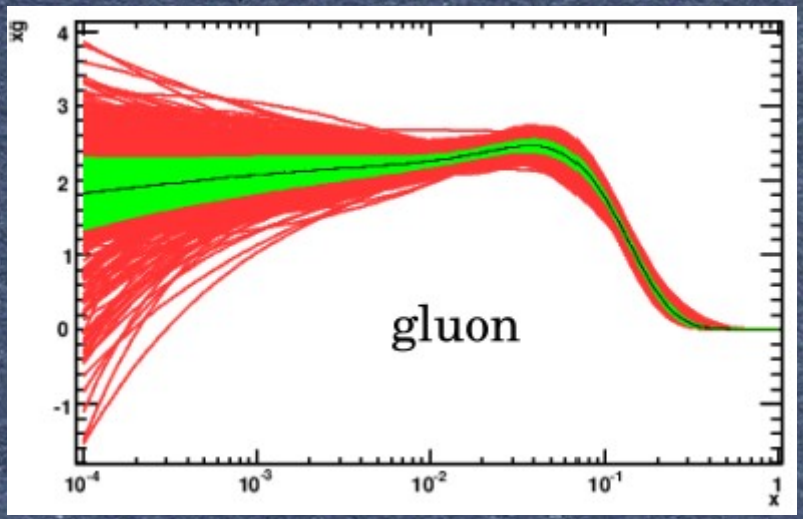
QCD Analysis Details

arXiv:1404.4234

QCD fit to inclusive HERA I data using HERAFitter
+ additional constraints and model assumptions (HF scheme, quark masses, etc.)

MC replica method used to preserve the correlations:

- ~1300 MC replicas are created by fluctuating input data within its uncertainties
- consistent PDF fit to each replica in different orders
- central PDF set corresponds to the average over replicas
- PDF uncertainty is the RMS of the replicas
- additional uncertainties on model and parametrisation, following HERAPDF prescription. Those are treated correlated between the orders.



Predictions vs Data

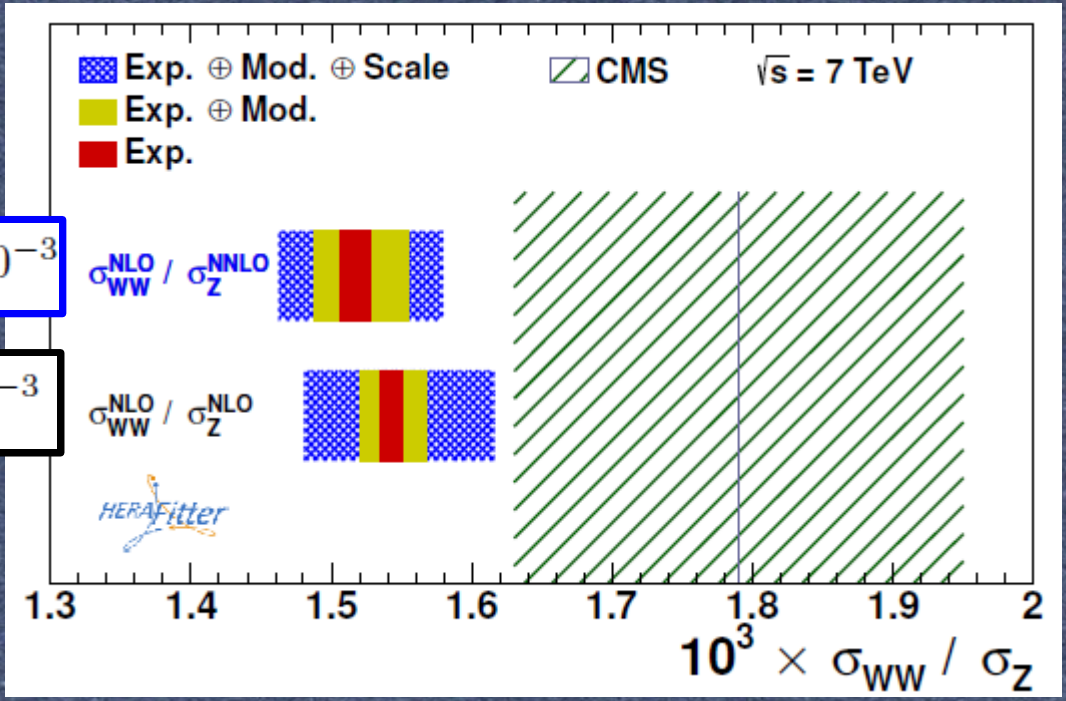
arXiv:1404.4234

- Predictions of the ratio WW to Z production cross sections are compared to the CMS measurement *(EPJC 73 (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

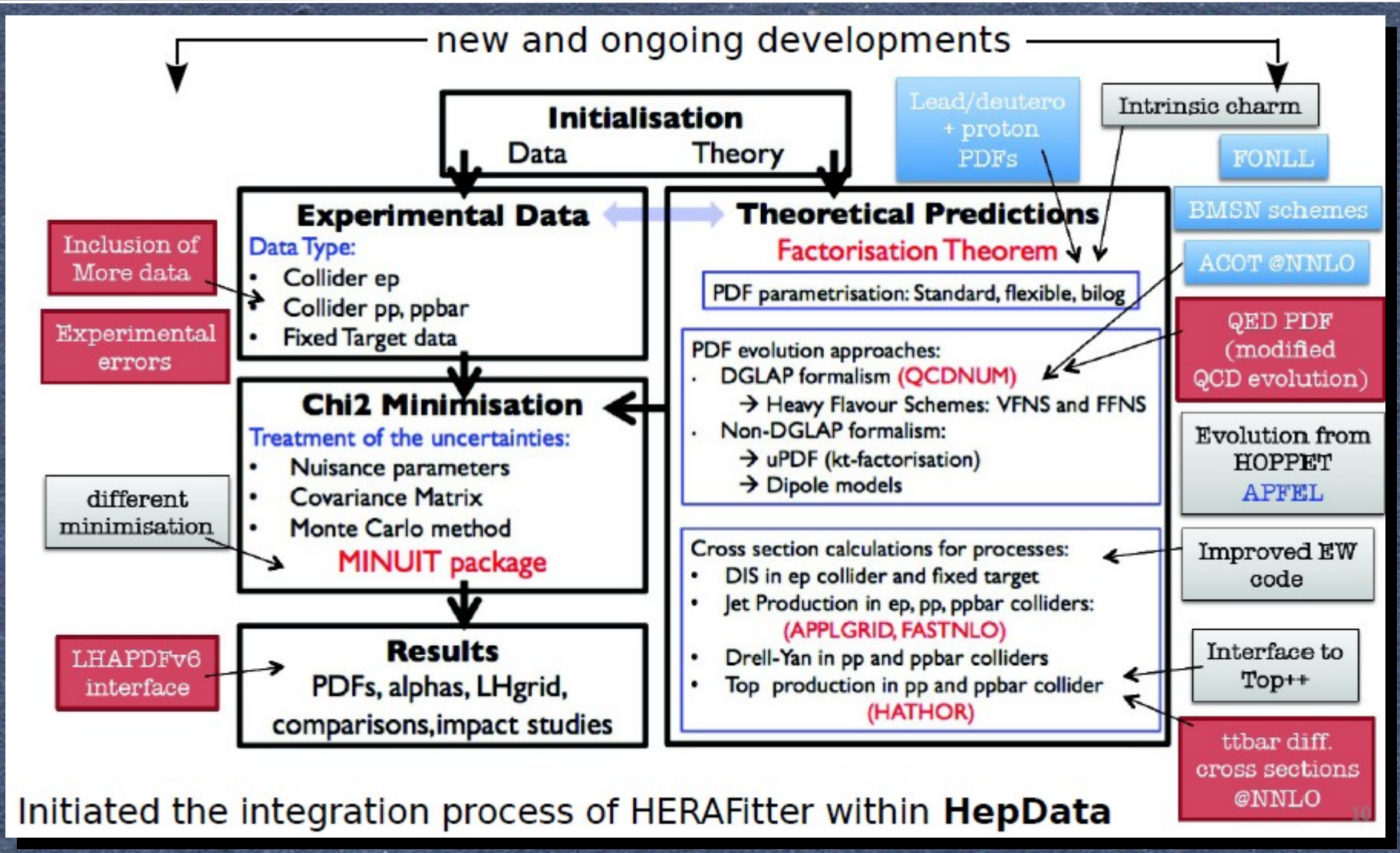
$$\sigma_{WW}^{\mathrm{NLO}}/\sigma_{Z}^{\mathrm{NNLO}} = [1.517^{+0.051}_{-0.047}] \times 10^{-3}$$

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

the total theoretical uncertainty is reduced by 30-40%



Future Developments



- Stable release available since winter → new release is expected in autumn
- A PDF school and workshop is planned at DESY: *http://indico.desy.de/conferenceDisplay.py?ovw=True&confId=9388*

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

  ➔ Open to everyone and everyone can contribute.
  ➔ Stable release: herafitter1.0.0, can be found at *www.herafitter.org*

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

  ➔ the total theoretical uncertainty is reduced for the mixed-order calculation by 30-40% due to reduced scale uncertainties