PRC 78 @ DESY, Zeuthen Oct 16, 2014

HERAFitter Project

Open Source QCD Fit framework

Voica Radescu
on behalf of the HERAFitter team

Legacy of DESY:

- Role of DESY (wikipedia):

DESY's function is to conduct fundamental research. It specializes in:

- **Particle accelerator** development, construction and operation.
- **Particle physics** research to explore the fundamental characteristics of matter and forces, including astroparticle physics
- **Photon science** research in surface physics, material science, chemistry, molecular biology, geophysics and medicine through the use of synchrotron radiation and free electron lasers

- **On 1st of January 1964 fundamental research at DESY has started:**
  - The first electrons were accelerated in the synchrotron and brought valuable contribution to the validation of Quantum ElectroDynamics.
  - **DORIS** (Doppel-Ring-Speicher, "double-ring storage"), built between 1969 and 1974:
    - an important contribution to the process of proving the existence of heavy quarks (ARGUS: beauty + first indication of heavy top mass)
  - **PETRA** (Positron-Elektron-Tandem-Ring-Anlage), built between 1975 and 1978:
    - The discovery of the gluon in 1979 is counted as one of the biggest successes.
  - **HERA** (Hadron-Elektron-Ring-Anlage, "Hadron Electron Ring Facility"), start built 1984
    - the first two experiments started taking data in 1992.
    - mainly used to study the structure of protons and the properties of quarks
    - crucial input for the recent discovery of the Higgs at the LHC

—> DESY represents an ideal site to continue the fundamental research on proton structure

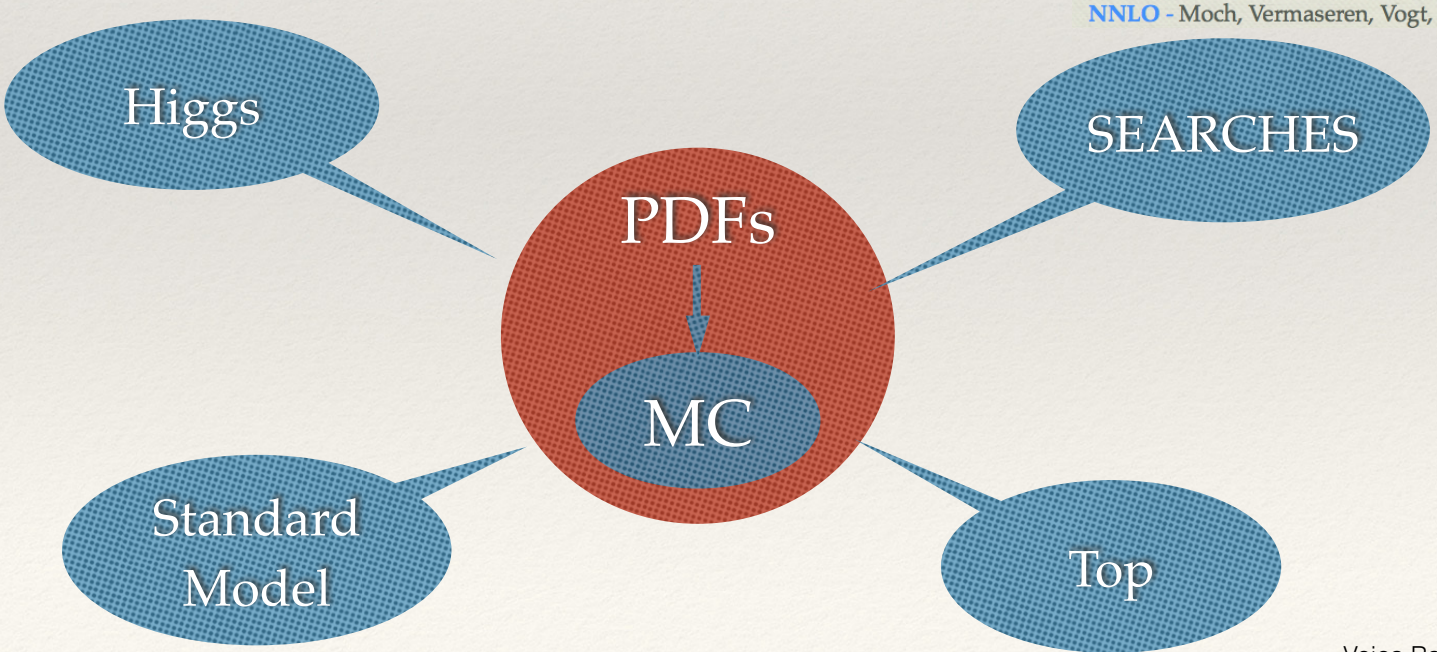
Why do we still need to care about PDFs?

- Discovery of new exciting physics relies on precise knowledge of proton structure.
- **Factorisation theorem:**
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with Parton Distribution Functions (PDFs):

$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD:

LO - Dokshitzer; Gribov, Lipatov; Altarelli, Parisi, 1977
NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, 1981
NNLO - Moch, Vermaseren, Vogt, 2004



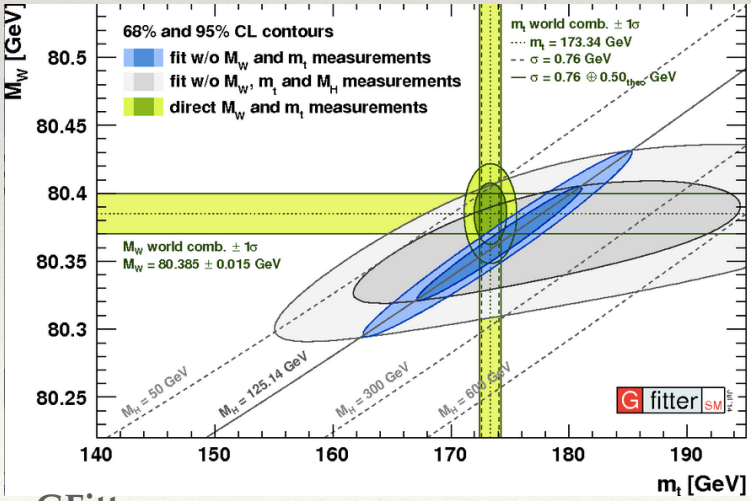
Why do we still need to care about PDFs?

- Discovery of new exciting physics relies on precise knowledge of proton structure.
- **Factorisation theorem:**
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with Parton Distribution Functions (PDFs):

$$\mathrm{d}\sigma(\mathrm{h_1 h_2} \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h_1}}(x_1, \mu_F^2) f_{b/\mathrm{h_2}}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

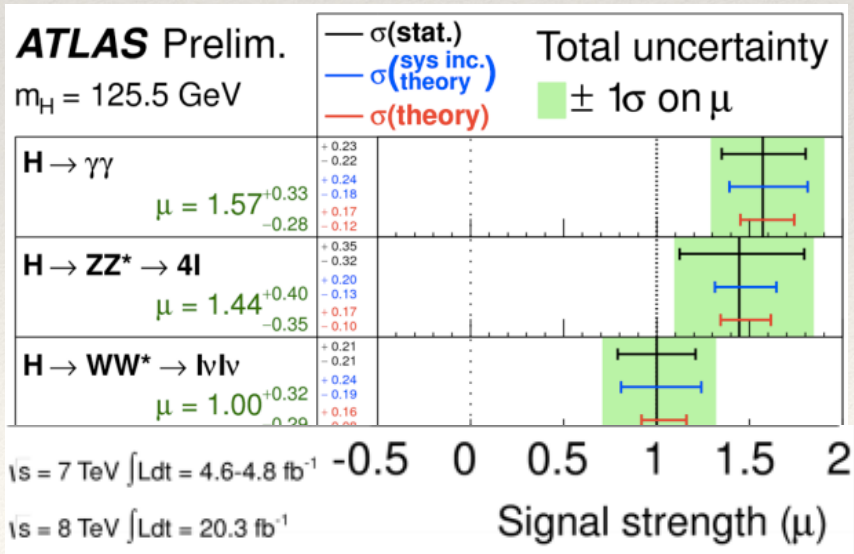
  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD

- PDFs are one of the main theory uncertainties in Mw measurement
- PDFs are one of main theory uncertainties in Higgs production.



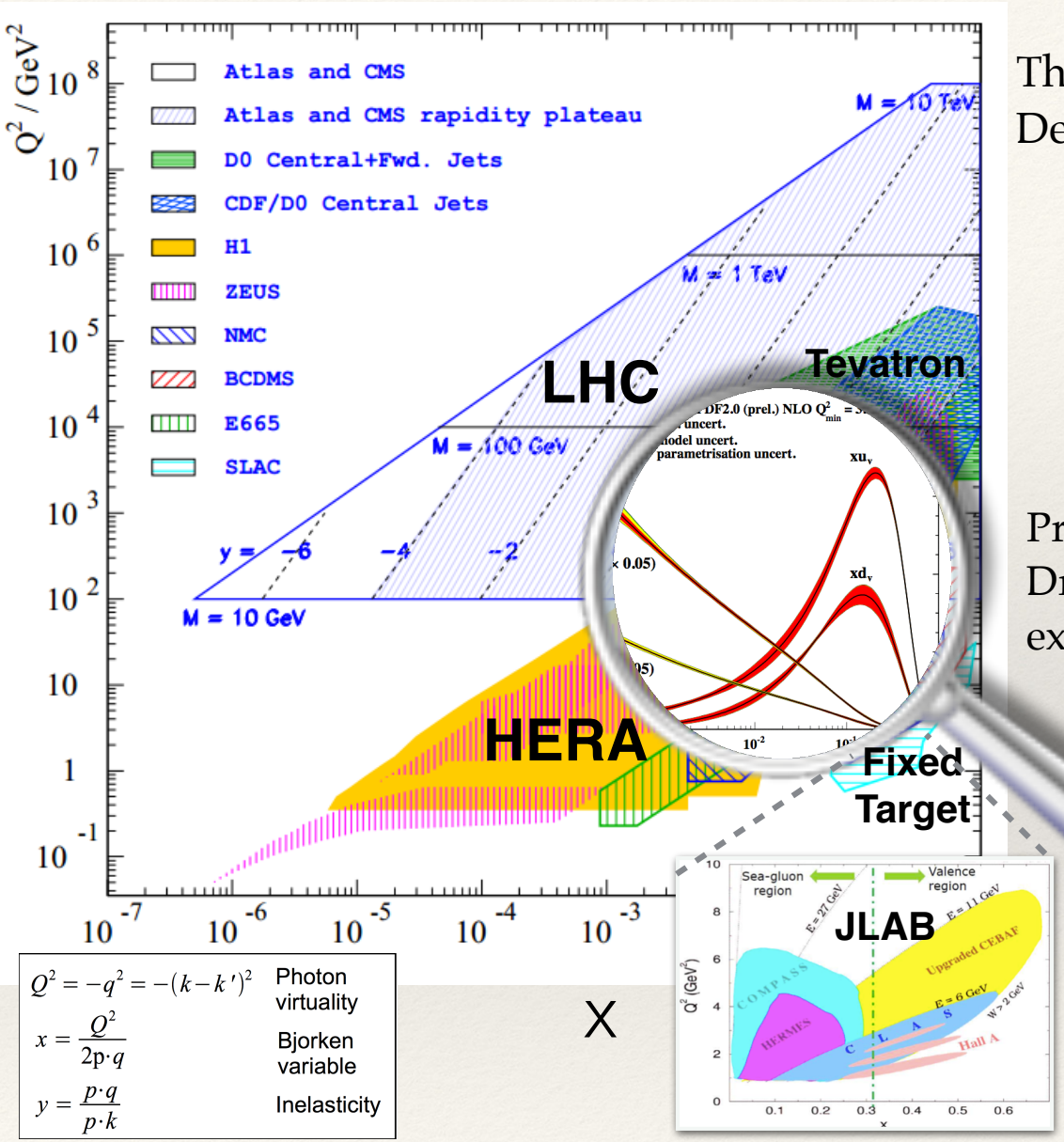
GFitter

ATLAS-CONF-2014-009



Theory:
~ 7-8 % PDF and αs ;
~ 7-8 % scale

Proton Structure Measurements



$$Q^2 = -q^2 = -(k-k')^2$$ Photon virtuality

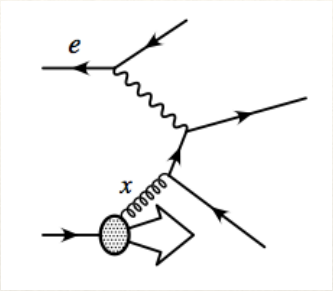
$$x = \frac{Q^2}{2p\cdot q}$$ Bjorken variable

$$y = \frac{p\cdot q}{p\cdot k}$$ Inelasticity

X

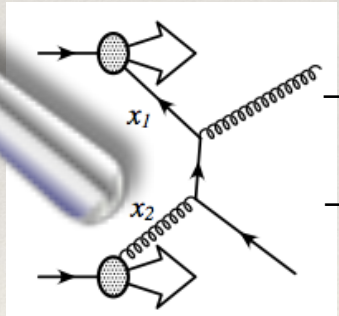
The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:

- Neutrinos, muons, electrons



—> probes linear combination of quarks

Precision of PDFs can be complemented by the Drell Yan [DY] processes at the collider experiments - [Tevatron and LHC]



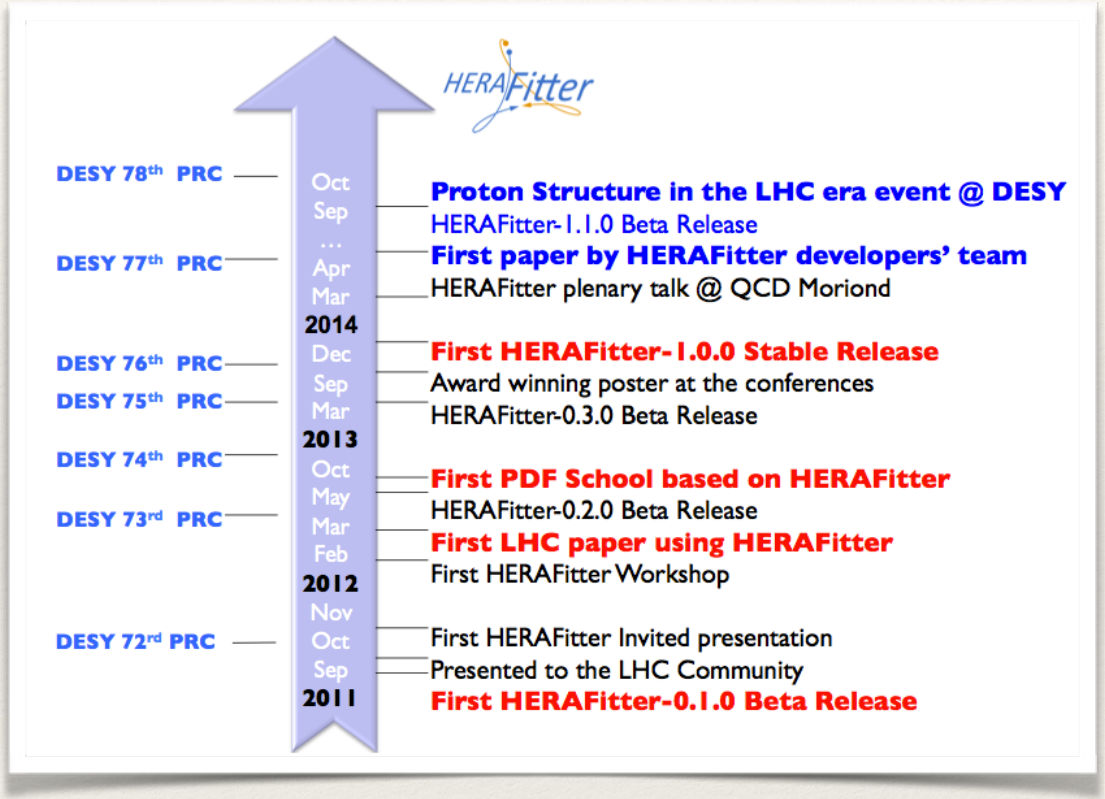
—> can provide flavour separation and more insight into gluons

—> probes bilinear combination of quarks

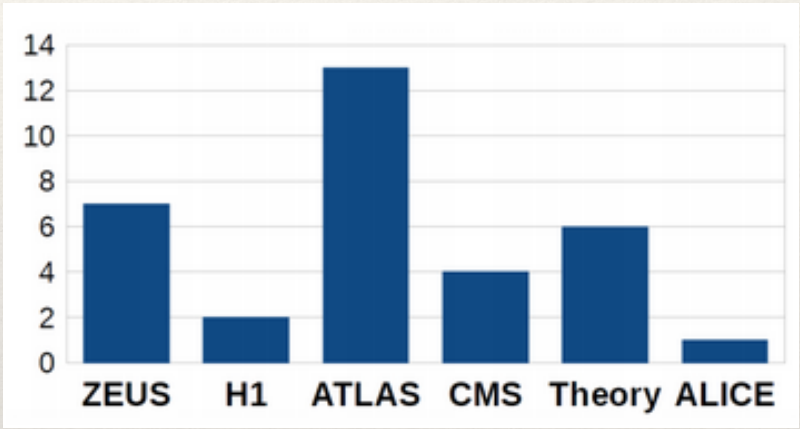
Different data constrain different parton combinations at different x, evolution with the scale is predicted by pQCD:

HERAFitter Project: www.herafitter.org

- HERAFitter Project was initiated in 2011 (presented from its early stages at the DESY PRC) as a necessity to transfer the legacy and expertise on proton structure from HERA to LHC:
  - a unique open source QCD Fit Platform:



Pool of HERAFitter developers:



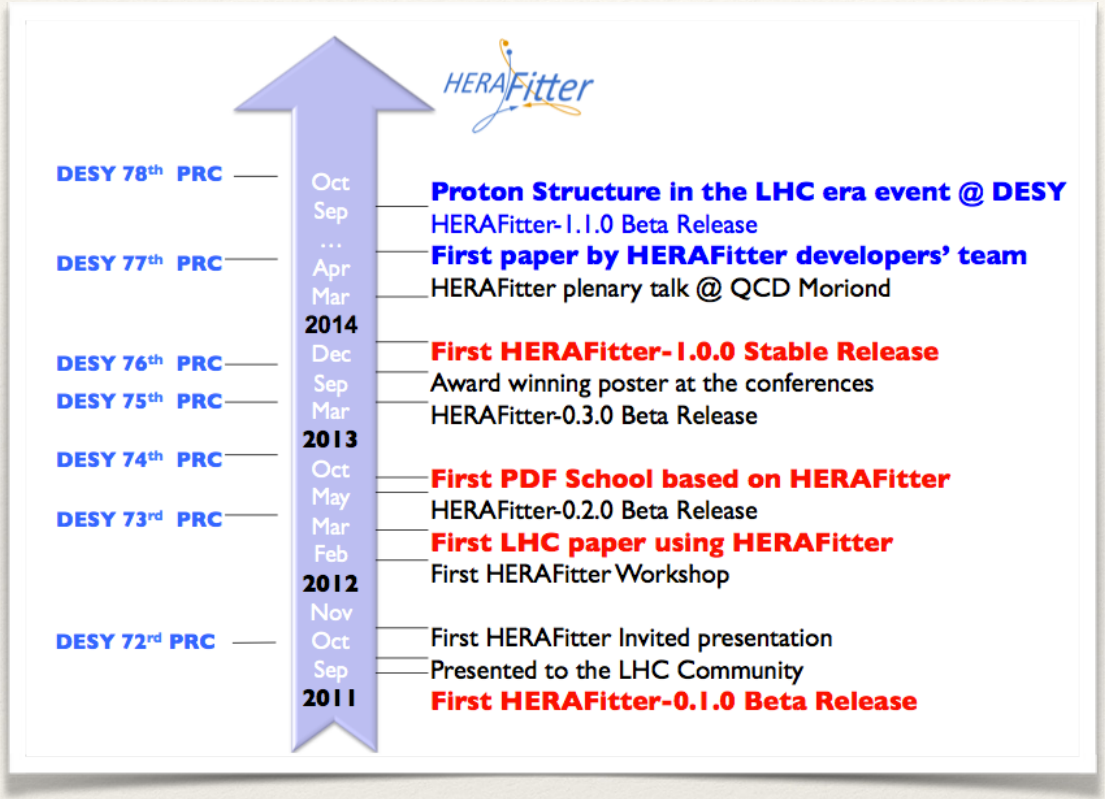
Originally from the H1 and ZEUS collaborations and now extended to the LHC experiments and theory groups:

DESY plays a leading role

- **HERAFitter:**
  - provides a unique QCD framework to address theoretical differences
  - provides means to the experimentalists to optimise the measurement and assess impact/consistency of new data

HERAFitter Project: www.herafitter.org

- HERAFitter Project was initiated in 2011 (presented from its early stages at the DESY PRC) as a necessity to transfer the legacy and expertise on proton structure from HERA to LHC:
  - a unique open source QCD Fit Platform:



List of releases:

Date	Version	Files
09/2014	**1.1.0**	herafitter-1.1.0.tgz
12/2013	1.0.0	herafitter-1.0.0.tgz
06/2013	0.3.1	herafitter-0.3.1.tgz
03/2013	0.3.0	herafitter-0.3.0.tgz
07/2012	0.2.1	herafitter-0.2.1.tgz
05/2012	0.2.0	herafitter-0.2.0.tgz
09/2011	0.1.0	herafitter-0.1.0.tgz

- Versioning convention: **i.j.k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.

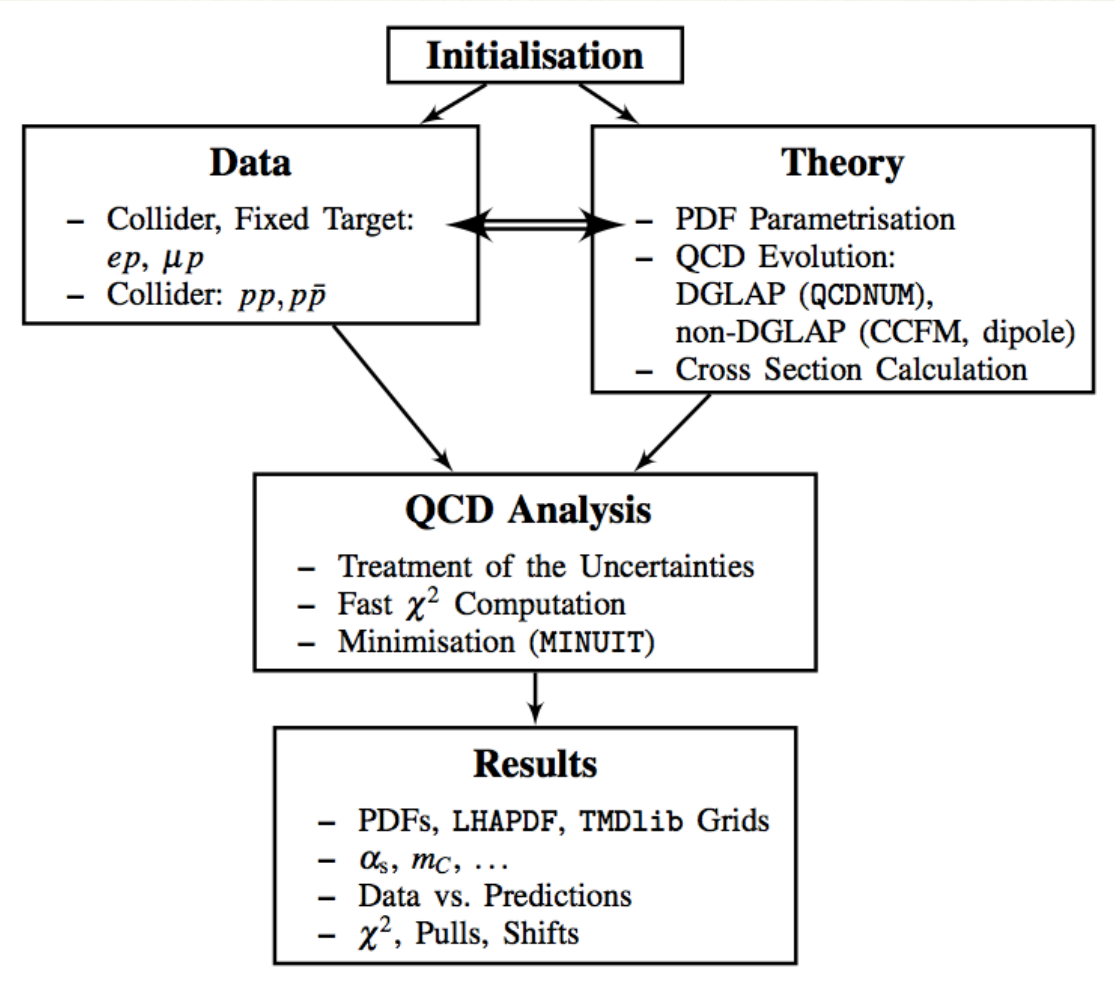
- **HERAFitter:**
  - provides a unique QCD framework to address theoretical differences
  - provides means to the experimentalists to optimise the measurement and assess impact/consistency of new data

Extraction of PDFs through QCD fits

Measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, they follow normal distribution which allows the use of chi square minimisation for PDF extraction.

Main Steps:

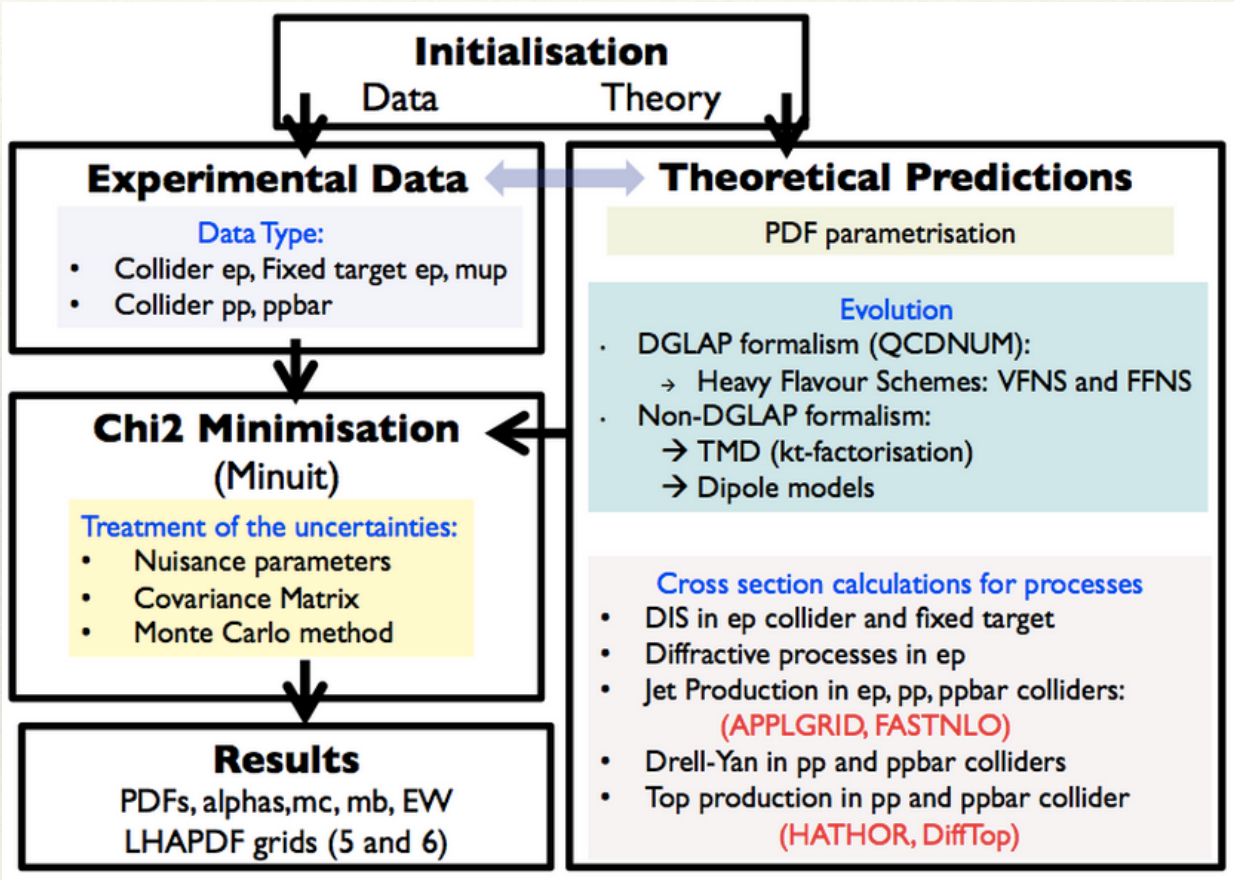
- Parametrise PDFs at the starting scale
- Evolve to the scale corresponding to data point
- Calculate the cross section
- Compare with data via chi2
- Minimize chi2 with respect to PDF parameters



HERAFitter Program at glance

- HERAFitter code is a combination of C++ and Fortran 77 libraries with minimal dependencies and modular structure with interface to external packages:
  - QCDNUM, APPLGRID, FASTNLO, ACOT, TR', OPENQCDRAD, TMD, HATHOR

Experimental Data	Process	Reaction	Theory schemes calculations
HERA, Fixed Target	DIS NC	$ep \to eX$ $\mu p \to \mu X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM), TMD (uPDFevolv)
HERA	DIS CC	$ep \to \nu_e X$	ACOT, ZM (QCDNUM), FFN (OPENQCDRAD)
	DIS jets	$ep \to e$ jets$X$	NLOJet++ (fastNLO)
	DIS heavy quarks	$ep \to ec\bar{c}X$, $ep \to eb\bar{b}X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM)
Tevatron, LHC	Drell-Yan	$pp(\bar{p}) \to l\bar{l}X$, $pp(\bar{p}) \to l\nu X$	MCFM (APPLGRID)
	top pair	$pp(\bar{p}) \to t\bar{t}X$	MCFM (APPLGRID), HATHOR, DiffTop
	single top	$pp(\bar{p}) \to tl\nu X$, $pp(\bar{p}) \to tX$, $pp(\bar{p}) \to tWX$	MCFM (APPLGRID)
	jets	$pp(\bar{p}) \to$ jets$X$	NLOJet++ (APPLGRID), NLOJet++ (fastNLO)
LHC	DY heavy quarks	$pp \to VhX$	MCFM (APPLGRID)



New Results from HERAFitter (2014)

- Research activities in HERAFitter are steered by demands of the users
- In 2014, HERAFitter has been used in ~11 publications (~21 overall):

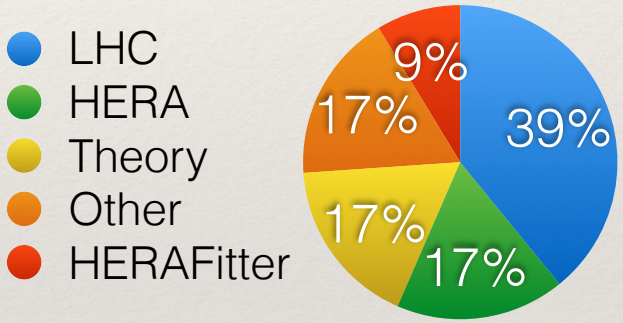
List of analyses by HERAFitter

NEW 10.2014	**HERAFitter team**	arXiv:1410.XXXX	HERAFitter Open Source QCD Fit Project	
NEW 04.2014	**HERAFitter team** ✔	EPJC (2014) 74: 3039, 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 09.2014	LHC/ATLAS ✔	arxiv:1406.7844	Comprehensive measurements of t-channel single top-quark production cross sections at s√=7 TeV with the ATLAS detector
NEW 09.2014	M.Guzzi, K.Lipka, S-O.Moch	arxiv:1406.0386	Top-quark pair production at hadron colliders: differential cross section and phenomenological applications with DiffTop
NEW 08.2014	PROSA	preliminary	Impact of the LHCb measurements of forward charm and beauty production on PDFs
NEW 08.2014	LHC/CMS ✔	PRD 90 (2014) 032004 / arXiv:1312.6283	Measurement of the muon charge asymmetry in pp W production at 7 TeV
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
04.2014	HERA ✔	preliminary	HERAPDF2.0
04.2014	LHC/ATLAS ✔	JHEP 06 (2014) 112, 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	JHEP05(2014)068, 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 ✔	Nucl. Phys. B 883, 1, PLBv736:293, 2014, arXiv:1312.7875	Transverse momentum dependent gluon density from DIS precision data

Overall distribution:
(of all publications)



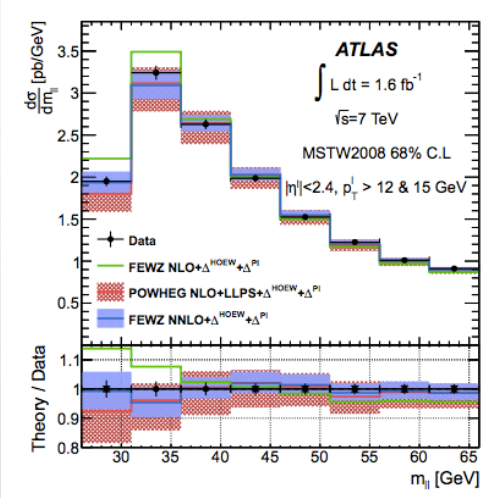
- New, herafitter-1.1.0, package was recently released

Quantitative assessment

- HERAFitter program can be used with external predictions (i.e. not built-in) to quantify the level of agreement when confronting theory with measurements, taking into account all sources of provided uncertainties (either exp. or th. like PDFs, scale)
- **Applied recent examples:**
  - Low Mass DY (ATLAS) data [arXiv:1404.1212]

Prediction	χ^2 (8 points) Nominal
POWHEG NLO+LLPS	22.4 (19.8)
FEWZ NLO	48.7 (28.6)
FEWZ NNLO	13.9 (12.9)

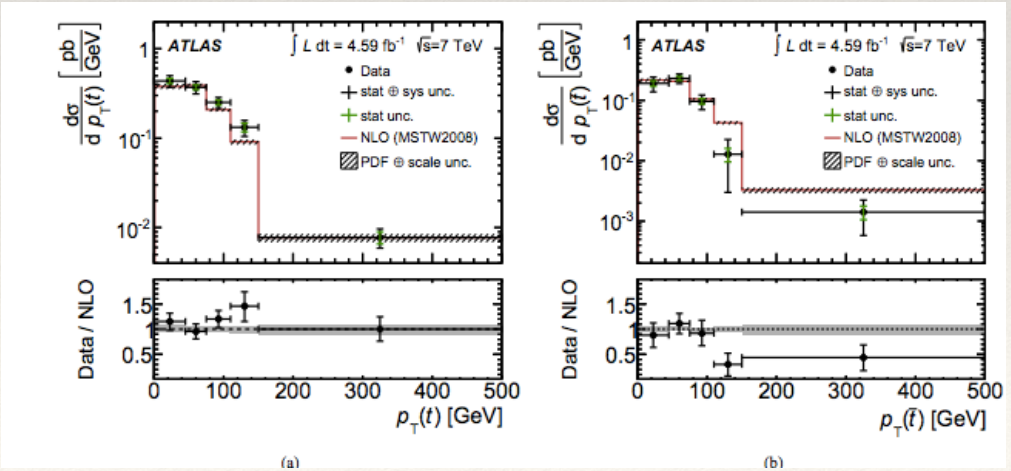
—> conclusion NNLO is needed to describe data



- t-channel single top-quark production cross sections (ATLAS) [arXiv:1406.7844]

TABLE VIII. Comparison between the measured differential cross sections and the predictions from the NLO calculation using the MSTW2008 PDF set. For each variable and prediction a χ^2 value is calculated with HERAfitter using the covariance matrix of each measured spectrum. The theory uncertainties of the predictions are treated as uncorrelated. The number of degrees of freedom (NDF) is equal to the number of bins in the measured spectrum.

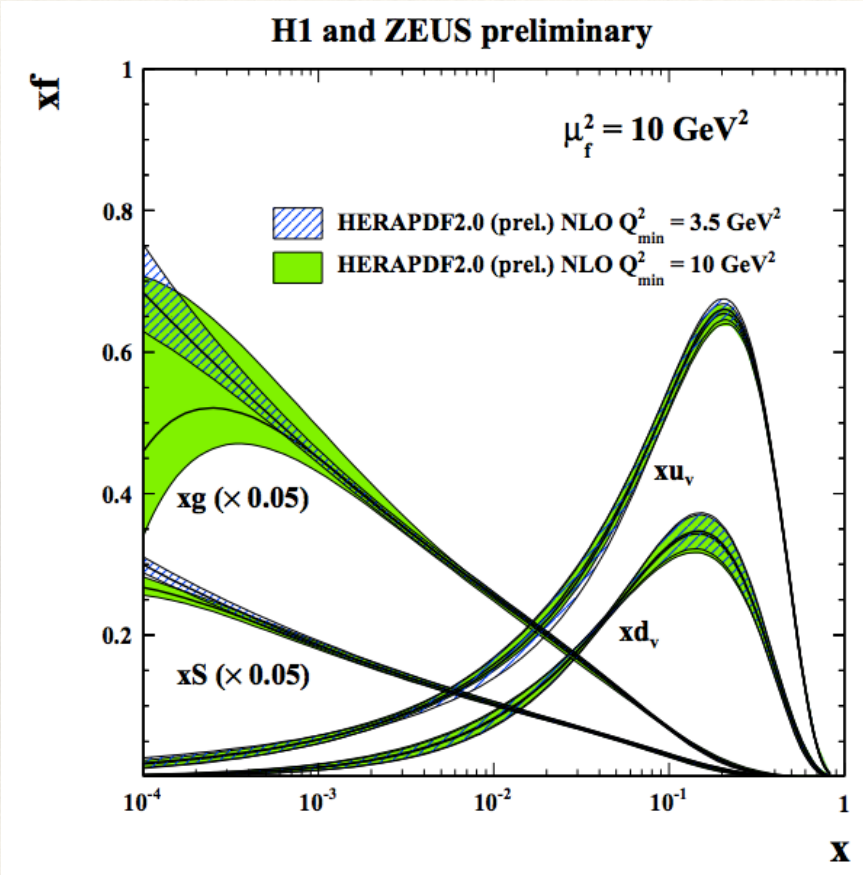
	$\frac{d\sigma}{dp_T(t)}$	$\frac{d\sigma}{dp_T(\bar{t})}$	$\frac{d\sigma}{d\lvert y(t)\rvert}$	$\frac{d\sigma}{d\lvert y(\bar{t})\rvert}$
χ^2/NDF	7.55/5	4.68/5	6.30/4	0.32/4

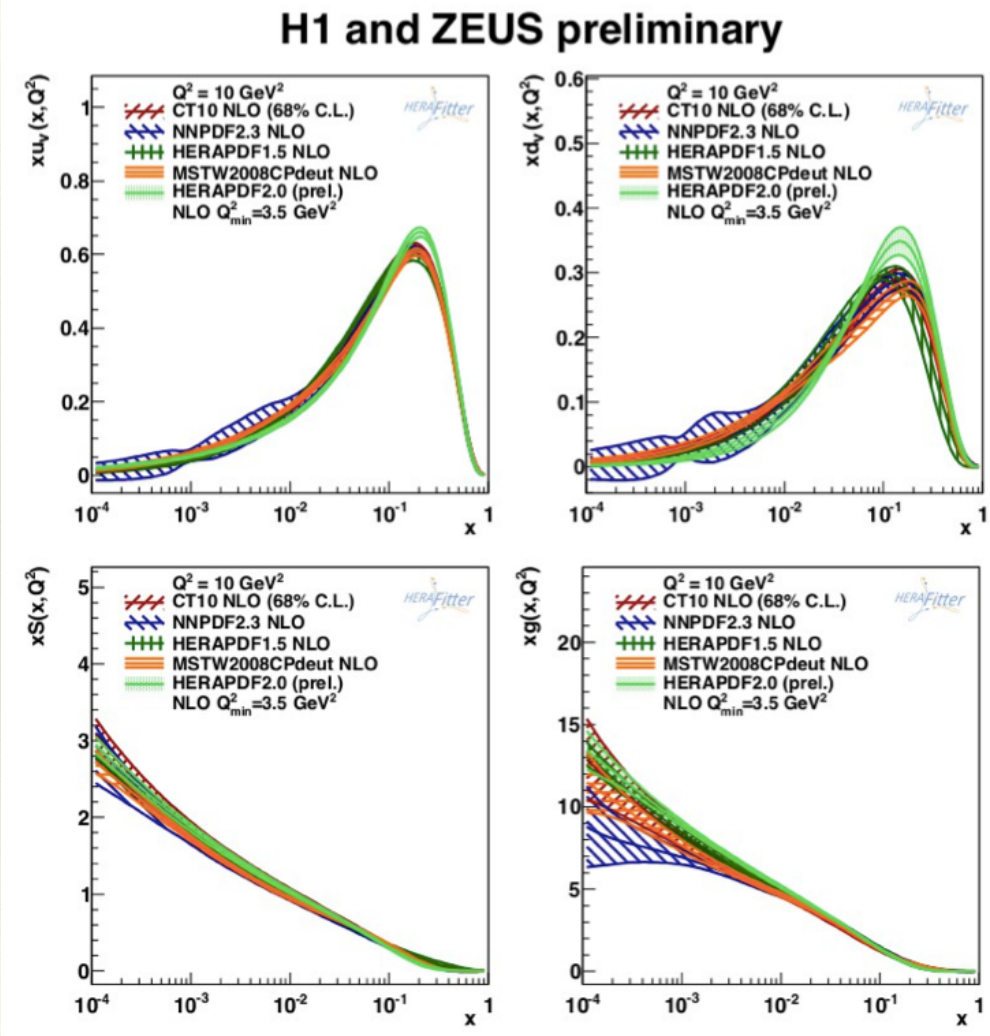


HERAPDF2.0prel with HERAFitter

HERA has finalised its separate measurements relevant to PDFs and there are ongoing efforts on combining final measurements to reach their ultimate precision:

- HERAFitter is used to extract PDFs, mc, mb, alphas …

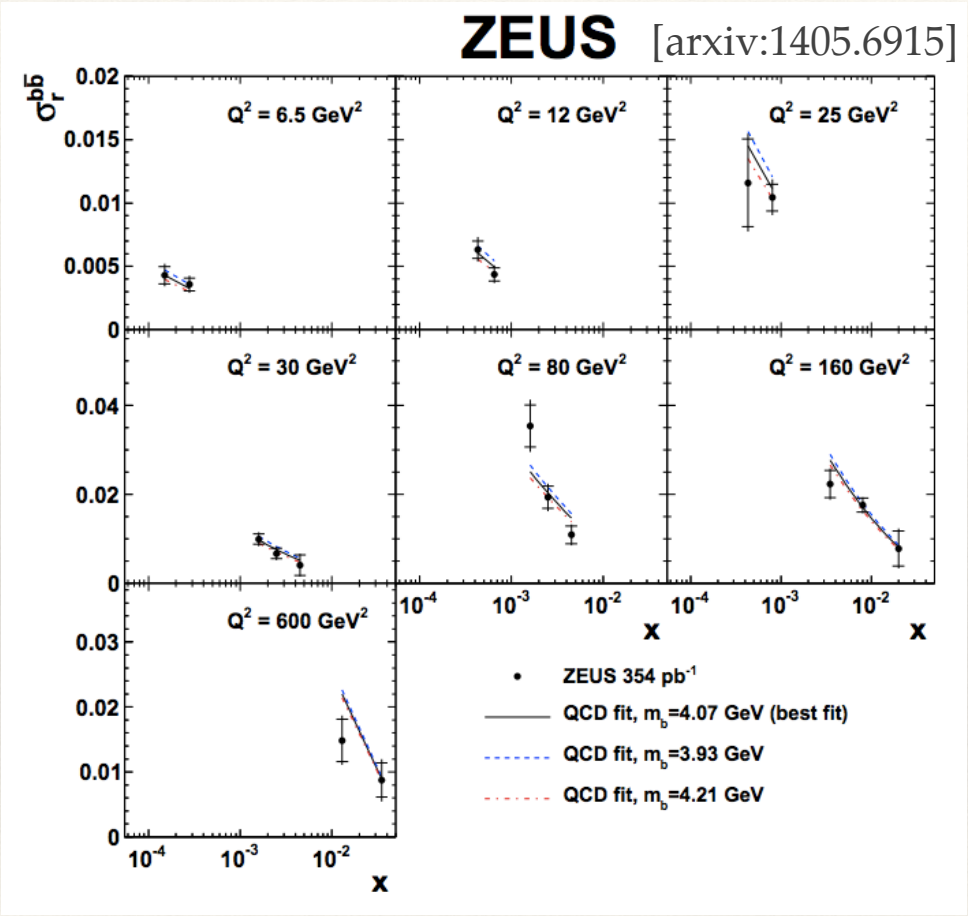




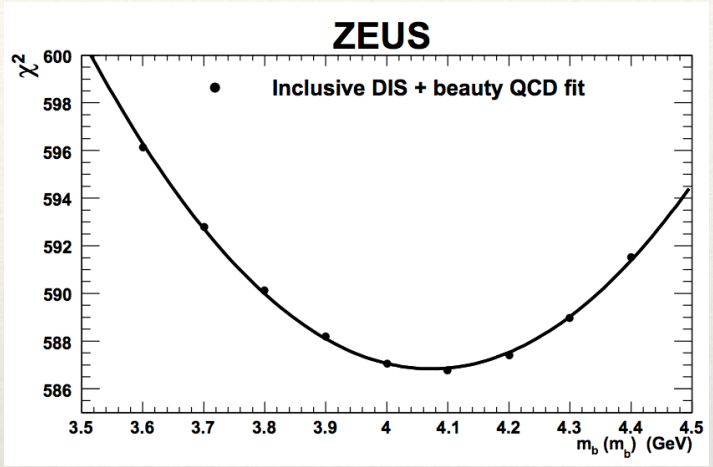
[see H. Pirumov's talk]

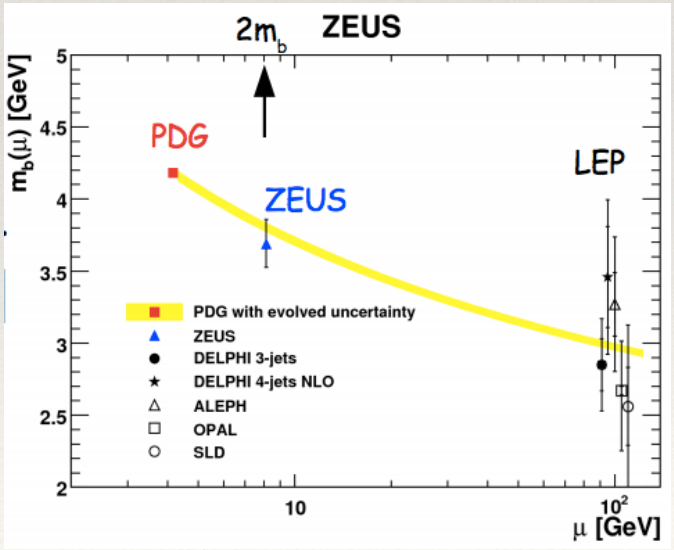
Running beauty mass from F2b

- The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.



QCD Fits
HERA I+beauty





The extracted $\overline{\text{MS}}$ beauty-quark mass is in agreement with PDG average and LEP results.

Transverse Momentum Distributions

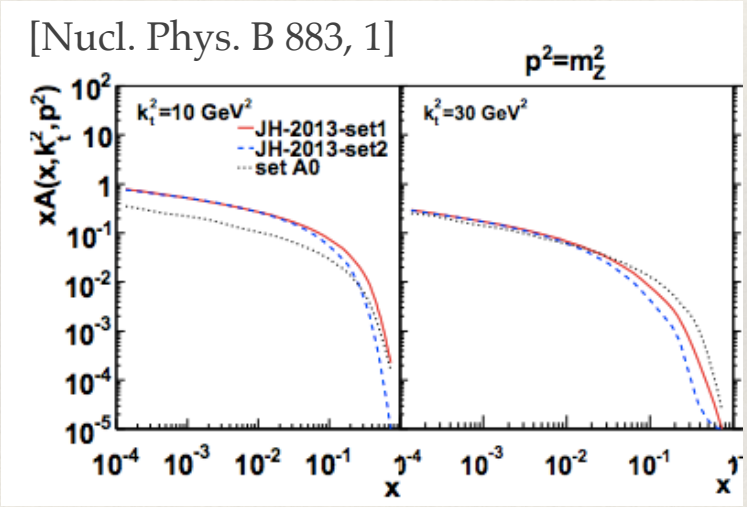
- QCD applications to multiple-scale scattering problems and complex final-state observables require in general formulations of factorisation which involve transverse-momentum dependent (TMD) - or known also as unintegrated PDFs.

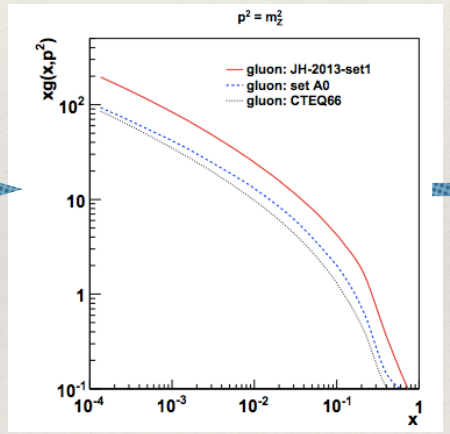
$$\sigma_j(x, Q^2) = \int_x^1 dz \int d^2k_t \; \hat{\sigma}_j(x, Q^2, z, k_t) \; \mathcal{A}(z, k_t, \mu)$$

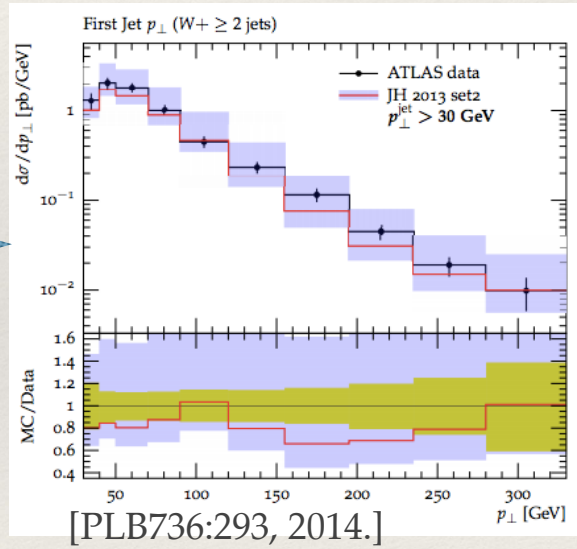
→ a convolution in both longitudinal and transverse momenta of TMD with off-shell partonic matrix elements

- Fits to combined measurements of proton's structure functions from HERA using transverse momentum dependent QCD factorisation and CCFM evolution is performed using HERAFitter platform

[Nucl. Phys. B 883, 1]





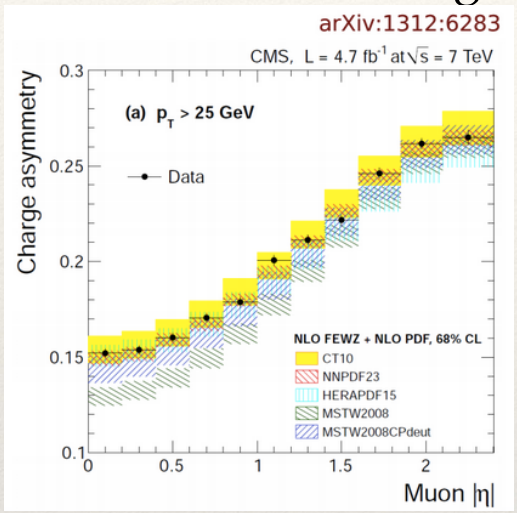


[PLB736:293, 2014.]

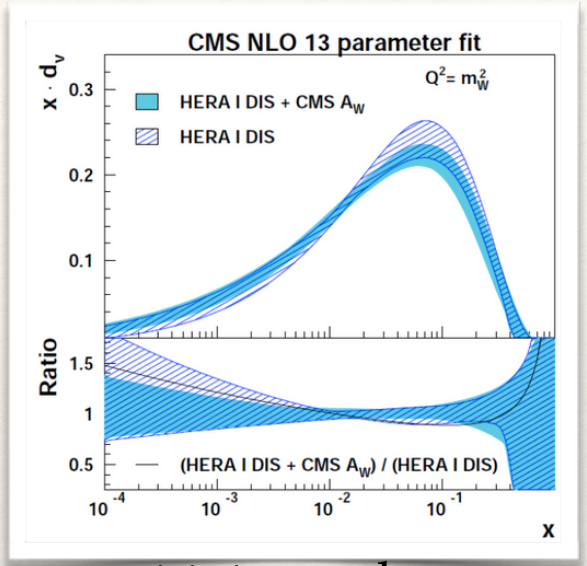
- The extracted gluon TMD with experimental and theory uncertainty [JH-2013-set1] is then used as prediction to vector boson+jet production process at the LHC [Phys. Rev. D 85 (2012) 092002.]
  - This process is important both for SM physics and for new physics searches at the LHC
  - Results compare well with the measurements of jet multiplicities and transverse momentum spectra within the pdf uncertainties

QCD interpretation of W production at CMS

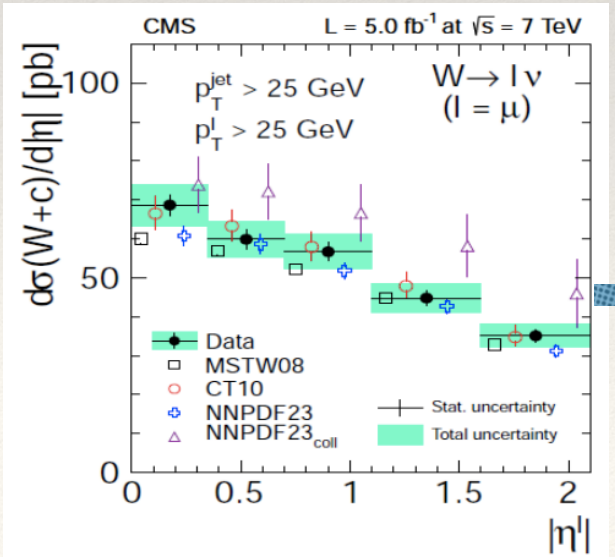
- Impact on valence PDFs from W asymmetry is investigated within the HERAFitter framework through a QCD fit analysis

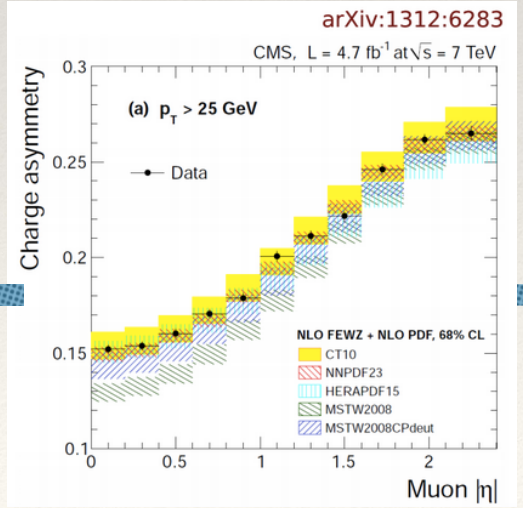


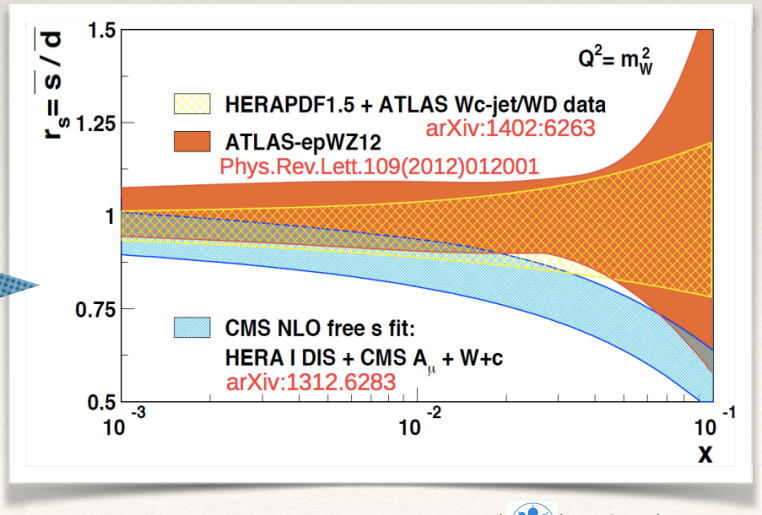
$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$



- In addition, W+charm data provides direct sensitivity to the strange quark







HERAFitter in the ggH benchmark studies

- Efforts in reducing the PDF uncertainties arising from discrepancy between PDF groups:
  - Benchmark comparisons of NNLO neutral current DIS cross sections (Exercise on HERA-I only data)

arxiv:1405.1067

Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

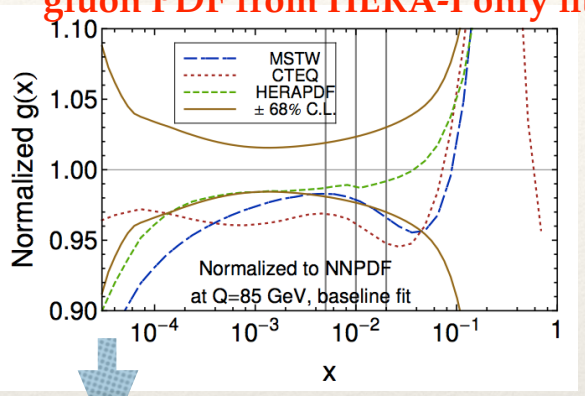
Conveners

Higgs physics: SM issues
D. De Florian (Theory), M. Kado (ATLAS), A. Korytov (CMS),
S. Dittmaier (Electroweak Contact)

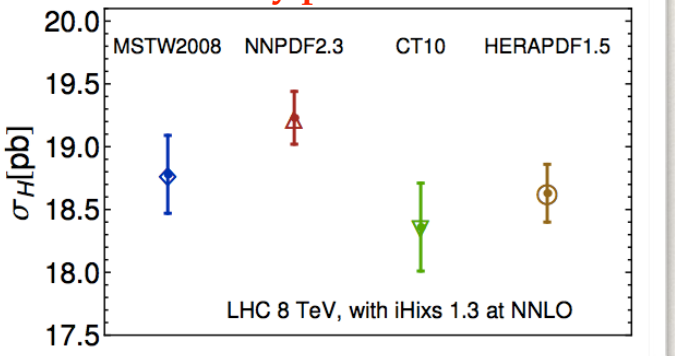
SM: Loops and Multilegs
N. Glover (Theory), J. Huston (ATLAS), G. Dissertori (CMS),
S. Dittmaier (Electroweak Contact)

Tools and Monte Carlos
F. Krauss (Theory), J. Butterworth (ATLAS), K. Hamilton (MC-NLO Contact),
G. Soyez (Jets Contact)

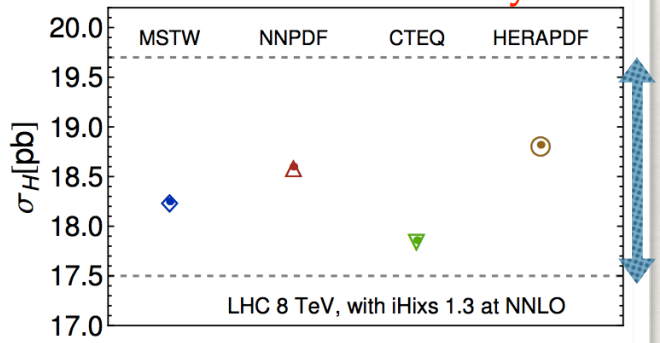
gluon PDF from HERA-I only fits



based on recently published NNLO PDFs.



based on HERA-I only fits



PDF uncert

  - predictions from MSTW, CT, NNPDF and HERAPDF all consistent within PDF uncertainties
  - however the tendency among NNPDF, MSTW and CT is maintained
- **Next step:**
  - continue this exercise by adding additional experimental data sets into the PDF fits sequentially:
  - benchmarking the theoretical predictions used by each group for the different observables -
  - **==> HERAFitter will continue to participate in these studies.**

HERAFitter Paper

Eur. Phys. J. C (2014) 74:3039

- Ratios of cross sections are used to reduce common uncertainties, however the theoretical calculations sometimes are not available at the same order of accuracy in pQCD

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}}{\hat{\sigma}_Y^{NLO} \otimes PDF_{NLO}}$$ PDF uncertainties cancel, large scale uncertainty

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}}$$ improved scale uncertainty, No cancellation of PDF uncertainty

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NNLO}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}}$$ PDF uncertainties cancel, improved scale uncertainty, not clear definition in pQCD

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF^{corr}_{NLO}}{\hat{\sigma}_Y^{NNLO} \otimes PDF^{corr}_{NNLO}}$$ PDF uncertainties cancel, improved scale uncertainty

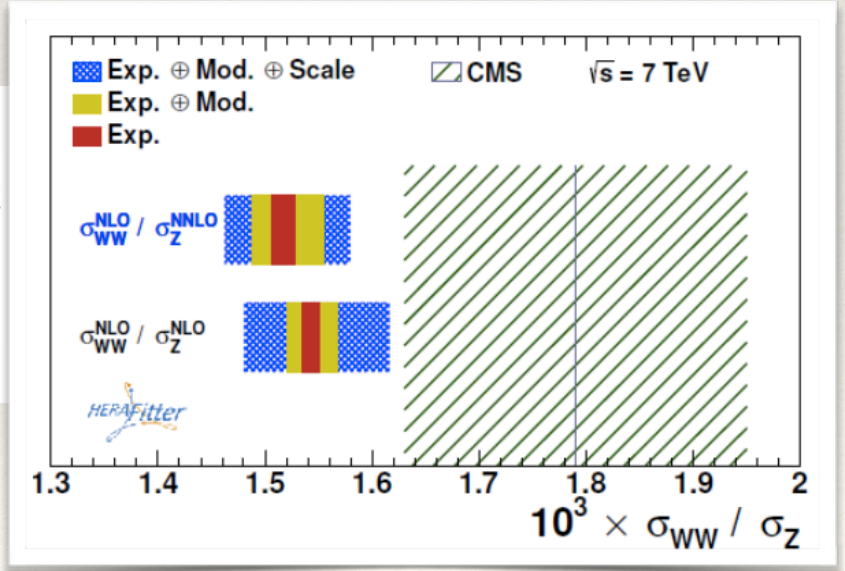
- HERAFitter provides possibility to account for correlations between PDFs at different orders which can lead to reduction of overall theoretical uncertainties:

Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders

HERAFitter developers' team Collaboration (P. Belov , D. Britzger, S. Camarda (DESY) , A.M. Cooper-Sarkar (Oxford U.) , C. Diaconu (Marseille, CPPM) , J. Feltesse (IRFU, Saclay) , A. Gizhko, A. Glazov (DESY) , V. Kolesnikov (Dubna, JINR) , K. Lohwasser (DESY, Zeuthen) , A. Luszczak (AGH-UST, Cracow) , V. Myronenko, H. Pirumov, R. Placakyte (DESY) , K. Rabbertz (Karlsruhe U., EKP) , V. Radescu (DESY) , A. Sapronov (Dubna, JINR) , A. Schönig (Heidelberg U.) , S. Shushkevich (DESY) , W. Slominski (Jagiellonian U.) , P. Starovoitov (DESY) , M. Sutton (Sussex U.) , J. Tomaszewska (Warsaw U. of Tech.) , O. Turkot (DESY) , G. Watt (Durham U., IPPP) , K. Wichmann, M. Lisovyi (DESY)) *Hide*

Apr 16, 2014 - 10 pages

Eur.Phys.J. C74 (2014) 3039
(2014-09-30)
DOI: 10.1140/epjc/s10052-014-3039-4
DESY-2014-054, DESY-14-054
e-Print: arXiv:1404.4234 [hep-ph] | PDF



- mixed-order calculations with correlated PDFs help to reduce PDF and scale uncertainties
  - total theoretical uncertainty is reduced by 30-40%

Summary

- HERAFitter project, with it's main expertise at DESY, is a multi-functional open source QCD software package that provides a framework for scrupulous interpretations of the QCD analyses.

  www.herafitter.org

  herafitter-1.1.0 latest release

- Steady developments which encode results from a wide range of experimental data in ep, pp, ppbar complemented with a variety of theoretical options for calculating PDF-dependent cross section predictions.

- The further progress of HERAFitter is driven by the latest QCD advances in theoretical calculations and in the precision of experimental data.

HERAFitter

Open Source QCD Fit Project

Version 1.0

S. Alekhin[1,2], O. Behnke[3], P. Belov[3,4], S. Borroni[3], M. Botje[5], D. Britzger[3], S. Camarda[3], A.M. Cooper-Sarkar[6], K. Daum[7,8], C. Diaconu[9], J. Feltesse[10], A. Gizhko[3], A. Glazov[3], A. Guffanti[11], M. Guzzi[3], F. Hautmann[12,13,14], A. Jung[15], H. Jung[3,16], V. Kolesnikov[17], H. Kowalski[3], O. Kuprash[3], A. Kusina[18], S. Levonian[3], K. Lipka[3], B. Lobodzinski[19], K. Lohwasser[1,3], A. Luszczak[20], B. Malaescu[21], R. McNulty[22], V. Myronenko[3], S. Naumann-Emme[3], K. Nowak[3,6], F. Olness[18], E. Perez[23], H. Pirumov[3], R. Plačakytė[3], K. Rabbertz[24], V. Radescu[3], R. Sadykov[17], G.P. Salam[25,26], A. Sapronov[17], A. Schöning[27], T. Schörner-Sadenius[3], S. Shushkevich[3], W. Slominski[28], H. Spiesberger[29], P. Starovoitov[3], M. Sutton[30], J. Tomaszewska[31], O. Turkot[3], A. Vargas[3], G. Watt[32], K. Wichmann[3]

[1] Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, D–15738 Zeuthen, Germany
[2] Institute for High Energy Physics,142281 Protvino, Moscow region, Russia
[3] Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
[4] Current address: Department of Physics, St. Petersburg State University, Ulyanovskaya 1, 198504 St. Petersburg, Russia
[5] Nikhef, Science Park, Amsterdam, the Netherlands
[6] Department of Physics, University of Oxford, Oxford, United Kingdom
[7] Fachbereich C, Universität Wuppertal, Wuppertal, Germany
[8] Rechenzentrum, Universität Wuppertal, Wuppertal, Germany
[9] Aix Marseille Universite, CNRS/IN2P3, CPPM UMR 7346, 13288 Marseille, France
[10] CEA, DSM/Irfu, CE-Saclay, Gif-sur-Yvette, France
[11] Niels Bohr Institute, University of Copenhagen, Denmark
[12] School of Physics and Astronomy, University of Southampton, UK
[13] Rutherford Appleton Laboratory, Chilton OX11 0QX, United Kingdom
[14] Dept. of Theoretical Physics, University of Oxford, Oxford OX1 3NP, United Kingdom
[15] FERMILAB, Batavia, IL, 60510, USA
[16] Elementaire Deeltjes Fysica, Universiteit Antwerpen, B 2020 Antwerpen, Belgium
[17] Joint Institute for Nuclear Research (JINR), Joliot-Curie 6, 141980, Dubna, Moscow Region, Russia
[18] Southern Methodist University, Dallas, Texas
[19] Max Planck Institut Für Physik, Werner Heisenberg Institut, Föhringer Ring 6, Mufichen
[20] T. Kosciuszko Cracow University of Technology
[21] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université, Paris-Diderot and CNRS/IN2P3, Paris, France
[22] University College Dublin, Dublin 4, Ireland
[23] CERN, European Organization for Nuclear Research, Geneva, Switzerland
[24] Institut für Experimentelle Kernphysik, Karlsruhe, Germany
[25] CERN, PH-TH, CH-1211 Geneva 23, Switzerland
[26] leave from LPTHE; CNRS UMR 7589; UPMC Univ. Paris 6; Paris 75252, France
[27] Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany
[28] Jagiellonian University, Institute of Physics, Reymonta 4, PL-30-059 Cracow, Poland
[29] PRISMA Cluster of Excellence, Institut für Physik (WA THEP), Johannes-Gutenberg-Universität, D-55099 Mainz, Germany
[30] University of Sussex, Department of Physics and Astronomy, Sussex House, Brighton BN1 9RH, United Kingdom
[31] Warsaw University of Technology, Faculty of Physics, Koszykowa 75, 00-662 Warsaw, Poland
[32] Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, United Kingdom

Received: date / Accepted: date

Abstract HERAFitter is an open-source package that provides a framework for the determination of the parton distribution functions (PDFs) of the proton and for many different kinds of analyses in Quantum Chromodynamics (QCD). It encodes results from a wide range of experimental measurements in lepton-proton deep inelastic scattering and proton-proton (proton-antiproton) collisions at hadron colliders. Those are complemented with a variety of theoretical options for calculating PDF-dependent cross section predictions corresponding to the measurements. The framework

HERAFitter Program at glance

- HERAFitter code is a combination of C++ and Fortran 77 libraries with minimal dependencies and modular structure with interface to external packages:
  - QCDNUM for evolution of PDFs
- DIS inclusive processes in ep and fixed target
  - Different schemes of heavy quark treatment
    - VFNS, FFNS:
      - OPENQCDRAD (ABM)
      - TR' (MSTW)
      - ACOT (CT)
  - Diffractive PDFs
  - Dipole Models
  - Unintegrated PDFs (TMDs)
- Jet production (ep, pp, ppbar)
  - FastNLO and APPLGRID techniques
- Drell-Yan processes (pp, ppbar)
  - LO calculation x NLO k-factors
  - APPLGRID technique
- Top pair production
  - total inclusive ttbar cross sections (HATHOR)
  - differential (DiffTop approx NNLO via fastNLO grids)

```
--enable-openmp          enable openmp support
--enable-trapFPE         Stop of floating point errors (default=no)
--enable-checkBounds     add -fbounds-check flag for compilation (default=no)
--enable-nnpdfWeight     use NNPDF weighting (default=no)
--enable-lhapdf          use lhapdf (default=no)
--enable-applgrid        use applgrid for fast pdf convolutions (default=no)
--enable-genetic         use genetic for general minimia search (defaults=no)
--enable-hathor          use hathor for ttbar cross section predictions
                         (default=no)
--enable-updf            use uPDF evolution (default=no)
--enable-doc             Build documentation (default=no)
```

Experimental Data	Process	Reaction	Theory schemes calculations
HERA, Fixed Target	DIS NC	$ep \to eX$ $\mu p \to \mu X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM), TMD (uPDFevolv)
HERA	DIS CC	$ep \to \nu_e X$	ACOT, ZM (QCDNUM), FFN (OPENQCDRAD)
	DIS jets	$ep \to e$ jets$X$	NLOJet++ (fastNLO)
	DIS heavy quarks	$ep \to ec\bar{c}X$, $ep \to eb\bar{b}X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM)
Tevatron, LHC	Drell-Yan	$pp(\bar{p}) \to l\bar{l}X$, $pp(\bar{p}) \to l\nu X$	MCFM (APPLGRID)
	top pair	$pp(\bar{p}) \to t\bar{t}X$	MCFM (APPLGRID), HATHOR, DiffTop
	single top	$pp(\bar{p}) \to tl\nu X$, $pp(\bar{p}) \to tX$, $pp(\bar{p}) \to tWX$	MCFM (APPLGRID)
	jets	$pp(\bar{p}) \to$ jets$X$	NLOJet++ (APPLGRID), NLOJet++ (fastNLO)
LHC	DY heavy quarks	$pp \to VhX$	MCFM (APPLGRID)