PDF4LHC - 3.11.2014 - CERN

HERAFitter Project

Open Source QCD Fit framework

Voica Radescu
on behalf of the HERAFitter team

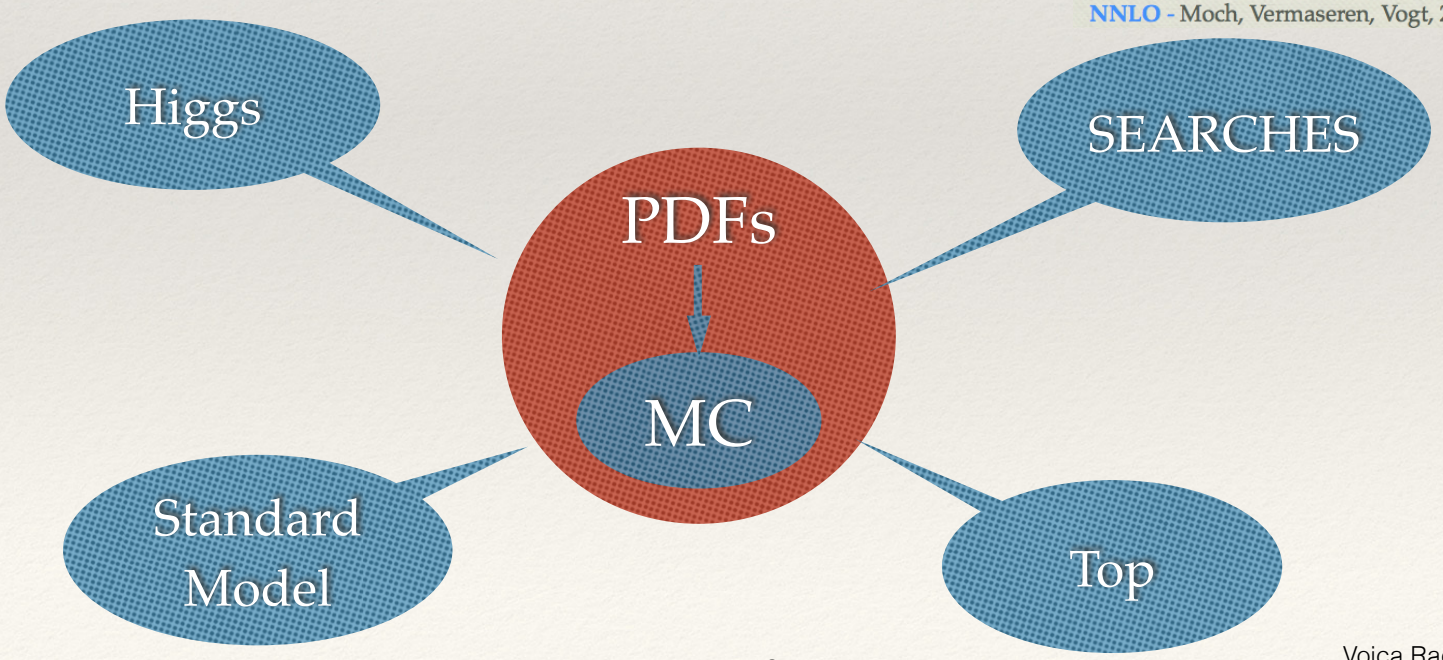
Why do we still need to care about PDFs?

- 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



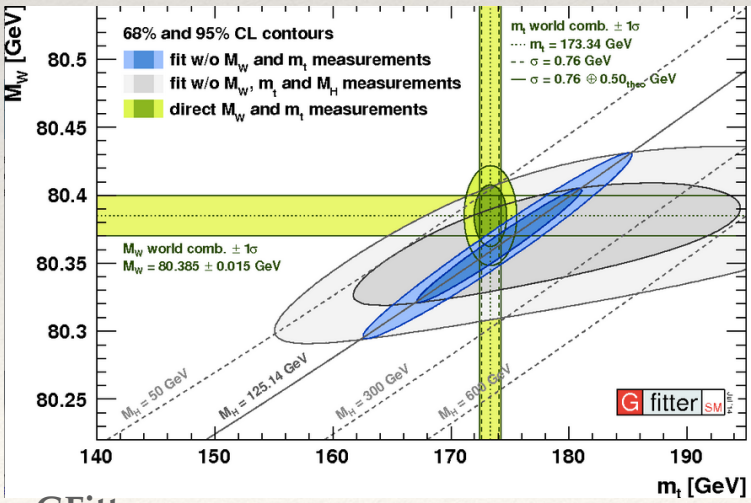
Why do we still need to care about PDFs?

- 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):

$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

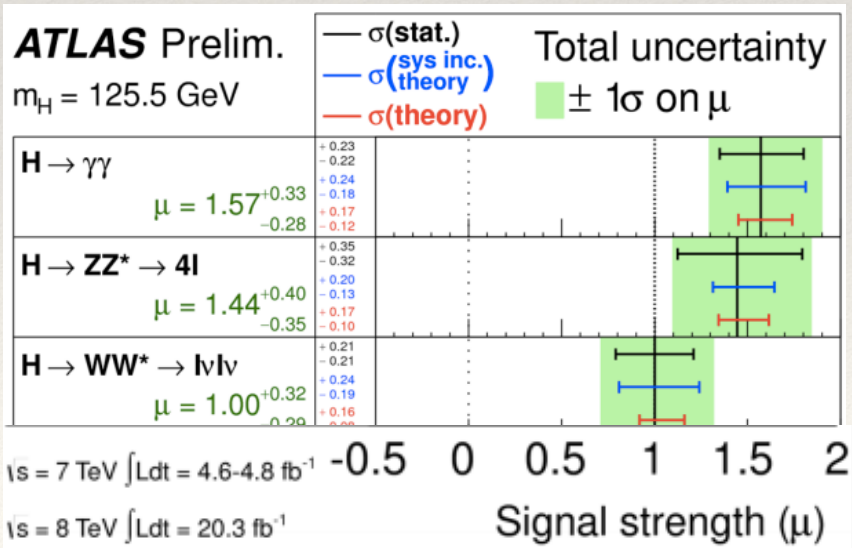
  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD

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



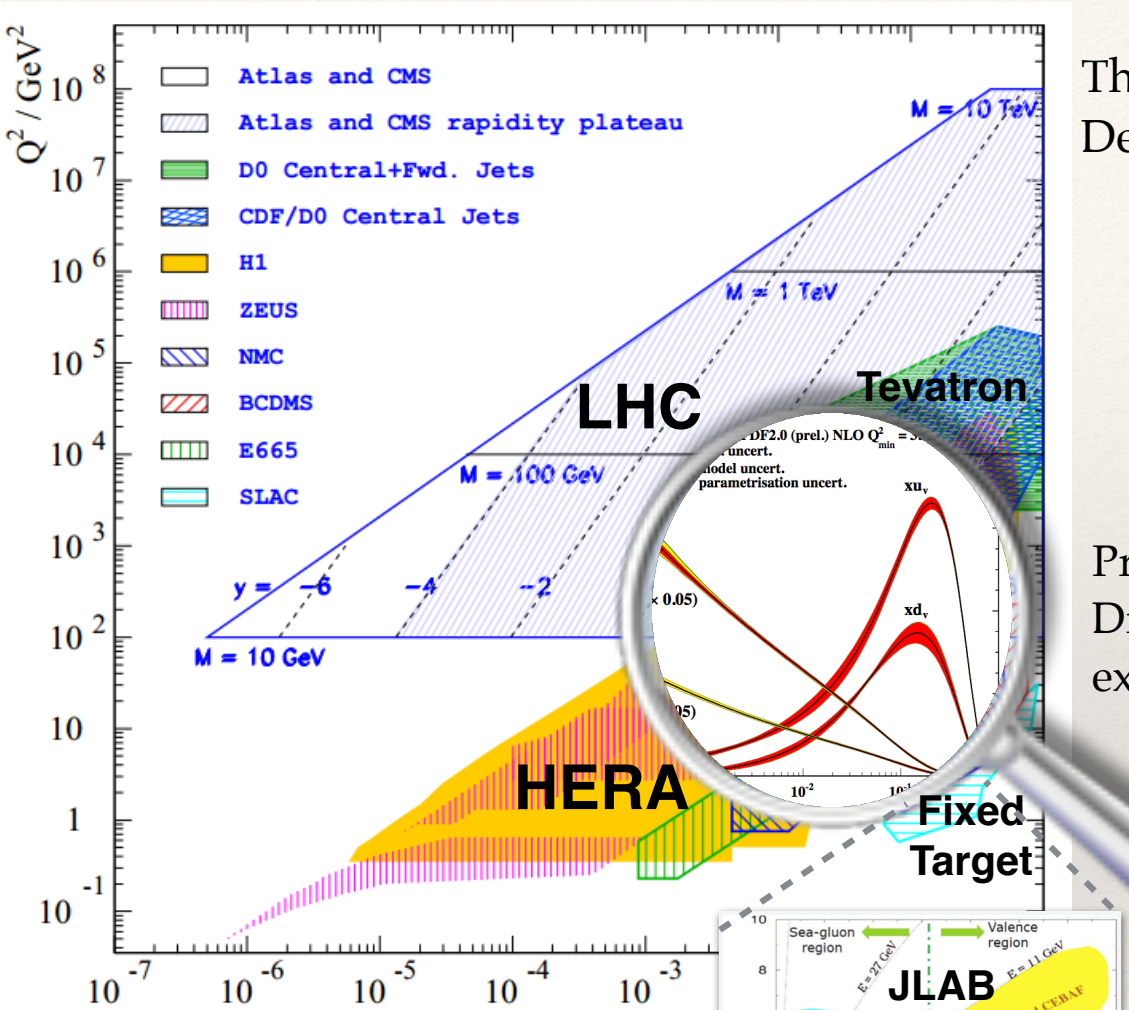
GFitter

ATLAS-CONF-2014-009



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

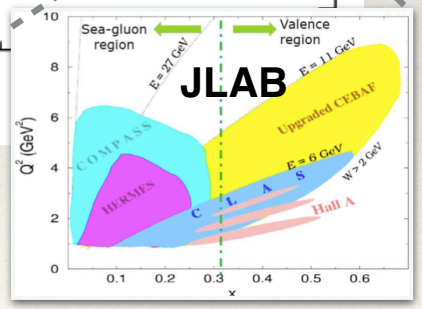
Proton Structure Measurements



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

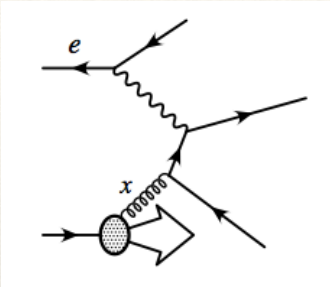
$x = \frac{Q^2}{2p\cdot q}$ Bjorken variable

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



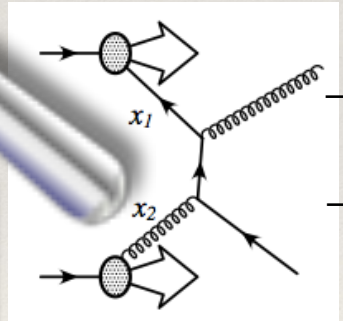
The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:

- 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 as a necessity to transfer the legacy and expertise on proton structure from HERA to LHC:
  - a unique open source QCD Fit Platform:

arXiv.org > hep-ph > arXiv:1410.4412

Search or

High Energy Physics – Phenomenology

HERAFitter, Open Source QCD Fit Project

S. Alekhin, O. Behnke, P. Belov, S. Borroni, M. Botje, D. Britzger, S. Camarda, A.M. Cooper-Sarkar, K. Daum, C. Diaconu, J. Feltesse, A. Gizhko, A. Glazov, A. Guffanti, M. Guzzi, F. Hautmann, A. Jung, H. Jung, V. Kolesnikov, H. Kowalski, O. Kuprash, A. Kusina, S. Levonian, K. Lipka, B. Lobodzinski, K. Lohwasser, A. Luszczak, B. Malaescu, R. McNulty, V. Myronenko, S. Naumann-Emme, K. Nowak, F. Olness, E. Perez, H. Pirumov, R. Placakyte, K. Rabbertz, V. Radescu, R. Sadykov, G.P. Salam, A. Sapronov, A. Schoening, T. Schoerner-Sadenius, S. Shushkevich, W. Slominski, H. Spiesberger, P. Starovoitov, M. Sutton, J. Tomaszewska, O. Turkot, A. Vargas, G. Watt, K. Wichmann

(Submitted on 16 Oct 2014)

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. These are complemented with a variety of theoretical options for calculating PDF-dependent cross section predictions corresponding to the measurements. The framework covers a large number of the existing methods and schemes used for PDF determination. The data and theoretical predictions are brought together through numerous methodological options for carrying out PDF fits and plotting tools to help visualise the results. While primarily based on the approach of collinear factorisation, HERAFitter also provides facilities for fits of dipole models and transverse-momentum dependent PDFs. The package can be used to study the impact of new precise measurements from hadron colliders. This paper describes the general structure of HERAFitter and its wide choice of options.

Comments: 18 pages, 8 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Report number: DESY Report 14-188
Cite as: arXiv:1410.4412 [hep-ph]
(or arXiv:1410.4412v1 [hep-ph] for this version)

- **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 Releases:

- https://www.herafitter.org/HERAFitter/HERAFitter/DownloadPage

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: Releases and Updates

September, 2014

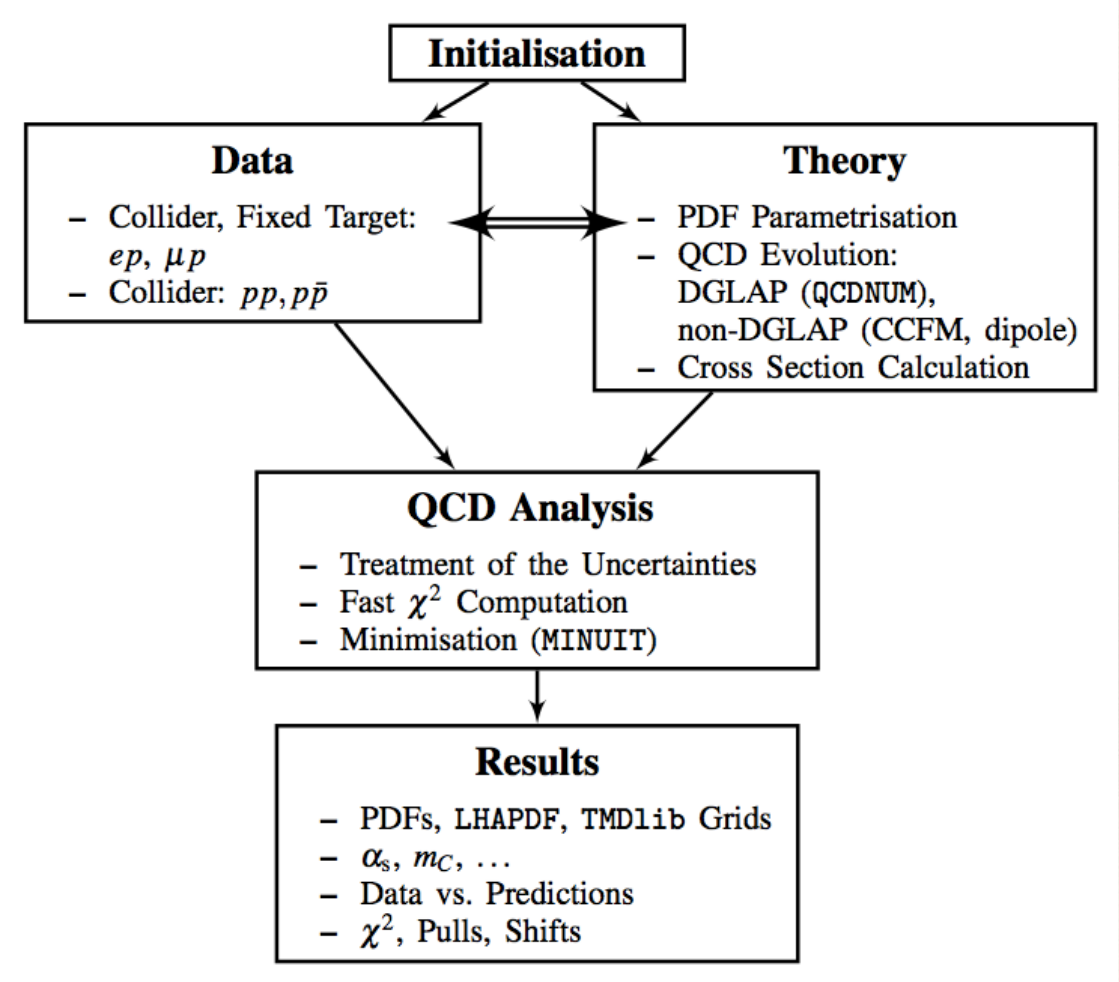
HERAFitter versions are labeled as **herafitter-i.j.k** where **i** is the stable release number, **j** is beta release number, and **k** is bug fixes.

Release	Date	Description
herafitter-1.1.0	29.09.2014	• Removed dependence on CERNLIB and related libraries. • Added interface to LHAPDFv6. • Added more and improved drawing options for visualisation of results. • Added possibility to deal with multi-dimensional data (virtual grids). • Additional options in parametrisation styles: added mixed forms between HERA style for gluon and sea and CTEQ style for valence. • Added new data from Tevatron, ATLAS and CMS. • Added improvements and more flexibility in the χ^2 and covariance matrix code: possibility to transform into nuisance representation for data with uncertainties given in the covariance form. • Included a new fastNLO version, which was generalised in order to accommodate DiffTop grids. • Added DiffTop grids via fastNLO.

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)



Latest Results from HERAFitter

- Research activities in HERAFitter are steered by demands of the users

List of analyses by HERAFitter

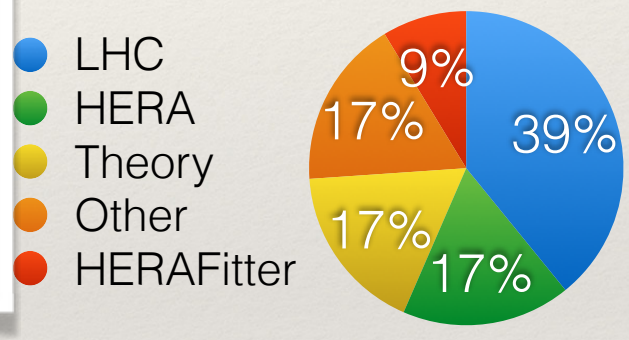
NEW 10.2014	**HERAFitter team**	arXiv:1410.4412	HERAFitter Open Source QCD Fit Project	
NEW 04.2014	**HERAFitter team**	EPJC (2014) 74: 3039, arXiv:1404.4234	Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders	Material

List of analyses using HERAFitter

Date	Group	Reference	Title
NEW 10.2014	LHC/ATLAS	ATL-PHYS-PUB-2014-015	Studies of theoretical uncertainties on the measurement of the mass of the W boson at the LHC
NEW 10.2014	LHC/CMS	arXiv:1410.6765 (CMS-SMP-12-028)	Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in pp collisions at sqrt(s) = 7 TeV
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

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

Overall distribution:
(of all publications)



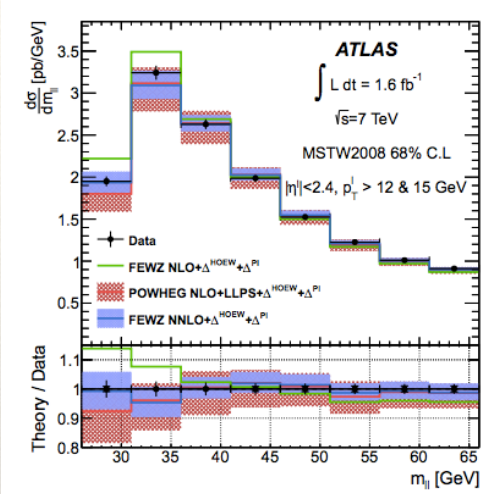
- New, herafitter-1.1.0, package was recently released

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)

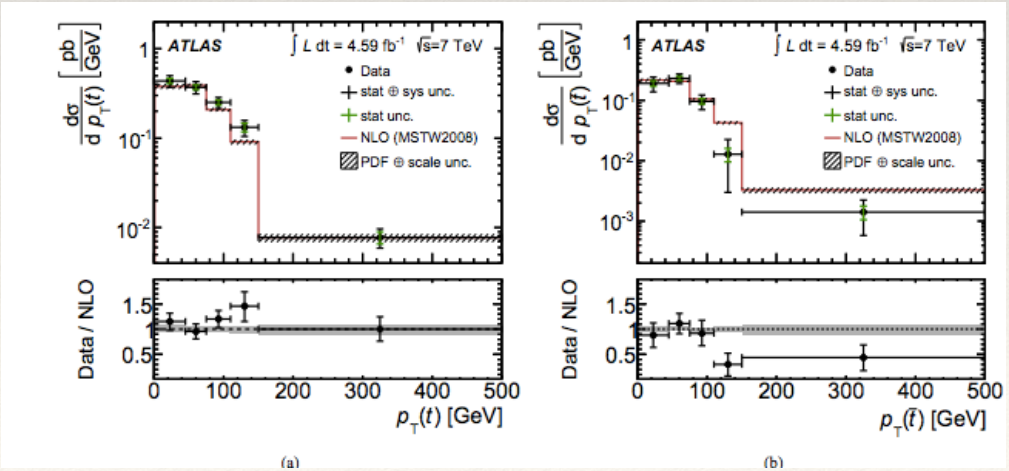
—> conclusion NNLO is needed to describe data



  - 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.

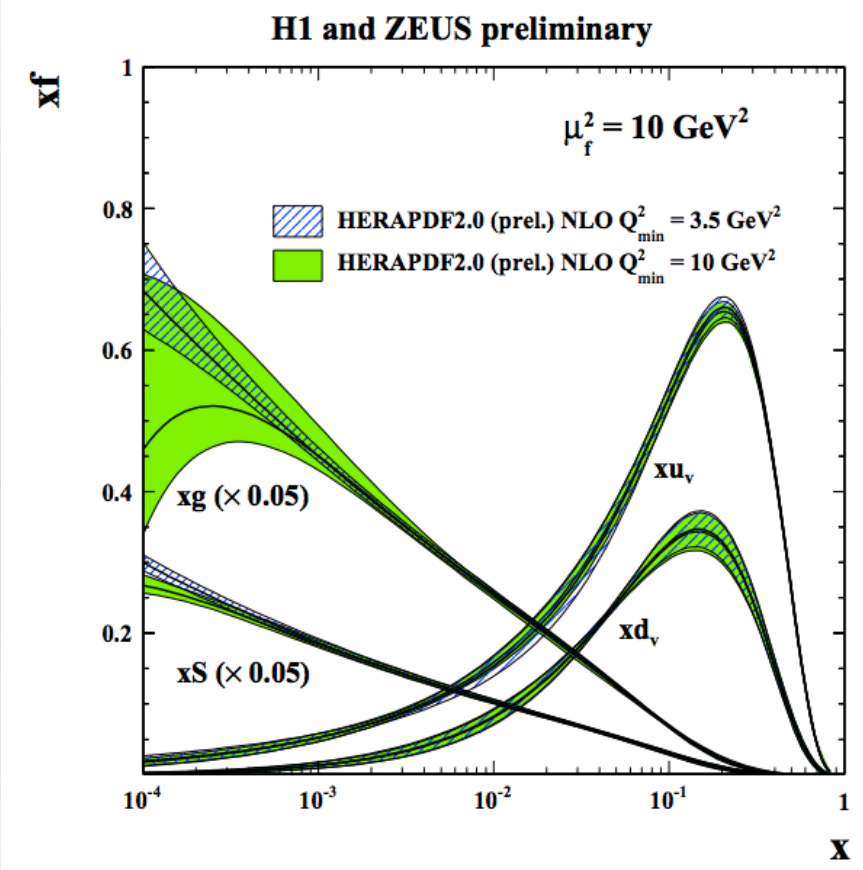
	$\frac{d\sigma}{dp_T(t)}$	$\frac{d\sigma}{dp_T(\bar{t})}$	$\frac{d\sigma}{d\lvert y(t)\rvert}$	$\frac{d\sigma}{d\lvert y(\bar{t})\rvert}$
χ^2/NDF	7.55/5	4.68/5	6.30/4	0.32/4

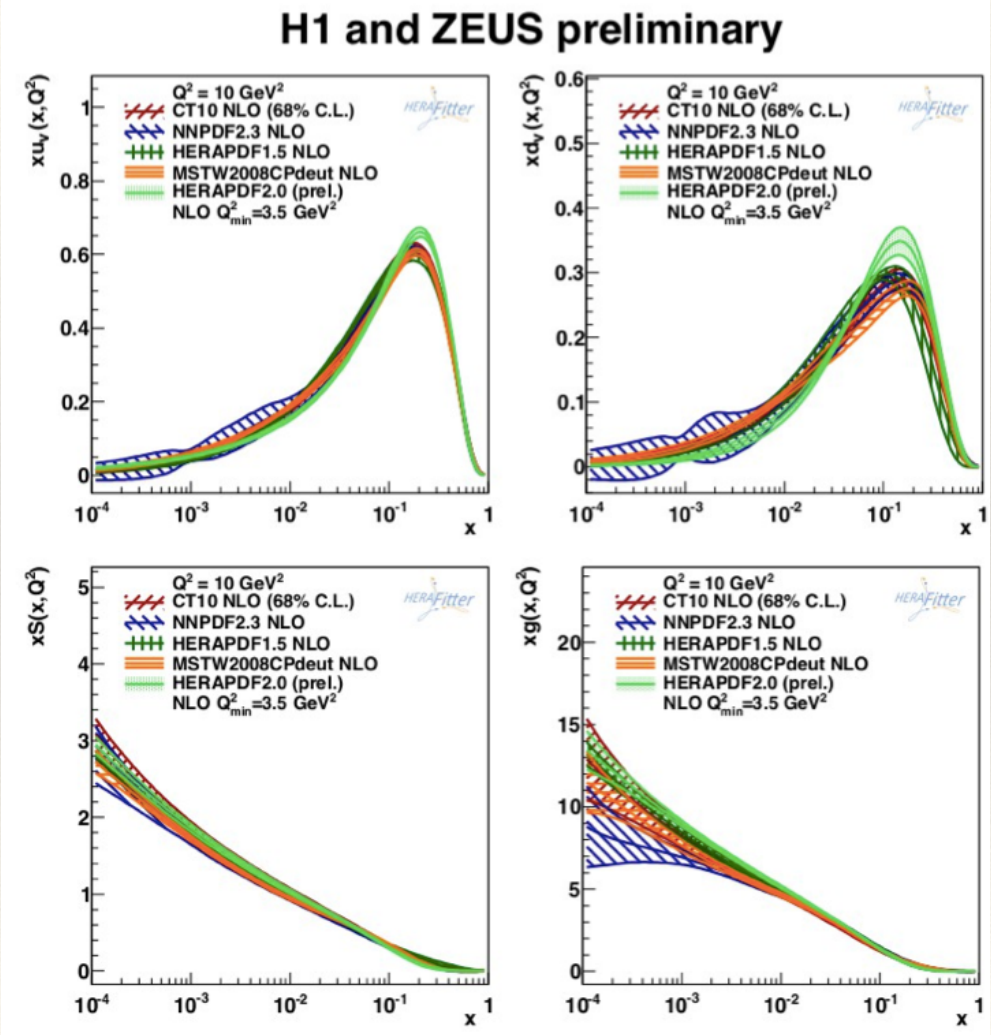


HERAPDF2.0prel with HERAFitter

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

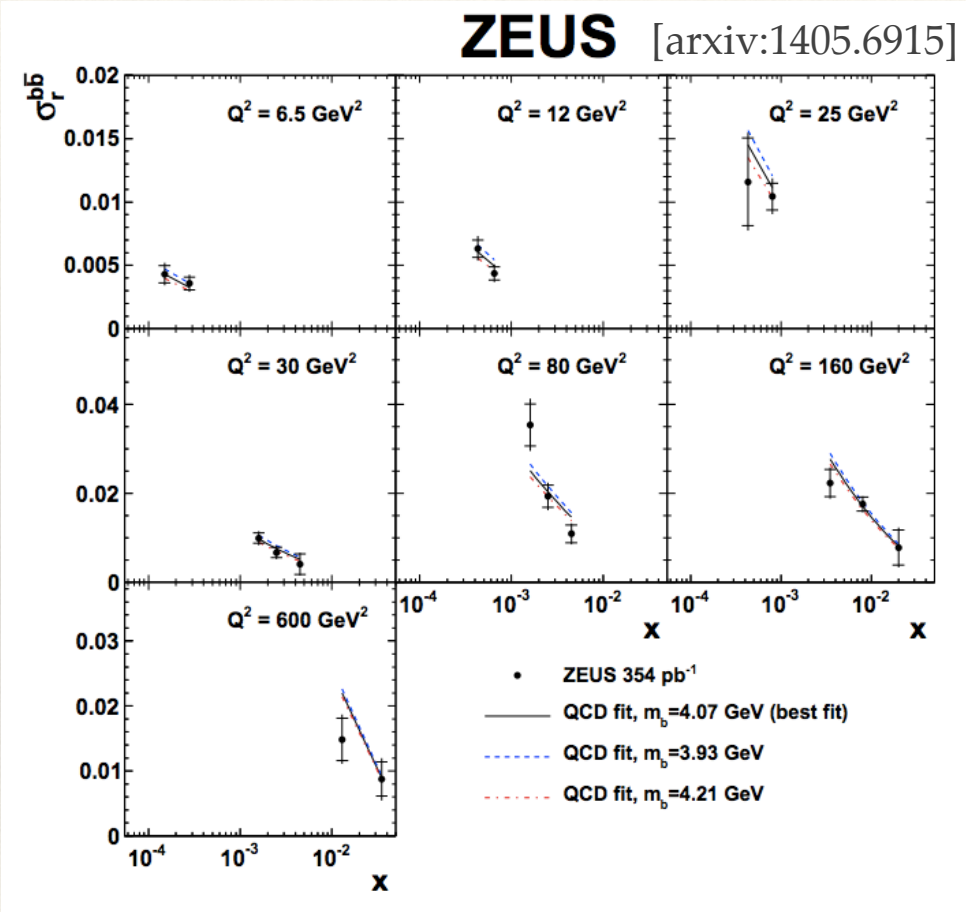
- HERAFitter is used to extract PDFs, mc, mb, alphas …





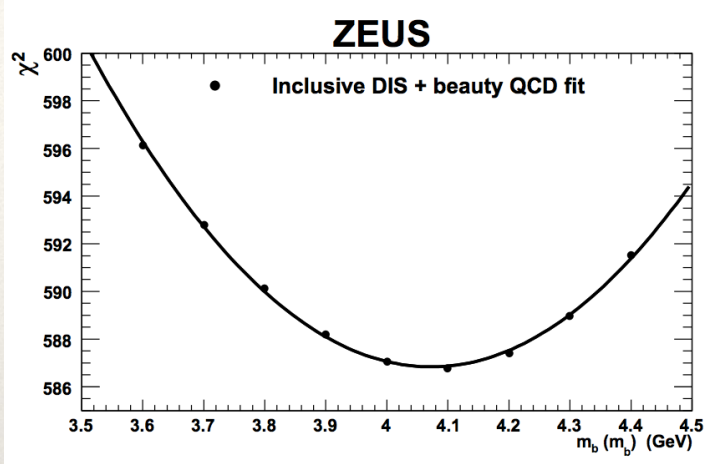
Running beauty mass from F2b

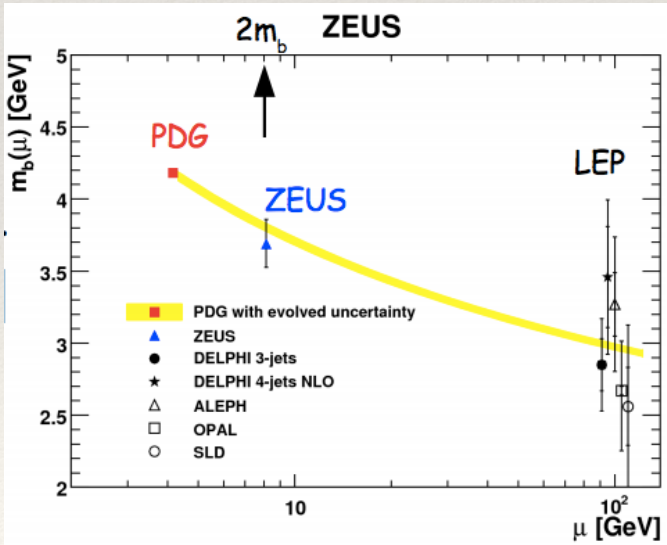
- The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.



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

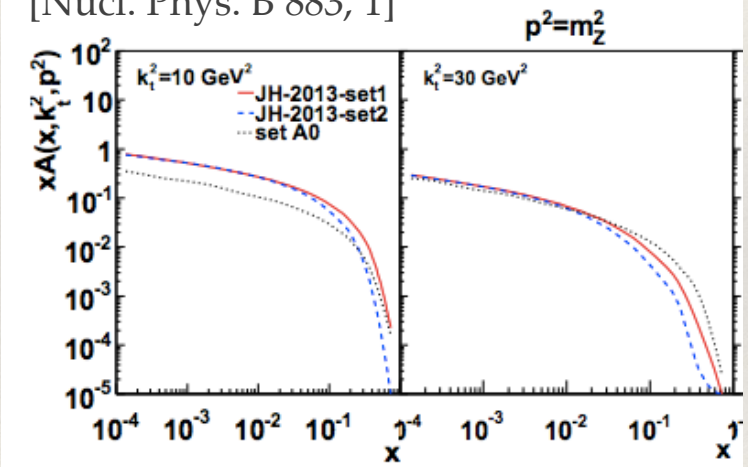
- QCD applications to multiple-scale scattering problems and complex final-state observables require in general formulations of factorisation which involve transverse-momentum dependent (TMD) - or known also as unintegrated PDFs.

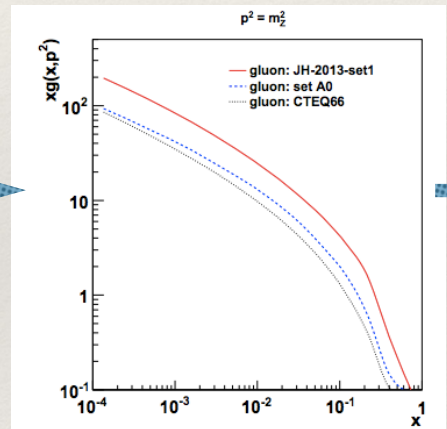
$$\sigma_j(x, Q^2) = \int_x^1 dz \int d^2k_t \; \hat{\sigma}_j(x, Q^2, z, k_t) \; \mathcal{A}(z, k_t, \mu)$$

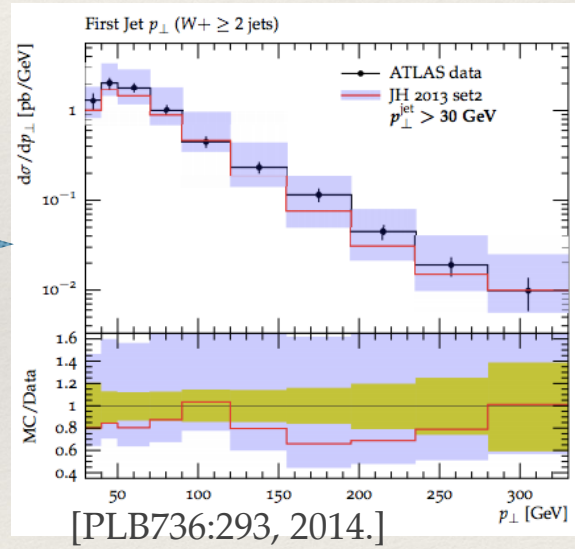
→ a convolution in both longitudinal and transverse momenta of TMD with off-shell partonic matrix elements

- 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]





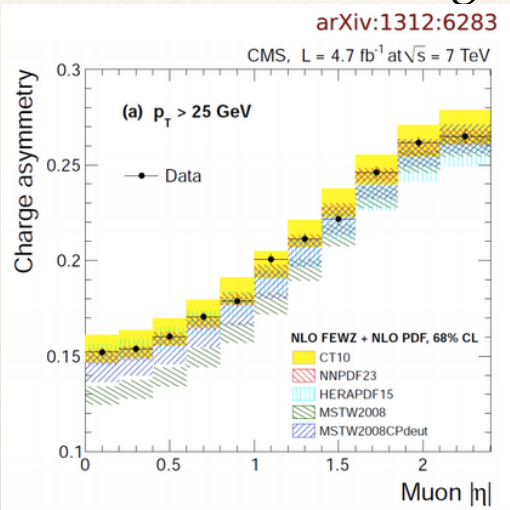


[PLB736:293, 2014.]

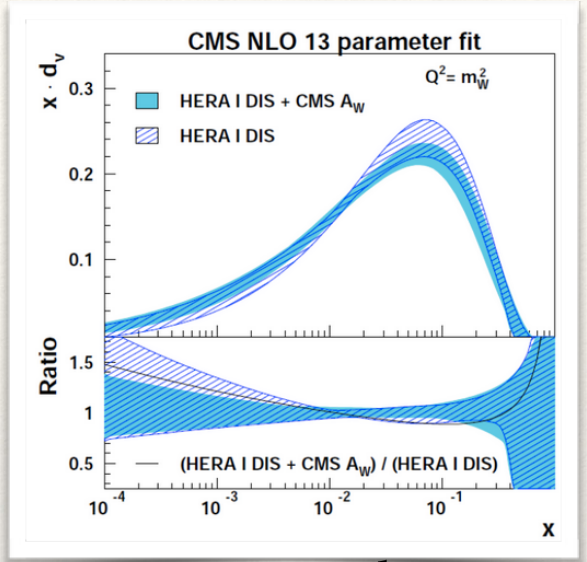
- The extracted gluon TMD with experimental and theory uncertainty [JH-2013-set1] is then used as prediction to vector boson+jet production process at the LHC [Phys. Rev. D 85 (2012) 092002.]
  - This process is important both for SM physics and for new physics searches at the LHC
  - Results compare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

QCD interpretation of W production at CMS

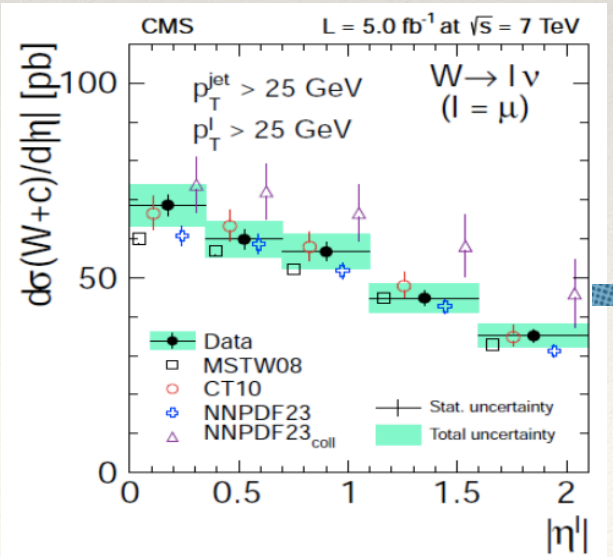
- Impact on valence PDFs from W asymmetry is investigated within the HERAFitter framework through a QCD fit analysis

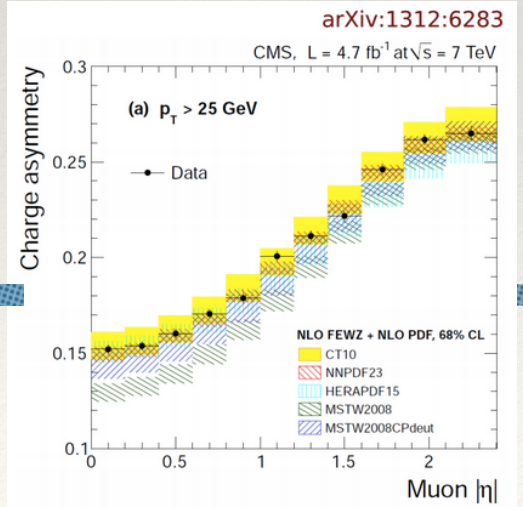


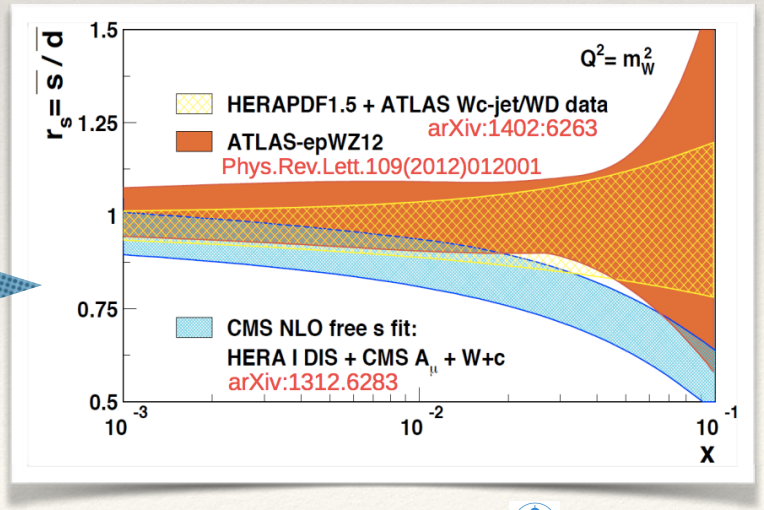
$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$



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



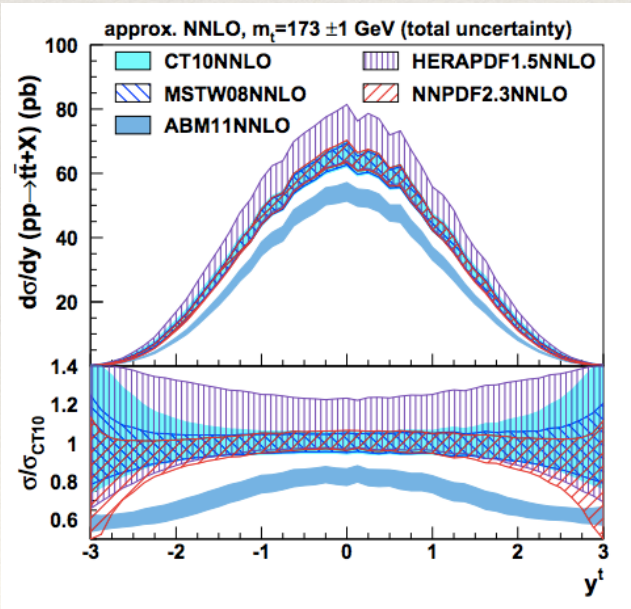


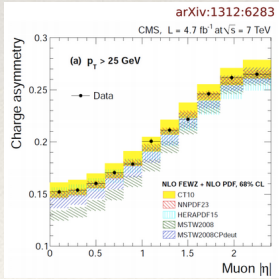


DiffTop in HERAFitter [arXiv:1406.0386]

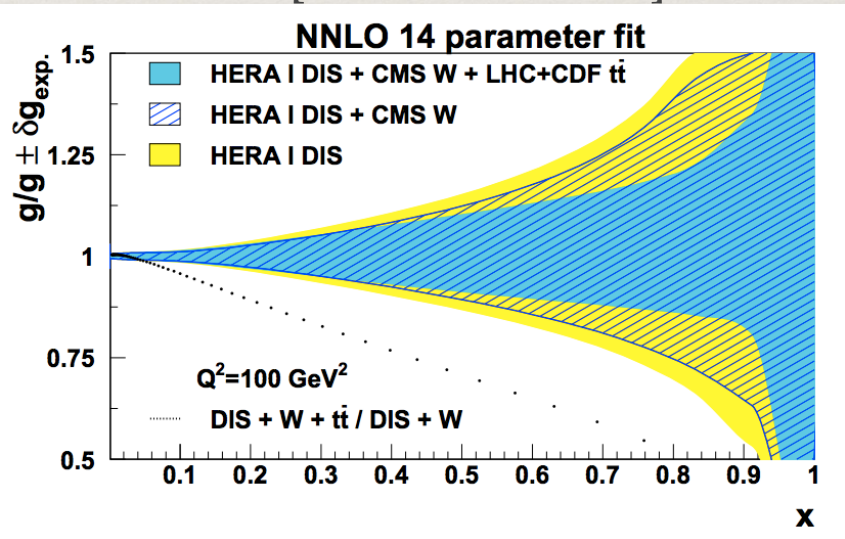
- Top-quark pair production at the LHC probes high-x gluon (x ≈ 0.1):
  —> there is a strong correlation between g(x), αs and the top-quark mass mt
- Precise measurements of the total and differential (normalised and absolute) cross section of ttbar pair production can constrain and de-correlate αs, gluon, mt
- DiffTop and its interface to FastNLO have been implemented into Herafitter.

- First exploratory PDF fits at NNLO have been performed by using differential cross sections of top-quark pair production together with other data sets [HERA I, W asymm.] to study the impact on the gluon at large x.





[arXiv:1406.0386]

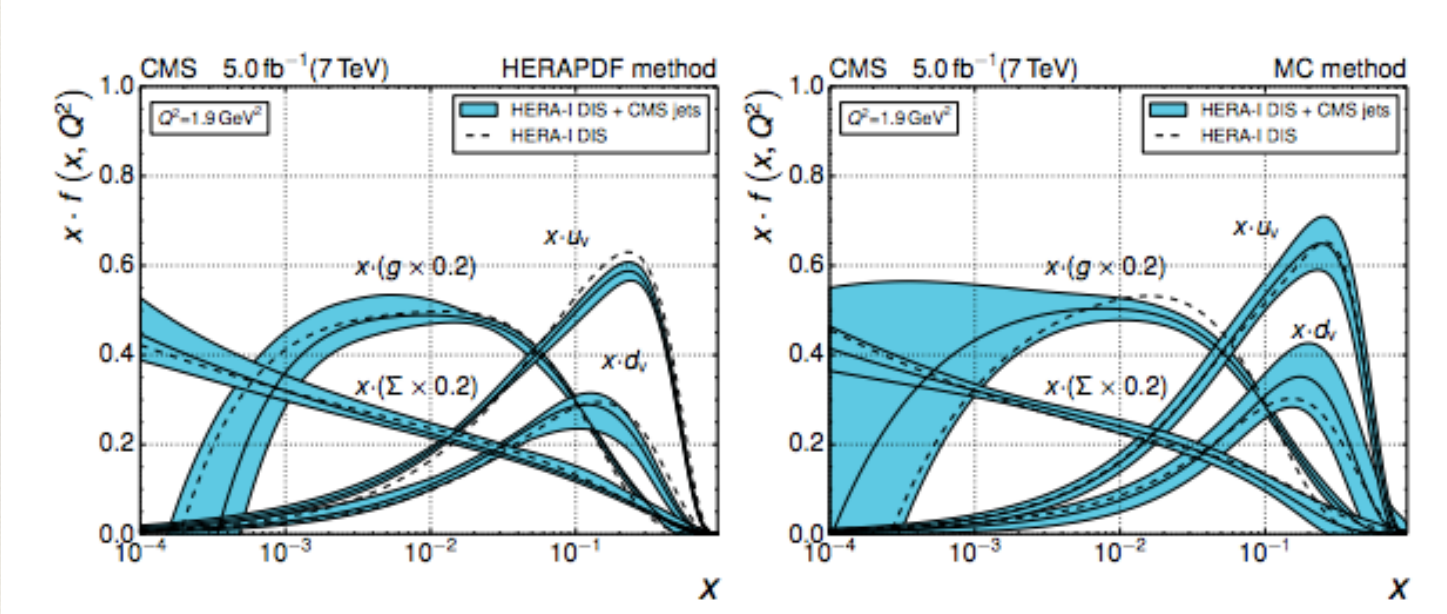


—> More data is needed: absolute differential cross section data will bring more information.

Impact of the inclusive jet CMS measurement on the PDFs

arXiv:1410.6765

- The inclusive jet cross section measured by CMS at 7TeV provide important input for the gluon density at high x and for the strong coupling constant at large energy scales.
- The impact of the CMS inclusive jet data on proton PDFs is investigated by including the jet cross section measurement in a combined fit with the HERA-I inclusive DIS cross sections.
  - Two prescriptions were used:
    - a la HERAPDF style: HERAPDF method
    - a la NNPDF style: MC method (data driven regularisation)

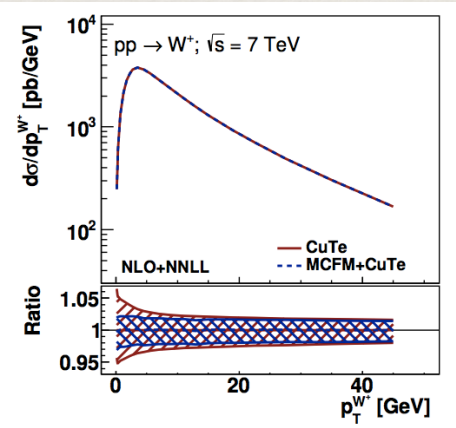


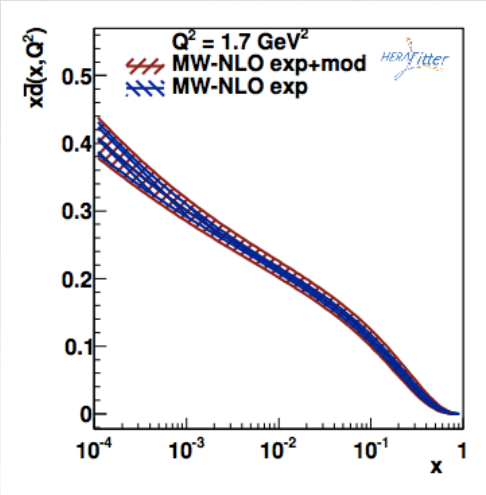
- Combined fit of PDFs and the strong coupling constant:
- HERAPDF method: $\alpha_S(M_Z) = 0.1192^{+0.0023}_{-0.0019}$ (all except scale). vs $\alpha_S(M_Z) = 0.1185 \pm 0.0034$ (all except scale).
- MC method: $\alpha_S(M_Z) = 0.1188 \pm 0.0041$ (all except scale).

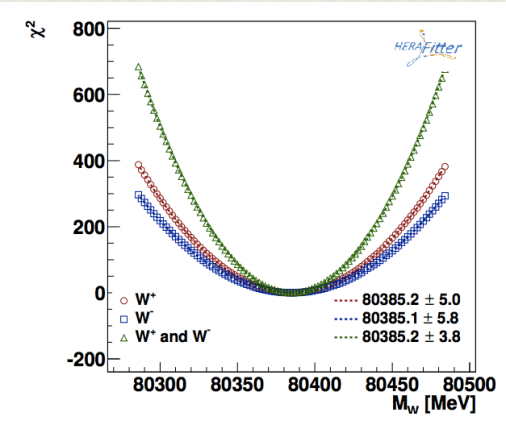
Studies of theoretical uncertainties of Mw mass at the LHC

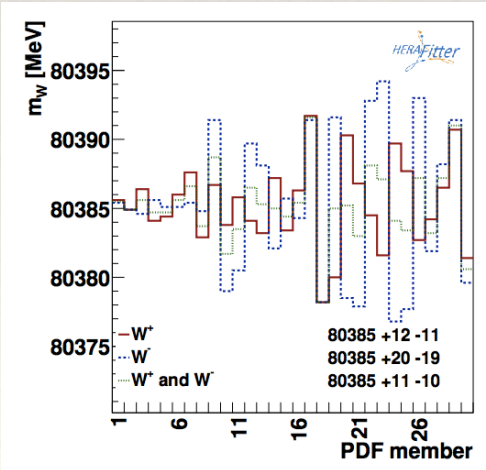
ATL-PHYS-PUB-2014-015

- The measurement of the mass of the W boson provides a stringent test of the SM
- At the LHC, the best experimental precision on Mw boson might be achieved from the pT distribution of the charged electron/muon from leptonic decay of W:
- A quantitative study of the theoretical uncertainties due to the incomplete knowledge of the quark PDF, and to the uncertainties on the modelling of the low-pT region of W/Z bosons, performed using HERAFitter platform.
  - Theoretical predictions is based on MCFM and CuTe (interfaced to APPLGRID)
  - A PDF set is generated using simply HERA I data to study the model variations (mc, strange) and propagated via chi2 profiling method to study the effect of PDF uncertainties









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

$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}^{corr}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}^{corr}}$$

PDF uncertainties cancel
improved scale uncertainty

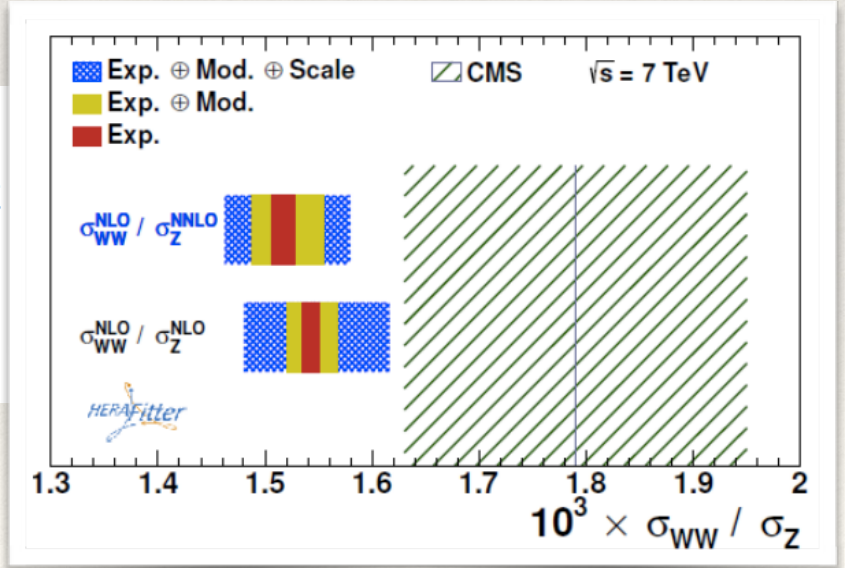
- HERAFitter provides possibility to account for correlations between PDFs at different orders which can lead to reduction of overall theoretical uncertainties:

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 and Outlook

- HERAFitter is an open source QCD software package which encodes 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.

  www.herafitter.org

  latest release: herafitter-1.1.0

- The further progress of HERAFitter is driven by the latest QCD advances in theoretical calculations and in the precision of experimental data:
  - QED +QCD via QEDEvol (R. Sadykov)
  - FONLL and low x resummation via APFEL (J.Rojo, V. Bertone, S. Carrazza)
  - ACOT @ NNLO (P. Nadolsky)

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)

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

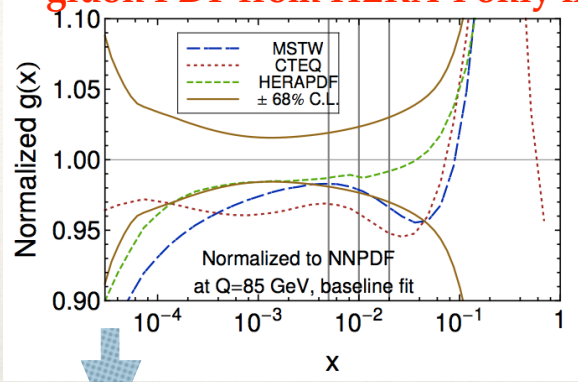
Conveners

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

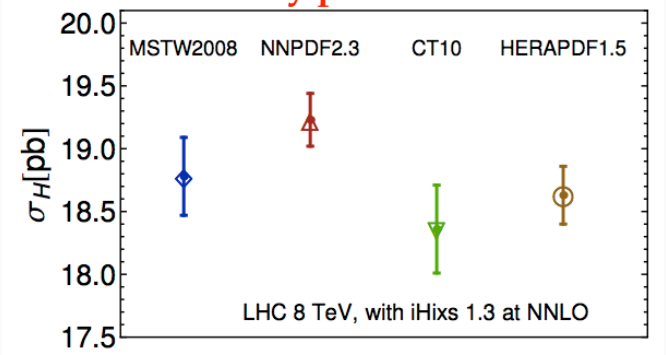
SM: Loops and Multilegs
N. Glover (Theory), J. Huston (ATLAS), G. Dissertori (CMS),
S. Dittmaier (Electroweak Contact)

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

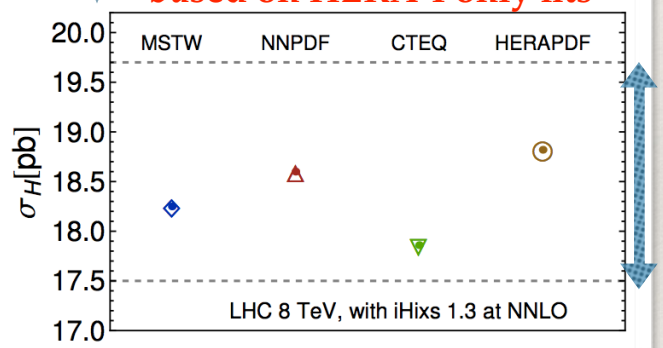
gluon PDF from HERA-I only fits



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.**