QCD@LHC 2015

Queen Mary University of London

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HERAFitter project and its related studies

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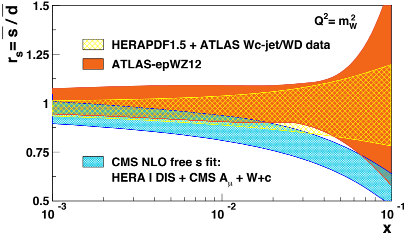
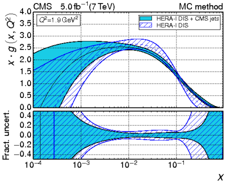
2 September 2015

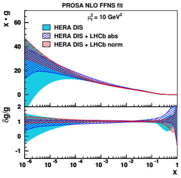
Motivation

The LHC data have an undoubted influence on the proton PDF determination.

- New kinematic coverage
- New initial state compositions
- + sensitive observables
- elaborate treatment and propagation of uncertainties at the analysis stage



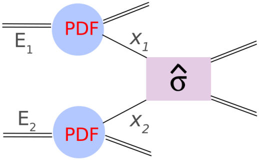




Motivation

Even if data do not have direct impact on PDFs their consistency is often qualified in QCD analysis.

This is possible due to PDF universality as implied by factorization theorem.

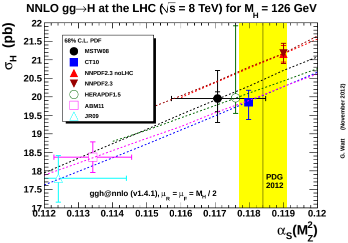


$$\sigma \approx \hat{\sigma} \otimes \mathrm{PDF}$$

While the PDFs are universal, different extraction techniques bring different results:

ABM12	CT14	MMHT14
HERAPDF2.0	GR14	NNPDF3.0
	CJ12	

The PDF determination uncertainty plus discrepancy between the groups compromise accuracy of theory predictions for important Higgs processes and BSM searches.

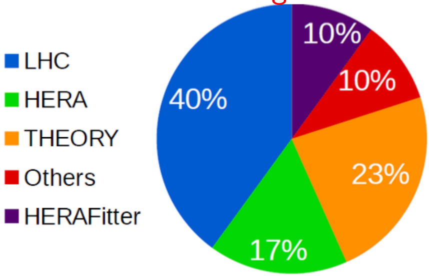


- Effort for metaPDFs.

HERAFitter project

HERAFitter is a QCD analysis tool aiming to tackle such issues:

www.herafitter.org



30 public results obtained using HERAFitter from the beginning of the project

- Perform QCD analysis of proton structure using experimental data
- Extract and improve precision of the PDFs
- Assess impact of the new data on PDF determination
- Check experimental data consistency
- Test different theoretical approaches to the proton structure description.

The project is developed and maintained by $\sim$ 30 developers from HERA and LHC experiments and theorists.

HERAFitter workflow

```
! PDF parameterisation style. Pos
!   '10p HERAPDF' -- HERAPDF-like
!   '13p HERAPDF' -- HERAPDF-like
!   '10p H12000'  -- H12000-like (
!   'CTEQ'                       ar
!   'CHEB'        -- CHEBYSHEV par
```

Initialization

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}},$$

$x\bar{D}(x)$

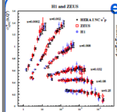
$xg(x)$

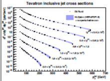
PDF parameterization

DGLAP: VFNS (RT, ACOT), FFNS (QCDNUM, ABM).
Dipole models
kT-facto

PDF NNLO evolution

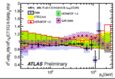
experimental input





experiments:
HERA, Tevatron, LHC, fixed target

DATA



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

processes: DIS, NC and CC DY, jets, top, diffraction, heavy quarks (c,b,t), W-prod
tools: MCFM (via APPLgrid), LO DY, Hathor, NLOjet++ (via FastNLO, APPLgrid)

Theory predictions

χ^2 minimization (MINUIT)

Output PDFs, LHAPDF grids, plots

HERAFitter code: what's new?

Two HERAFitter releases v1.1.0 and v1.1.1 since previous QCD@LHC:

- Many technical additions, LHAPDFv6 interface, CERNLIB independence, drawing tools, etc.
- Bugfixes and optimizations
- New data from Tevatron, ATLAS and CMS.

Next release (~this autumn) will include:

- **APFEL interface**. Tested with FONLL schemes for NLO and NNLO evolution. Available FONLL A, B and C schemes.
- **Hessian profiling**. Hessian PDF uncertainties are added to the χ^2 as nuisance parameters.

$$\chi^2(\boldsymbol{\beta}_{\mathbf{exp}}, \boldsymbol{\beta}_{\mathbf{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2 \, .$$

The shifts can be profiled to the new data and rotated along new orthogonal directions.

HERAFitter general paper is out

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

List of analyses by HERAFitter

NEW 03.2015	**HERAFitter team**	to be submitted to EPJC, arXiv:1503.05221	QCD analysis of W- and Z-boson production at Tevatron	Material
10.2014	**HERAFitter team**	submitted to EPJC, arXiv:1410.4412	HERAFitter Open Source QCD Fit Project	
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

HERAFitter

Open Source QCD Fit Project

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]

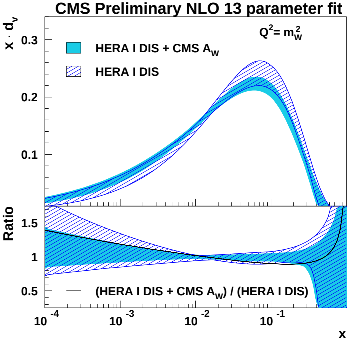
EPJC (2015), 75:304

arXiv:1410.4412

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. 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.

Recent results using HERAFitter

- Impact of the LHCb measurements of forward charm and beauty production on PDFs. LHCb/PROSA, [arXiv:1503.04581].
- Measurement of the forward-backward asymmetry of e and m pair-production in pp collisions at 7 TeV with the ATLAS detector. ATLAS, [arXiv:1503.03709]
- Measurement of the muon charge asymmetry in inclusive pp$\rightarrow$W+X production at 8 TeV. CMS, [PAS SMP-14-022]
- Combination of Measurements of Inclusive Deep Inelastic e+-p Scattering Cross Sections and QCD Analysis of HERA Data II. HERA/H1 and ZEUS, [submitted to EPJC]



QCD analysis of Tevatron W and Z data

W-charge asymmetry and Z-boson inclusive production data are studied:

Observable	Experiment	Integrated luminosity	Kinematic requirements	Used in the nominal fit	Ref.
$d\sigma(Z)/dy$	D0	0.4 fb^{-1}	$71 < m_{ee} < 111$ GeV	yes	Phys Rev D 76 (2007) 012003
$d\sigma(Z)/dy$	CDF	2.1 fb^{-1}	$66 < m_{ee} < 116$ GeV	yes	Phys Lett B 692 (2010) 232
A_μ $W \to \mu\nu$	D0	7.3 fb^{-1}	$p_T^\mu > 25$ GeV, $p_T^\nu > 25$ GeV	yes	Phys Rev D 88 (2013) 091102
A_e $W \to e\nu$	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	no	Phys Rev D 91 N3 (2015) 032007
A_W $W \to e\nu$	CDF	1.0 fb^{-1}	none	yes	Phys Rev Lett 102 (2009) 181801
A_W $W \to e\nu$	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	yes	Phys Rev Lett 112 N15(2014)151803

Revised correlation model:

- uncertainties of data-driven corrections are treated as bin-to-bin uncorrelated (lepton ID, trigger and charge efficiencies).
- reasonable assumption, since they are affected by stat. noise

Theory predictions are based on fast fixed order calculations: MCFM+APPLGRID

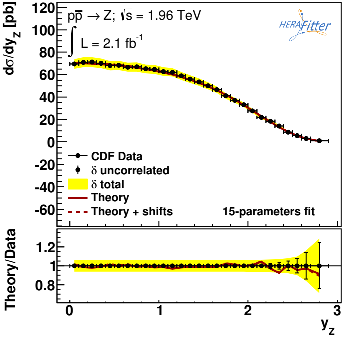
The D0 data on lepton asymmetry were used in other recent analysis [arXiv:1508.07923] to constrain light quark parton densities.

QCD analysis of Tevatron W and Z data

The PDF parametrisation is extended by additional 5 parameters compared to initial 10 (baseline HERA I data): exponential, linear and quadratic terms in x.

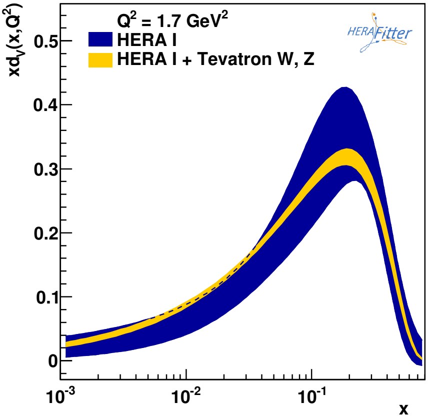
$$f(x) = Ax^B(1-x)^C \times e^{Fx}(1 + Dx + Ex^2)$$

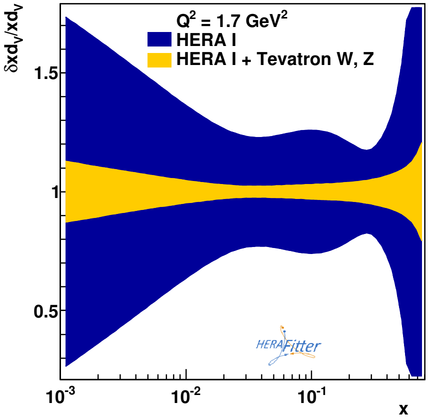
Data set	Experiment	χ^2/points
DIS	H1 - ZEUS	516/550
Z $d\sigma/dy$	D0	23/28
Z $d\sigma/dy$	CDF	33/28
W μ-asymmetry	D0	12/10
W asymmetry	CDF	15/13
W asymmetry	D0	16/14
Total χ^2/dof		615/628



Impact on valence quarks

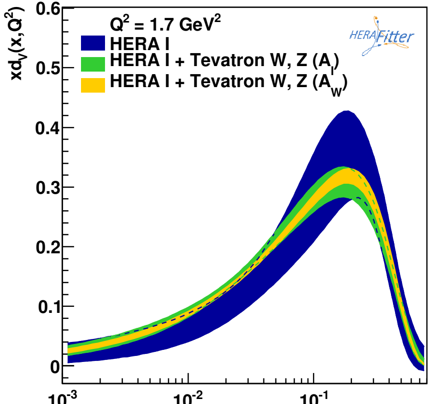
The Tevatron W and Z data exhibit significant impact on valence quarks relative to HERA-I data alone. Especially on d-quark.

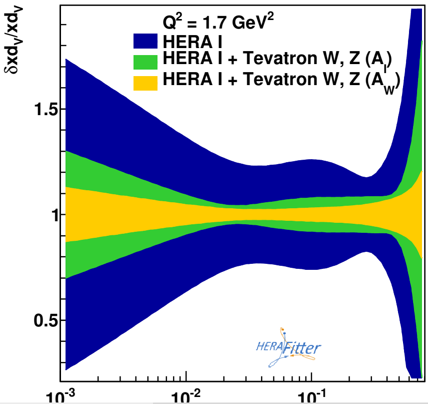




W charge asymmetry

- W charge asymmetry measurement is model-dependent. It assumes fixed W mass and infers missing longitudinal momentum of neutrino on statistical basis.
- To test possible bias, the W asymmetry data are replaced with lepton charge asymmetry data.

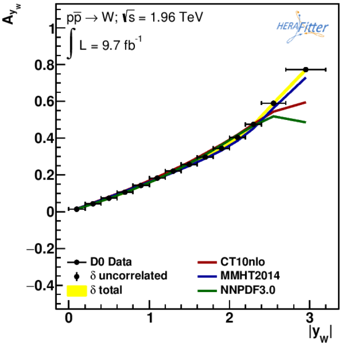


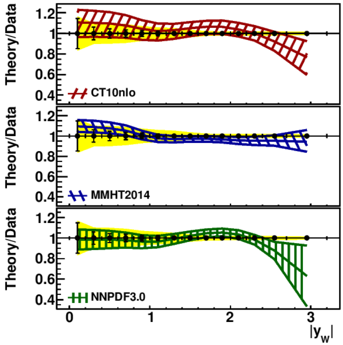


Modern PDF predictions vs Tevatron data

- Test the compatibility of the Tevatron data with other global PDF sets
- Consider only the data sets which are not yet included in the PDF fits

PDF	χ^2/dof
CT10nlo	47/37
MMHT2014nlo	14/14
NNPDF3.0nlo	39/37





Experimental uncertainties much smaller than PDF uncertainties

Good agreement between W asymmetry data and NLO predictions with global PDF sets

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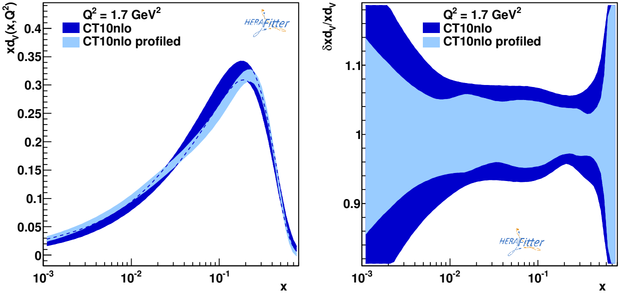
Impact of Tevatron data on PDF determination

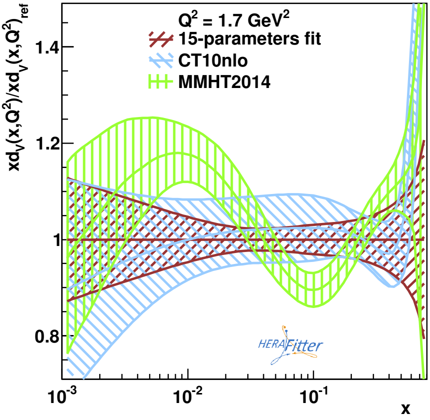
- The influence is estimated using profiling technique:
- - add hessian PDF uncertainties as nuisance parameters to the χ^2 definition $\chi^2(\beta_{exp}) \to \chi^2(\beta_{exp}, \beta_{th})$
- - minimize and profile PDF shifts β to the data
- - propagate the shifts and reduction of uncertainty to PDFs



similar to PDF fit, the d_v uncertainty is noticeably reduced.

Impact of Tevatron data on PDF determination

The profiling also improves agreement between the PDFs themselves



These results highlight the importance of the Tevatron W- and Z-boson production data to constrain d-quark and valence PDFs.

Summary

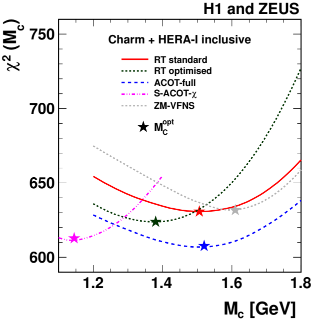
- The HERAFitter project provides tools for QCD analysis of experimental data obtained at colliders.
- The technical update v1.1.1 is available for download www.herafitter.org
- A new release version is under preparation and will be available this autumn.
- Several LHC analyses used HERAFitter package to qualify and evaluate data constrains on PDFs.
- The successful inclusion of Tevatron W and Z data performed in the HERAFitter, which shows their importance for valence quark determination, especially d-quark.
- The corresponding data tables and APPLgrids are available at the project's web page.

Back-up slides

HERAFitter functionality

QCD evolution:

- **DGLAP formalism:** – performed with QCDNUM with different schemes of heavy quark treatment:
  - VFNS: RT(MSTW), ACOT(CTEQ)
  - FFNS (pole and running mass)
- **non-DGLAP formalism:**
  - Dipole models (GBW, IIM, BGK) – an alternative approach to the low-x region
  - Unintegrated PDFs (CCFM evolution)



Processes (ep, pp, $p\bar{p}$):

- DIS for ep collisions
- W, Z/γ^* production
- Jet production
- Top pair production

The calculation precision of NLO, NNLO (k-factors) is achieved using FastNLO and APPLgrid technique

Full NNLO $t\bar{t}$ total cross section with HATHOR.

HERAFitter functionality, χ^2, unc.

Several types of χ^2 definitions can be used (D - data, T -theory)

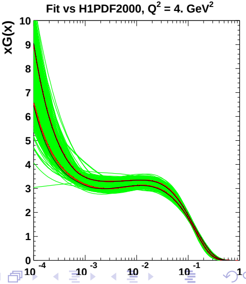
- nuisance parameters: $\chi^2 = \sum_i \frac{(D_i - T_i^*)^2}{(\delta^2_{unc})}, \quad T_i^* = T_i + \sum_j \xi_j \delta_i^{cor,j}$

- covariance matrix: $\chi^2 = \sum_{i,j} (D_j - T_i) Cov^{-1}_{i,j} (D_i - T_j)$

- their mixture

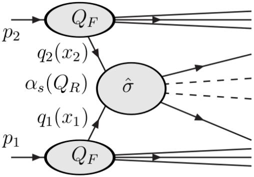
Various types of uncertainty treatment for experimental data:

- Hessian: – nuisance parameters are fitted, χ^2 tolerance > 1 can also be used to account for marginally compatible input data sets
- Offset method – nuisance parameters are applied as 1σ shifts
- Monte Carlo – data points are shifted randomly within 1σ limits to form MC replicas



Fast theory evaluation

- The grid methods FastNLO and APPLgrid allow fast evaluation of a fixed order cross section for a given binning and cuts. The approach consists in building a 3d-grid of perturbative weights $w(x_1^m, x_2^n, Q^{2^k})$ once and then convolution for arbitrary PDF and couplings.



E.g. the APPLgrid *Eur.Phys.J.C66:503-524,2010* method consists of steps:

1. Collect perturbative weights to 3d grids:

$$d\hat{\sigma}^{ij}/dX \to w(x_1^m, x_2^n, Q^{2^k})$$

2. Convolute grid with PDFs:

$$\sum_{m,n,k} w_{m,n,k}\left(\frac{\alpha_S(Q_k^2)}{2\pi}\right)F(x_{1m}, x_{2n}, Q_k^2) \to \frac{d\sigma}{dX}$$