HERAFitter - an open source QCD fit framework and related studies

Ringailė Plačakytė

on behalf of the HERAFitter team



Calculations for Modern and Future Colliders,

CALC2015, Dubna, July 23 - 30

Parton Distribution Functions

Parton Distribution Functions (PDFs) are of crucial for precision physics at hadron colliders because:

→ PDFs limit **the accuracy of the SM predictions** (including Higgs)

→ **reach of new physics** searches depends on PDF knowledge at high Bjorken-x

QCD factorisation:

measured cross section = PDF hard-scattering ME

$$\sigma(\alpha_s,\mu_R^2,\mu_F^2)=\sum_{a,b}\int_0^1 f_a(x_1,\mu_F^2)f_b(x_2,\mu_F^2)\hat{\sigma}(x_1,x_2;\alpha_s,\mu_R^2,\mu_F^2)+\ldots$$

precision measurements of HERA, LHC data

PDF determination, heavy quark treatment, QCD analysis tools

parton cross section (calculable in pQCD)

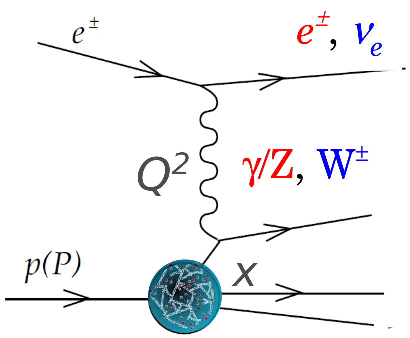
Parton Distribution Functions: from HERA to LHC

QCD factorisation:

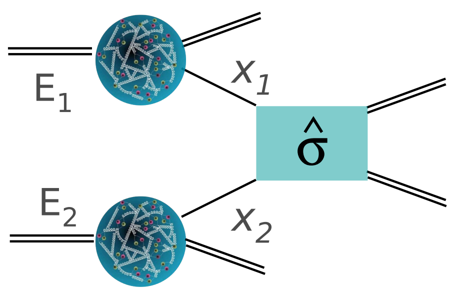
PDF — hard-scattering ME

$$\sigma(\alpha_s,\mu_R^2,\mu_F^2)=\sum_{a,b}\int_0^1 f_a(x_1,\mu_F^2)\,f_b(x_2,\mu_F^2)\,\hat{\sigma}(x_1,x_2;\alpha_s,\mu_R^2,\mu_F^2)+\dots$$

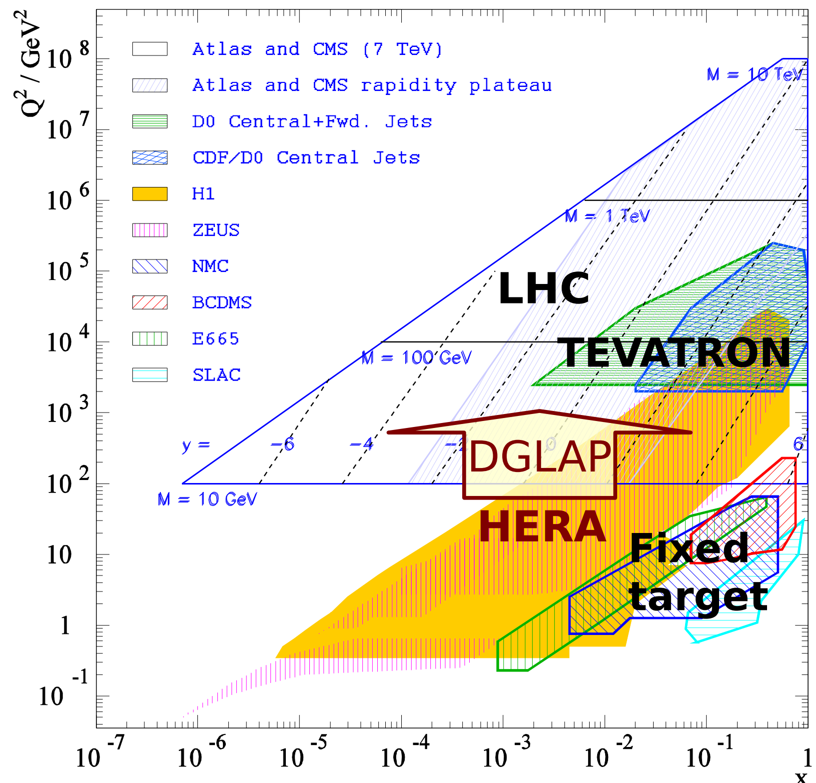
Deep Inelastic Scattering (**DIS**):
unique opportunity to study PDFs



same PDFs can be used to predict
pp collisions



LHC data improve PDFs further



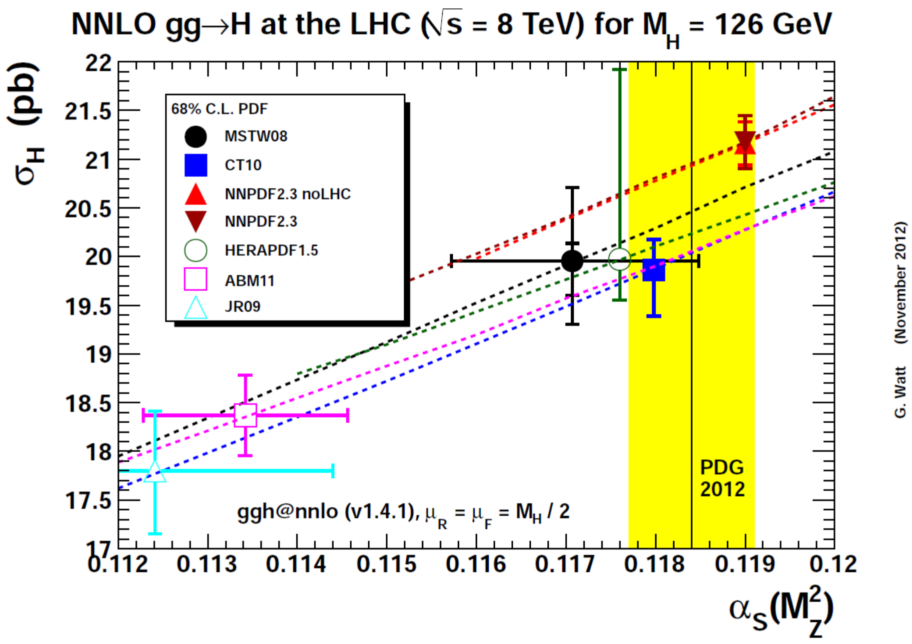
evolution in Q^2 via DGLAP

HERAFitter: Motivation

PDF provided by main fitting groups (**CT, MMHT, NNPDF, HERAPDF, ABM, JR**) may differ due to:

→ fitted different data sets
→ method of 'best fit' determination
→ uncertainty treatment/sources
→ assumptions in procedure (parametrisation)
→ heavy flavour treatment
→ PDF and α_s correlation

→ lead to differences in the predicted cross sections



HERAFitter is an open source QCD fit framework ready to extract PDFs

→ can be used to benchmarking and understanding differences in PDFs

→ provides tools to assess impact of new data

HERAFitter Project

www.herafitter.org

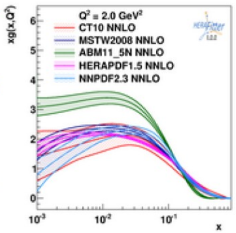
→ open access

→ no registration required (subscription optional)

Welcome to HERAFitter

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.

The HERAFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data which we would like to present here. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.



Downloads of HERAFitter software package

NEW! HERAFitter-1.1.1 release is publicly available.

All the HERAFitter releases can be accessed HERE .

Description: http://arxiv.org/abs/1410.4412

HERAFitter Meetings

- NEW! HERAFitter Meeting in Heidelberg: https://indico.cern.ch/event/382006/
- User's Meetings: monthly meetings to enhance communication between users and developers (open access)
- Developer's Meeting: technical weekly meetings to ensure communication among developers (restricted access)
- Steering Group's Meeting (restricted access)

HERAFitter representation

- List of results
- List of collected talks

Developers Info (restricted to developers)

- Internal Developments

Organisation

Steering Group is composed of:

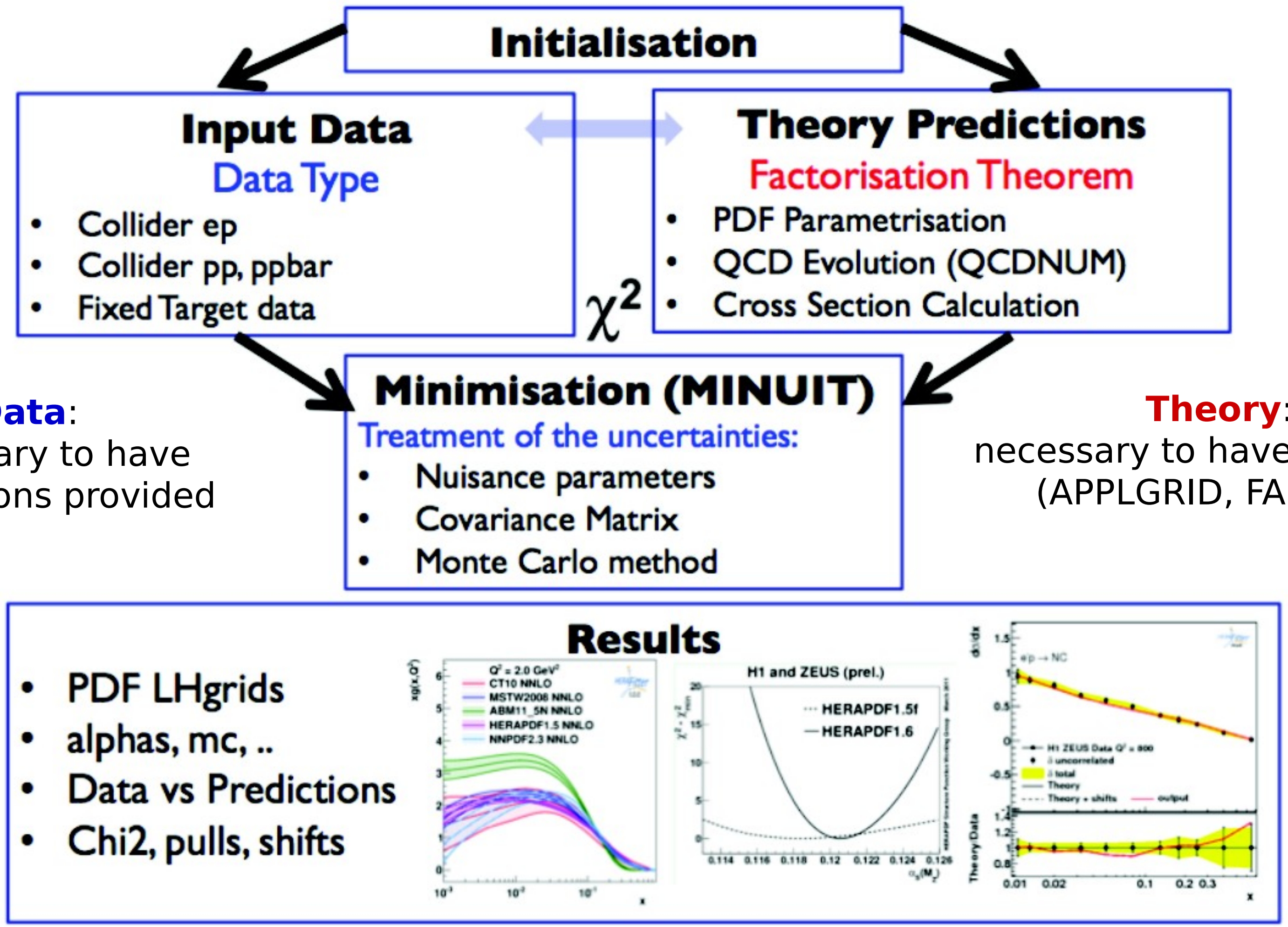
- **Conveners:** Voica Radescu, Ringaile Placakyte, Amanda Cooper-Sarkar
- **Release coordinator** (revision of the release candidates): Sasha Glazov
- **Librarian** (continuous revision/development of the main code and doxygen): Hayk Pirumov
- **Contact Persons:** Cristi Diaconu (H1),Klaus Rabbertz (CMS), Bogdan Malaescu (ATLAS), Olaf Behnke (ZEUS), Ronan McNulty (LHCb), Gavin Salam (theory)
- **DESY IT Contact:** Yves Kemp, Bogdan Lobodzinsky

Getting help

Send email to herafitter-help@desy.de

HERAFitter Code Structure

A flow diagram of the PDF extraction in the HERAFitter package:



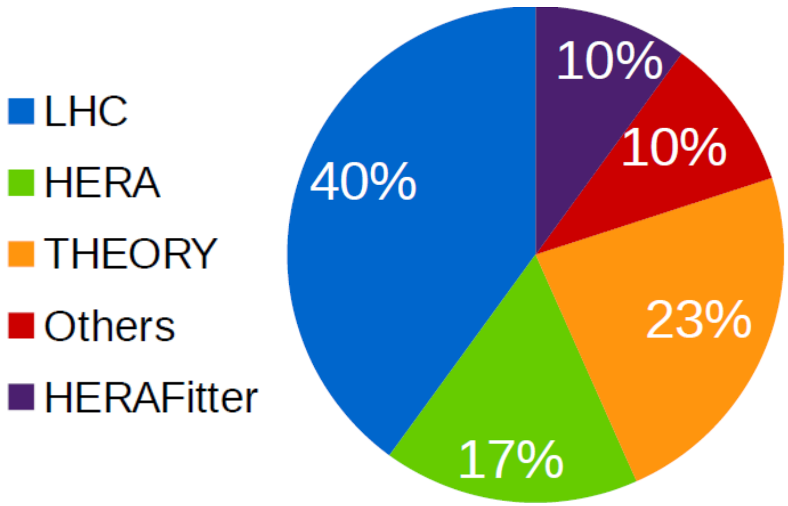
Data:
necessary to have
correlations provided

Theory:
necessary to have fast tools
(APPLGRID, FASTNLO)

Results Obtained with HERAFitter

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

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



LHC experiments provide the main developments and usage of HERAFitter platform

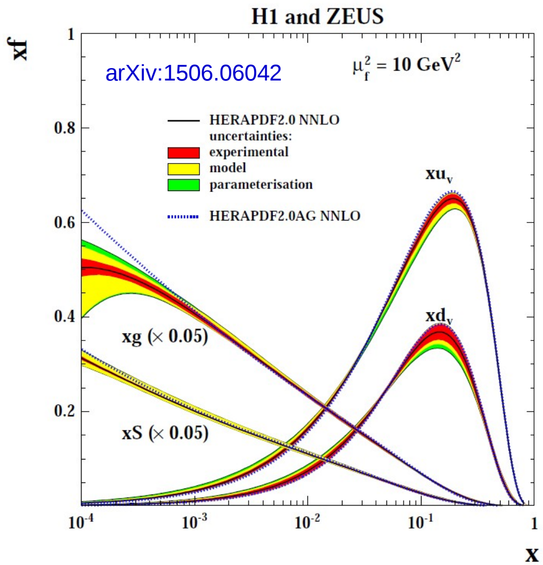
HERAFitter publications:

List of analyses using HERAFitter

NEW 03.2015	**HERAFitter team**	submitted to EPJC, arXiv:1503.05221	QCD analysis of W- and Z-boson production at Tevatron
10.2014	**HERAFitter team**	EPJC (2015), 75:304, 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

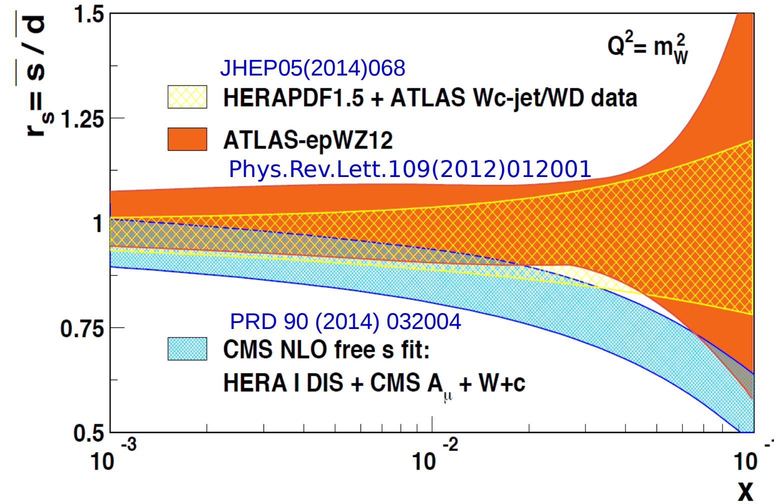
Results Obtained with HERAFitter: Examples

DIS inclusive processes in *ep* (fixed target)

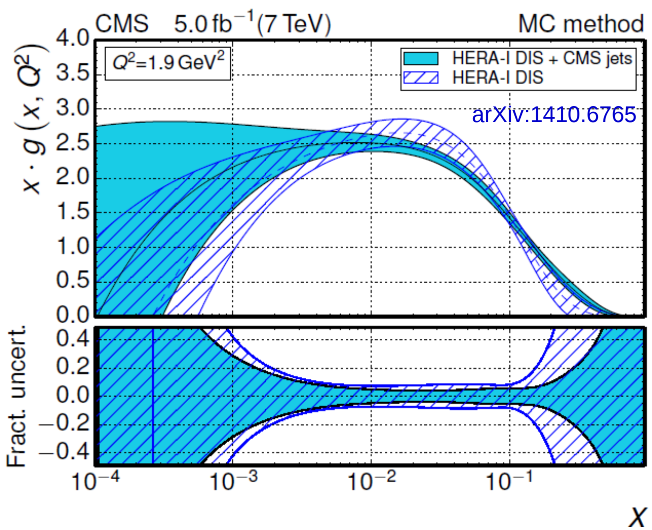


Drell-Yan processes (*pp, ppbar*)

→ strange quark density determination

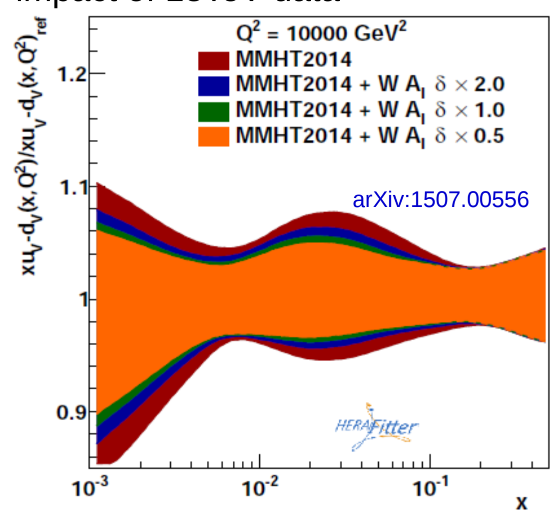


Jet production (*ep, pp, ppbar*)



PDF4LHC report (benchmarking)

→ impact of 13TeV data



HERAFitter: PDF Correlations Between Orders

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

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

HERAFitter developers' team ·
P. Belov[1,12] · D. Britzger[1] · S. Camarda[1] · A.M. Cooper-Sarkar[2] · C. Diaconu[3] · J. Feltesse[13] · A. Gizhko[1] · A. Glazov[1] · V. Kolesnikov[4] · K. Lohwasser[14] · A. Luszczak[5] · V. Myronenko[1] · H. Pirumov[1] · R. Plačakytė[1] · K. Rabbertz[6] · V. Radescu[1] · A. Sapronov[4] · A. Schöning[10] · S. Shushkevich[1] · W. Slominski[7] · P. Starovoitov[1] · M. Sutton[8] · J. Tomaszewska[9] · O. Turkot[1] · G. Watt[11] · K. Wichmann[1] and M. Lisovyi[1]

Abstract Sets of parton distribution functions (PDFs) of the proton are reported for the leading (LO), next-to-leading (NLO) and next-to-next-to leading order (NNLO) QCD calculations. The parton distribution functions are determined with the HERAFitter program using the data from the HERA experiments and preserving correlations between uncertainties for the LO, NLO and NNLO PDF sets. The sets are used to study cross-section ratios and their uncertainties when calculated at different orders in QCD. A reduction of the overall theoretical uncertainty is observed if correlations between the PDF sets are taken into account for the ratio of WW di-boson to Z boson production cross sections at the LHC.

EPJC (2014) 74: 3039

Motivation

Predictions for various processes at LHC are available at different orders in pQCD

→ PDFs and coefficient functions ideally should be paired at the same order

→ Factorisation theorem: $\sigma \approx \hat{\sigma} \otimes \text{PDF}$

uncertainties rise from PDFs and coefficient functions

missing higher order uncertainties often determined by the scale variation

Ratios of cross sections are used to reduce theoretical uncertainties:

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

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

Requires preserved correlations in PDF uncertainties at different orders

QCD Analysis Settings

EPJC (2014) 74: 3039

A QCD fit to HERA I data (JHEP 1001, 2010, 109) using HERAFitter

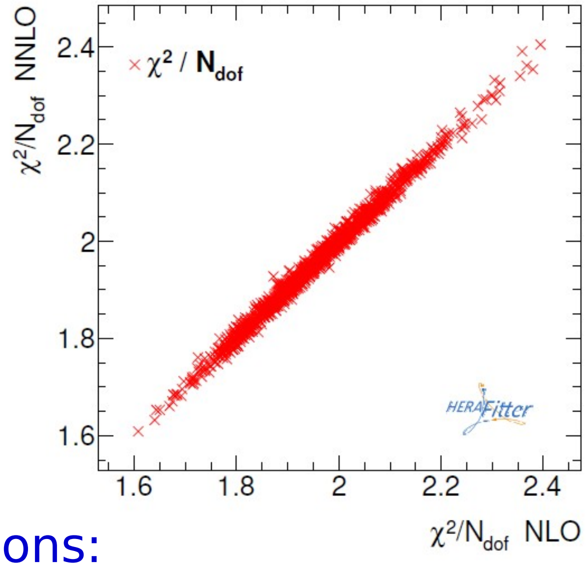
Parametrisation: $xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$

+ additional constraints and assumptions

Settings	LO	NLO	NNLO
HF scheme	TR' opt	TR' opt	TR' opt
r_s (s fraction)	1.0	1.0	1.0
m_c (GeV)	1.38	1.38	1.32
m_b (GeV)	4.75	4.75	4.75
α_s	0.13	0.1184	0.1184
Q^2_0 (GeV^2)	1.7	1.7	1.7
Q^2_{min} (GeV^2)	7.5	7.5	7.5

→ vary model parameters and parametrisation following HERAPDF prescription (JHEP 1001, 2010, 109)

correlation of χ^2 between orders



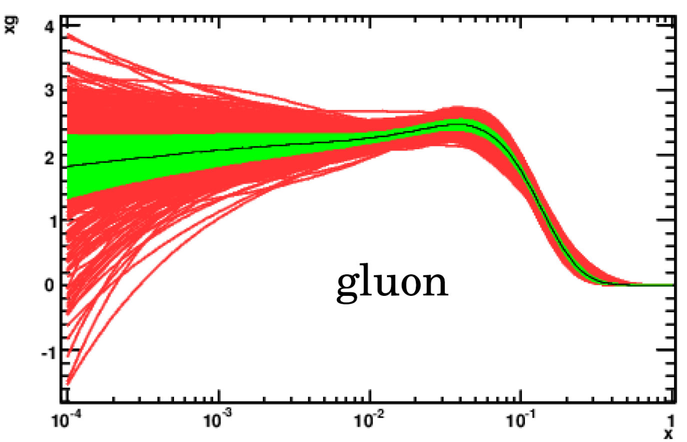
MC replica method used to preserve the correlations:

→ 1337 MC replicas of the data fluctuating the inputs within uncertainties using Gaussian prob densities

→ perform a consistent fit of PDFs at different orders to each replica

central PDF = average over replicas,
PDF uncertainty = RMS over replicas

model and param uncertainties treated correlated between orders



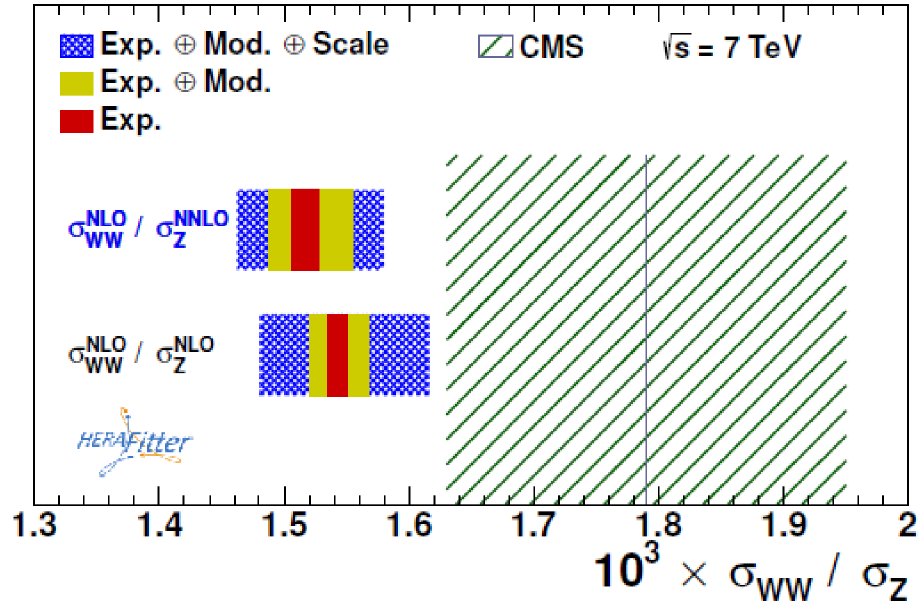
Comparison with Data

EPJC (2014) 74: 3039

Used case example: WW/Z ratio measurement from CMS (arXiv:1306.1126)

→ build the cross section ratio using the correlated PDFs

Ratio	Value $\times 10^{-3}$	Exp. PDF $\times 10^{-3}$	Mod. PDF $\times 10^{-3}$	Scale $\times 10^{-3}$
$\frac{\sigma^{NLO}_{WW}}{\sigma^{NLO}_{Z}}$	1.543	±0.008	$^{+0.023}_{-0.021}$	$^{+0.069}_{-0.058}$
$\frac{\sigma^{NLO}_{WW}}{\sigma^{NNLO}_{Z}}$	1.517	±0.010	$^{+0.036}_{-0.027}$	$^{+0.050}_{-0.046}$



→ predictions agree with the data within 1-2σ

→ the total theoretical uncertainty is reduced by 30-40%

→ mixed-order calculations with correlated PDFs help to reduce PDF and scale uncertainties

HERAFitter: QCD Analysis of Tevatron W, Z Data

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

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QCD analysis of W- and Z-boson production at Tevatron

HERAFitter developers' team: S. Camarda[1] · P. Belov[1,2] · A.M. Cooper-Sarkar[3] · C. Diaconu[4] · A. Glazov[1] · A. Guffanti[5] · A. Jung[6] · V. Kolesnikov[7] · K. Lohwasser[8] · V. Myronenko[1] · F. Olness[9] · H. Pirumov[1] · R. Plačakytė[1] · V. Radescu[10] · A. Sapronov[6] · W. Slominski[11] · P. Starovoitov[1] ·

arXiv:1503.05221

Abstract Recent measurements of the W-boson charge asymmetry and of the Z-boson production cross sections, performed at the Tevatron collider in Run II by the D0 and CDF collaborations, are studied to assess their impact on the proton parton distribution functions (PDFs), using the HERAFitter framework. The Tevatron measurements, together with deep-inelastic scattering data from HERA, are included in a QCD analysis performed at next-to-leading order, and compared to the predictions obtained using other PDF sets from different groups. Good agreement between measurements and theoretical predictions is observed. The Tevatron data provide significant constraints on the d-valence quark distribution.

1 Introduction

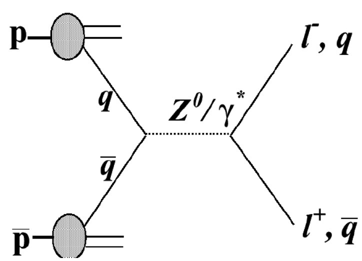
Accurate knowledge of the parton distribution functions (PDFs) is essential for predictions at hadron colliders. The primary source of information on the proton PDFs comes from deep-inelastic scattering (DIS). Measurements at fixed target experiments and at the HERA $e^{\pm}p$ collider provide constraints on the quark and gluon densities, and discrimination of the quark flavours. The DIS proton data mostly constrain the u-type quark density, due to the greater couplings to the photon at low absolute four momentum transfers, Q^2, whereas the d-type quark densities are only constrained at high Q^2 with limited precision. Even more chal-

Motivation

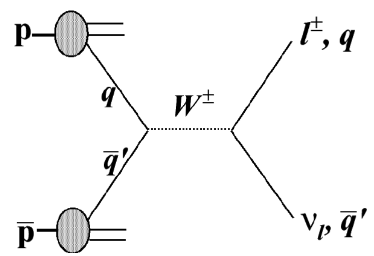
W and Z boson production at Tevatron is valence quark dominated

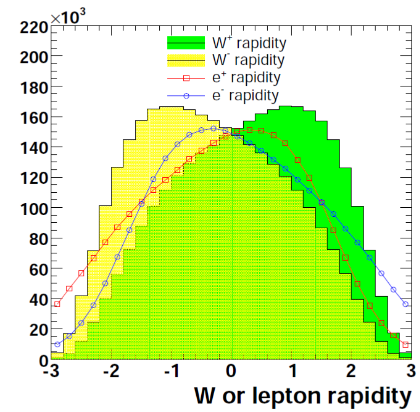
→ W and Z measurements at Tevatron can be used to improve valence quark PDFs, especially the d-quark type (less constrained by DIS data)

Z rapidity

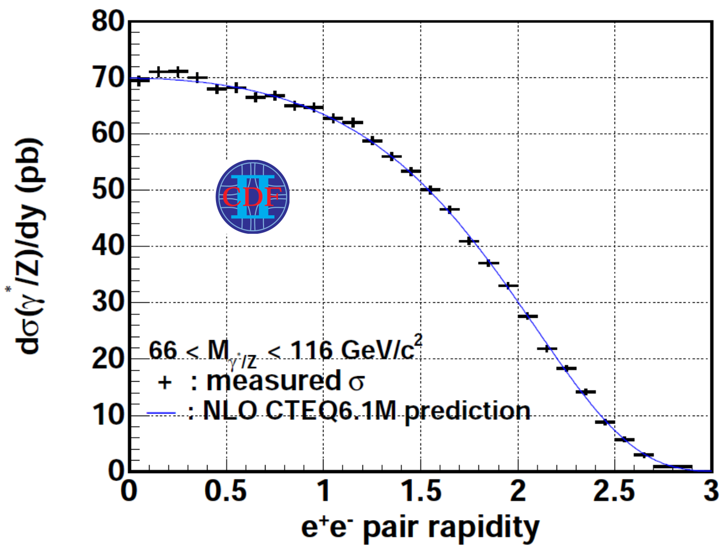


W and lepton charge asymmetry

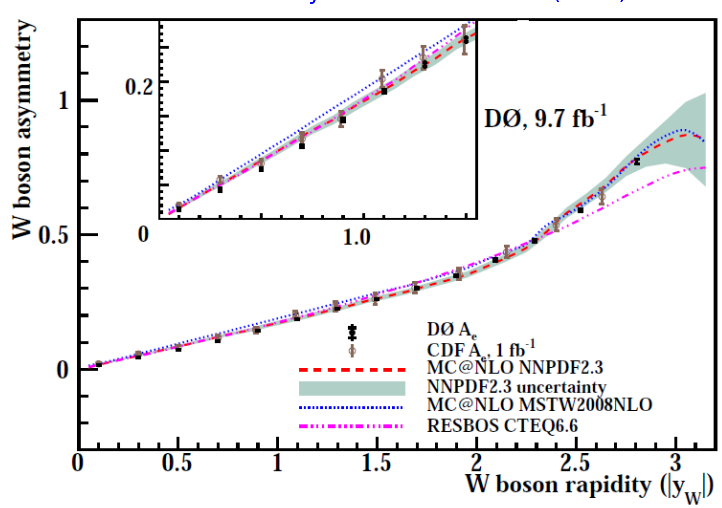




Phys Lett B 692 (2010) 232



Phys Rev Lett 112 no15 (2014)151803



W and Z Measurements at Tevatron

Tevatron W and Z production data sets (used in the QCD analysis)

Observable	Experiment	Integrated luminosity	Kinematic requirements	Used in the nominal fit	Ref.
$d\sigma(Z)/dy$	D0	$0.4\ \mathrm{fb}^{-1}$	$71 < m_{ee} < 111$ GeV	yes	Phys Rev D 76 (2007) 012003
$d\sigma(Z)/dy$	CDF	$2.1\ \mathrm{fb}^{-1}$	$66 < m_{ee} < 116$ GeV	yes	Phys Lett B 692 (2010) 232
A_μ $W \to \mu\nu$	D0	$7.3\ \mathrm{fb}^{-1}$	$p_T^\mu > 25$ GeV, $p_T^\nu > 25$ GeV	yes	Phys Rev D 88 (2013) 091102
A_e $W \to e\nu$	D0	$9.7\ \mathrm{fb}^{-1}$	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	no	Phys Rev D 91 no3 (2015) 032007
A_W $W \to e\nu$	CDF	$1.0\ \mathrm{fb}^{-1}$	none	yes	Phys Rev Lett 102 (2009) 181801
A_W $W \to e\nu$	D0	$9.7\ \mathrm{fb}^{-1}$	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	yes	Phys Rev Lett 112 no15 (2014)151803

Revised correlation model:

→ uncertainties of data-driven corrections are treated as bin-to-bin uncorrelated (lepton ID, trigger and charge efficiencies)

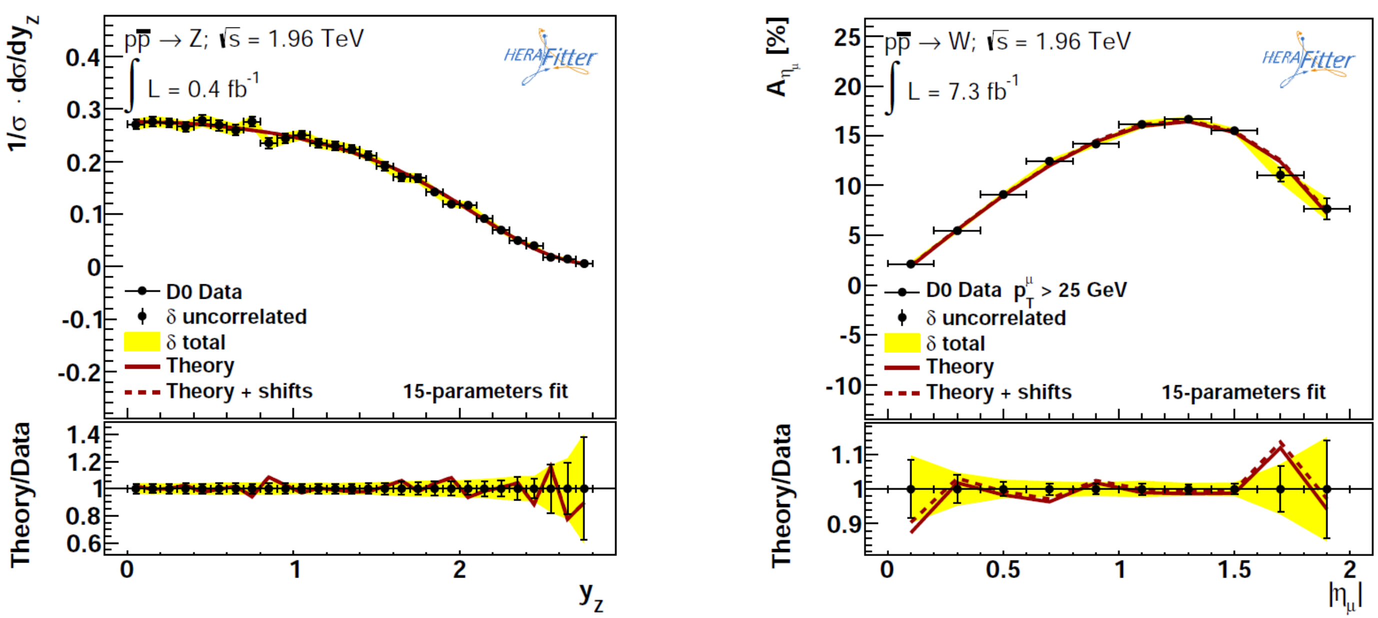
In the QCD analysis HERA I data sets (JHEP 1001 (2010) 109) used in a simultaneous fit with Tevatron W and Z production data

(Fast) theoretical predictions: MCFM+APPLGRID

QCD Analysis Results

Good total and partial (per data set) χ^2 of the fit:

Data set	HERA I χ^2 / number of points	HERA I + Tevatron W, Z χ^2 / number of points
NC DIS cross sections H1-ZEUS combined e^-p.	112 / 145	106 / 145
NC DIS cross sections H1-ZEUS combined e^+p.	326 / 337	334 / 337
CC DIS cross sections H1-ZEUS combined e^-p.	20 / 34	19 / 34
CC DIS cross sections H1-ZEUS combined e^+p.	27 / 34	33 / 34
HERA I correlated χ^2	21	23
D0 $d\sigma(Z)/dy$	-	23 / 28
CDF $d\sigma(Z)/dy$	-	33 / 28
D0 muon charge asymmetry in $W \to \mu\nu$	-	12 / 10
CDF W charge asymmetry in $W \to e\nu$	-	15 / 13
D0 W charge asymmetry in $W \to e\nu$	-	16 / 14
Total χ^2_{min} / dof	505 / 535	615 / 628

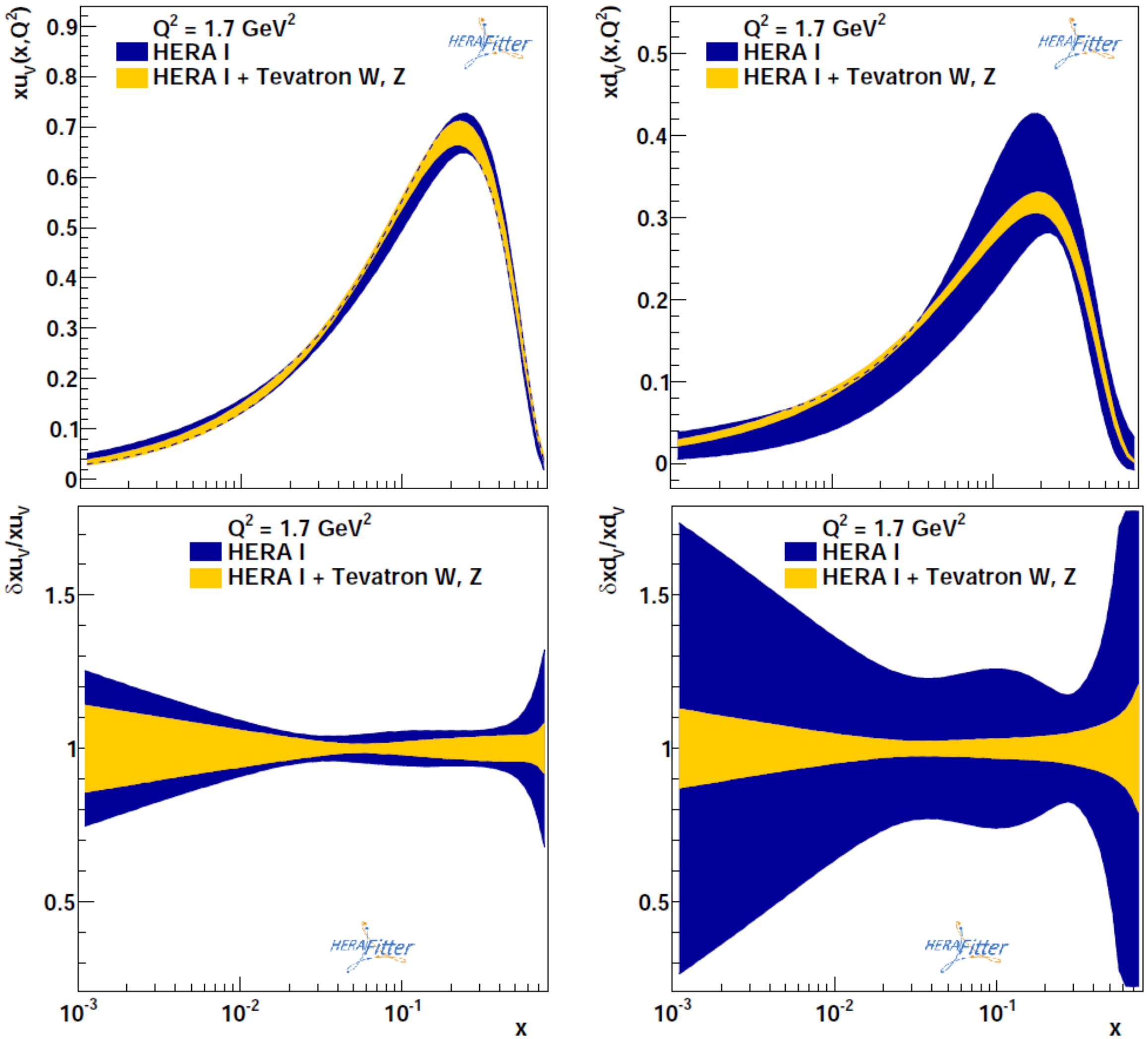


Impact on Valence Quarks

Significant impact of the W and Z boson measurements on the valence quarks and particularly on the d-type quarks

→ comparison of PDFs from a fit to the HERA data alone to a fit to the HERA and Tevatron data

→ after the inclusion of Tevatron data, the uncertainties of u_v and d_v become comparable in size



Comparison of Tevatron Data with Modern PDFs

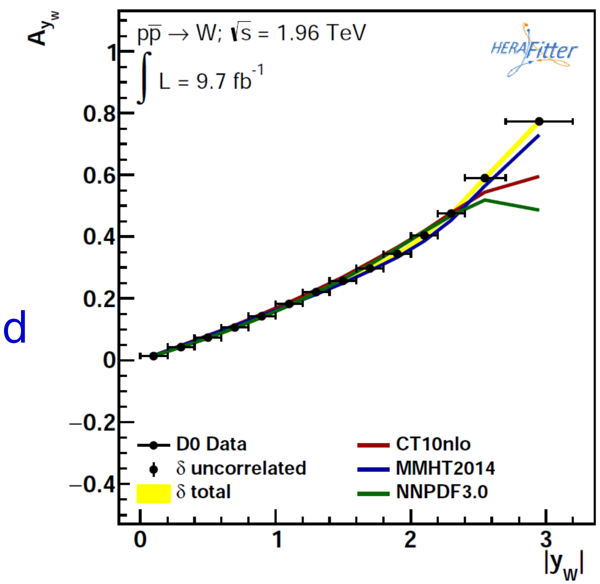
→ consider only the data sets which are not yet included in the PDF fits

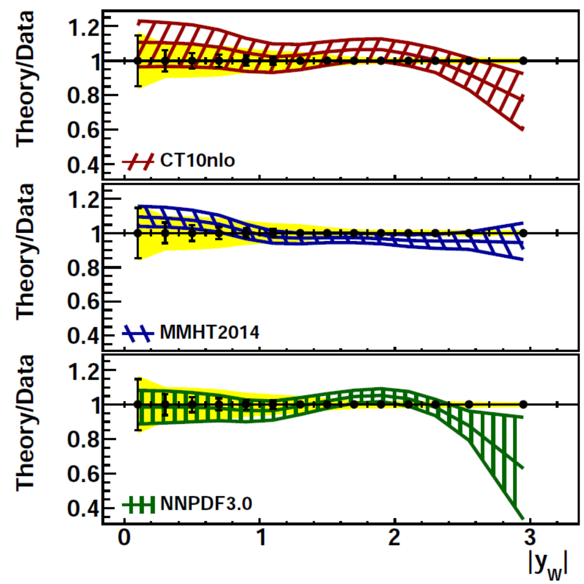
w/wo taking into account theory uncertainties: $\chi^2 = \sum_i \left(\frac{\mu_i - m_i \left[1 + \sum_j b_j^{\text{exp}} \gamma_{ji}^{\text{exp}} + \sum_j b_j^{\text{theo}} \gamma_{ji}^{\text{theo}} \right]}{\Delta_i} \right)^2 + \sum_j (b_j^{\text{exp}})^2 + \sum_j (b_j^{\text{theo}})^2$

PDF set	CT10nlo	MMHT2014	NNPDF3.0
	χ^2 / number of points	χ^2 / number of points	χ^2 / number of points
D0 muon charge asymmetry in $W \to \mu\nu$	13 / 10	-	12 / 10
CDF W charge asymmetry in $W \to e\nu$	15 / 13	-	17 / 13
D0 W charge asymmetry in $W \to e\nu$	15 / 14	10/14	3 / 14
PDF correlated χ^2	4	3	6
Total χ^2 / dof	47 / 37	14 / 14	39 / 37
Total χ^2 / dof without PDFs uncertainties	368/37	42/14	846 / 37

Good description

→ no tension between Tevatron data observed



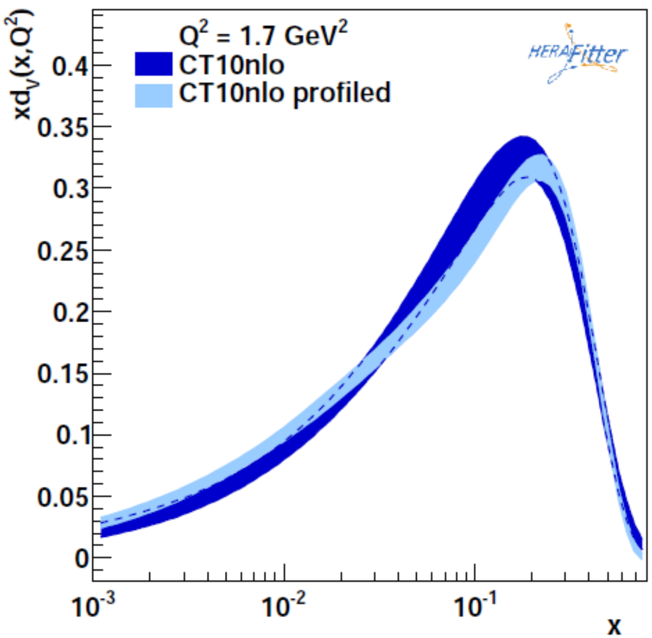


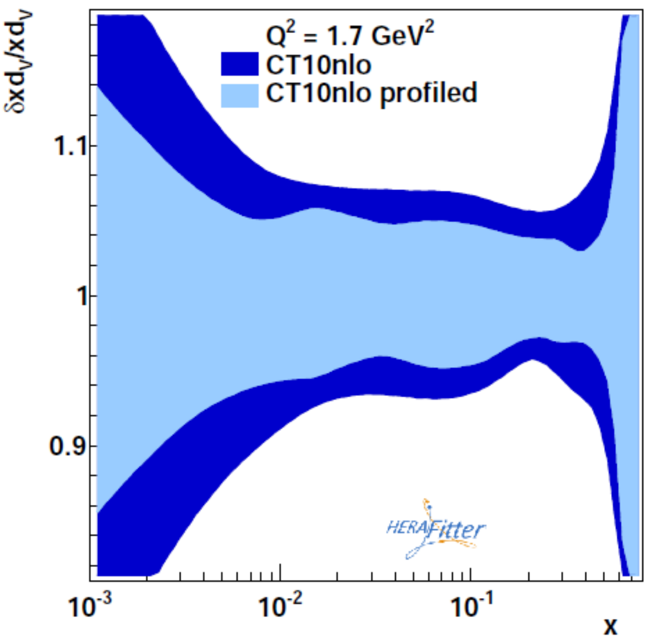
Impact on PDFs Using Profiling Technique

Impact of Tevatron data on PDFs can be studied by minimizing data to theory χ^2 vs nuisance parameters corresponding to PDF eigenvectors (“profiling”)

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

μ_i - data, m_i – theory, β_j^{theo} – nuisance parameters of theory uncertainties (PDF) (asymmetric uncertainties are taken into account)

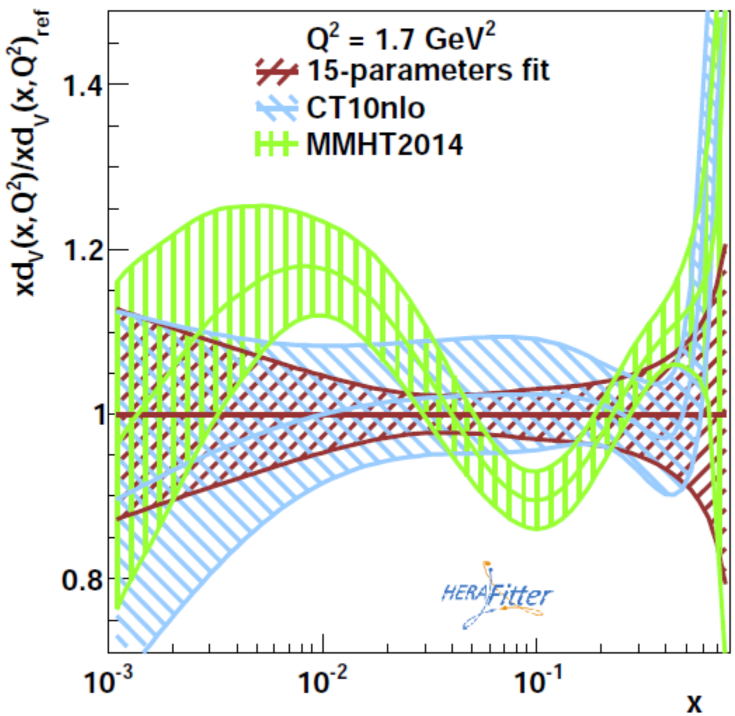


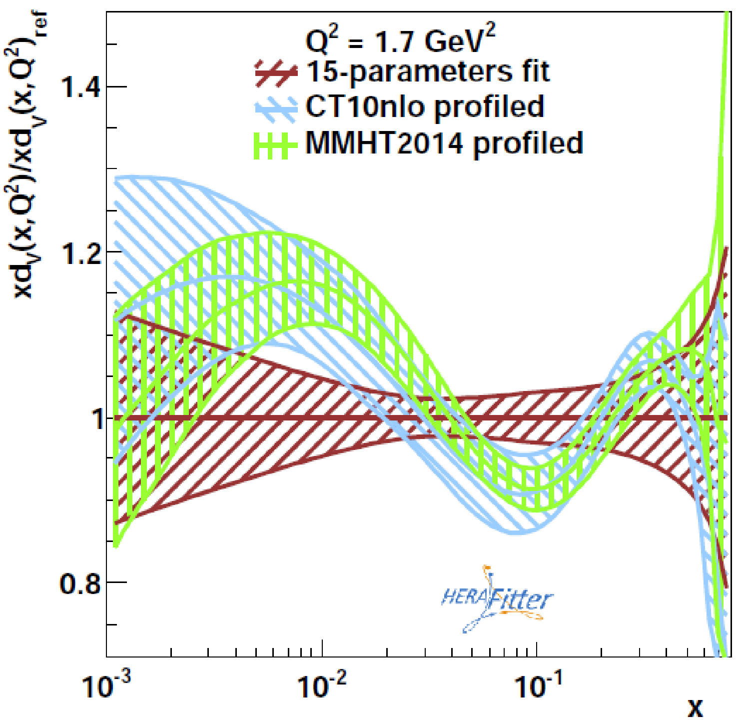


→ similar as in PDF fit case, a significant reduction on the d_v quark is observed

Impact on PDFs Using Profiling Technique

Original CT and MMHT PDFs → Profiled CT and MMHT PDFs





only the measurements that are not included in the each of PDF sets are considered for the profiling

→ improved agreement of the d-valence distribution between the MMHT2014 and CT10nlo PDF sets

Summary

HERAFitter project - a multi-functional QCD framework well integrated into the high energy community (both, experimental and theory)

→ various physics cases
→ various options for data uncertainty treatment
→ different parametrisation styles

EPJC (2015) 75: 304

herafitter-1.1.1 latest (recommended) release

Project is open to everyone and everyone can contribute

Sets of **LO, NLO and NNLO PDFs with correlated uncertainties at different orders**

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

EPJC (2014) 74: 3039

Successful inclusion of the latest **Tevatron W and Z data** in a PDF fit

→ highlighting the importance Tevatron data for constraining valence quark PDFs

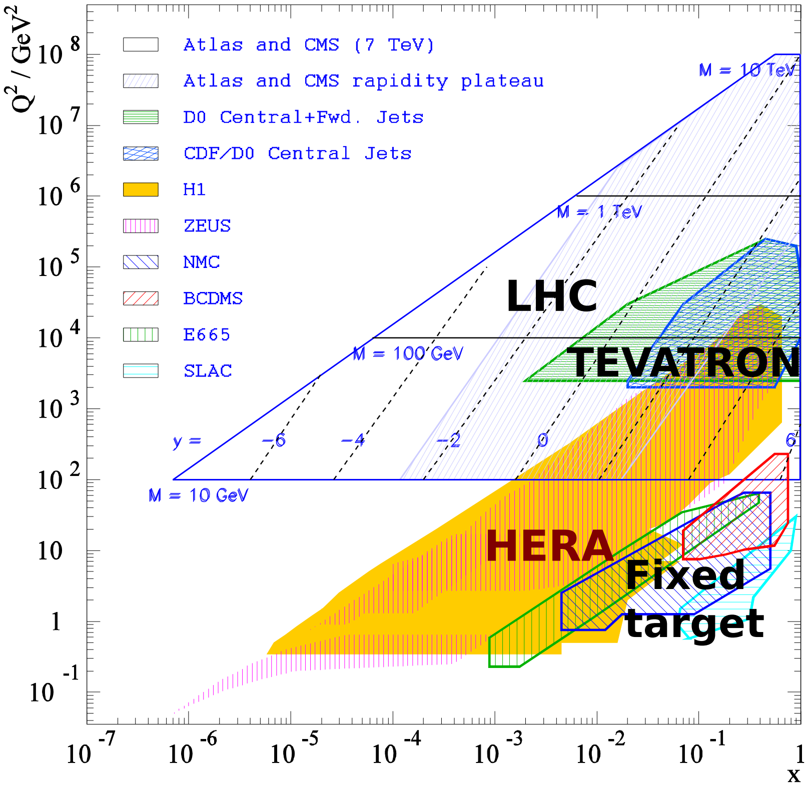
→ data tables and APPLGRID theory predictions to fit the Tevatron data are available in www.herafitter.org

arXiv:1503.05221

Back-up Slides

HERAFitter Project

Different experimental data can be used for QCD studies in HERAFitter:



- **LHC**
  - → Drell-Yan
  - → jet production
  - → top quark pair production
- **TEVATRON**
  - → Drell-Yan
  - → jet production
  - → top quark pair production
- **HERA**
  - → inclusive DIS
  - → jet production
  - → diffraction
  - → low-x data
- **Fixed target**

Understanding of the correlations in the measurement is important for the proper inclusion of data into PDF fits

HERAFitter provides tools to test correlations and assess impact of new data on PDFs

PDF Determination

based on **QCD factorisation**

PDF / hard-scattering ME

$$\sigma(\alpha_s,\mu_R^2,\mu_F^2)=\sum_{a,b}\int_0^1 f_a(x_1,\mu_F^2)f_b(x_2,\mu_F^2)\,\hat{\sigma}(x_1,x_2;\alpha_s,\mu_R^2,\mu_F^2)+\ldots$$

Experimentally measured $\sigma(x,Q^2)$

Q^2 dependence of σ is given in perturbative QCD: DGLAP evolution equations

x-dependence of PDFs is not calculable in perturbative QCD

- parametrise PDFs at the starting scale Q^2_0
- evolve PDFs using DGLAP equations to $Q^2 > Q^2_0$
- χ^2-fit to the experimental data $\chi^2(p)=\sum_{i=1}^{N}\left(\frac{\text{data}(i)-\text{theory}(i,p)}{\text{error}(i)}\right)^2$

Eigenvector Representation

EPJC (2014) 74: 3039

Eigenvector representation is often more convenient than MC replica

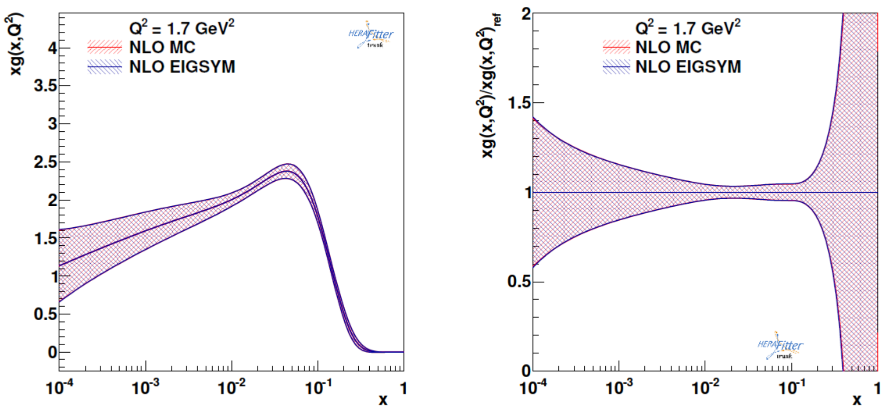
employ the method suggested for extraction of META PDFs (arXiv:1401.0013)

→ build the covariance matrix

→ diagonalise matrix and keep only leading eigenvectors

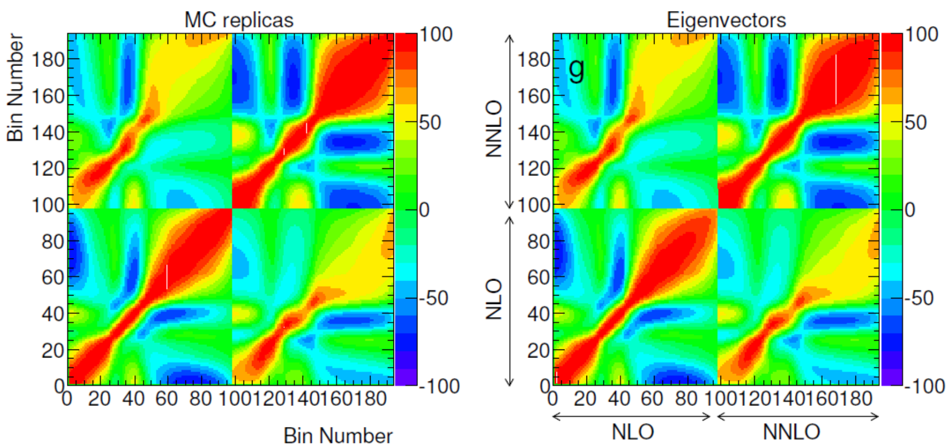
→ evolve tabulated values (central and eigenvectors) using DGLAP evolution

Comparison of PDFs determined with MC method and its eigenvector representation



→ very good agreement between PDFs

Correlation coefficients among PDFs:



→ PDFs show high degree of correlation at neighboring x bins (smoothness of parametrisation)

→ strong correlation between NLO and NNLO PDFs

QCD Analysis Settings

In the QCD analysis HERA I data sets (JHEP 1001 (2010) 109) used in a simultaneous fit with Tevatron W and Z production data

Parametrisation functional form:

→ optimisation via paramterisation scan

→ 15 parameter central parametrisation which includes linear and exponential terms

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1 + D_g x)\,; \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} e^{F_{u_v} x}\,; \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} e^{F_{d_v} x}\,; \\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}} (1 + D_{\bar{u}} x)\,; \\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}} (1 + D_{\bar{d}} x)\,.
\end{aligned}
$$

$x\bar{U}=x\bar{u}$ and $x\bar{D}=x\bar{d}+x\bar{s}$ at the starting scale Q^2 = 1.7 GeV^2 ($x\bar{s}=r_s x\bar{D}$ with $r_s=1.0$)

A_g, A_{uv}, A_{dv} are fixed by the sum rules, $B_{\bar{u}}=B_{\bar{d}}$ and $A_{\bar{u}}=A_{\bar{d}}$

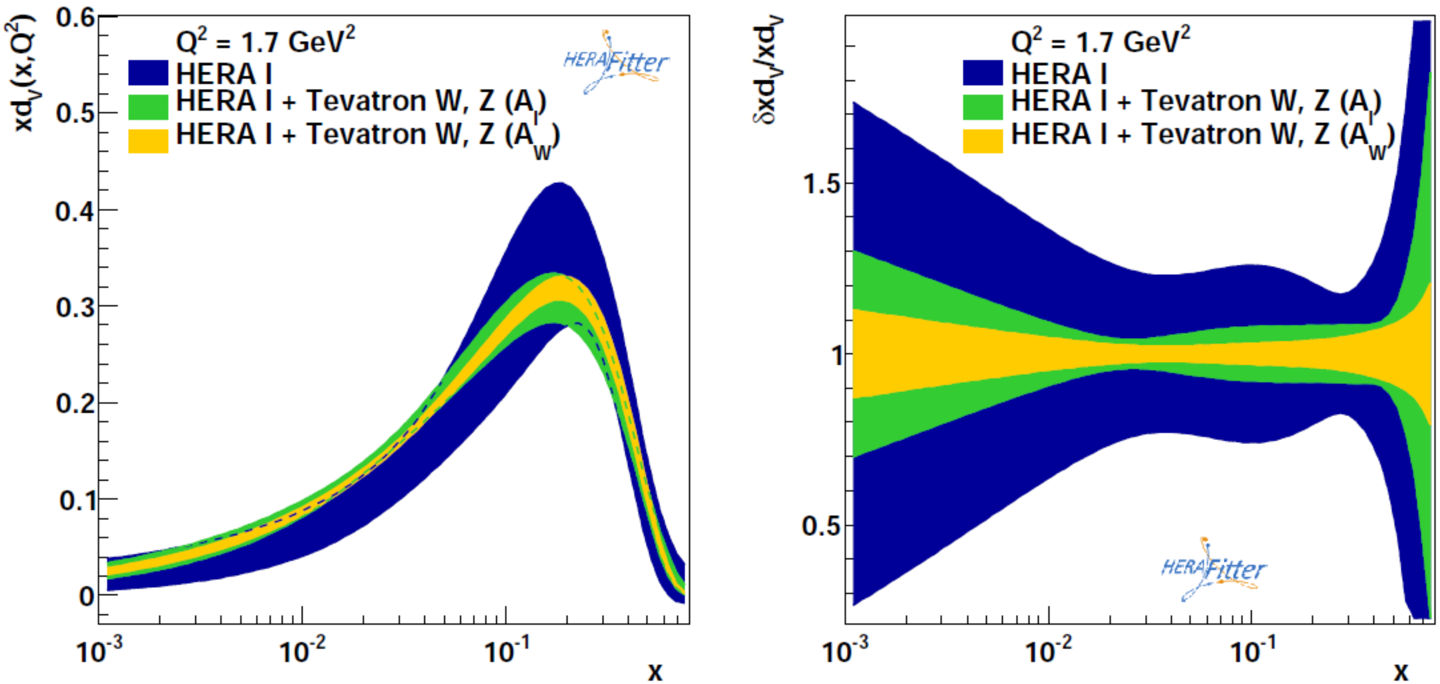
W vs Lepton Asymmetry

W boson charge asymmetries rely on the reconstruction of the W boson rapidity

→ requires assumptions on the longitudinal momentum of the neutrino

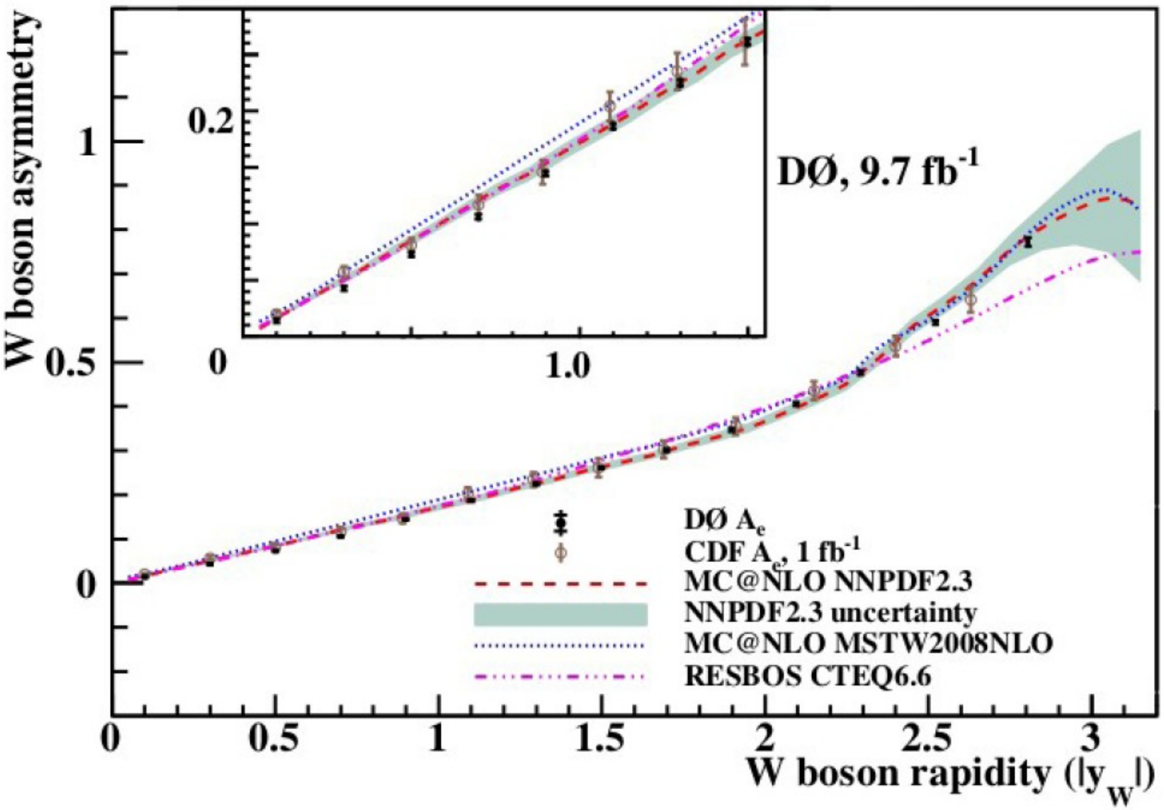
→ model dependence is introduced

→ study of possible bias via alternative fit, excluding W and including lepton asymmetries



→ compatible results but larger uncertainties in a fit with lepton asymmetries

Comparison of W Asymmetry in CDF and D0



CDF and D0 measurements are defined in different kinematic space

CDF
no cuts

D0
$E_T(e) > 25$ GeV
$p_T(\nu) > 25$ GeV

Apparent tension between CDF and D0, if the comparison is performed without correcting for the different phase space definitions of the two measurements

S. Camarda, PDF4LHC, Apr 13