Quark PDFs at the LHC

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QCD Tools for LHC Physics: From 8 to 14 TeV. What is needed and why?

14-15 November, 2013

Content:

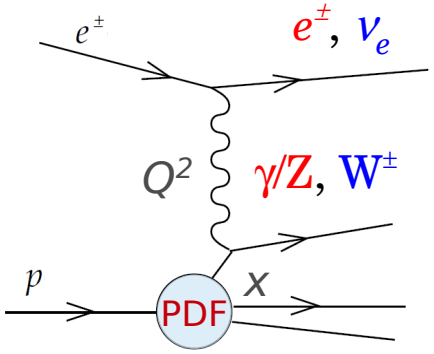
- Introduction
- LHC measurements constraining quark PDFs
- HERAFitter project and functionality
- Outlook and summary

Introduction

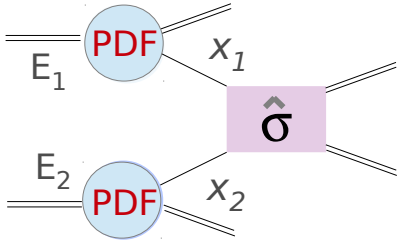
QCD factorisation: hadronic cross section is a convolution of the PDFs and perturbatively calculable hard-scattering coefficients:

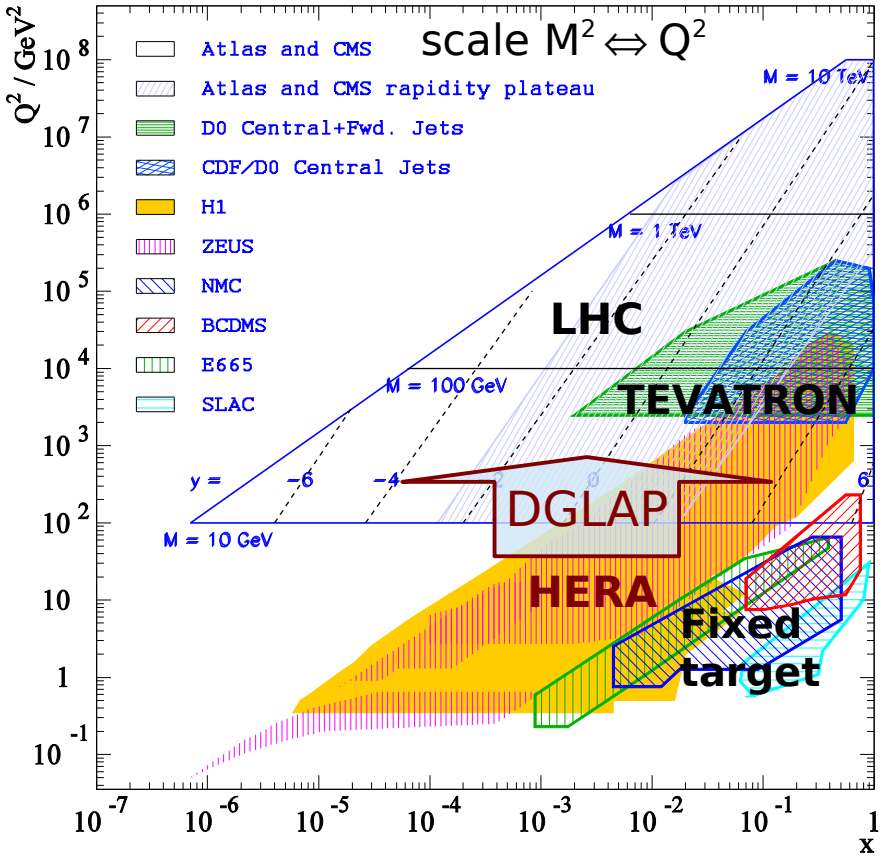
$$\sigma \approx \hat{\sigma} \otimes \text{PDF}$$

Deep Inelastic Scattering (DIS): strongest constraints on PDFs so far



same PDFs can be used to predict *pp* collisions





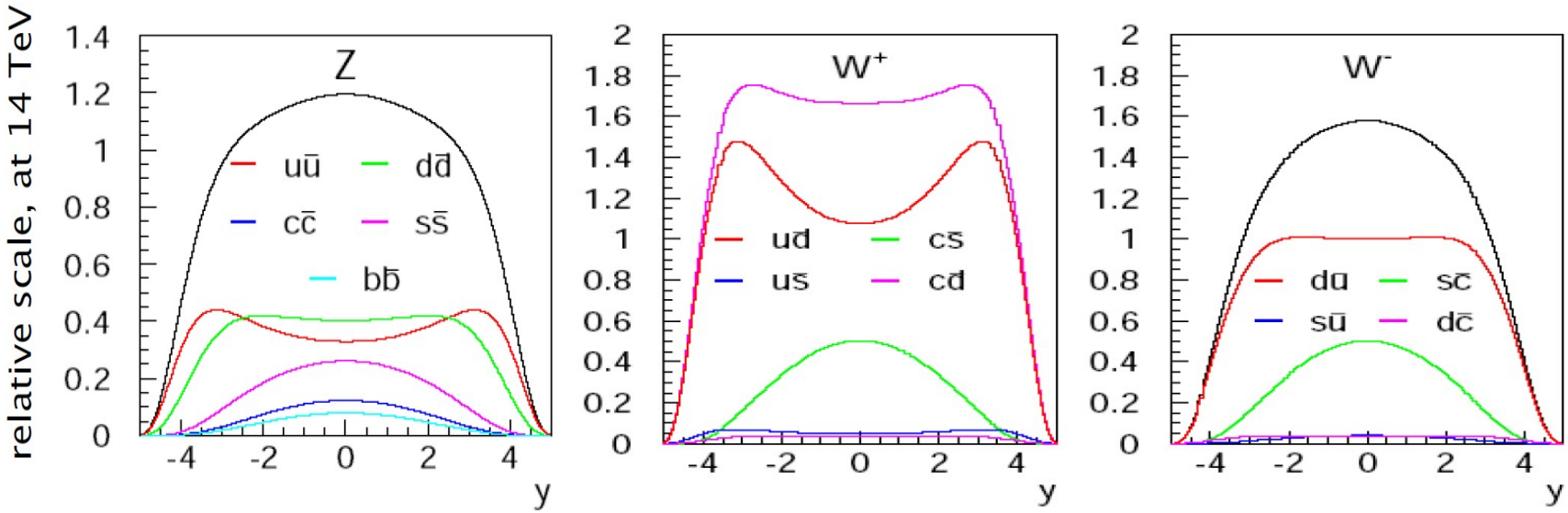
PDFs at LHC will be probed/constrained in a different kinematic region: PDFs precision will be improved

Constraints on the quark PDFs from LHC data

Quark PDF are constrained by LHC data:

Z and W production

→ probe different flavour combinations
→ sensitivity to d/u ratio and valence
→ access to strange and charm quarks in the central rapidity region



→ u and d quarks dominate for W, all flavours contribute to Z

Theory and tools for Z,W production at LHC

Main available theory calculations for Z, W production predictions:

FEWZ, DYNNLO, RESBOS, MCFM, VRAP, POWHEG, aMC@NLO, …

→ fully differential inclusive NNLO QCD cross sections:

FEWZ Y. Li and F. Petriello, Phys.Rev. D86 (2012) 094034, 1208.5967

DYNNLO S.Catani, L. Cieri, G. Ferrera, D.de Florian, and M. Grazzini, Phys.Rev.Lett. 103 (2009) 082001, 0903.2120

RESBOS Balazs and Yuan, Phys. Rev. D (1997) hep.pa.msu.edu/resum (NLO and approx NNLO)

EW corrections @NLO: FEWZ 3.1, SANC D. Bardin et al., arXiv:1207.4400

Many theory calculations are time consuming: using them in PDF fits can be problematic

Tools for theory predictions at LHC

Theory calculations are time consuming → using in PDF fits can be problematic

Possible solutions:

→ use Kfactor technique (LO+ NLO Kfactors)

→ using fast interfaces based on separation of perturbative coefficients from PDFs and storing them into look-up tables:

APPLGRID http://applgridhepforge.org, Eur.Phys.J.C66:503-524,2010

interfaces to MCFM J. M. Campbell, R. K. Ellis, Phys.Rev. D60, 113006 (1999), Nucl.Phys.Proc.Suppl. 205, 10 (2010)

NLOjet++ Z. Nagy, Phys.Rev.Lett. 88, 122003 (2002)

work ongoing to interface DYNNLO, aMC@NLO

FastNLO http://fastNLO.hepforge.org, hep-ph/1208.3641

interfaces to NLOjet++ Z. Nagy, Phys.Rev.Lett. 88, 122003 (2002)

Z and W measurements at LHC

Very successful LHC operation (~30 fb^{-1} of luminosity in 2010-2012)

Z,W boson production measurements relevant for quark PDFs:

W and Z production cross sections
7TeV, 315 nb^{-1} (2010) JHEP 1012(2010) 060

W muon charge asymmetry
7TeV, 31 pb^{-1} (2010) Phys.Lett. B701(2011) 31

W,Z incl cross sections in e and μ channels
7TeV, 36 pb^{-1} (2010) Phys.Rev. D 85 (2012) 072004

Strange quark density determination
Z,W 36 pb^{-1} (2010), Phys.Rev.Lett.109(2012)012001

High-mass Drell-Yan differential cross sections
7TeV, 4.9 fb^{-1} (2011), Phys.Lett.B725(2013) 223

W+c production
7TeV, 4.6 fb^{-1} (2011), ATLAS-CONF-2013-045

W electron charge asymmetry
7TeV, 840 pb^{-1} (2011) Phys.Rev.Lett. 109(2012)111806

Z rapidity and transverse momentum
7TeV, 36 pb^{-1} (2010) Phys.Rev. D 85 (2012) 032002

W muon charge asymmetry
7TeV, 4.7 fb^{-1} (2011) SMP-12-021

Drell-Yan differential cross sections at 7 TeV
7TeV, 4.8 fb^{-1} (2011), SMP-13-003, arXiv:1310.7291

W+c differential cross sections
7TeV, 5 fb^{-1} (2011), SMP-12-002, arXiv:1310:1138

Inclusive W and Z production
7TeV, 37 pb^{-1} (2010) J High En. Phys. 06 (2012) 058

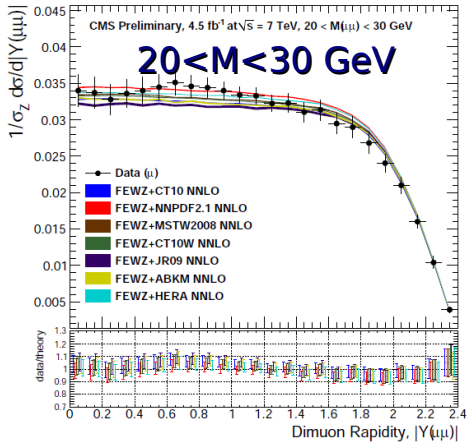
Z production (μ and e channels)
7TeV, 1 fb^{-1} (2011), LHCb-CONF-2013-007 (μ), J High En. Phys. 02 (2013) 106 (e)

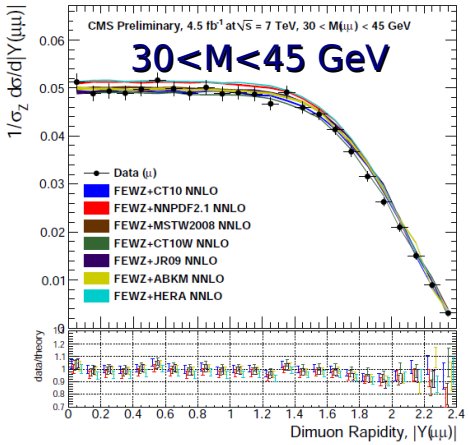
CMS Z double differential measurement

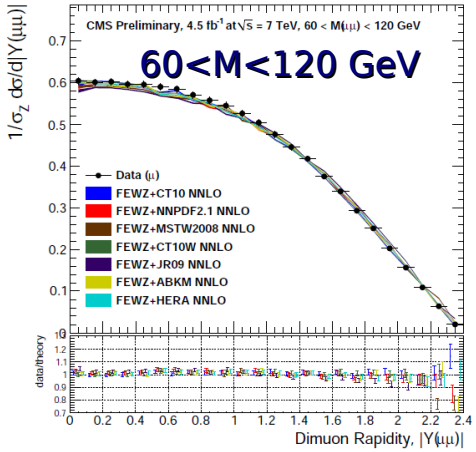
Z boson rapidity y is directly related to the momentum fraction x of the interacting partons: $x_{\pm} \approx M/\sqrt{s}\, e^{\pm y}$

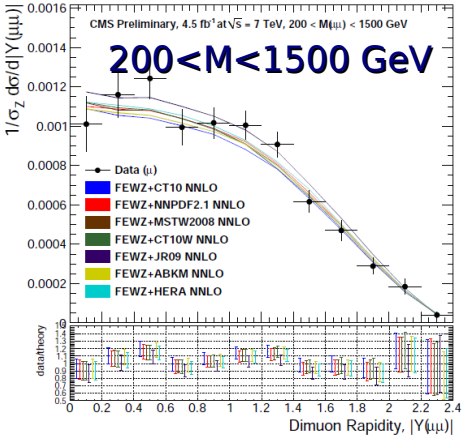
Z rapidity differential and double differential measurement at 7 TeV

→ 4.8 fb^{-1} e (p^T>20,10 GeV) and 4.5 fb^{-1} μ (p^T>14,9 GeV) channels combined









arXiv:1310.7291

→ normalised to Z peak

→ <2% statistical uncertainty

→ compared to all NNLO (FEWZ) PDFs

→ consistent with most of PDFs

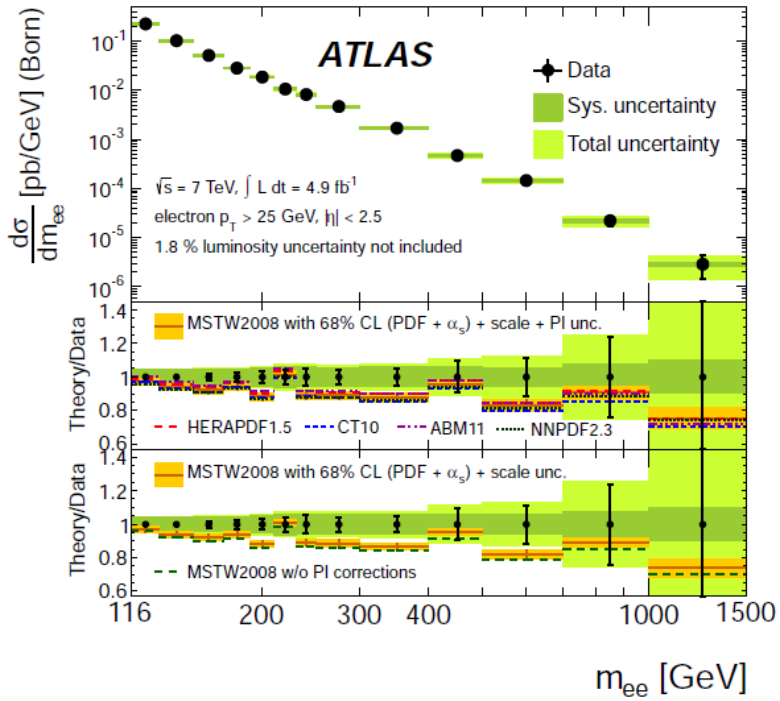
→ expect to improve PDFs (quarks and anti-quarks)

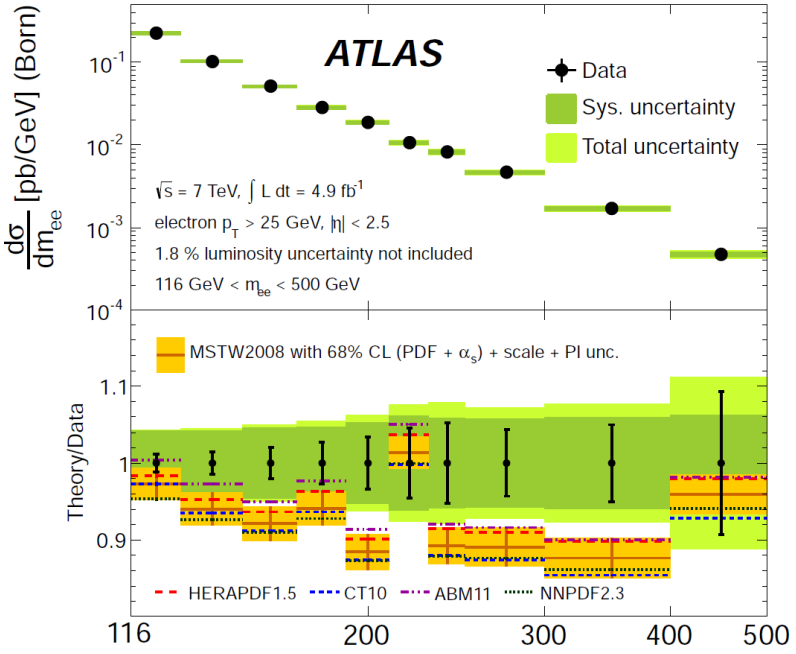
ATLAS High-Mass Drell-Yan measurement

DY differential measurement at 7 TeV

→ 4.7 fb^{-1} e (p^T>20 GeV) in 116 < M_{ee} < 1500 GeV

Phys.Lett.B725(2013) 223





→ compared to different PDFs (FEWZ v3.1 NNLO QCD+NLO EW)

→ photon induced (PI) corrections considered

→ similar size as the sum of PDF, as and scale uncertainties together

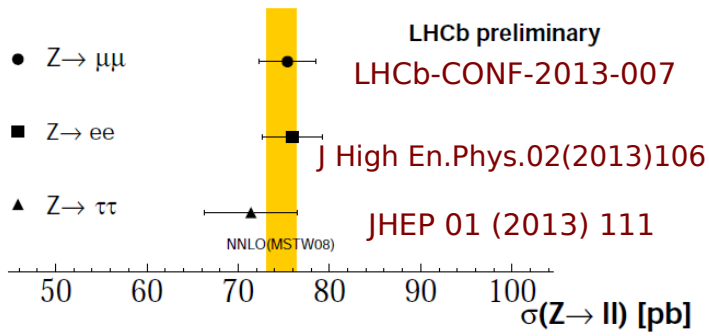
→ potential to constrain high-x quark and antiquark PDFs

LHCb Z production measurements

Measurement of Z production at LHCb

$Z \to \mu\mu$ is the most precise (~4% for η=3)

1 fb^{-1}, p^T>20 GeV, 2.0<η<4.5, 60 < M < 120 GeV

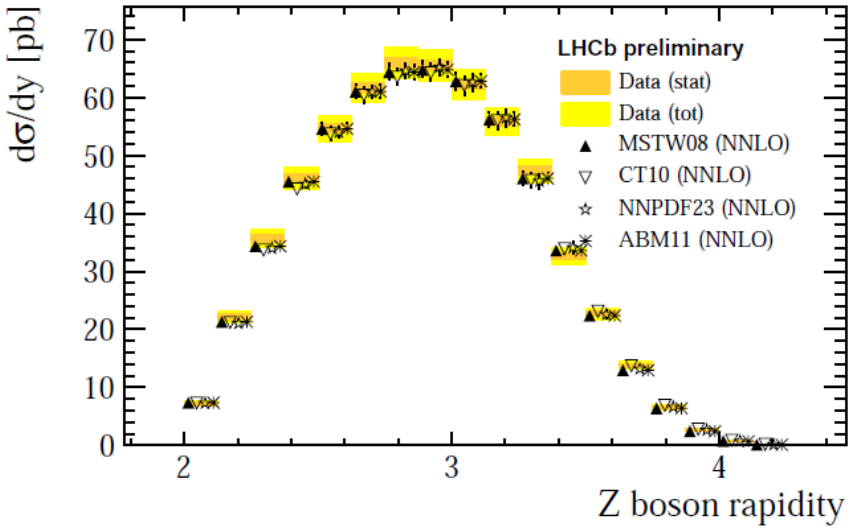


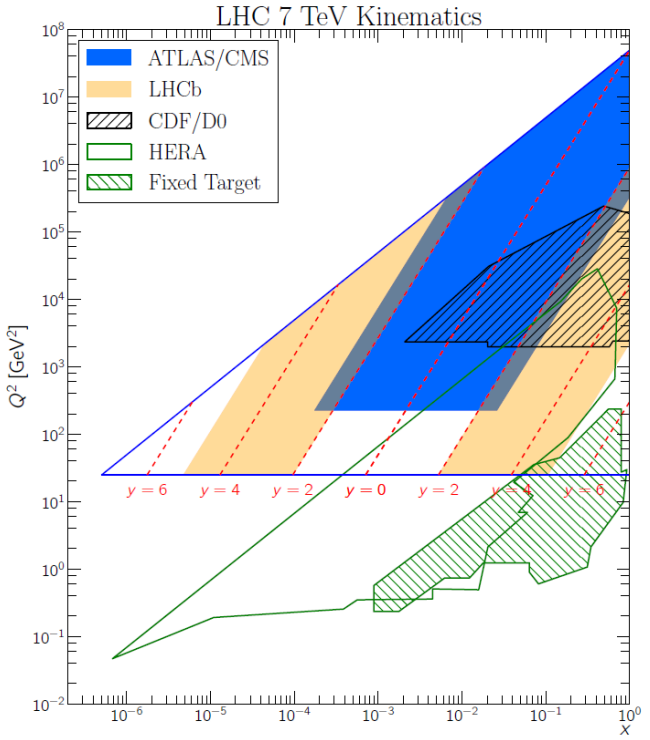
LHCb-CONF-2013-007

J High En.Phys.02(2013)106

JHEP 01 (2013) 111

LHCb-CONF-2013-007





→ significant extension in η range compared to ATLAS/CMS measurements

→ PDF constraints in the low-x region

W lepton charge asymmetry

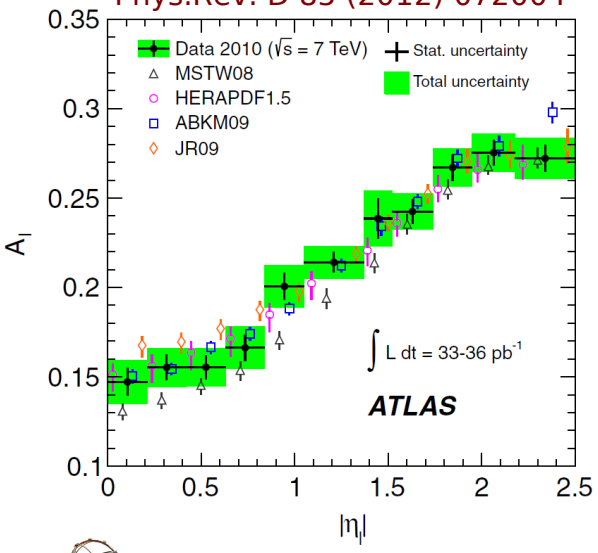
W lepton asymmetry measurement

→ overall excess of W^+ over W^- due to presents of two valence *u* quarks in the proton

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

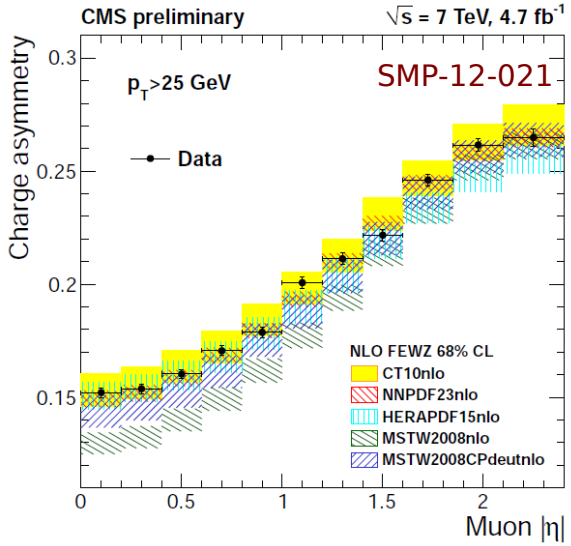
→ probe valence quarks and PDFs rations (u_v, d_v, d/u, d_v/u_v, dbar/ubar):

Phys.Rev. D 85 (2012) 072004



→ P^T_l>20, P^T_ν>25, m^T>40 GeV

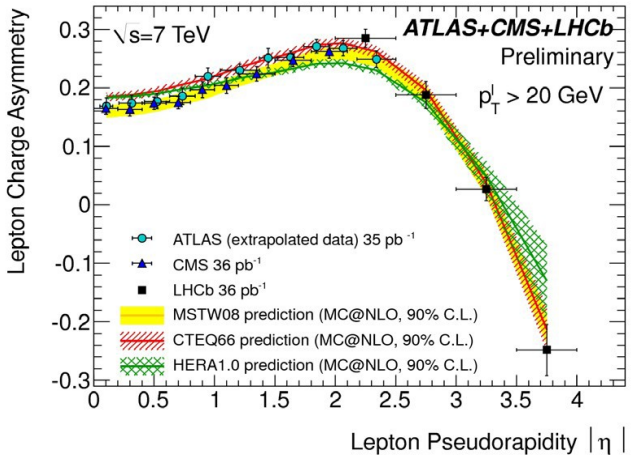
→ full experimental correlations reported



→ P^T_l>25 and 35 GeV

→ most precise measurement to date (2-4% uncertainty)

→ in the process of publication



→ extended η region

→ interesting region (due to V–A structure of W to lepton coupling)

Strange quark density determination

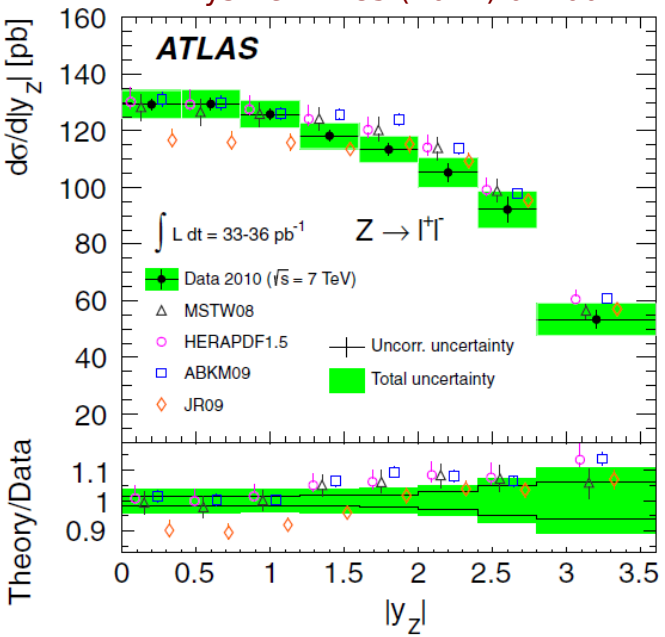
Strange quark density in the proton is still poorly known

→ mainly constrains come from fixed target data (NuTeV, HERMES, NOMAD)

→ LHC Z,W and W+charm data sensitive to strange quark density

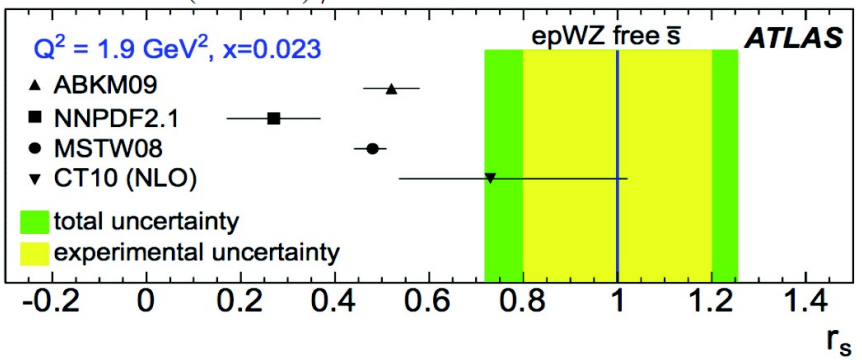
The differential ATLAS $W^{\pm}$, Z data used to measure strange quark density

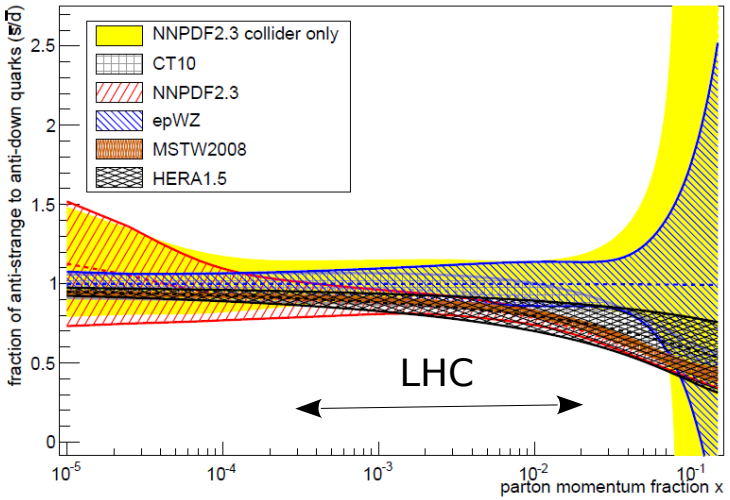
Phys.Rev. D 85 (2012) 072004



→ data suggests light quark sea at low x favor symmetric

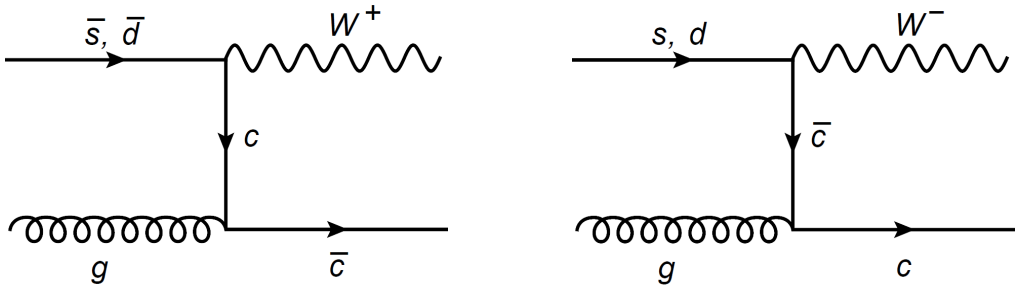
$r_s = 0.5(s+\bar{s})/\bar{d}$ Phys.Rev.Lett.109(2012)012001



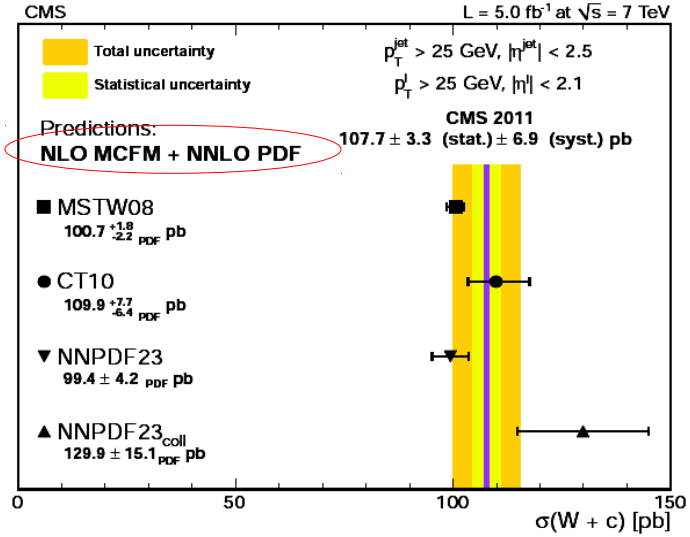


W+charm measurements at LHC

W+charm data → direct sensitivity to the strange quark (LO)

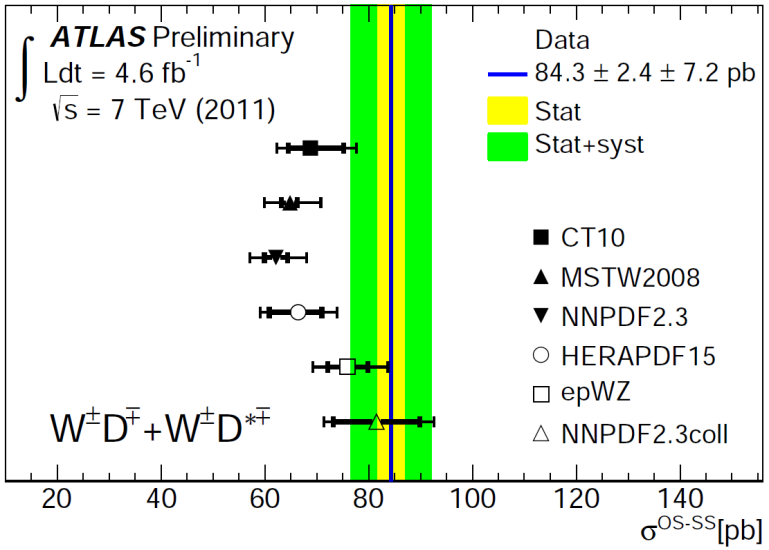


arXiv:1310:1138



aMC@NLO (NLO PDFs)

ATLAS-CONF-2013-045



→ with CT10 as reference one can see that CMS and ATLAS results are compatible

W+charm measurements at LHC

ATLAS and CMS measurements (both at 7 TeV and 4.6/5 fb^{-1})

Identification:

→ W decays to charged leptons (e or μ) and neutrino

→ the charm quark is tagged by the presence of the c hadron: $D^{+}(D^{-})$, $D^{*+}(D^{*+})$, D0)

: reconstructed tracks

$P^{T}_{l}>20$ GeV, $|\eta_{l}|<2.5$, $p^{T}_{\nu}>25$GeV ($M_{T}^{W}<40$GeV)

: jets identified (secondary vertices), semileptonic decay with well identified μ

$P^{T}_{l}>25(35)$ GeV, $|\eta_{l}|<2.1$ ($p^{T}_{jet}>25$GeV, $|\eta_{jet}|<2.5$)

Background subtraction: perform by

subtracting the Same Sign (SS) from the Opposite Sign (OS) distributions

→ does not affect the signal

→ most of background processes (e.g. W→ccbar) have same SS and OS → significant reduction

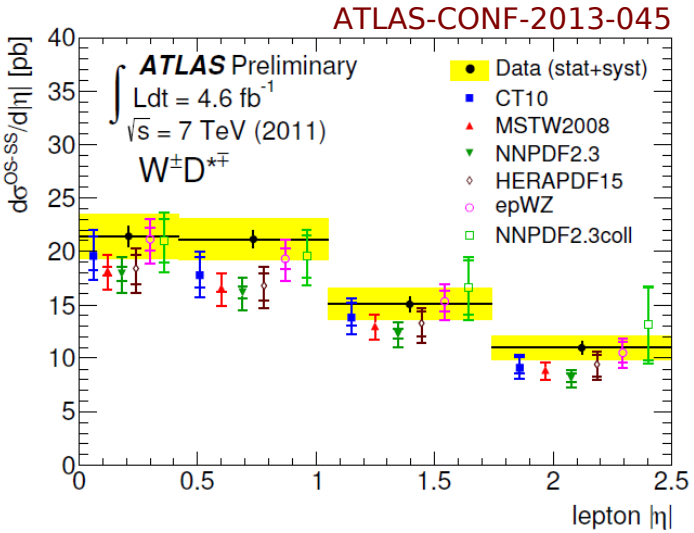
Theory comparison:

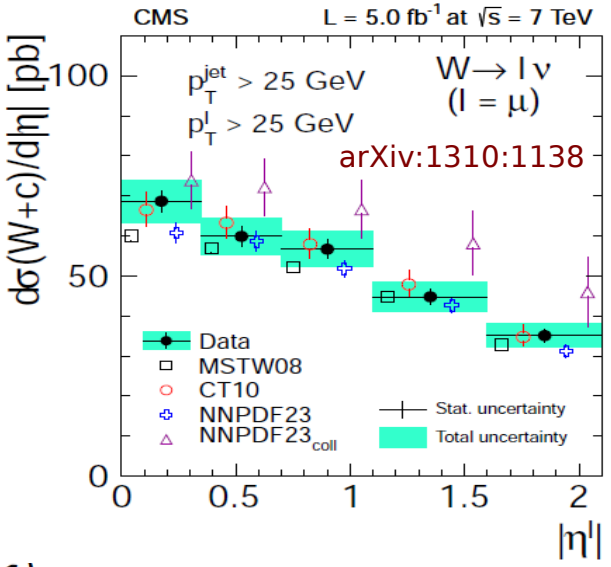
: aMC@NLO (NLO, parton level correction is an issue)

: MCFM (NLO with NNLO PDFs)

W+charm measurements at LHC

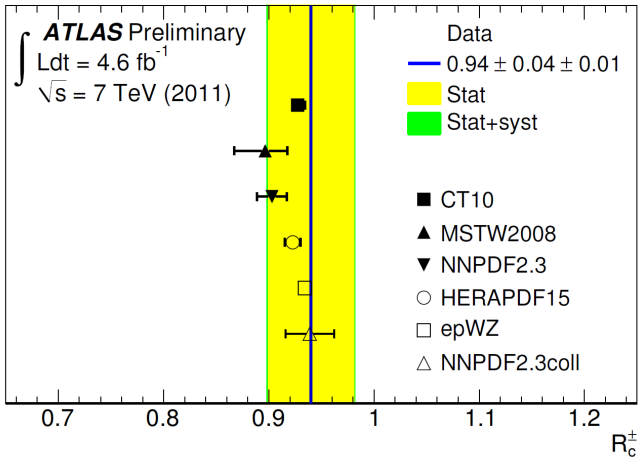
Differential measurement: → direct sensitivity to s quark density

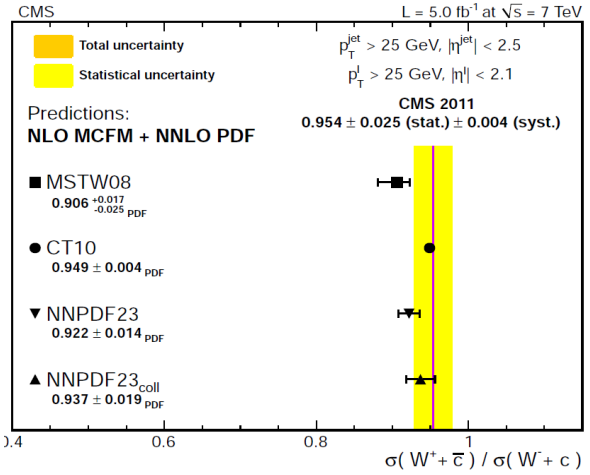




Cross section ratio (R_c): $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$

→ can be used to study s-sbar asymmetry in PDFs



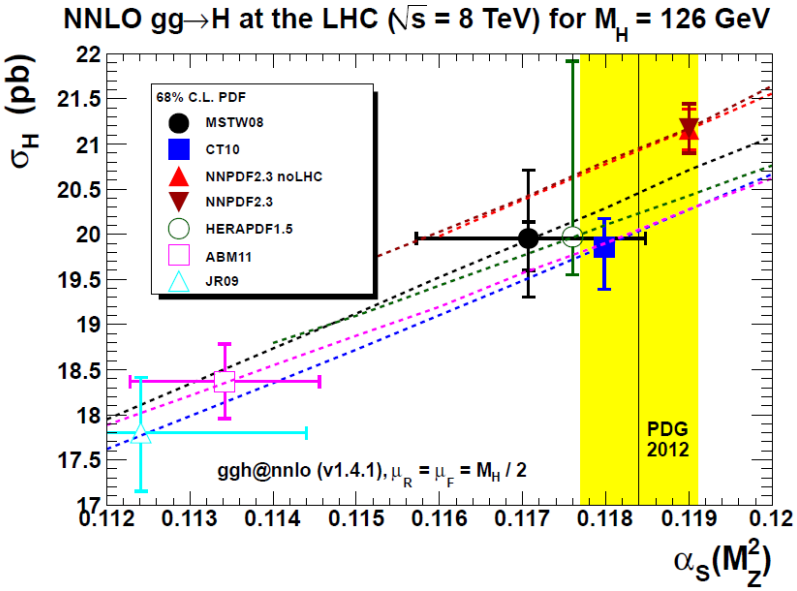


HERAFitter: Motivations

Different PDF fitting groups (CT, MSTW, NNPDF, HERAPDF, ABM, JR) use different data and methodologies to extract PDFs

→ lead to differences in the predicted cross sections

HERAFitter is an open source QCD platform which can be used for benchmarking and understanding such differences



LHC and HERA experiments published several papers with results obtained using HERAFitter

HERAFitter provides tools to assess the impact of new data on PDFs

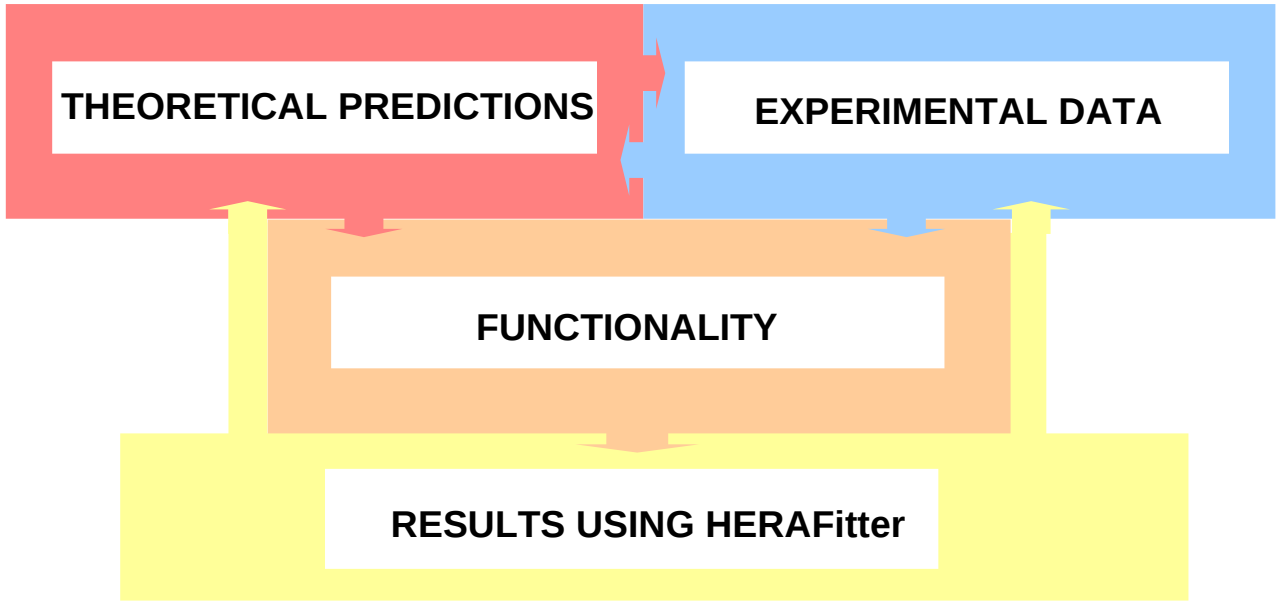
HERAFitter Project

HERAFitter project is a QCD fit framework ready to extract PDFs and assess the impact of new data

www.herafitter.org

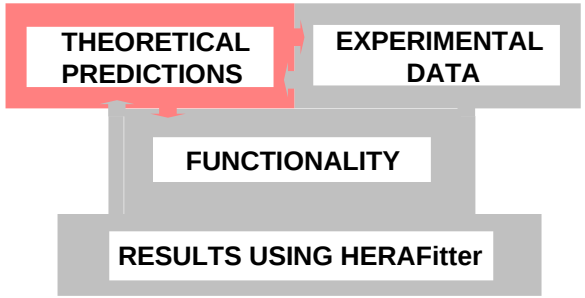
→ everyone is welcome to download it and use it

Project modular structure:

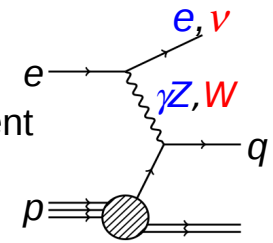


→ many improvements and additions in the planned stable release HERAFitter-1.0.0

Theoretical Predictions



DIS inclusive processes in *ep* and fixed target



DGLAP formalism:

different schemes of heavy quark treatment
VFNS: RT (MSTW), ACOT (CTEQ)
FFNS (pole and running mass)

Electroweak corrections for *ep* scattering

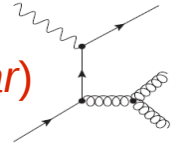
Diffractive PDFs

non-DGLAP formalism:

Dipole Models (GBW, IIM, BGK)
– an alternative approach for the low x region

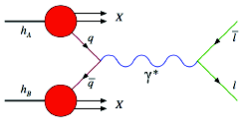
Unintegrated PDFs
– based on CCFM evolution

Jet production (*ep, pp, ppbar*)



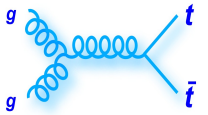
FastNLO and APPLGRID techniques
- decoupled hard scattering coefficients from PDFs stored on grids

Drell-Yan processes (*pp, ppbar*)



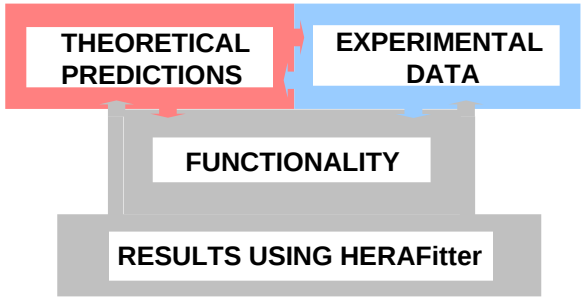
LO calculation x NLO k-factors
APPLGRID technique

Top pair production



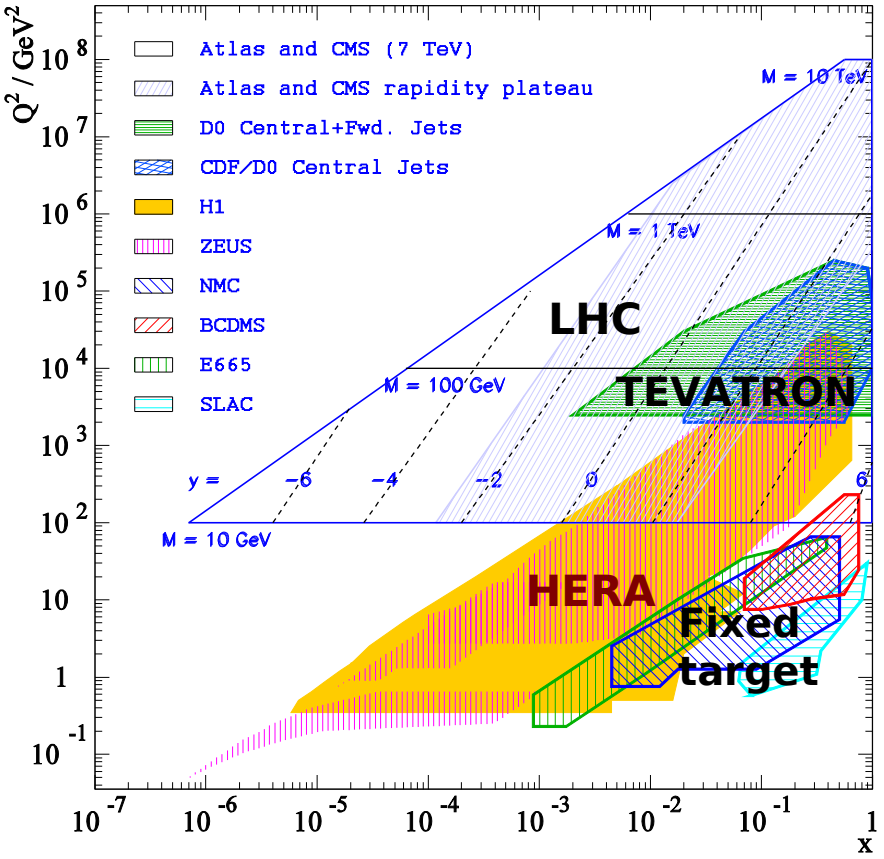
total ttbar cross section
(work ongoing on the differential at approx NNLO)

Experimental Data

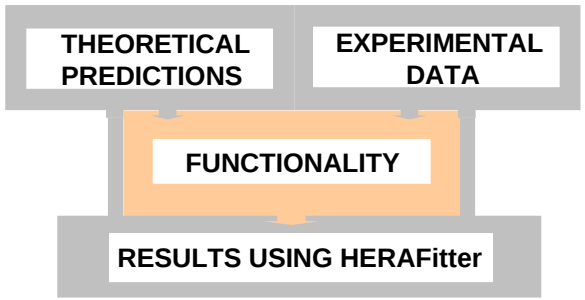


Different experimental data can be used in HERAFitter:

- **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**



HERAFitter Functionality



χ^2 function

→ nuisance parameters

→ covariance matrix

→ mixed

Various types of uncertainty treatment for experimental data:

Hessian - error inflation by a tolerance parameter (nuisance) to accommodate inconsistencies between data sets

Monte Carlo - MC replica method shifting data cross section points randomly within their uncertainties

Offset – correlated sources accommodated in uncertainties

Various forms of parametrisation ansatz

→ HERAPDF, CTEQ style, Chebyshev, bi-log normal

Bayesian Reweighting technique

→ a method to study data sensitivity on PDFs without fitting the data

Regularisation methods

→ constrain PDFs in a flexible parametrisation style

Tools

→ PDFs in LHAPDF format, tools for pulls and uncertainties

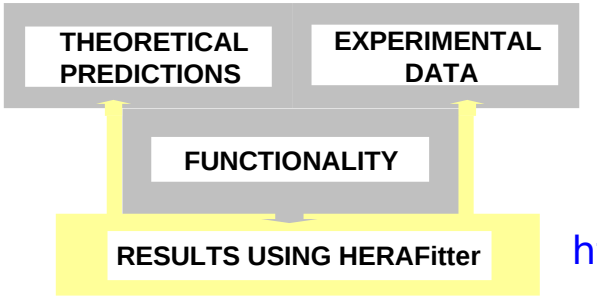
Generic minima finding solution tool

in HERAPDF1.0.0

Lead PDFs

in HERAPDF1.0.0

HERAFitter Usage



PDFs sets produced with HERAFitter (LHAPDF5.9.1):
HERAPDF1.0, HERAPDF1.5, ATLAS-epWZ12, LHECNLO

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

"Determination of the strange quark density of the proton from ATLAS measurements of the W→lν and Z→ll cross sections" Phys.Rev.Lett. 109 (2012) 012001

"Measurement of the inclusive jet cross section in pp collisions at √s = 2.76 TeV and comparison to the inclusive jet cross section at √s = 7 TeV using the ATLAS detector" EPJC (2013) 73 2509

"Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at √s = 7 TeV with the ATLAS detector" Phys. Lett. B 725 (2013) 223

In CMS several analyses are using HERAFitter for PDF constraints
→ jets, DY, W+charm data

"Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep Inelastic ep Scattering at HERA" Eur. Phys. J. C73 (2013) 2311

"Inclusive Deep Inelastic Scattering at High Q2 with Longitudinally Polarised Lepton Beams at HERA" JHEP 1209 (2012) 061

LHeC impact studies J.Phys.G39 (2012)

Theory: A.Glazov, A.Moch, V.Radescu "Parton Distribution Uncertainties using Smoothness Prior" Phys.Lett. B 695 (2011) 238

updates of ACOT scheme module (with CTEQ group)

inclusion of photon PDF in QCDNUM (publication is planned)

HERAFitter: Future Developments

Longer term developments planed in HERAFitter:

- **Theory side:**

→ QED+QCD PDFs (generalised evolution in QCDNUM)

→ possibility to interface APFEL (A PDF Evolution with QED corrections)

Top sector:

→ ttbar differential cross sections

→ inclusion of Top++ (total top pair production)

Heavy flavour sector:

→ ACOT scheme at NNLO

→ ACOT scheme inclusion in QCDNUM

→ intrinsic charm

- **Interfaces and code:**

→ APPLGRID interfaces to DYNNLO

→ LHAPDF6 (C++) interface

→ OpenMP (currently exist for RT scheme, planned to extend to ACOT)

- **Others:**

→ fitting photon PDFs

→ different evolution codes, ...

Summary and Outlook

Quark PDFs at LHC mainly constrained by the W and Z production measurements

W lepton asymmetry:

→ impose constrains on the valence quark PDFs

→ plays an important role in the understand of *d/u* ratio at low x which currently poorly constrained

Z rapidity distribution:

→ constrains to quarks and anti-quarks in PDFs

W+c differential measurement:

→ access s quark density

some 7 TeV analyses are still being finalised, 8 TeV data yet to come.

High precision of LHC data provides PDF constraints

→ are used (e.g. NNPDF2.3) or started to be used in global PDF fits

Tools exist for fast interface to theory calculations in PDFs (APPLGRID, FastNLO)

open source multi-functional QCD framework: HERAFitter

well integrated into the high energy community (both, experimental and theory)

HERAFitter herafitter-help@desy.de

Monthly meetings: https://herafitter.org/HERAFitter/HERAFitter/HERAFitterMeetings

Back-up

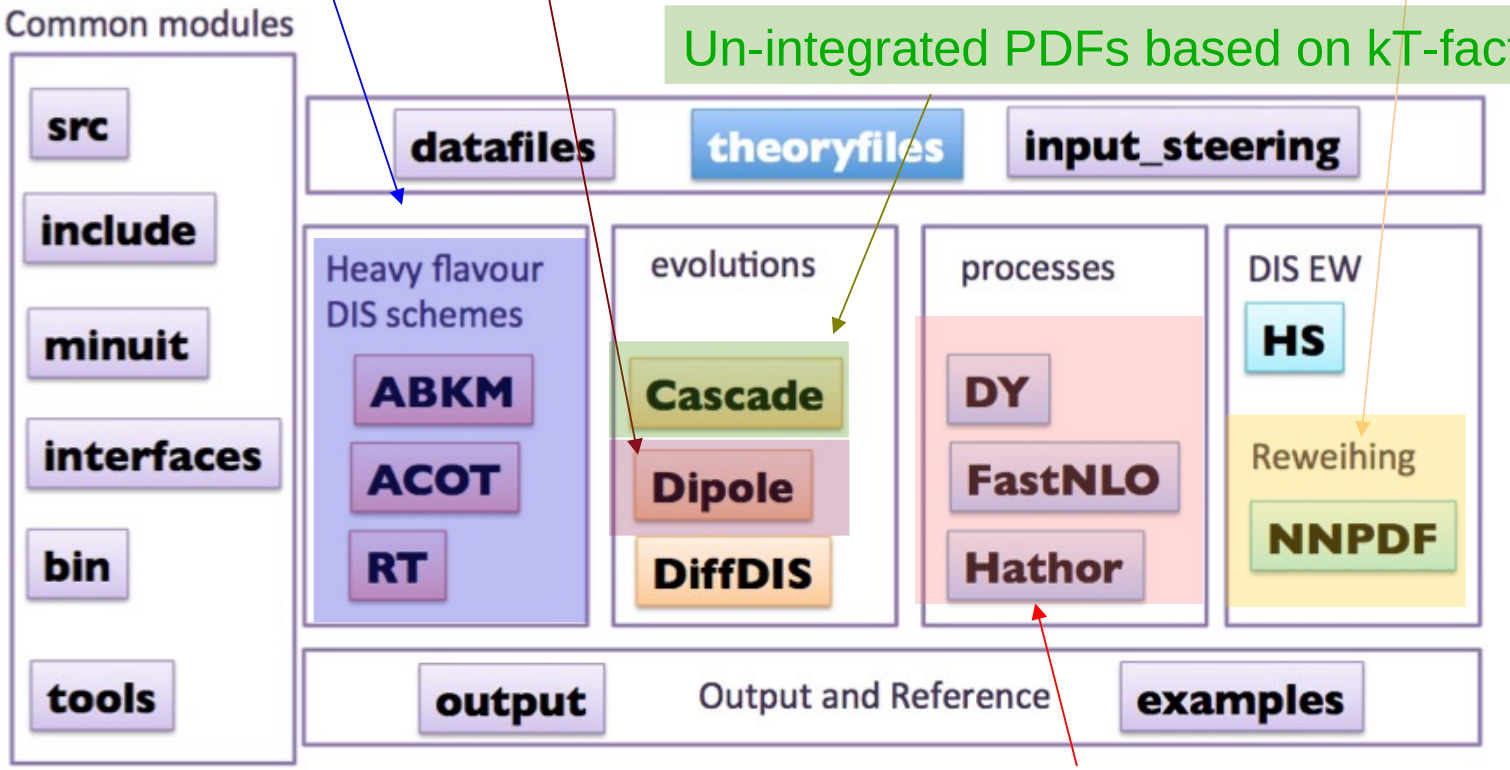
HERAFitter functionality

DIS: VFNS (ACOT, RT, ZM) and FFNS

Different dipole models

Regularisation techniques (data driven or external)

Un-integrated PDFs based on kT-factorisation



Various χ^2 representations,
Hessian and MC replica methods,
various data uncertainty treatments,
etc...

Interfaces to:
APPLGRID
FastNLO
HATHOR

Download

HERAFitter / DownloadPage

Releases of the HERAFitter QCD analysis package

- Versioning convention: **i.j.k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: HERAFitter_release_notes.pdf.

Date	Version	Files	Remarks
06/2013	0.3.1	herafitter-0.3.1.tgz	fix release includes manual-0.3.1.pdf and decoupled theoryfiles.tgz
03/2013	0.3.0	herafitter-0.3.0.tgz	release includes manual-0.3.1.pdf and decoupled theoryfiles.tgz
07/2012	0.2.1	herafitter-0.2.1.tgz	fix release for 0.2.0
05/2012	0.2.0	herafitter-0.2.0.tgz	added functionality for LHC users
09/2011	0.1.0	herafitter-0.1.0.tgz	first release

Documentation

- From 0.3.0 on a manual is provided together with an example directory.
- The **README** file (accessible via the package) gives an explanation for a quick start.

Web access to SVN

- For users with a valid DESY account, the SVN repository is accessible on the web at https://svnsrv.desy.de/k5viewvc/h1fitter .
- For users without DESY account, the SVN repository is accessible on the web at https://svnsrv.desy.de/basviewvc/h1fitter/ with herafitter-user@desy.de account and PDFfits password.

Doxygen Documentation

- The doxygen documentation is located here

Links to external packages

External packages that could be run with HERAFitter via configuration flags can be accessed for convenience HERE .

HERAverager data combination package

Information can be accessed here https://wiki-zeuthen.desy.de/HERAverager.

Subscription

We encourage users to subscribe to mailing list for news and updates related to the HERAFitter webpage. (average rate of e-mails is once a month), please contact herafitter-help@desy.de (or by creating a user account to this wiki we get a notification)

Releases (publicly accessible)

Documentation: manual, release notes, README, DOXYGEN

External packages

CMS Z differential measurement

Z boson rapidity *y* is directly related to the momentum fraction *x* of the interacting partons: $x_{\pm} \approx M/\sqrt{s}\, e^{\pm y}$

Z rapidity differential and double differential measurement at 7TeV

→ 4.8 fb^{-1} e (p^T>20,10 GeV) and 4.5 fb^{-1} μ (p^T>14,9 GeV) channels combined

→ differential measurement in 15 < M < 1500 GeV

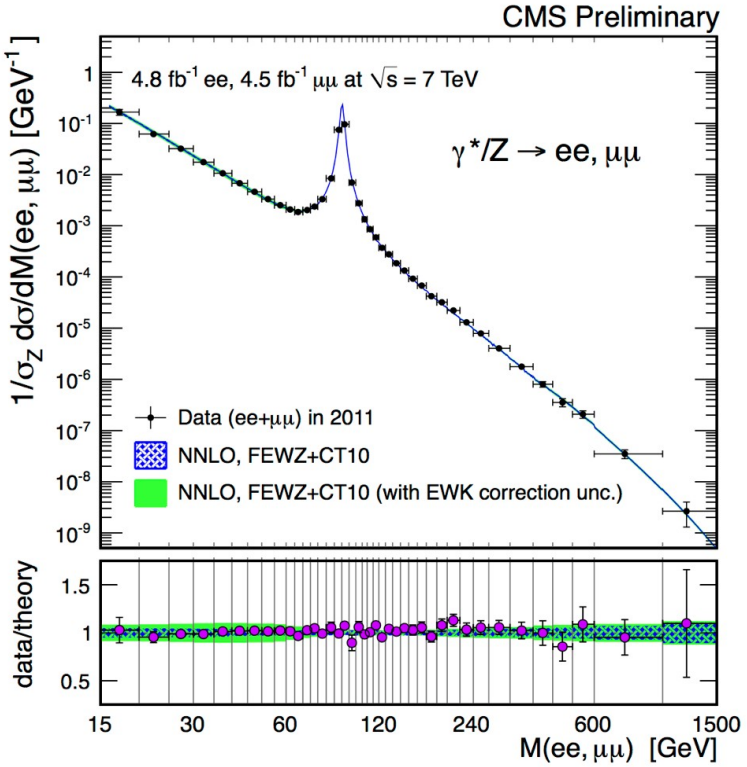
→ normalised to the Z peak (60<M<120GeV)

<2% statistical uncertainty

<12% systematical uncertainty (<200GeV)

→ theory predictions: NNLO FEWZ

arXiv:1310.7291



Blue: theory (FEWZ) + PDF uncertainty

Green: + EWK correction

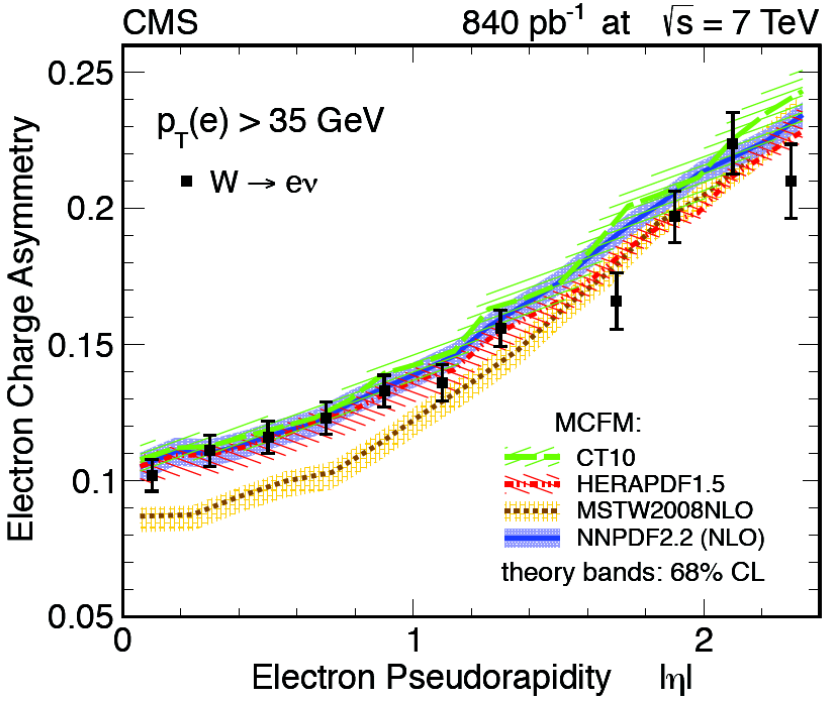
W lepton charge asymmetry

CMS W lepton asymmetry measurement

→ overall excess of W^+ over W^- due to presents of two valence u quarks in the proton

→ probe valence quarks and PDFs rations (u_v, d_v, d/u, d_v/u_v, dbar/ubar):

PRL 109 (2012) 111806



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

Electron charge asymmetry:

→ P^T_l>35 GeV, 11 bins

→ 4-5% total uncertainty

→ already included in e.g. NNPDF2.3

W lepton charge asymmetry

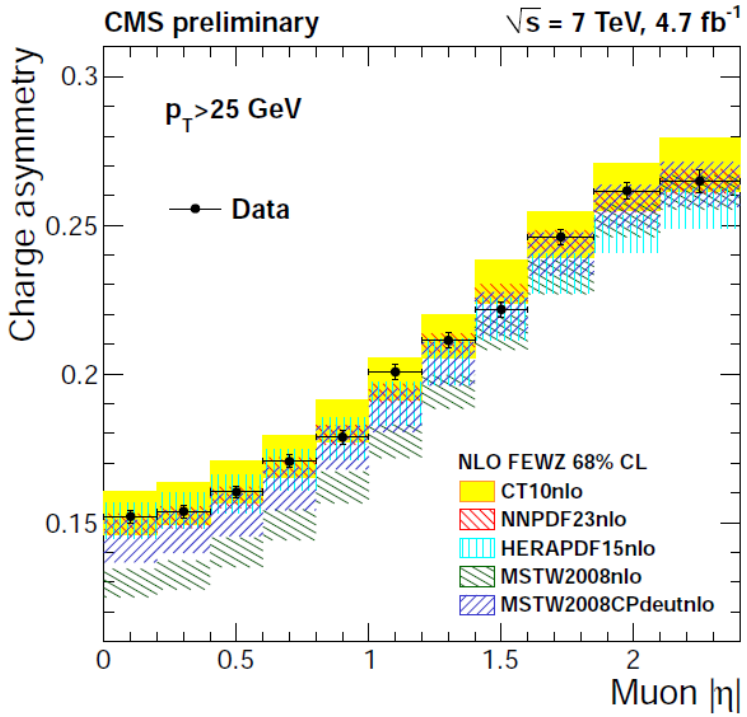
CMS W muon asymmetry measurement

→ 13M W^+ and 9M W^- events

→ better resolution for MET using Hadronic Recoil: $u = -MET - \Sigma p_{\eta}^{T}$

→ DY sample for normalisation correction

→ binned maximum likelihood fits of MET are used to extract signal



SMP-12-021

Muon charge asymmetry:

→ P^{T}_{l}>25 and 35 GeV, 11 bins

→ 2-4% total uncertainty

→ in the process of publication

W+c measurements at CMS

CMS W+charm measurement

Identification:

→ W decays to charged leptons (e or μ) and neutrino

→ c: charm-quark jets with p^{T}_{jet}>25GeV, $|\eta_{jet}|$<2.5

jets identified: secondary vertex $D^+ \to K^-\pi^+\pi^+$ ($D^- \to K^+\pi^-\pi^-$)

$D^{*+}(2010) \to D^0\pi^+$ ($D^{*-}(2010) \to \bar{D}^0\pi^-$)

$D^0 \to K^-\pi^+$ ($\bar{D}^0 \to K^+\pi^-$)

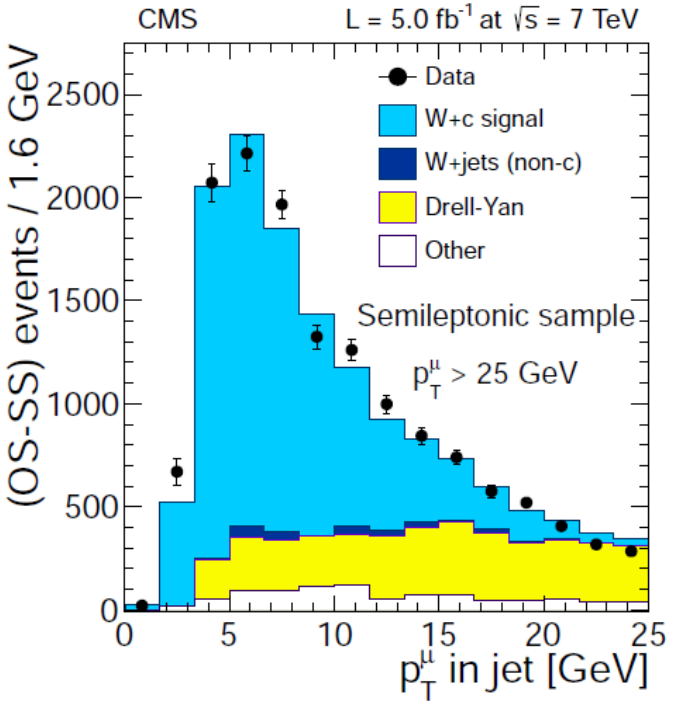
semileptonic decay with well identified muon

Background subtraction: perform by subtracting the Same Sign (SS) from the Opposite Sign (OS) distributions

→ does not affect the signal

→ most of background processes (W→ccbar,...) has same SS and OS → significant reduction

arXiv:1310.1138



W+c measurements at CMS

CMS W+charm measurement

Total cross section:

→ P^T_l>25 and 35 GeV

→ 6-7% total uncertainty (systematic dominant)

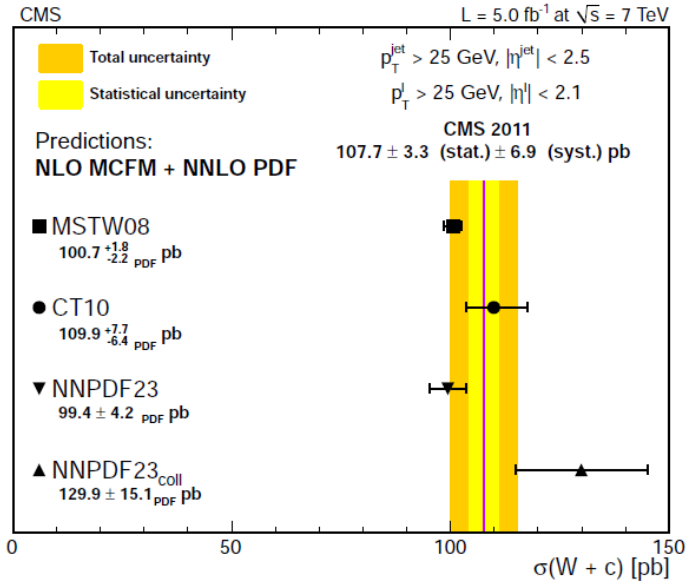
Cross section ratio:

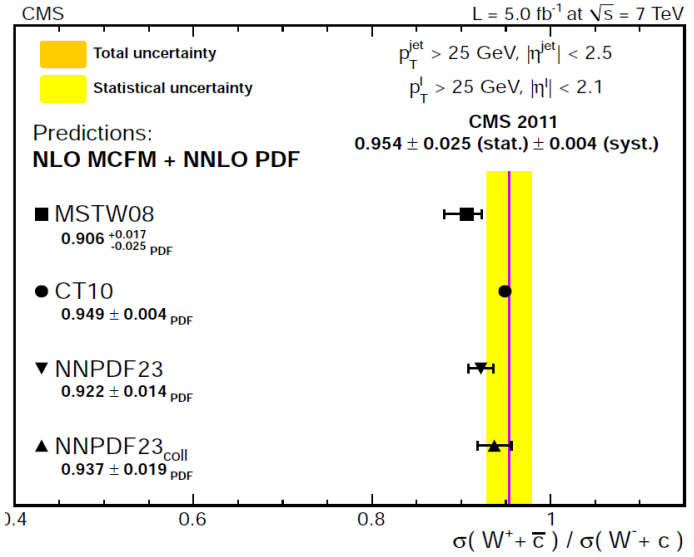
$$\sigma(W^+ + \bar{c})/\sigma(W^- + c)$$

→ P^T_l>25 and 35 GeV

→ can be used to study s-sbar asymmetry in PDFs

arXiv:1310.1138





W+c measurements at CMS

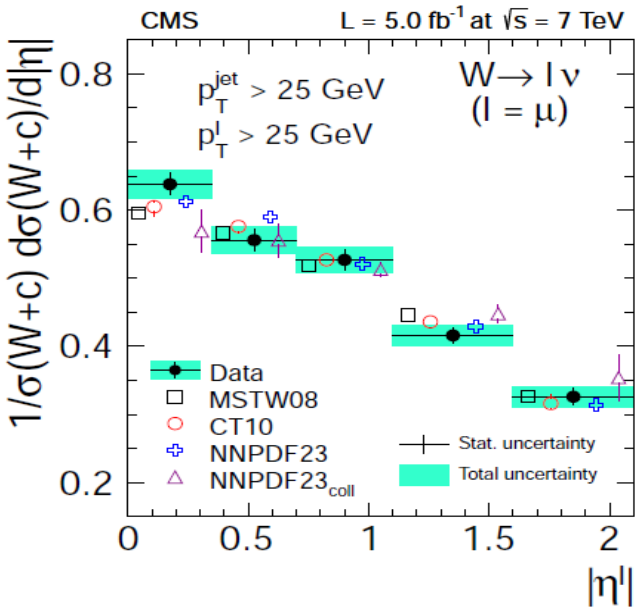
CMS W+charm measurement

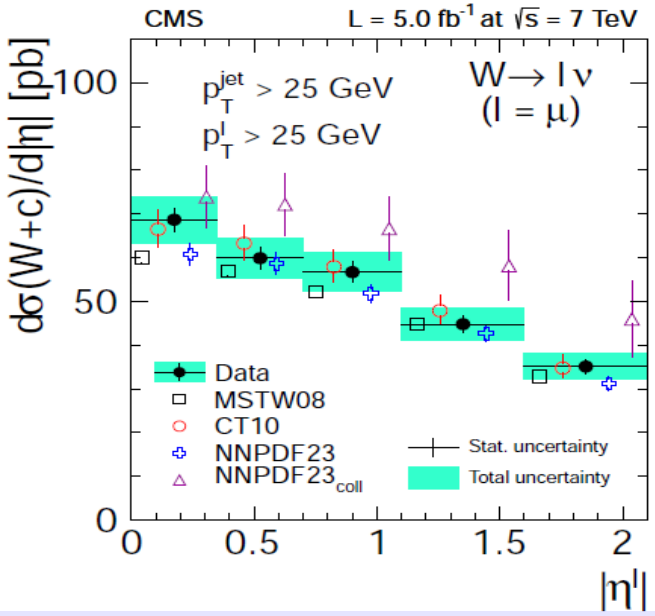
Differential measurement:

→ P^{T}_{l}>25 (e) and 35 GeV (e+η)

→ normalised and absolute cross sections

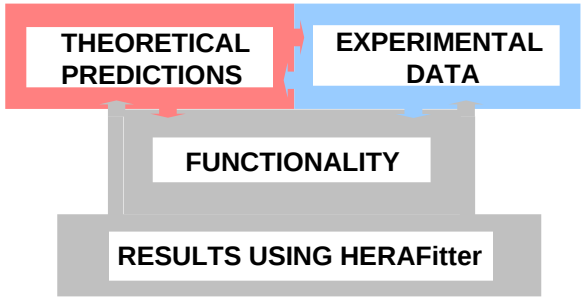
→ direct sensitivity to s quark density





arXiv:1310.1138

Experimental Data



DIS inclusive processes in *ep* and fixed target

DGLAP formalism:

different schemes of heavy quark treatment
VFNS: RT (MSTW), ACOT (CTEQ)
FFNS (pole and running mass)

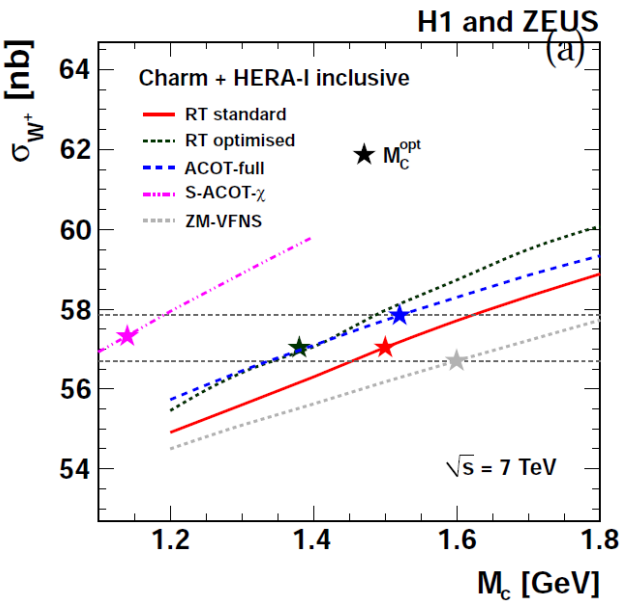
Combination and QCD Analysis of Charm Production in DIS at HERA

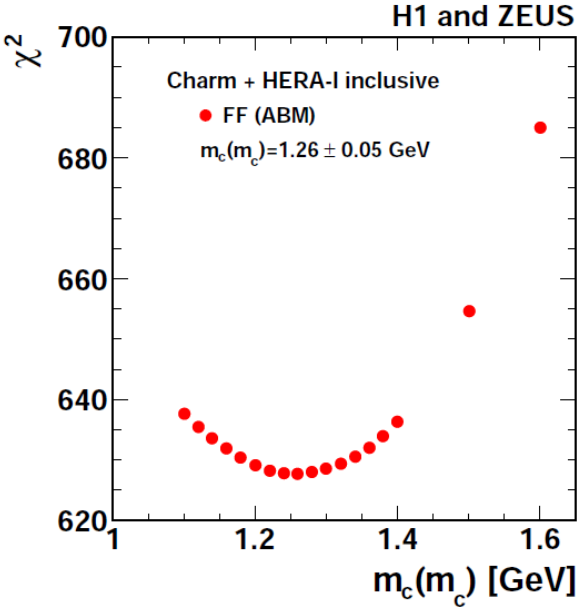
- various heavy flavour schemes and an impact on DY cross sections at LHC studied

  → possible only with HERAFitter

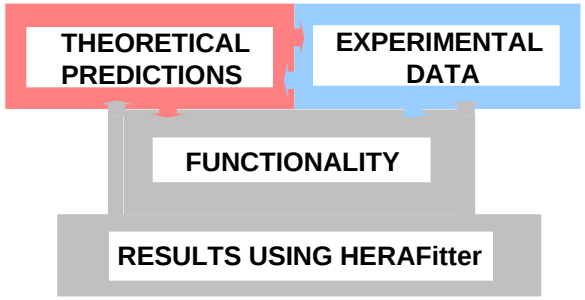
- running mass of charm quark determined

Eur. Phys. J. C73 (2013) 2311





Experimental Data



Jet production (*ep*, *pp*, *ppbar*)

FastNLO and APPLGRID techniques

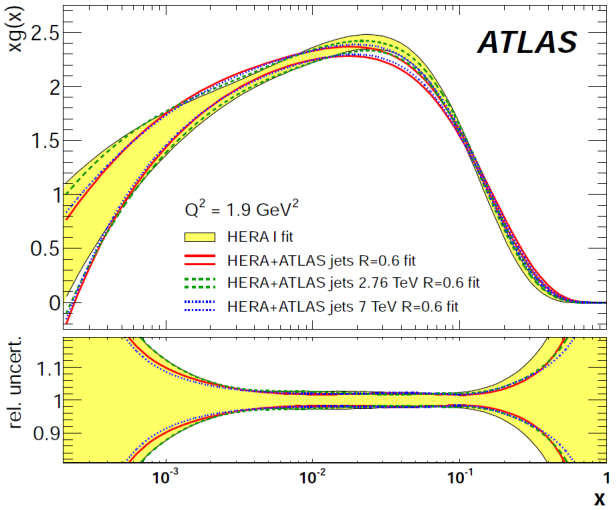
- decoupled hard scattering coefficients from PDFs stored on grids

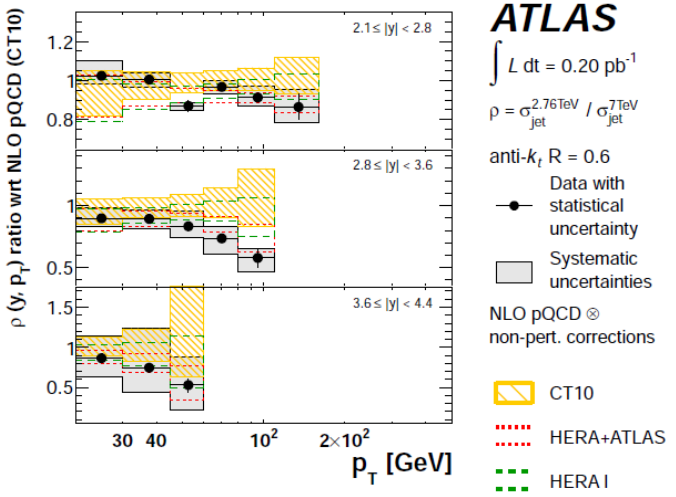
Measurement of the inclusive jet cross section at √s = 2.76 TeV and comparison to the inclusive jet cross section at √s = 7 TeV

- an NLO QCD analysis using inclusive jet data

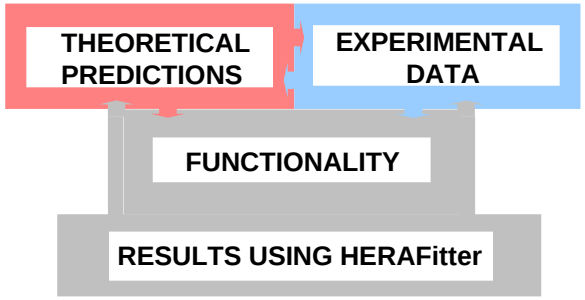
→ impact on gluon and sea distributions

EPJC (2013) 73 2509





Experimental Data



Drell-Yan processes (*pp, ppbar*)

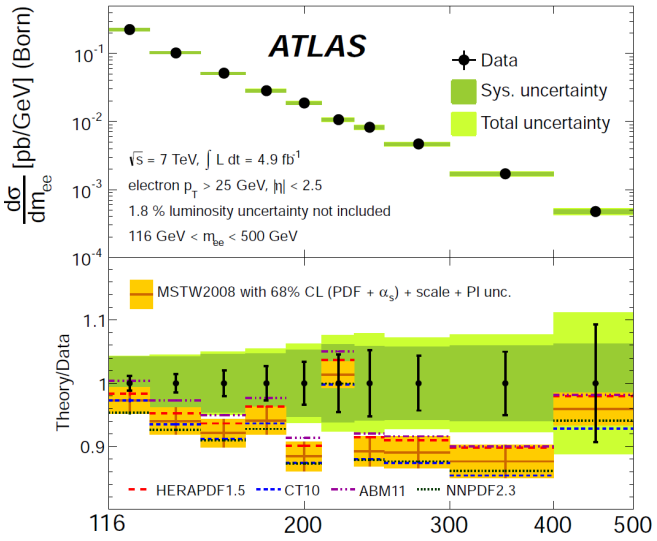
LO calculation x NLO k-factors

APPLGRID technique

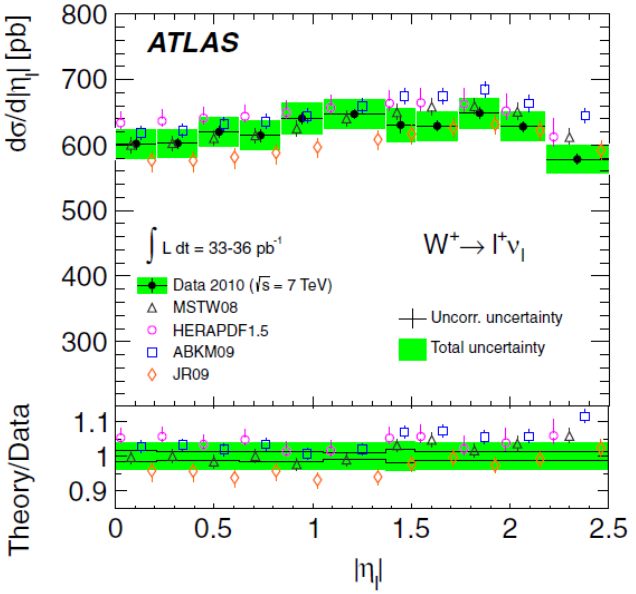
Measurement of the inclusive W and Z/γ cross-section in pp collisions at √s = 7 TeV*

Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at √s = 7 TeV

- comparison with various PDFs
- determination of strange quark density from DY data

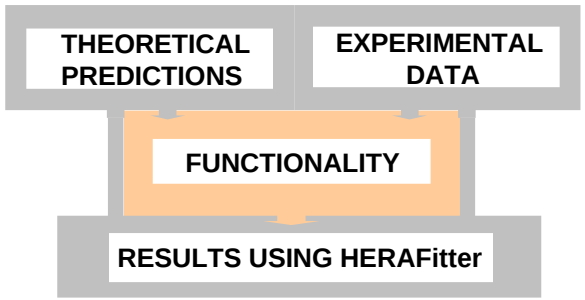


Phys. Lett. B 725 (2013) 223



Phys. Rev. D 85 (2012) 072004

HERAFitter Functionality



χ^2 function

D - Data
T - Theory

→ nuisance parameters

$$\chi^2 = \sum_i \frac{\left(D_i - T_i^*\right)^2}{\left(\delta_i^{unc}\right)^2}$$

$$T_i^* = T_i + \sum_j \xi_j \delta_i^{cor,j}$$

Correlated error

Nuisance parameter

→ covariance matrix

$$\chi^2 = \sum_{i,j} \left(D_i - T_i\right) Cov_{i,j}^{-1} \left(D_j - T_j\right)$$

→ mixed

→ uncertainties can be treated as multiplicative or additive

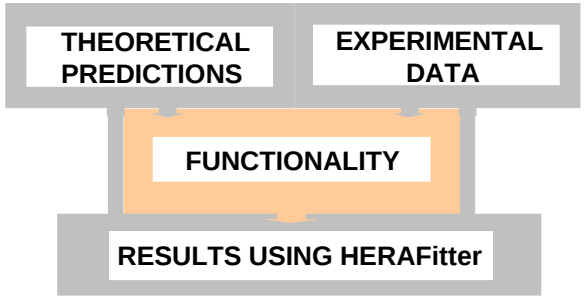
→ various models for bias corrections

→ tool to transform covariance matrix to nuisance parameter representation

in HERAPDF1.0.0

→ each correlated systematic source can be modified individually

HERAFitter Functionality



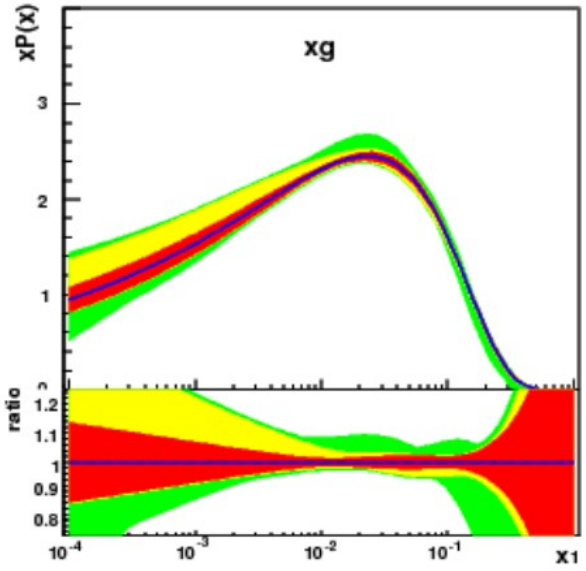
Tools

→ PDFs in LHAPDF format tools for pulls and uncertainties

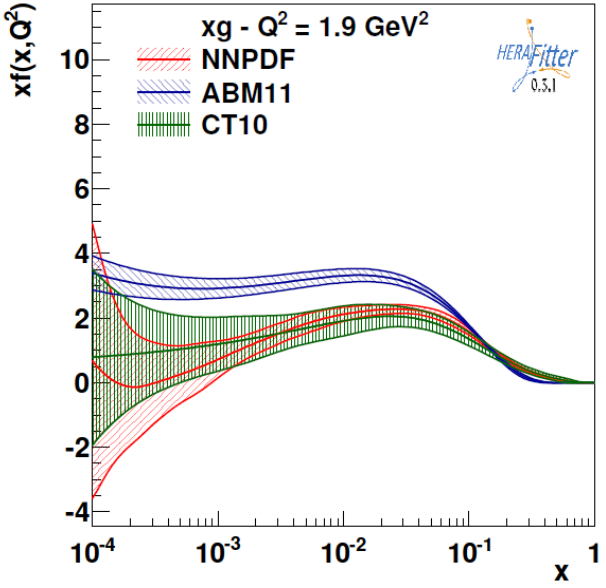
→ PDFs sets available in LHAPDF5.9.1: HERAPDF1.0, HERAPDF1.5, ATLAS-epWZ12, LHECNLO

in HERAPDF1.0.0

Drawing of different uncertainties (experimental, model, parametrisation)



Calculation of theory uncertainties (symmetric and asymmetric, access PDFs via LHAPDF interface)



Data - theory comparison (with uncertainty band and pulls)