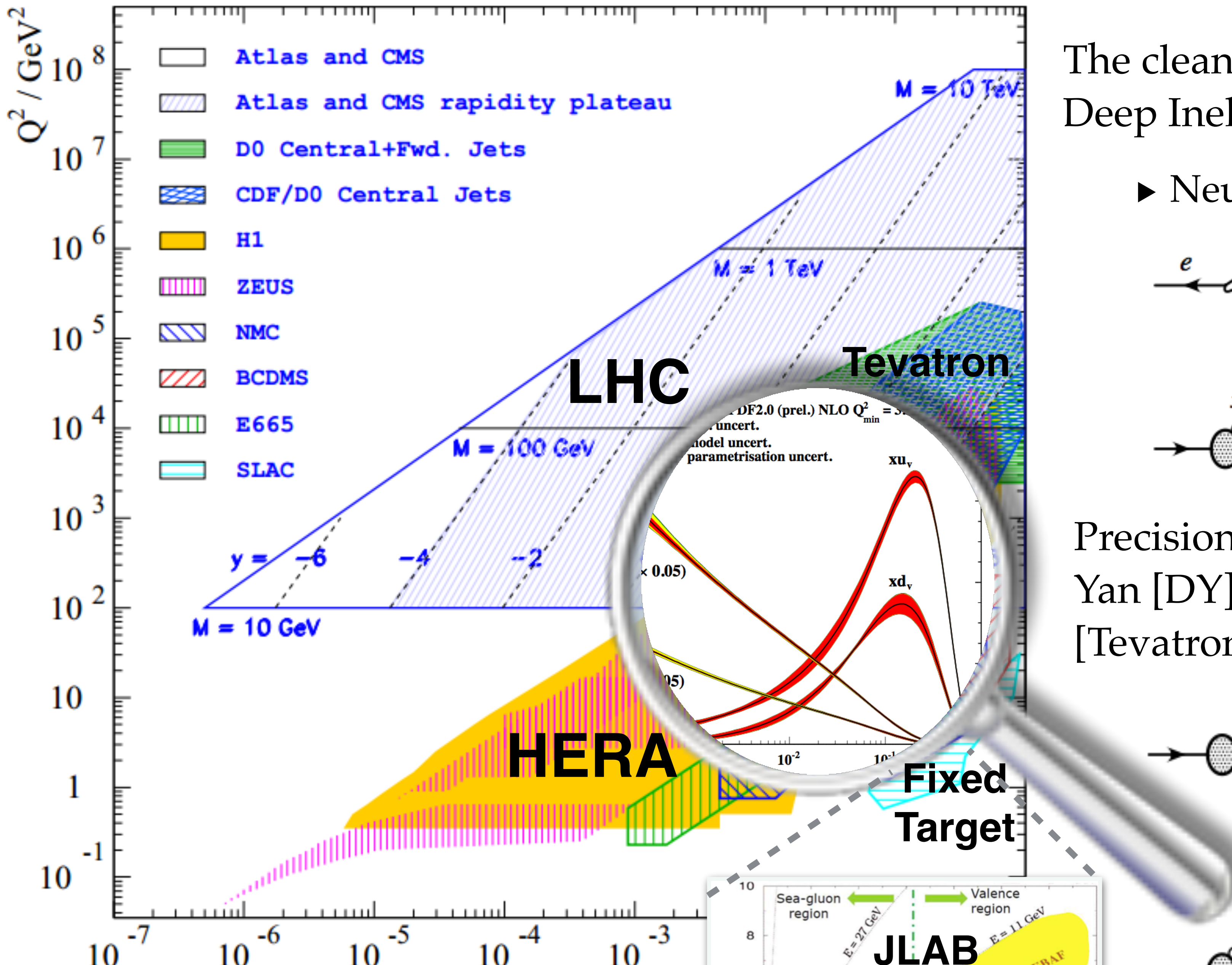
HERAFitter Project

Open Source QCD Fit framework

Voica Radescu
on behalf of the HERAFitter team

HERAFitter

Proton Structure Measurements

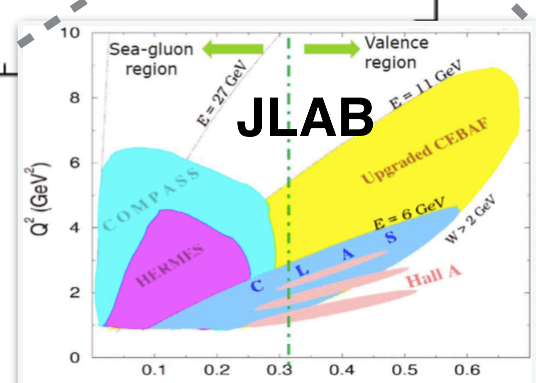


$$Q^2 = -q^2 = -(k-k')^2$$ Photon virtuality

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

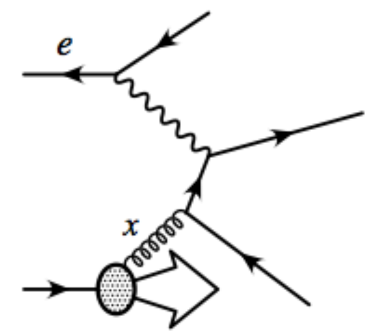
$$y = \frac{p \cdot q}{p \cdot k}$$ Inelasticity

X



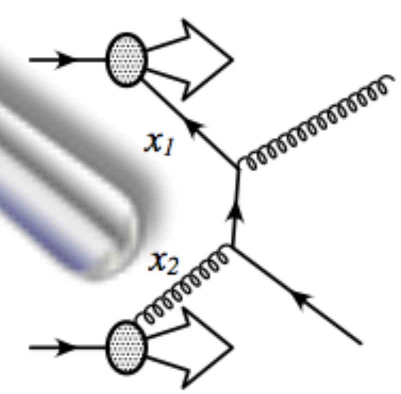
The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:

- Neutrinos, muons, electrons



—> probes linear combination of quarks

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



—> can provide flavour separation and more insight into gluons

—> probes bilinear combination of quarks

An intensive QCD program in the past years to analyse all these data to extract the QCD free parameters

Why more PDF precision?

- Discovery of new exciting physics relies on precise knowledge of proton structure.

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

- **Factorisation theorem:**
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with Parton Distribution Functions (PDFs):

$$d\sigma(h_1h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1,\mu_F^2) f_{b/h_2}(x_2,\mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2,\mu_F^2)$$

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

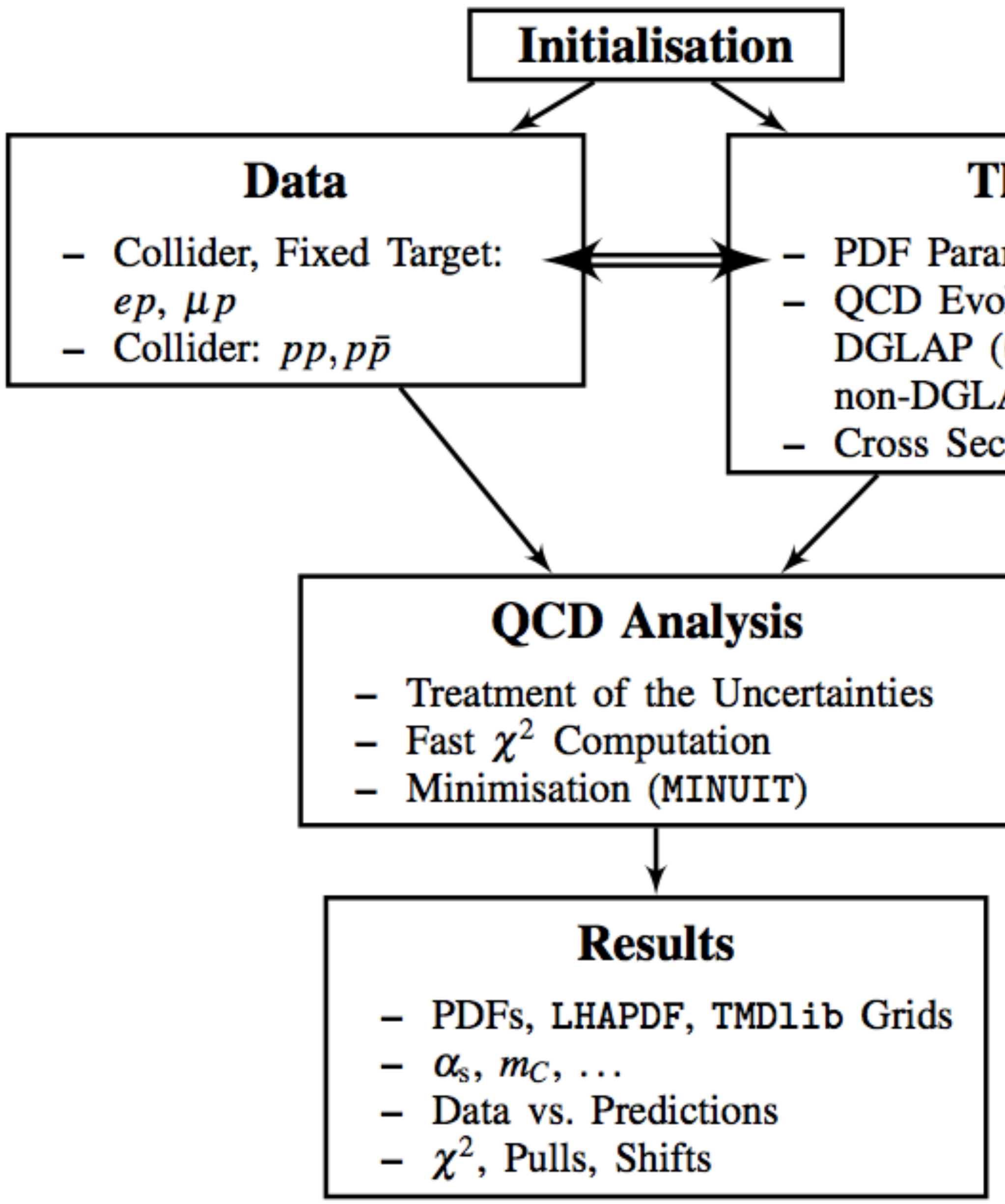
- PDF uncertainties can be controlled better by:
  - more targeted precision measurements
  - a comprehensive theoretical framework that can test various methods/models

- **HERAFitter Project: based on open source software code with regular releases** www.herafitter.org
  - provides a unique QCD framework to address theoretical differences
  - provides means to the experimentalists to optimise the measurement and assess impact/consistency of new data

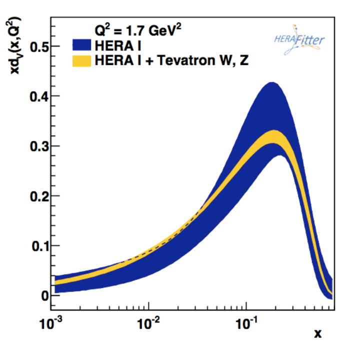
HERAFitter Project at Glance:

Main Steps for a QCD fit:

- Parametrise PDFs at the starting scale
  - multiple options for functional forms
    - Standard Polynomial, Chebyshev, etc
- Evolve to the scale corresponding to data point
  - DGLAP evolution codes [QCDNUM, APFEL]
  - kt ordered evolution, Dipole models
- Calculate the cross section
  - various heavy flavour schemes:
    - RT, ACOT, FONLL, FFNS
  - fast grid techniques interfaced to DY:
    - APPLGRID, FASTNLO
- Compare with data via χ2:
  - multiple forms to account for correlations
- Minimize χ2 with respect to PDF parameters
  - MINUIT, data driven regularisation

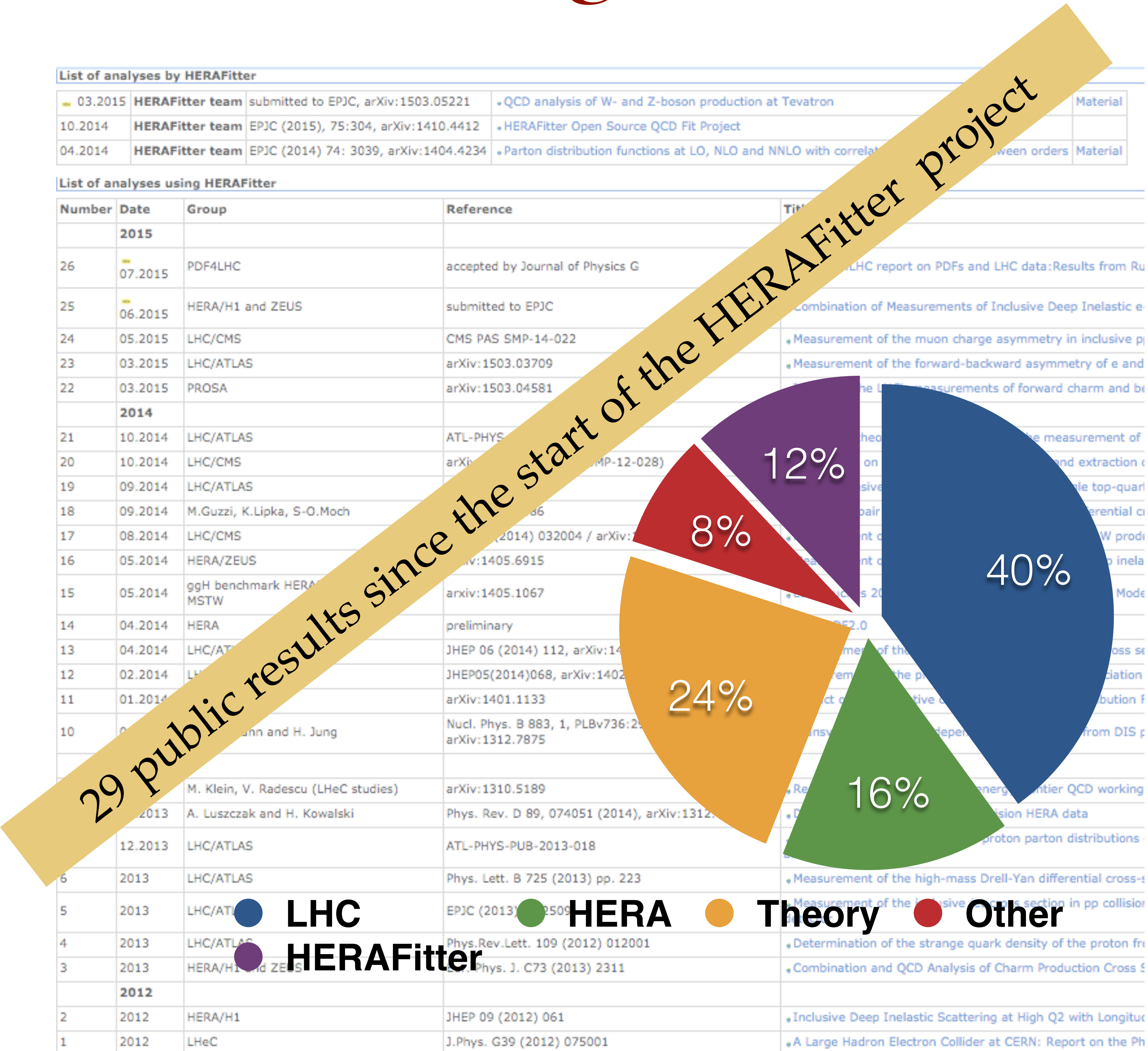


~2000 iterations



HERAFitter: EPJC (2015), 75:304

Results using HERAFitter

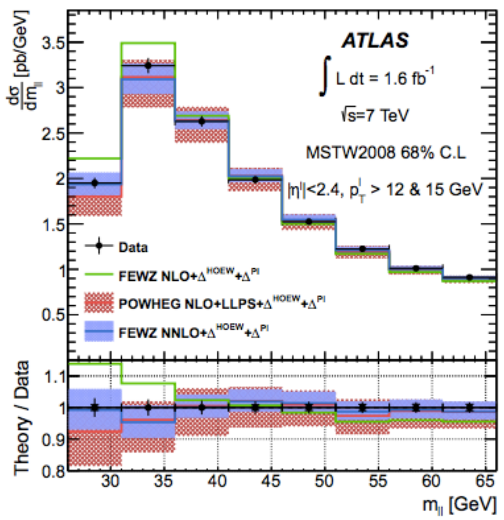


- LHC experiments provide the main developments and usage of HERAFitter platform

- 3 HERAFitter publications carried out by HERAFitter developers [~30]

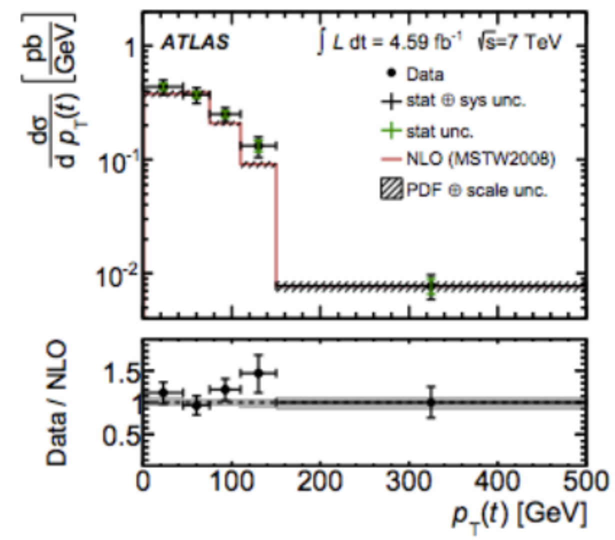
Highlighted Results using HERAFitter

- **HERAFitter platform can be used for quantitative assessment** in level of agreement between measurements and SM theoretical predictions, accounting for all uncertainties:
  - Low Mass DY (ATLAS) data [arXiv:1404.1212]



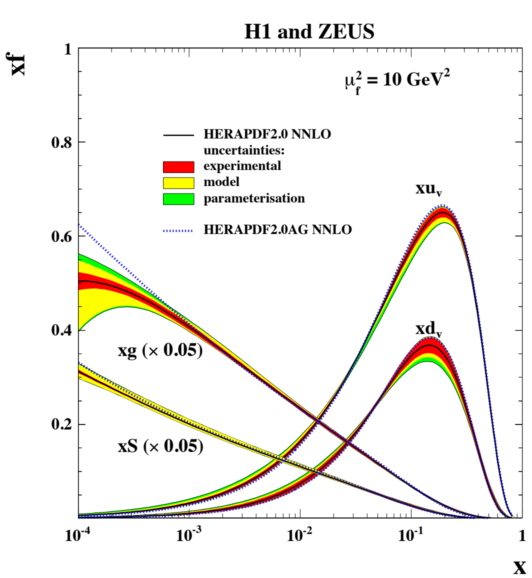
Prediction	χ^2 (8 points) Nominal
POWHEG NLO+LLPS	22.4 (19.8)
FEWZ NLO	48.7 (28.6)
FEWZ NNLO	13.9 (12.9)

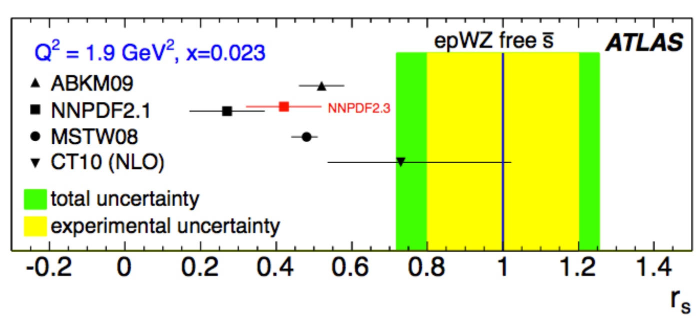
t-channel single top-quark production cross sections (ATLAS) [arXiv:1406.7844]

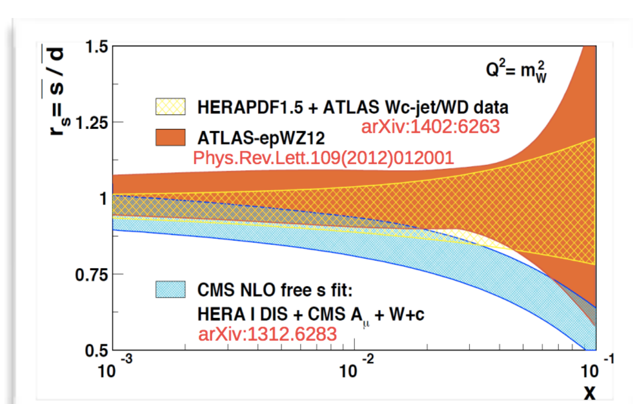


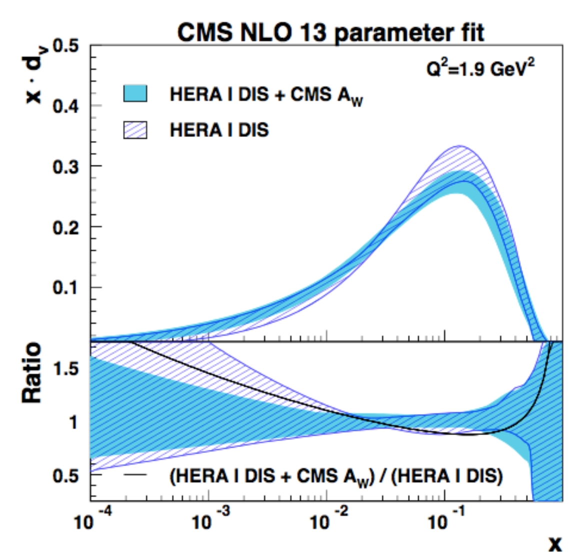
	$\frac{d\sigma}{dp_T(t)}$
χ^2/NDF	7.55/5

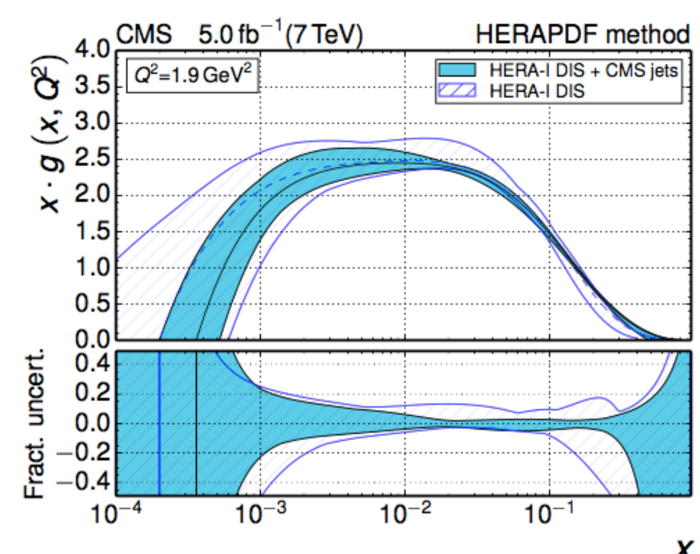
- **HERAFitter platform can be used for QCD fits to extract PDFs or to study the impact of new data on PDFs**
  - HERAPDF2.0 (H1 and ZEUS), ATLASepWZ2012, CMS PDF fits using W+c, W asymmetry, CMS PDF+alphas from jets











Potential impact of 13TeV data on PDFs

PDF4LHC studies accepted by JPG, arXiv:1507.00556

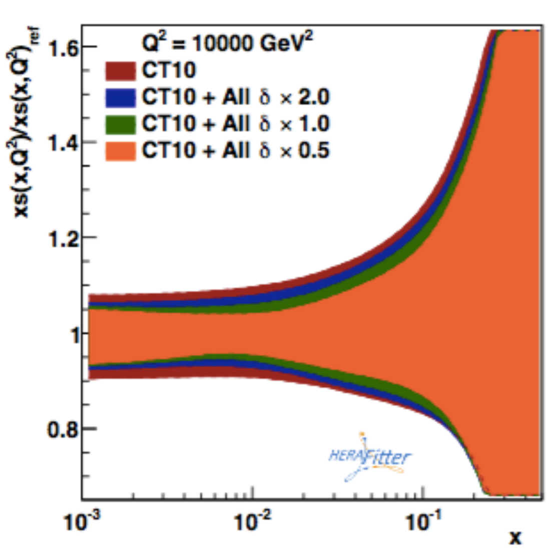
- HERAFitter provides possibility to study the potential impact of Run II data on the current precision of PDFs using profiling method:
  - Profiling method uses the minimisation of the χ2 function that includes both data and PDF uncertainties

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

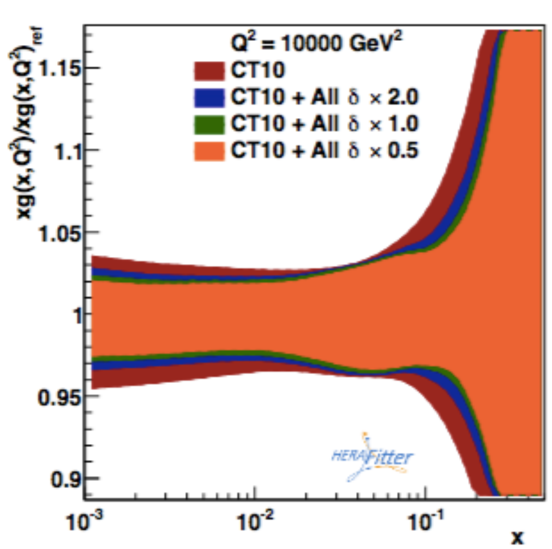
β - nuisance parameters
Γ - influence on data/theory

- Using global PDFs: CT10, MMHT, NNPDF3.0 and benchmark measurements: **inclusive W, Z and $t\bar{t}$ production**
  - generated pseudo data: uncertainties are based on Run 1 results as published by ATLAS and CMS:
    - baseline scenario: data uncertainties are taken to be similar to those of the Run I measurements
    - conservative scenario: data uncertainties are scaled up by factor of two
    - aggressive scenario: data uncertainties are reduced by factor of two.

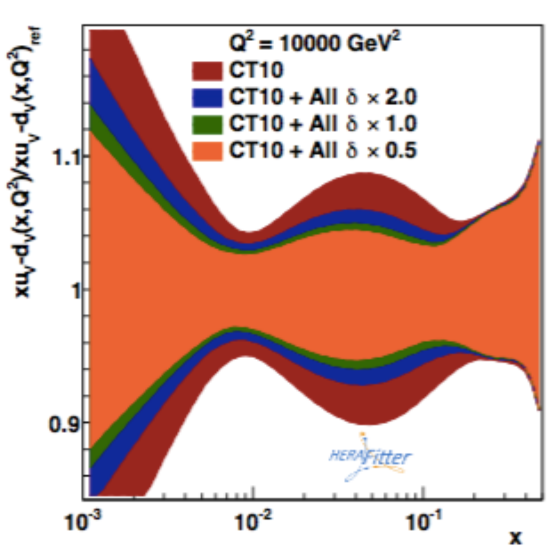
	$R_{W/Z}$	$R_{t\bar{t}/Z}$	A_ℓ	y_Z
Kinematic range			$p_{t,\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$	
Number of bins	1	1	10	12
Baseline accuracy per bin	1%	2%	≈ 1.5%	≈ 1.5%



σ_W/σ_Z, y_Z~xs(x)



σ_{ttbar}/σ_Z ~xg(x)



W lepton asymmetry~(uv-dv)

—> early 13TeV data can be very interesting already

Correlations of PDF uncertainties at LO, NLO, NNLO

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:
  - how to minimize theory error on predictions of cross-section ratio?

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

PDF uncertainties cancel
large scale uncertainty

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

PDF uncertainties cancel
improved scale uncertainty
not clear definition in pQCD

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

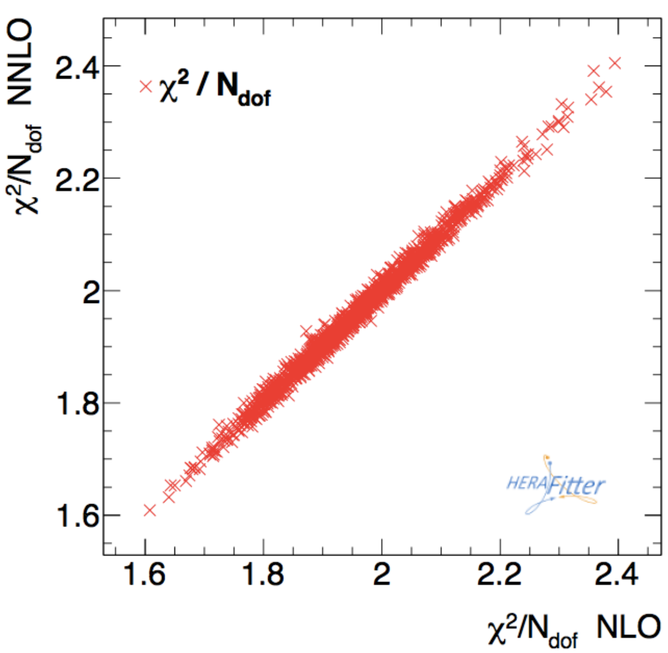
improved scale uncertainty
No cancellation of PDF uncertainty

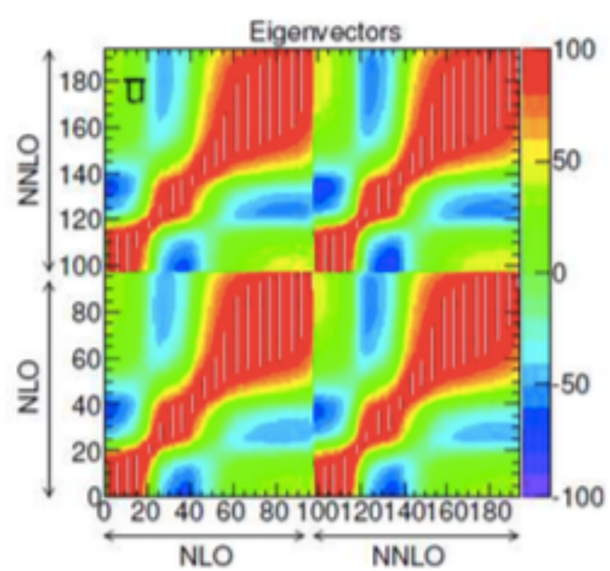
$$\frac{\hat{\sigma}_X^{NLO} \otimes PDF_{NLO}^{corr}}{\hat{\sigma}_Y^{NNLO} \otimes PDF_{NNLO}^{corr}}$$

PDF uncertainties cancel
improved scale uncertainty

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

—> PDFs extracted using HERA I data with syncronised uncertainties at NLO and NNLO using MC method with synchronised seeds





High correlations for PDFs at similar x values [binned 1-100(NLO), 101-200(NNLO)].

HERAFitter

Correlations of PDF uncertainties at LO, NLO, NNLO

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  - how to minimize theory error on predictions of cross-section ratio?

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

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

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

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

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

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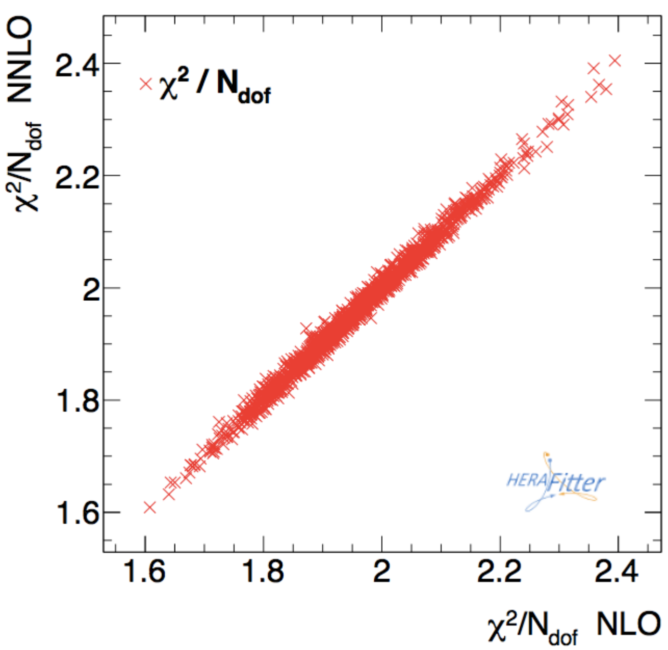
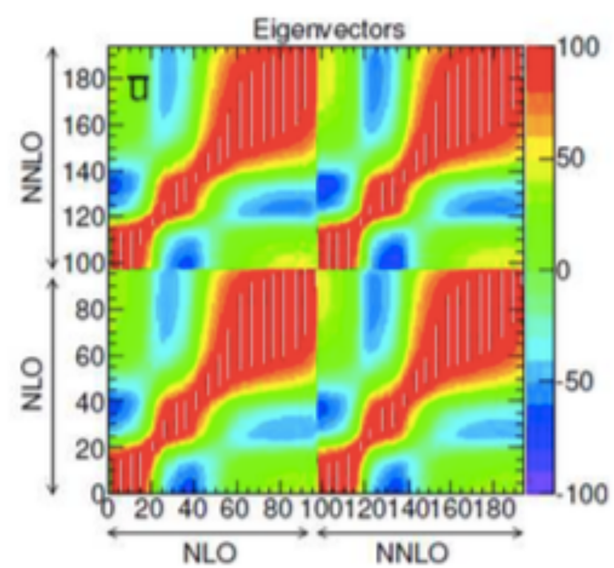
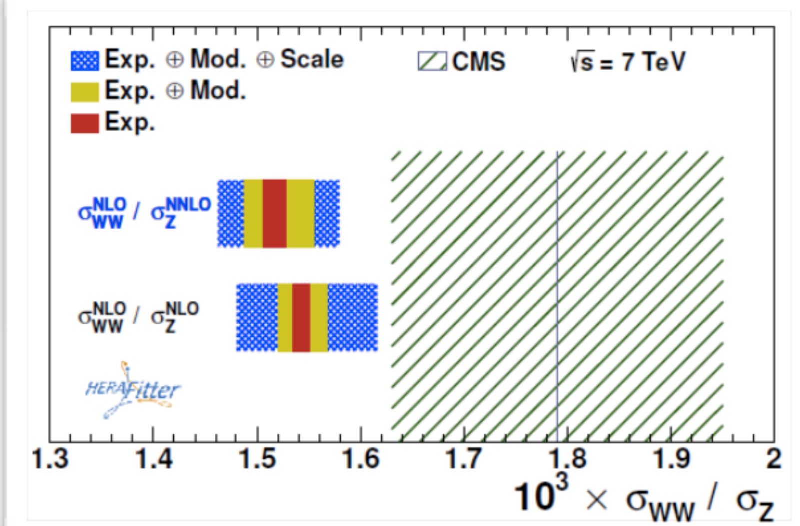
Propagated to use case scenario of Z boson and *WW* diboson production at the LHC.





High correlations for PDFs at similar *x* values [binned 1-100(NLO), 101-200(NNLO)].



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

QCD Analysis of W and Z production at Tevatron

submitted to Eur. Phys. J. C, arXiv:1503.05221

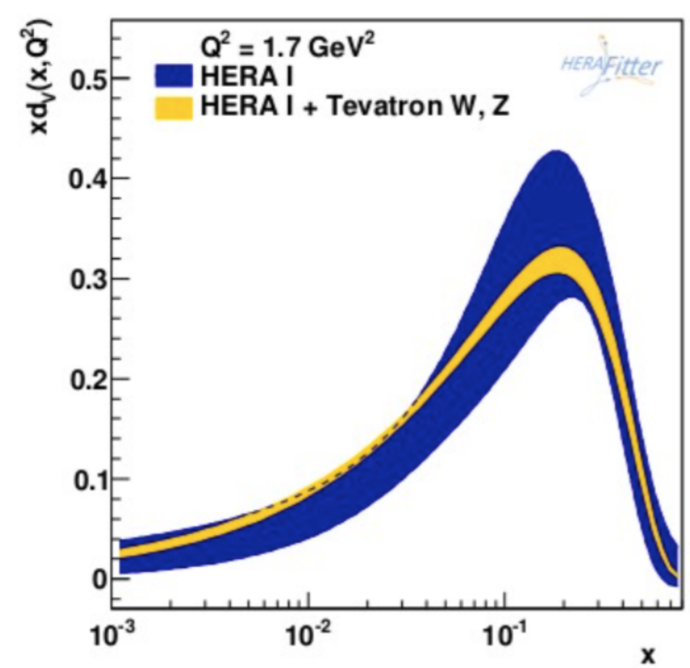
- In proton-antiproton collisions at Tevatron, DY processes of W and Z production are valence-quark dominated
  - —> they can be used to improve quark valence PDFs - especially the d-quark type
  - However, long history of tensions between CDF and D0 W asymmetry
- HERAFitter team examines the compatibility of the Tevatron data with QCD for:
  - Z rapidity distributions [CDF and D0]
  - Lepton charge asymmetry in W—> l,ν [D0]
  - W charge asymmetry [CDF and D0]

Ref: arXiv:0702025, arXiv:0908.3914, arXiv:1309.2591, arXiv:0901.2169, arXiv:1312.2895, arXiv:1412.2862

- A QCD Fit analysis is performed at NLO, using HERA I data as a reference and adding Tevatron data on top:
  - a revised correlation model is used by treating the uncertainties of data-driven corrections as bin-to-bin uncorrelated: lepton ID, trigger, and charge efficiencies
  - it required a more flexible parametrisation wrt to fits to HERA I data:

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

Data set	Experiment	χ^2/points
DIS	H1 - ZEUS	516/550
Z dσ/dy	D0	23/28
Z dσ/dy	CDF	32/28
W μ-asymmetry	D0	12/10
W asymmetry	CDF	14/13
W asymmetry	D0	8/14
Total χ^2/dof		606/628



Large impact on d-valence PDF

Good χ2 (partial and overall) for the QCD analysis

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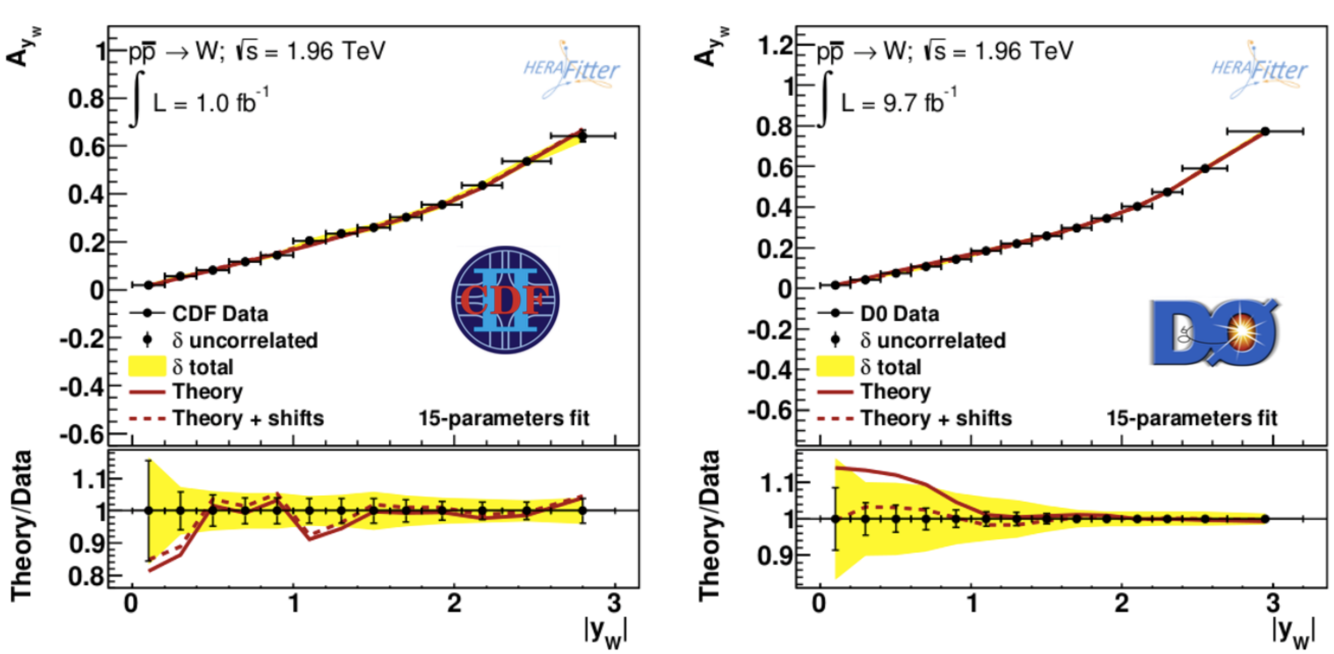
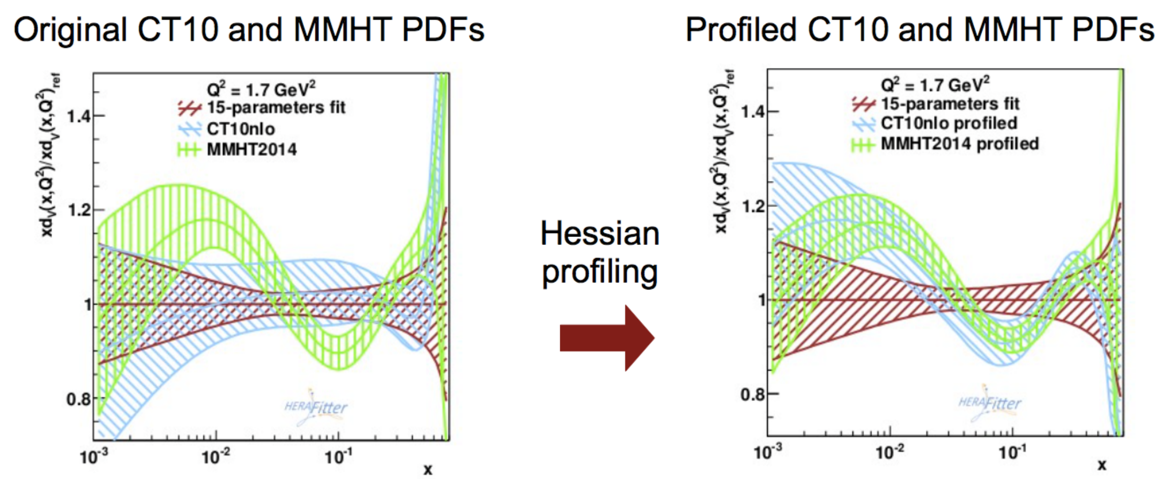


Good agreement between latest CDF and D0 W asymmetry data!



The inclusion of the the Tevatron W asymmetry data improves the agreement between CT10 and MMHT

Summary

- HERAFitter project is based on a multi-functional open source QCD software package that provides a framework for scrupulous interpretations of the QCD analyses.

  www.herafitter.org

  herafitter-1.1.1 latest release

- HERAFitter provides state-of-the-art calculations for LO,NLO,NNLO predictions and fast minimisation tools to perform a complete QCD fit analysis.

- HERAFitter is actively used by the LHC experiments and theory community.

- Highlighted in this talk most recent studies by HERAFitter developers:
  - Correlated PDFs for different orders allows to reduce theoretical uncertainties for cross-section ratios, calculated at different order.
  - Fits and profiling studies of the recent Tevatron W, Z data show importance of them to constrain d valence, which is essential for the W-boson mass measurement at the LHC
  - Profiling techniques as implemented in HERAFitter can be used in assessing the impact of future data.

extra (not necessarily useful)

Observable	Experiment	Integrated luminosity	Kinematic requirements	Used in the nominal fit
$d\sigma(Z)/dy$	D0	0.4 fb^{-1}	$71 < m_{ee} < 111$ GeV	yes
$d\sigma(Z)/dy$	CDF	2.1 fb^{-1}	$66 < m_{ee} < 116$ GeV	yes
A_μ	D0	7.3 fb^{-1}	$p_T^\mu > 25$ GeV, $p_T^\nu > 25$ GeV	yes
$A_{W\to e\nu}$	CDF	1.0 fb^{-1}	none	yes
$A_{W\to e\nu}$	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	yes
A_e	D0	9.7 fb^{-1}	$E_T^e > 25$ GeV, $p_T^\nu > 25$ GeV	no

Data set	(partial) χ^2/dof	partial χ^2/dof vs PDF set		
		CT10	MMHT14	NNPDF3.0
D0 $d\sigma(Z)/dy$	23 / 28	—	—	—
CDF $d\sigma(Z)/dy$	32 / 28	—	—	—
D0 A_μ	12 / 10	13/10	—	12/10
CDF $A_{W\to e\nu}$	14 / 13	14/13	—	15/13
D0 $A_{W\to e\nu}$	8 / 14	8/14	5/14	2/14
Total χ^2_{min} (incl. HERA) / dof	606 / 628	—	—	—

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	$ep \to e\ \text{jets}X$	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	$pp(\bar{p}) \to \text{jets}X$	NLOJet++ (APPLGRID), NLOJet++ (fastNLO)
LHC	DY heavy quarks	$pp \to VhX$	MCFM (APPLGRID)

Transverse Momentum Distributions

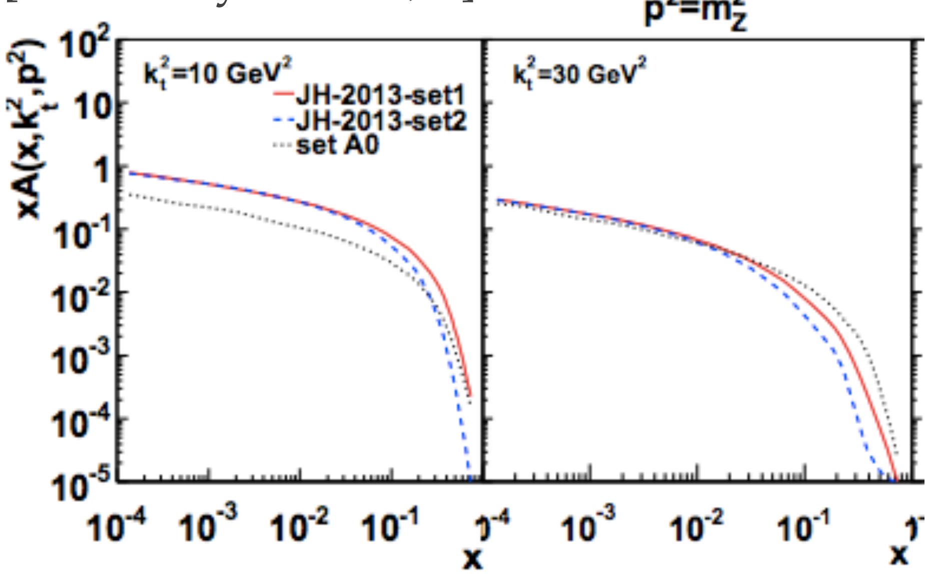
- QCD applications to multiple-scale scattering problems and complex final-state observables require in general formulations of factorisation which involve transverse-momentum dependent (TMD) - or known also as unintegrated PDFs.

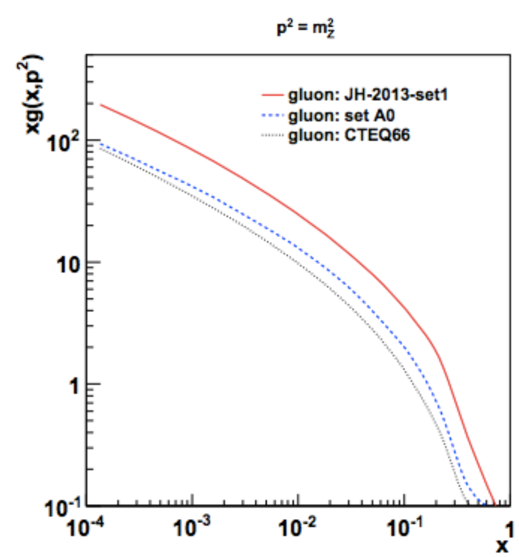
$$\sigma_j(x, Q^2) = \int_x^1 dz \int d^2k_t \; \hat{\sigma}_j(x, Q^2, z, k_t) \; \mathcal{A}(z, k_t, \mu)$$

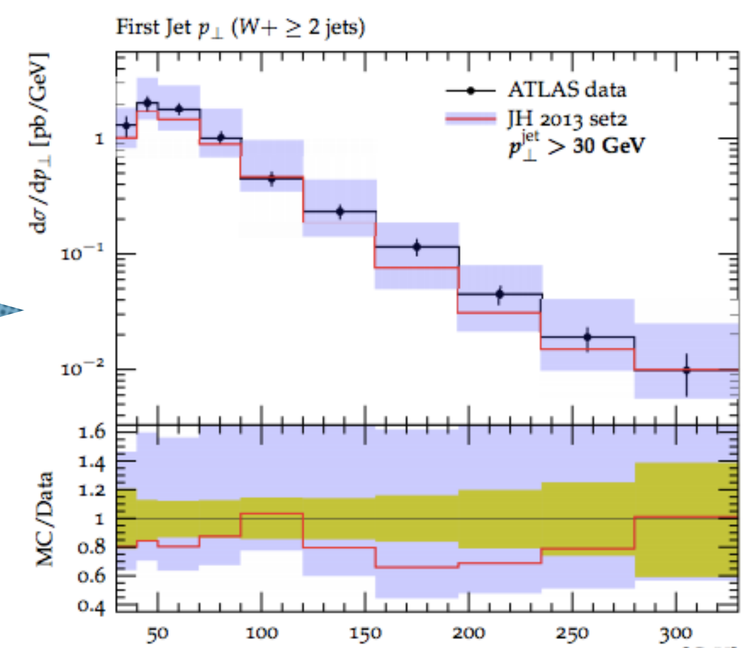
→ a convolution in both longitudinal and transverse momenta of TMD with off-shell partonic matrix elements

- 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]







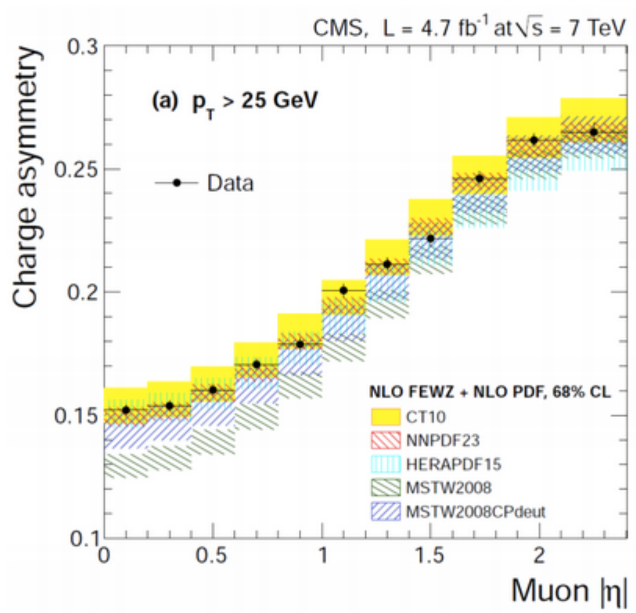
[PLB736:293, 2014.]

- 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

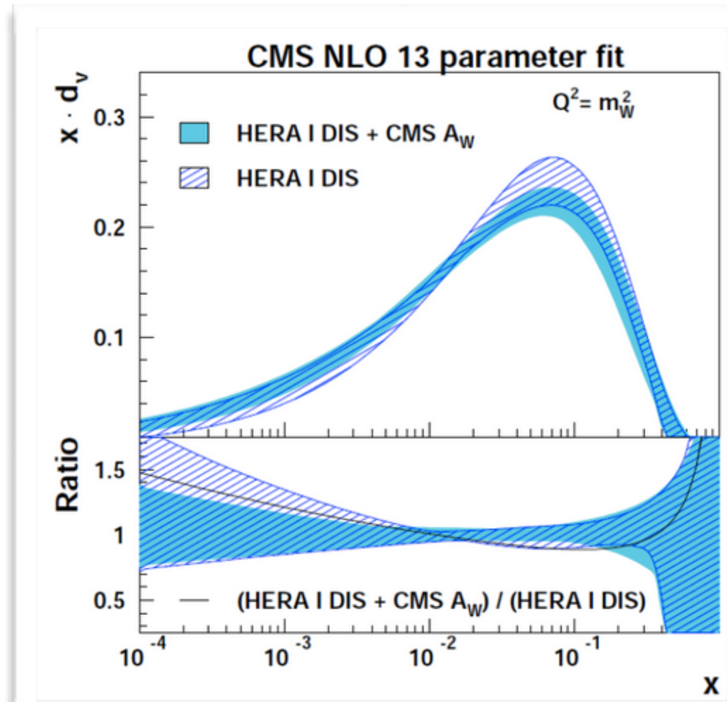
QCD interpretation of W production at CMS

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

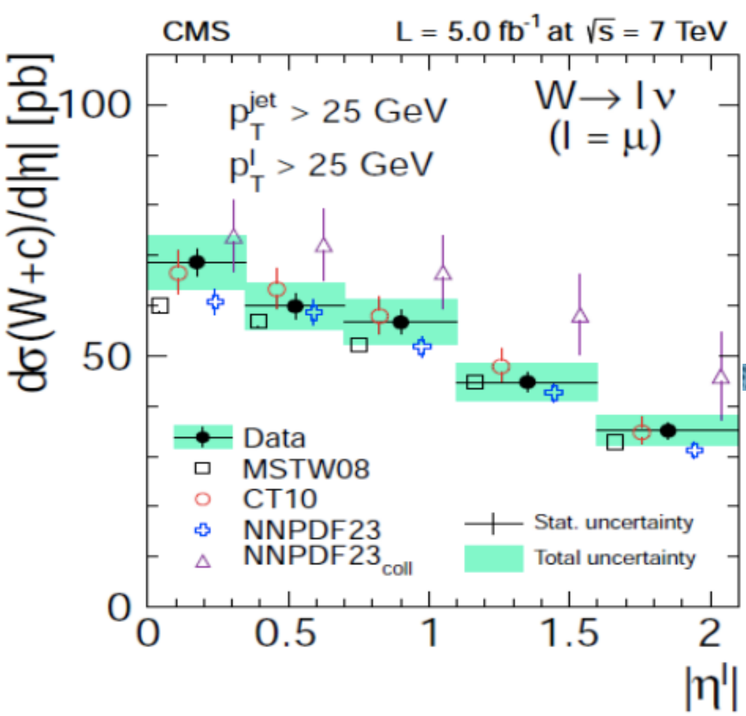
arXiv:1312:6283



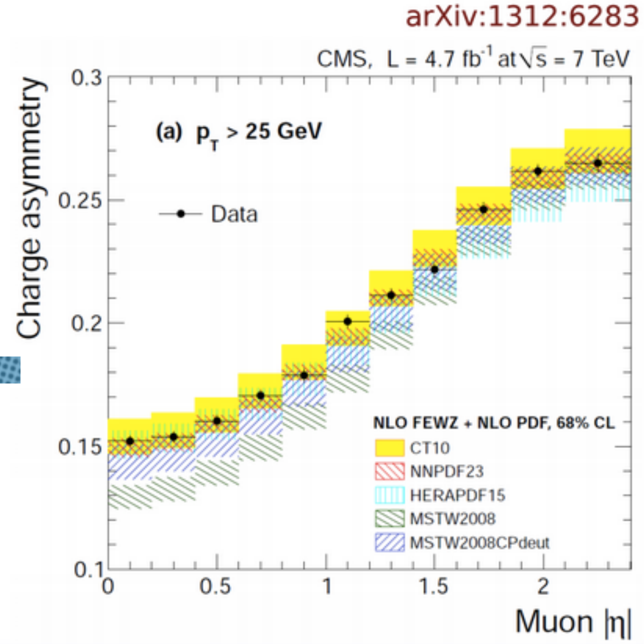
$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

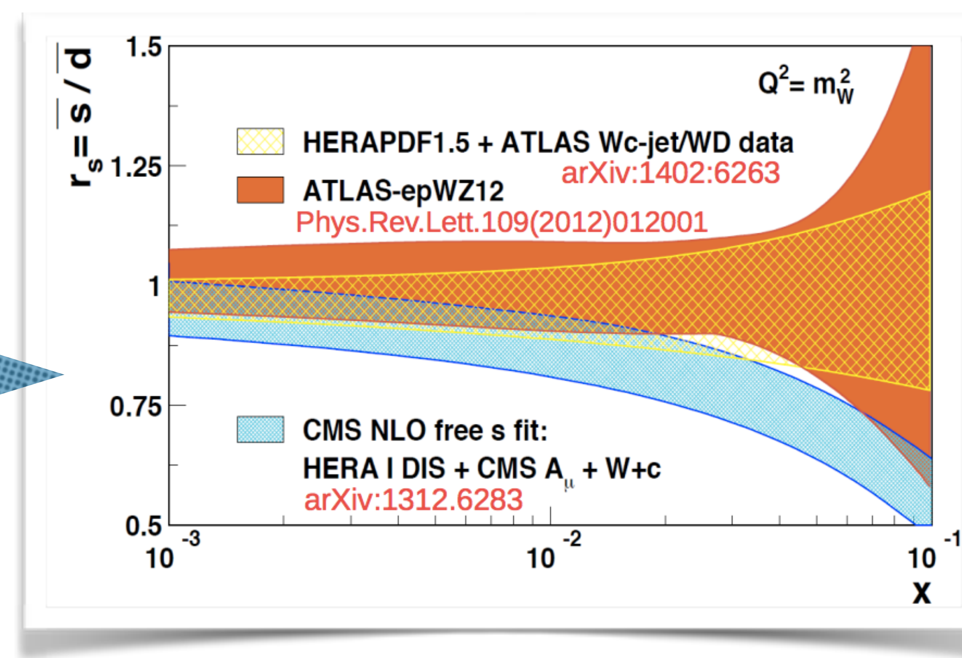


- In addition, W+charm data provides direct sensitivity to the strange quark



arXiv:1312:6283

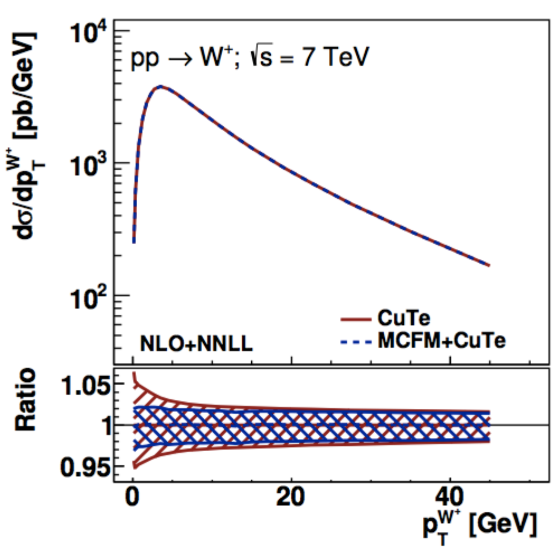


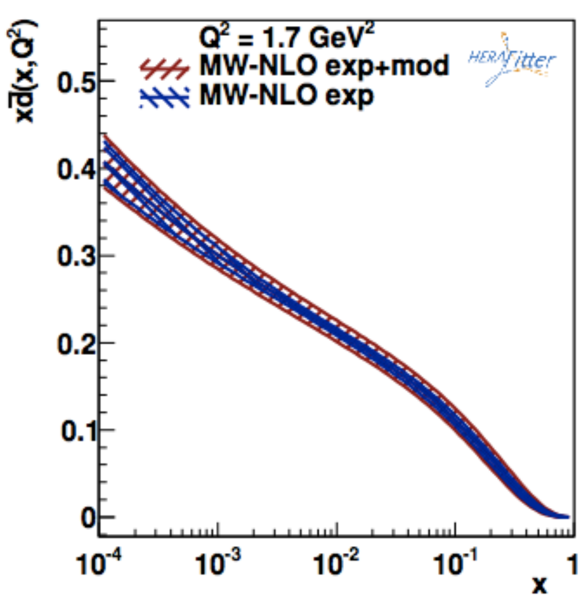


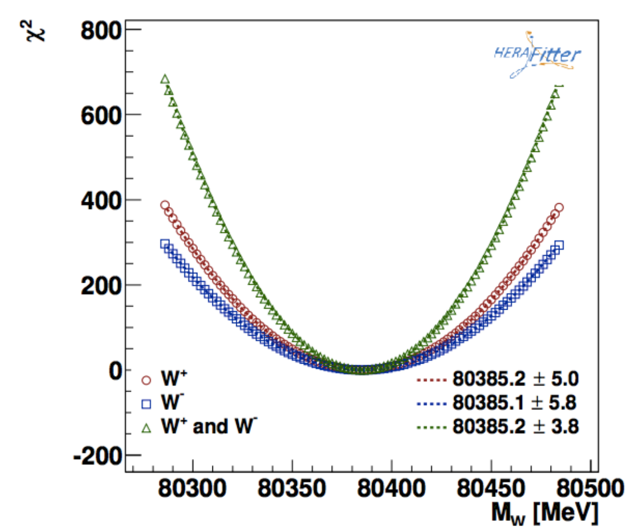
Studies of theoretical uncertainties of Mw mass at the LHC

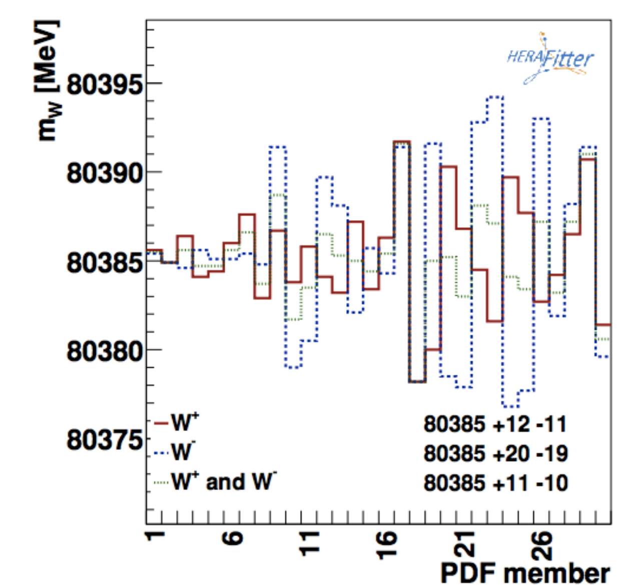
ATL-PHYS-PUB-2014-015

- 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 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, was 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



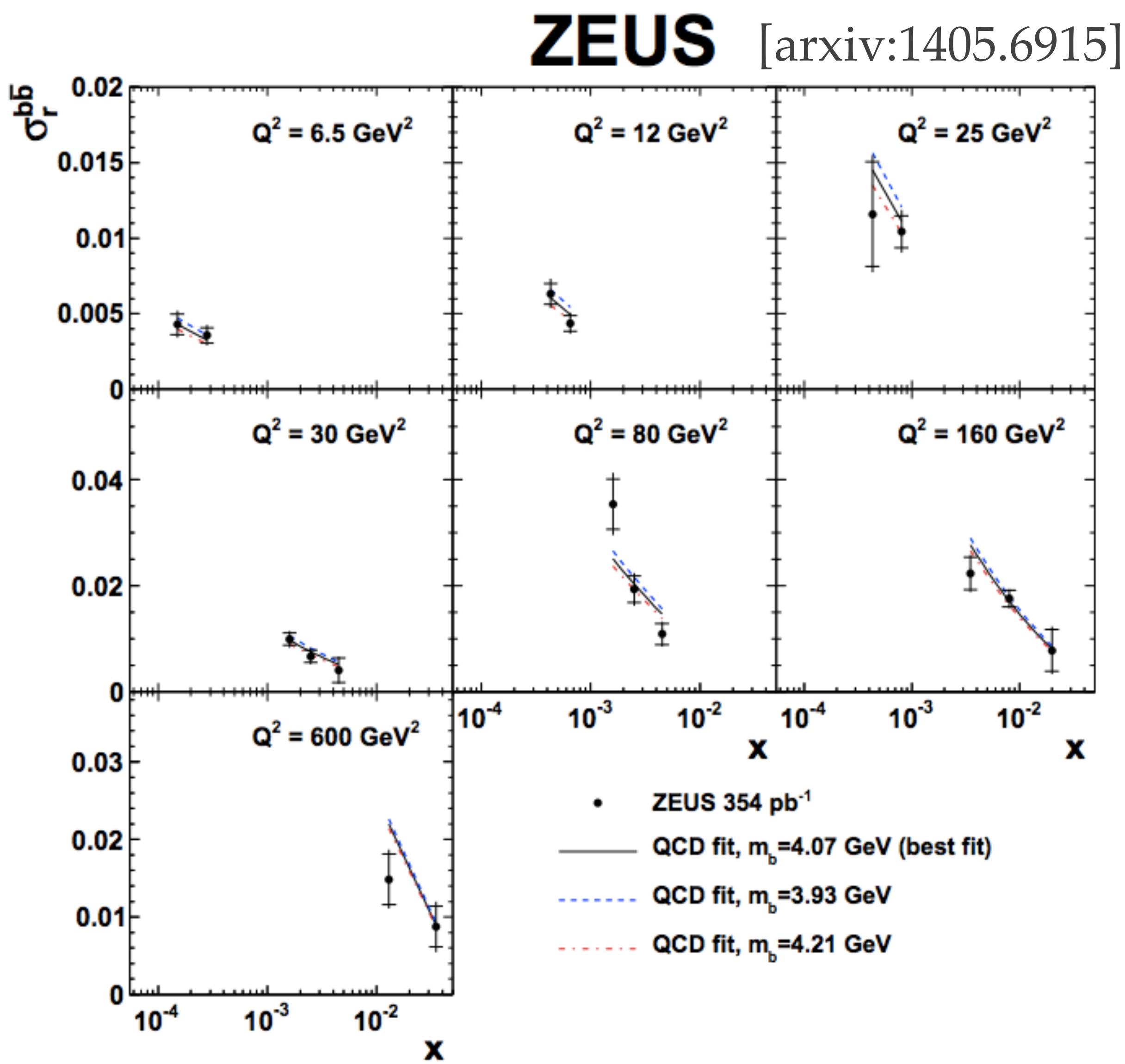






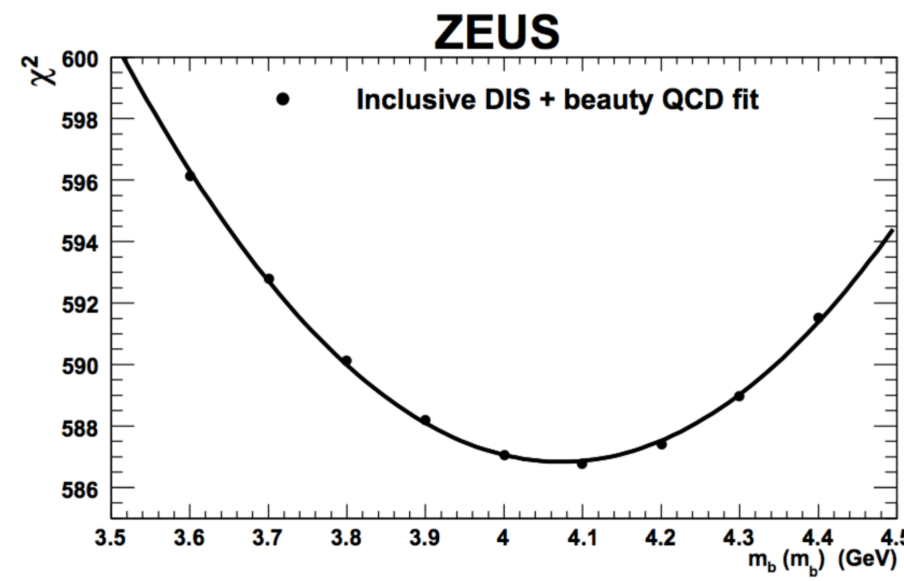
Running beauty mass from F2b

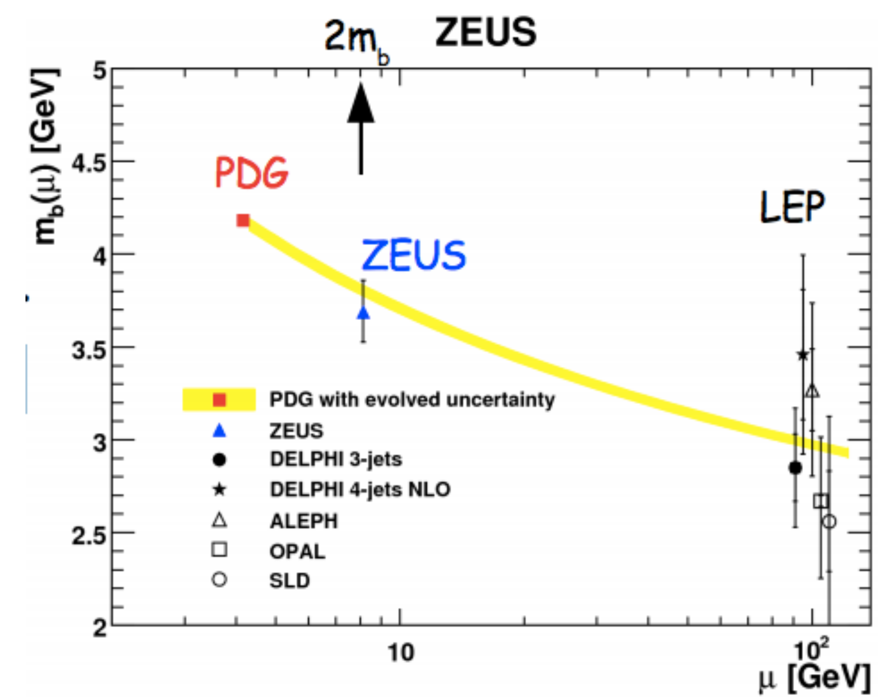
- The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
    - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{MS}$ scheme.



QCD Fits

HERA I+beauty





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