The photon PDF from high-mass DY data at the LHC using xFitter

F. Giuli (on behalf of the xFitter team)

EPS-HEP 2017 - Conference of High Energy Physics
Venice, Italy
06/07/2017

Oxford Physics

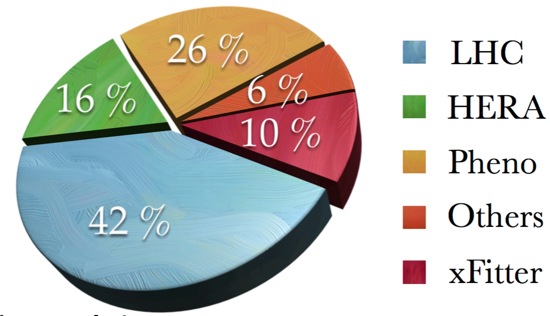
PDF4BSM
Parton Distributions in the Higgs Boson Era

erc
European Research Council
Established by the European Commission

xFitter

The xFitter Project

- The xFitter project (former HERAFitter) is an **unique open-source QCD fit framework**
- GitLab (CERN) is now the main repository of the project: https://gitlab.cern.ch/fitters/xfitter (open access to download for everyone – read only)
- This code allows users to:
  - **extract PDFs** from a large variety of experimental data,
  - assess the **impact** of **new data on PDFs**,
  - check the **consistency** of experimental data,
  - test different **theoretical assumptions**



- Around 30 active developers between experimentalists and theorists
- More than **40 publications** obtained using xFitter from the beginning of the project: https://www.xfitter.org/xFitter/xFitter/results
- LHC experiments provide the main developments and usage of the xFitter platform

List of analyses by xFitter

The link to the list of analyses using former HERAFitter can be accessed here

5	01.2017	F. Giuli, xFitter Developers' team and M. Lisovyi	arXiv:1701.08553	The photon PDF from high-mass Drell Yan data at the LHC
4	03.2016	xFitter and APFEL teams and A. Geiser	JHEP 1608 (2016) 050, arXiv:1605.01946	A determination of mc(mc) from HERA data using a matched heavy flavor scheme

!!!

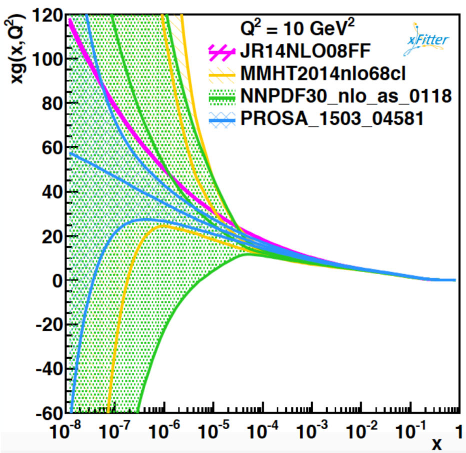
List of analyses using xFitter

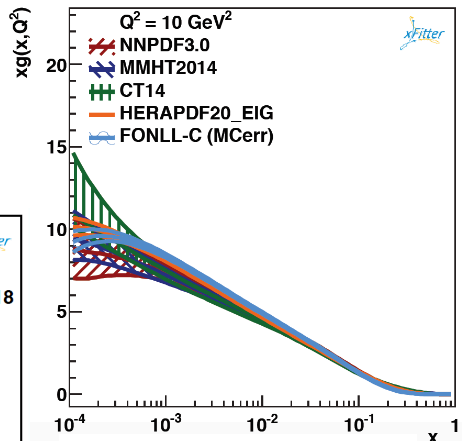
Number	Date	Group	Reference	Title
2016				
42	03.2017	CMS	arXiv:1703.01630, submitted to EPJC (TOP-14-013)	Measurement of double differential cross sections for top quark pair production in pp collisions at 8 TeV and impact on PDFs
41	02.2017	A. Aleedaneshvara, M. Goharipour, S. Rostami	Chin Phys C 41, 2 (2017) 023101	Uncertainty of parton distribution functions due to physical observables in a global analysis
40	01.2017	Y.G. Gbedo, M. Mangin-Brinet	arXiv:1701.07678	Markov Chain Monte Carlo technics applied to PDF determination: proof of concept
39	01.2017	ABMP	arXiv:1701.05838	Parton Distribution Functions, α_s and Heavy-Quark Masses for LHC Run II
38	12.2016	ATLAS	arXiv:1612.03636	Measurements of top-quark pair to Z-boson cross-section ratios at s = 13; 8; 7 TeV with the ATLAS detector

Latest results… More in preparation!

xFitter in a Nutshell

- **Parametrise** PDFs at the initial scale:
  - several functional forms available ("standard", Chebyshev, etc.)
  - define parameters to be fitted
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM, ABF)
- **Compute** predictions for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, RT, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions** via χ^2:
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise** the χ^2 w.r.t. the fitted parameters
  - using MINUIT or by Bayesian reweighting
- **Useful drawing tools**





Gluon PDF $xg(x, Q^2)$

xFitter release 2.0.0

xFitter

xFitter/xFitterTalks » xFitter/../xFitterDevel.. » xFitter/../Meeting2017-.. » xFitter » xFitter/DownloadPage

Wiki
- WikiPolicy
- RecentChanges
- FindPage
- HelpContents
- xFitter/DownloadPage

Page
- Immutable Page
- Info
- Subscribe
- Add Link
- Attachments
- More Actions:

xFitter / DownloadPage

Releases of the xFitter 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: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xfitter
- The script to download coupled data and theory files xfitter-getdata.sh.
- Data and theory files are also stored in hepforge and can be accessed from there ("List of Data Files").

Date	Version	Files	Remarks
03/2017	**2.0.0 FrozenFrog**	xfitter-2.0.0.tgz	stable release with decoupled data and theory files
07/2016	**1.2.2**	xfitter-1.2.2.tgz	release with decoupled data and theory files
05/2016	**1.2.1**	xfitter-1.2.1.tgz	release with decoupled data and theory files
02/2016	**1.2.0**	xfitter-1.2.0.tgz	release with decoupled data and theory files

Sample data files:
LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: …

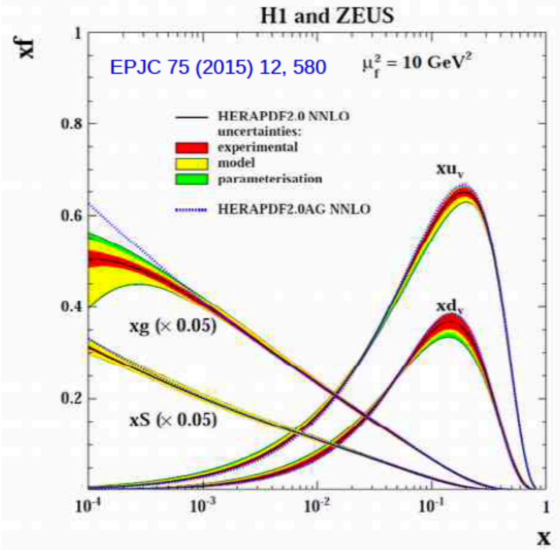
xFitter 2.0.0 FrozenFrog

- By default, only final combined HERA I+II data are distributed
- **getter-xfitter.sh script** to download data with corresponding theory files
- in directory 'datasets' located all available files

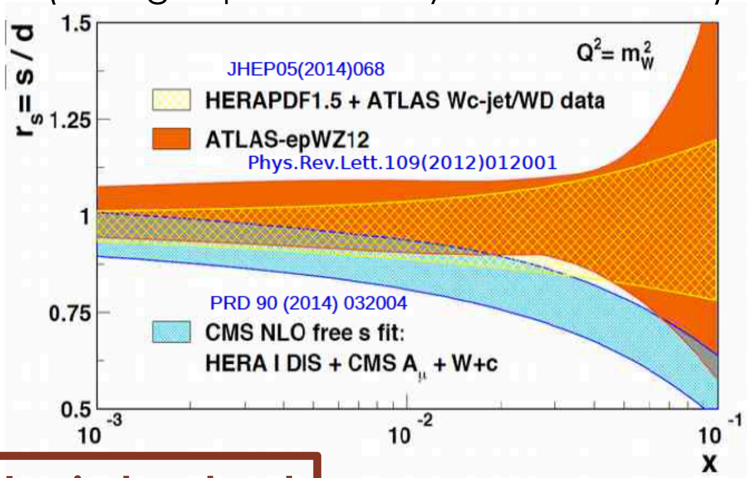
https://www.xfitter.org/xFitter/xFitter/DownloadPage

Results obtained with xFitter: Examples (1)

DIS inclusive processes (ep)

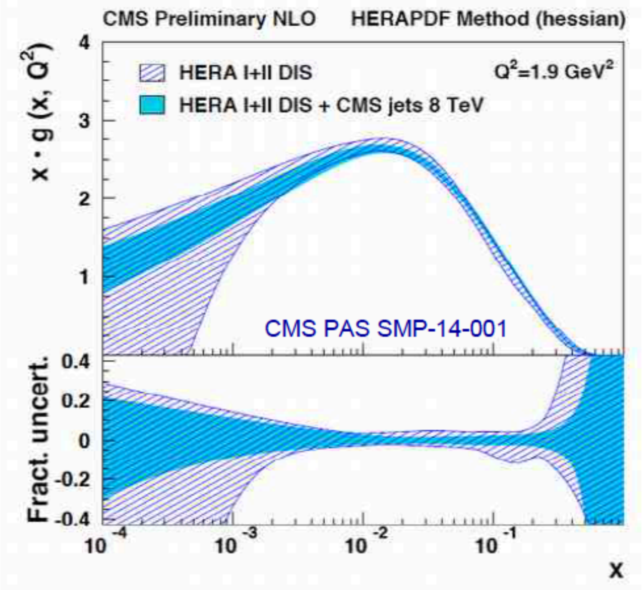


Drell-Yan processes ($pp, p\bar{p}$)
(strange quark density determination)

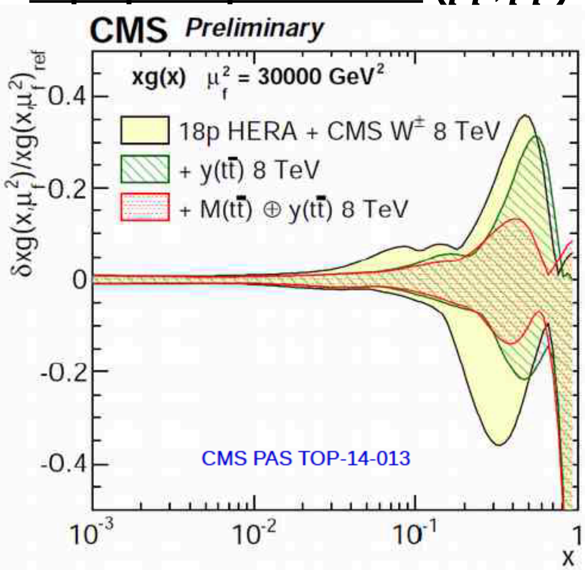


More examples in backup!

Jet production ($ep, pp, p\bar{p}$)



Top-quark production ($pp, p\bar{p}$)

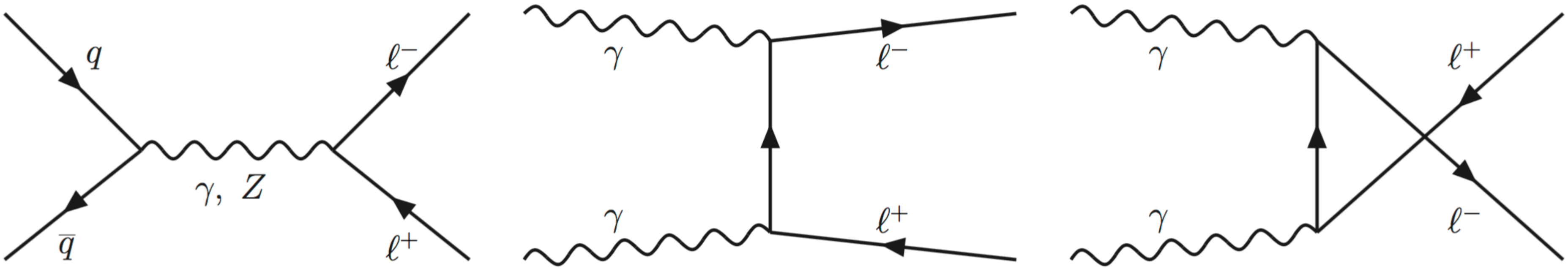


Photon PDF determination - Motivations

- Interpretation of the LHC data requires theoretical calculations that include not only QCD corrections, but also the EW effects for the TeV region:
  - pure weak corrections
  - **QED corrections → photon PDF**

arXiv:1701.08553
EPJ-C 77 (2017) 400

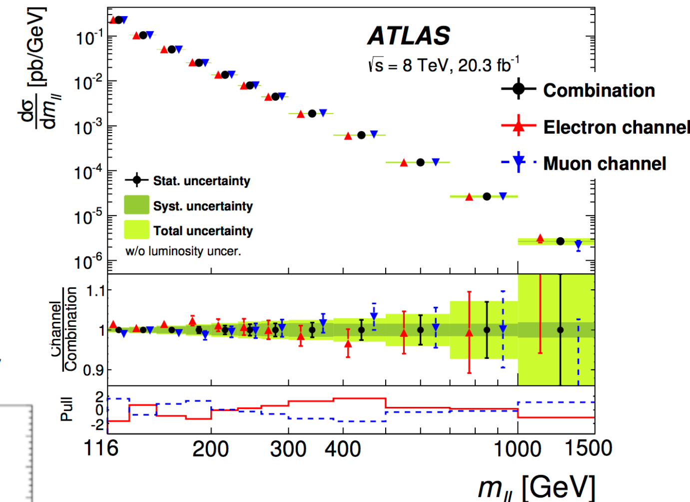
- The photon PDF is a crucial ingredient that needs to be determined accurately:
  - Historically, the first set was MRST2004 QED: photon taken from a model and tested on direct photon production at HERA
  - NNPDF2.3 QED provided a first model independent determination from fits to DY LHC data
  - More photon PDFs followed: CT14qed, NNPDF30qed
  - A new approach from LUXqed: photon PDF calculated from inclusive lepton-proton DIS structure functions (% level precision); similarly HKR16
- **Drell-Yan data at LHC** provide direct handle on the **photon PDF**:

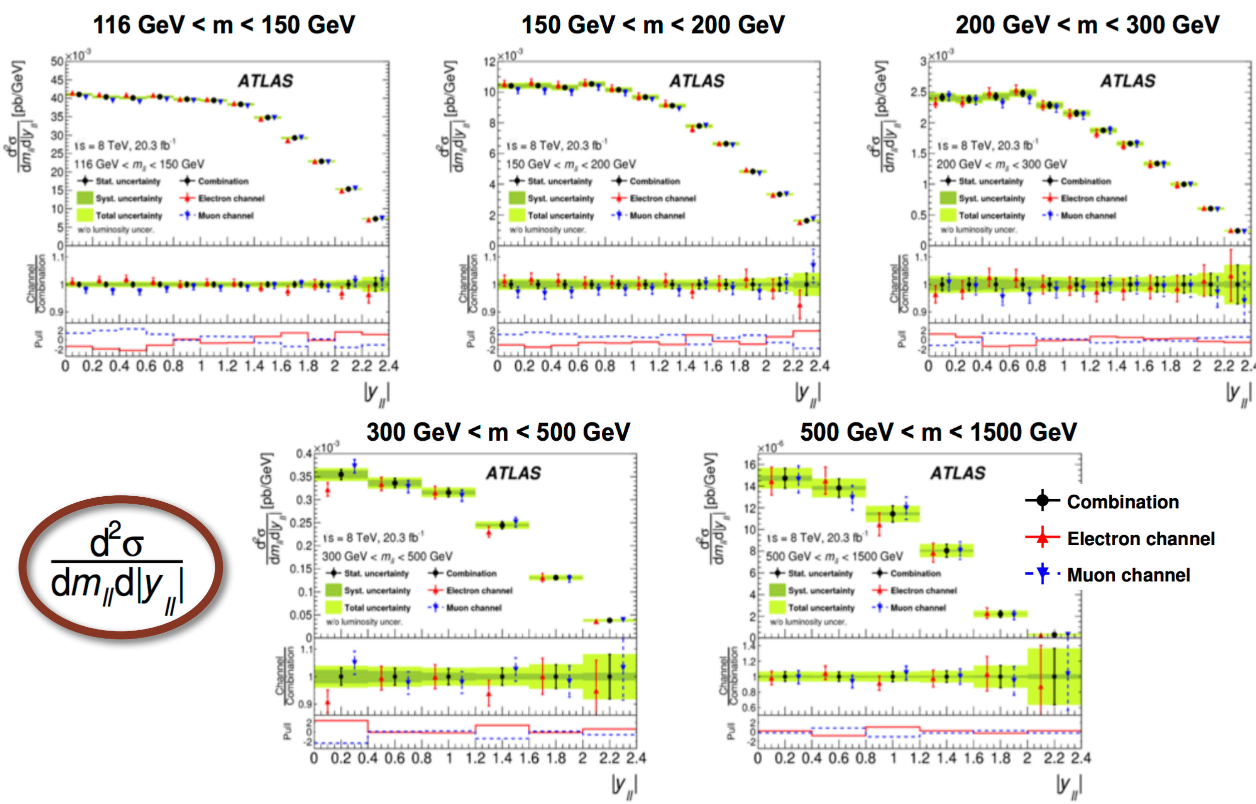


Input dataset

JHEP 1608 (2016) 009

- ATLAS high mass Drell Yan at 8 TeV (published in June '16) arXiv:1606.01736
- 1D (dilepton mass distribution)
- 2D in mass and rapidity bins distribution
  - 48 data points
  - this is expected to provide most sensitivity to PDFs





$$\frac{d^2\sigma}{dm_{ll}d|y_{ll}|}$$

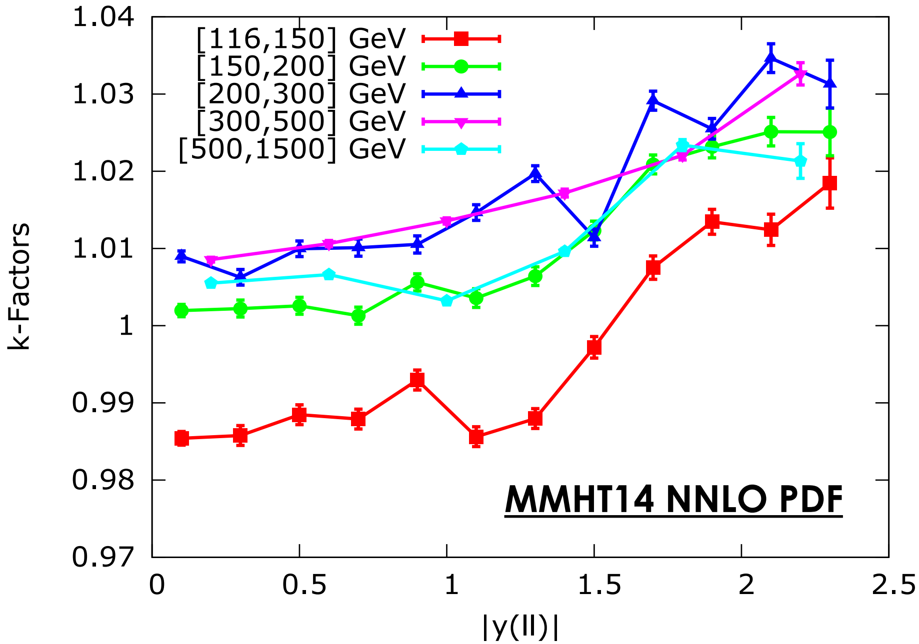
- Quite precise data! (less of 5% unc. up to 700 GeV)
- Also 2D in mass and $\Delta\eta$ bins distribution
- Inclusive HERA I+II used as the base (7 data sets) – for full PDF coverage

Theory inputs (1)

- PDF evolution and DIS cross sections via APFEL program:
  - Accurate up to NNLO in QCD + NLO in QED
  - Includes relevant mixed QCD + QED correction → **NOVELTY!**
  - FONLL general-mass scheme
- LHC hmDY cross sections calculated via Madgraph5_aMC@NLO which includes PI diagrams
  - Interfaced to APPLgrid via aMCfast
  - Tailored version of APPLgrid used to account for photon contributions

$$k_F(m_{ll}, |y_{ll}|) \equiv \frac{NNLO\ QCD + NLO\ EW}{NLO\ QCD + LO\ EW}$$

- NNLO QCD + NLO QED corrections to DY obtained using FEWZ3.1



Determined by the technique of saturation of the χ^2

$$\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}, \\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1 + E_g x^2), \\
x\gamma(x) &= A_\gamma x^{B_\gamma} (1-x)^{C_\gamma} (1 + D_\gamma x + E_\gamma x^2).
\end{aligned}$$

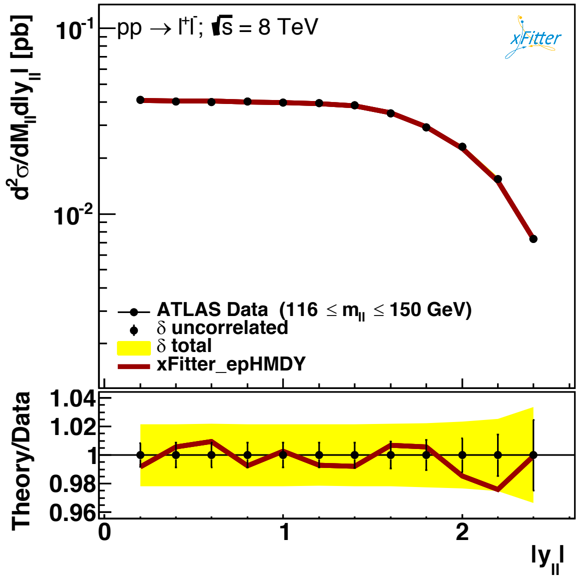
PDF parameterisation

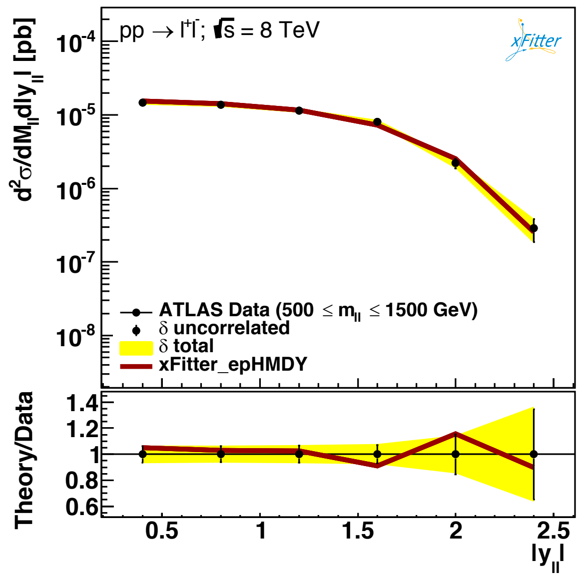
(the number of parameters is increased one by one until the χ^2 does not improve further)

Results (1)

➢ Good description of the dataset (remarkably, for DY data χ^2/N_{data} = 48/48)

Dataset	χ^2/N_{dat}
HERA I+II	1236/1056
high-mass DY 116 GeV $\leq m_{ll} \leq$ 150 GeV	9/12
high-mass DY 150 GeV $\leq m_{ll} \leq$ 200 GeV	15/12
high-mass DY 200 GeV $\leq m_{ll} \leq$ 300 GeV	14/12
high-mass DY 300 GeV $\leq m_{ll} \leq$ 500 GeV	5/6
high-mass DY 500 GeV $\leq m_{ll} \leq$ 1500 GeV	4/6
Correlated (high-mass DY) χ^2	1.17
Log penalty (high-mass DY) χ^2	-0.12
Total (high-mass DY) χ^2/N_{dat}	48/48
Combined HERA I+II and high-mass DY χ^2/N_{dof}	1284/1083

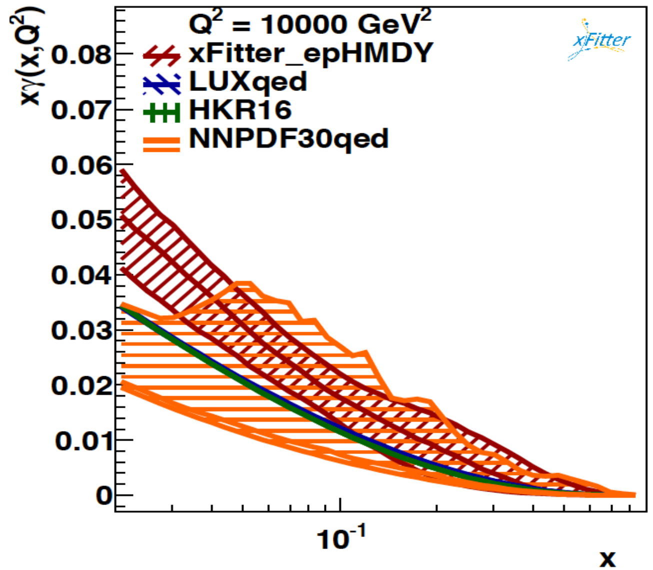




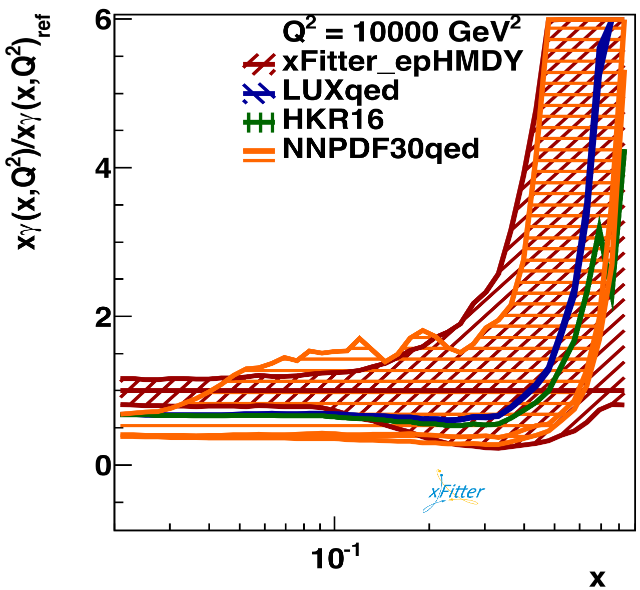
Results (2)

- Good description of the dataset (remarkably, for DY data χ^2/N_{data} = 48/48)

Dataset	$\chi^2\ /N_{\text{dat}}$
HERA I+II	1236/1056
high-mass DY 116 GeV $\leq m_{ll} \leq$ 150 GeV	9/12
high-mass DY 150 GeV $\leq m_{ll} \leq$ 200 GeV	15/12
high-mass DY 200 GeV $\leq m_{ll} \leq$ 300 GeV	14/12
high-mass DY 300 GeV $\leq m_{ll} \leq$ 500 GeV	5/6
high-mass DY 500 GeV $\leq m_{ll} \leq$ 1500 GeV	4/6
Correlated (high-mass DY) χ^2	1.17
Log penalty (high-mass DY) χ^2	-0.12
Total (high-mass DY) χ^2/N_{dat}	48/48
Combined HERA I+II and high-mass DY χ^2/N_{dof}	1284/1083

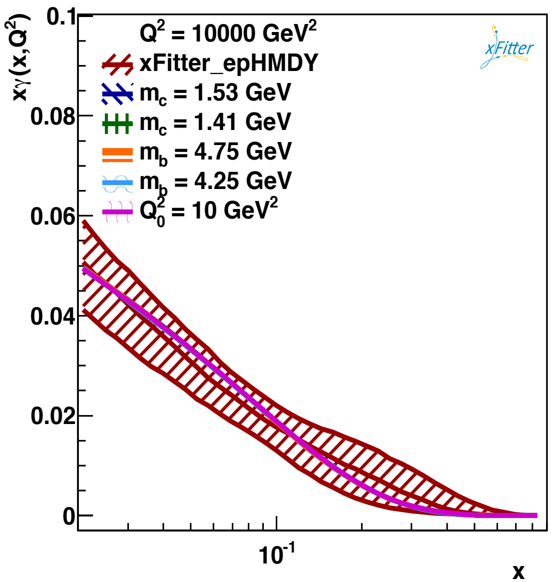


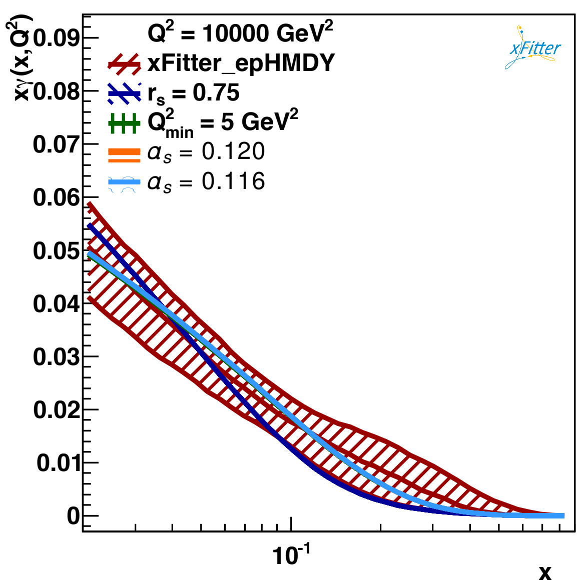
- Agreement within uncertainties for all determinations for $x \geq 0.1$ (1σ level)
- For $0.1 < x$ LUXqed and HKR16 are softer than xFitter_epHMDY (agreement at 2σ level)
- Smaller uncertainty as compared to NNPDF3.0qed (~30% below $x = 0.1$) – the only other direct determination
- **Direct determination not competitive with theoretical calculations, but fully consistent with them**

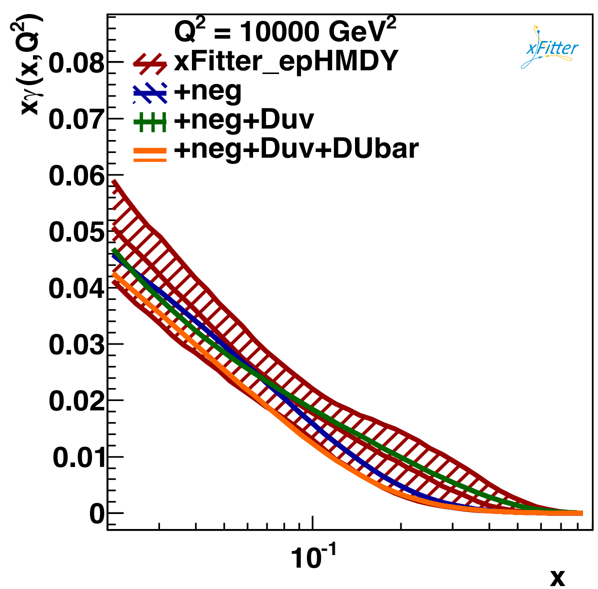


Results (3)

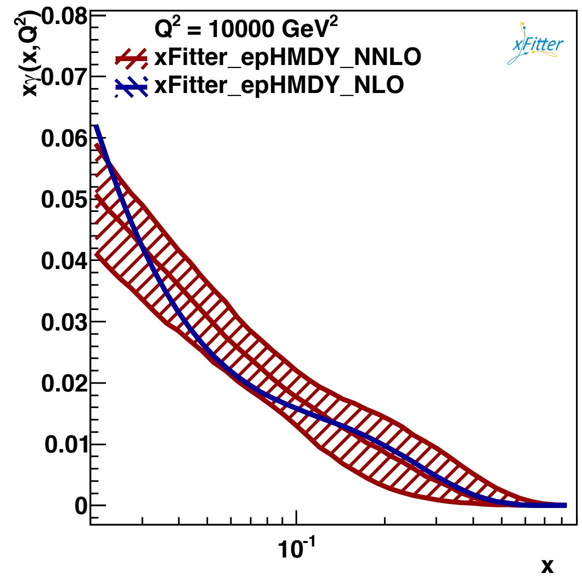
- Good description of the dataset (remarkably, for DY data χ^2/N_{data} = 48/48)







- Agreement within uncertainties for all determinations for $x \geq 0.1$ (1σ level)
- For $0.1 < x$ LUXqed and HKR16 are softer than xFitter_epHMDY (agreement at 2σ level)
- Smaller uncertainty as compared to NNPDF3.0qed (~30% below $x = 0.1$) – the only other direct determination
- Robustness of the fit and his perturbative stability studied (NLO vs NNLO)
- Experimental uncertainties: **MC vs. Hessian**



Summary

- **xFitter** (former **HERAFitter**) is a unique **open-source** package oriented to fits of PDFs that provides a framework for the **interpretation** and the **analysis** of the experimental data
- xFitter is presently widely used for many analyses of the **LHC data** to quantify the **constraints on PDFs**
- **xFitter-2.0.0** is latest (recommended) release – **Frozen Frog**
- Over 40 public results obtained using xFitter
- Several published dedicated physics studies (developers team publications), more studies are ongoing
- I have presented one of the many recent results obtained with xFitter:
  - an extraction of the photon PDF based on the recent ATLAS 8 TeV high mass Drell-Yan data
- **We welcome new ideas and developers :)**

xFitter 2.0.0
FrozenFrog

https://www.xfitter.org/

Thanks for your attention!

Ringaile Placakyte
(almost five year of convenorship)

Voica Radescu
(founder and convener)

Best wishes and have fun with the new work

Backup Slides

Motivation

- The **factorisation theorem** for a hadronic cross section read:

$$d\sigma_{\rm had} = W_{ij} \otimes f_i \otimes f_j \, d\Phi$$

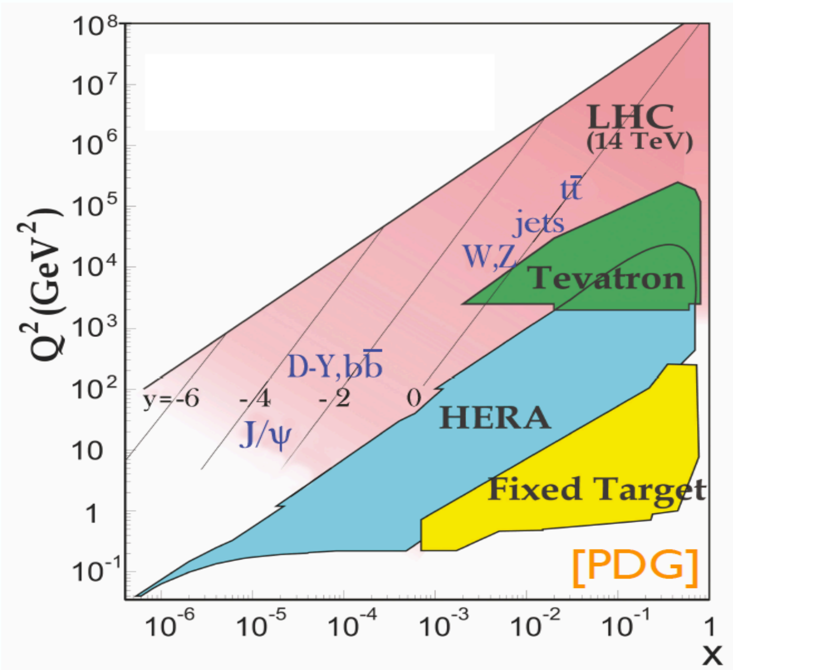
Partonic cross sections:
- Process dependent
- High-energy dominated
- Computable in perturbation theory

Parton distribution functions:
- Universal (for a given hadronic species)
- Low-energy dominated
- Perturbation theory inapplicable

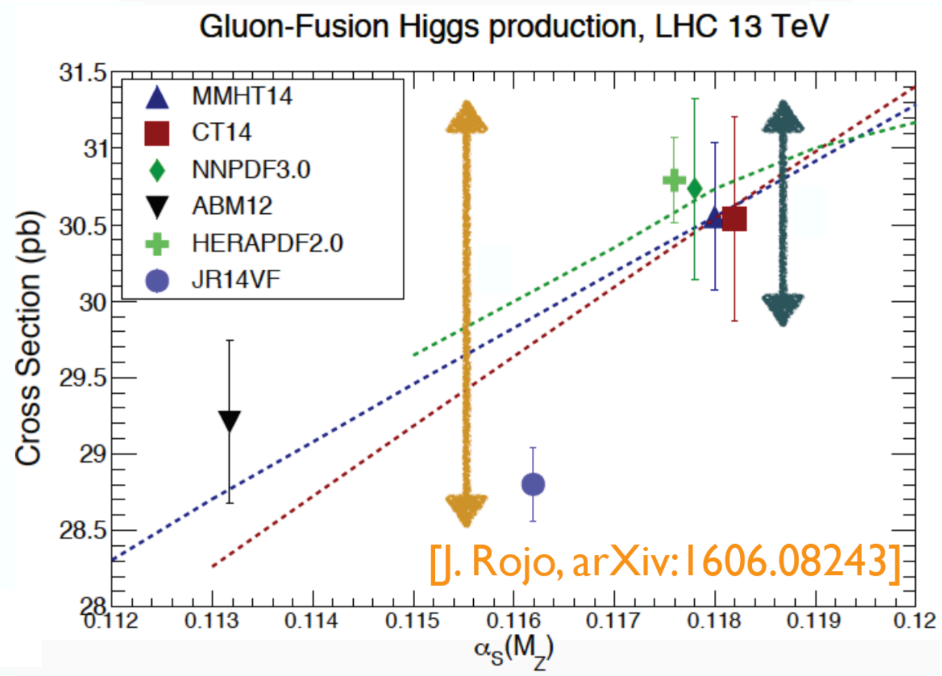
How do we determine parton distribution functions (PDFs)?

Presently, the most accurate and reliable way is through fits to data
and reliable way is through **fits to data**

Introduction



- Fitting PDFs is a **complex** task
- **Datasets**:
  - as large and varied as possible
  - Spanning a wide kinematic range
- Estimate of the **uncertainties**:
  - include full experimental uncertainties
  - ensure a faithful representation
- Choice of the **parametrisation**:
  - avoid parametrisation biases
- **Theoretical inputs**:
  - higher order corrections
  - Heavy-quarks mass effect
  - …
- Different choices my lead to different results



xFitter on Hepforge: data access

http://xfitter.hepforge.org/

- Home
- Source Code
- List of Data Files
- xFitter Wiki
- xFitter Releases
- Contact

xFitter

An Open Source QCD Fit Project

Welcome! This site is under development.
(use: xFITTER site .)

- This website contains complementary information to https://www.xfitter.org/
- Possibility to download data files (including theory)
- Updated automatically with new data added to svn

Your feedback is welcome! ☺
(via email xfitter-help@desy.de)

http://xfitter.hepforge.org/data.html

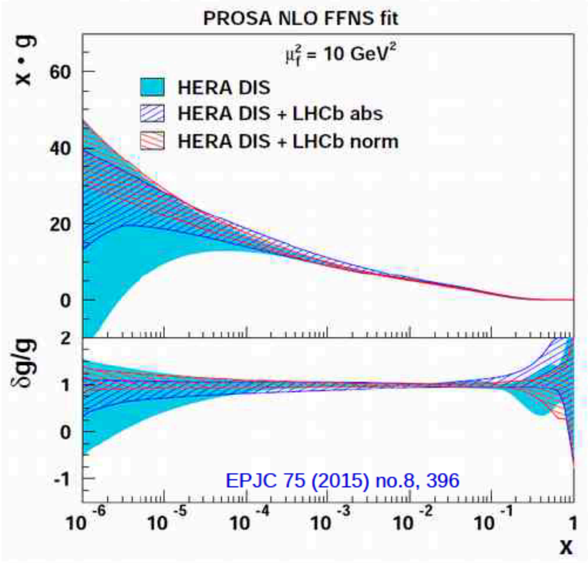
This page contains the list of publicly available experimental data sets (with corresponding theory grids if available) in the xFitter package.
To download data set please click on the arXiv link (and open/save tar.gz file).

No	Collider	Experiment	Reaction	arXiv	Readme
1	fixedTarget	bcdms	inclusiveDis	cern-ep-89-06	README
2	hera	h1	beautyProduction	0907.2643	
3	hera	h1	inclusiveDis	1012.4355	
4	hera	h1	jets	0706.3722	README
5	hera	h1	jets	0707.4057	README
6	hera	h1	jets	0904.3870	README
7	hera	h1	jets	0911.5678	README
8	hera	h1	jets	1406.4709	README
9	hera	h1zeusCombined	charmProduction	1211.1182	
10	hera	h1zeusCombined	inclusiveDis	0911.0884	
11	hera	h1zeusCombined	inclusiveDis	1506.06042	
12	hera	zeus	beautyProduction	1405.6915	
13	hera	zeus	diffractiveDis	0812.2003	
14	hera	zeus	jets	0208037	
15	hera	zeus	jets	0608048	
16	hera	zeus	jets	1010.6167	
17	lhc	atlas	drellYan	1305.4192	
18	lhc	atlas	drellYan	1404.1212	
19	lhc	atlas	jets	1112.6297	

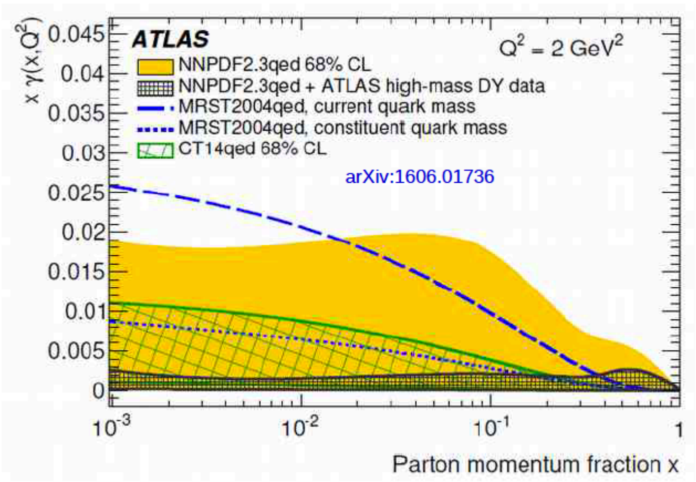
(more datasets available on the website)

Results obtained with xFitter: Examples (2)

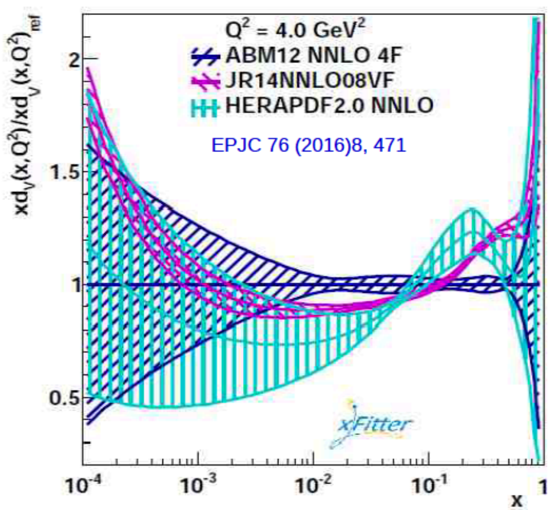
Heavy quark production($ep, pp, p\bar{p}$)



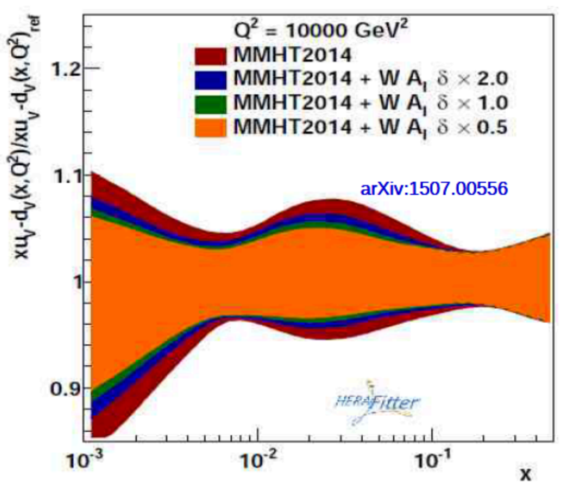
DY data sensitivity to photon PDF



Evolution of moder PDFs (benchmarking)



PDF4LHC report (benchmarking)



Novelties in xFitter 2.0.0 (1)

Release	Date	Description
xfitter-2.0.0 (FrozenFrog)	20.03.2017	**Physics related additions:** • Implementation of switching scales for heavy quarks (APFEL) • Fast convolution using APFELGRID ("fk" tables) • Write out top LHAPDF if top mass is below kinematic limit (5 and 6 flavour PDFs) • Extra PDF parameters of the photon parametrisation • Improvements to QED evolution interface (QEDevol) • (optionally) Produce symmetric hessian PDF sets using minuit HESSE covariance matrix computation instead of default ITERATE method. • Updates to dipole steering files, saturation flag added • Extra option to separate statistical uncertainty from total covariance matrix, when it is uncorrelated **Technical improvements:** • Move to QCDNUM 17-01-13 new PDF interfaces. Make use of fast PDF calls. • Update fastNLO to latest version. Switch from APPLGRID → FastNLO to native FastNLO. • `install-xfitter` script uses cvmfs (recommended way to install xFitter) • `xfitter-getdata.sh` script added to download datasets • Added new datasets from LHC and HERA, and LHeC simulated data. • Synchronisation of the lhapdf6 output grid with initialisation from QCDNUM • Restore optional LHAPDFv5 usage

!!

Novelties in xFitter 2.0.0 (2)

Release	Date	Description
xfitter-2.0.0 (FrozenFrog)	20.03.2017	**Physics related additions:**

- Possibility to force PDFs to be positive after processing (`xfitter-process` tool)
- Adjustment of internal systematic arrays to to run with all data. Reduction of other internal arrays to keep memory footprint low
- Improvements in configuration and makefiles to work with different compilers and operation systems
- If `OUTPUTDIR` directory exists when running xfitter, it will be moved to `OUTPUTDIR_OLD`
- Increased the possible length of the output directory name
- Clean up (removing/renaming functions, suppressing unneeded outputs)
- Updates to README, INSTALLATION, steering files, manual, doxygen config
- Add error message if combine utility is used with LHAPDFv 5.x
- Cleanup of warning messages, better indication of potential problems
- Restore `make dist` functionality
- Added extra automatic checks
- Add feature to draw individual sets by using set:ID:dir syntax
- Additional option `--loose-mc-replica-selection`
- Add strict check for second option of MC-replica path matching
- Other small fixes in drawing options (logo, coloured error bands, etc)

Bug Fixes:

- Fix in the gluon parametrisation (affecting HERAPDF parameterisation sum-rule)
- Enable compilation with LHAPDF6 and without APPLgrid
- Fixes in non-standard parameterisations (e.g. using Chebyshev polynomials)
- Fix few conflicting fortran symbols.

flavour PDFs)
SE covariance
matrix, when
PDF calls.
NLO to native
Fitter)
ta.
QCDNUM

xFitter Developers Meeting

External xFitter's meeting in Oxford: https://indico.cern.ch/event/578304/

- 33 participants
- 2.5 days workshop with number of talks and many discussions

xFitter workshops

xFitter examples (CTEQ school)

http://qcd2016.desy.de/

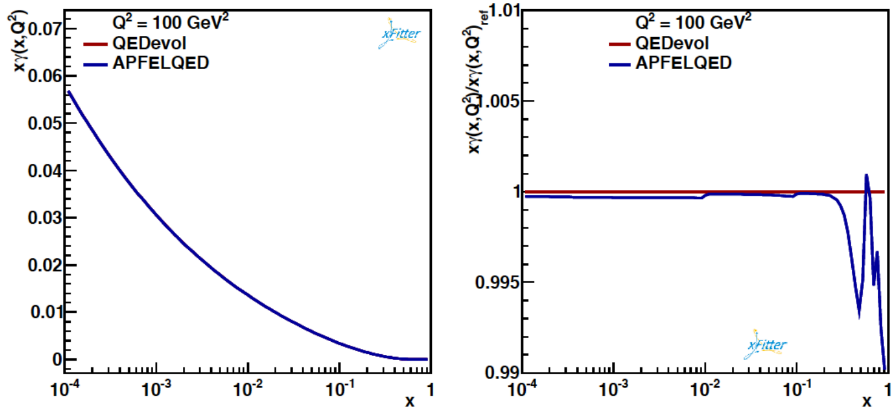
Stefano Camarda
Ringailé Plačakyté

A list of educational examples are provided in the package - prepared for the CTEQ summer school 2016:

- **Exercise 1:** PDF fit
  - learn the basic settings of a QCD analysis, based on HERA data only
- **Exercise 2:** Simultaneous PDF fit and as
  - learn the basic of an as extraction using H1 jet data
- **Exercise 3:** LHAPDF analysis
  - how to estimate impact of a new data without fitting:
  - profiling and reweighting techniques
- **Exercise 4:** Plotting LHAPDF files
  - direct visualisation of PDFs from LHAPDF6 using simple python scripts
- **Exercise 5:** Equivalence of χ^2 representations
  - understand different χ^2 representations (nuisance parameters and covariance matrix χ^2 formulas)

Physics cases in xFitter

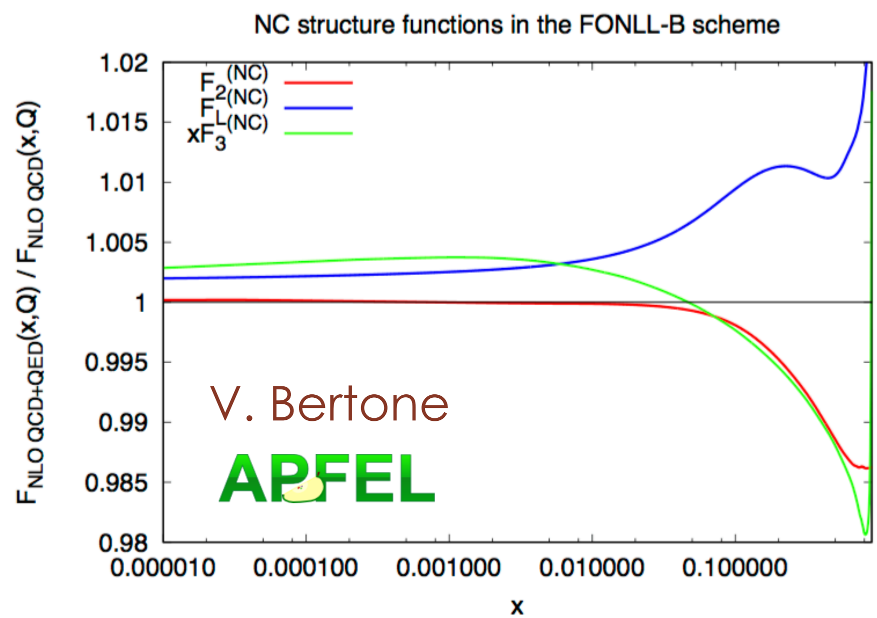
- **New QED PDFs up to NNLO QCD + NLO QED** in FFNS and VFNS are now available via evolutions in:
  - QCDNUM adjusted for DGLAP+QED [R. Sadykov] http://www.nikhef.nl/~h24/qcdnum
  - APFEL DGLAP+QED as used by NNPDF2.3 [V. Bertone et al.] https://apfel.hepforge.org/
  - plan to add NLO QED, interface APPLGRID to SANC https://apfel.hepforge.org/mela.html



[Plots produced by R. Sadykov and V. Bertone]

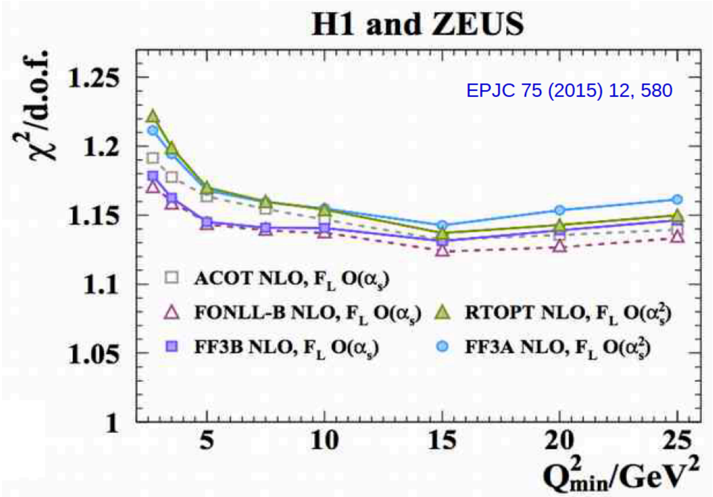
Perfect agreement between QEDEVOL and APFEL

- **NLO QCD + QED via APFEL in xFitter:**
  - implementing the $O(\alpha\alpha_S)$ and the $O(\alpha^2)$ corrections to the DGLAP splitting functions on top of the $O(\alpha)$ ones
  - implementing $O(\alpha\alpha_S^2)$ and the $O(\alpha^2)$, $O(\alpha^2\alpha_S)$ corrections to β functions
  - when including NLO QED corrections, not only the evolution is affected but also the DIS structure functions

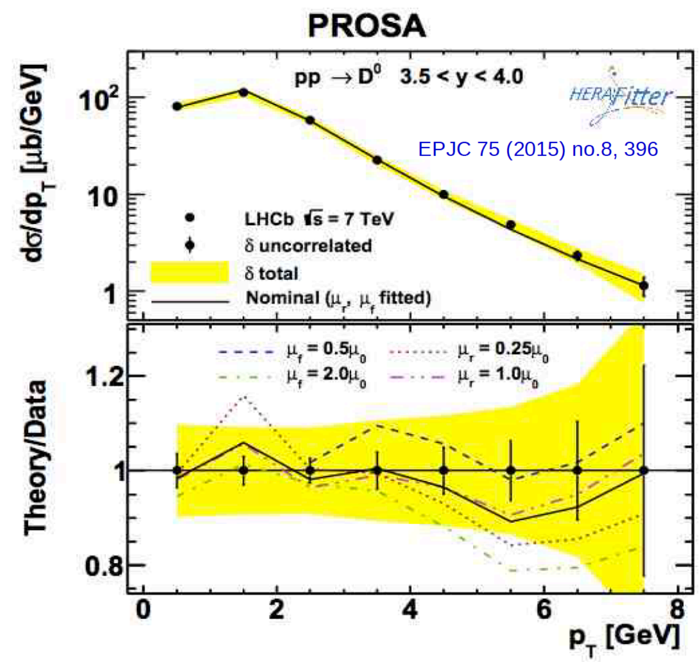


Physics cases in xFitter (2)

- Addition of new Heavy Flavour Scheme: **FONLL VFNS**
  - it is available thanks to collaboration with APFEL
  - various FONLL options available via interface to APFEL https://apfel.hepforge.org/
  - ABM scheme was up-to-dated to OPENQCDRAD v 2.0b4 http://www-zeuthen.desy.de/~alekhin/OPENQCDRAD

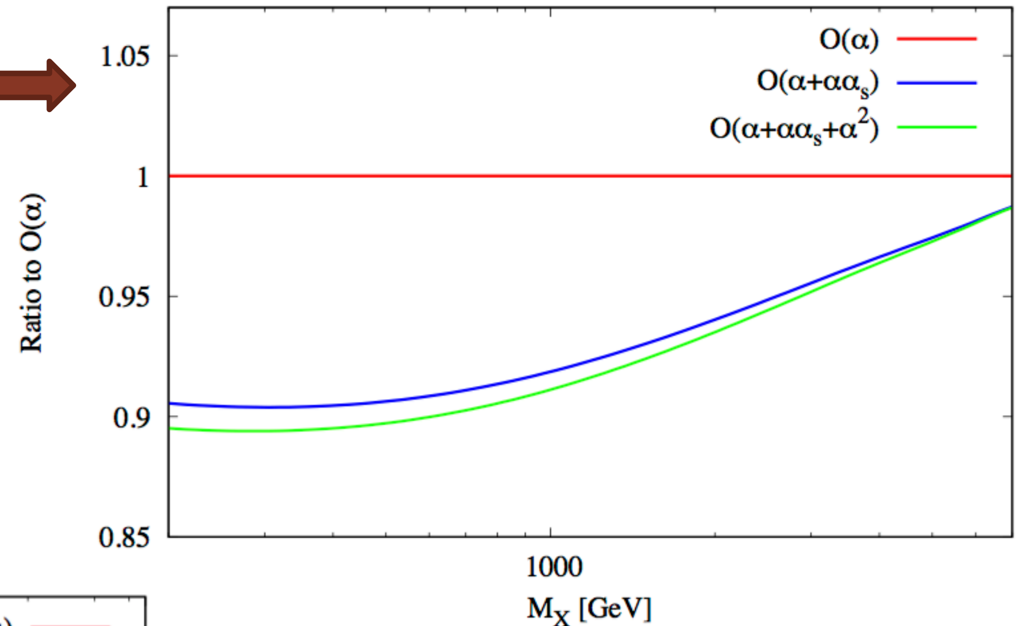


- **Interface to Mangano-Nason-Ridolfi** (MNR, NPB 373 (1992) 295) theory code added in xFitter:
  - was used for analysing the heavy-flavour production at
  - LHCb and at HERA (via OPENQCDRAD)
  - use of FFNS for accounting of heavy quark masses at NLO
  - added corresponding LHCb data



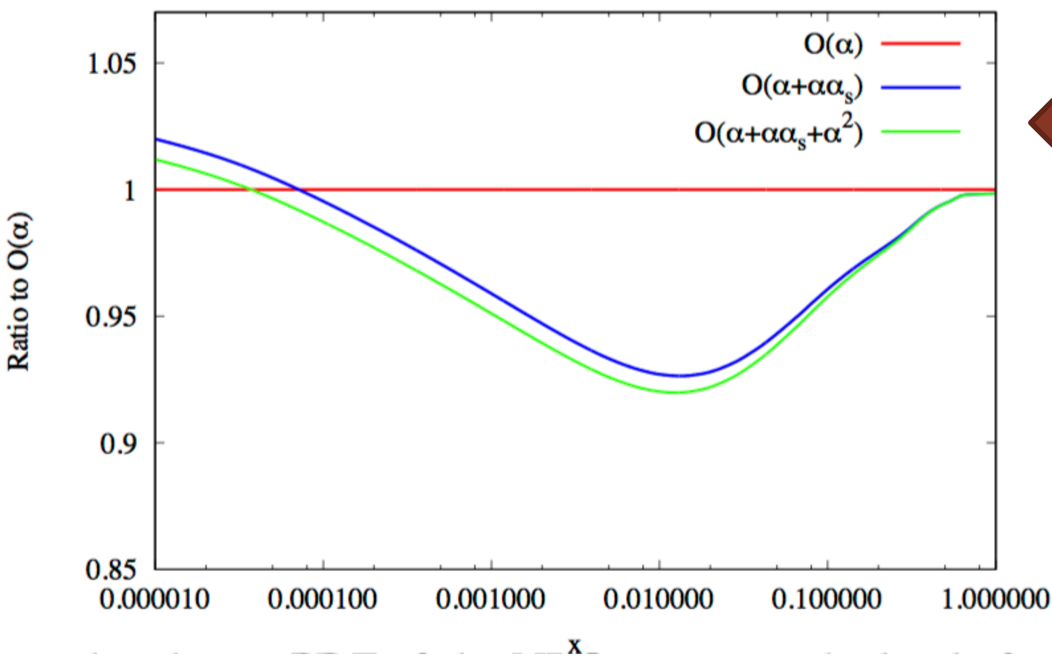
- **Added extra reweighing option** using Giele-Keller weights

Electroweak Corrections



DGLAP Evolution: **the $\gamma\gamma$ luminosity**

Sizeable effect of the EW corrections (10% for low masses)



DGLAP Evolution: **the photon PDF**

Effect on the photon PDF of the NLO QED corrections ~5%

Latest xFitter Developers Team Pubblications

arXiv.org > hep-ph > arXiv:1605.01946

JHEP 1608 (2016)

High Energy Physics – Phenomenology

A determination of mc(mc) from HERA data using a matched heavy-flavor scheme

APFEL

xFitter Developers' team: Valerio Bertone, Stefano Camarda, Amanda Cooper-Sarkar, Alexandre Glazov, Agnieszka Luszczak, Hayk Pirumov, Ringaile Placakyte, Klaus Rabbertz, Voica Radescu, Juan Rojo, Andrey Sapranov, Oleksandr Zenaiev, Achim Geiser

(Submitted on 6 May 2016)

- Determination obtained using the FONLL general mass scheme
- Formulation of the FONLL scheme in terms of the $\overline{MS}$ masses (improvement of perturbative convergence w.r.t. the pole mass definition)
- All the formalism is implemented in APFEL (available in xFitter)
- Inclusive and charm data in DIS is directly sensitive to the charm mass (exploit the precise HERA I+II combined data to extract the charm mass)
- FONLL-C scheme used – NLO accuracy in the massive sector
- Also tested in Fixed Flavour Number Scheme (FFNS) at NLO

$$m_c(m_c) = 1.335 \pm 0.043(\mathrm{exp})^{+0.019}_{-0.000}(\mathrm{param})^{+0.011}_{-0.008}(\mathrm{mod})^{+0.033}_{-0.008}(\mathrm{th})\ \mathrm{GeV}$$

Analysis settings (1)

- The **datasets**:
  - combined HERA I+II charm production cross sections
  - combined HERA I+II inclusive DIS cross sections
  - cut on data with $Q^2 < Q_{min}{}^2 = 3.5$ GeV^2
- The **parametrisation**:

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}, \\
xu_v(x) = xu(x) - x\bar{u}(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2), \\
xd_v(x) = xd(x) - x\bar{d}(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) = x\bar{u}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) = x\bar{d}(x) + x\bar{s}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

$$B_{\bar{U}} = B_{\bar{D}}, \quad A_{\bar{U}} = A_{\bar{D}}(1-f_s)$$

- and its variations:
  - strangeness fraction: $f_s = 0.4 \pm 0.1$
  - initial scale: $Q_0{}^2 = 1 - 1.5$ GeV^2 (bound to be below the charm mass)
  - functional form variation: inclusion of the D_{u_v} linear term in $xu_v(x)$

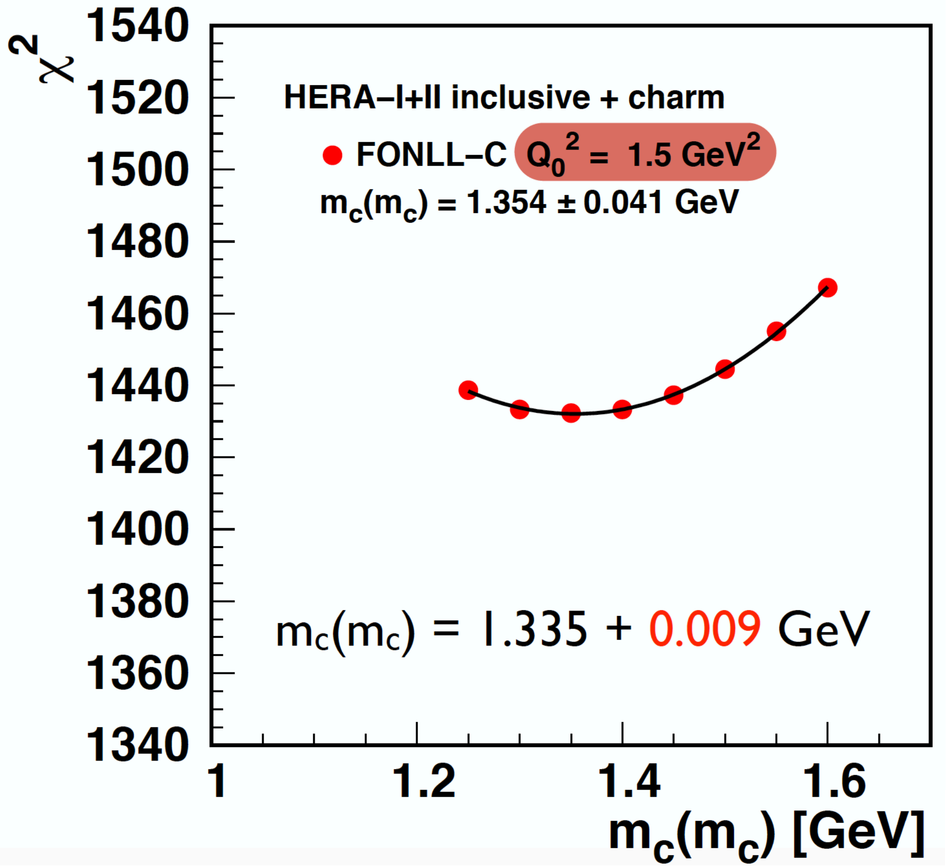
Analysis settings (2)

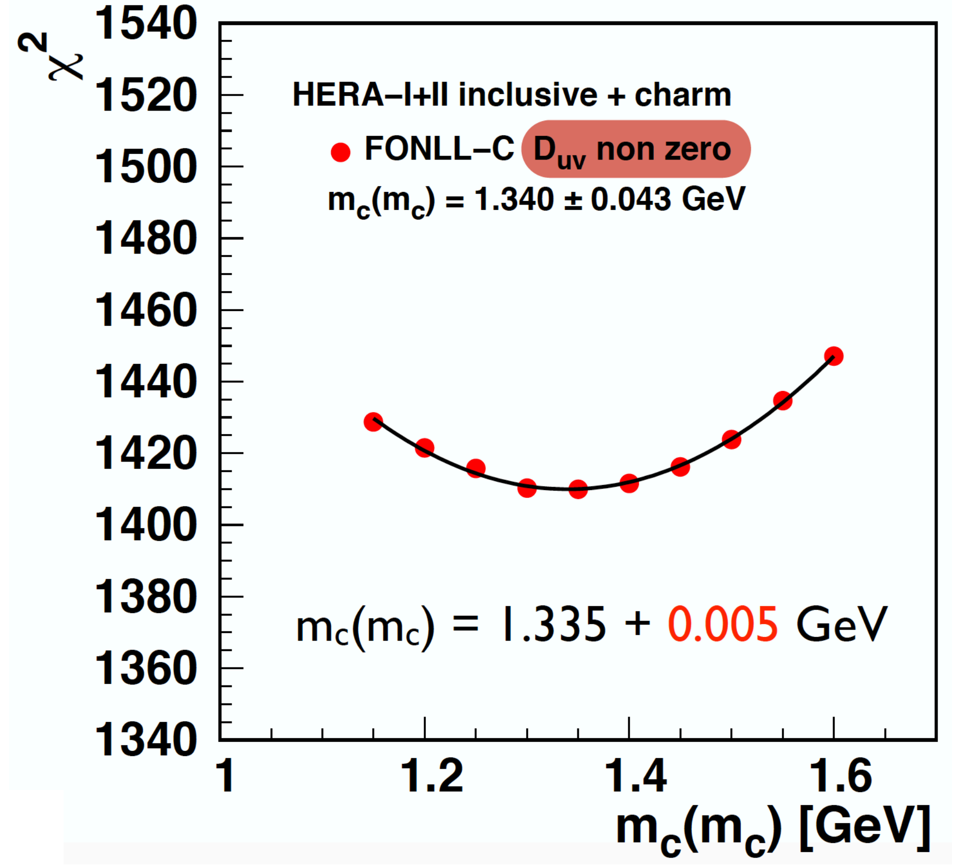
- The **model (QCD) settings** and their variations:
  - strong coupling: $\alpha_s(M_Z) = 0.118 \pm 0.0015$
  - all heavy quark masses are defined in the $\overline{MS}$ renormalization scheme:
    - charm mass: $m_c(m_c)$ scan in the range $[1.10 - 1.60]$ GeV with steps of 0.05 GeV
    - bottom mass: $m_b(m_b) = 4.18 \pm 0.25$ GeV (PDG value and conservative variation)
    - top mass: $m_t(m_t) = 160$ GeV (PDG value and no variation)

- The **theory settings** and their variations:
  - central scales: $\mu_R^2 = \mu_F^2 = Q^2$
  - scale variations: $\mu_R^2 = \mu_F^2 = \frac{Q^2}{2}$ and $\mu_R^2 = \mu_F^2 = 2Q^2$
  - variation of the damping factor (only for FONLL)

Parametric uncertainty

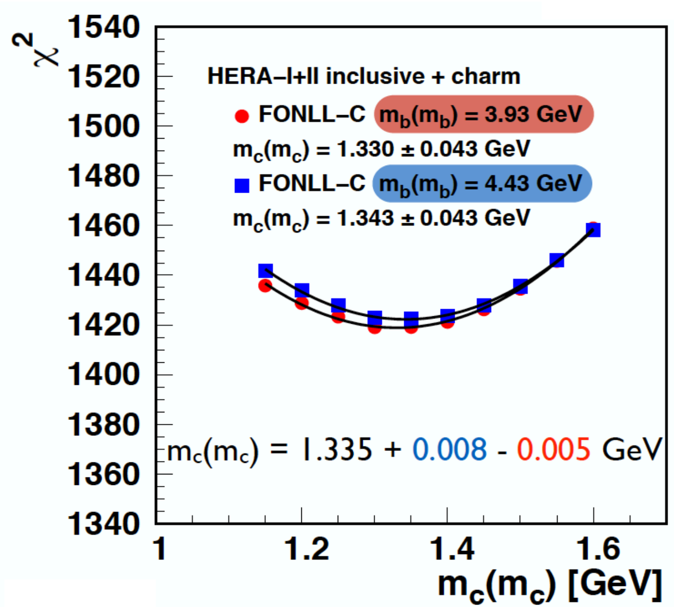
- The parametric uncertainty is estimated varying:
  - the initial scale Q_0^2 from 1 to 1.5 GeV^2
  - including the linear proportional D_{u_v} into the $xu_v(x)$ distribution (variation with the largest impact)

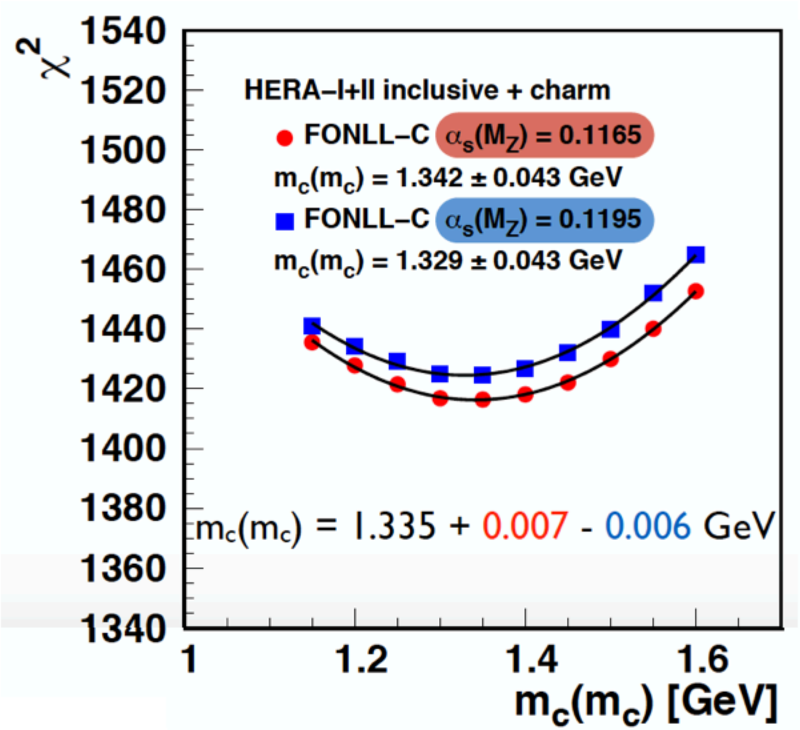


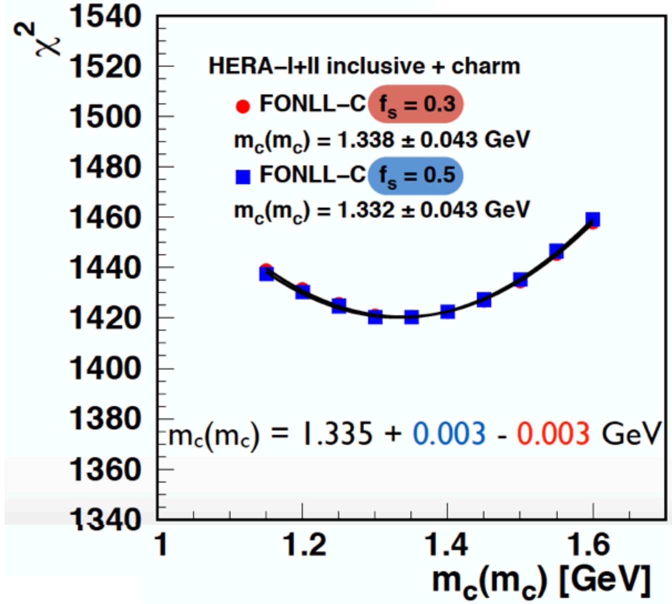


Model uncertainty

- The model uncertainty is estimated varying:
  - $\alpha_S(M_Z)$ by 0.0015 around 0.118
  - $m_b(m_b)$ by 0.25 GeV around 4.18 GeV
  - f_s by 0.1 around 0.4

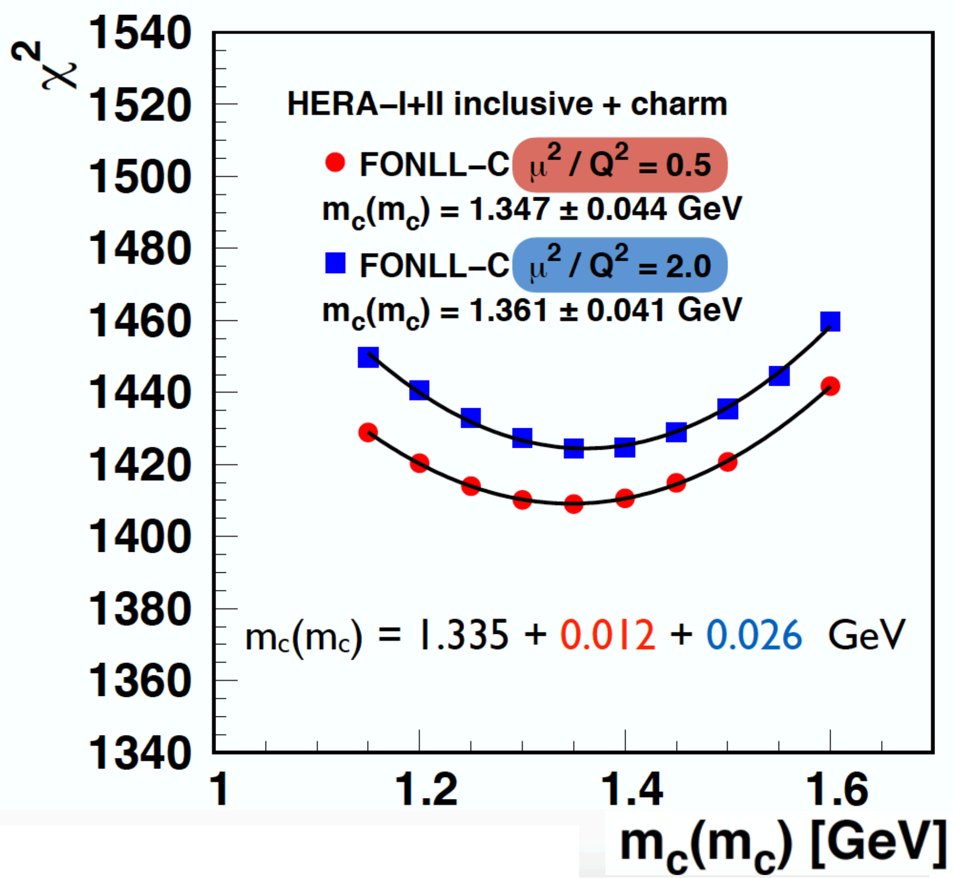


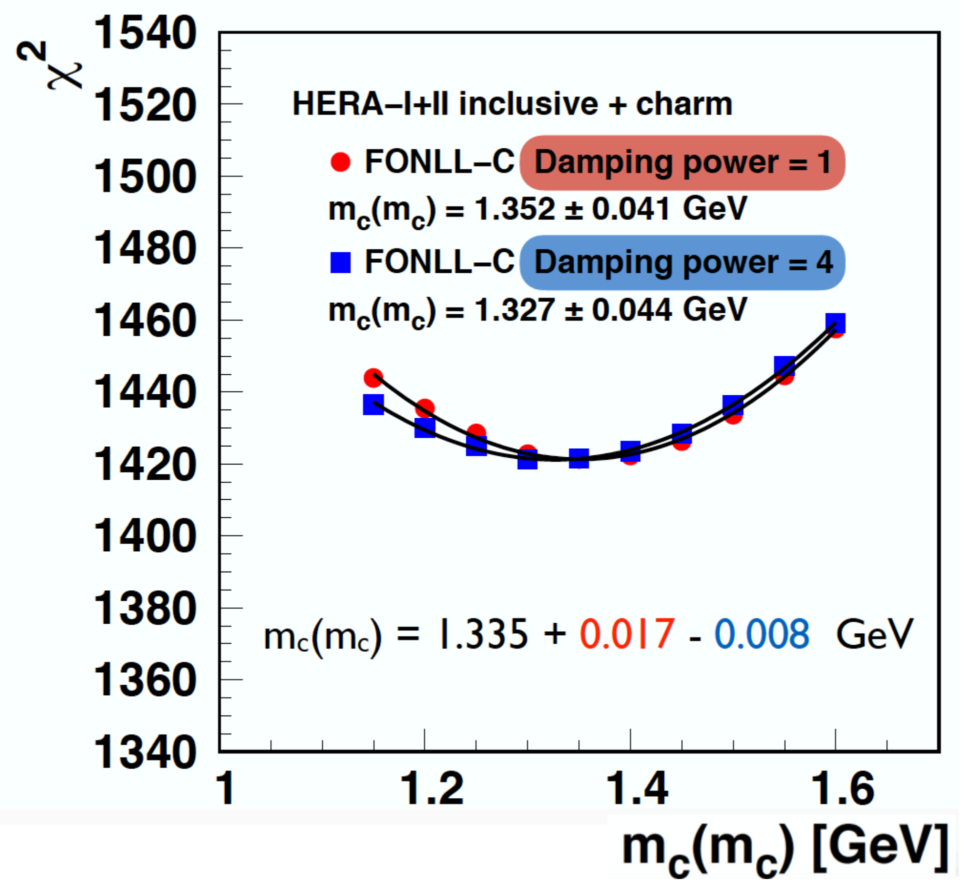




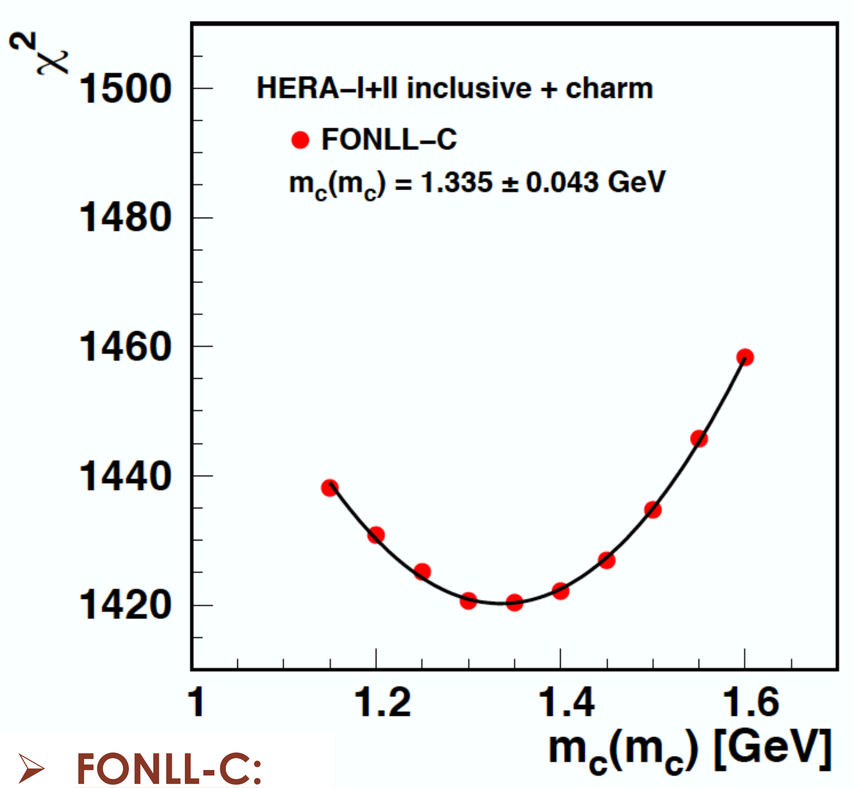
Theory uncertainty

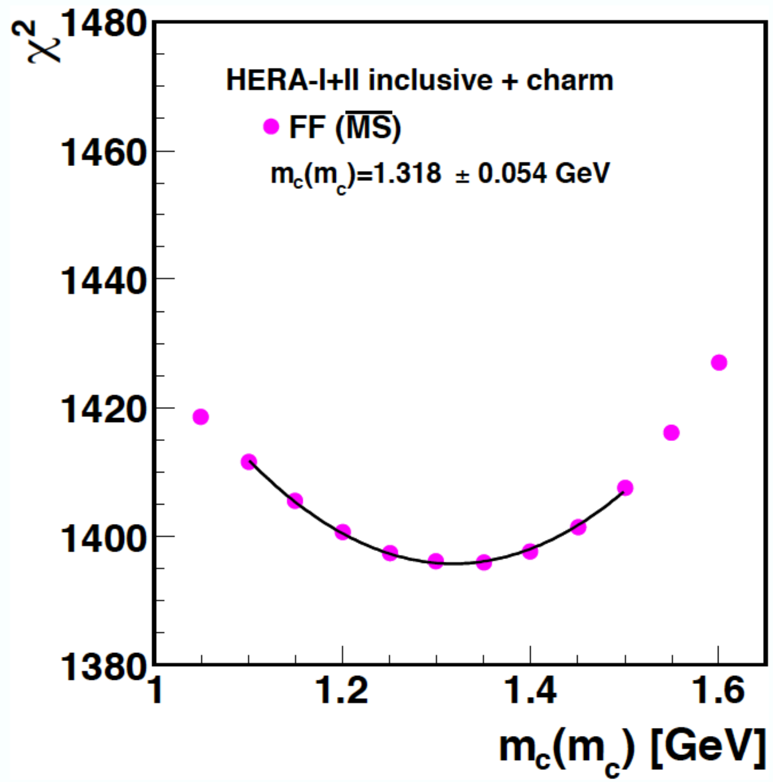
- The theoretical uncertainty is estimated varying:
  - μ_R^2 and μ_F^2 up and down by a factor of two around $\mu_R^2 = \mu_F^2 = 2Q^2$ (only for heavy quark contribution)
  - the suppression power of the FONLL damping factor from 2 to1and 4





Charm mass determination





- **FONLL-C:**

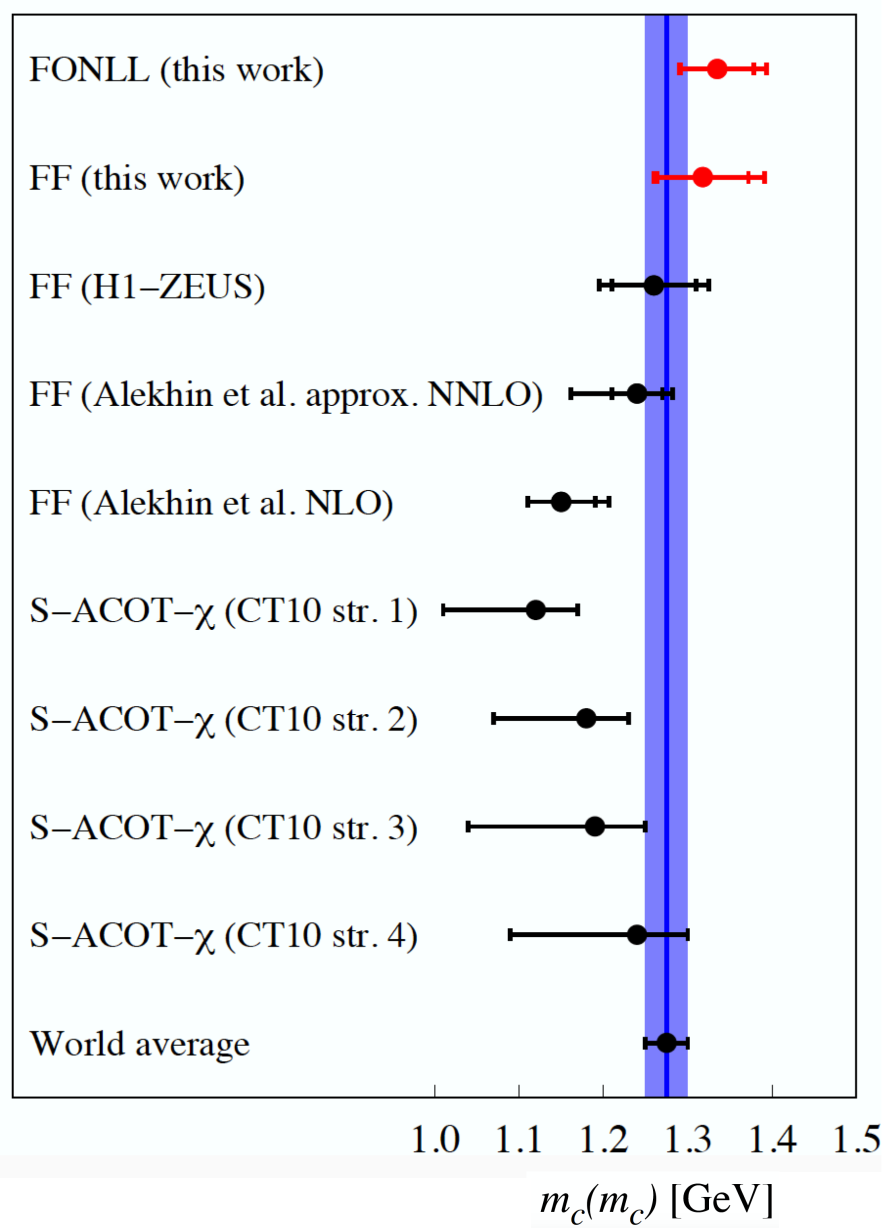
$$m_c(m_c) = 1.335 \pm 0.043(\mathrm{exp})^{+0.019}_{-0.000}(\mathrm{param})^{+0.011}_{-0.008}(\mathrm{mod})^{+0.033}_{-0.008}(\mathrm{th})\ \mathrm{GeV}$$

- **FFNS:**

$$m_c(m_c) = 1.318 \pm 0.054(\mathrm{exp})^{+0.011}_{-0.010}(\mathrm{param})^{+0.015}_{-0.019}(\mathrm{mod})^{+0.045}_{-0.004}(\mathrm{th})\mathrm{GeV}$$

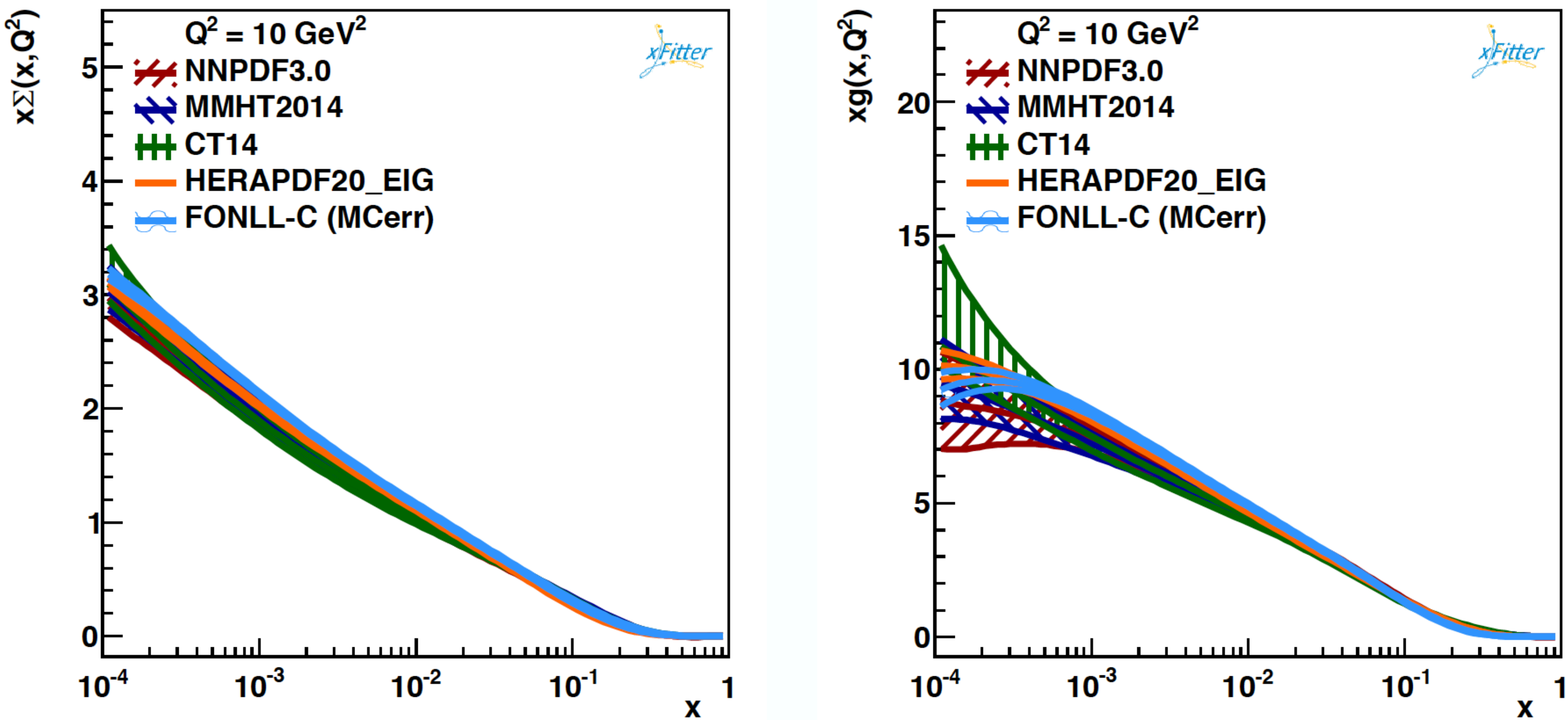
Charm mass determination (2)

- Our determinations are **compatible with each other**
- Compatible with the **PDG world average**
- **Competitive uncertainty**
- General agreement with most of the **past determinations**
- Differently from the other determinations, ours tend to be **above the PDG value**
- The **recent combined HERA I+II** inclusive cross sections tend to pull the value of $m_c(m_c)$ up



Results: PDFs

- Comparison with other PDF sets based on a GM-VFNS:

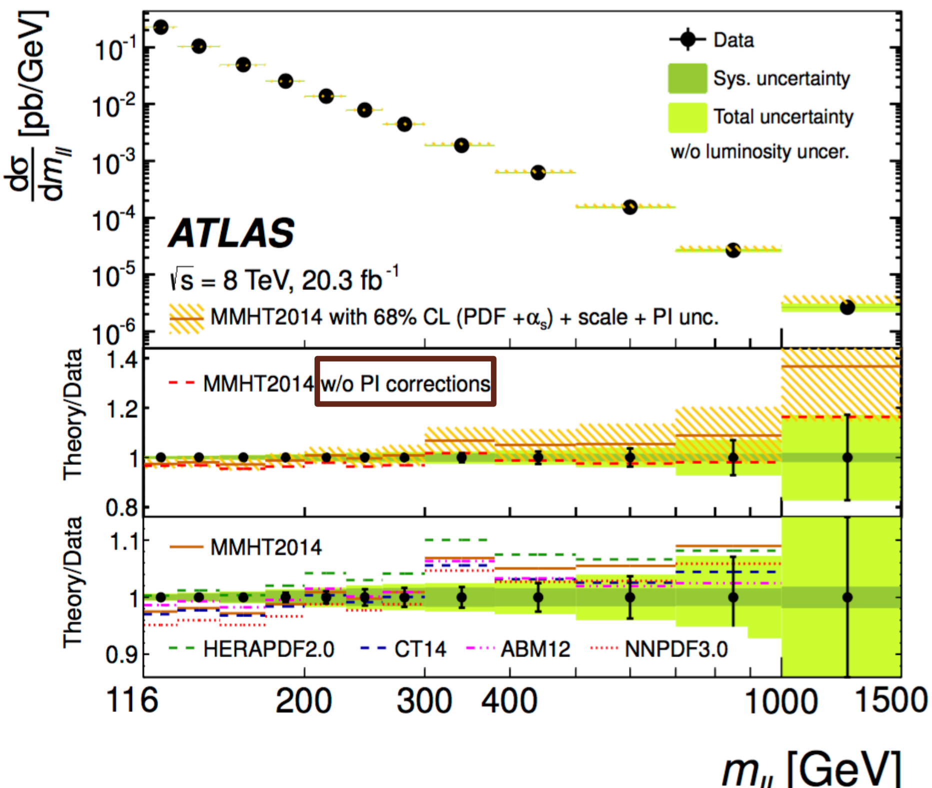


- **General good agreement**

- A detailed study at the level of PDFs is beyond the scope of this work

Theory comparison

- The measured cross sections are compared to theoretical predictions using a selection of recent PDF sets (HERAPDF2.0, CT14, ABM12, NNPDF30)
- Theory = NNLO pQCD ⊗ NLO EW + LO PI; pQCD uses MMHT14 NNLO PDF set
- LO PI uses NNPDF23qed for photon PDF ± 68% of replicas; $\alpha_s = 0.118 \pm 0.001$
- Scale error: envelope of μ_F and μ_R varied by factors of 2

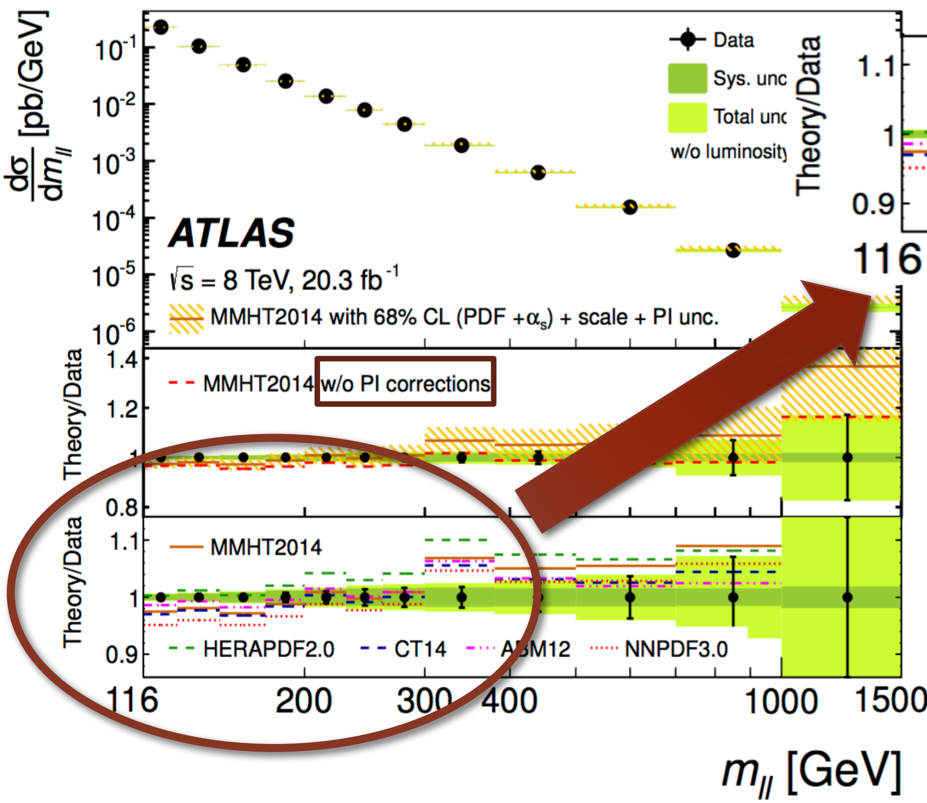


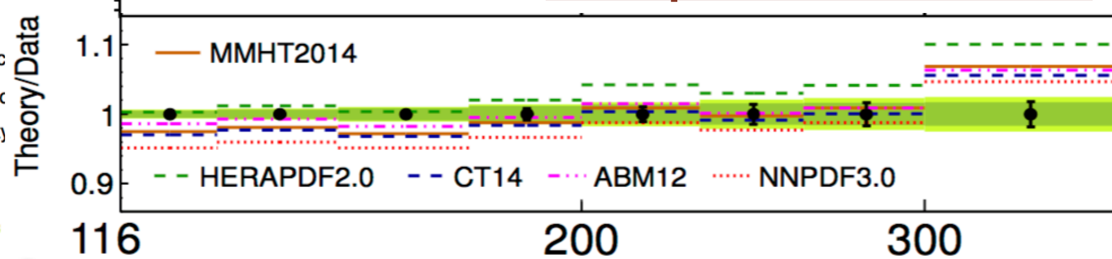
- Theory uncertainties are larger than data uncertainties → potential for PDF constraints
- Theory generally in agreement with data
- Photon induced contribution reaches 15% at large m
- Where PI contribution is large, theory uncertainty dominated by the PI piece
- Else PDF uncertainty dominates theory precision

Theory comparison

- The measured cross sections are compared to theoretical predictions using a selection of recent PDF sets (HERAPDF2.0, CT14, ABM12, NNPDF30)
- Theory = NNLO pQCD ⊗ NLO EW + LO PI; pQCD uses MMHT14 NNLO PDF set
- LO PI uses NNPDF23qed for photon PDF ± 68% of replicas; α_s = 0.118 ± 0.001
- Scale error: envelope of μ_F and μ_R varied by factors of 2

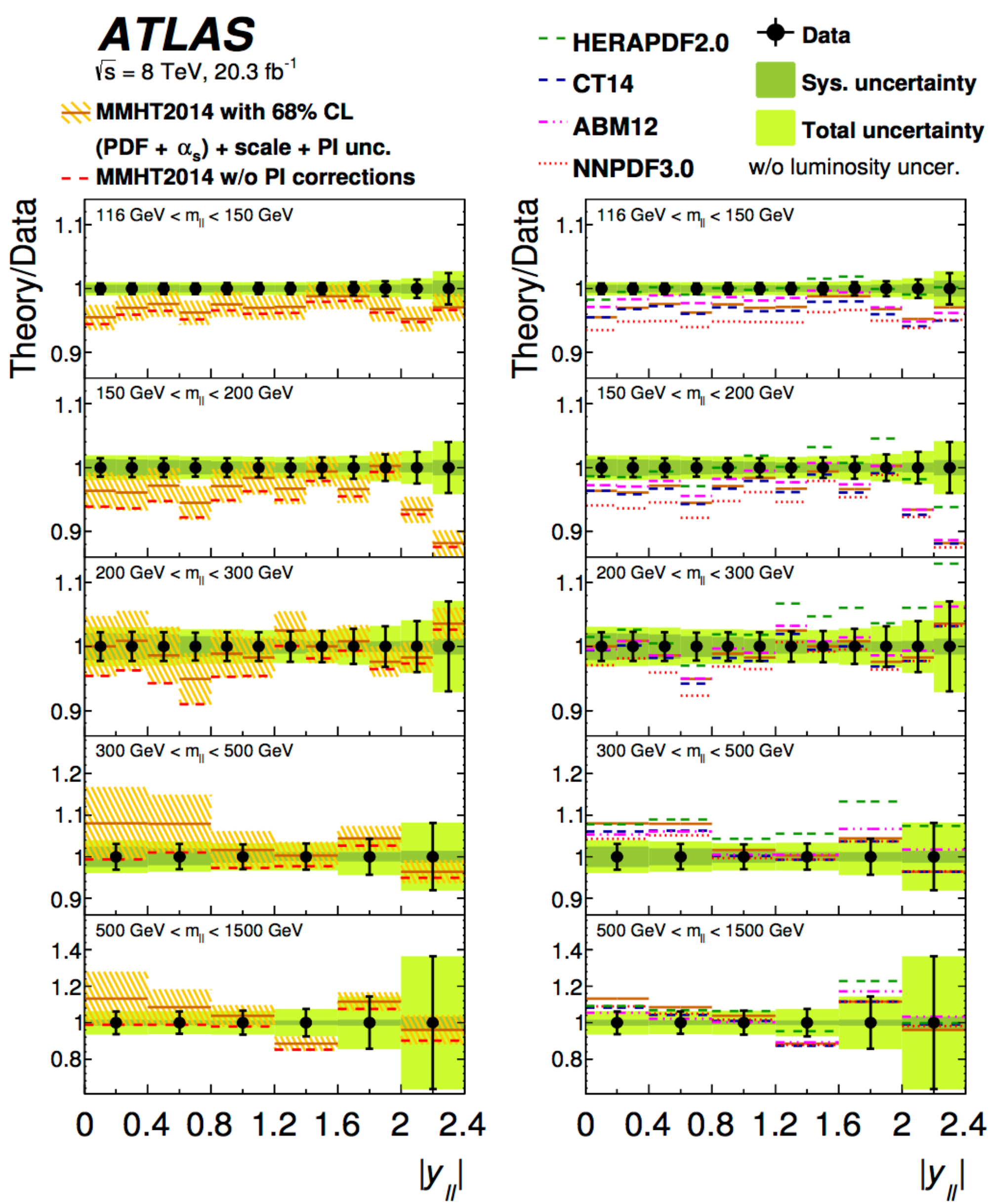
0.6% precision reached





At low m_{ll} observe large spread of predictions from different PDFs compared to experimental accuracy
→ **large potential to constrain PDFs!**

Theory comparison



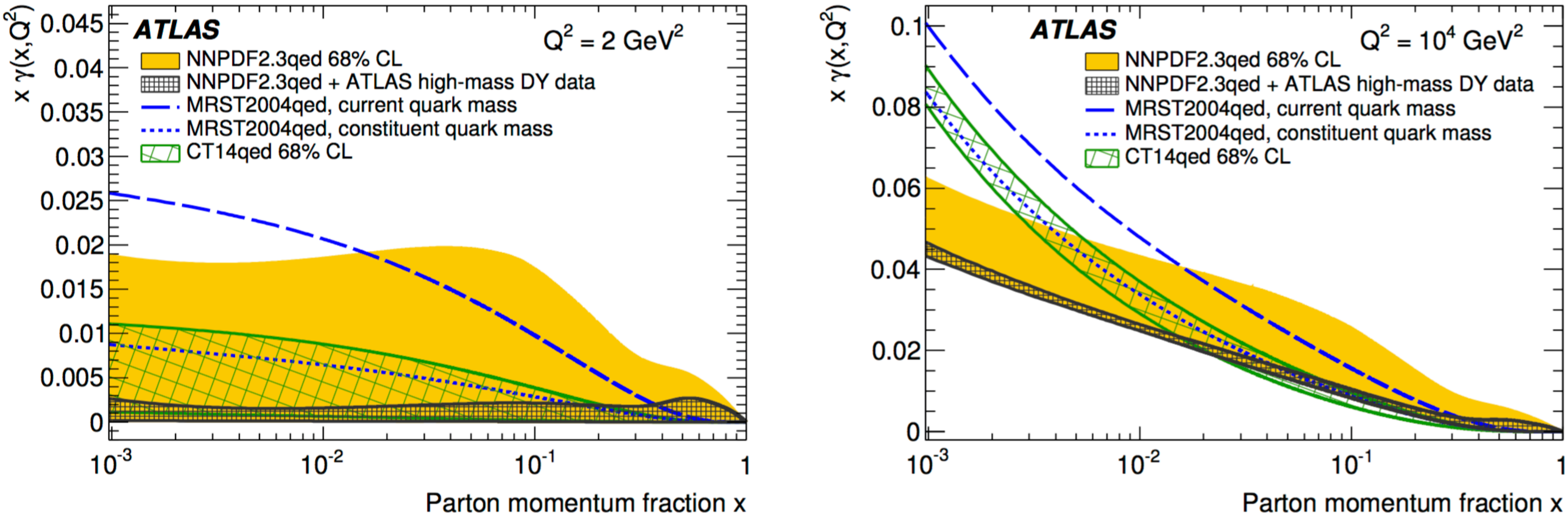
$$\frac{d^2\sigma}{dm_{ll}\,d|y_{ll}|}$$ **data/theory ratio**

- Really precise data!
- Photon-induced (PI) contribution increases with m_{ll} and decreasing $|y_{ll}|$
- PDF uncertainties calculated for each PDF scaled to 68% CL
- Compatibility of data to predictions with other PDFs test with χ^2 function

	$m_{\ell\ell}$	$\lvert y_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$
MMHT2014	18.2/12	59.3/48	62.8/47
CT14	16.0/12	51.0/48	61.3/47
NNPDF3.0	20.0/12	57.6/48	62.1/47
HERAPDF2.0	15.1/12	55.5/48	60.8/47
ABM12	14.1/12	57.9/48	53.5/47

Data in good agreement with SM predictions

Photon PDF



- Assess impact of new data on photon PDF → use Bayesian reweighting of NNPDF replicas
- Each replica receives a weight according to χ^2 function (poorly fitting replicas receive a small weight; replicas fitting the data well receive a large weight)
- New PDF central value is estimated from mean of weighted replicas
- New PDF uncertainty determined from 68% CL
- **Original NNPDF uncertainty dramatically reduced in reweighting**

APPLgrid settings

- The APPLgrids are produced using aMCfast (v01-03-00) and MG5_aMC@NLO (v2.4.3) – **one of the latest tag available**) technology and then transferred to xFitter for fitting

- Because photon PDF is a new addition to the lhapdf format type, a mapping of the indices is needed to assure that that the photon PDF contribution is actually accounted for:
  - use of the tailored APPLgrid for photon PDF (thanks to V. Bertone / S. Carrazza) https://github.com/ scarrazza/applgridphoton
  - use of the modern interface to LHAPDF (v6.1.6)
  - use of a dedicated branch of xFitter that is linked to the adjusted APPLgrid (PI_apfel_for_lhaGridQED)

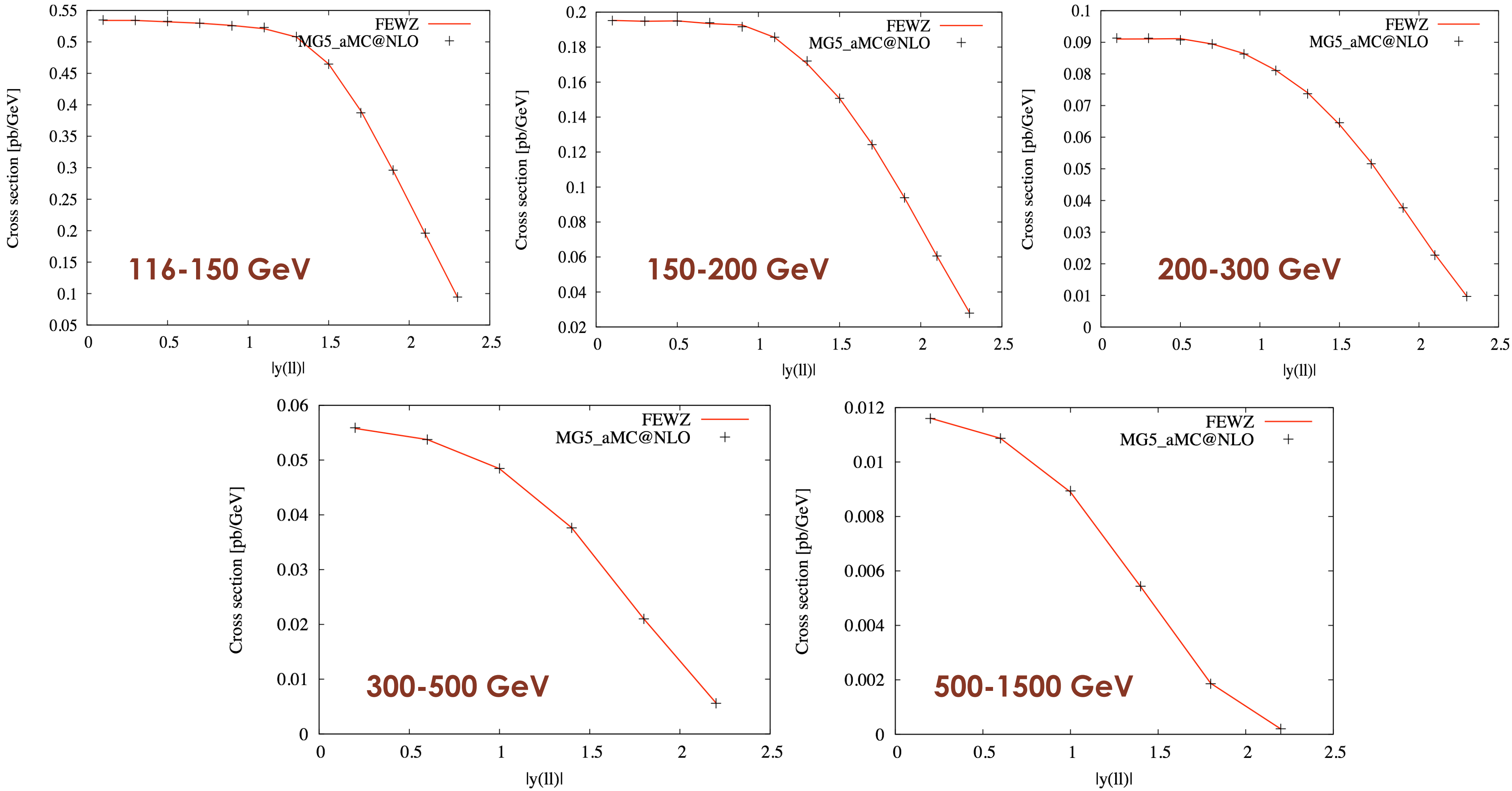
- Validation procedure then is performed using:
  - standalone reader of the APPLgrids (thanks to V. Bertone)
  - xFitter reader of the predictions

Following suggestion made by S. Glazov during one of the Internal xFitter meeting: increment the number of points in the grids and play a bit with Q^2_{min} and Q^2_{max} … So I modified the following piece of code in my analysis:

```
*
*    Grid parameters
*
    appl_Q2min   = (lower mass bin edge – 5 GeV)^2d0
    appl_Q2max   = (higher mass bin edge + 5 GeV)^2d0
    appl_xmin    = 1d-5
    appl_xmax    = 1d0
    appl_nQ2     = 10     (for QCD 1D distribution and for all LO PI = 70)
    appl_Q2order = 3
    appl_nx      = 30     (for QCD 1D distribution and for all LO PI = 50)
    appl_xorder  = 3
```

I'm also optimising the cut on m_{ll} at the generation level (lower mass bin edge – 5 GeV) and I'm using dynamical scales, set to the invariant mass of the lepton pair: in setscale.f

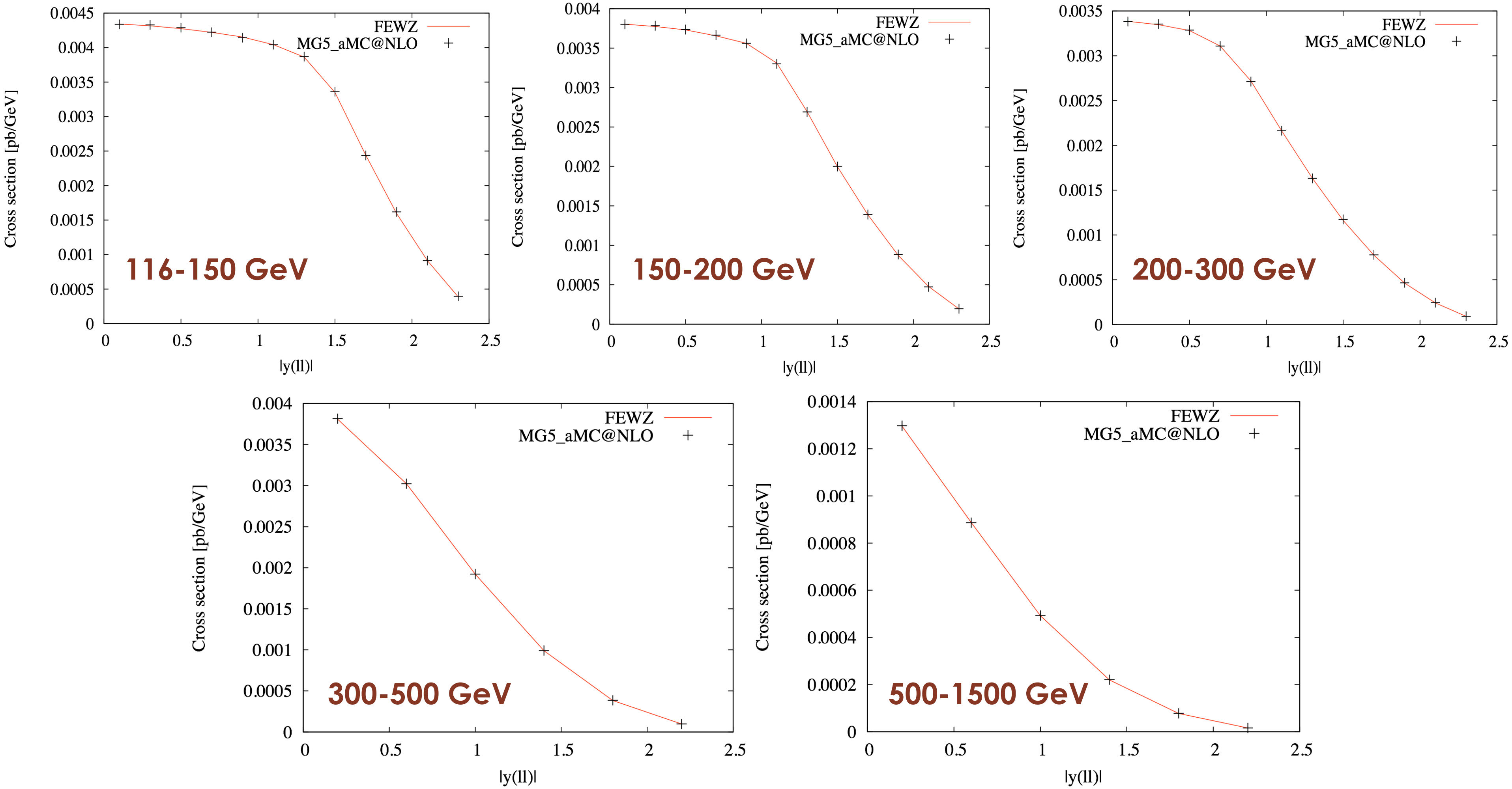
```
elseif(dynamical_scale_choice.eq.0) then

      temp_scale_id='Mll' ! use a meaningful
string
      tmp=dsqrt(2d0*dot(pp(0,3),pp(0,4)))
```



Here the NLO QCD predictions for MG5_aMC@NLO 2.4.3 and FEWZ 3.1

Cross section as a function of $|y_{ll}|$ in five invariant mass bins

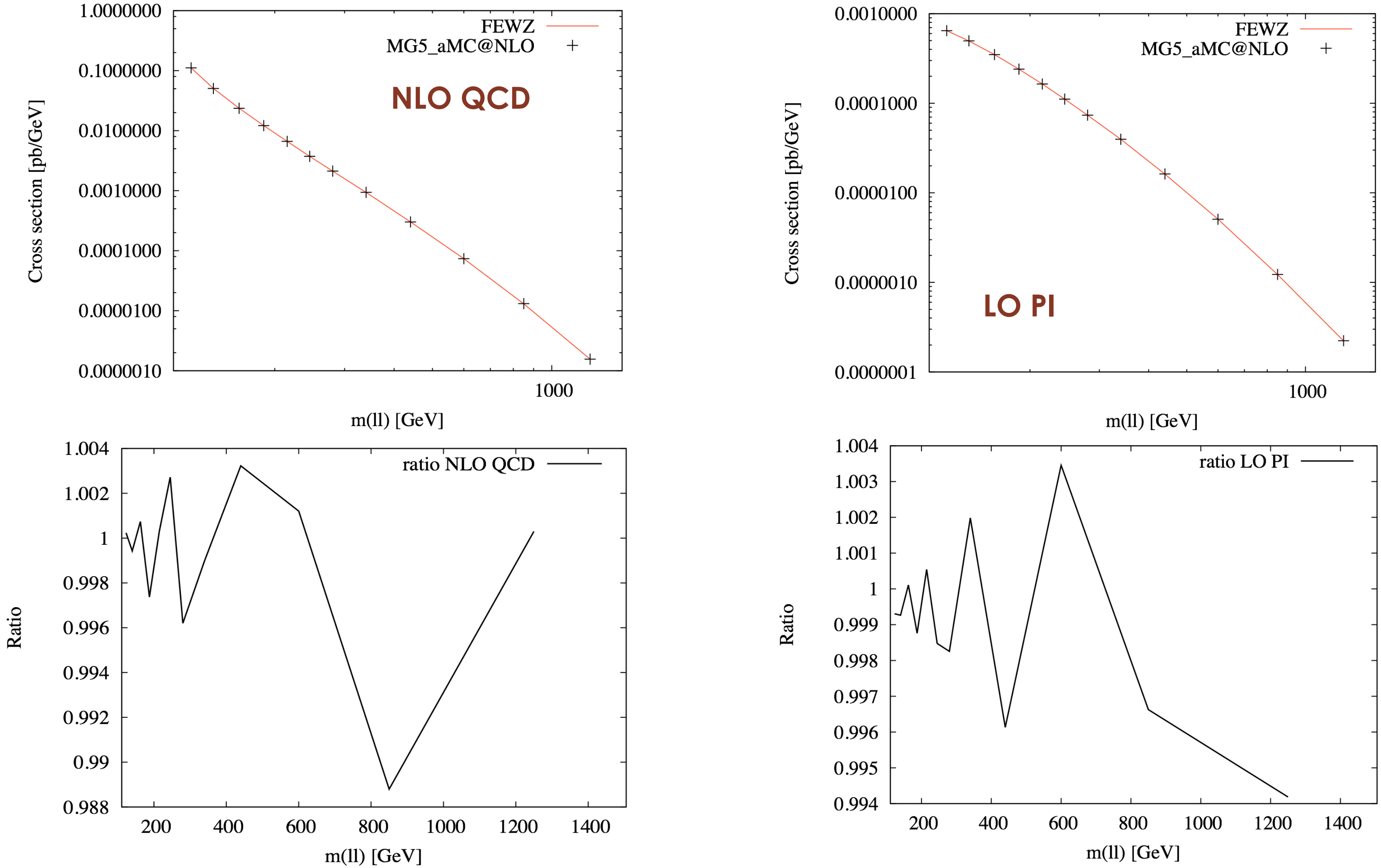
Difference between the two predictions at most 1%



Here the LO PI predictions for MG5_aMC@NLO 2.4.3 and FEWZ 3.1

Cross section as a function of $|y_{ll}|$ in five invariant mass bins

Difference between the two predictions at most 1% as well



Here the predictions for MG5_aMC@NLO 2.4.3 and FEWZ 3.1 regarding the 1D distribution $d\sigma/(dM_{ll})$

Difference between the two predictions at most 1.5% for NLO QCD, around 4 per mille as regards LO PI

LO PI contribution to total xsection

m_{ll} [GeV]	$\lvert y_{ll}\rvert$	QED/QCD
116 – 150	0.0 – 0.2	0.0252
116 – 150	0.2 – 0.4	0.0252
116 – 150	0.4 – 0.6	0.0250
116 – 150	0.6 – 0.8	0.0245
116 – 150	0.8 – 1.0	0.0241
116 – 150	1.0 – 1.2	0.0234
116 – 150	1.2 – 1.4	0.0227
116 – 150	1.4 – 1.6	0.0214
116 – 150	1.6 – 1.8	0.0184
116 – 150	1.8 – 2.0	0.0160
116 – 150	2.0 – 2.2	0.0138
116 – 150	2.2 – 2.4	0.0127
150 – 200	0.0 – 0.2	0.0524
150 – 200	0.2 – 0.4	0.0520
150 – 200	0.4 – 0.6	0.0507
150 – 200	0.6 – 0.8	0.0491
150 – 200	0.8 – 1.0	0.0473
150 – 200	1.0 – 1.2	0.0442
150 – 200	1.2 – 1.4	0.0380
150 – 200	1.4 – 1.6	0.0315
150 – 200	1.6 – 1.8	0.0263
150 – 200	1.8 – 2.0	0.0223
150 – 200	2.0 – 2.2	0.0188
150 – 200	2.2 – 2.4	0.0174

As expected:

- LO PI contribution increases when m_{ll} increases
- LO PI contribution decreases when $\lvert y_{ll}\rvert$ increases
- LO PI contribution reached ~12% of the total σ in the last invariant mass bin
- LO PI contribution evaluated with our fit as PDF input; QCD part with MMHT14_nnlo_68cl
- Difference to prediction computed wrt. NNPDF30qed_nnlo_as_0118_qed ~3%

m_{ll} [GeV]	$\lvert y_{ll}\rvert$	QED/QCD
200 – 300	0.0 – 0.2	0.0837
200 – 300	0.2 – 0.4	0.0822
200 – 300	0.4 – 0.6	0.0793
200 – 300	0.6 – 0.8	0.0737
200 – 300	0.8 – 1.0	0.0643
200 – 300	1.0 – 1.2	0.0525
200 – 300	1.2 – 1.4	0.0421
200 – 300	1.4 – 1.6	0.0339
200 – 300	1.6 – 1.8	0.0279
200 – 300	1.8 – 2.0	0.0231
200 – 300	2.0 – 2.2	0.0202
200 – 300	2.2 – 2.4	0.0178
500 – 1500	0.0 – 0.4	0.1184
500 – 1500	0.4 – 0.8	0.0910
500 – 1500	0.8 – 1.2	0.0580
500 – 1500	1.2 – 1.6	0.0362
500 – 1500	1.6 – 2.0	0.0239
500 – 1500	2.0 – 2.4	0.0182
500 – 1500	0.0 – 0.4	0.1216
500 – 1500	0.4 – 0.8	0.0816
500 – 1500	0.8 – 1.2	0.0493
500 – 1500	1.2 – 1.6	0.0308
500 – 1500	1.6 – 2.0	0.0221
500 – 1500	2.0 – 2.4	0.0250

Theory inputs (2)

- PDF evolution and DIS cross sections via APFEL program:
  - Accurate up to NNLO in QCD + NLO in QED
  - Includes relevant mixed QCD + QED correction → **NOVELTY!**
  - FONLL general-mass scheme
- LHC hmDY cross sections calculated via Madgraph5_aMC@NLO which includes PI diagrams
  - Interfaced to APPLgrid via aMCfast
  - Tailored version of APPLgrid used to account for photon contributions
- NNLO QCD + NLO QED corrections to DY obtained using FEWZ3.1
- Chi2 definition: from H1 paper (arXiv:1206.7007)
- $Q_0^2 = 7.5$ GeV^2 (also Q^2 cut on data)
- $r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.0$ (ATLAS W,Z data)
- $M_c = 1.41$ GeV
- $M_b = 4.5$ GeV

(includes corrections for possible biases from statistical fluctuations and treats the systematic uncertainties multiplicatively)

$$\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1-\sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i \left(1-\sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i}{\delta_{i,\mathrm{unc}}^2 \mu_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i^2}$$

Parameterisation variation

Starting point →10p from HERA + Euv: **1340.22/1088** (1.230) - χ^2 / #degrees of freedom

	Dg	Eg	neg	Duv	Euv	Ddv	Edv	DUbar	EUbar	DDbar	EDbar	Dph	Eph
-	1311.27	1316.13	1312.98	1314.41	-	1309.50	1302.23	1313.55	1308.85	1313.82	1313.37	**1285.24**	X
+ Dph	1287.42	1289.77	1285.26	1287.24	-	1287.29	1287.33	1283.40	**1280.64**	1287.43	1285.53	-	**1283.30**
+ Eph	1283.30	1278.25	**1274.66**	1282.51	-	1280.41	1283.19	1277.93	1276.51	1283.32	1281.80	-	-
+ neg	1274.64	1274.39	-	**1267.91**	-	1274.49	1274.63	1272.20	1269.05	1274.42	1271.23	-	-
+ Duv	1267.92	1267.65	-	-	-	1267.79	1267.78	**1253.34**	1260.77	1267.89	1265.36	-	-
+ DUbar	1253.32	1253.10	-	-	-	1253.12	1253.23	-	1253.29	1253.30	**1250.33**	-	-
+EDbar	1250.32	1250.23	-	-	-	1249.81	1250.04	-	1250.28	**1244.87**	-	-	-

- Euv + Dph + Eph is our central fit (**NNLO**)
- We include the solutions +neg, +Duv, +DUbar (4th, 5th and 6th line) as parameterisation variation
- +DDbar solution didn't converge so we cannot take it into account
- Beyond +neg,Duv,DUbar no really significant decrease of the χ^2
- More checks on parameterisation scan in the following slide

Extra checks on the parameterisation scan

- **NNLO fit with +Euv+Dph+Eph our baseline…** Are we sure that is the best solution?

- I performed a reversed parameterisation scan:

  - 16p:

    After minimisation 1283.80 1088 1.180

  - 15p (no Eph):

    After minimisation 1287.30 1089 1.182

  - 15p (no Dph):

    After minimisation 1286.58 1089 1.181

  - 15p (no Euv):

    After minimisation 1359.14 1089 1.25

- The impact of Dph, Eph on the chi2 is marginal but there's an improvement so it justifies our choice to have 13p+Euv+Dph+Eph as central fit

Results

- **After minimisation 1283.80 1083 1.185** (χ^2/ #degrees of freedom)

HMDY 8 TeV

Dataset 1 8.96(-0.01) 12 HMDY rap 116-150
Dataset 2 15.36(+0.00) 12 HMDY rap 150 200
Dataset 3 13.81(-0.21) 12 HMDY rap 200 300
Dataset 4 4.82(+0.02) 6 HMDY rap 300 500
Dataset 5 3.96(+0.07) 6 HMDY rap 500 1500
Correlated Chi2 1.16547881441444461
Log penalty Chi2 -0.119848315006466678

χ^2/#points = 47.96/48

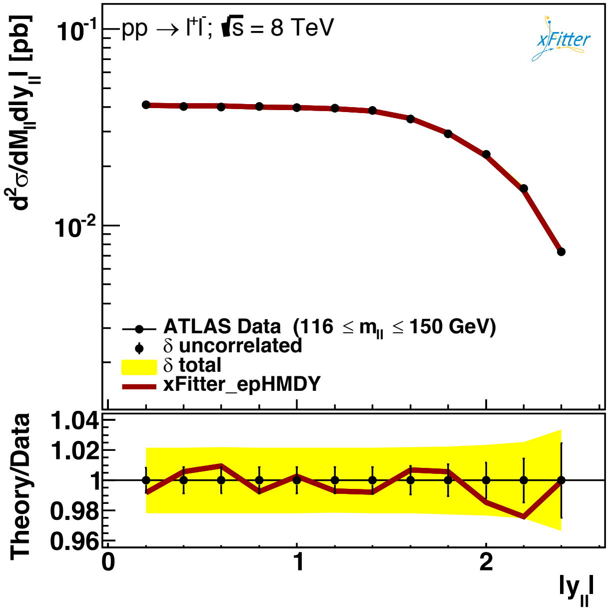
(data described well)

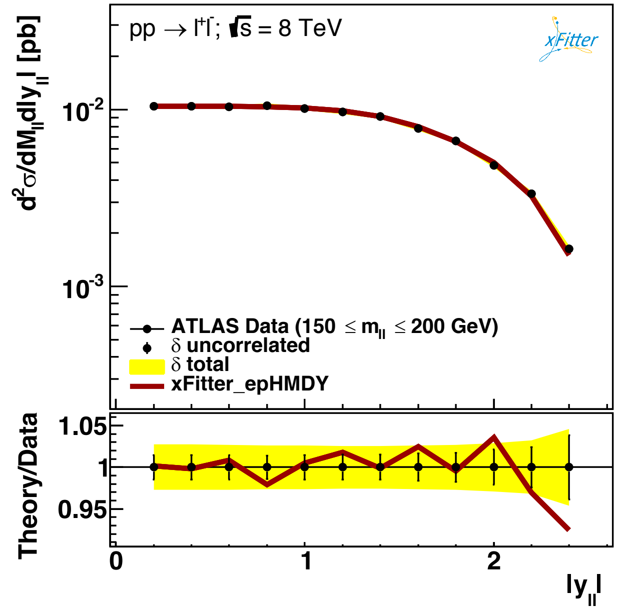
HERAI+II

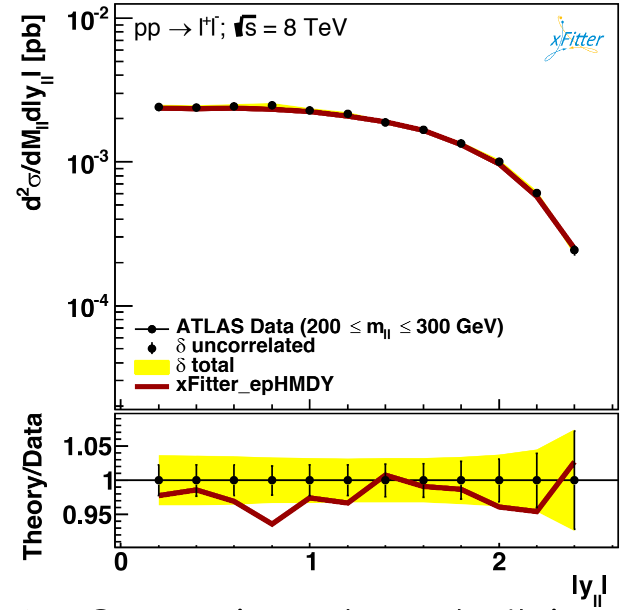
Dataset 1 218.79(-1.59) 159 HERA1+2 NCem
Dataset 2 383.22(+2.13) 332 HERA1+2 NCep 920
Dataset 3 60.49(-0.81) 63 HERA1+2 NCep 820
Dataset 4 197.41(+2.98) 234 HERA1+2 NCep 575
Dataset 5 207.41(-1.55) 187 HERA1+2 NCep 460
Dataset 6 54.61(-2.21) 42 HERA1+2 CCem
Dataset 7 48.52(+0.00) 39 HERA1+2 CCep
Correlated Chi2 66.4488724391
Log penalty Chi2 -1.0519009775

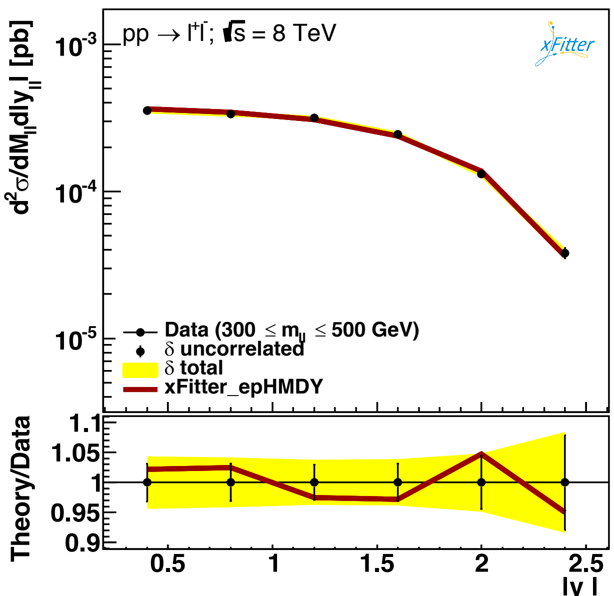
χ^2 /#points =1235.85/1056

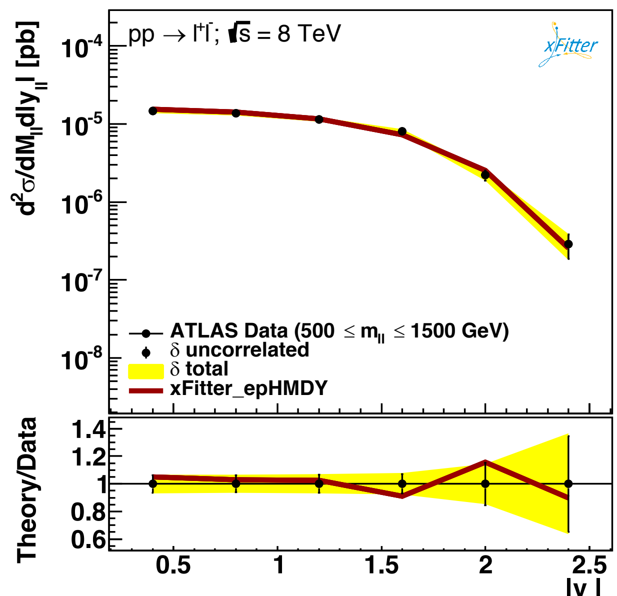
Data Vs Theory





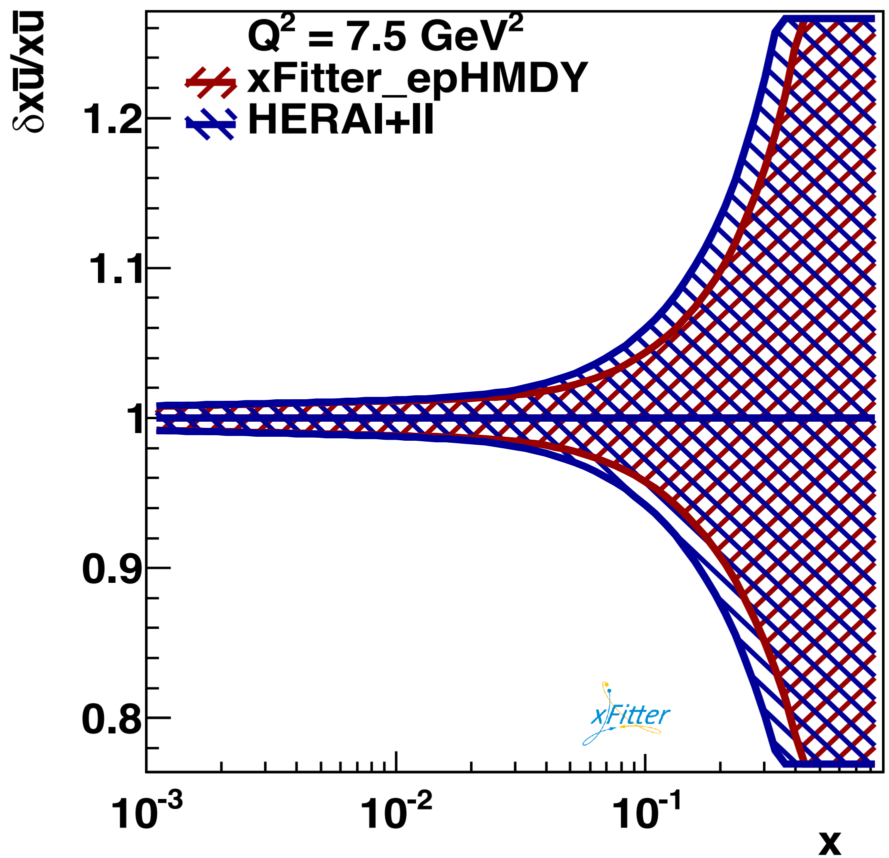


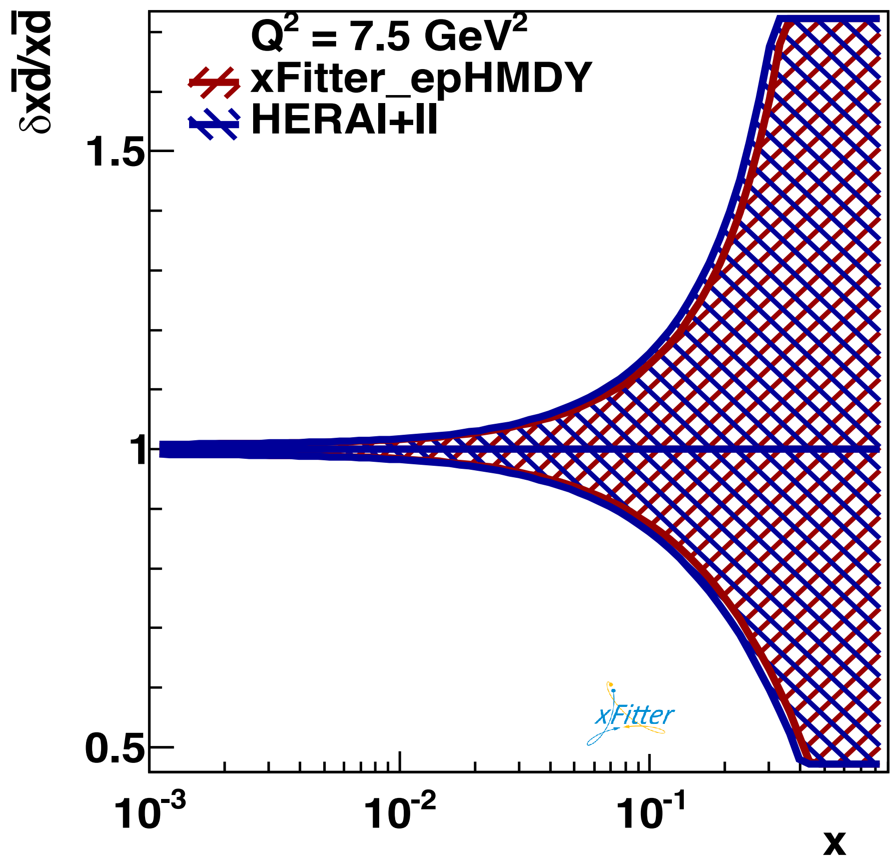




- Comparisons shown both in an absolute scale and as ratios to the central value of the experimental data
- Error bars on data correspond to statistical uncertainties
- Yellow bands indicate the size of the correlated systematic uncertainties
- **Good agreement between ATLAS data and NNLO theory predictions**

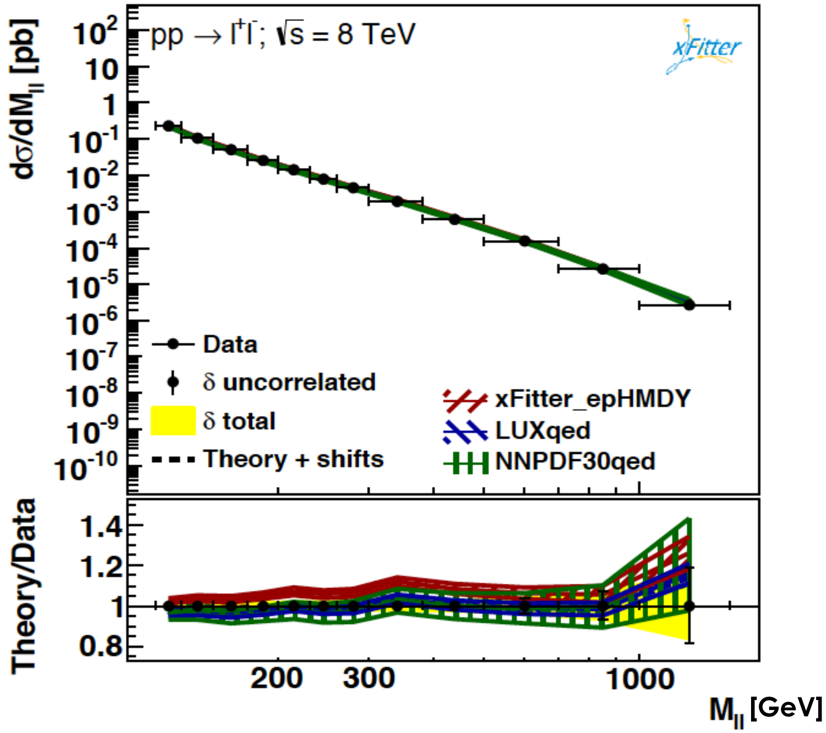
Impact on the antiquark PDFs





The impact in the medium and large-x antiquark distributions from the high mass DY data are rather moderate

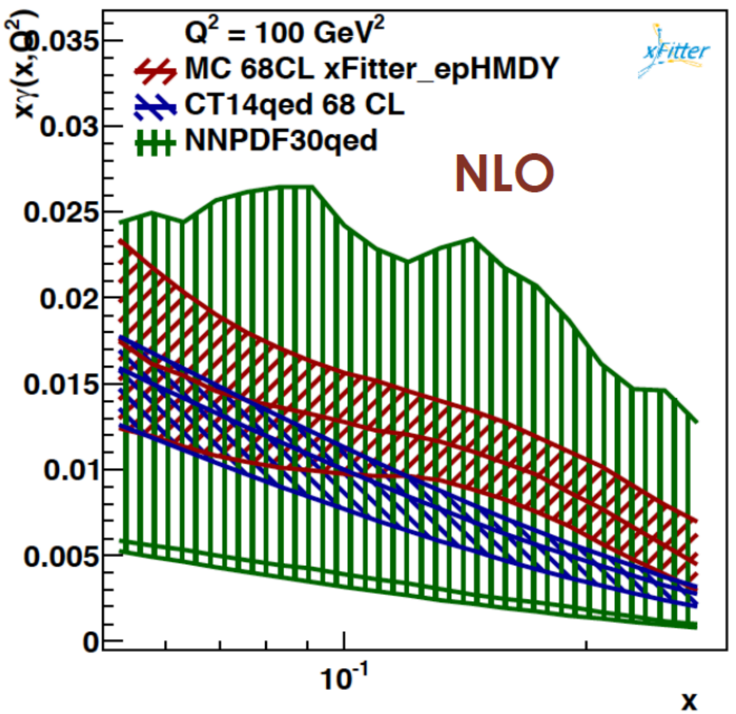
Data Vs Theory (1D)

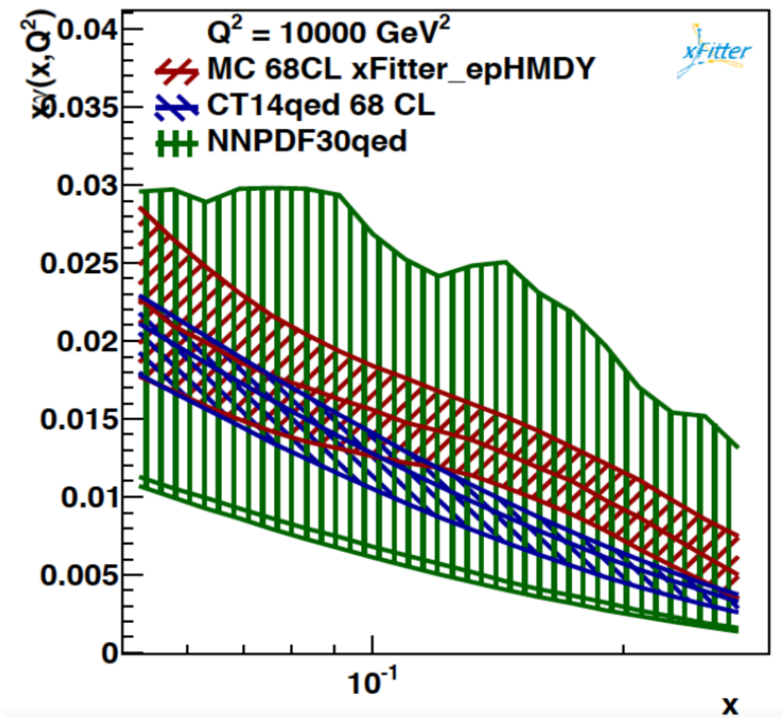


Dataset	xFitter epHMDY	LUXqed	NNPDF30qed
HMDY Mass	11 / 12	12 / 12	12 / 12
Correlated χ^2	5.8	4.5	5.3
Log penalty χ^2	+0.30	+0.11	+0.04
Total χ^2 / dof	17 / 12	17 / 12	17 / 12
χ^2 p-value	0.15	0.16	0.15

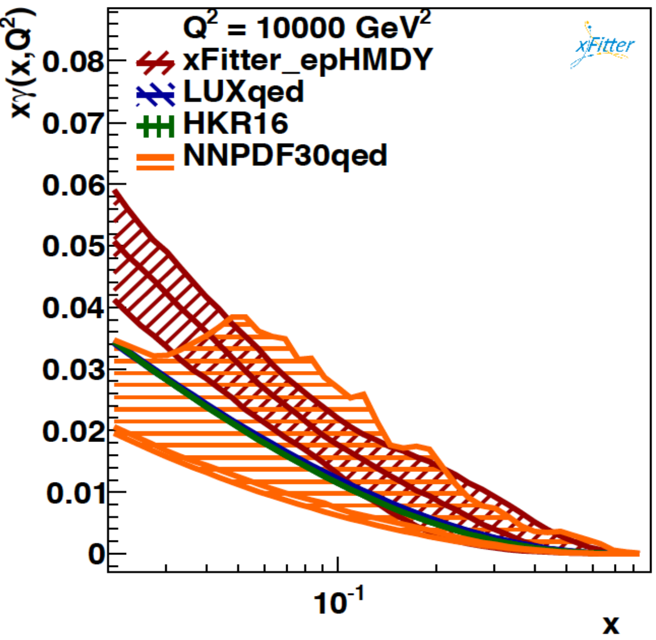
- Comparisons shown both in an absolute scale and as ratios to the central value of the experimental data
- Error bars on data correspond to statistical uncertainties
- Yellow bands indicate the size of the correlated systematic uncertainties
- **Good agreement between ATLAS data and NNLO theory predictions**
- Here, also comparison with two other NNLO PDF set: **LUXqed** and **NNPDF30qed**
- Compatible χ^2 between different predictions and all around 1 (pretty good data description)

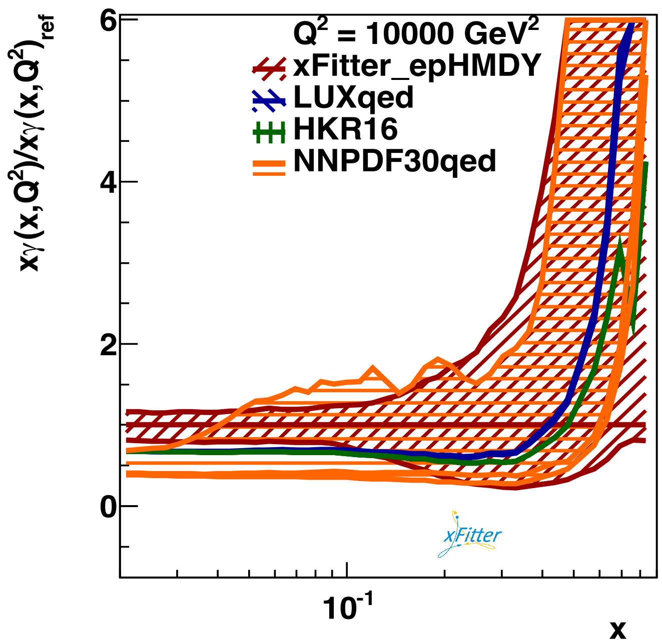
NLO fit results

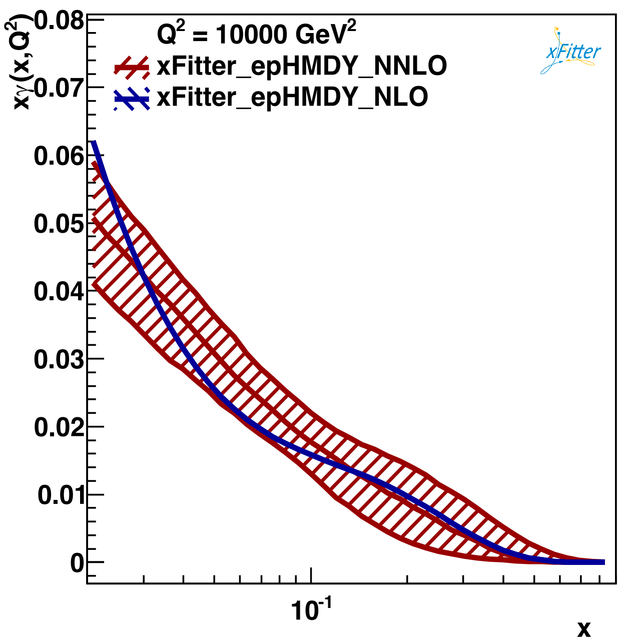


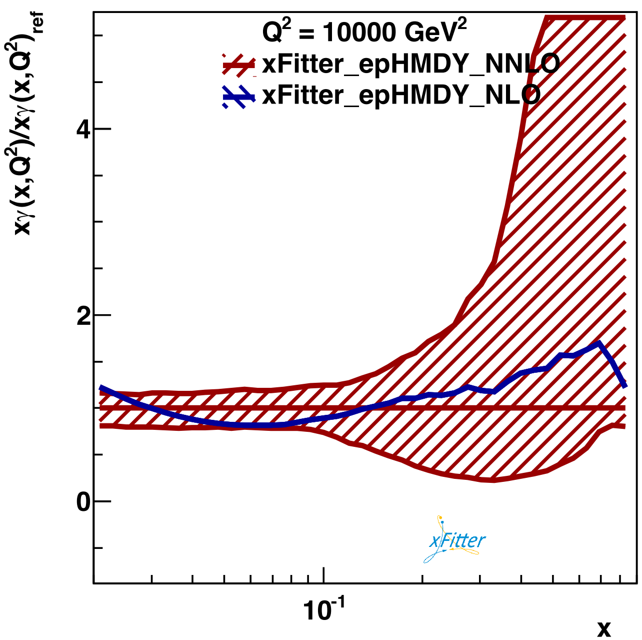


- Drastically improvement in the errors size band compared to NNPDF30qed
- Agreement at 1σ level with CT14qed prediction in the low-x region
- In the medium-/high-x region, agreement at 1.5 σ level





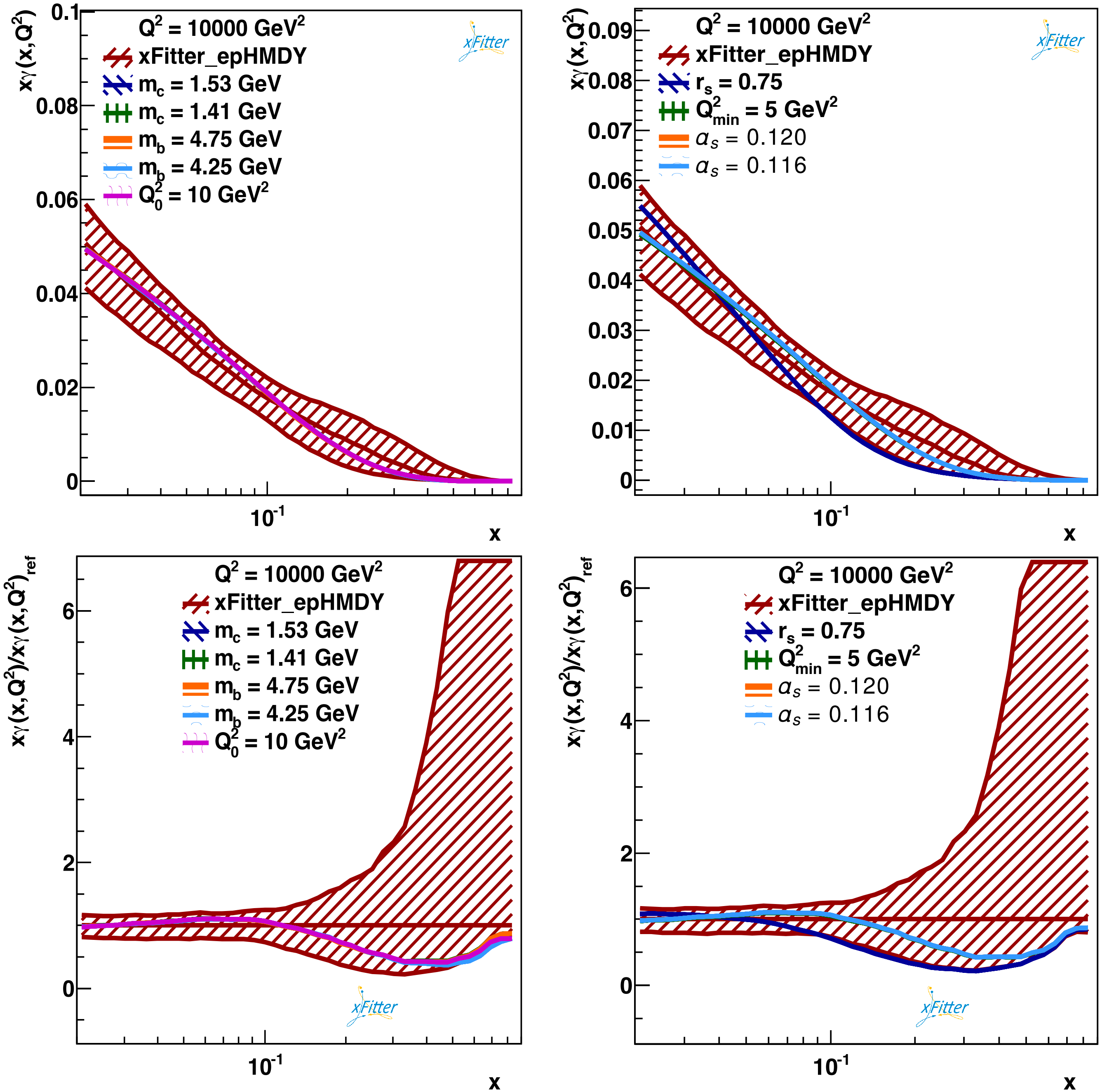




Comparison between **NLO vs NNLO** photon PDF

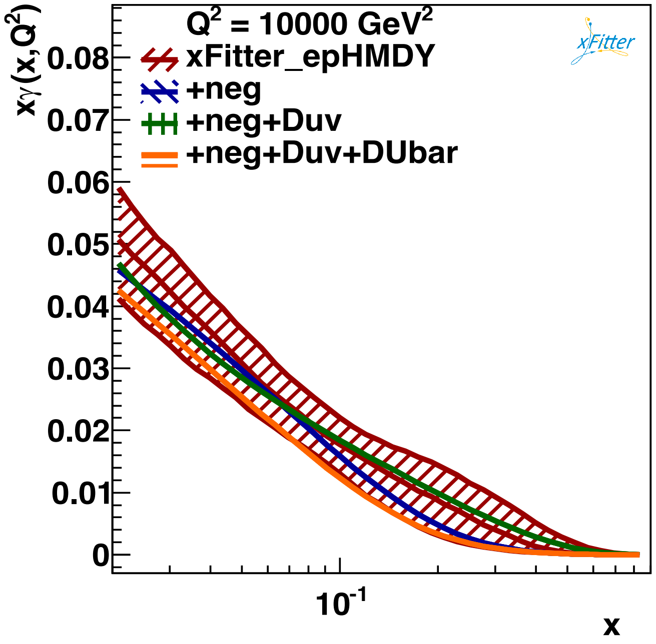
To quantify perturbative stability of photon PDF determination (QED part of the calculation identical in both cases)

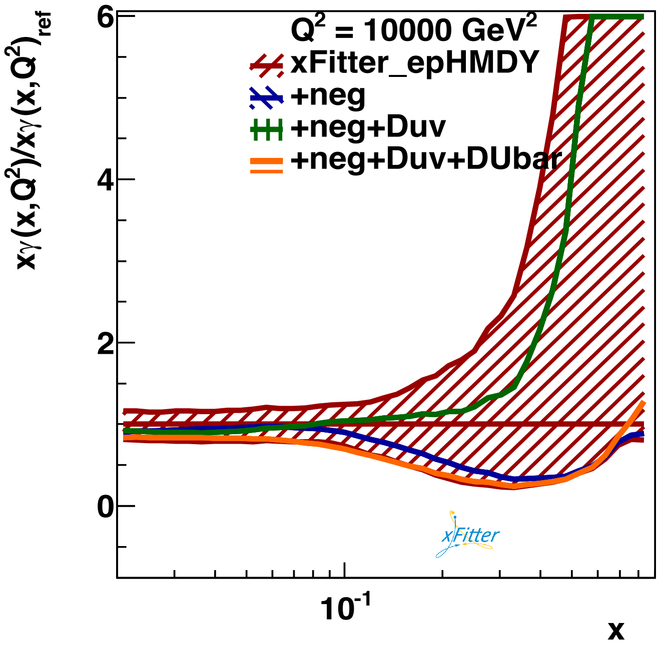
The fit exhibits a reasonable perturbative stability, since the central value of the NLO fit is always contained in the 1σ PDF uncertainty band (only exp. unc.)



- Here, **NNLO Hessian** results for nine model variations:
  - a_s = 0.116
  - a_s = 0.120
  - r_s = 0.75
  - Q^2 cut = 5 GeV^2
  - m_b down = 4.25 GeV
  - m_b up = 4.75 GeV
  - m_c down = 1.41 GeV
  - m_c up = 1.53 GeV
  - Q_0^2 cut = 10 GeV^2
- No changes in the chi2
- All the central fit are inside the MC error bands (some of them overlap and they are not visible)

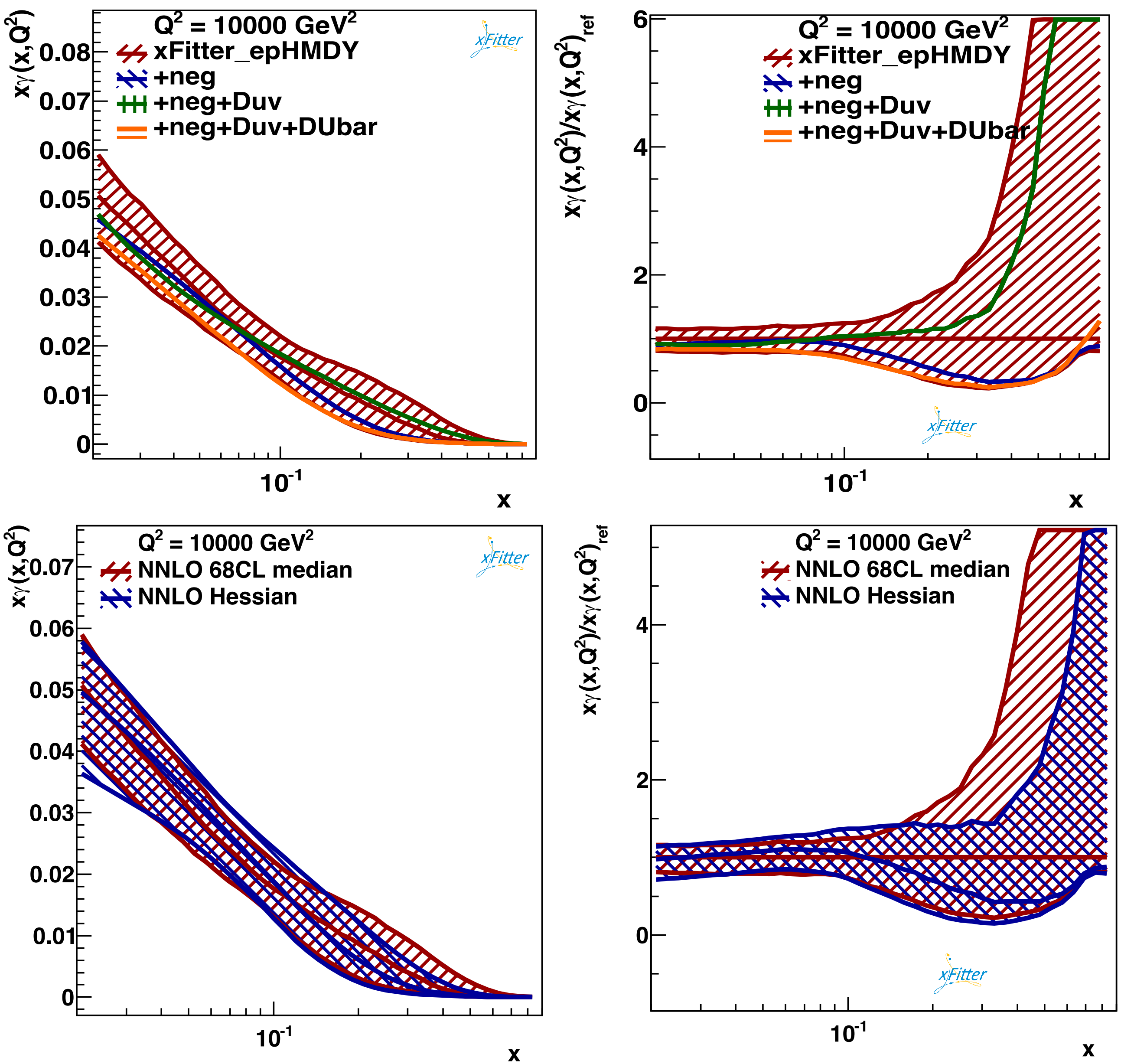
$$r_s = (s + \bar{s})/2\bar{d}$$





- Here, I'm showing the **NNLO Hessian results** for parameterisation variations:
  - +neg
  - +neg+Duv
  - +neg+Duv+DUbar
- All the central fit are inside the MC error bands

Median ± 68% CL vs Hessian (asym)



- Bands = experimental uncertainties only
- Reasonable agreement between the two methods
- Central values with different fitting techniques similar to each other
- MC uncertainties larger than Hessian ones (expecially for $x \gtrsim 0.2$, indicating deviations with respect to the Gaussian behaviour of the photon PDF)