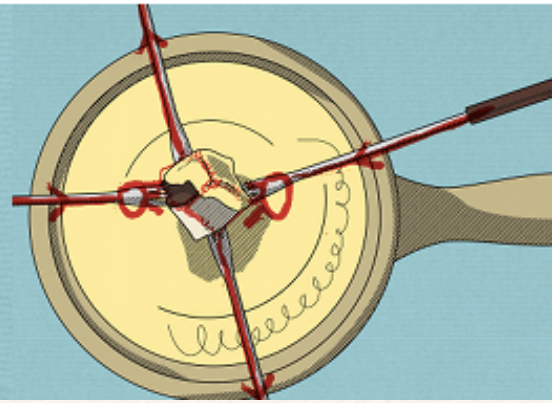


QCD@LHC 2016

22 - 26 August 2016, Zurich, Switzerland

QCD@LHC

22<sup>ND</sup>–26<sup>TH</sup> AUGUST  
INTERNATIONAL CONFERENCE ZURICH 2016



*August 2016, Zurich*

---

# Review on PDFs

Voica Radescu  
University of Oxford





# Search for new Physics

direct searches  
for new physics

indirect searches via  
consistency test of SM

control of QCD background  
and SM parameters

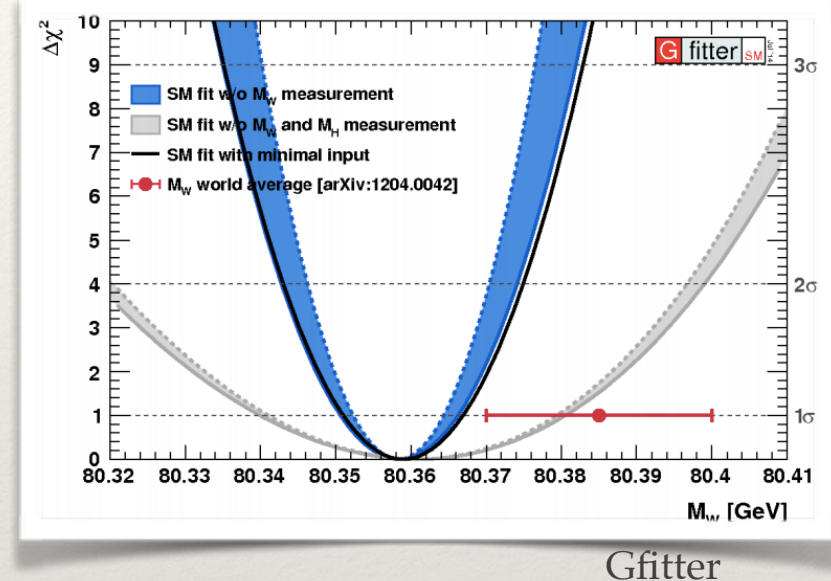
Interpretation of any cross section  
measurement which involves  
hadron in the initial state relies on  
factorisation concept:

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

calculable

from data

[arXiv:1410.6810v2]



Improvement of PDFs precision demands high precision theory & experimental measurement



# Search for new Physics

direct searches  
for new physics

indirect searches via  
consistency test of SM

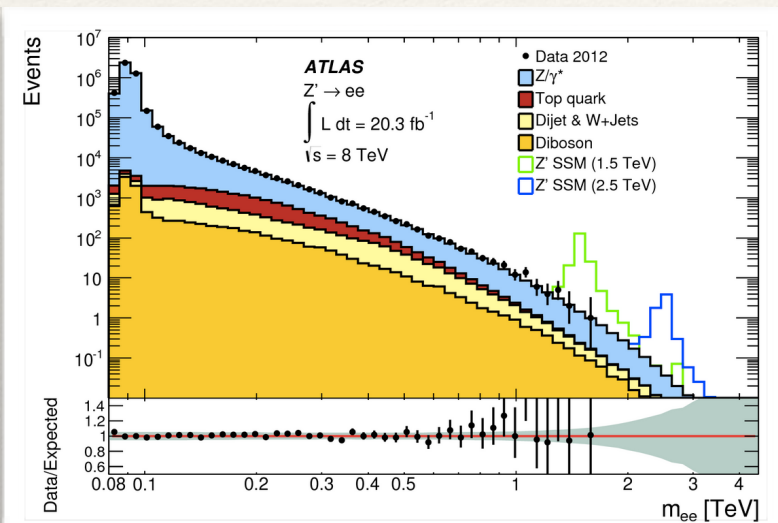
control of QCD background  
and SM parameters

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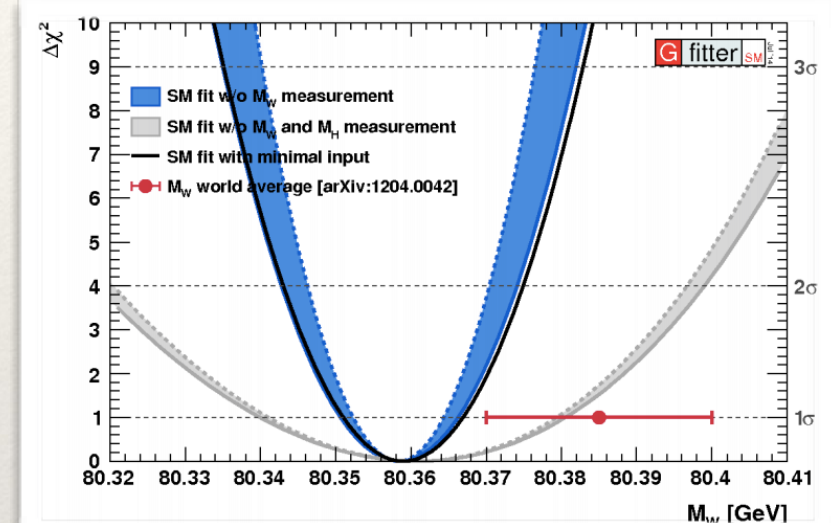
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calculable

from data



[arXiv:1410.6810v2]



Gfitter

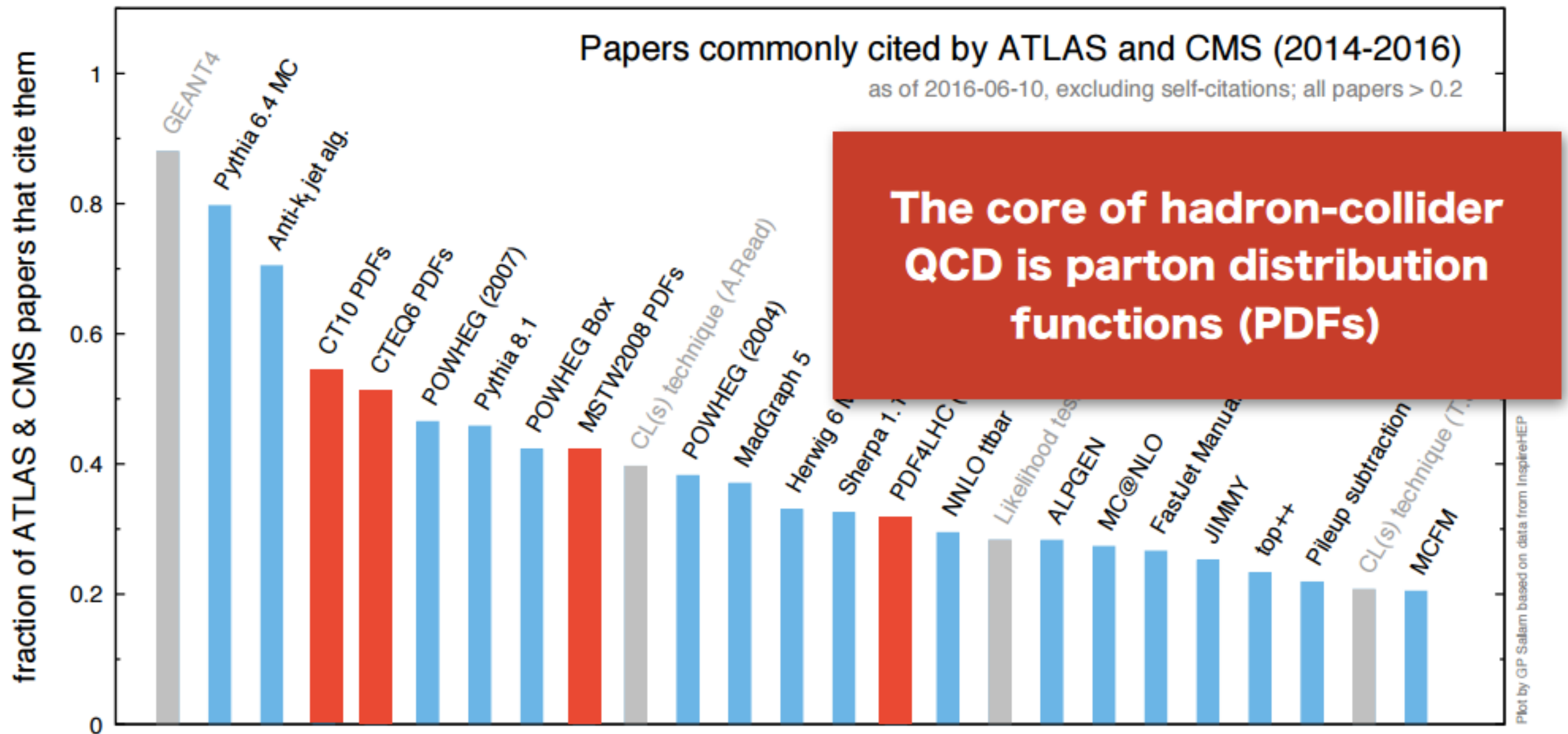
Last decade have seen a lot of developments:

- ❖ State of the art for many processes is now NNLO, there is N3LO Higgs (it needs N3LO PDFs)
- ❖ Many automation tools which allowed for fixed order + PS, or resummations, etc..



# Most frequent citations @ LHC

- ❖ Gavin Salam looked at what experiments at the LHC cite the most:

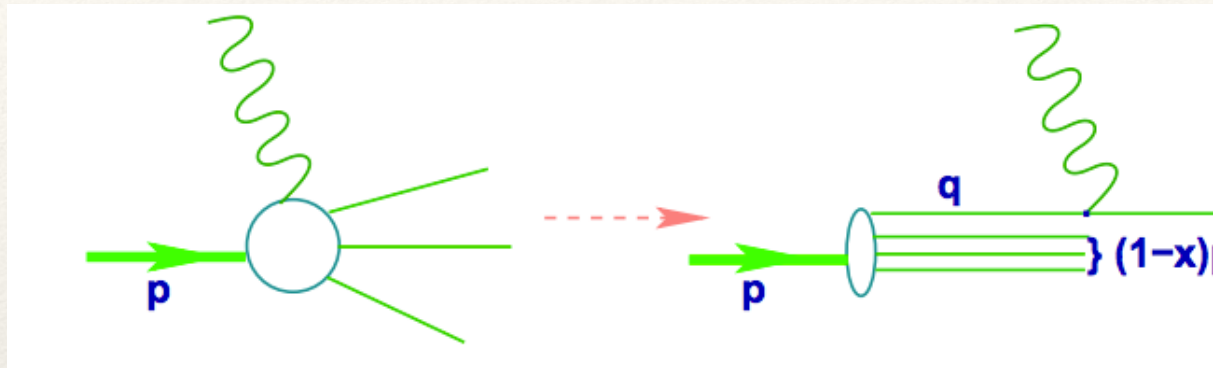


G. Salam, Crete-ICNFP 2016

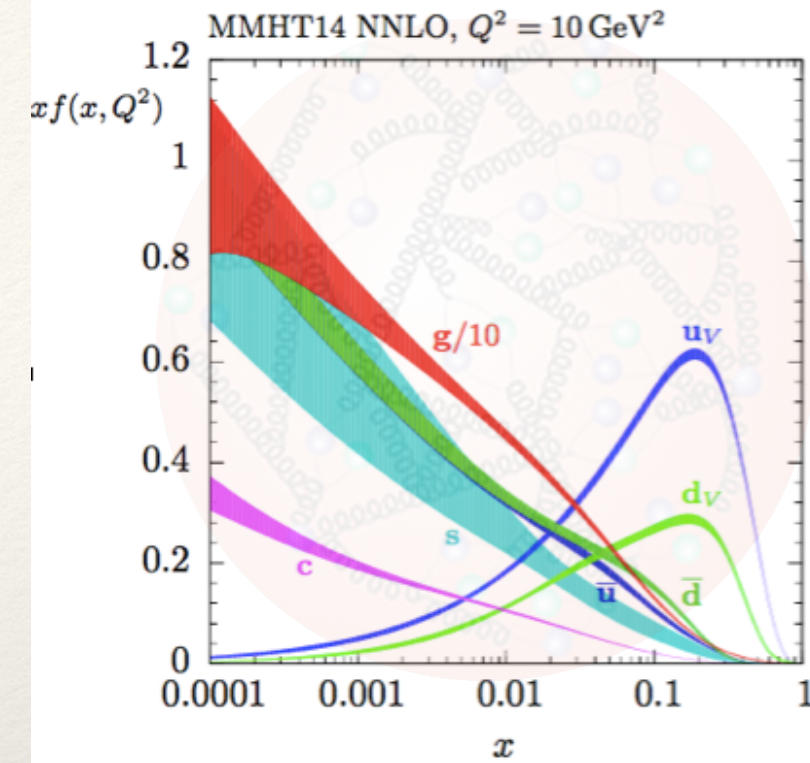


# Proton's Parton Distribution Functions

- PDFs are understood as the probability of finding a parton of a given flavour that carries a fraction  $x$  of the total proton's momentum (at LO pQCD)

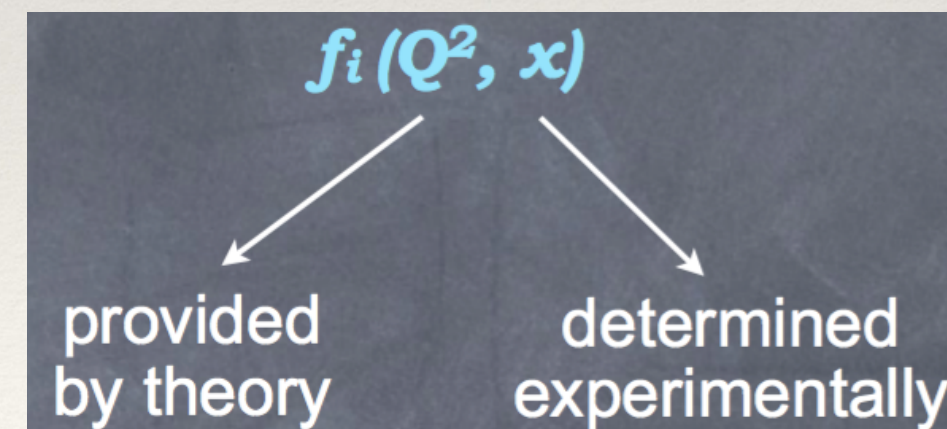


- Once QCD corrections included, PDFs become scheme dependent
  - Shape and normalisation of PDFs are very different for each flavour, reflecting the different underlying dynamics that determines them.
- PDFs cannot be calculated in perturbative QCD, however their evolution with the scale is predicted by pQCD [DGLAP equations]



calculable in pQCD

$$\frac{d}{d \ln \mu} \begin{pmatrix} q(x, \mu) \\ g(x, \mu) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix} (z, \alpha_s) \cdot \begin{pmatrix} q(x/z, \mu) \\ g(x/z, \mu) \end{pmatrix}$$





# Mechanism of extracting PDFs:

- ❖ Extraction of PDFs relies on both precision measurements to challenge theory

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

## Main Steps:

1. Parametrise PDFs at a starting scale
2. Impose counting sum rules (p: uud) and momentum sum rules
3. Evolve PDFs to the scale corresponding to data point
- 4. Calculate the cross section**
5. Compare with data via  $\chi^2$
6. Minimise  $\chi^2$  with respect to PDF parameters

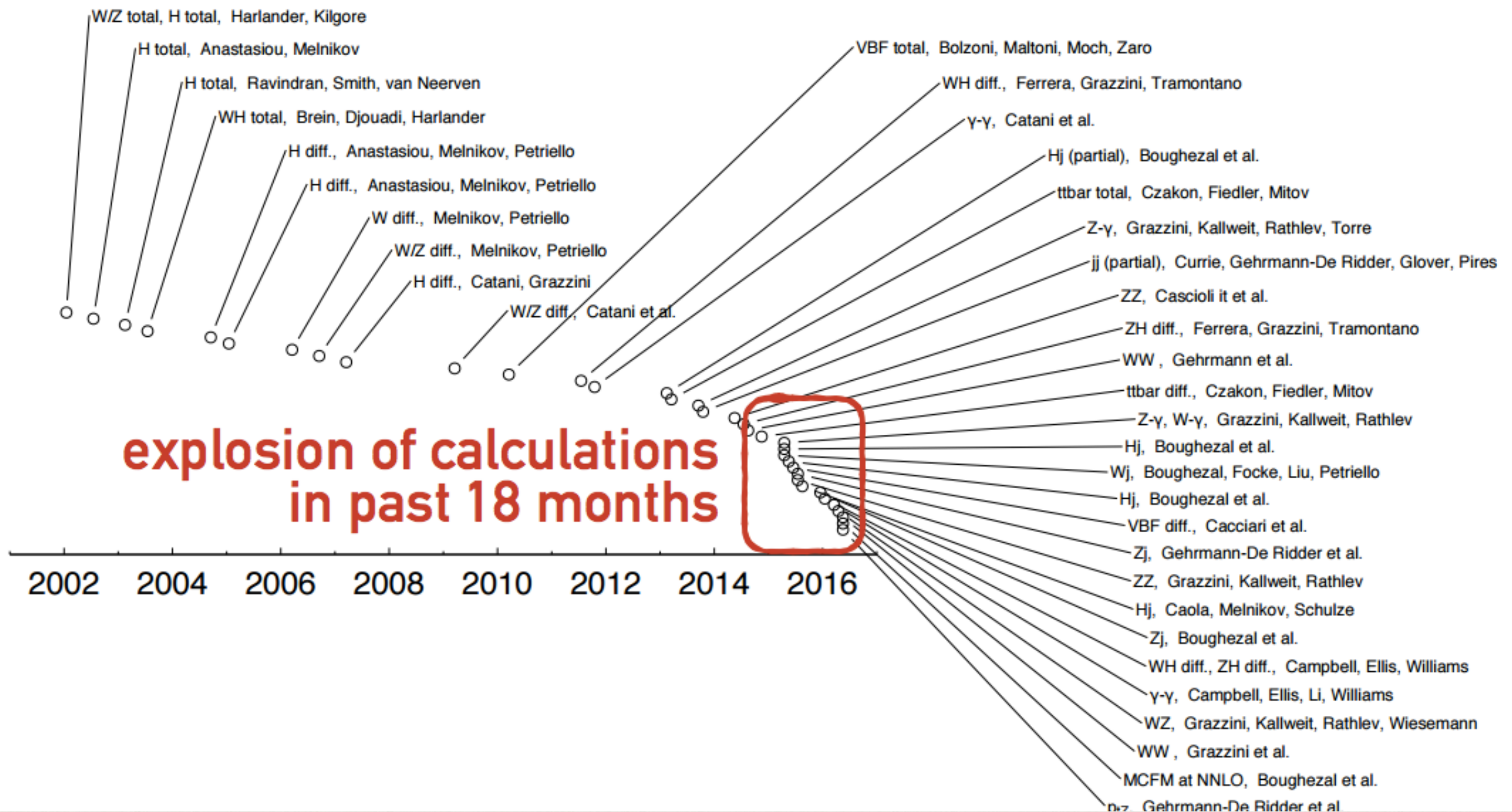




# NNLO hadron-collider calculations v. time

as of mid June

[credit G. Salam]



—> state of the art NNLO, however, need automation tools to speed up the computation for a fit that requires ~2000 iterations (2000 x calculations per data point)

APPLGRID, FASTnlo, Apfelgrids, APPLfast, k-factors ...

[D. Britzger, M. Sutton]

—> enormous boost of precision to analyse data at % level



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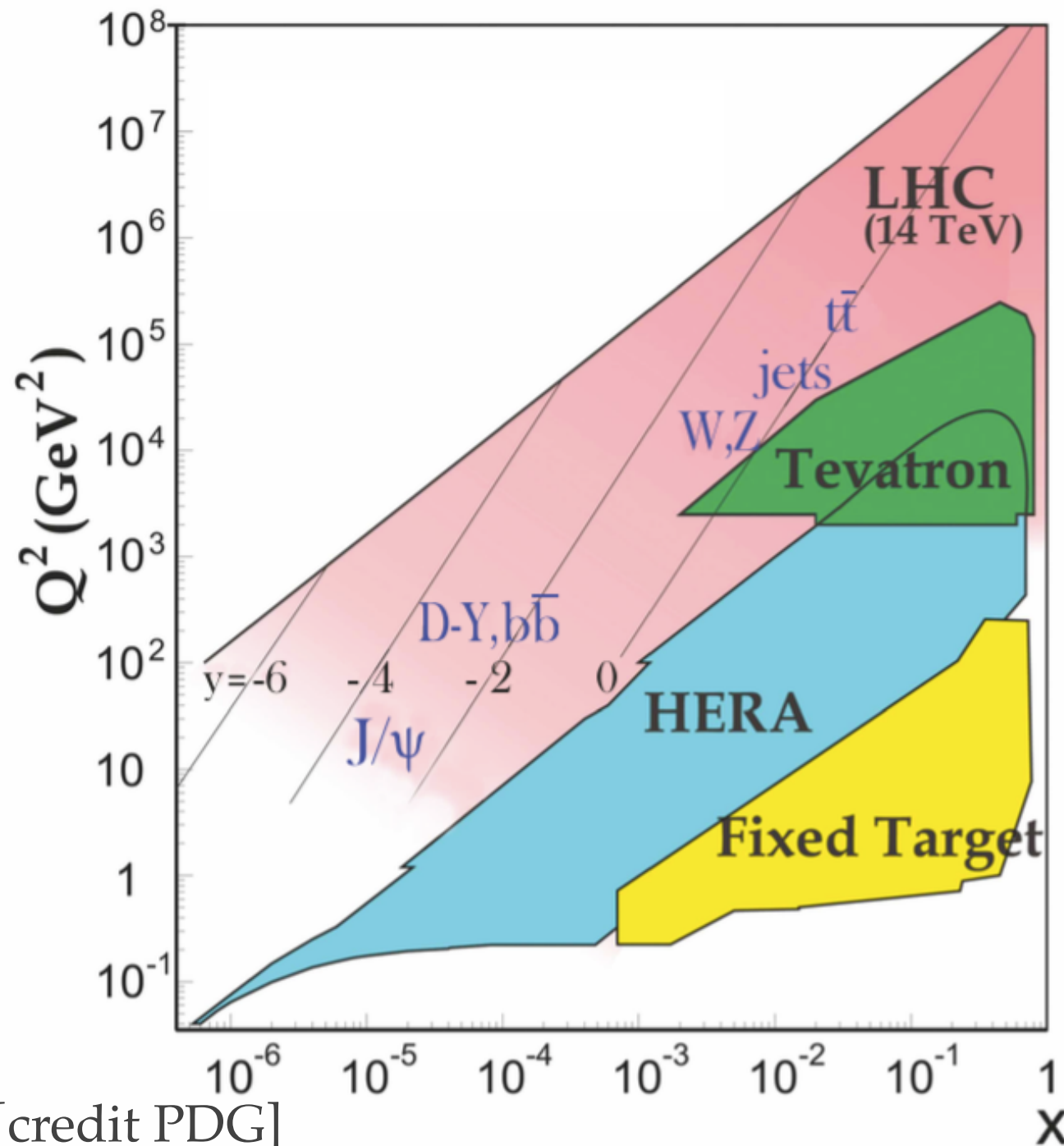
Tools for QCD Fits: xFitter, APFEL, Alpos, OPENQCDRAD, QCDNUM ...

[see VR talk] ↓





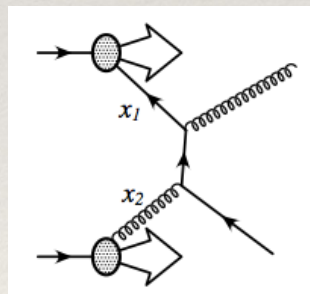
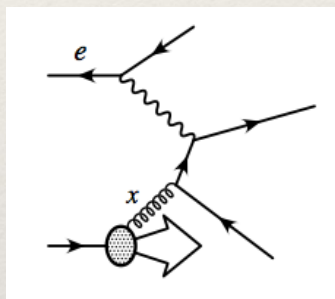
# Data for studying Proton Structure



$Q^2$ : resolving power of experiment  
 $x$ : fraction of proton's momentum

Persistent experimental effort over the last 40 years both by fixed-target and collider experiments around the world supported by the intense theoretical developments

- The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:
- Precision of proton structure can be complemented by the Drell Yan [DY] processes at the collider experiments



Multiple precision measurements from Fixed target, HERA, Tevatron, and LHC

Many PDF groups to analyse these data and extract PDFs





# PDF Groups

- ❖ The extraction of PDFs is subject to many choices —> many PDF Groups
  - ❖ data selection
  - ❖ data treatment (corrections, uncertainties)
  - ❖ theory calculations for each process: formalism, automation, assumptions
  - ❖ parametrisation of unknown and fit methodology
  - ❖ treatment of uncertainties (from data to theory)

- ❖ Current Groups:

CT14	arXiv:1506.07443
MMHT14	arXiv:1412.3989
NNPDF3.0	arXiv:1410.8849
HERAPDF2.0	arXiv:1506.06042
CJ15	arXiv:1212.1702
ABM12 (ABMP15)	arXiv:1310.3059
JR14	arXiv:1403.1852
Nuclear PDFs	nCTEQ, NNPDF, CJ
Dedicated PDF	studies by LHC experiments, xFitter, Prosa

D. Stump

R. Thorne

J. Rojo

S. Alekhin

VR, E. Nocera, L. Harland-Lang  
R. Placakyte, K. Lohwasser





# Data sets for PDF sets:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ12(15)	JR14
HERA data	HERA I+ charm	HERA I charm jets	HERA I+ H1 and ZEUS II charm	HERA I+II	HERA I charm	HERA I	HERA I charm jets
Fix. Target DIS	✓	✓	✓	✗	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	✗	✗/✓	✓	✗
Tevatron Jets	✓	✓	✓	✗	✗	✗	✓
Fix. Target DY	✓	✓	✓	✗	✓	✓	✓
LHC WZ	✓	✓	✓	✗	✓	✗	✗
LHC jets	✓	✓	✓	✗	✗	✗	✗
LHC top	✗	✓	✓	✗	✓	✗	✗
LHC charm	✗	✗	✓	✗	✗/✓	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

## Type of processes:

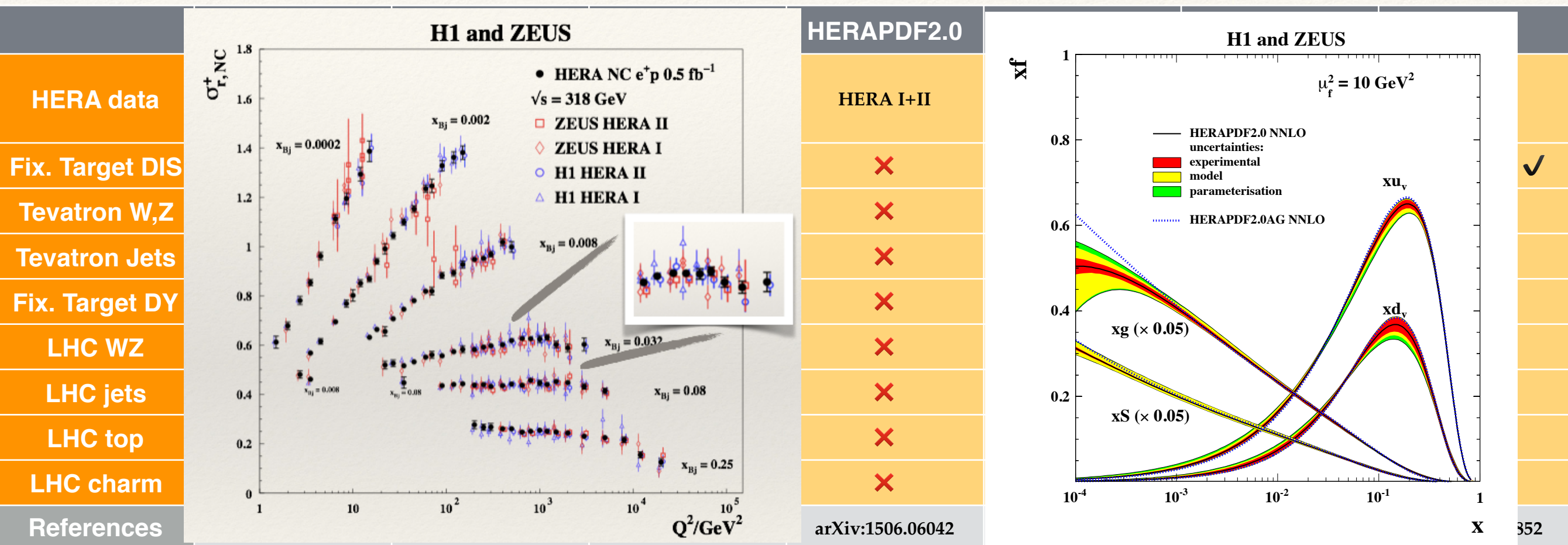
- ❖ inclusive / purely leptonic
- ❖ processes with jets
- ❖ current precision of data  $\sim < 5\%$
- ❖ The aim is to find more processes that could provide important feedback

see: E. Rizvi, R. Placakyte, K. Lohwasser, S. Glazov, K. Mueller  
S. Camarda, J. Bossio ...





# Data sets for PDF sets:



HERA data is the basis of any PDF extraction

HERAPDF is not a global PDF, but only from ep collider

—> last word from HERA:

—> interesting set to test PDF universality

—> it is free of corrections related to the target, nuclear medium and higher twist effects

However, PDFs extracted from HERA:

- ❖ do not provide sea decomposition
- ❖ there is no data for  $x < 10^{-4}$
- ❖ lack precision at high  $x$



# PDF differences:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT- $\chi$ )	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NNLO	NLO	NLO, NNLO
$\alpha(M_z)$	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
$\alpha(M_z)$ LO $\alpha(M_z)$ NLO $\alpha(M_z)$ NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1( $x>0$ ) u/d=1 ( $x>0$ )	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar ( $x>0$ ) sbar=0.67*dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian 2 stages: $\Delta\chi^2=100$ 90% CL region	Hessian $\Delta\chi^2$ Dynamical (68% CL)	Monte Carlo (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

The analyses differ in many areas:

- different treatment of quarks with masses
- inclusion of various data sets and account for possible tensions
- different assumption on values of strong couplings
- different assumptions in procedure (parametrisation, corrections)





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order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NNLO	NLO	NLO, NNLO
$\alpha(M_z)$	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
$\alpha(M_z)$ LO $\alpha(M_z)$ NLO $\alpha(M_z)$ NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1( $x>0$ ) u/d=1 ( $x>0$ )	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar ( $x>0$ ) sbar=0.67*dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian 2 stages: $\Delta\chi^2=100$ 90% CL region	Hessian $\Delta\chi^2$ Dynamical (68% CL)	Monte Carlo (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)	Hessian $\Delta\chi^2=1$ (68% CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
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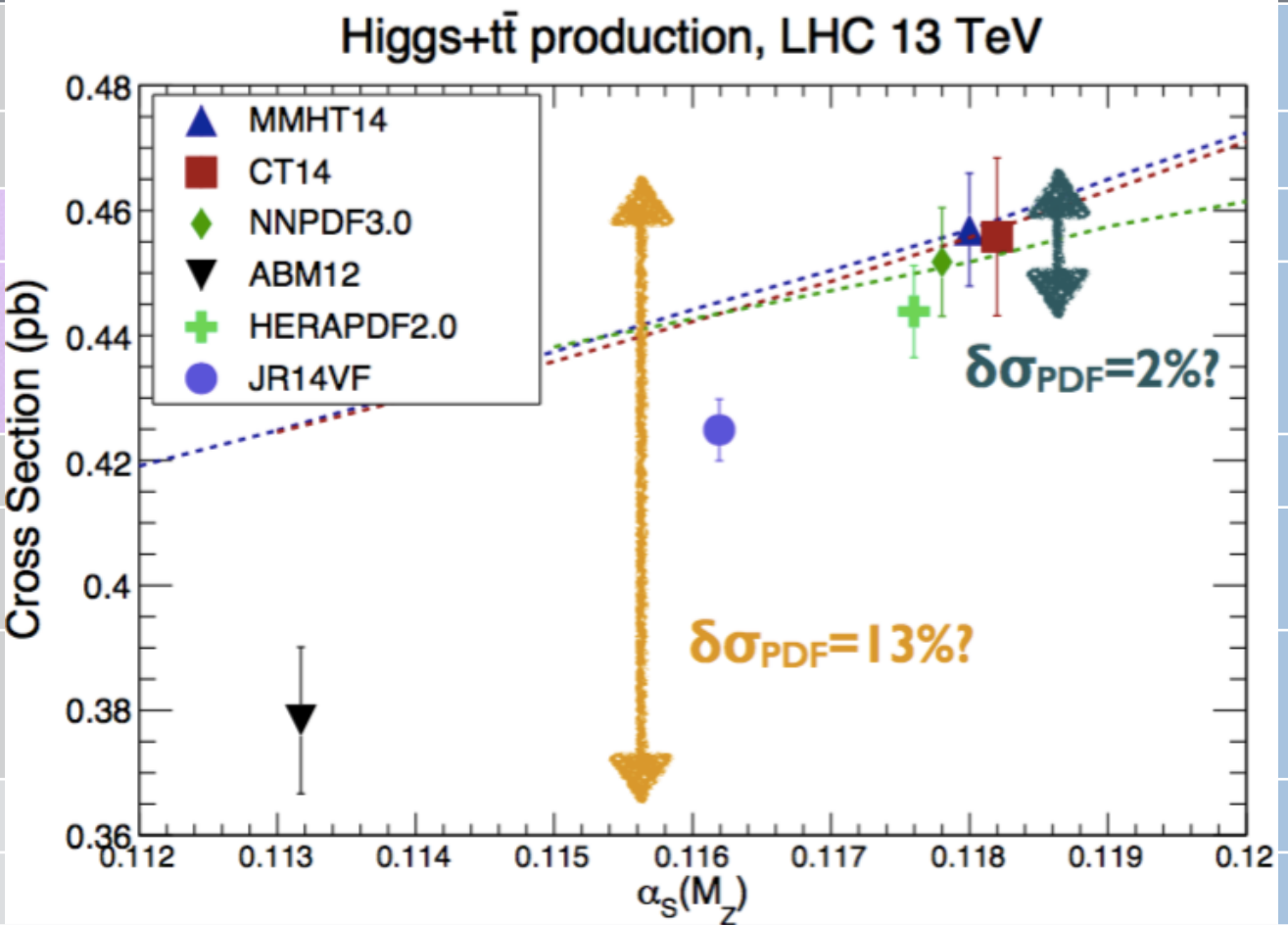
uncert from single PDF  
+  
uncert. from difference  
among PDFs

.. differences in PDFs lead to the differences in the cross section predictions



# PDF differences:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT- $\chi$ )	VFNS (TR opt)	VFNS (FONLL)				
order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO				
$\alpha(M_z)$	fixed(fitted)	fixed (fitted)	fixed				
$\alpha(M_z)$ LO $\alpha(M_z)$ NLO $\alpha(M_z)$ NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180				
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)				
PDF assumptions	ubar/dbar=1( $x > 0$ ) u/d=1 ( $x > 0$ )	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit				
Stat. treatm.	Hessian 2 stages: $\Delta\chi^2=100$ (90% CL region)	Hessian $\Delta\chi^2$ Dynamical (68% CL)	Monte Carlo (68% CL)				
Q2min	2	2	3.5				
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849				



Credit: J. Rojo

used for PDF4LHC recommendation  
**arXiv:1510.03865 : PDF4LHC sets**

PDF4LHC sets: a statistical combination PDFsets

—> Different settings of extracting PDFs  
 can lead to different results that  
 could affect the real ambiguity of  
 cross section certainty



# PDFsets differences:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme					FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
order in pQCD					NNLO	NLO	NLO, NNLO
$\alpha(M_Z)$					fitted	fixed	fitted
$\alpha(M_Z)$ LO $\alpha(M_Z)$ NLO $\alpha(M_Z)$ NNLO					- - 0.1132	- 0.118 -	- 0.1158 0.1136
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References					arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

used for PDF4LHC recommendation  
arXiv:1510.03865 : PDF4LHC sets

reaction: a critique to PDF4LHC  
recommendation —> arXiv:1603.08906

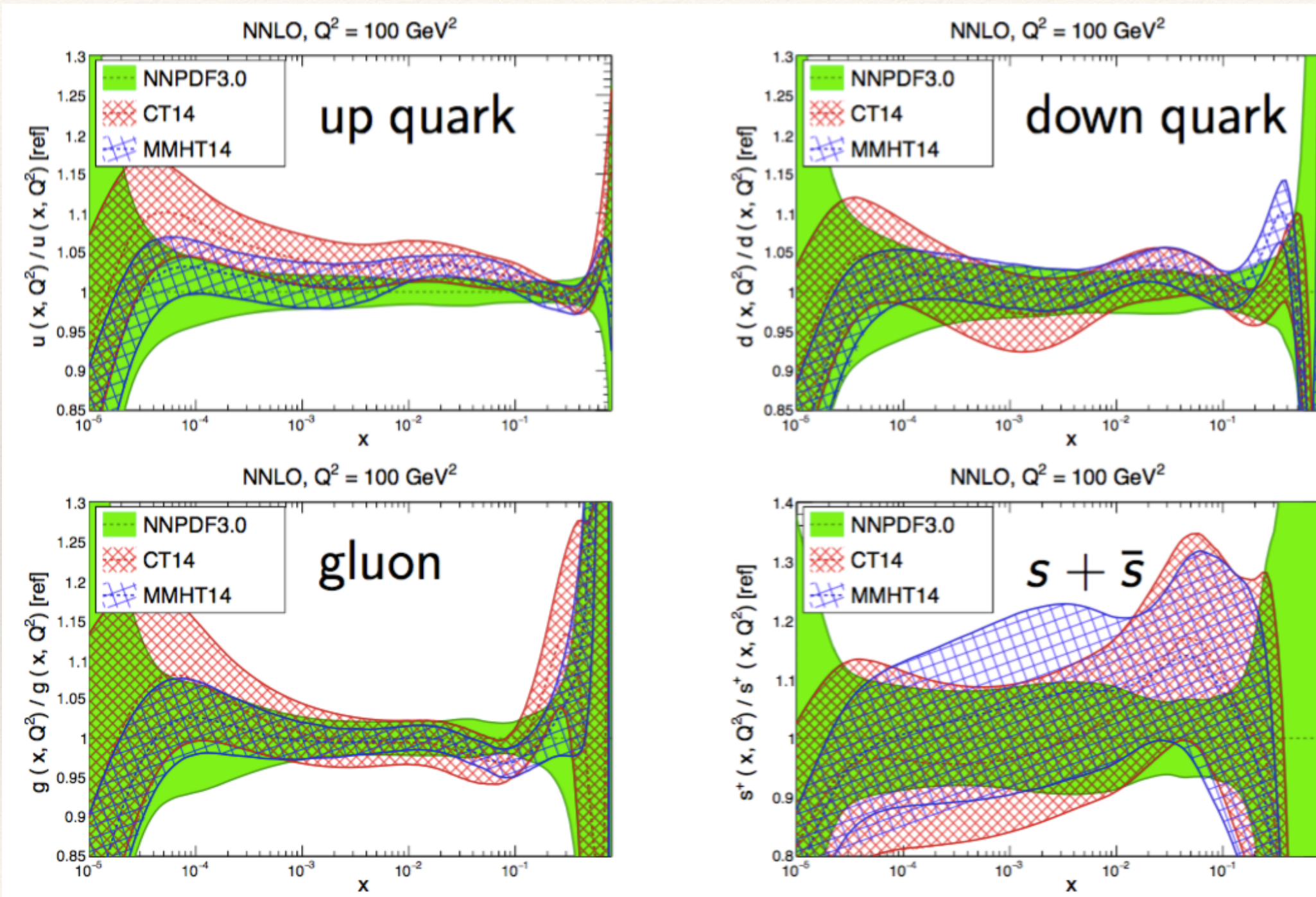
—> advocates the use of all single PDF sets  
in fear to miss signal by having over-estimated  
PDF uncertainties for searches  
(here  $W'$  is shown in terms of relative uncertainties for  
different Mass scenarios)





# Precise enough?

- Looking at the benchmarked PDFs [based on GMVFNS]:



in the region  
 $10^{-3} - 10^{-1}$   
a precision of  $<10\%$   
on PDFs

however, in the  
outside this region  
very uncertain  
PDFs

[plots credit: APFEL]

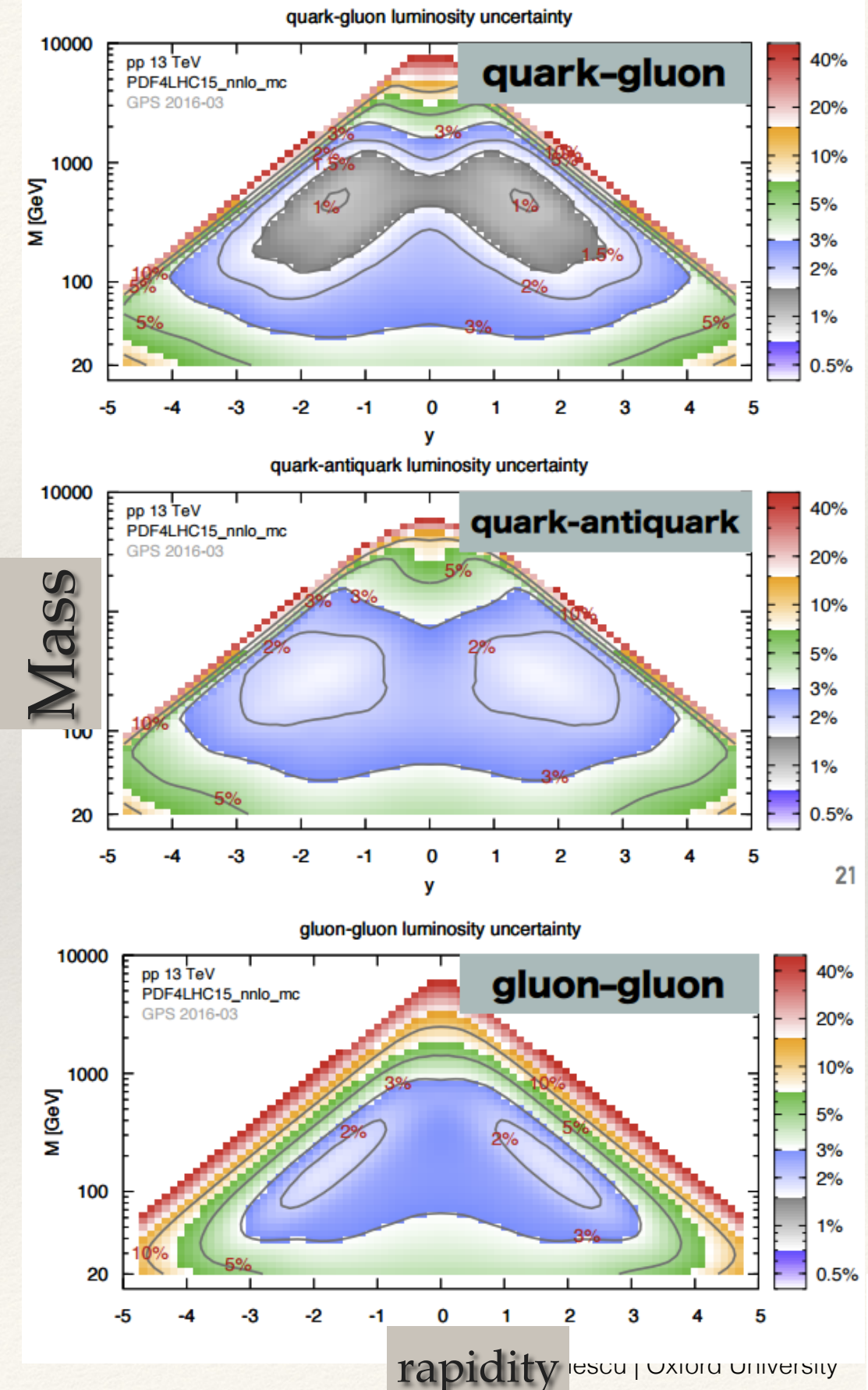


# In terms of Uncertainties on Partonic Luminosities

$$\sigma \propto f_{q/p}(x_1, \mu^2) f_{q/p}(x_2, \mu^2)$$

With increased mass ranges the PDF uncertainties increase considerable (especially for gluon initiated processes)

hence there is need to improve the uncertainties for the high mass reaches  
—> precision measurements



Credit: G. Salam



# Expectations from LHC data

## ❖ Gluon:

- ❖ Inclusive jets, dijets, trijets —> medium / large  $x$
- ❖ Isolated photon and photon+jets —> medium / large  $x$
- ❖  $t\bar{t}$  production —> large  $x$
- ❖  $Z_{pt}$  spectrum —> small / medium  $x$

LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV

13 TeV data extend this considerably [see J. Bossio]

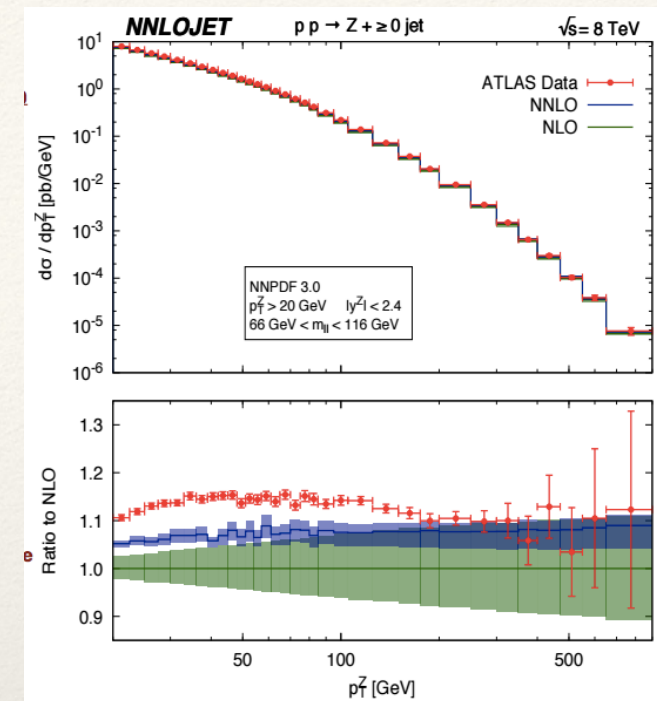
Theory at NNLO QCD + electroweak corrections are a must!

Typical uncertainties are dominated by the scale (missing HO)

—> NNLO can really help

—> efforts to interface them

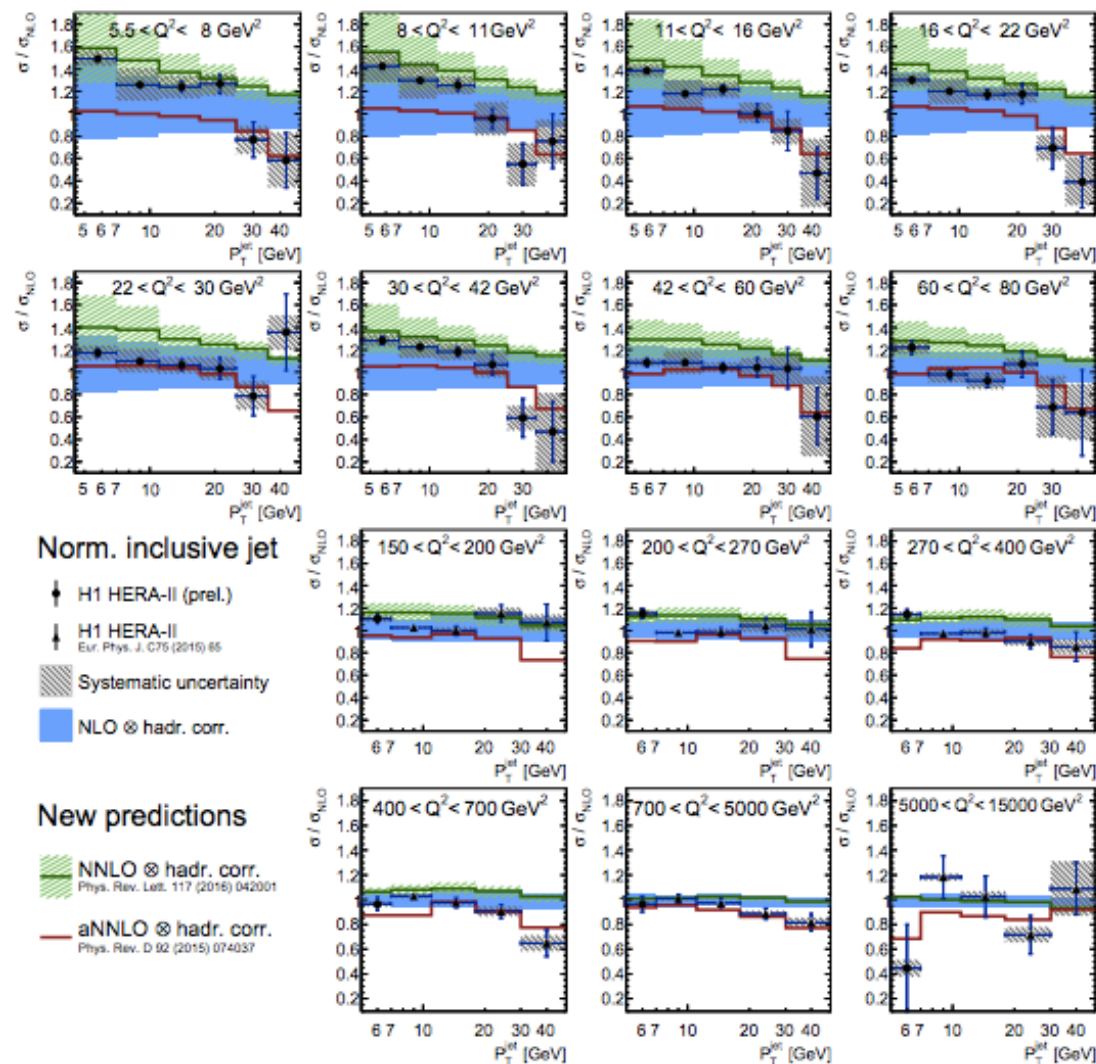
(Applgrid, FastNLO, aMCFast, **APPLfast**) [see M. Sutton]





# First NNLO for jets @ H1, HERA

H1prelim-16-062



Predictions	NLO	aNNLO	NNLO
Jet cross sections			
Program	nlojet++	JetViP	NNLOJET
pQCD order	NLO [8]	approximate NNLO [12]	NNLO [15]
Calculation detail	Dipole subtraction	NLO plus NNLO contributions from unified threshold resummation formalism	Antenna subtraction
NC DIS cross sections			
Program	QCDNUM	APFEL	APFEL
Heavy quark scheme	ZM-VFNS	FONLL-C	FONLL-C
Order	NLO	NNLO	NNLO
PDF	NNPDF3.0_NLO	NNPDF3.0_NNLO	NNPDF3.0_NNLO
$\alpha_s(M_Z)$	0.118	0.118	0.118
Hadronisation corrections	Djangoh and Rapgap		
Available for			
Normalised inclusive jet	✓	✓	✓
Normalised dijet	✓		✓
Normalised trijet	✓		

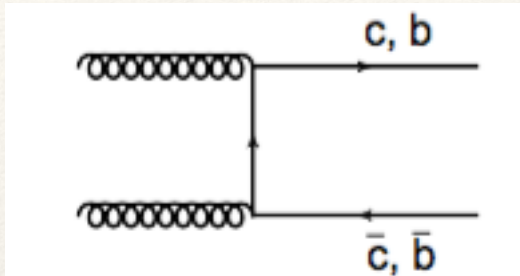
[see D. Britzger]

❖ next  $\longrightarrow$  a boost to re-analyse Tevatron and LHC jets !



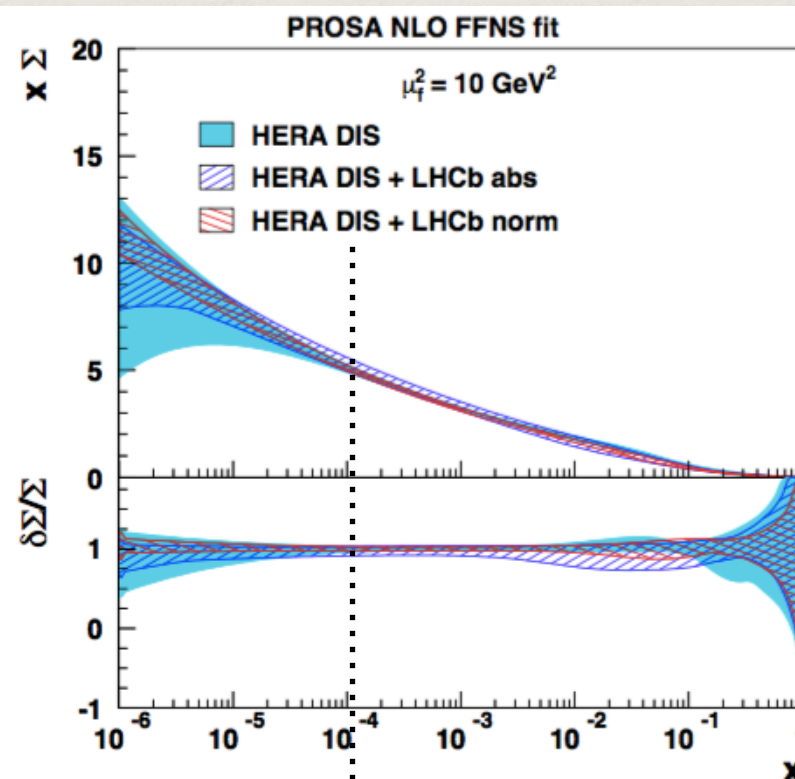
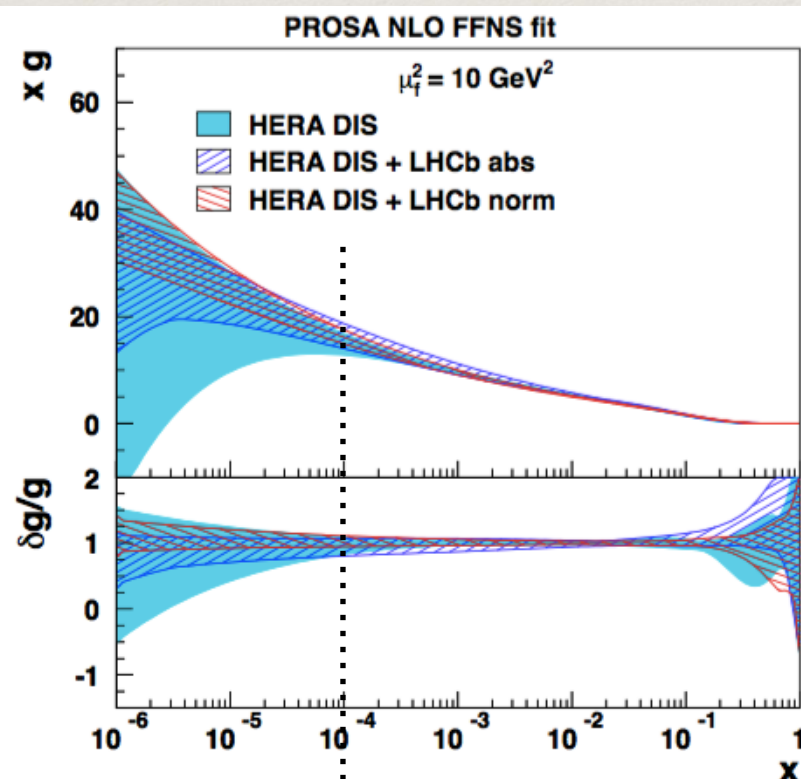
# Gluon Sensitivity from heavy quark production at low $x$

- ❖ LHCb brings advantage in covering low  $x$  region with its forward detector design



—> Heavy-quarks are produced in pp via gluon fusion

- ❖ A joint analysis of HERA heavy quark production with the LHCb following data:
  - ❖ charm [Nucl. Phys. B871 (2013) 1]
  - ❖ beauty [JHEP 08 (2013) 117]



Eur.Phys.J. C75 (2015) 8, 396

confirmed by  
NNPDF analysis

Access to low  $x$  which reduces uncertainties on gluon and sea quarks



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- ❖  $t\bar{t}$  production —> large  $x$
- ❖  $Z_{pt}$  spectrum —> small / medium  $x$

## ❖ Quarks:

- ❖ W and Z rapidity spectra —> medium  $x$
- ❖ High  $p_T$  W+jets —> medium / large  $x$
- ❖ Low mass and high mass DY —> small / large  $x$
- ❖ W+c rapidity spectrum —> strange at medium  $x$
- ❖ single top differential —> medium / high  $x$

see dedicated talks:

E. Rizvi, S. Camarda, K. Lohwasser, R. Placakyte  
HQ: R. Gauld, R. Silva Coutinho B. Isildak...





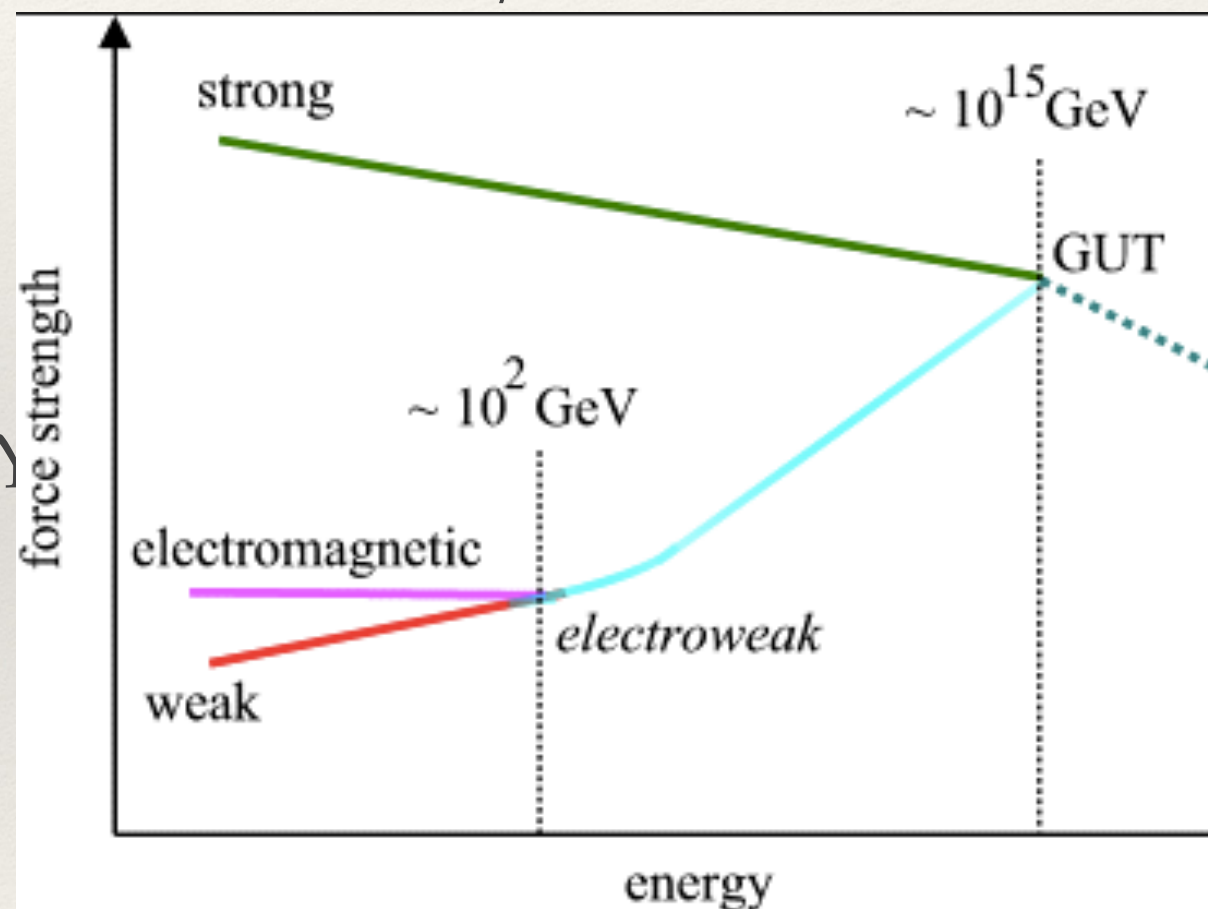
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- ❖ High  $p_T$  W+jets
- ❖ Low mass and high mass DY
- ❖ W+c rapidity spectrum
- ❖ single top differential



## ❖ Photon:

- ❖ WW production
- ❖ High Mass DY

At the LHC the QED effects start to bring an important contributions due to access to high scales processes:

- ❖ high mass DY,  $t\bar{t}$ , di-boson, EW Higgs

[see D. Pagani]





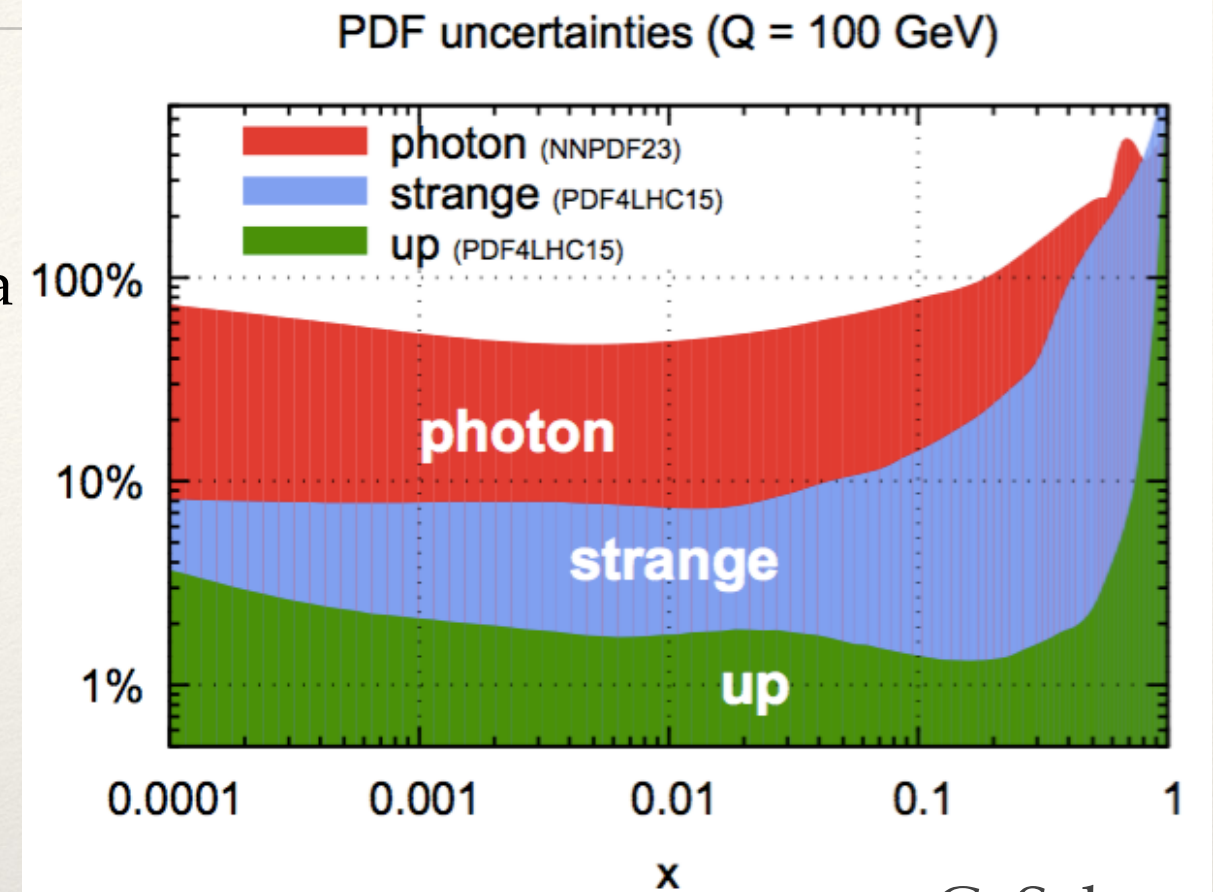
# New Developments for PDF extraction: photon PDF

- ❖ It starts to become relevant implementation of combined QCD+QED evolution in determining a complete set of PDFs including photon PDFs.

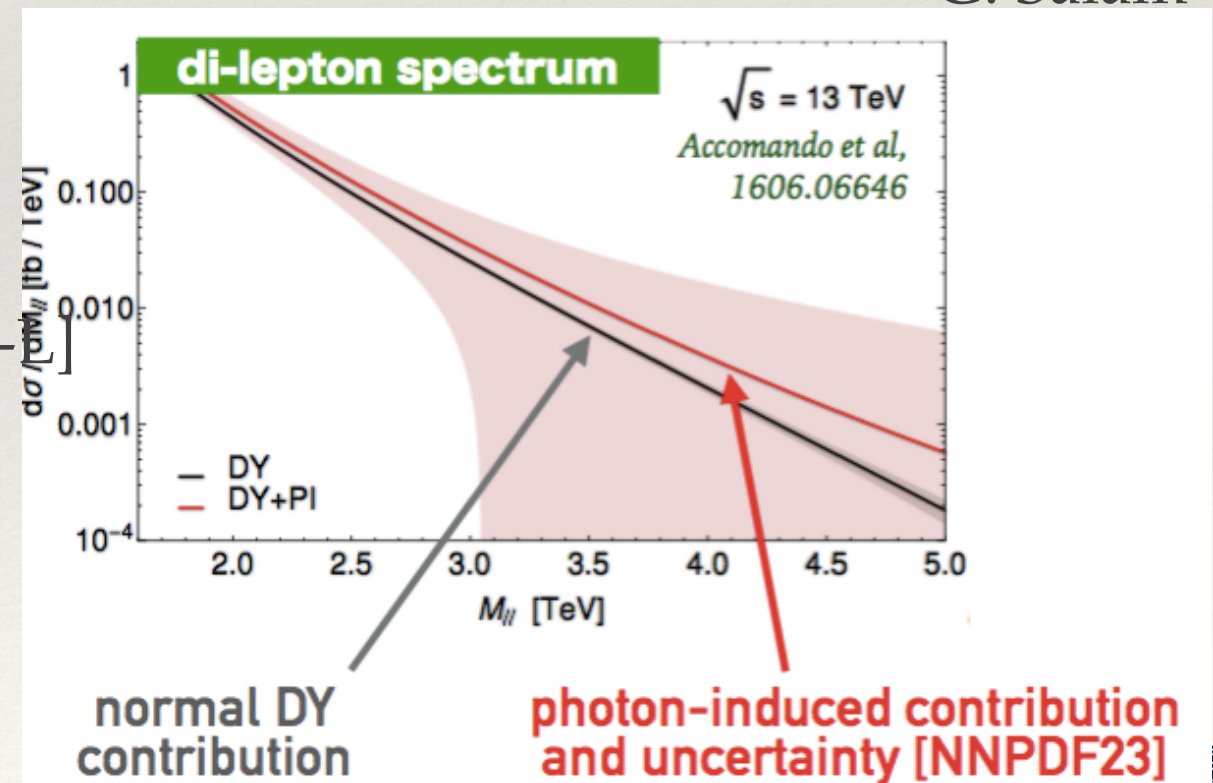
limited experimental constraints

- ❖ **Studies that account for the photon PDF:**

- ❖ Gluck, Pisano, Reya 2002
- ❖ MRST2004 QED
- ❖ NNPDF2.3 QED  $\rightarrow$  NNPDF3.0 QED
  - ❖ fit to data
- ❖ CT14 QED, CT14 QED\_inc [see D. Stump]
- ❖ Harland-Lang, Khoze, Ryskin 2016 [see L. H-]
- ❖ LUXqed 2016: Manohar, Nason, Salam, Zanderighi
  - ❖ use ep scattering and construct a hypothetical model for neutral lepton



G. Salam





# New Developments for PDF extraction: photon PDF

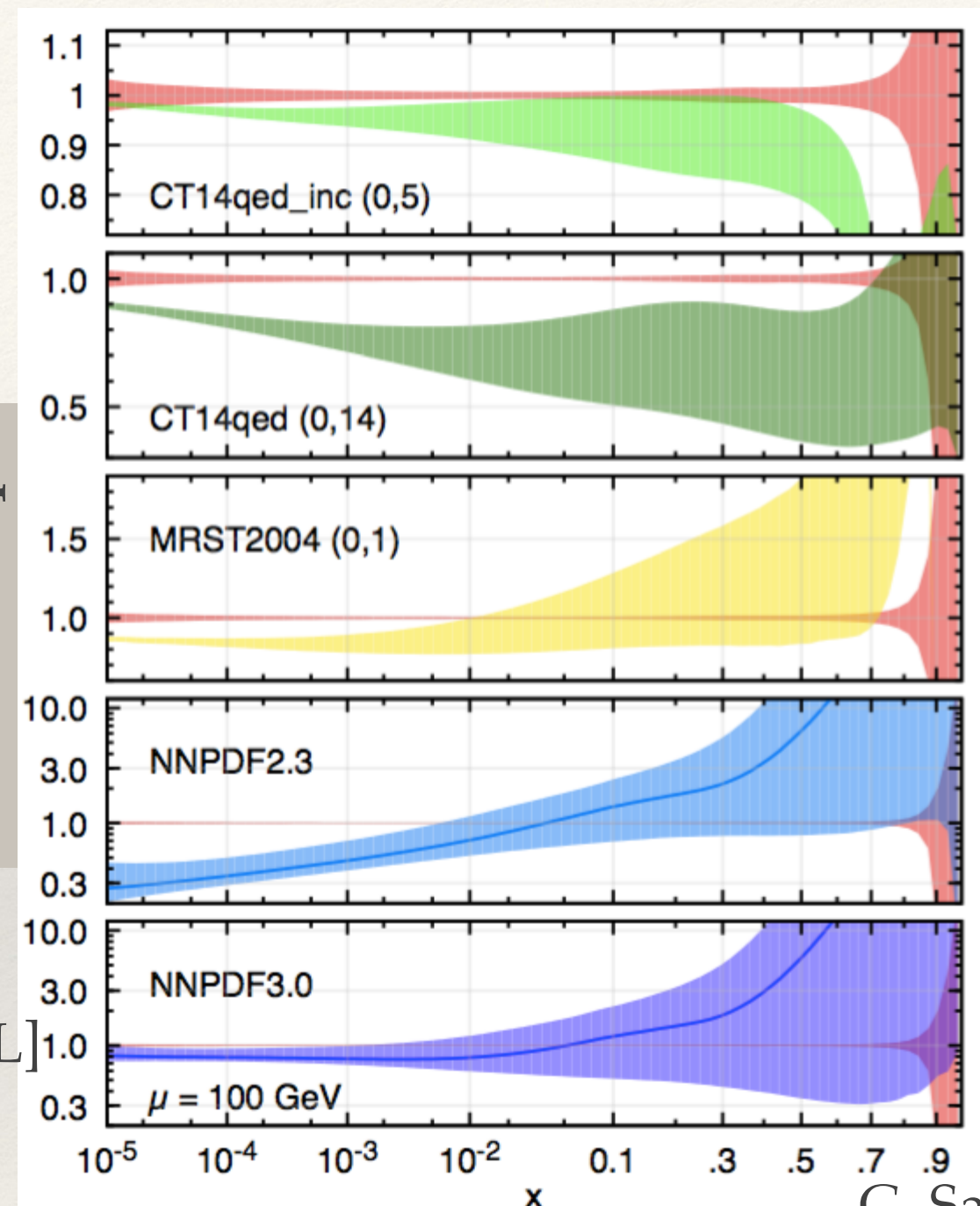
- ❖ It starts to become relevant implementation of combined QCD+QED evolution in determining a complete set of PDFs including photon PDFs.

limited experimental constraints

- ❖ **Studies that account for the photon PDF:**

- ❖ Gluck, Pisano, Reya 2002
- ❖ MRST2004 QED
- ❖ NNPDF2.3 QED  $\rightarrow$  NNPDF3.0 QED
  - ❖ fit to data
- ❖ CT14 QED, CT14 QED\_inc [see D. Stump]
- ❖ Harland-Lang, Khoze, Ryskin 2016 [see L. H-L]
- ❖ LUXqed 2016: Manohar, Nason, Salam, Zanderighi
  - ❖ use ep scattering and construct a hypothetical model for neutral lepton

ratio to LUXqed



G. Salam

$\rightarrow$  interesting to confront these models with data



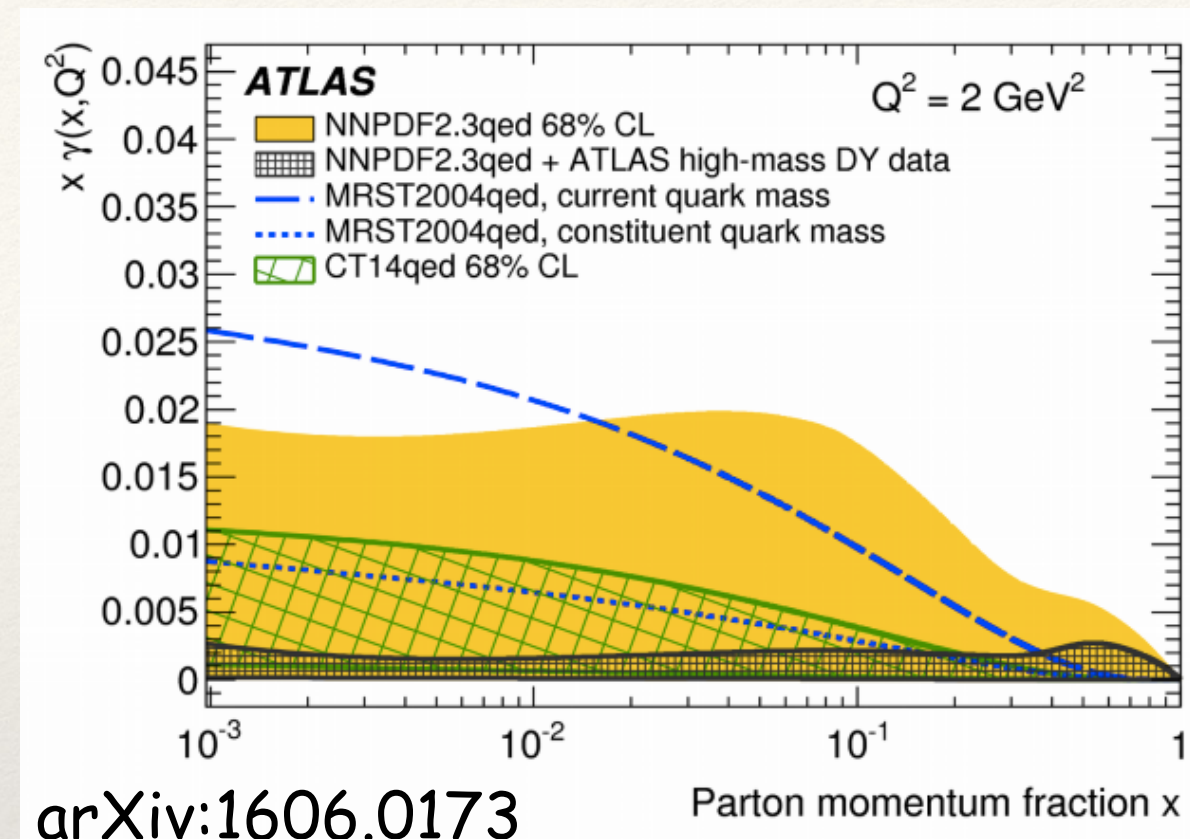


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  - ❖ use ep scattering and construct a hypothetical model for neutral lepton



[see E. Rizvi]

Data has a lot of potential



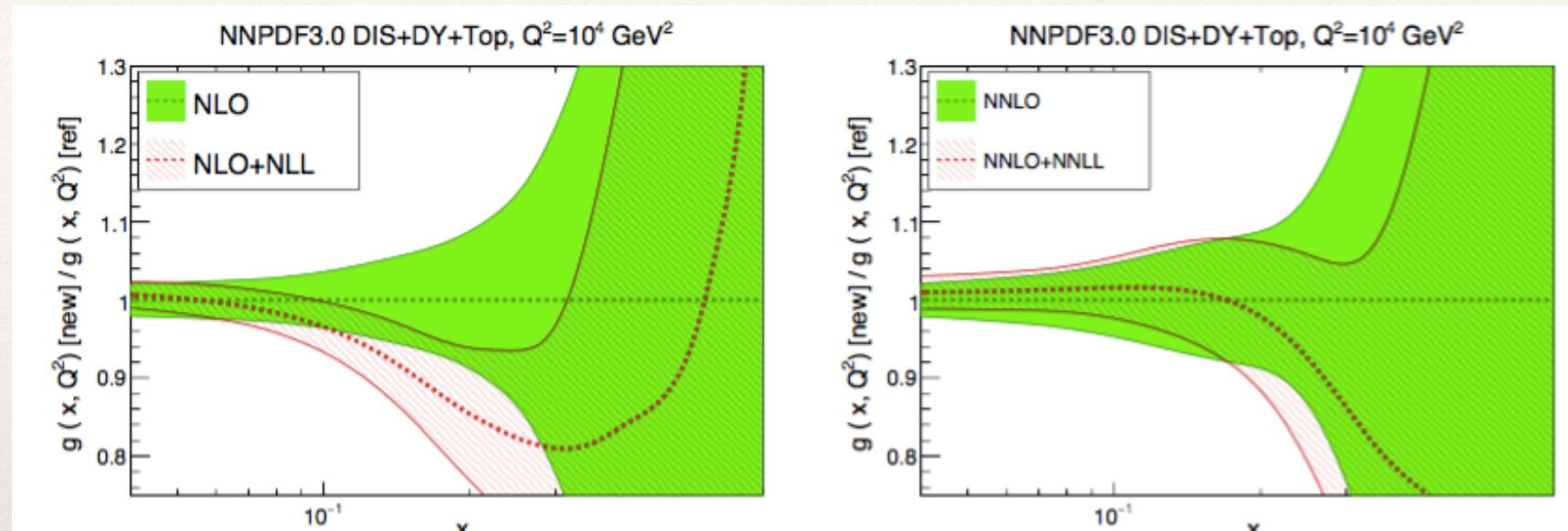


# Other Developments: PDFs from resummed calculations

- Fixed order calculations don't always work and in order to improve the quality of PDF fits in small/high  $x$  regions there have been efforts in providing PDFs consistent with Resummed Computations

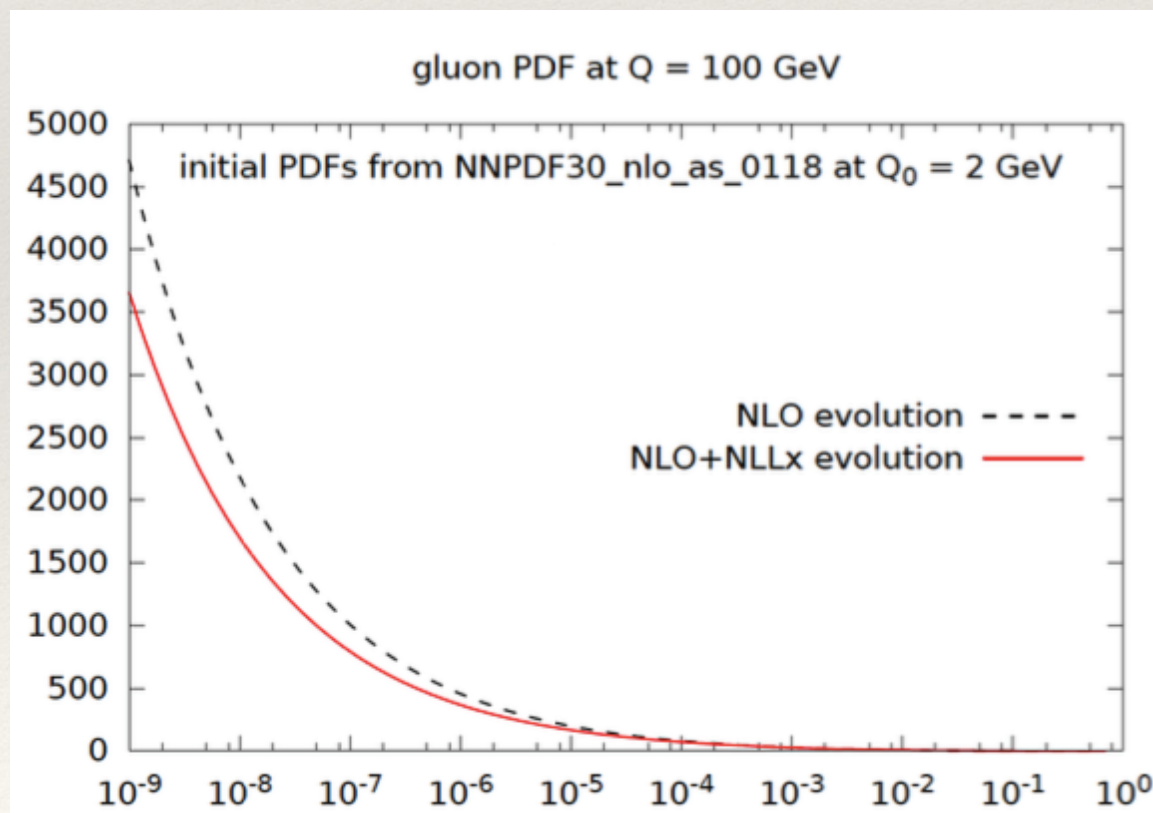
[using NNPDF framework]

- PDF fits with threshold resummation were tested for data DIS + DY ( $Z/\gamma$ ) +  $t\bar{t}$ 
  - sizeable effect at NLO+NLL, smaller effect at NNLO+NNLL



- PDF fits with high-energy resummation show promising results
  - NLO+NLL $\times$  evolution

[See: M. Bonvini]

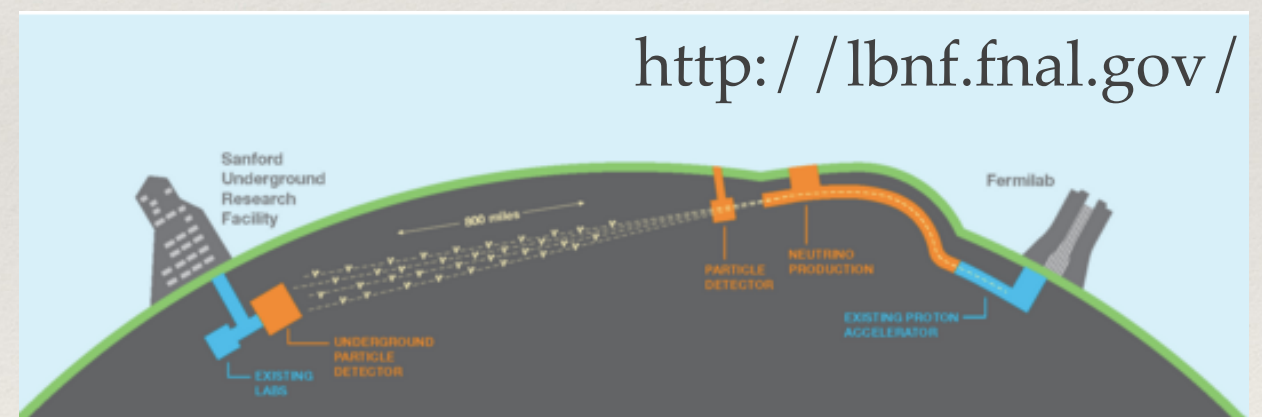
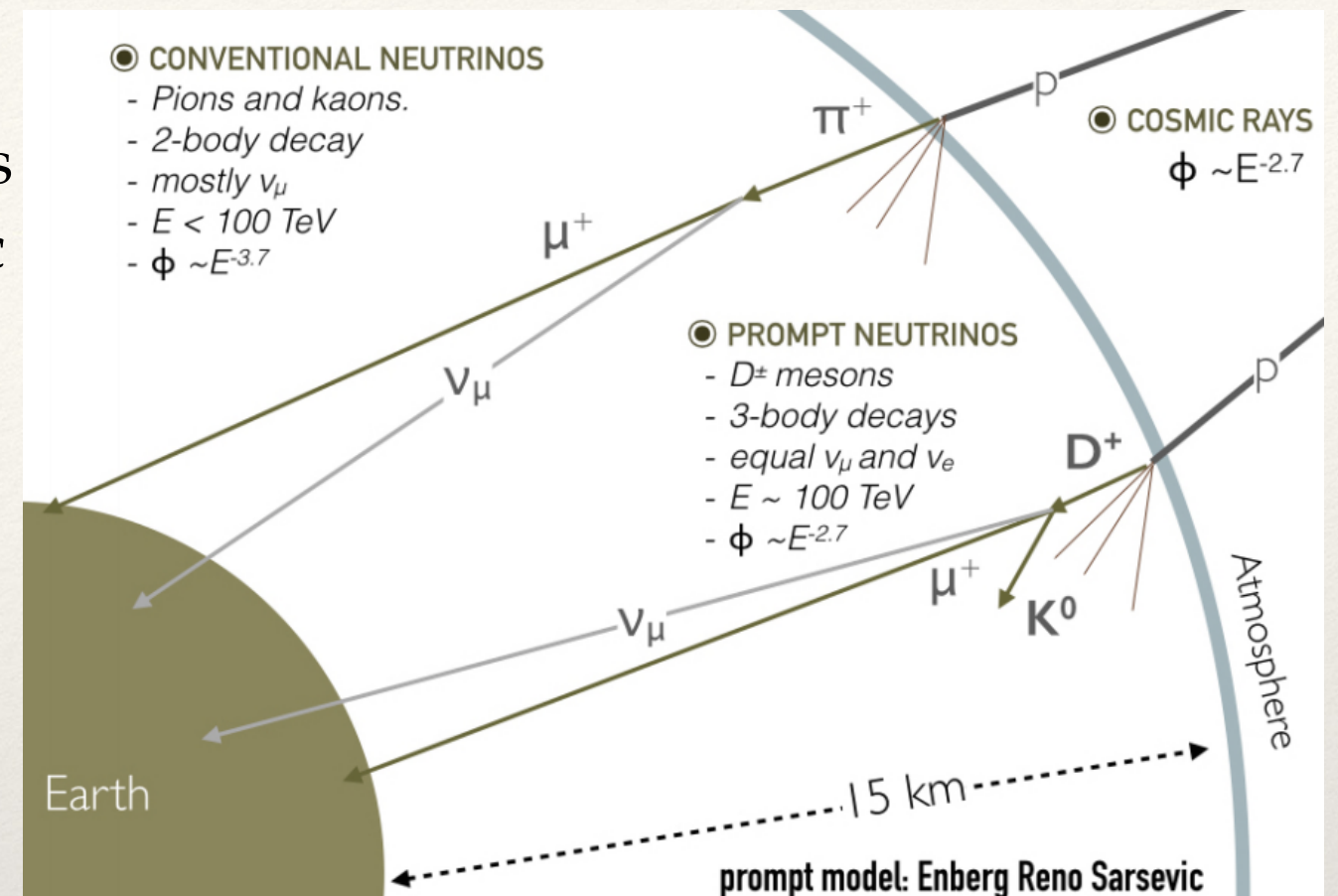


[APFEL, FONLL, HELL]



# Role of PDFs in Neutrino Sector

- ❖ The main background for astrophysical neutrinos at IceCube is the flux of neutrinos from the decays of charm mesons in cosmic ray collisions in the atmosphere:
  - ❖  $\rightarrow$  heavy quark production data from LHC could validate calculations of the prompt neutrino flux
- ❖ The physics prospects by DUNE at LBNF with high resolution and unprecedented statistics may lead to discoveries of new physics:
  - ❖ Modelling of the neutrino interaction physics requires a good control of the cross section model which is used at the end for the determination of the event kinematics



synergy between LBNF, LBL, CERN



# Summary

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- ◆ PDFs are very important as they still limit our knowledge of cross sections whether SM or BSM.
- ◆ Enormous progress achieved in pushing towards percent level precision on theory and experimental measurements:
  - theory

    - ◆ availability of NNLO state-of-the-art calculations
    - ◆ inclusion of the QED effects
    - ◆ special-purpose PDFs:
      - ◆ resummed calculations, parton showering, intrinsic charm
    - ◆ advanced statistical methods (MC, reweighting, profiling)
    - ◆ discussions on inclusion of theoretical uncertainties in extracting PDFs: scales, schemes..
  - data

    - ◆ pushing for precision measurements for constraining PDFs:
      - ◆ clean processes (e.g. Z pT)
      - ◆ reliable flavour separation
      - ◆ correlation information to help cross-calibrate systematic uncertainties
      - ◆ smaller bin size to provide more shape feedback to PDFs
- ◆ We don't know what we will find, but it will surely depend on how well we control all our parameters.

# Thank you!



# Resources

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- ♦ G. Salam "QCD theory overview: towards precision at the LHC "(Plenary talk at the Fourth Annual Large Hadron Collider Physics Conference, Lund, Sweden, June 2016
- ♦ G. Salam "Proton structure: the last light parton" (talk in the "Guido Altarelli memorial session at the 5th International Conference on New Frontiers in Physics, Crete, July 2016
- ♦ J. Rojo " The PDF4LHC 2015 recommendations for Run II", DIS2016, DESY Hamburg, April 2016.
- ♦ J. Rojo "Updates in the NNPDF global analysis", DIS2016, DESY Hamburg, April 2016.
- ♦ R. Placakyte "Recommendations for PDF usage in LHC predictions", DIS2016, DESY Hamburg, April 2016.
- ♦ S. Camarde "xFitter Tutorial", CTEQ Summer School 2016, DESY, July 2016
- ♦ papers of MMHT, CT14, NNPDF30, ABM, photon PDF developments
- ♦ xFitter and APFEL activities



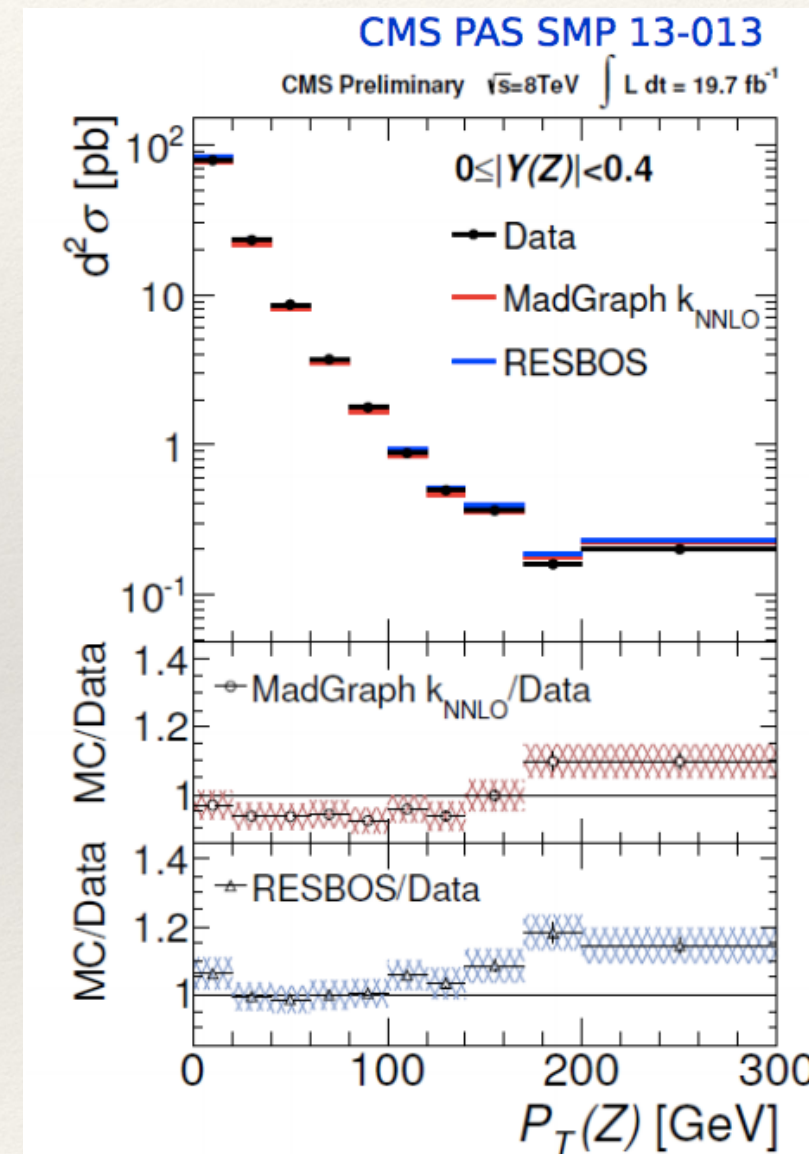
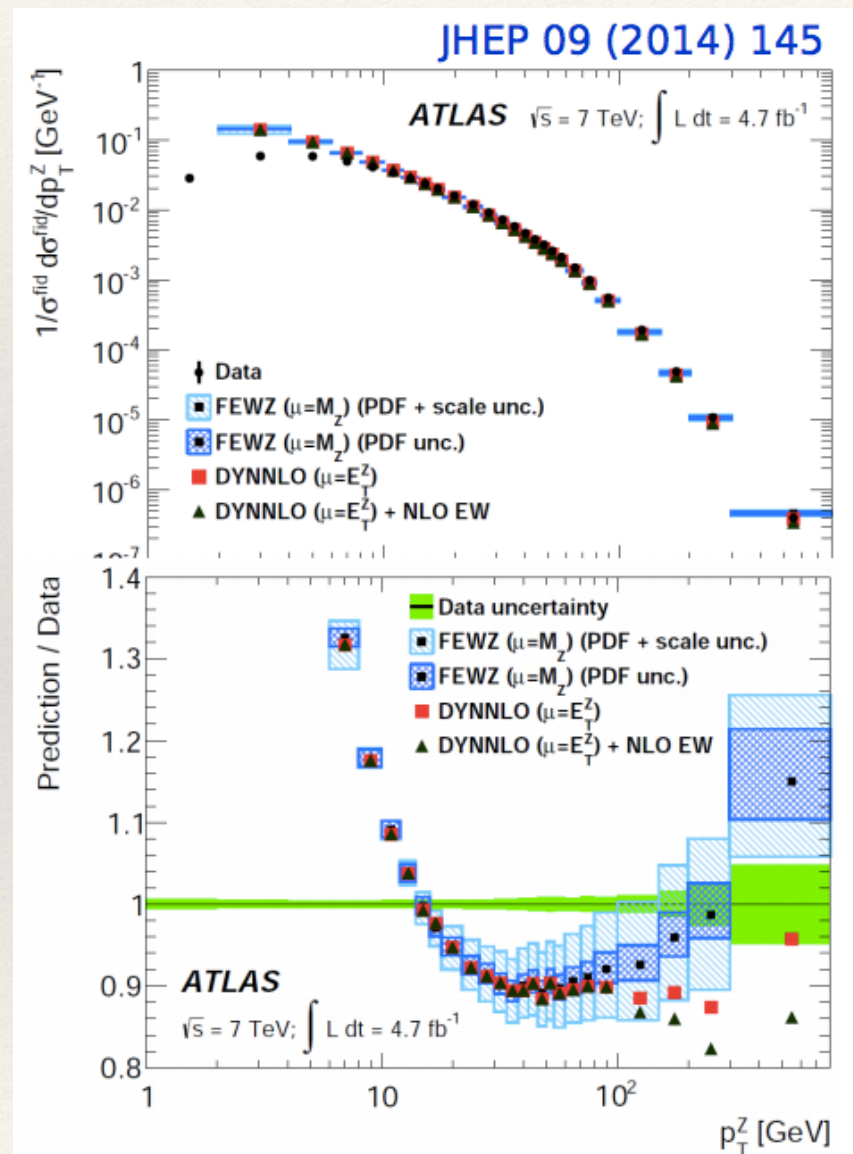






# Vector boson Pt spectrum at the LHC

- ❖ ATLAS and CMS both studied the Pt spectrum in rapidity bins
  - ❖ low Pt region: dominated by the emission of soft partons (resummation and shower models, fixed order calculations don't work)
  - ❖ high Pt region: quark-gluon scattering (PDFs)

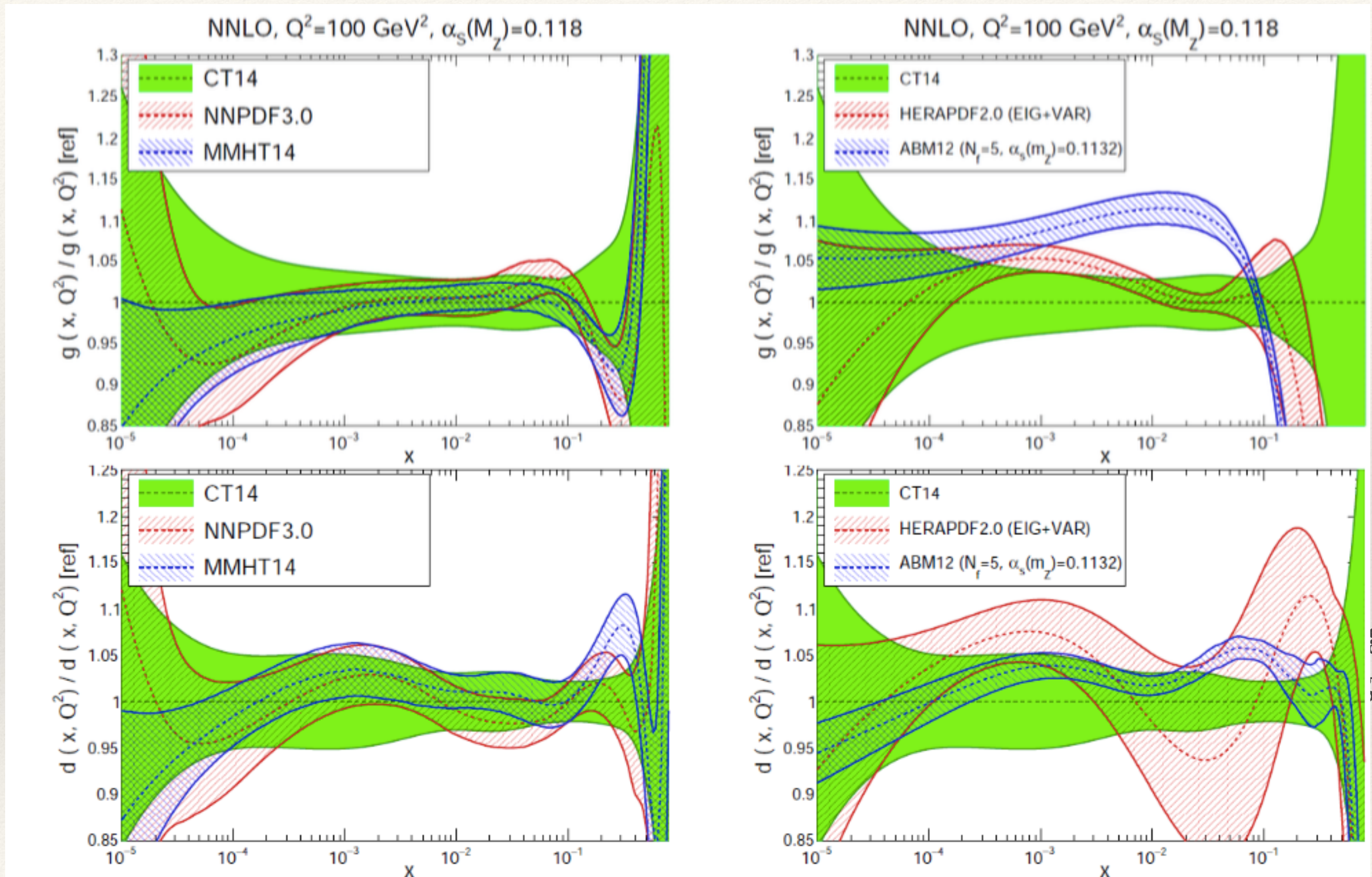


- ❖ sensitive data for W mass measurement, PDFs at high x
- ❖ currently, limited by precision in theory (needs NNLO and EW corrections)





# State-of-the-art PDFs:

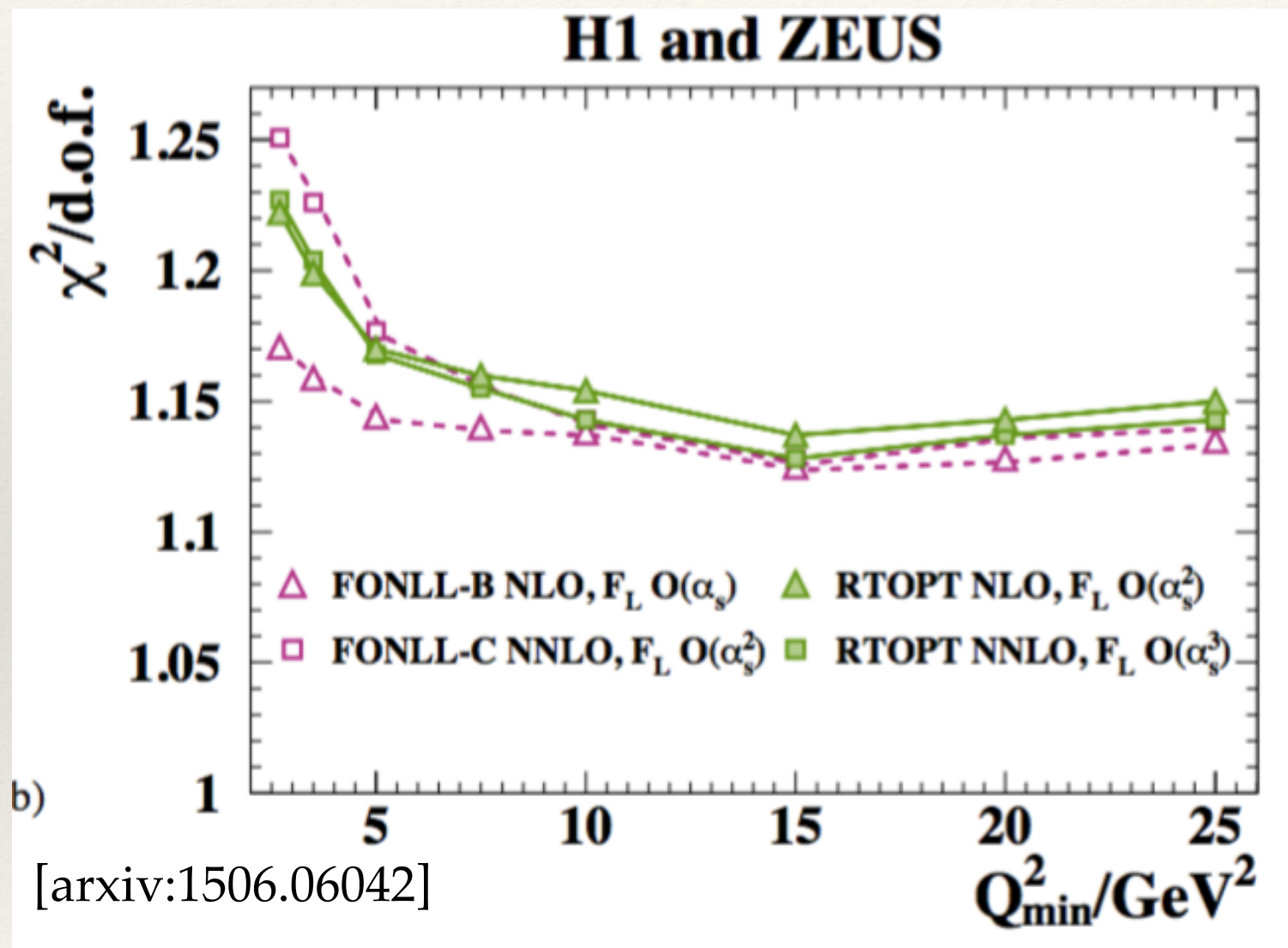


\*plots taken from PDF4LHC recommendation arxiv:1510.03865



# $Q^2$ cut dependence

- ❖ HERA data provides a unique access to the low  $x$ , low  $Q^2$  region to investigate:
  - ❖ the validity of the DGLAP mechanism
  - ❖ the various scheme dependence (fixed vs variable flavours)



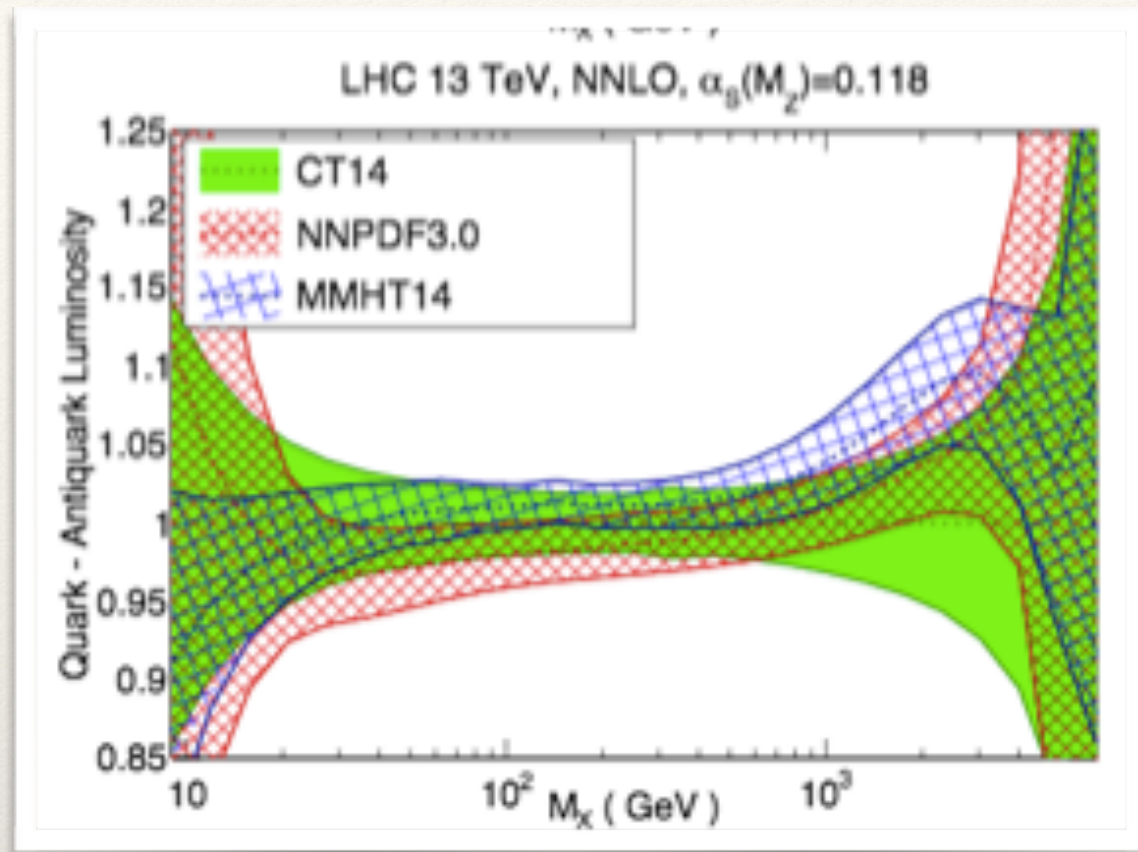
Treating FL to  $O(\alpha_s)$  yields better  $\chi^2$  than treating FL to  $O(\alpha_s^2)$  quasi independent of heavy flavour scheme

Low  $Q^2$  remains an interesting region to investigate (low  $x$  phenomenology)



# Search for new physics at high scales:

[arXiv:1410.6810v2]



For masses  $>1$  TeV, PDF uncertainties increase to  $> 15\%$

—> can we then distinguish a possible signal?

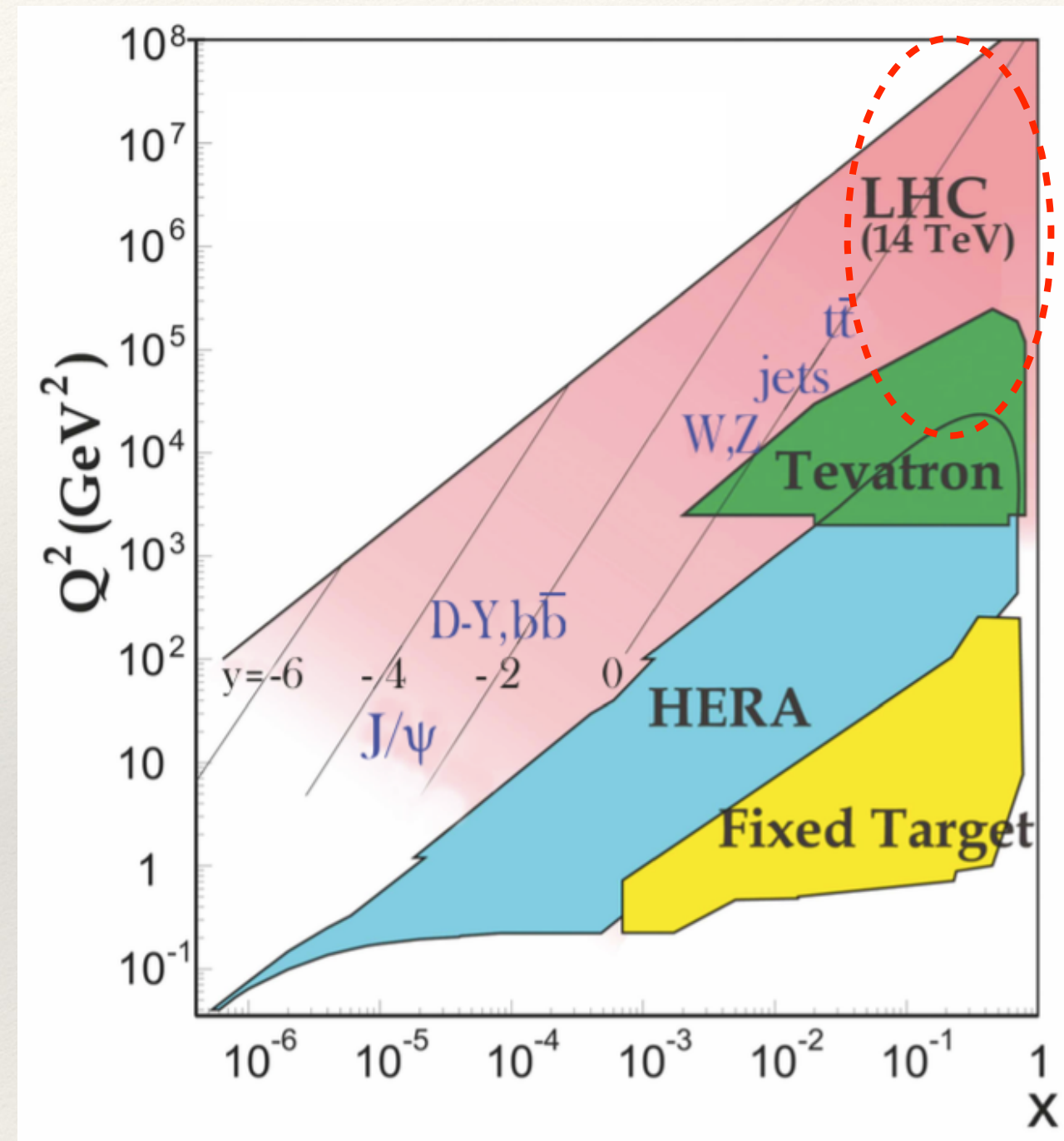
—> scale uncertainties (missing HO) vs PDFs

PDFs then drive the main theory uncertainty

how to improve?

LHC data vs state-of-the-art theory (@NNLO)

- ❖  $t\bar{t}$  can be interesting channel
- ❖ high mass DY can extend to high lever arm reach
- ❖ jet data



high mass  $\longleftrightarrow$  high  $x$



# QCD Fit Open Source Packages:



The screenshot shows the xFitter website interface. At the top is the DESY logo and the xFitter name. Below the header is a navigation bar with links like 'xFitter/xFitterInternal', 'xFitter/Installation..', etc. On the left is a sidebar with 'Wiki' and 'Page' sections. The main content area has a 'Welcome to xFitter (former HERAFitter)' message, followed by a paragraph about PDFs and the xFitter project. Below this is a 'Downloads of xFitter software package' section with a link to the xFitter-1.2.2 release. Further down is an 'xFitter Meetings' section with a list of meetings and a photo of a group of people. At the bottom are sections for 'xFitter representation' and 'Developers Info (restricted to developers)'.

**Welcome to xFitter (former HERAFitter)**

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

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

**Downloads of xFitter software package**

💡 **xFitter-1.2.2 release is publicly available.**  
All the xFitter releases can be accessed [HERE](#).  
All the former (HERAFitter) releases can be accessed [HERE](#).  
Description: <http://arxiv.org/abs/1410.4412>

**xFitter Meetings**

- **User's Meetings:** meetings to enhance communication between users and developers (open access)
- **Developer's Meeting:** technical weekly meetings to ensure communication among developers (restricted access)
- **Steering Group's Meeting** (restricted access)

**xFitter representation**

- [List of results](#)
- [List of collected talks](#)

**Developers Info (restricted to developers)**

- [Internal Developments](#)

**Organisation**



**Alpos**



C++-based tool for data-to-theory comparisons and fits

Every day's work

- Compare data to theory
- Judge about agreement
- Draw conclusions on
  - Theory parameters
  - Understanding of experimental uncertainties



Profit from and exchange with HERA/xFitter experience

Profit from C++ (heavily object-oriented design)

Well defined interface to 3 components: data, theory, tasks

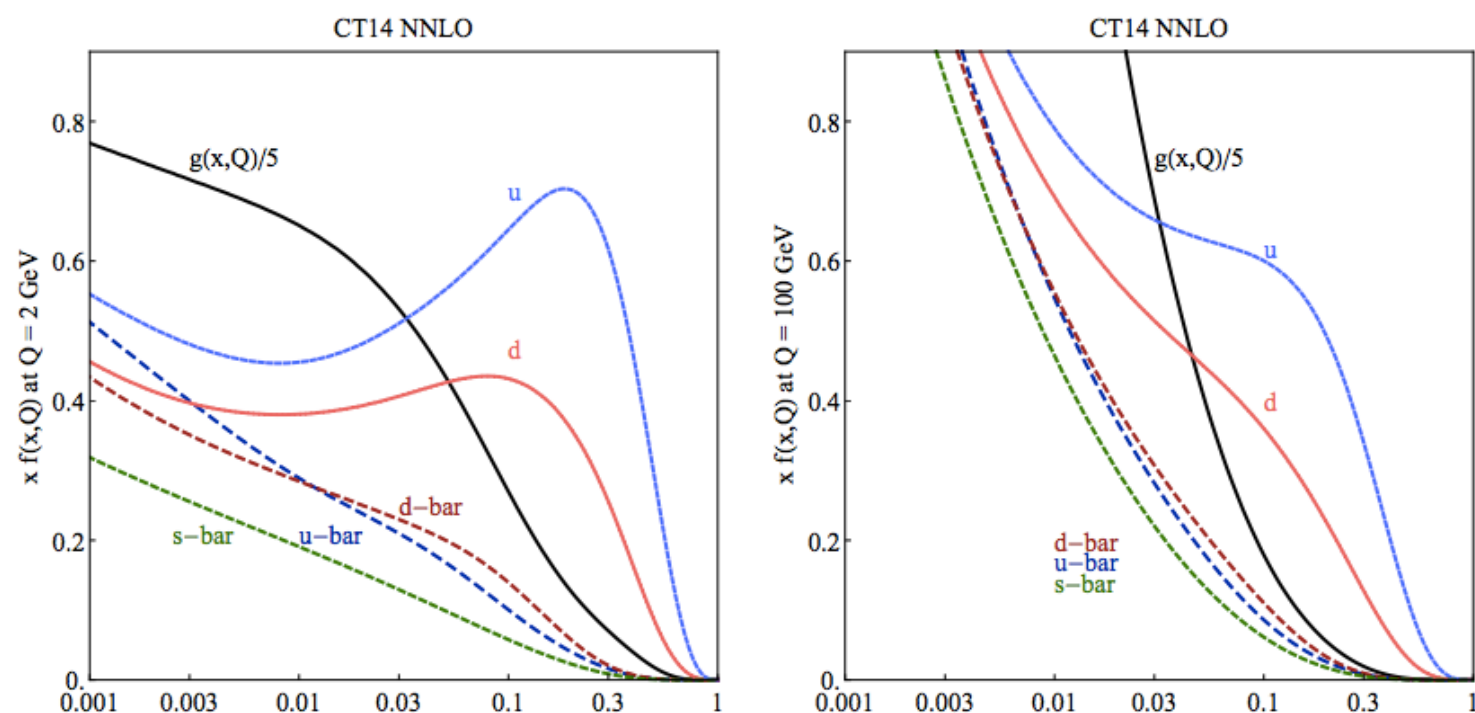
Attractive to contribute for new students





# CT14 (90%CL) 1506.07443

- ❖ CT14 includes LHC data and only HERA I data
- ❖ It increased number of free parameters from 25 to 28 wrt CT10:
  - ❖ use of Bernstein polynomials
- ❖  $m_c=1.3$  GeV (pole mass),  $\alpha_s=0.118$  (preferred though is 0.115)
- ❖ removed  $u/d \rightarrow 1$  assumption for  $x \rightarrow 0$  which made uncertainties increase at low  $x$
- ❖ Tolerance: two step: 1)  $T \sim 10$  2) define the confidence region via penalty
- ❖ Theory:
  - ❖ DIS SACOT-chi NNLO, NLO ME for neutrino CC
  - ❖ Resbos for W, Z and ptz
  - ❖ jets @ NLO (NLOJET++) with extra matrix for scale variations (using larger cone)
  - ❖ LM DY using VRAP



ID#	Experimental data set	$N_{pt,n}$	$\chi^2_n$	$\chi^2_n/N_{pt,n}$
101	BCDMS $F_2^p$ [24]	337	384	1.14
102	BCDMS $F_2^d$ [25]	250	294	1.18
104	NMC $F_2^d/F_2^p$ [26]	123	133	1.08
106	NMC $\sigma_{red}^p$ [26]	201	372	1.85
108	CDHSW $F_2^p$ [27]	85	72	0.85
109	CDHSW $F_3^p$ [27]	96	80	0.83
110	CCFR $F_2^p$ [28]	69	70	1.02
111	CCFR $x F_3^p$ [29]	86	31	0.36
124	NuTeV $\nu\mu\mu$ SIDIS [30]	38	24	0.62
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS [30]	33	39	1.18
126	CCFR $\nu\mu\mu$ SIDIS [31]	40	29	0.72
127	CCFR $\bar{\nu}\mu\mu$ SIDIS [31]	38	20	0.53
145	H1 $\sigma_r^b$ [32]	10	6.8	0.68
147	Combined HERA charm production [33]	47	59	1.26
159	HERA1 Combined NC and CC DIS [34]	579	591	1.02
169	H1 $F_L$ [35]	9	17	1.92

ID#	Experimental data set	$N_{pt,n}$	$\chi^2_n$	$\chi^2_n/N_{pt,n}$
201	E605 Drell-Yan process [37]	119	116	0.98
203	E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$ [38]	15	13	0.87
204	E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$ [39]	184	252	1.37
225	CDF Run-1 electron $A_{ch}$ , $p_{T\ell} > 25$ GeV [40]	11	8.9	0.81
227	CDF Run-2 electron $A_{ch}$ , $p_{T\ell} > 25$ GeV [41]	11	14	1.24
234	DØ Run-2 muon $A_{ch}$ , $p_{T\ell} > 20$ GeV [42]	9	8.3	0.92
240	LHCb 7 TeV 35 pb <sup>-1</sup> W/Z $d\sigma/dy_\ell$ [43]	14	9.9	0.71
241	LHCb 7 TeV 35 pb <sup>-1</sup> $A_{ch}$ , $p_{T\ell} > 20$ GeV [43]	5	5.3	1.06
260	DØ Run-2 Z rapidity [44]	28	17	0.59
261	CDF Run-2 Z rapidity [45]	29	48	1.64
266	CMS 7 TeV 4.7 fb <sup>-1</sup> , muon $A_{ch}$ , $p_{T\ell} > 35$ GeV [46]	11	12.1	1.10
267	CMS 7 TeV 840 pb <sup>-1</sup> , electron $A_{ch}$ , $p_{T\ell} > 35$ GeV [47]	11	10.1	0.92
268	ATLAS 7 TeV 35 pb <sup>-1</sup> W/Z cross sec., $A_{ch}$ [48]	41	51	1.25
281	DØ Run-2 9.7 fb <sup>-1</sup> electron $A_{ch}$ , $p_{T\ell} > 25$ GeV [14]	13	35	2.67
504	CDF Run-2 inclusive jet production [49]	72	105	1.45
514	DØ Run-2 inclusive jet production [50]	110	120	1.09
535	ATLAS 7 TeV 35 pb <sup>-1</sup> incl. jet production [51]	90	50	0.55
538	CMS 7 TeV 5 fb <sup>-1</sup> incl. jet production [52]	133	177	1.33





# Towards NNPDF3.1

NNPDF3.1 is the next update of the NNPDF global analyses

- Several new additional datasets included: the legacy HERA data, the final Tevatron W asymmetries, ATLAS 2011 inclusive jets, new W,Z data from ATLAS, CMS and LHCb, differential top quark pair rapidity distributions, the Z p<sub>T</sub> from ATLAS and CMS, .....
- All theory calculations now based on the public x-space code APFEL
- Pole and running heavy quark mass fits, for a wide range of charm and bottom masses
- Charm PDF treated on equal footing as the light quark flavors
- Extended positivity constraints, more robust estimate of large-x PDF errors
- Improved determination of preprocessing ranges from the effective behaviour of PDFs at small and large-x

$$\alpha_{f_i}(x, Q^2) \equiv \frac{\partial \ln[x f_i(x, Q^2)]}{\partial \ln x}, \quad \beta_{f_i}(x, Q^2) \equiv \frac{\partial \ln[x f_i(x, Q^2)]}{\partial \ln(1-x)},$$

see also [arXiv:1604.00024](#) and

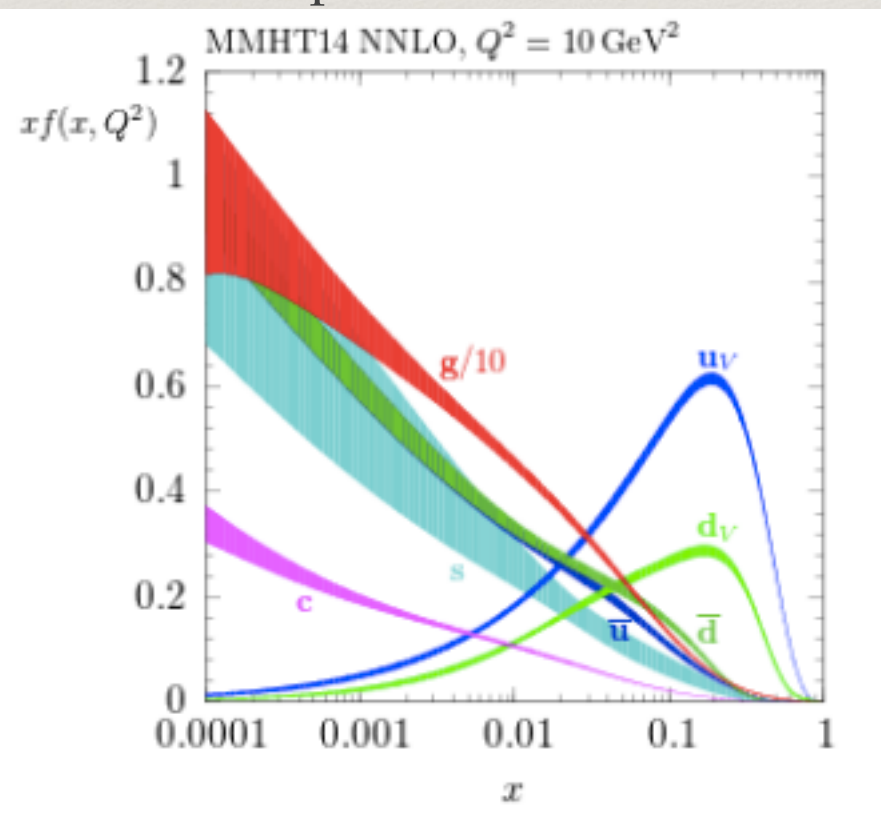
## New datasets in NNPDF3.1

Measurement	Data taking	Motivation
LHCb W,Z rapidity dists 7,8 TeV	2011+2012	small-x and large-x quarks
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z p <sub>T</sub> 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z p <sub>T</sub> , y 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 8 TeV and 2.76 TeV jets	2012	medium and large-x gluon



# MMHT14 (68%CL) 1412.3989

- ❖ MMHT includes LHC data, HERA I data
- ❖ comes with 25 eigenvector pairs:
  - ❖ There are 37 free PDF parameters
    - ❖ with alphas free (found 0.117)
  - ❖ use of Chebyshev polynomial
- ❖ change in the deuteron correction, improvement in the branching ratio  $B_\mu$  which leads to larger uncertainty on strange
- ❖ dynamical tolerance criteria ( average  $\sim 3$ )
- ❖ Theory: based on APPLgrid mostly for LHC
  - ❖ NLO for jets, studies of NNLO impact
  - ❖ use of optimal RT GMVNS scheme

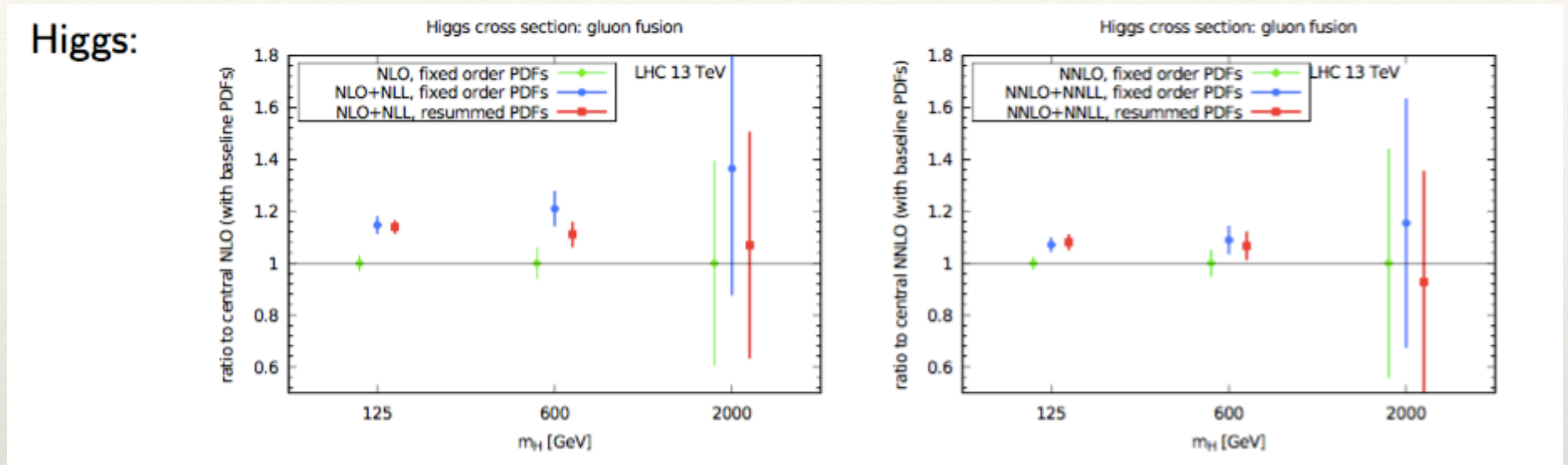


Data set	LO	NLO	NNLO
BCDMS $\mu p F_2$ [125]	162 / 153	176 / 163	173 / 163
BCDMS $\mu d F_2$ [19]	140 / 142	143 / 151	143 / 151
NMC $\mu p F_2$ [20]	141 / 115	132 / 123	123 / 123
NMC $\mu d F_2$ [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 $\mu p F_2$ [22]	59 / 53	60 / 53	65 / 53
E665 $\mu d F_2$ [22]	52 / 53	52 / 53	60 / 53
SLAC $ep F_2$ [23, 24]	21 / 18	31 / 37	31 / 37
SLAC $ed F_2$ [23, 24]	13 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC/HERA $F_L$ [20, 125, 24, 63, 64, 65]	113 / 53	68 / 57	63 / 57
E866/NuSea $pp$ DY [88]	229 / 184	221 / 184	227 / 184
E866/NuSea $pd/pp$ DY [89]	29 / 15	11 / 15	11 / 15
NuTeV $\nu N F_2$ [29]	35 / 49	39 / 53	38 / 53
CHORUS $\nu N F_2$ [30]	25 / 37	26 / 42	28 / 42
NuTeV $\nu N xF_3$ [29]	49 / 42	37 / 42	31 / 42
CHORUS $\nu N xF_3$ [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \rightarrow \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \rightarrow \mu\mu X$ [31]	53 / 40	38 / 40	43 / 40
HERA $e^+p$ NC 820 GeV [61]	125 / 78	93 / 78	89 / 78
HERA $e^+p$ NC 920 GeV [61]	479 / 330	402 / 330	373 / 330
HERA $e^-p$ NC 920 GeV [61]	158 / 145	129 / 145	125 / 145
HERA $e^+p$ CC [61]	41 / 34	34 / 34	32 / 34
HERA $e^-p$ CC [61]	29 / 34	23 / 34	21 / 34
HERA $ep F_2^{\text{charm}}$ [62]	105 / 52	72 / 52	82 / 52
H1 99-00 $e^+p$ incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [119]	125 / 110	116 / 110	119 / 110
CDF II $p\bar{p}$ incl. jets [118]	78 / 76	63 / 76	59 / 76
CDF II $W$ asym. [66]	55 / 13	32 / 13	30 / 13
DØ II $W \rightarrow \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \rightarrow \nu \mu$ asym. [68]	16 / 10	19 / 10	21 / 10
DØ II $Z$ rap. [90]	34 / 28	16 / 28	16 / 28
CDF II $Z$ rap. [70]	95 / 28	36 / 28	40 / 28
ATLAS $W^+, W^-, Z$ [10]	94/30	38/30	39/30
CMS $W$ asymm $p_T > 35$ GeV [9]	10/11	7/11	9/11
CMS asymm $p_T > 25$ GeV, 30 GeV [77]	7/24	8/24	10/24
LHCb $Z \rightarrow e^+e^-$ [79]	76/9	13/9	20/9
LHCb $W$ asymm $p_T > 20$ GeV [78]	27/10	12/10	16/10
CMS $Z \rightarrow e^+e^-$ [84]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [83]	42/13	21/13	17/13
CMS double diff. Drell-Yan [86]	—	372/132	149/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [91]–[97]	53/13	7/13	8/13
ATLAS jets (2.76 TeV+7 TeV) [108, 107]	162/116	106/116	—
CMS jets (7 TeV) [106]	150/133	138/133	—
All data sets	3706 / 2763	3267 / 2996	2717 / 2663



# PDFs with resummed calculations

- ❖ Impact of the resummed PDFs vs fixed order PDFs:



- ❖ Tools for fitting development:
  - ❖ HELL: High-Energy Large Logarithms interfaced to APFEL
    - ❖ based on the ABF approach for resummation
    - ❖ which delivers resummed splitting functions and coefficient functions
    - ❖ Therefore could be used for fitting using resummed evolution together with the resummed coefficient functions