XLVI International Symposium on Multiparticle Dynamics (ISMD2016)

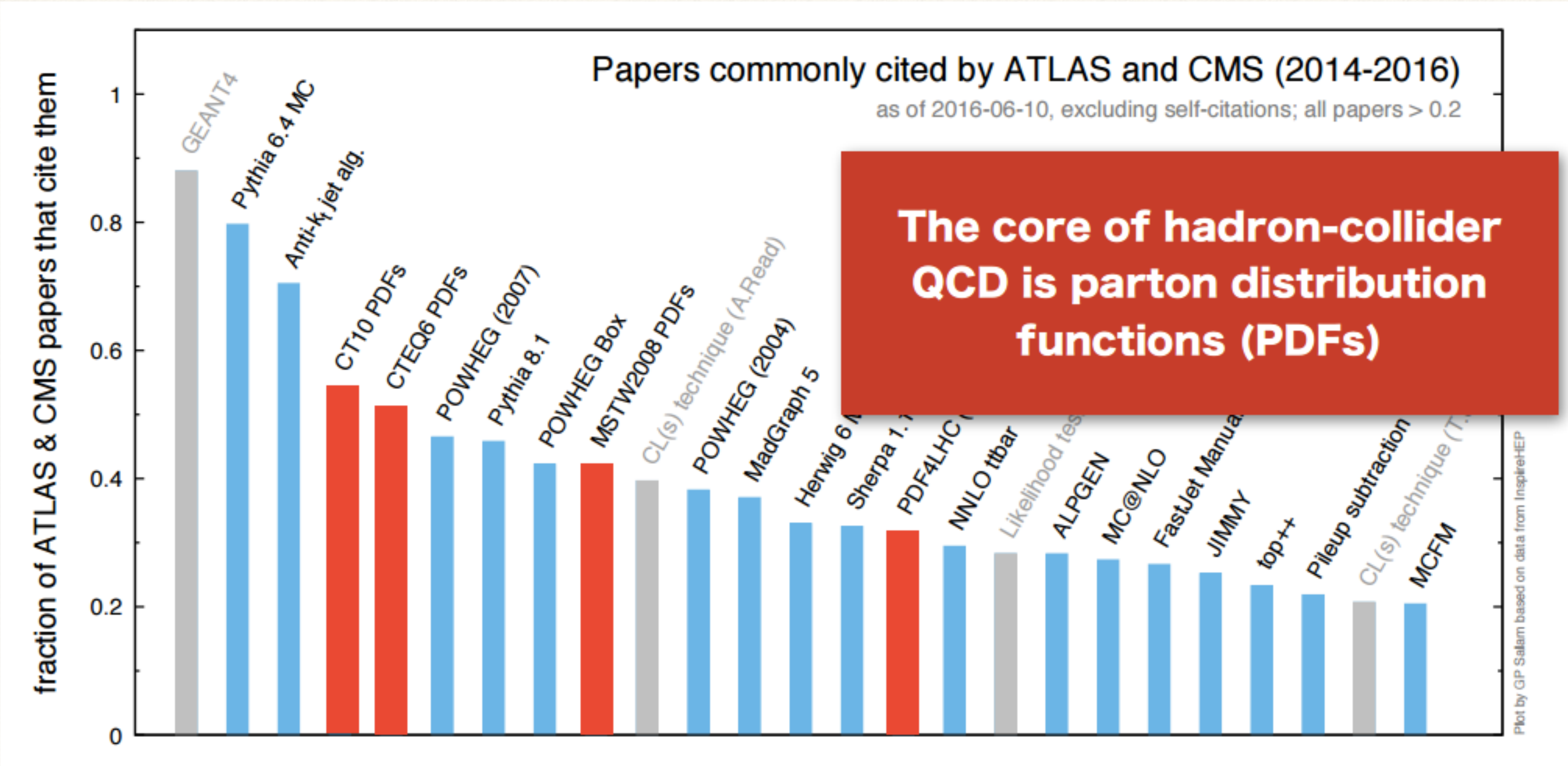
Jeju Island, South Korea

Parton Distribution Functions and the role of forward region data

Voica Radescu
University of Oxford

Most frequent citations @ LHC

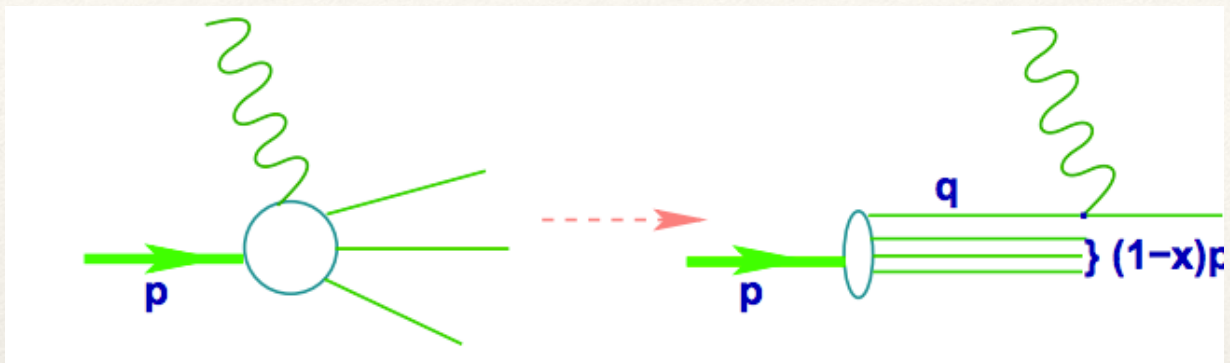
- Gavin Salam looked at what experiments at the LHC cite the most:

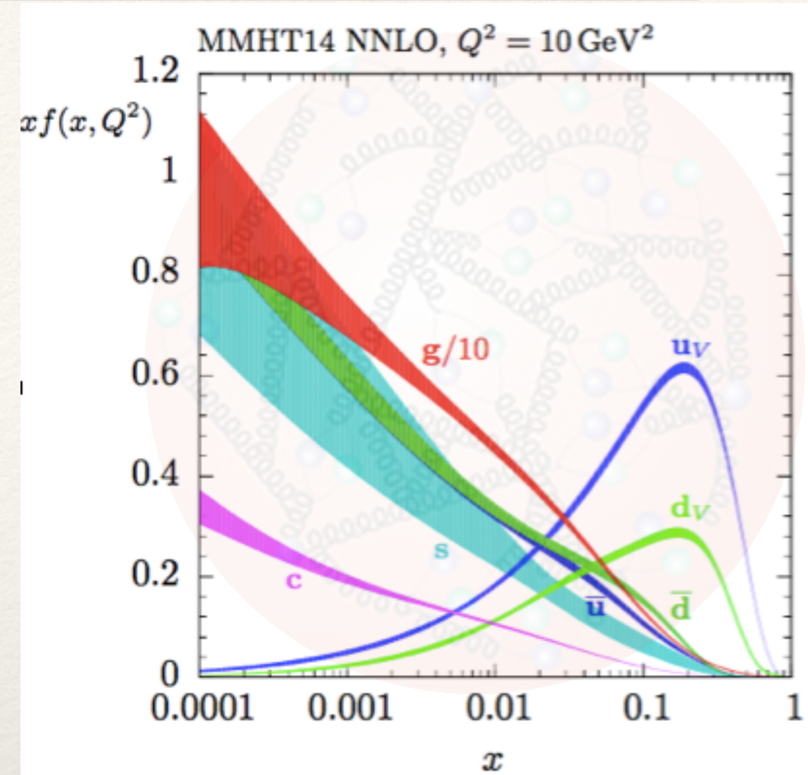


G. Salam, Crete-ICNFP 2016

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)



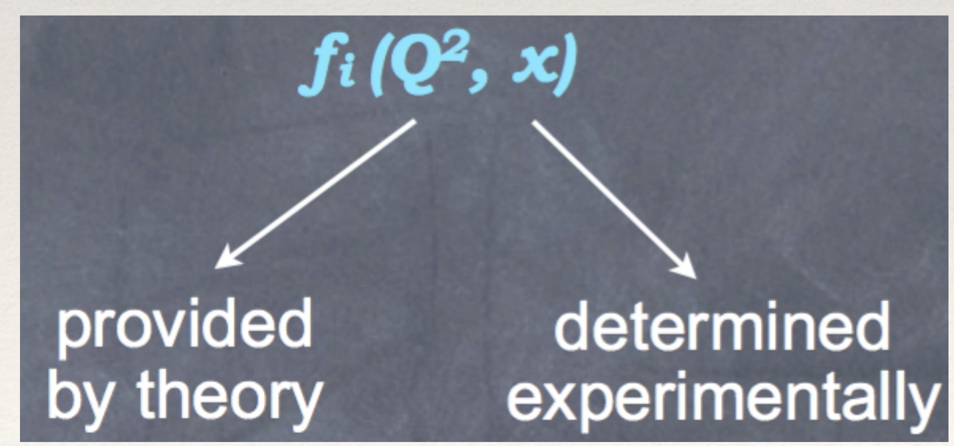


- Once QCD corrections included, PDFs become scheme dependent
  - Shape and normalisation of PDFs are very different for each flavour, reflecting the different underlying dynamics that determines them.

- PDFs cannot be calculated in perturbative QCD, however their evolution with the scale is predicted by pQCD [DGLAP equations]

calculable in pQCD

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



Voica Radescu | Oxford University

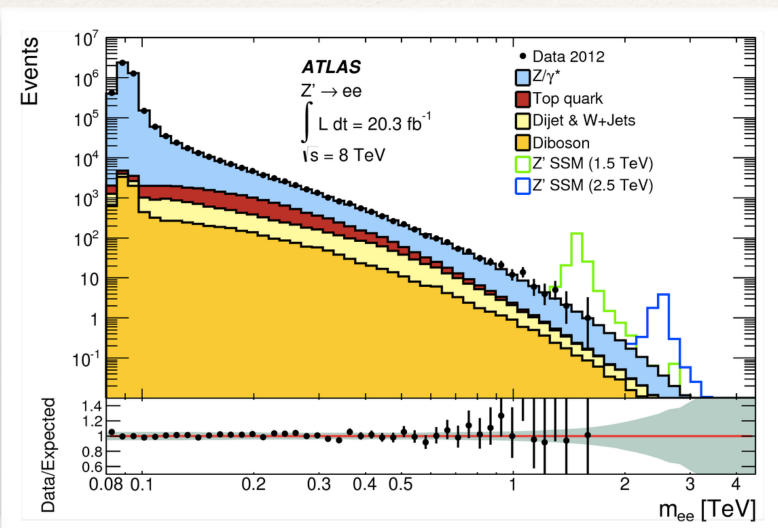
Search for new Physics

direct searches for new physics

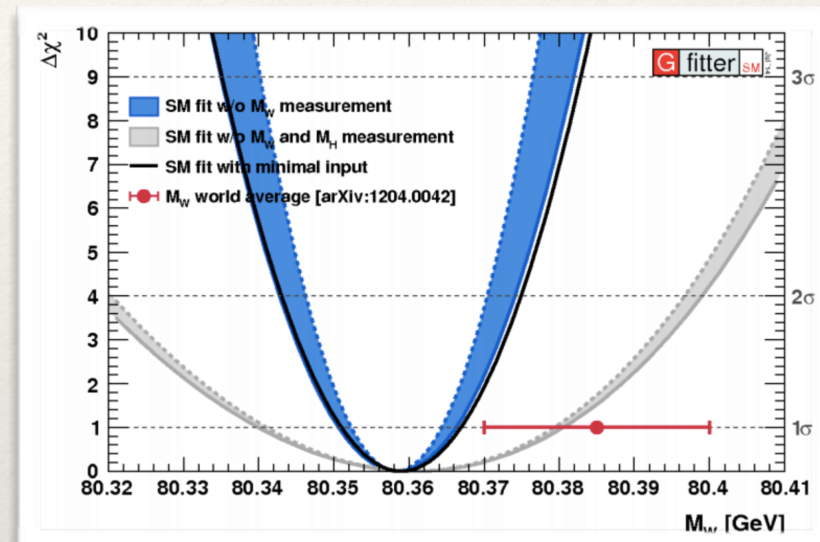
indirect searches via consistency test of SM

control of QCD background and SM parameters

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



[arXiv:1410.6810v2]



Gfitter

$$\underbrace{\sigma(x,Q^2)}_{hadronic\ x-sec.} = \sum_{a,b}\int_0^1 dx_1 dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs} \times \underbrace{\hat{\sigma}(x_1,x_2,Q^2)}_{partonic\ x-sec}$$

↓ taken from data

↓ calculable

Improvement of PDFs precision demands high precision theory & experimental measurement:

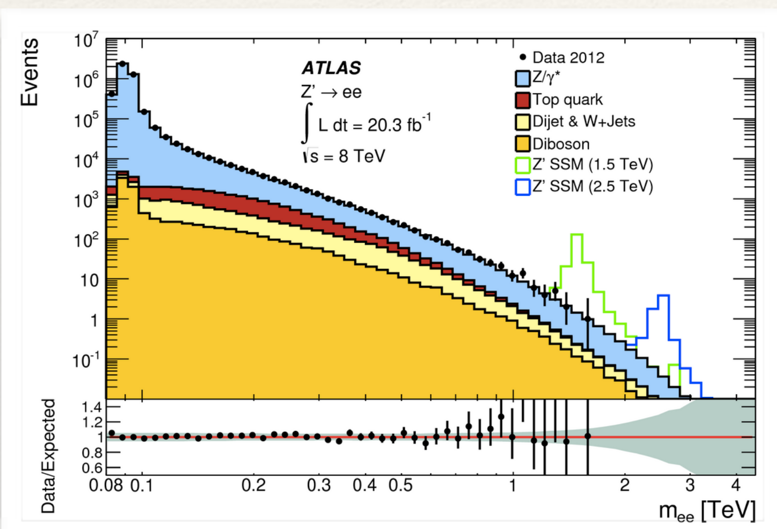
Search for new Physics

direct searches for new physics

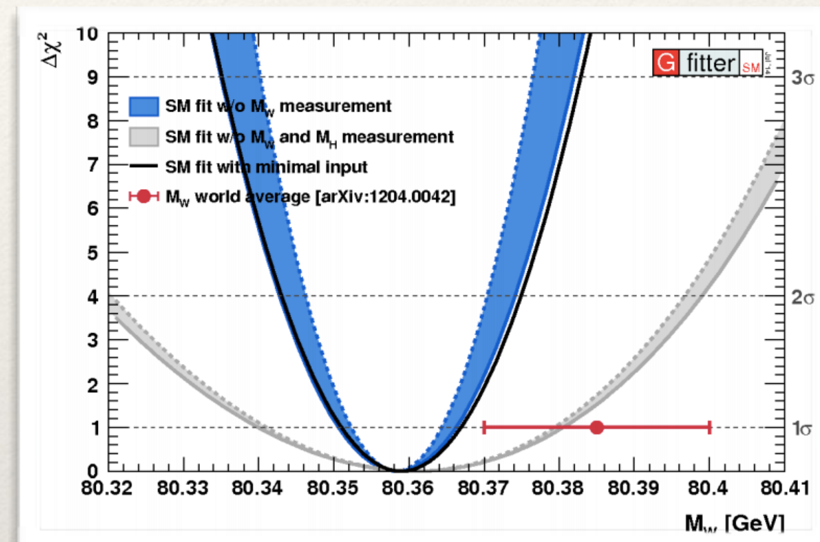
indirect searches via consistency test of SM

control of QCD background and SM parameters

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



[arXiv:1410.6810v2]



Gfitter

$$\underbrace{\sigma(x,Q^2)}_{hadronic\ x-sec.} = \sum_{a,b} \int_0^1 dx_1 dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs} \times \underbrace{\hat{\sigma}(x_1,x_2,Q^2)}_{partonic\ x-sec}$$

PDFs ↓ taken from data

partonic x−sec ↓ calculable

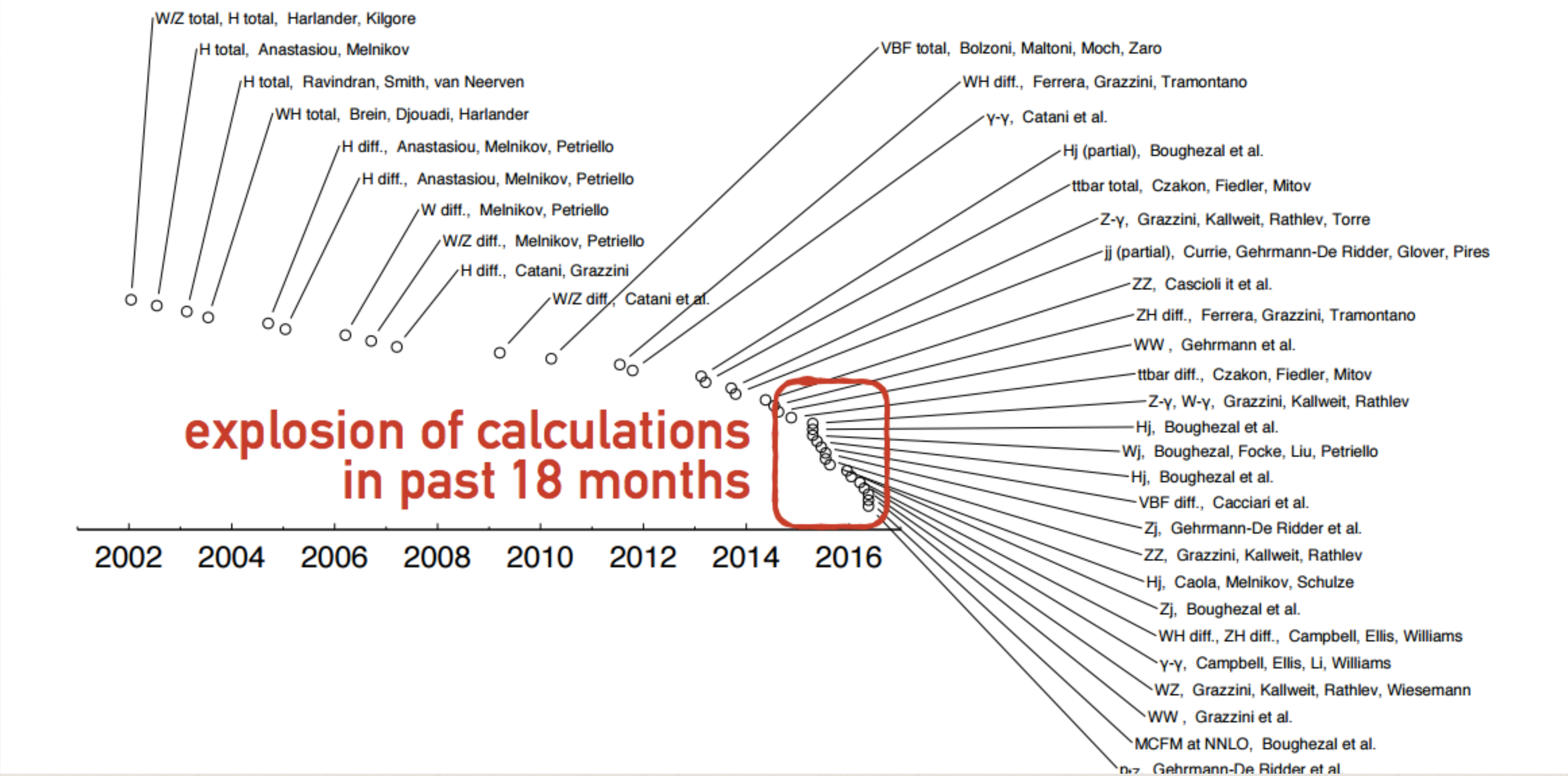
Last decade have seen a lot of developments:

- **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..**

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 …

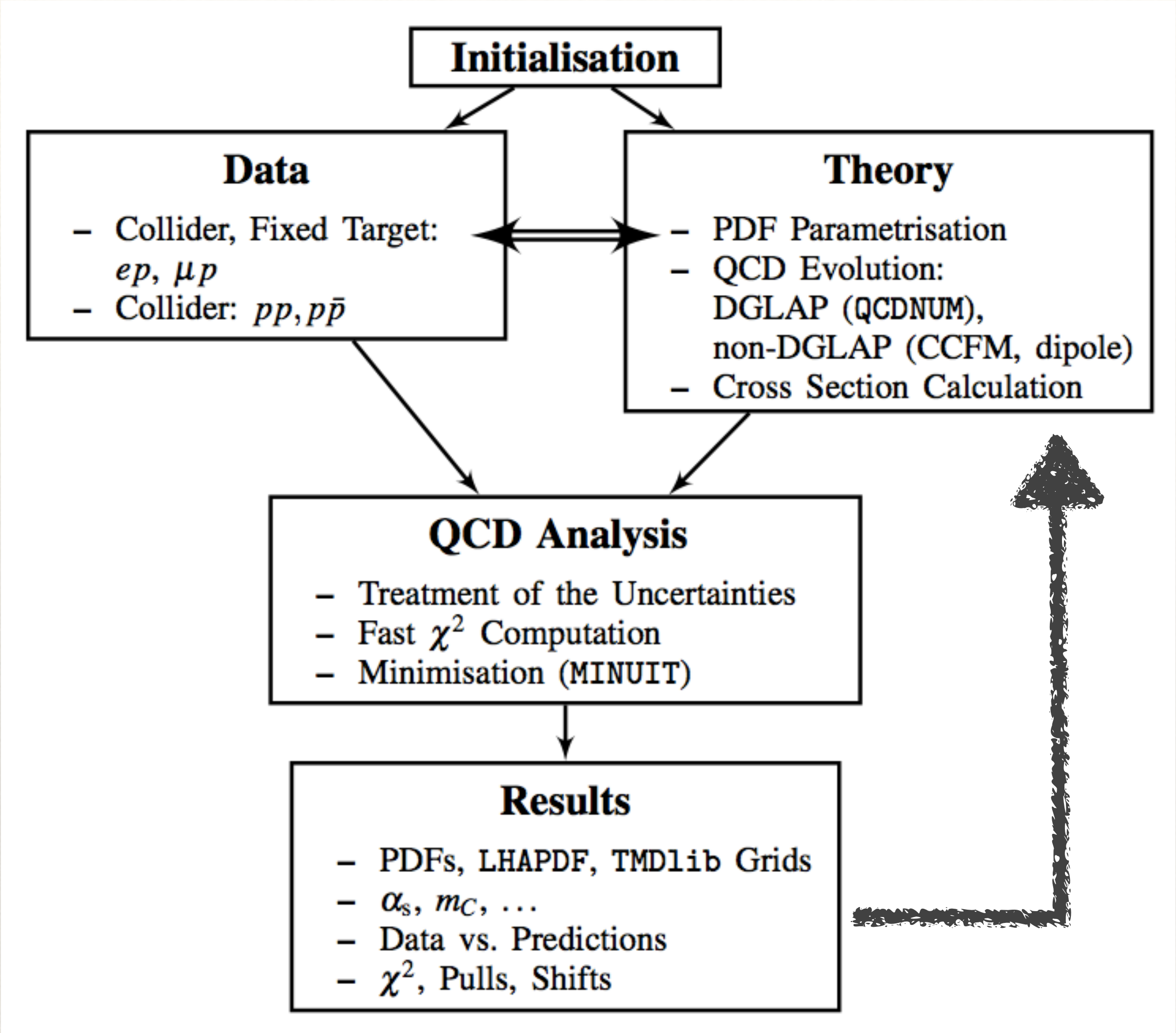
—> enormous boost of precision to analyse data at % level

Mechanism of extracting PDFs:

- Extraction of PDFs relies on precision measurements to challenge theory

interplay between data and theory

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



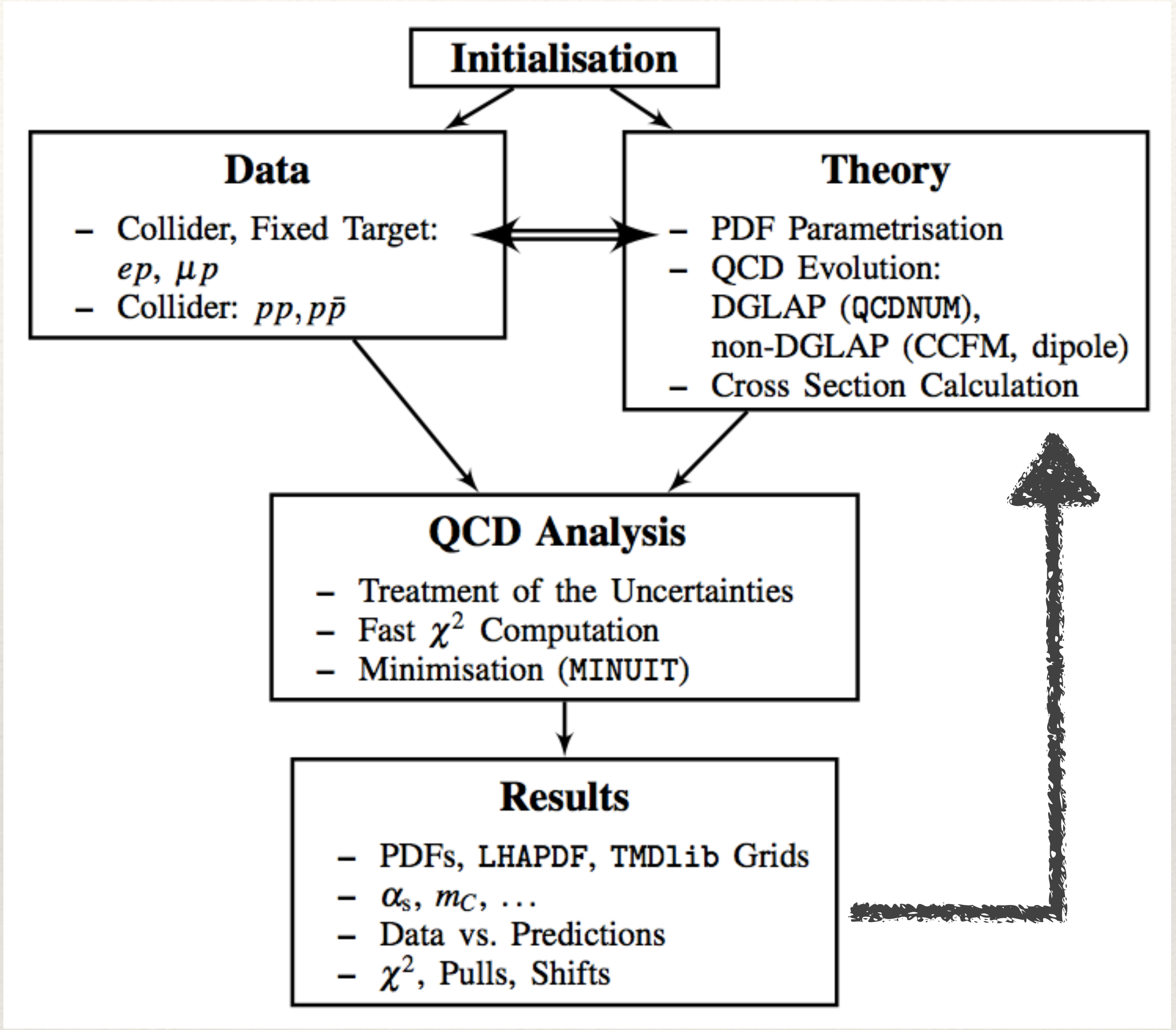
xFitter EPJC (2015), 75:304

~2000 iterations

Mechanism of extracting PDFs:

- Extraction of PDFs relies on precision measurements to challenge theory

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

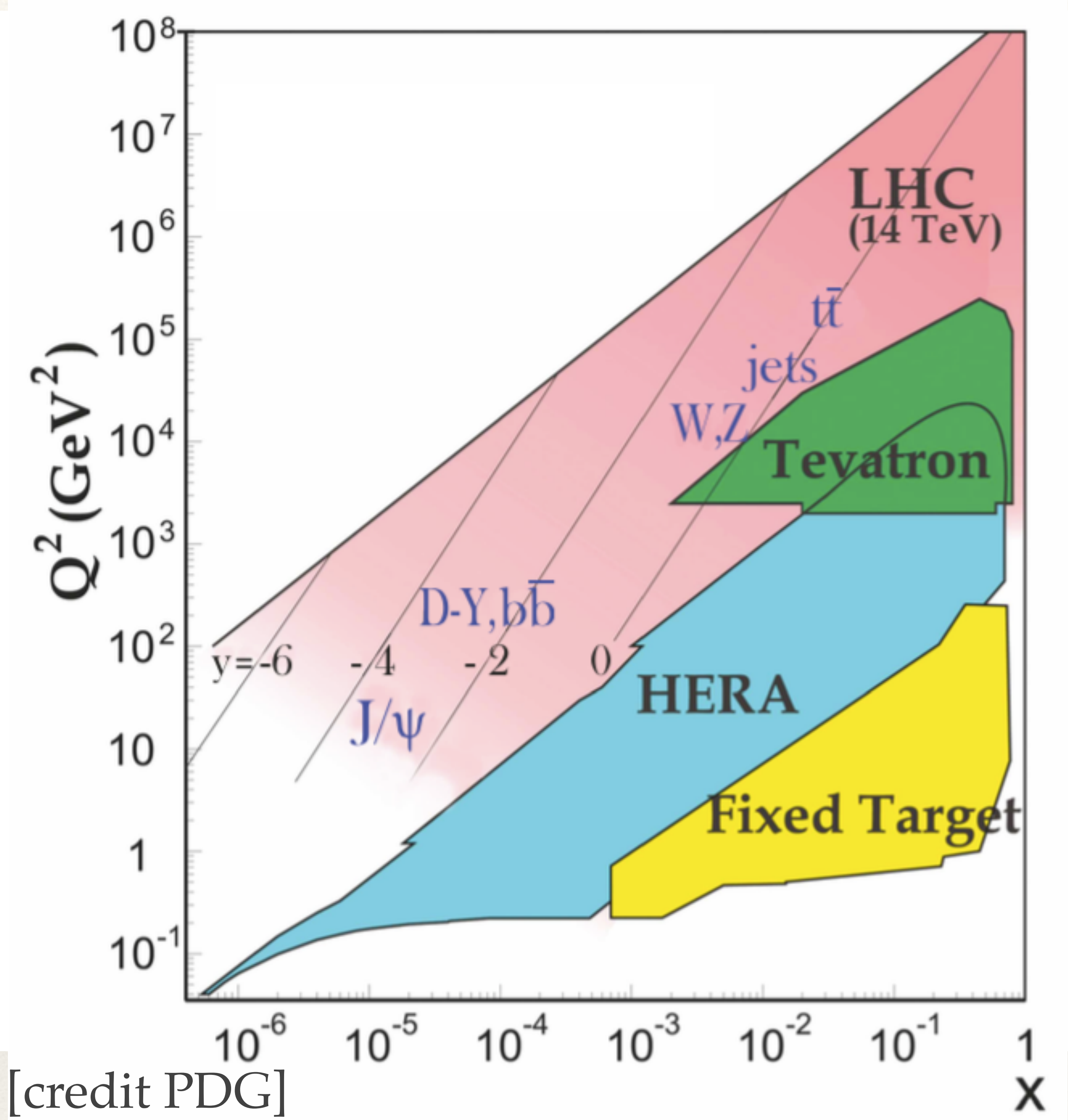


xFitter EPJC (2015), 75:304

~2000 iterations

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

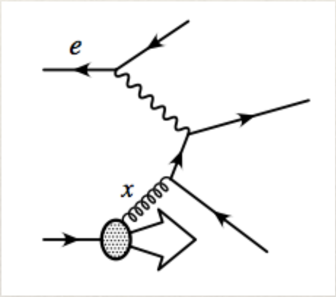
Data for studying Proton Structure



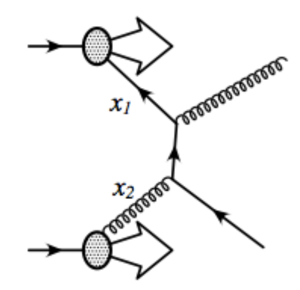
[credit PDG]

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



Q2: resolving power of experiment
x: fraction of proton's momentum

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, HKN, EPS, DSSZ	**arXiv:1509.00792, 0709.3038, 0902.4154, 1112.6324**
Dedicated PDF	studies by LHC experiments, xFitter, Prosa

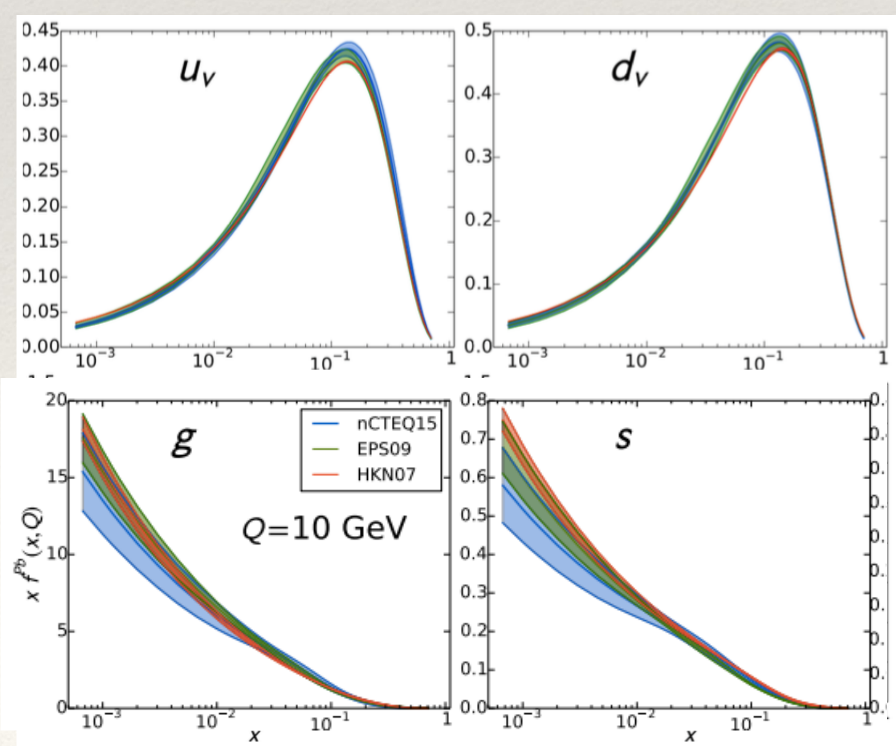
Nuclear PDFs

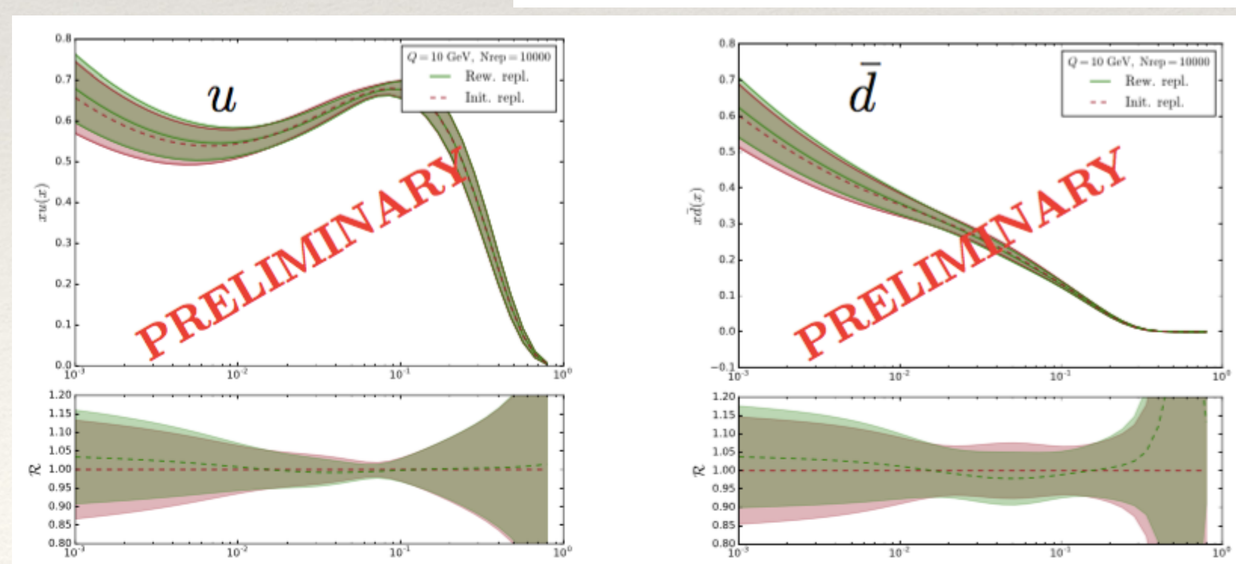
- Analysis of nuclear data to extract nuclear PDFs relies on:
  - Isospin symmetry $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$
  - Assumption that bound proton PDFs obey the same evolution equations and sum rules as the free proton PDFs

- nCTEQ framework: [arXiv:1509.00792]
  - use the framework of the free proton PDFs, where the observable is calculated using A, Z
  - data sets on different targets: NC DIS+DY, single pion production

W/Z Data from LHC on pPb can provide extra constraint on u,d quarks

- ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
- CMS [arXiv:1512.06461, arXiv:1503.05825]
- LHCb [arXiv:1406.2885]
- ALICE [arXiv:1511.06398]





At the moment, LHC data uncertainty too large

[credit: O. Kusina, DIS2016]

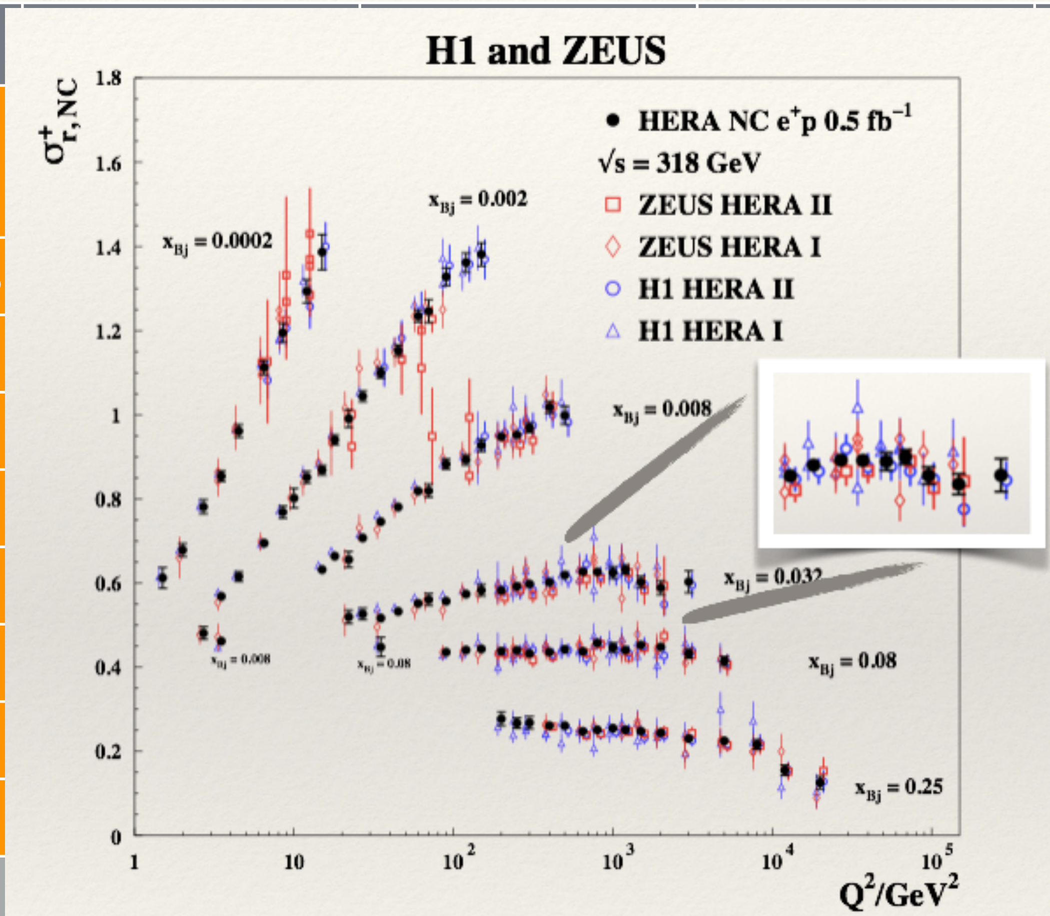
Data sets for proton PDF sets:

	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

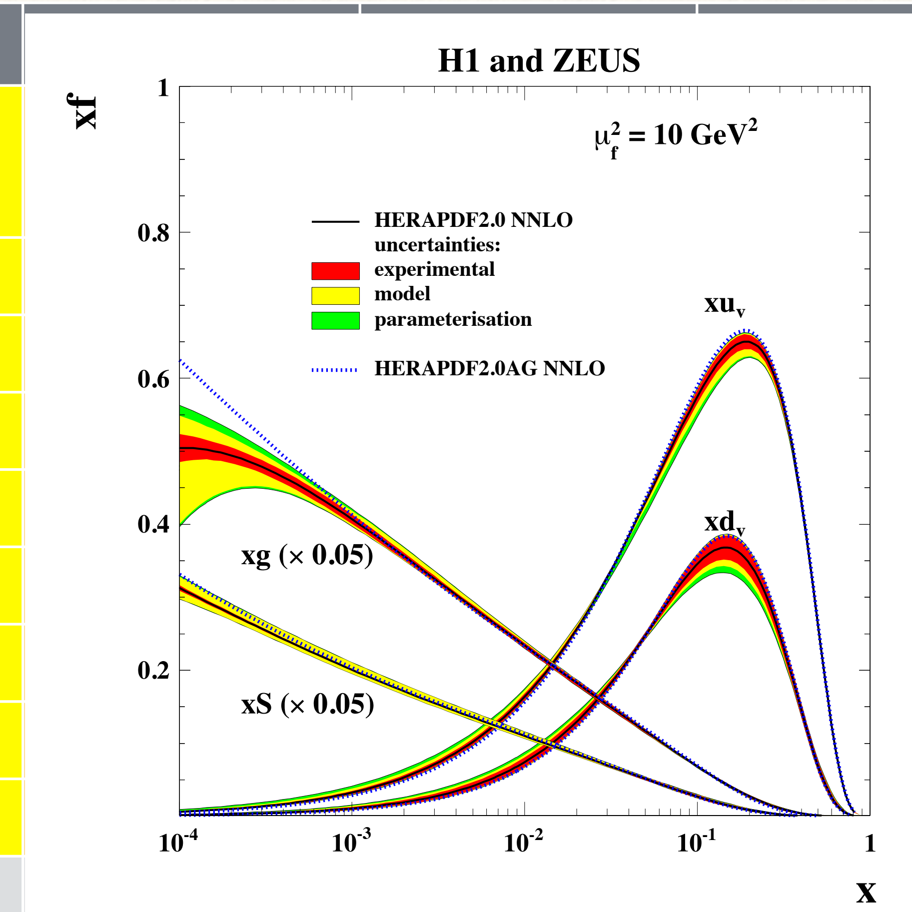
Type of processes:

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

Data sets for PDF sets: HERA



	HERAPDF2.0	
HERA data	HERA I+II	
Fix. Target DIS	✗	✓
Tevatron W,Z	✗	
Tevatron Jets	✗	
Fix. Target DY	✗	
LHC WZ	✗	
LHC jets	✗	
LHC top	✗	
LHC charm	✗	
References	arXiv:1506.06042	352



[see talk by K. Tokushuku]

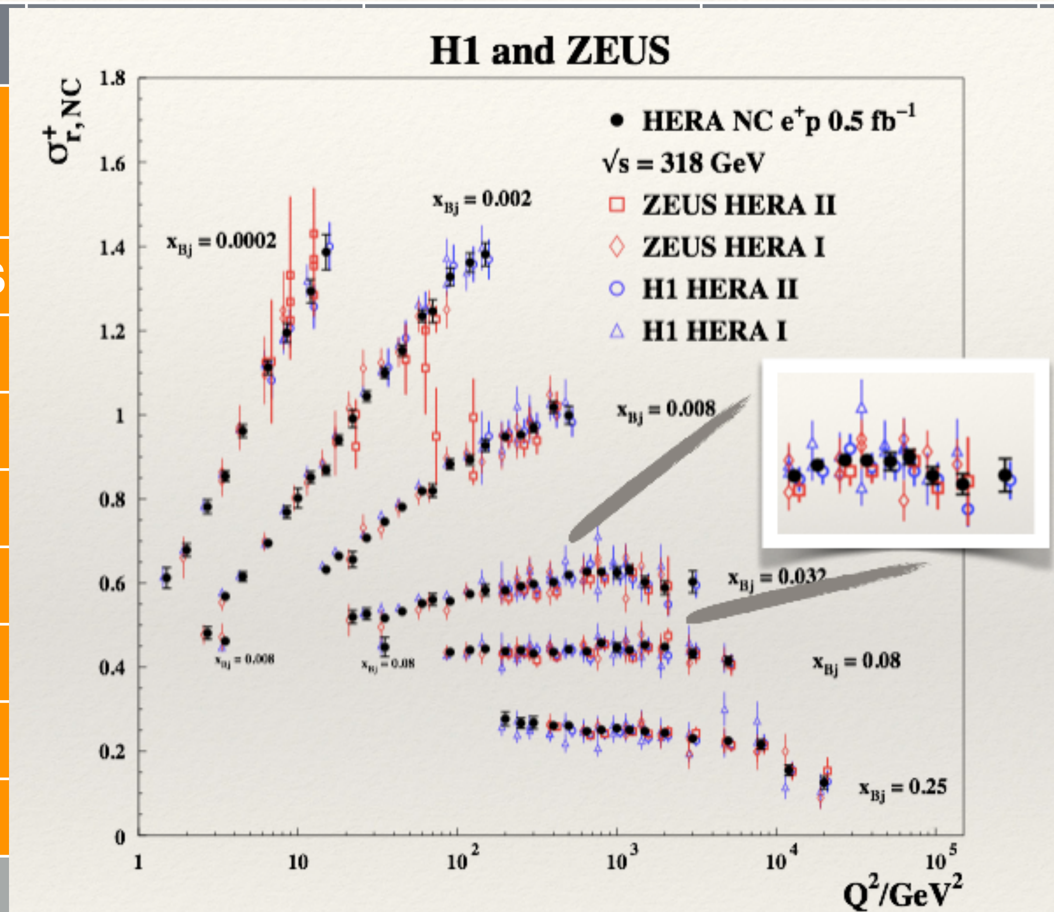
HERA data is the basis of any PDF extraction

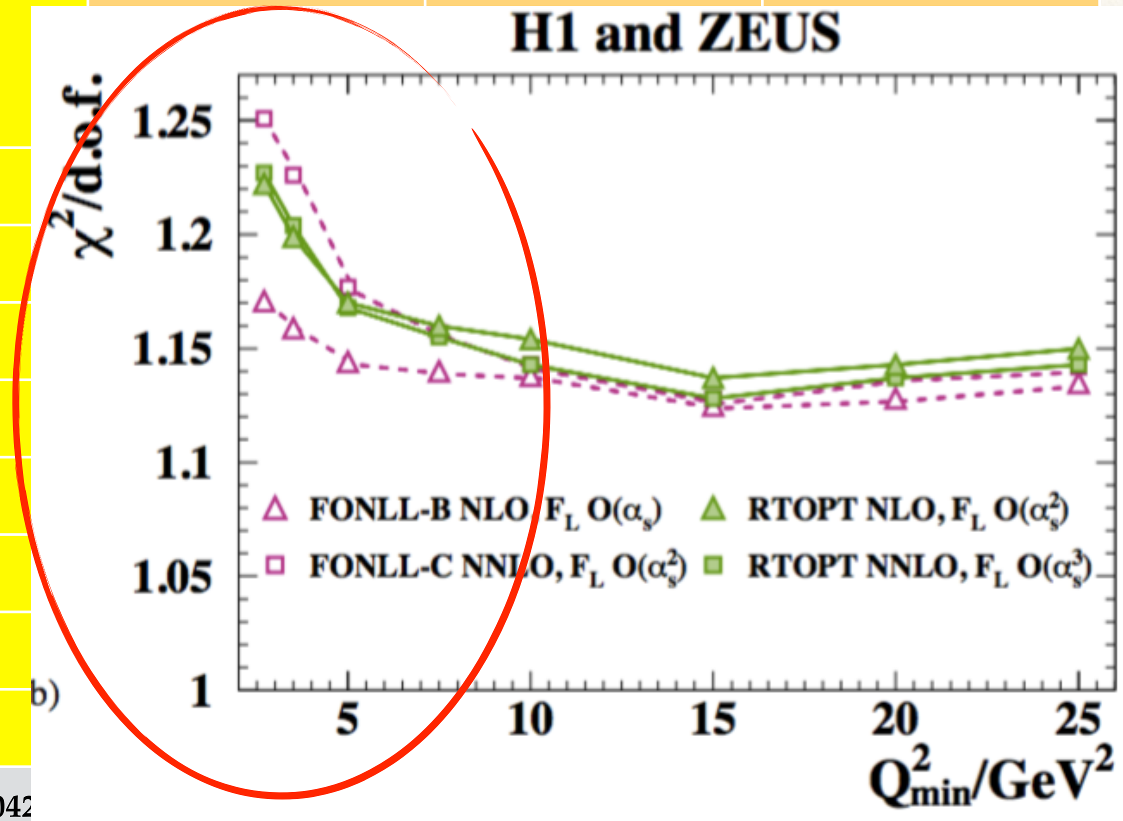
However, PDFs extracted from HERA do not provide sea decomposition and there is no data for $x<10^{-4}$ lack precision at high x

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

Data sets for PDF sets: HERA

	HERAPDF2.0	ABM12(ABMP)	CJ12(15)	JR14
HERA data	HERA I+II			
Fix. Target DIS	✕			
Tevatron W,Z	✕			
Tevatron Jets	✕			
Fix. Target DY	✕			
LHC WZ	✕			
LHC jets	✕			
LHC top	✕			
LHC charm	✕			
References	arXiv:1506.0604[illegible]			





HERA data is the basis of any PDF extraction

Low x, Q2 region remains an interesting exploration area!

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

PDF differences:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT-χ)	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
α(Mz)	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) 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: $\Delta\chi2$=100 90% CL region	Hessian $\Delta\chi2$ Dynamical (68% CL)	Monte Carlo (68% CL)	Hessian $\Delta\chi2$=1 (68% CL)	Hessian $\Delta\chi2$=1 (68% CL)	Hessian $\Delta\chi2$=1 (68% CL)	Hessian $\Delta\chi2$=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)

PDF differences:

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT-χ)	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
α(Mz)	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) 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:

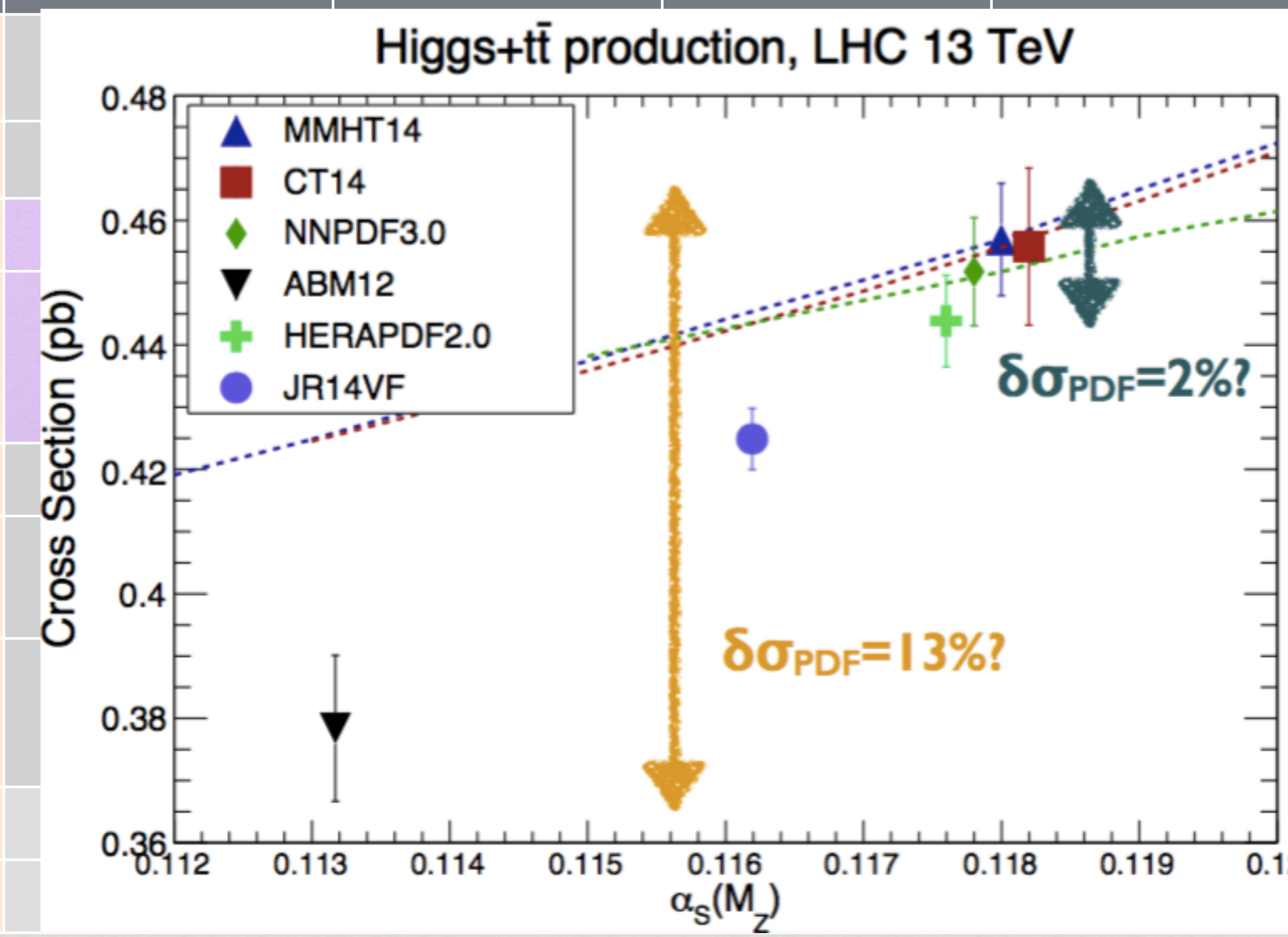
- different treatment of quarks with masses
- inclusion of various data sets and account for possible tensions
- different assumption on values of strong couplings
- different assumptions in procedure (parametrisation, corrections)

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-χ)	VFNS (TR opt)	VFNS (FONLL)				
order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO				
α(Mz)	fixed(fitted)	fixed (fitted)	fixed				
α(Mz) LO α(Mz) NLO α(Mz) 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: $\Delta\chi2$=100 (90%CL region)	Hessian $\Delta\chi2$ 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

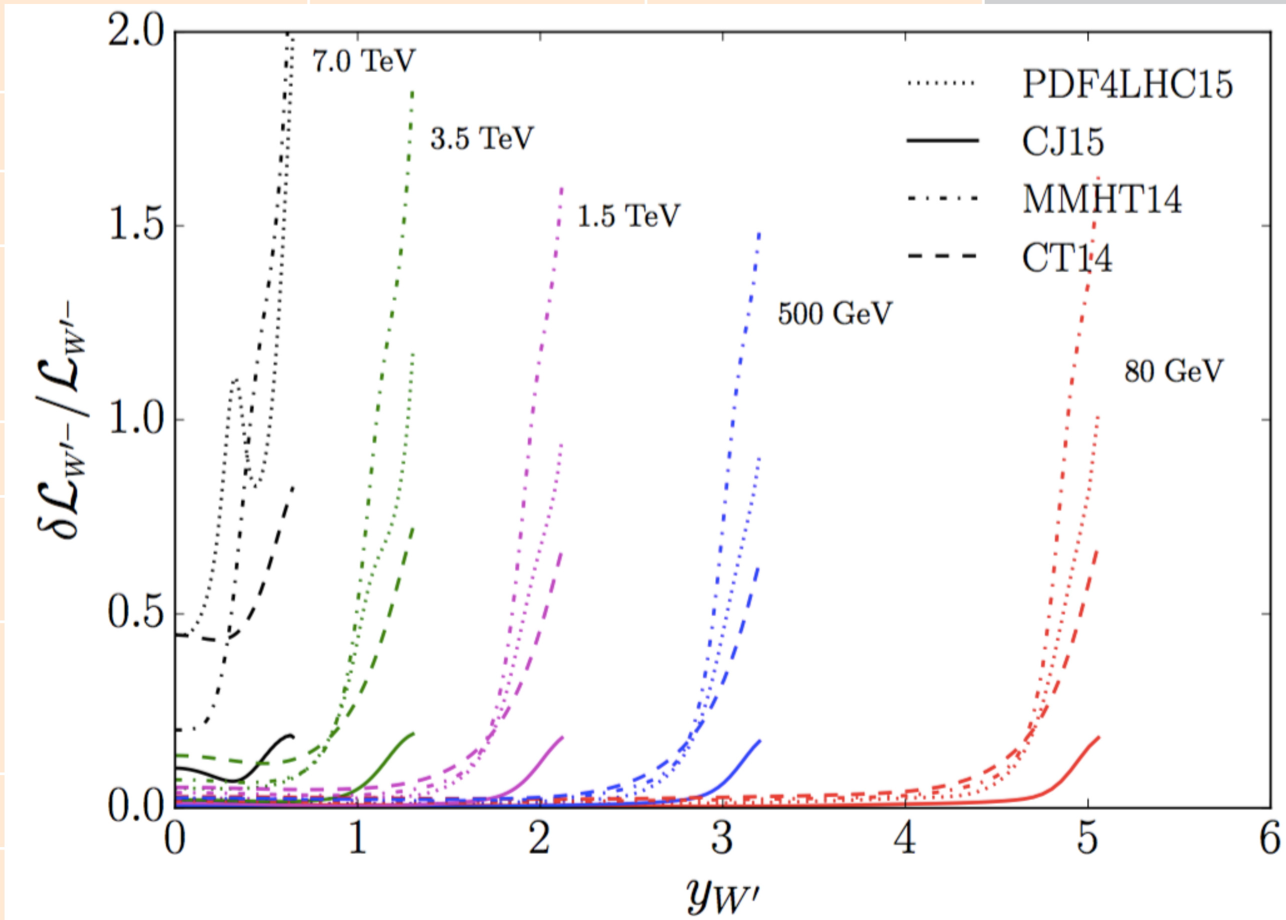
arXiv:1510.03865 : PDF4LHC sets

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
α(Mz)					fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) NNLO					- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.					Pol. 24	Pol. 22	Pol.25
PDF assumptions					s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.					Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)
Q2min					2.5	1.69	2
References					arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852



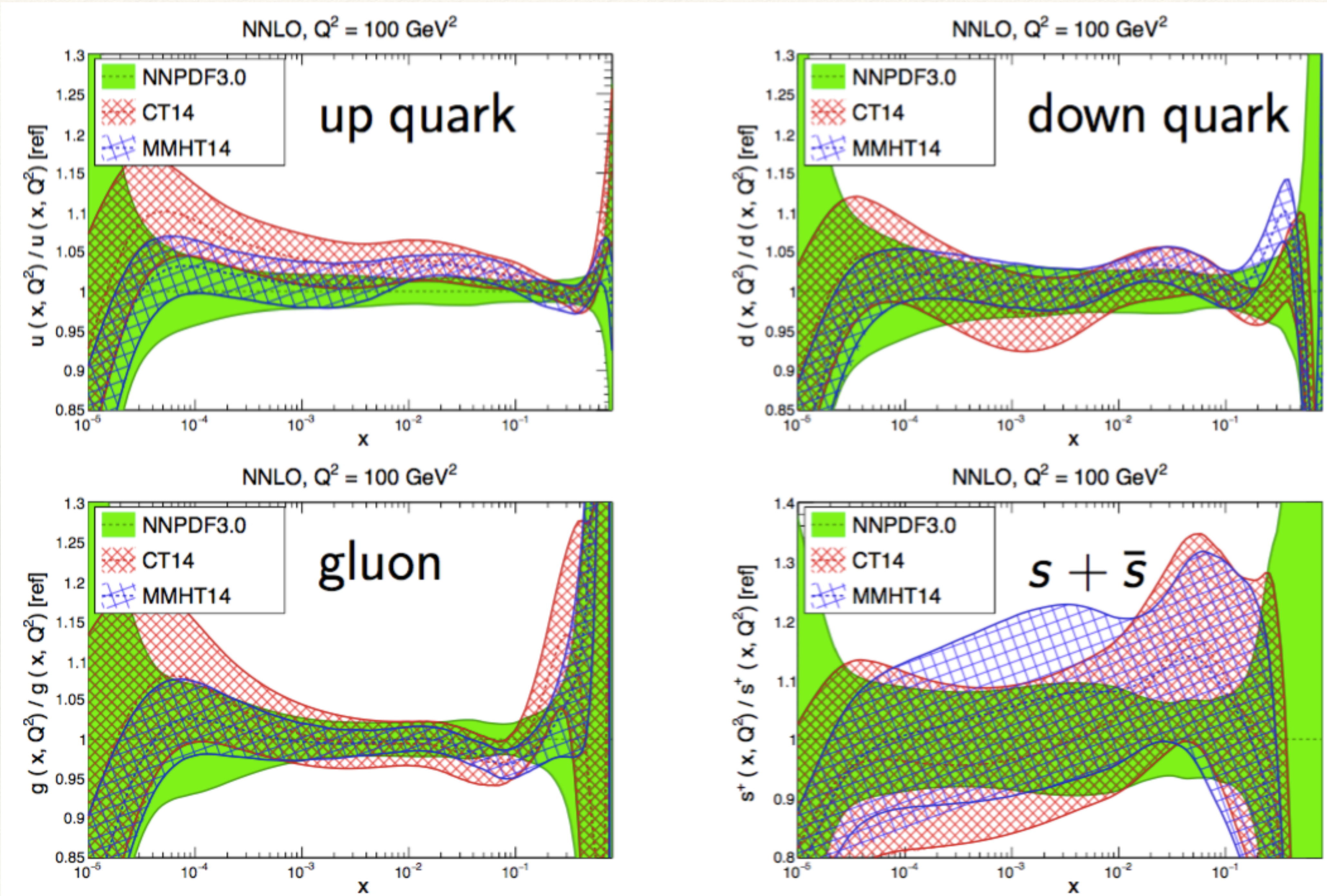
—> advocates the use of all single PDF sets in fear to miss ignal by having over-estimated PDF uncertainties for searches (here W' interms of relative uncertainties for different Mass scenarios)

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

	JLab & BONUS	HER MES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	Large-x treatment: Nucl.	HT TMC	Flex d	low-W DIS
CJ15 *	✓	✓	✓	✓		✗	✓	✓	✓	✓

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]

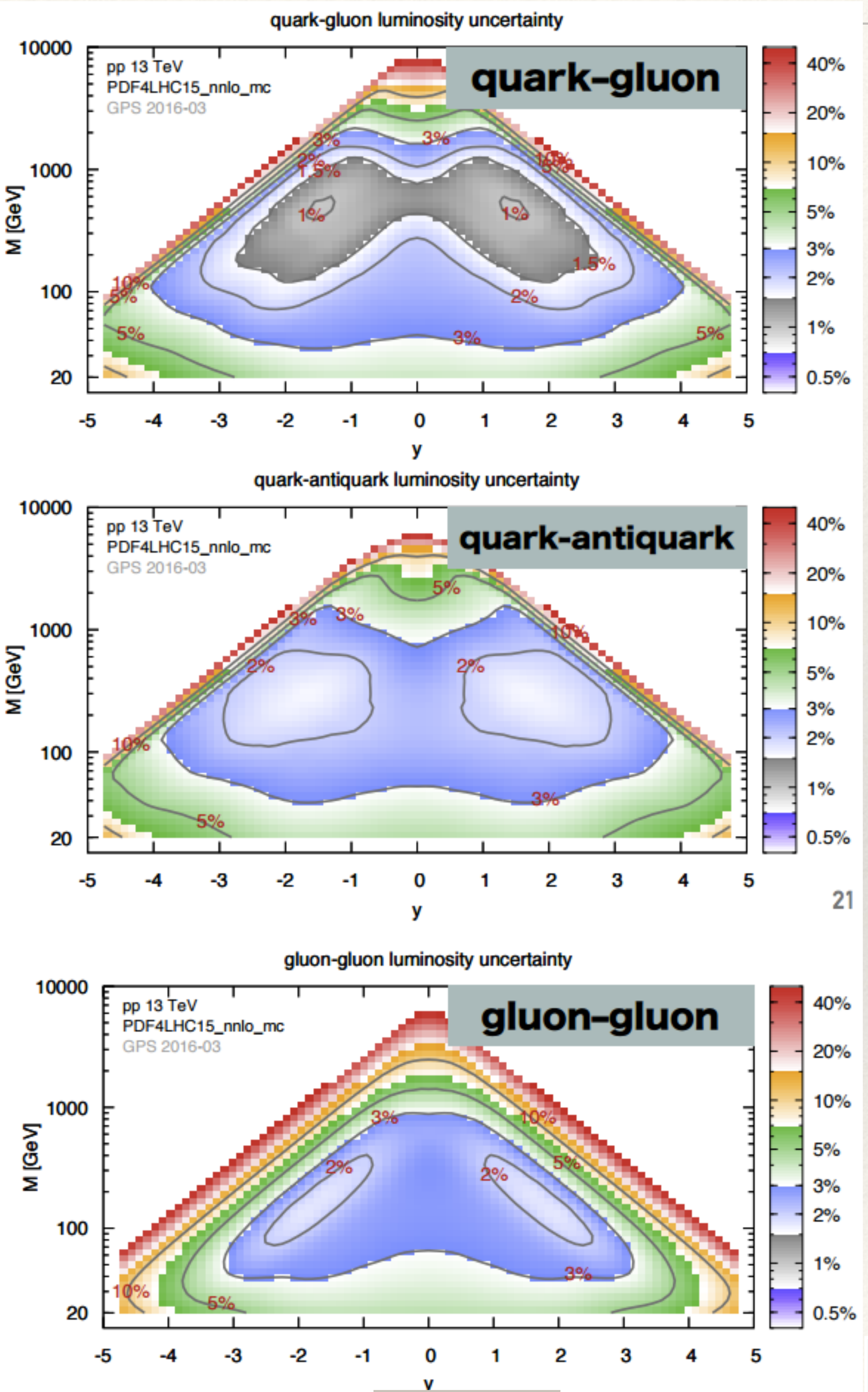
In terms of Uncertainties on Partonic Luminosities

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

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

Mass



rapidity

< 3%

~5%

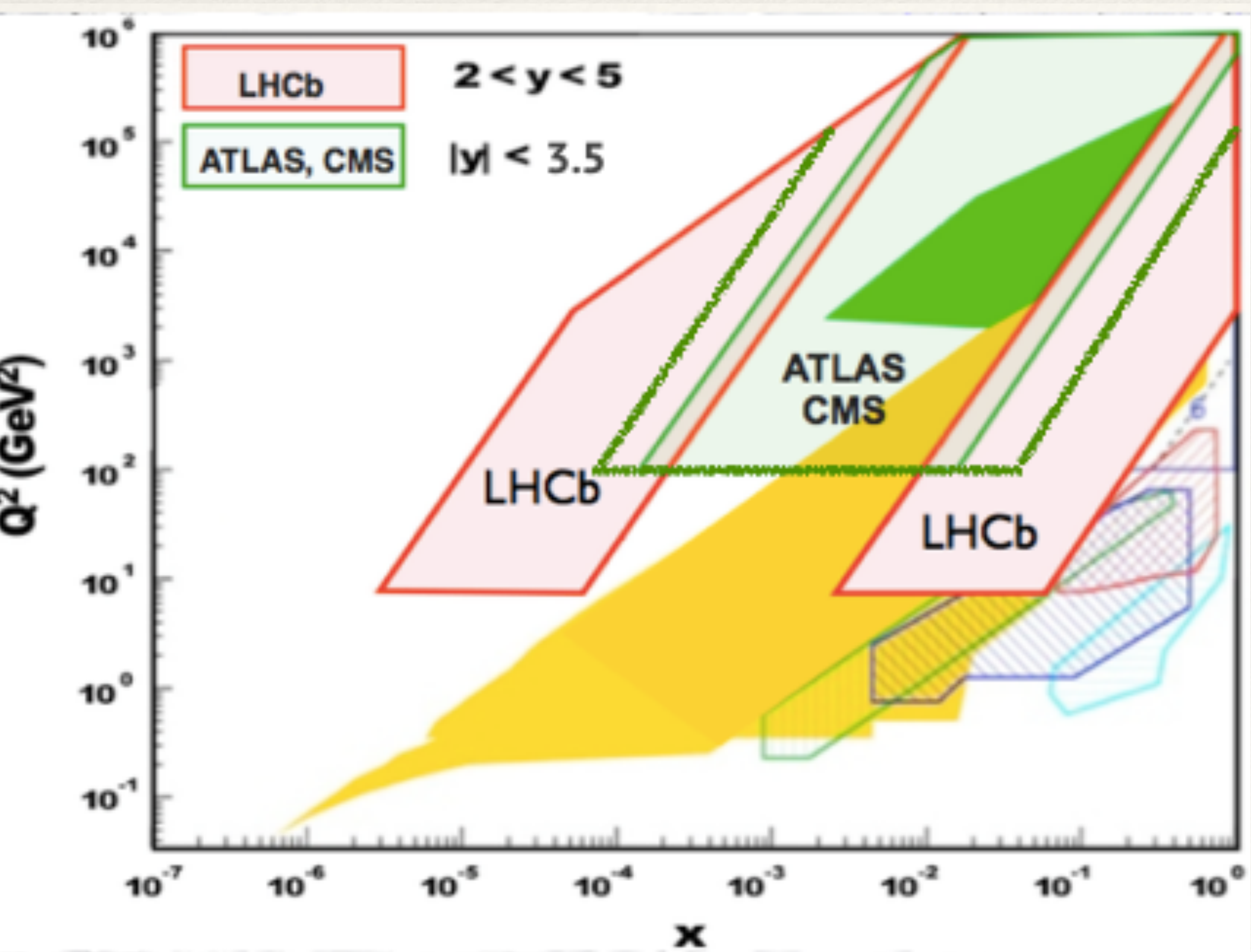
> 25%

Credit: G. Salam

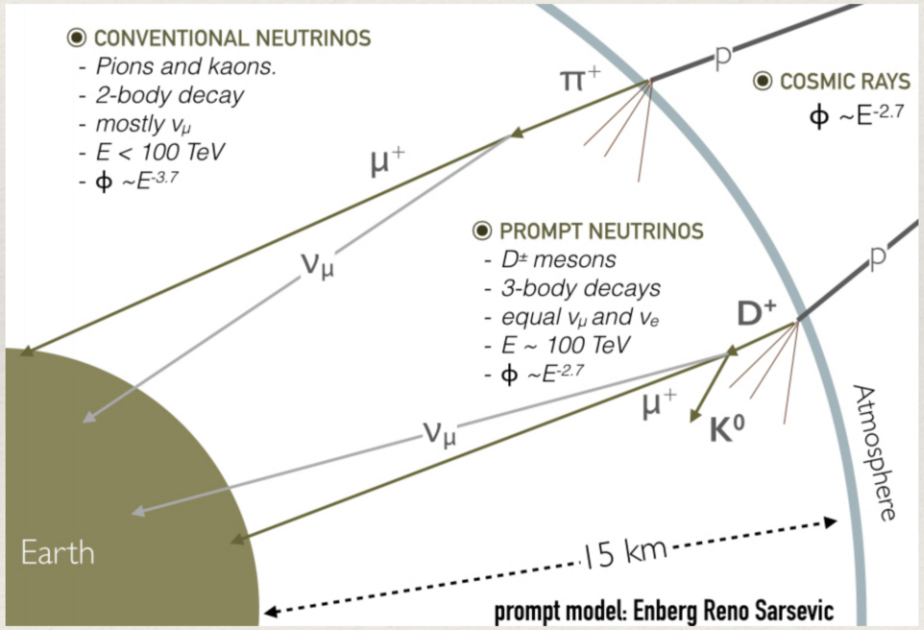
The LHC measurements: ATLAS-CMS vs LHCb

- LHC provides an extended kinematic range in x by its three experiments:
  - ATLAS, CMS and LHCb
  - coverage in x is what's needed, because QCD gives us Q2 dependence

LHCb low x regime can be linked to 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

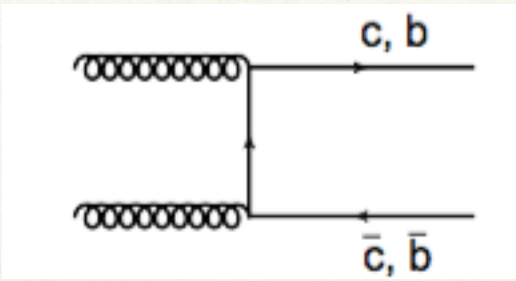


- Heavy quark production data from LHC could validate calculations of the prompt neutrino flux

Voica Radescu | Oxford University

Gluon Sensitivity from heavy quark production at low x

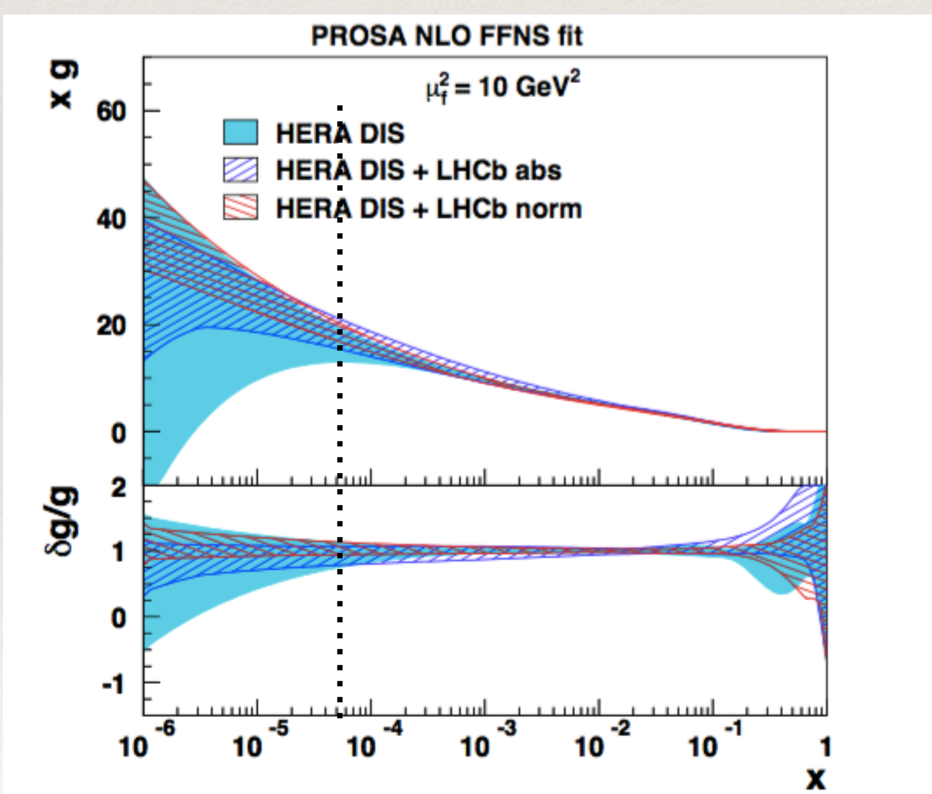
- LHCb brings advantage in covering low x region with its forward detector design

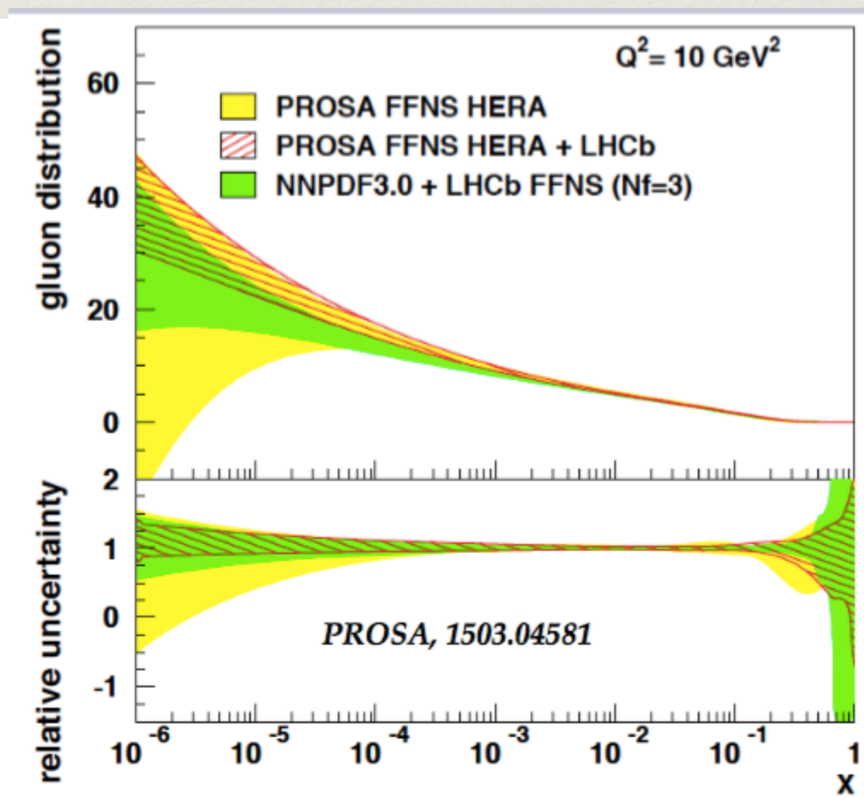


—> Heavy-quarks are produced in pp via gluon fusion

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

confirmed by NNPDF analysis



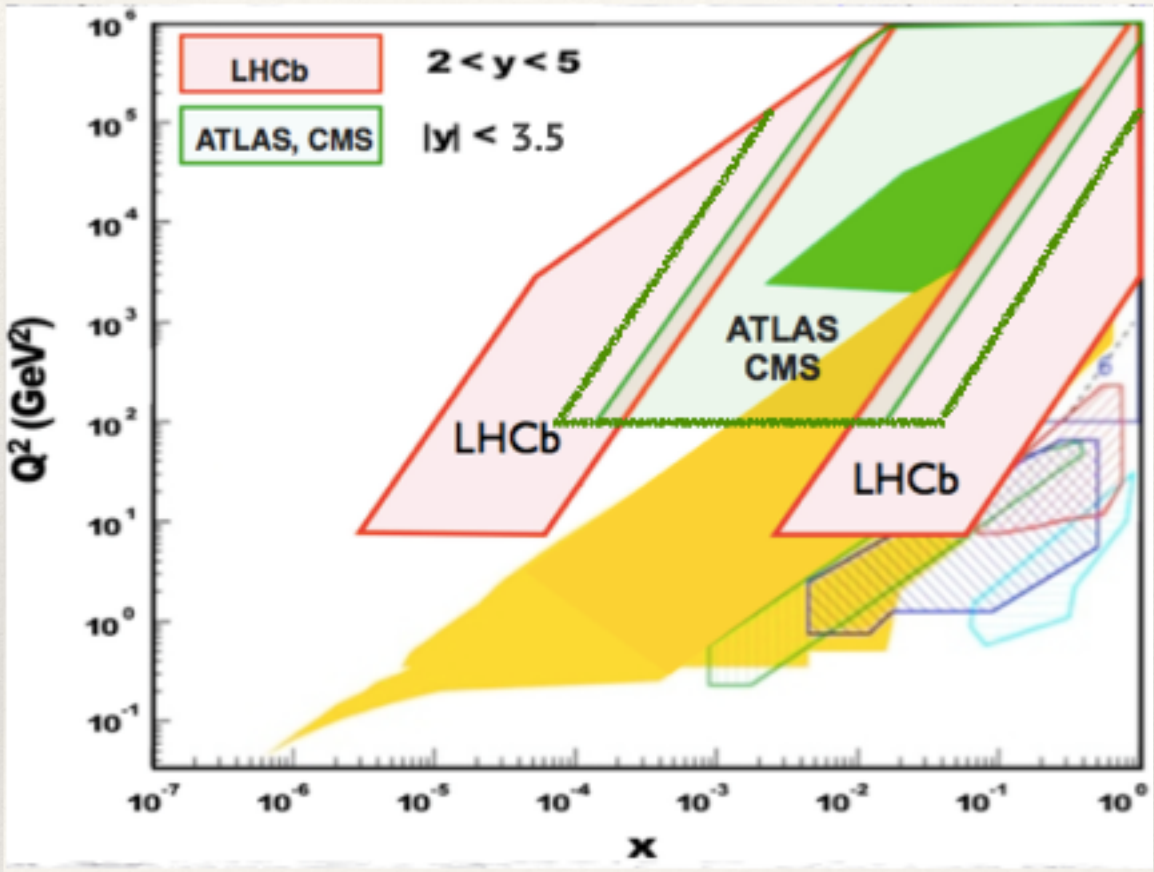


Eur.Phys.J. C75 (2015) 8, 396

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

The LHC measurements: ATLAS-CMS

- LHC provides an extended kinematic range in x by its three experiments:
  - ATLAS, CMS and LHCb
  - coverage in x is what's needed, because QCD gives us Q2 dependence



NNLO calculations —> a boost to re-analyse jets !

- **Gluon:**
  - Inclusive jets, dijets, trijets —> medium/large x
  - Isolated photon and photon+jets —> medium/large x
  - ttbar production —> large x
  - Zpt spectrum —> small/medium x
- **Quarks:**
  - W and Z rapidity spectra —> medium x
  - High pT 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
- **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:

- **PDF discrimination**

by confronting theory with data

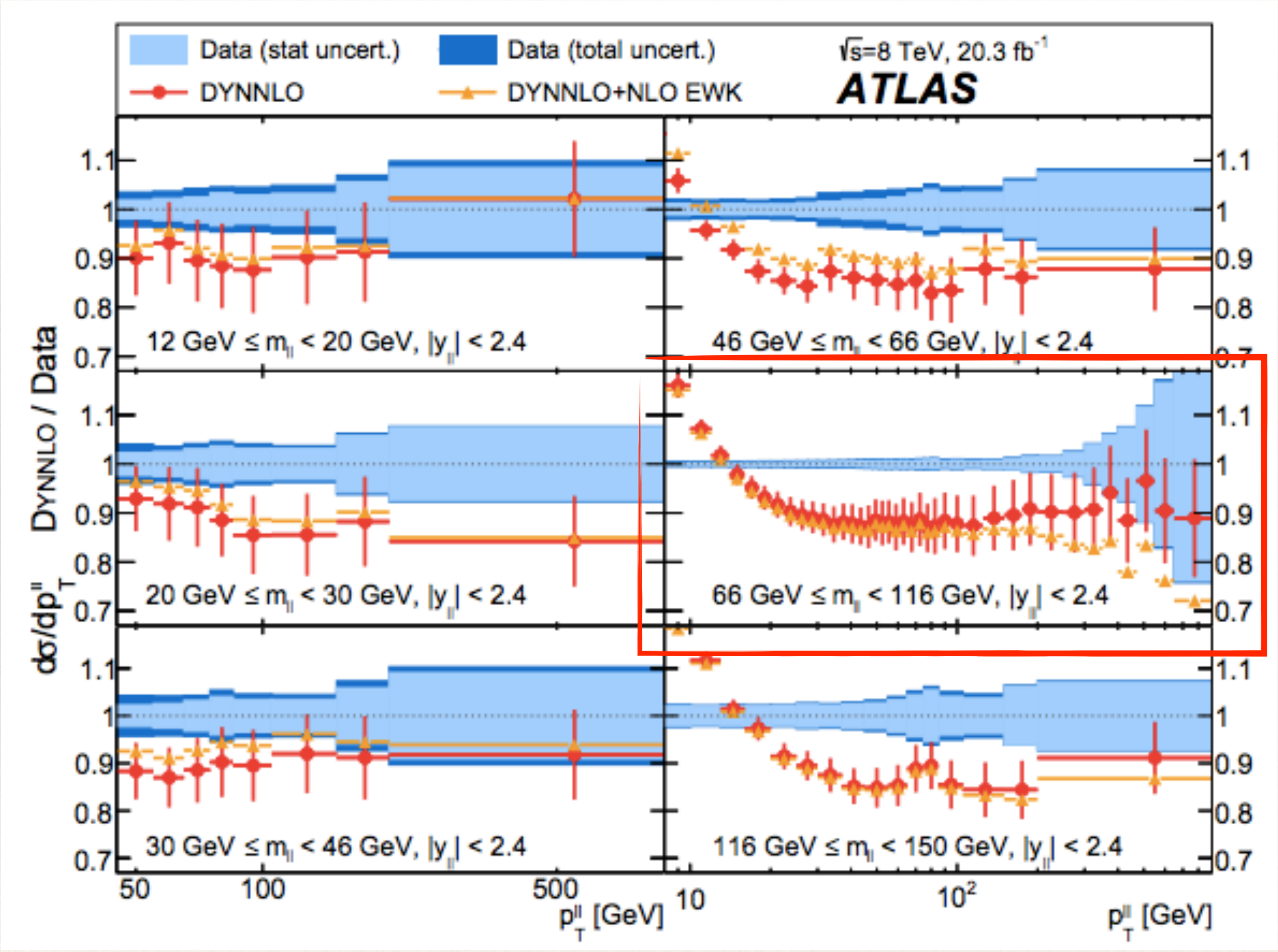
- **PDF improvement**

by using LHC data

Vector boson pT spectrum at the LHC

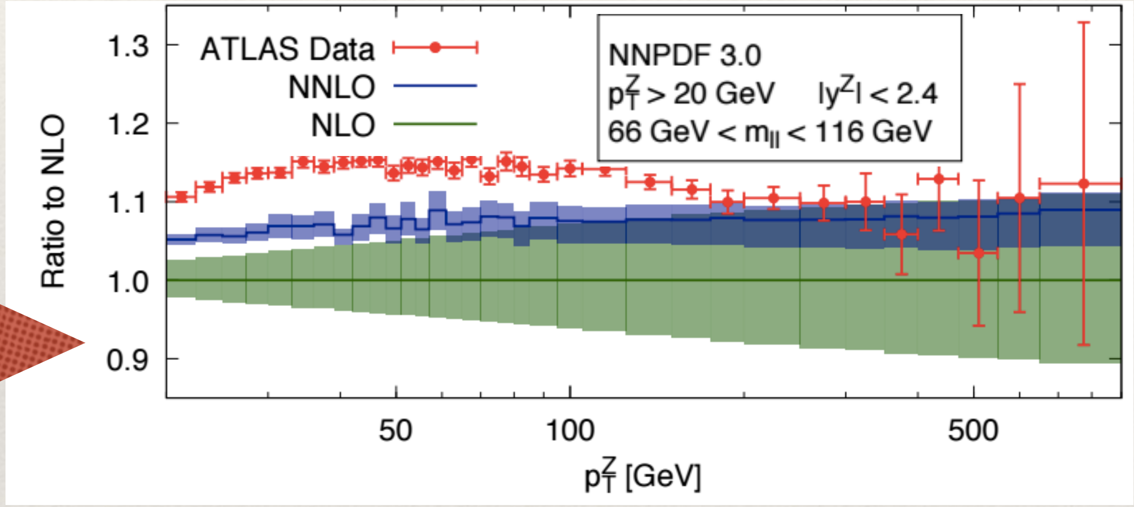
- ATLAS and CMS both studied the Z pT spectrum in rapidity bins
  - **high pT region:** f.o. calculations up to O(α_s^2) and now even O(α_s^3) + EW corrections

comparison to fixed order: *EPJC 76 (2016) 291*



Higher Order corrections would improve data -theory agreement

arxiv:1605.04295

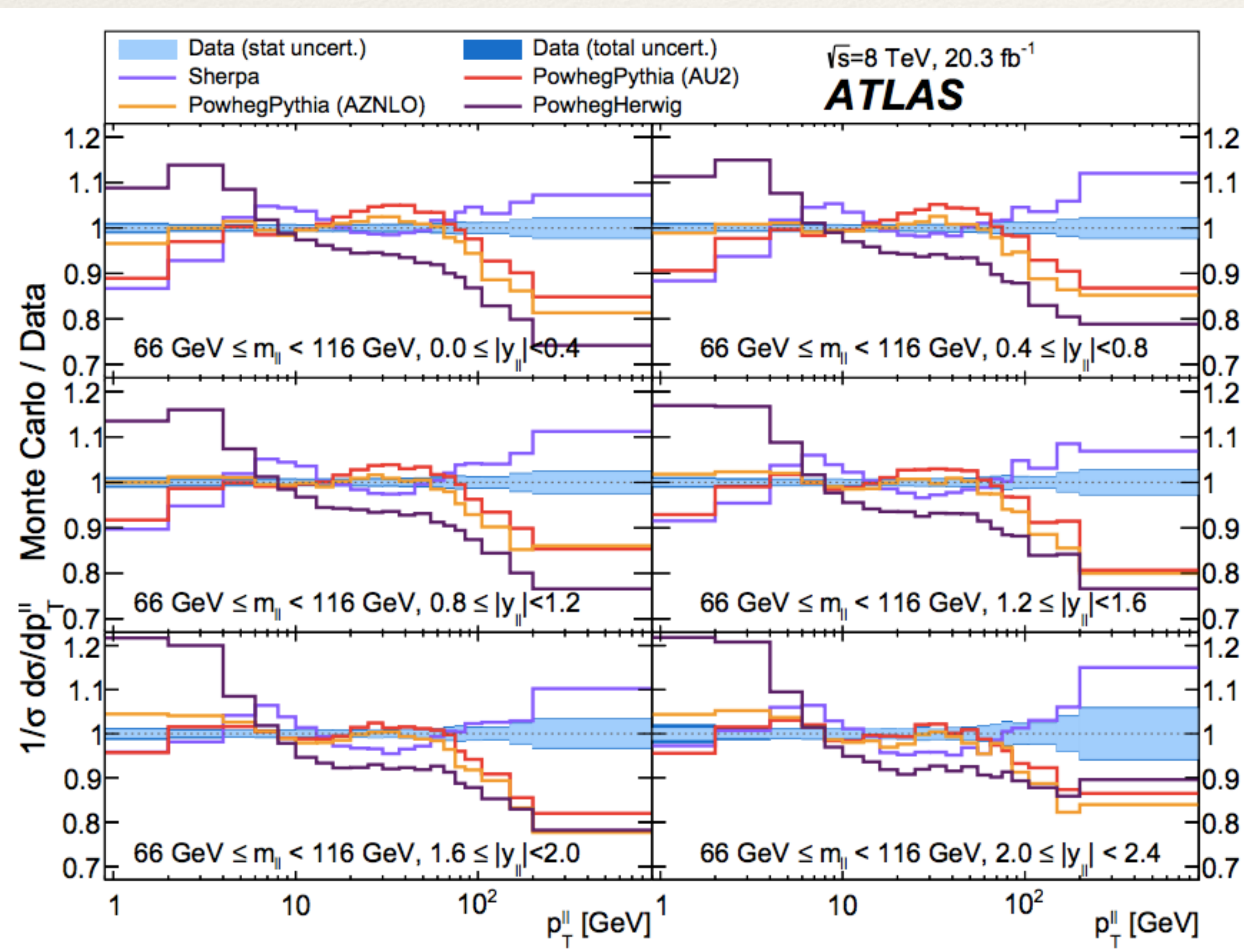


Measurement with constraining powers for PDFs and alphas

Vector boson pT spectrum at the LHC

- ATLAS and CMS both studied the Z pT spectrum in rapidity bins
  - **low pT region:** dominated by the emission of soft gluons
    - fixed order calculations don't work —> resummation and shower models

comparison to MC: Precise data for MC tuning! *EPJC 76 (2016) 291*

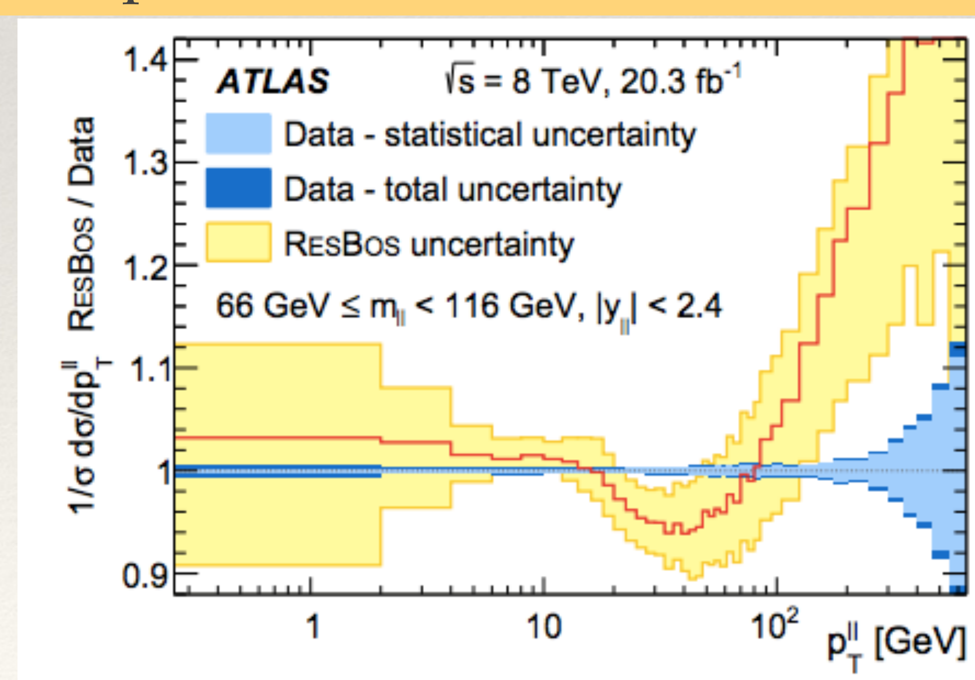


$66\ \text{GeV} \leq m_{ll} < 116\ \text{GeV}$

MC with different PS models are compared

- Powheg+Pythia AZNLO [tuned to 7 TeV Z p_T]
  - Good description in the phase space of the tune (66<M<116 GeV and pT<100 GeV), but it fails at low masses and large rapidity

comparison to resummed calculations:



[Ref: ACTA PHYSICA POLONICA B: Vol. 46 (2015)]

New developments: Transverse Momentum Distributions

- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/high x regions —>a challenge to merge DGLAP, BFKL, cascade evolutions

- MC simulation combines f.o. partonic calculations with PS and hadronisation

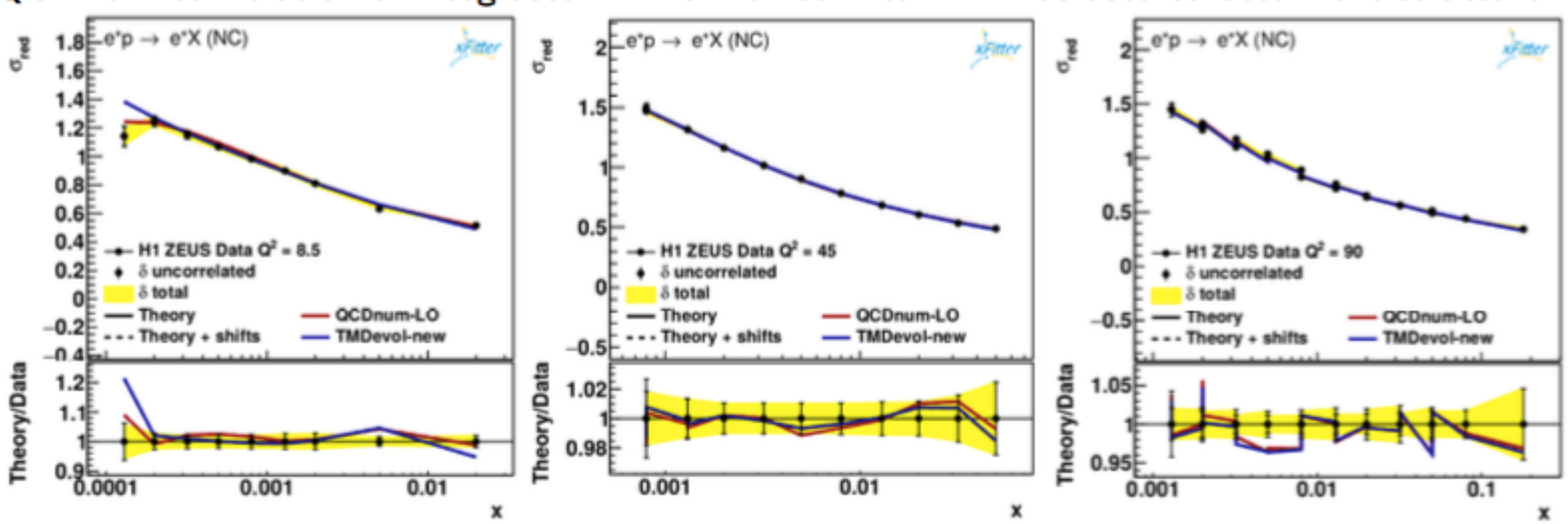
—> needs reshuffling of kinematic variables after PS generations

—> TMDs are introduced for a proper simulation of parton showers:

  - generalisation of QCD factorisation with an explicit dependence on transverse momentum and polarisations
  - they obey the evolution equations which generalise the ordinary RGE of collinear PDFs

First fit of full integrated TMDs to HERA H1 and Zeus data — WORK IN PROGRESS

Integrated TMDs for gluon, valence and sea from updfevolv were used in xFitter to fit F_2.
QCDNum convolution of integrated TMDs with collinear ME was used to obtain the structure function.



Fits works reasonably well for the whole x range and $Q^2 > 8.5\mathrm{GeV}^2$ ($\chi^2/ndf \approx 1.07$).

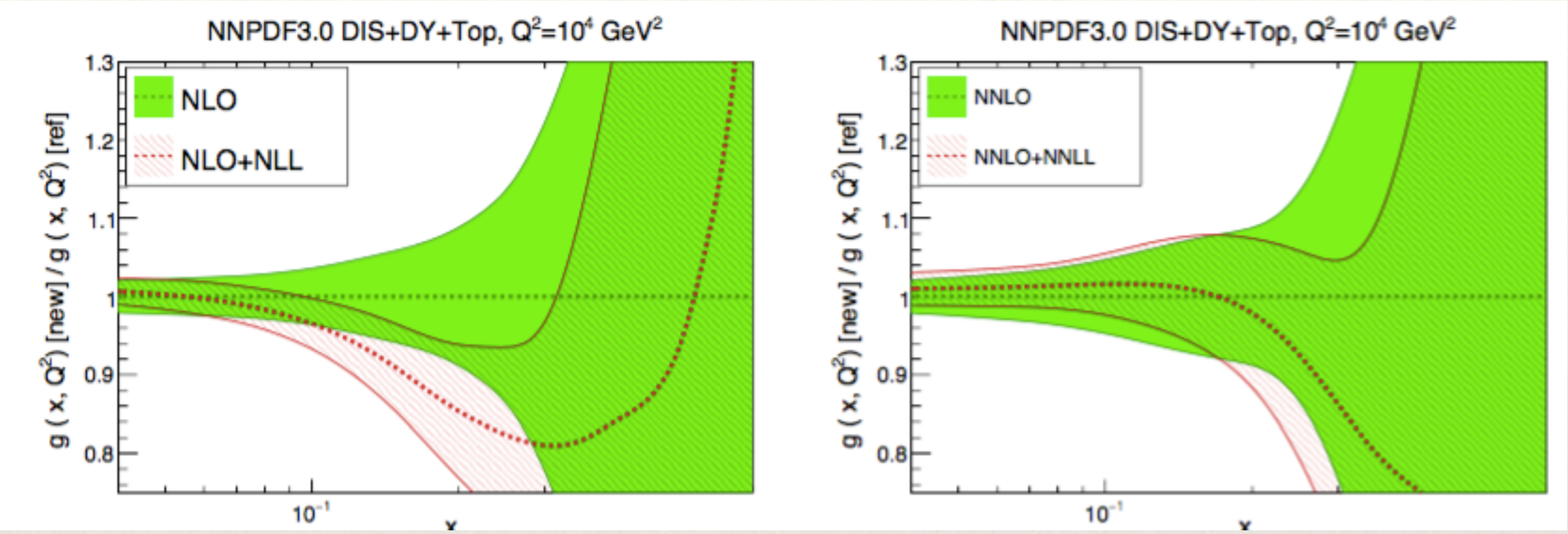
[using TMDs in xFitter] credit: H. Jung, F. Hautmann, A. Lelek

—> results consistent with QCDNUM
next: NLO

New developments: PDFs from resummed calculations

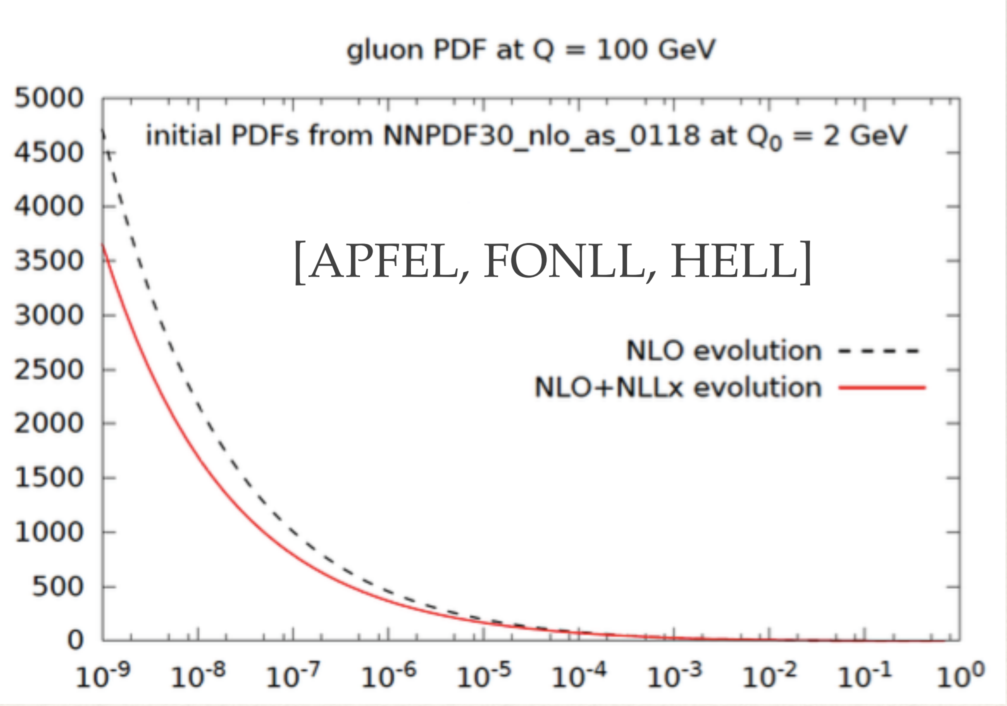
- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/high x regions there have been efforts in providing PDFs consistent with Resummed Computations

[using NNPDF framework]



- PDF fits with threshold resummation tested [high x]
  - sizeable effect at NLO+NLL, smaller effect at NNLO+NNLL

- PDF fits with high-energy resummation show promising results [low x]
  - NLO+NLLx evolution



[ref: M. Bonvini QCD@LHC2016]

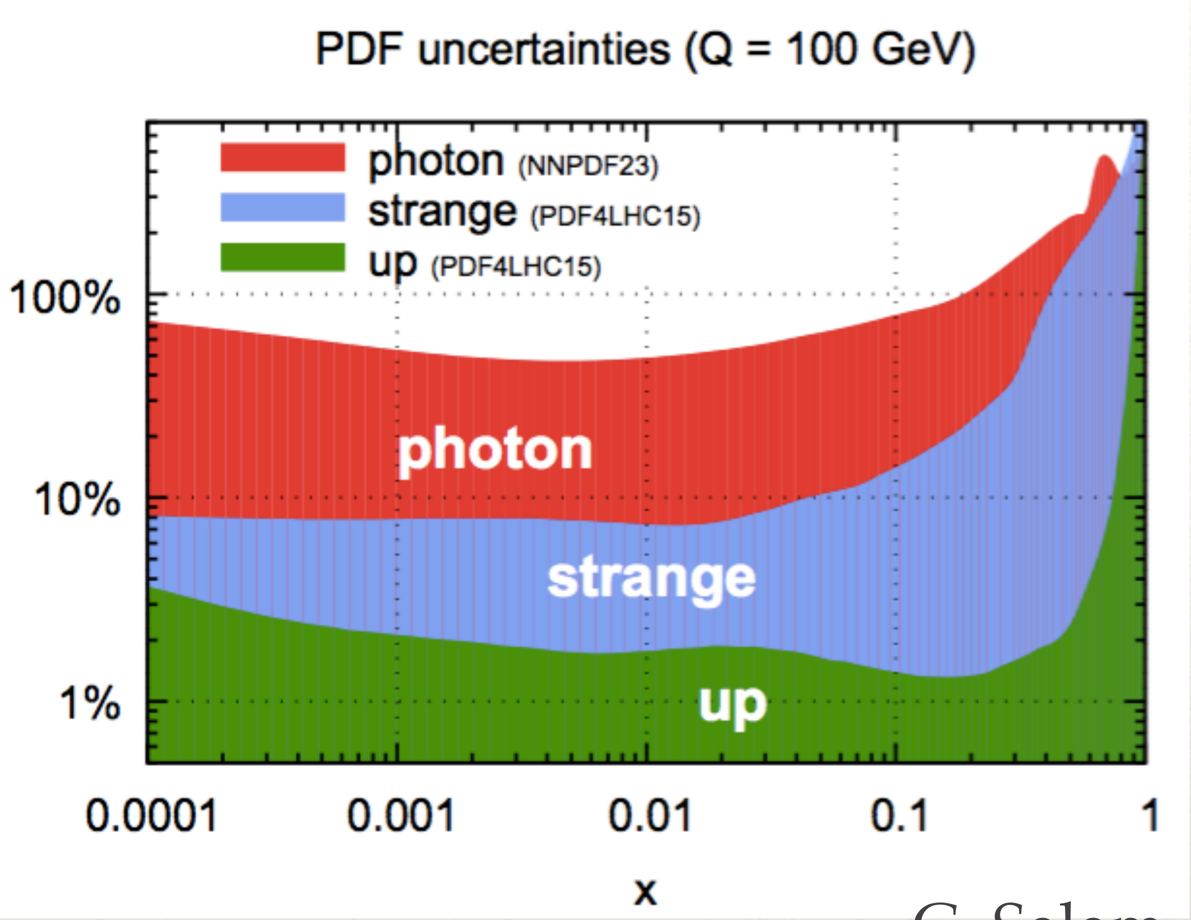
It would be interesting to see the effects combined: PDFs with resummed threshold and high-energy

New Developments for PDF extraction: photon PDF

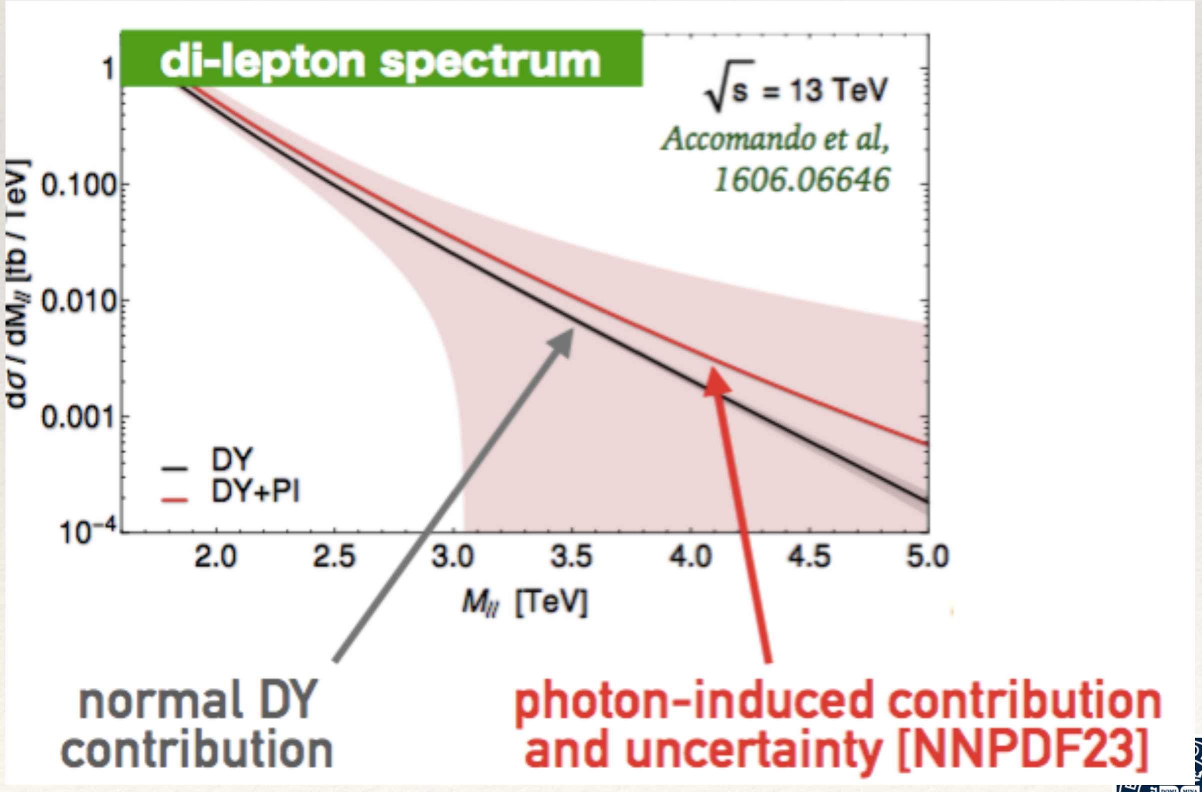
- It starts to become relevant implementation of combined QCD+QED evolution in determining a complete set of PDFs including photon PDFs.

limited experimental constraints

- **Studies that account for the photon PDF:**
  - Gluck, Pisano, Reya 2002
  - MRST2004 QED
  - NNPDF2.3 QED —> NNPDF3.0 QED
    - fit to data
  - CT14 QED, CT14 QED_inc
  - Harland-Lang, Khoze, Ryskin 2016
  - LUXqed 2016: Manohar, Nason, Salam, Zanderighi
    - use ep scattering and construct a hypothetical model for neutral lepton



G. Salam



Summary

- 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!

Nuclear PDFs

Available nuclear PDFs [credit: O. Kusina, DIS2016]

- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\, f_i^{free\ proton}(x_N, \mu_0)$$

  - **HKN**: Hirai, Kumano, Nagai [PRC 76, 065207 (2007), arXiv:0709.3038]
  - **EPS**: Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065, arXiv:0902.4154]
  - **DSSZ**: de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012), arXiv:1112.6324]

- **Native nuclear PDFs**
  - nCTEQ [PRD 80, 094004 (2009), arXiv:0907.2357, arXiv:1509.00792]

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

Compared to other global analyses (HKN07, EPS09, and DSSZ) there are a number of important differences:

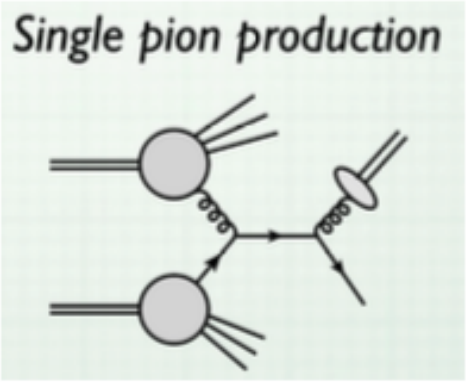
- In contrast to the other analyses, we parameterize the nuclear PDFs directly instead of the nuclear corrections factors.
- In addition, our u- and d-valence distributions are parametrized independently.
- Other differences arise from the selection of data points used in the fit. In particular we impose more conservative kinematic cuts in order to minimize effects from higher twists and target mass corrections.

Data sets

- NC DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)

- Single pion production



RHIC - PHENIX & STAR

N = Au

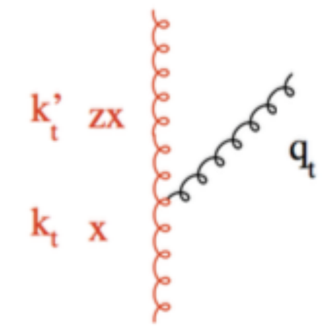
MC evolution of parton densities

https://updfevolv.hepforge.org/

- Evolution consists of step-by-step simulation of individual branchings
  - **at each branching, exact energy-momentum conservation is applied, including k_t**

$$\vec{k'}_t = \vec{k}_t + \vec{q}_t$$

  - with this, a TMD can be constrcuted, once q_t is known
  - evolution happens in q_t (for DGLAP) case with $q'_t \gtrsim q_t$
    - evolution in CCFM would be different ..
  - since only real splittings are simulated, z_{max} must be specified for splitting function.
    - virtual corrections are correctly treated with Sudakov form factor (see presentation by Ola at Dubna meeting)



- Apart from TMD densities, automatically (integrated) collinear densities are obtained:
  - evolution itself does not depend on k_t
- k_t enters the kinematics fro the x-section only

new version:

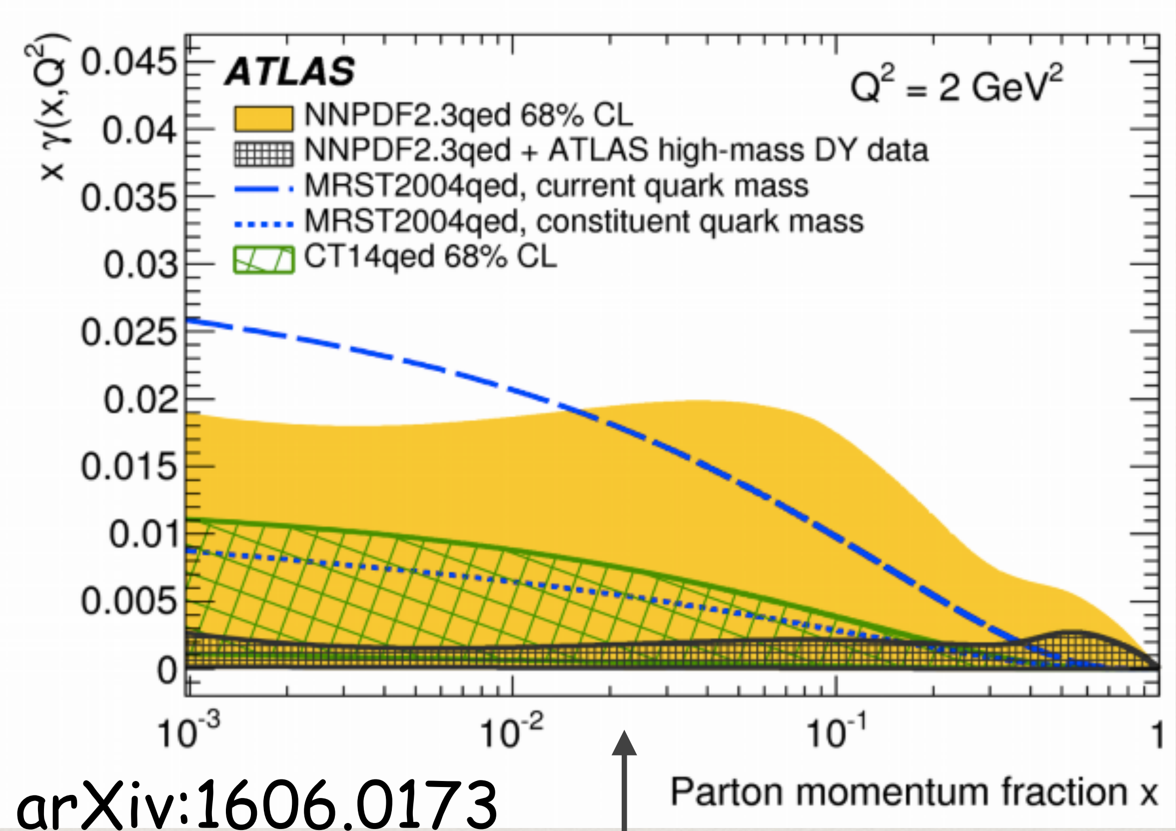
- full coupled quark and gluon DGLAP evolution (gluon, sea and valence evolution)
- fixed flavour number scheme (only u,d,s)
- LO in $P(z)$ (we plan to have NLO in $P(z)$),
- 1-loop-α_s (but also 2-loop-α_s implemented).
- $xf(x, t)$,

Evolution over the whole range in x, Q^2 and all kinematically allowed k_T.

[H. Jung, xFitter meeting]

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.



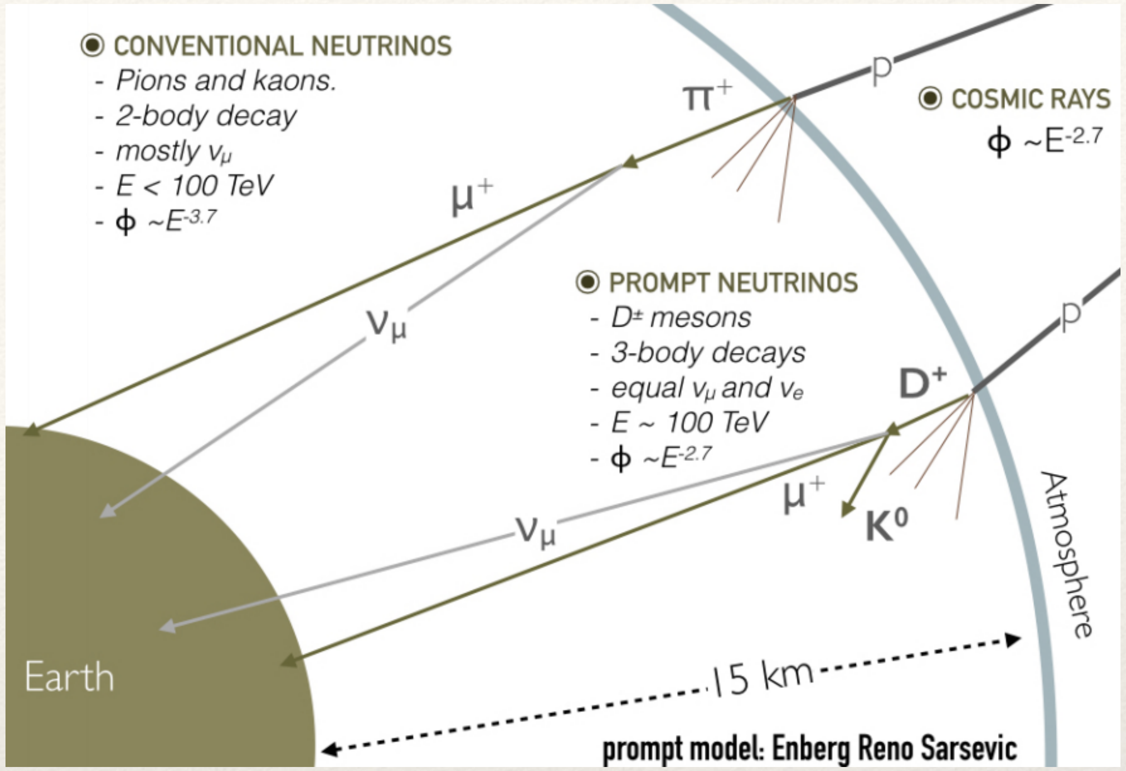
arXiv:1606.0173

- **Studies that account for the photon PDF:**
  - Gluck, Pisano, Reya 2002
  - MRST2004 QED
  - NNPDF2.3 QED —> NNPDF3.0 QED
    - fit to data
  - CT14 QED, CT14 QED_inc
  - Harland-Lang, Khoze, Ryskin 2016
  - LUXqed 2016: Manohar, Nason, Salam, Zanderighi
    - use ep scattering and construct a hypothetical model for neutral lepton

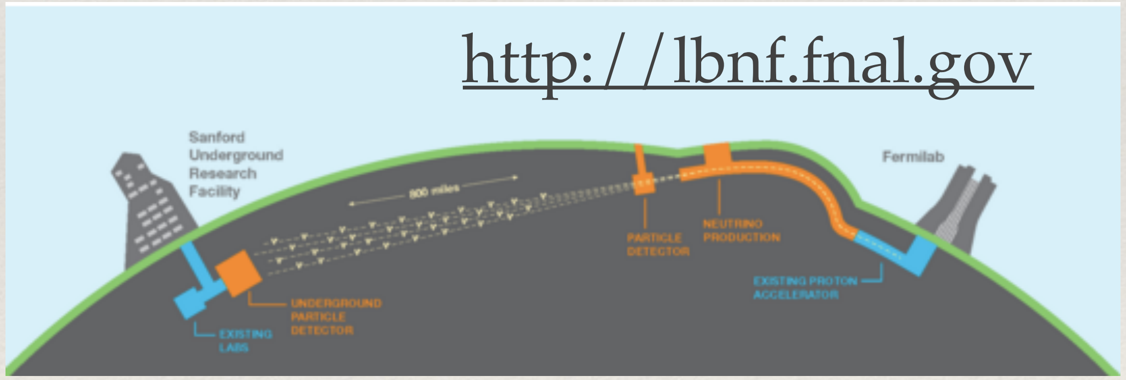
Data has a lot of potential

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
- Heavy quark production data from LHC could validate calculations of the prompt neutrino flux



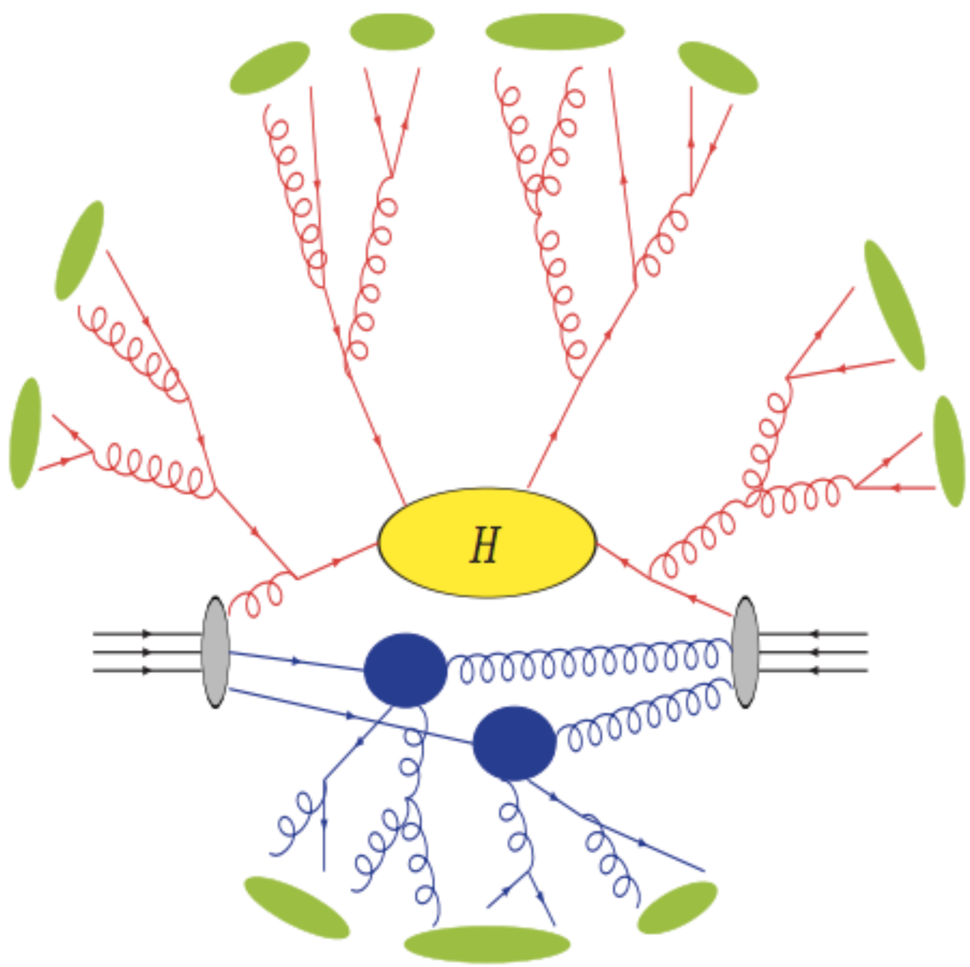
- The physics prospects by DUNE at LBNF with high resolution and unprecedented statistics may lead to discoveries of new physics:
  - it requires a good control of the cross section model which is used at the end for the determination of the event kinematics



synergy between LBNF, LBL, CERN

Roles of PDFs in MC tuning

- Structure of an event at the LHC (courtesy of Z. Nagy)

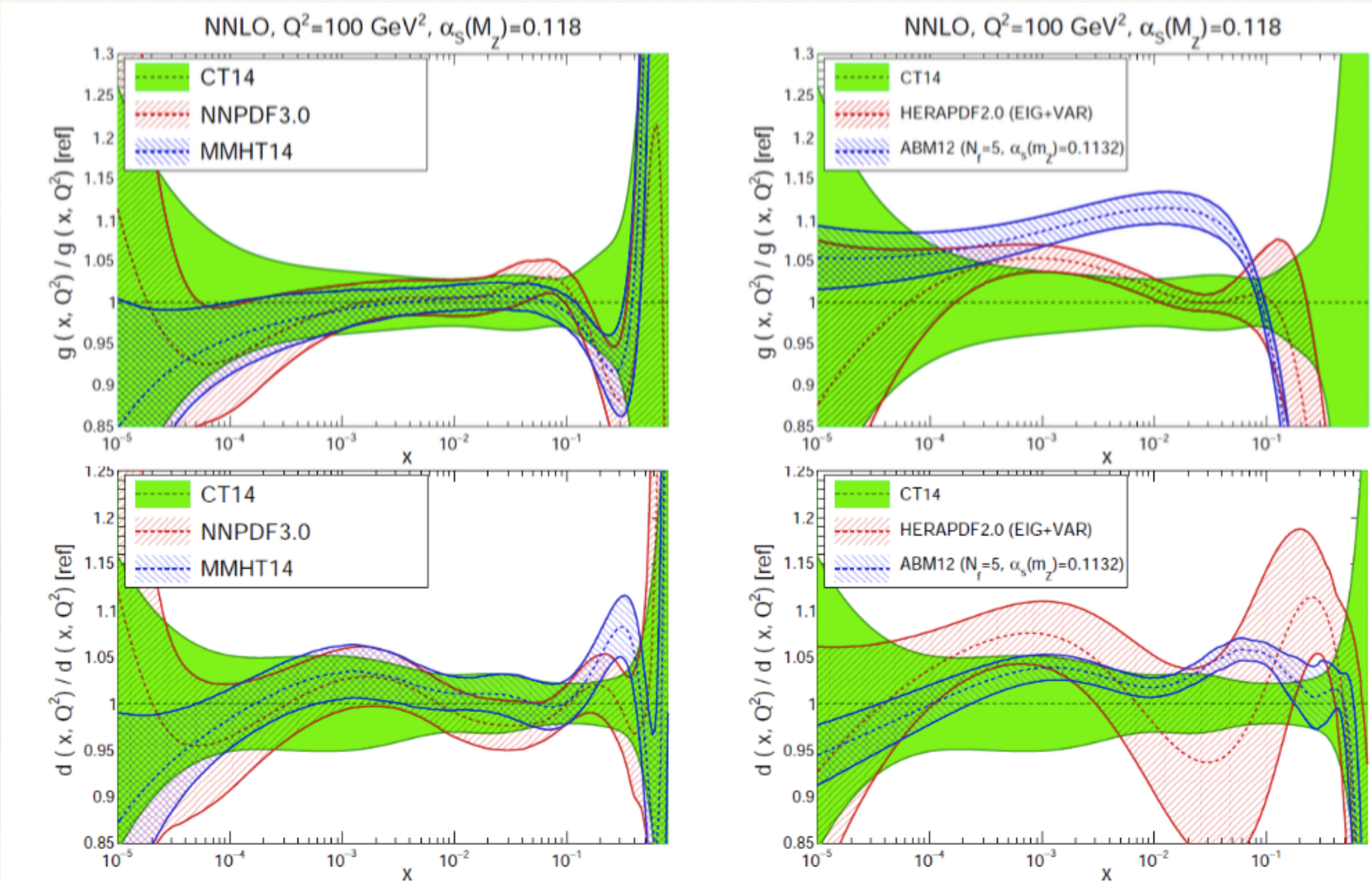


1. Incoming hadron (gray bubbles)
   - Parton distribution function
   - Multi parton distribution functions
2. Hard part of the process (yellow bubble)
   - Matrix element calculation, cross sections at LO, NLO, NNLO level
3. Radiation (red graphs)
   - Parton shower calculation
   - Partonic decay
   - Matching to NLO, NNLO
4. Underlying event (blue graphs)
   - Models based on multiple interaction
   - Diffraction
5. Hardonization (green bubbles)
   - Universal models
   - Hadronic decay
   - ....

Perturbative framework:

- LO: easy to calculate: several matrix element generators are available:
  - ALPGEN, HELAC, MADGRAPH, SHERPA
  - Strong dependence on the unphysical scales
  - well defined with LO PDF
- NLO is the New Standard: HELAC, MADGRAPH, SHERPA+BLACKHAT, AUTODIPOLE, TEVJET, AMC@NLO
  - The scale dependence can be still big in some processes
- NNLO & NkLO: Resummation - Parton Showers: POWEHEG

State-of-the-art PDFs:



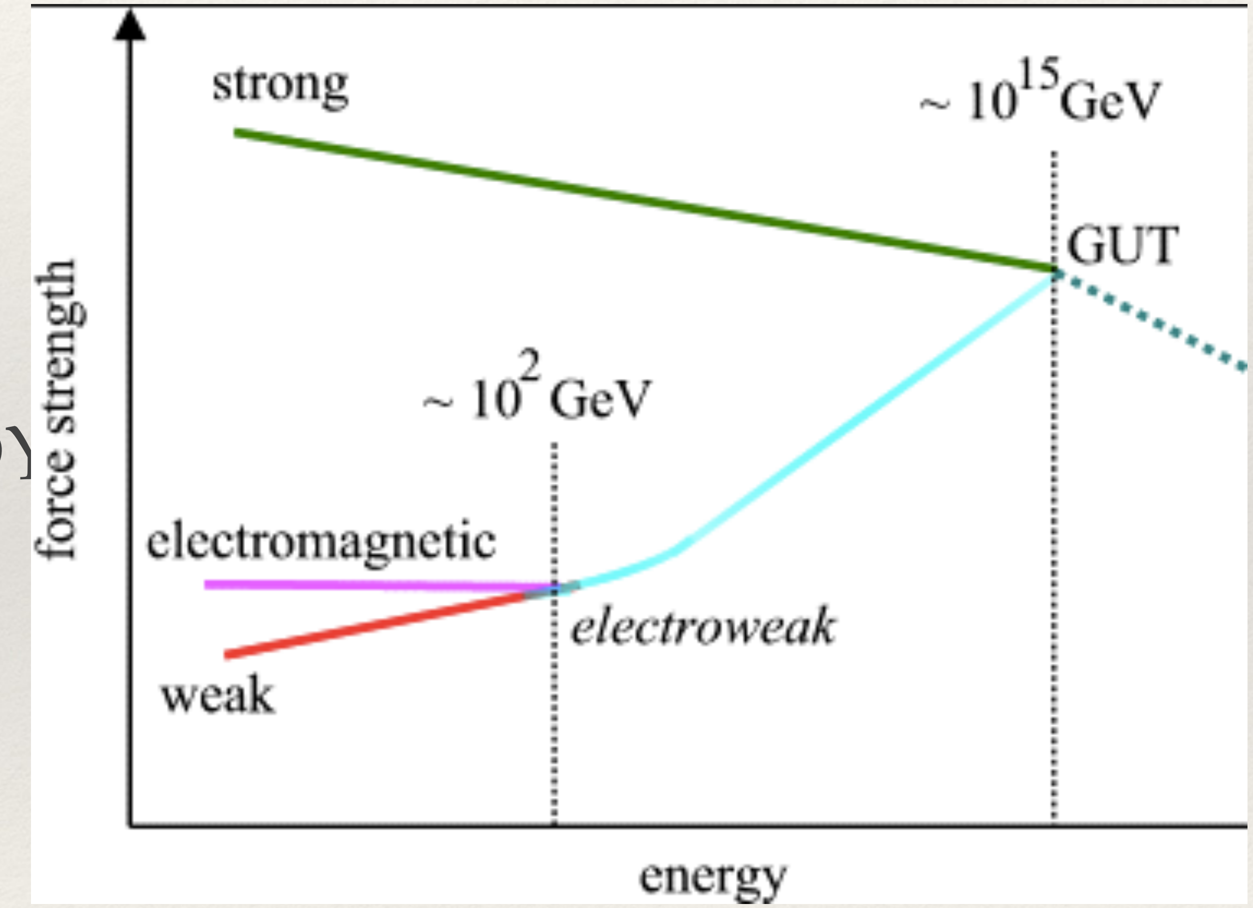
global

*plots taken from PDF4LHC recommendation arxiv:1510.03865

Expectations from LHC data

- **Gluon:**
  - Inclusive jets, dijets, trijets —> medium/large x
  - Isolated photon and photon+jets —> medium/large x
  - ttbar production —> large x
  - Zpt spectrum —> small/medium x

- **Quarks:**
  - W and Z rapidity spectra
  - High pT W+jets
  - Low mass and high mass DY
  - W+c rapidity spectrum
  - single top differential



- **Photon:**
  - WW production
  - High Mass DY

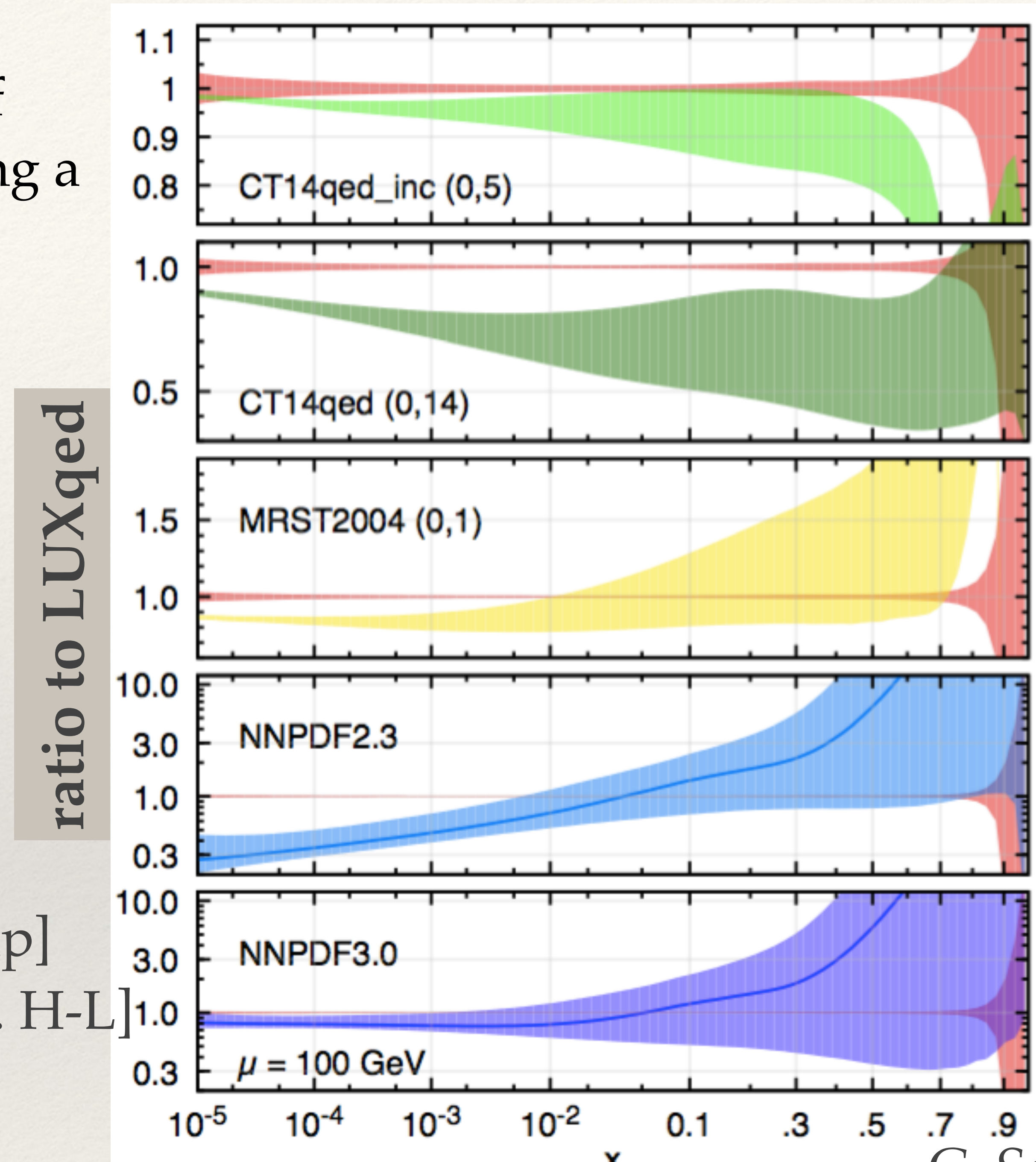
At the LHC the QED effects start to bring an important contributions due to access to high scales processes:
- high mass DY, ttbar, di-boson, EW Higgs

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 —> 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

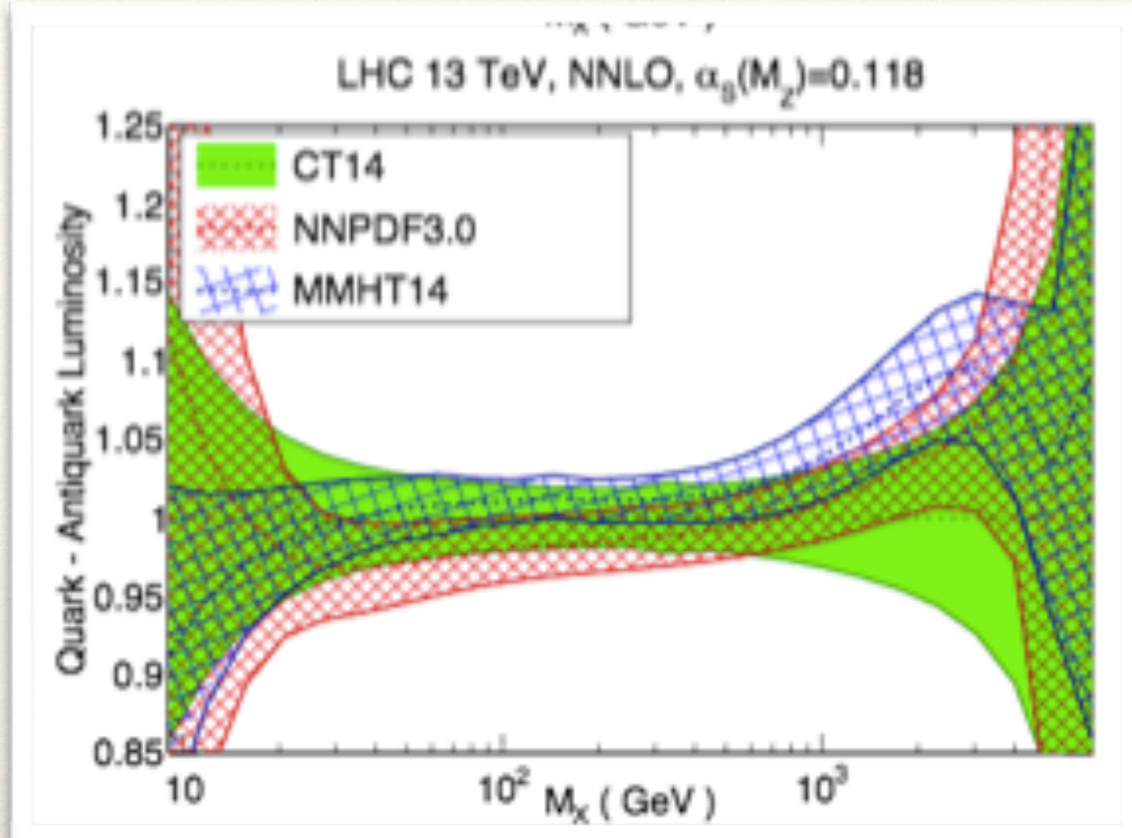


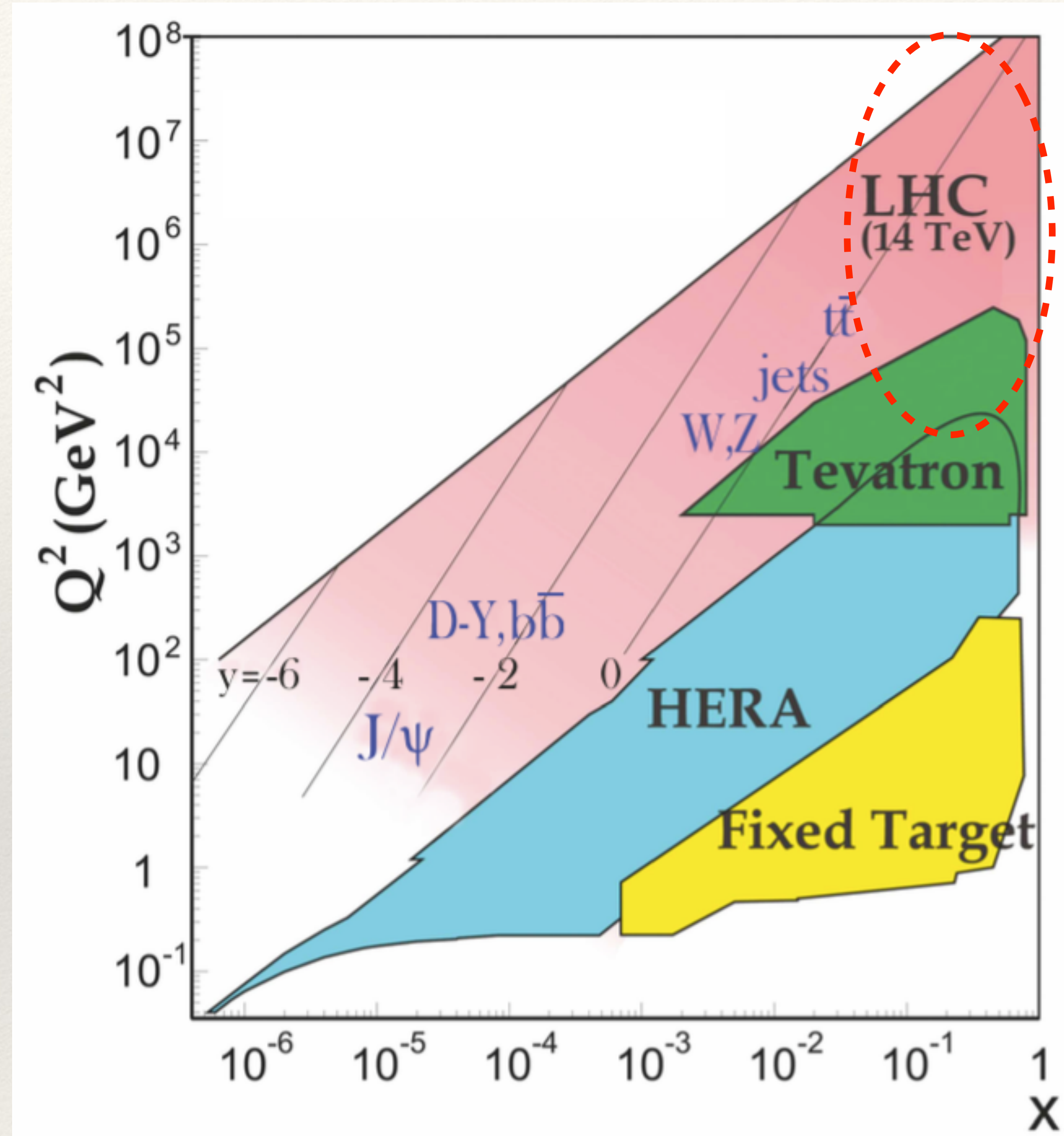
G. Salam

—> interesting to confront these models with data

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)

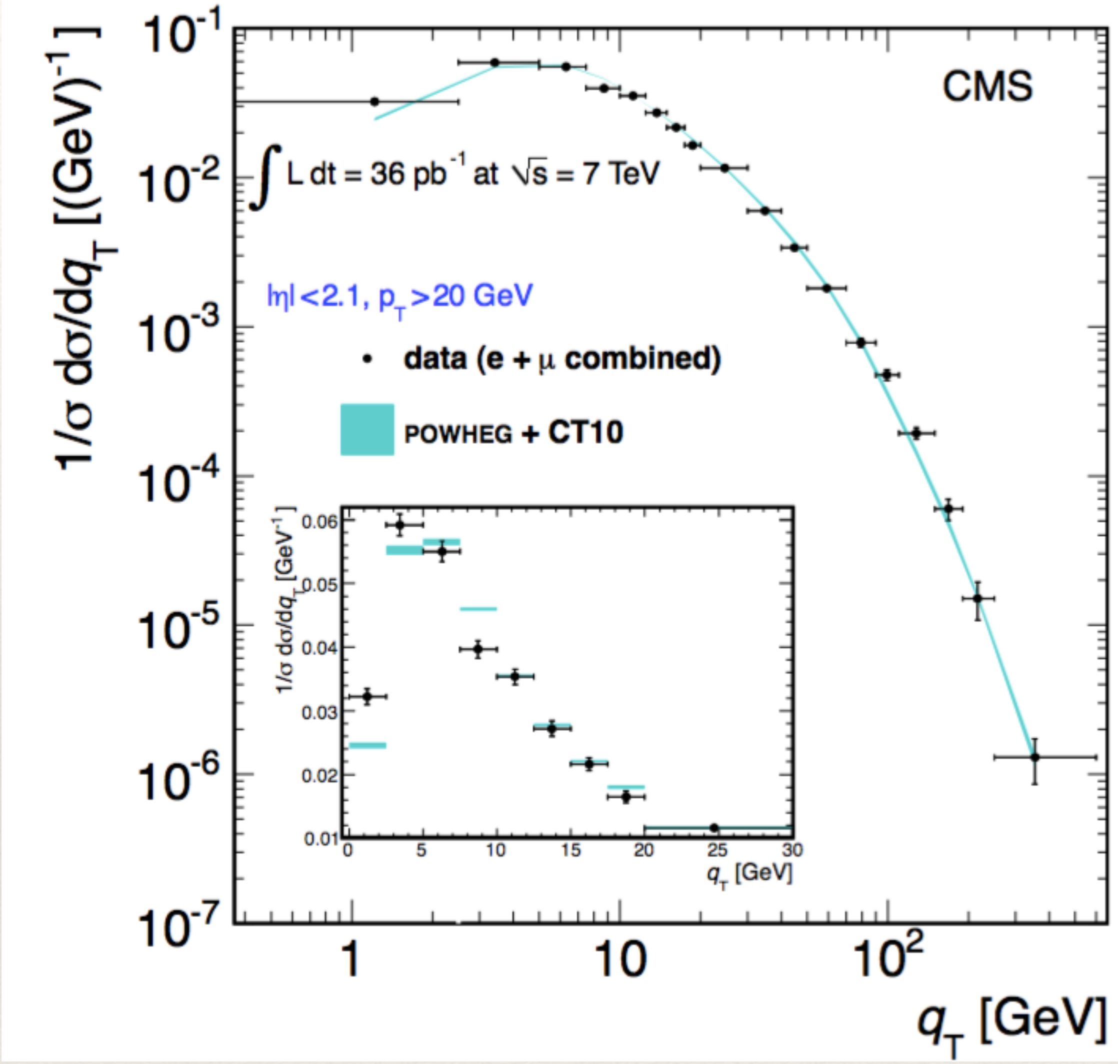
- ttbar can be interesting channel
- high mass DY can extend to high lever arm reach
- jet data

high mass <—> high x

Fixed order calculations vs Resummed or + PS

- Fixed order calculations dont 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

- high-qT region
  - it is expected to be described by f.o
- at low and peak qT
  - QCD radiation not described by truncated pQCD
  - it requires methods to resum arbitrary many parton emissions



low peak high

There are different approaches to address the failure of f.o. calculations

TMDs

- Fixed order calculations dont 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

MC simulation combine f.o. partonic calculations with PS and hadronisation —> need reshuffling of kinematic variables after PS generations required by energy-momentum conservation

generalisation of QCD factorisation where now the explicit dependence on transverse momentum and polarisations —> TMDs
they obey the evolution equations which generalise the ordinary RGE of collinear PDFs —> allows resummations of large logs (M/qT) to all orders in alphas

New approach to solve coupled gluon and quark DGLAP evolution equation for Monte Carlos:

Advantages:

- a full TMD pdf evolution including gluon, sea and valence quarks over the full range in x and Q^2 with the k_T dependence in the whole kinematically available range (not limited to the small k_T),
- reproduce semi-analytical solution (results consistent with QCDNum),
- direct usage in PS matched calculation.

[using TMDs in xFitter]
credit: H. Jung, F. Hautmann, A. Lelek

QCD Fit Open Source Packages:

Search | Titles | Text

DESY **xFitter**

xFitter/xFitterInternal » xFitter/../Installation.. » xFitter/../xFitterDevel.. » xFitter/../Meeting2016-.. » xFitter

Wiki
- WikiPolicy
- RecentChanges
- FindPage
- HelpContents
- xFitter

Page
- Edit (Text)
- Edit (GUI)
- Info
- Subscribe
- Add Link
- Attachments
- More Actions:

xFitter

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

xFitter release: 1.2.2 [July 2016]

Release xFitter1.2.2.tgz available at: *https://www.xfitter.org/xFitter/xFitter/DownloadPage*

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 / 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 getter-xfitter.sh.

Date	Version	Files	Remarks
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

Documentation

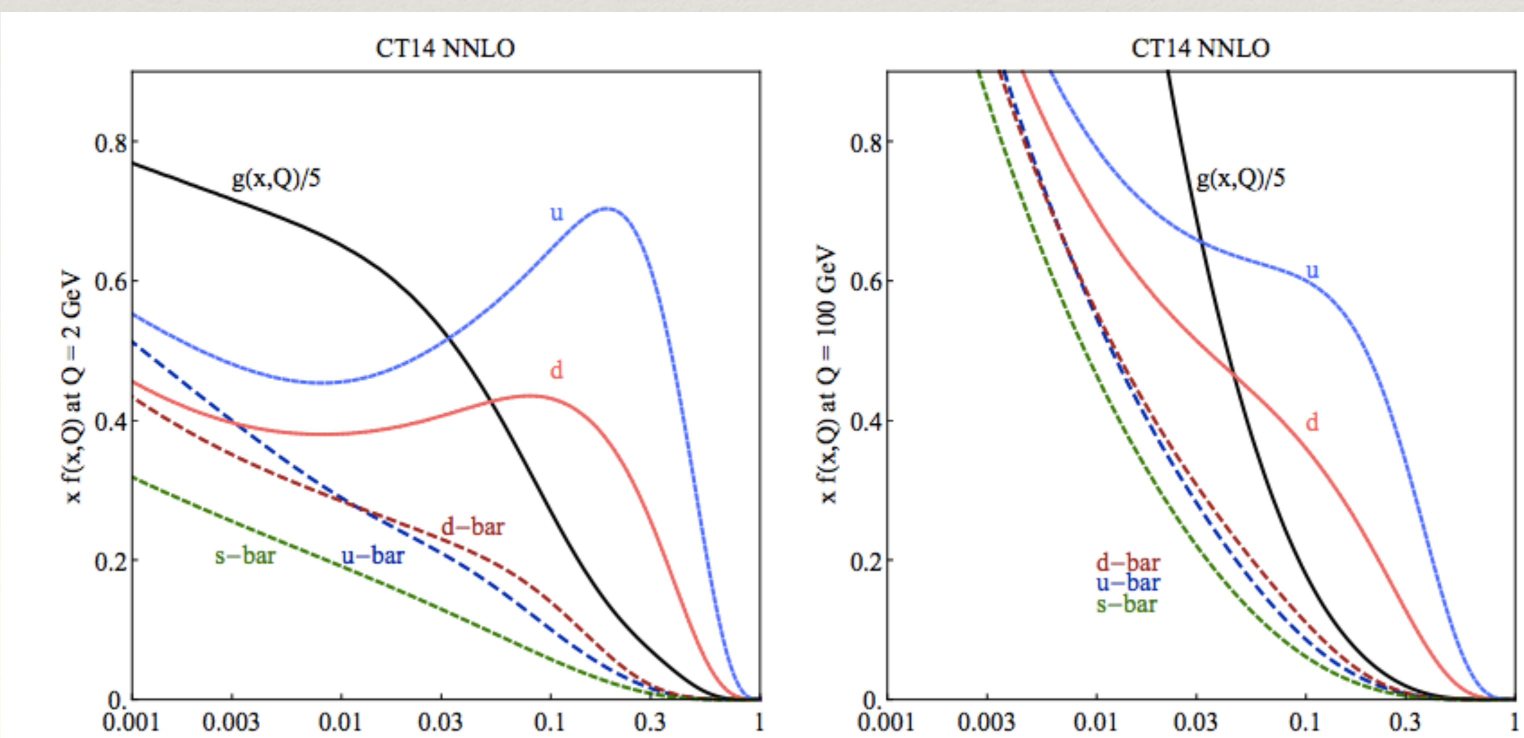
- A list of datasets which can be downloaded with the help of getter script.
- Manual (under continuous improvement) can be accessed here.
- The **README** file (accessible via the package) gives an explanation for a quick start.
- The **INSTALLATION** file (accessible via the package) provides information for package installation and usage instructions.
- The package is licensed under GNU GPL, please see **LICENCE** for mode details (accessible via the package).

- By default only final combined HERA I+II data are distributed
  - (xfitter-)getter.sh script to download data with corresponding theory files already adjusted for the xfitter format.
- A complete installation script is also provided (tested under different platforms)
- A release note to keep track of changes between releases is included

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
- mc=1.3 GeV (pole mass), alphas =0.118 (preferred though is 0.115)
- removed u/d ->1 assumption for x—>0 which made uncertainties increase at low x
- Tolerance: two step: 1) T~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		$N_{pt,n}$	χ^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 σ^p_{red}	[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 xF_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 σ_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		$N_{pt,n}$	χ^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^{-1} W/Z $d\sigma/dy_\ell$	[43]	14	9.9	0.71
241	LHCb 7 TeV 35 pb^{-1} 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^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	[46]	11	12.1	1.10
267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV	[47]	11	10.1	0.92
268	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	[48]	41	51	1.25
281	DØ Run-2 9.7 fb^{-1} 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^{-1} incl. jet production	[51]	90	50	0.55
538	CMS 7 TeV 5 fb^{-1} 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_T 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***

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

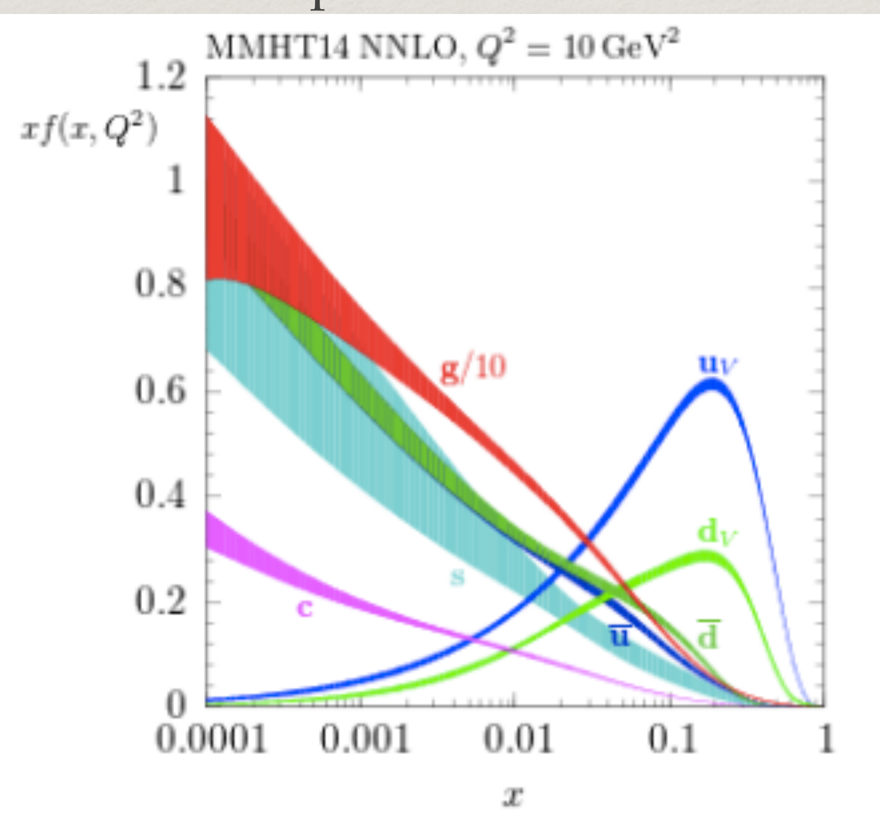
see also arXiv:1604.00024 and

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 pT 7,8 TeV	2011+2012	medium-*x* gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-*x* gluon
CMS Z pT,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

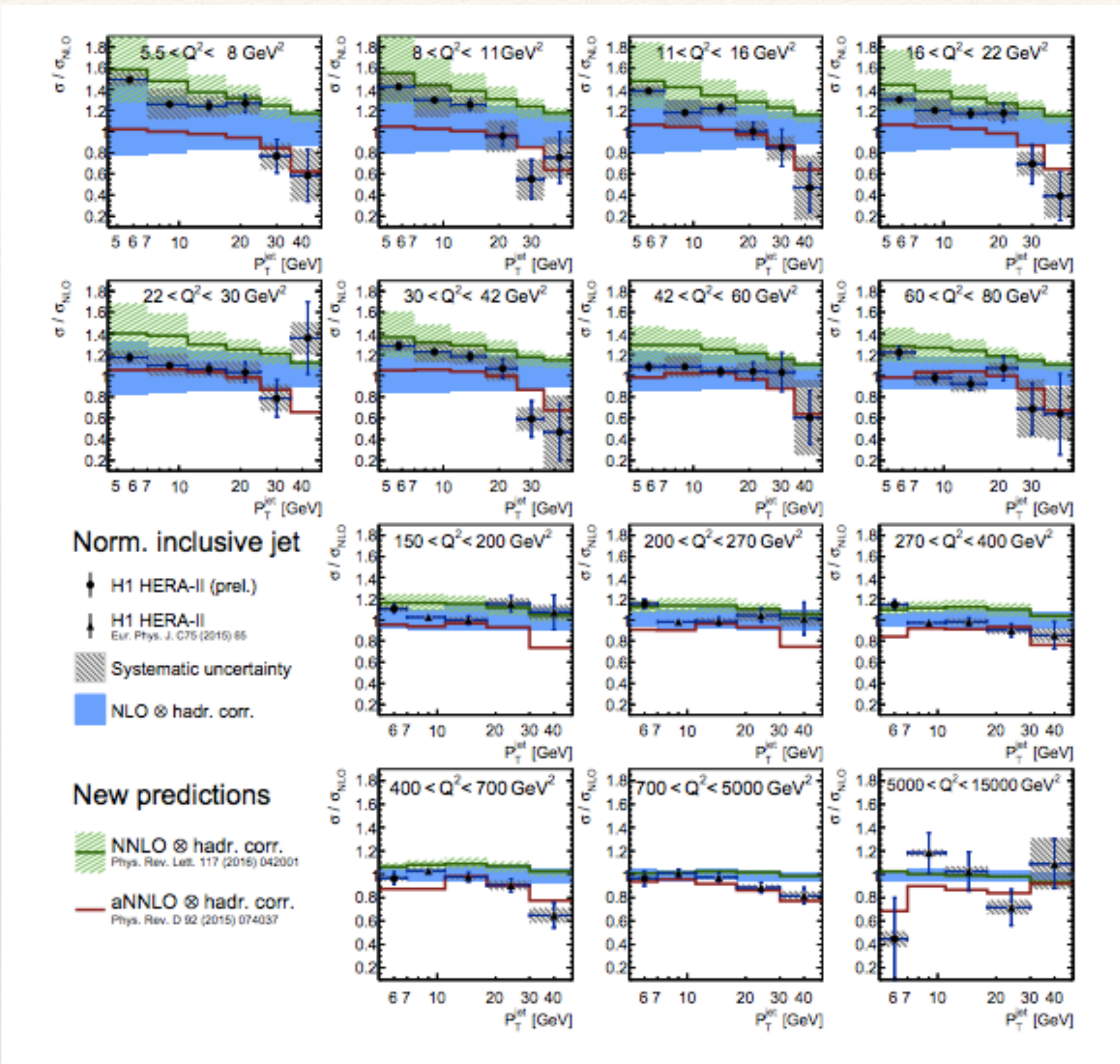
- MMHT includes LHC data, HERA I data
- comes with 25 eigenvector pairs:
  - There are 37 free PDF parameters
    - with alphas free (found 0.117)
  - use of Chebyshev polynomial
- change in the deuteron correction, improvement in the branching ratio Bμ which leads to larger uncertainty on strange
- dynamical tolerance criteria (average ~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 μp F_2 [125]	162 / 153	176 / 163	173 / 163
BCDMS μd F_2 [19]	140 / 142	143 / 151	143 / 151
NMC μp F_2 [20]	141 / 115	132 / 123	123 / 123
NMC μd F_2 [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [22]	59 / 53	60 / 53	65 / 53
E665 μd 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 νN F_2 [29]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [30]	25 / 37	26 / 42	28 / 42
NuTeV νN xF_3 [29]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [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 $F_2^{\rm charm}$ [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 $W \to \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \to \nu\mu$ 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 $Z \to e^+e^-$[79]	76/9	13/9	20/9
LHCb W asymm $p_T > 20$ GeV[78]	27/10	12/10	16/10
CMS $Z \to e^+e^-$ [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**

First NNLO for jets @ H1, HERA

H1prelim-16-062



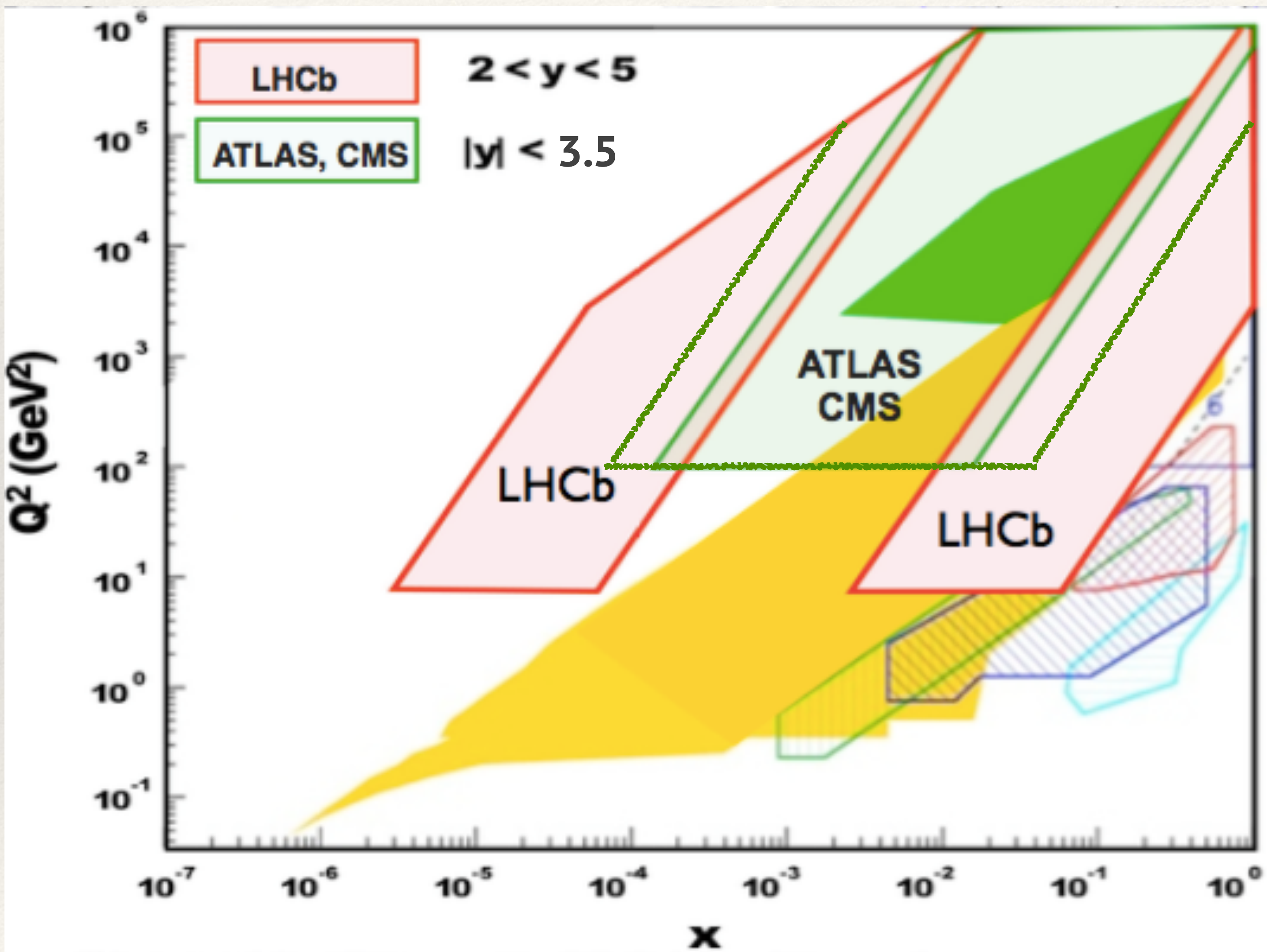
Predictions	NLO	aNNLO	NNLO
Jet cross sections			
Program	nlojet++	JetViP	NNLOJET
pQCD order	NLO [8]	approximate NNLO [12]	NNLO [15]
Calculation detail	Dipole subtraction	NLO plus NNLO contributions from unified threshold resummation formalism	Antenna subtraction
NC DIS cross sections			
Program	QCDNUM	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	✓		

- This opens up a new avenue for PDF fits

  —> a boost to re-analyse Tevatron and LHC jets !

The LHC measurements: ATLAS-CMS vs LHCb

- LHC provides an extended kinematic range in x by its three experiments:
  - ATLAS, CMS and LHCb
  - coverage in x is what's needed, because QCD gives us Q2 dependence



- **PDF discrimination** by confronting theory with data
- **PDF improvement** by using LHC data

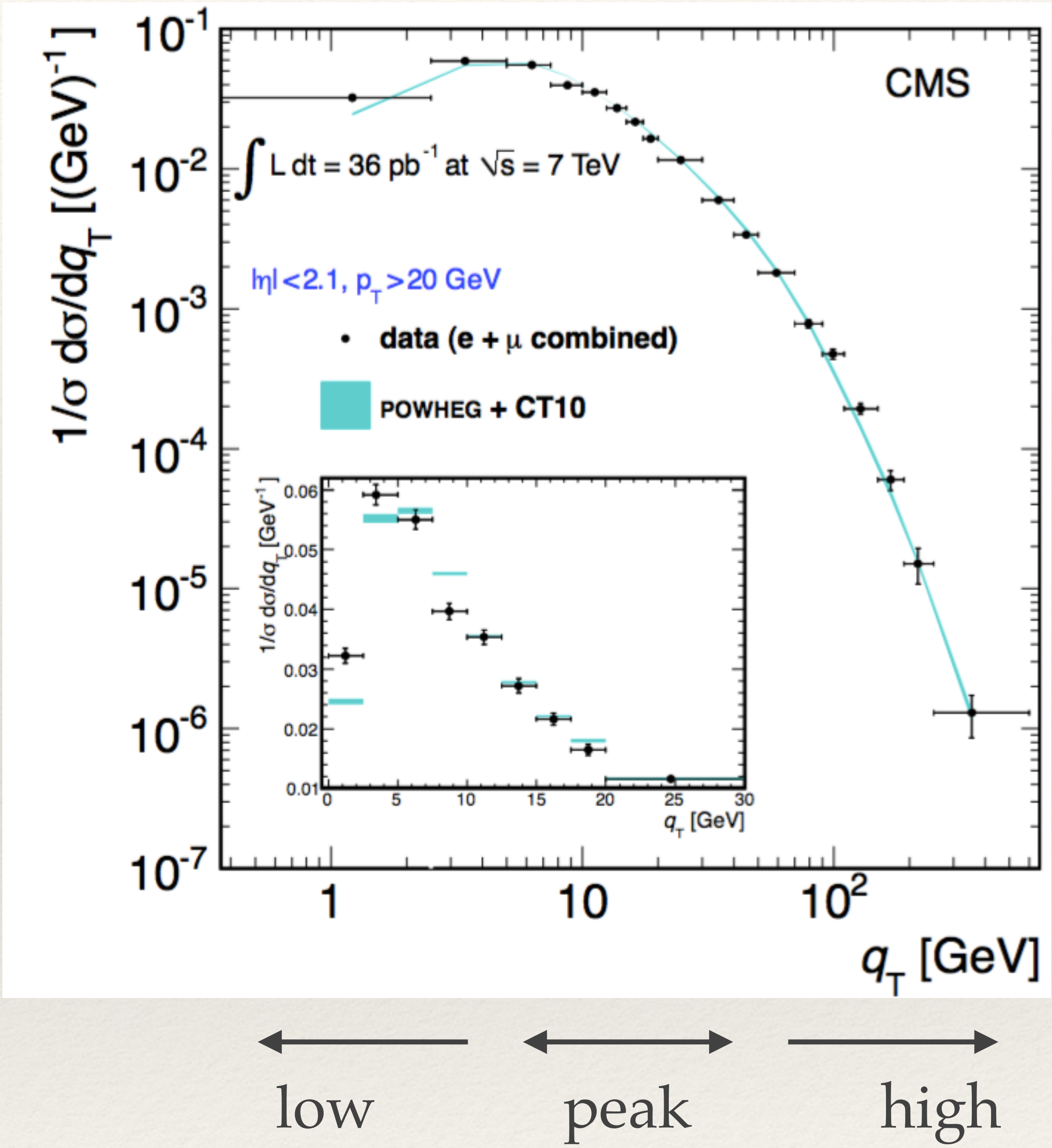
—> can provide needed flavour separation and more insight into gluons

Voica Radescu | Oxford University

Fixed order calculations vs Resummed or + PS

- Fixed order calculations dont 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

- high-qT region
  - it is expected to be described by f.o
- at low and peak qT
  - QCD radiation not described by truncated pQCD
  - it requires methods to resum arbitrary many parton emissions



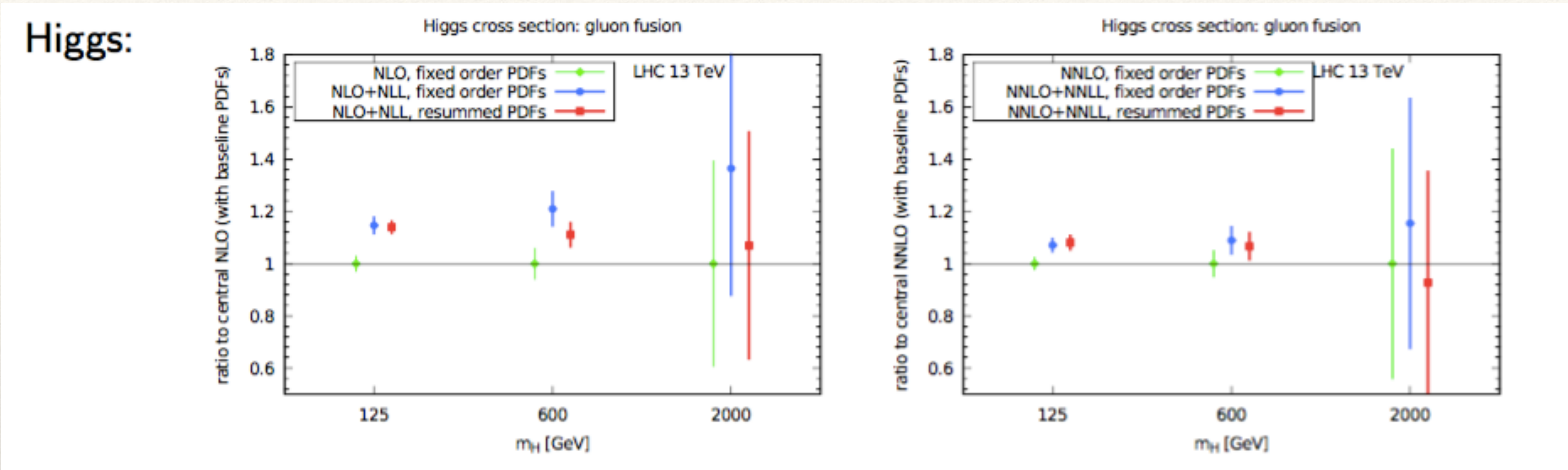
There are different approaches to address the failure of f.o. calculations

Expectations from LHC data

- **Gluon:**
  - Inclusive jets, dijets, trijets —> medium/large x
  - Isolated photon and photon+jets —> medium/large x
  - ttbar production —> large x
  - Zpt spectrum —> small/medium x
- **Quarks:**
  - W and Z rapidity spectra —> medium x
  - High pT 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
- **Photon:**
  - WW production
  - High Mass DY

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