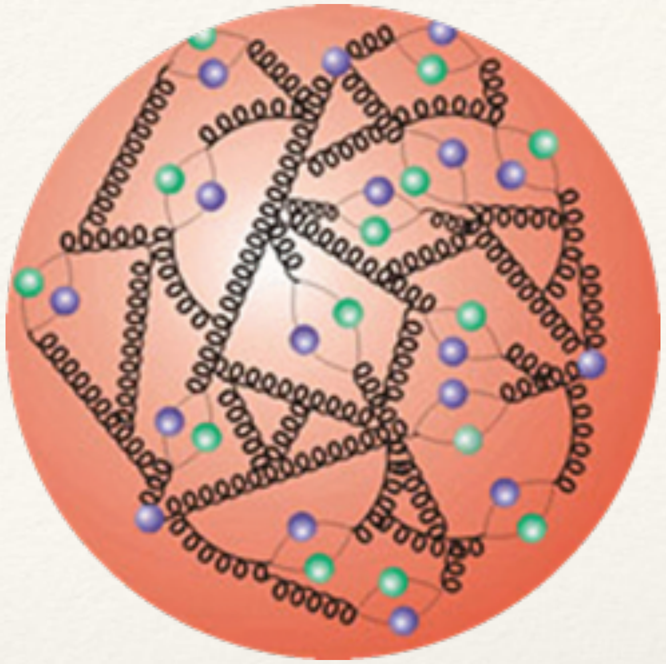


March 2016, Liverpool

Precision for discoveries

Voica Radescu
University of Oxford

Cornering Standard Model

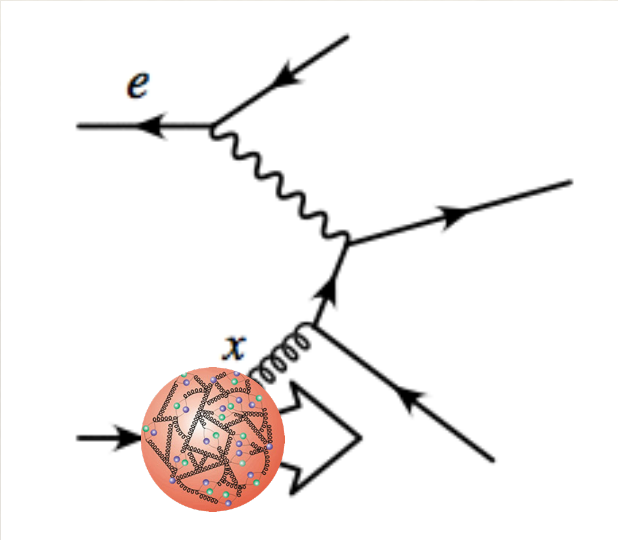
direct searches
for new physics

indirect searches via
consistency test of SM

control of QCD background
and SM parameters

Interpretation of any cross section measurement is given in the context of the factorisation concept:

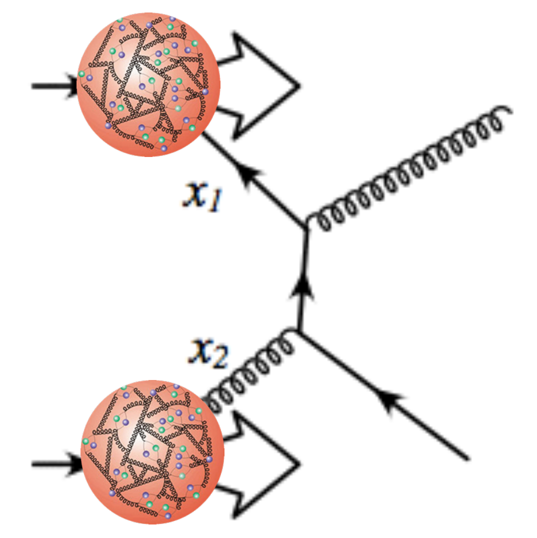
DIS
processes



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

calculable

from data



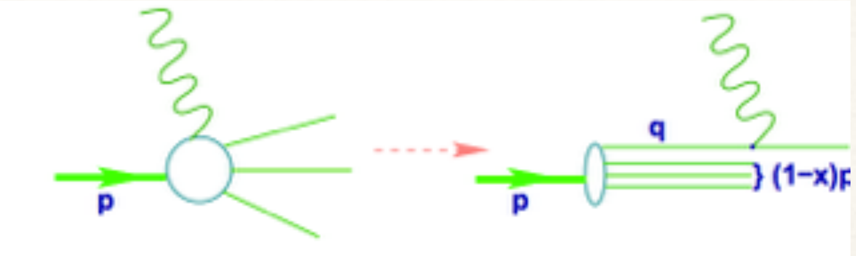
DY
processes

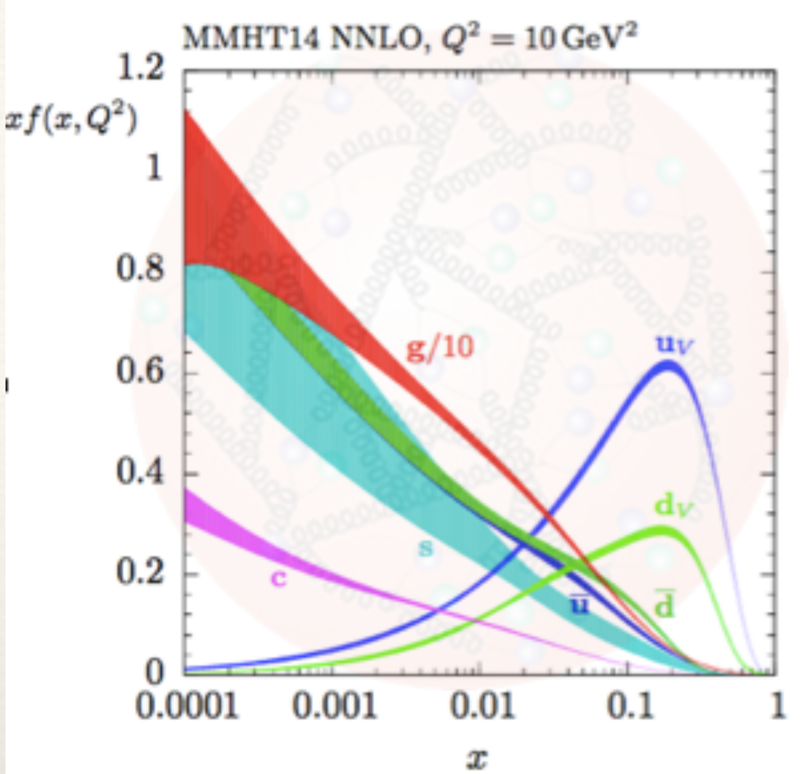
Multiple precision measurements from Fixed target, HERA, Tevatron, and LHC allowed our knowledge on QCD to be pushed forward on many fronts

Improvement of PDFs precision demands theory & experiment collaboration and implies a variety of high precision measurements and theory calculations

Parton Distribution Functions (PDFs)

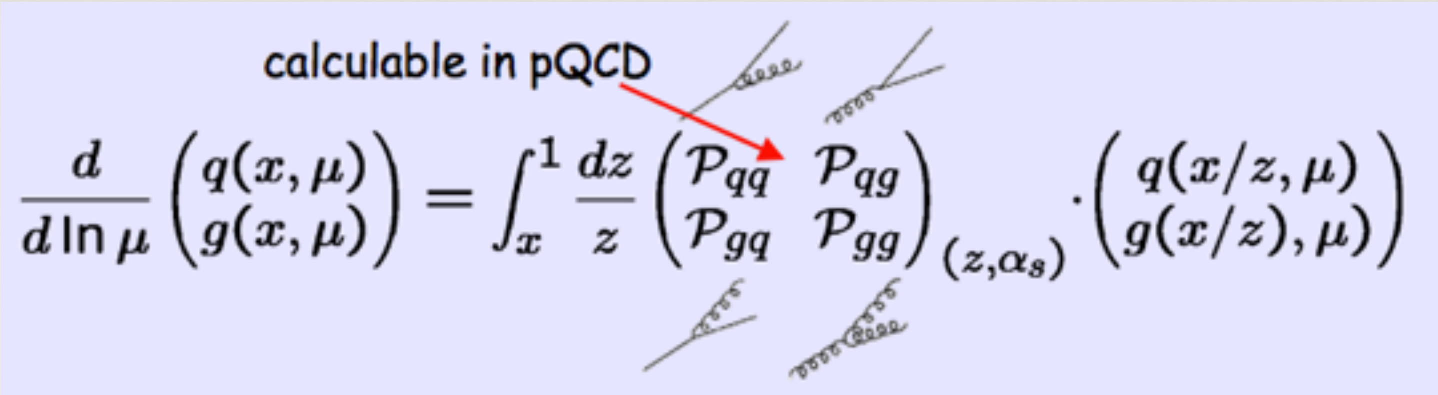
- PDFs are understood as the probability of finding a parton of a given flavour that carries a fraction x of the total proton’s momentum (at LO pQCD)



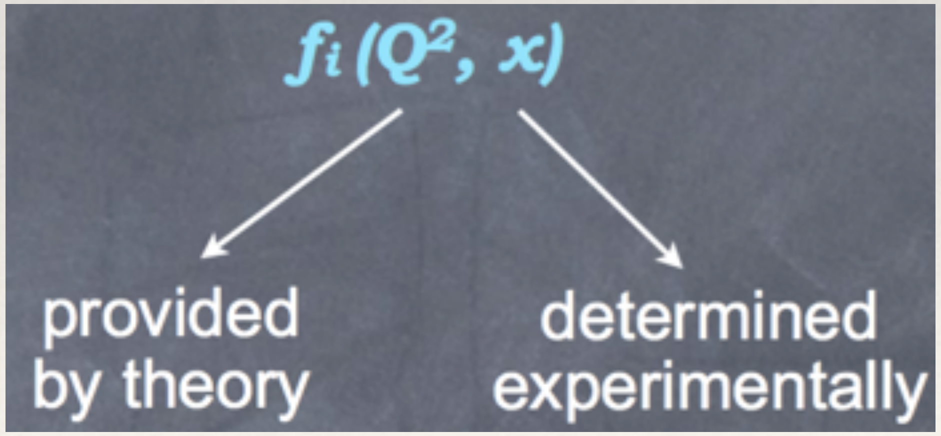


- Once QCD corrections included, PDFs become scheme dependent
  - Shape and normalisation of PDFs are very different for each flavour, reflecting the different underlying dynamics that determines them.

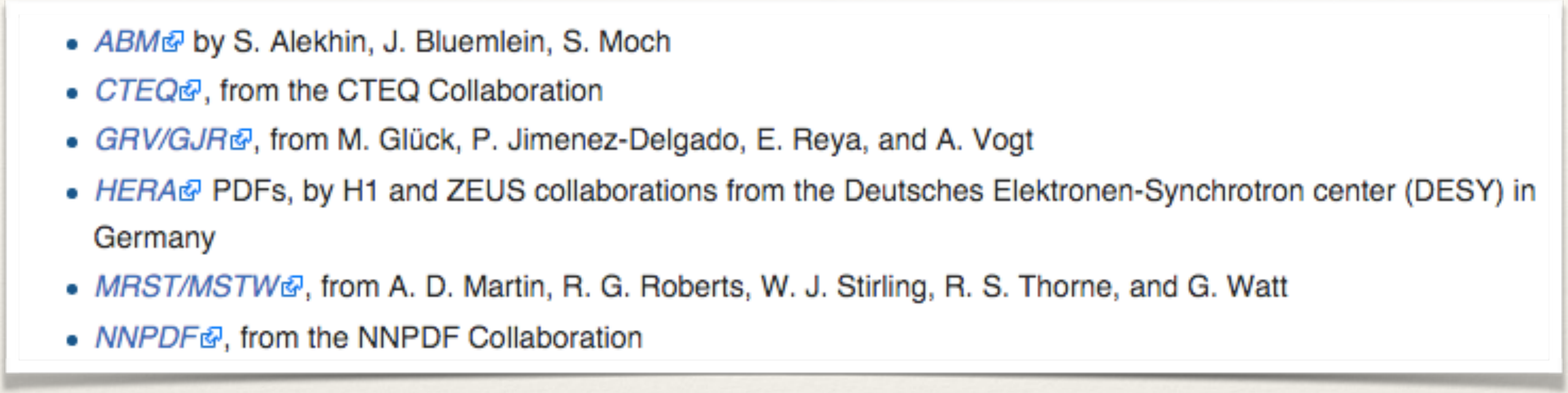
- PDFs cannot be calculated in perturbative QCD, however their evolution with the scale is predicted by pQCD [DGLAP equations]



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



PDF Sets on the market



- *ABM* by S. Alekhin, J. Bluemlein, S. Moch
- *CTEQ*, from the CTEQ Collaboration
- *GRV/GJR*, from M. Glück, P. Jimenez-Delgado, E. Reya, and A. Vogt
- *HERA* PDFs, by H1 and ZEUS collaborations from the Deutsches Elektronen-Synchrotron center (DESY) in Germany
- *MRST/MSTW*, from A. D. Martin, R. G. Roberts, W. J. Stirling, R. S. Thorne, and G. Watt
- *NNPDF*, from the NNPDF Collaboration

The analyses differ in many areas:

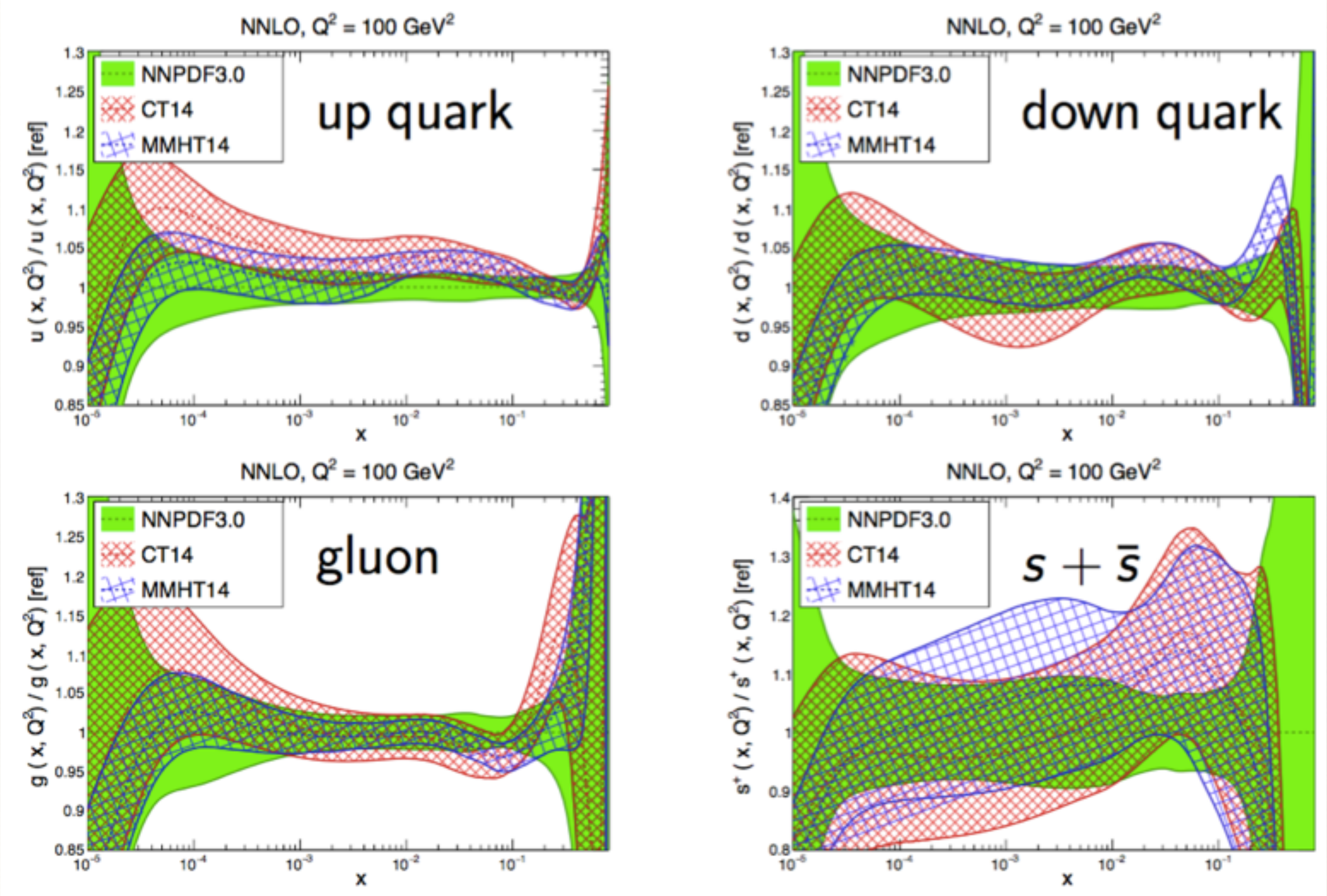
- different treatment of quark with masses
- inclusion of various data sets and account for possible tensions
- different assumption on values of strong couplings
- different assumptions in procedure (parametrisation, corrections)

*Also ATLAS and CMS provide PDFs sets to demonstrate the impact of new measurements

- … differences in PDFs lead to the differences in the cross section predictions!

Precision of current PDFs:

- [From last PDF4LHC recommendation based on GMVFNS PDFs]



in the region
10^-3- 10^-1
a precision of <10%
on PDFs

however, in the
outside this region
very uncertain
PDFs

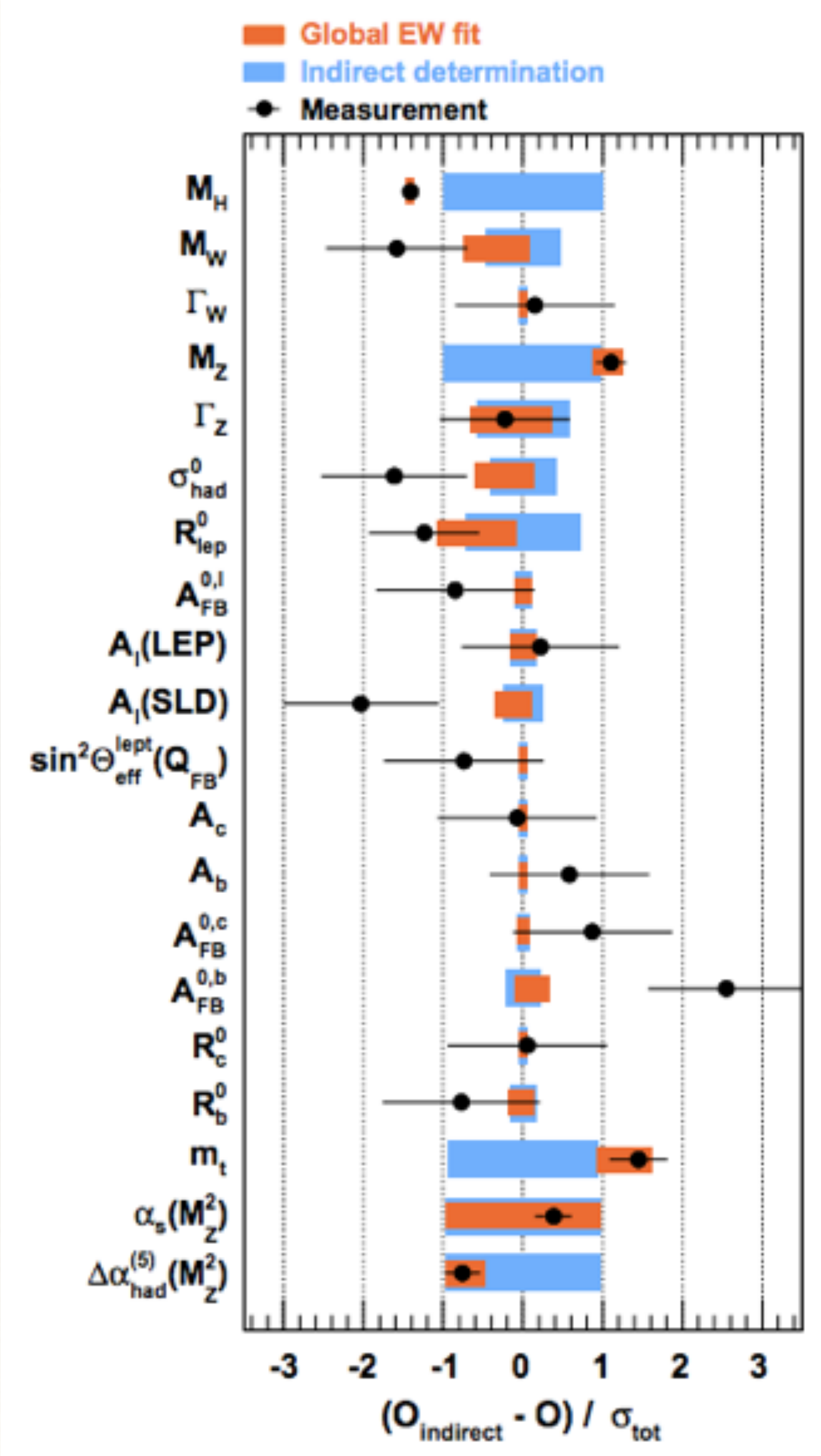
so what precision do we aim for?

Precise enough?

- Now all basic parameters of the SM are known and precision of these allows:

  —> for stringent stress test of the SM parameters

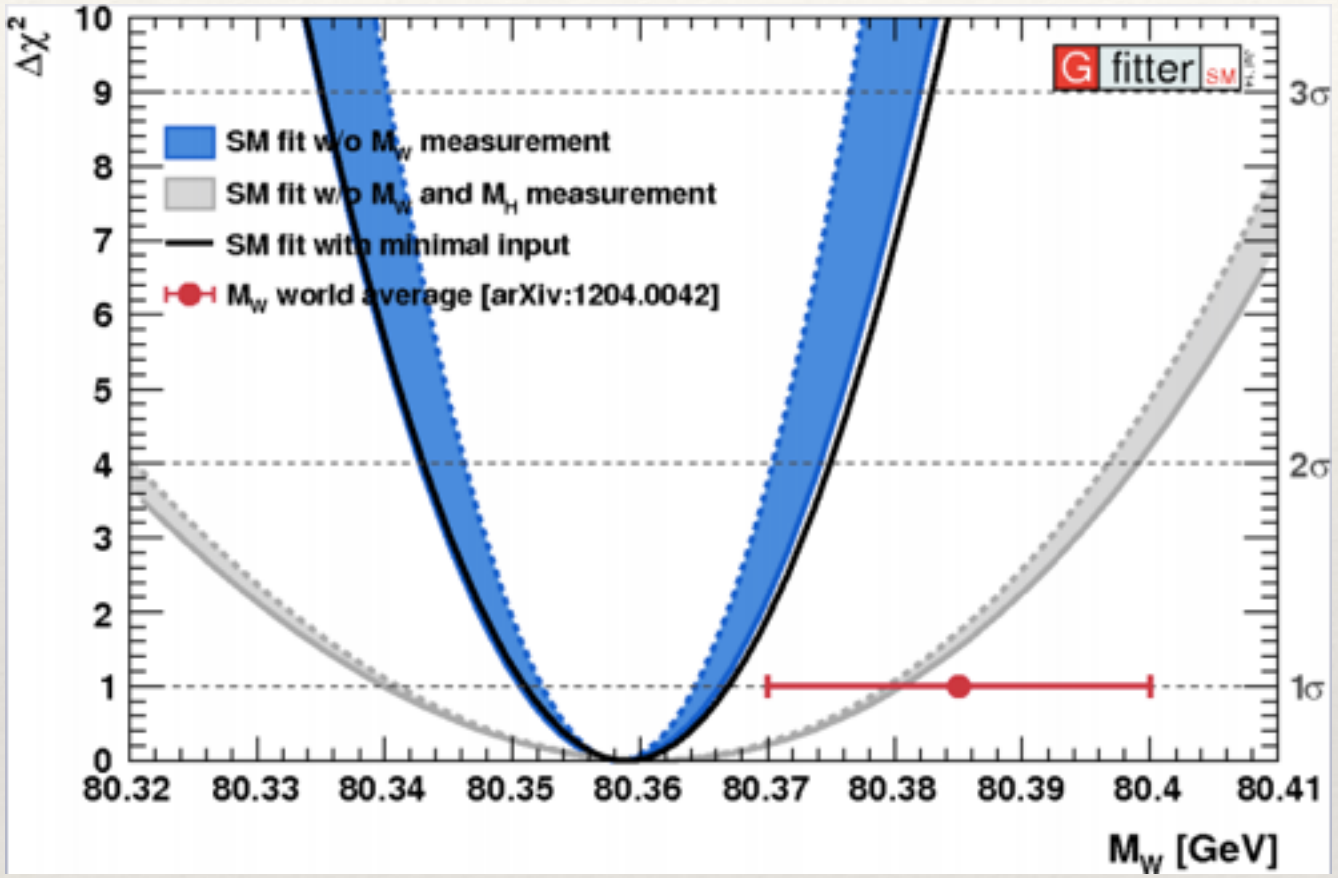
  —> look for hints of new physics (indirect)



http://arxiv.org/pdf/1407.3792v1.pdf

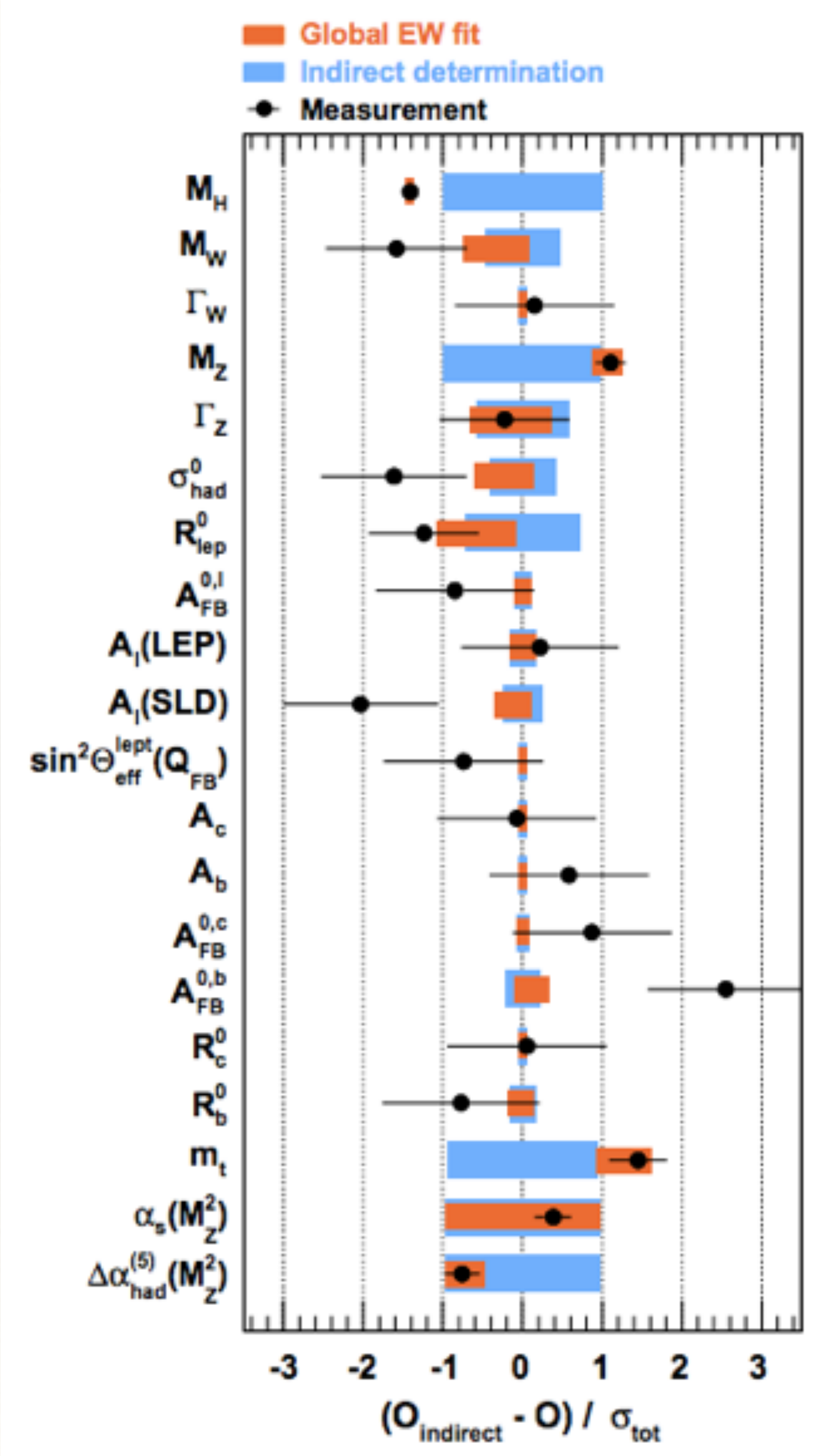
Precise enough?

- Now all basic parameters of the SM are known and precision of these allows:
  - **—> for stringent stress test of the SM parameters**
  - **—> look for hints of new physics (indirect)**



The indirect (EW fit) determination of W mass (δMW = 8 MeV) is more accurate than the measured value (δMW = 15 MeV) including the latest measurements of CDF and DØ - 1.8 sigma tension!

→ **natural goal at the LHC would be δMW < 10 MeV**

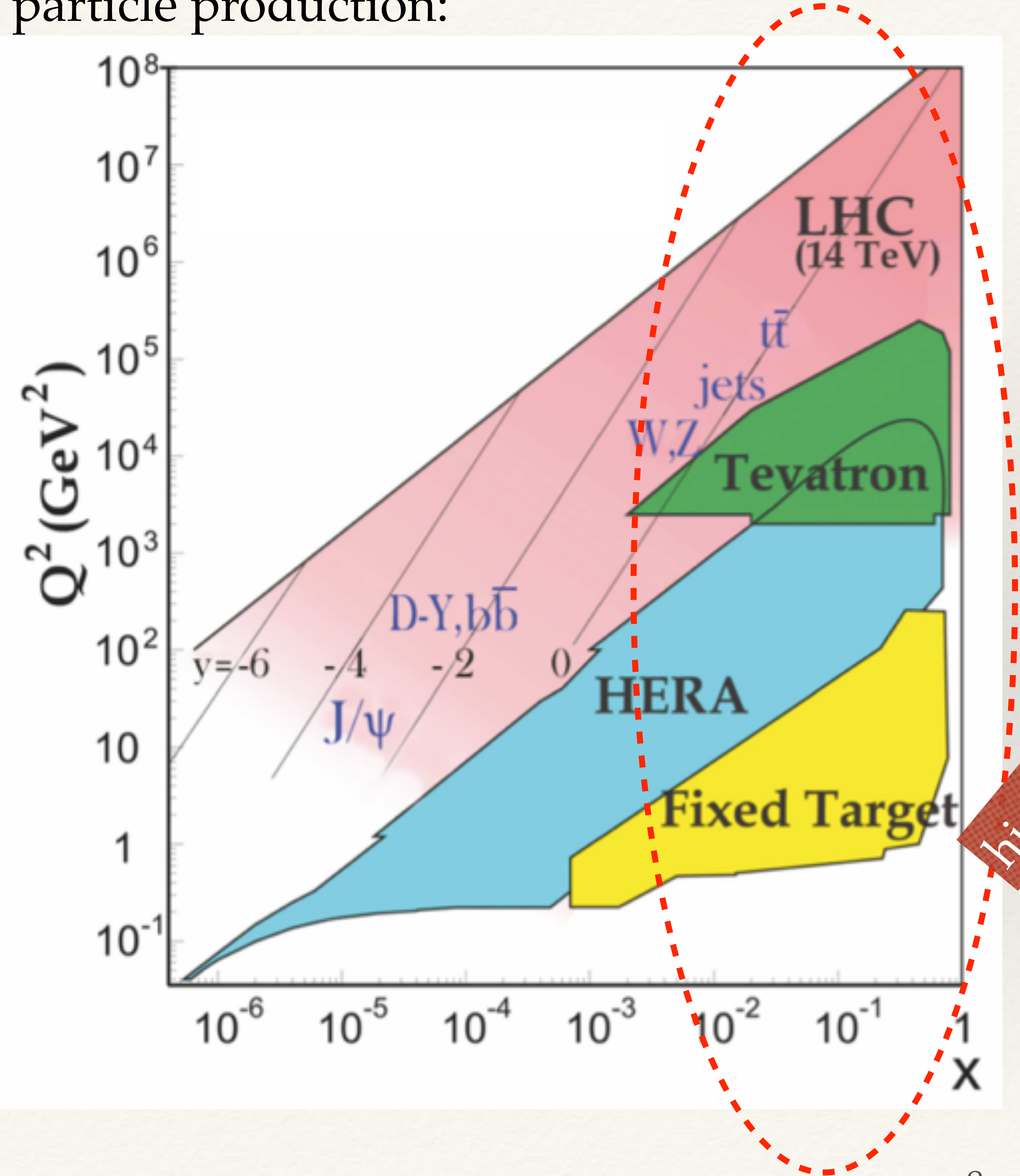


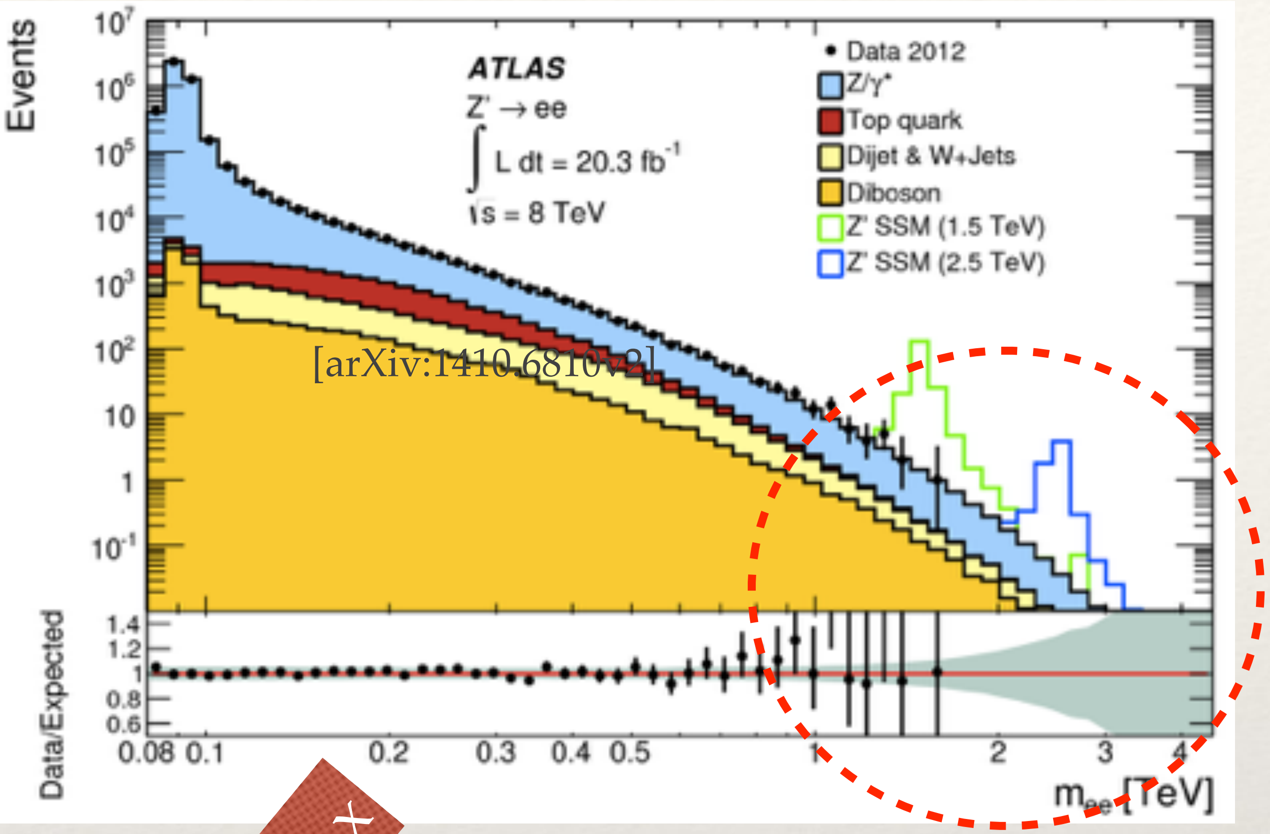
http://arxiv.org/pdf/1407.3792v1.pdf

PDF represents the dominant uncertainty

Role of PDFs in BSM heavy particle production

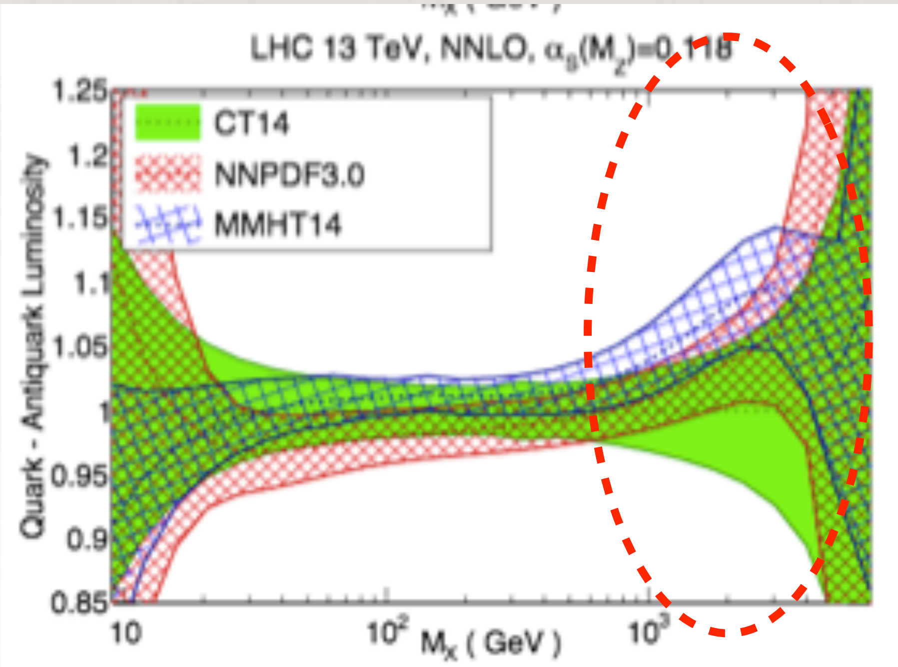
PDFs are the dominant uncertainty in heavy particle production:





[arXiv:1410.6810v2]

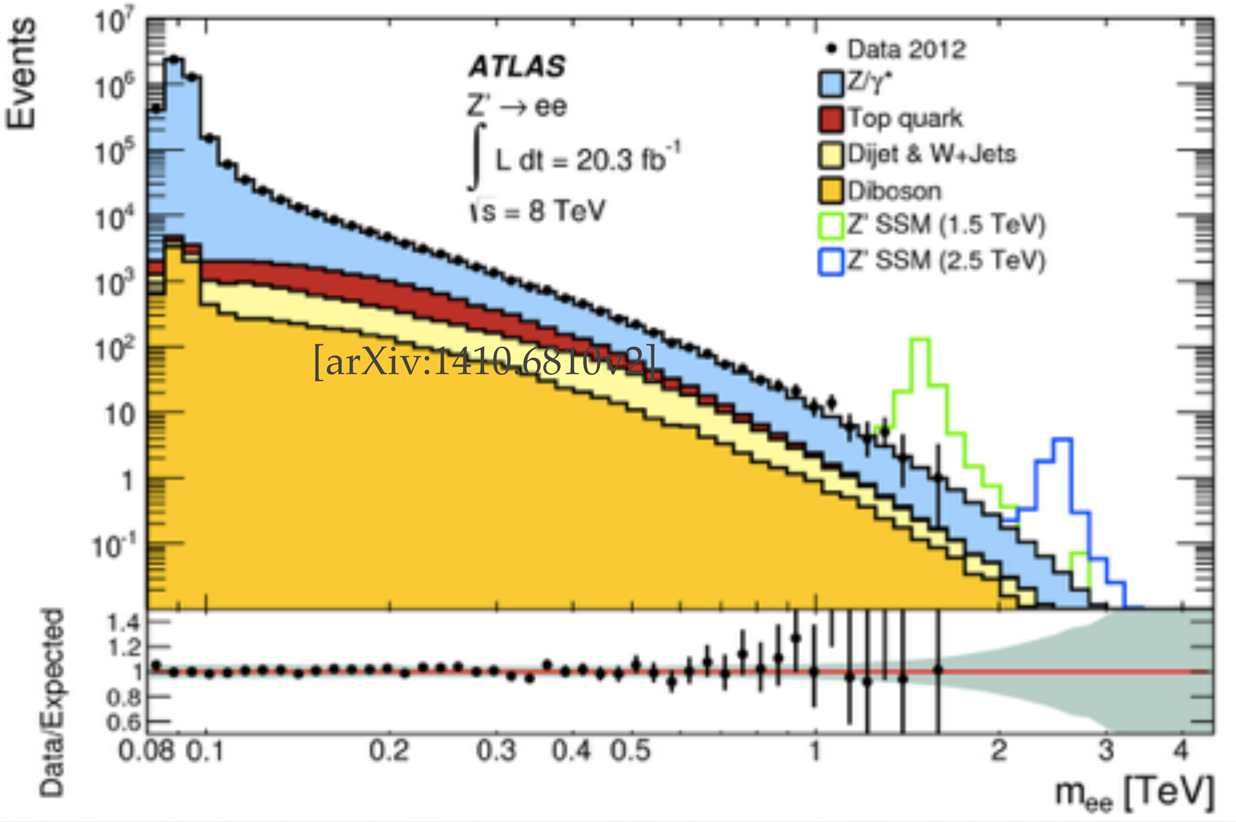
high mass <—> high x



Role of PDFs in BSM heavy particle production

PDFs are the dominant uncertainty in heavy particle production:

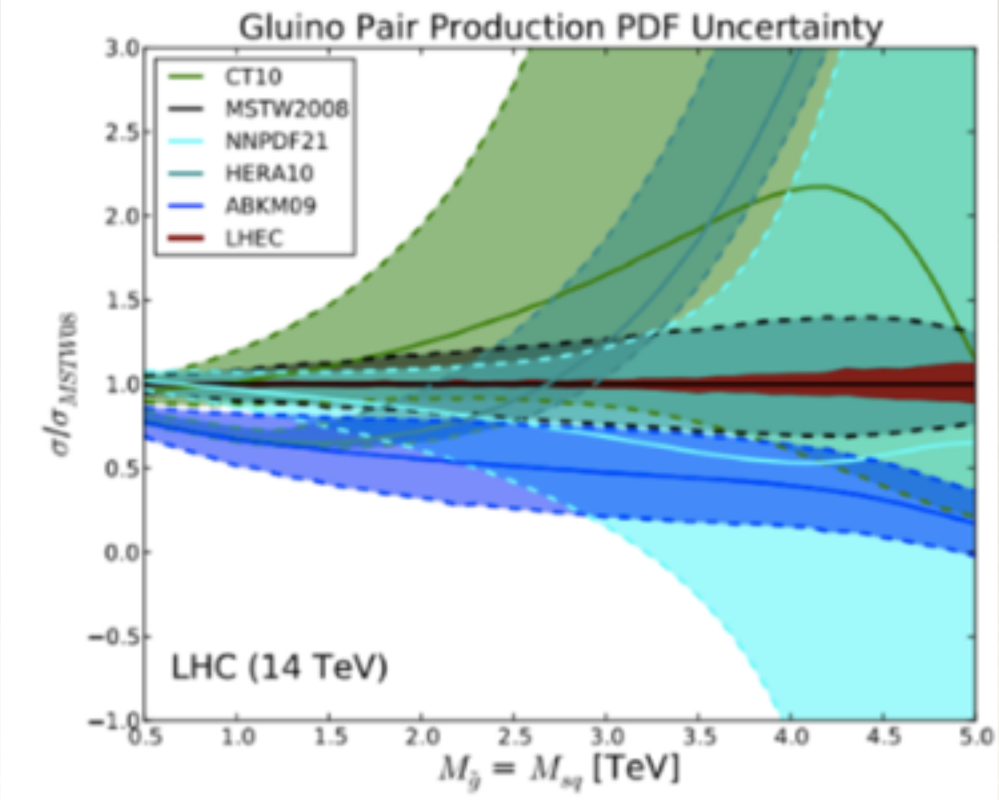
- invariant mass distributions with two selected heavy particles Z′ signals



[arXiv:1410.6810v2]

Very large PDF uncertainties for heavy particle production
-> from differences among various PDFs
-> from imprecision of PDFs at high x

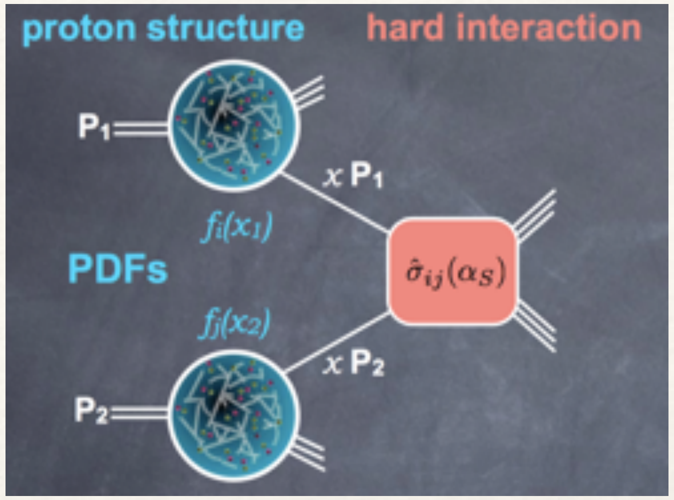
Gluino signal is not detectable beyond 2 TeV with current PDF uncertainties (blue-green)
—> need high x precision (e.g. burgundy: LHeC potential)



Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation:

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



Main Steps:

$$xf_j(x) = A_j x^{B_j}(1-x)^{C_j}P_j(x)$$

with $P_j(x) = (1+\varepsilon_j\sqrt{x}+D_jx+E_jx^2)$

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 χ^2
6. Minimise χ^2 with respect to PDF parameters

—> it takes about ~2000 iterations:

—> it is crucial to have fast tools, i.e. fastNLO, APPLGRID

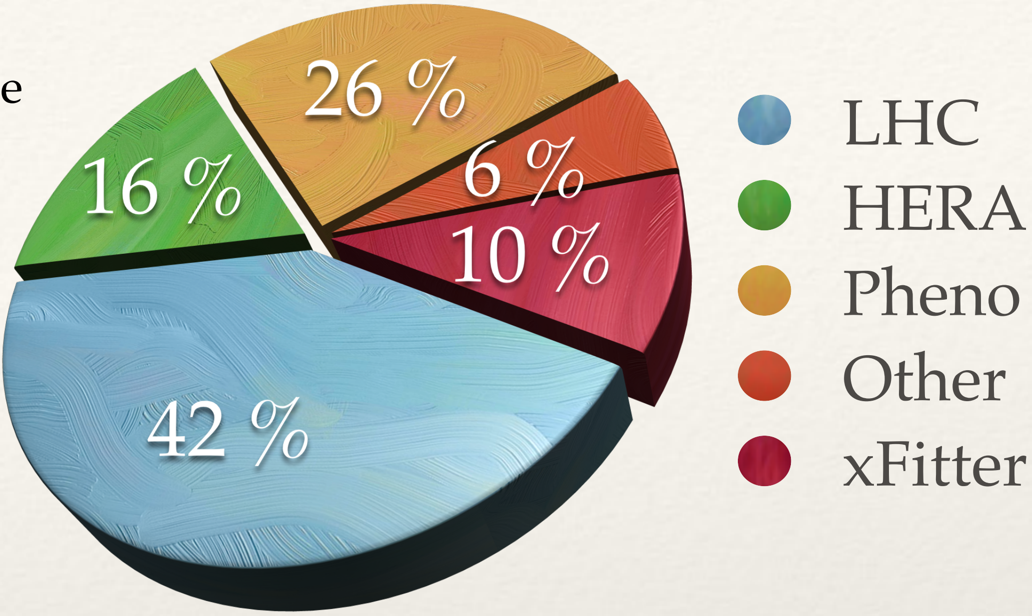
xfitter.org: open source QCD platform

arxive:1503.05221

xFitter (former HERAFitter) www.xfitter.org

- **2011 Open Source Revolution:** EPJC (2015), 75
  - Establishing the first open source QCD Fit Platform which started the wave of sharing QCD fit codes
  - From sole developer to a growth of ~30 developers:
    - LHC/HERA/theory/independent
    - several releases since 2011 —> **xfitter-1.2.0**
    - ~30 publications that have used the framework

synergy between experiment and theory groups



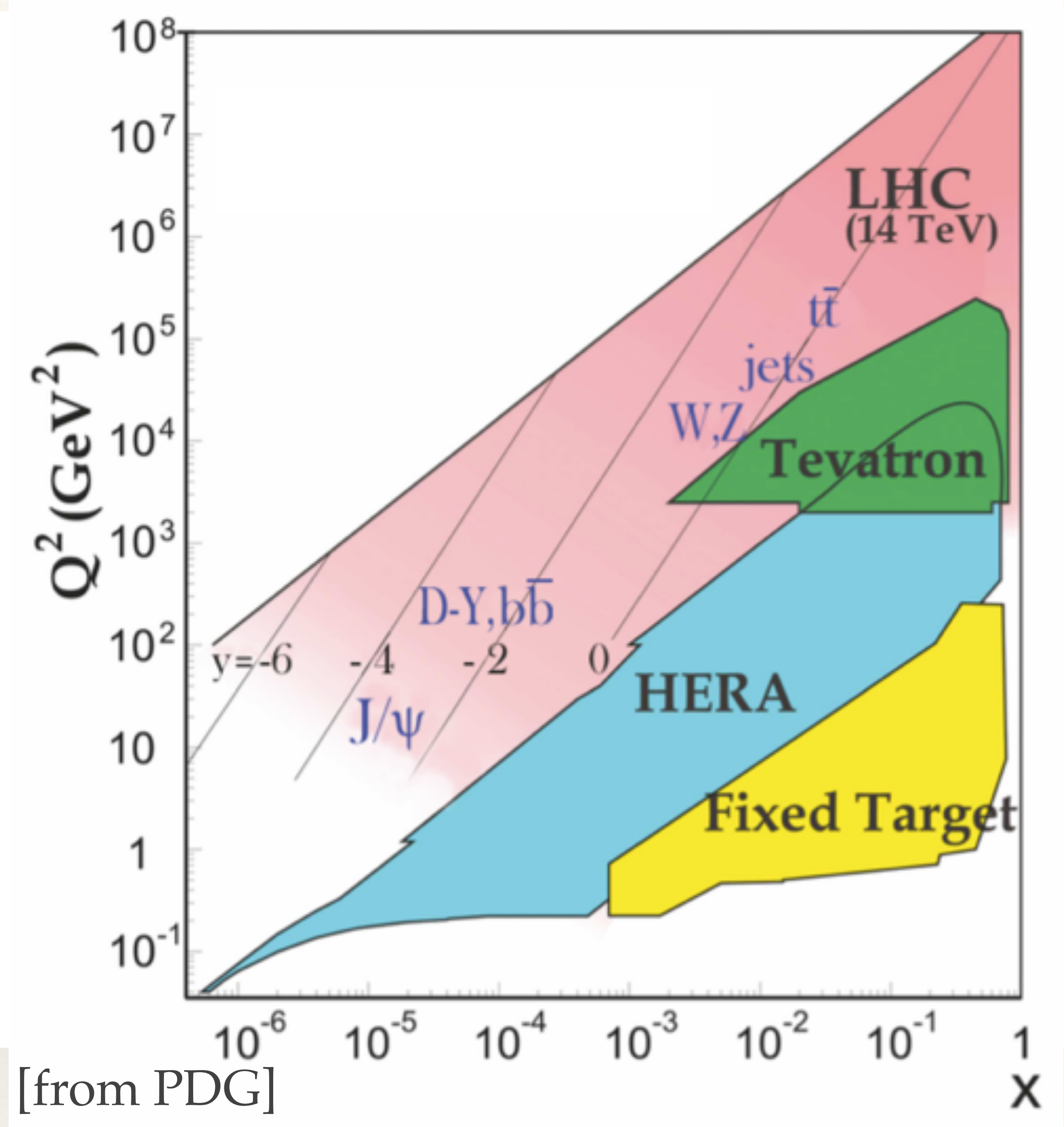
- **provides a unique QCD framework to address theoretical differences:**

  —> benchmark exercises/collaborative efforts/topical studies
- **provides means to the experimentalists to optimise the measurements:**

  —> assess impact/consistency of new data

- **Dedicated studies [xFitter developers]**
  - method in preserving correlation between PDFs extracted at different orders in pQCD EPJC (2014) 74
  - address consistency of Tevatron measurement and evaluate their collective impact on valence EPJC (2015), 75
  - determination of the running mass in MS scheme (ongoing)

Today's data on proton structure

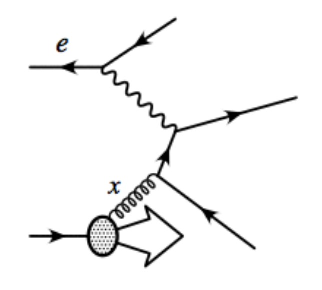


[from PDG]

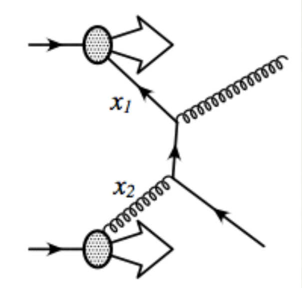
Q2: resolving power of experiment
x: fraction of proton's momentum

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

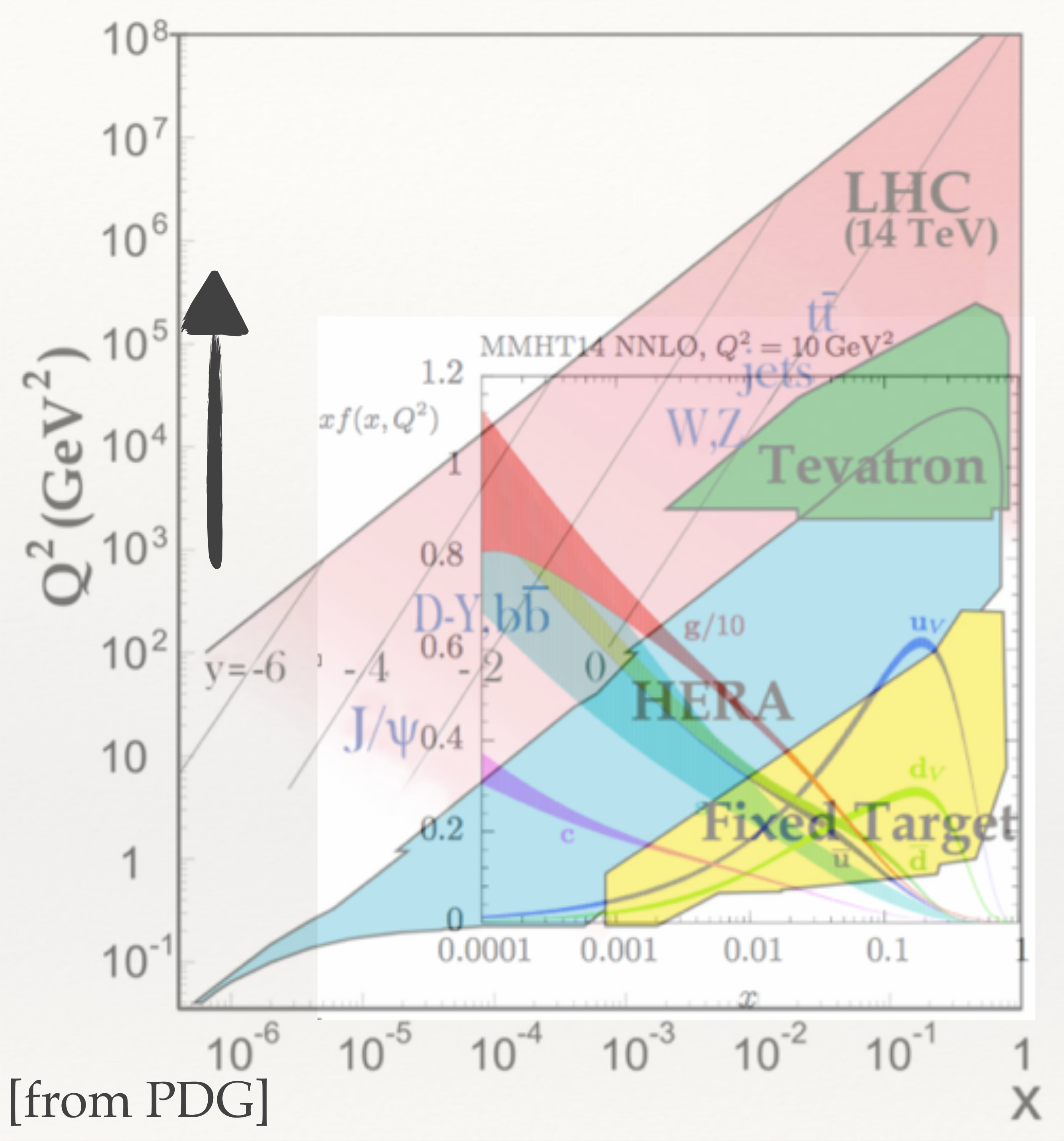
- The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:



- Precision of proton structure can be complemented by the Drell Yan [DY] processes at the collider experiments



Today's data on proton structure

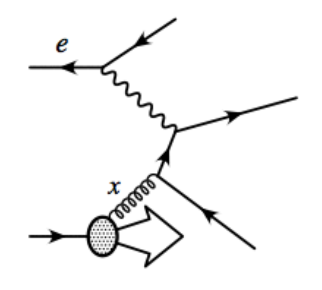


[from PDG]

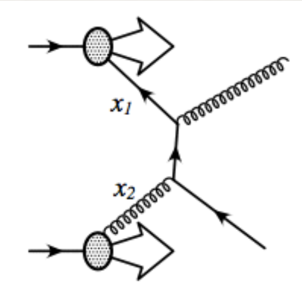
Q2: resolving power of experiment
x: fraction of proton's momentum

Different data constrain different parton combinations at different x, evolution with the scale is predicted by pQCD:

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

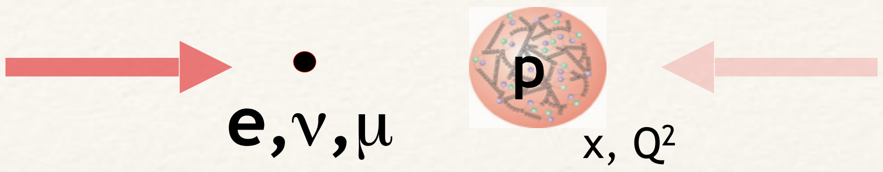


- Precision of proton structure can be complemented by the Drell Yan [DY] processes at the collider experiments

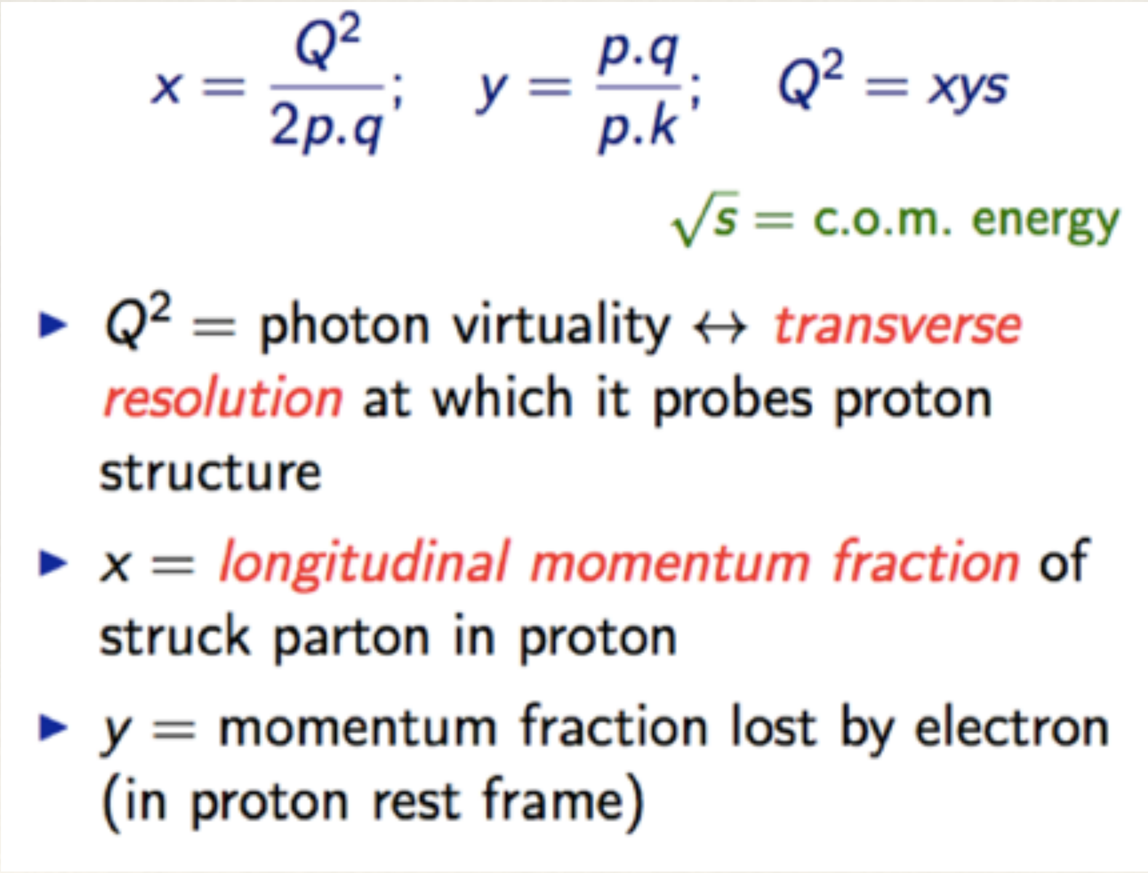


Probing the Proton Structure

- Start with something simpler: Deep Inelastic Scattering (DIS)
  - Proton can be probed via elementary particles as electrons, muons, neutrinos:



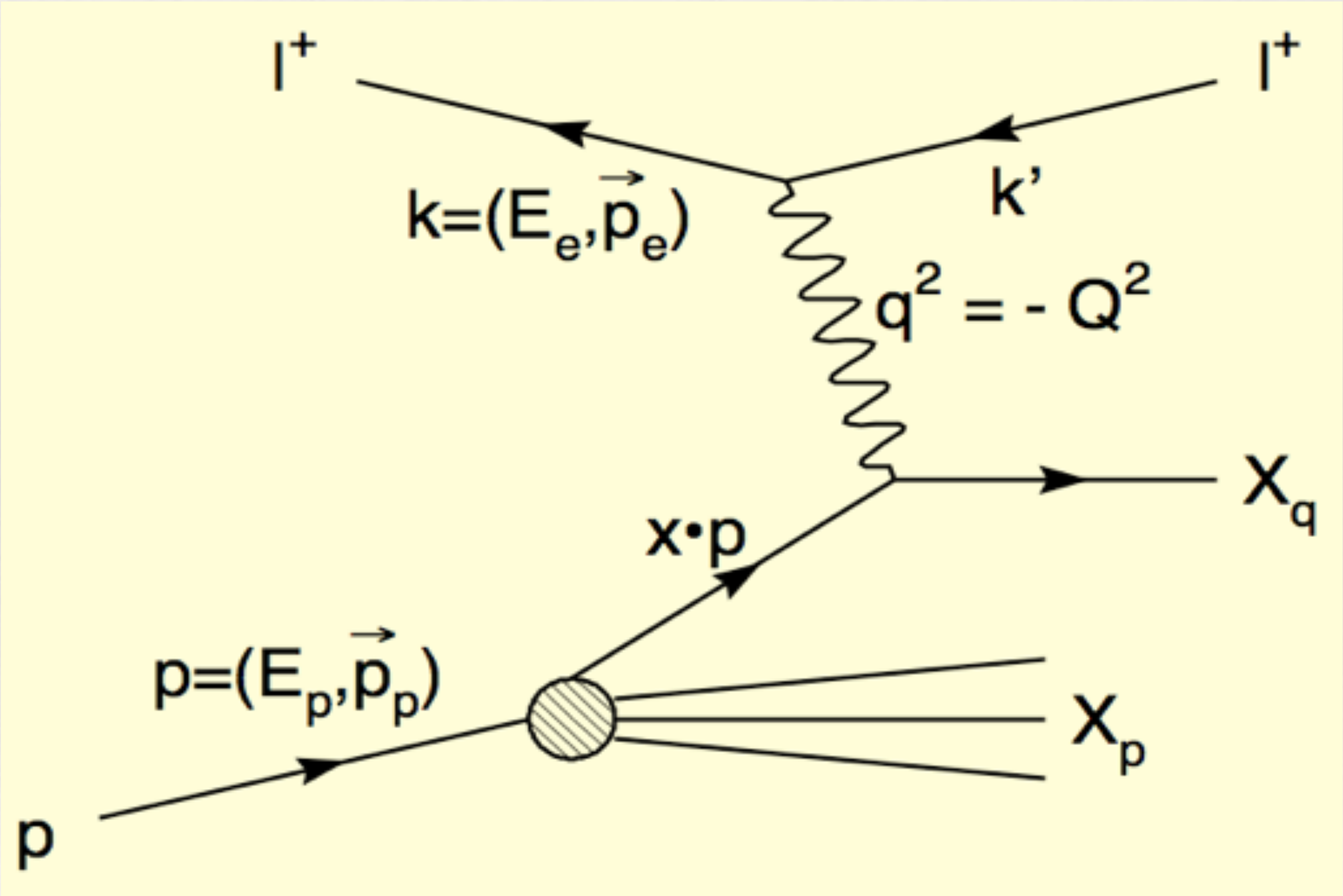
- Kinematic relations:



$$x = \frac{Q^2}{2p.q}; \quad y = \frac{p.q}{p.k}; \quad Q^2 = xys$$

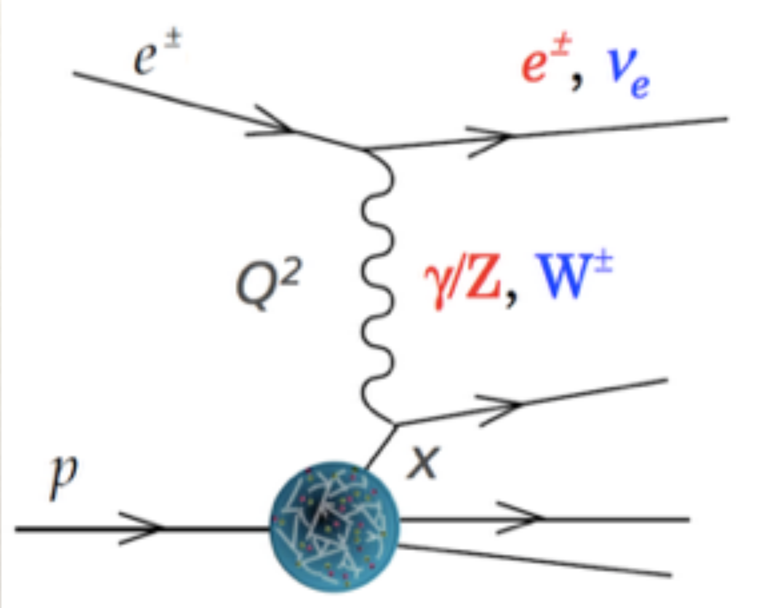
$\sqrt{s}$ = c.o.m. energy

- Q^2 = photon virtuality ↔ *transverse resolution* at which it probes proton structure
- x = *longitudinal momentum fraction* of struck parton in proton
- y = momentum fraction lost by electron (in proton rest frame)



HERA ep collider (1992-2007) @ D

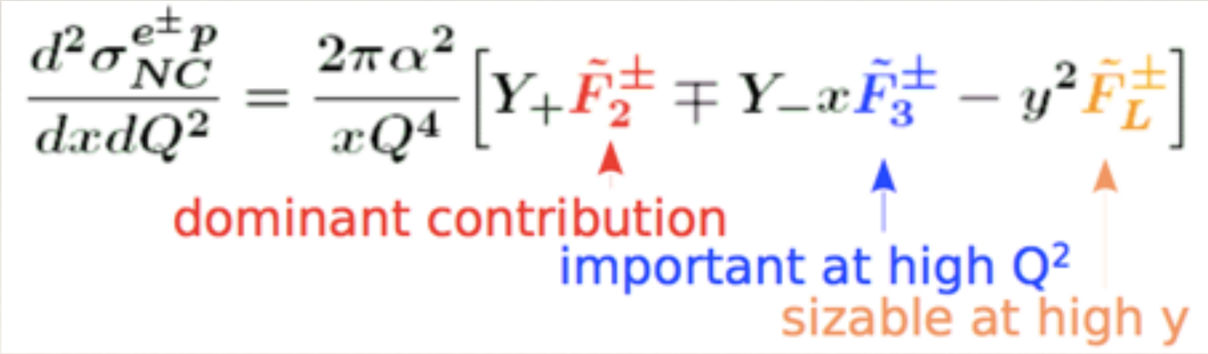
- H1 and ZEUS experiments at HERA collected ~1/fb of data
  - Ep=460/575/820/920 GeV and Ee=27.5 GeV
- 4 type of processes accessed at HERA: **Neutral Current and Charged Current ep**



Determination of the Event Kinematics:

- using lepton information (E_e',θ_e)
- using hadronic final state particles
- using both lepton and hadronic final state variables

$$s = 4E_eE_p$$
$$Q^2 = E_eE'(1+\cos\theta_e)$$
$$y = 1 - \frac{E'}{E_e}\frac{1}{2}(1-\cos\theta_e)$$
$$x = \frac{Q^2}{sy}$$

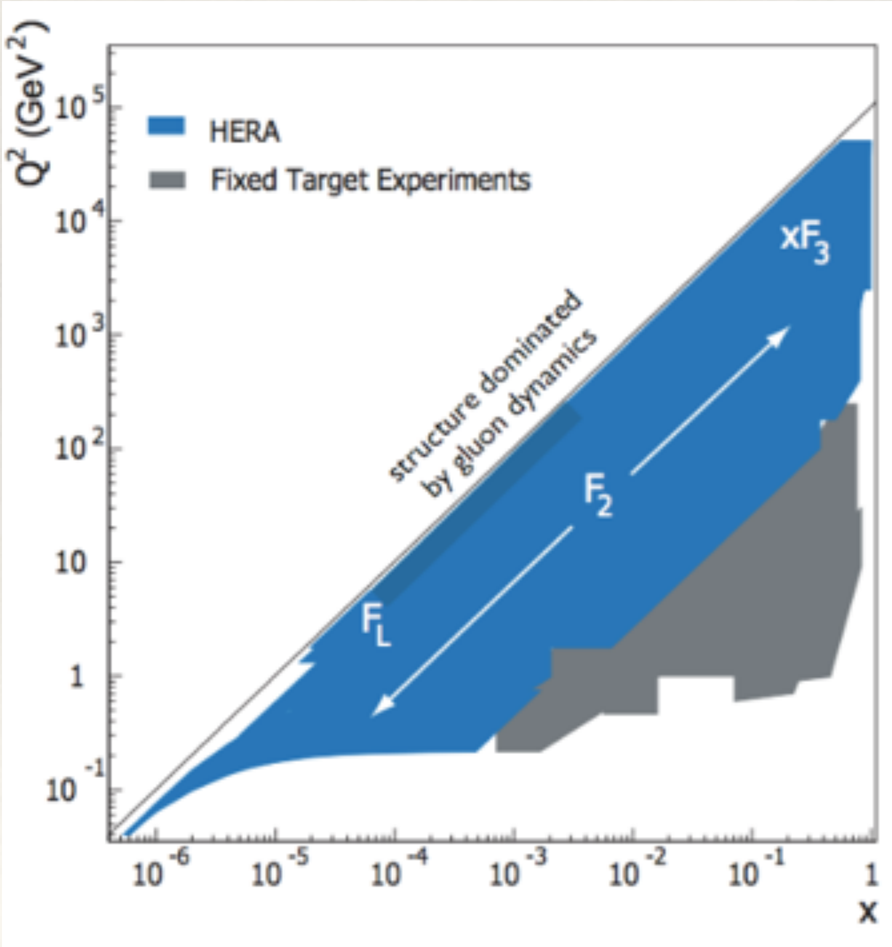


$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\pm} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}\right]$$

dominant contribution

important at high Q^2

sizable at high y



HERA's last word

FINAL HERA I+II inclusive data combination [arxiv:1506.06042]

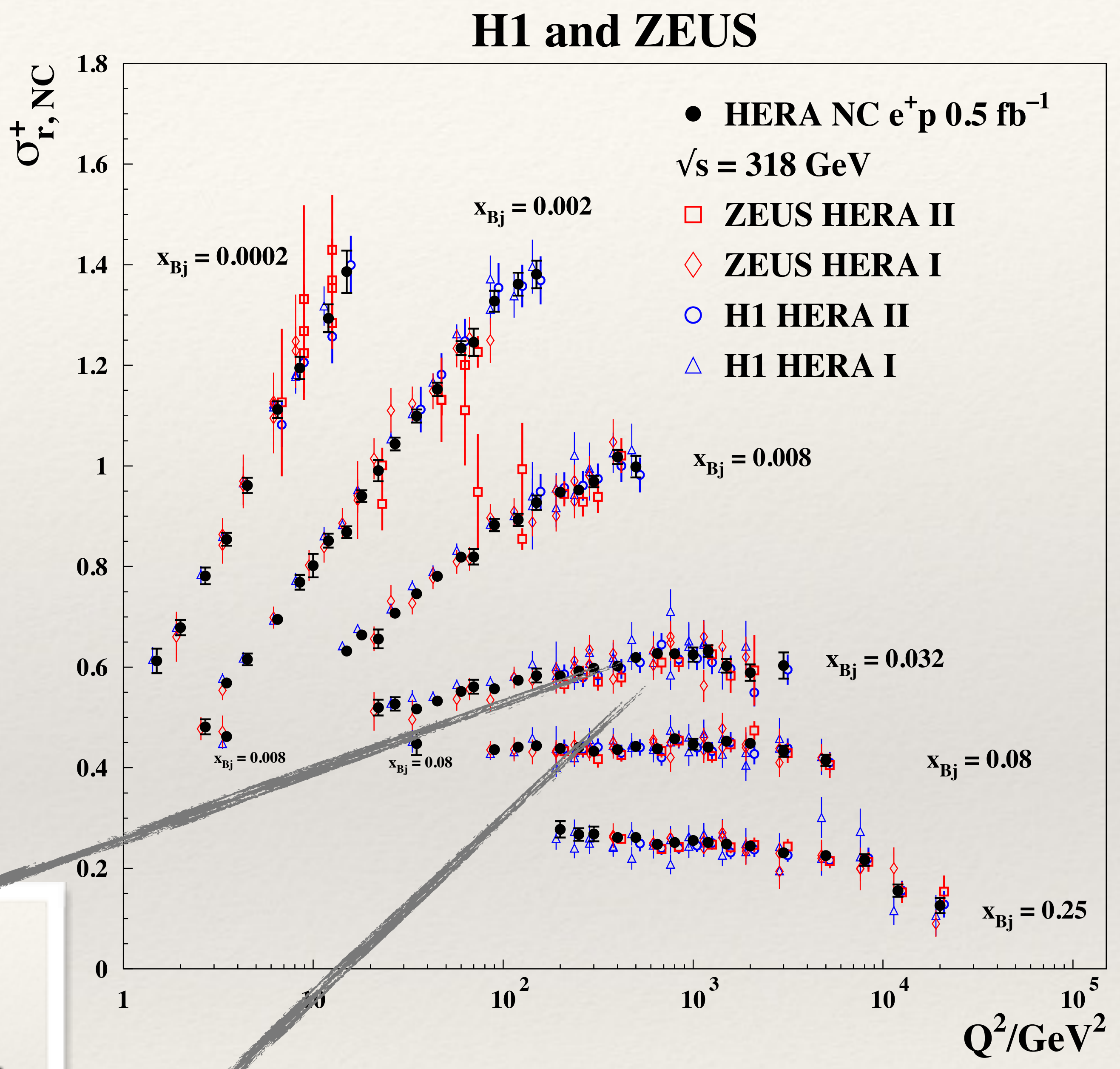
- Ultimate precision is obtained by combining the H1 and ZEUS measurements

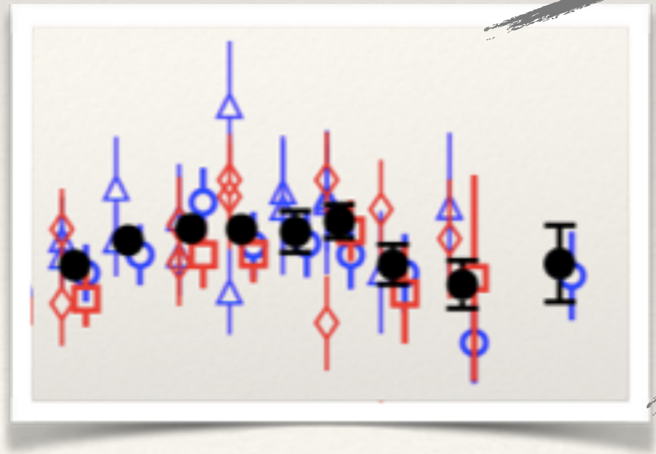
$0.045 < Q^2 < 50000$ GeV^2 $\quad$ $6.\,10^{-7} < x_{Bj} < 0.65$

- The combination procedure is performed before QCD analysis using χ^2 minimisation
    - χ^2 / dof =1687/1620

- Improvement on Statistical precision
- Improvement of Systematic precision

—> total uncertainty < 1 % for Q2 up to 500 GeV2





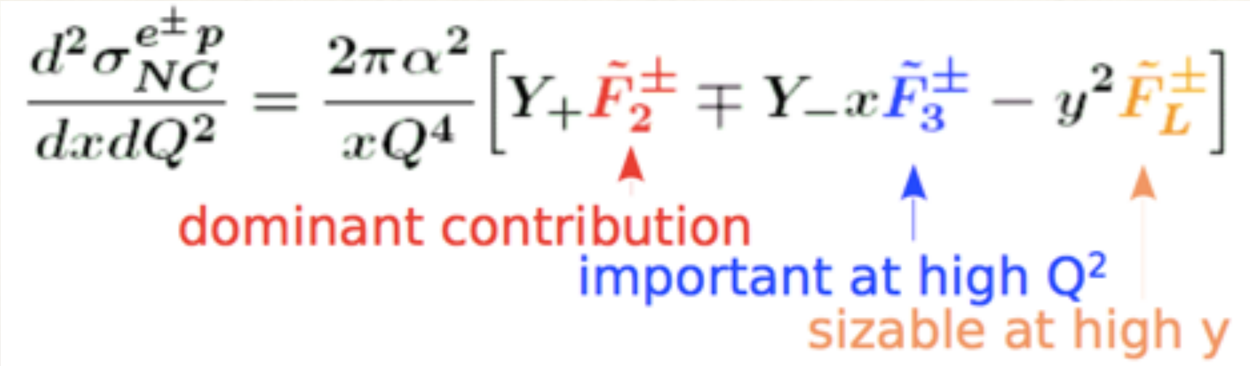
$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^\pm p}_{\mathrm{NC}}}{dx_{\mathrm{Bj}}dQ^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}}$$

HERA data is the backbone of any precision PDF

PDFs from HERA - HERAPDFs

HERAPDF uses only HERA data from the combined H1 and ZEUS measurements:

—>an interesting set to test PDF universality



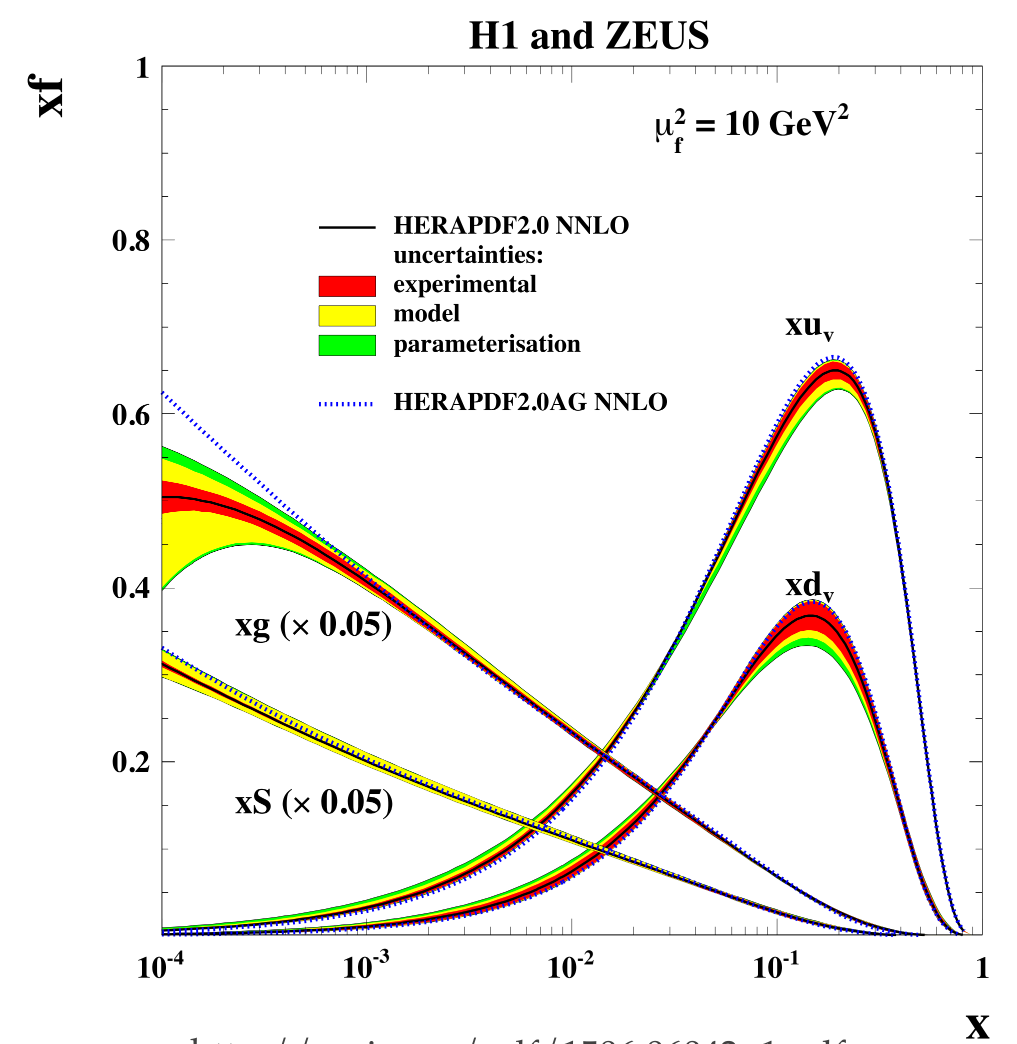
$$\frac{d^2\sigma^{e^\pm p}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

dominant contribution

important at high Q^2

sizable at high y

- HERA data can constrain:
    - sum of all quarks (through F2)
    - valence (through xF3)
    - gluon from scaling violations



http://arxiv.org/pdf/1506.06042v1.pdf

- HERAPDF sets were extracted using xFitter open source platform [xfitter.org, arxive:1503.05221]

Different types of PDF uncertainties are considered:

- **From the experimental precision**
- **From the input model ansatz**
- **From the parametric form assumed**

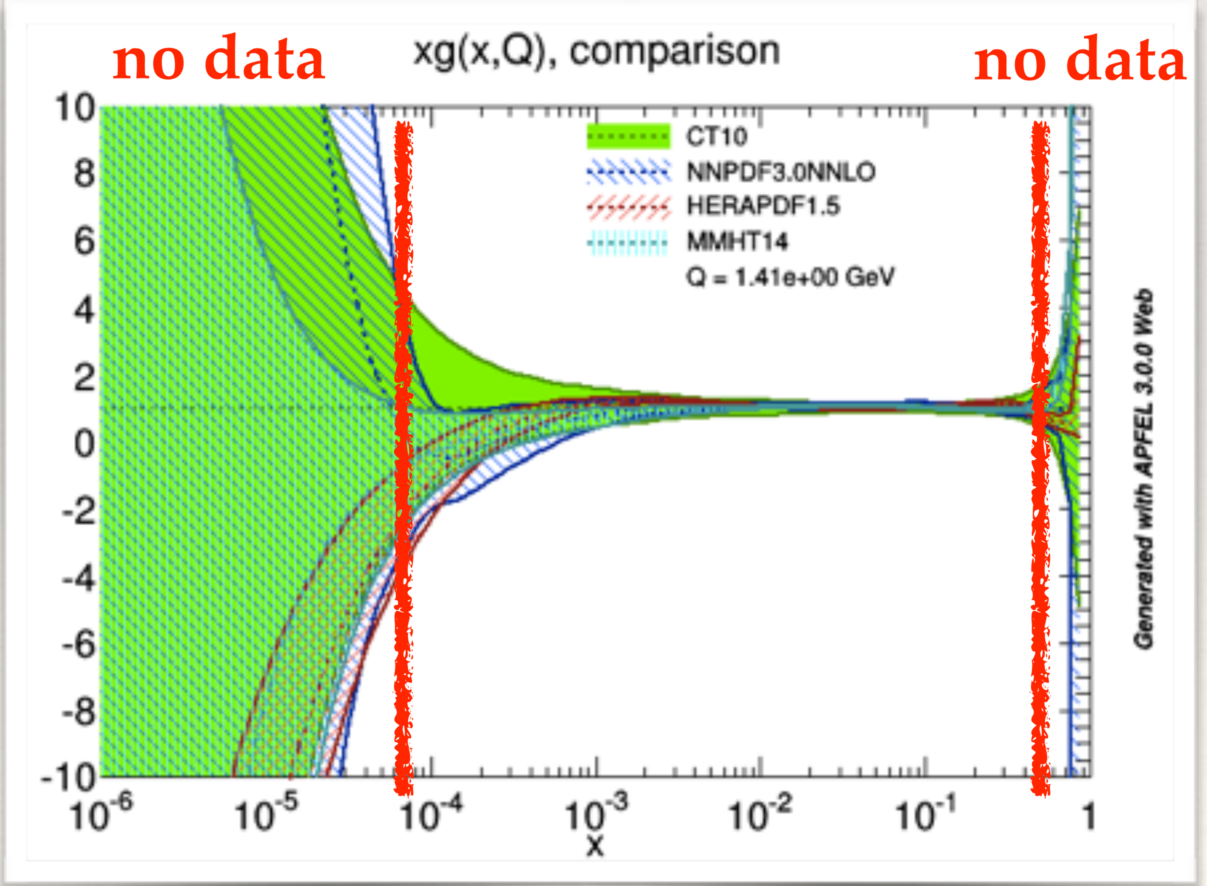
PDFs from HERA - HERAPDFs

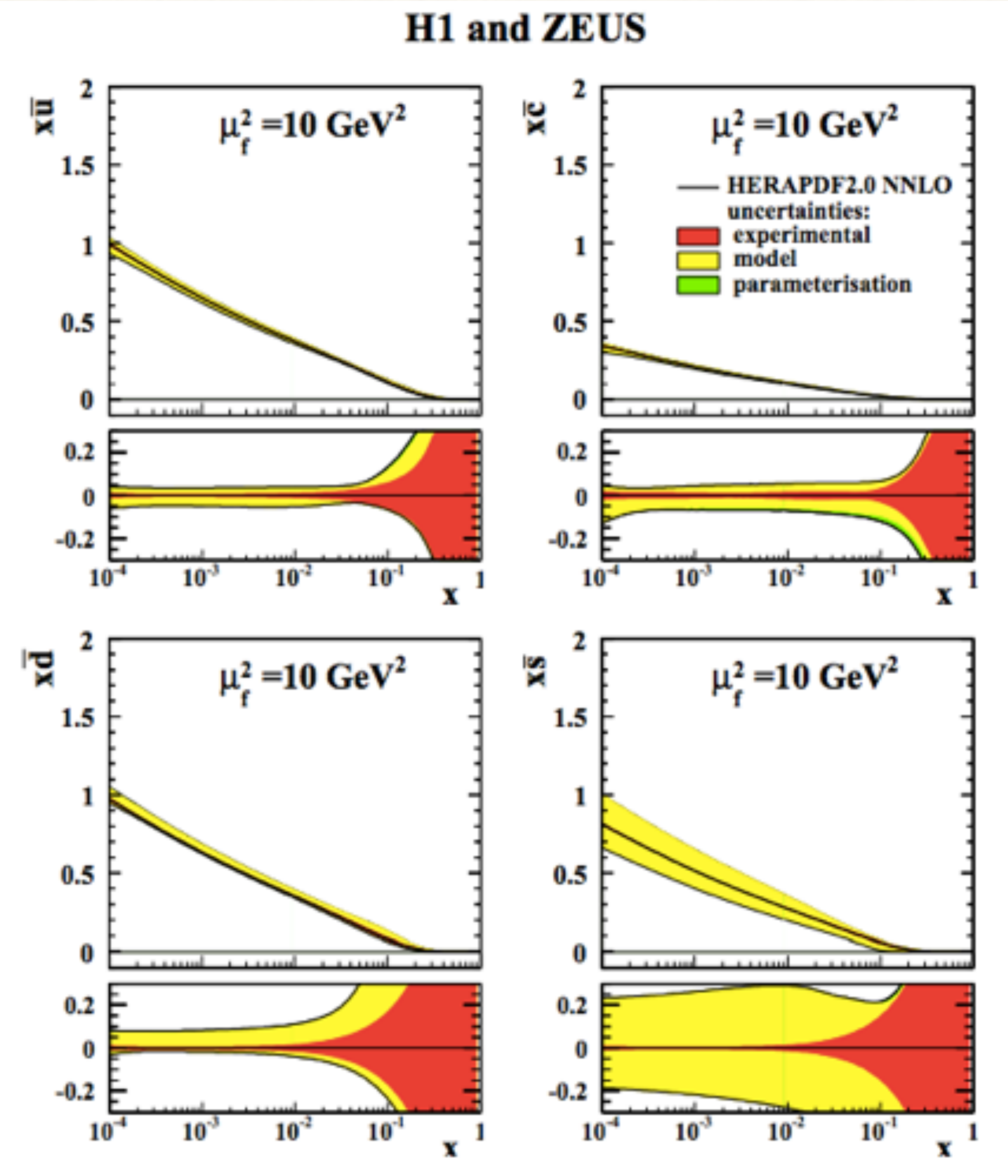
However, PDFs extracted from HERA:

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

Ansatz:

- ubar=dbar as x—>0
- sbar~0.7*dbar (suppressed strange)



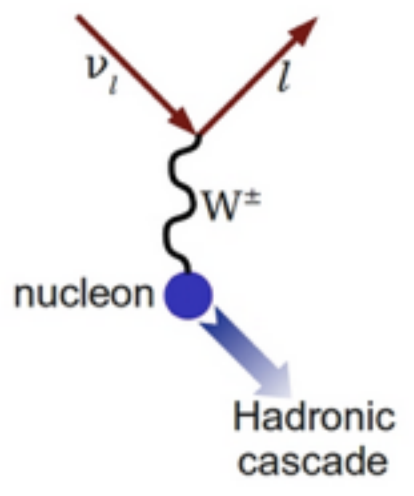


http://arxiv.org/pdf/1506.06042v1.pdf

PDF constraints from Neutrino Experiments

- Neutrino fixed target experiments (DIS) provide valuable constraints on PDFs:

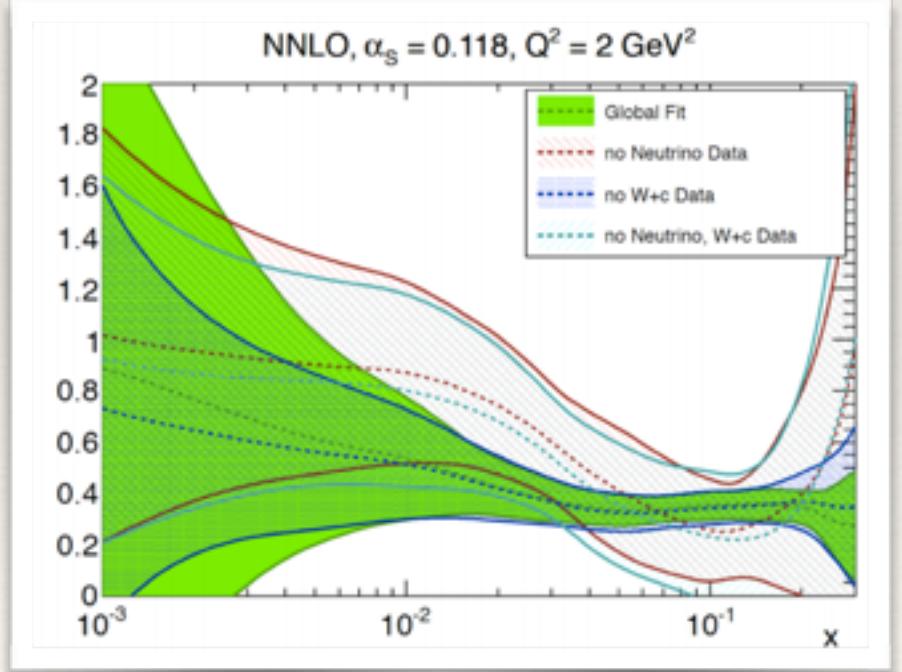
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}\right)F_2^{\nu(\bar{\nu})} + \frac{y^2}{2}2xF_1^{\nu(\bar{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\bar{\nu})}\right]$$



  - direct access to xF3 —> constraints on valence quarks
  - **direct access to s, sbar via dimuon data**
- Neutrino data is included in the global PDF analyses:

impact on sbar/dbar if there is NO neutrino data

sbar/dbar



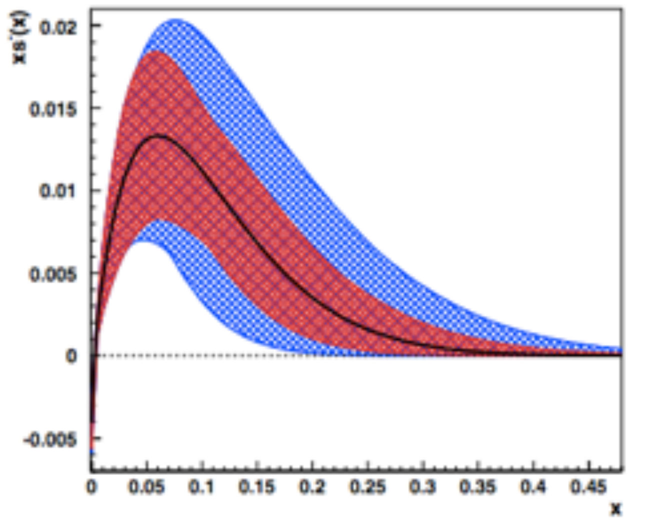
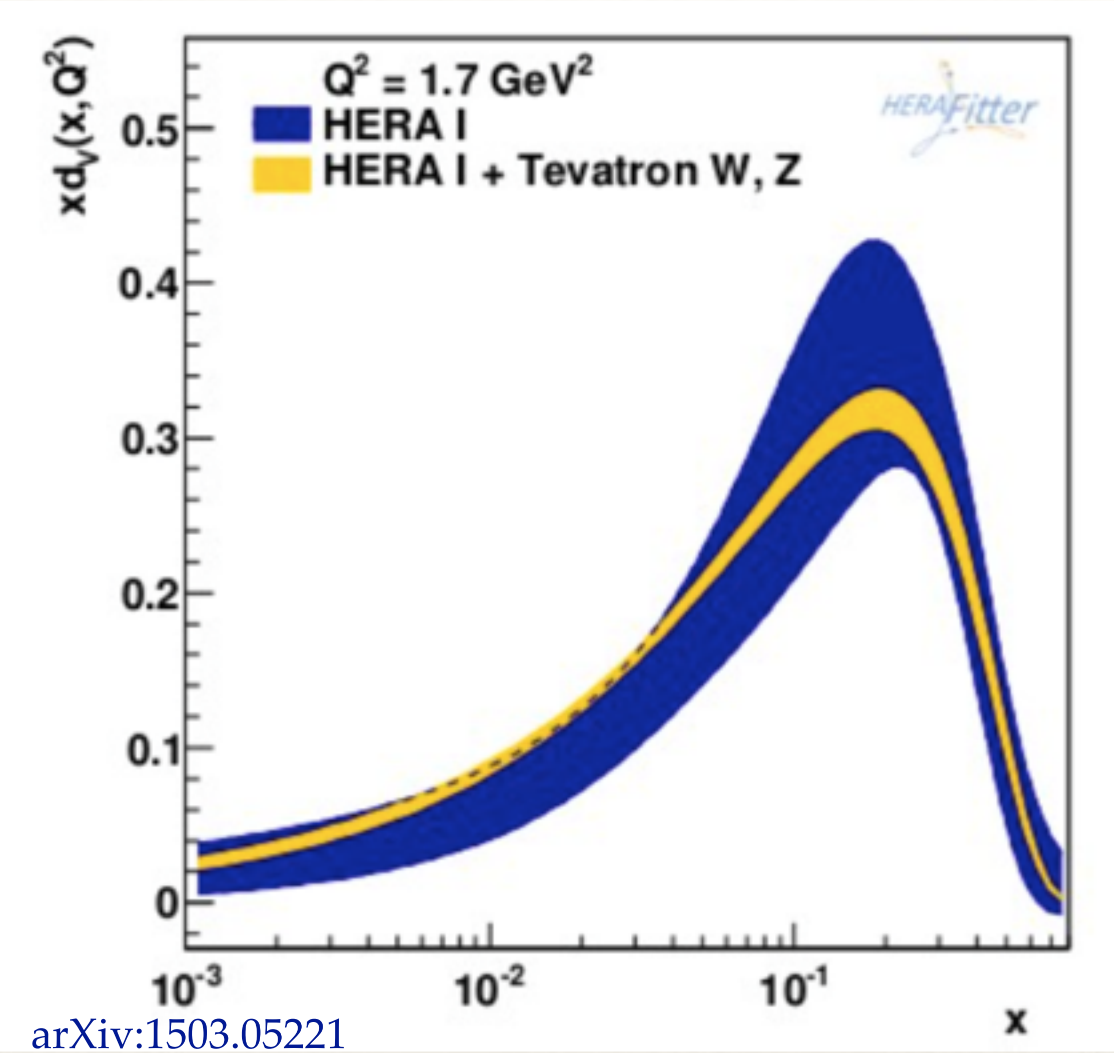


FIG. 3 (color online). $xs^-(x)$ vs x at $Q^2 = 16$ GeV^2. Outer band is combined errors; inner band is without B_c uncertainty.

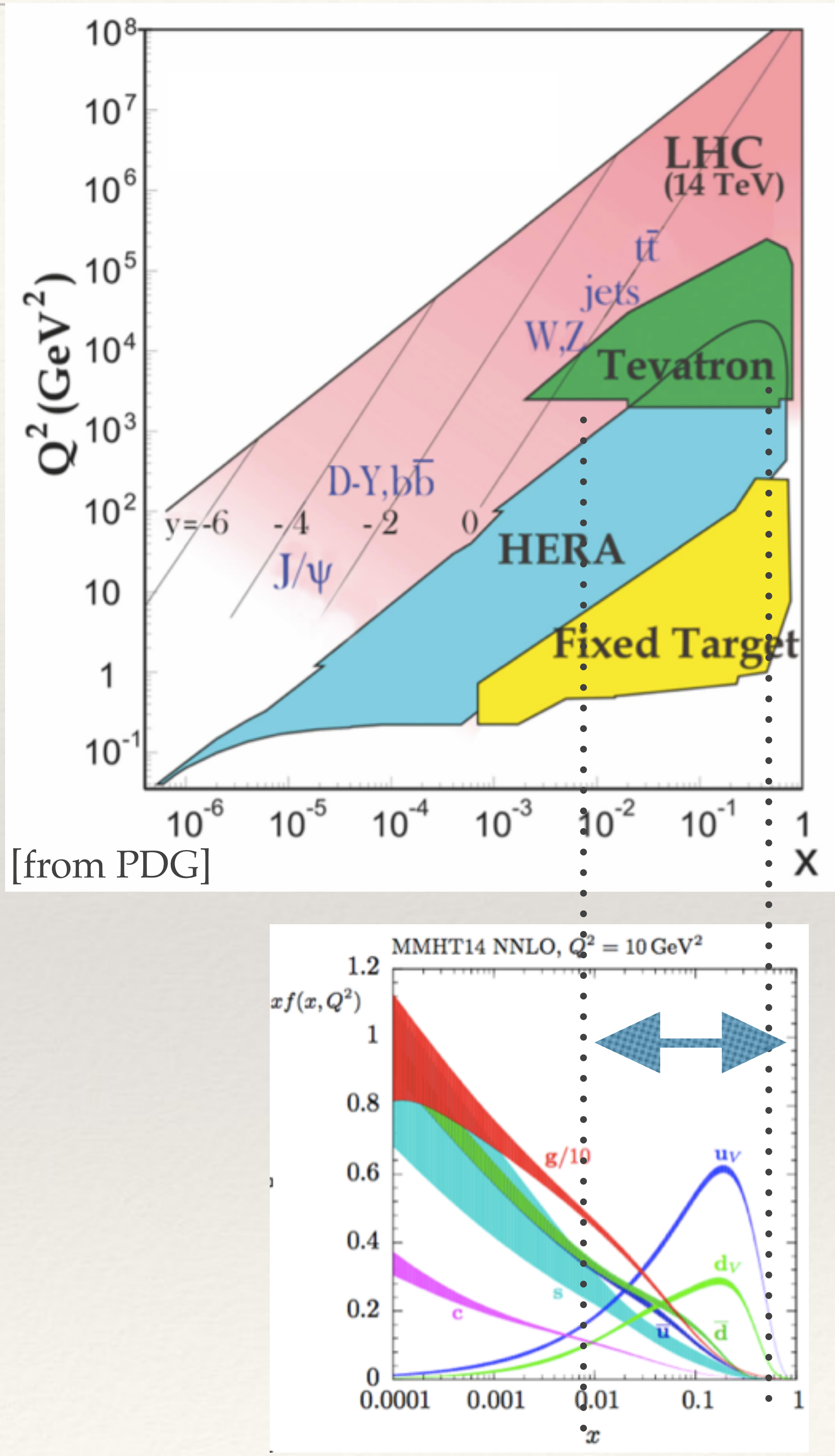
- However, care must be given to account for the nuclear medium (not a free proton) and low energy domains
  - extensive efforts in understanding nuclear effects, higher twist, target mass (Minerva, JLAB)

Constraints on PDFs from ppbar collider at Tevatron

- In proton-antiproton collisions at Tevatron, DY processes of W and Z production are valence-quark dominated
  - —> they can be used to improve quark valence PDFs - especially the d-quark type:



arXiv:1503.05221

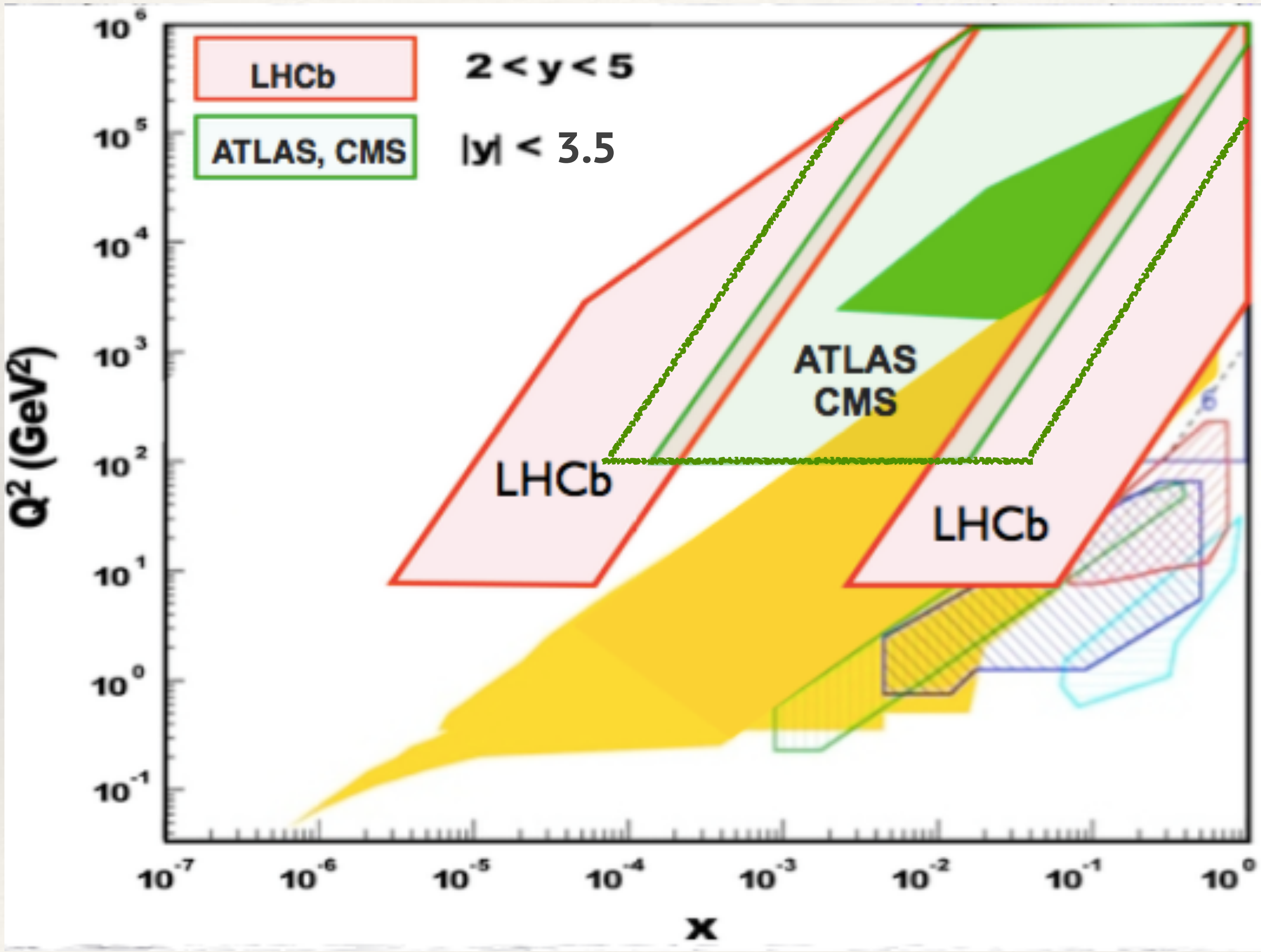


[from PDG]

- Jet measurements also provide an important constraint at higher x for the gluon distribution

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

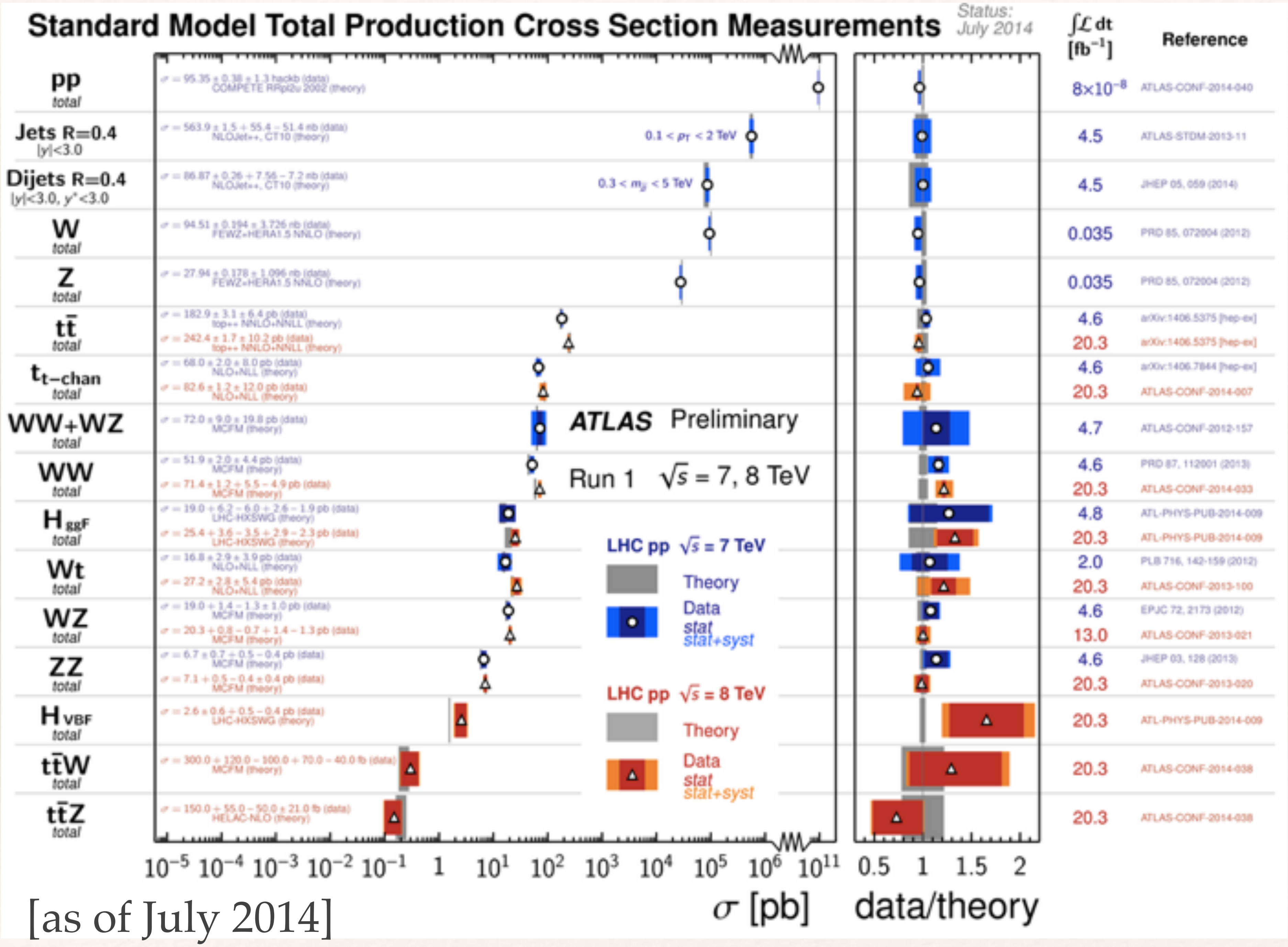
- **PDF improvement**

by using LHC data

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

The LHC measurements from Run1

- Hadron colliders can give us more insight into the hard QCD, the PDFs, non-perturbative effects, and the least known fundamental constant - strong coupling



[as of July 2014]

Remarkable agreement with SM predictions! Much of theory error is from PDFs —> it is crucial to improve our knowledge on PDFs

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

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

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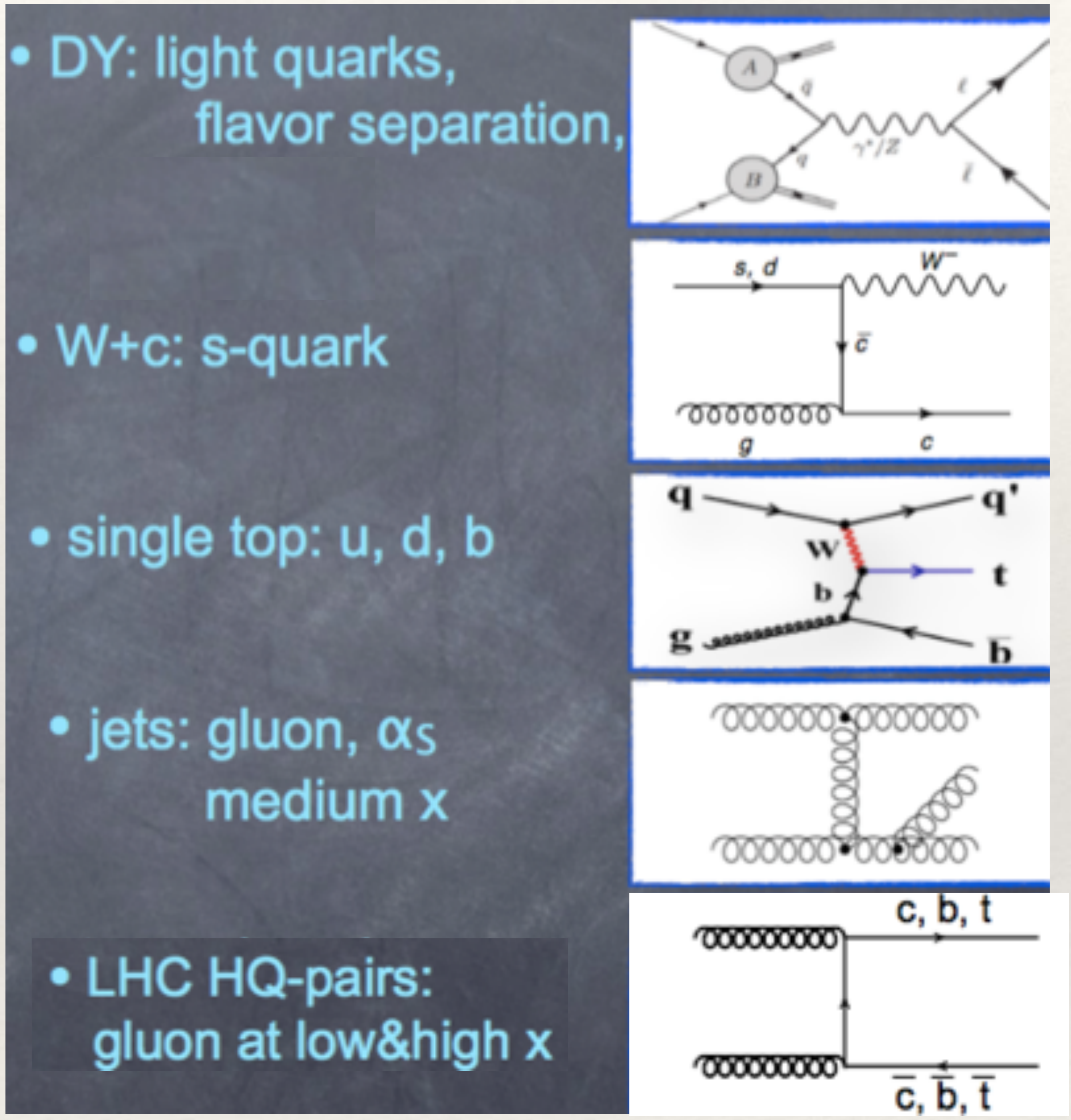


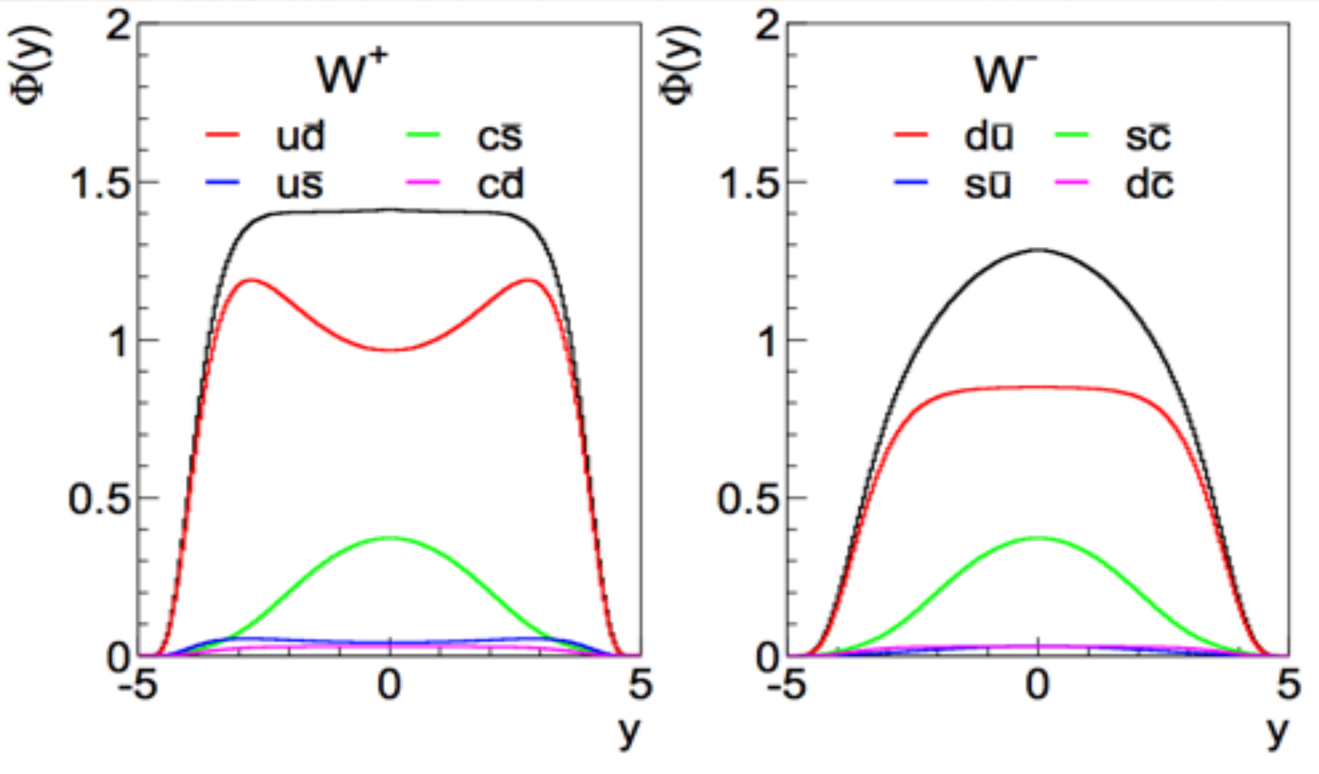
- DY: light quarks, flavor separation,
- W+c: s-quark
- single top: u, d, b
- jets: gluon, α_s medium x
- LHC HQ-pairs: gluon at low&high x

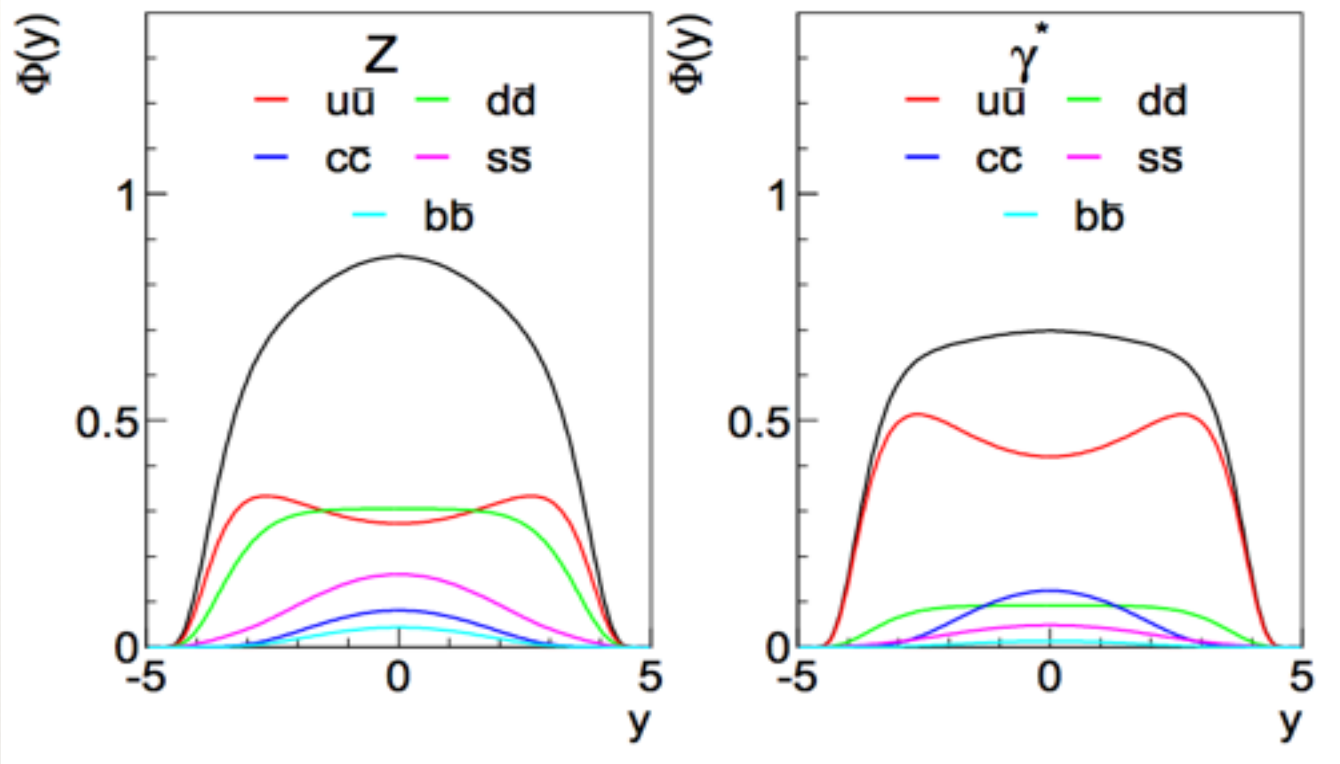
- **PDF discrimination**
by confronting theory with data
- **PDF improvement**
by using LHC data

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

Flavour decomposition of W, Z at LHC

W and Z are produced in abundance at LHC with clear experimental signature and the inclusive cross sections of W and Z are well understood theoretically at NNLO

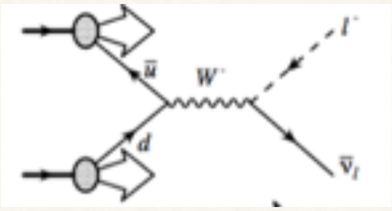


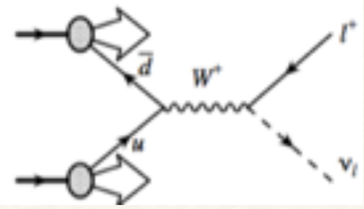


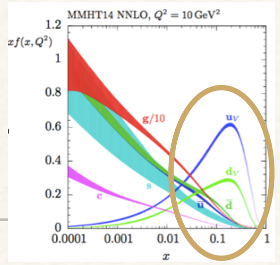
W^+ vs W^- —> impact on the valence quarks
Z —> impact on the strange distribution

We can exploit different PDF flavour sensitivity than these provided by DIS data

W charge asymmetry







The interplay between the flavour asymmetries can be enhanced via ratio measurements:

- W-asymmetry measurement
  - sensitive to uv, dv

$$A_W^l = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}}$$

$$A_W \approx \frac{u_v - d_v}{u + d}$$

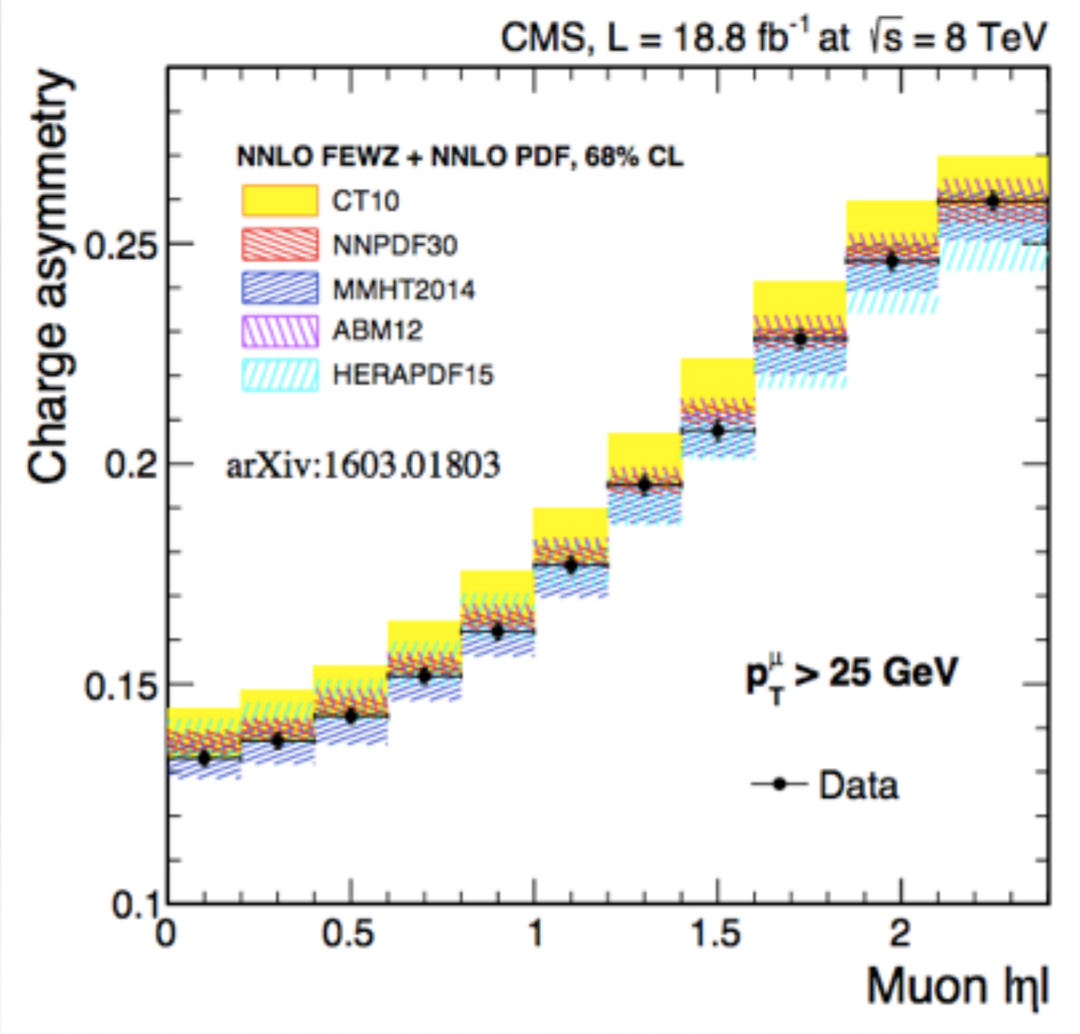
Measured by ATLAS, CMS and LHCb:

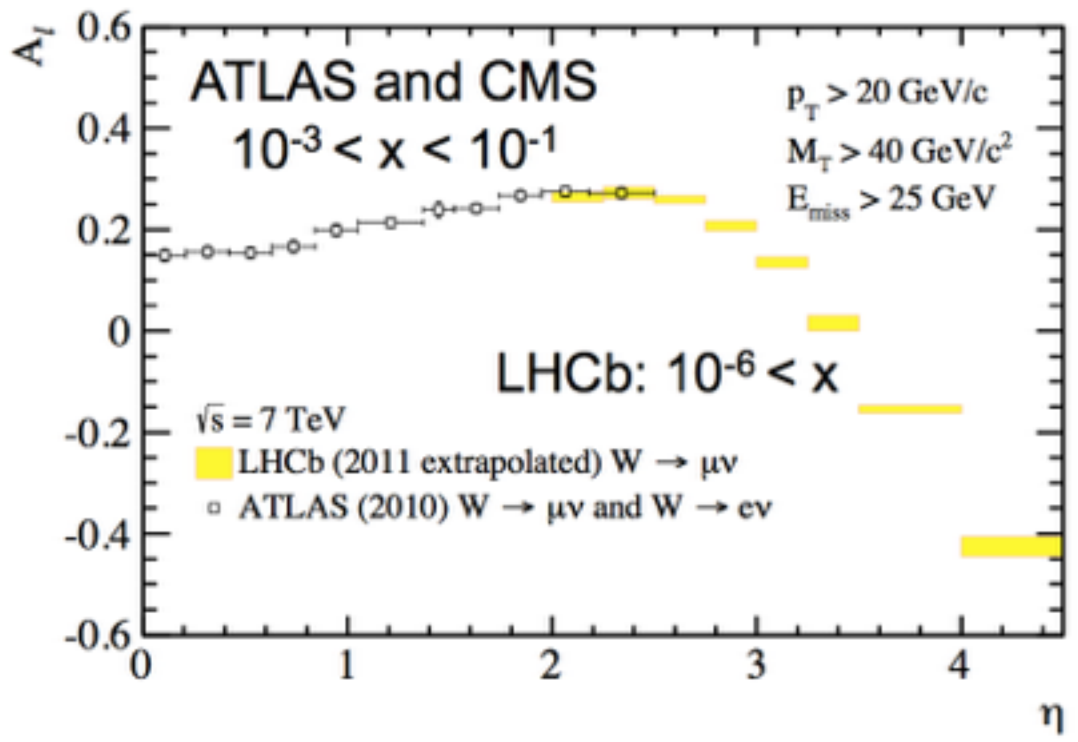
- LHCb extends the measurements to forward region

* For comparison, results are extrapolated to the fiducial volume of ATLAS, correcting for $M_T > 40$ and $E_T > 20$

LHCb

CMS





[LHCb] JHEP 12 (2014) 079

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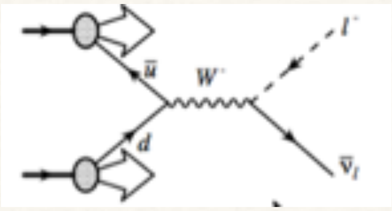

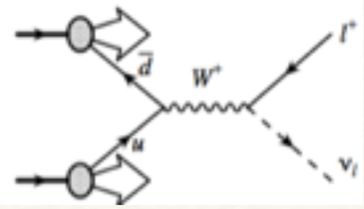

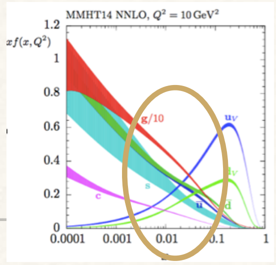

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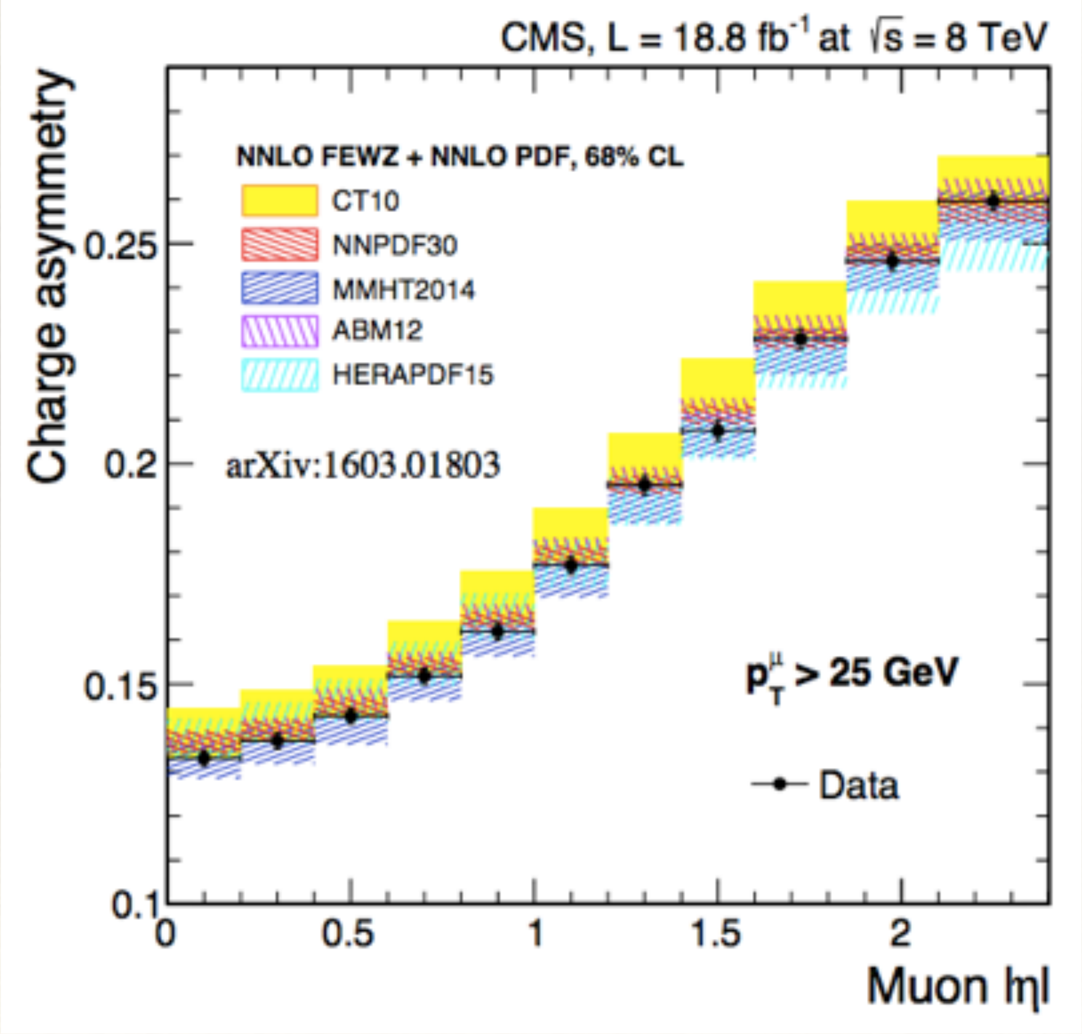
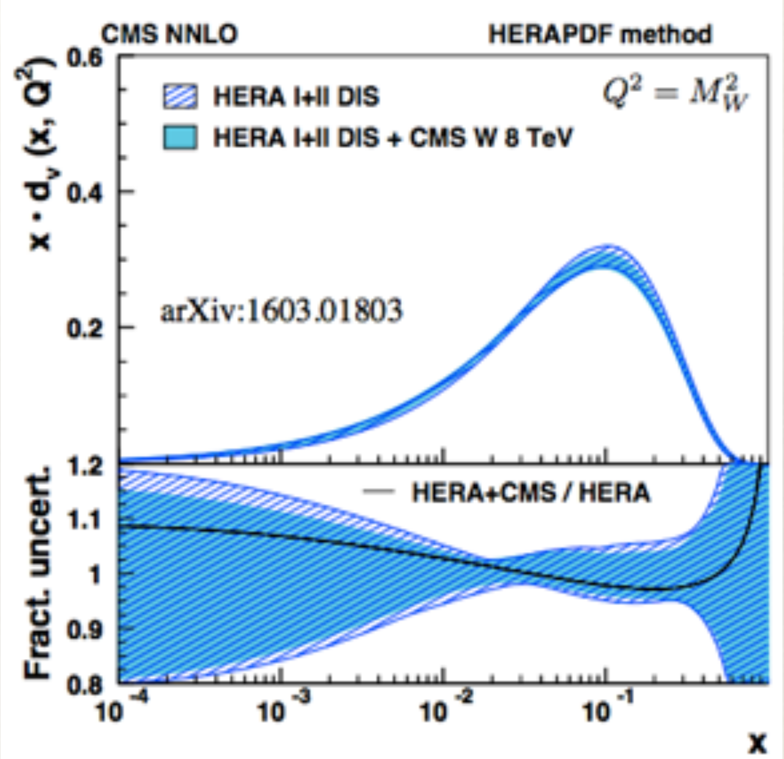
$$A_W \approx \frac{u_v - d_v}{u + d}$$

A QCD Fit analysis via xFitter shows the potential of the measurements on constraining d valence

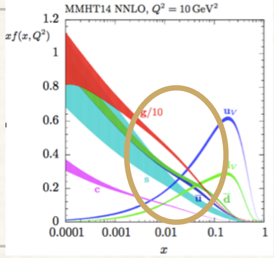
CMS

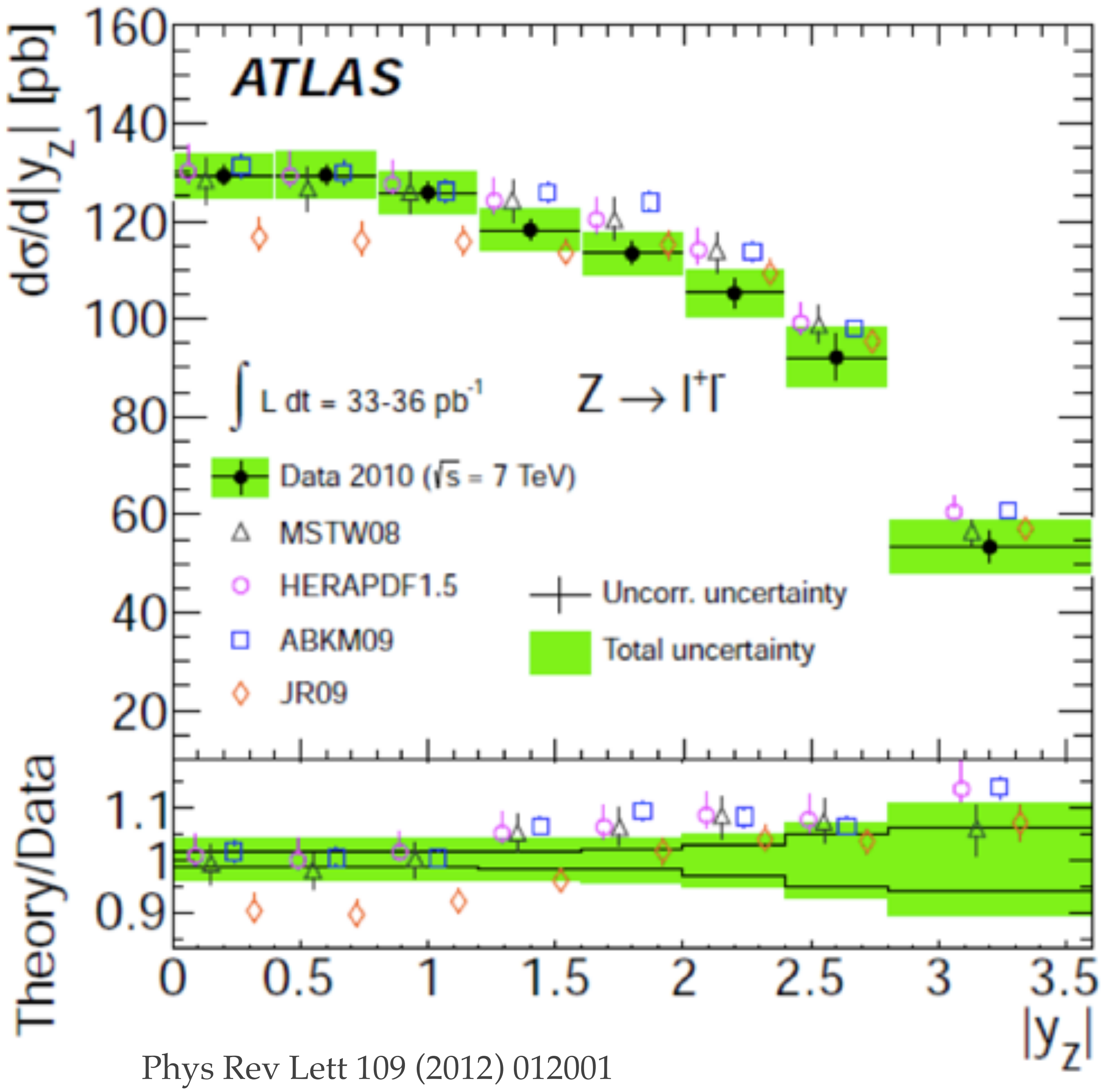




A PDF fit of these CMS muon asymmetry data together with the combined HERA inclusive deep inelastic scattering (DIS) data shows the potential of the LHC data to improve valence precision

Constraining PDFs with W, Z at LHC



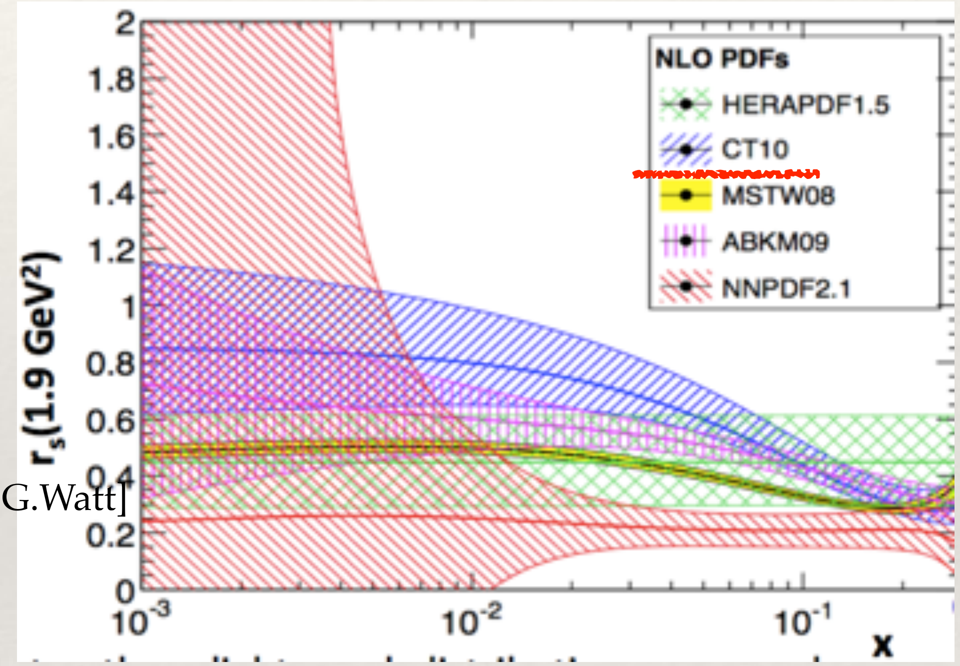


Phys Rev Lett 109 (2012) 012001

—> discrimination among PDFs

Before LHC, the dominant information on strange quark was from neutrino di-muon data:

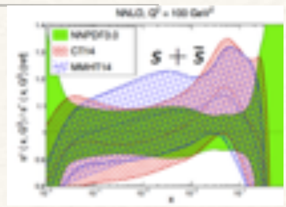
prefers rather strongly suppressed strange (s/d~1/2)



[G.Watt]

PDF Groups assume different suppression factor for sbar vs dbar —> W, Z data shows sensitivity to this assumption!

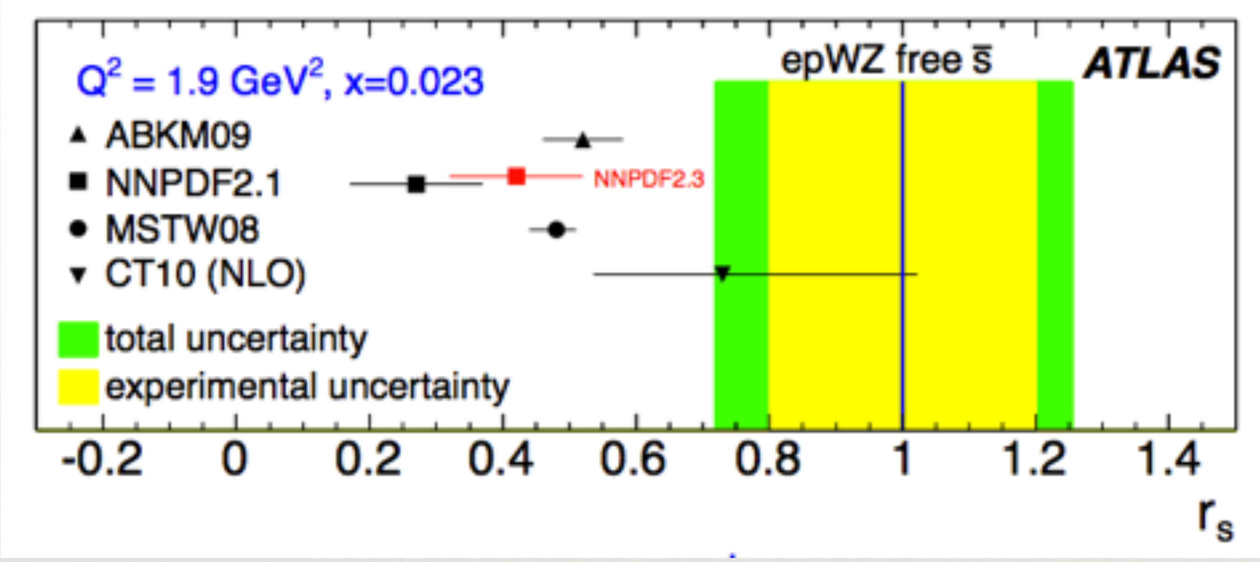
Enhanced strange at LHC

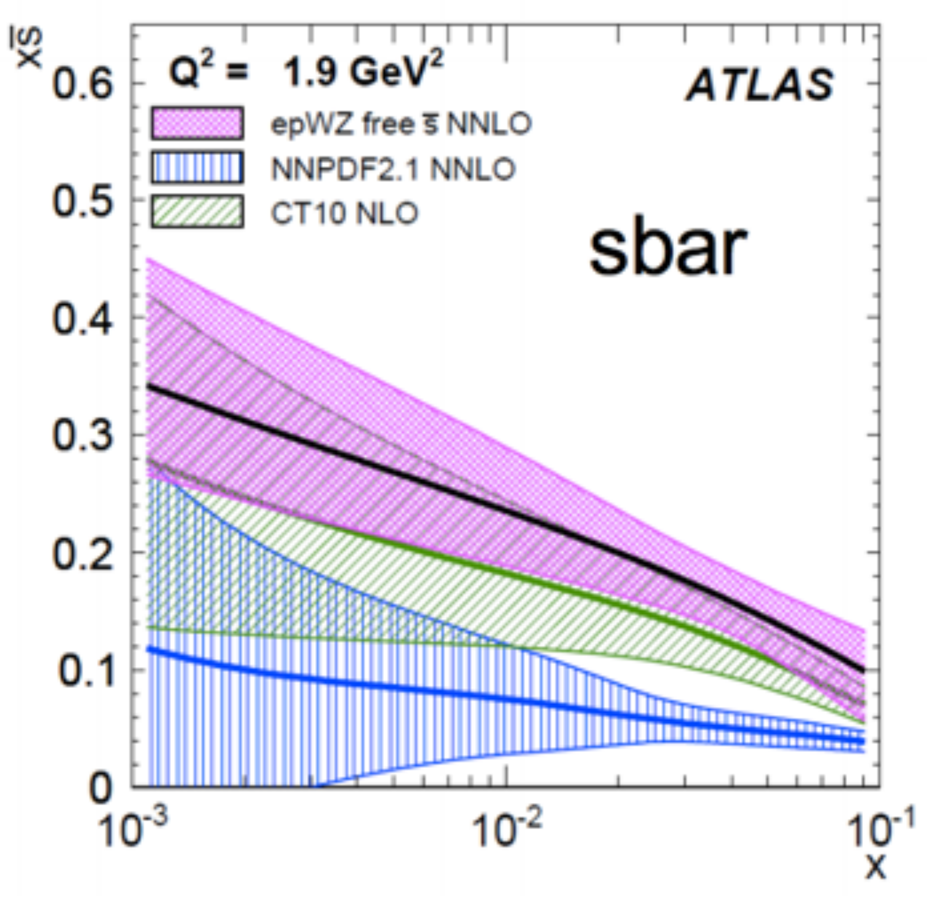


- In 2010, at LHC the EW boson data was used to constrain strange quark through a QCD fit analysis

xFitter

$r_s(x) = 0.5(s(x) + \bar{s}(x))/\bar{d}(x)$





—> measurement supports the idea that

s(x)=u(x)=d(x)

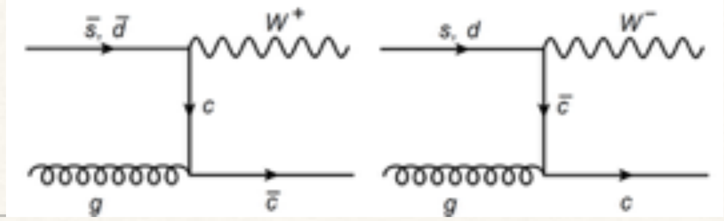
i.e. SU(3) symmetry for light sea quarks

—> Results confirmed by dedicated ATLAS W+c production measurement

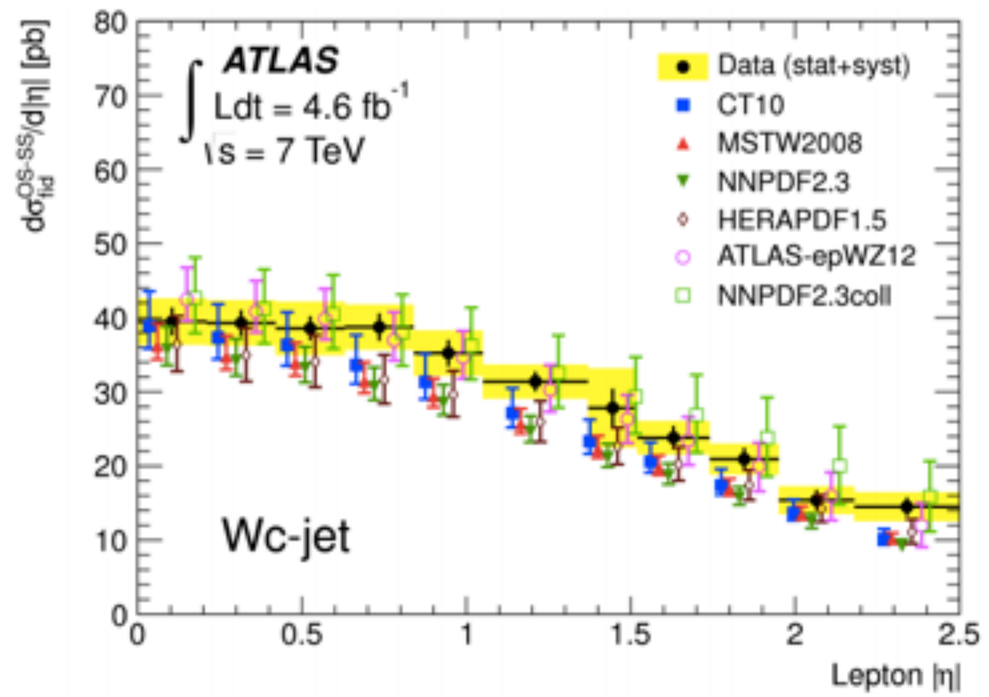
—> total light sea $x\Sigma = 2x(\bar{u} + \bar{d} + \bar{s})$ is enhanced by ~ 8 % sea quark.

This could pose interesting implications for other phenomena:
do the strange quarks play a role in the bound state structure or what's the implicatiom for Strange Matter?

W+c sensitivity to strange

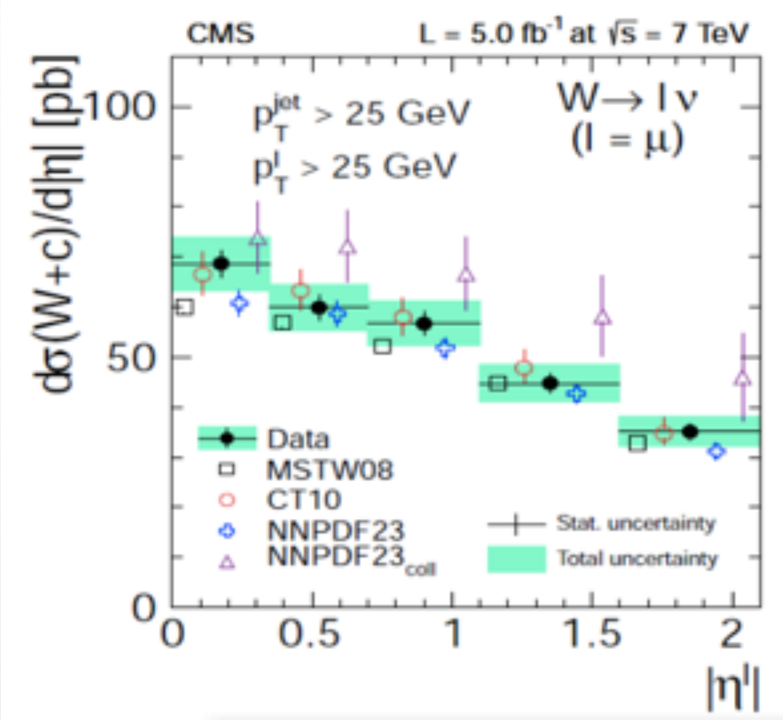


- W + charm data is directly sensitive to the strange quark density
- ATLAS, CMS and LHCb have performed dedicated measurements
  - ATLAS @ particle level [arXiv:1402.6263v1]
  - CMS @parton level [arXiv:1310.1138]



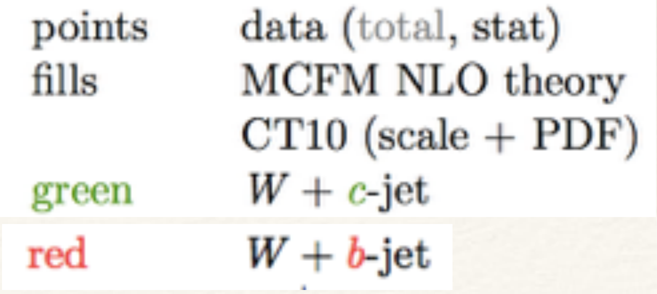
—>consistent with ATLAS-epWZ12 (PDF set from ATLAS Z, W inclusive)

—> consistent with CT10

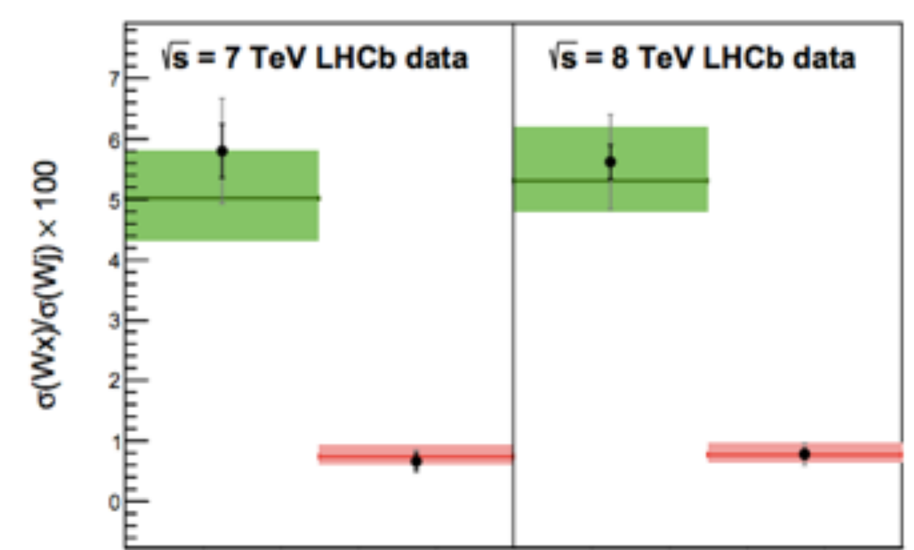


—>consistent with CT10

- LHCb @parton level comparison Phys. Rev. D 92 (2015)

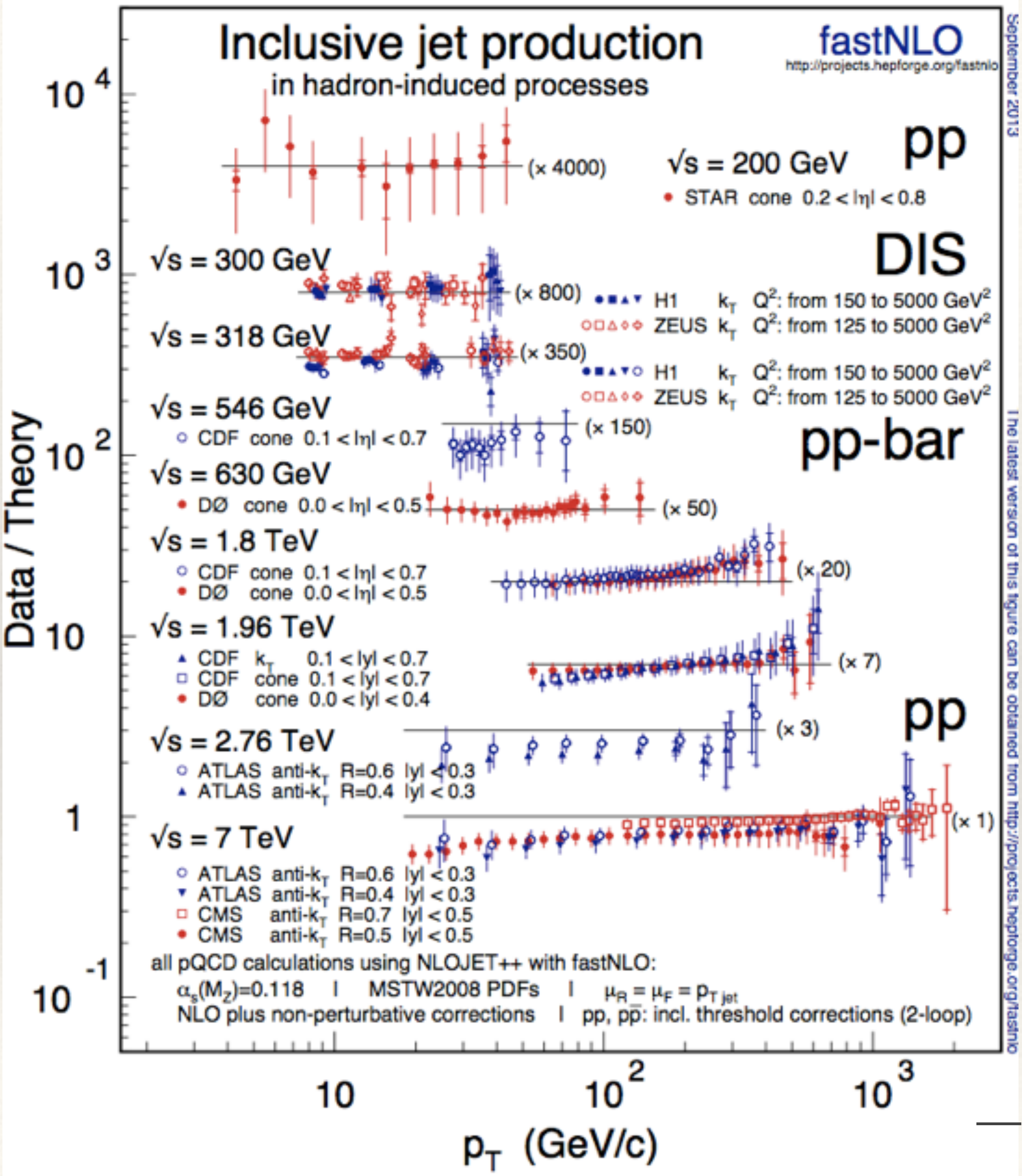


points	data (total, stat)
fills	MCFM NLO theory CT10 (scale + PDF)
green	$W + c$-jet
red	$W + b$-jet

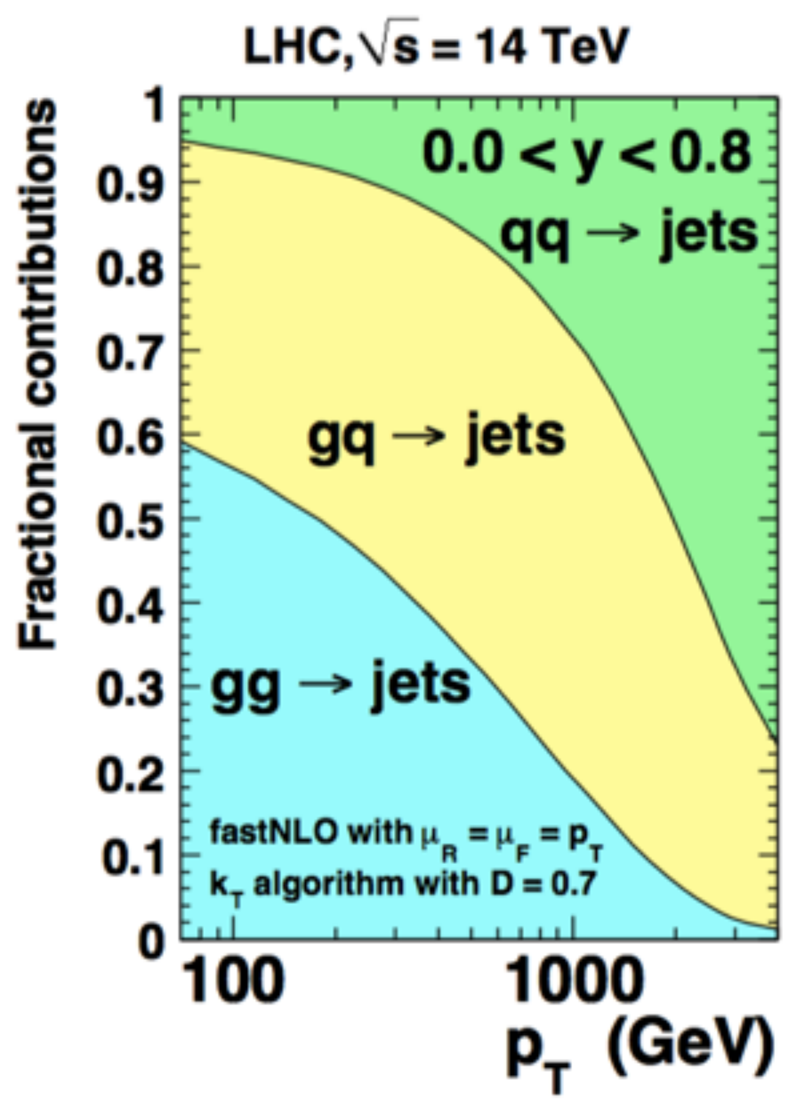


—>consistent with CT10

Jet Production at the LHC



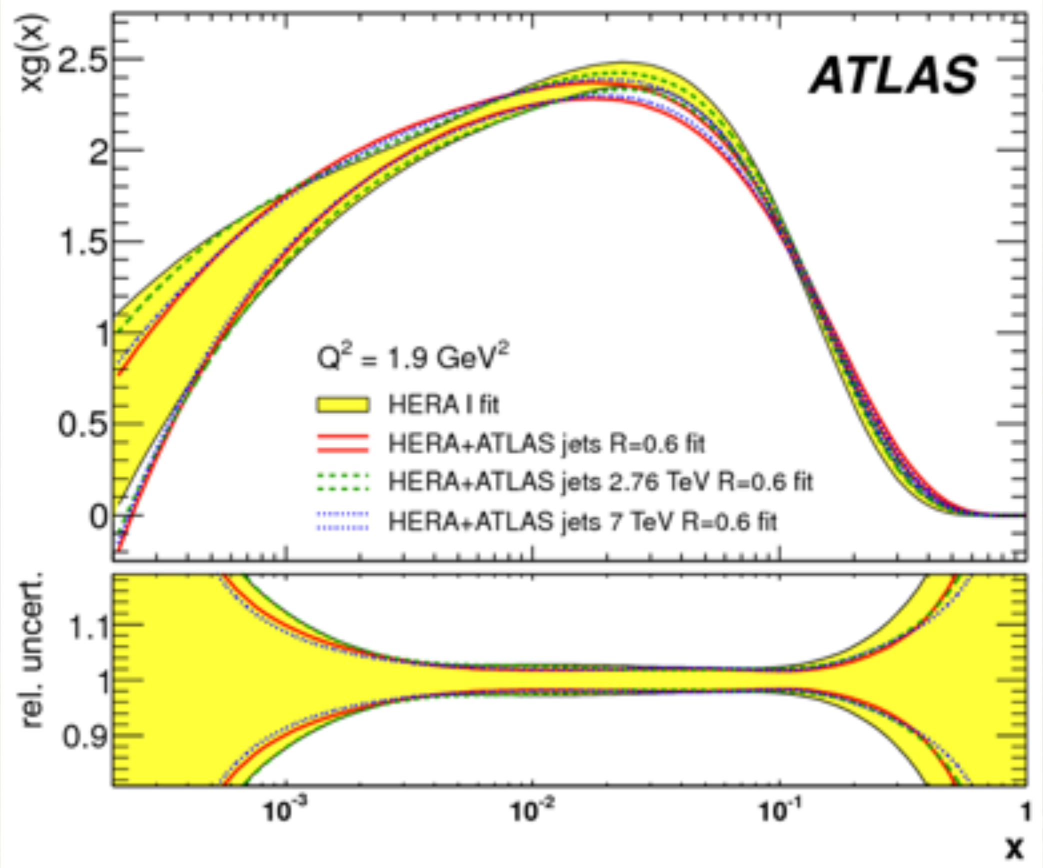
Jet production at the highest scales may reveal new physics and the reliability of the predictions depends on how well we know the high-x gluon PDF



—> a large fraction of jets are gluon induced

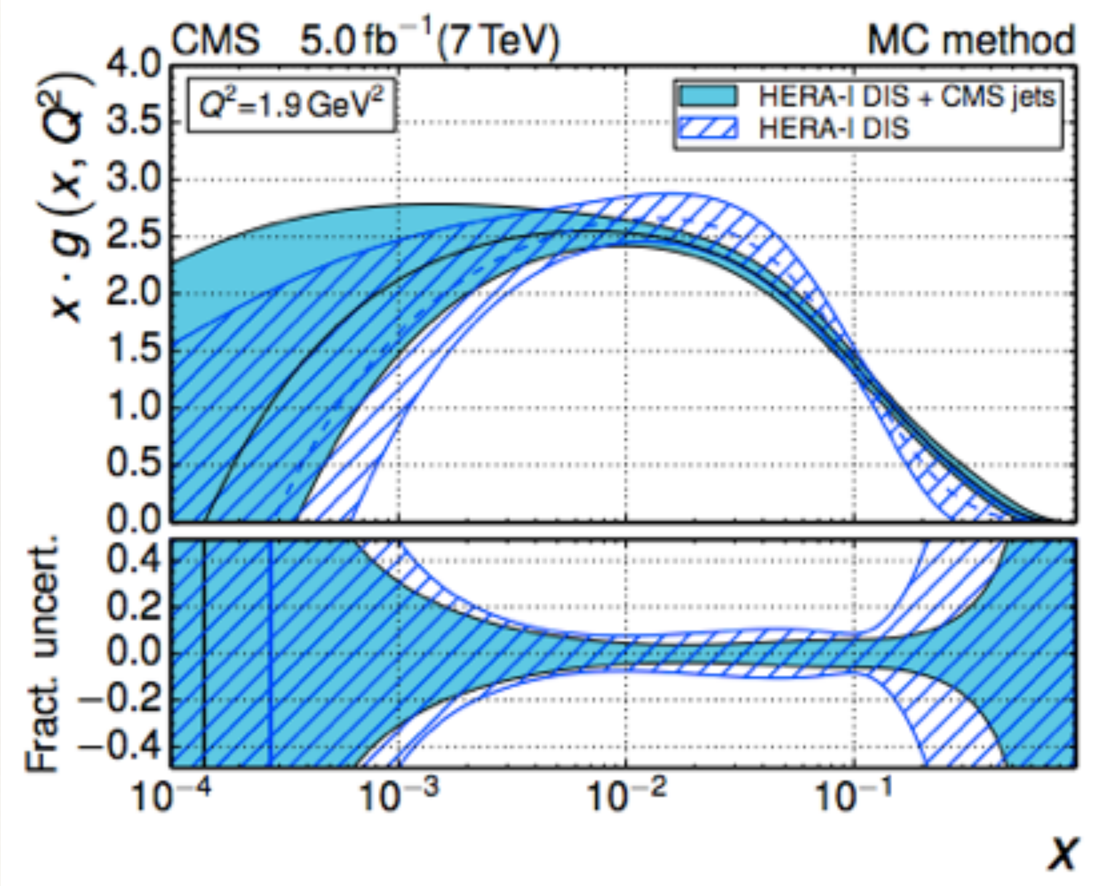
Inclusive Jet Production at the LHC

- To enhance the impact of jet data, it’s smart to consider ratios:
    - the major experimental systematic - the Jet Energy Scale - cancels out, i.e. 2.76 vs 7 TeV
- The impact of the LHC 7 TeV inclusive jet data on proton PDFs was investigated by including the jet cross section measurement in a combined fit with the HERA-I inclusive DIS cross sections.



EPJC (2013) 73 2509

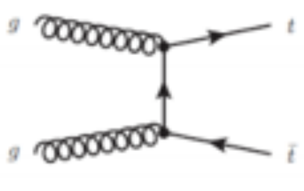
xFitter



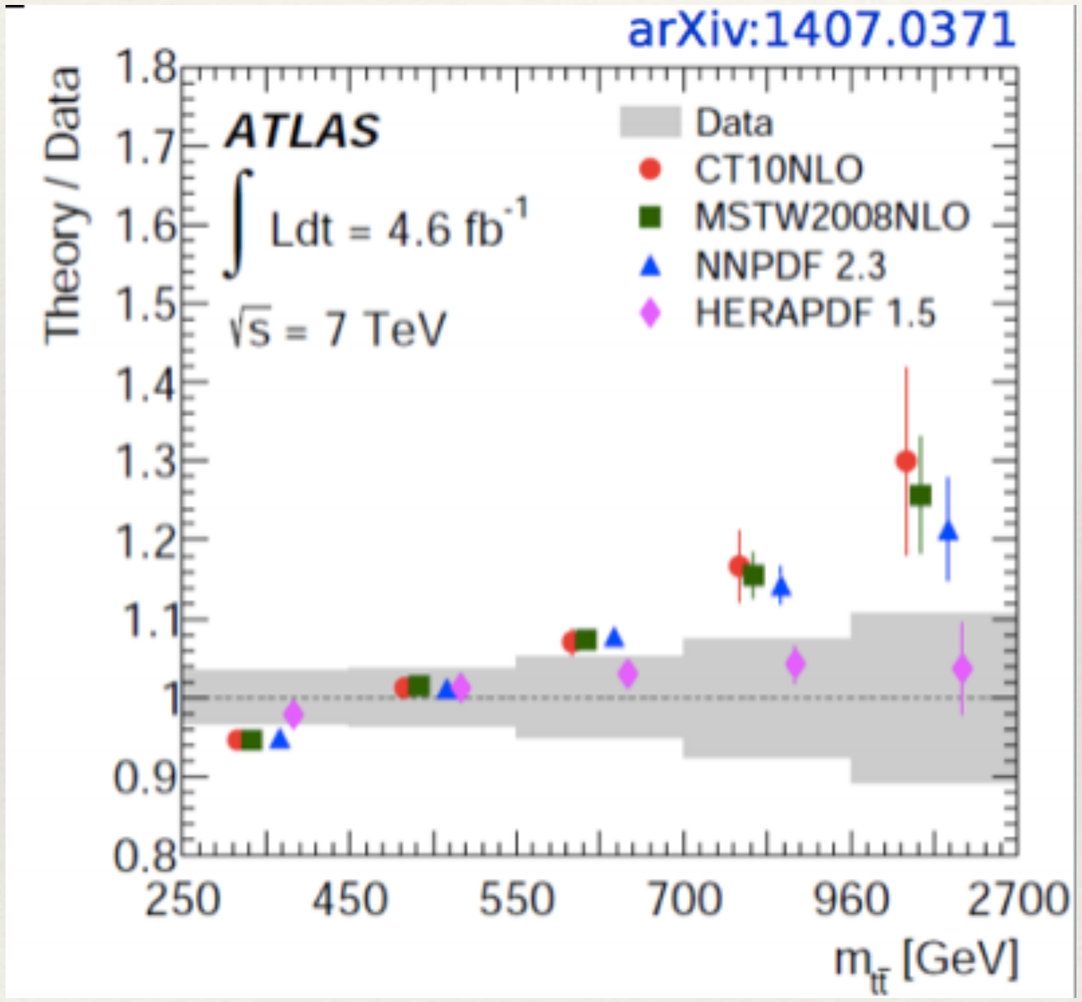
arXiv:1410.6765

jet data can help to improve gluon in high-x region —> but NNLO calculations would help

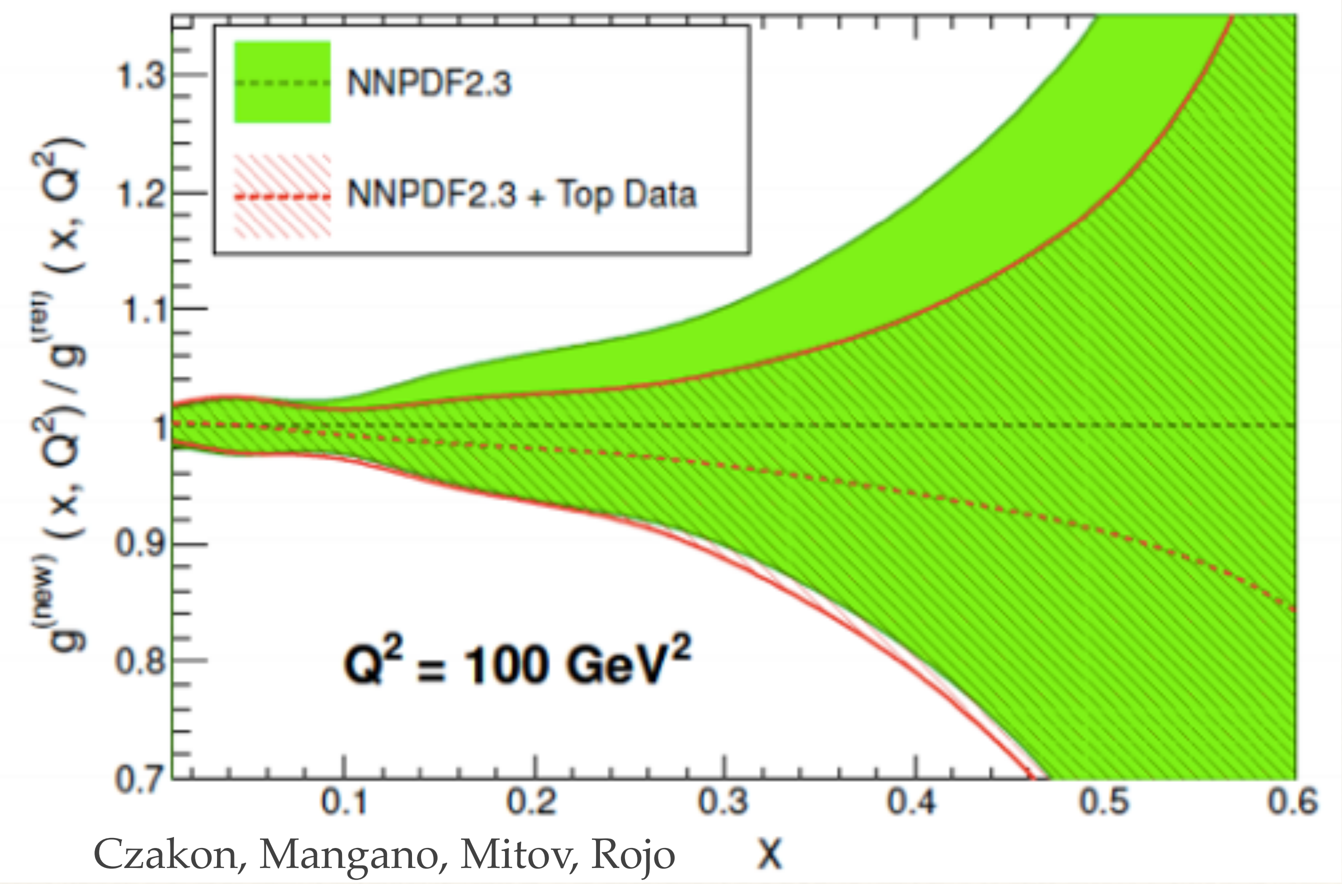
Gluon Sensitivity from ttbar Production at high x



- Top-quark pair production at the LHC probes high-x gluon (x ≈ 0.1):
  —> there is a strong correlation between g(x), αs and the top-quark mass mt
  - compared with theory (NLO) using different PDFs
  - NNLO theory calculations are becoming available …



The precise 7 and 8 TeV LHC data can be used to discriminate between PDF sets and to reduce the PDF uncertainties on the poorly known large-x gluon

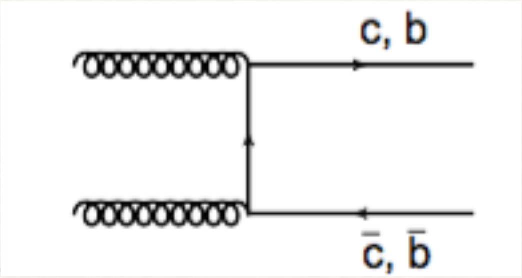


Czakon, Mangano, Mitov, Rojo

The improved large-x gluon leads to more accurate theory predictions for BSM searches

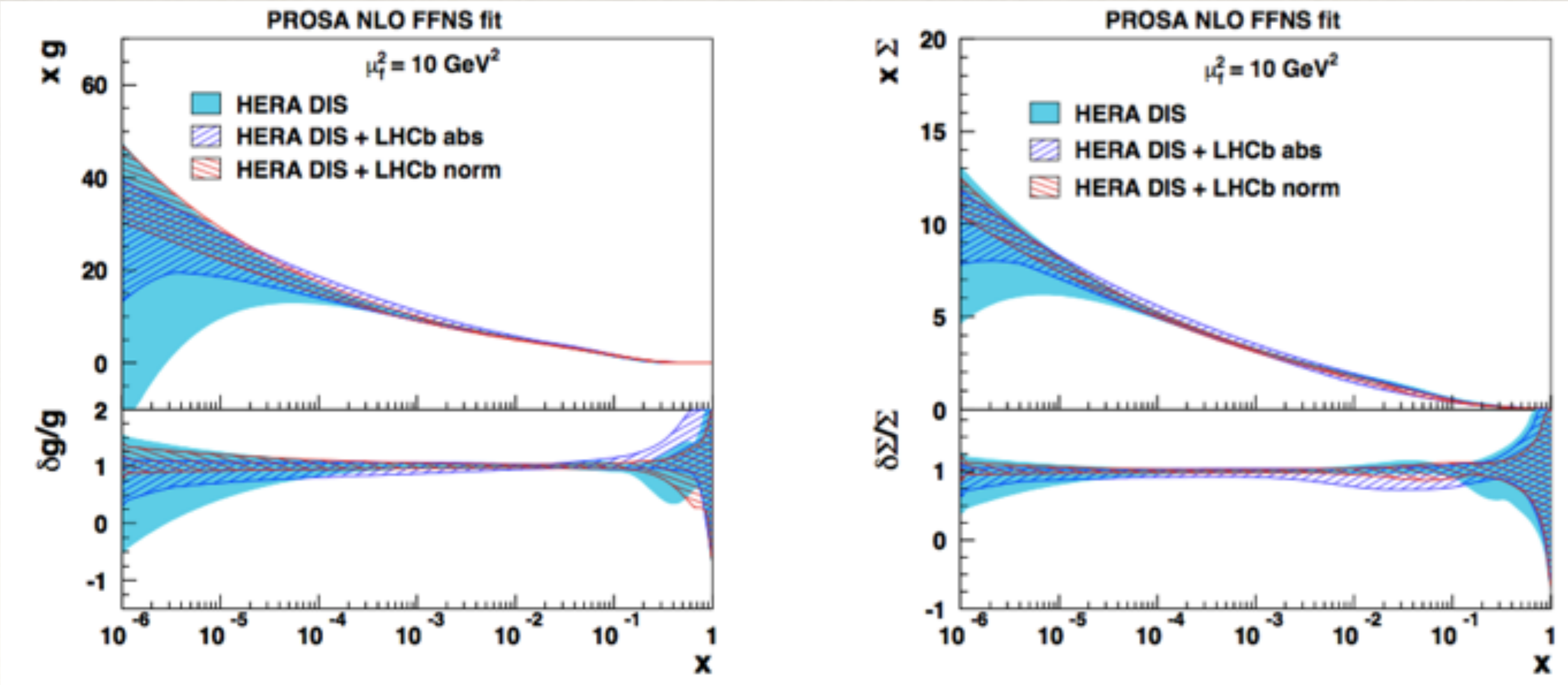
Gluon Sensitivity from heavy quark production at low x

- 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 $(D^0, D^+, D^{*+}, D^+{}_s, \Lambda_c)$ 7 TeV $L = 15 nb^{-1}$ [Nucl. Phys. B871 (2013) 1]
  - beauty$(B^+, B^0, B_s{}^0)$ 7 TeV $L = 0.36\ fb^{-1}$ [JHEP 08 (2013) 117]

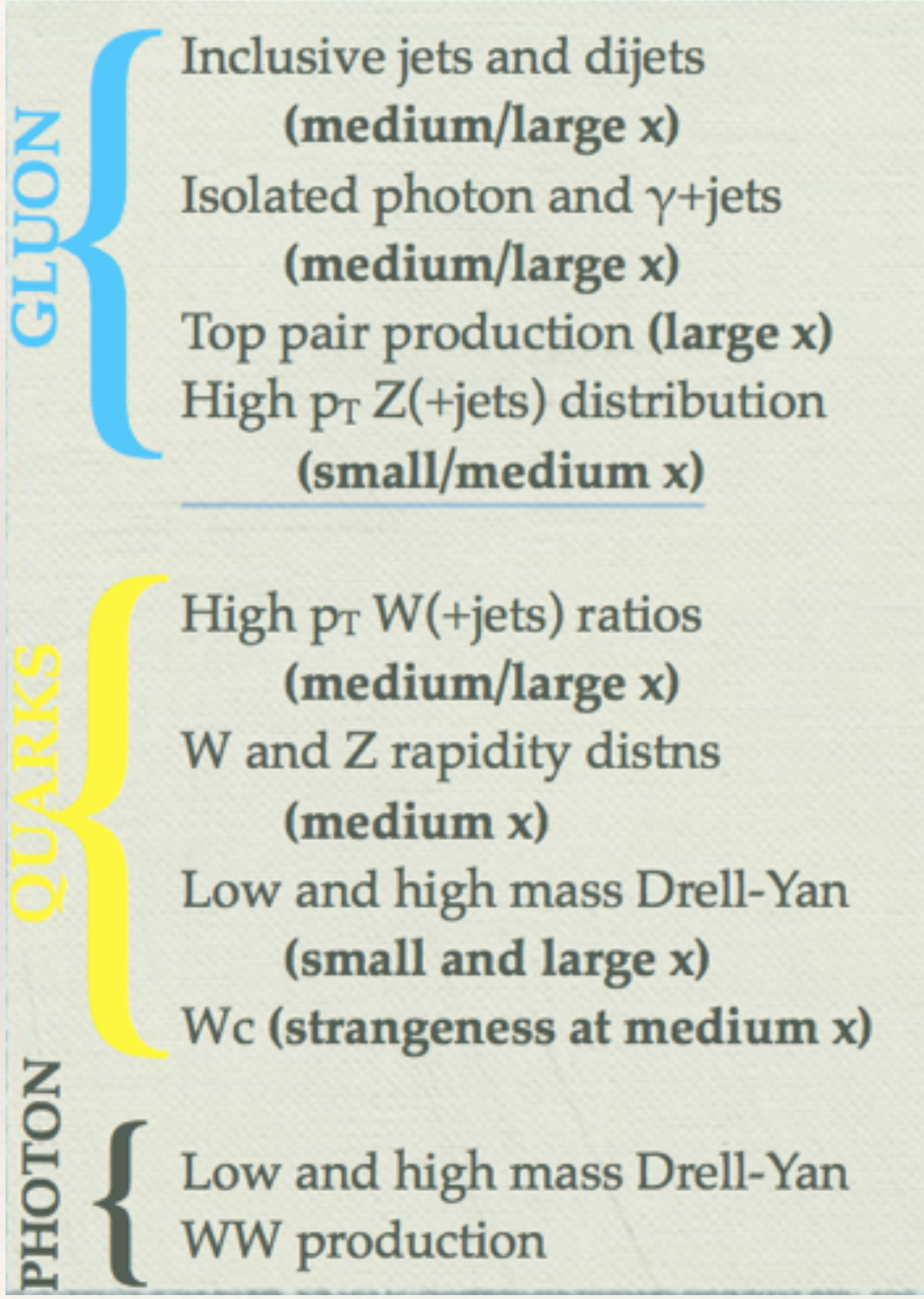


confirmed by NNPDF analysis

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

Impact of LHC data on PDFs

- Some of the global PDF groups started to include these data in their fit:

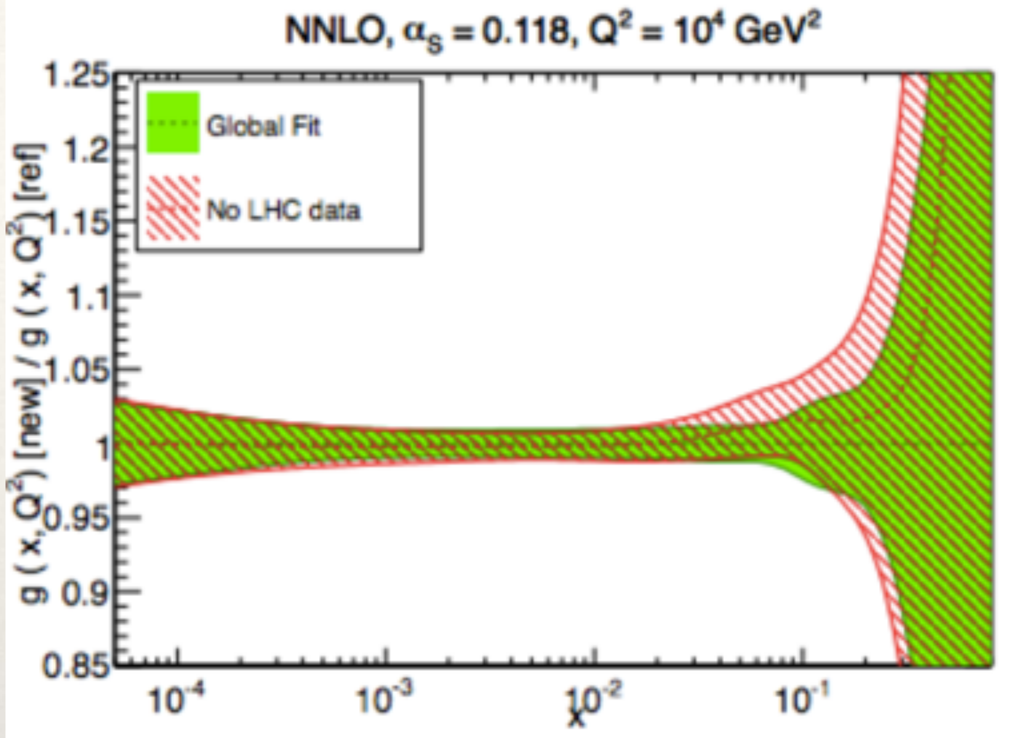


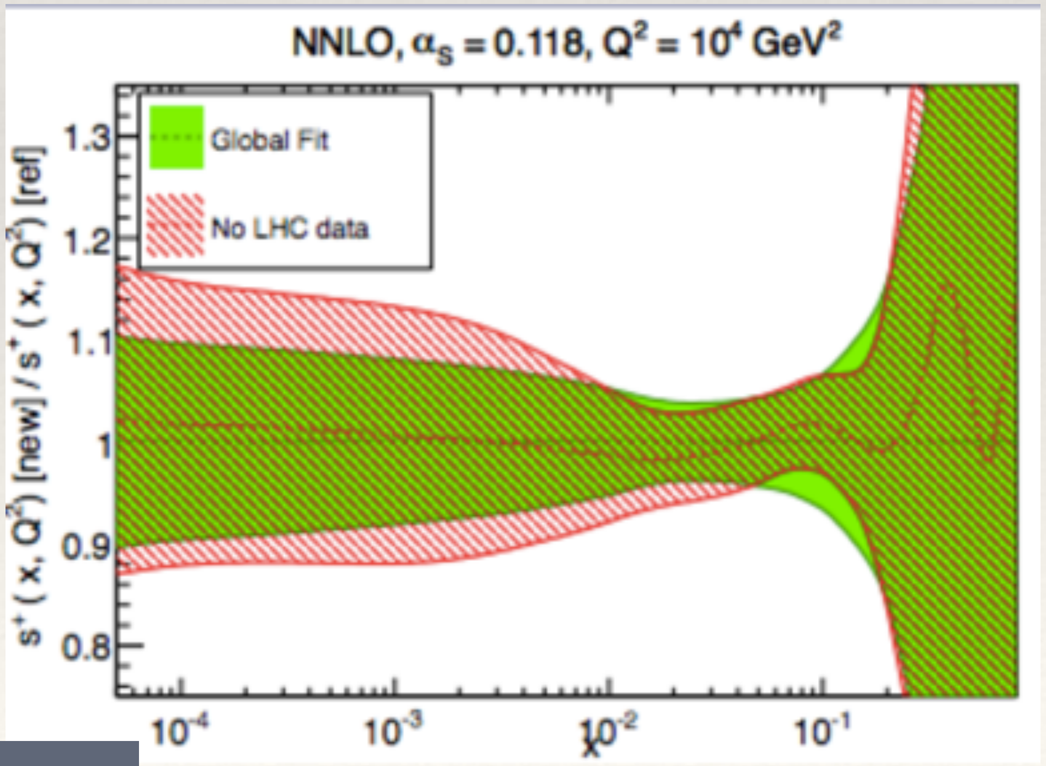
GLUON
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T Z(+jets) distribution **(small/medium x)**

QUARKS
- High p_T W(+jets) ratios **(medium/large x)**
- W and Z rapidity distns **(medium x)**
- Low and high mass Drell-Yan **(small and large x)**
- Wc **(strangeness at medium x)**

PHOTON
- Low and high mass Drell-Yan
- WW production

Intense activity of global PDF groups to include these measurements in the new PDF releases in time for Run2 data.

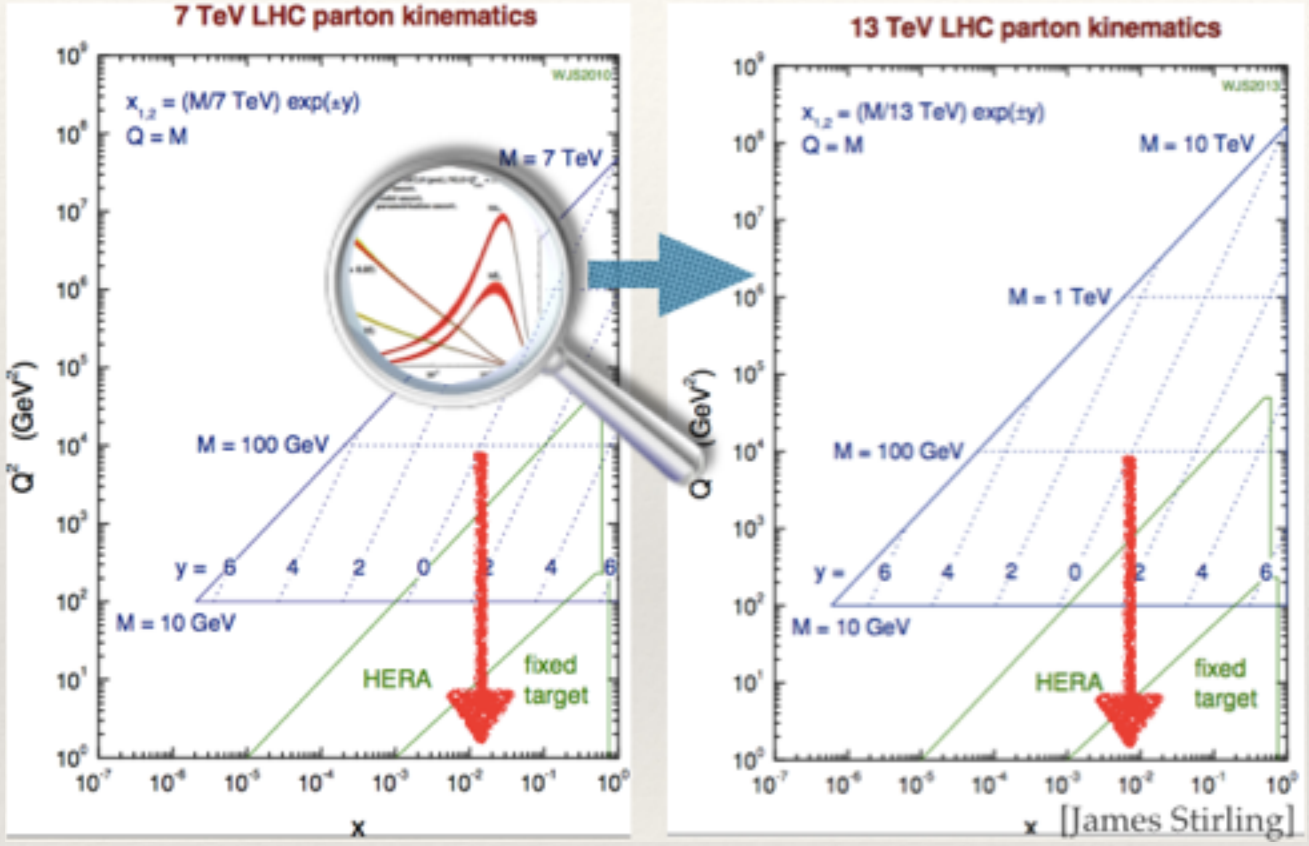


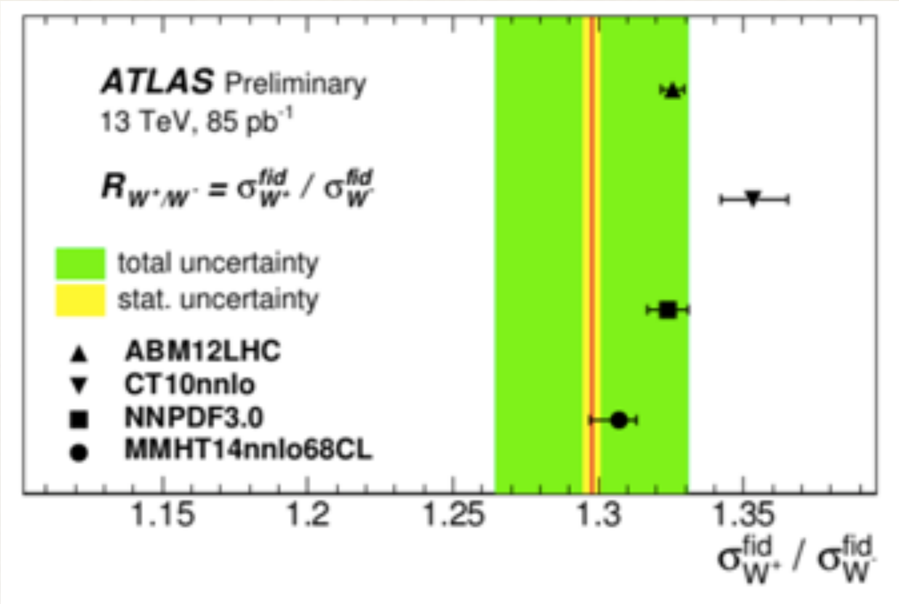


More precise data from Run 1 to have an impact on PDFs

W, Z at 13 TeV

- Motivation for measuring W, Z inclusive cross sections with Run-2 LHC data:
  - validate the Run-1 results and test of the SM at highest scales ever
  - access to a different kinematic region in x which provides different PDF sensitivity:





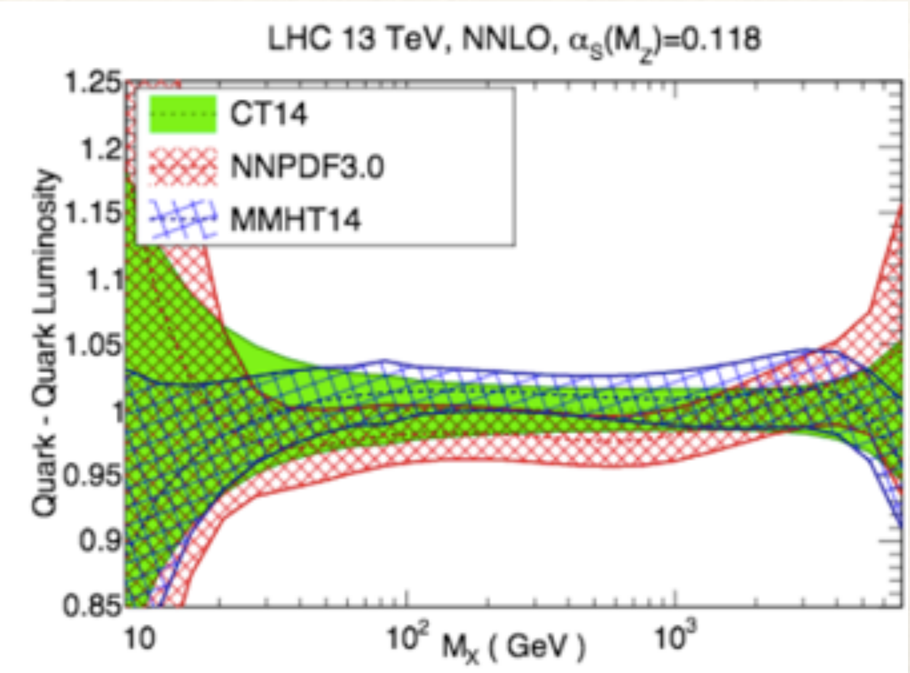
- Ratio Measurements powerful in providing targeted constraint:
  - R(W+/W-) —> sensitive to u_V and d_V at low-x
  - R(W/Z) —> sensitive to strange quark
  - R(ttbar/Z) —-> sensitive to gluon and light sea quarks

ATLAS-CONF-2015-039

First results confirm the findings in Run 1 and provide extra handle to better constrain PDFs

Neutral Current DY measurements at Run 2

- **What precision do we want for our measurements?**
  - Aim to have better experimental uncertainties than theoretical precision:
    - Theory precision is ~5% for $m_{ll} < 400$ GeV
    - huge theory uncertainty for $m_{ll} < 20$ GeV

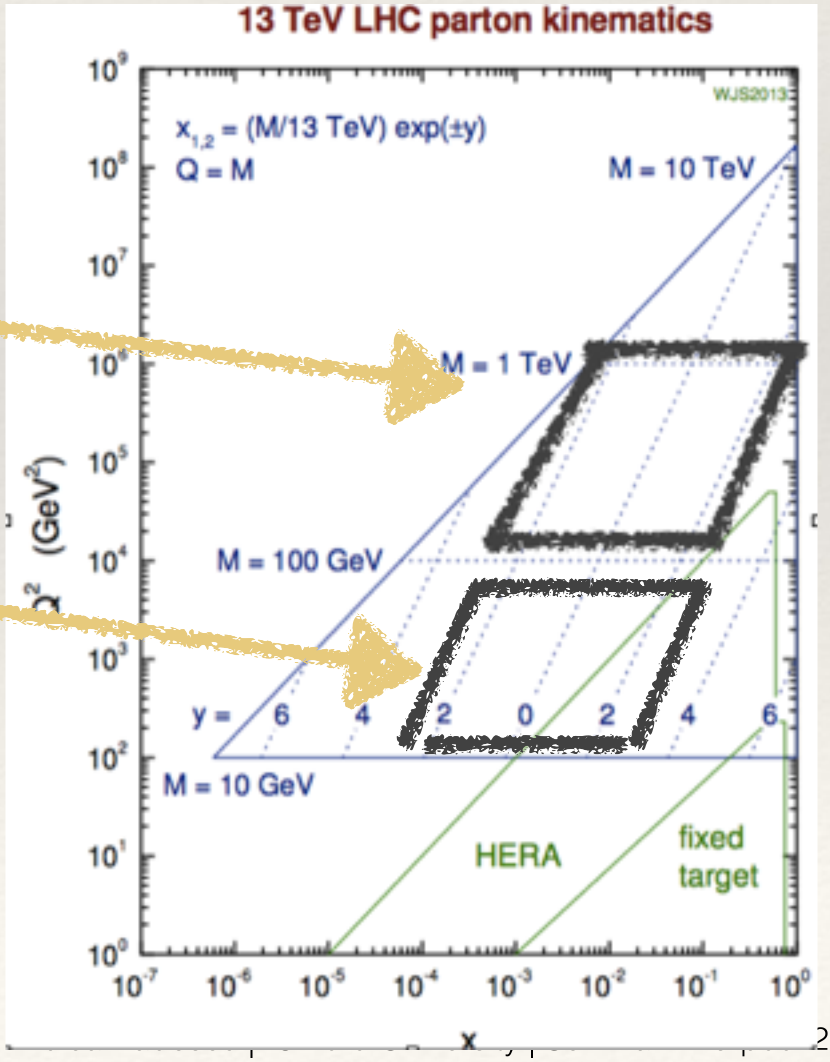


- **High Mass DY** measurement can extend the di-lepton mass distribution up to 3 TeV:

—> **an extra lever arm in x for constraining PDFs**

- **Low Mass DY** can reach down to x ~ 10^{-4}:

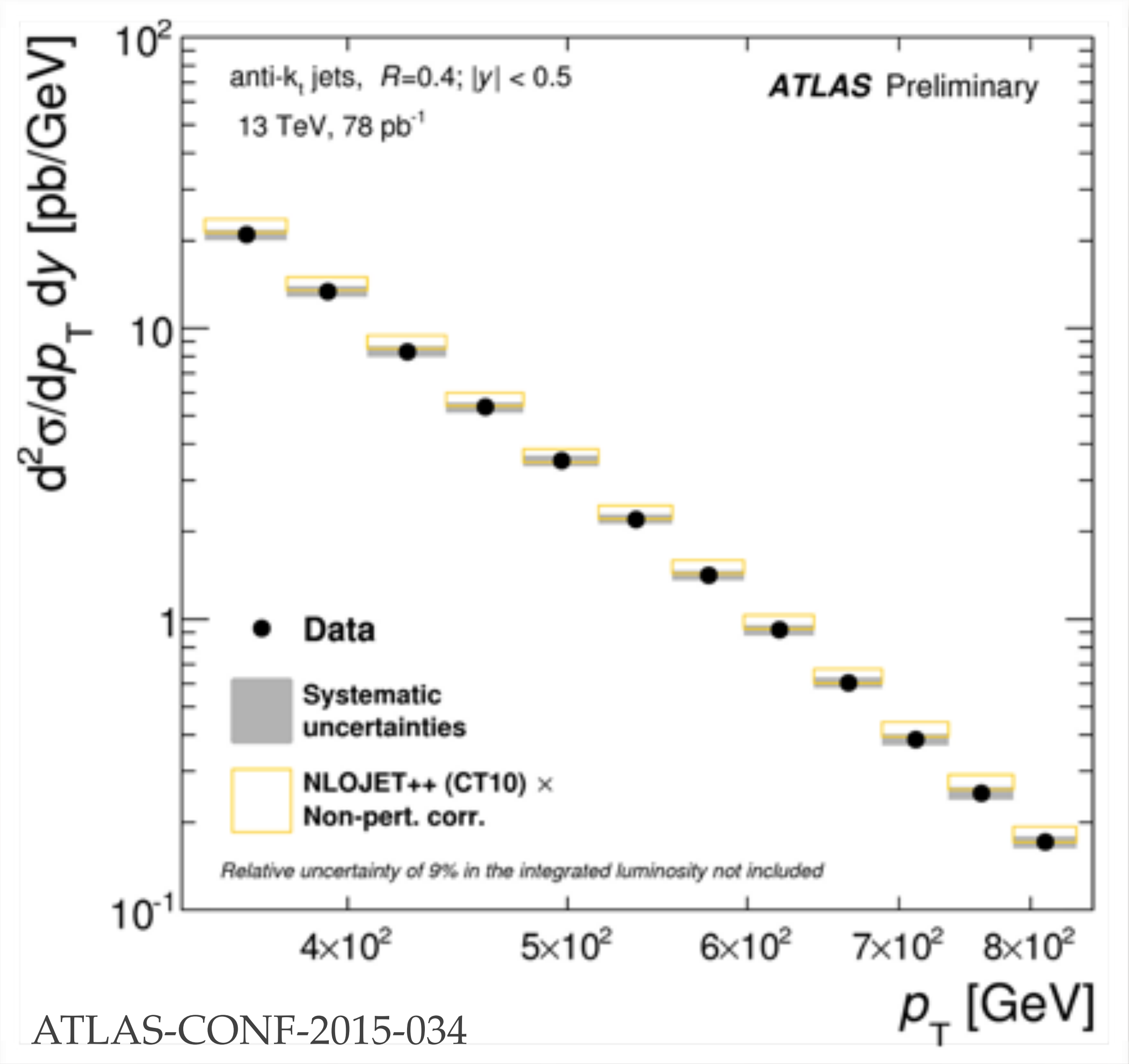
—> **sensitivity to the low x effects?**



Inclusive Jet Production at Run 2

- Jet measurements of 2015 bring a new kinematic reach with jet p_T up to 3.5 TeV, interesting to observe if it will help to further constrain PDFs

- Exploiting ratio measurements to better control the dominant JES uncertainty, as done for 2010 data, would enhance its impact.



ATLAS-CONF-2015-034

New results at 13 TeV - good agreement with SM (so far)
NNLO calculations for jets will bring more edge to the tests of SM

Looking further ahead

Many outstanding questions that aim at getting hints of what is beyond Standard Model:

- Higgs boson and Electroweak symmetry breaking
- Dark Matter
- Quark and Leptons
- Physics at the highest energy scales
- neutrinos

Could not be a better time for Particle Physics!

- Many of these questions can be answered by the LHC with its long range plan via **HL-LHC**

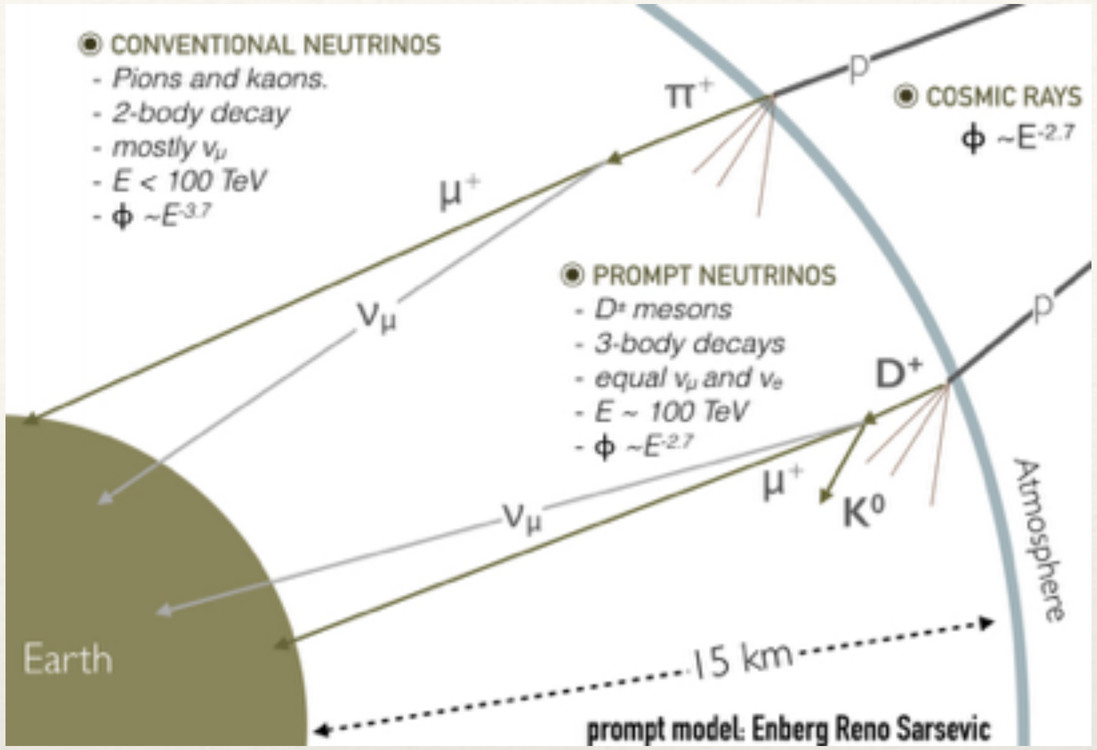
with HL-LHC we achieve much higher statistics (300/fb —> 3000/fb):

ZZ, WZ become much more precise -> could be one of the first measurements to benefit

GET READY FOR WHAT LIES AHEAD

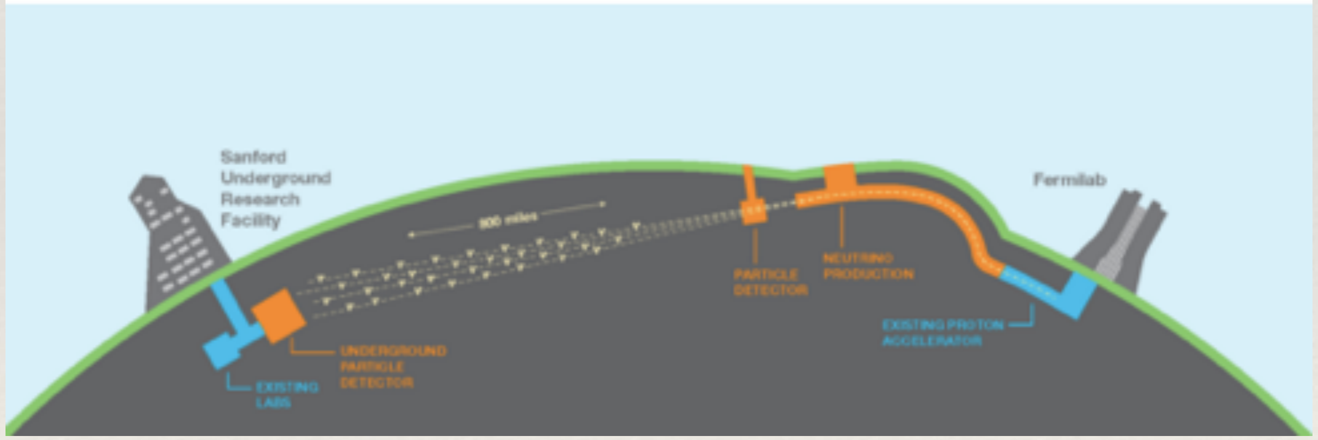
- **An attractive solution would be also LHeC:**
  - it would pin down the PDF uncertainties for the full kinematic coverage
  - it would extract a per mile accurate alphas
  - it would complement LHC for Higgs physics, new physics

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:
    - We could use heavy quark production data from LHC to validate our 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
    - Strange and charm production; weak mixing angle; precision tests of isospin symmetry; etc.
    - 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
        - i.e. GENIE neutrino MC Generator



synergy between LBNF, LBL, CERN

Summary

- PDFs are very important as they still limit our knowledge of cross sections whether SM or BSM.
    - HERA has finalised its separate measurements relevant to PDFs and ongoing efforts on combining final measurements to reach its ultimate precision:
    - Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement

… Many more valuable measurements are already available, but not covered in this talk …

- More precision measurements from LHC to come from Run I and in future from Run 2

- Could not be a better time in particle physics: many prospects!
    - rich neutrino program, HL-LHC
    - possible LHeC, FCC, etc..

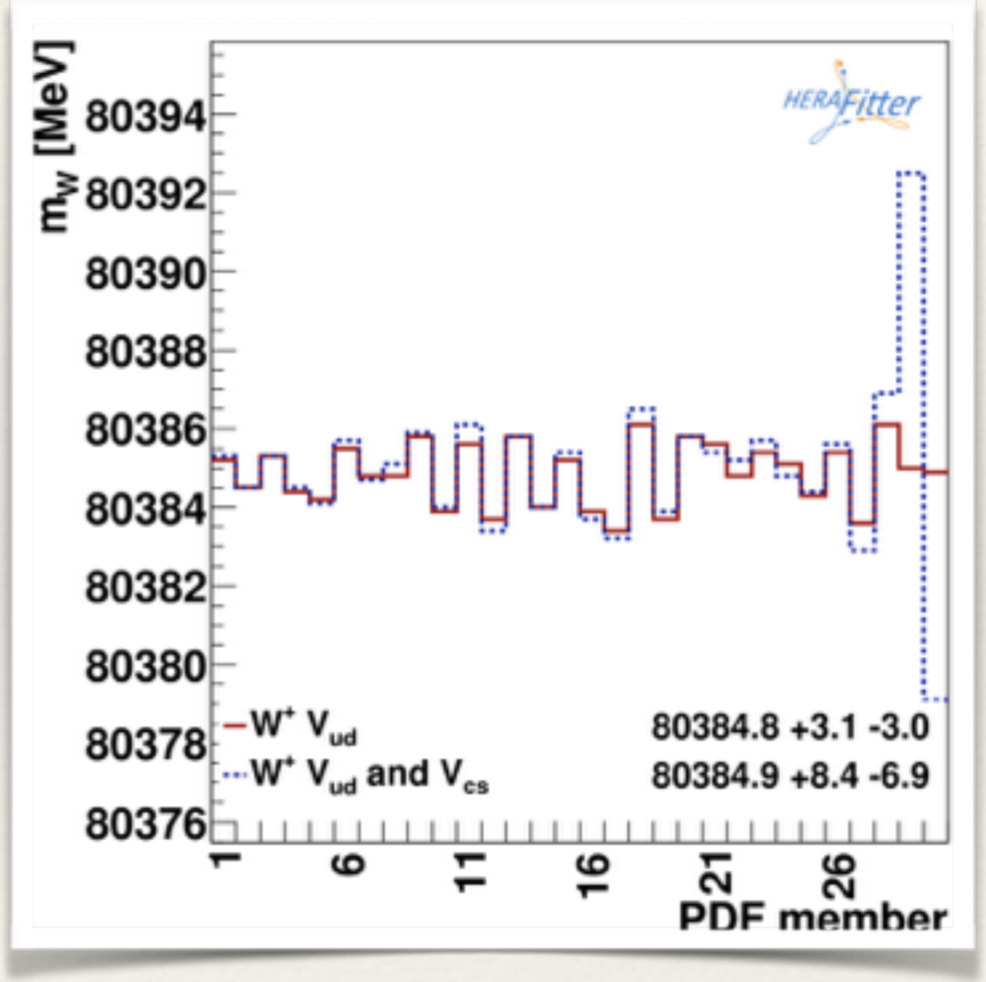
- We don't know what we will find, but it will surely depend on how well we control all our parameters!

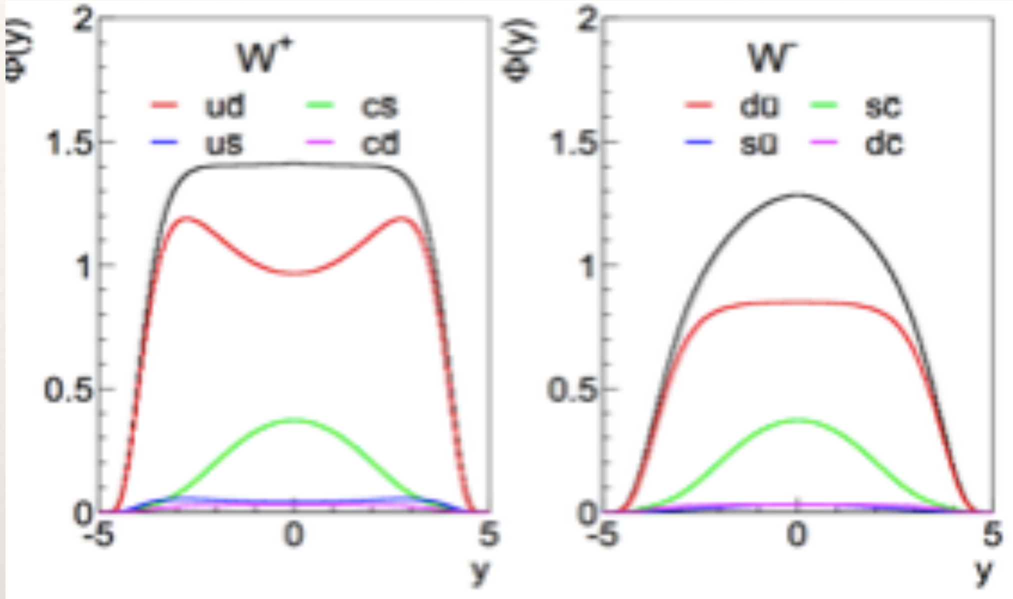
W mass measurement and PDF uncertainties

At the LHC, the best experimental precision on Mw might be achieved from the p_T distribution of the charged electron/muon from leptonic decay of W:

- sensitive to p^W_T modelling, which is different for cs vs uv production.

ATL-PHYS-PUB-2014-015





A dedicated PDF set, produced with HERAFitter and HERA I data was used to study the PDF decomposition that impacts Mw measurement:

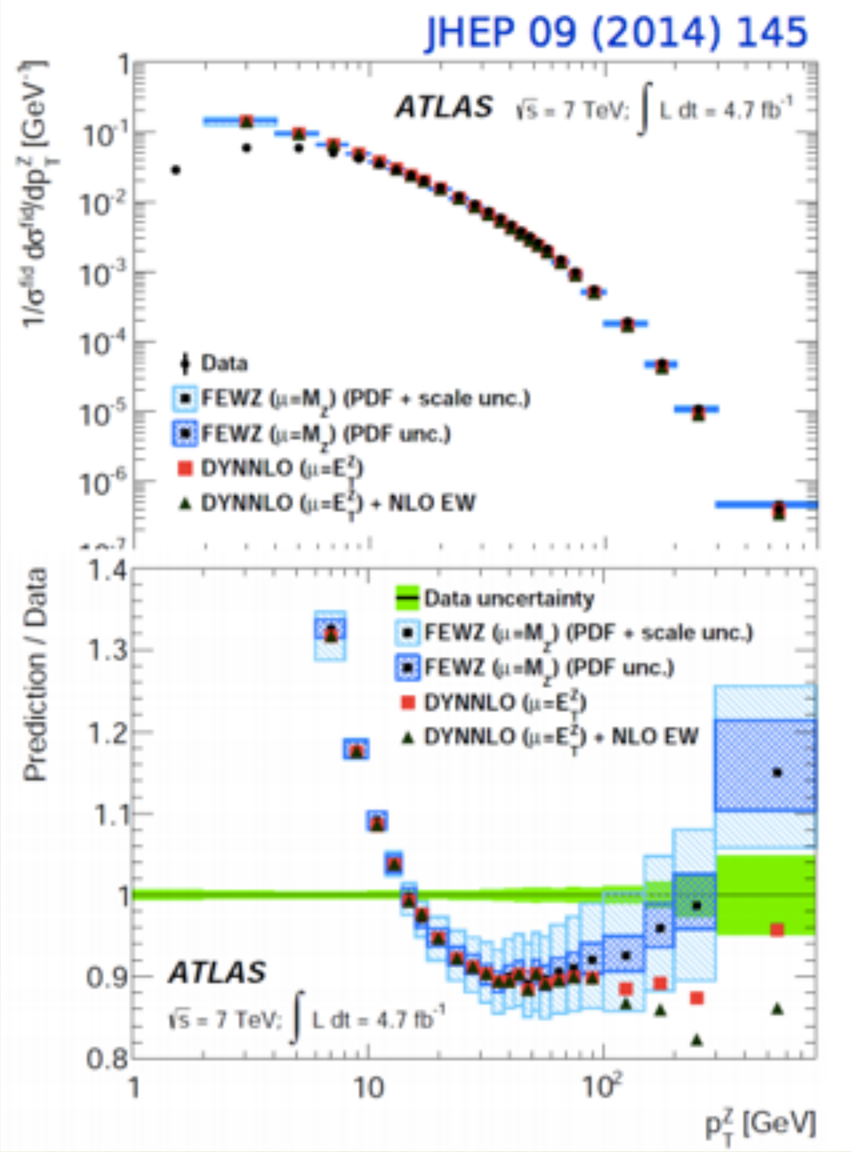
Large impact from:

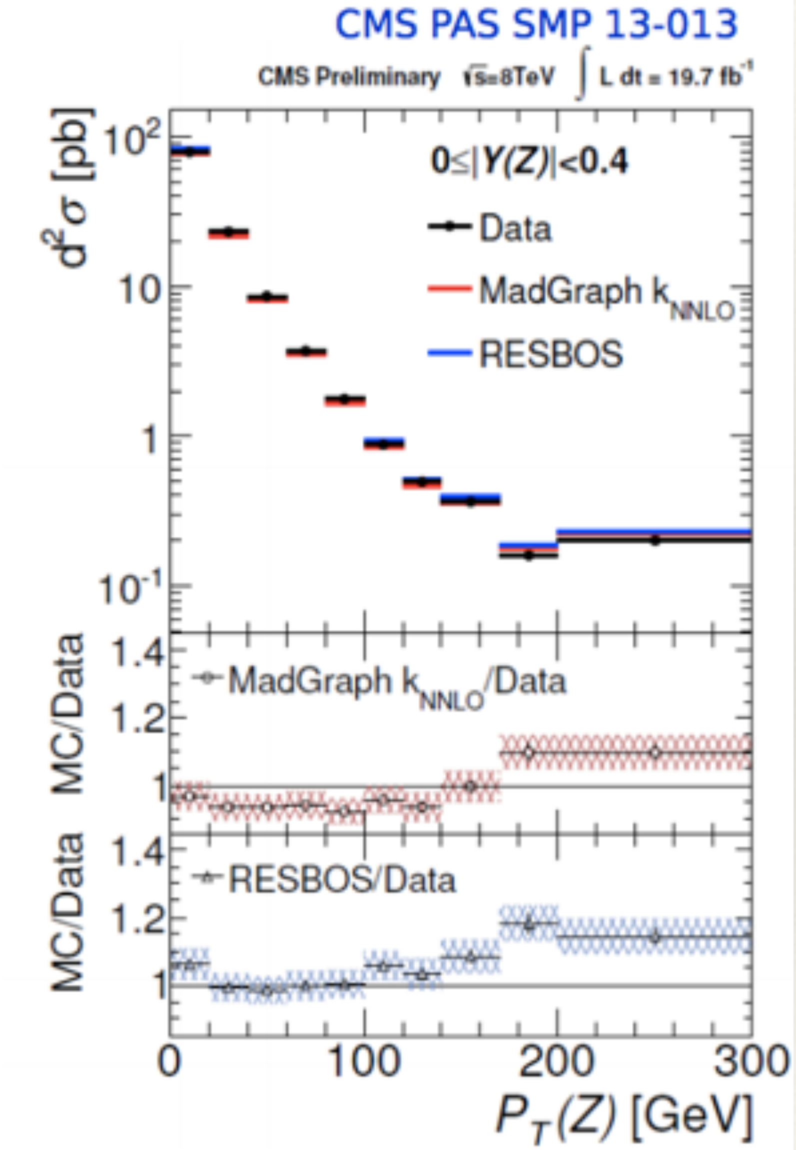
- charm-mass variations: PDF members 27-28
- strange-fraction variations affecting cs fraction (29-30)

strange density and valence quarks at low x are essential for W mass measurement

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)


JHEP 09 (2014) 145

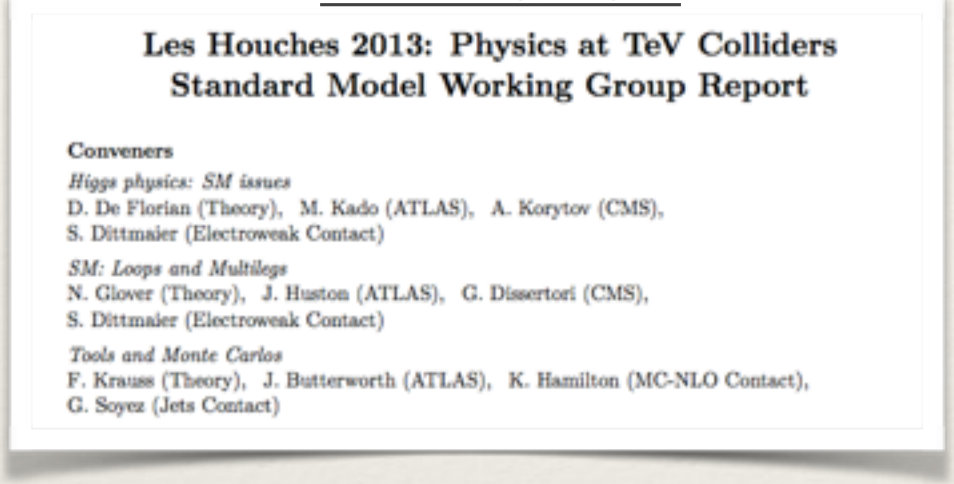

CMS PAS SMP 13-013

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

ggH benchmark studies

- Efforts in reducing the PDF uncertainties arising from discrepancy between PDF groups:
  - Benchmark comparisons of NNLO neutral current DIS cross sections (Exercise on HERA-I only data)

arxiv:1405.1067



Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

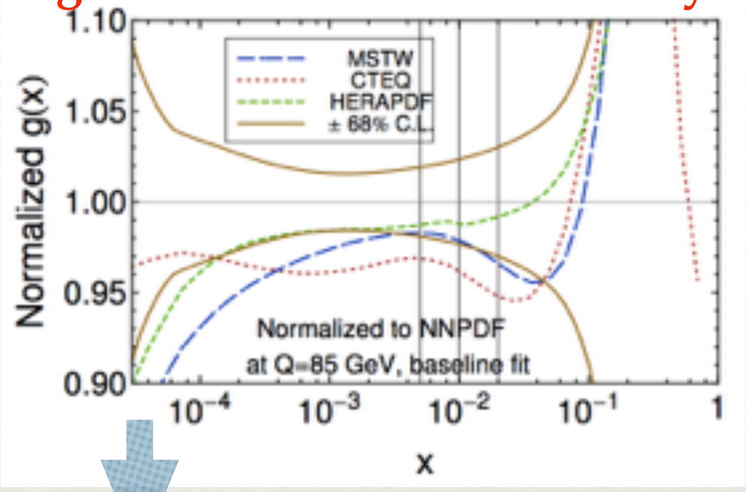
Conveners

Higgs physics: SM issues
D. De Florian (Theory), M. Kado (ATLAS), A. Korytov (CMS),
S. Dittmaier (Electroweak Contact)

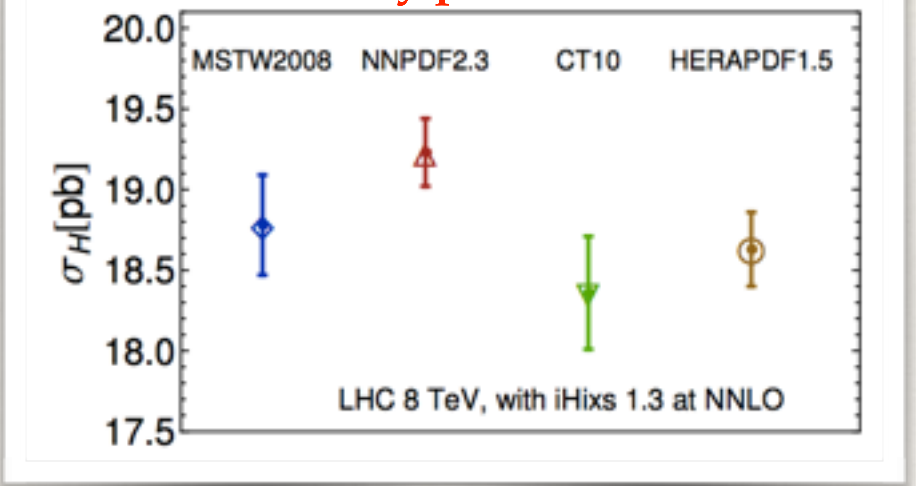
SM: Loops and Multilegs
N. Glover (Theory), J. Huston (ATLAS), G. Dissertori (CMS),
S. Dittmaier (Electroweak Contact)

Tools and Monte Carlos
F. Krauss (Theory), J. Butterworth (ATLAS), K. Hamilton (MC-NLO Contact),
G. Soyez (Jets Contact)

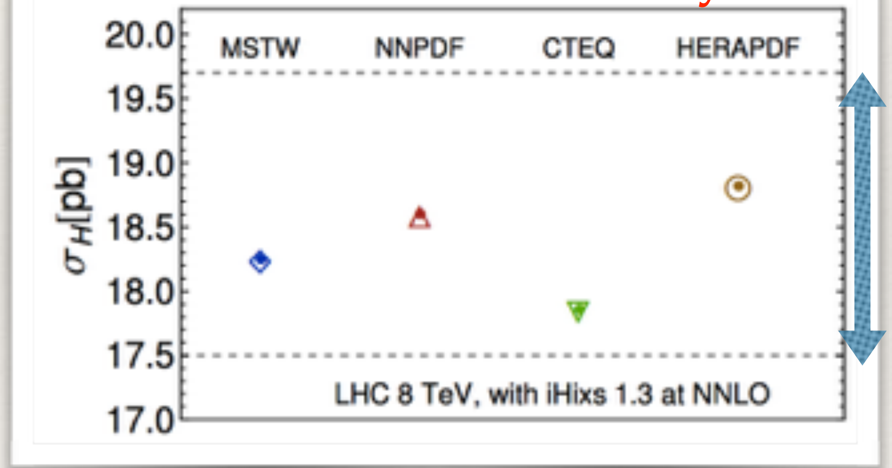
gluon PDF from HERA-I only fits



based on recently published NNLO PDFs.



based on HERA-I only fits



PDF uncert

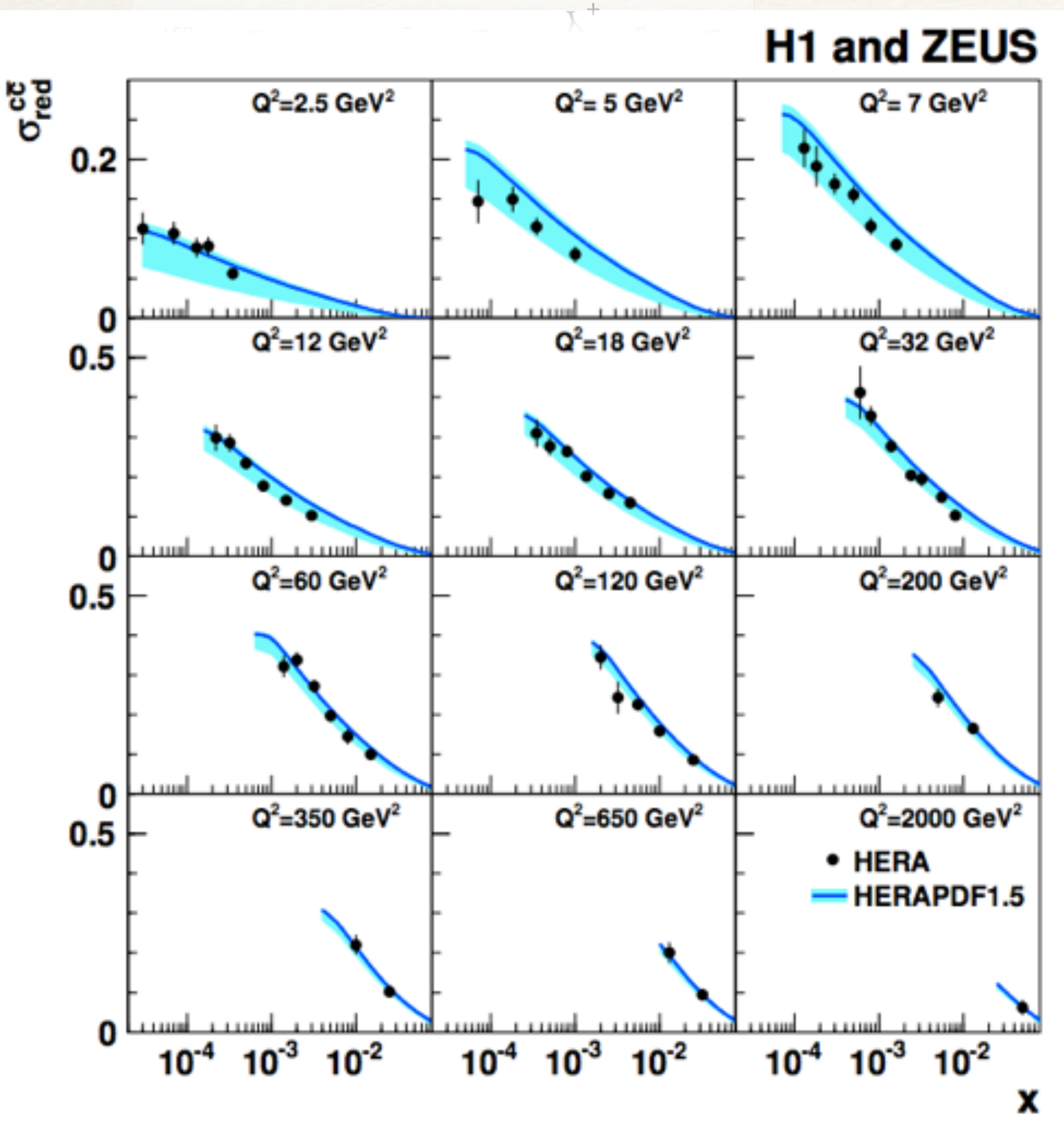
- predictions from MSTW, CT, NNPDF and HERAPDF all consistent within PDF uncertainties
- however the tendency among NNPDF, MSTW and CT is maintained
- **Next step:**
  - continue this exercise by adding additional experimental data sets into the PDF fits sequentially:
  - benchmarking the theoretical predictions used by each group for the different observables -
  - **==> HERAFitter will continue to participate in these studies.**

F2 charm Structure Function

EPJC 73 (2013) 2311

- Rates at HERA in DIS regime σ(b) : σ(c) ≈ O(1%) : O(20%) of σ_{TOT}
- Charm data combination is performed at charm cross sections level:
  - they are obtained from xsec in visible phase space and extrapolated to full space

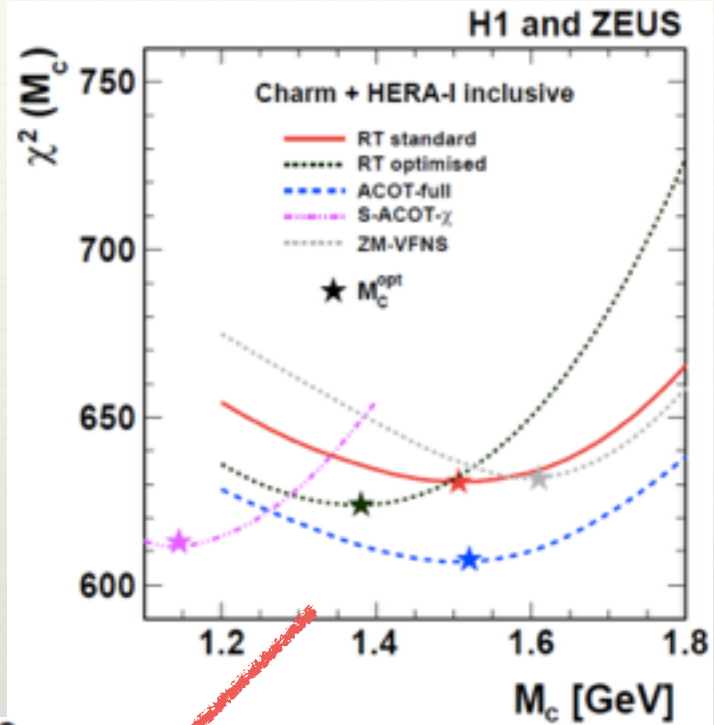
$$\sigma_{red}^{c\bar{c}}(x,Q^2,s) = F_2^{c\bar{c}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x,Q^2)$$

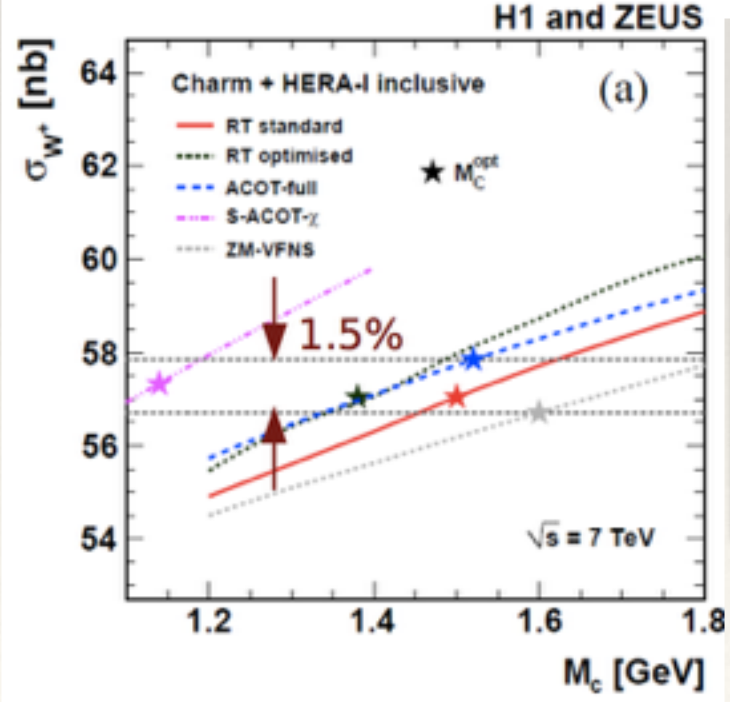


QCD Fits

HERA I+charm

Different calculation schemes prefer different Mc

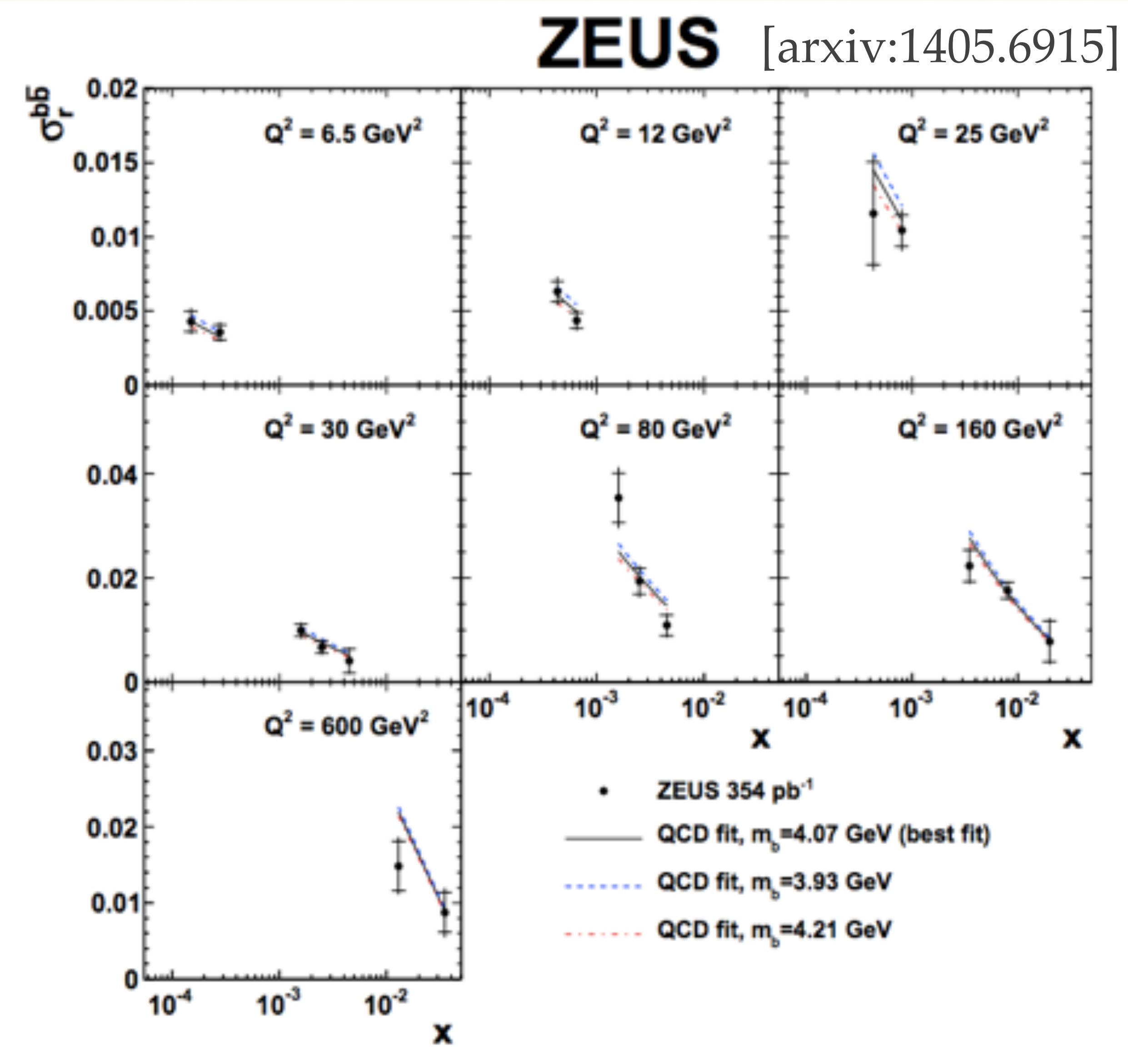




measurements help reduce uncertainties of predictions for the LHC

Running beauty mass from F2b

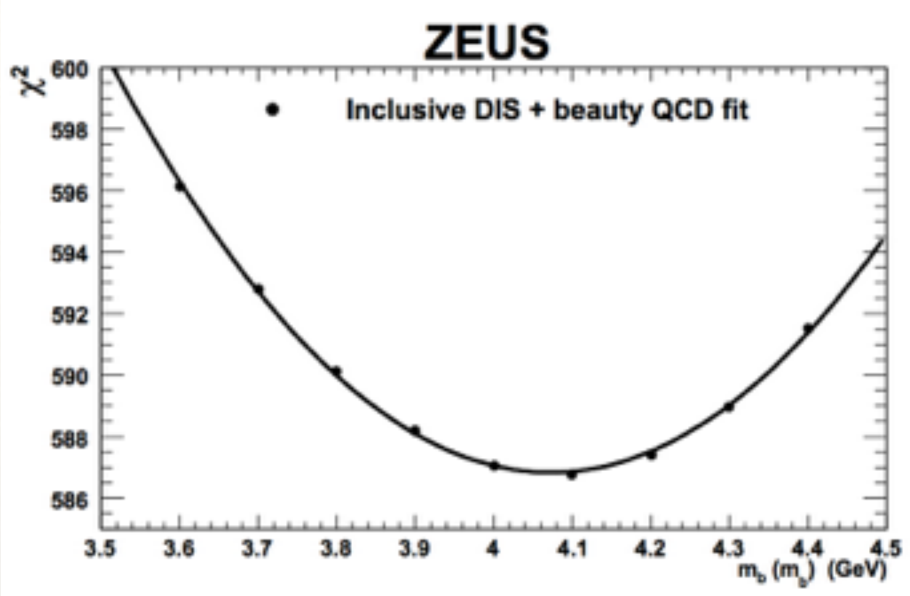
- The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.

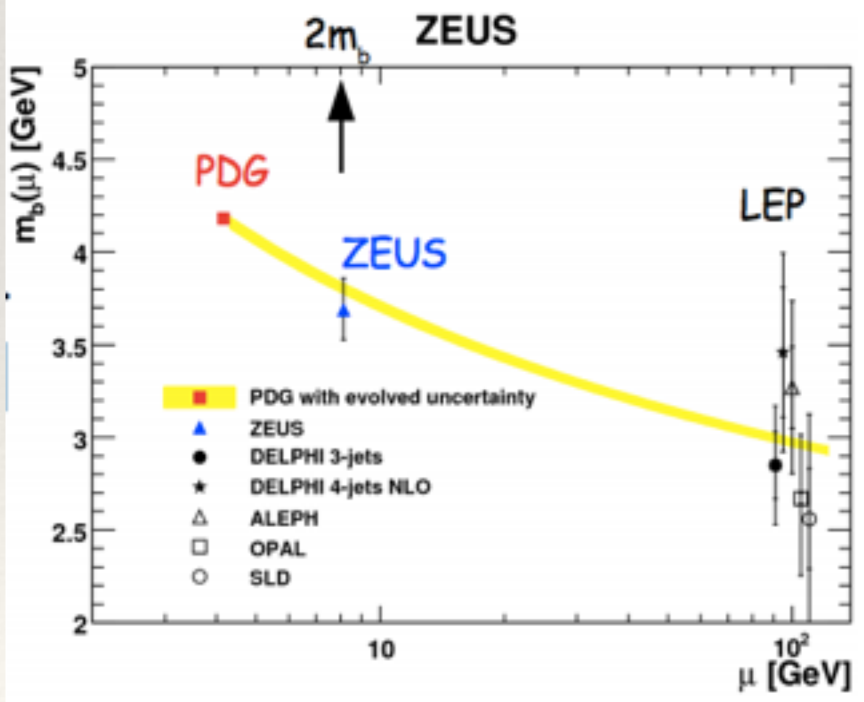


[arxiv:1405.6915]

QCD Fits

HERA I+beauty



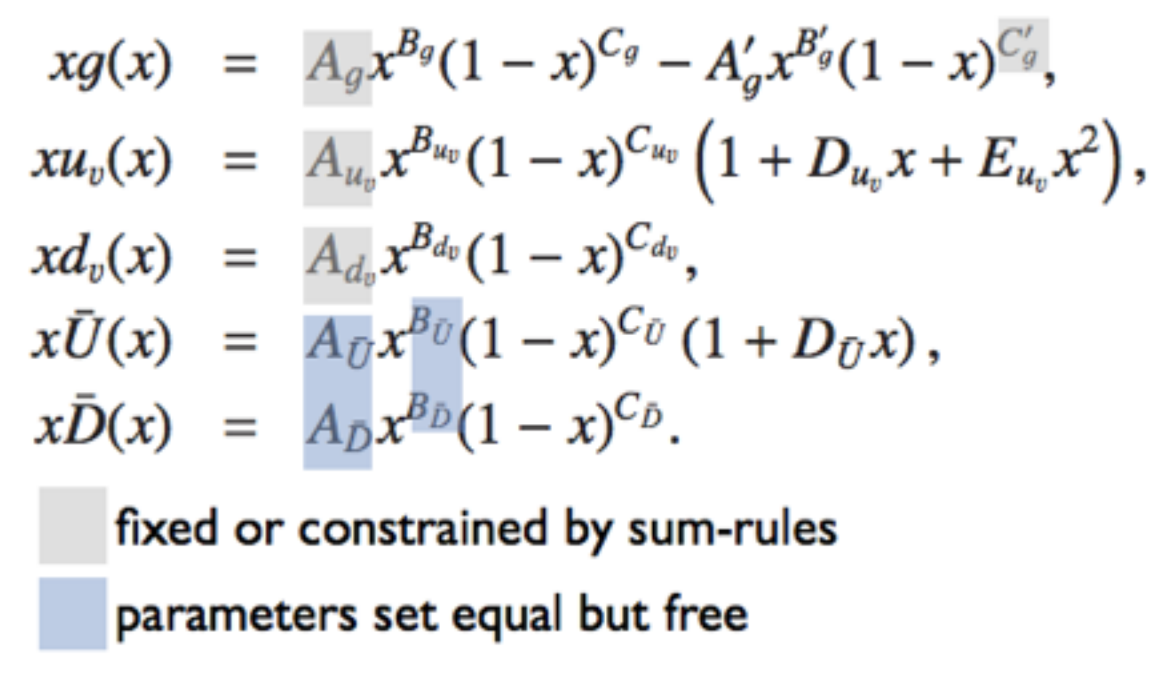


The extracted $\overline{\text{MS}}$ beauty-quark mass is in agreement with PDG average and LEP results.

QCD Settings for HERAPDF2.0

The QCD settings are optimised for HERA measurements of proton structure functions:

PDFs are parametrised at the starting scale Q_0^2=1.9 GeV^2 as follows:



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

⬜ fixed or constrained by sum-rules

🟦 parameters set equal but free

NC structure functions

$$F_2 = \frac{4}{9}\left(xU + x\bar{U}\right) + \frac{1}{9}\left(xD + x\bar{D}\right)$$

$$xF_3 \sim xu_v + xd_v$$

CC structure functions

$$W_2^- = x(U + \overline{D})\,, \qquad W_2^+ = x(\overline{U} + D)$$

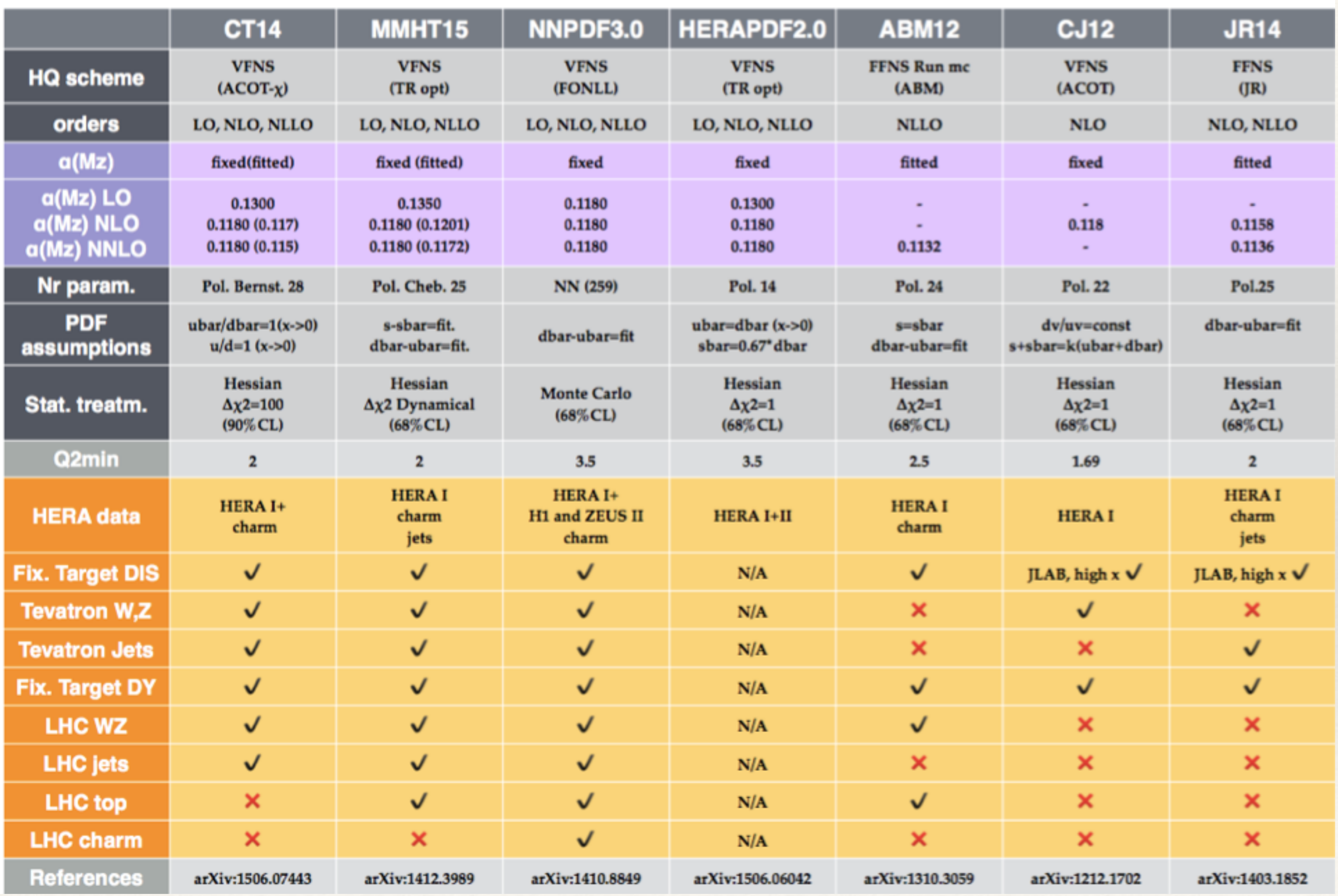
$$xW_3^- = x(U - \overline{D})\,, \qquad xW_3^+ = x(D - \overline{U})$$

Due to increased precision of data, more flexibility in functional form is allowed —> 15 free parameters

- PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (as(MZ)=0.118)
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MSTW
- Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

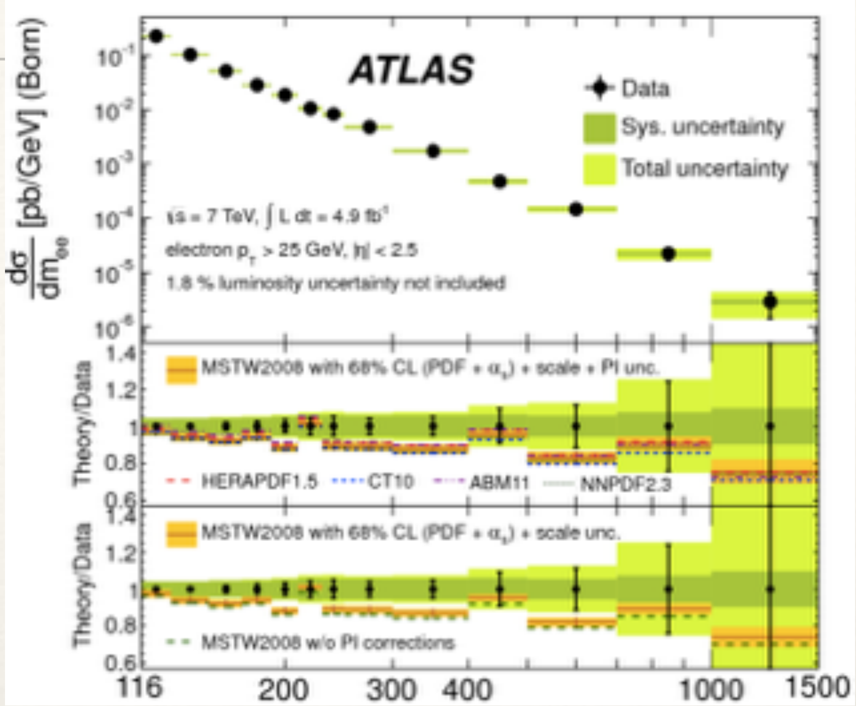
$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{\left[\mu^i - m^i\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,stat}\mu^i m^i\left(1 - \sum_j \gamma^i_j b_j\right) + \left(\delta_{i,unc} m^i\right)^2} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,unc} m_i^2 + \delta^2_{i,stat}\mu^i m^i}{\delta^2_{i,unc}\mu_i^2 + \delta^2_{i,stat}\mu_i^2}$$

Active PDF groups



	CT14	MMHT15	NNPDF3.0	HERAPDF2.0	ABM12	CJ12	JR14
HQ scheme	VFNS (ACOT-χ)	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
orders	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	NLLO	NLO	NLO, NLLO
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 Δχ2=100 (90%CL)	Hessian Δχ2 Dynamical (68%CL)	Monte Carlo (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
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	✓	✓	✓	N/A	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	N/A	✗	✓	✗
Tevatron Jets	✓	✓	✓	N/A	✗	✗	✓
Fix. Target DY	✓	✓	✓	N/A	✓	✓	✓
LHC WZ	✓	✓	✓	N/A	✓	✗	✗
LHC jets	✓	✓	✓	N/A	✗	✗	✗
LHC top	✗	✓	✓	N/A	✓	✗	✗
LHC charm	✗	✗	✓	N/A	✗	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

Neutral Current DY measurements



- High Mass DY measurement with the 13 TeV centre of mass energy can extend the di-lepton mass distribution up to 3 TeV:
  - differential measurements in m_{ll}, y

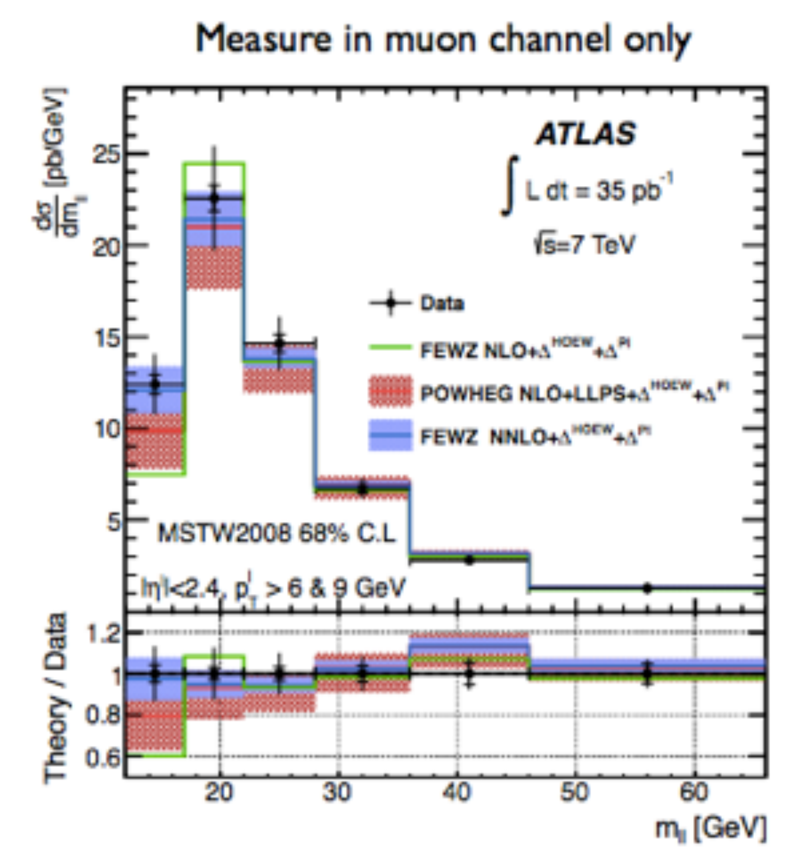
—> an extra in lever arm in x for constraining PDFs

  - 13 TeV data can bring considerable improvement in the statistical uncertainty compared to Run 1
    - Statistical uncertainty dominates for $m_{ll} > 400$

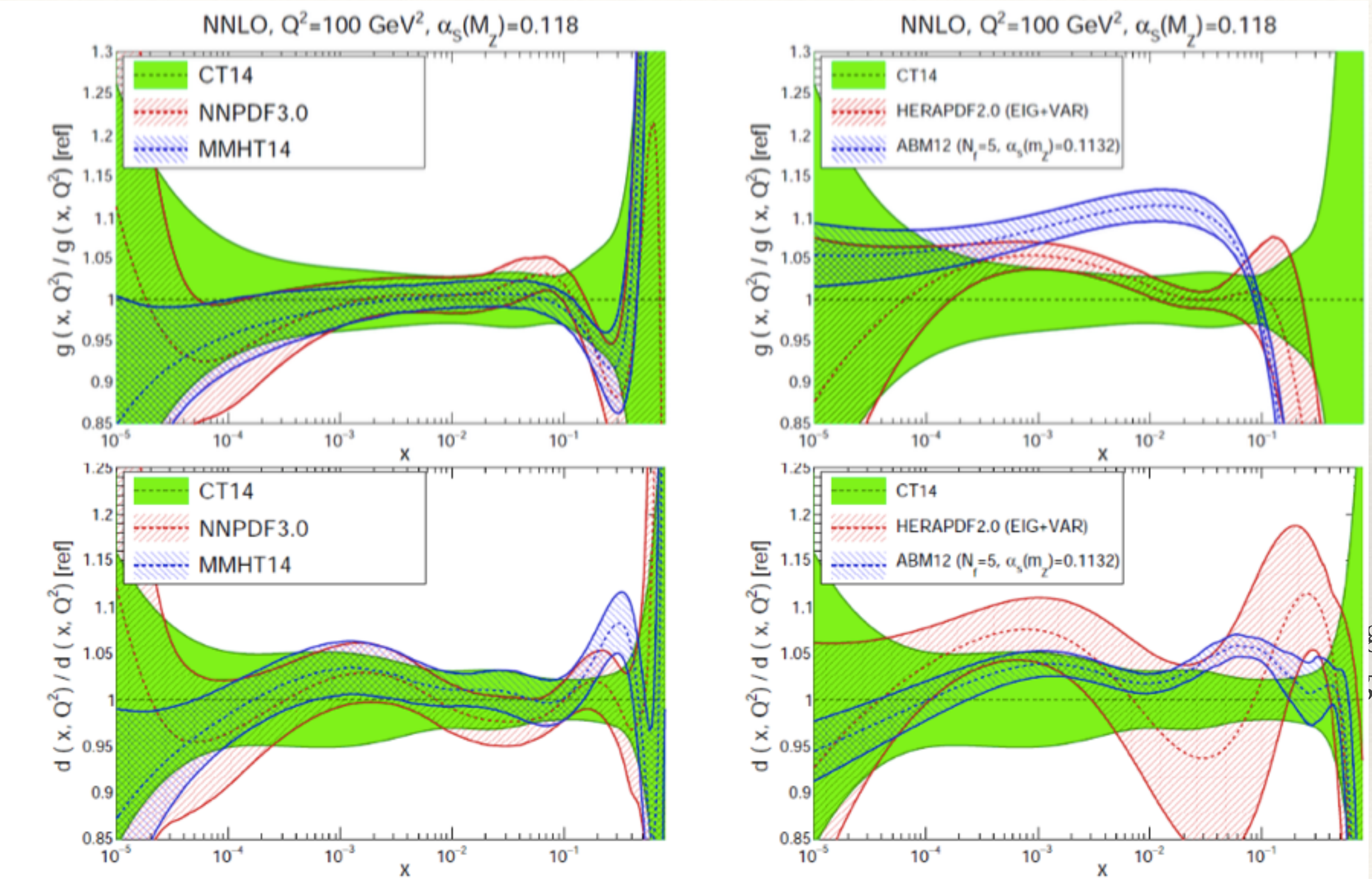
- Low Mass DY is an interesting measurement as it accesses with its low mass ranges $12<m_{ll}<60$ GeV PDFs down to x ~ 10^{-4}:
  - exploit the interference effects between Z and γ* (u,d)

—> sensitivity to the low x effects?

  - 13 TeV data could provide an increased experimental precision in the lower mass bins of m_{ll} distribution
  - Theoretical uncertainty can be reduced when using lower pt muon cuts and resummed calculations



HERAPDF2.0 vs other PDF sets: gluon and d quark

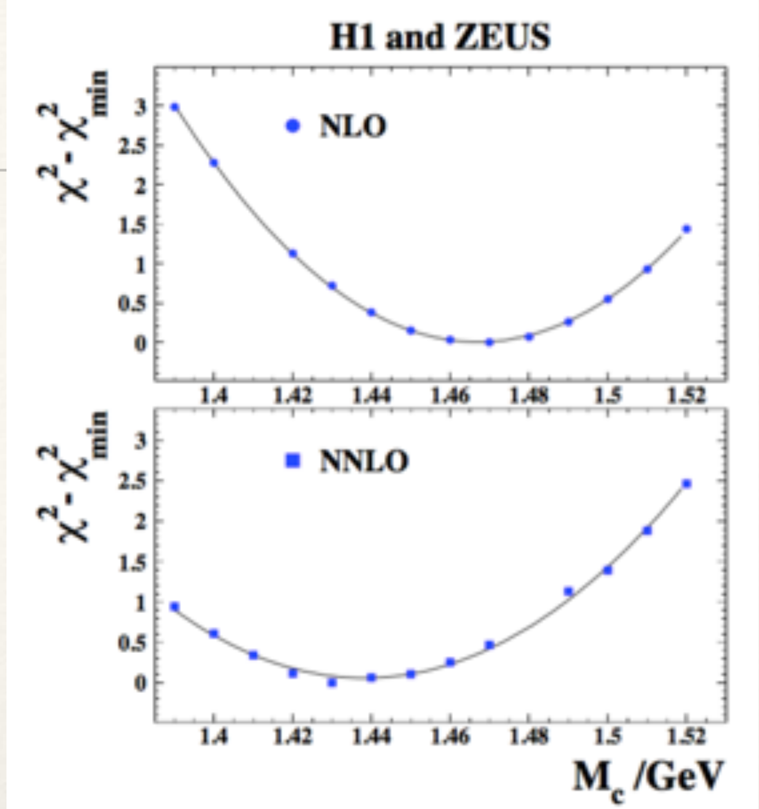


global

ge

*plots taken from PDF4LHC recommendation arxiv:1510.03865

HERAPDF2.0Jets

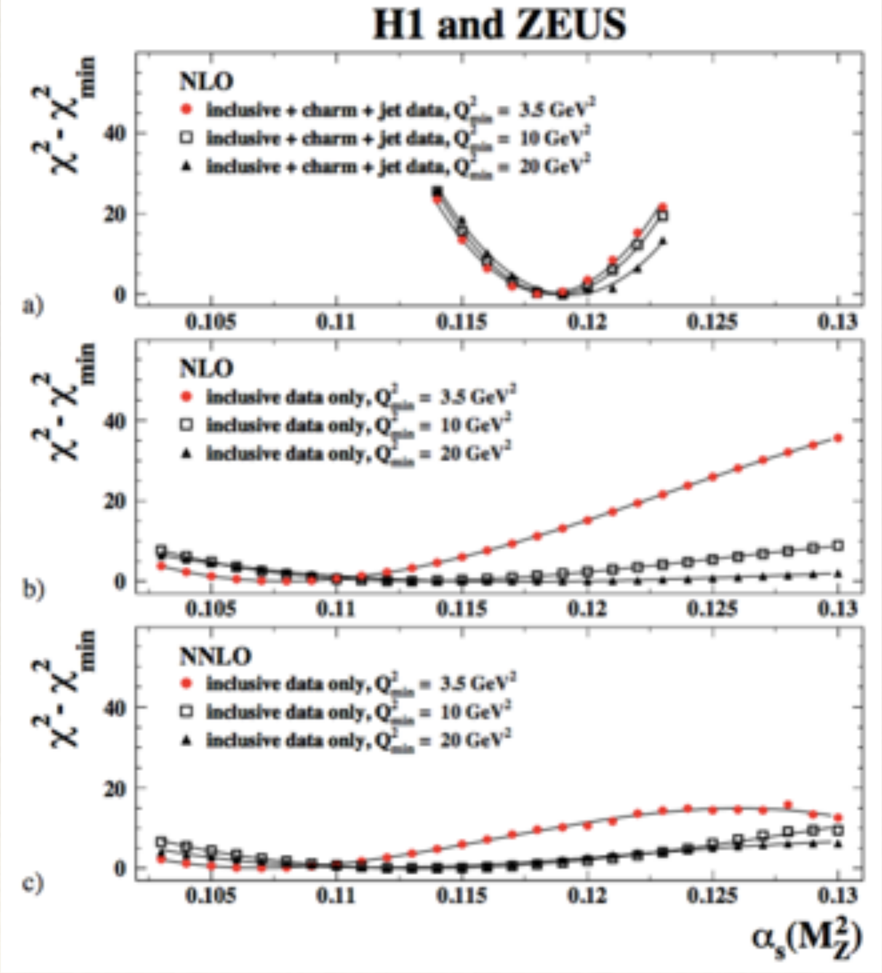


HERAPDF2.0Jets is based on inclusive + charm + jet data:

- data from the HERA charm combination has its main effect to determine the optimal charm mass parameter and determine its variation for the standard HERAPDF2.0.
  - This variation is much reduced compared to HERAPDF1.0
- Seven data sets on inclusive jet, dijet, trijet production at low and high Q^2, from ZEUS and H1 have been added to the HERAPDF2.0 fit

  PLB547(2001)164, EPJC70(2010)965, EPJC67(2010)1, PLB653(2007)134 and EPJC75(2015)2

  - Inclusive data alone cannot determine $\alpha_S(M_Z)$ reliably either at NLO or at NNLO When jet data are added one can make a simultaneous fit for PDF parameters and $\alpha_S(M_Z)$ at NLO

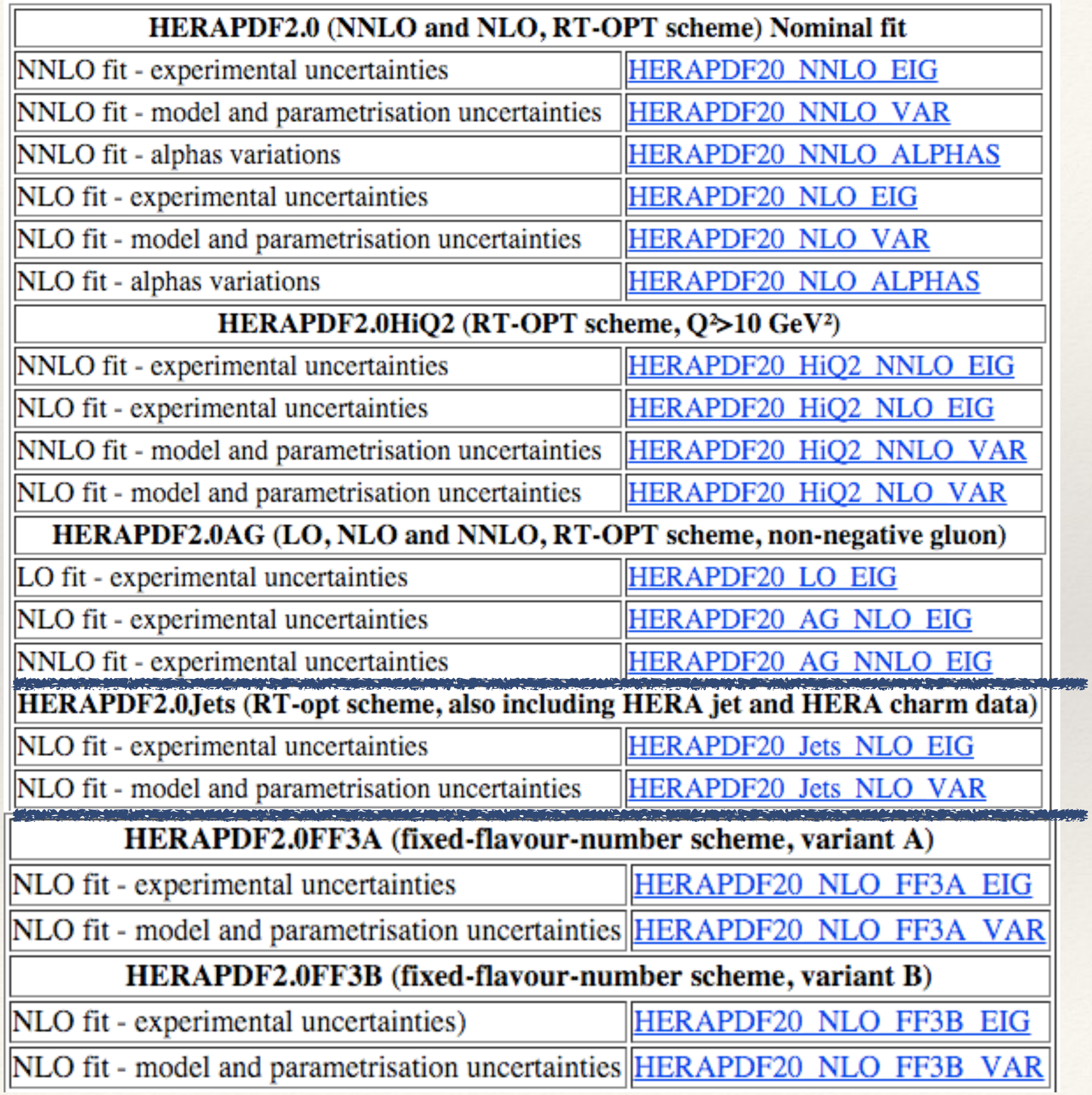


$$\alpha_S(M_Z) = 0.1183 \pm 0.0009_{(exp)} \pm 0.0005_{(model/param)} \pm 0.0012_{(had)} \, {}^{+0.0037}_{-0.0030}(\text{scale})$$

the fitted value is in agreement with the chosen fixed value —> PDFs are similar for fixed vs fitted

HERAPDF sets:

https://www.desy.de/h1zeus/herapdf20/



HERAPDF2.0 (NNLO and NLO, RT-OPT scheme) Nominal fit	
NNLO fit - experimental uncertainties	HERAPDF20_NNLO_EIG
NNLO fit - model and parametrisation uncertainties	HERAPDF20_NNLO_VAR
NNLO fit - alphas variations	HERAPDF20_NNLO_ALPHAS
NLO fit - experimental uncertainties	HERAPDF20_NLO_EIG
NLO fit - model and parametrisation uncertainties	HERAPDF20_NLO_VAR
NLO fit - alphas variations	HERAPDF20_NLO_ALPHAS
HERAPDF2.0HiQ2 (RT-OPT scheme, Q^2>10 GeV^2)	
NNLO fit - experimental uncertainties	HERAPDF20_HiQ2_NNLO_EIG
NLO fit - experimental uncertainties	HERAPDF20_HiQ2_NLO_EIG
NNLO fit - model and parametrisation uncertainties	HERAPDF20_HiQ2_NNLO_VAR
NLO fit - model and parametrisation uncertainties	HERAPDF20_HiQ2_NLO_VAR
HERAPDF2.0AG (LO, NLO and NNLO, RT-OPT scheme, non-negative gluon)	
LO fit - experimental uncertainties	HERAPDF20_LO_EIG
NLO fit - experimental uncertainties	HERAPDF20_AG_NLO_EIG
NNLO fit - experimental uncertainties	HERAPDF20_AG_NNLO_EIG
HERAPDF2.0Jets (RT-opt scheme, also including HERA jet and HERA charm data)	
NLO fit - experimental uncertainties	HERAPDF20_Jets_NLO_EIG
NLO fit - model and parametrisation uncertainties	HERAPDF20_Jets_NLO_VAR
HERAPDF2.0FF3A (fixed-flavour-number scheme, variant A)	
NLO fit - experimental uncertainties	HERAPDF20_NLO_FF3A_EIG
NLO fit - model and parametrisation uncertainties	HERAPDF20_NLO_FF3A_VAR
HERAPDF2.0FF3B (fixed-flavour-number scheme, variant B)	
NLO fit - experimental uncertainties)	HERAPDF20_NLO_FF3B_EIG
NLO fit - model and parametrisation uncertainties	HERAPDF20_NLO_FF3B_VAR

—>fits with Q2>3.5

—>fits with Q2>10

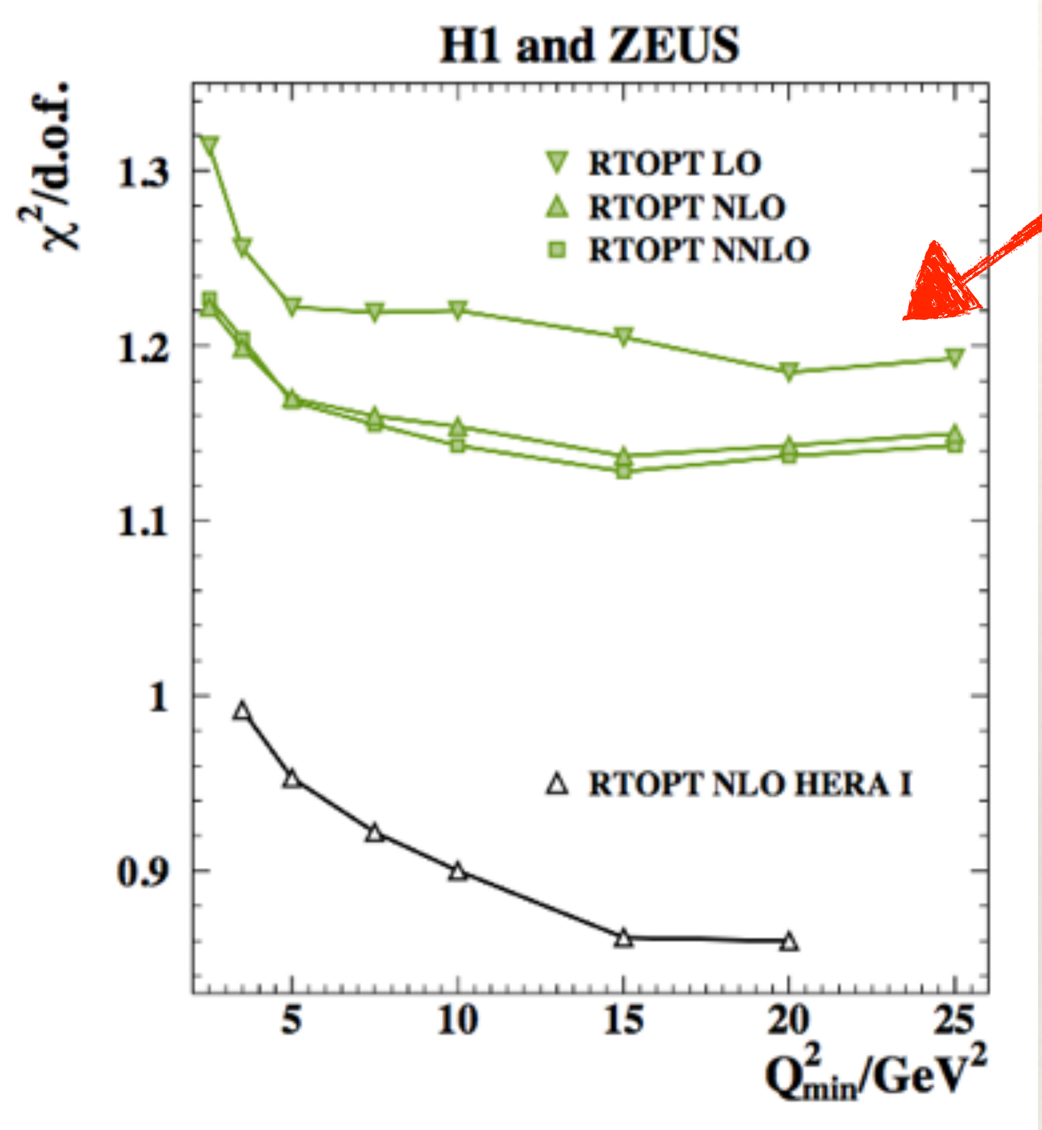
—>fits with positive definite gluon

—>fits with free alphas,
adding jet and charm data

—>fits using FFNS

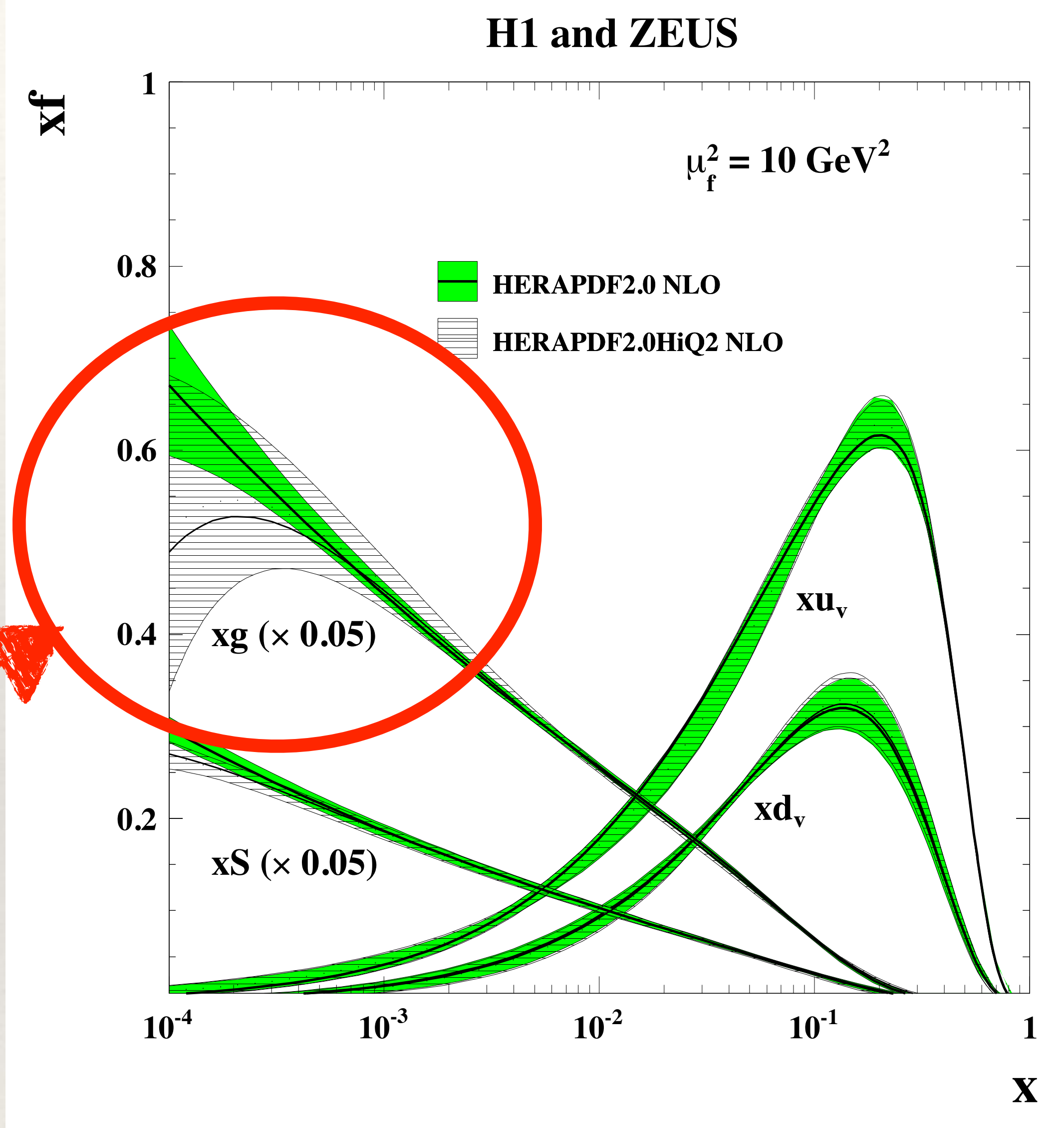
Q^2 cut dependence on PDFs

- HERA data provides a unique access to the low x, low Q^2 region to investigate:
  - the validity of the DGLAP mechanism



NLO is significantly better than LO, but NNLO is not obviously better than NLO

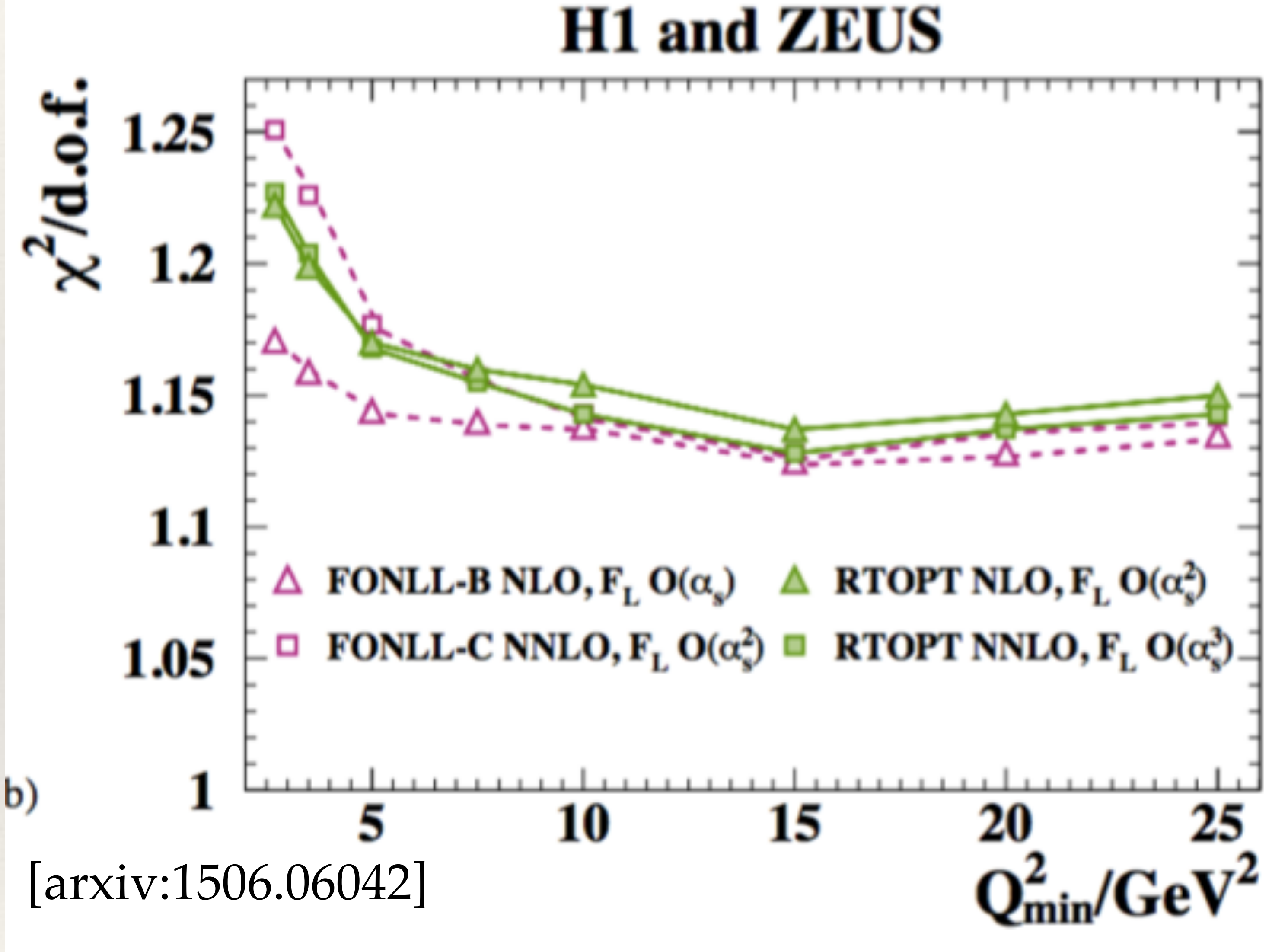
low Q² data very important to constrain low x PDFs!



- LHAPDF sets for HERAPDF are presented for both variants:
  - Q2 > 3.5 HERAPDF2.0 (LO, NLO, NNLO) - nominal
  - Q2> 10 HERAPDF2.0HiQ2 (NLO, NNLO)

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)

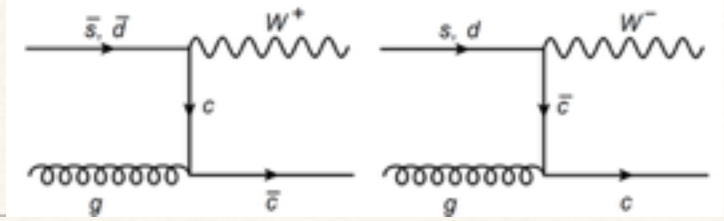


[arxiv:1506.06042]

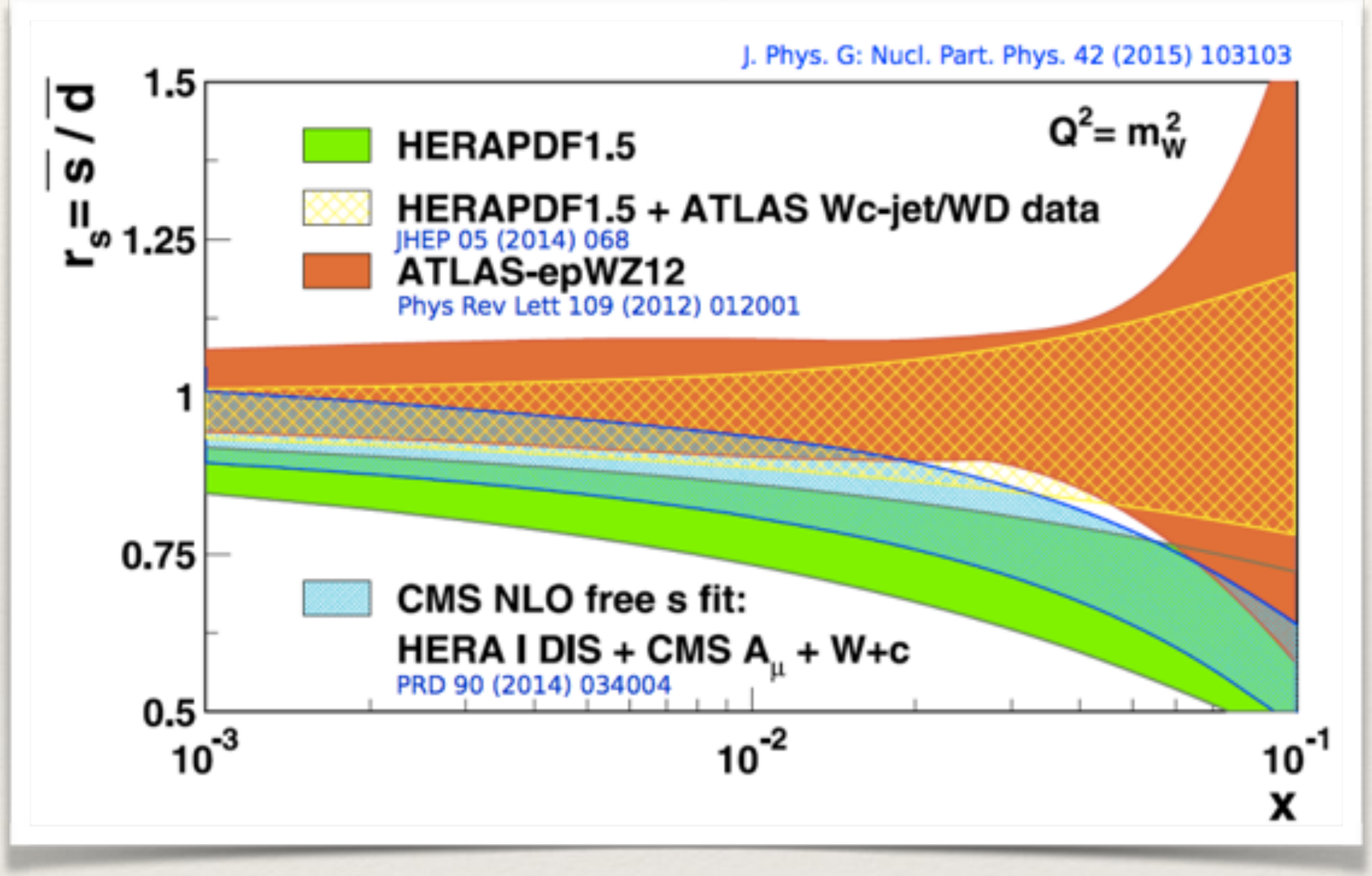
Treating FL to O(αS) yields better χ2 than treating FL to O(αS2) quasi independent of heavy flavour scheme

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

W+c sensitivity to strange



- W + charm data is directly sensitive to the strange quark density
- ATLAS, CMS and LHCb have performed dedicated measurements
    - ATLAS @ particle level [arXiv:1402.6263v1] CMS @parton level [arXiv:1310.1138]


J. Phys. G: Nucl. Part. Phys. 42 (2015) 103103

Strange fraction determined in CMS is lower than in ATLAS but results are still consistent …