January 2017, FCC Week CERN

QCD measurements at FCC-ep

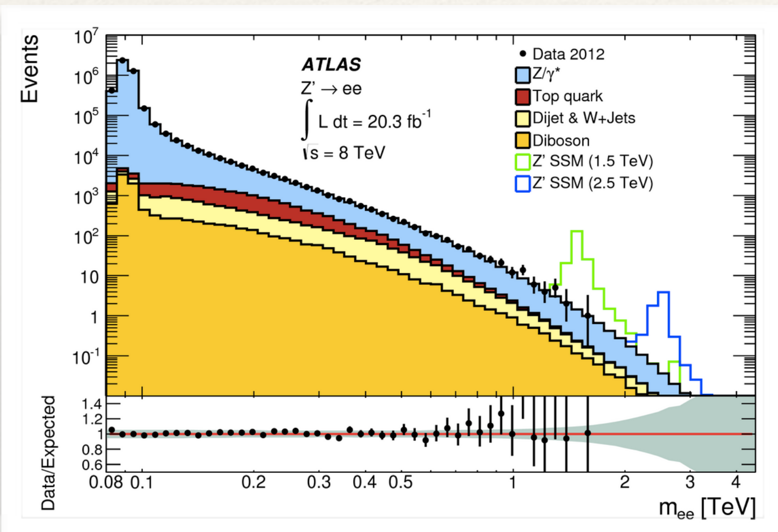
Stefano Camarda
Voica Radescu
for the FCC-eh study groups

Search for new Physics

direct searches for new physics

indirect searches via consistency test of SM

control of QCD background and SM parameters

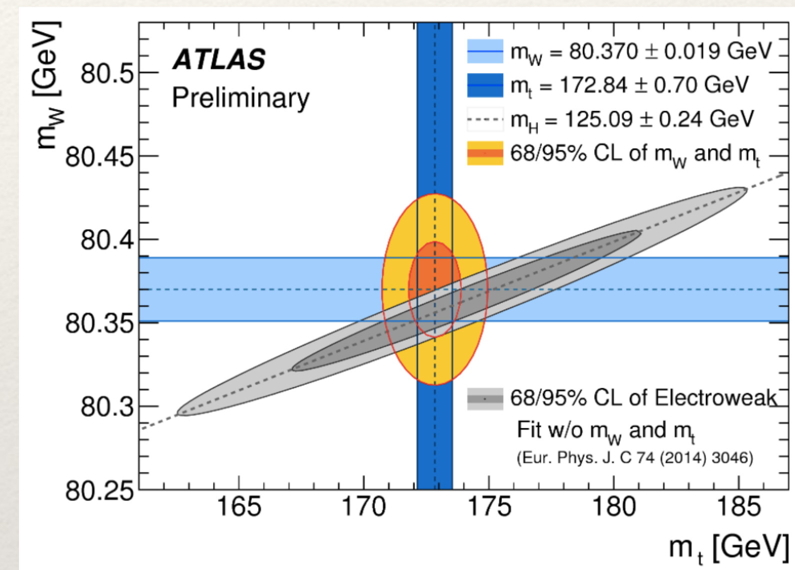


[arXiv:1410.6810v2]

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

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

calculable from data

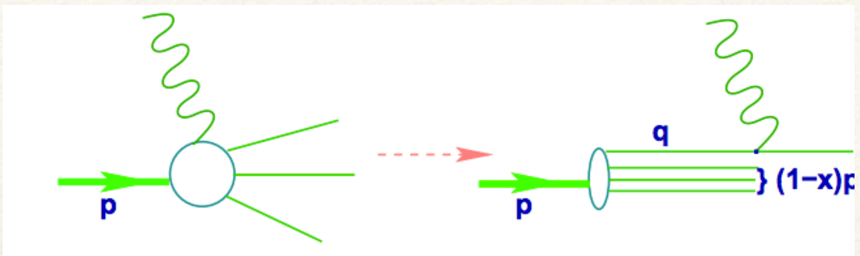


ATLAS-CONF-2016-113 /

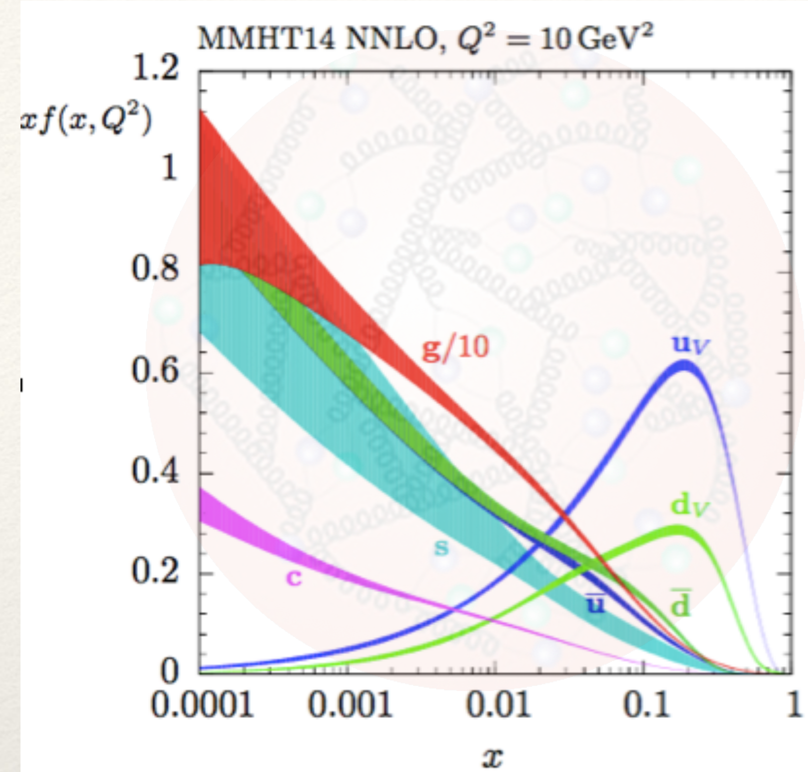
Improvement of PDFs precision demands high precision theory & experimental measurement

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 and their x shape is determined from fits to experimental data

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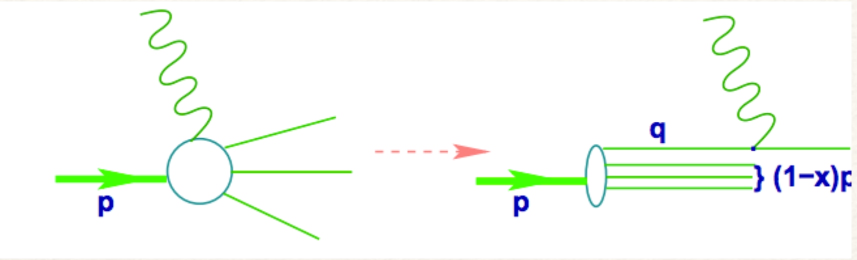

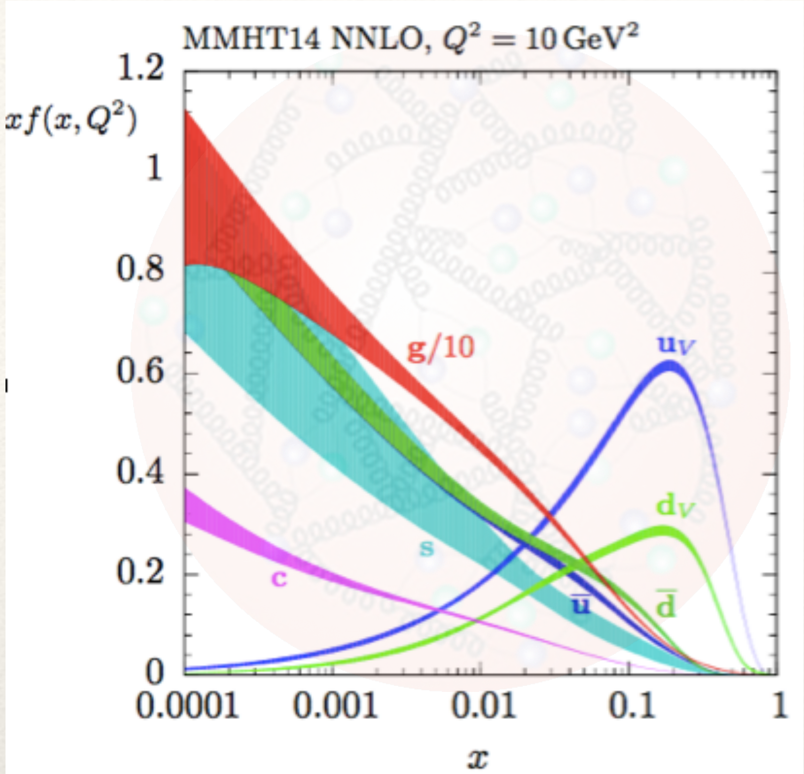

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List of modern PDF sets::

- *MMHT14* from A. D. Martin, R. S. Thorne, P. Motylinski, L.A. Harland
- *NNPDF3.0* from the Neural-Network PDF Collaboration
- *CT14* from the CTEQ-TEA Collaboration
- *HERAPDF2.0* from the H1 and ZEUS Collaborations: based only on ep HERA data
- *CJ15* from the CTEQ-JLAB Collaboration: high-x phenomenology
- *nCTEQ* from the CTEQ Collaboration: nuclear PDFs
- *ABM12* from S. Alekhin, J. Bluemlein, S. Moch
- *JR14* from P. Jimenez-Delgado, E. Reya (previously GRV/GRJ)

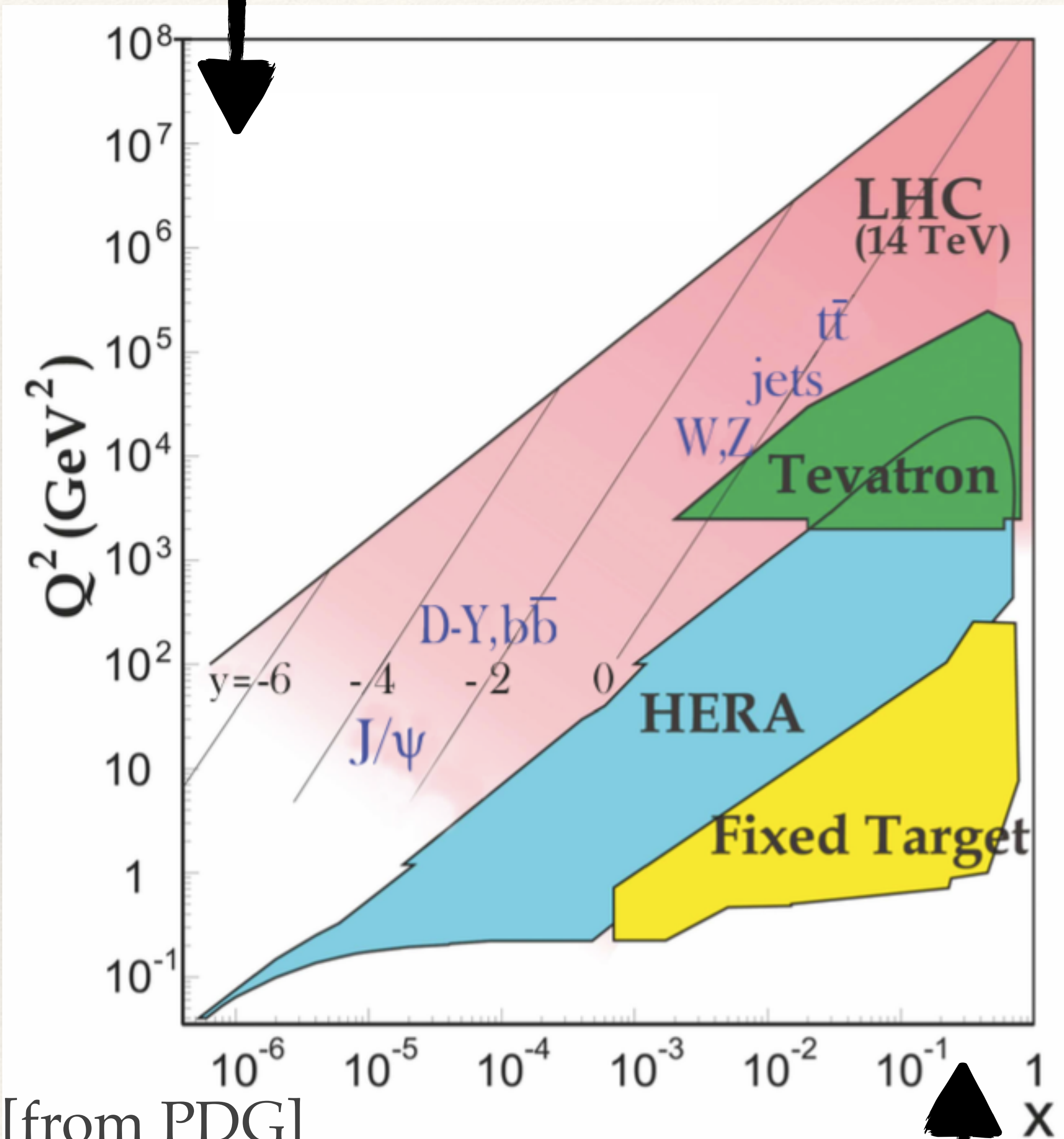
The analyses differ in many areas:

- 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)

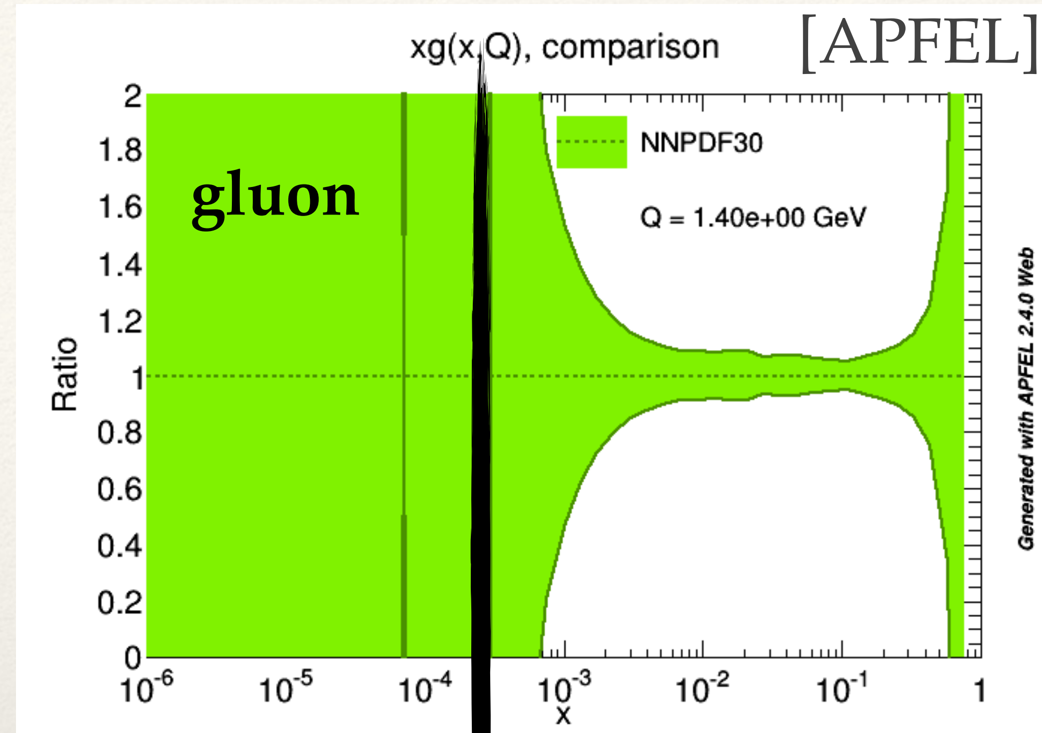
… differences in PDFs lead to the differences in the cross section predictions!

Kinematic coverage today:

we don't know where at low x DGLAP breaks,
parton saturation?



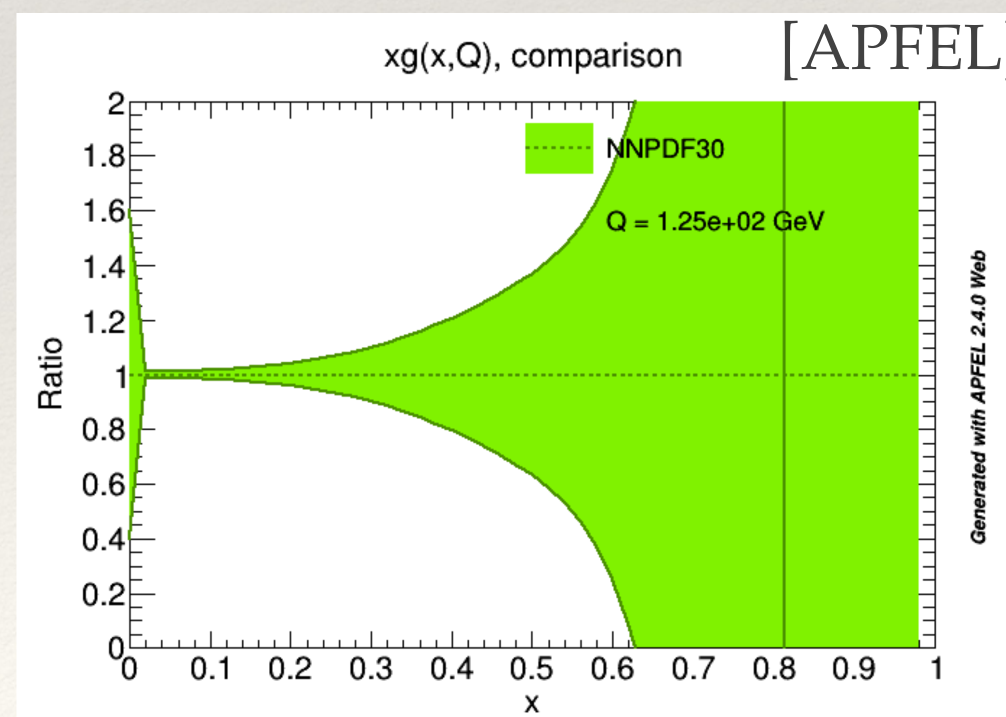
[from PDG]



[APFEL]

NO DATA<—

uncertainties >100%!



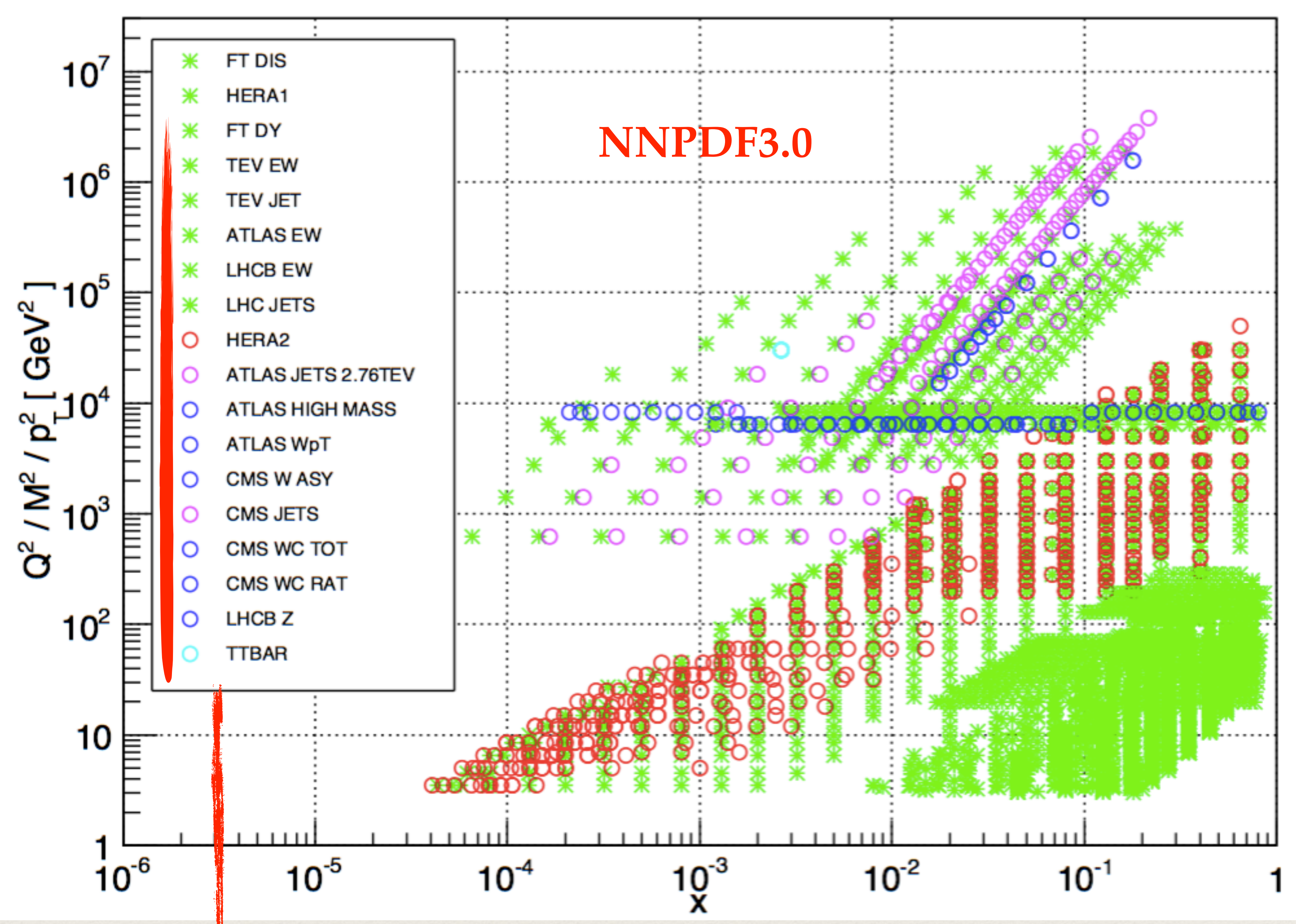
[APFEL]

High x is the Discovery Region —> must do better!

Example of data sets entering into a global PDF:

- 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] , jet processes at the collider experiments



[slide by S. Forte]

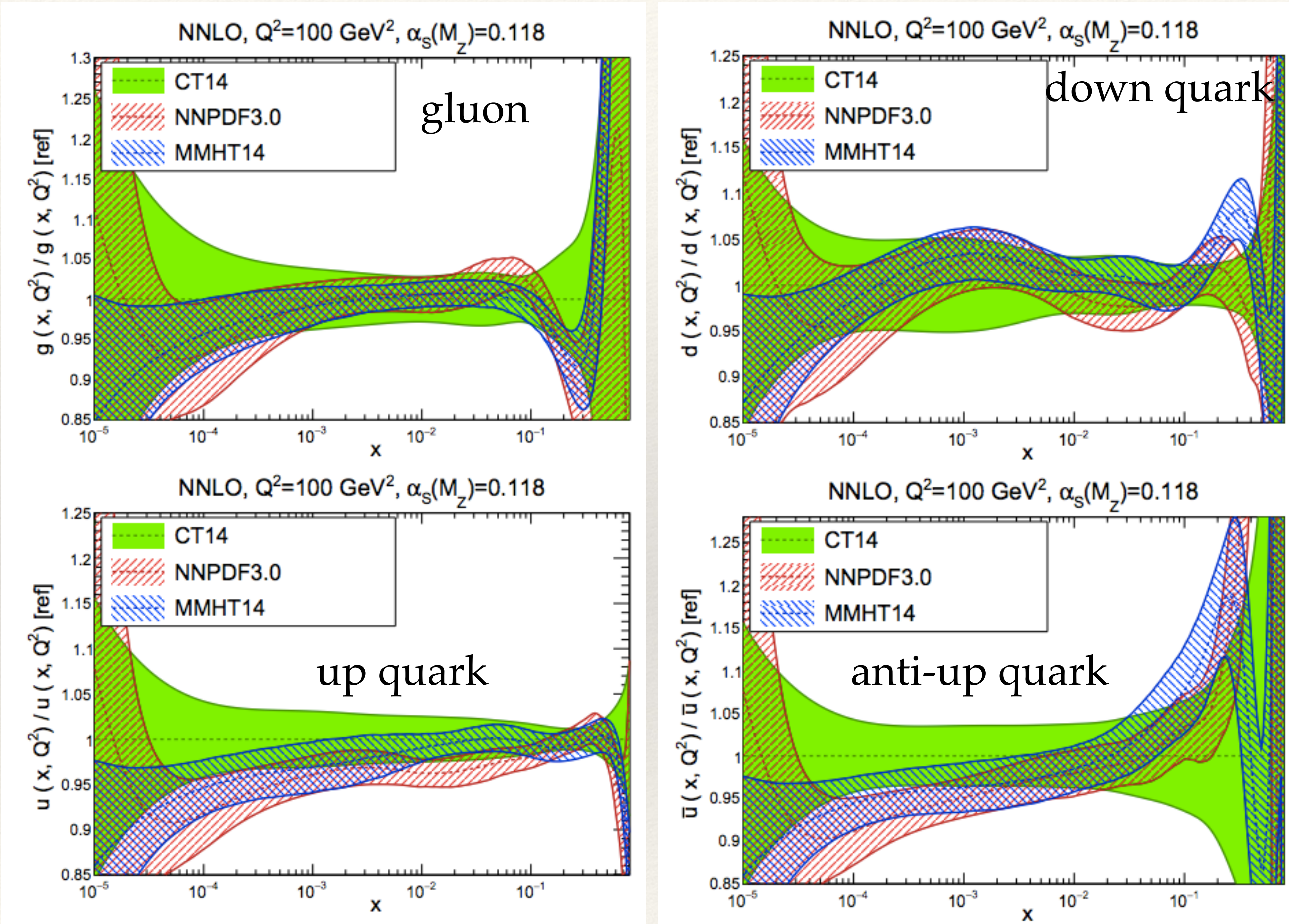
Many Data Sets:

- account for possible tensions
- account for corrections/ assumptions

Are we precise enough?

- [From last PDF4LHC recommendation based on GMVFNS PDFs]

arXiv:1510.03865



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

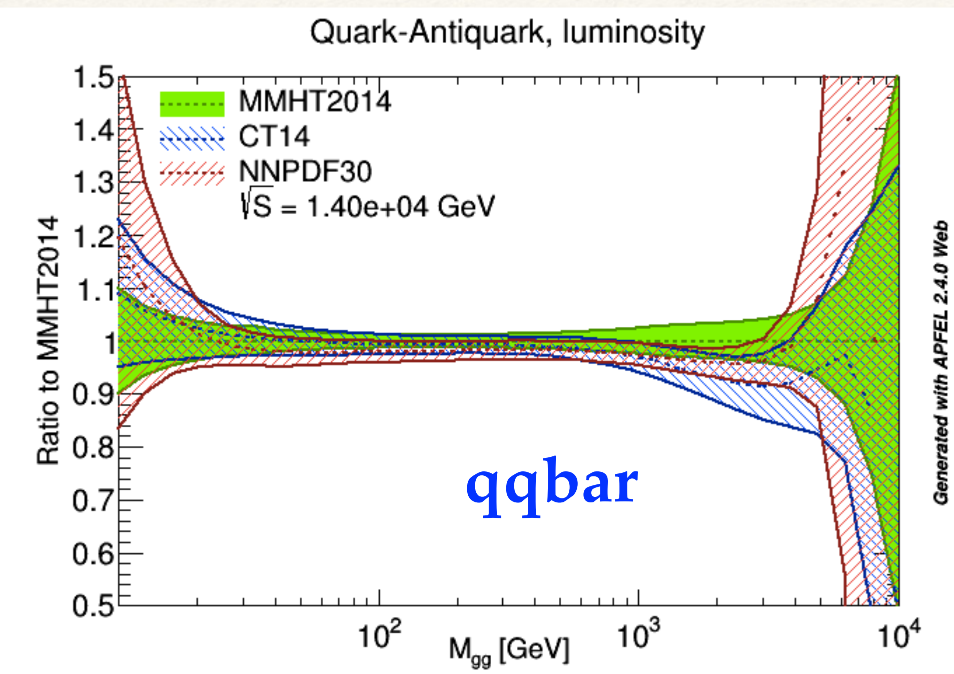
in the outside this
region very
uncertain
PDFs

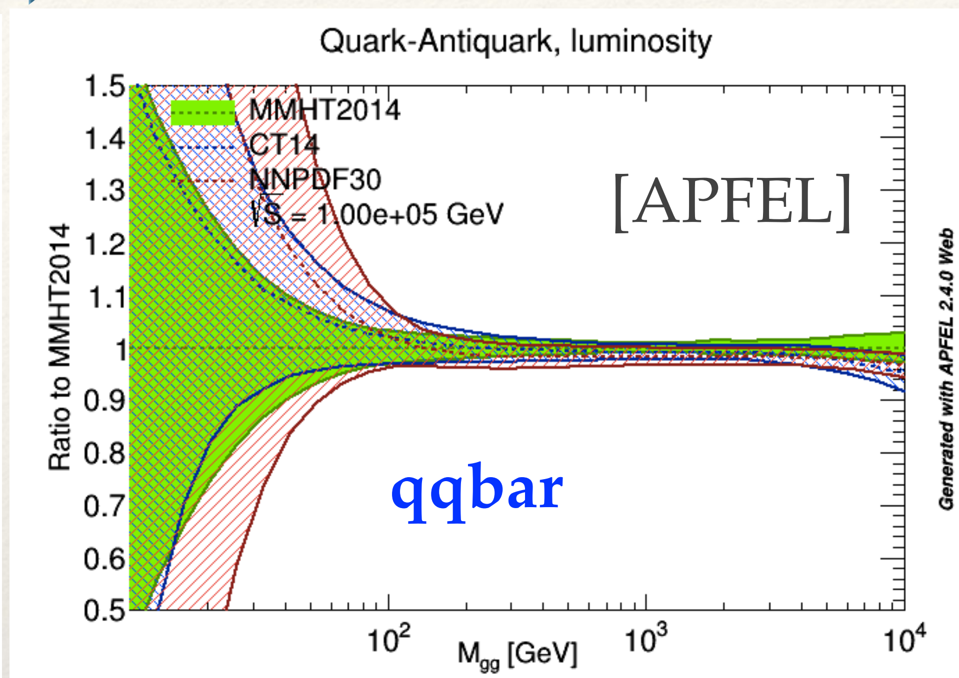
and how about in the region below <10^-4 and >0.5

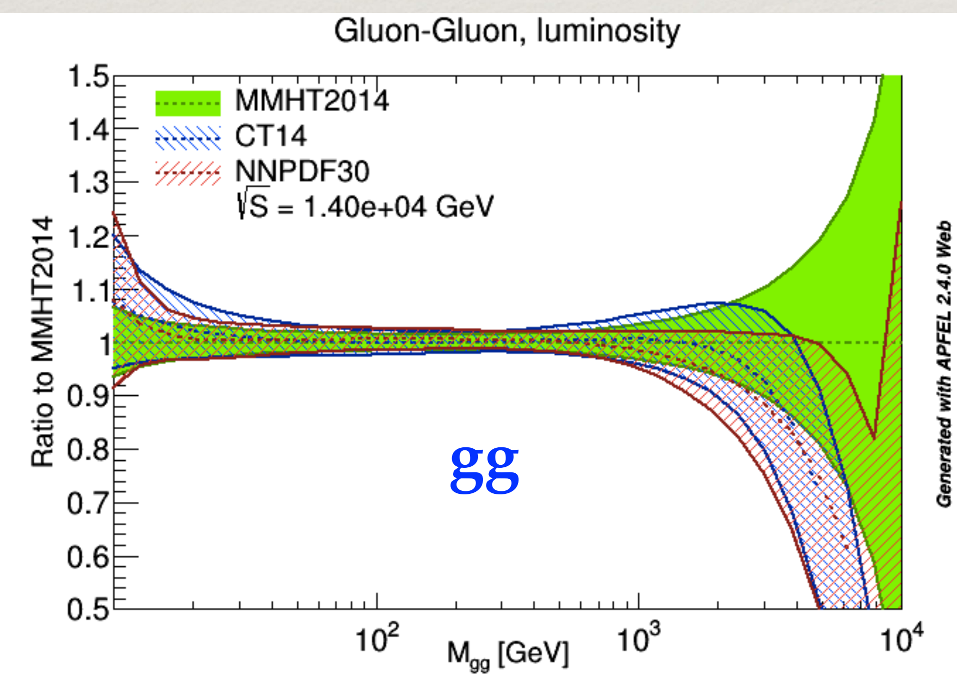
Parton Luminosities From 14 TeV to 100 TeV

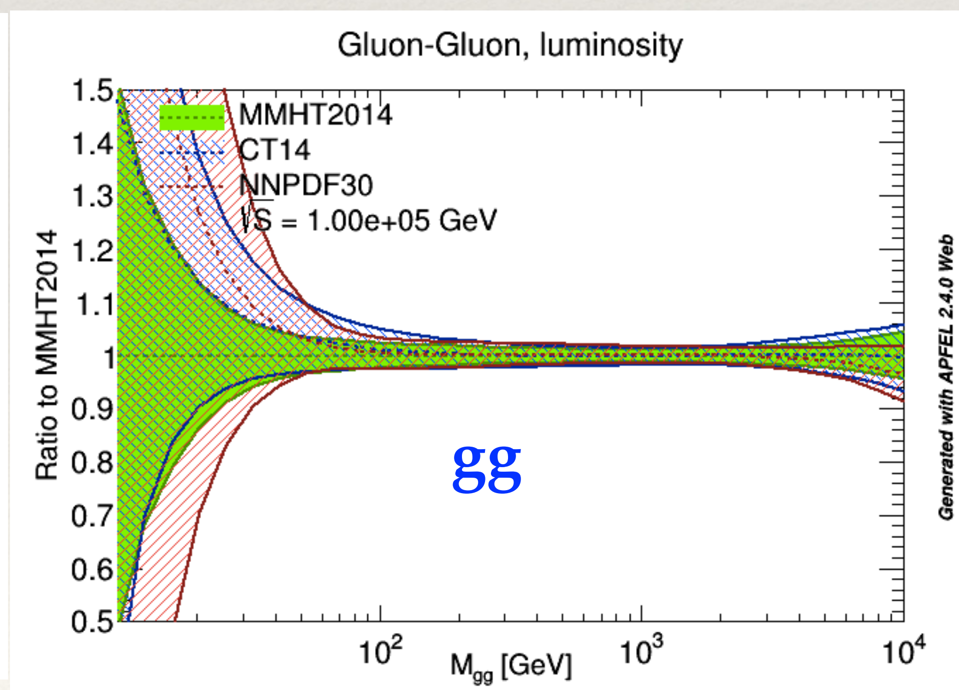
14 TeV —> 100 TeV

$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_\tau^1 \frac{dx}{x} f_a(x, Q^2) f_b(\tau/x, Q^2)$$









3 Regions:

Low x/Mx —> à novel QCD/unitarity

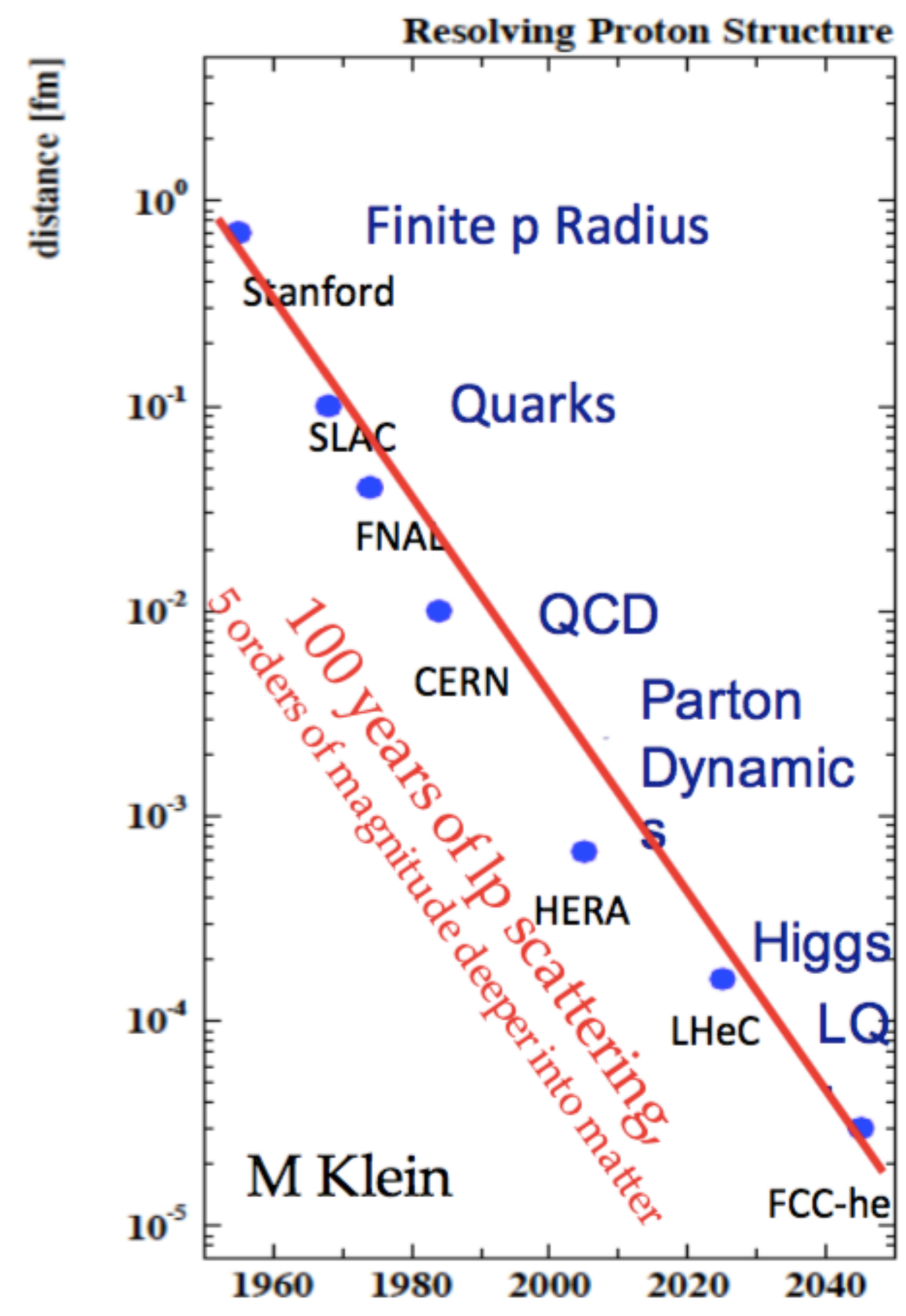
Medium x/Mx —> precision H and EW

High x/Mx —> new particle mass frontier

- Current Precision <10%:
  - M[100 GeV - 10 TeV]
- low masses M<100 GeV become challenging at very high energy colliders

—> need 1% precision in bulk region, e.g. for H couplings at LHC

The story of resolving proton structure



HERA: the only ep collider (1992-2007)
—> established detailed proton structure (PDFs)
—> has finalised its precision measurements
—> HERA is the basis of today's PDFs

Ep=460, 575, 820, 920 GeV Ee=27.5 GeV

LHC: pp collider
—> current machine to search for new physics
—> abundant data for complementarity

LHeC: future ep collider
—>projected to operate with HL LHC, Ee=60 GeV

FCC eh: further future ep collider:
—> integrated with FCC-hh
—> further kinematic extension wrt LHeC

Ep=50 TeV Ee=100 GeV

Schematic overview on key physics topics:

- Rich physics goals at "eh"
- This talk only touches few subjects.

QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \bar{q}$, instanton, odderon, low x: (n0) saturation, $\bar{u} \neq \bar{d}$
Higgs	WW and ZZ production, $H \to b\bar{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\bar{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \bar{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronisation inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

arXiv:1211:4831

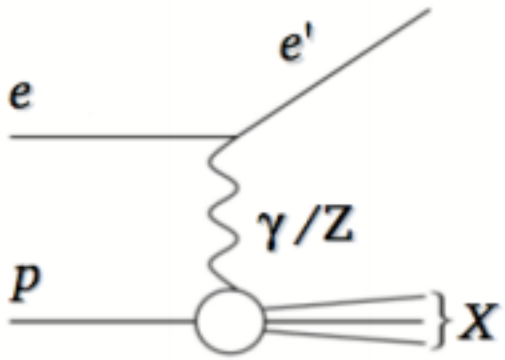
FCC eh settings in a context:

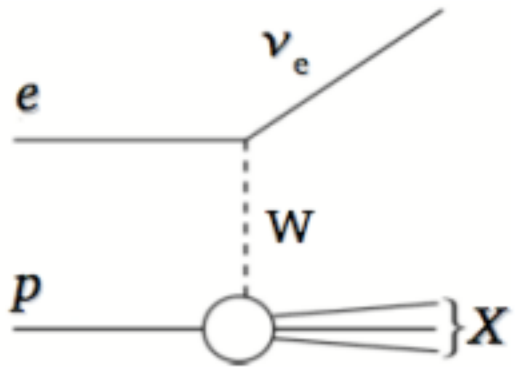
ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC hh ee he
$\sqrt{s}$/GeV	**13**	**35**	**122**	**319**	**1000**	**1300**	**3375**	**3464**
$L/10^{33}$ $cm^{-2}s^{-1}$	0.4	5.6	1.5	0.04	4.8	**16**	8.9	**10**
E_e/GeV	3	5	15.9	27.6	120	**60**	80	**60**
E_p/GeV	15	60	250	920	2100	**7000**	35600	**50000**
f /MHz	500	750	9.4	10.4	20	40	40	40
$N_{e/p}10^{10}$	3.7/0.54	2.5/0.42	3.3/3	3/7	1.3/16.7	0.4/22	3.3/5	0.5/10
$\varepsilon_{e/p}$ /µm	.03/.15	54/.35	32/.27	4.6/.09y	250/1	20/2.5	7.4/2.4	10/2
$\beta^*_{e/p}$/cm	10/2	10/2	5/5	28/18 y	4.2/10	10/5	9.3/75	9/40
comment	Lanzhou	full acc.	"Day1"	HERA II	Booster	**ERL** (H)	$E_e = M_W$	**ERL** (HH)
source	X.Chen July 14	McKoewn POETIC14	Litvinenko S.Brook 14	B.Holzer at CERN 2008	Y.Peng Oct. 2014	Frank Z. LHeC 2014	Y.Peng Oct. 2014	Frank Z. IPAC 2014

ep Kinematics

- DIS is best tool to probe structure of the proton:
  - Processes:

NC : $e\,p \to e'\,X$ CC : $e\,p \to \nu_e\,X$





  - Kinematic variables:

$$Q^2 = -q^2 = -(k - k')^2$$
Virtuality of the exchanged boson

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

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

$$s = (k + p)^2 = \frac{Q^2}{xy}$$ Invariant c.o.m.

ep vs pp vs ee @ FCC
Ep =50 TeV, Ee = 100 GeV:

pp: sqrt(s) = 2Ep
—> highest energy - discovery
ee: sqrt(s) = 2Ee
—> low energy - EW precision
ep: sqrt(s) = 2sqrt(EpEe)
—> intermediate energy
—> QCD+H precision

$$\sigma_r(x, Q^2) = \frac{d^2\sigma(e^\pm p)}{dx dQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+}F_L(x, Q^2) \mp \frac{Y_-}{Y_+}xF_3(x, Q^2)$$

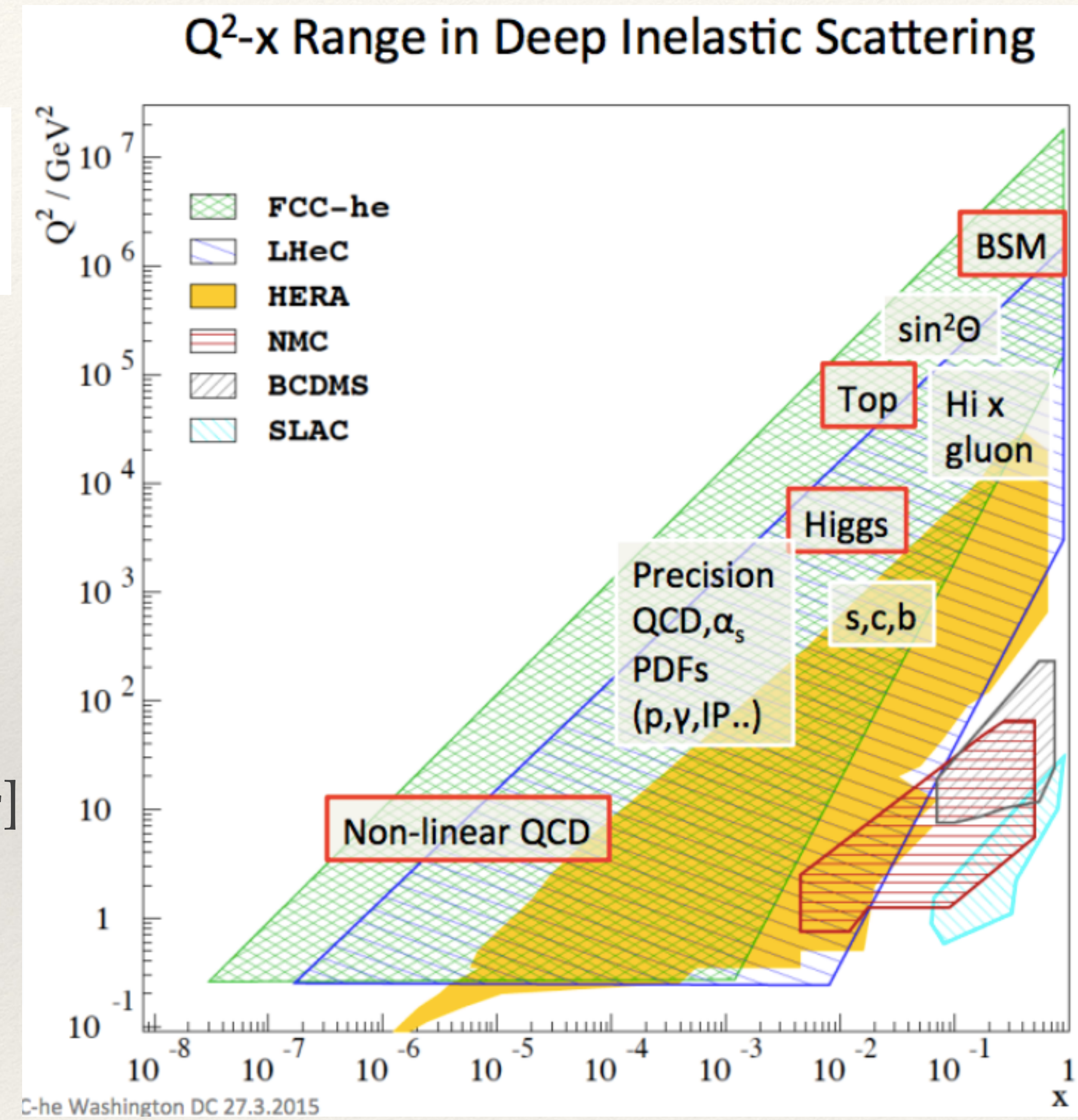
- F_2 dominates
  - sensitive to all quarks
- xF_3
  - sensitive to valence quarks
- F_L
  - sensitive to gluons

also we have F2yZ, sCC+, sCC-

Physics Program with FCCeh

Diverse physics goals require precision in a large kinematic region:

- VERY SMALL MOMENTUM FRACTIONS $x \lesssim 10^{-6}$ REACHED AT LOW SCALE $Q \sim 1$ GEV
- VERY LARGE SCALE $Q \sim 1$ TEV REACHED AT LARGE $x \sim 0.5$
- VERY LARGE $x \sim 0.9$ REACHED IN WIDE RANGE OF SCALES $10 \lesssim Q \lesssim 1000$ GEV



- alphas, PDFs
- Higgs couplings (b, c)

- single top (Vtb, FCNC)
- the weak mixing angle

  [see M. Klein/D. Britzger]
- "ALICE" physics:
  - high density QCD
  - Saturation
  - diffraction

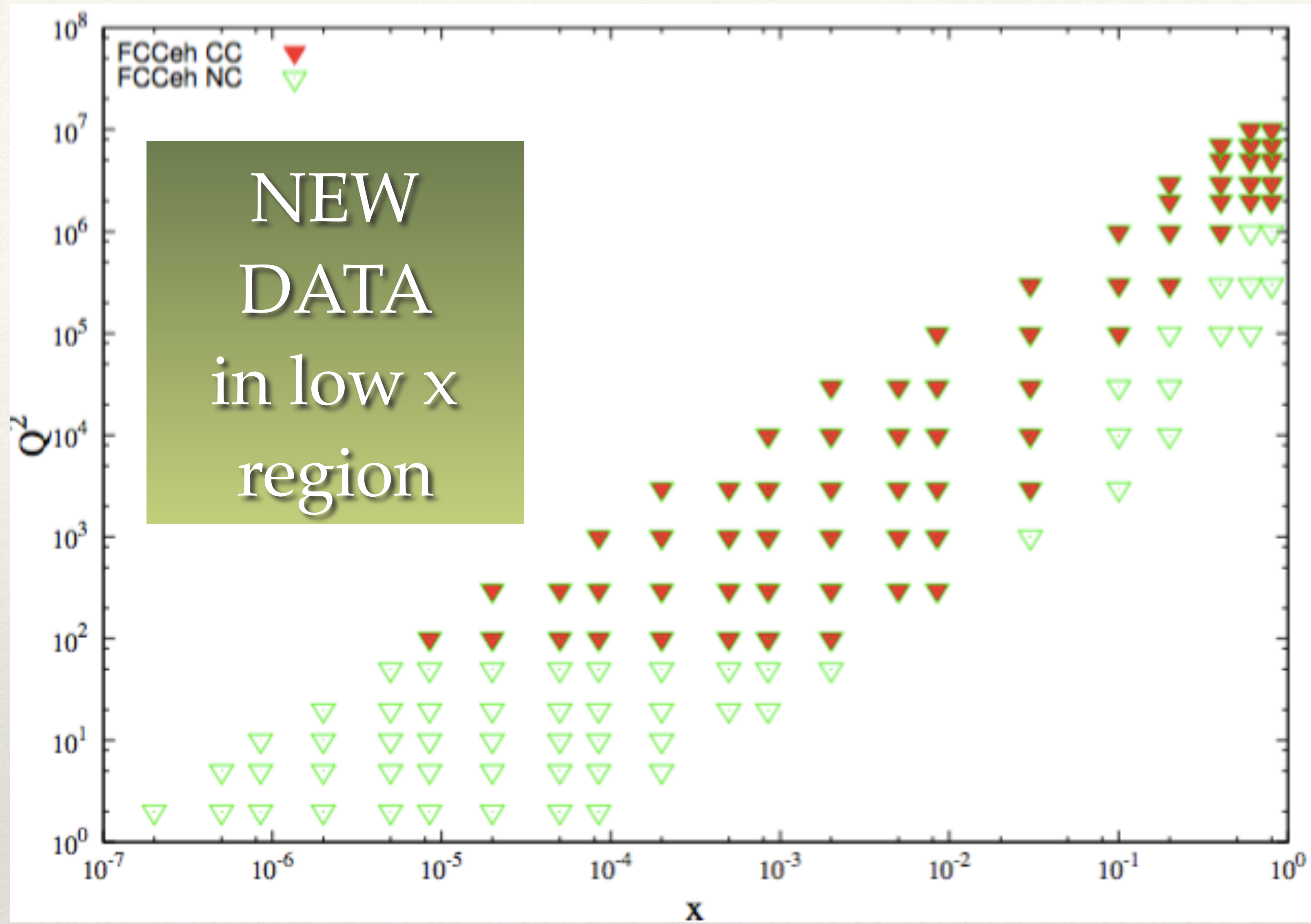
  [see N.Armesto]

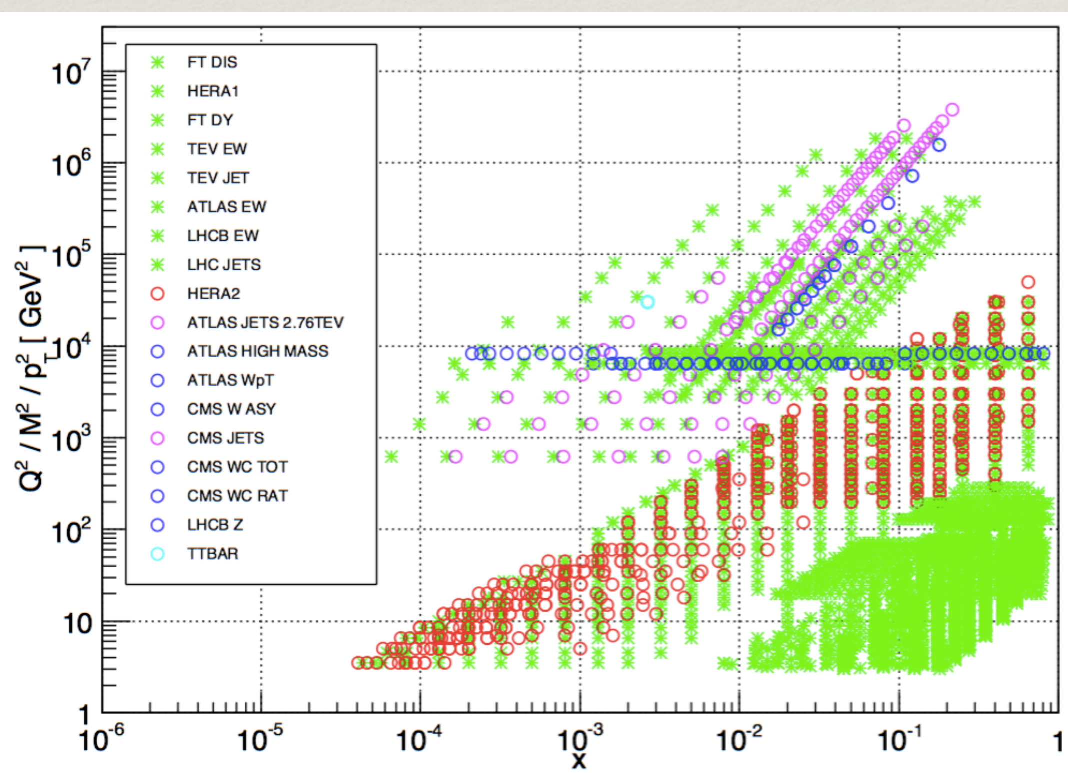
Synchronous running of pp and ep : Compelling synergy for exploring the EW and QCD

FCC eh study (work in progress)

FCC eh study based on:

- Ep = 50 TeV, Ee = 100 GeV:
- polarised e- with negative polarisation -80%: 1000/fb, NC, CC
- **Coverage:**
  - down to 2x10-7 in x
  - up to 10,000,000 GeV² in Q²
- **Estimated Precision:**
  - stat 0.1% - 30% (highest Q²)
  - uncor 0.7%
  - sys ~1% - 5% (highest Q²)





<—There is no data below 10^-4 to be used in fits!!

NB: did not consider yet for thisstudy the unpolarised data, strange, charm, beauty, top which can ALL be precisely measured

FCC eh study scenario

FCC eh study based on:

- Ep = 50 TeV, Ee = 100 GeV:
- polarised e- with negative polarisation -80%: 1000 / fb, NC, CC
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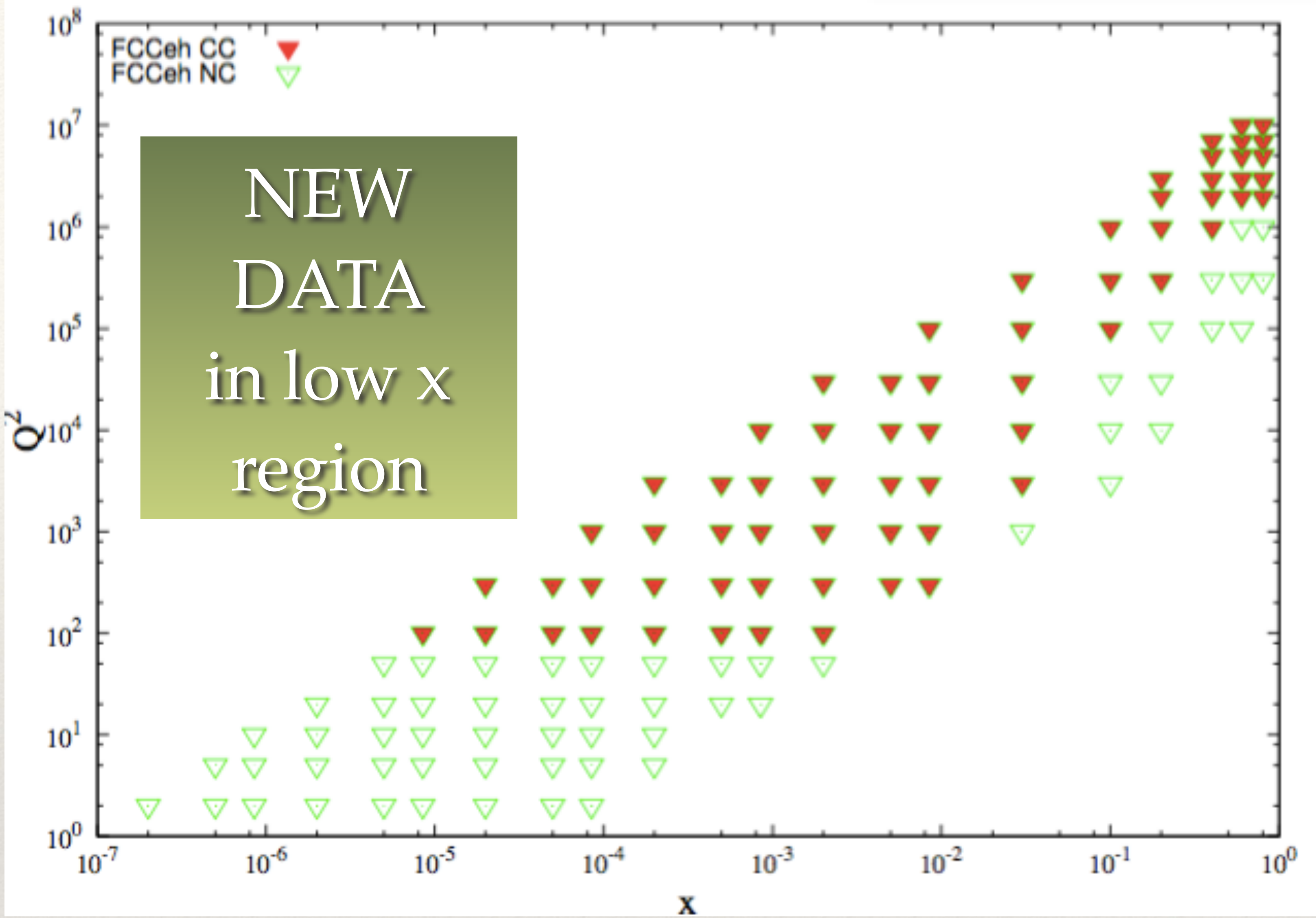
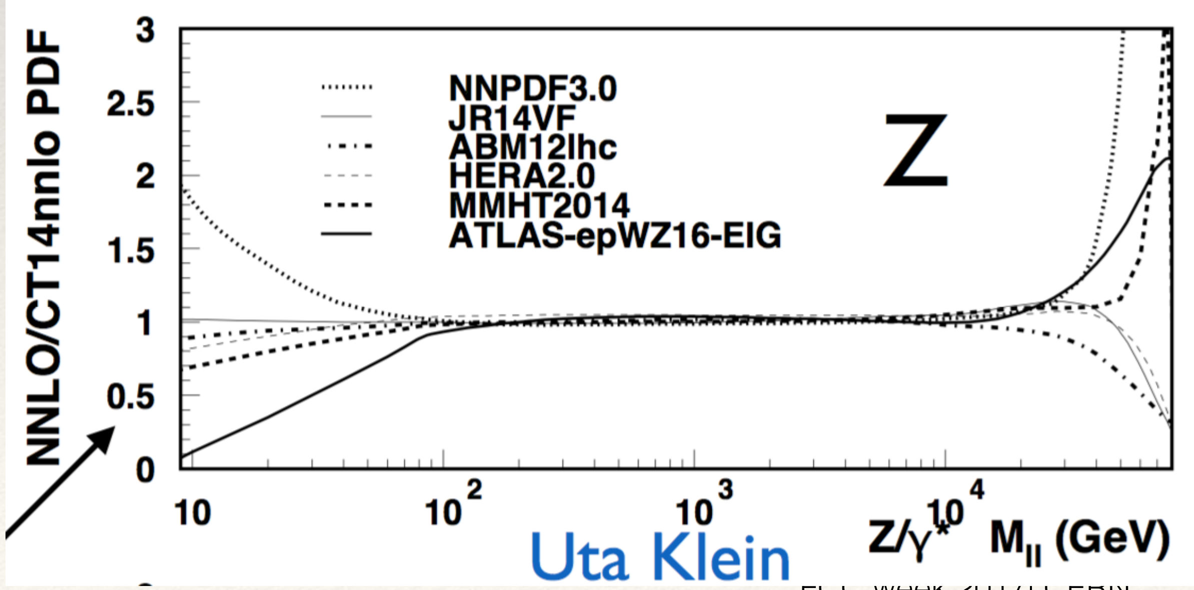


synergy between ep and pp

FCCeh can further improve lower x range which would allow for precision FCCpp standard candle measurements



Uta Klein

Potential of FCCeh on PDFs

Settings for PDF extraction: using xFitter platform and the PDF parametrisation a la HERAPDF (with positive gluon)

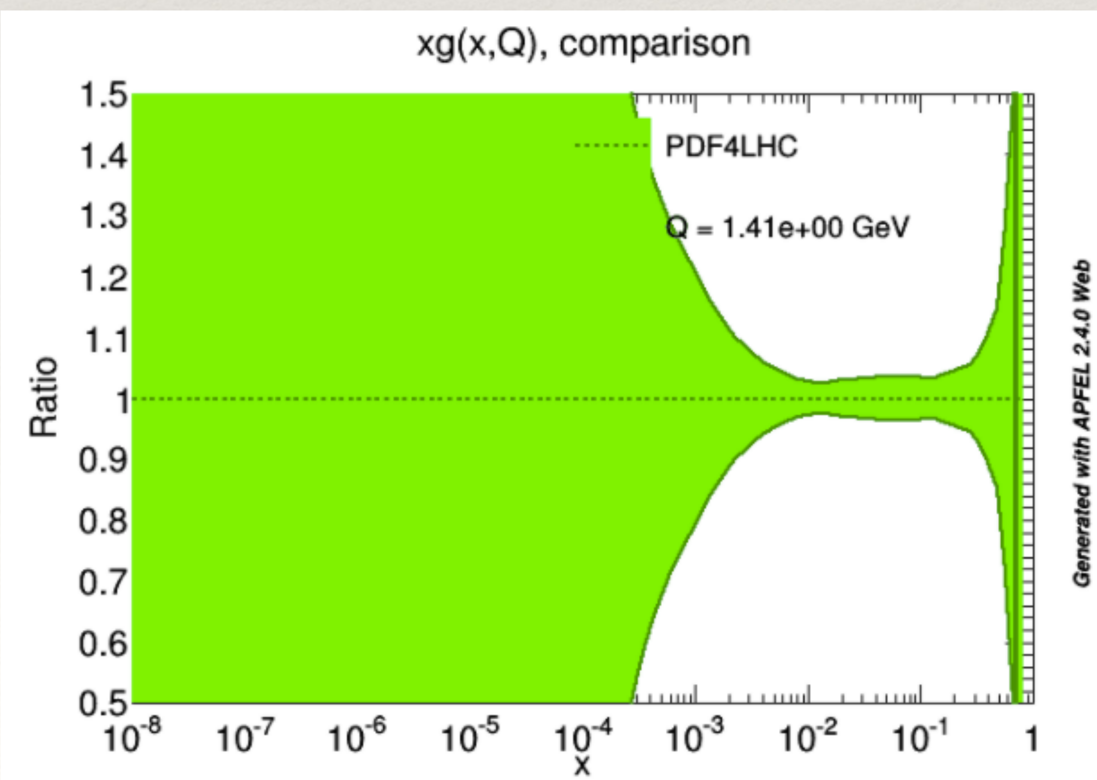
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x)\,, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2)\,, \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}\,, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\,, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}\,.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

➔ LHAPDF grid

(14 free parameters)

Gluon

Currently (PDF4LHC)



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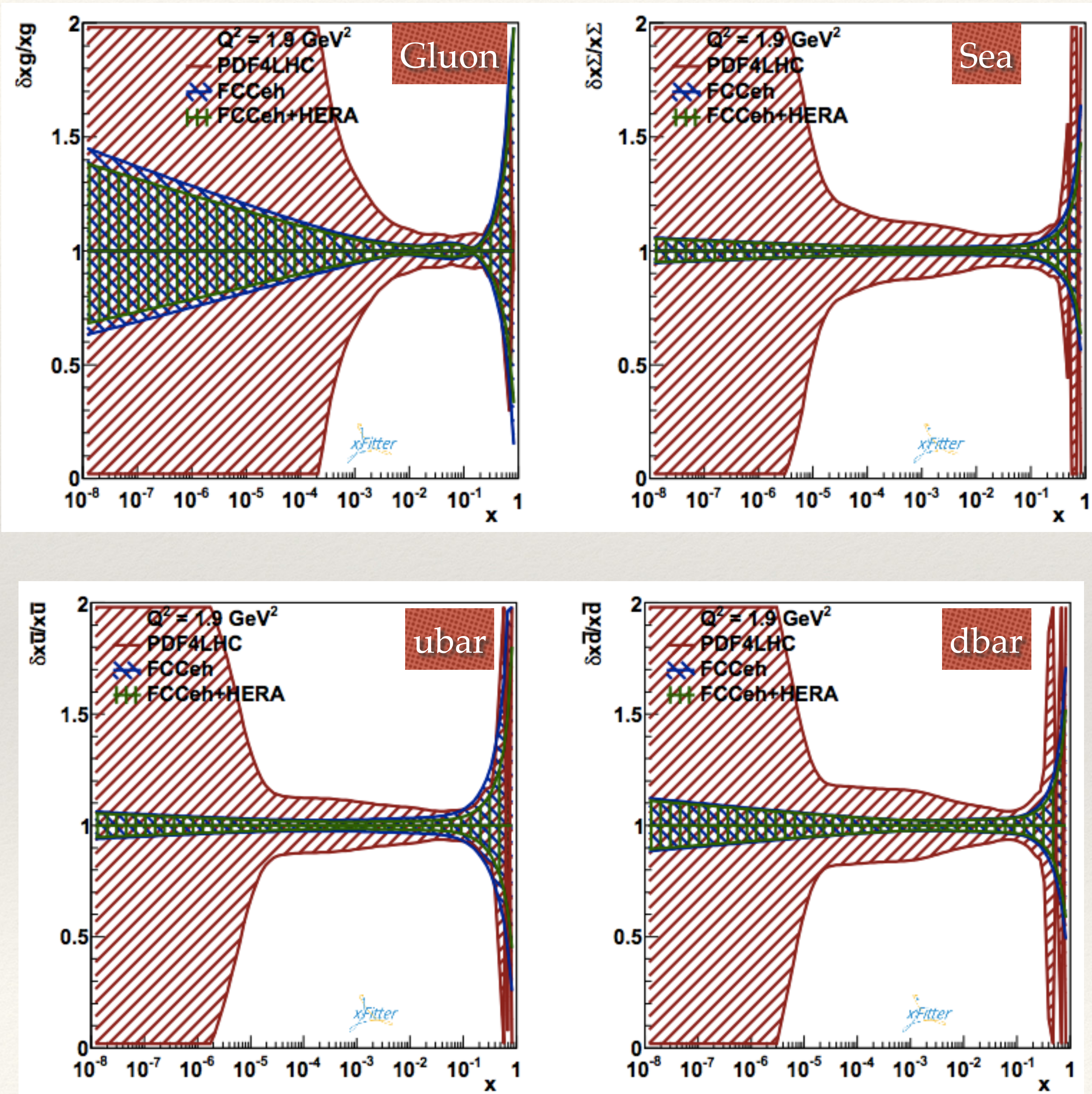
Potential of FCCeh on PDFs vs current state of the art PDFs



PDF4LHC set

vs

FCCeh (+HERA)

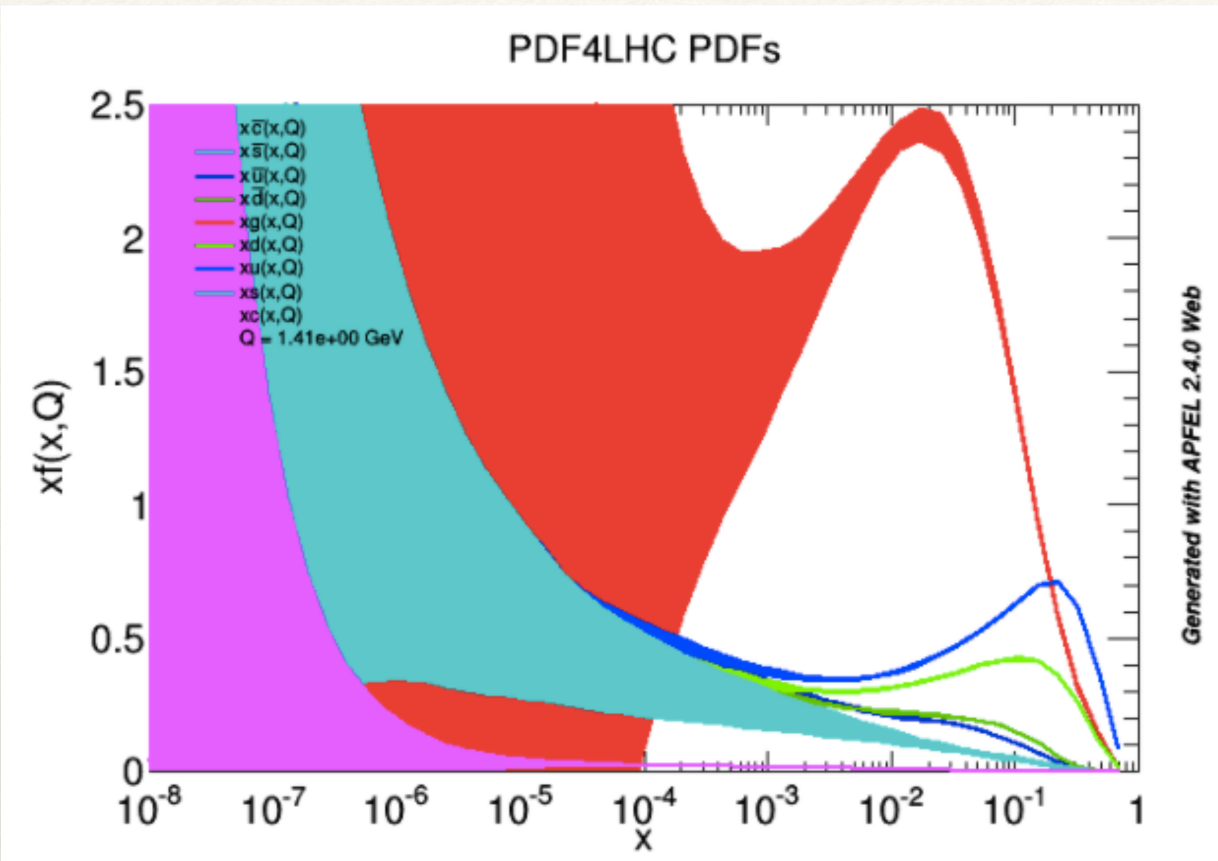
at starting scale

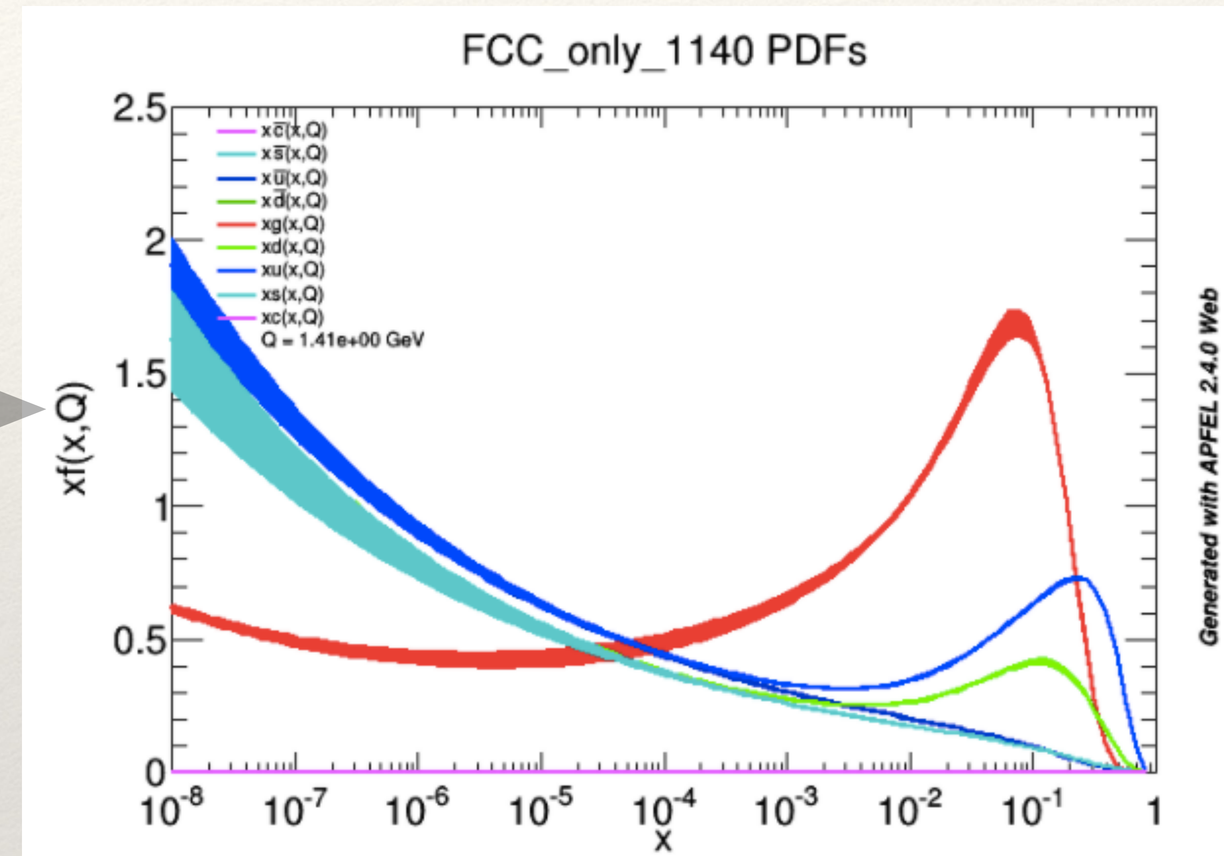
FCCeh brings substantial impact at low x

important for the FCCpp as it will probe much lower x regions for standard processes

PDF comparisons

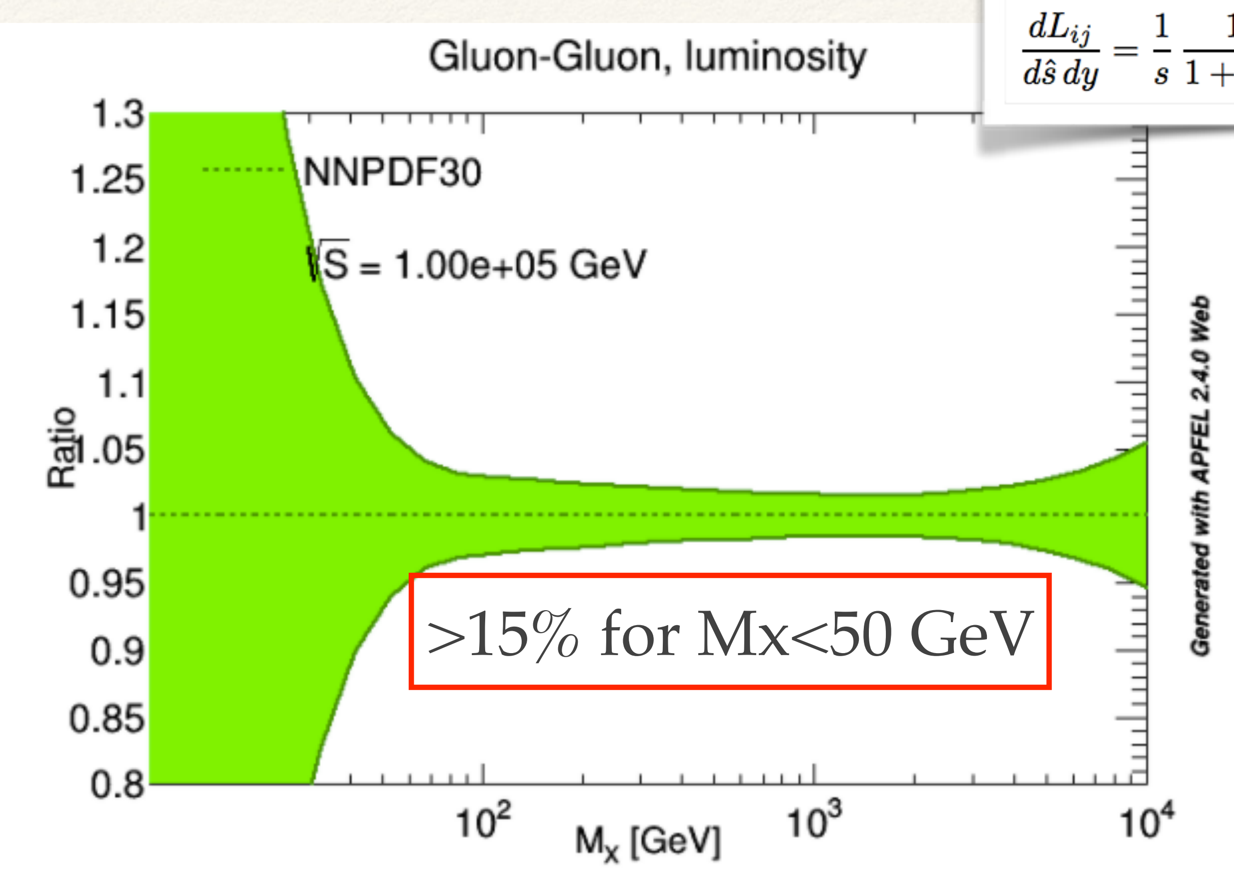
Current vs FCCeh

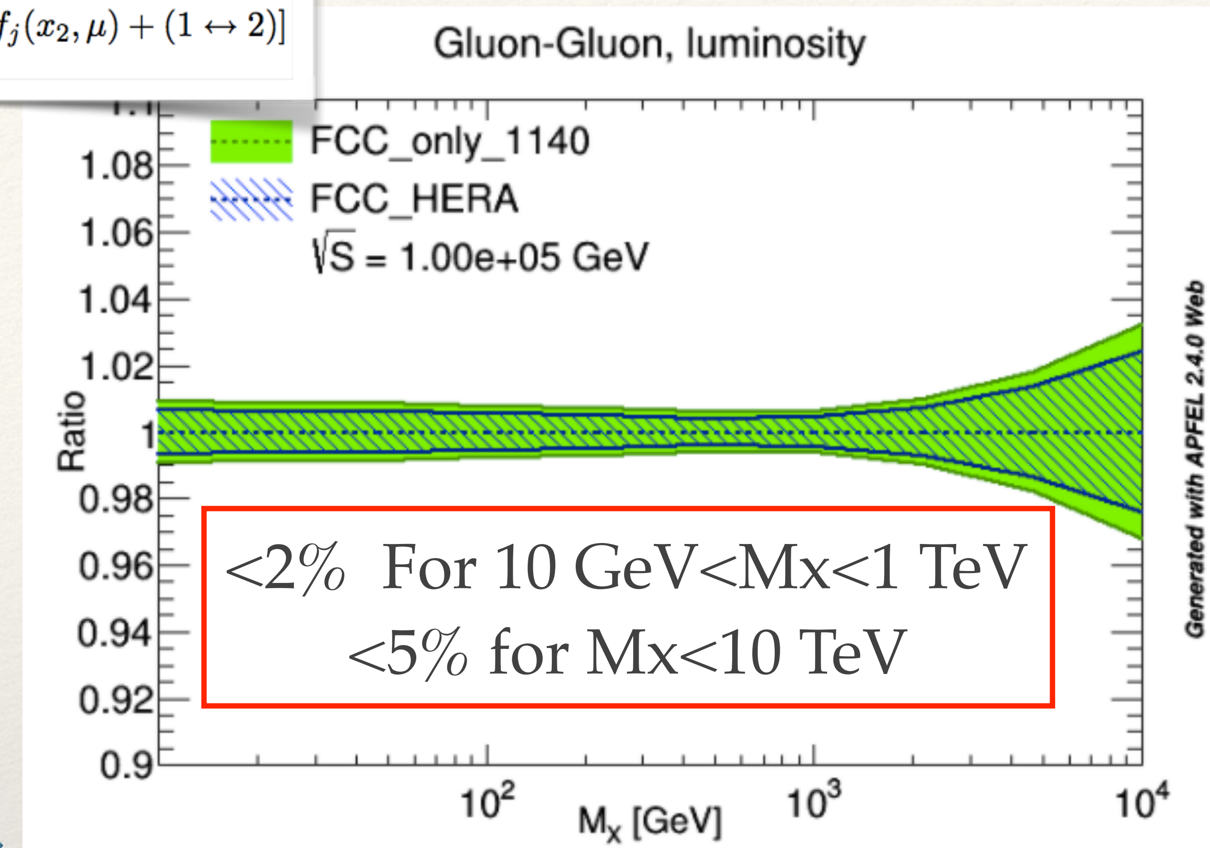


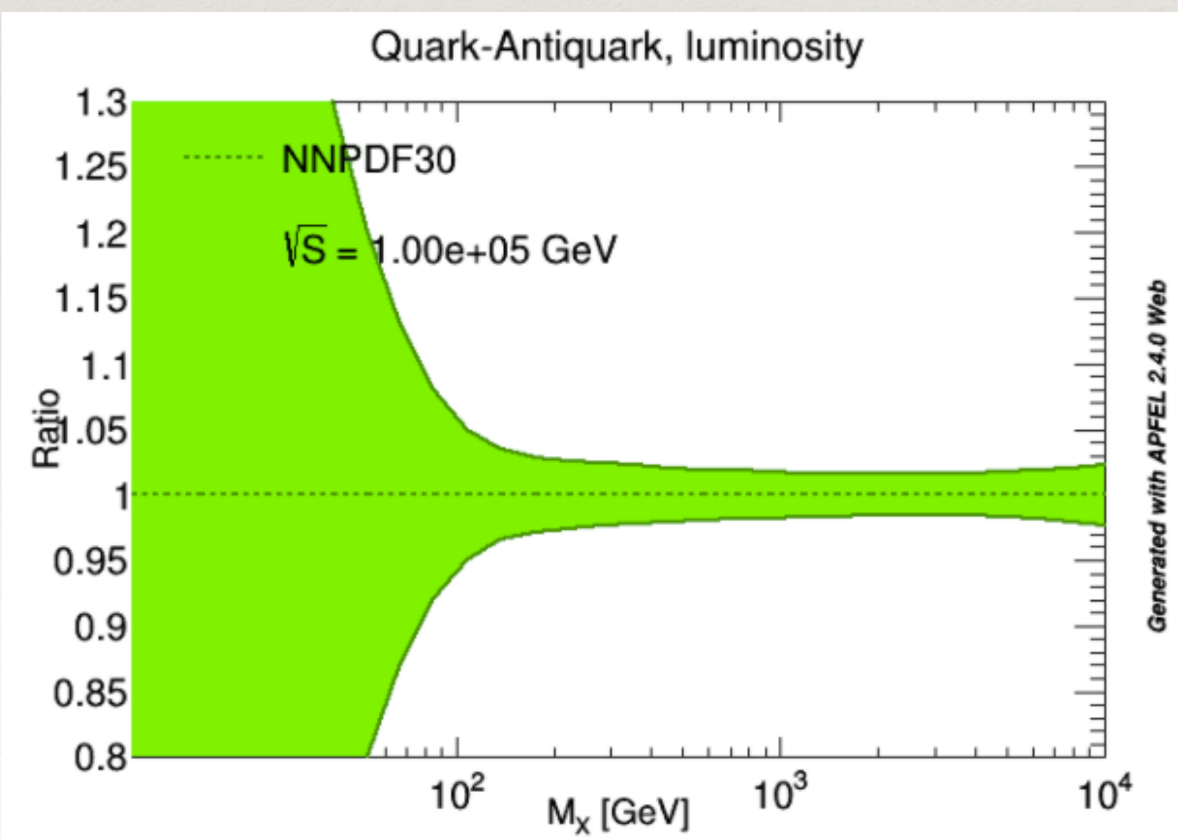


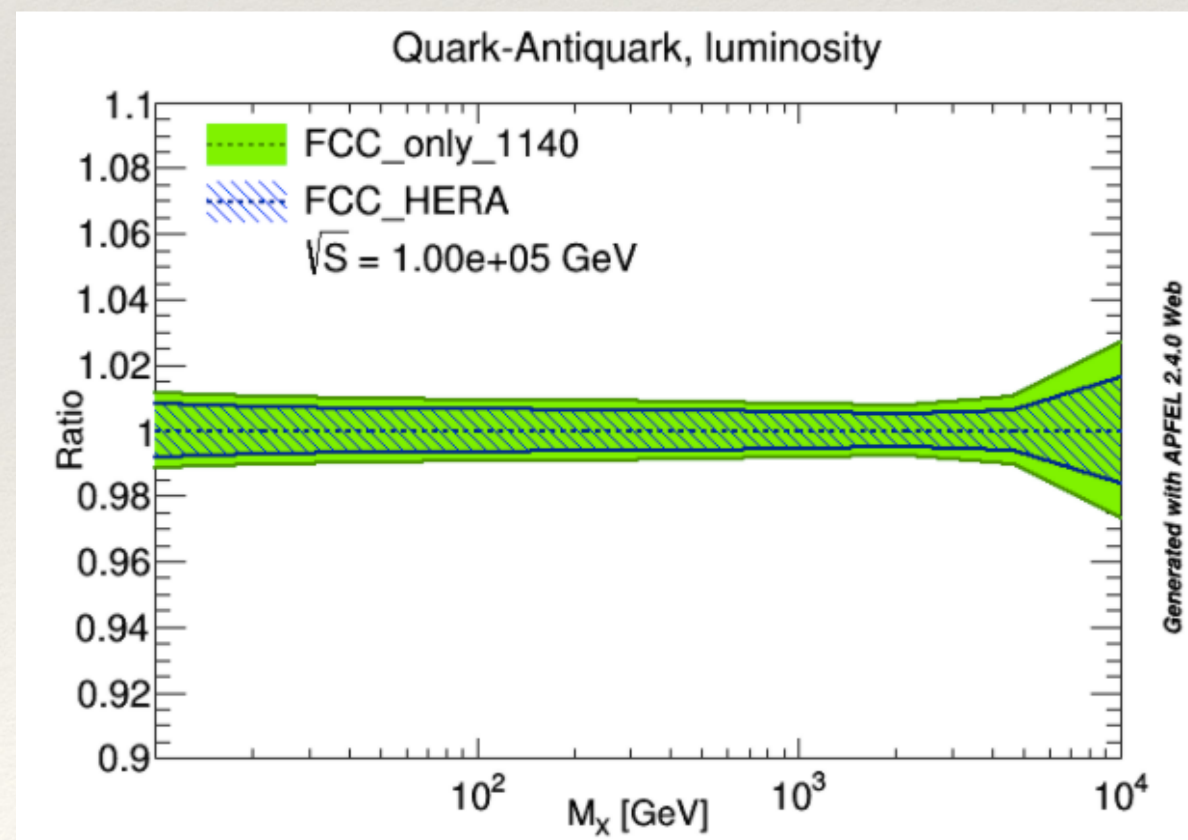
Parton Luminosities from FCCep to FCCpp

$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$









Strong coupling

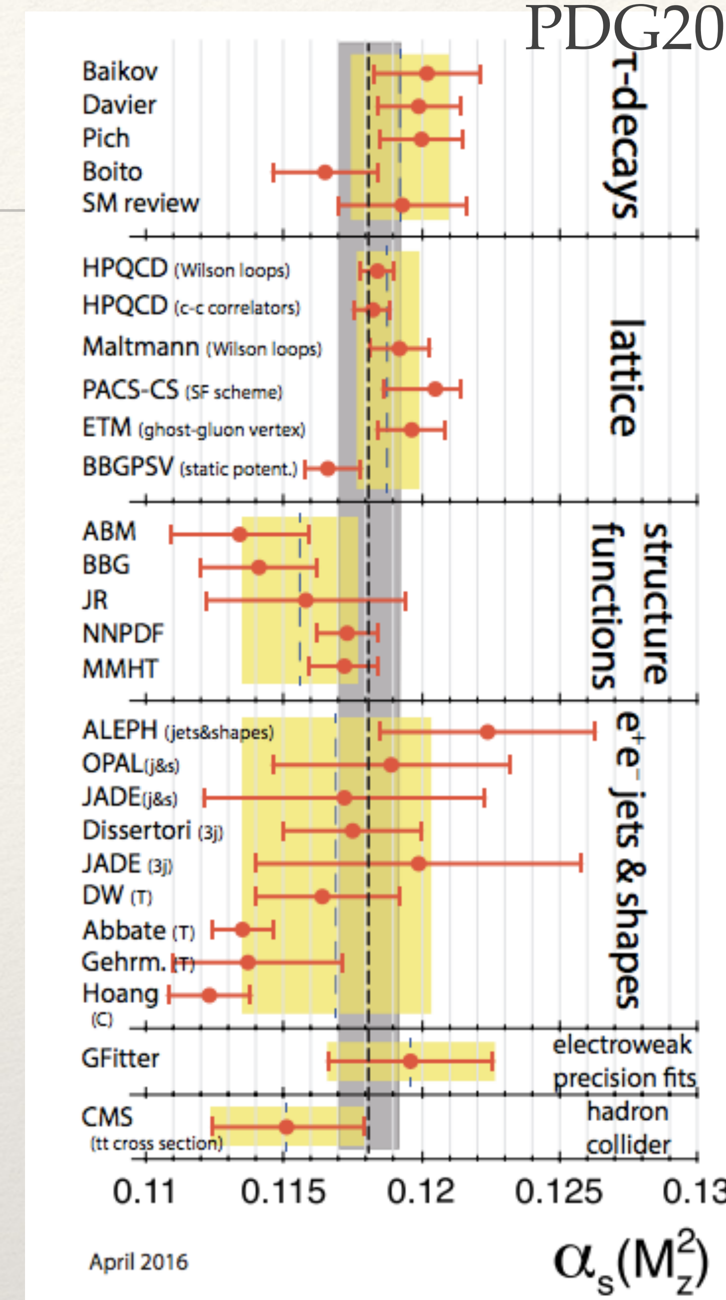
PDG2017

- The size of αs is not given by theory, but can be extracted from experimental measurements at e+e−, ep, pp, and $p\bar{p}$ colliders, as well as from lattice QCD calculations.

$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

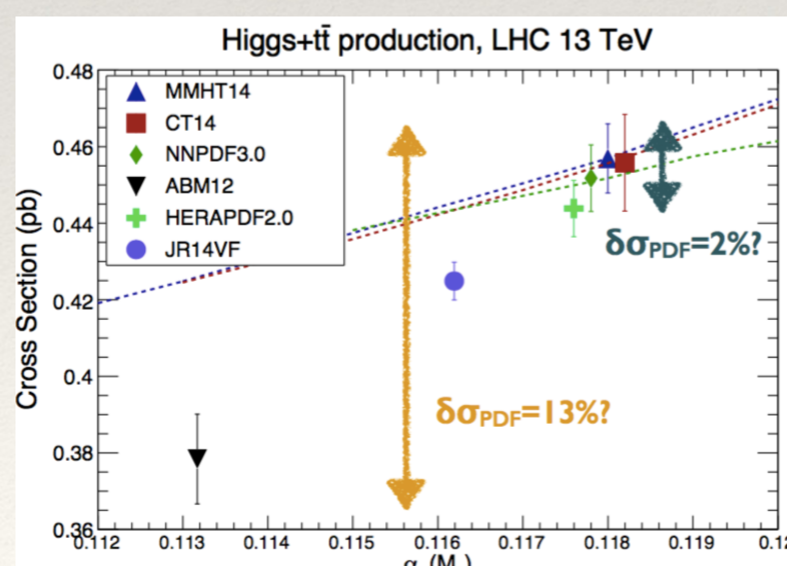
current world average

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0011 \quad (\text{w/o } \tau \text{ results; } \chi_0^2/\text{d.o.f.} = 3.3/4),$$
$$\alpha_s(M_Z^2) = 0.1174 \pm 0.0016 \quad (\text{w/o lattice results; } \chi_0^2/\text{d.o.f.} = 2.9/4),$$
$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0013 \quad (\text{w/o DIS results; } \chi_0^2/\text{d.o.f.} = 2.0/4),$$
$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0010 \quad (\text{w/o } e^+e^- \text{ results; } \chi_0^2/\text{d.o.f.} = 3.5/4),$$
$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0012 \quad (\text{w/o hadron collider; } \chi_0^2/\text{d.o.f.} = 2.4/4) \text{ and}$$
$$\alpha_s(M_Z^2) = 0.1180 \pm 0.0010 \quad (\text{w/o e.w. precision fit; } \chi_0^2/\text{d.o.f.} = 3.4/4).$$



However, extractions of strong coupling involves many inconsistent measurements

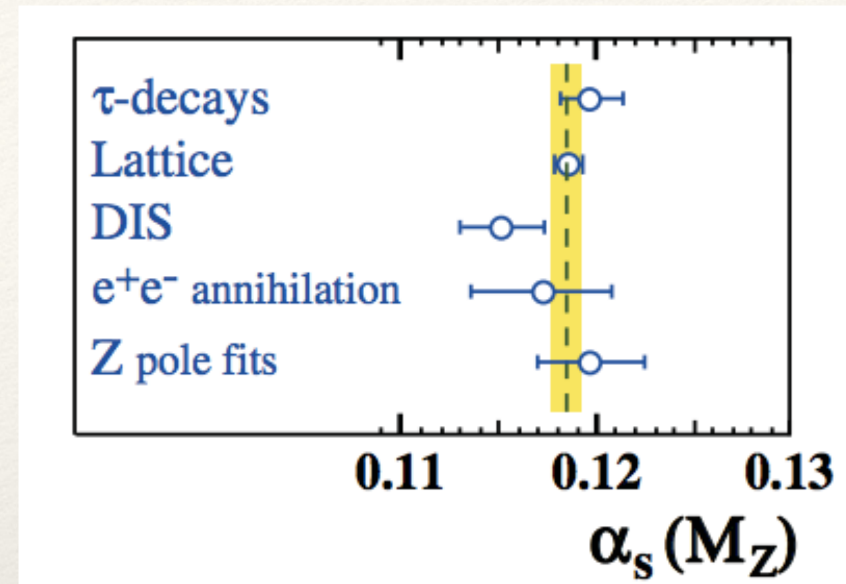
- a long standing differences between alphas from DIS vs alphas involving jets
- difference in choice of alphas can lead to large discrepancy among PDFs
  - see ABM vs other PDF groups

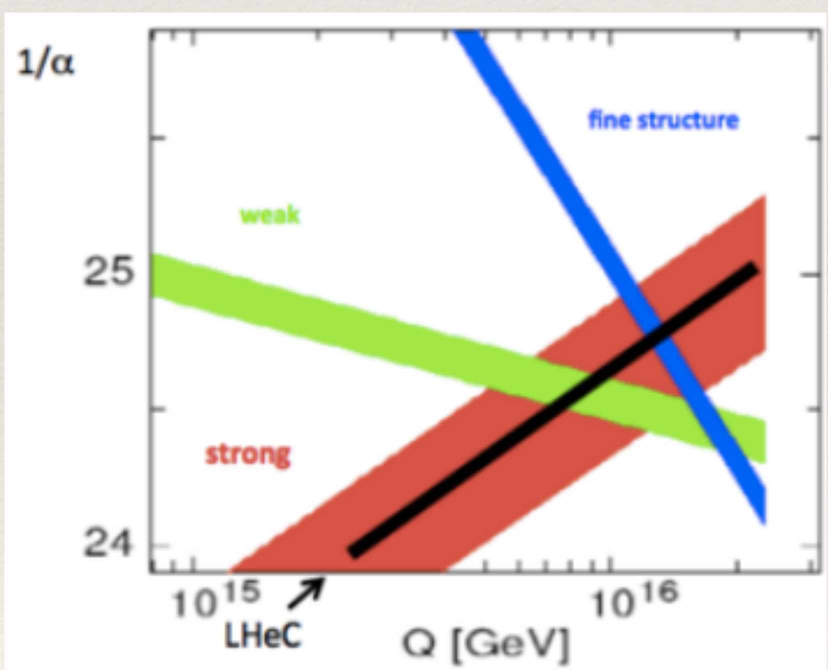


Strong coupling from FCCeh

- With the precision of the FCC eh data one can extract the alphas directly from the scaling violations of the Structure Functions:
  - Fits using PDF+alphas free:
  - FCCeh inclusive data alone: 0.6 % precision
  - FCCeh + HERA: 0.5% precision
    - using only HERA inclusive lacks precision
      - —> requires jets
    - (while for LHeC would be 0.3%)

current precision ~1% (no lattice)





Per mil precision can address GUT

- α_s least known of coupling constants
Grand Unification predictions need smaller $\delta\alpha_s$

- Is α_s(DIS) lower than world average (?)

- LHeC: per mille - independent of BCDMS!

FCCeh can also provide compelling answers

- High precision from inclusive data – α_s(jets)??

- Challenge lattice QCD [cf L Del Debbio, this conf]

Summary:

- FCC opens up an incredible possibility to widen the search hunt for new physics:
  - Precision of PDFs and alphas required by discovery and precision
  - Rich QCD physics available with “eh" scenario

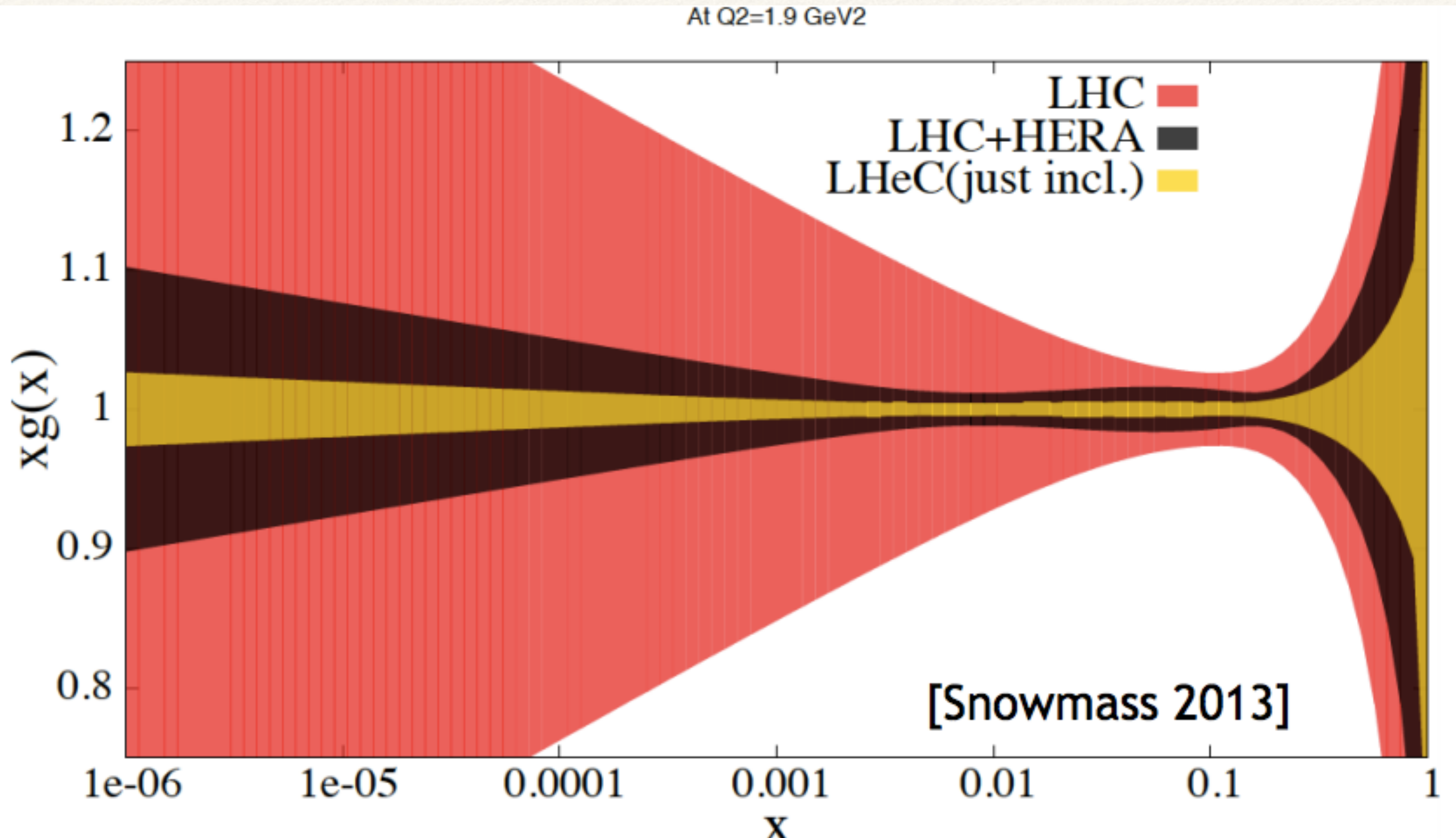
- At FCCpp energies, all standard candle precision measurements of MZ, MH, Mt are at much lower x than LHC —-> need QCD parameters / PDFs from FCCeh

- Synergy between FCC study groups for ee, eh, hh
  - Control of QCD background for searches —> need precise PDFs and alphas
  - Control of PDFs, alphas, low x phenomenology.
  - High-precision (<1% uncertainty) strong coupling determination

- This study has been directed to precision within the 'known' framework, however, LHeC and FCCeh will fundamentally change this field!
- the qiestion is thus not "only" how precise, this we ask to LHC analyses, the questions are also quantitative, theoretical —> how would precise PDFs impact the field?

Here is why we need "eh"

- let's see what we can achieve ONLY with LHC:



- LHC = current LHC W, Z and jet data

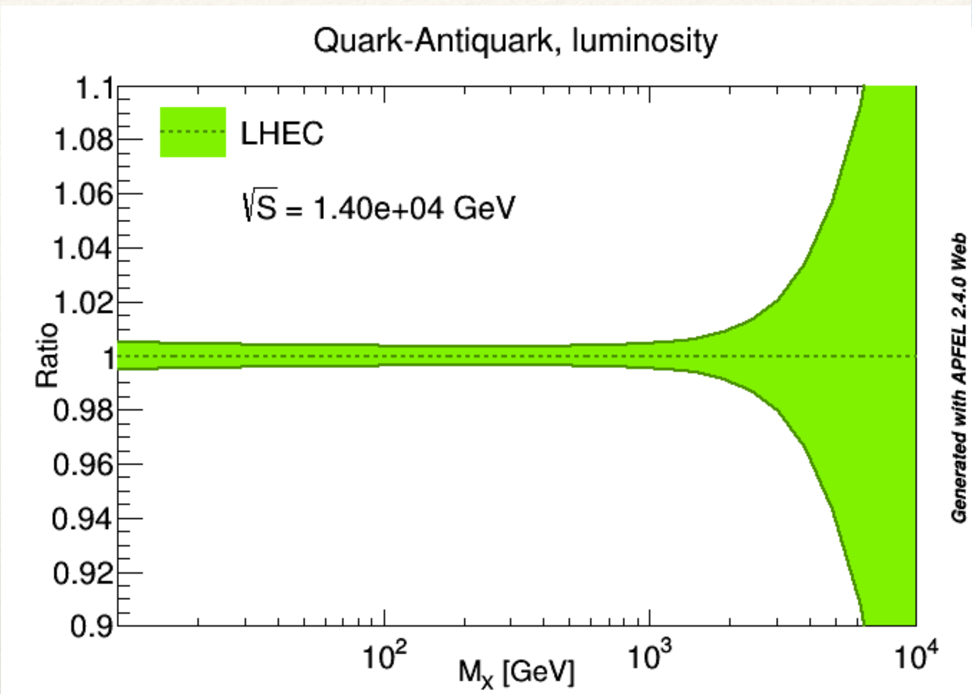
W, Z sensitivity M(W, Z) —> x

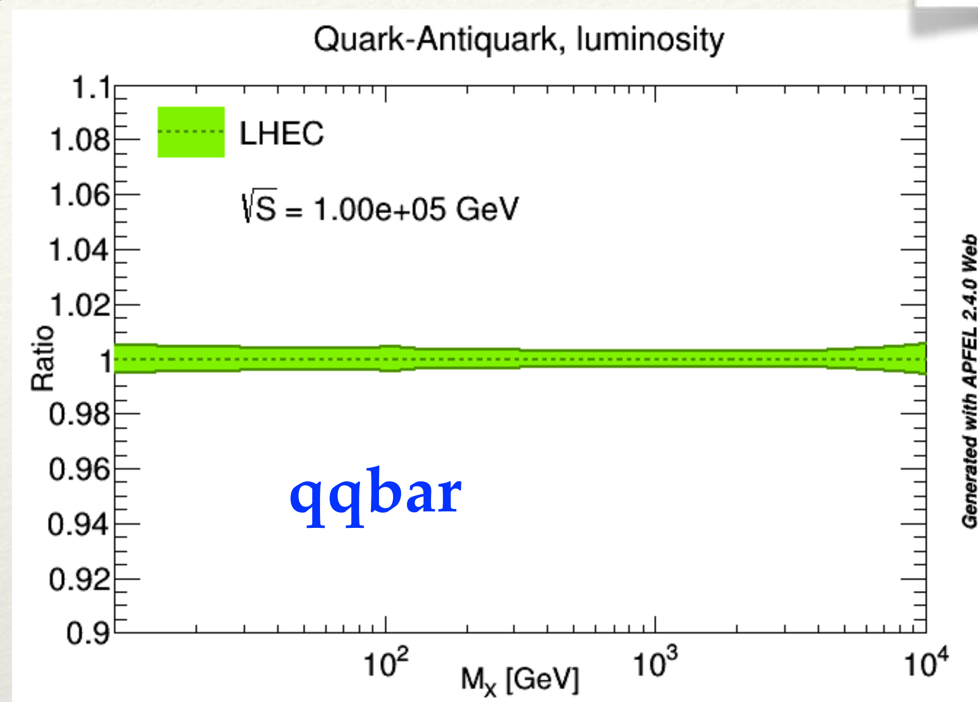
Precision From 14 TeV to 100 TeV with LHeC

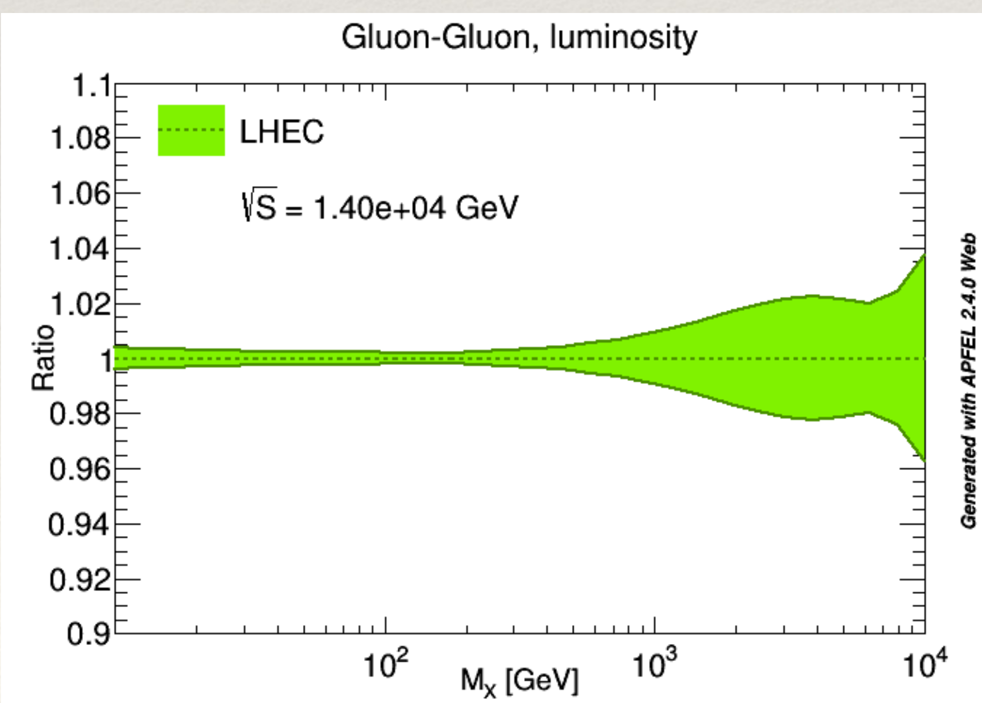
14 TeV

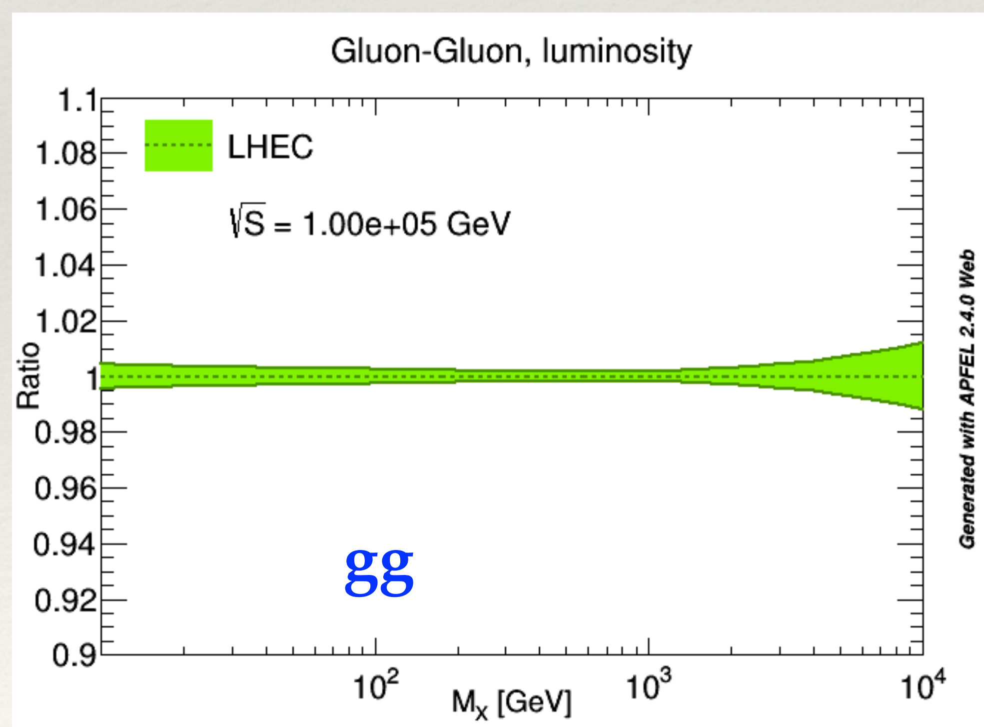
100 TeV

$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$



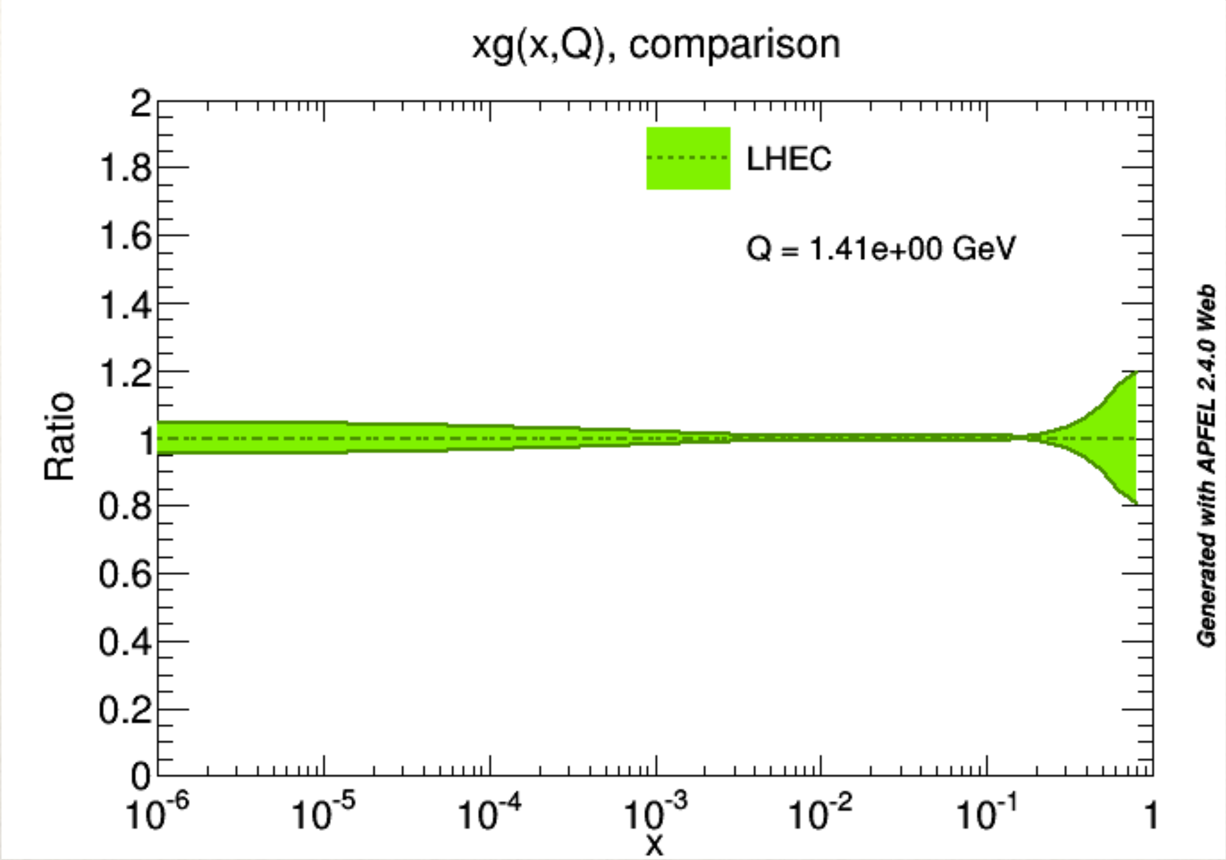


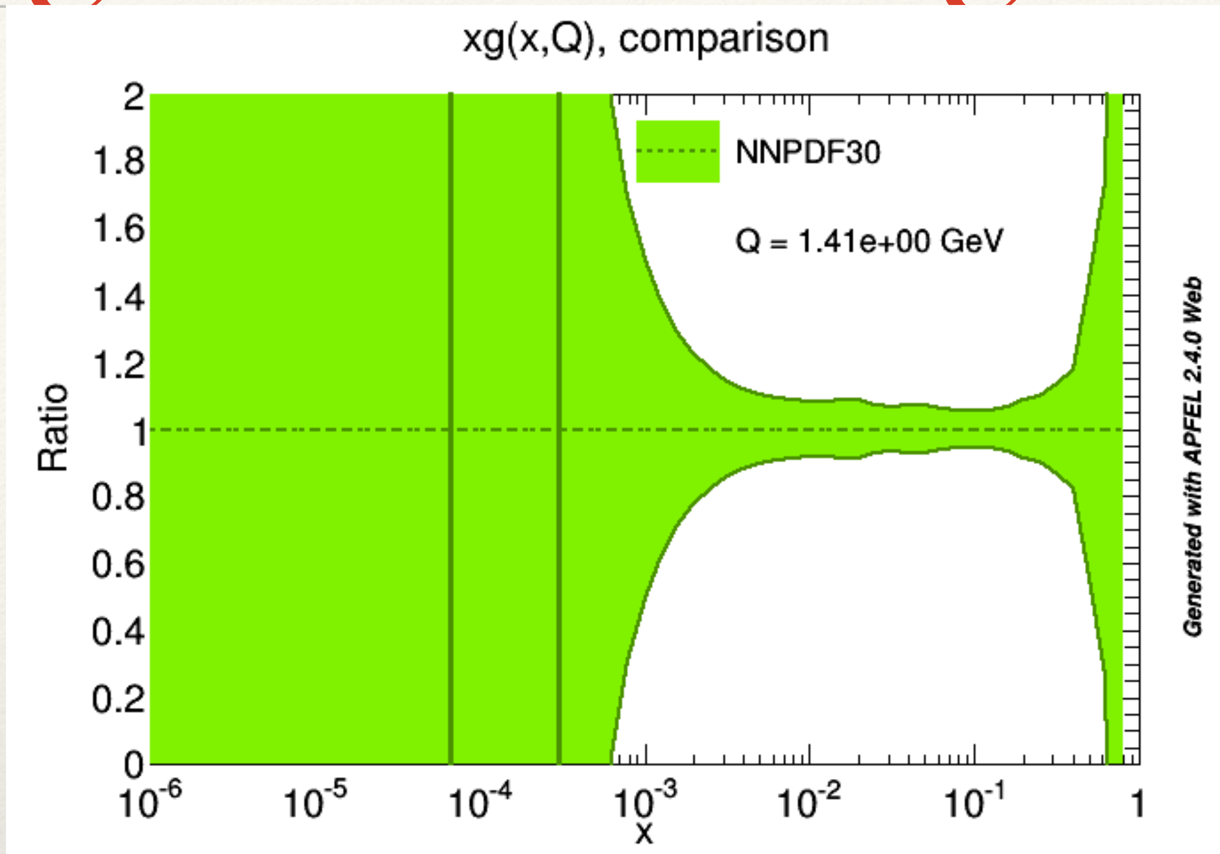


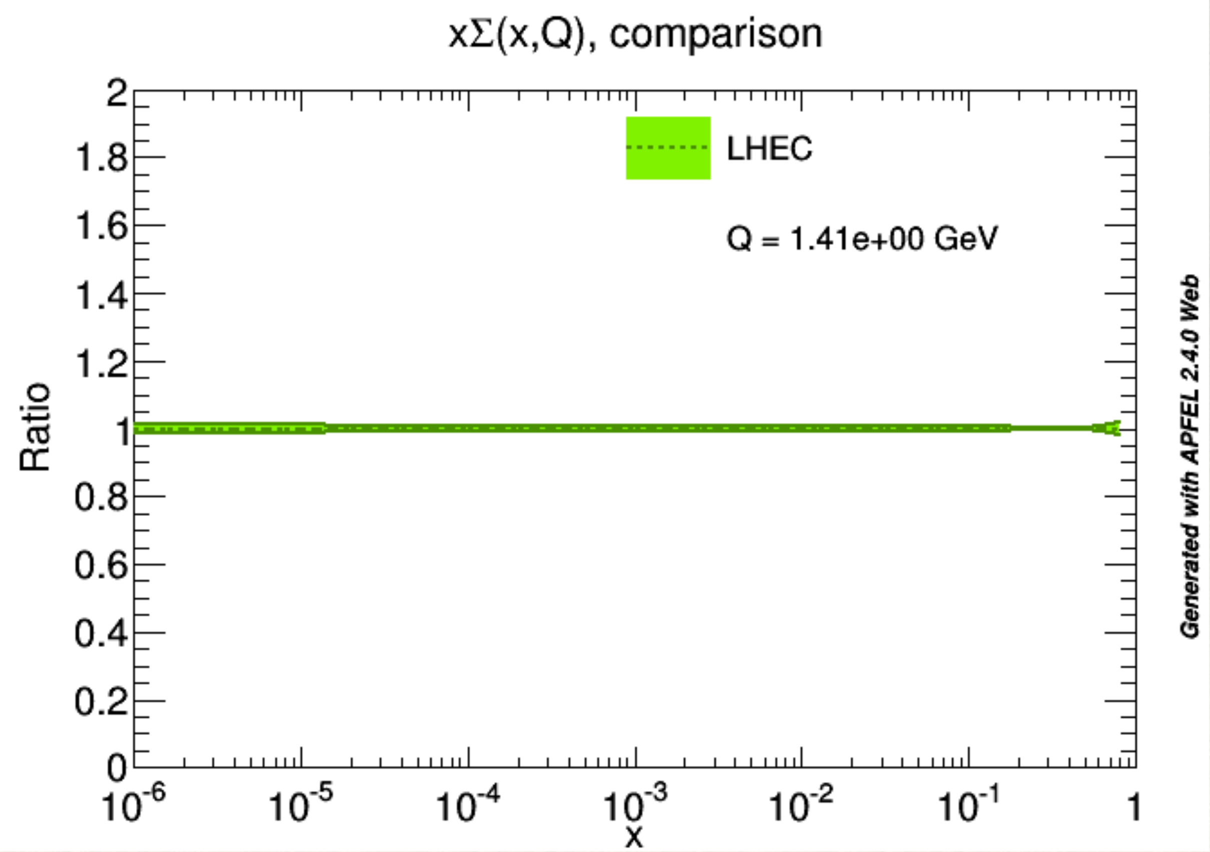


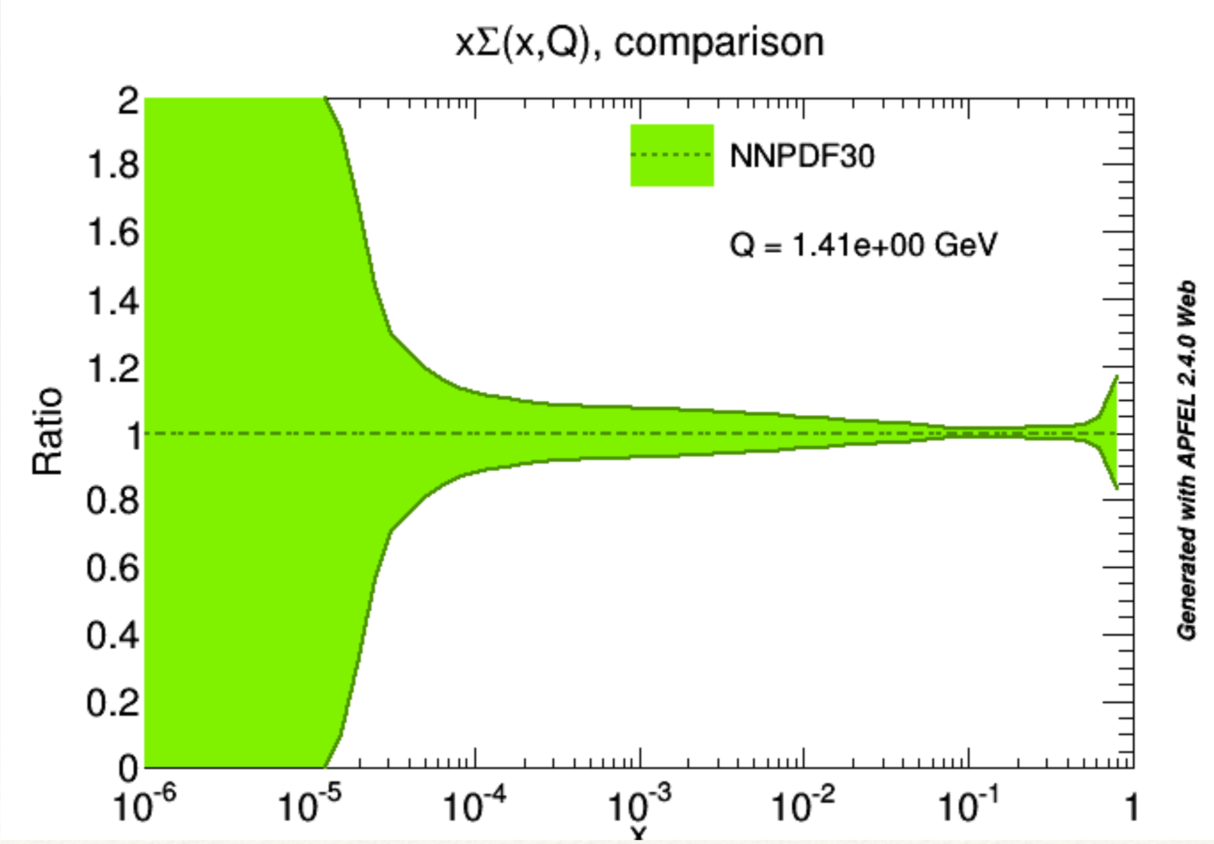
- With LHeC PDFs:
- at 14 TeV:
  - high invariant masses for qqbar mechanism more uncertain (~ 10%)
  - for gluon-gluon <5% accuracy
- at 100 TeV
  - PDFs are under control with <2%

PDF comparisons: gluon and singlet

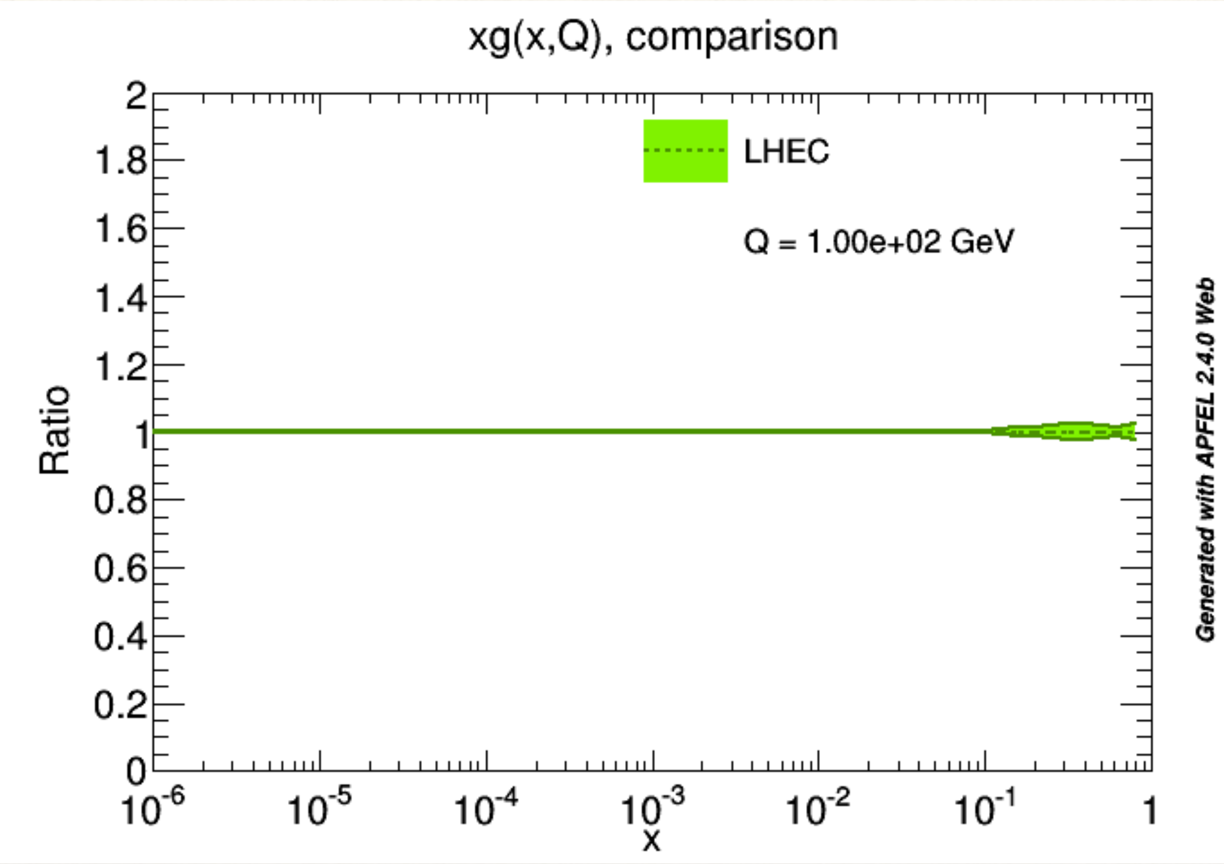


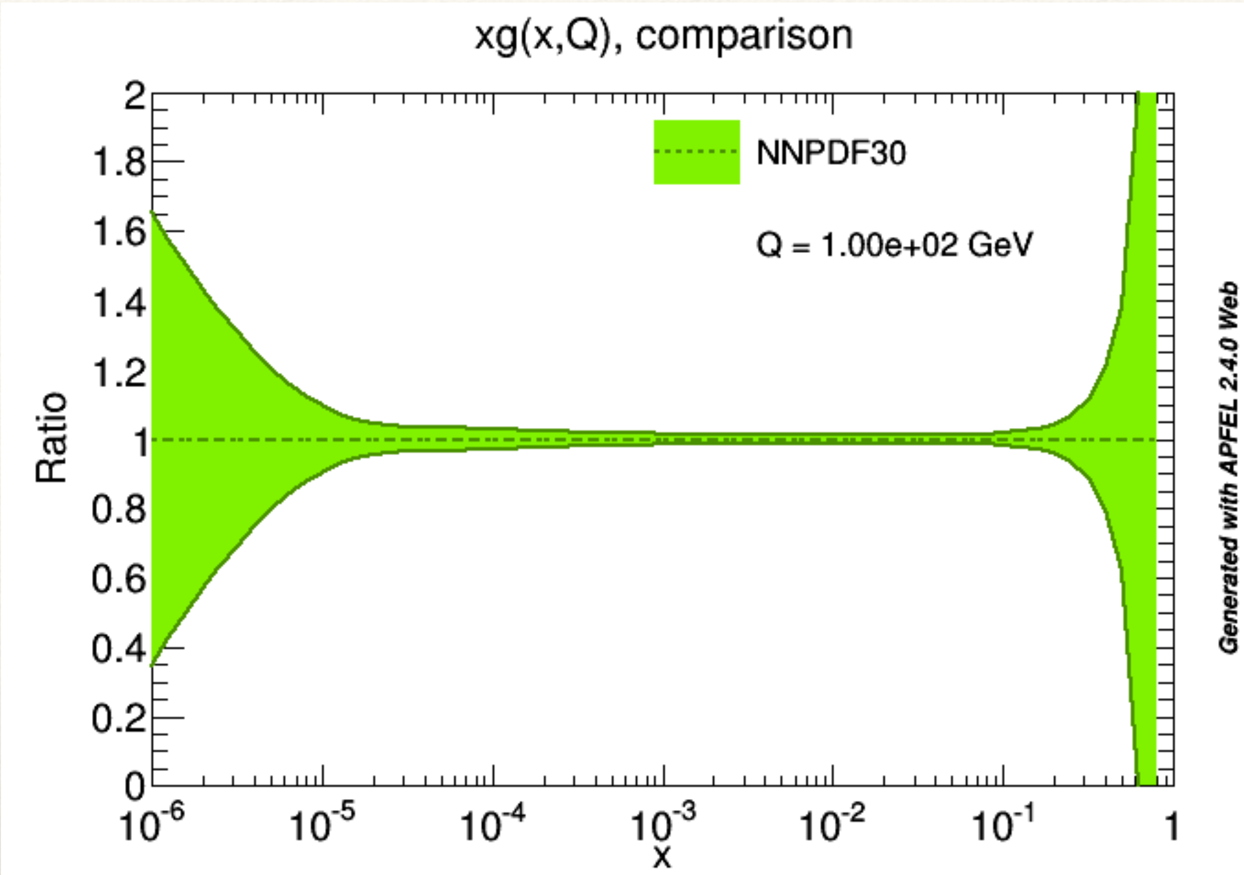


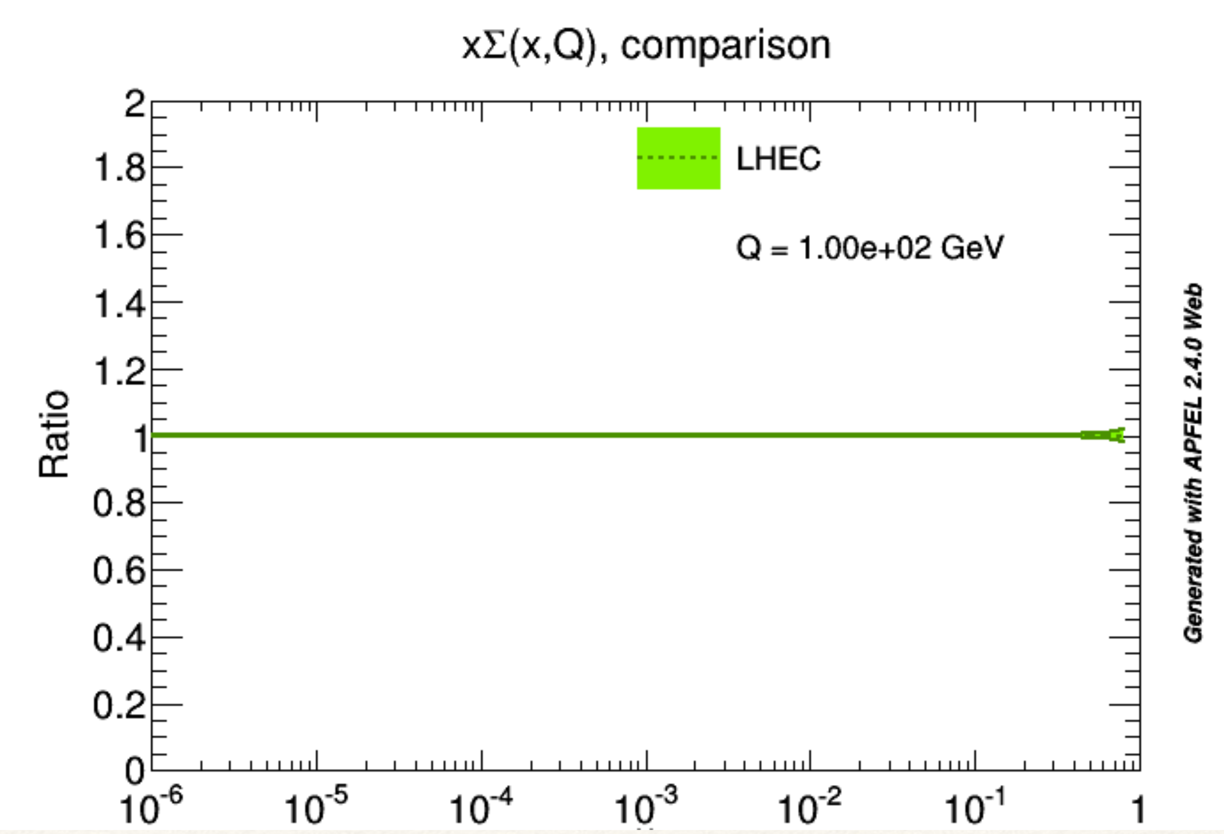


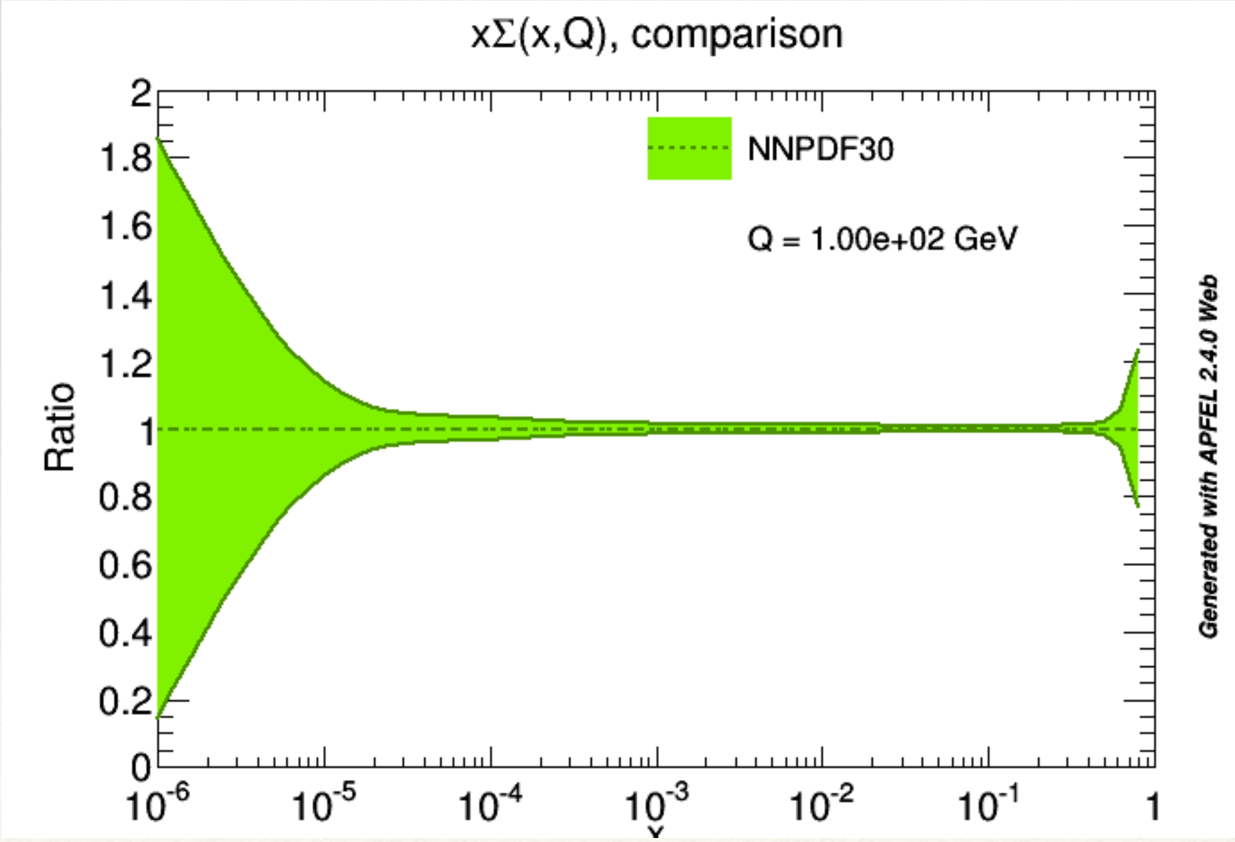


PDF comparisons at Q=100







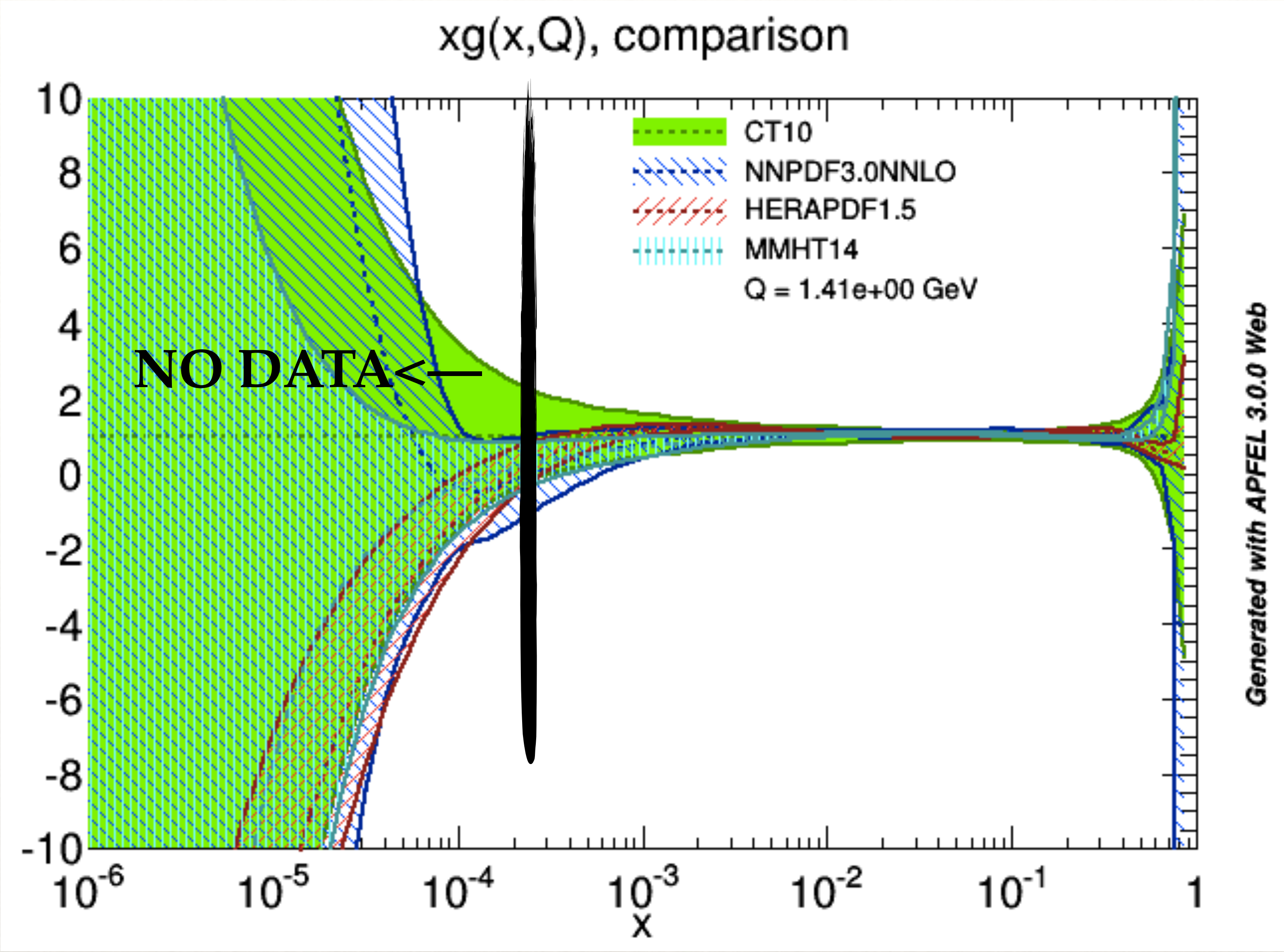


Improving PDFs with FCC

- FCC will access smaller x, larger Q^2
- Currently there is no data to constrain PDFs for $x < 10^{-4}$
    - we rely purely on extrapolation

    - Low x physics: we don't know where at low x, BFKL effects start to become important

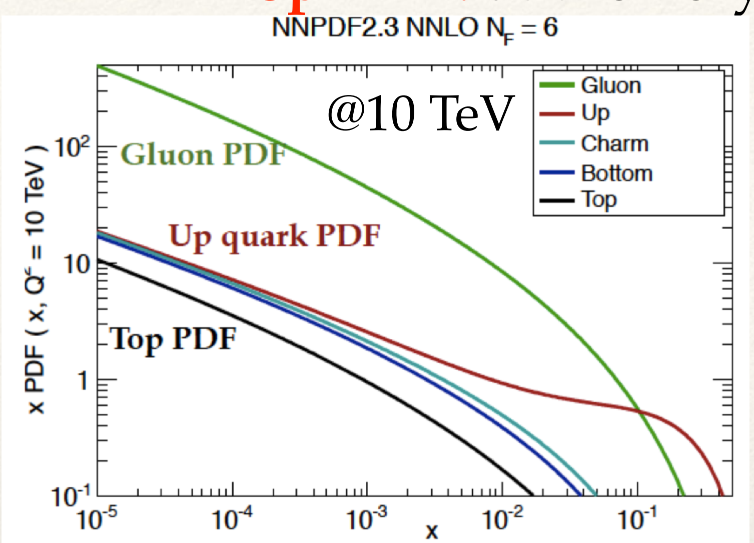
- Poor constraints as well for high x
    - PDFs at high masses (Q^2) rely on DLAP evolution
    - we know at large Q^2 EW effects also become important



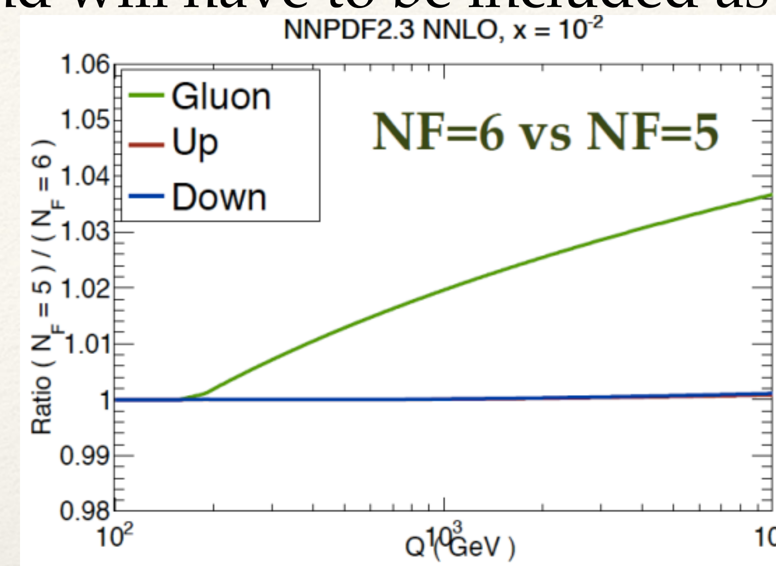
The 100 TeV data will be useful in determining PDFs in these new kinematic regions

What can/will matter for FCC:

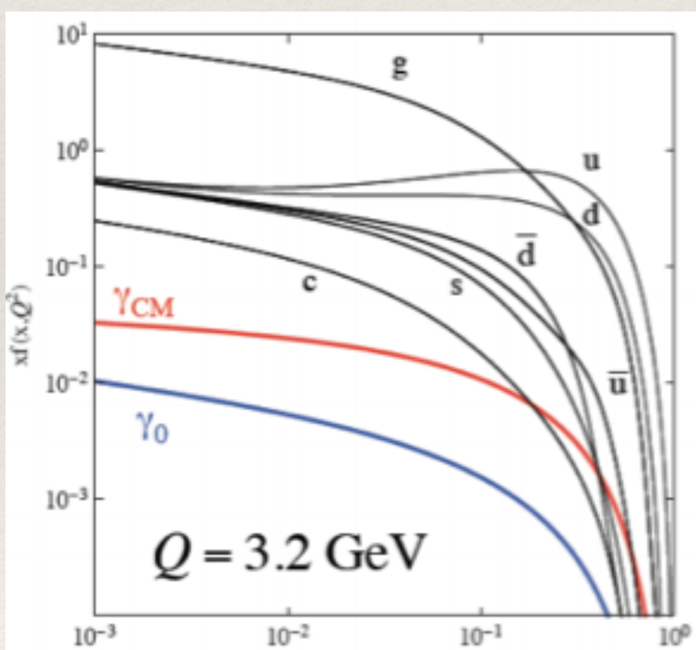
- **Top PDF:** at the very high Q^2, top becomes small and will have to be included as 6f PDFs



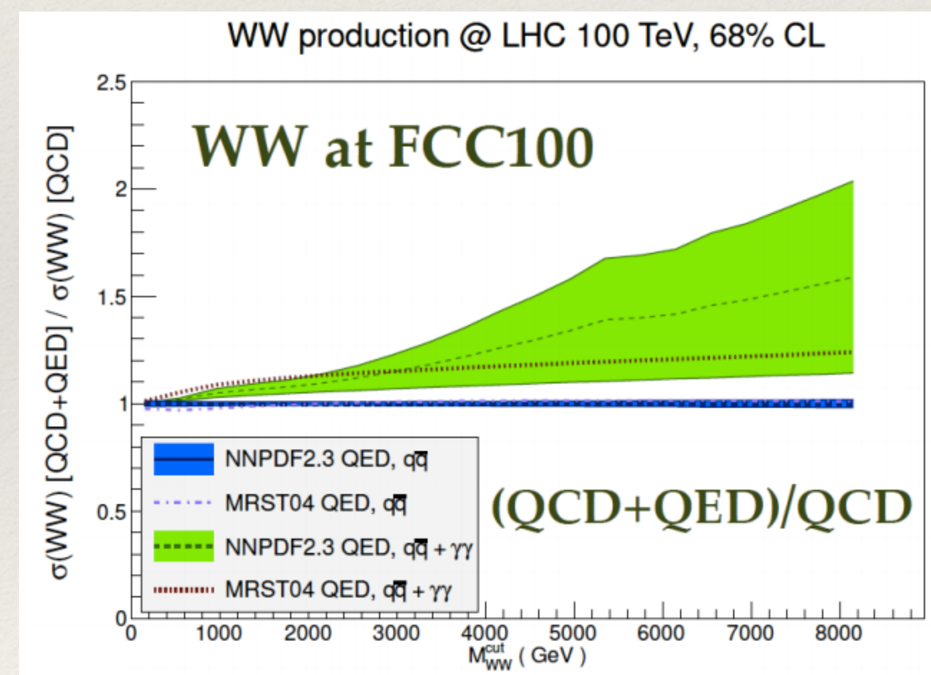
inclusion of top
affects the gluon



- **Photon PDF:** will become important as energies increase
  - the LHC is a $\gamma\gamma$ collider —> more photons at 100 TeV collider



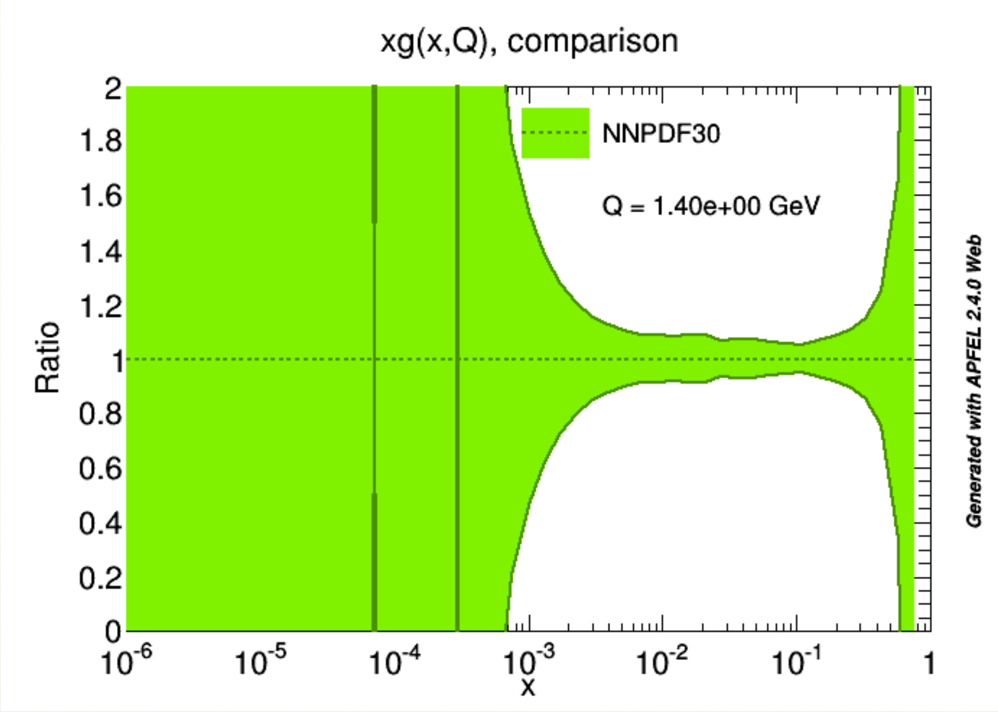
substantial uncertainties
from large x-region

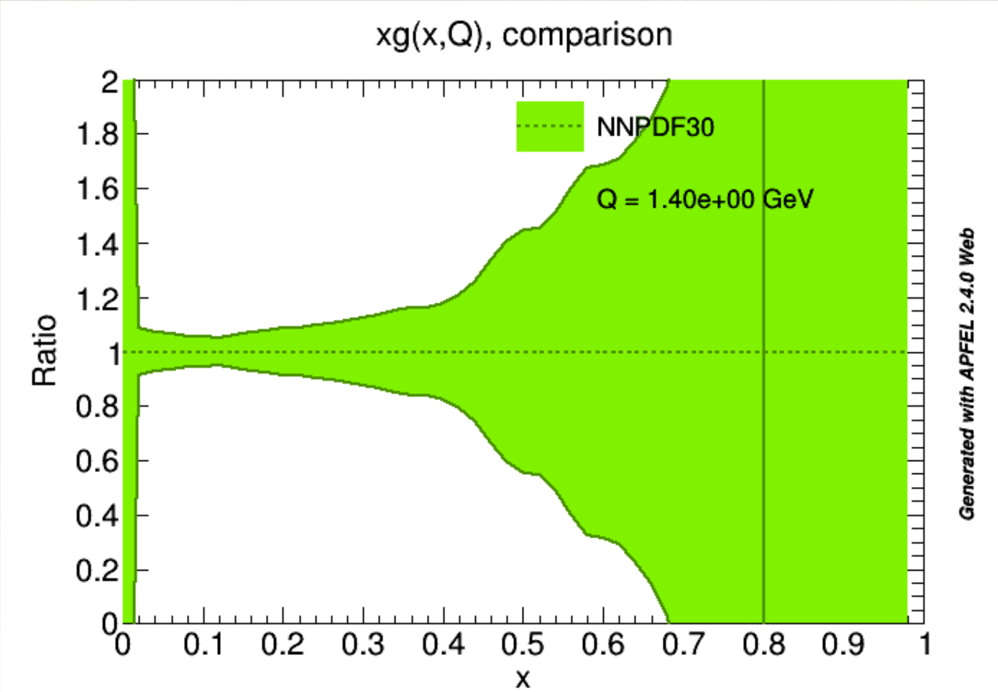


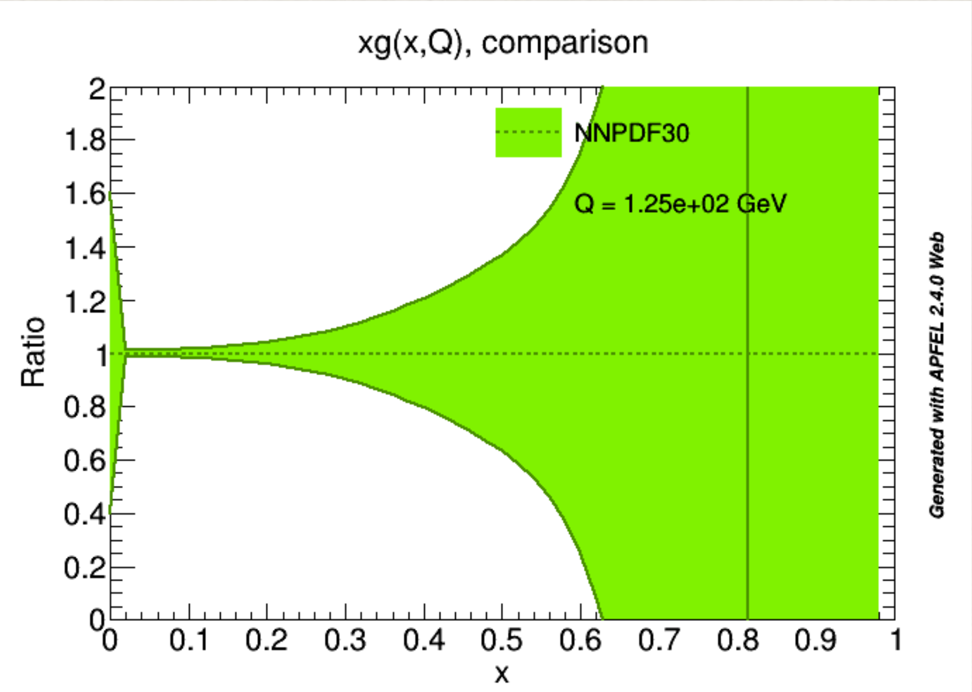
- **NNNLO PDFs:** might be needed if the scale is not a dominant uncertainty and the precision of the data is such that it needs a better theory discrimination

—> it's important to learn what is ok to absorb in PDF and what is not!

Improving PDFs with FCC



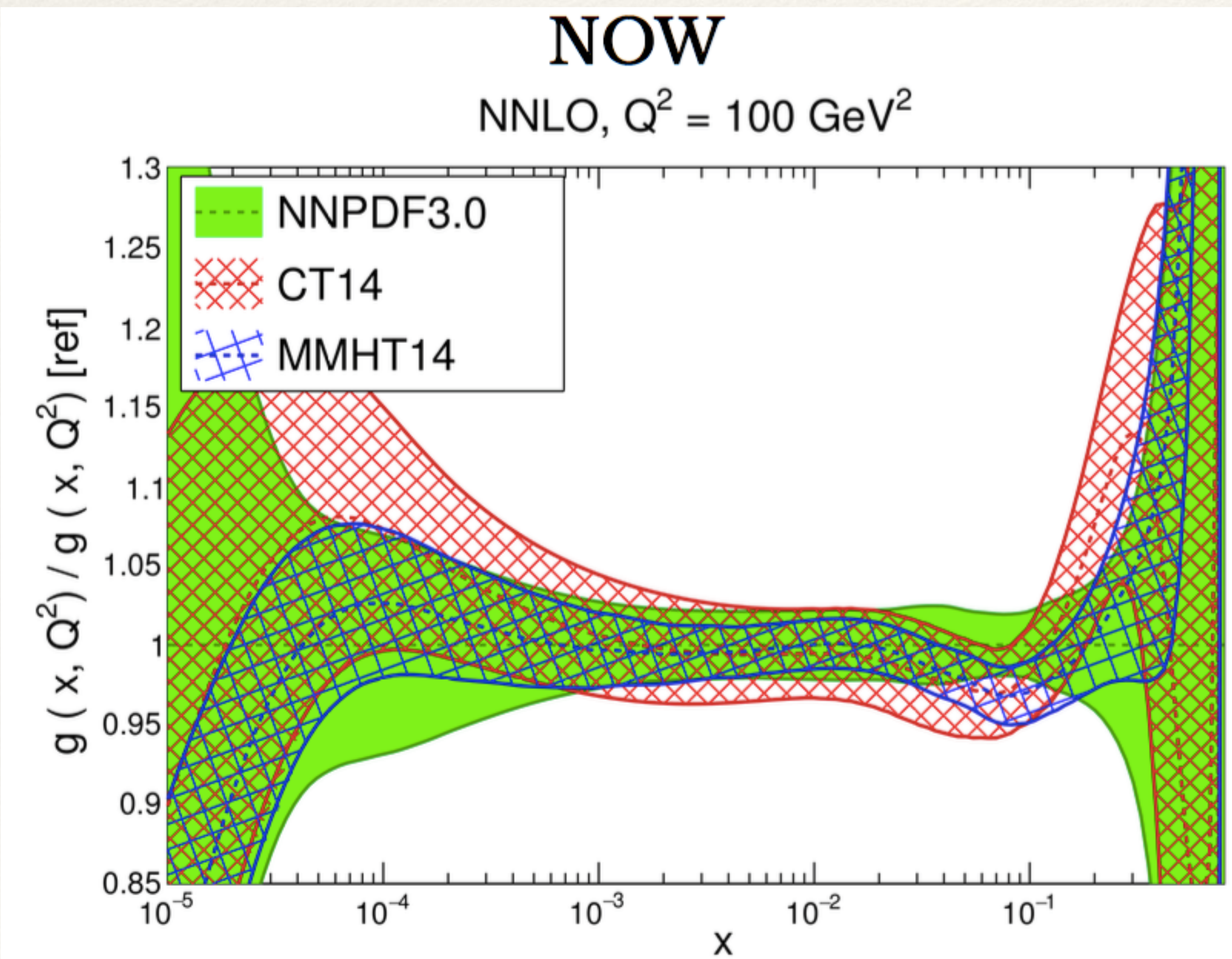


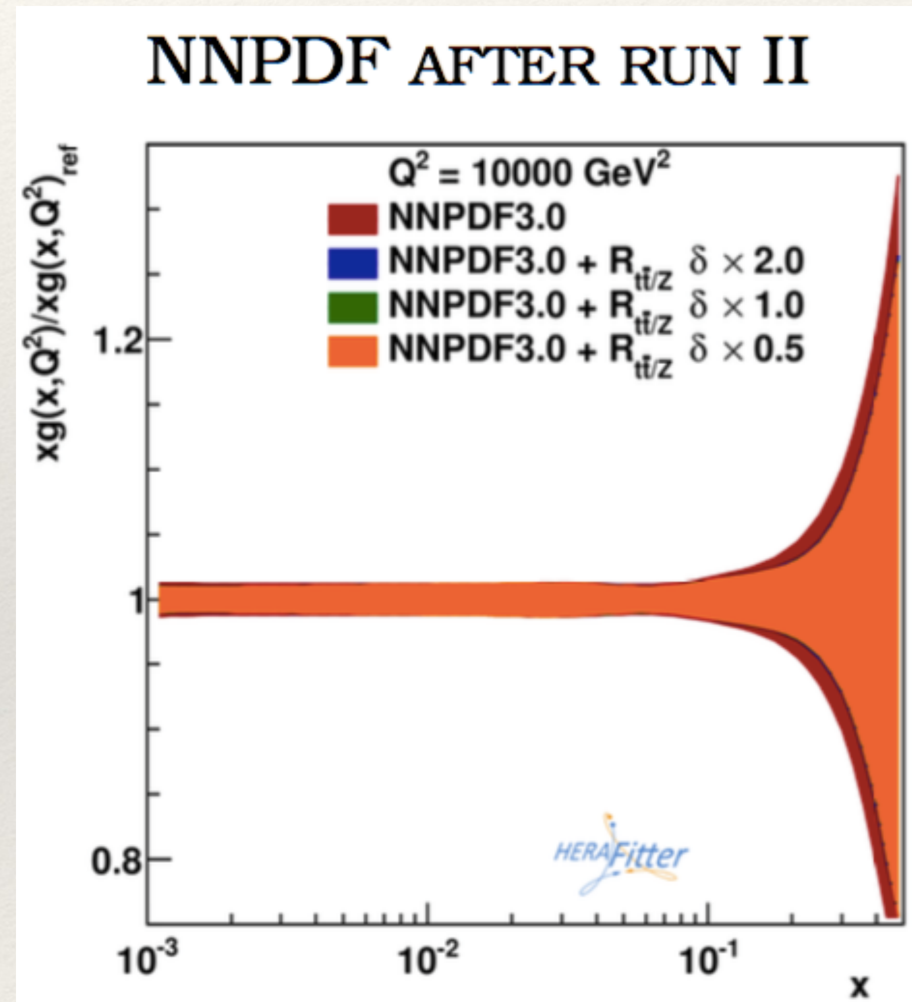


The 100 TeV data will be useful in determining PDFs in these new kinematic regions

LHC with Run II

- LHC Run extends the kinematic coverage which helps to add extra PDF constraints
- However, very difficult to reduce uncertainties to <5% in high x region





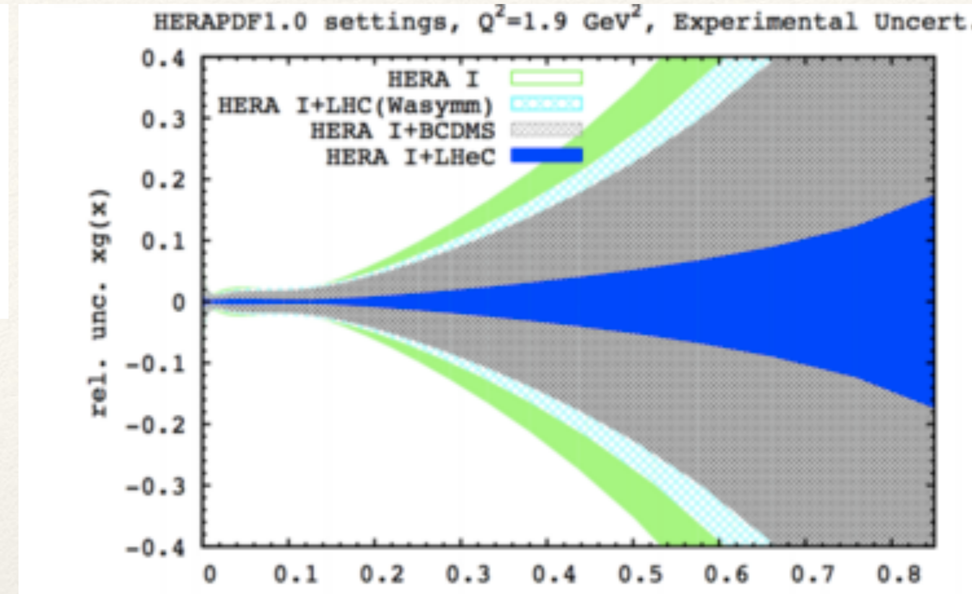
PDF4LHC: 1507.00556

Fit settings evolution:

- **2010:**

  - $u_{val}, d_{val}, g, \bar{U} = \bar{u} + \bar{c}, \bar{D} = \bar{d} + \bar{s}$
    - Sea $S(x)=\bar{U}(x)+\bar{D}(x)$
    - Strange $s(x)=fs\bar{D}(x)=\bar{d}(x)fs/(1-fs)$ with constant $fs=0.31$ at $Q_0^2=1.9$ GeV^2
  - Impose the fermion and momentum sum rules
  - One B parameter for sea and one for valence

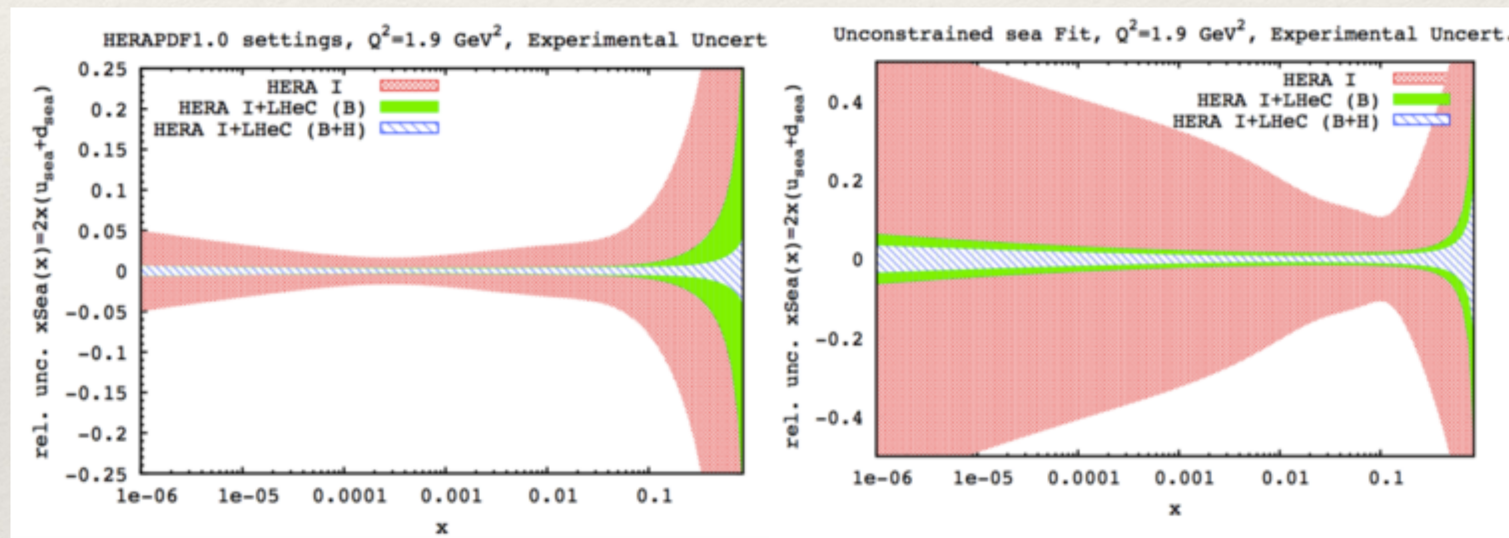
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}},\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.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



- **2010+** Relaxing the assumption at low x that u=d

- Scenario B:
  - E(e$^\pm$) = 50 GeV
  - E(p) = 7 TeV
  - Pol = ±0.4
  - Lumi e$^+$p = 50 fb^{-1}
  - Lumi e$^-$p = 50 fb^{-1}

- Scenario H:
  - E(e$^-$) = 50 GeV
  - E(p) = 1 TeV
  - Pol=0
  - Lumi e$^-$p = 1 fb^{-1}

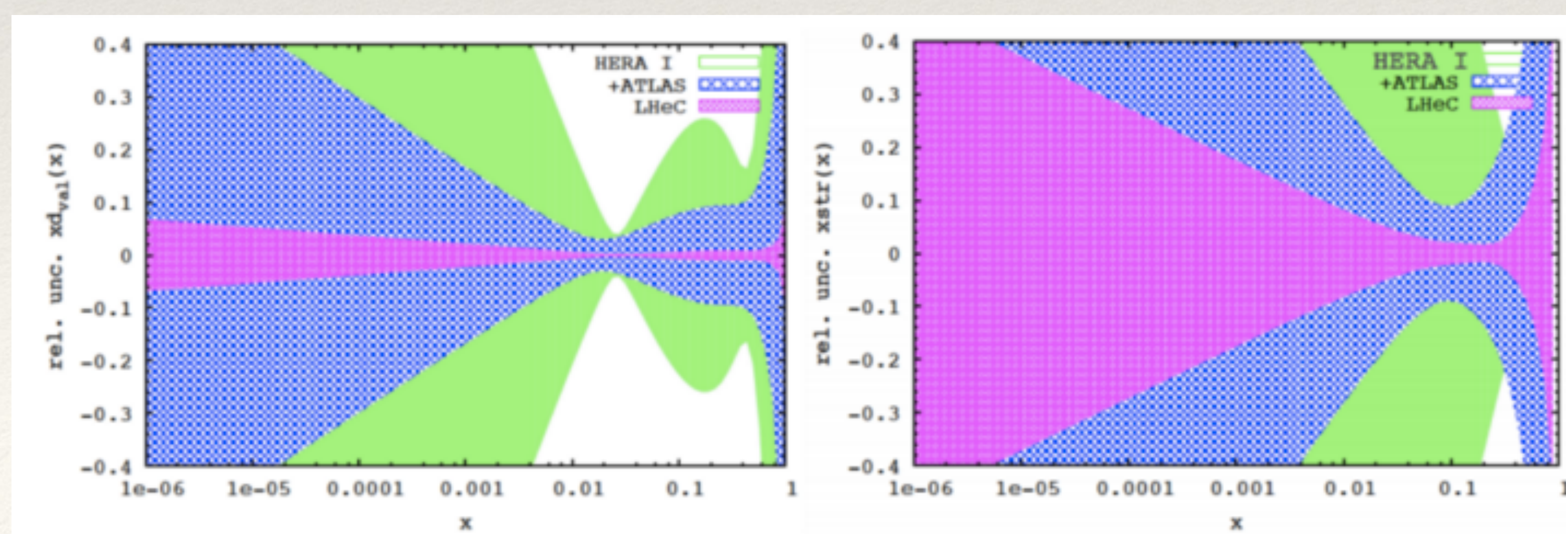


- **2012**

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x),\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}},\\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}},\\
xs(x) &= r_s A_s x^{B_s}(1-x)^{C_s}
\end{aligned}
$$

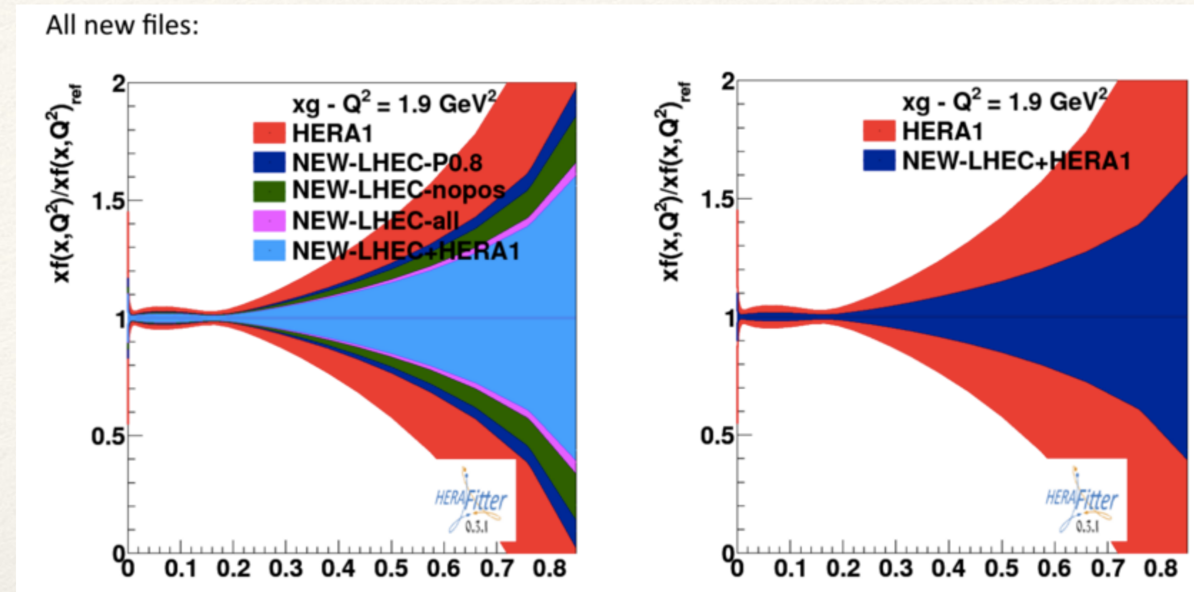
low x

$$B_{u_v} \neq B_{d_v},\quad A_{\bar{u}} \neq A_{\bar{d}},\ B_{\bar{u}} \neq B_{\bar{d}},$$



Fit settings evolution:

- 2014: new LHeC reference:
  - Ep=7 TeV, Ee= 60 GeV
    - 15p fit free strange, no neg gluon, but Dg
    - red- world data
    - blue world data+ lhec new scenario only NC/CC



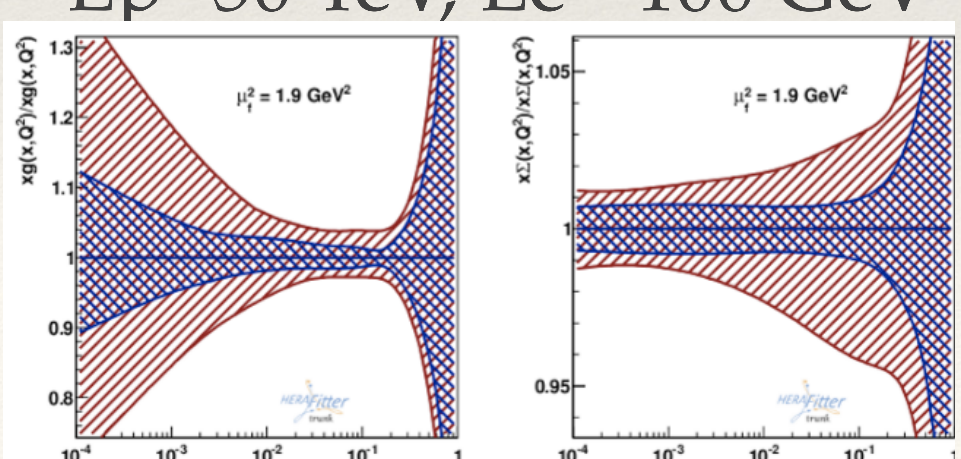
all for ep: Ee=60 GeV, Ep=7000GeV, MSTWLO

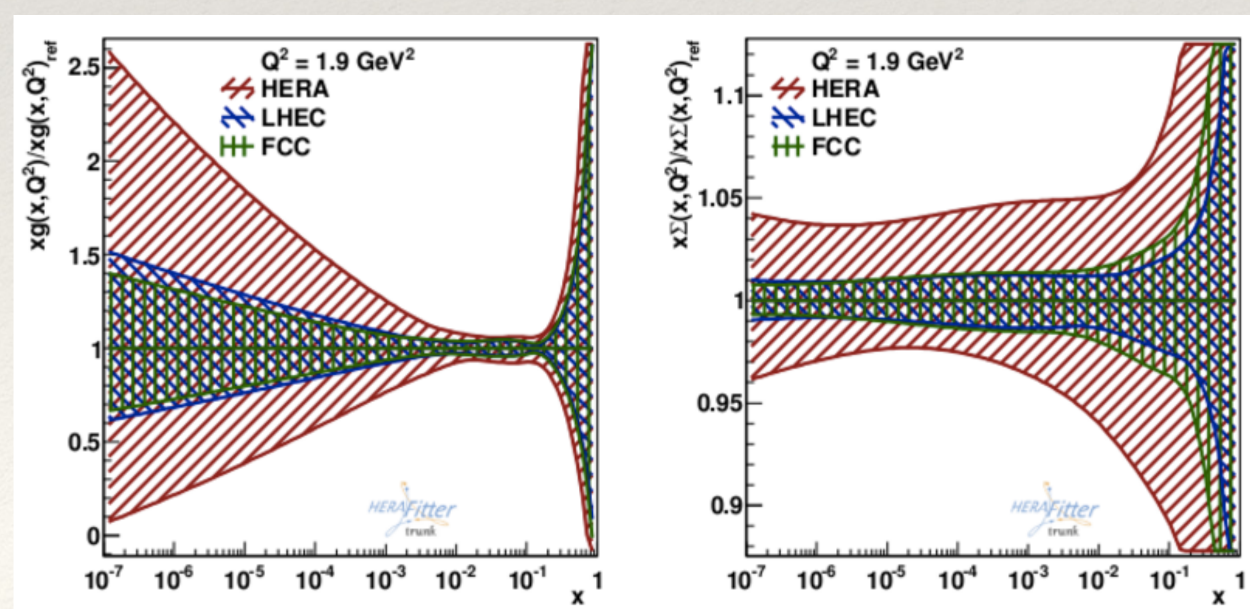
acronym	charge	polarisation	luminosity (fb-1)
mimi	-	-0.8	500
mipl	-	+0.8	50
plnu	+	0	5

adding F2c and Strange:

http://www.desy.de/~voica/for_claire/lhec.vs.varscenarios.pdf

- 2015: add FCC scenario
  - Ep=50 TeV, Ee =100 GeV

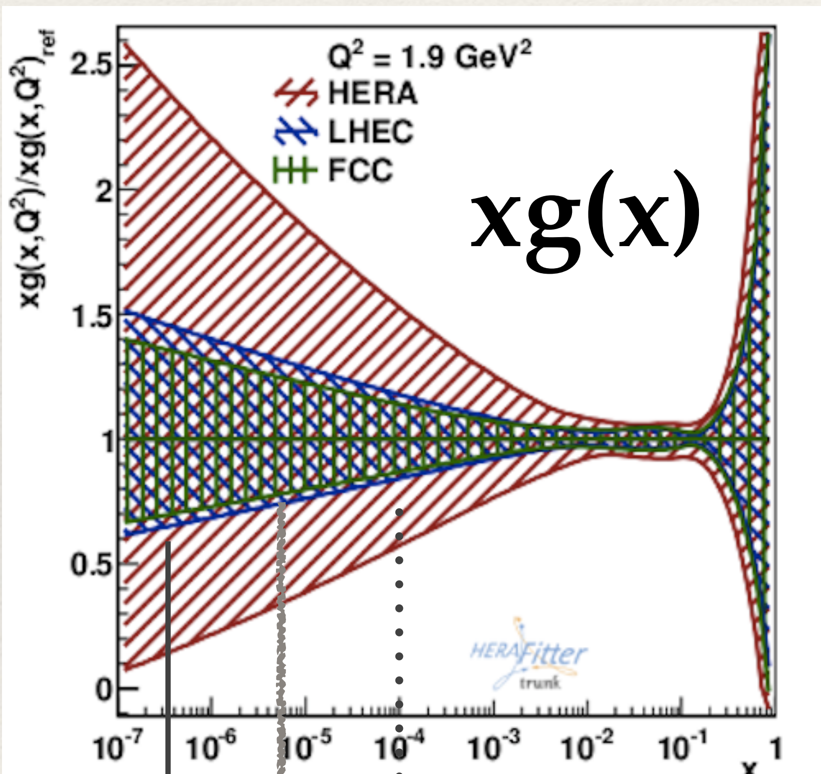




FCC eh vs LHeC vs HERA for PDFs

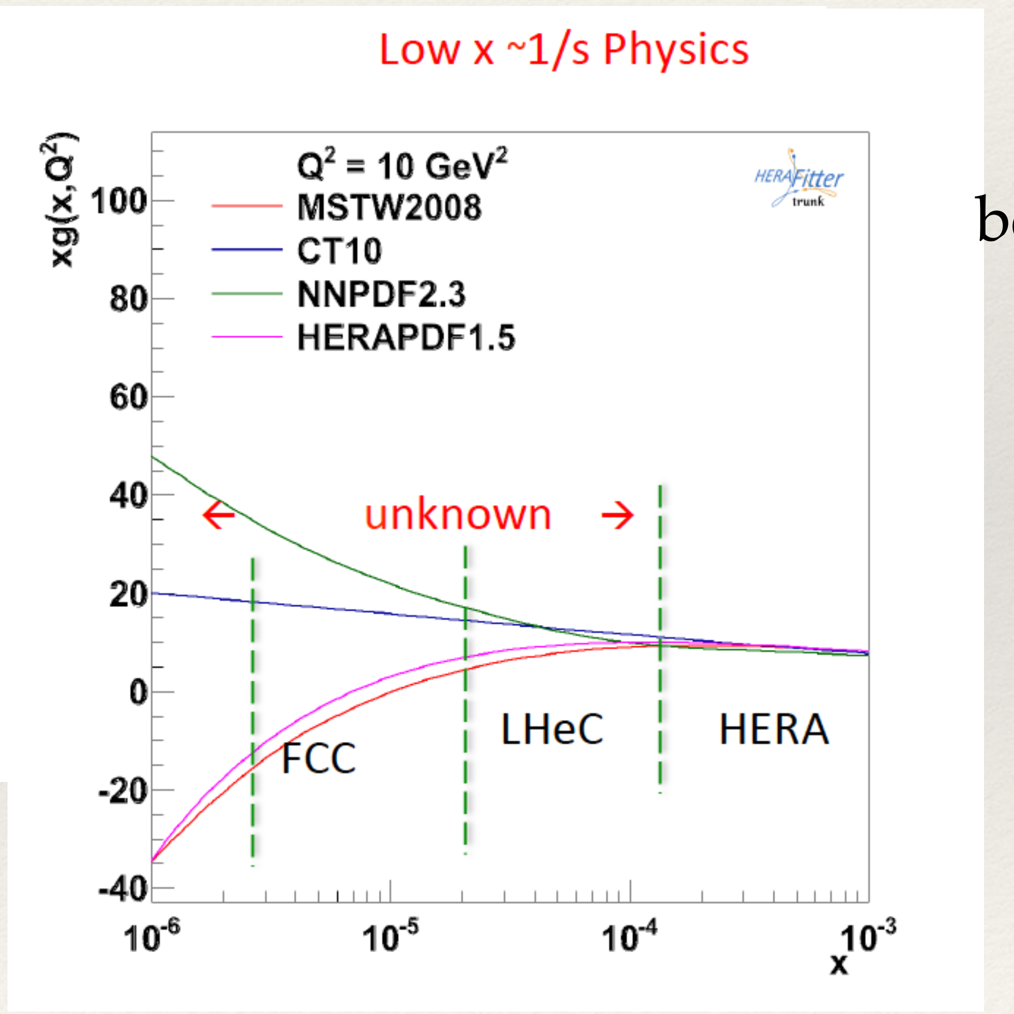
A new QCD Analysis performed using SM central predictions based on:
[HERAFitter - open source QCD fit platform: www.herafitter.org]

- simulated data
- evolved PDFs are **xg, xuv, xdv, xub, xdb, xstr**
- parametric form: **$xf(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$ —> 14 free parameters**



FCC LHeC HERA

HERA sensitivity stops at ~10^{-4}
—>uncer. driven by parametrisation

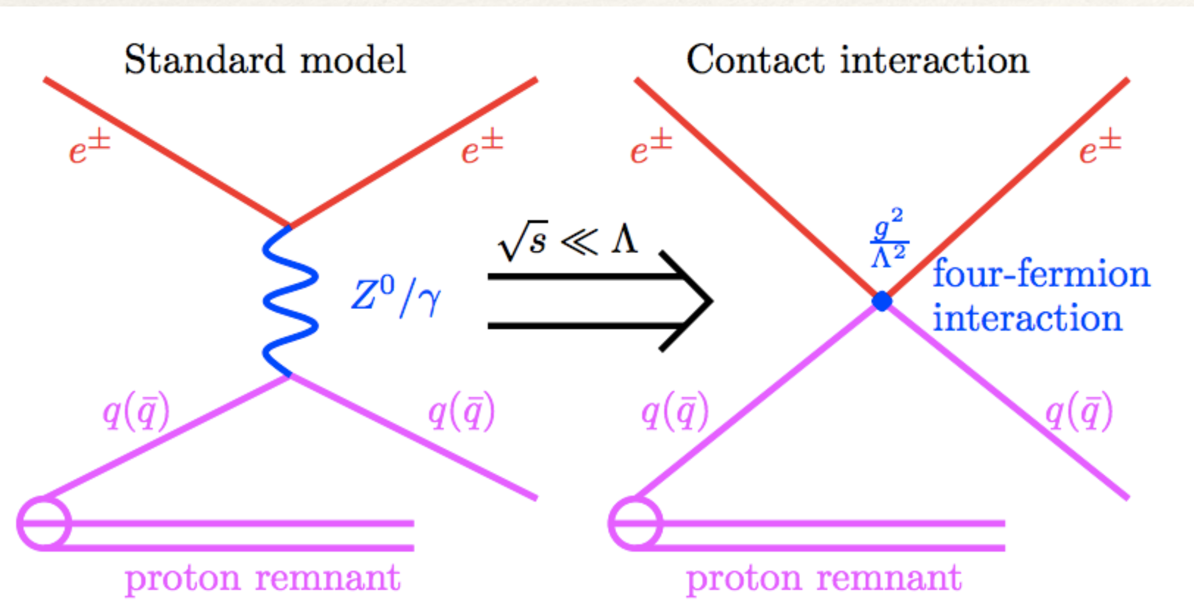


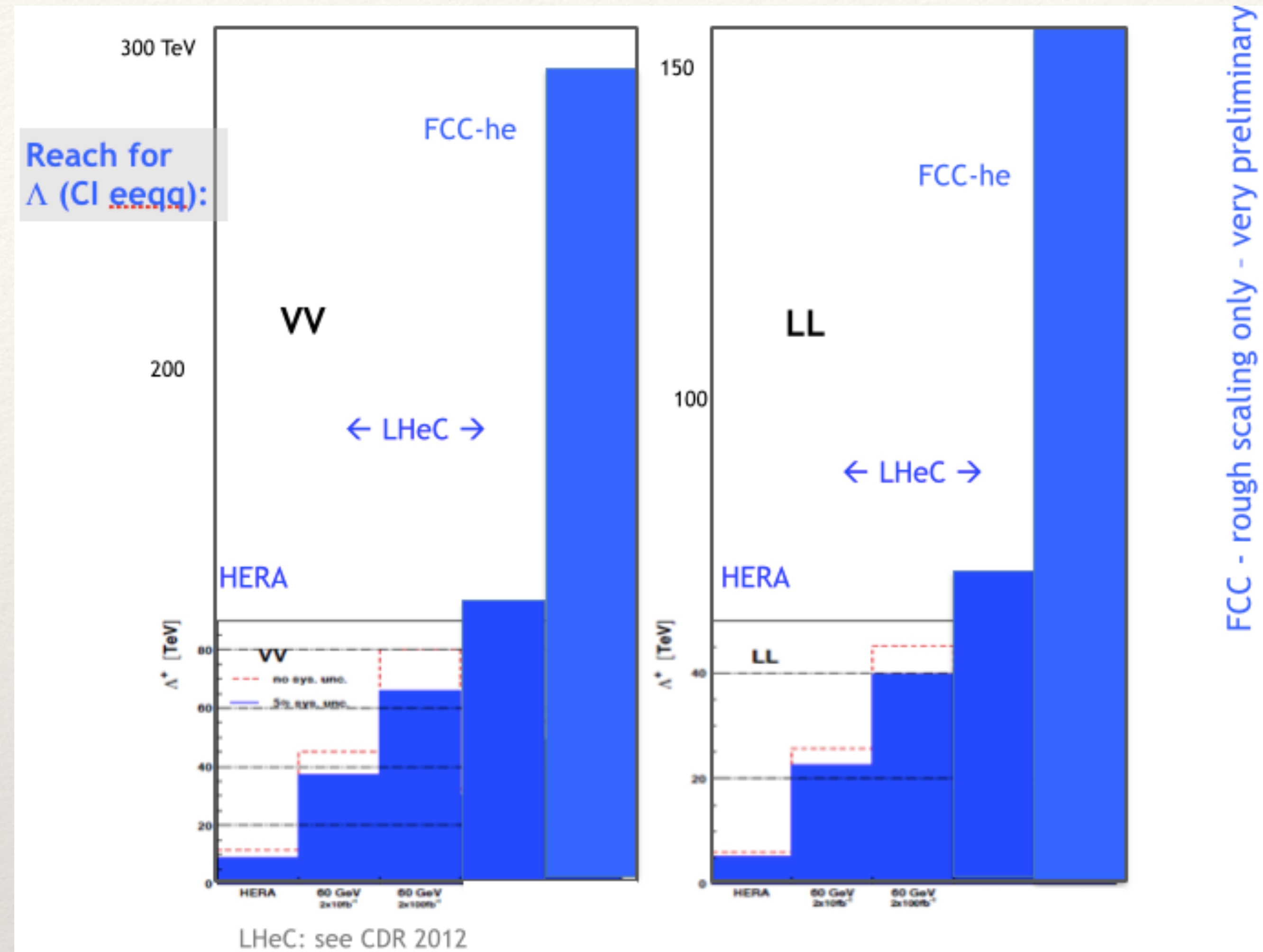
—> Level of agreement between Current Global PDFs

FCC eh allows for Low x phenomenology

High Precision DIS data at high scale

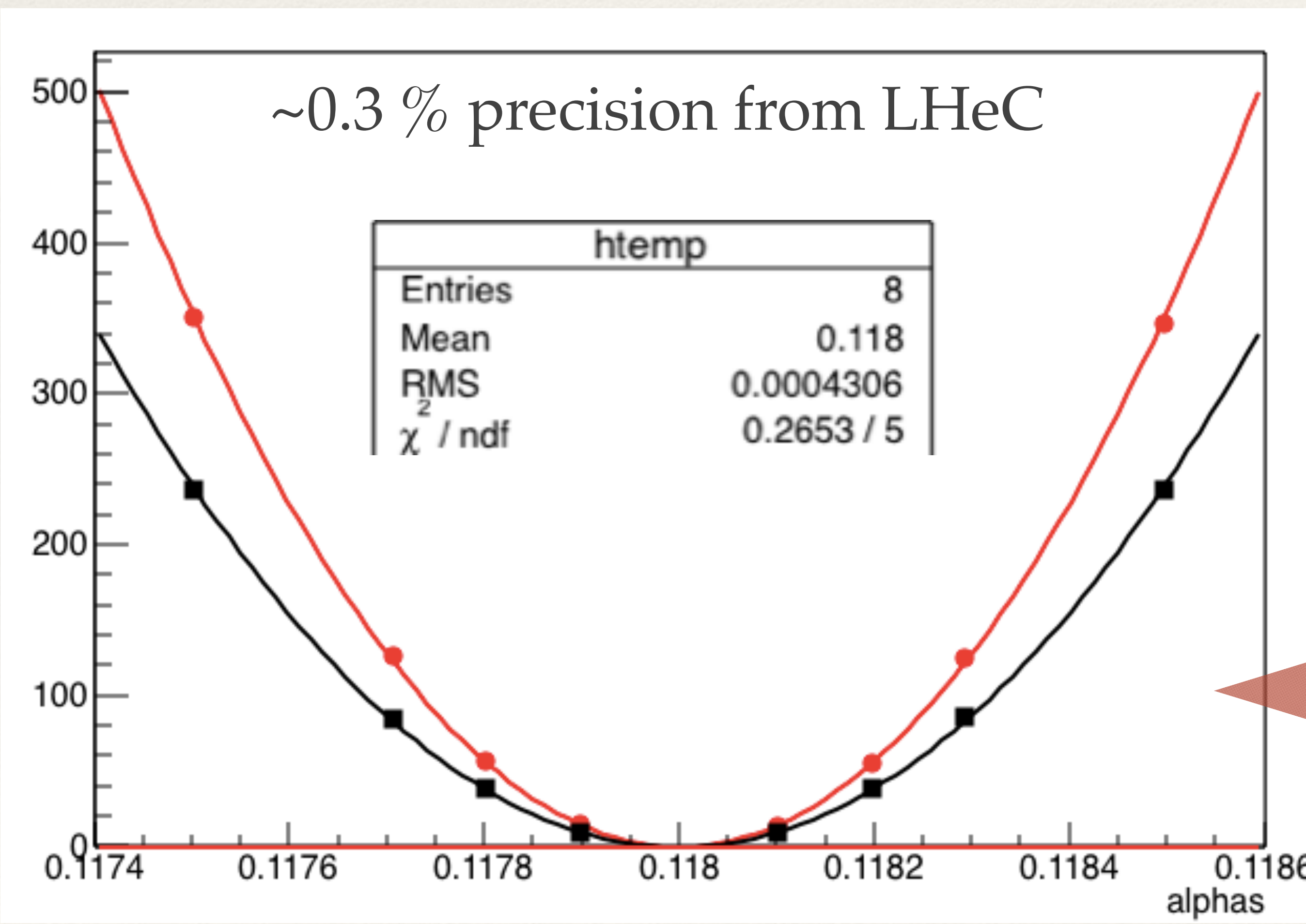
- The very high Q2 data would allow to search for CI (eeqq)

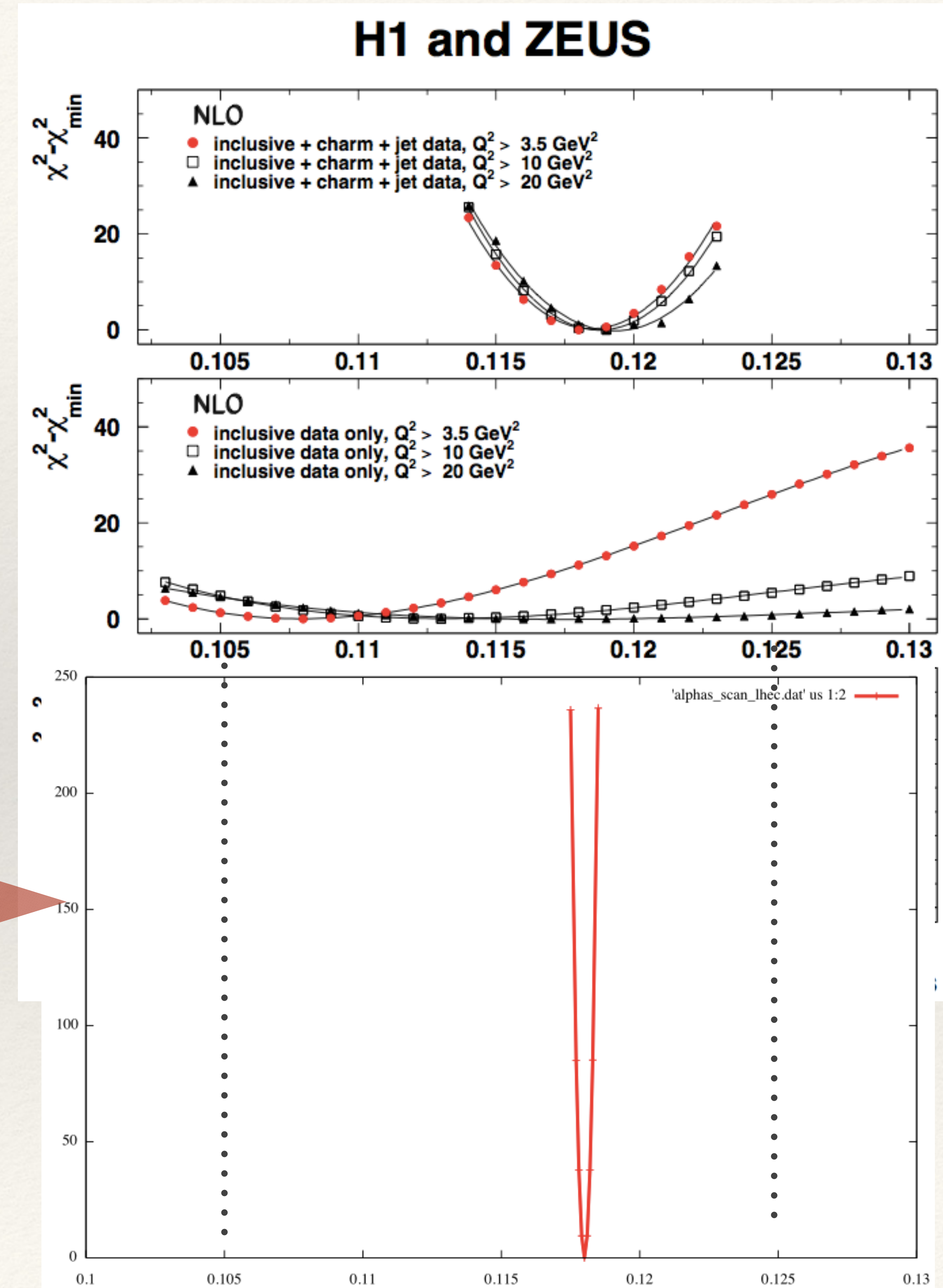




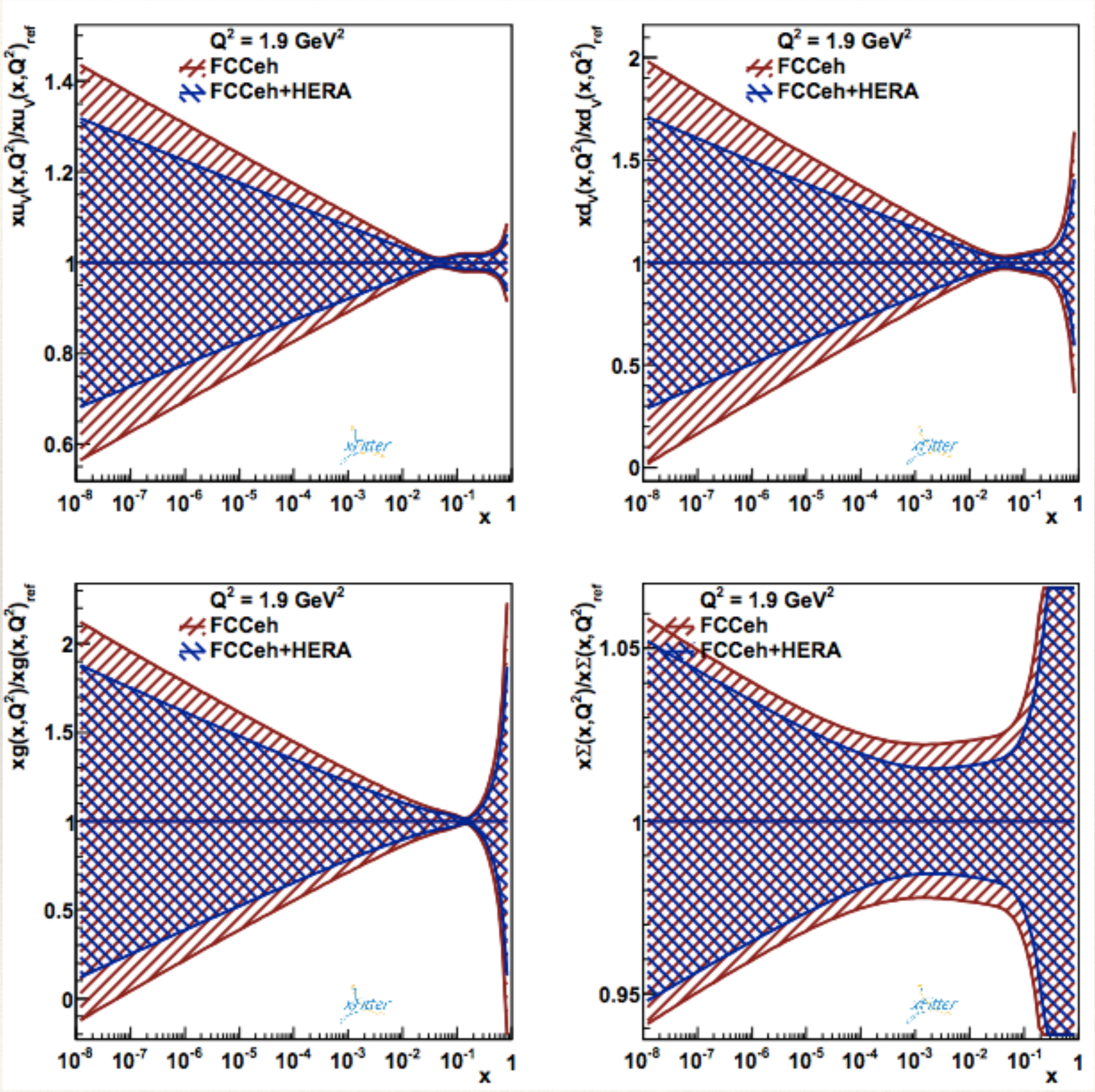
Strong coupling from FCC eh

- The much reduced PDFs impose better constraints on various SM and BSM parameters:
  - alphas small in DIS or high with jets?
    [over 30 years old puzzle HERA couldn't solve]





Potential of FCCeh on PDFs



Summary of current alphas uncert.

http://arxiv.org/pdf/1310.5189v1.pdf

(snow mass report)

Method	Current relative precision	Future relative precision	
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)	~1%
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)	
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)	<1%
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)	<1%
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])	~1%
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])	<0.5%

- **per mile accuracy can test QCD Lattice calculations**