PDFs at the FCC-eh and strong coupling at the LHeC

Claire Gwenlan, Oxford

for the LHeC and FCC-eh study groups

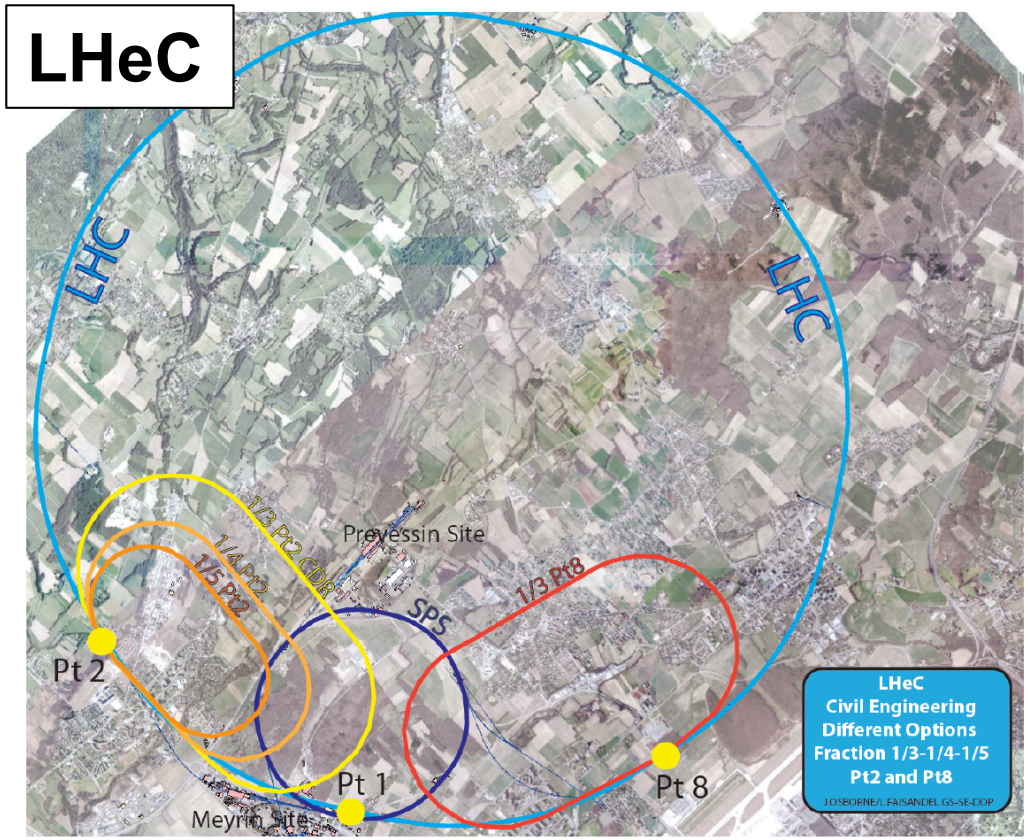
DIS17 workshop

Birmingham, UK

April 2017

(with thanks to M. Klein and V. Radescu)

LHeC and FCC-eh



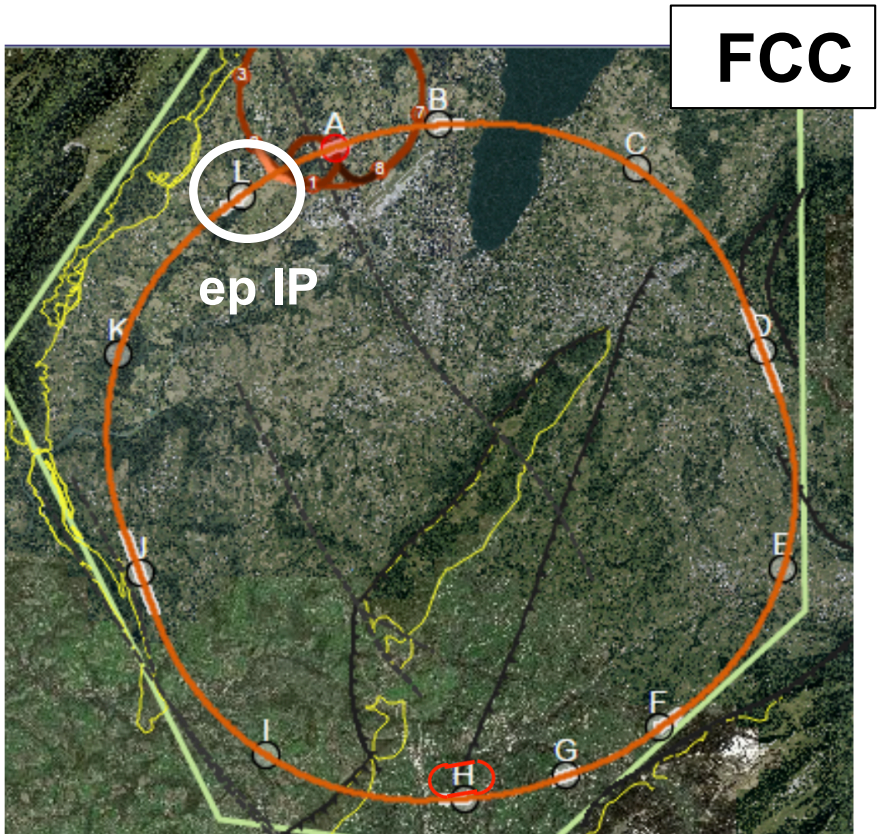
(M Klein, Rencontre du Vietnam, Sept 2017)

LHeC and **FCC-eh**

energy recovery LINAC

e-beam: 60 GeV

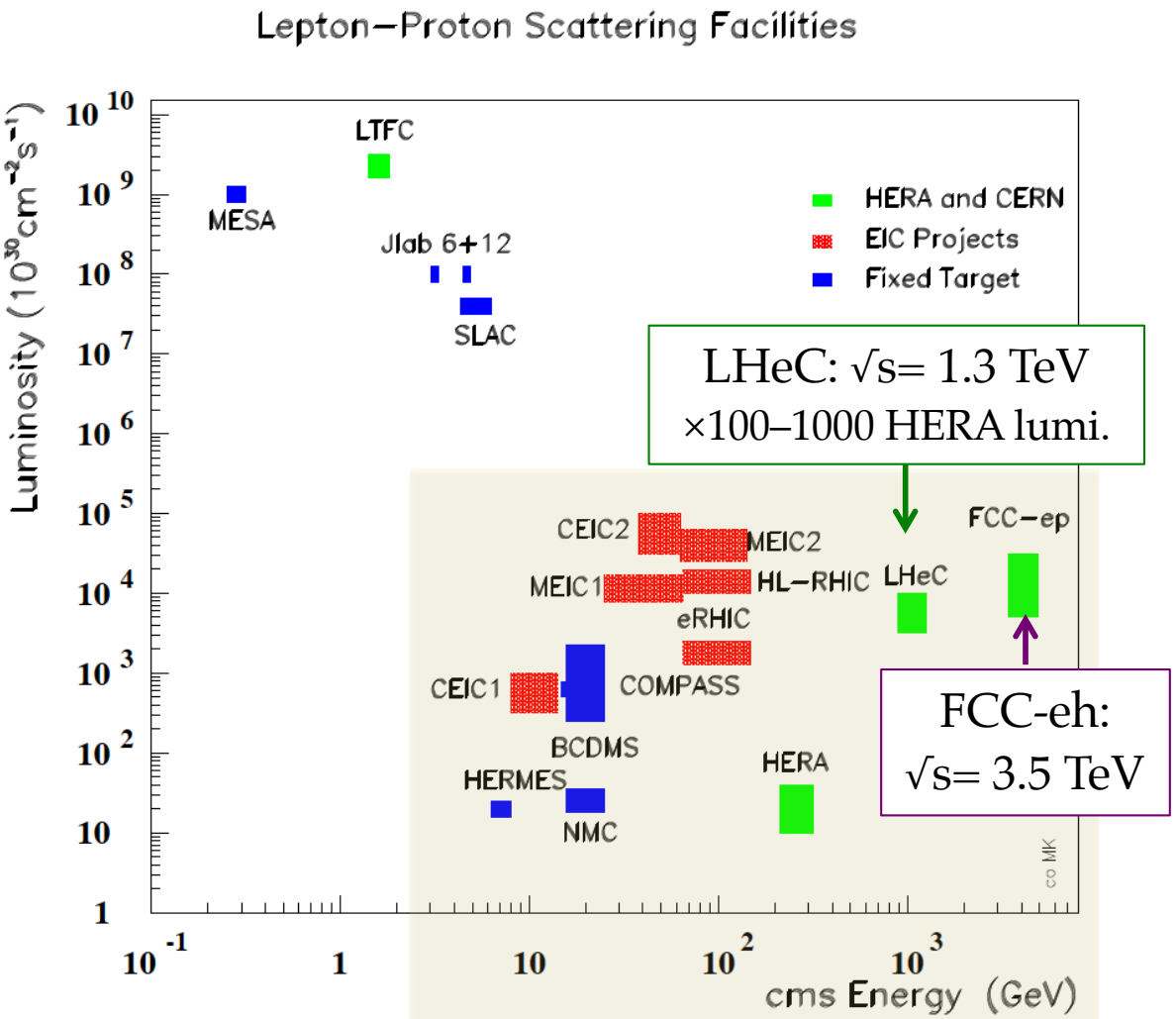
$L_{int} \rightarrow 1\ ab^{-1}$



for collider and detector, see talks by: D Pellegrini, M Klein

LHeC (**FCC-eh**) complementary to, synchronous with, **HL-LHC** (**FCC**)

LHeC and FCC-eh



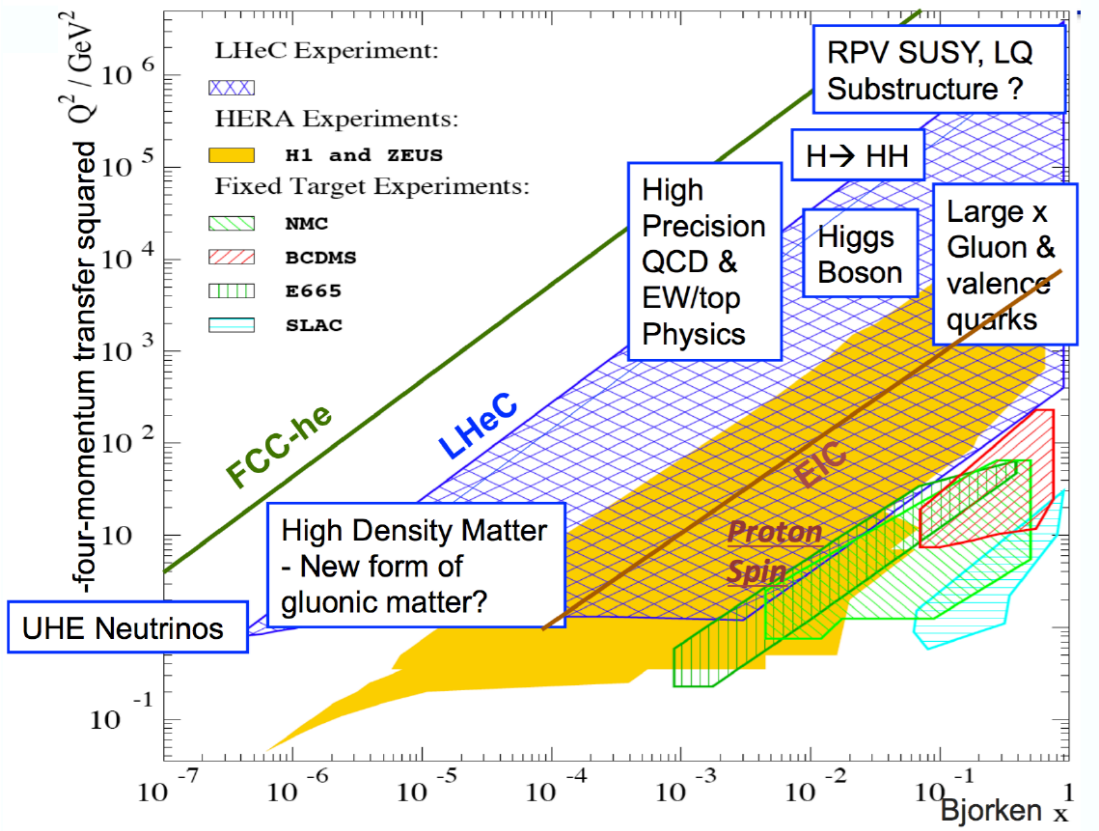
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

LHeC: future ep (eA) collider, proposed to run concurrently with HL-LHC; CDR arXiv:1206.2913 (complementary; additional discovery channels; precision PDFs and αs)

FCC-eh: further future ep collider, integrated with FCC; (further kinematic extension wrt **LHeC**)

LHeC (**FCC-eh**) complementary to, synchronous with, **HL-LHC** (**FCC**)

LHeC and FCC-eh



LHeC kinematic reach:

Q^2 up to 10^6 GeV^2

x down to 10^{-6}

FCC-eh extends further,

Q^2 to 10^7 GeV^2, x to 10^{-7}

- **outline of this talk:**
- PDFs at FCC-eh
- strong coupling (α_s)

- very rich physics programme; see also other talks in this workshop:

(**PDFs at the LHeC** (A Cooper-Sarkar); **nPDFs** (H Paukkunen); **EW** (D Britzger); **top quark physics** (H Sun); **diffraction** (P Newman); **SM Higgs** (M Tanaka); **BSM Higgs and Di-Higgs** (M Kumar))

parton distribution functions, and FCC

- **improved understanding of proton structure (PDFs) crucial** for maximising physics potential of LHC and **future hadron colliders** (Higgs, Mw, BSM searches, …)
- **see also talk by A.Cooper-Sarkar for improved PDFs from the LHeC**

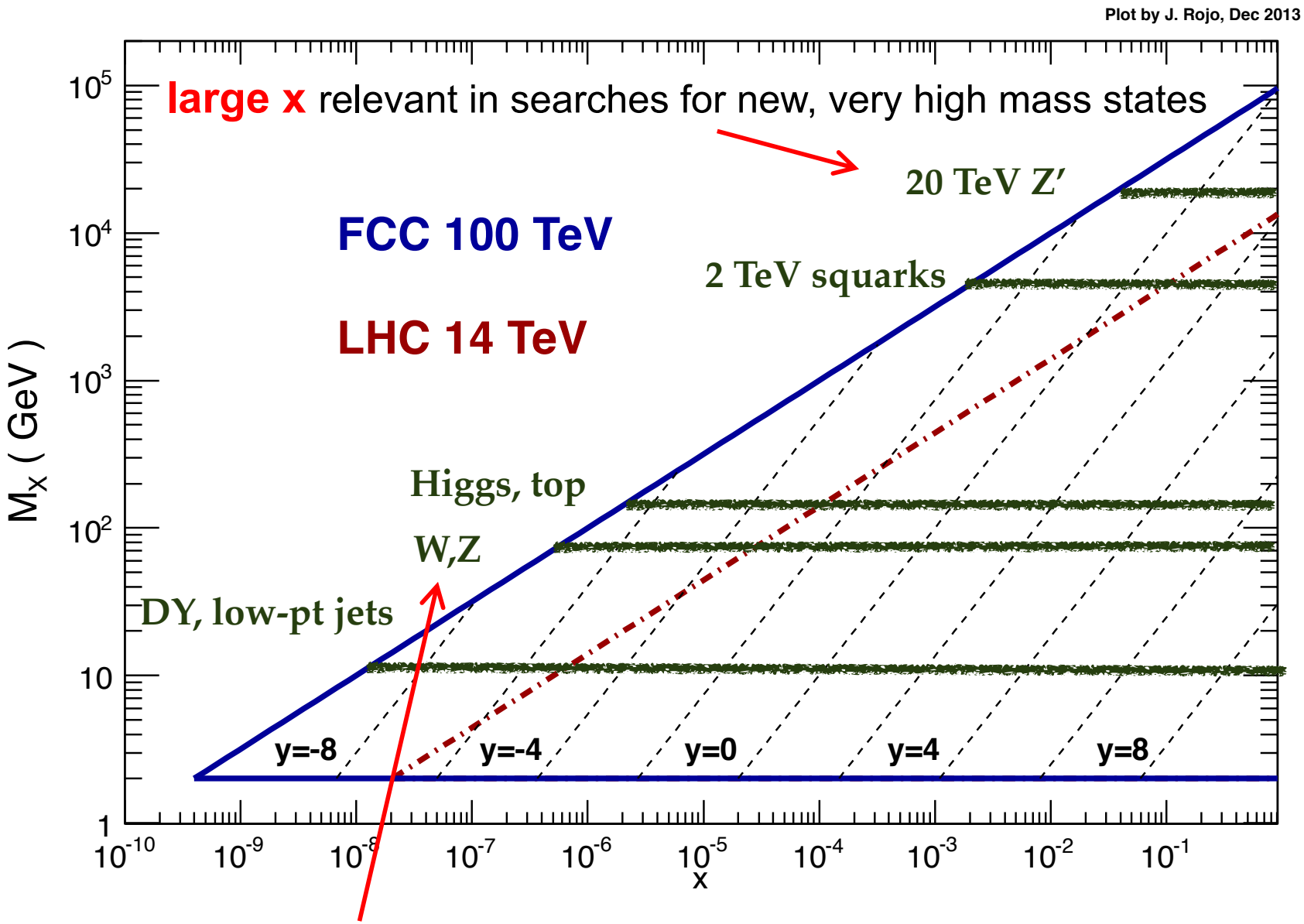
- **FCC: potential future proton-proton collider, E_{CM} = 100 TeV**
- will probe proton PDFs in unexplored regions of ultra-low x, and high Q^2

- **PROGRESS IN PDF DETERMINATION FOR FCC DEPENDS ON:**

– complete **exploitation of LHC** and **HL-LHC** measurements
– developments in **higher order calculations** and techniques

– **future ep collider** before (EG. LHeC) and/or in parallel (**FCC-eh**) with FCC would vastly improve situation

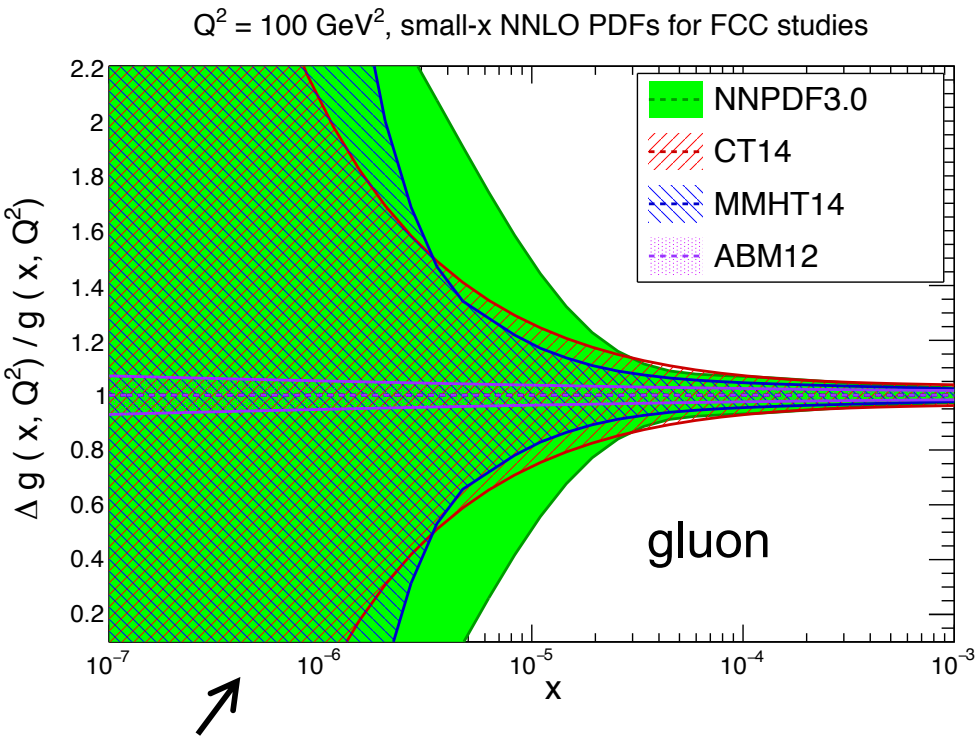
Kinematics of a 100 TeV FCC

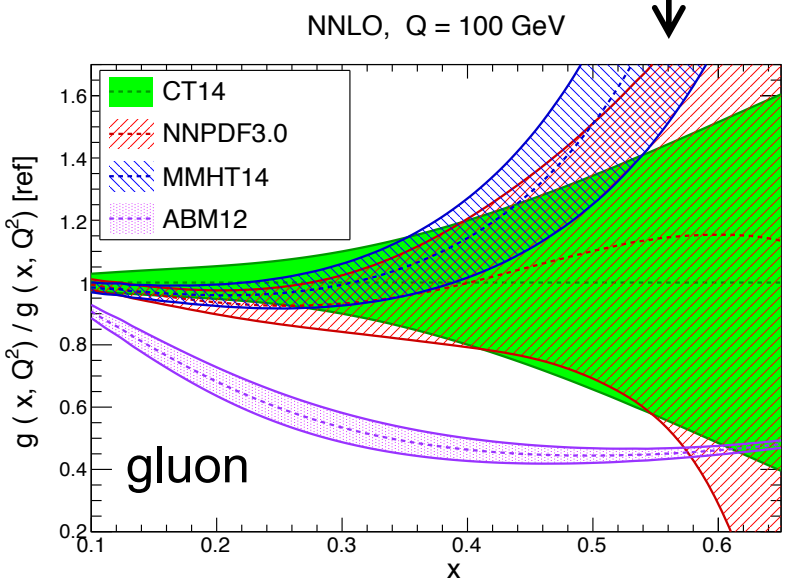


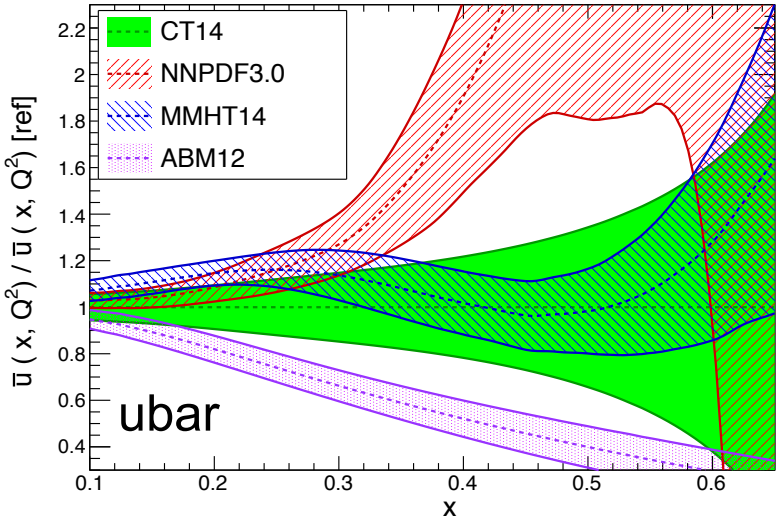
small x becomes relevant even for “common” physics (EG. W, Z, H, t)

situation today

zoom in on large x





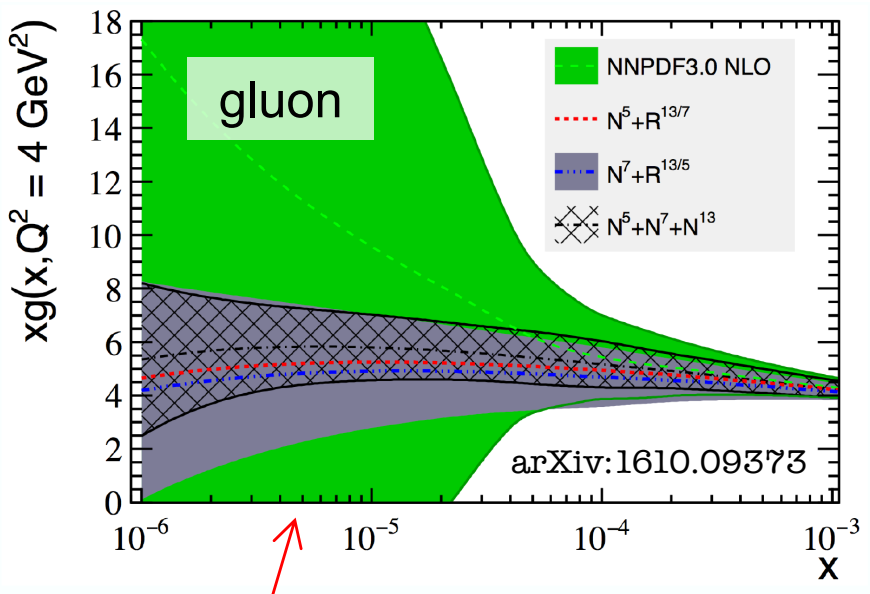


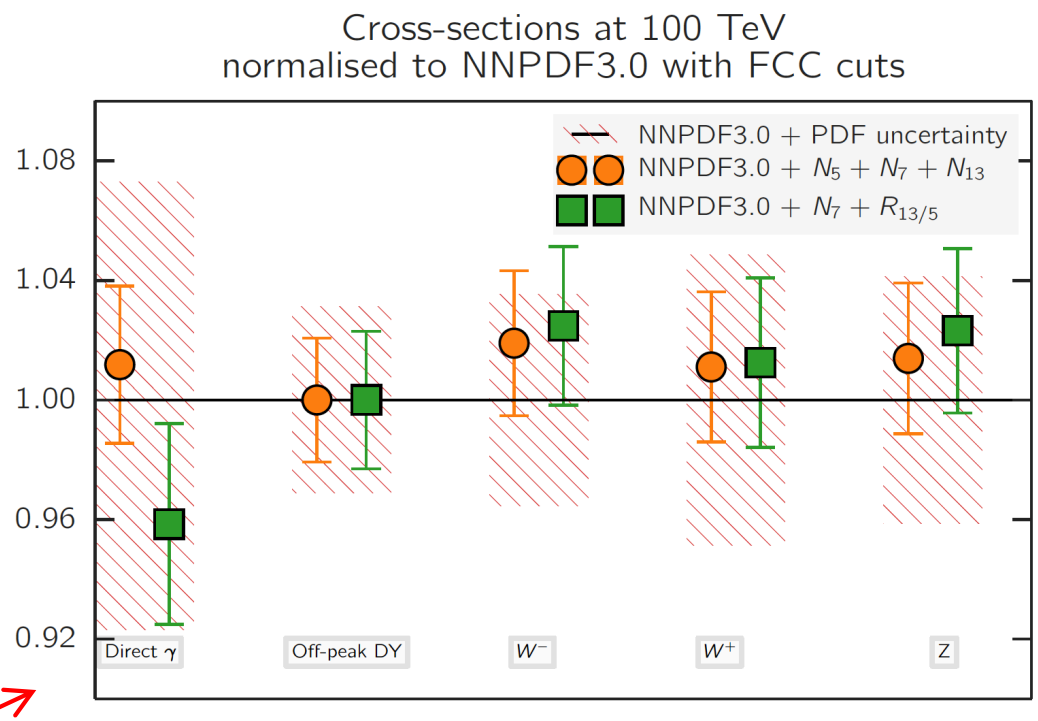
- **small x:** no current data constrain x ≤ 10^{-4}
- … and we don't know where DGLAP breaks down!
- FCC: small x becomes relevant even for W, Z, H, t
- **large x:** crucial for new physics searches in extended kinematic regime

(plots from arXiv:1607.01831)

LHC constraints for FCC?

EG: prospects for better control of **small x gluon** using **LHCb forward charm**





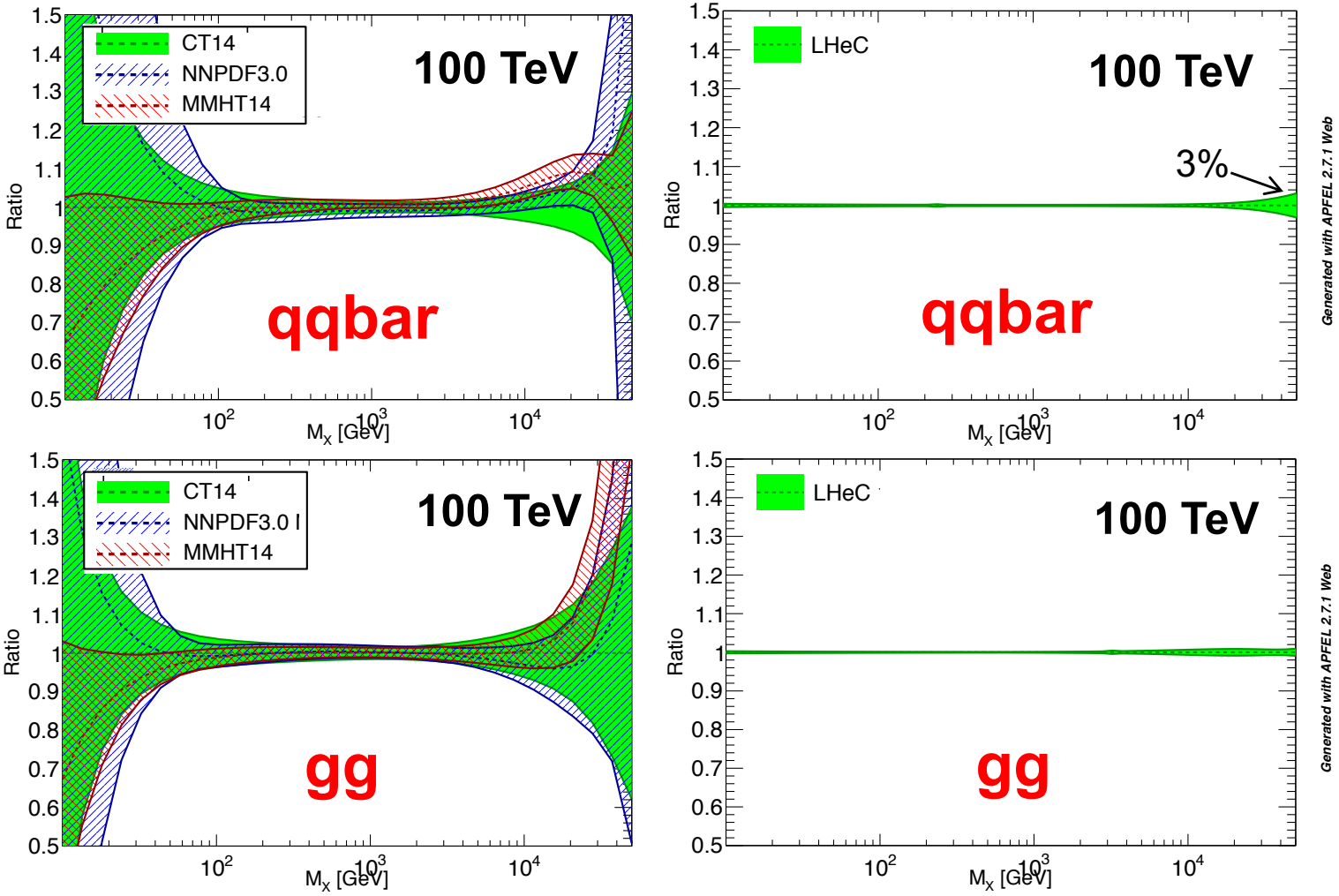
E. Slade, 1st FCC workshop, CERN, Jan 2017

improved **small x gluon** using combinations of **LHCb forward charm** cross sections:– stabilises FCC predictions

other LHC data will also constrain PDFS; must be exploited, but cannot resolve parton distributions precisely (also see talk by A.Cooper-Sarkar)

what about future ep colliders?

today FCC parton luminosities **… then,** if we have



Mx [GeV] Mx [GeV]

LHeC: extremely precise PDFs across full mass range, up to the very high scales accessible at **FCC**

(see also talk by A. Cooper-Sarkar)

and now, what can the **FCC-eh** do?

new

simulated FCC-eh data

new simulated **inclusive NC** and **CC DIS data** for latest running scenarios

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]	
NC	60 (60)	50 (7)	−0.8	−1	1000	e−, neg. pol.
CC	60 (60)	50 (7)	−0.8	−1	1000	
NC	60 (60)	50 (7)	+0.8	−1	300	e−, pos. pol.
CC	60 (60)	50 (7)	+0.8	−1	300	
NC	60 (60)	50 (7)	0	+1	100	e+, unpol.
CC	60 (60)	50 (7)	0	+1	100	
NC	20 (60)	7 (1)	0	−1	100	low energy
CC	20 (60)	7 (1)	0	−1	100	

* second and third columns show FCC-eh (LHeC)

(M.Klein)

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%

more data, and more options c.f. previous studies

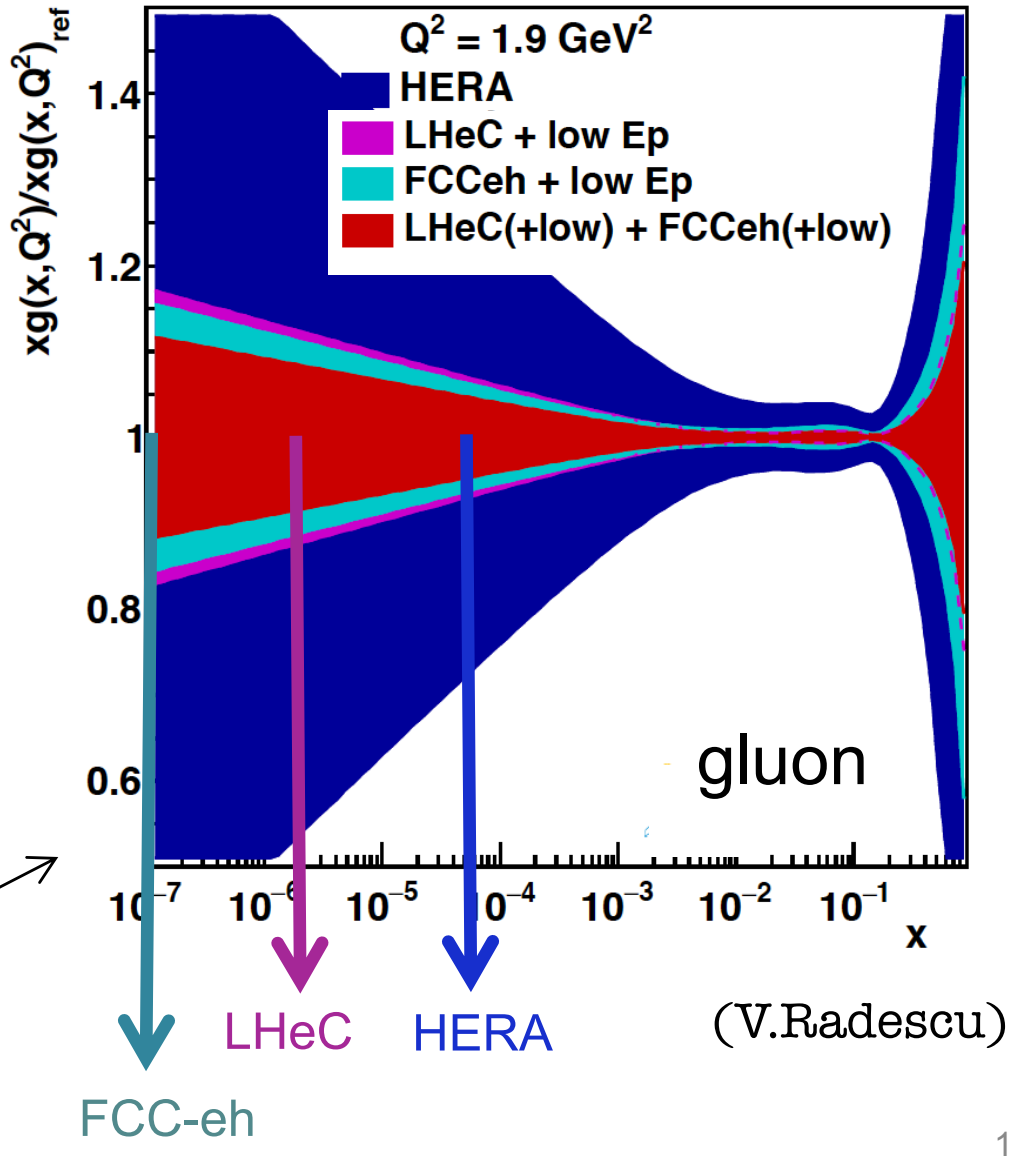
all work in progress

FCC-eh vs LHeC

- seen already how precisely **LHeC** can control **PDFs**
- need **FCC-eh** to explore below $x = 10^{-6}$
- **FCC-eh** may further improve, and explore **small x** phenomenology

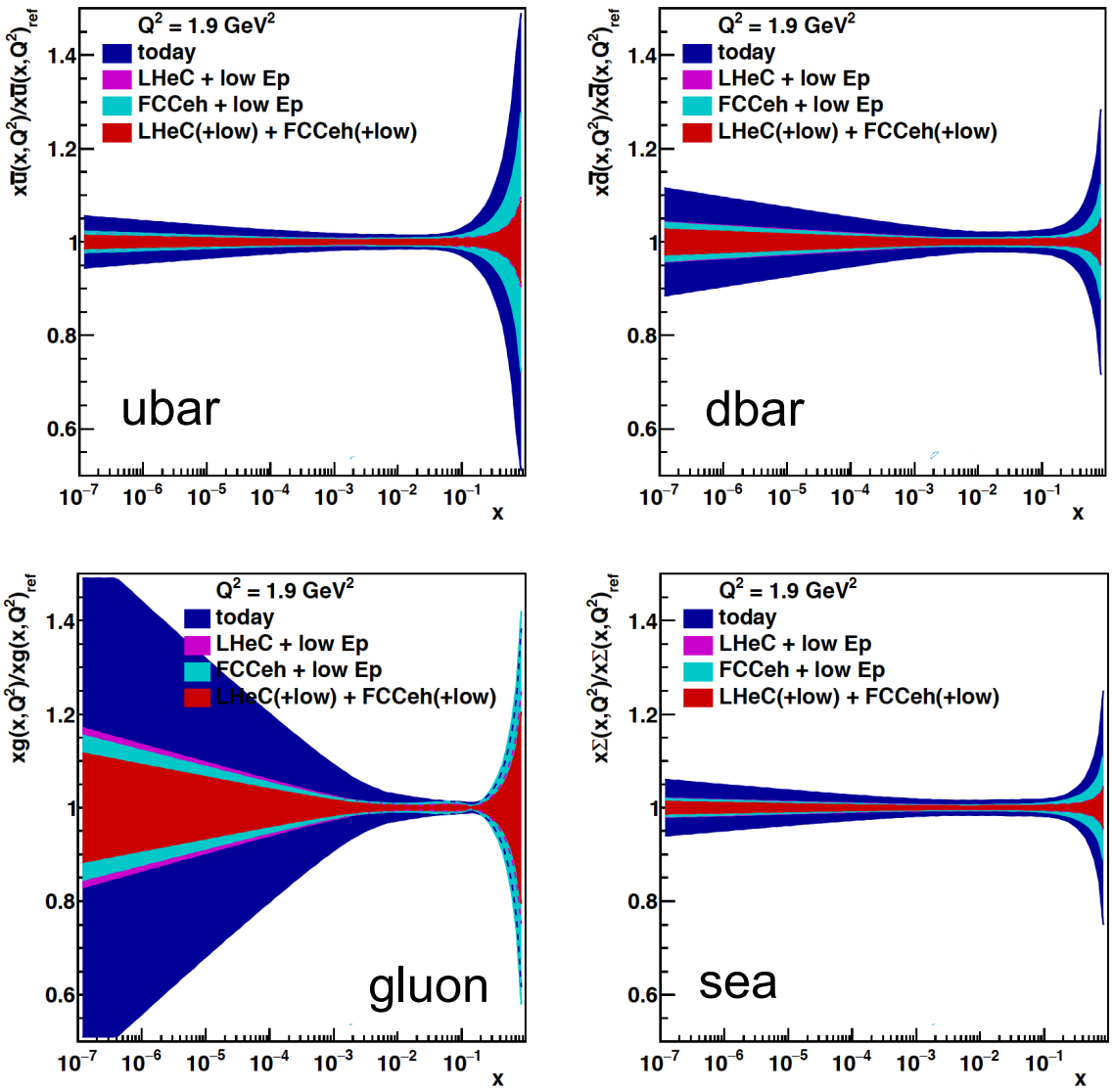
(adding low Ep data has small impact here)

NLO QCD fit, using xFitter
parameterisation details in backups



(V.Radescu)

FCC-eh vs LHeC



(V.Radescu)

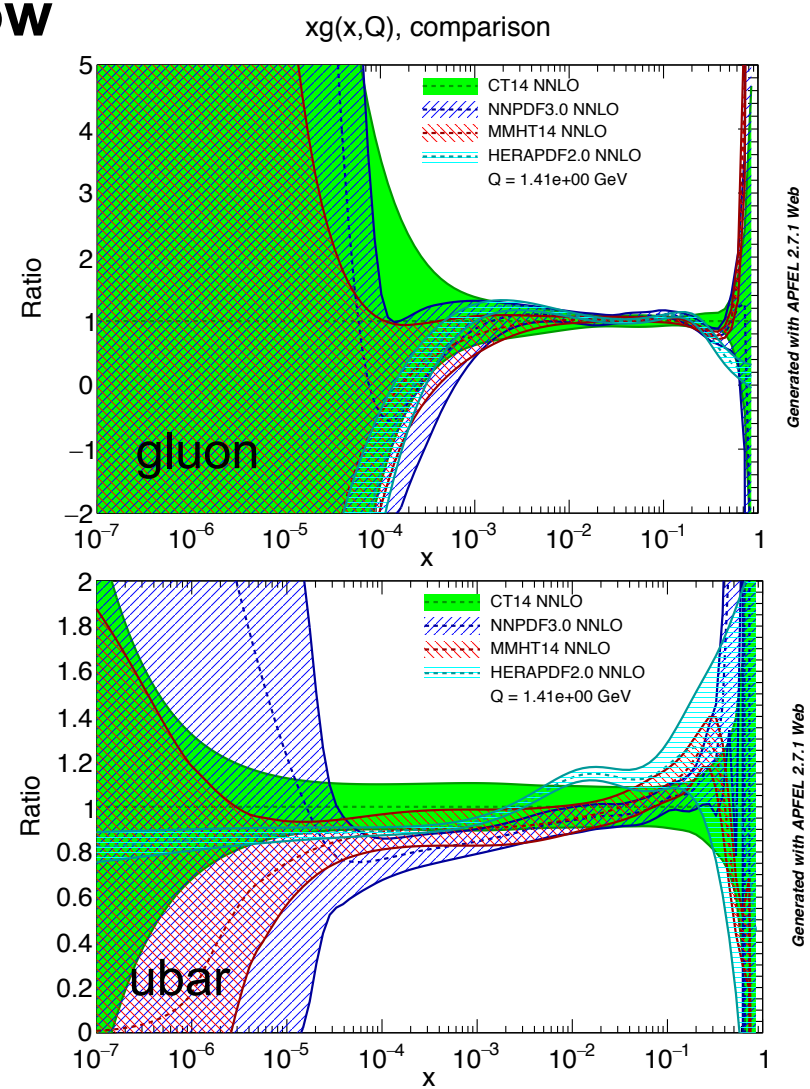
- similar uncertainties at **low x** from **FCC-eh** cf. LHeC
- LHeC: no data below $x=10^{-6}$; need **FCC-eh** to directly constrain
- **combination** beneficial

"today": **same** fit set up

50 data sets from fixed target to colliders using ep, pp, ppbar, and from DIS to jets, DY

versus situation today – low x

now



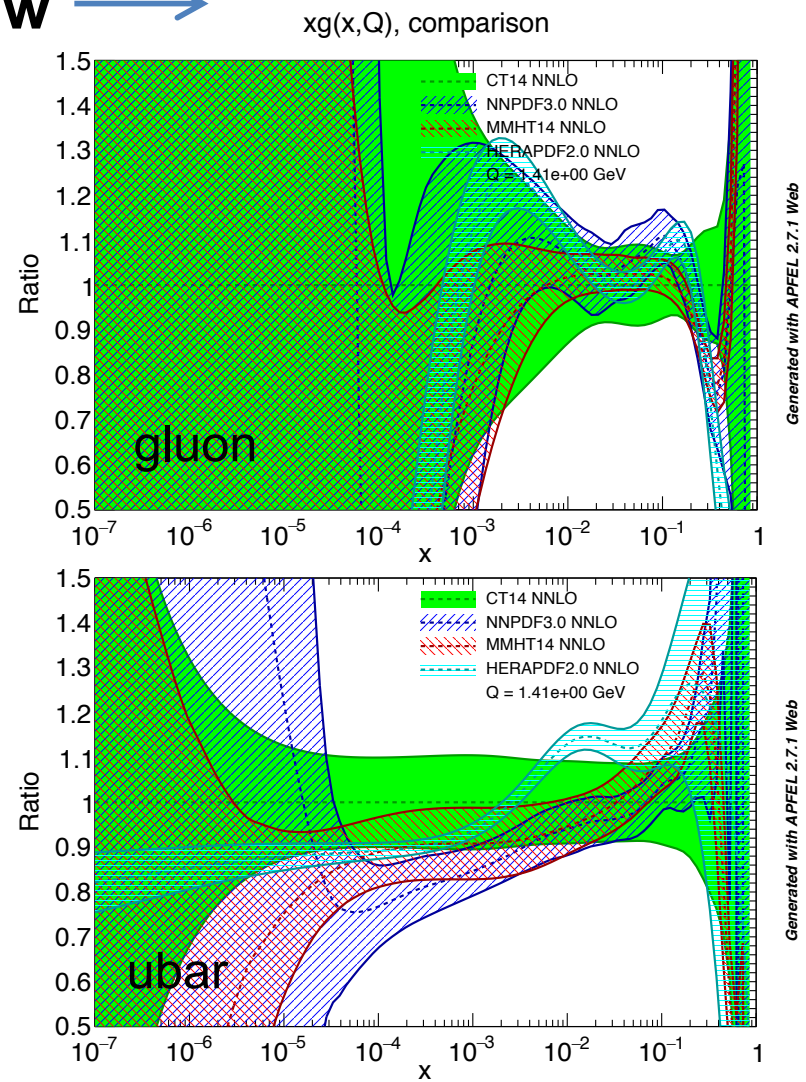
EG. gluon and ubar

and recall – no current data much below $x=10^{-4}$ to directly constrain; even this is an extrapolation for low x

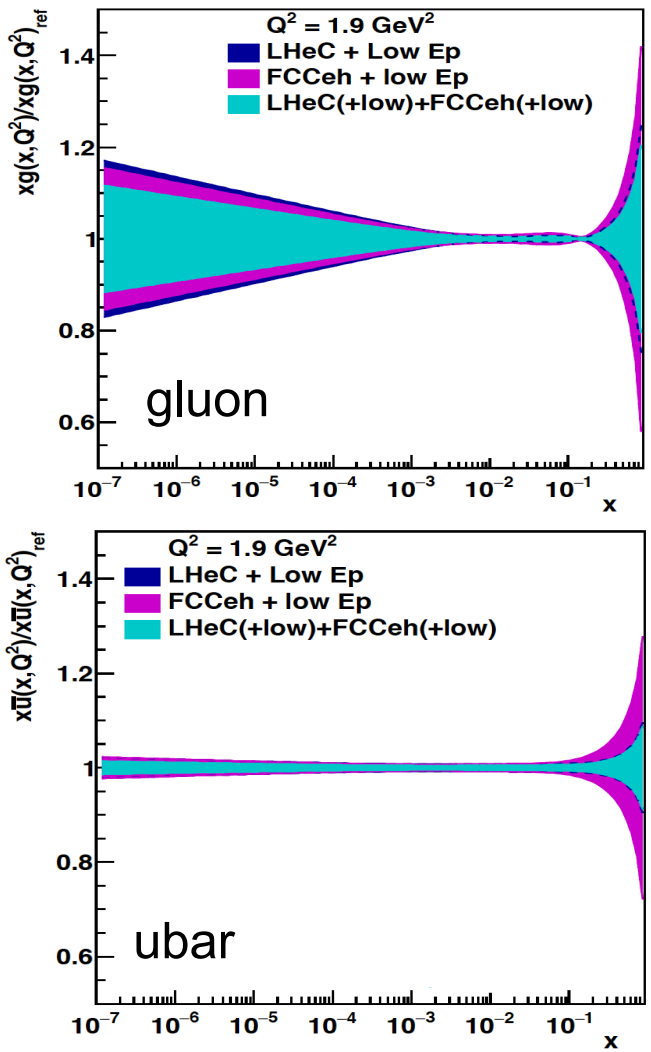
same y-scale

versus situation today – low x

now →



then

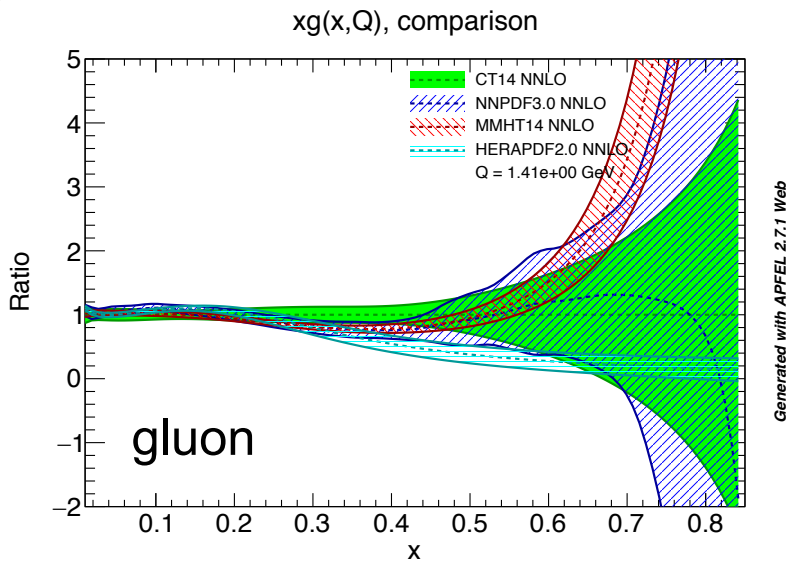


FCC-eh (or LHeC) would provide single, precise and unambiguous dataset

(explore low x QCD, DGLAP vs BFKL, non-linear evolution, gluon saturation; implications also for ultra high energy CR)

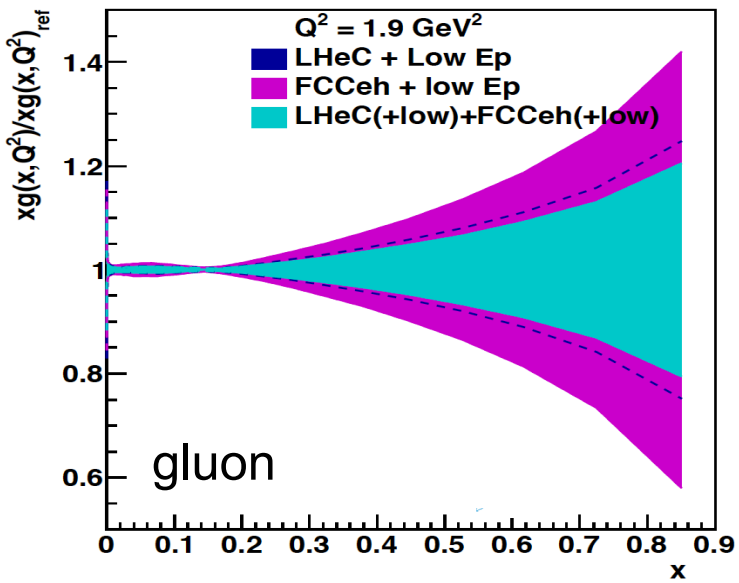
gluon and sea at high x

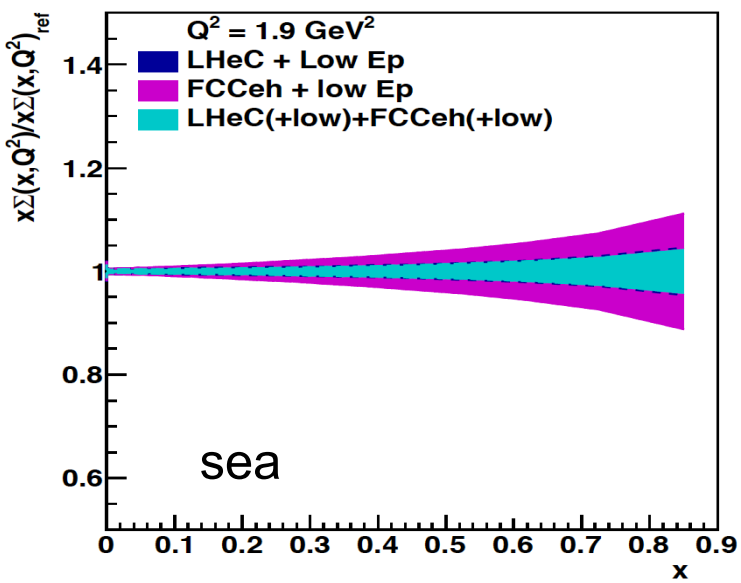
now



- **very strong high x constraints;** **crucial for new physics searches**
- LHeC does better with current simul. conditions:– **FCC-eh** extends to smaller x than LHeC; correspondingly, more difficult at large x

then

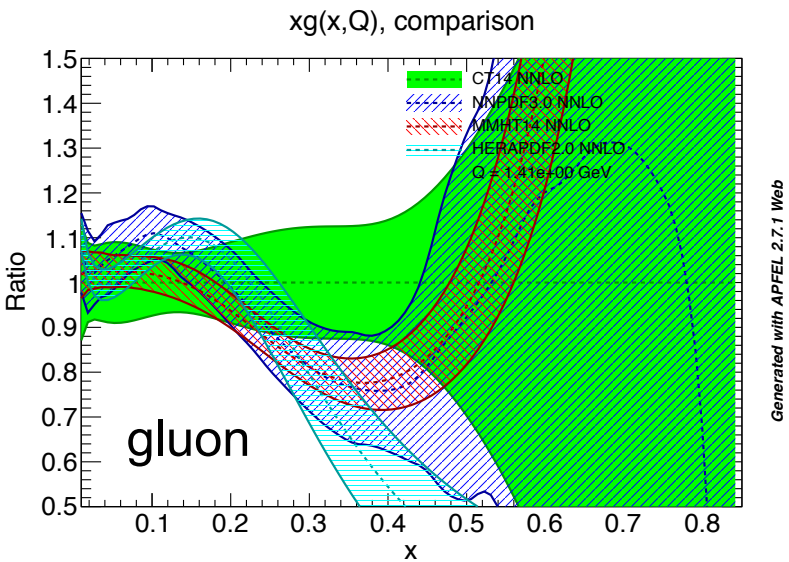




same y-scale

gluon and sea at high x

now



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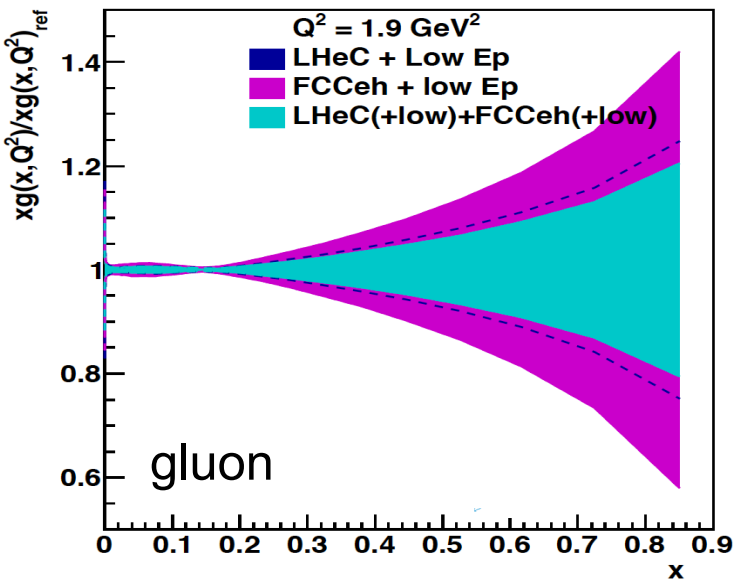
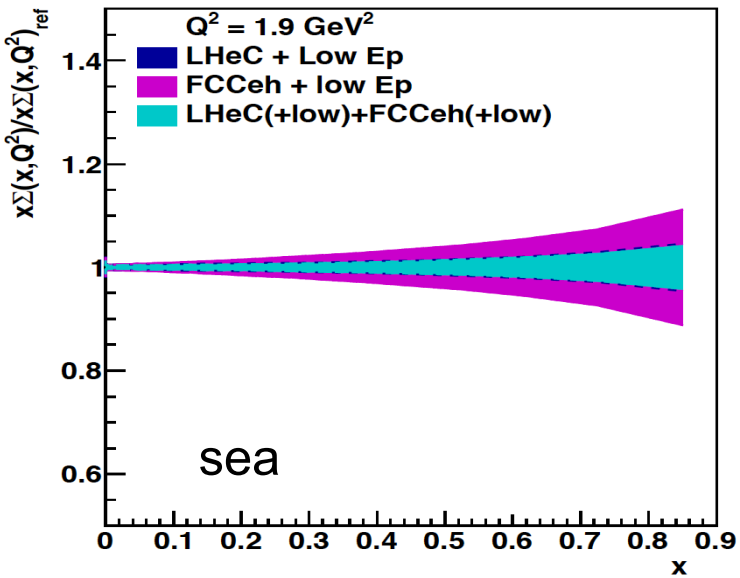


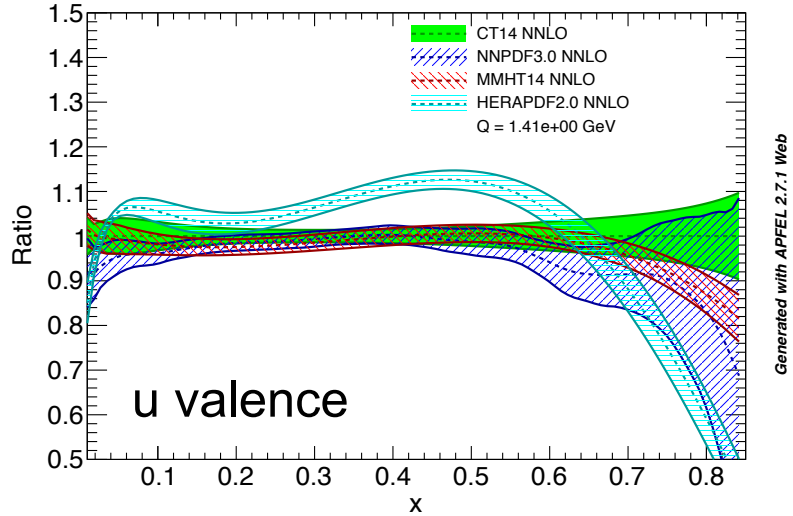


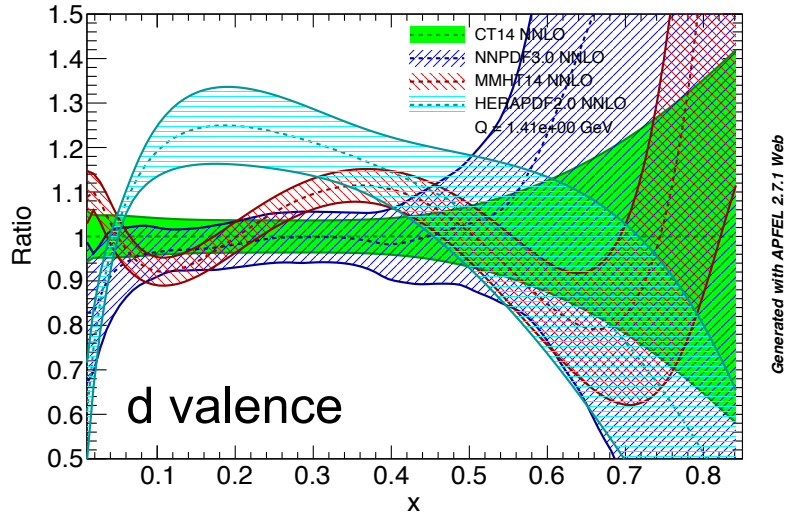
same y-scale

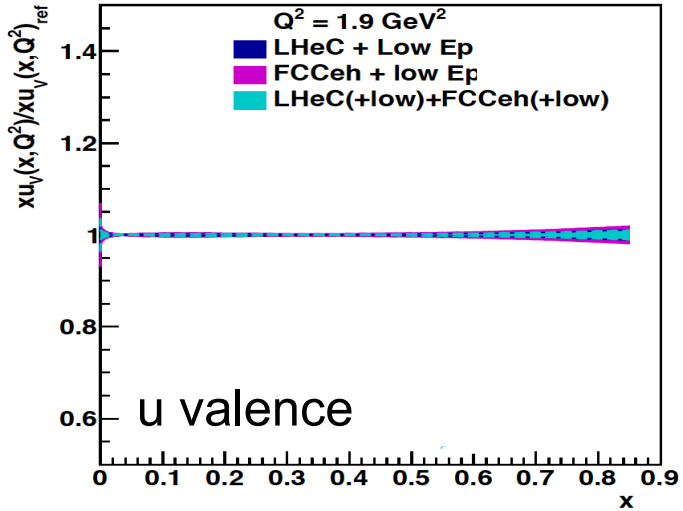
valence quarks

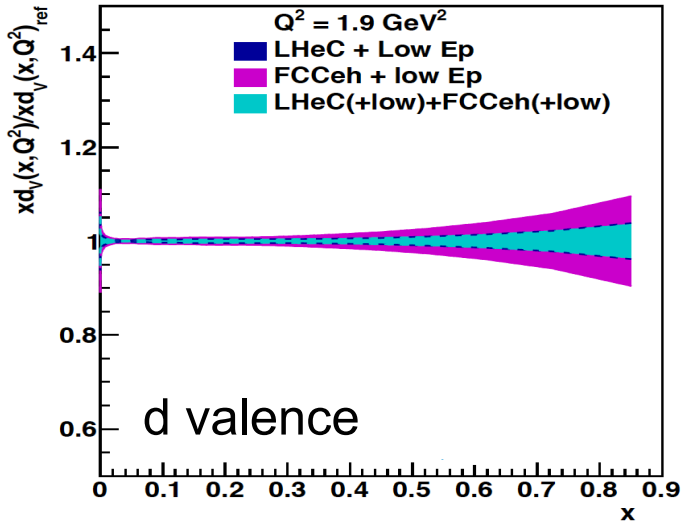
now →

then



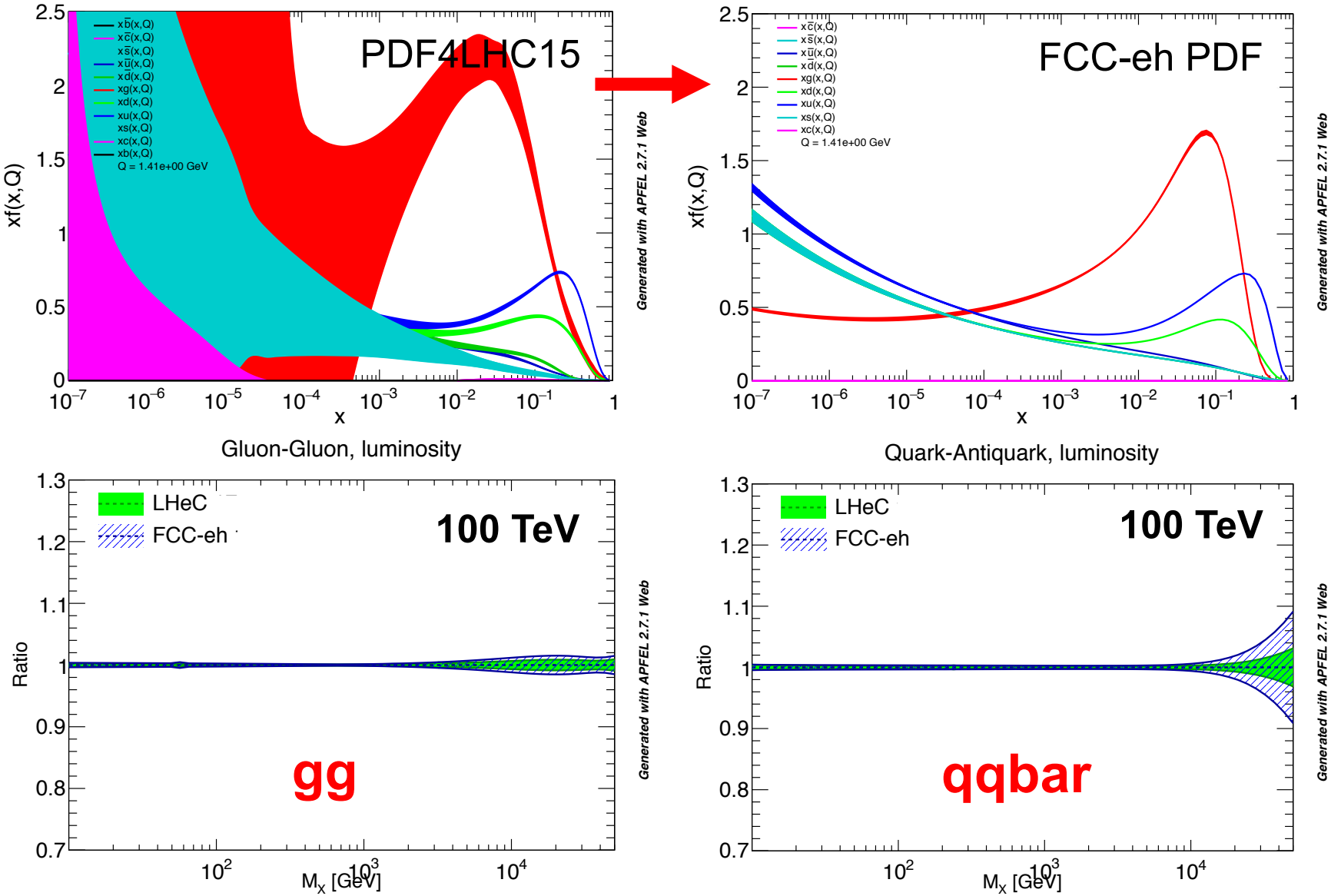






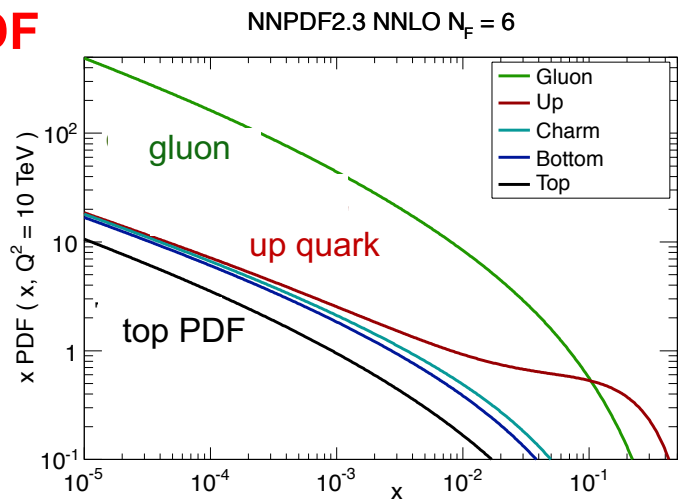
ep: precise determination, free from higher twist corrections and nuclear uncertainties

summary of FCC-eh PDFs

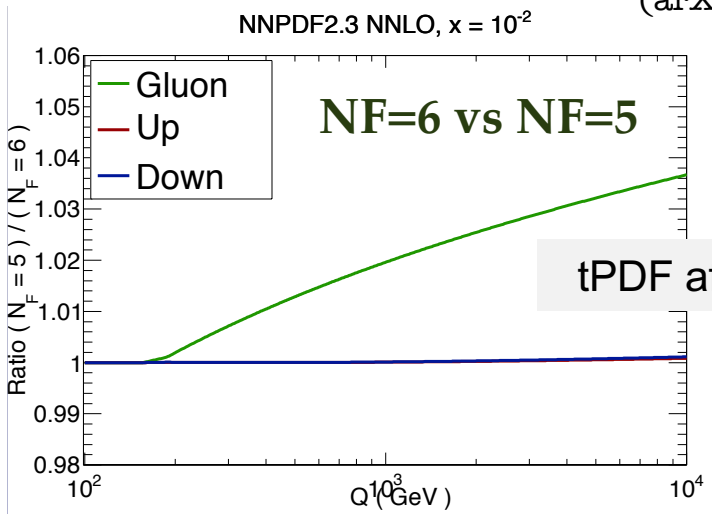


some other considerations

top PDF



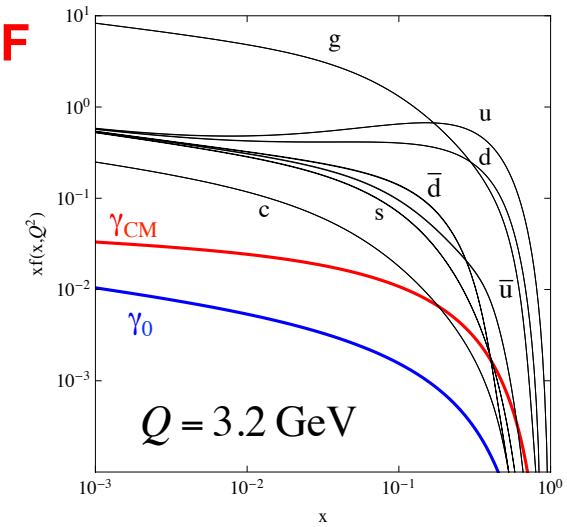
(arXiv:1607.01831)

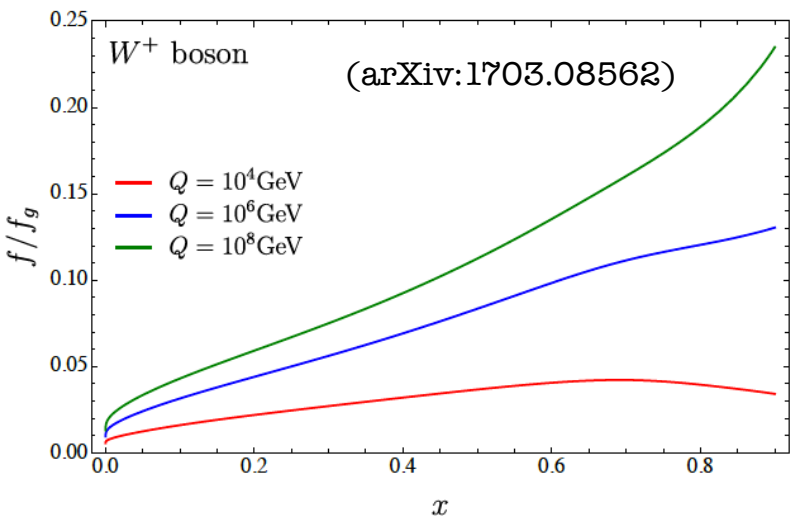


tPDF affects gluon

photon PDF

already visible impact on high scale LHC data



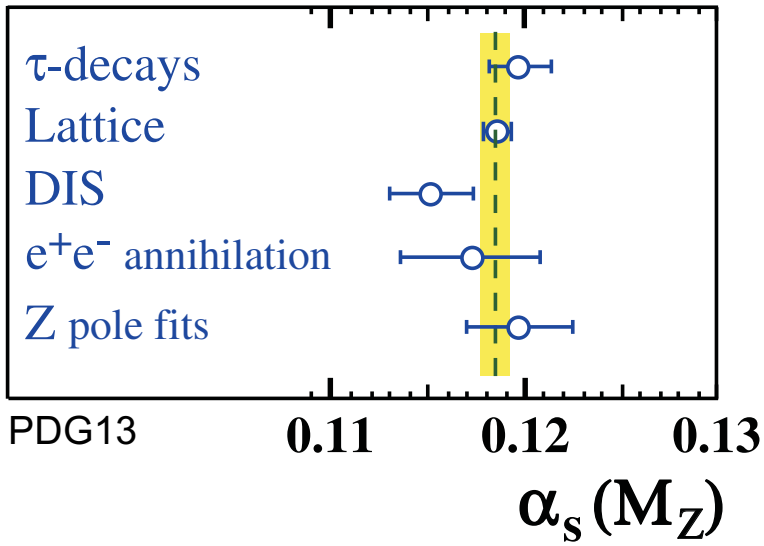


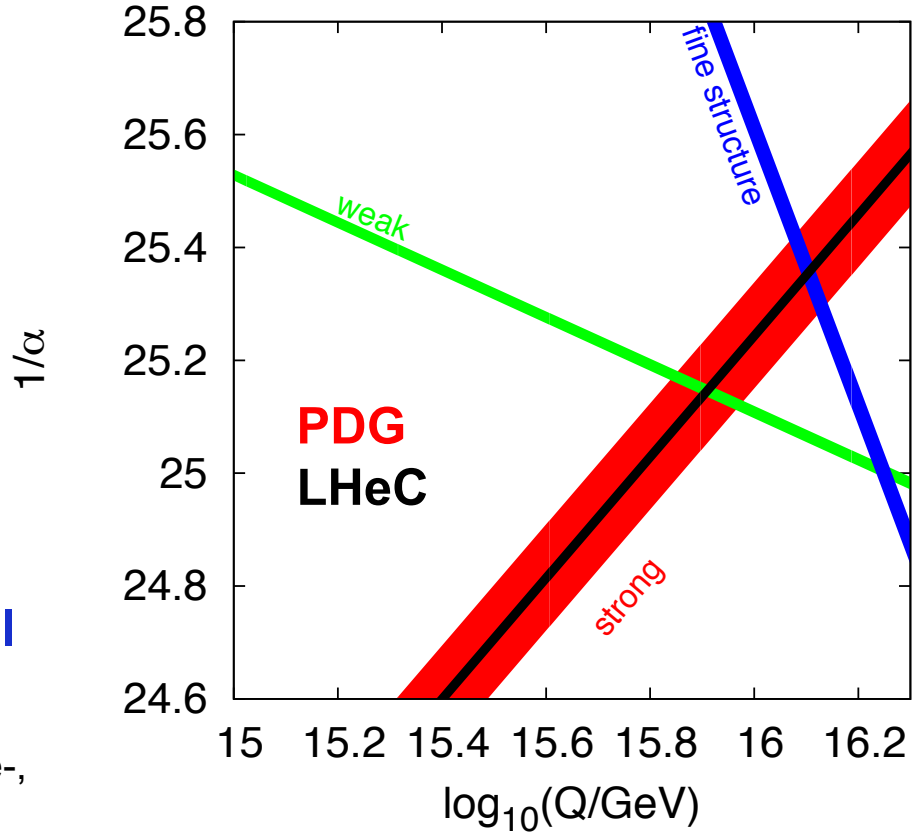
EW PDFs

also start to contribute at FCC

FCC not simply a scaled version of LHC (qualitatively new phenomena introduced)

strong coupling





strong coupling, α_s, is a fundamental parameter, not given by theory

extracted from experimental measurements in e+e-, ep, pp, and from lattice QCD calculations

PDG16 world average: $\alpha_s(M_Z)=0.1181\pm0.0011$

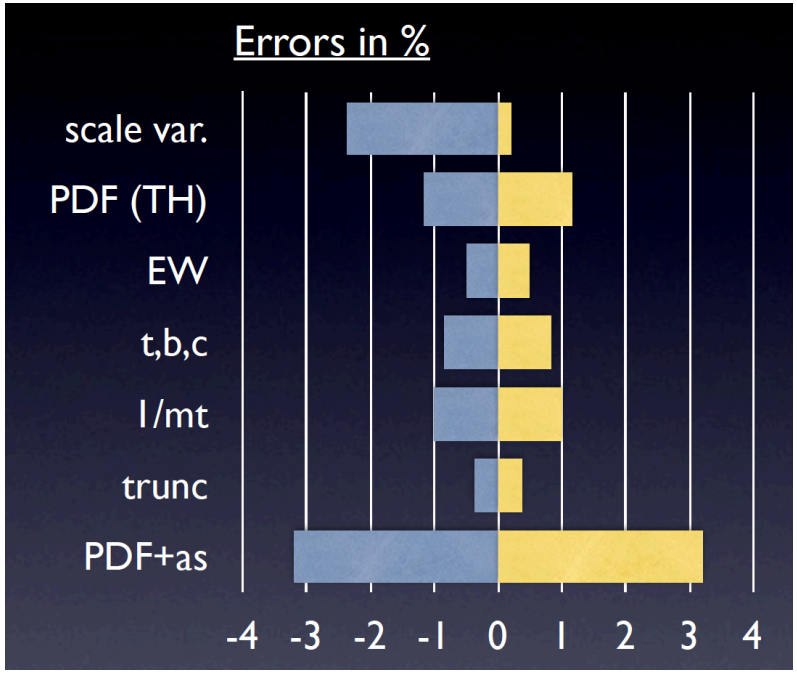
cf. PDG13: $\alpha_s(M_Z)=0.1184\pm0.0006$ with QCD lattice treated less conservatively cf. PDG16

BUT measurements **not all consistent**: what is true central value; true uncertainty; role of lattice calculations; is α_s(DIS) smaller than world average?

α_s is least known of coupling constants

precision α_s needed to constrain GUT scenarios

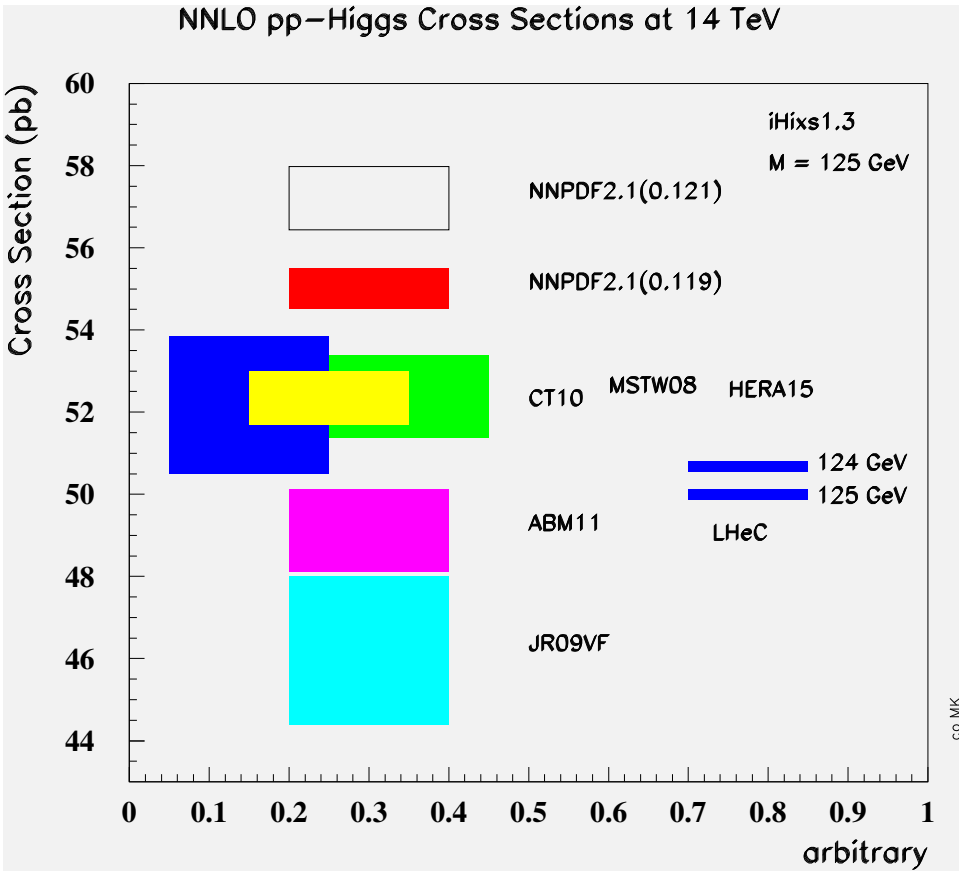
strong coupling, and Higgs



uncertainty on inclusive Higgs production

G. Zanderighi, Moriond, March 2016

(from C. Anastasiou et al., arXiv:1602.00695)

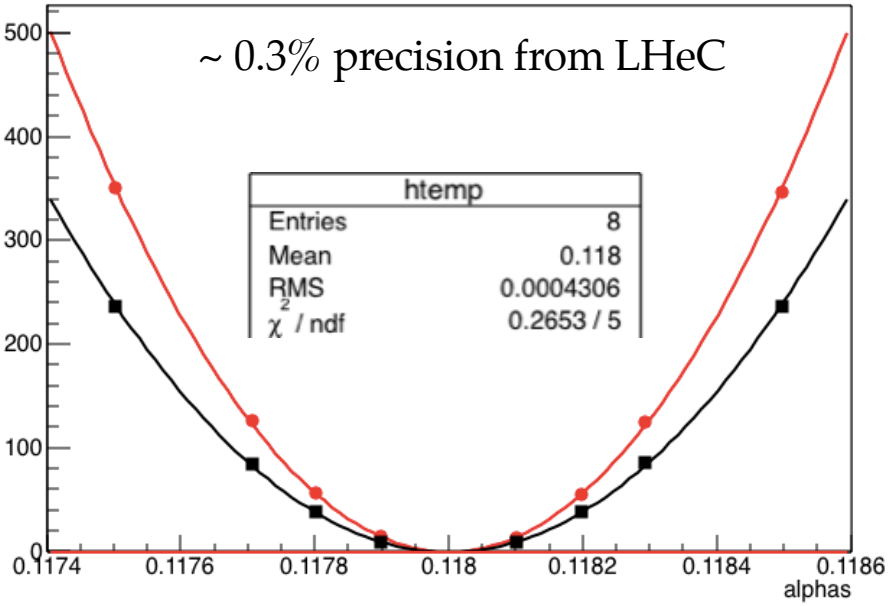


PDF+α_s dominates Higgs cross section uncertainty

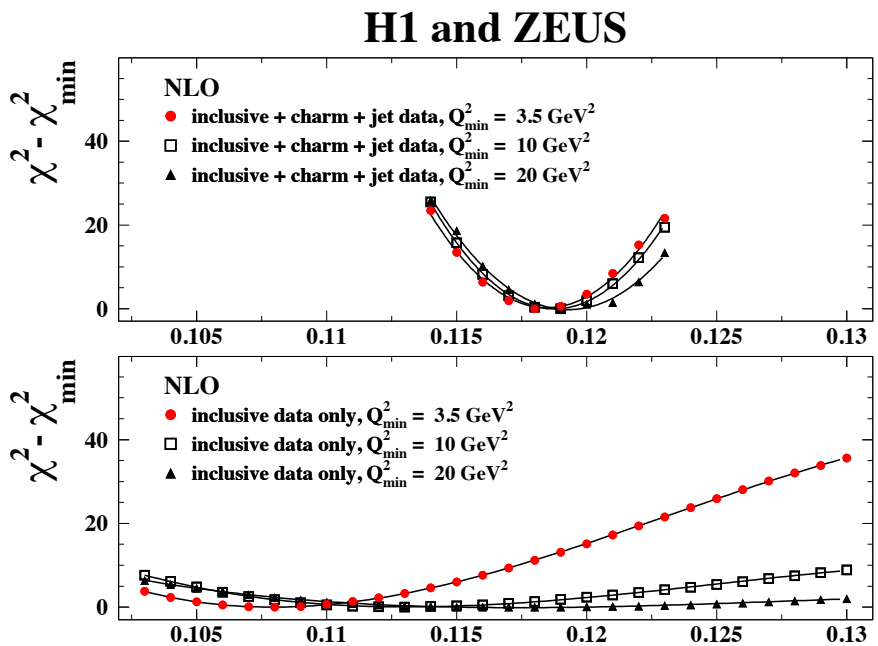
… and of course translates into uncertainty on all hadronic cross sections

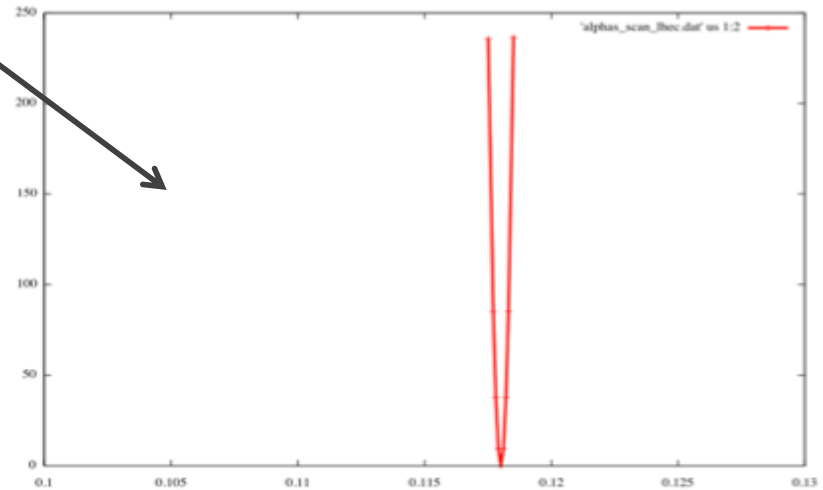
strong coupling from LHeC

PDF+α_s fit using LHeC simulated data



(M Klein, V Radescu)





LHeC could resolve a > 30-year old puzzle:

α_s consistent in inclusive DIS, versus jets?

strong coupling from LHeC

(V Radescu)

case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

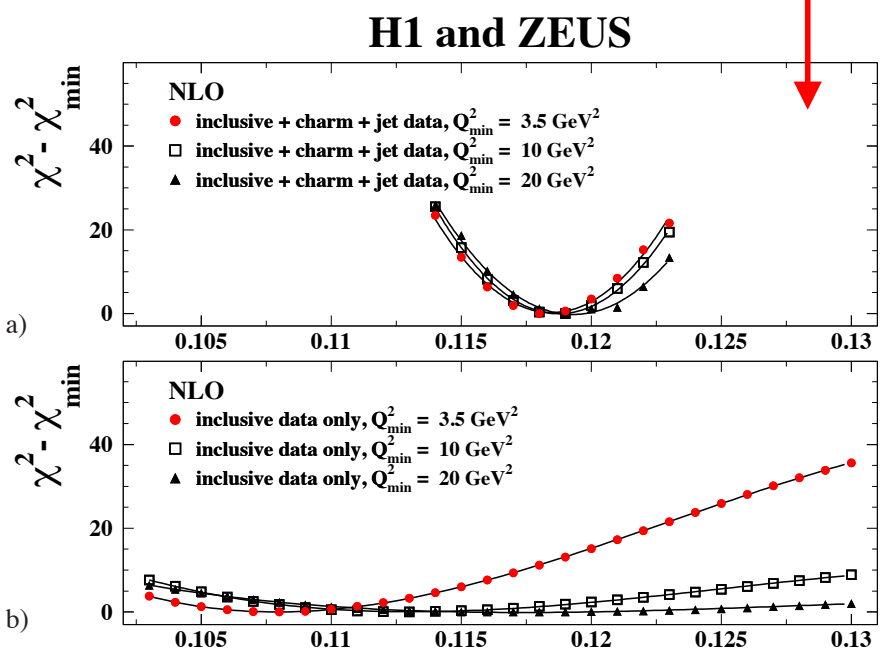
α_s to per mille precision when combined with HERA data

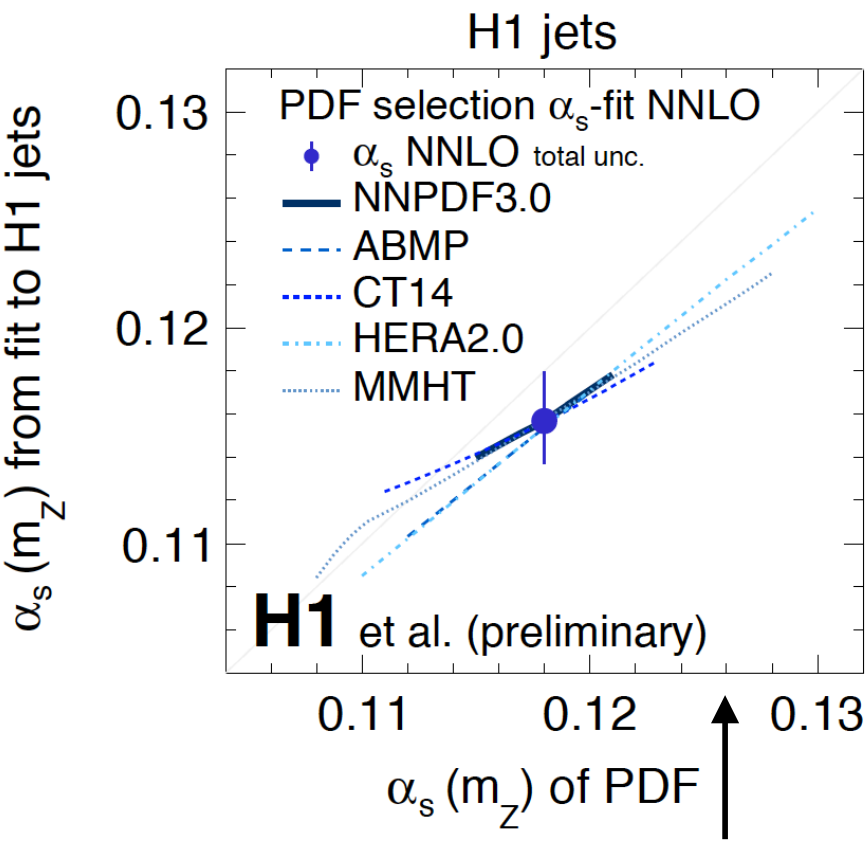
(two independent QCD analyses, using **LHeC+HERA** and **LHeC+BCDMS** (T Kluge))

strong coupling from jet data in ep

ep jet data can provide additional constraints

cf. inclusive DIS data alone



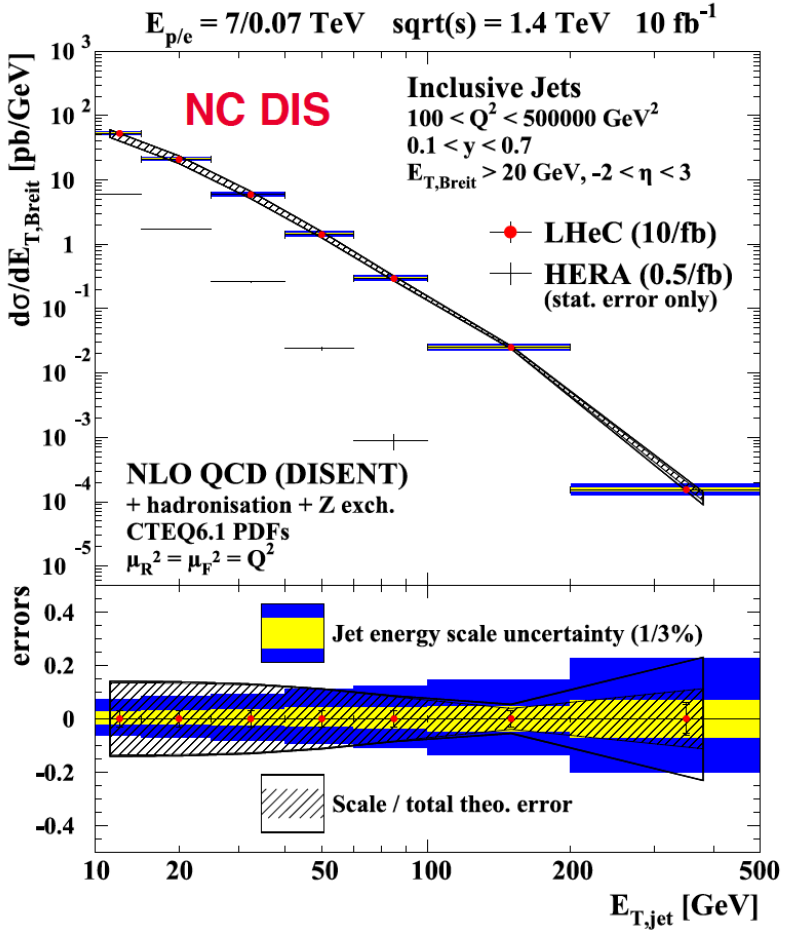


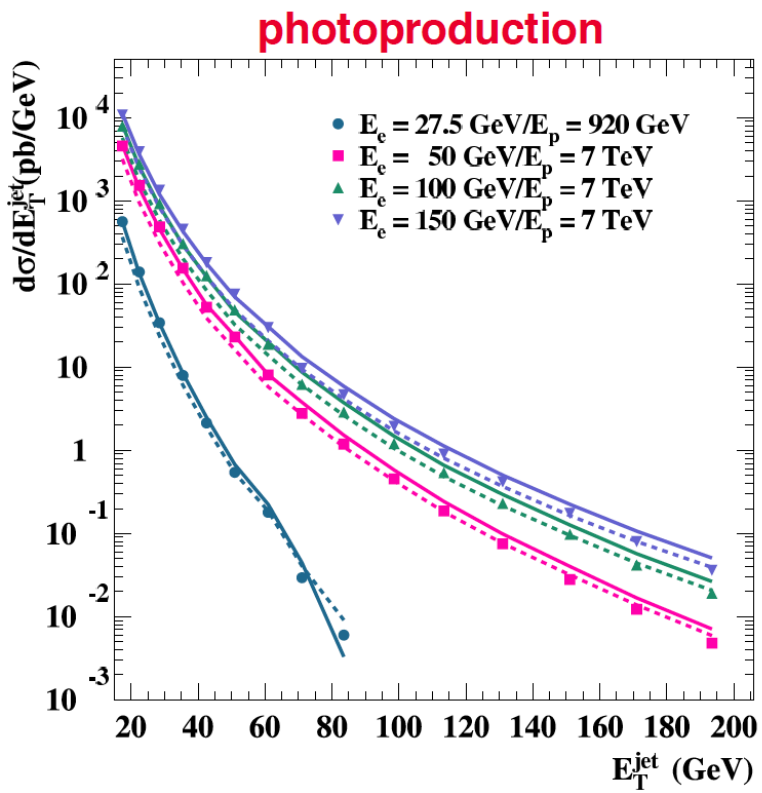
NNLO fit now also possible

EG. new H1 et al. preliminary result (H1prelim-17-031; see talk by D. Britzger, this conference)

strong coupling from LHeC and FCC-he simulated **DIS jet data** to come…

LHeC jet data





(plots from LHeC CDR – illustrative)

impact of **LHeC jet data** on α_s (and PDFs) expected to be substantial

summary of α_s uncertainties

(Snowmass13 report, arXiv:1310.5189)

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim$ 1% (LEP) thry $\sim$ 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.)
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, $\sim$ 10 yrs)
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, $\sim$ 10 yrs)
ep colliders	$\sim$ 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)
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])
lattice	$\sim$ 0.5% (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim$ 0.3% ($\sim$ 5 yrs [38])

per mille

per mille

α_s from LHeC (and FCC-he) stands in own right as a highest precision result,
not just complementary to other colliders

* TLEP = old name for FCC-ee

summary

- **improved understanding of proton structure crucial for LHC, and** even more so for **future hadron colliders**

- **FCC** will probe unexplored regions of ultra-low x and very high Q^2, where **proton PDFs poorly known and unconstrained**
- **FCC-eh** proposed as ep option to run **synchronously** with FCC
- studies show dramatic improvement of PDFs from FCC-eh
- similar level of PDF precision as **LHeC** (FCC-eh extends to **lower x**; LHeC simulations show some additional constraint at high x)

- **α_s, fundamental param., limits precision on important processes**
- per mille precision possible (LHeC; FCC-eh studies underway)

- **several results shown here are hot off the press – further WORK IN PROGRESS:** further examine simulation assumptions; relax QCD fit assumptions; inclusion of jet, heavy flavour (PDFs, α_s); nuclear PDFs; …

extras

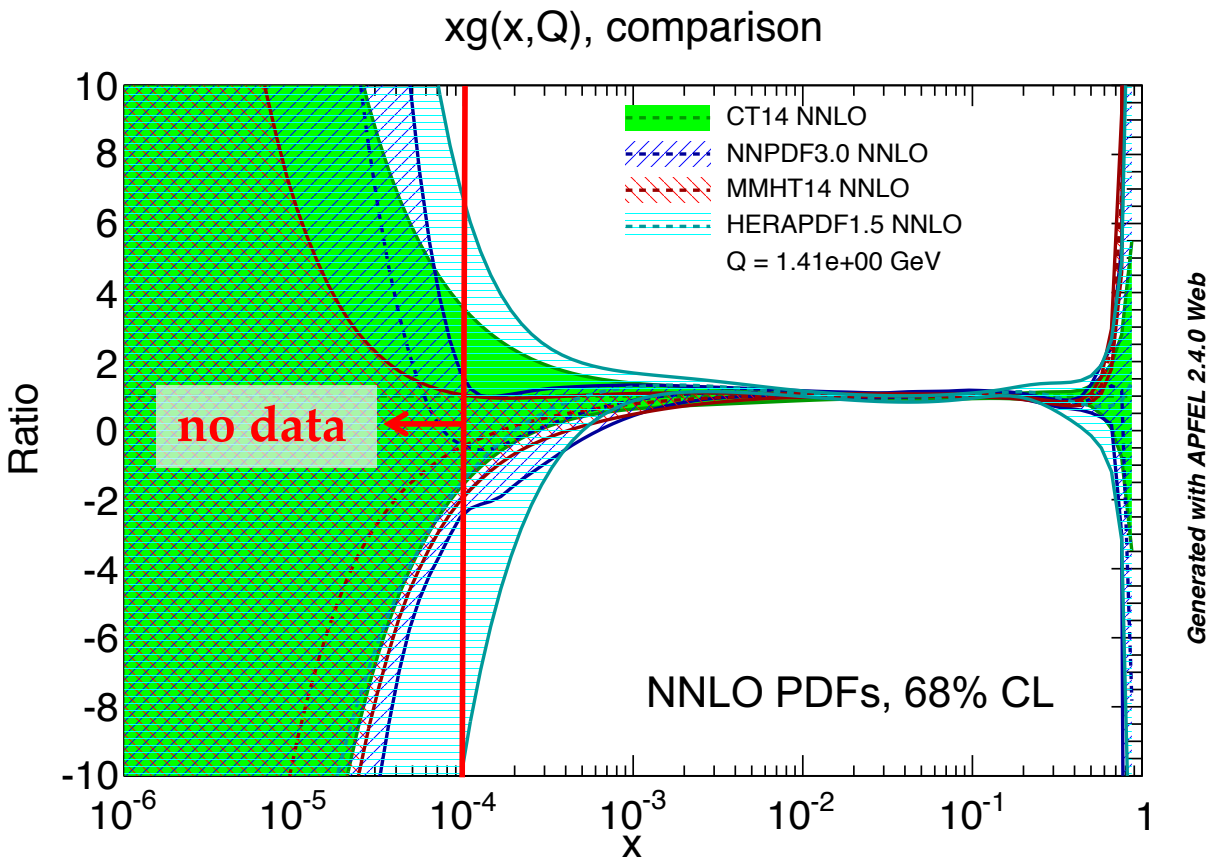
FCC – x regions probed

(arXiv:1607.01831)

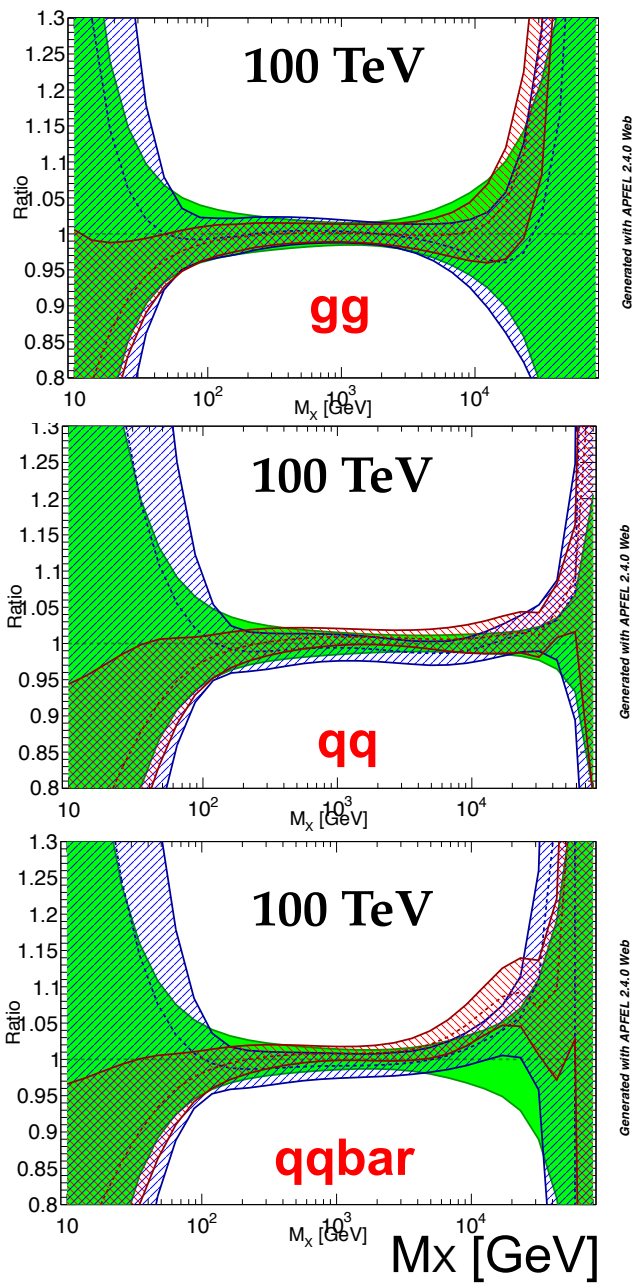
Process	M_X	$x_{\min}$		
		$y = 0$	$\lvert y\rvert = 2$	$\lvert y\rvert = 4$
Soft QCD Charm pair production Low-mass Drell-Yan	1 (10) GeV	10^{-5} (10^{-4})	$1.4 \cdot 10^{-6}$ $(1.4 \cdot 10^{-5})$	$1.8 \cdot 10^{-7}$ $(1.8 \cdot 10^{-6})$
W and Z production Top pair production Inclusive Higgs	80 (400) GeV	$8 \cdot 10^{-4}$ $(4 \cdot 10^{-3})$	$1.1 \cdot 10^{-4}$ $(5.4 \cdot 10^{-4})$	$1.5 \cdot 10^{-5}$ $(7.3 \cdot 10^{-5})$
Heavy New Physics	5 (25) TeV	0.05 (0.25)	0.007 (-)	–

Table 1: Kinematical coverage in the (x, M_X) plane for representative processes at a 100 TeV hadron collider. For each type of process (low mass, electroweak scale processes, and heavy new physics) we indicate the relevant range for the final-state invariant mass M_X and the approximate minimum value of x probed in the PDFs, $x_{\min} = (M_X/\sqrt{s})\exp(-|y|)$, for central ($y = 0$), intermediate ($|y| = 2$) and forward ($|y| = 4$) rapidities.

PDFs today



PDF luminosities



low-x: no current data to constrain $x \leq 10^{-4}$

rely purely on extrapolation

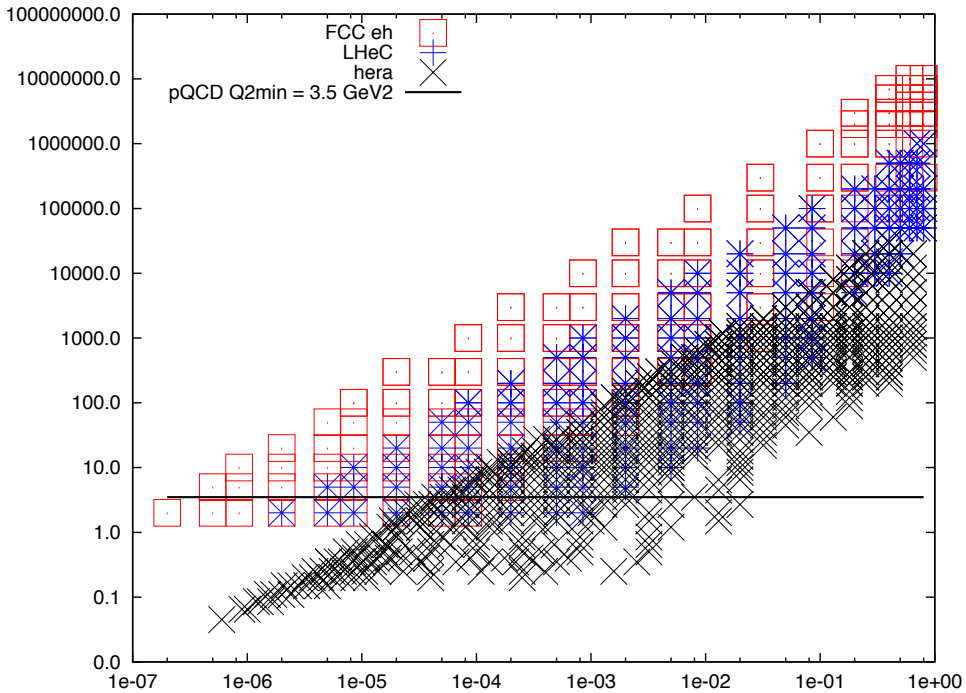
also, we don't know when DGLAP breaks down

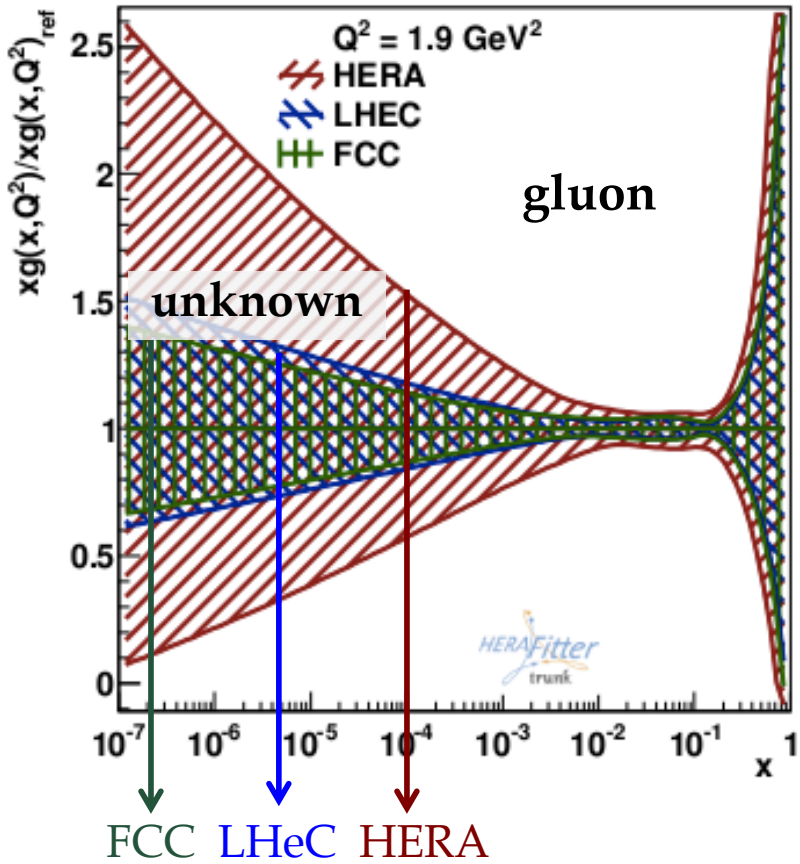
Higgs is at small x at $\sqrt{s}$=100TeV!

high-x: crucial for new physics searches

FCC-eh vs LHeC vs HERA

previous simulation





FCC-eh: E_p=50 TeV, E_e=100 GeV

NC and CC: e-p, P=80%, $\mathcal{L}$=1000 fb^{-1}

stat: 0.1–30%, uncorr: 0.7%, syst: 1–5%

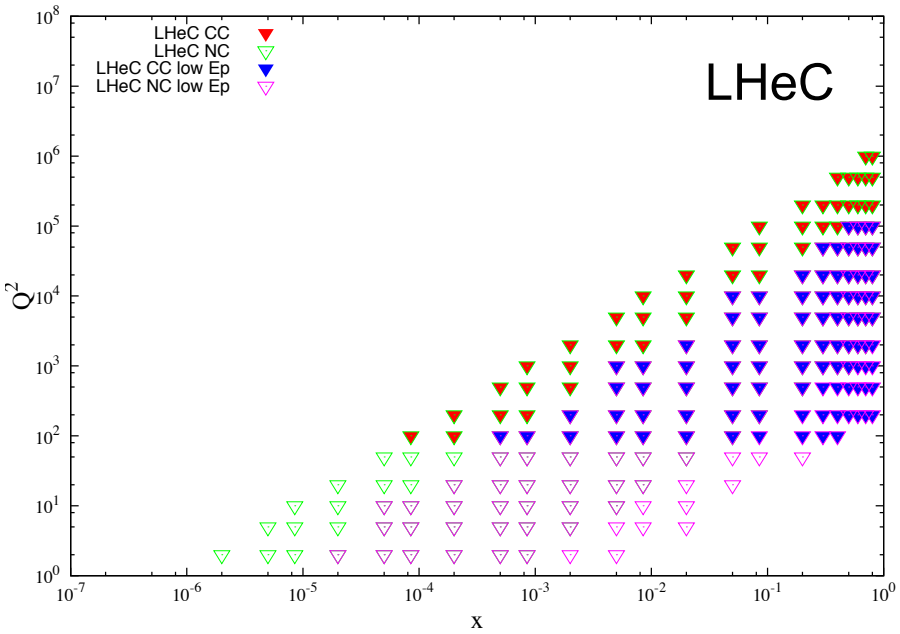
coverage down to x=2×10^{-7}, up to Q^2 = 10^7 GeV^2

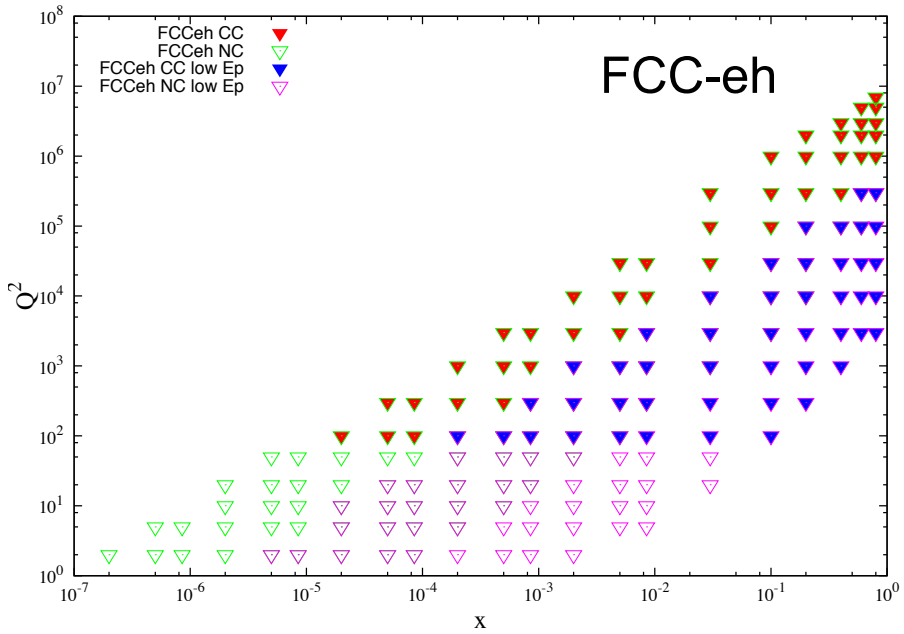
need FCC to constrain much below x=10^{-5}

FCC-he can further improve on LHeC, and explore low-x phenomenology

FCC-eh vs LHeC kinematic coverage

new simulated **inclusive NC** and **CC DIS data** for latest running scenarios



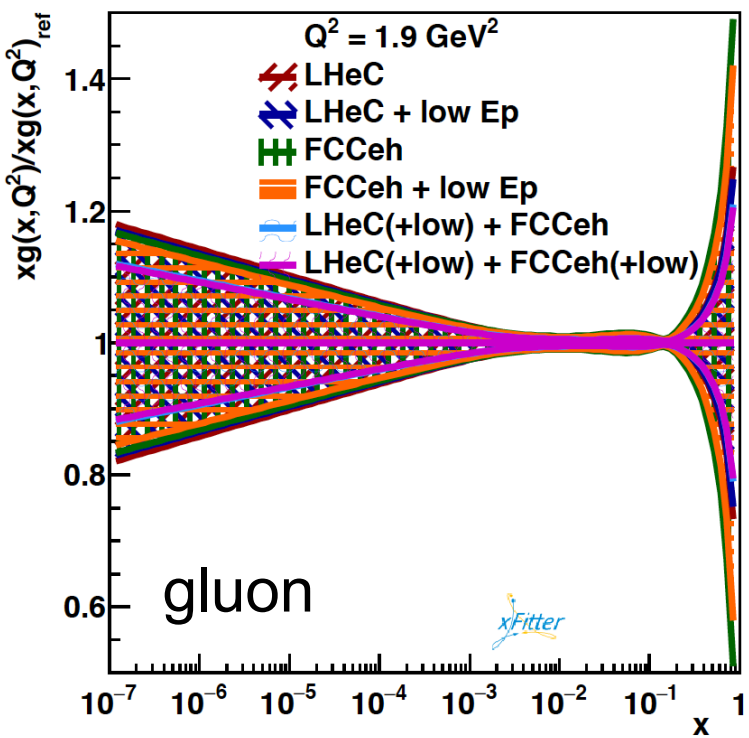


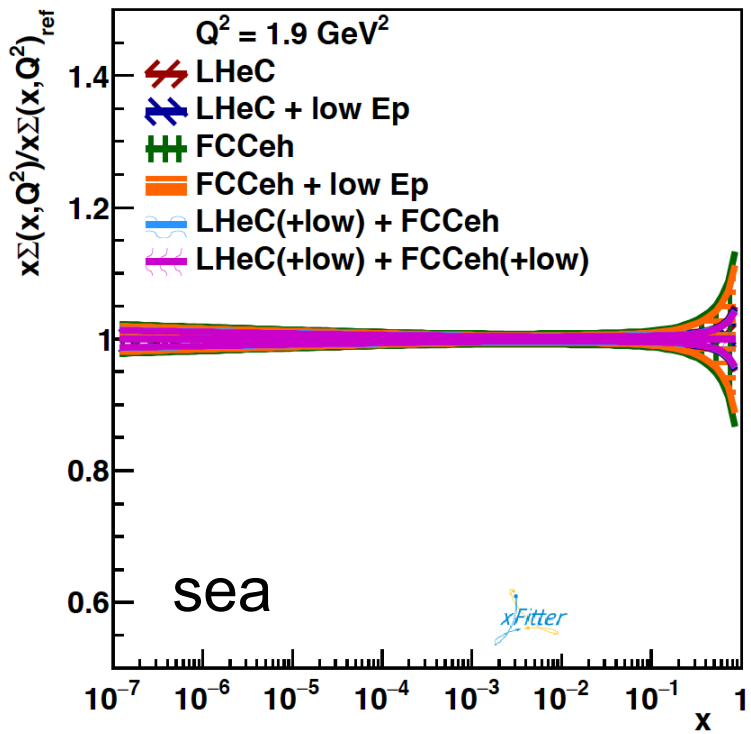
QCD fit parameterisation

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

FCC-eh vs LHeC

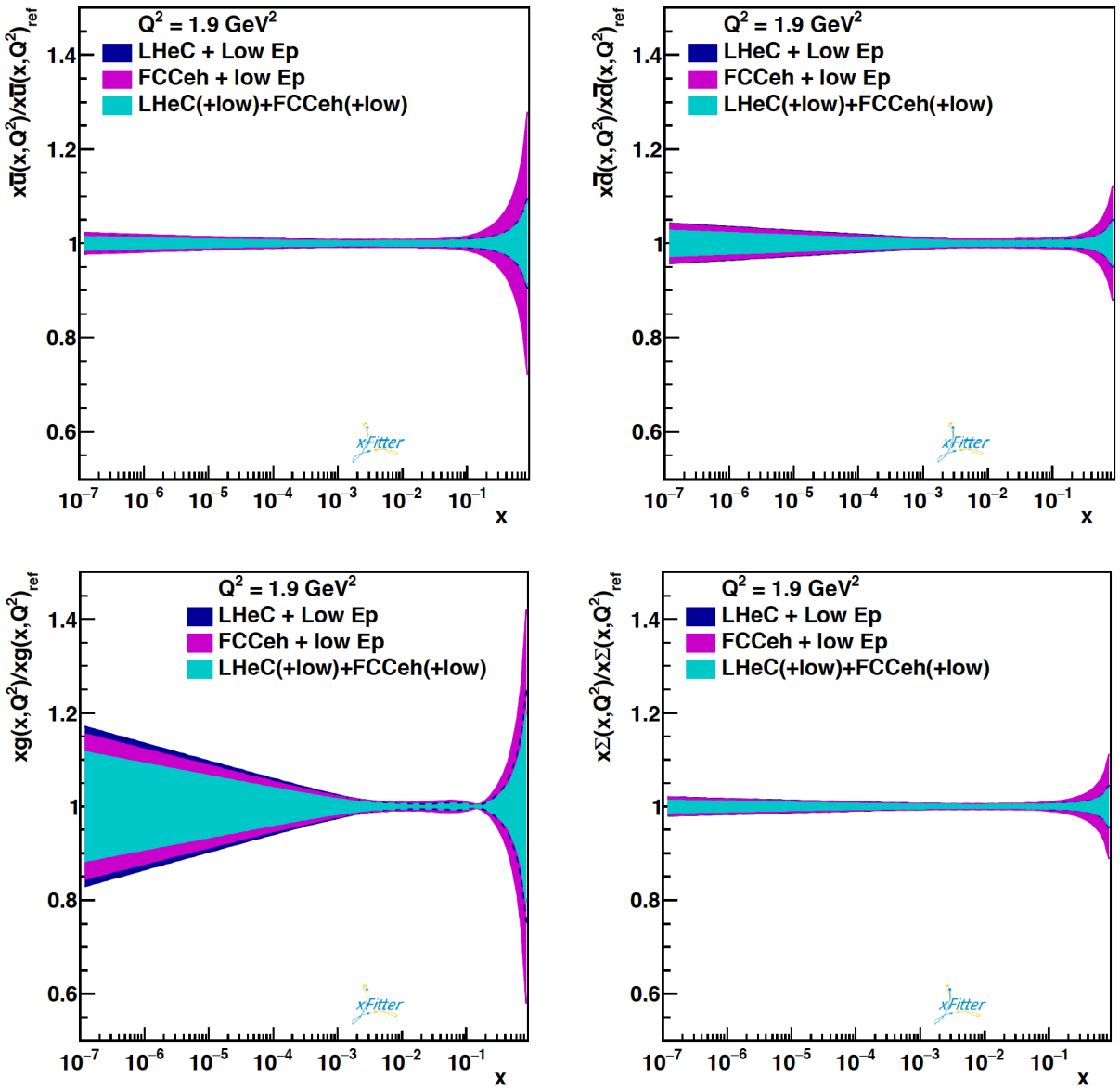
impact with and without low energy data shown separately





(V.Radescu)

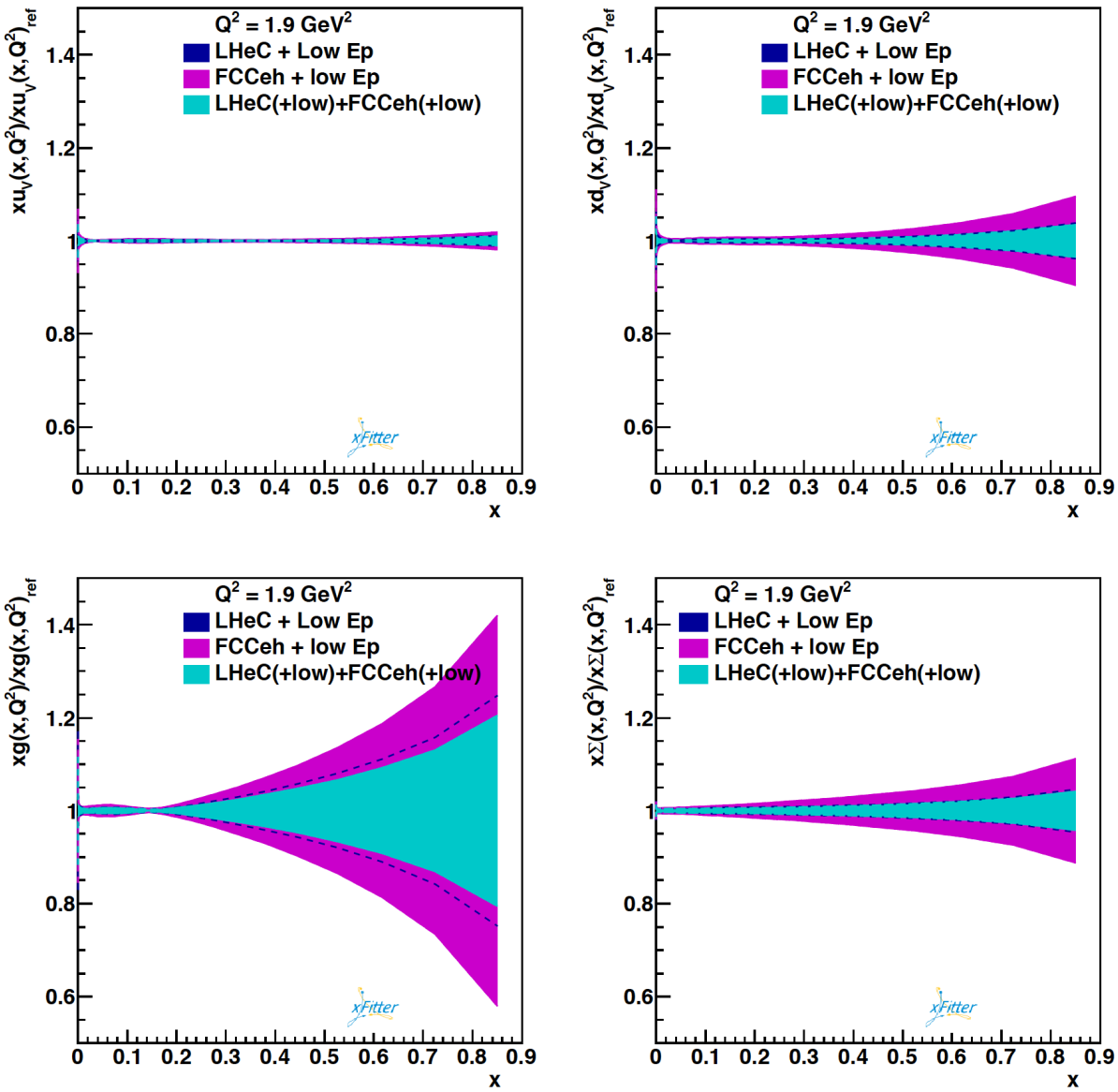
low x PDFs



- similar uncertainties at **low x** from **FCC-eh** cf. LHeC
- LHeC: no data below $x=10^{-6}$; need **FCC-eh** to directly constrain
- **combination** beneficial

(V.Radescu)

high x PDFs



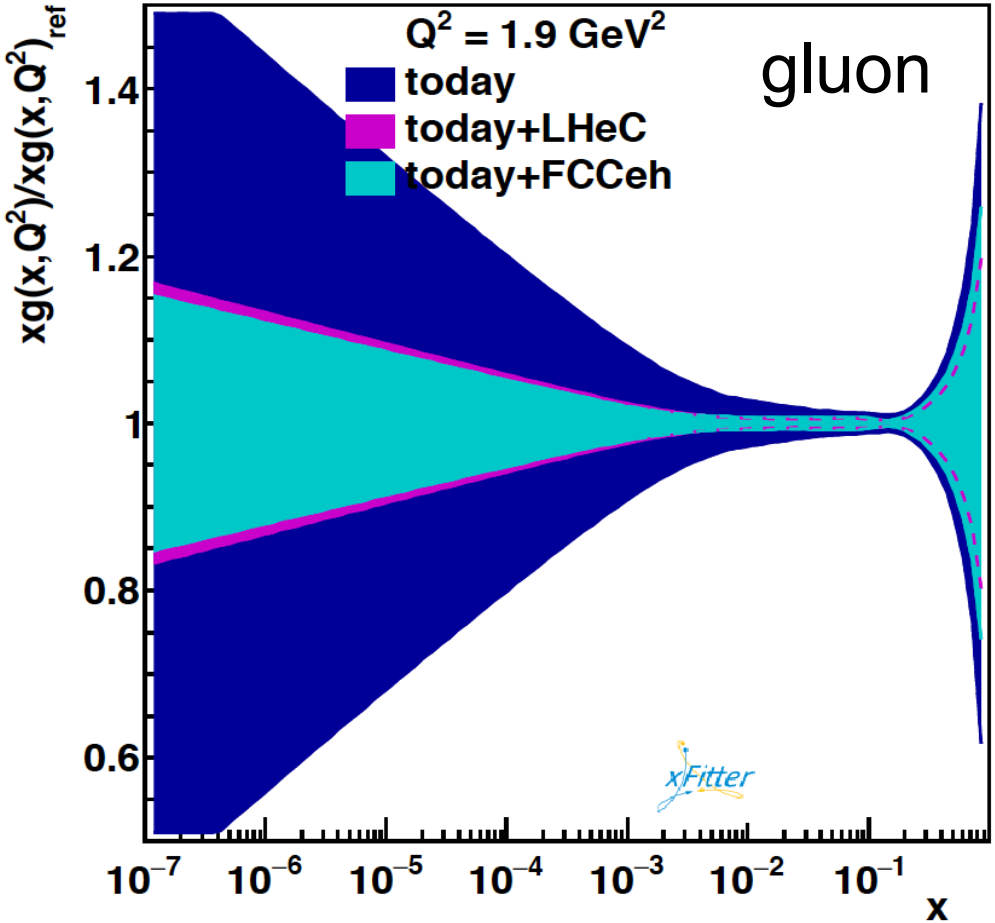
- **very strong high x constraints**
- LHeC does better with current simulation conditions:– **FCC-eh** extends to smaller x than LHeC; correspondingly, more difficult at large x

(V.Radescu)

vs same fit with world data

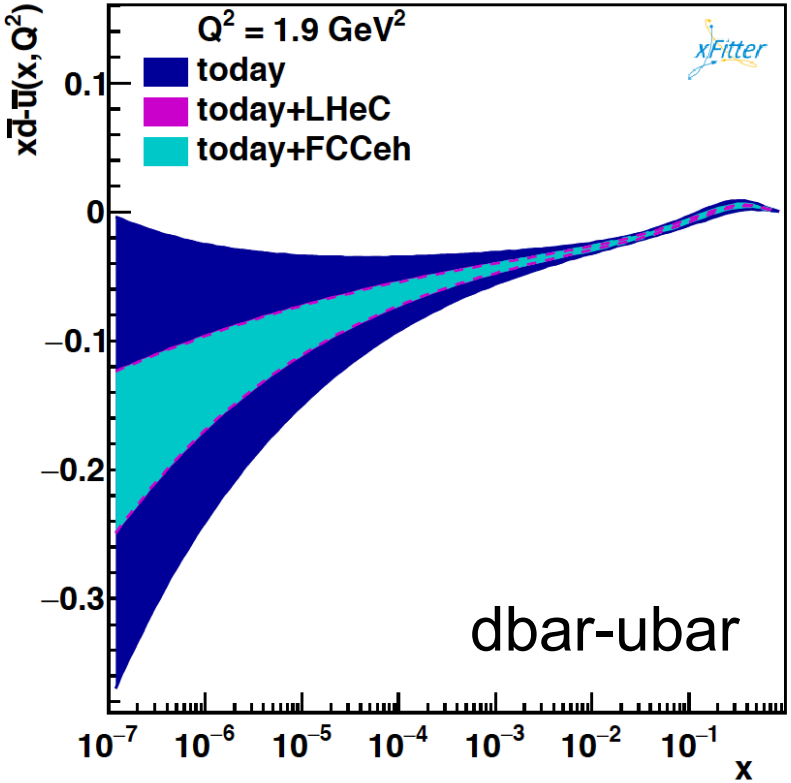
(V.Radescu)

ATLAS Jet data 0 ≤ |y| < 0.3 R=0.6
ATLAS Jet data 0.3 ≤ |y| < 0.8 R=0.6
ATLAS Jet data 0.8 ≤ |y| < 1.2 R=0.6
ATLAS Jet data 1.2 ≤ |y| < 2.1 R=0.6
ATLAS Jet data 2.1 ≤ |y| < 2.8 R=0.6
ATLAS Jet data 2.8 ≤ |y| < 3.6 R=0.6
ATLAS Jet data 3.6 ≤ |y| < 4.4 R=0.6
ZEUS inclusive jet 98-00 data
ZEUS inclusive dijet 98-00/04-07 data
H1 inclusive jet 99-00 data
H1 low Q2 inclusive jet 99-00 data
ZEUS inclusive jet 96-97 data
CDF inclusive jets
CDF Z rapidity 2010
D0 pp jets
D0 Z rapidity 2007
D0 W asymmetry 2013
D0 W→mu nu lepton asymmetry ptl > 35 GeV
CDF W asymmetry 2009
BCDMS F2p 100GeV
ATLAS high mass DY mass 2011
BCDMS F2p 200GeV
BCDMS F2p 280GeV
HERA1+2 CCep
HERA1+2 CCem
HERA1+2 NCem
HERA1+2 NCep 820
HERA1+2 NCep 920
HERA1+2 NCep 460
HERA1+2 NCep 575
ATLAS low mass DY 2011
ATLAS DY mass 2010 extended data
CMS inclusive jets 2011
CMS Norm. differential ttbar vs pt 7 TeV
ATLAS Norm. differential ttbar vs pT 7 TeV
CMS total ttbar 7TeV mt=173.3 GeV
ATLAS total ttbar 7TeV mt=173.3 GeV
CMS electon Asymmetry rapidity
CMS Boson rapidity
CMS W muon asymmetry
H1 normalised inclusive jets with unfolding
H1 normalised dijets with unfolding
H1 normalised trijets with unfolding
ATLAS low mass Z rapidity 2011
ATLAS peak CC Z rapidity 2011
ATLAS peak CF Z rapidity 2011
ATLAS high mass CC Z rapidity 2011
ATLAS high mass CF Z rapidity 2011
ATLAS W- lepton rapidity 2011
ATLAS W+ lepton rapidity 2011

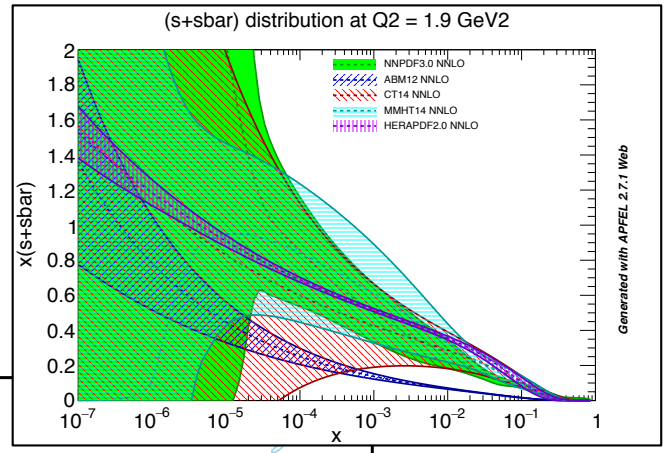


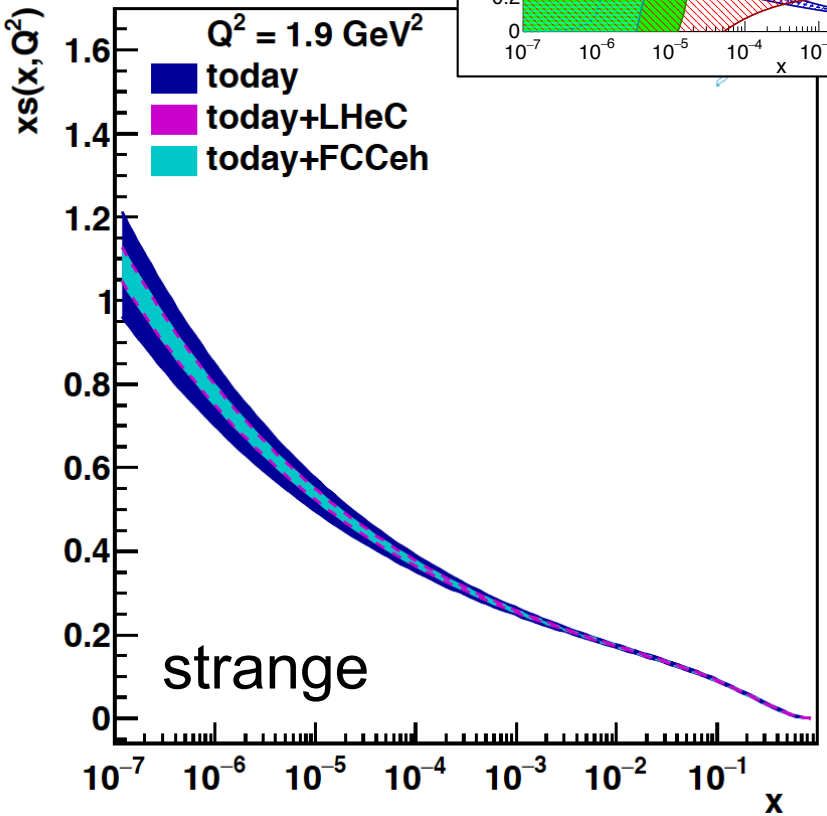
"today": 50 data sets from fixed target to colliders using ep, pp, ppbar, and from DIS to jets, Drell-Yan (same fit setup)

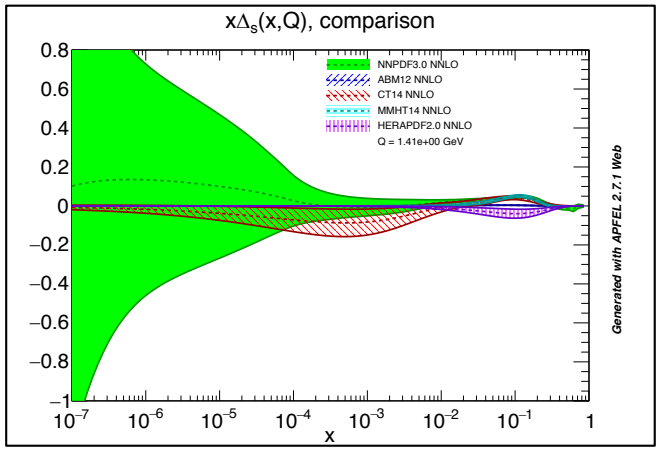
vs same fit with world data



current global fits →
for strange

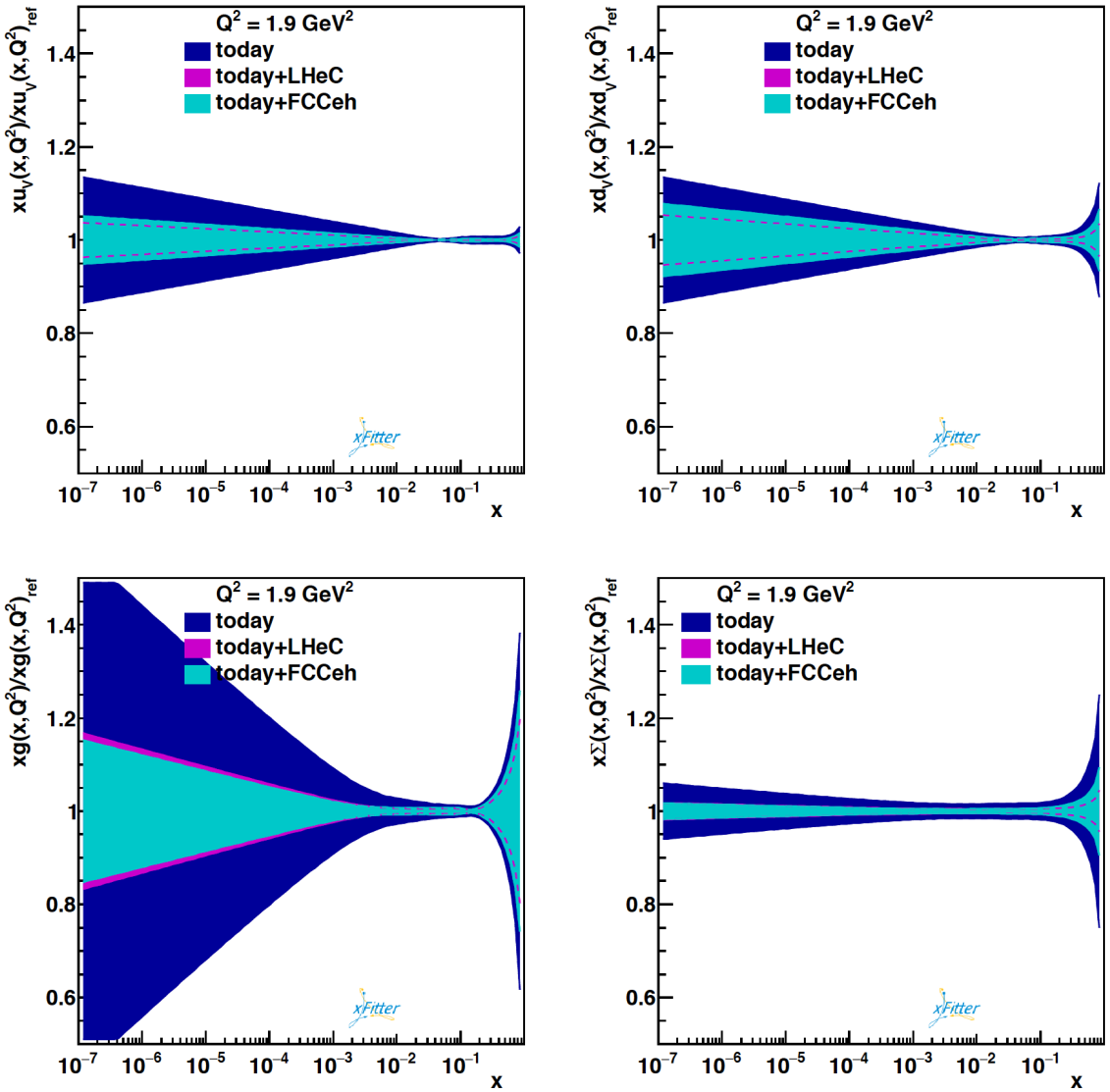




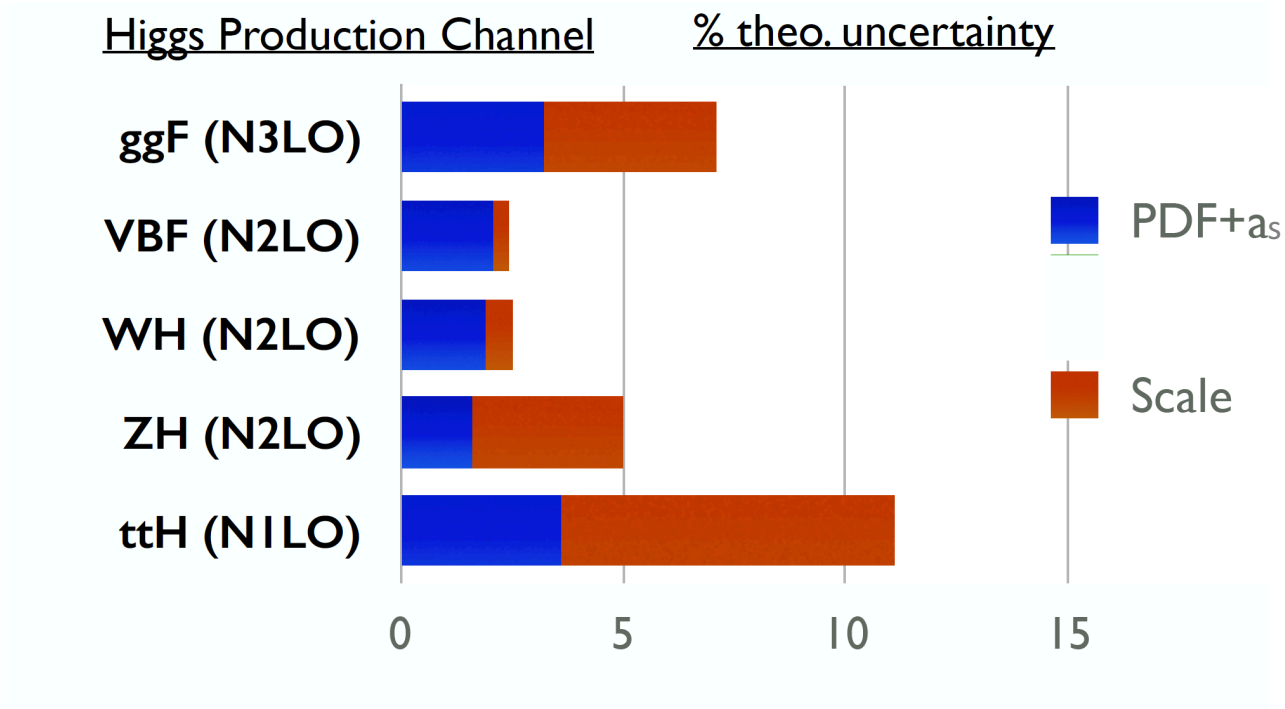


current
global fits
← for
dbar-ubar

vs same fit with world data – low x



Higgs



uncertainty on Higgs production

M. Ubiali, this conference