Parton Distributions with LHeC

History
The Science of PDFs
Simulations
LHeC vs current PDFs
Heavy Quarks
Strong Coupling
F_2, F_L and small x
Relation to LHC/FCChh

Claire Gwenlan (Oxford) and Max Klein (Liverpool)

References: HERA papers, CDR 2012 and 2020, talk of CW at ICHEP22, Papers of PDF fit Groups and PDF4LHC Study

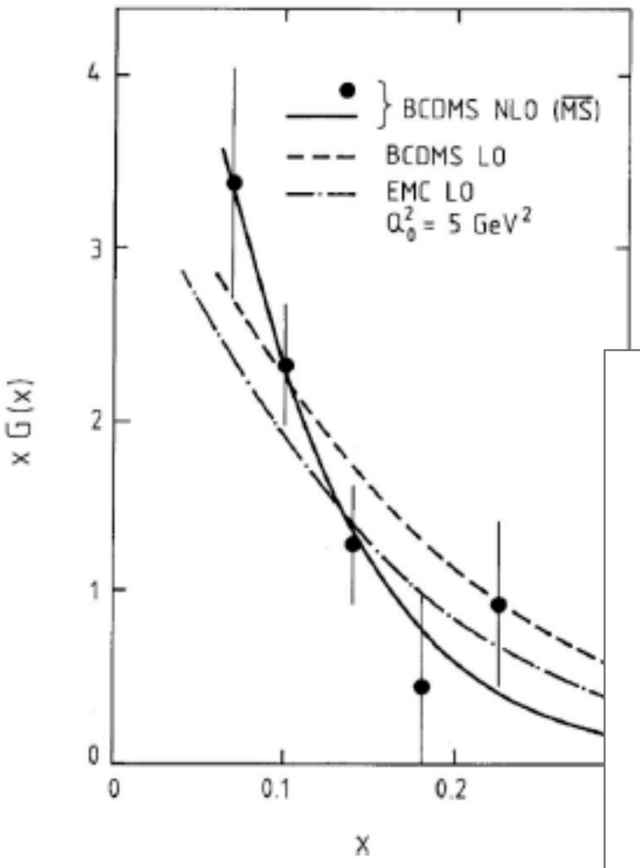
LHeC/PERLE/FCC-eh Workshop, Orsay IJC Laboratory, 26.10.2022

Early Deep Inelastic Scattering

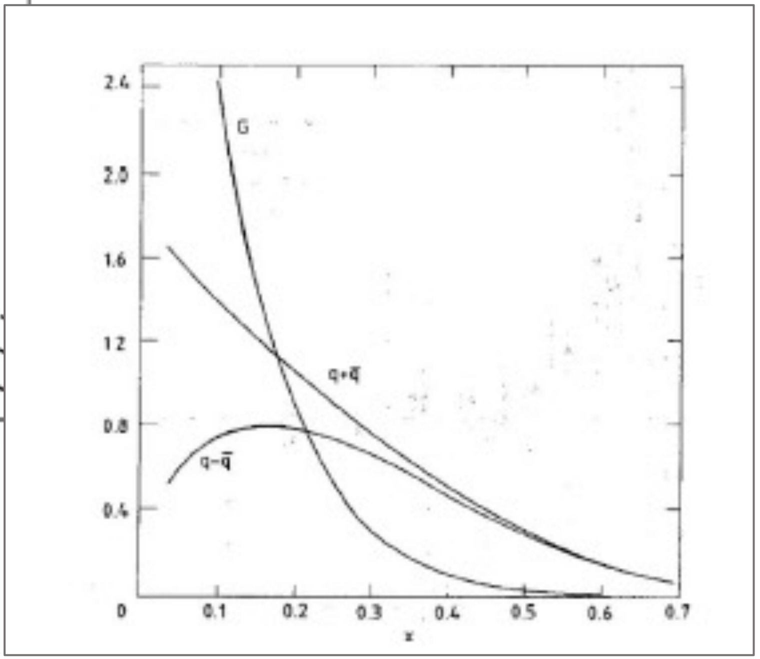
Thirty years ago

Forty years ago

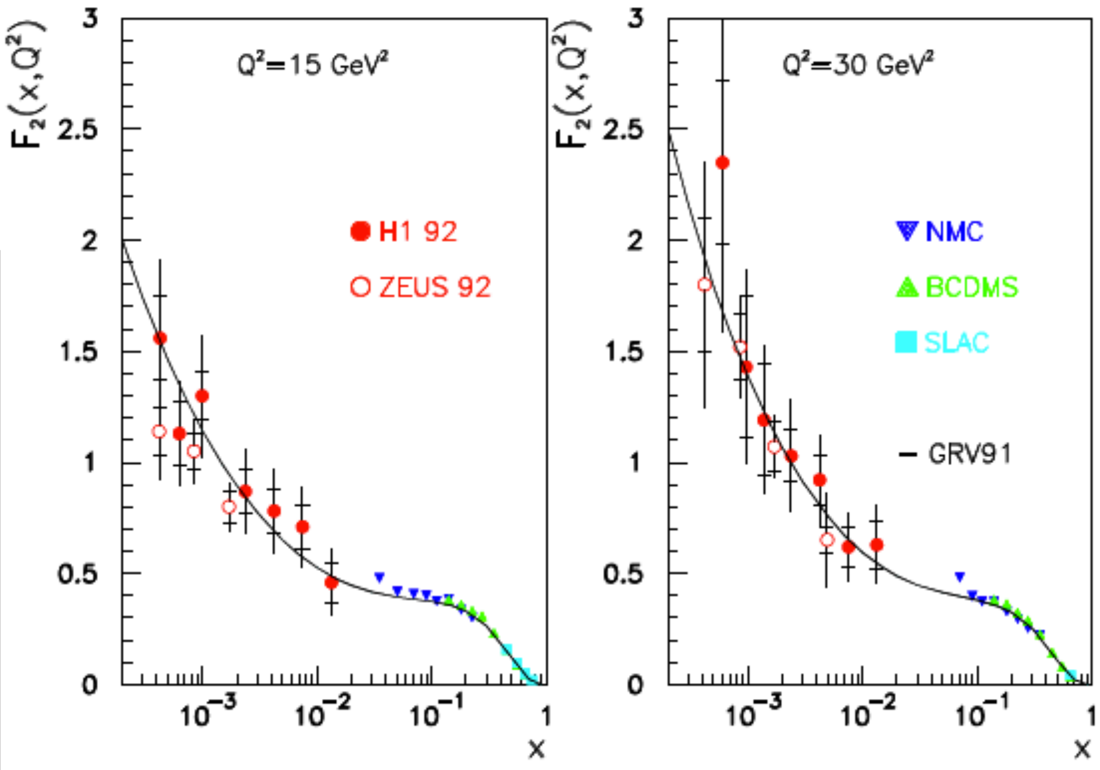
Valence, Sea and xG
from CDHS



Gluon from BCDMS



$0.03\,\mathrm{pb}^{-1}$ of data, taken in 1992.



HERA discovers the rise of parton densities to low x

Fixed target muon and neutrino exps constrained F_2,xg for x >0.01

From MK Photon2009, slides and proceedings

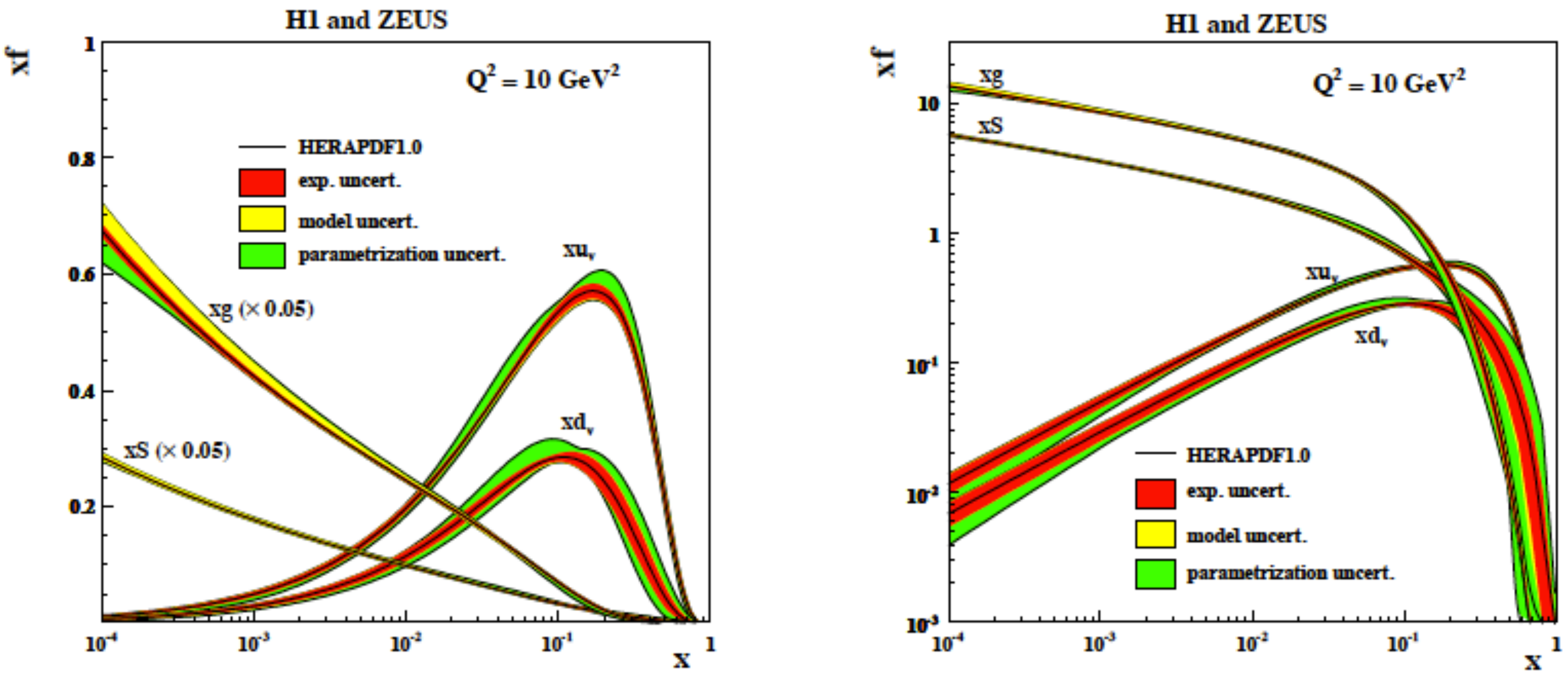


Figure 10: Parton distributions as determined by the QCD fit to the combined HERA I data at $Q^2 = 1.9$ GeV^2 (top) and at $Q^2 = 10$ GeV^2 (bottom). The inner error bands show the experimental uncertainty, the middle error bands include the theoretical model uncertainties of the fit assumptions, and the outer error band represents the total uncertainty including the parameterisation uncertainty. Here $xS = 2x(\overline{U} + \overline{D})$ denotes the total sea quark density.

HERApdf1.0, HERA I data taken before 2001: the beginning of the art of PDF extractions (thy and exp)

The value of the LHeC PDF programme

- For the first time it will resolve the partonic structure of the proton (and nuclei) completely, i.e. determine the u_v, d_v, u, d, s, c, b, and gluon momentum distributions through neutral and charged current cross section as well as direct heavy quark PDF measurements, performed in a huge kinematic range of DIS, from $x = 10^{-6}$ to 0.9 and from Q^2 above 1 to $10^6\,\text{GeV}^2$. The LHeC explores the strange density and the momentum fraction carried by top quarks [40] which was impossible at HERA.
- Very high luminosity and unprecedented precision, owing to both new detector technology and the redundant evaluation of the event kinematics from the leptonic and hadronic final states, will lead to extremely high PDF precision.
- Because of the high LHeC energy, the weak probes (W, Z) dominate the interaction at larger Q^2 which permits the up and down sea and valence quark distributions to be resolved in the full range of x. Thus no additional data will be required [2]: that is, there is no influence from higher twists nor nuclear uncertainties or data inconsistencies, which are main sources of uncertainty of current so-called global PDF determinations.

2007.14491, chapter 3 on PDFs

Science Issues on PDFs and their Importance

8 PDF science topics

Examples of issues of fundamental interest for the LHeC to resolve are: i) the long awaited resolution of the behaviour of u/d near the kinematic limit ($x \to 1$); ii) the flavour democracy of the light quark sea (is $d \simeq u \simeq s$?); iii) the existence of quark-level charge-symmetry [41]; iv) the behaviour of the ratio $\bar{d}/\bar{u}$ at small x; v) the turn-on and the values of heavy quark PDFs; vi) the value of the strong coupling constant and vii) the question of the dynamics, linear or non-linear, at small x where the gluon and quark densities rise.

Of special further interest is the gluon distribution, for the gluon self-interaction prescribes all visible mass, the gluon-gluon fusion process dominates Higgs production at hadron colliders (the LHC and the FCC) and because its large x behaviour, essentially unknown today, affects predictions of BSM cross sections at the LHC.

2007.14491, chapter 3 on PDFs

It needs the LHeC for its range and precision since PDFs are much more than ”tools” to simulate LHC data and novel BSM effects at high mass require external input to be correctly interpreted. This involves a precision test of QCD factorisation, broken in diffraction. ep and eA in one experiment at the LH(e)C resolve nuclear structure with an extension by four orders of magnitude in kinematic range

Ask Stan Brodsky if you want to really understand the richness and depth of parton dynamics

Simulation of NC and CC LHeC Data

Source of uncertainty	Uncertainty
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale $\Delta E_h/E_h$	0.5 %
Radiative corrections	0.3 %
Photoproduction background (for $y > 0.5$)	1 %
Global efficiency error	0.5 %

Numeric calculation of cross section uncertainties (J Bluemlein and MK, 1990), verified with H1 MCarlo

Simplest reconstruction methods (electron+mixed) such that the uncertainties are overestimated , also because the assumptions (left) will be conservative

Simulated data sets: studied influence of luminosity, charge, polarisation. Also added s,c,b data to some fits

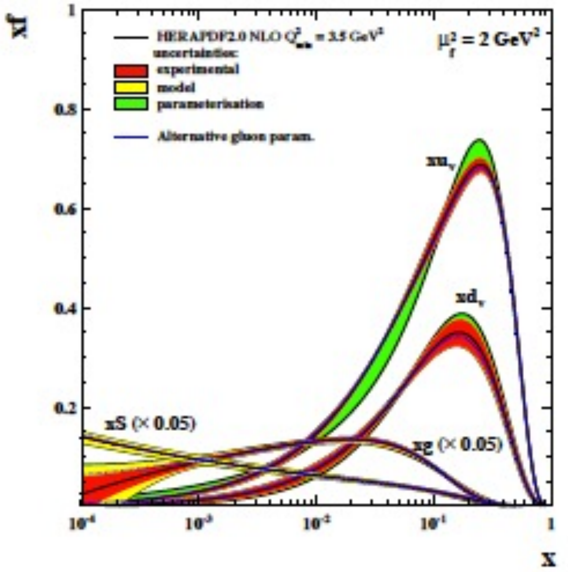
Parameter	Unit	Data set								
		D1	D2	D3	D4	D5	D6	D7	D8	D9
Proton beam energy	TeV	7	7	7	7	1	7	7	7	7
Lepton charge		-1	-1	-1	-1	-1	$+1$	$+1$	-1	-1
Longitudinal lepton polarisation		-0.8	-0.8	0	-0.8	0	0	0	$+0.8$	$+0.8$
Integrated luminosity	fb^{-1}	5	50	50	1000	1	1	10	10	50

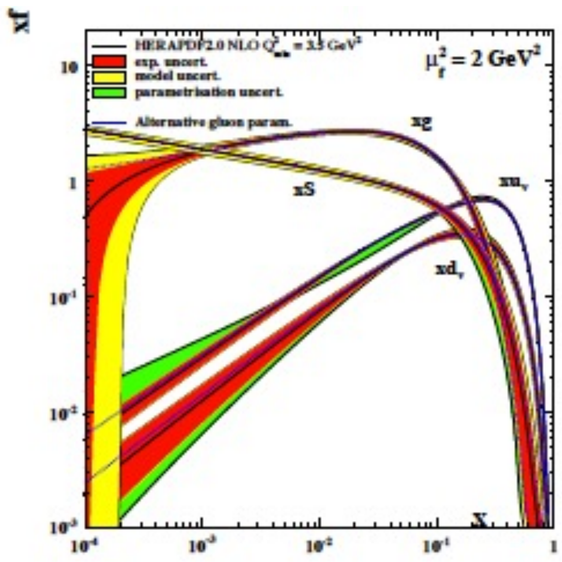
2007.14491, chapter 3 on PDFs

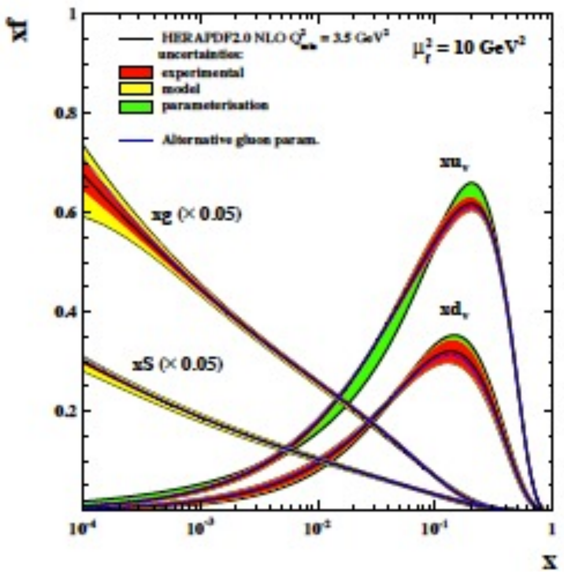
HERAPDF2.0 for illustration

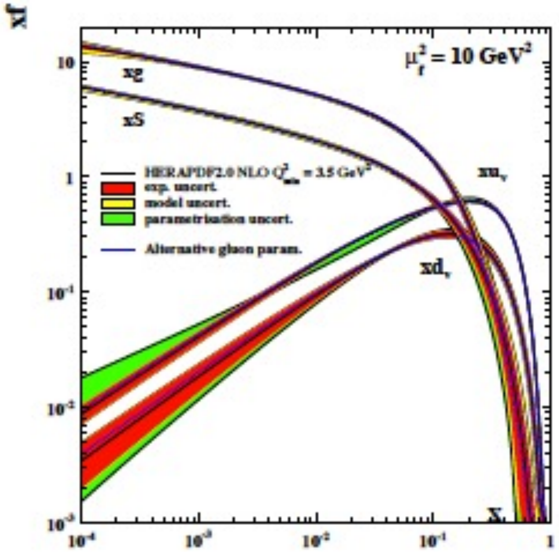
Linear scale

Logarithmic scale









An introduction to PDF Comparisons

Valence quarks (u_v,d_v) – non singlet, no Q^2 evolution
Up is better known than Down and larger, p = uud
Valence densities peak at x 0.3 – equi-momentum distr.
and become very small at large x, dv/uv at x → 1 ??

Sea has Up and Down part, which HERA did not resolve.
Ubar = Usea + uv, same for down. The sea density
rises towards low x, as discovered at HERA. strange
is part of the light sea (?), c, b are heavy, t short lived.

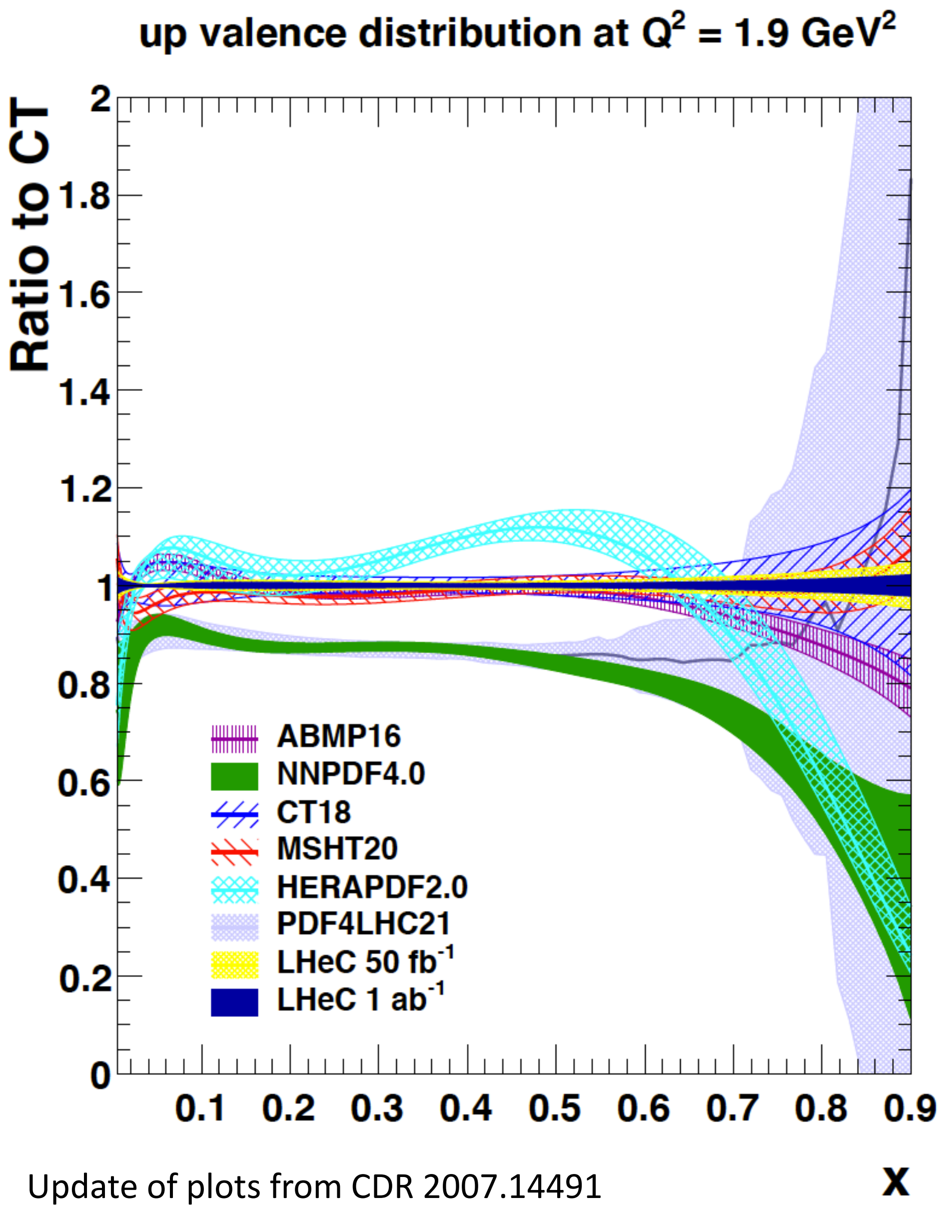
The gluon density dominates at small x. It has a valence
like shape at Q_0^2 and then evolves. pp →H at LHC
is dominantly gg fusion. Higgs is an example for why
one needs ep and pp (and ee). xg can precisely be
only measured through the Q2 variation of the NC
cross section (F_2 at smaller x). This requires a large
lever arm, i.e. high energy which is why LHeC can
provide xg and EIC not (so well).

The gluon density is independently measured by F_L,
so $dF_2/dlnQ^2$ and F_L are the ultimate quantities to
determine the parton interactions at low x, such as gg

LHeC is to resolve ALL pdfs in uncovered range, p and A!

Valence Quarks (ratio to CT18)

Up



Large differences of 20%-30%

PDF4LHC follows NNPDF..

Uncertainties and central values are both uncertain

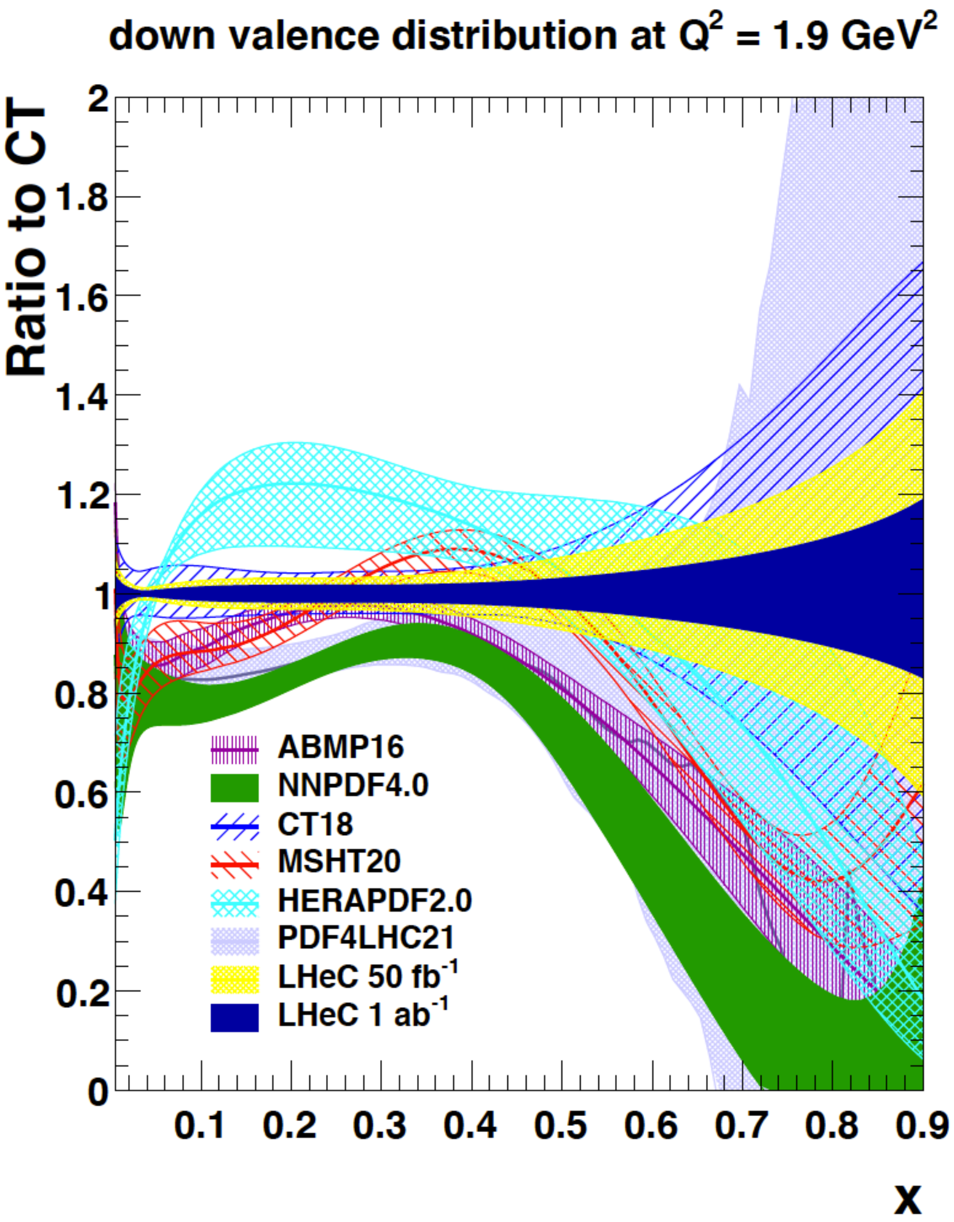
Note the huge variety in LHC data sets included and in the uncertainty treatment

LHeC with initial data set of 10 or 50fb^{-1} (yellow) to resolve that.

Full LHeC data precise to %
Lumi important only for hi x

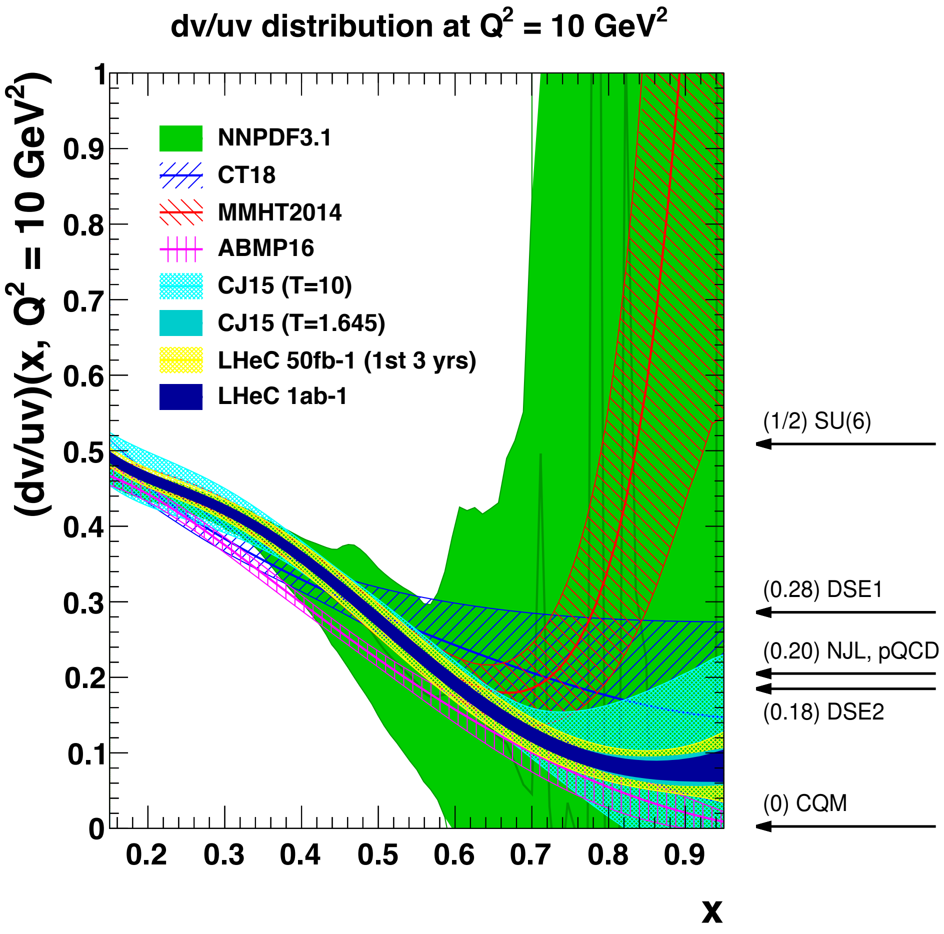
Note the fit only considers NC and CC data, unlike LHC Fits which take "everything" .

Down



Update of plots from CDR 2007.14491

Valence Quarks and d/u at $x \to 1$



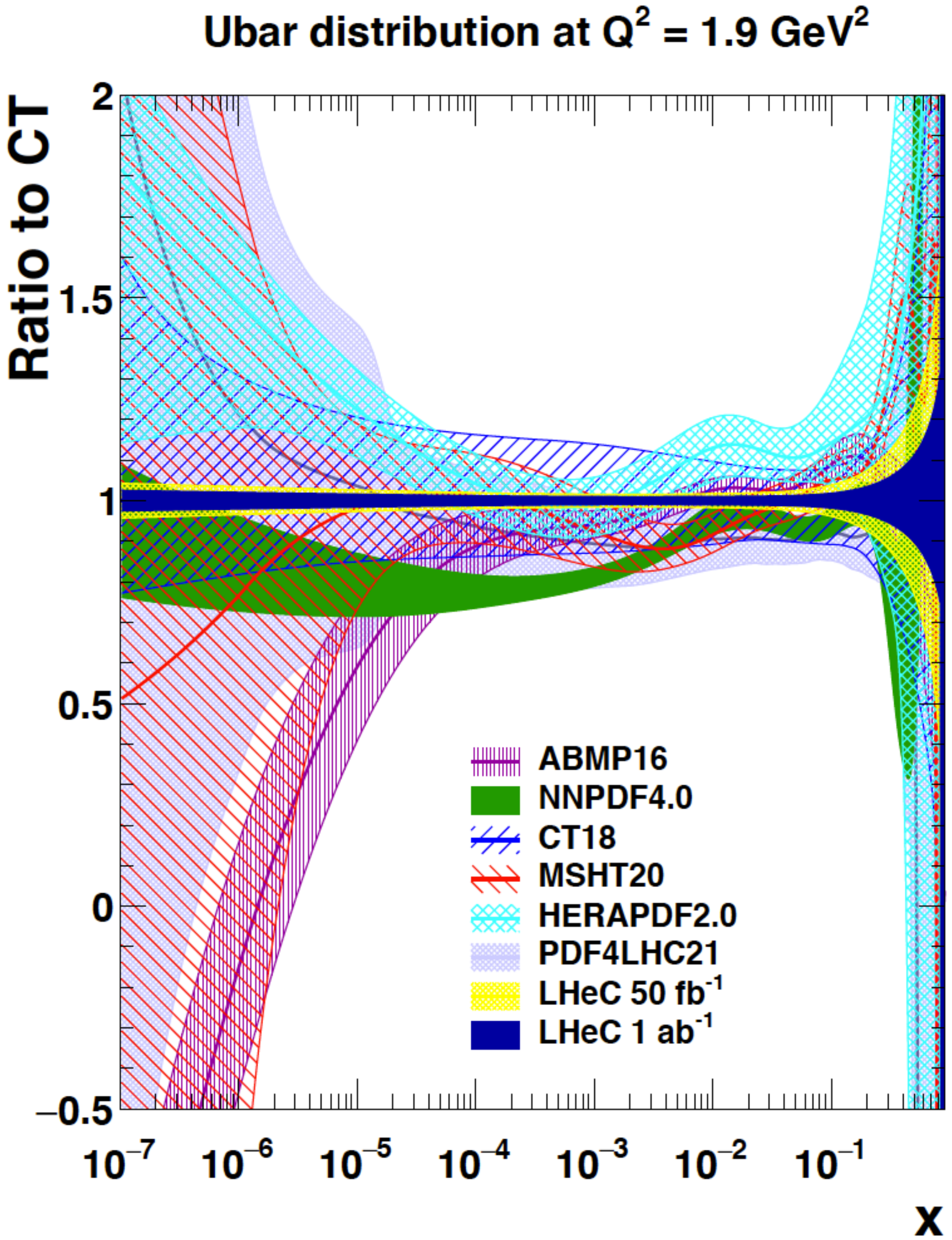
After 60 years of DIS:
d/u at large x still unknown

- no predictive power from current pdfs;
- conflicting theory pictures;
- data inconclusive as dF2 ~ 1/(1-x)
- large nuclear uncertainties

LHeC extends Q^2 range, such that CC becomes precision tool and the need for deuteron data for this topic disappears.

Very high luminosity leads to Accurate data at x near to 1

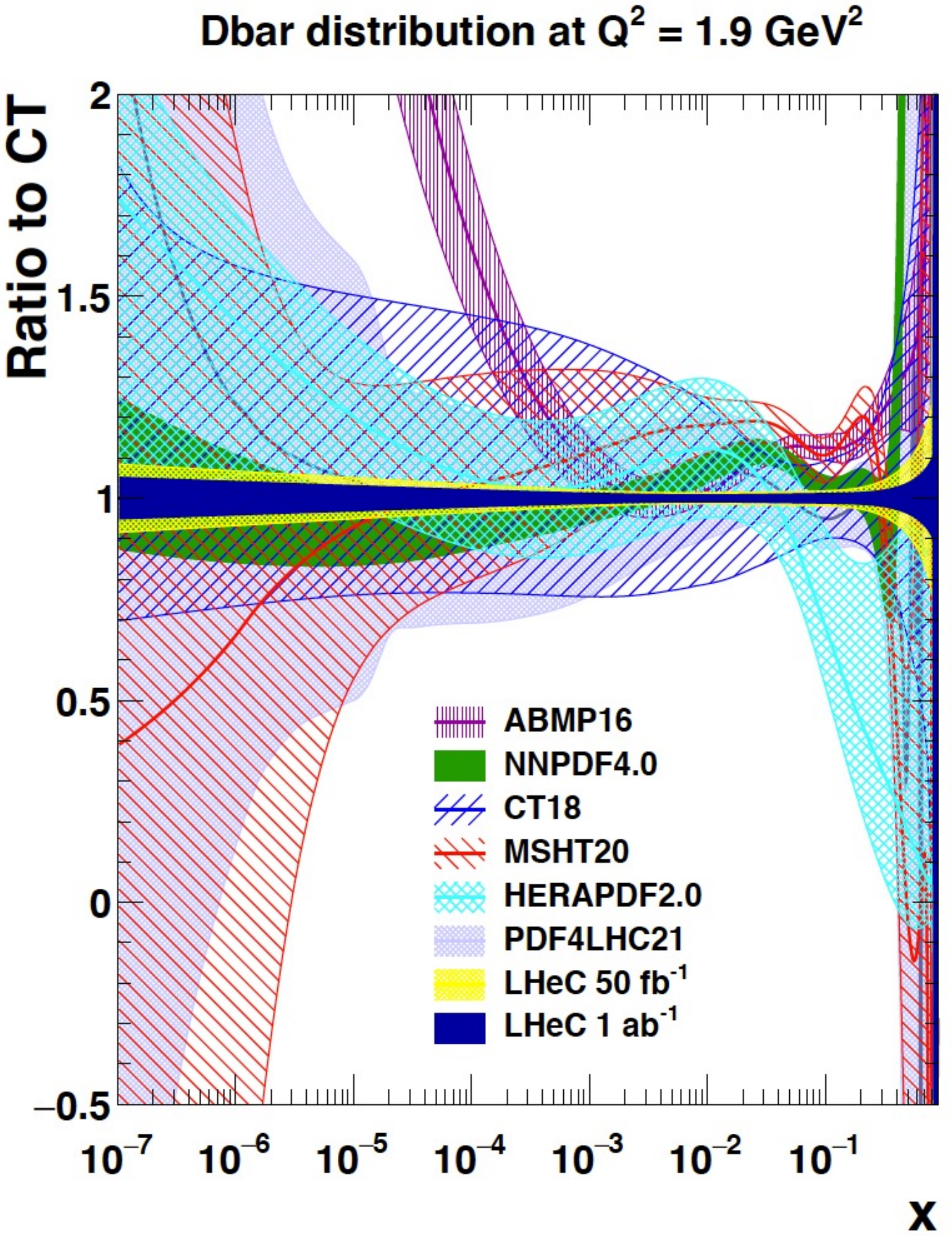
Therefore, the LHeC (FCC-eh) resolves long-standing mystery of the d/u ratio at large x



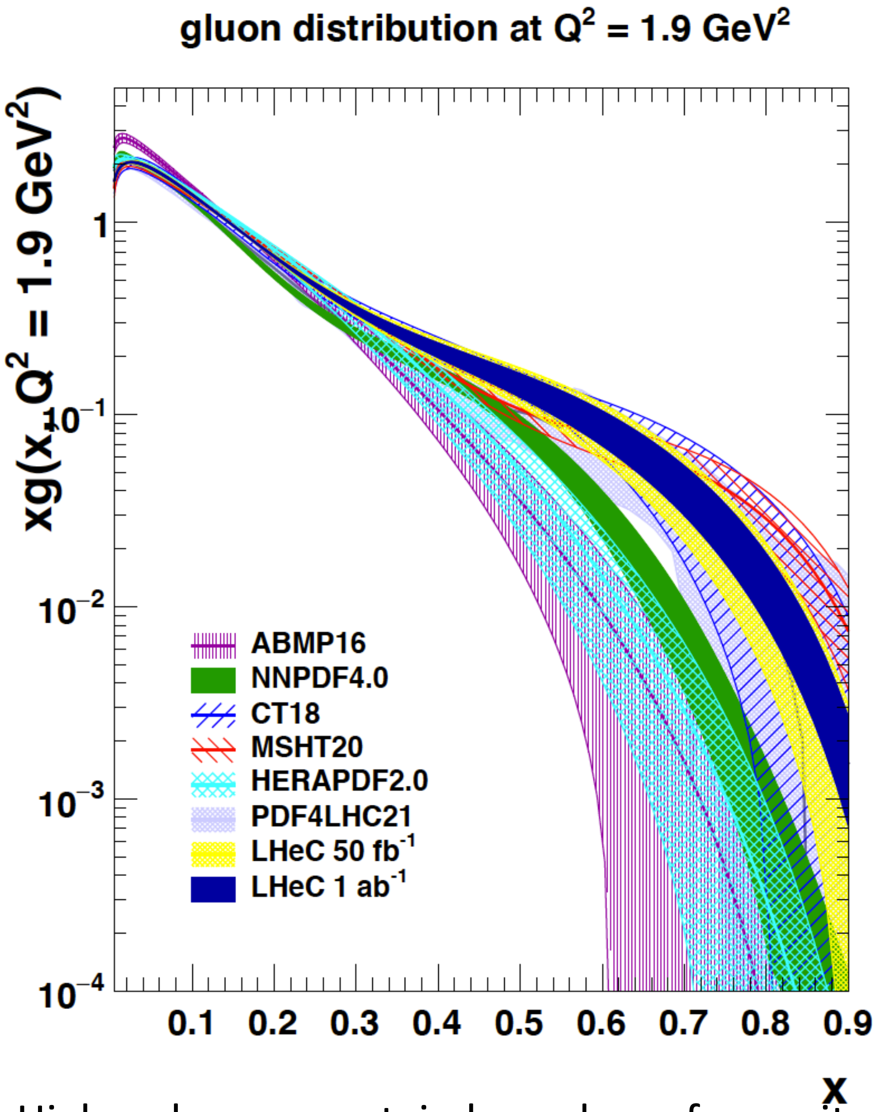
Sea Quarks

Low log x ranges for sea quarks

Fixed target	-2..3
EIC	-4
HERA	-5
LHeC	-6
FCC-eh	-7



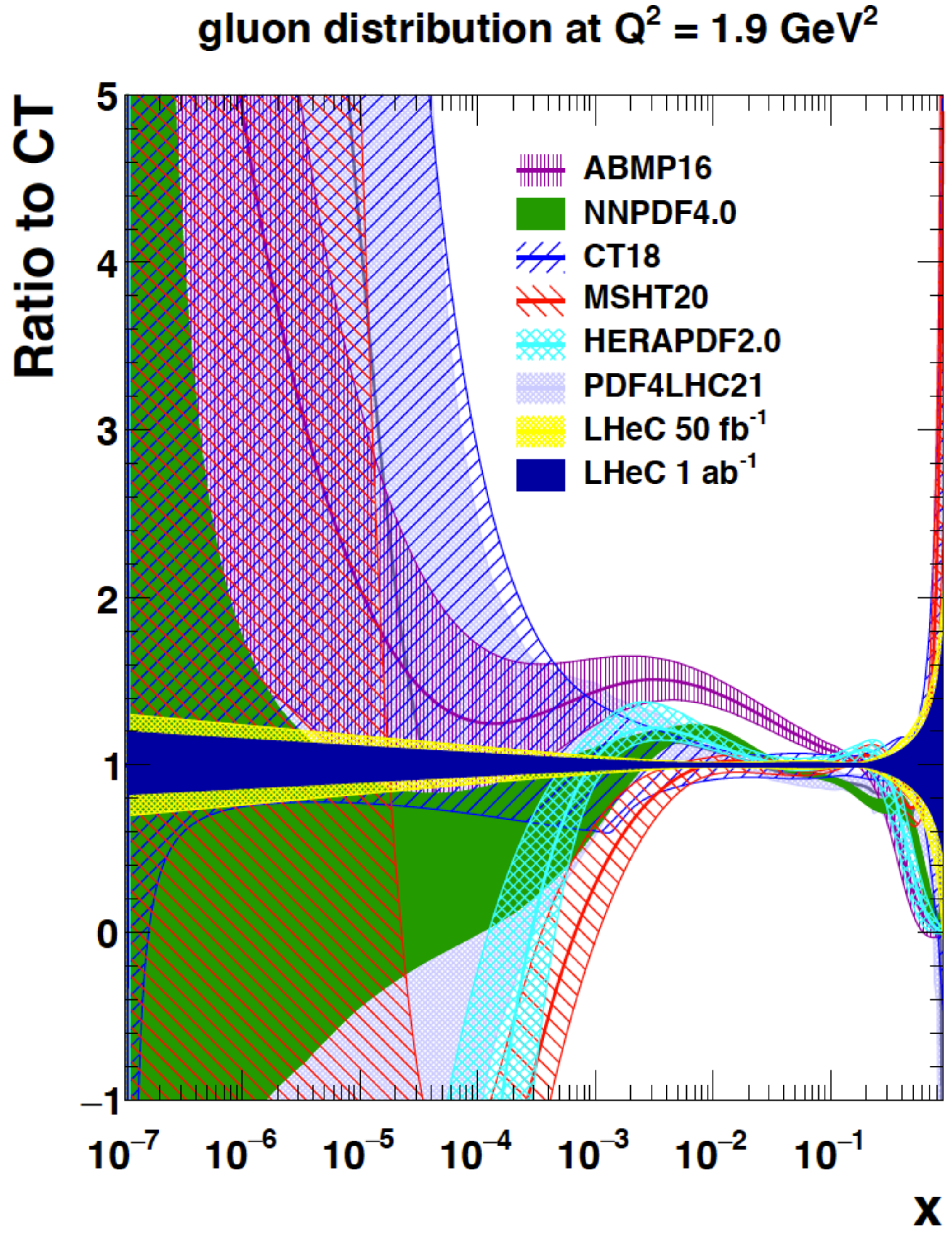
Gluon Density



$dF_2/dlnQ^2$
$\sim\alpha_s$ xg

Small coupling yields large xg

Low log x ranges for gluon density	
Fixed target	-1..2
EIC	-3
HERA	-4
LHeC	-5
FCC-eh	-6



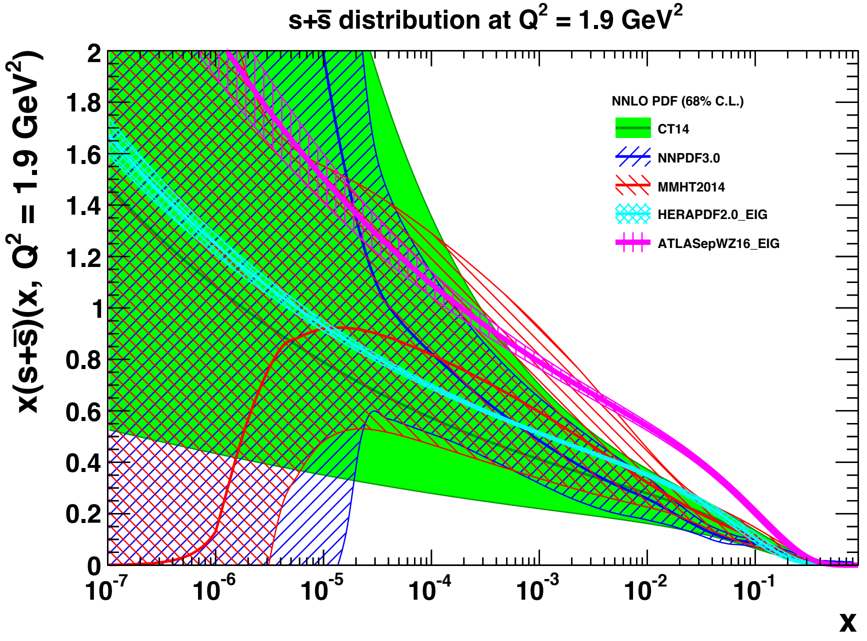
High x gluon uncertain by orders of magnitude
DIS even better when jets are involved (not here)

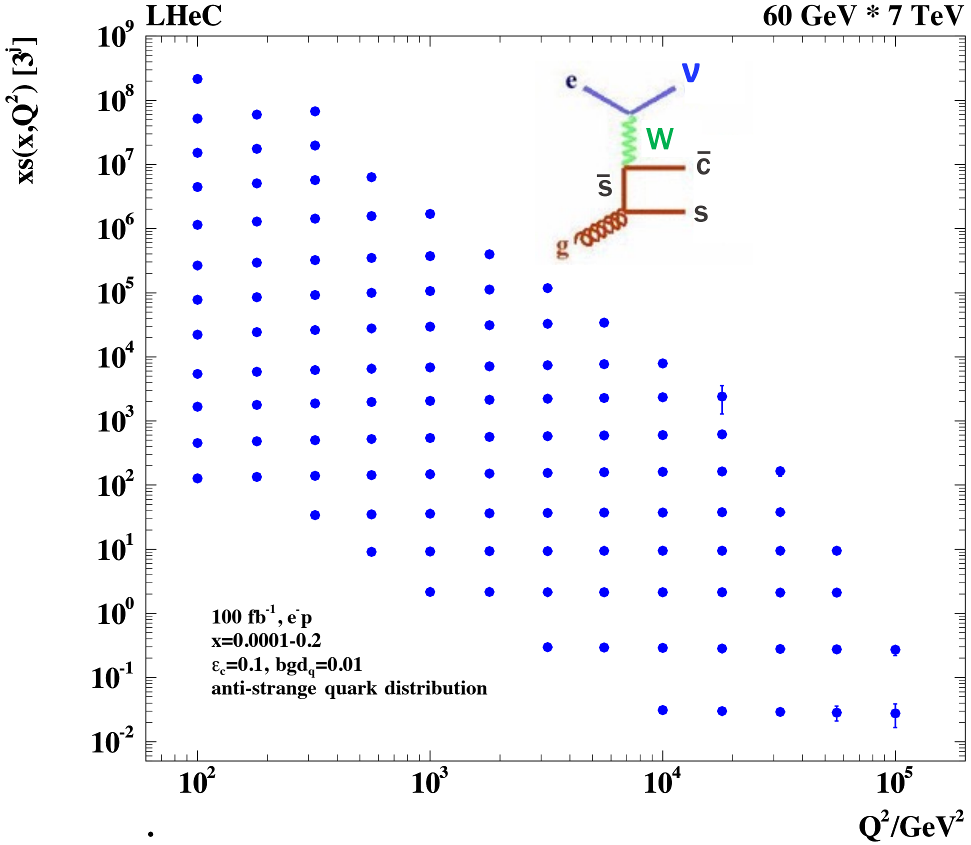
Strange Quark Density

- **strange pdf** poorly known
- suppressed cf. other light quarks?
- ATLAS 2012: s ~ d,u??
- strange valence?

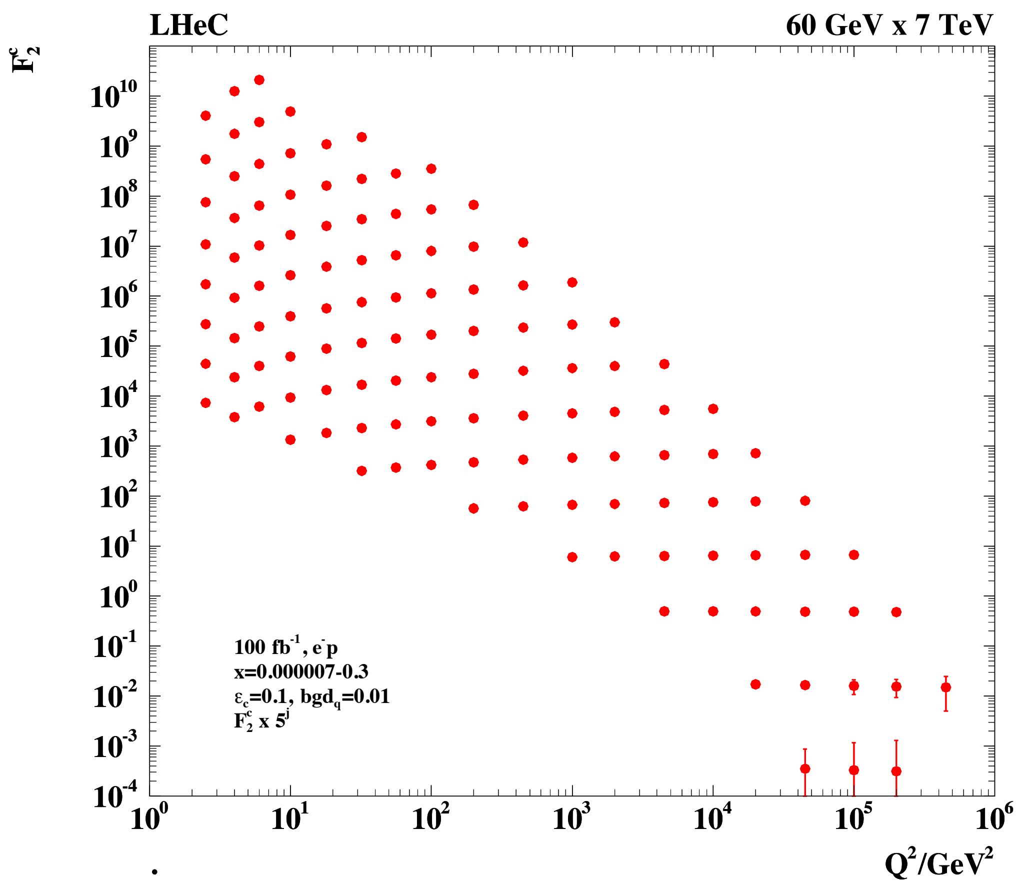
direct sensitivity via charm tagging in Ws→c

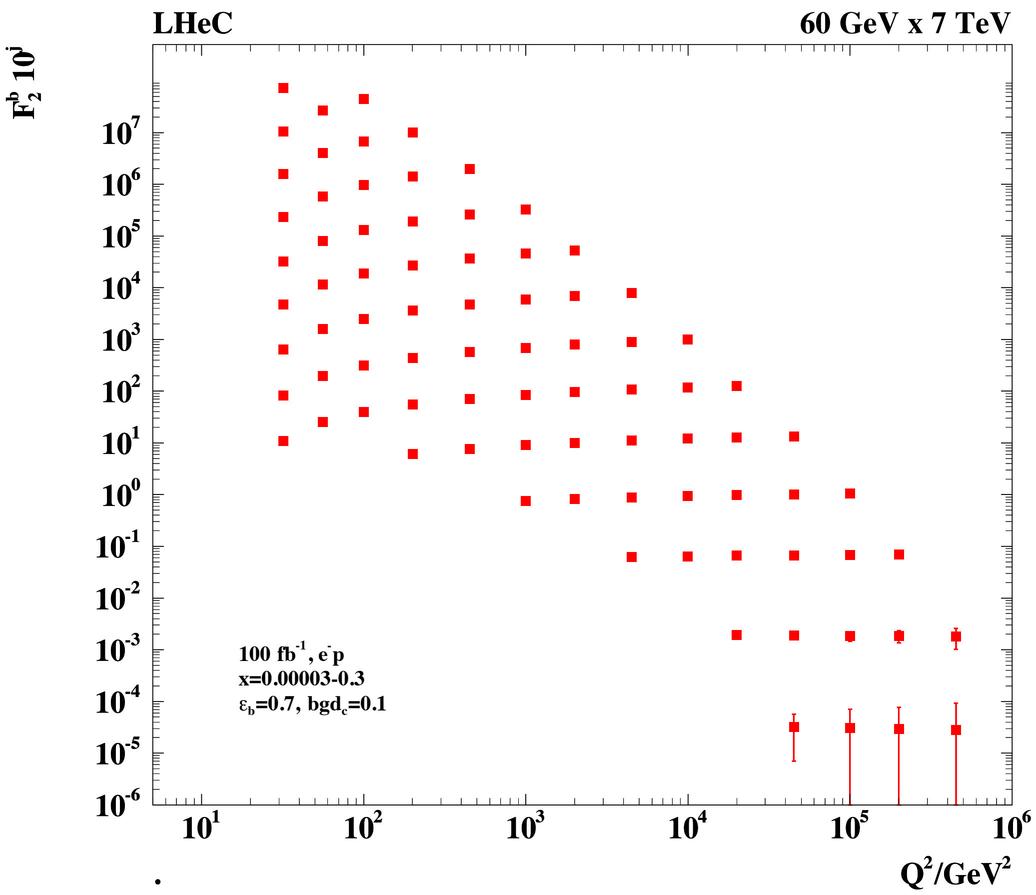
(x,Q²) mapping of strange density for first time





Charm + Beauty Quark Densities

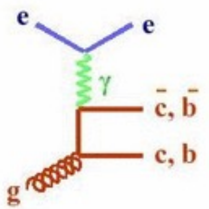




c,b tagging in NC → Si tracker

LHeC: enormously extended range and much improved precision c.f. HERA

- **δMc = 50 (HERA)** to **3 MeV**: impacts on αs, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via bb → A



Top? also accessible (EG. G.R. Boroun, PLB 744 (2015) 142; 741 (2015) 197)

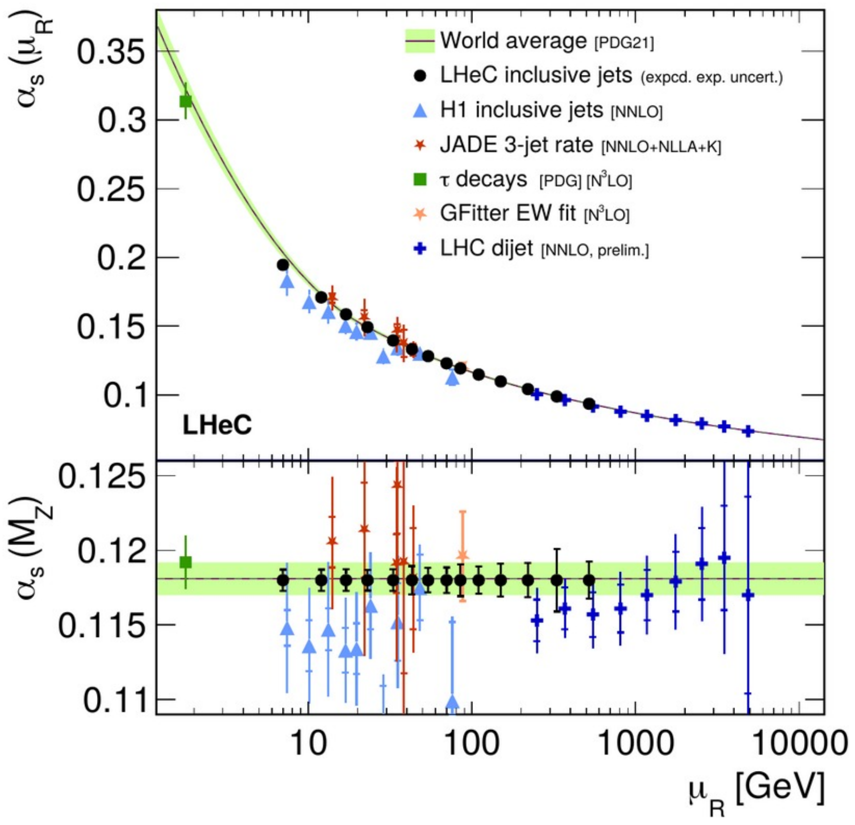
Strong Coupling

arXiv:2007.14491
featured in Snowmass α_s White Paper,
arXiv:2203.08271

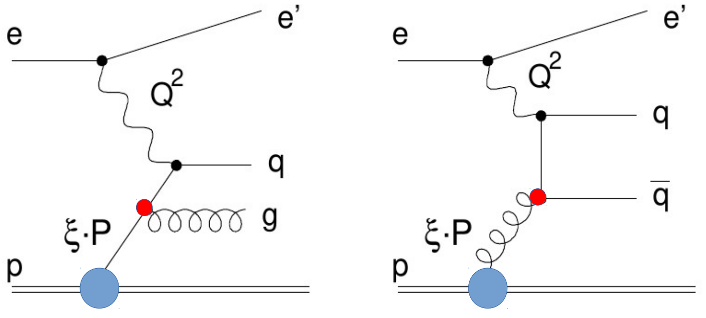
- α_s: least known coupling constant
- current state-of-the-art: $\delta\alpha_s/\alpha_s = \mathcal{O}(1\%)$

- **LHeC** simultaneous **PDF+α_s** fit:
- $\Delta\alpha_s(M_Z)$[incl. DIS] = **±0.00022**$_{\text{(exp+PDF)}}$
- $\Delta\alpha_s(M_Z)$= ± **0.00018** for incl. DIS together with **ep jets**

- achievable precision: **$\mathcal{O}$(0.1%)**
  ×5–10 better than today



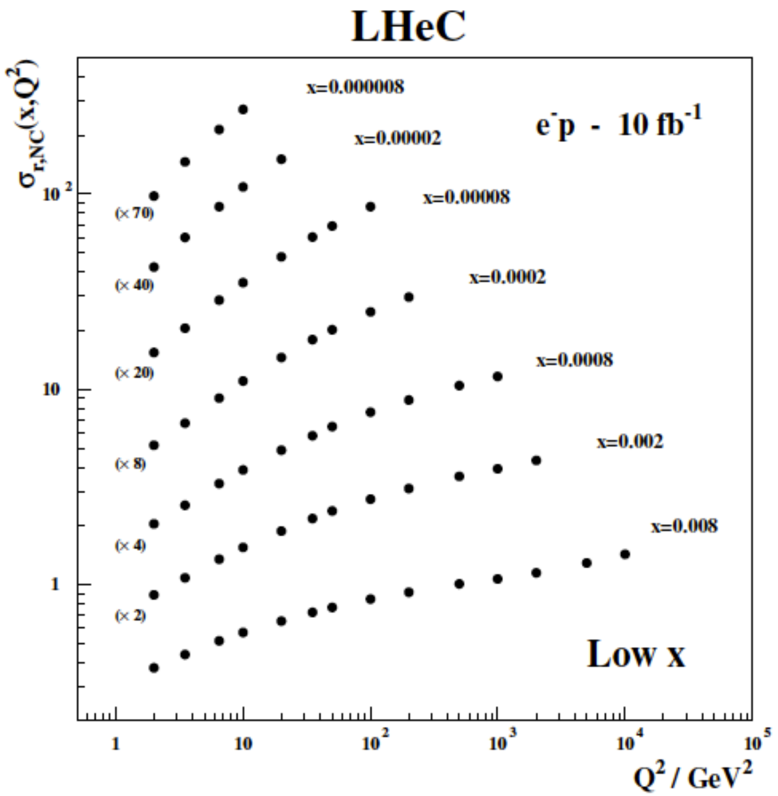
ep jets:



- **α_s** from fits to **ep** jet production (**LHeC**)
- connects **τ**-decays to Z-pole and beyond
- **FCC-eh** further increases precision and range

Resolution of Low x Parton Interaction Dynamics

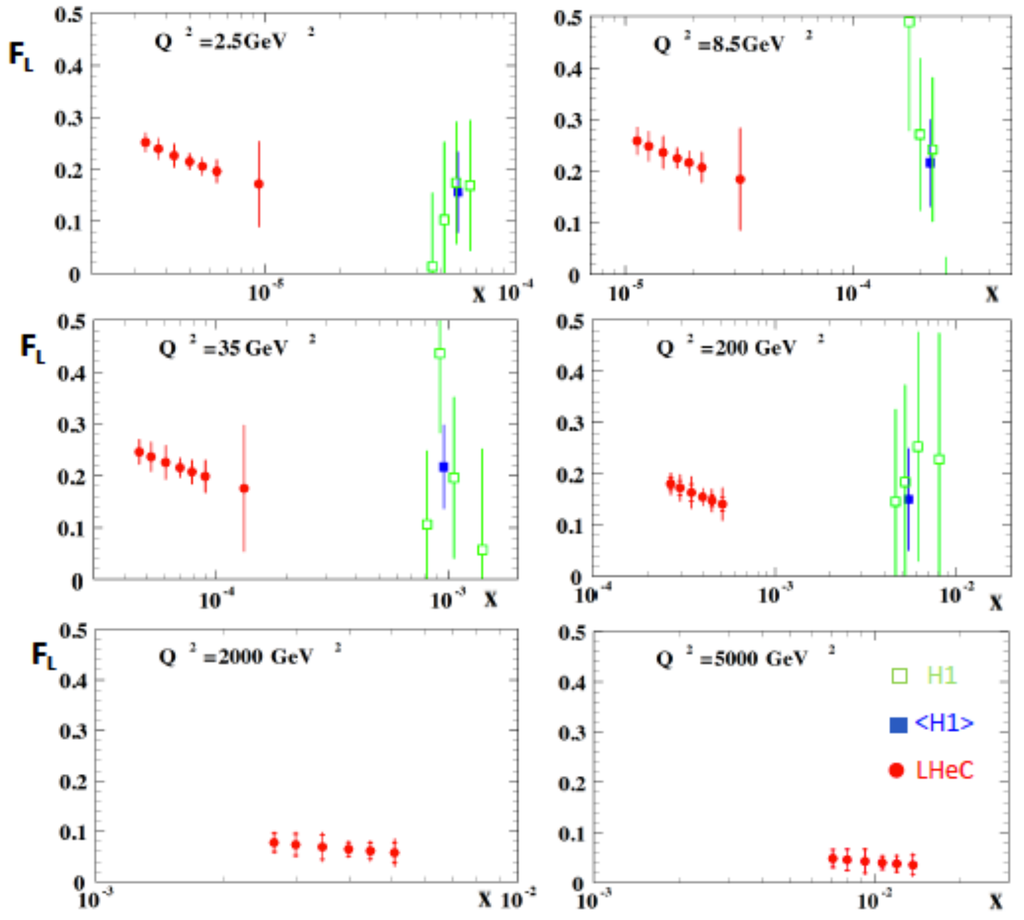
$$\frac{Q^4 x}{2\pi\alpha^2 Y_+} \cdot \frac{d^2\sigma}{dxdQ^2} = \sigma_r \simeq F_2(x,Q^2) - f(y) \cdot F_L(x,Q^2)$$



Very high precision F_2 to get Q_2 derivative
Needs small luminosity only (large wrt HERA)

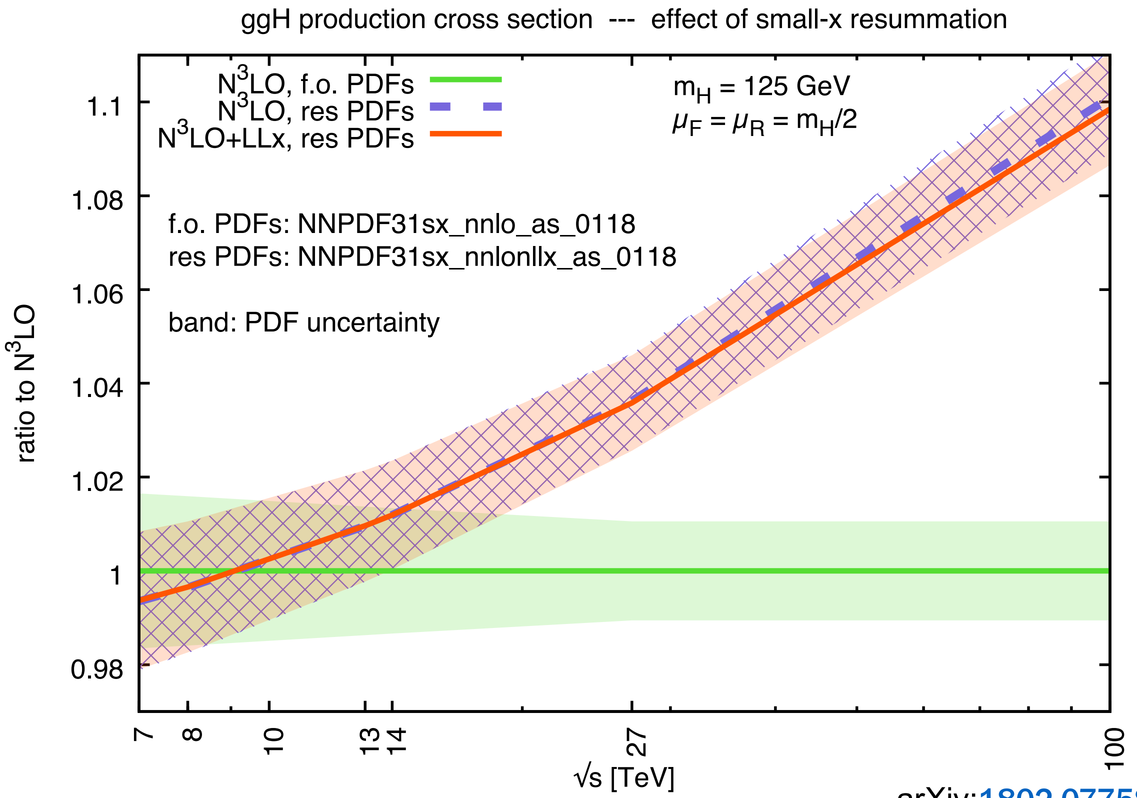
Vary y through E_e to access F_L independently of F_2
Reaching high y requires small set of positron data

Simulation of FL at LHeC with full error correlation



Theory: resummation, N^3LO, BFKL type non linear gg dynamics

Impact of Low x QCD Dynamics on pp Phenomenlogy



arXiv:1802.07758, 1805.08785

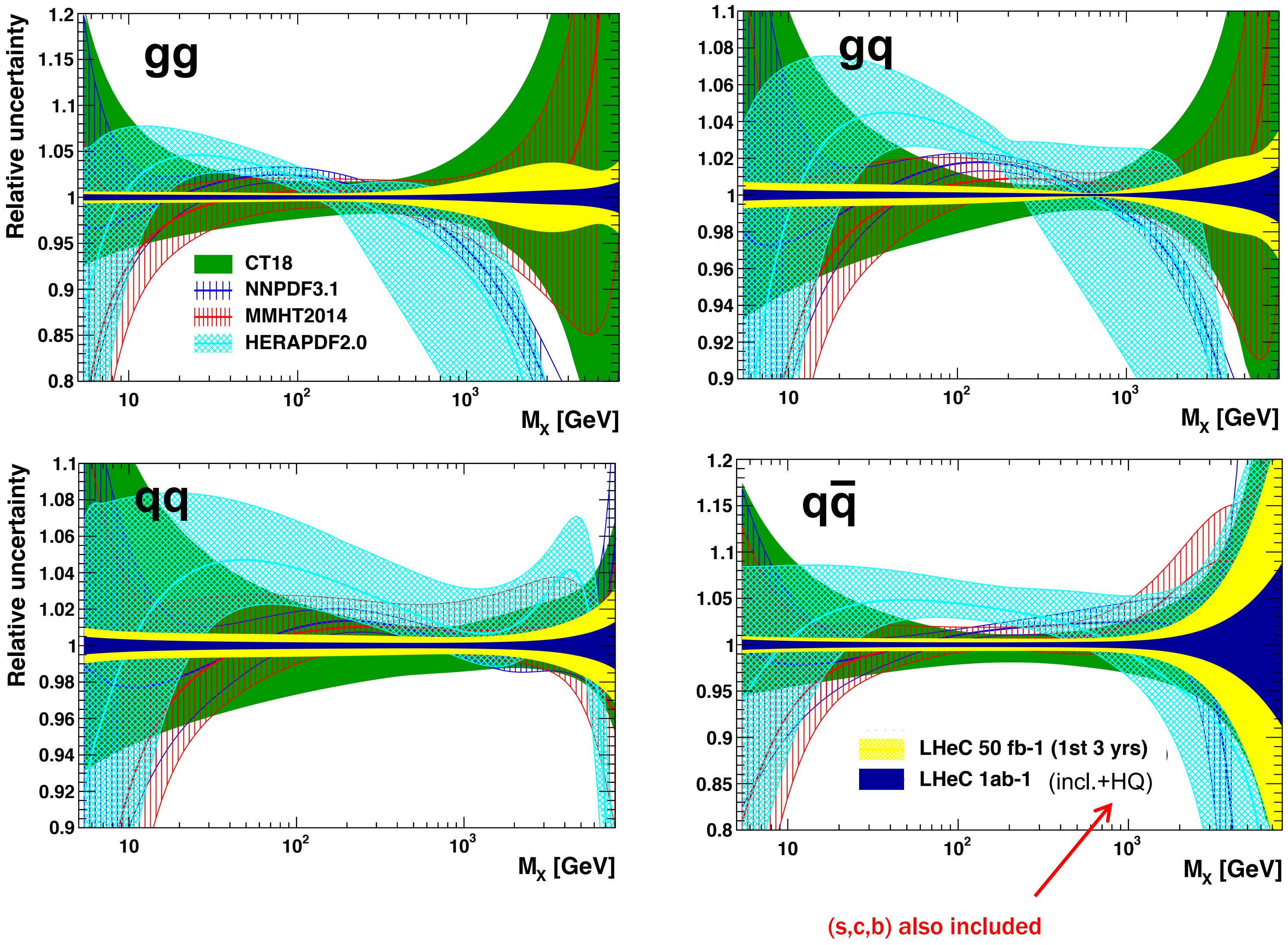
- effect of small x resummation on gg→H cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

(see also recent work on forward Higgs production, arXiv:2011.03193; other processes in progress)

Parton-parton "luminosities" @ 14 TeV

Very high precision x section predictions for LHC

Side remark: HERA data Taking ended In 2007, we now elect(ed) new spokes.. 15 years later.



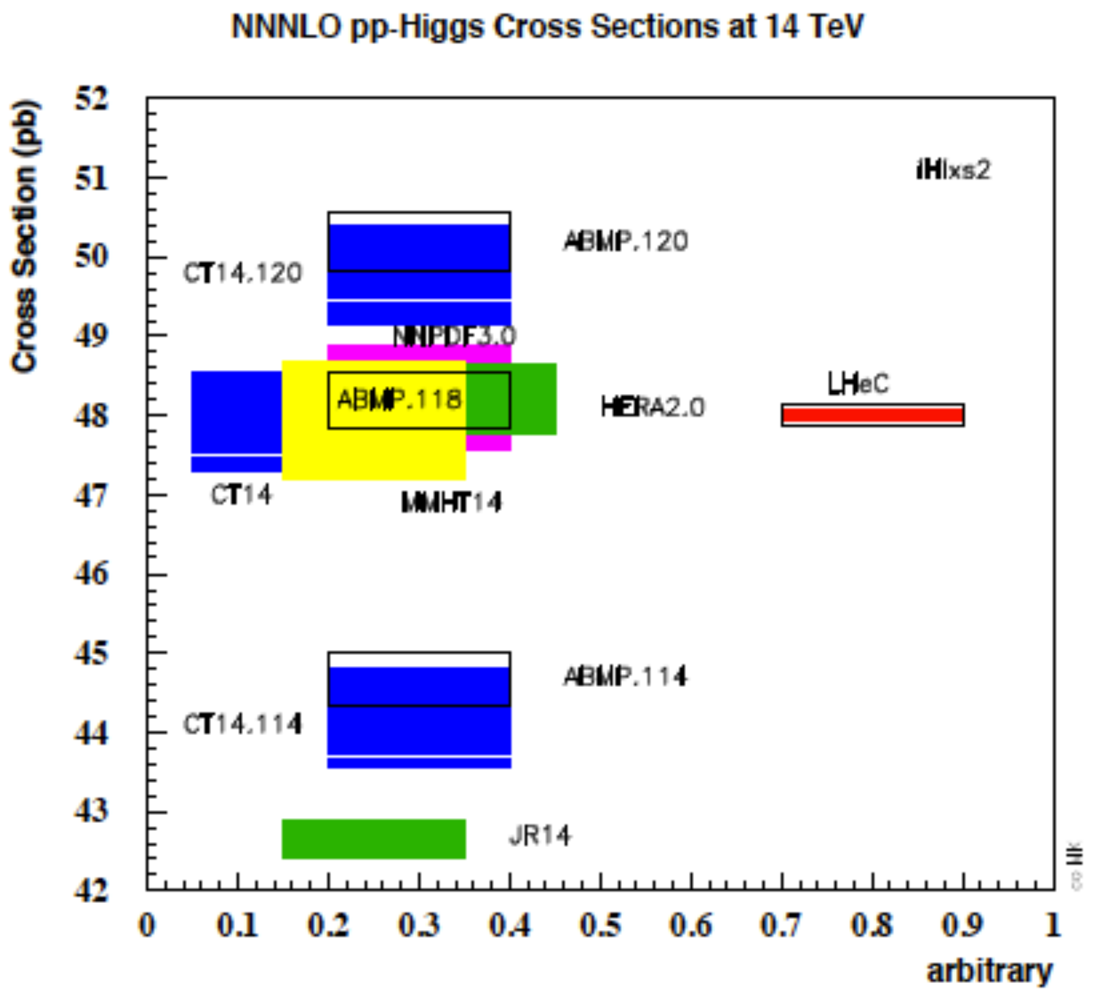


Figure 9.5: Cross sections of Higgs production calculated to N^3LO using the iHix program [723] for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side). The widths of the areas correspond to the uncertainties as quoted by the various sets, having rescaled the CT14 uncertainties from 90 to 68 % C.L. Results (left) are included also for different values of the strong coupling constant $\alpha_s(M_Z^2)$, from 0.114 to 0.120. The inner LHeC uncertainty band (red) includes the expected systematic uncertainty due to the PDFs while the outer box illustrates the expected uncertainty resulting from the determination of α_s with the LHeC.

Some residual comments

With the LHeC the determination of the PDFs, quarks and gluons, will be put on a completely new base:

- Determination of all quark PDFs, including d/u, s, c, b
- Mapping of the gluon distribution from nearly 10^{-5} to x=1
- Determination of the strong coupling to permille level

This puts severe requirements to detector design, precision and acceptance of tracking and calorimetry.

The e-h redundant reconstruction and the clean environment determine PDFs to (sub)% level.

The common treatment of PDF uncertainties at the LHC is indeed in contradiction to the observed diversity.

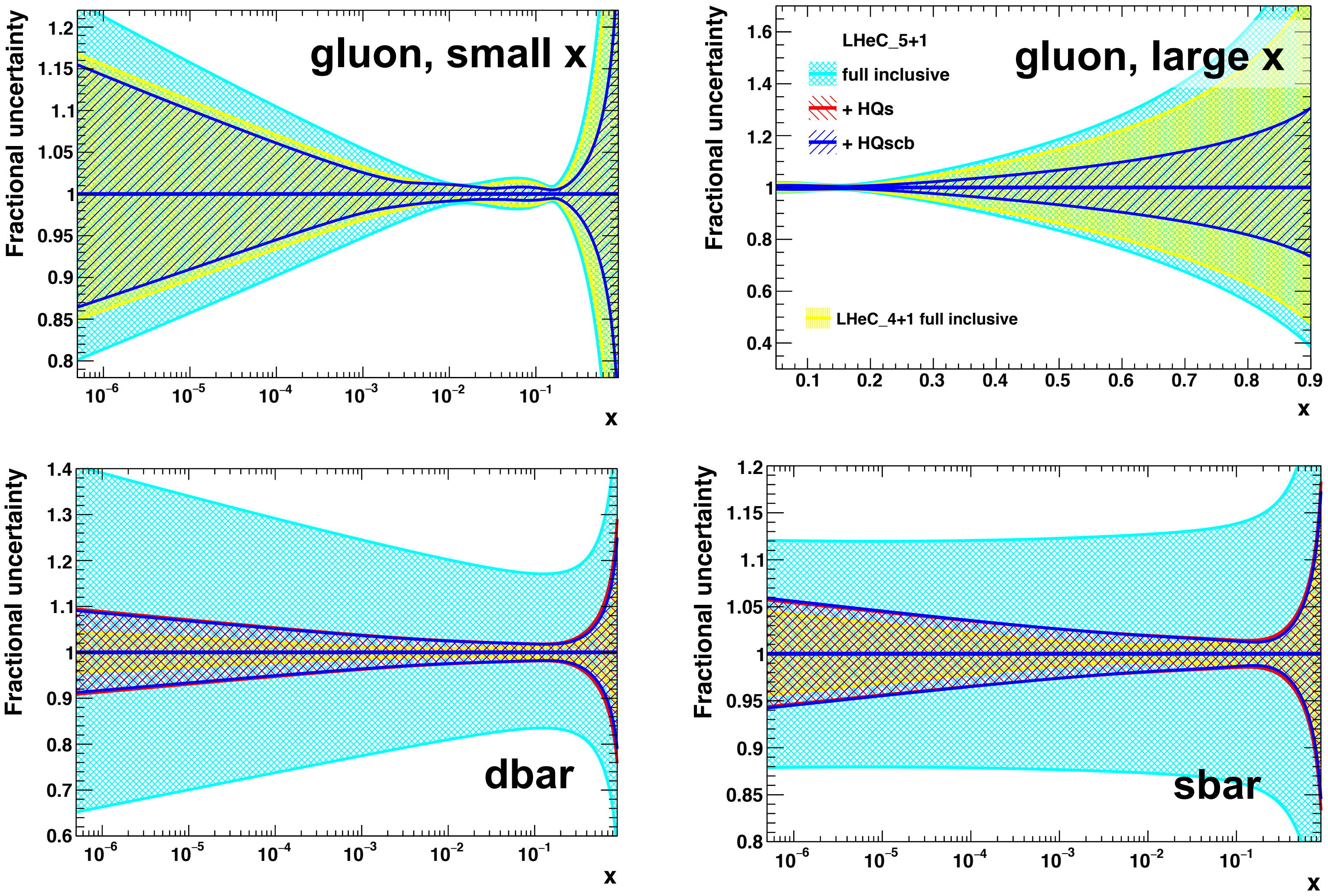
The LHeC provides much further insight to jets, photon, neutron, nuclear, Pomeron structure.

LHeC is the most reliable way to clarify the dynamics at small x. Theory may also provide N^3 or N^4LO framework to respond to LHeC precision. DIS is the cleanest process to determine the nucleon substructure.

Almost all of the PDF program can be performed with ~ 100 fb^{-1}. LHeC should operate eventually for this program is a major boost to QCD, to the LHC facility and its physics potential (precision, Higgs,BSM)

backup

Impact of s, c, b



- **4+1** xuv, xdv, xUbar, xDbar + xg (14)
- **5+1** xuv, xdv, xUbar, xdbar, xsbar + xg (17)