Parton Distributions with FCC-eh

FCC-eh Configuration and Parameters

PDFs in Deep Inelastic Scattering and Status

Simulations and Kinematics

Fit and PDF Results

Heavy Quarks

Extra Constraints (Weak NC and F_L)

Importance for pp Experiments

Summary

Max Klein and Claire Gwenlan, CERN, FCC Physics Week, January 15, 2020

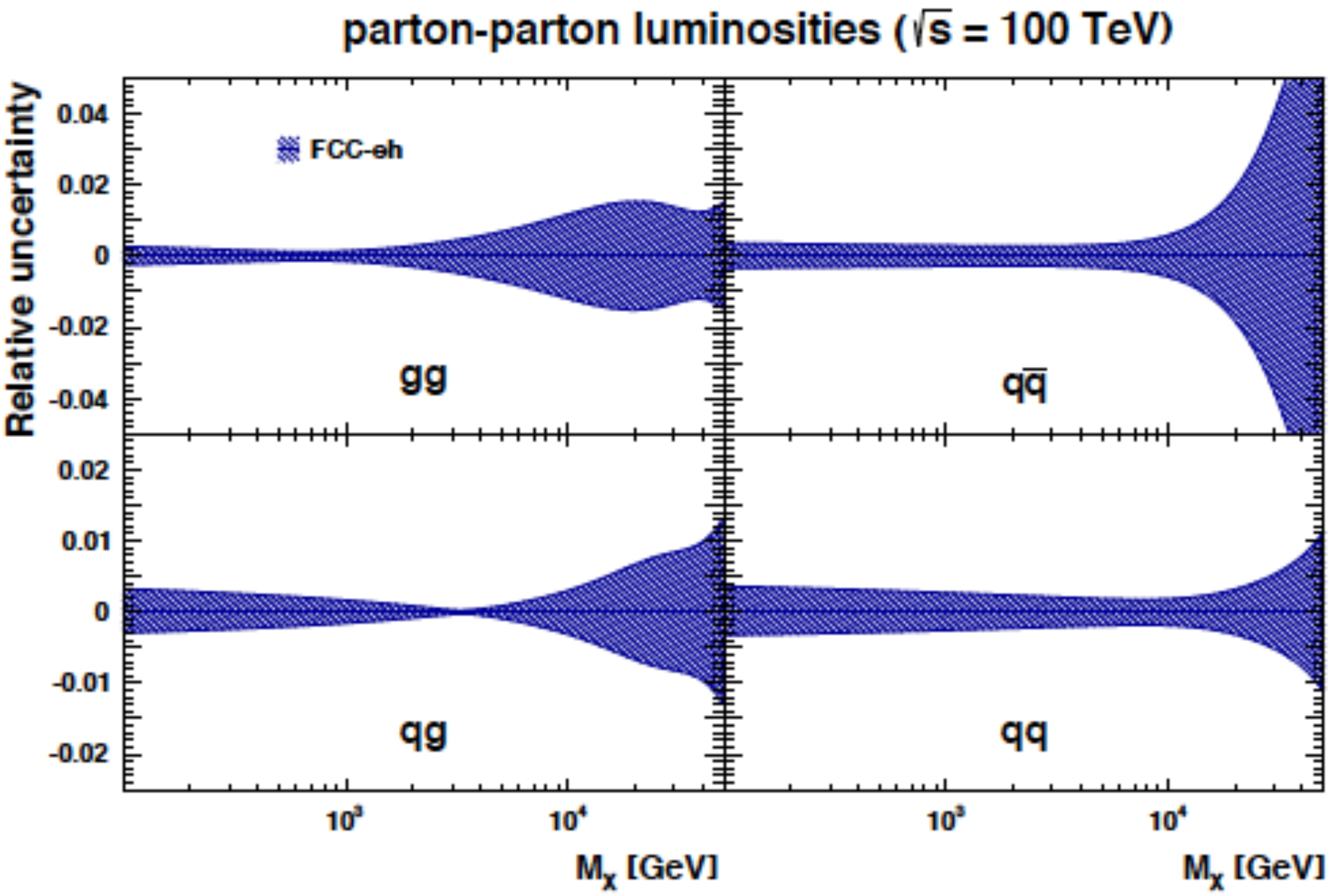
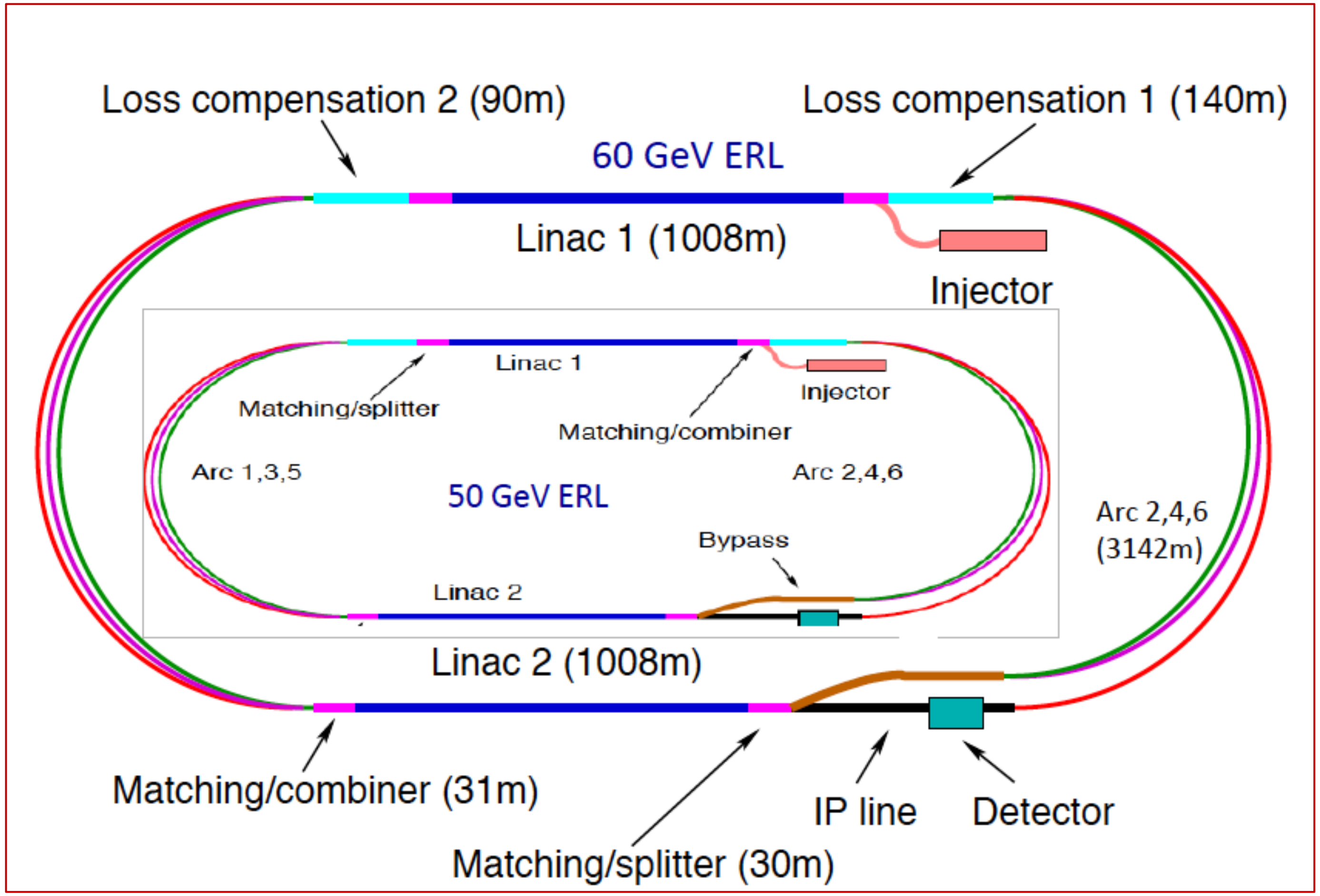
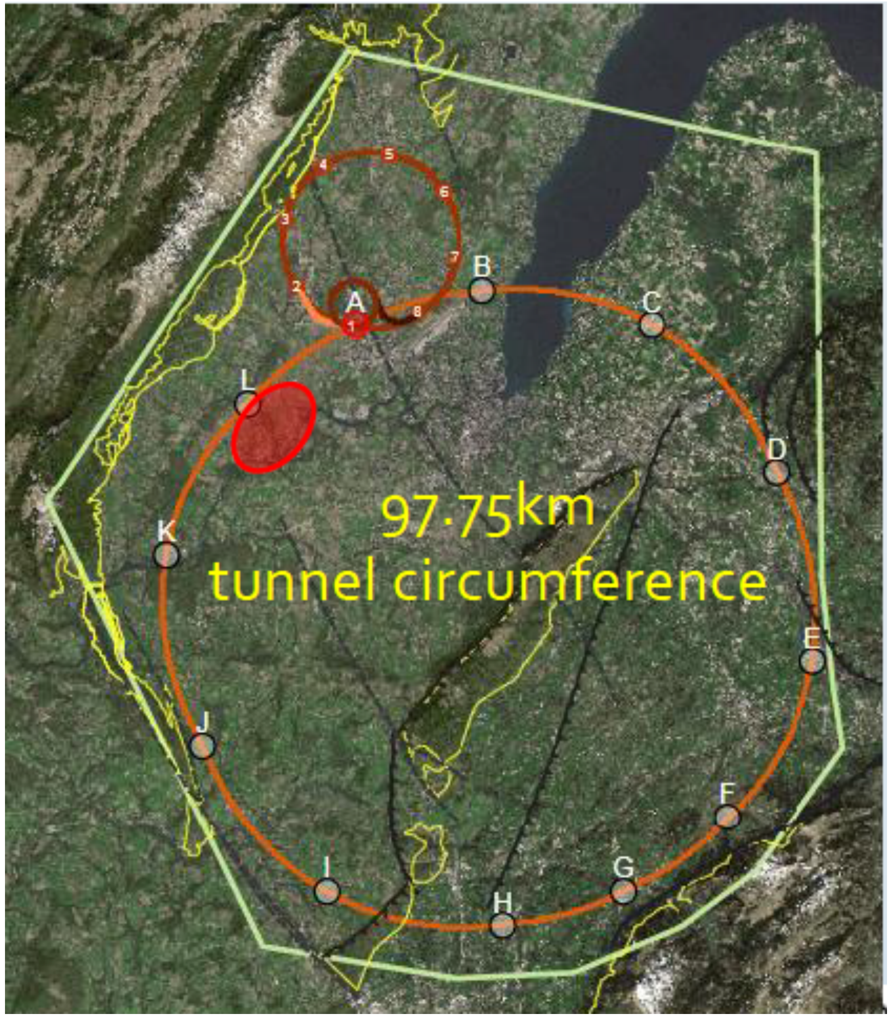


Figure S.7: Relative PDF uncertainties on parton-parton luminosities, resulting from the FCC-eh PDF set, as a function of the mass of the heavy object produced, M_X, at $\sqrt{s} = 100$ TeV. Shown are the gluon-gluon (top left), quark-antiquark (top right), quark-gluon (bottom left) and quark-quark (bottom right) luminosities.

There is still more to be and being studied than the main FCC CDR plot shows.

Electron Energy Recovery Linac for FCC-eh

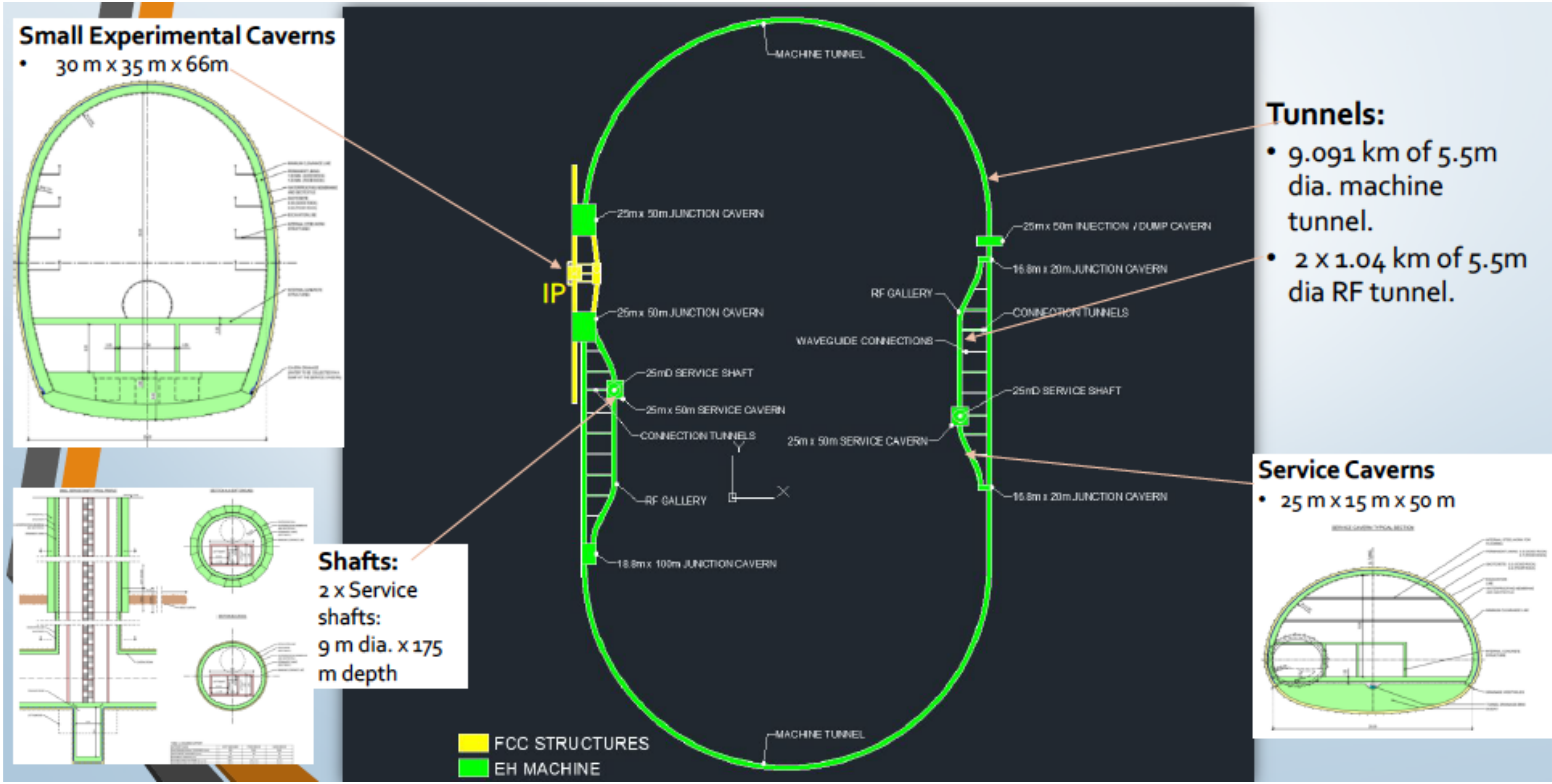




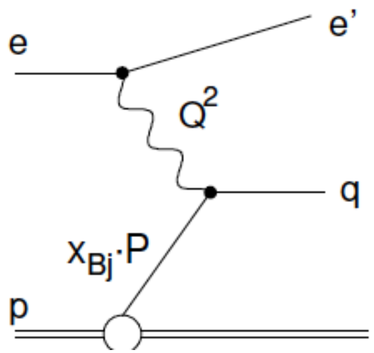
Currently we think of 1/5 (50 GeV) for LHeC and 1/3 (60 GeV) for FCC-eh

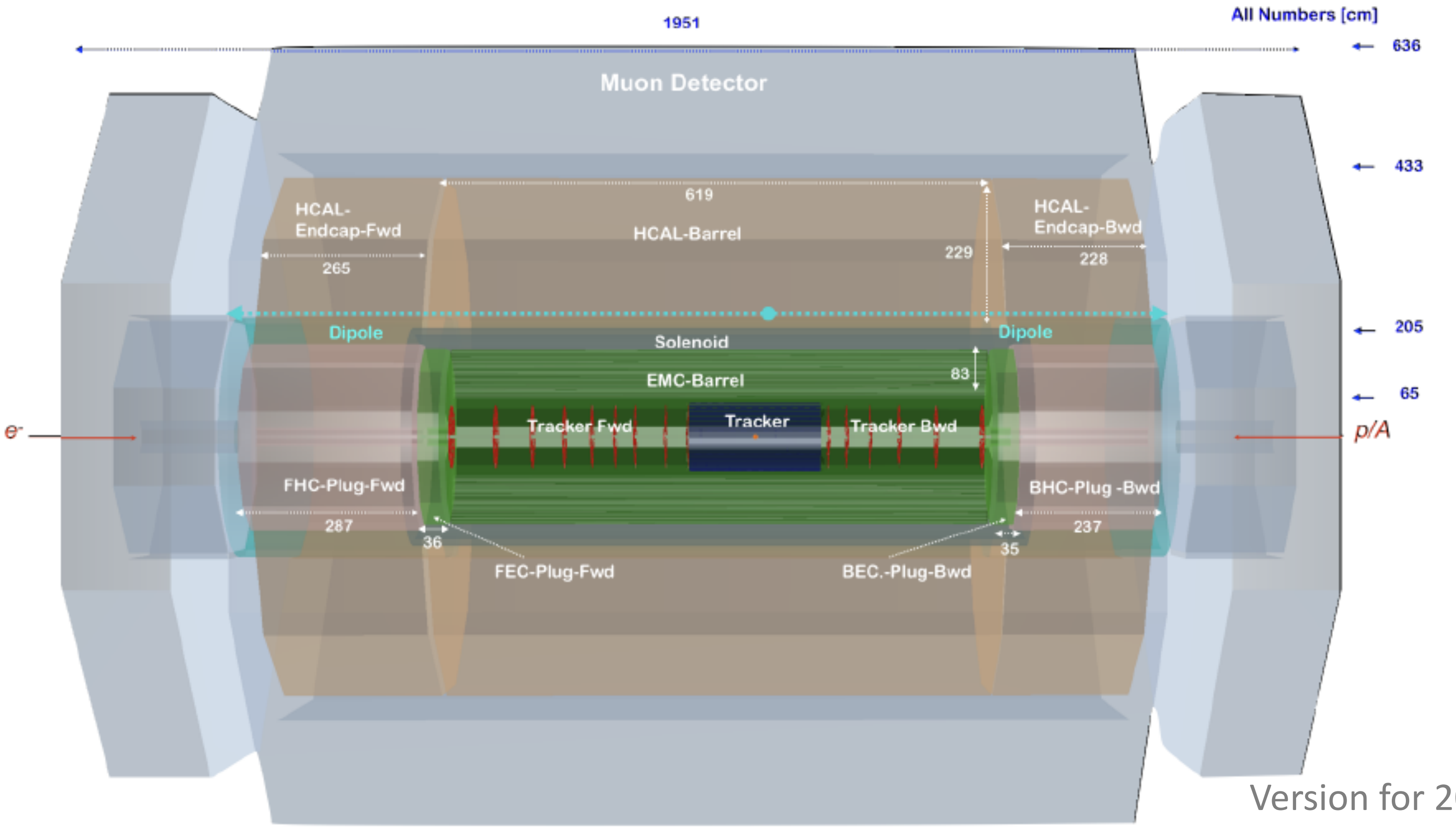
Development of high current, 3-turn, 802 MHz (FCC-ee top) technology with PERLE at Irene Curie Laboratory Orsay

FCC-eh underground facilities



FCC-eh Detector





Version for 20 TeV E_p

Inclusive (CC,NC) [for PDFs, eweak..] and semi-inclusive [Higgs, top, BSM..] deep inelastic scattering

Large acceptance, e-hadron cross calibration, high resolution tracker and calorimeters, 3.5T, taggers for p,n,e, photon
The pile-up at LHeC is 0.1 and at FCC-he about 1. Clean NC/CC distinction.

DIS Energy Frontier Configurations - Luminosity

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15

Table 2.3: Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone *ep* phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in synchronous operation.

Integrated Luminosity in ab^{-1}:
LHeC: 1, FCC-eh: 2 for both E_p

CERN-ACC-NOTE-2020-002 (to be published)

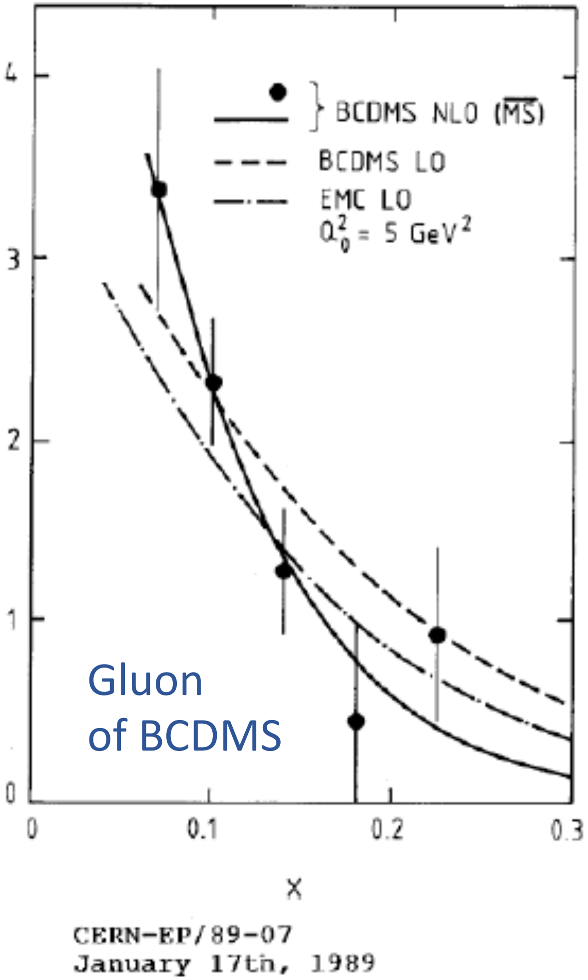
NLO QCD: y > 0.14
Non-singlet: x>0.275 (xg=0)
Singlet+non-singlet (xg ~(1-x)^c)

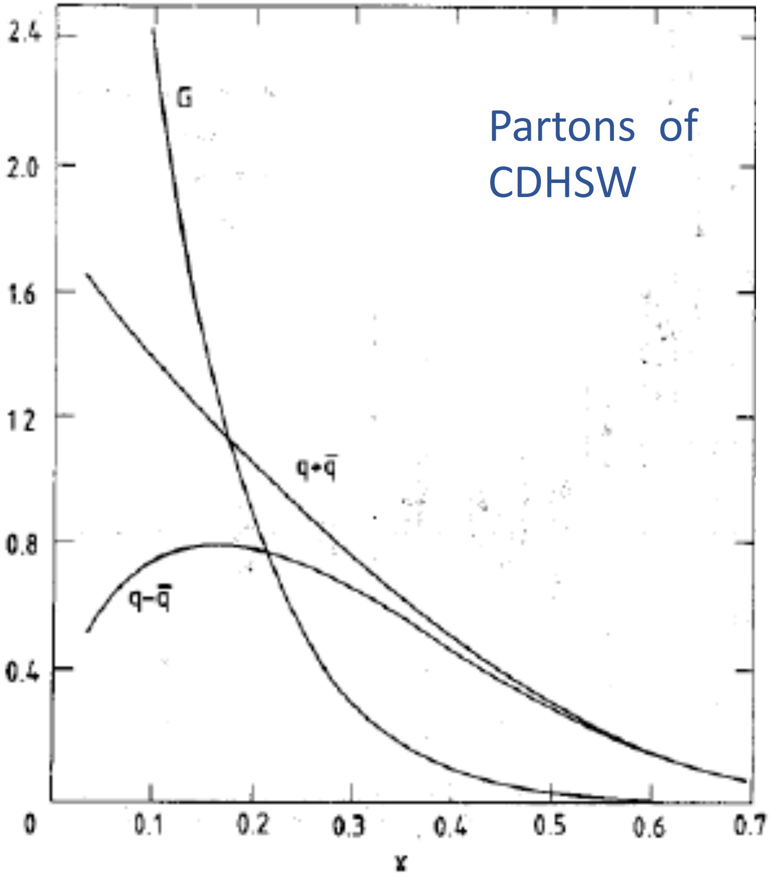
Λ = 220 ± 15 (st)± 50(sy) MeV

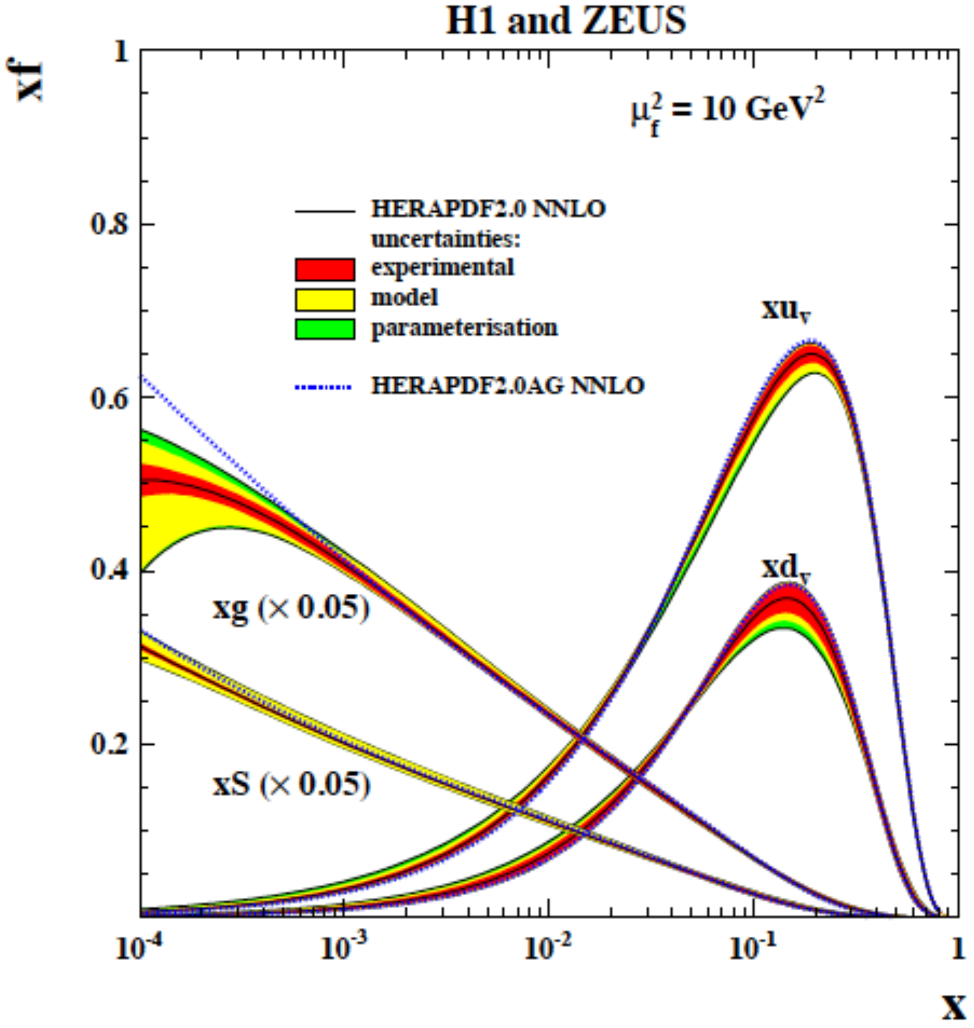
Parton Distributions in DIS

High precision (BCDMS)

Flavour separation (CDHSW)



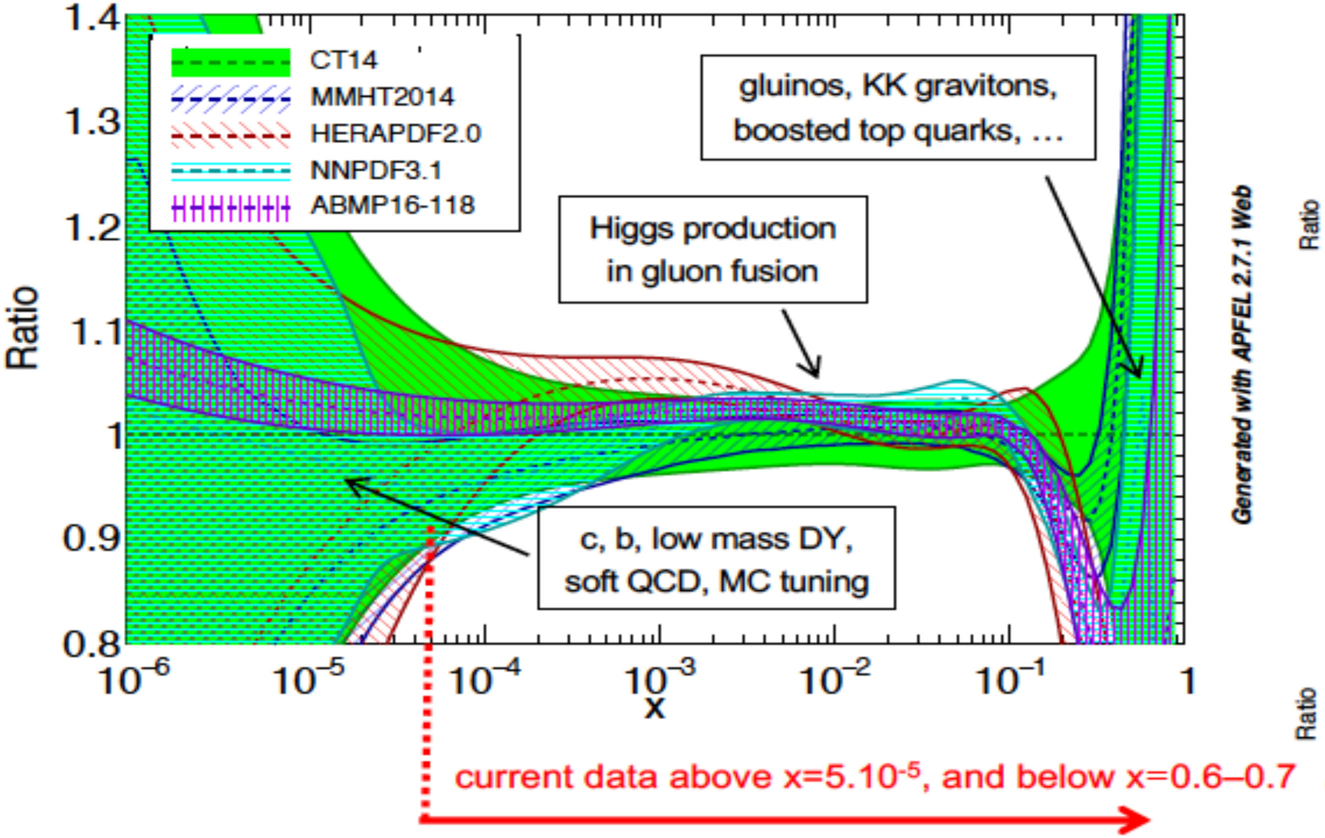




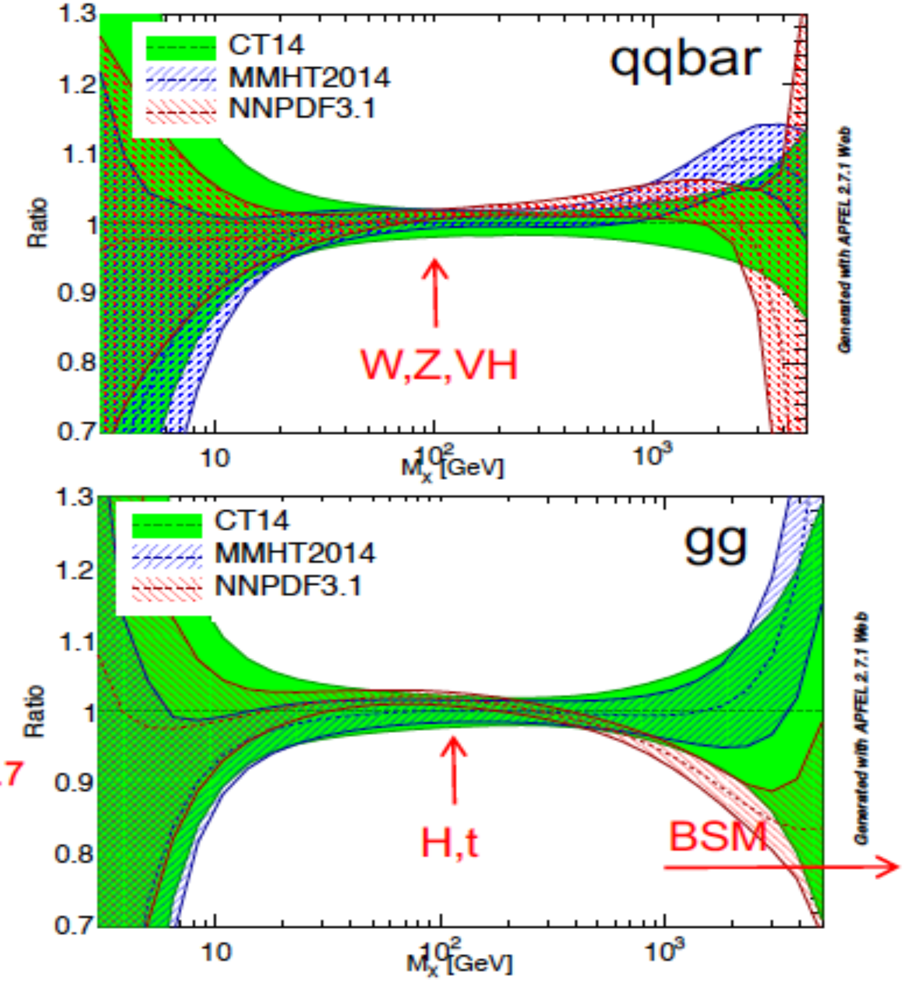
Gluon and sea, rising towards small x

pdfs: the situation today

xg(x,Q), NNLO, Q^2=100 GeV^2, $\alpha_s(M_Z)$=0.118



pdf luminosities (LHC@14TeV)

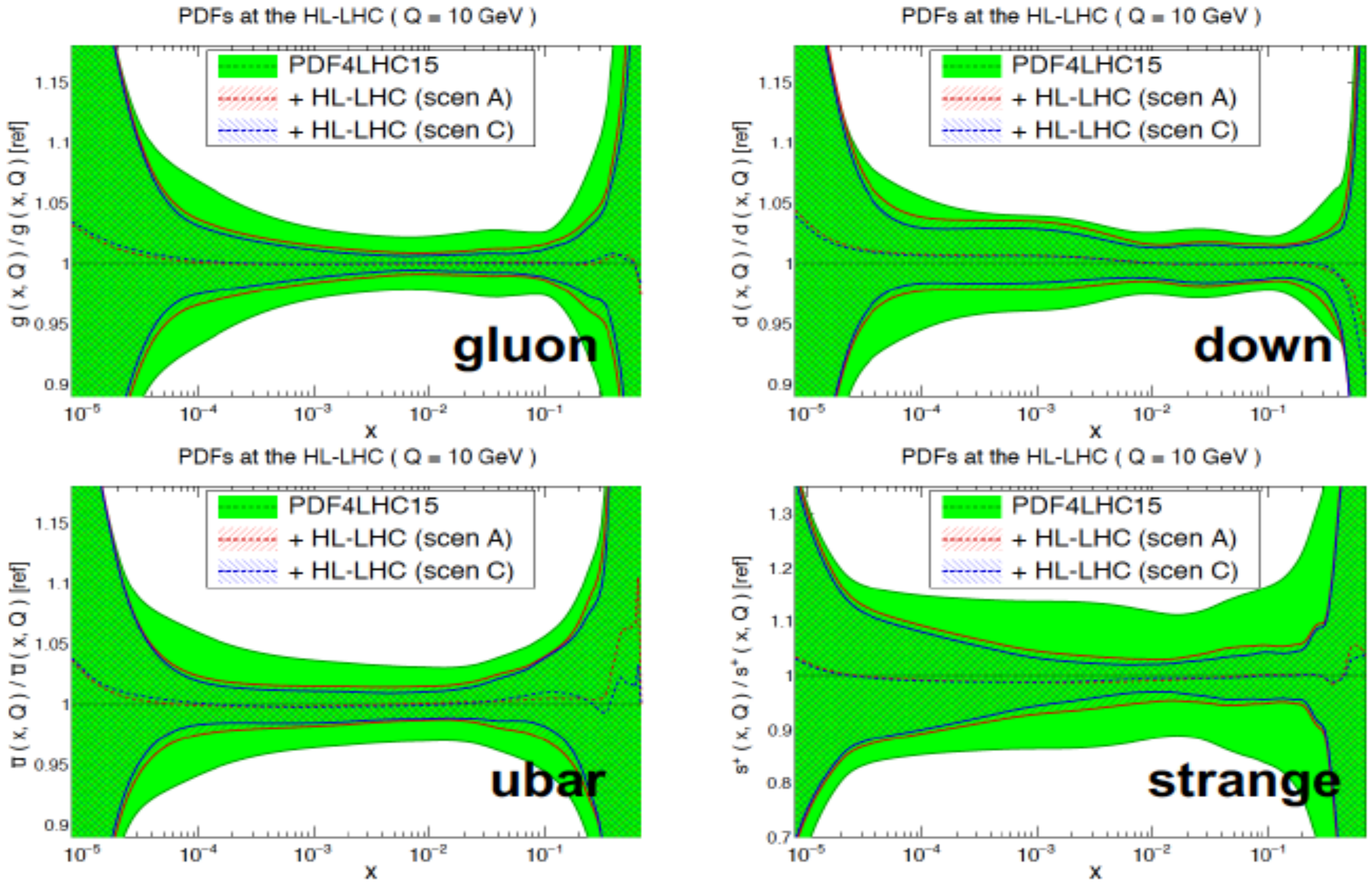


pdfs poorly known at large and small x

higher precision needed also for H, W, t

HL-LHC pdfs

BUT can't we get precision pdfs from the LHC itself?



HL-LHC projections suggest it can go quite some way!

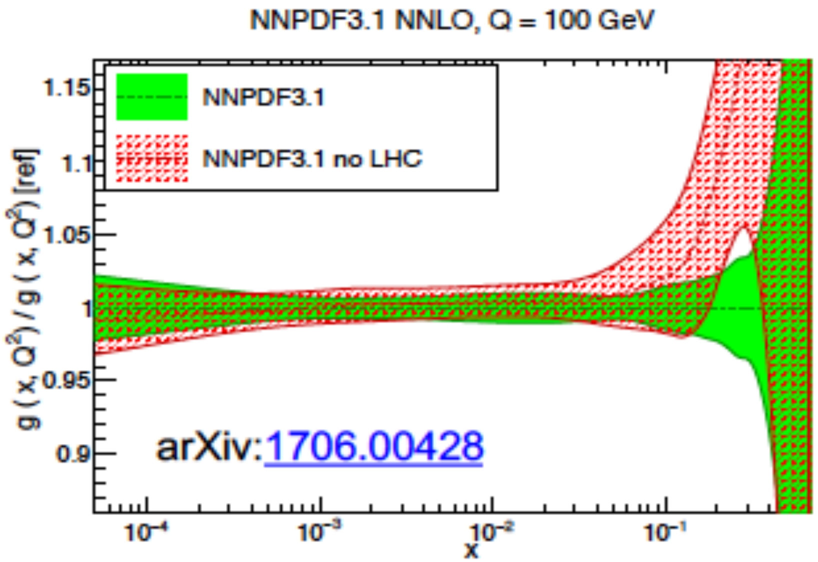
arXiv:1810.03639

BUT projections are in an ideal world, where **many different types of LHC measurements** have well understood systematics, correlations, and no data inconsistencies

single, consistent DIS data set is a tried and tested reliable way to achieve precision

pp vs ep ?

LHC data constrain **pdfs**, BUT do not precisely **determine** them



pp: providing useful constraints in global fits and also interesting results (EG. non-suppressed strange at x ~ 0.01 from ATLAS); must nevertheless be aware that it is not **ep** …

cf. ep

- complete q,g unfolding at all x
- **α**s to order permille precision (not in pp)
- clear theory (EG. N3LO, scale choice, hadronisation)
- strong effects from Q^2 variation (which cannot come from EG. W, Z at $Q^2=10^4$ GeV^2)
- HQ separation: s,c,b,(t)
- understanding of small x dynamics, EG. BFKL, saturation, … (comes from F_2 and F_L)
- gives external precision input for QCD subtleties (EG. factorisation, resummation), and for subtle discoveries
- single DIS dataset a tried and tested reliable way to achieve precision (**Δ**X^2=1; cf. current LHC measurements; issues understanding systematics, correlations, data inconsistencies, …)

New Simulations to understand variations

dataset	e charge	e pol.	lumi (fb-1)	
NC/CC	–	–0.8	5, 50, 1000	luminosity
NC/CC	+	0	1, 10	positron
NC/CC	–	0	50	polarisation (important for EW)
NC/CC	–	+0.8	10, 50	
NC/CC	–	0	1	low-E (p: 1 TeV)

uncert. assumptions:
elec. scale: 0.1%
hadr. scale 0.5%
radcor: 0.3%
γp at high y: 1%
uncorrelated uncert.: 0.5%
CC syst.: 1.5%
luminosity: 0.5%

*corresponds to possibility of smaller ERL cf. previous 60 GeV simulations †except for low-E

various combinations studied;
shown frequently in following slides:

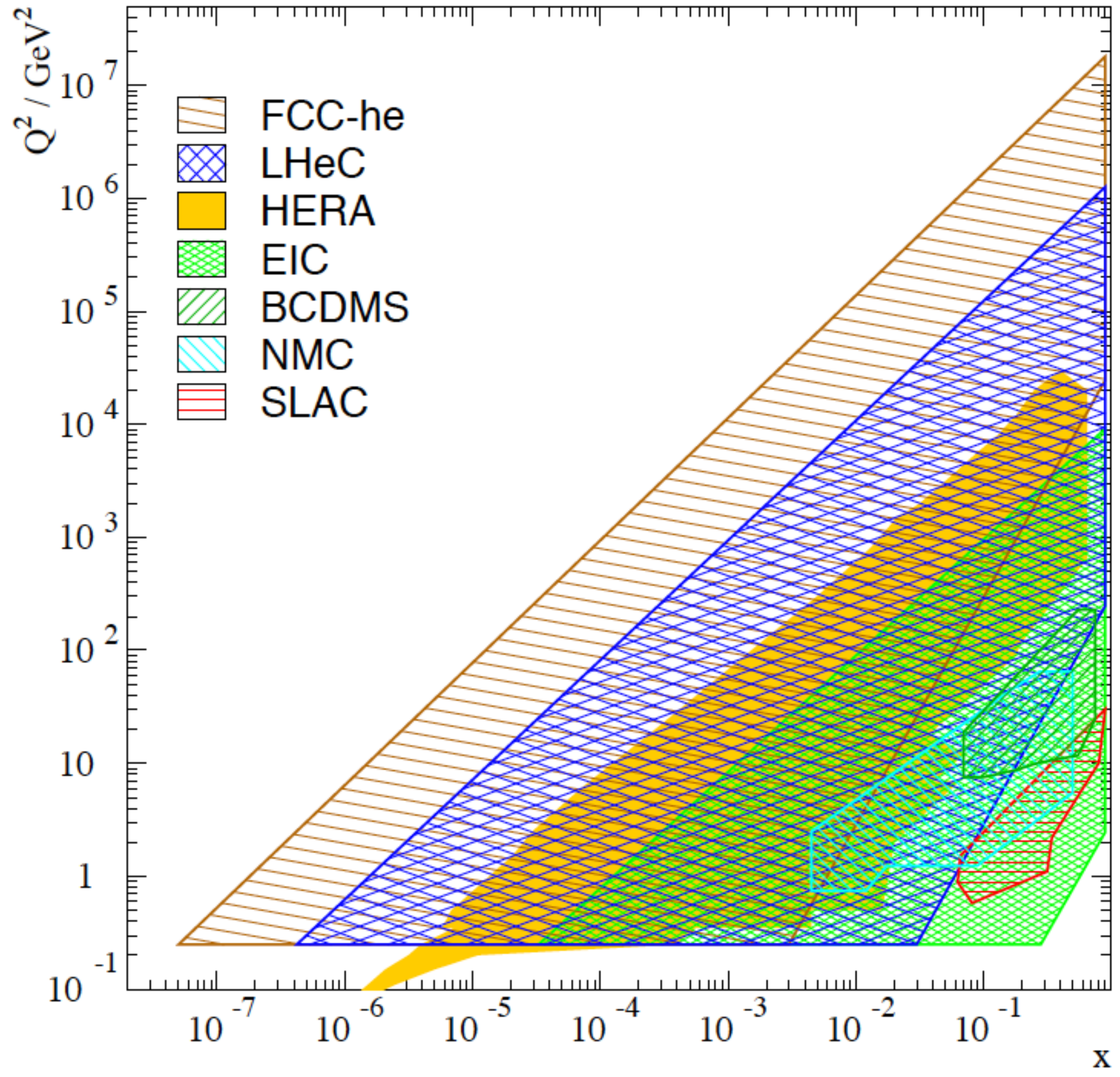
LHeC 1st Run
(50 fb^{-1} e– only; 3 yrs)

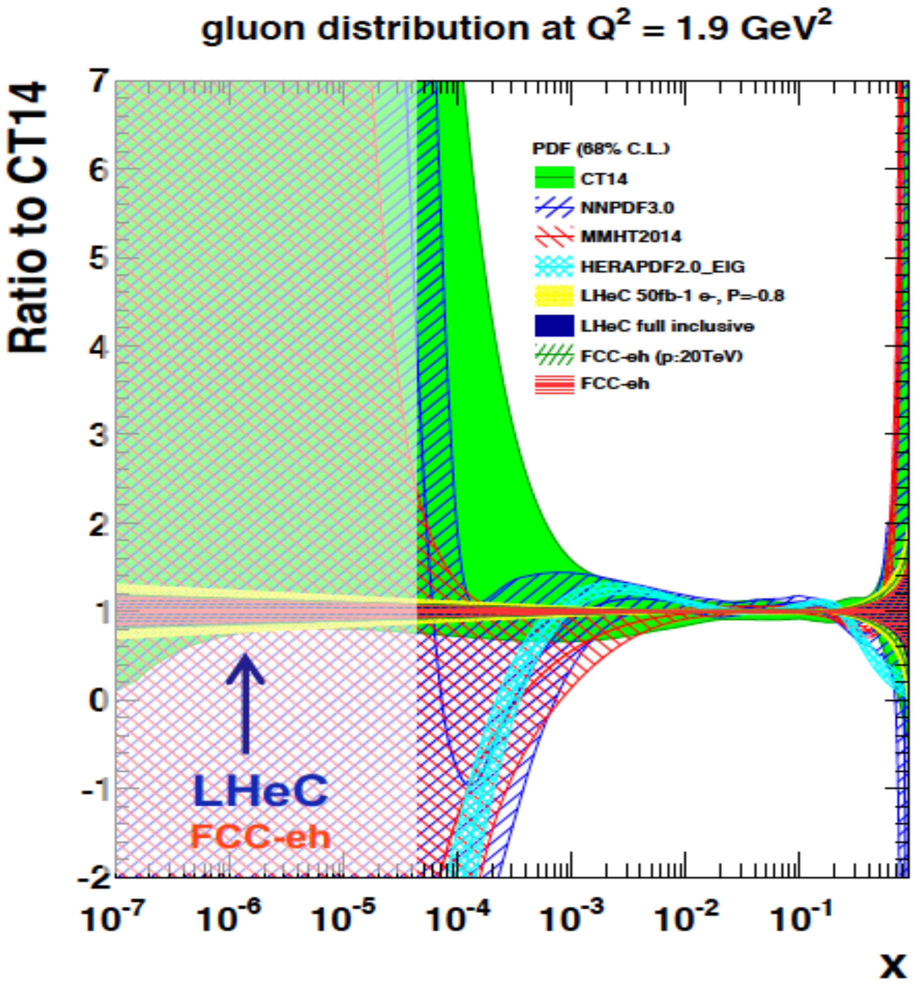
LHeC full inclusive

Similarly new pseudo data for **FCC-eh (20 TeV)**

Inclusive, e^-, up to 2ab^{-1}

Kinematics and the Gluon





Proton at small x is gluon dominated.

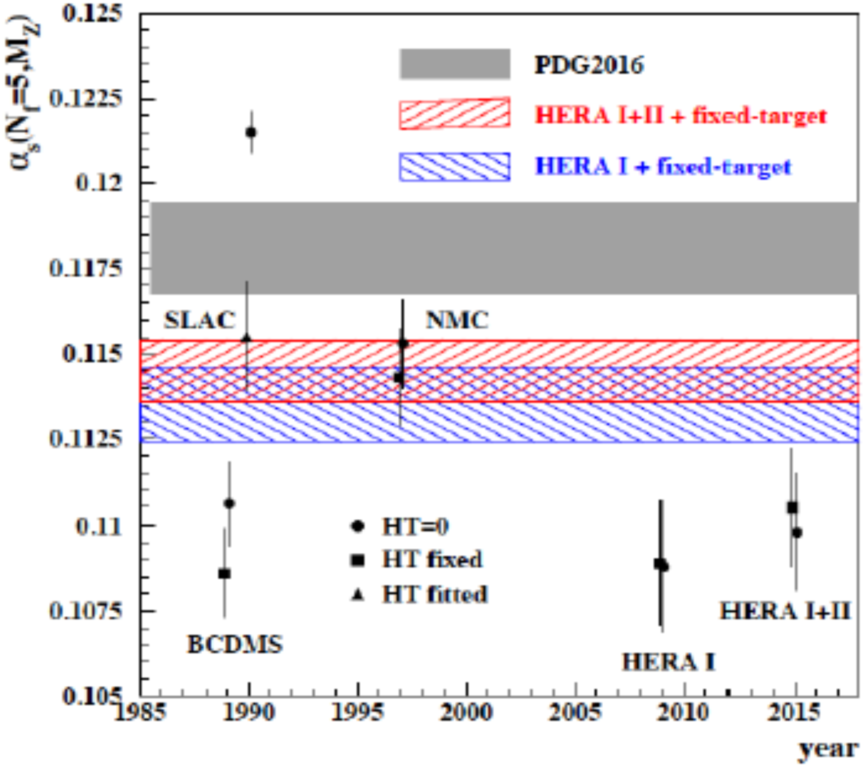
To measure xg one has to control the log derivative of F_2

This requires data for up to Q^2 of 20 GeV^2

Thus the EIC/HERA/LHeC/FCC-eh precision on xg ends at Bjorken a few times 10^{-3} / 10^{-4} / 10^{-5} / 10^{-6}

EIC measures xg where we know it best. FCC-eh max range

$\alpha_s(\mu)$ in Deep Inelastic Scattering



ABMP 2017 $\alpha_s = 0.1140 \pm 0.0009$

DIS: Fixed target: higher twist corrections $1/Q^2$, nuclear corrections, small lever arm, gluon?

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\,(exp)\,{}^{+0.0009}_{-0.0005}\,(model)$$

H1 inclusive (1998) NLO
hep-ph/0012053 – highest cited H1 only

$$\alpha_s(M_Z^2) = 0.1157 \pm 0.0020\,(exp) \pm 0.0029\,(thy)$$

H1 only jets (2017) NNLO jets!

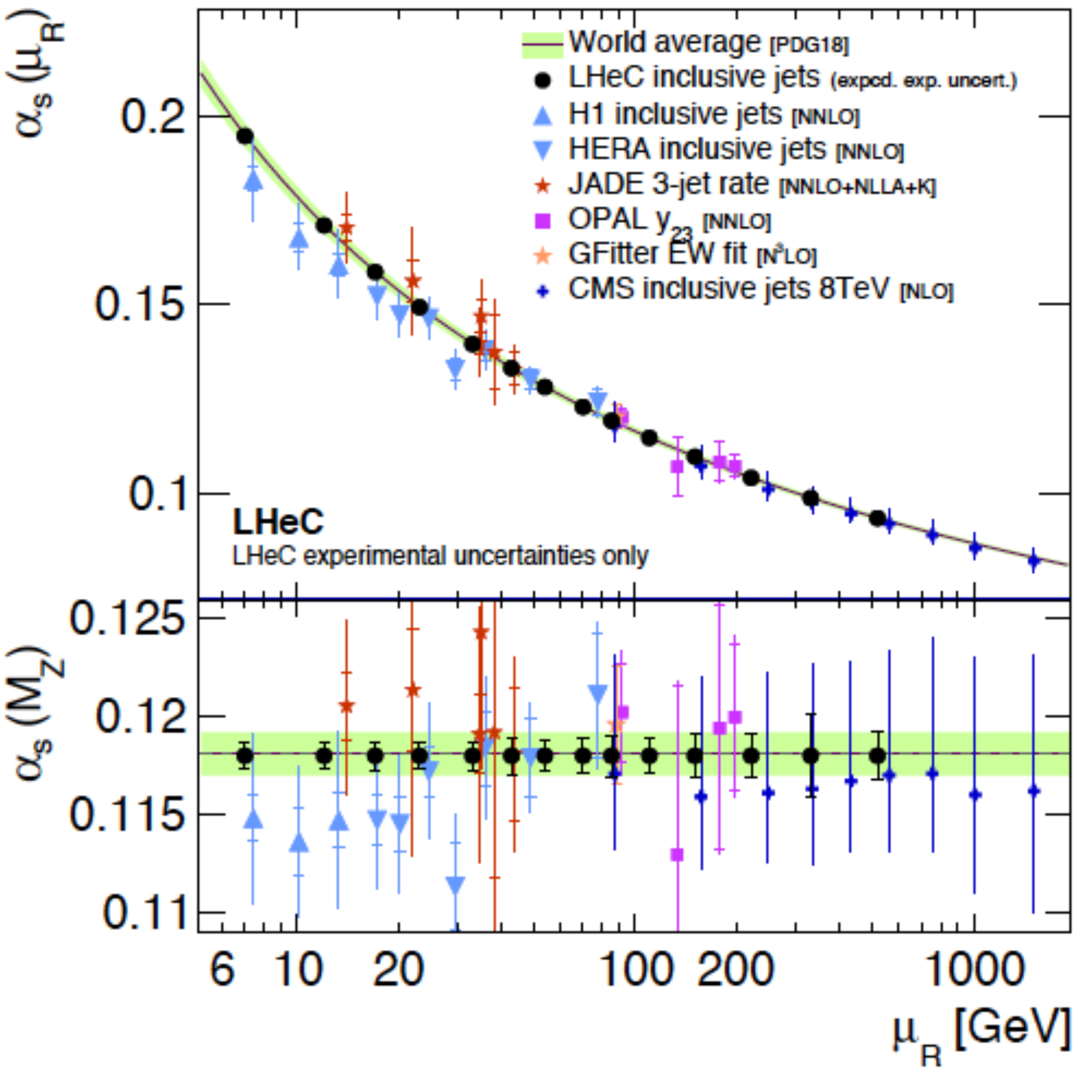
$$\alpha_s = 0.1142 \pm 0.0028\ (\mathrm{tot})$$

H1 inclusive and jets (2017) NNLO

→ It is well possible that α_s is smaller than hitherto assumed. Current practice to exclude ABM is questionable. Like in the lattice case, one constructs, for perhaps respectable reasons, a norm, which gives the impression of higher accuracy than a critical evaluation would lead to.

Current strong coupling precision at best 1-2%: FCC ee and eh want 1-2 per mille

Strong Coupling

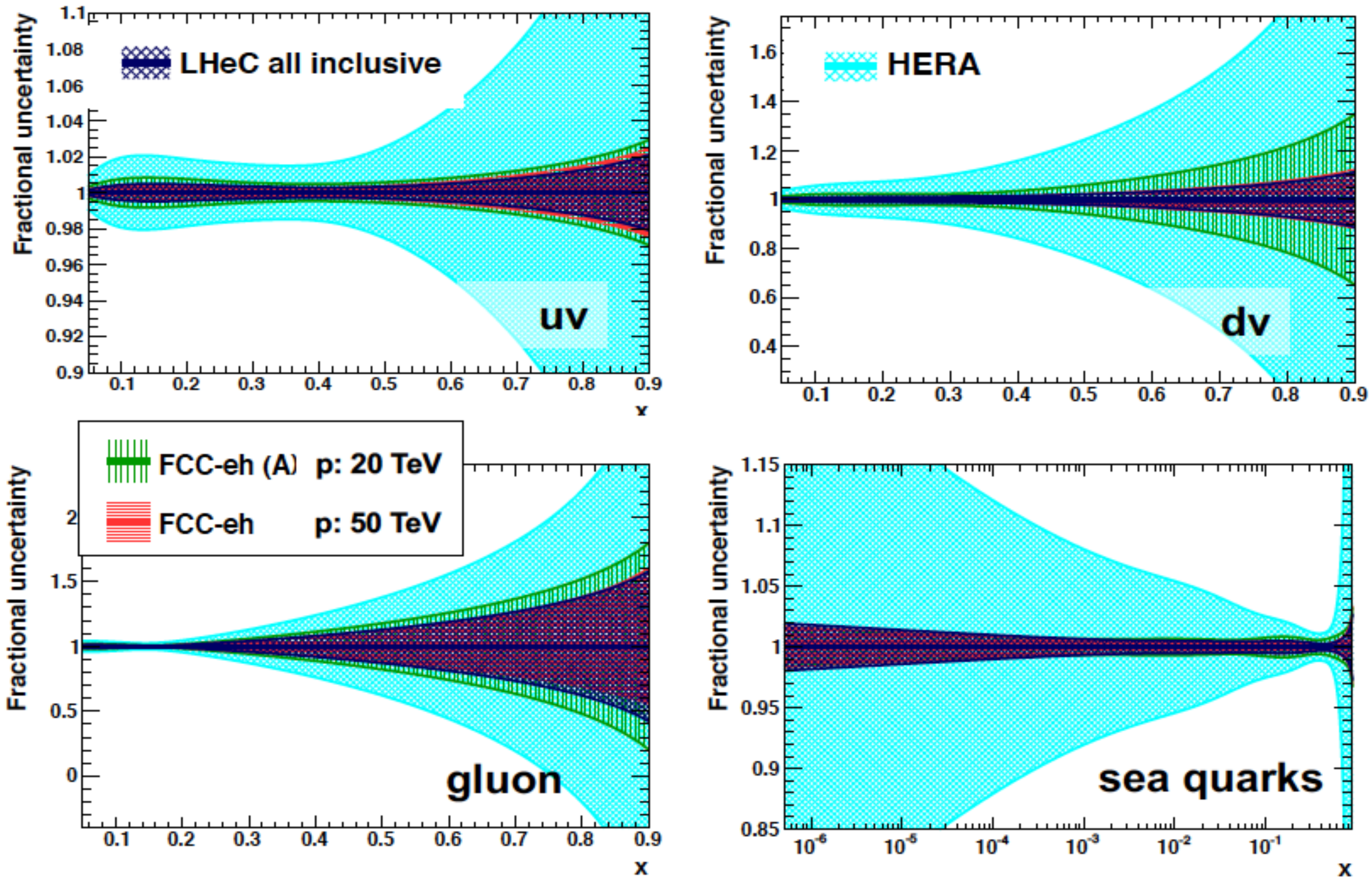


New study, so far on LHeC only, of expectation for Jets
both inclusive and Jets yield 0.1% type precision:
GUT, lattice, inclusive-jets, DIS – e^+e^-

Exp. uncertainty	Shift	Size on σ [%]
Statistics with 1 ab^{-1}	min. 0.15 %	0.15 – 5
Electron energy	0.1 %	0.02 – 0.62
Polar angle	2 mrad	0.02 – 0.48
Calorimeter noise	±20 MeV	0.01 – 0.74
Jet energy scale (JES)	0.5 %	0.2 – 4.4
Uncorrelated uncert.	0.6 %	0.6
Normalisation uncert.	1.0 %	1.0

$$\Delta\alpha_s(M_Z)(\mathrm{jets}) = \pm 0.00013_{(\mathrm{exp})} \pm 0.00010_{(\mathrm{PDF})}$$

Standard Fit



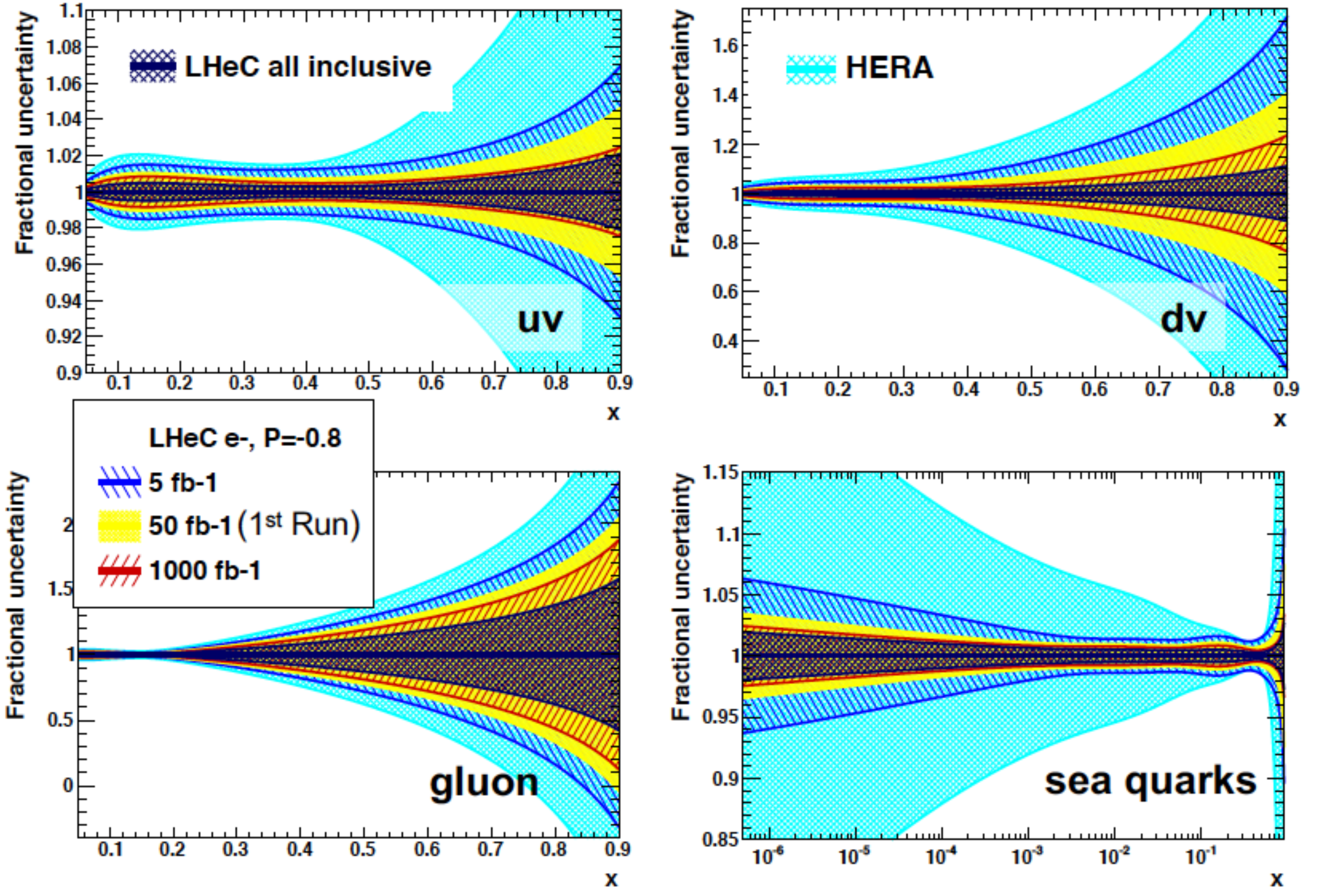
Classic HERA Fit using simulated eh data

LHeC, FCC-eh with sqrt(s) from 1.3 to 3.5 TeV

FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (**NB, NO e+ yet; impact especially in dv**)

FCC-eh: CDR, volume 1, EPJ C79 (2019), no.6, 474

Impact of Luminosity

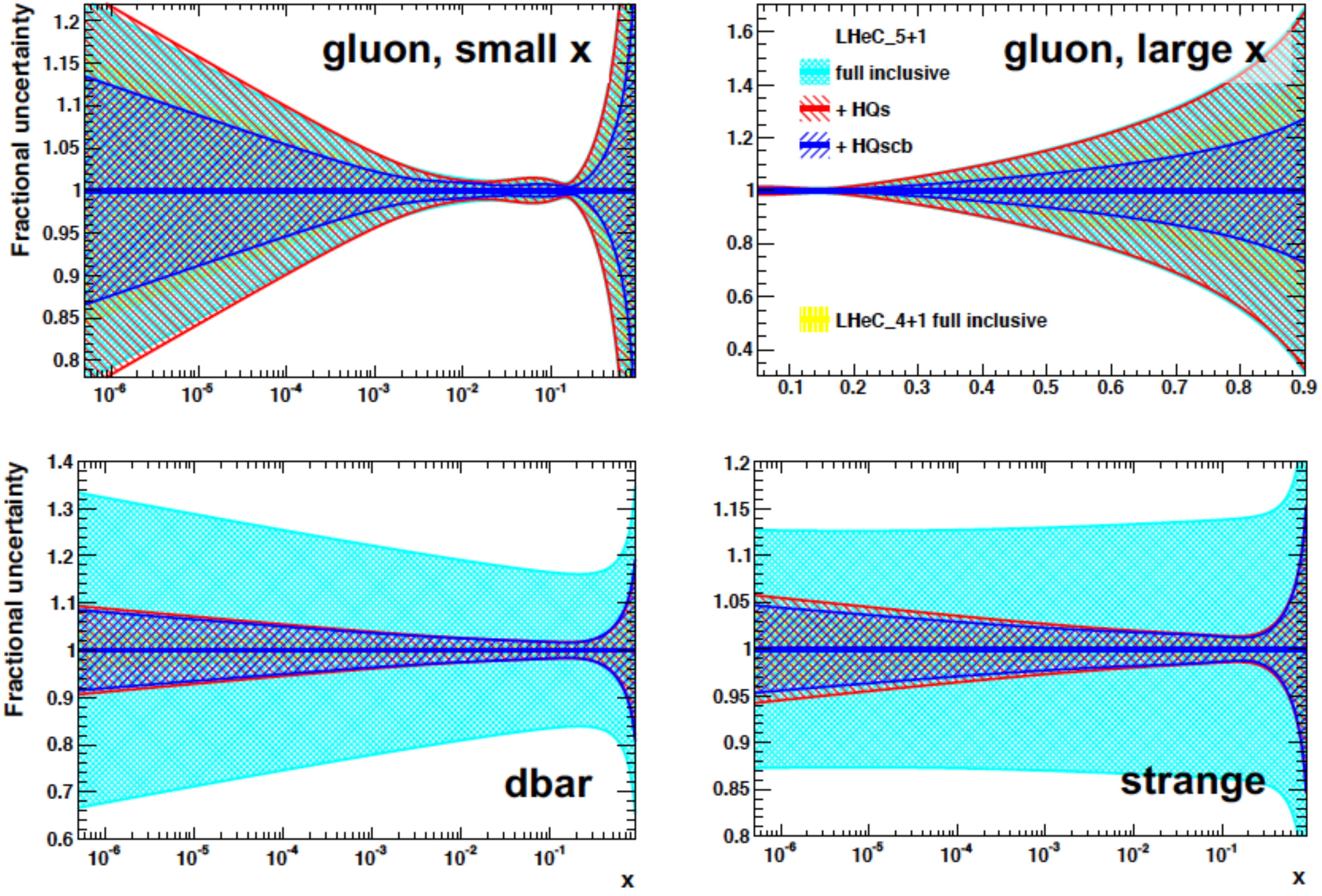


Example study for LHeC:

Main results follow with 5 or 50fb^{-1}
Which is 10 -100 x H1
But extended range.

Important special runs:
Low E_e, low E_p, e^+

Atobarn^{-1} are crucial
For Higgs and BSM,
Good for high x, but
not decisive for PDFs



more flexible parameterisation (5+1): **xuv, xdv, $x\bar{U}$, $x\bar{d}$, $x\bar{s}$** and **xg**

Ansatz Variation

Inclusive NC+CC
Sensitive to 4 PDFs +xg

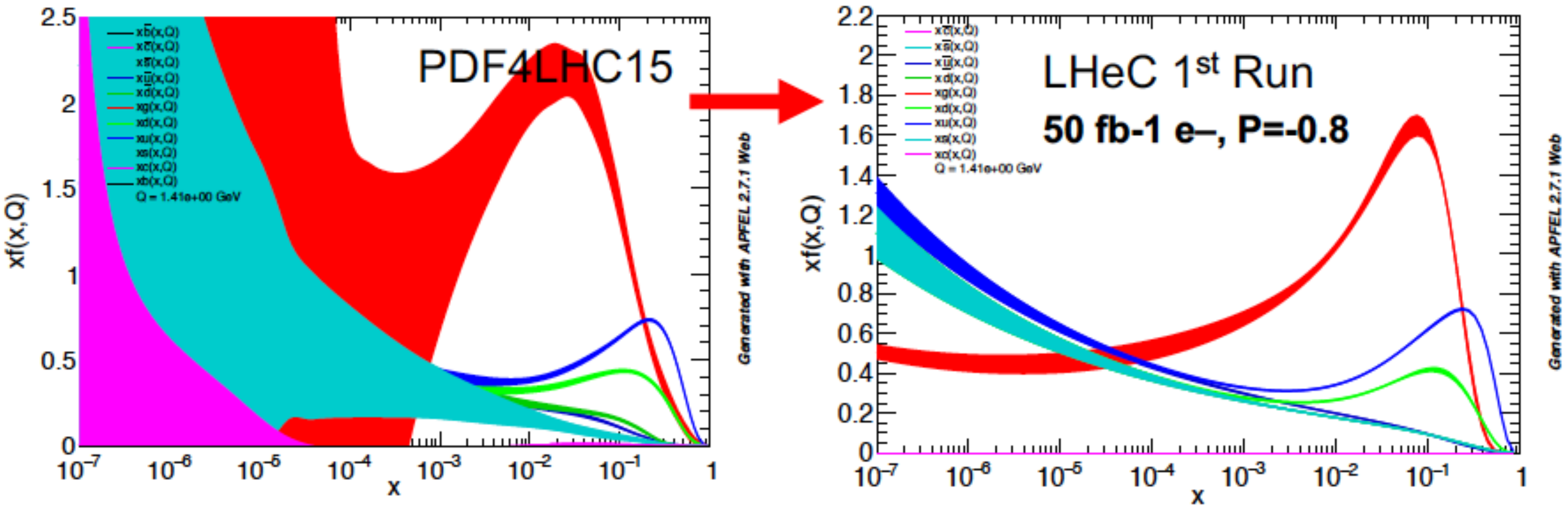
Fitting > 4 is impossible
without extra input.

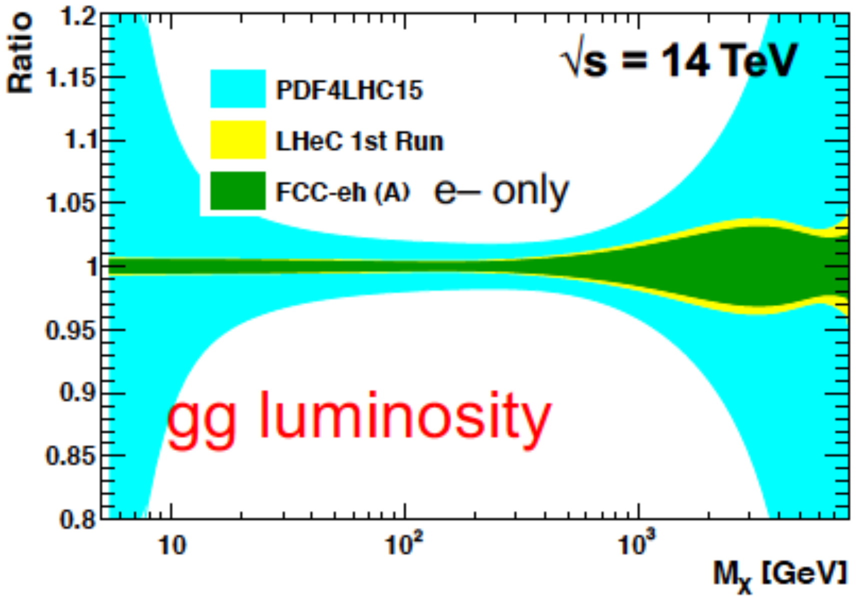
FCC-eh (LHeC) measures
Strange, bottom, charm
Through precise tagging

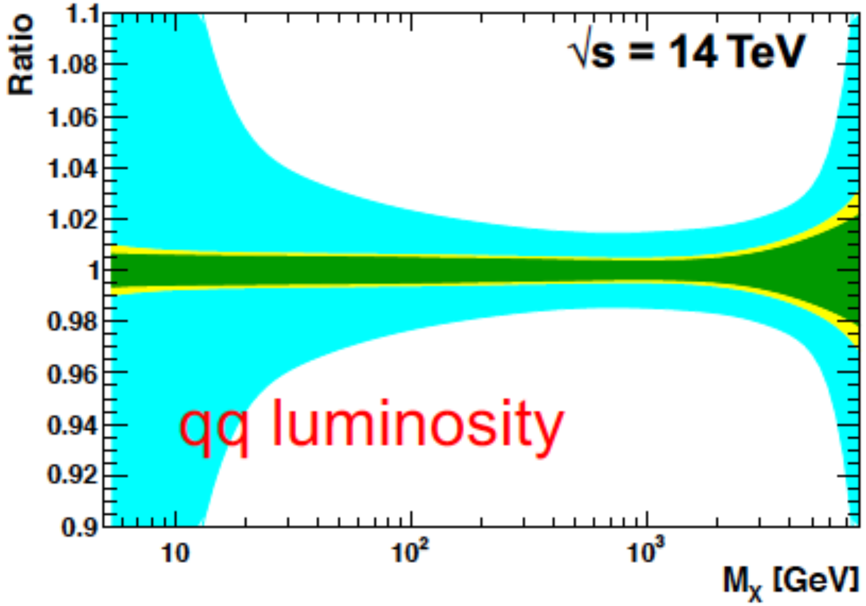
c, b usually added via
boson-gluon fusion

fit, up, down and s

→ Recover high
Precision and resolve
Parton structure fully.
- Impossible at HERA

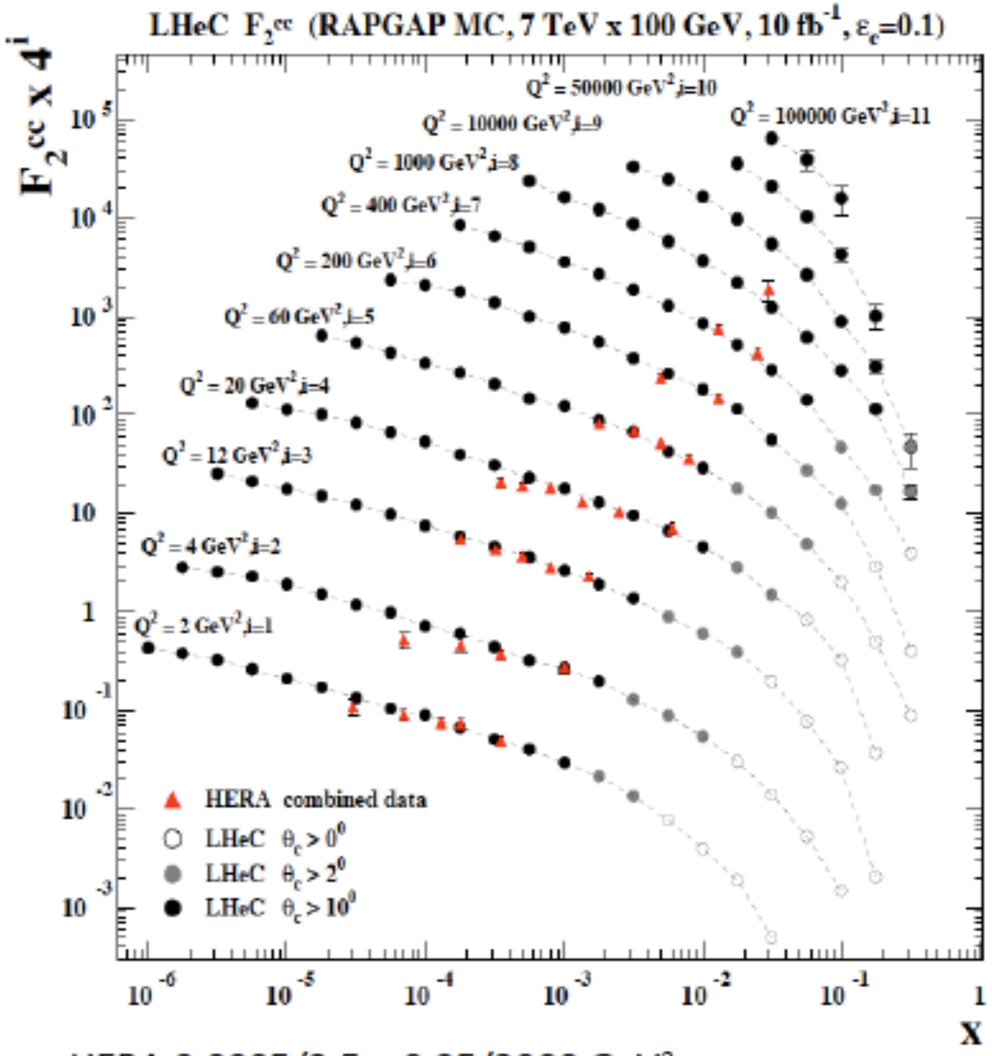

PDF4LHC15
LHeC 1st Run
50 fb-1 e–, P=-0.8
xf(x,Q)
x
Q = 1.41e+00 GeV
Generated with APFEL 2.7.1 Web


√s = 14 TeV
PDF4LHC15
LHeC 1st Run
FCC-eh (A)
e– only
gg luminosity
Ratio
M_X [GeV]


√s = 14 TeV
qq luminosity
Ratio
M_X [GeV]

Charm F_2^{cc} and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005/2.5 .. 0.05/2000 GeV^2
LHeC 0.00001/1 .. 0.2/200000 GeV^2

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

Heavy Flavour with LHeC
Beam spot (in xy): 7µm
Impact parameter: better than 10µm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

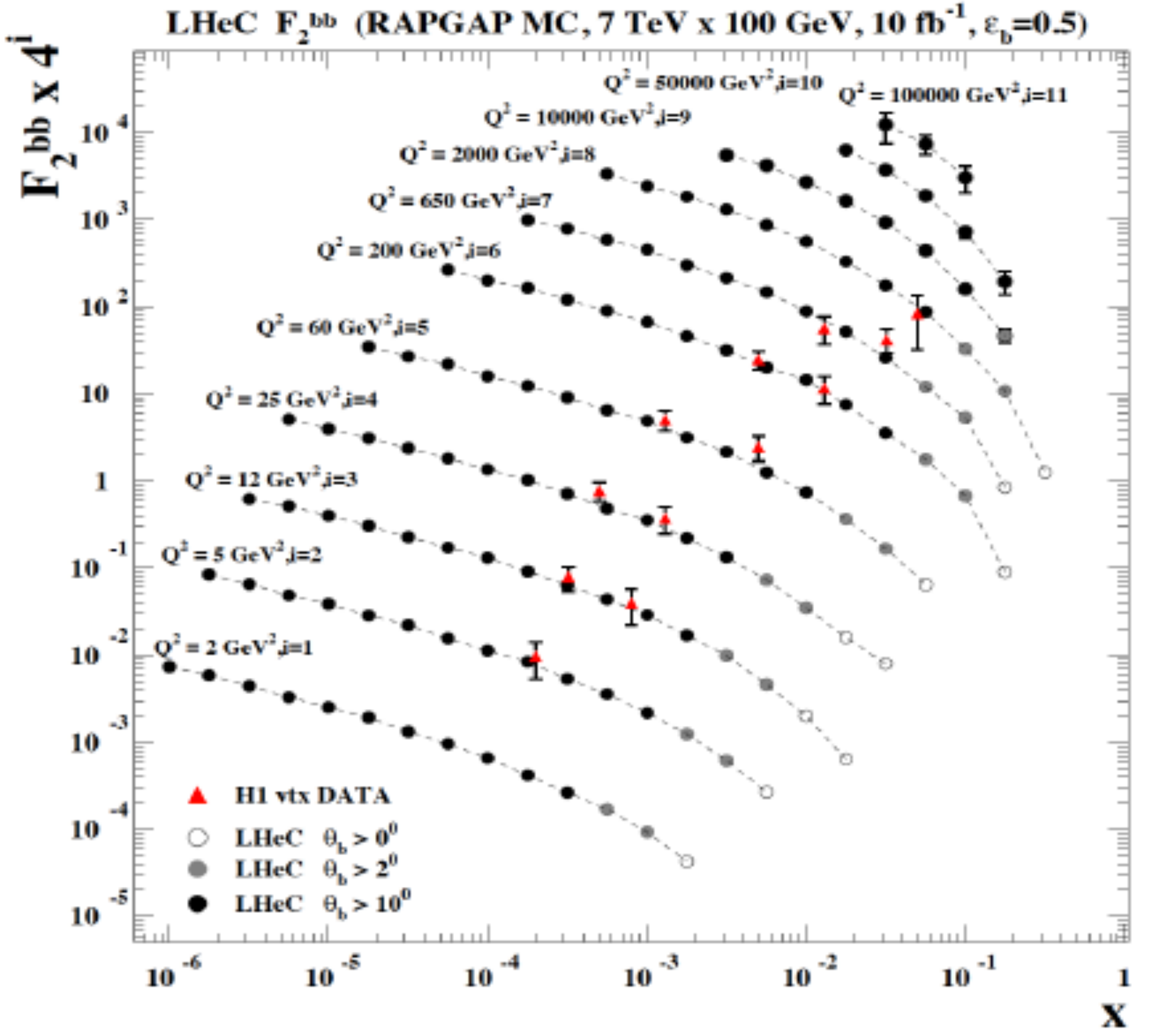
	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

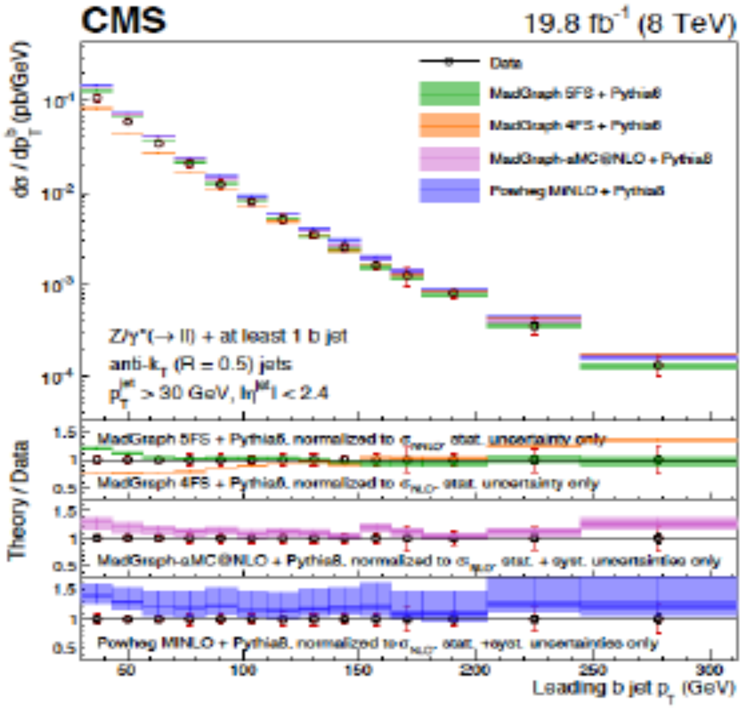
LHeC determines strong coupling to 0.1%
High precision PDF data will reduce the mod and par errors by a very large amount.

Determination of charm mass to 3 MeV: crucial for M_W in pp or H→ cc in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs

Bottom F_2^{bb} and Mass

LHeC CDR arXiv:1206.2913





Huge improvement vs HERA for the same reasons as for charm

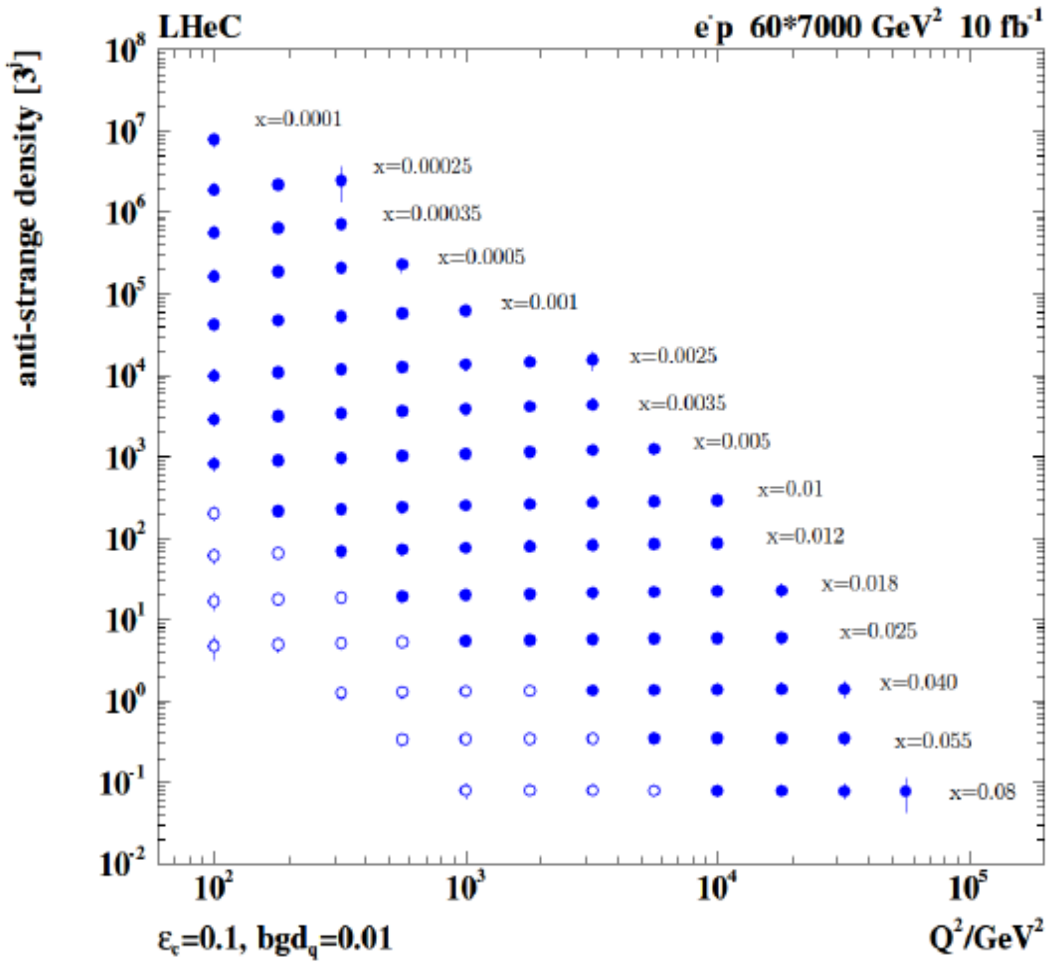
Bottom density not well known

Scheme dependence affects LHC interpretations

In MSSM: Higgs from bb→ H not gg (we only miss the MSSM..)

$m_b(m_b)$ with LHeC to 10 MeV

Strange Quark Density



High luminosity

High Q^2

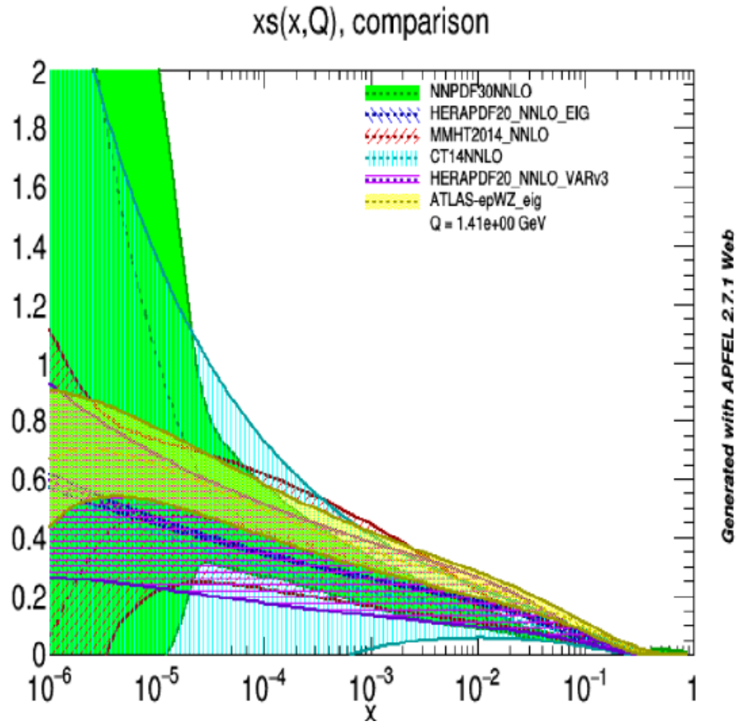
Small beam spot

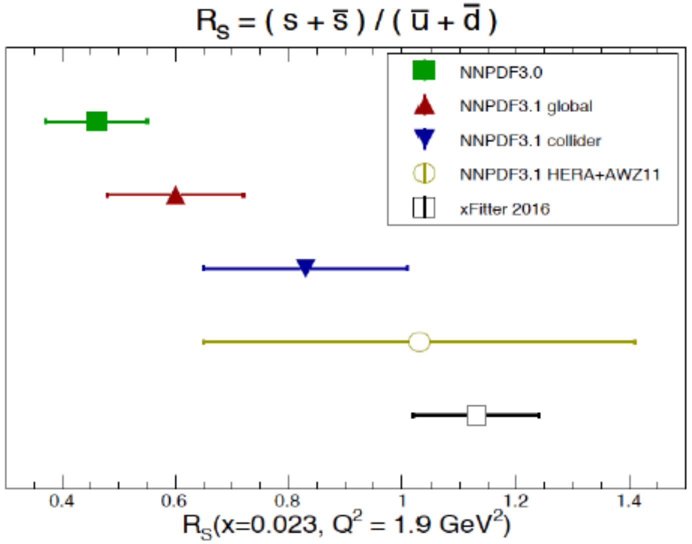
Modern Silicon

NO pile-up..

→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} .. 0.1$
$Q^2 = 100 – 10^5\ GeV^2$





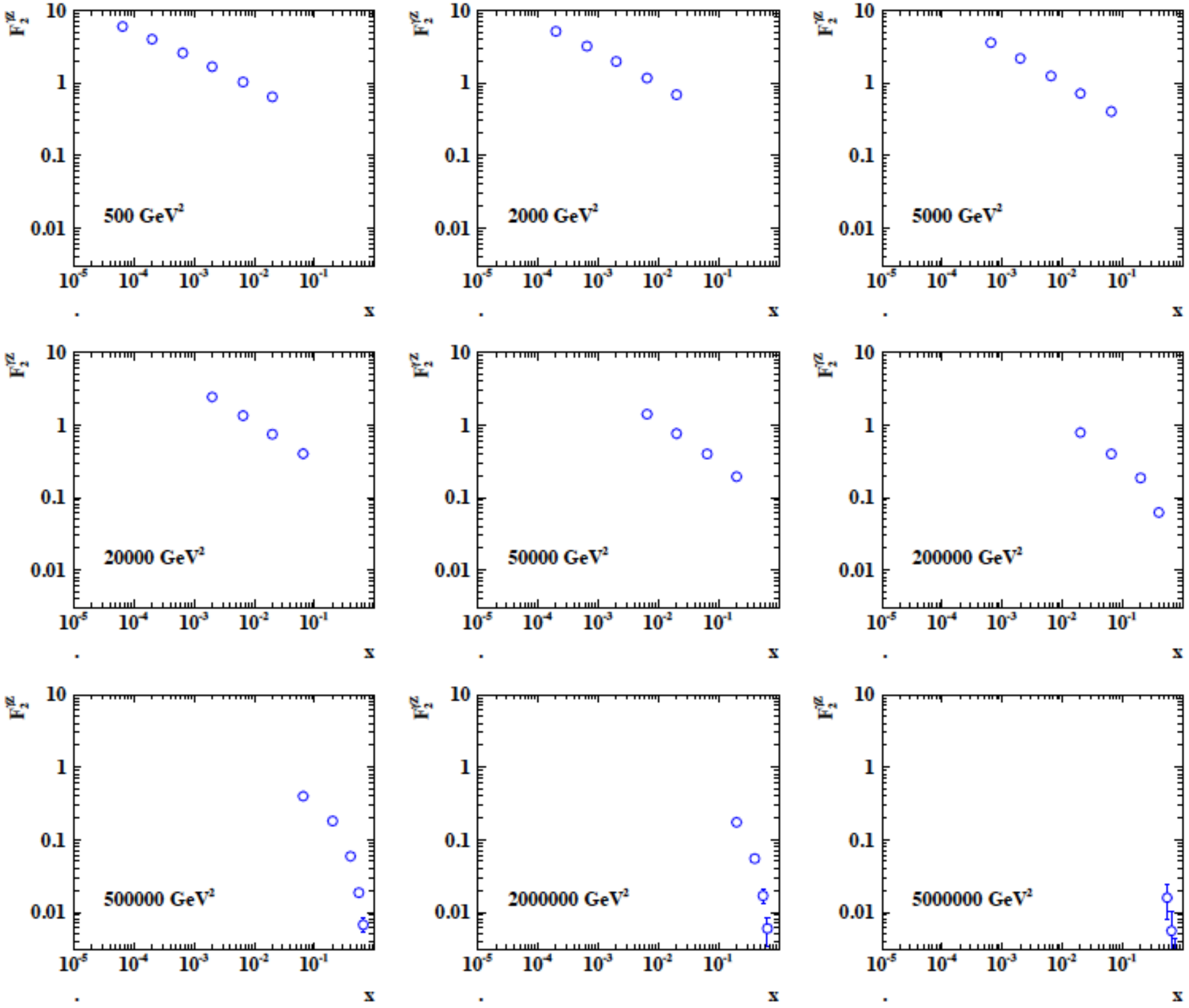
Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

Strange density from charm tagging in CC. FCC-eh extends to 10^{-5} in x

update will be very similar..

NC Weak Interactions

FCC-eh with 100 fb^{-1}



$$\frac{\sigma^{\pm}_{r,NC}(P_L)-\sigma^{\pm}_{r,NC}(P_R)}{P_L-P_R} =$$

$$\kappa_Z[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z}] \simeq \mp \kappa_Z a_e F_2^{\gamma Z}$$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = x \sum (e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q})$$
$$(xF_3^{\gamma Z}, xF_3^Z) = 2x \sum (e_q a_q, v_q a_q)(q - \bar{q}),$$

$$\frac{2}{P_L - P_R} \cdot A^{\pm} \simeq \pm \kappa \frac{1 + d_v/u_v}{4 + d_v/u_v}.$$

d/u at high x: Q^2 ~ TeV^2

$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta)$$

Sea-antiquarks and small x valence

New constraints on parton distributions from high Q^2: NC Z exchange

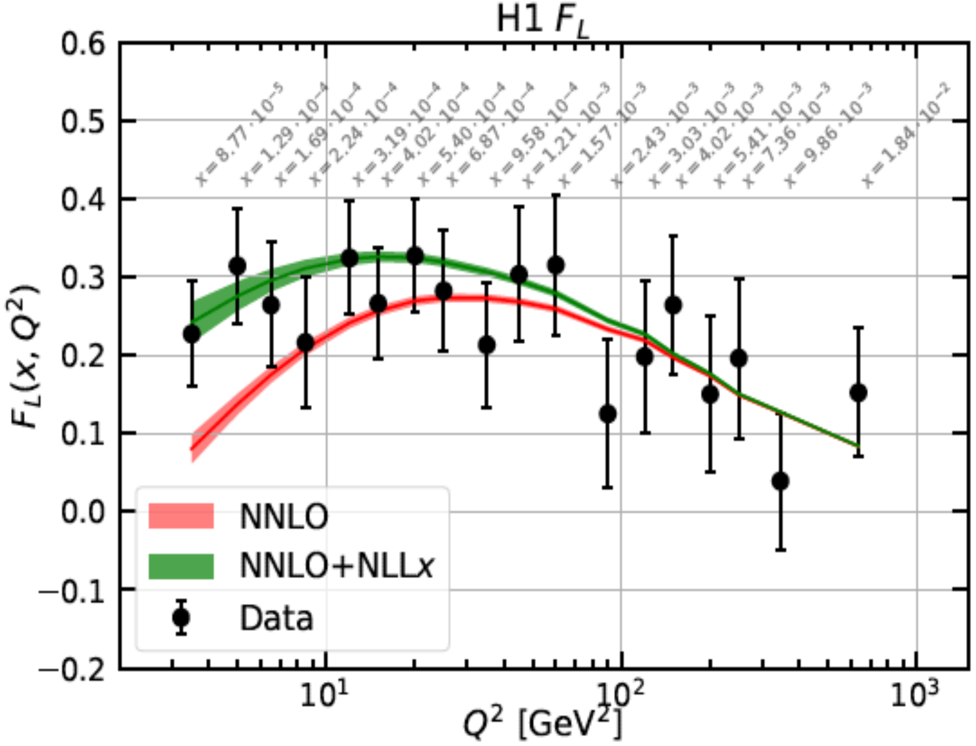
MK, T Riemann, 10.1007/BF01571719

Polarisation asymmetry measurement in e$^-$p: huge Parity Violation (C Prescott 1978).

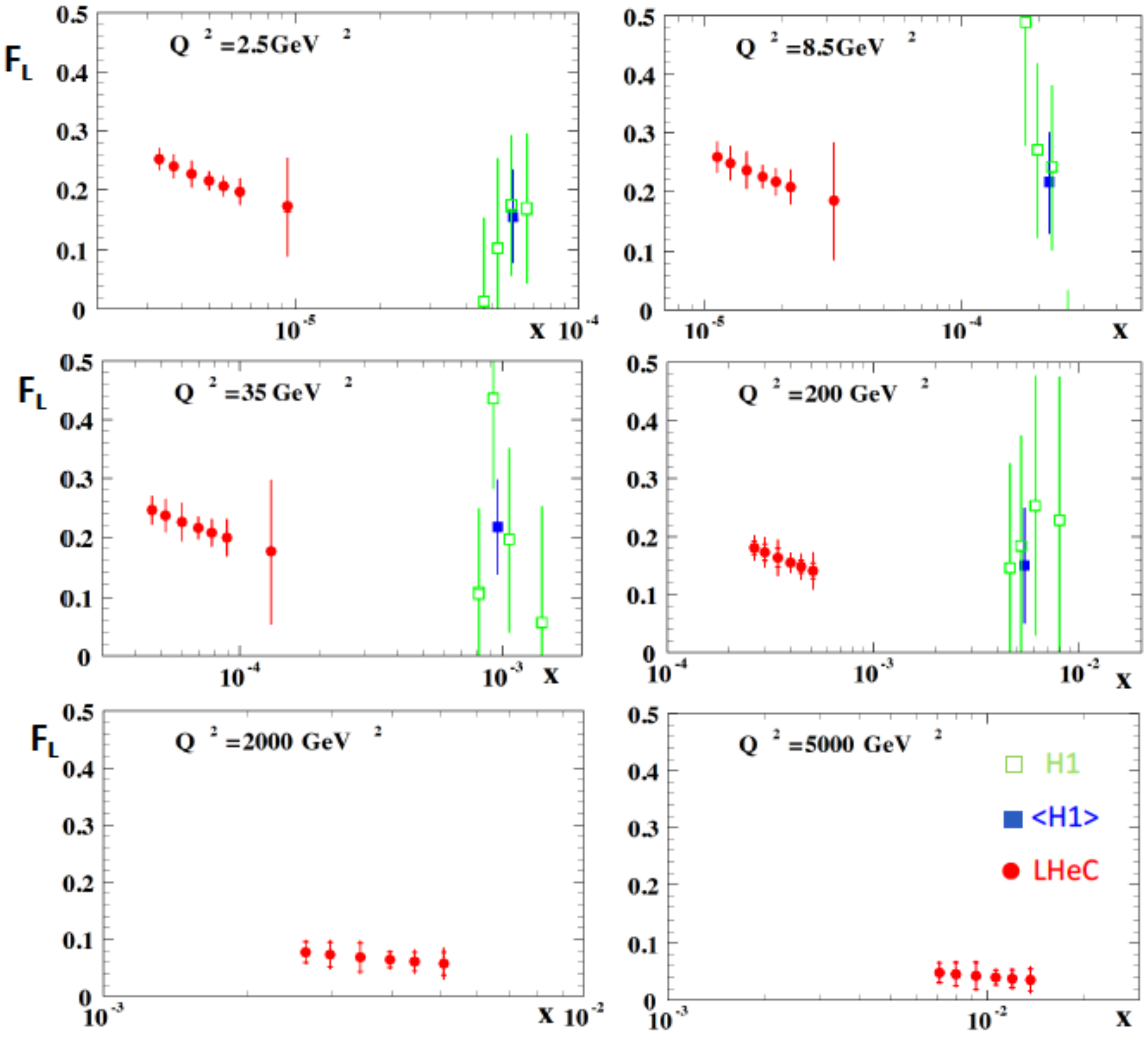
$$\frac{Q^4 x}{2\pi\alpha^2 Y_+}\cdot\frac{d^2\sigma}{dx dQ^2} = \sigma_r \simeq F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2)$$

F_L is an independent measure of xg

Small x theory: resummation affects F_L

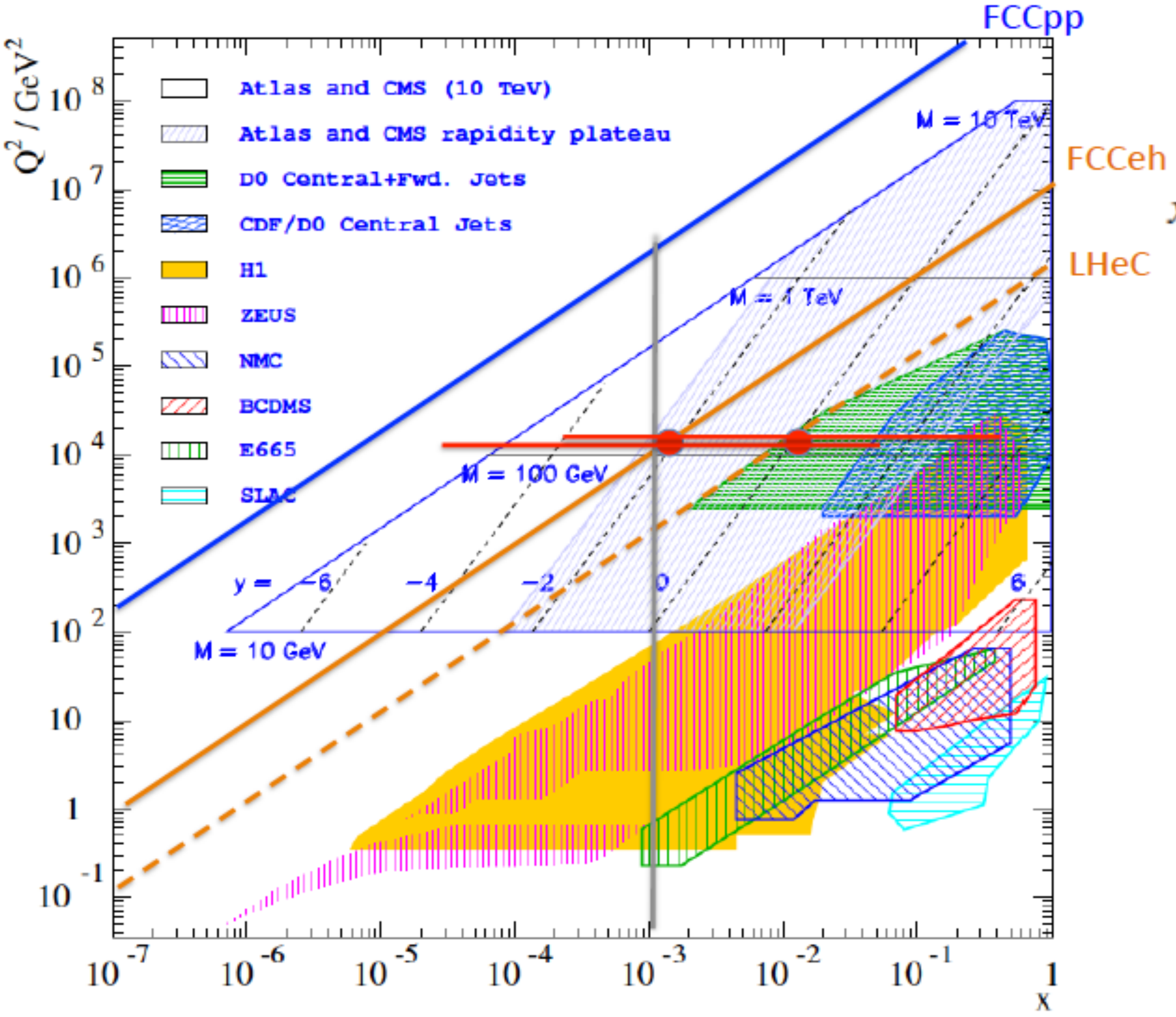


→ Needs much higher precision than H1's



High precision from very low x 10^{-6} (LHeC) → 10^{-7} (FCC)

Very challenging measurement (cf H1 paper), lumi O(1) fb^{-1}



$$x = Me^{\pm y}/\sqrt{s}$$

y=0: $x_0 = M/2E_p$

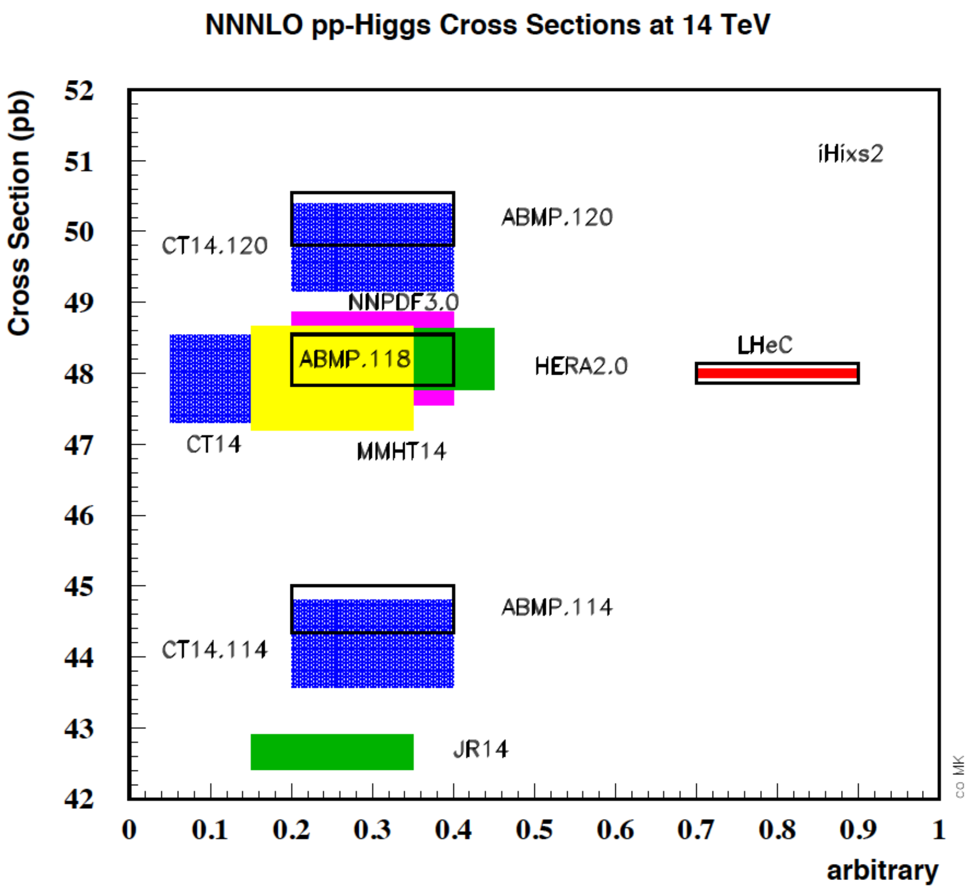
Higgs at LHC:

$x_0 = 0.0089$

$x_0 = 0.0013$

Higgs physics is and becomes low x physics

PDFs and Precision Physics in pp (for HL-LHC)

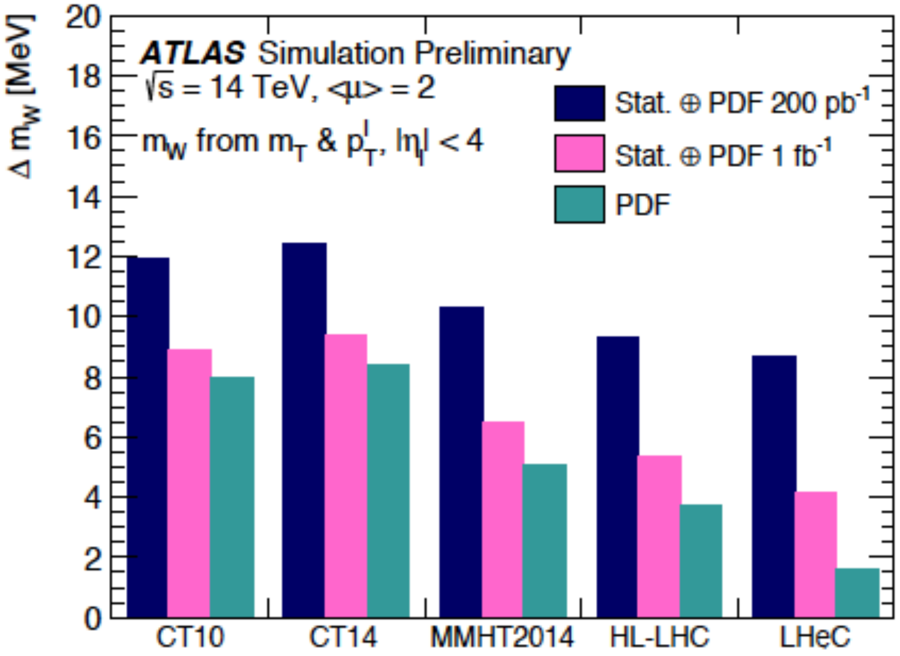


N[3]LO PDF uncertainty of pp → H Cross Section ~ $[\alpha_s xg]^2$

High Precision Higgs Physics
(for ep, and ep+pp cf U.Klein tomorrow)

Model	Limit [TeV] $\mathcal{L} = 36\text{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\text{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\text{ab}^{-1}$ (LHeC)
LL (constr.)	28	58	96
LL (destr.)	21	49	77
RR (constr.)	26	58	84
RR (destr.)	22	61	75
LR (constr.)	26	49	81
LR (destr.)	22	45	62

Large extension of search range through precision PDFs at high x



W mass and mixing angle as examples of strong influence of precision PDFs on LHC e.weak measurements

An area worth studying for FCC-hh+eh

Measuring PDFs is only a small part of strong interaction physics at FCC

Developments

AdS/CFT
Instantons
Odderons
TOTEM ? CERN EP 2017-335

Non pQCD, Spin
Quark Gluon Plasma

QCD of Higgs boson

N^kLO, Monte Carlos..
Resummation
Saturation and BFKL

Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3 D view on hadrons..

Discoveries

CP violation in QCD?
Massless quarks?? Would solve it..
Electric dipole moment of the neutron?
Axions, candidates for Dark Matter

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

New kind of coloured matter

Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future with the FCC

Testing QCD is in fact more difficult than testing the electroweak sector.

Guido Altarelli, Moriond 1983, Cited by R K Ellis, Nuovo Cim 39C (2016) 355

MK „QCD at FCC“, Amsterdam

The FCC-eh and the LHeC are the best telescopes for the substructure that indeed mankind can build, for which CERN is in a unique position. This will bring a major step forward in understanding strong interaction and possibly enable discoveries in the QCD sector and beyond the SM

2 CHRIS QUIGG

arXiv:2001.01879

ERL for 10^{34} at high energies is a technology and operation challenge:

This illustrates Bob Wilson's dictum that "Money and effort that would go into an overly conservative design might better be used elsewhere . . . A major component that works reliably right off the bat is, in one sense, a failure—it is over-designed.[2]

[2] R. R. Wilson, "Sanctimonious Memo #137," July 11, 1969.

Many Thanks to

LHeC and FCC-eh pdfs WG

lhec.web.cern.ch
fcc.web.cern.ch

PDFs and Low x Working Groups

LHeC and FCC-eh

Conveners:

- Nestor Armesto Perez (Universidade de Santiago de Compostela (ES))
- Paul Newman (University of Birmingham (UK))
- Anna Stasto (Penn State (US))
- Claire Gwenlan (University of Oxford (GB))
- Fred Olness (Southern Methodist University (US))

Working Group Meetings

A list of all LHeC+FCC-eh related Indico meetings is here https://indico.cern.ch/category/1874/

everyone is welcome!

since the LHeC (arXiV:1206.2913) and FCC (vol1, EPJ C79 (2019), no.6, 474) CDRs,
many additional studies, with updated running scenarios etc.

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Future Collider Options timelines of funding (cost for Europe) and operation