ICHEP2018 SEOUL
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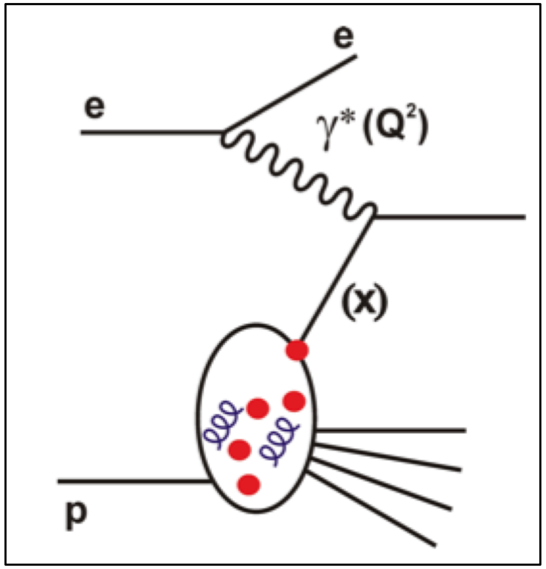
PDFs, QCD and small x physics in energy frontier DIS with the LHeC and FCC-eh

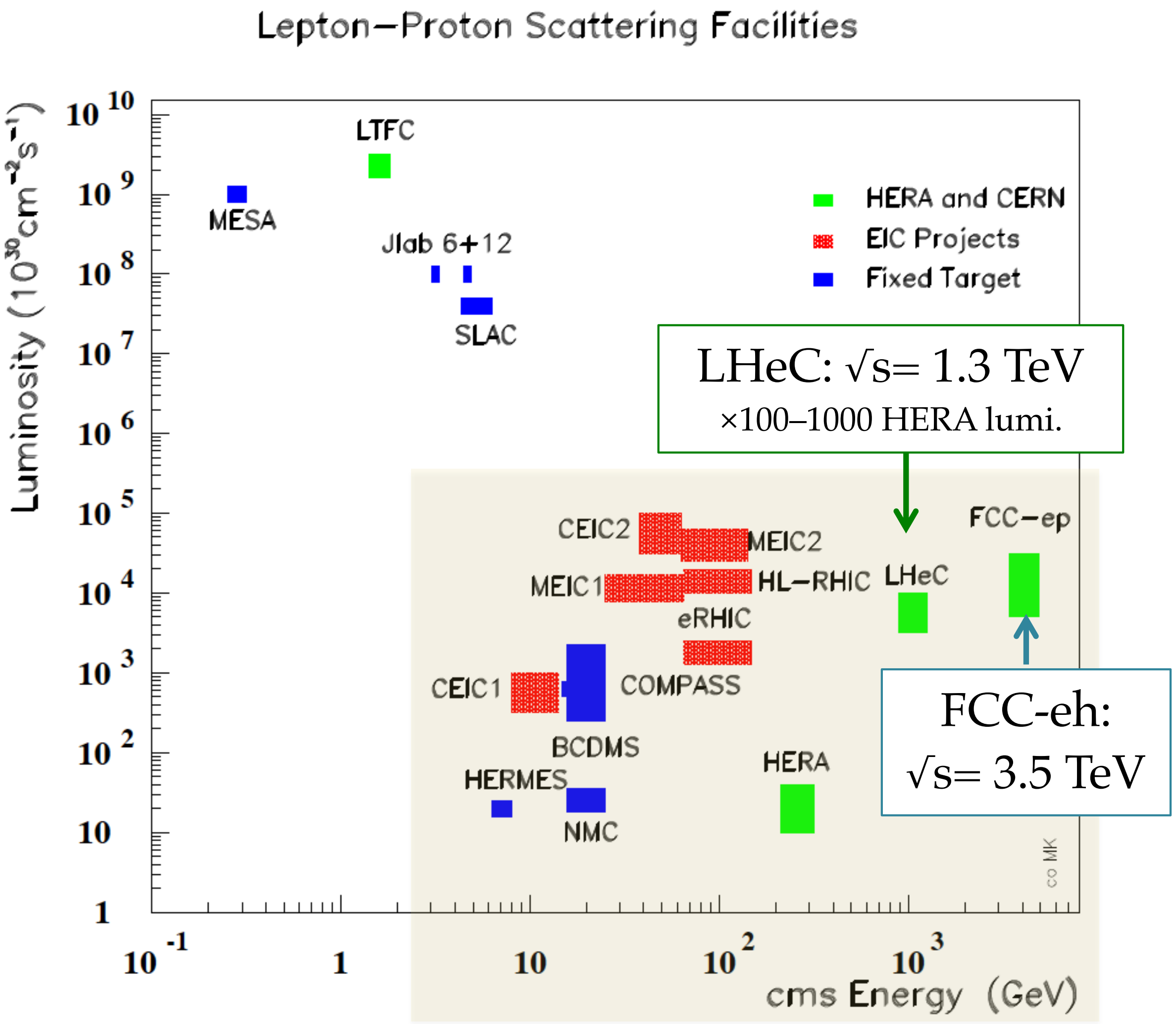
Claire Gwenlan, Oxford

for the LHeC and FCC-eh study groups



special thanks to Max Klein, Uta Klein and Gavin Pownall

LHeC and FCC-eh



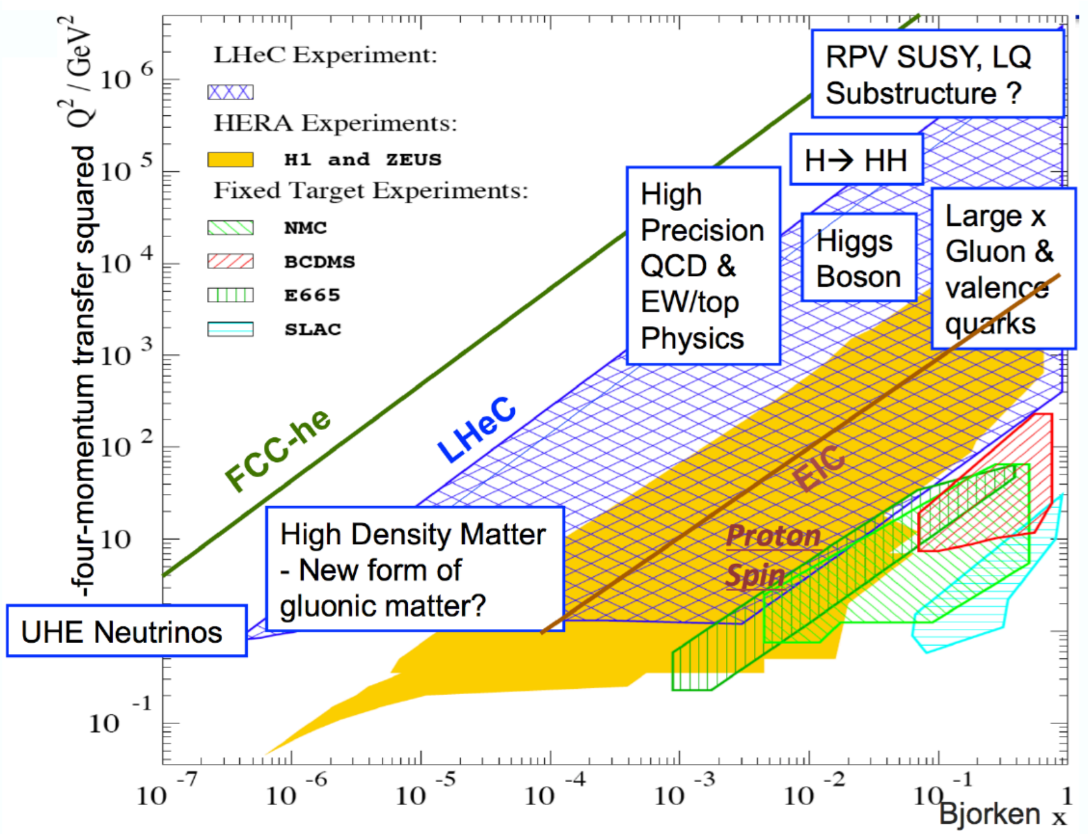
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

LHeC: future ep (eA) collider, proposed to run concurrently with HL/HE-LHC; CDR arXiv:1206.2913 (complementary to LHC; extra discovery channels; Higgs; precision pdfs and **α**s)

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

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

kinematic coverage



LHeC:

Q^2 to 10^6 GeV^2, x: $10^{-6} \longrightarrow 1$

FCC-eh:

Q^2 to 10^7 GeV^2, x: $10^{-7} \longrightarrow 1$

($\times$**15**/**120** extension in Q^2,1/x reach vs HERA)

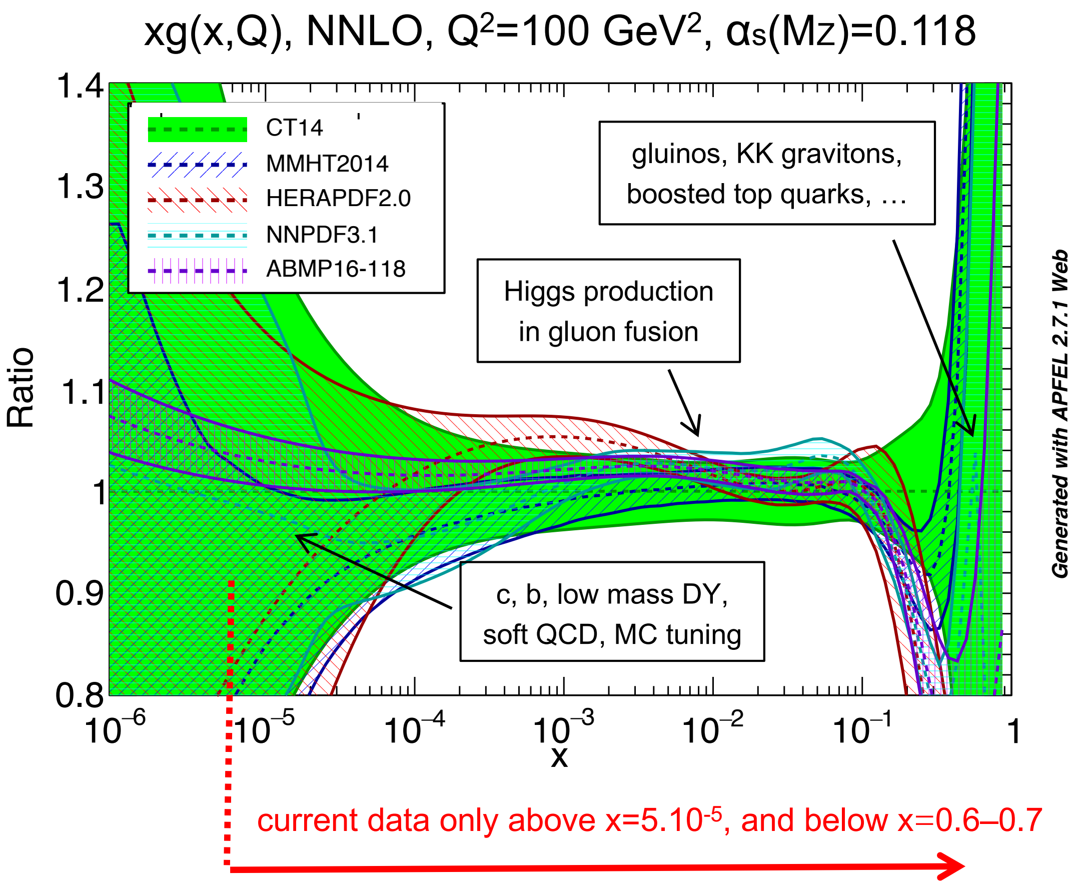
- **outline of this talk:**
- proton pdfs
- α_s, electroweak

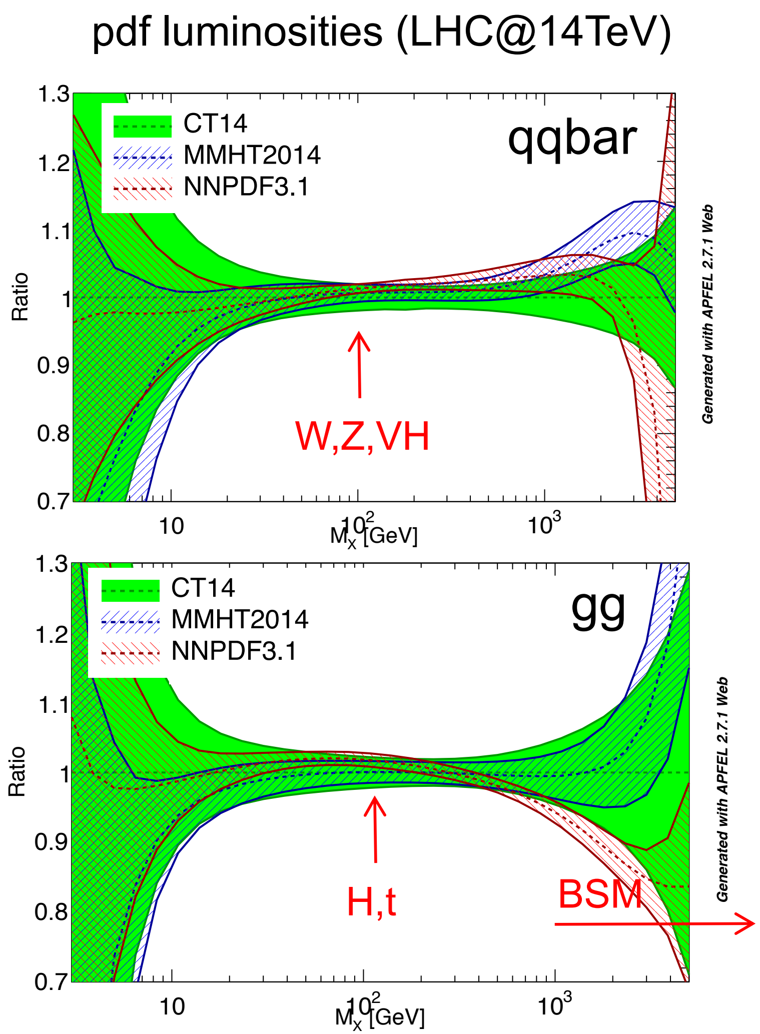
- very rich physics programme; see also other talks in this workshop:

LHeC and FCC-eh machine (D Schulte); BSM (D Britzger); eA (Z Zhang); SM and BSM Higgs (C Zhang)

see also very fruitful LHeC and PERLE workshop, LAL-Orsay, 26 – 29 June 2018

proton pdfs today

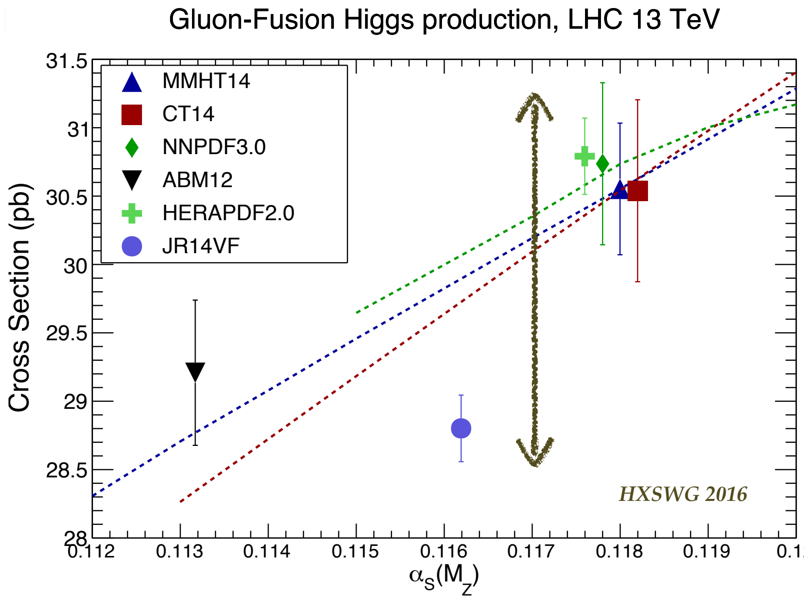




pdfs poorly known at large and small x

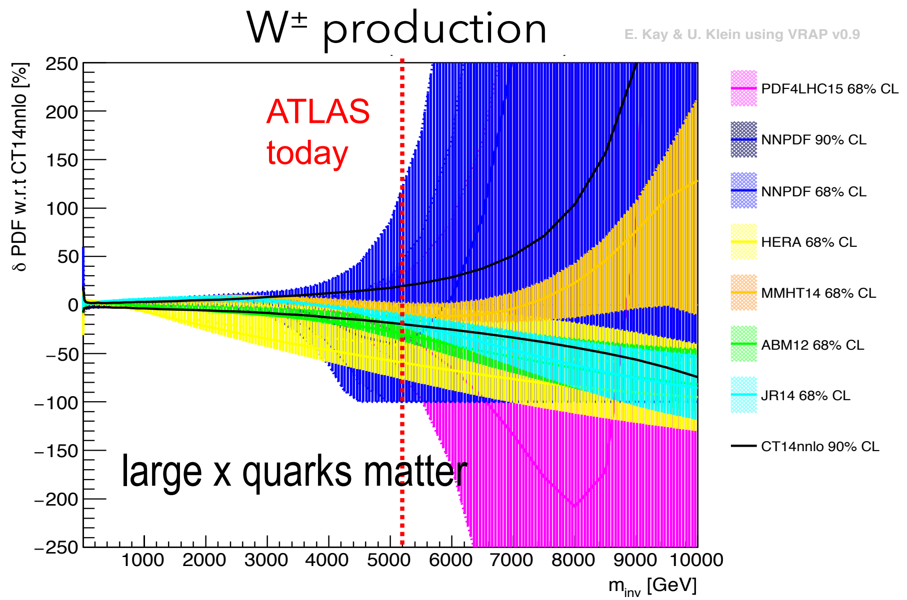
higher precision needed also for H, W, t

pdfs today



ATLAS 2017

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

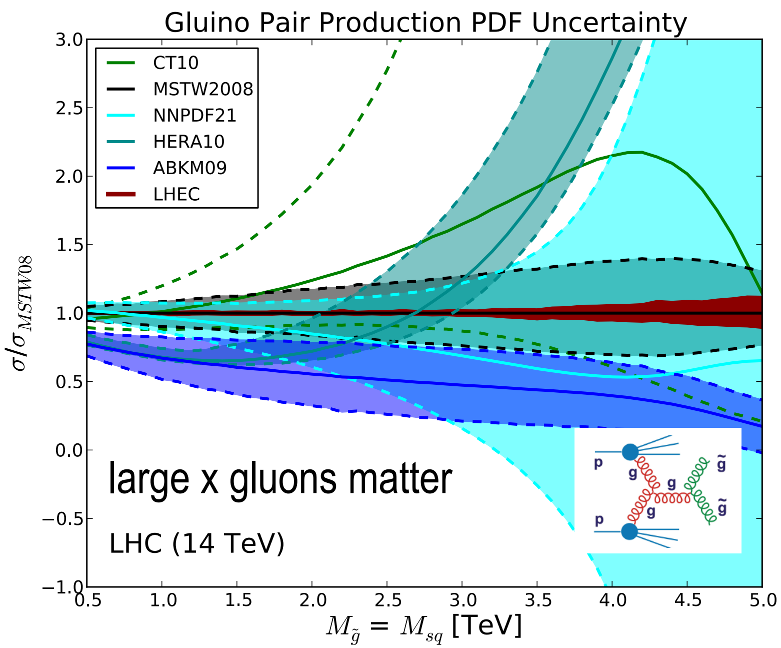


Mw

Higgs

BSM

…



with higher luminosity and energy machines on horizon,

will need **transformation** in precision

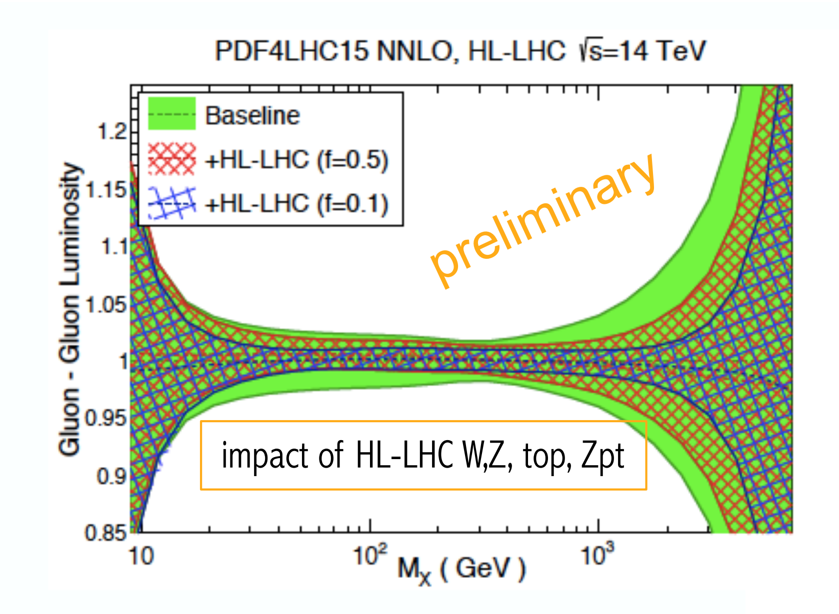
HL-LHC ‘ultimate’ pdf projections

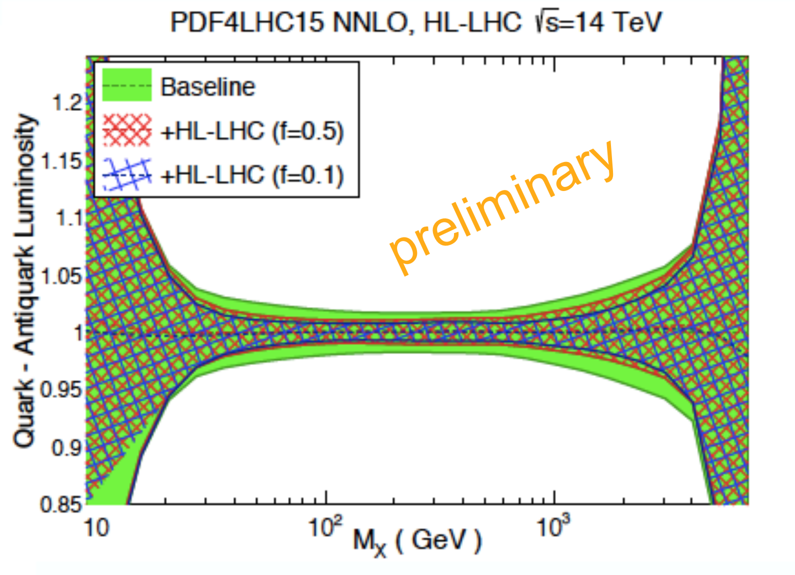
LHC measurements are providing useful pdf constraints (EG. see previous talk); should certainly be exploited; and currently we have nothing else …

is there a NEED for future ep collider for pdfs?

will we improve the precision of pdfs sufficiently using LHC data?

HL-LHC ultimate pdf projection studies ongoing:



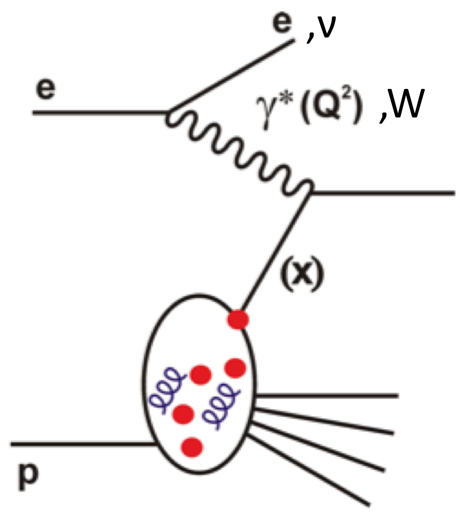


(L Harland-Lang, HL/HE-LHC WS, CERN, June 2018)

LHeC and FCC-eh pdf programme

NC/CC	Ee [GeV]	Ep [TeV]	P(e)	charge	lumi. [fb-1]
NC CC	60 (60) 60 (60)	7 (50) 7 (50)	-0.8 -0.8	-1 -1	1000 1000
NC CC	60 (60) 60 (60)	7 (50) 7 (50)	+0.8 +0.8	-1 -1	300 300
NC CC	60 (60) 60 (60)	7 (50) 7 (50)	0 0	+1 +1	100 100
NC CC	60 (20) 60 (20)	1 (7) 1 (7)	0 0	-1 -1	100 100

LHeC (FCC-eh) simulated NC and CC inclusive



simulation: M Klein
QCD analysis: V Radescu, G Pownall

+NEW: additional LHeC simulation with 1/10th integrated luminosity (no low energy data)

LHeC (FCC-eh) goals: completely resolve all **proton pdfs,** and **αs** to permille precision

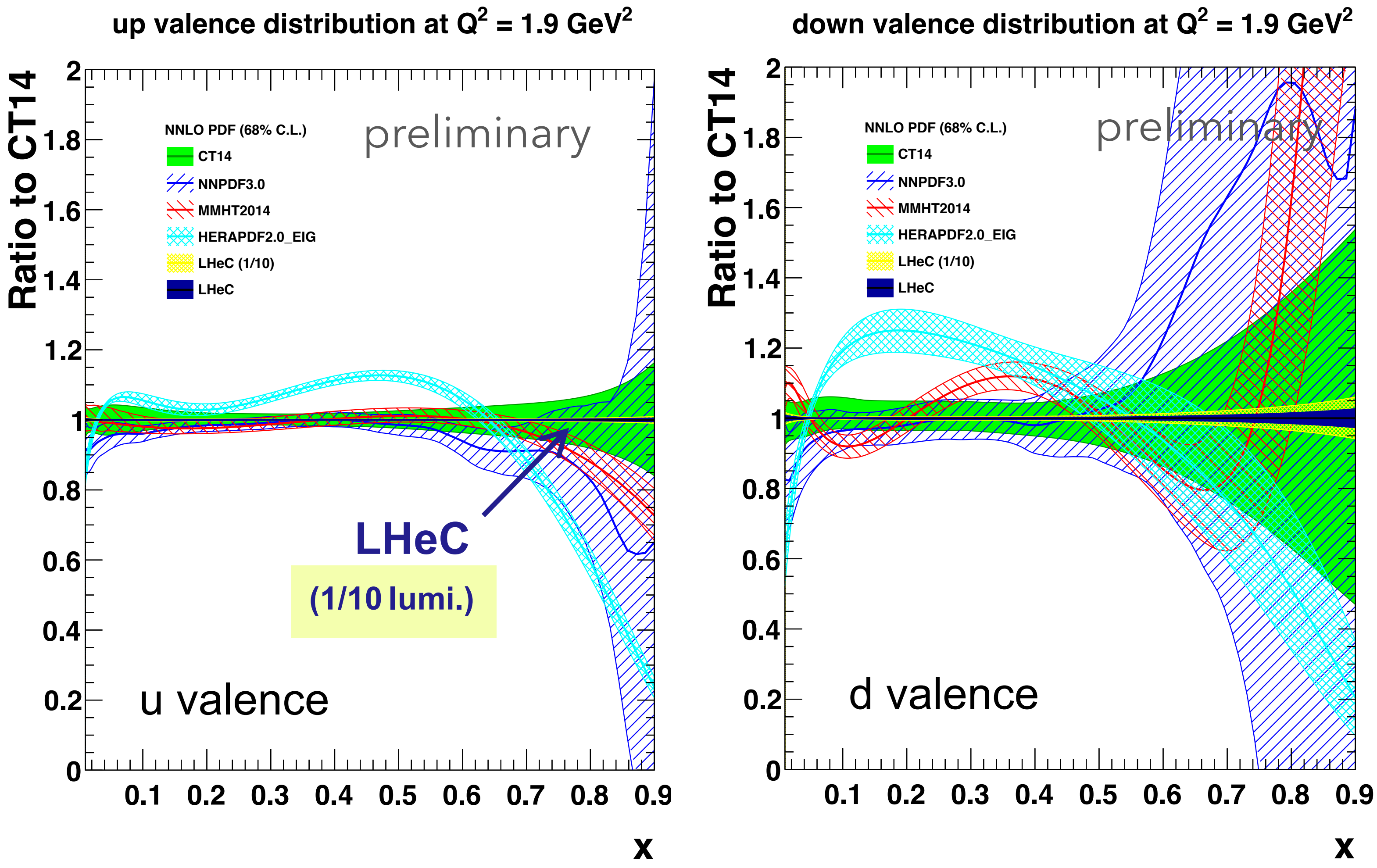
ubar, uv, dbar, dv, s, c, b, t, xg and **αs**

no higher twist, no nuclear corrs., free of sym. assumptions, factorization proven, N3LO (on the way)

NB, fit studies do not yet include simulated s, c, b, t or FL data

all work in progress

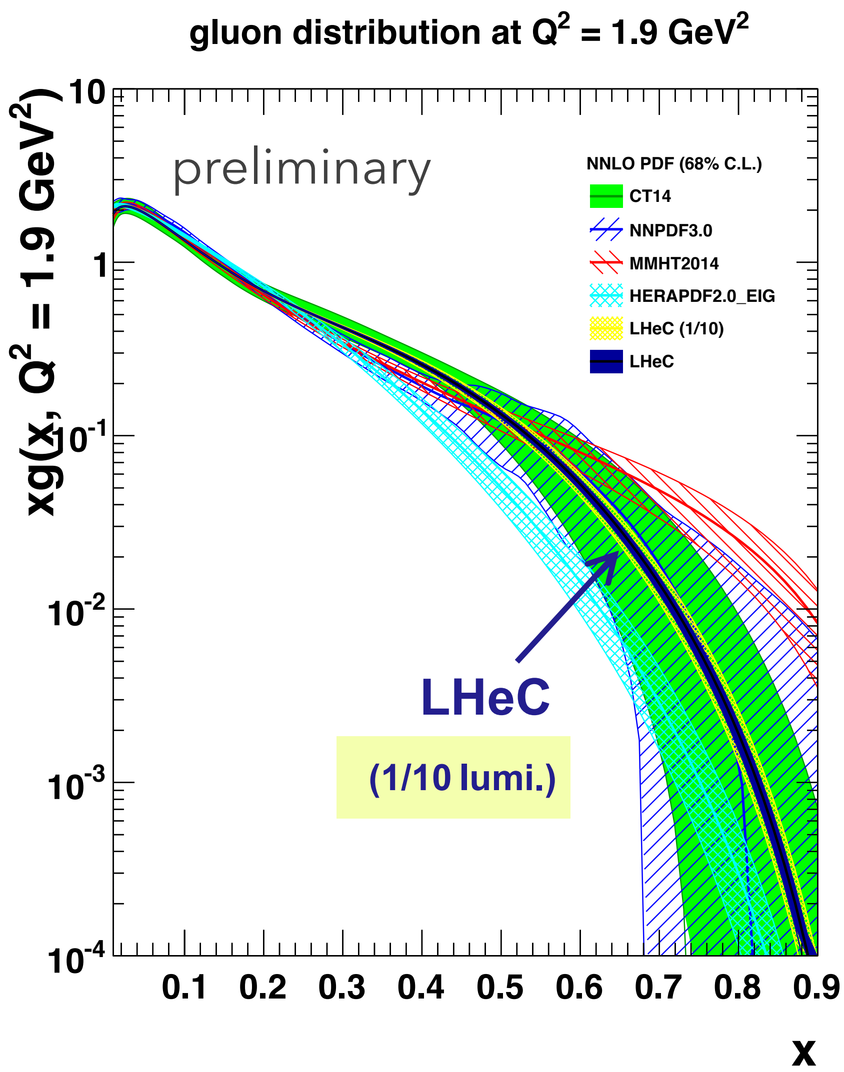
valence quarks from LHeC



precision determination, free from higher twist corrections and nuclear uncertainties

large x crucial for searches; relevant for DY, Mw; resolve mystery of d/u at large x; …

gluon at large x



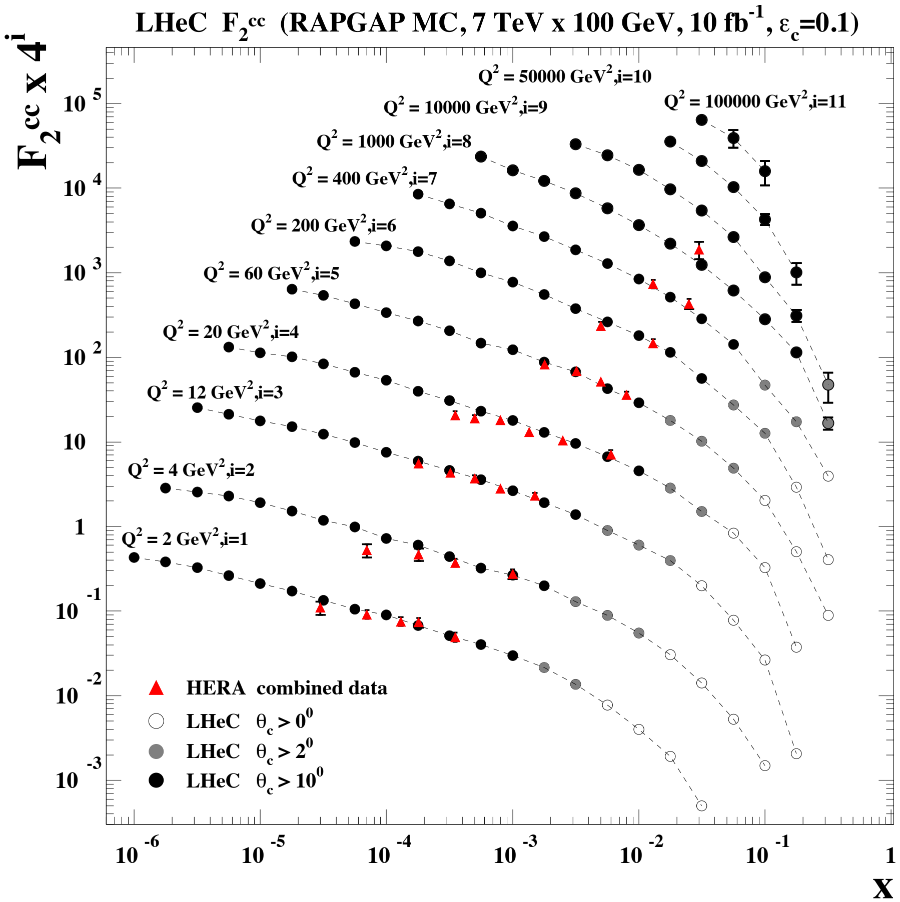
gluon at large x is small and currently very poorly known;
crucial for new physics searches

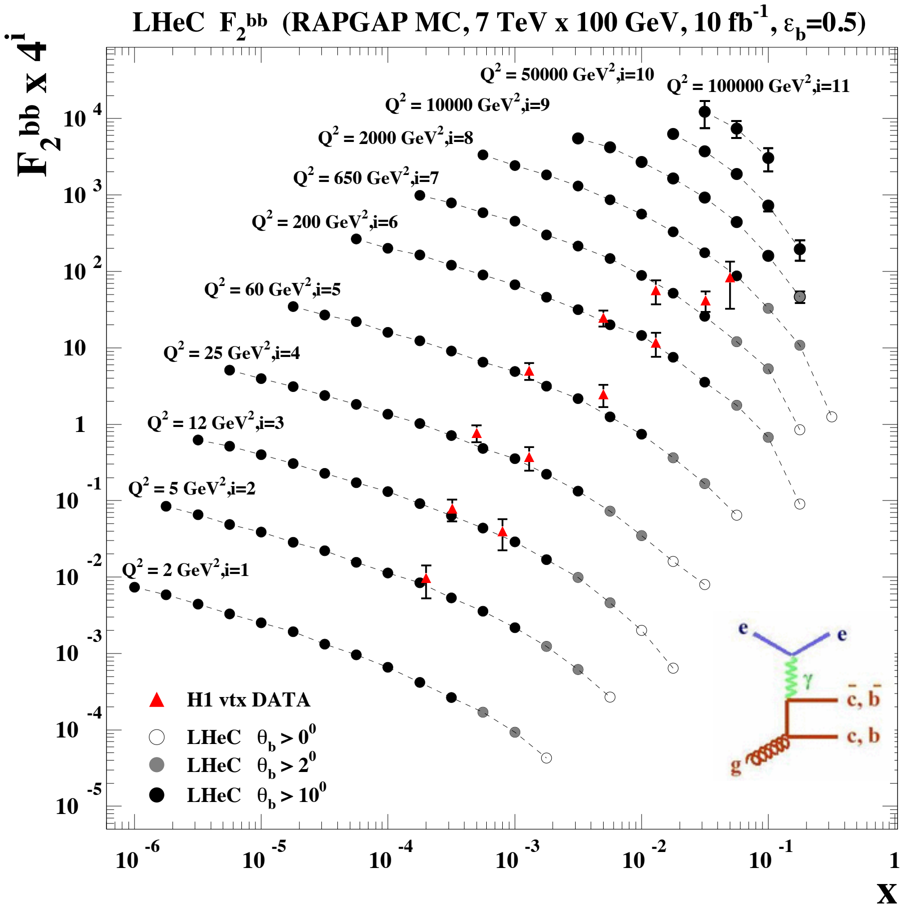
LHeC sensitivity at large x comes as part of overall package

high luminosity (×100–1000 HERA);
fully constrained quark pdfs; low x;
momentum sum rule

gluon and sea intimately related
LHeC can disentangle sea from valence quarks at large x, with precision measurements of **CC** and **NC** $F2^{\gamma Z}$, $xF3^{\gamma Z}$

c, b quarks



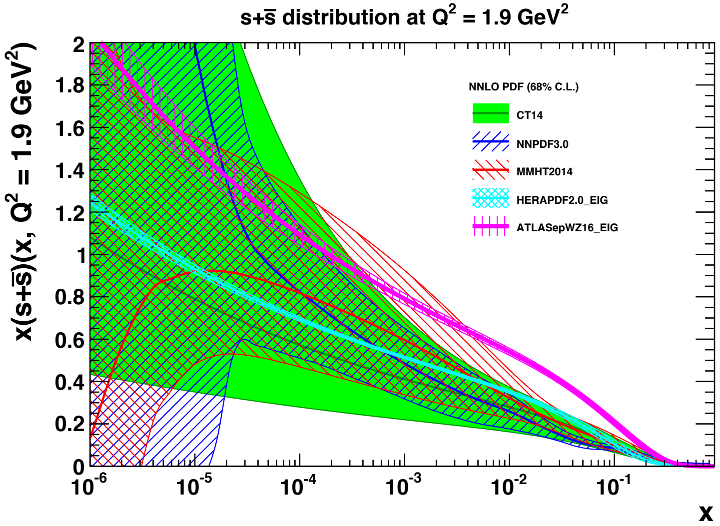


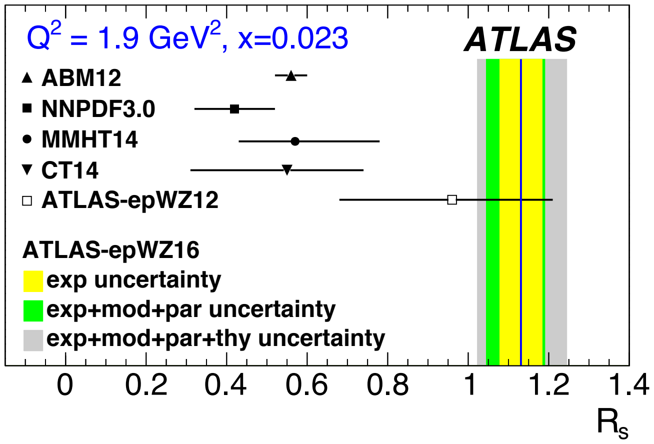
LHeC: enormously extended range and much improved precision c.f. HERA

- **δMc = 60 (HERA) to 3 MeV**: impacts on αs, regulates ratio of charm to light, crucial for precision t, H
- MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$

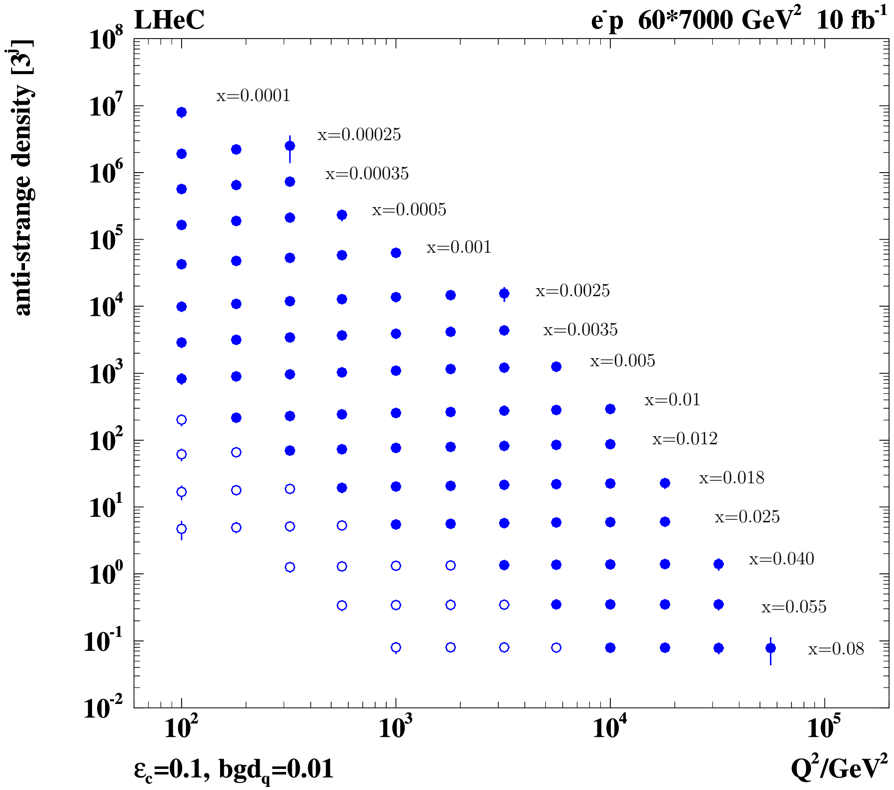
strange

strange pdf poorly known; suppressed cf. other light quarks? strange valence?





ATLAS† see large strange fraction at mean x~0.01



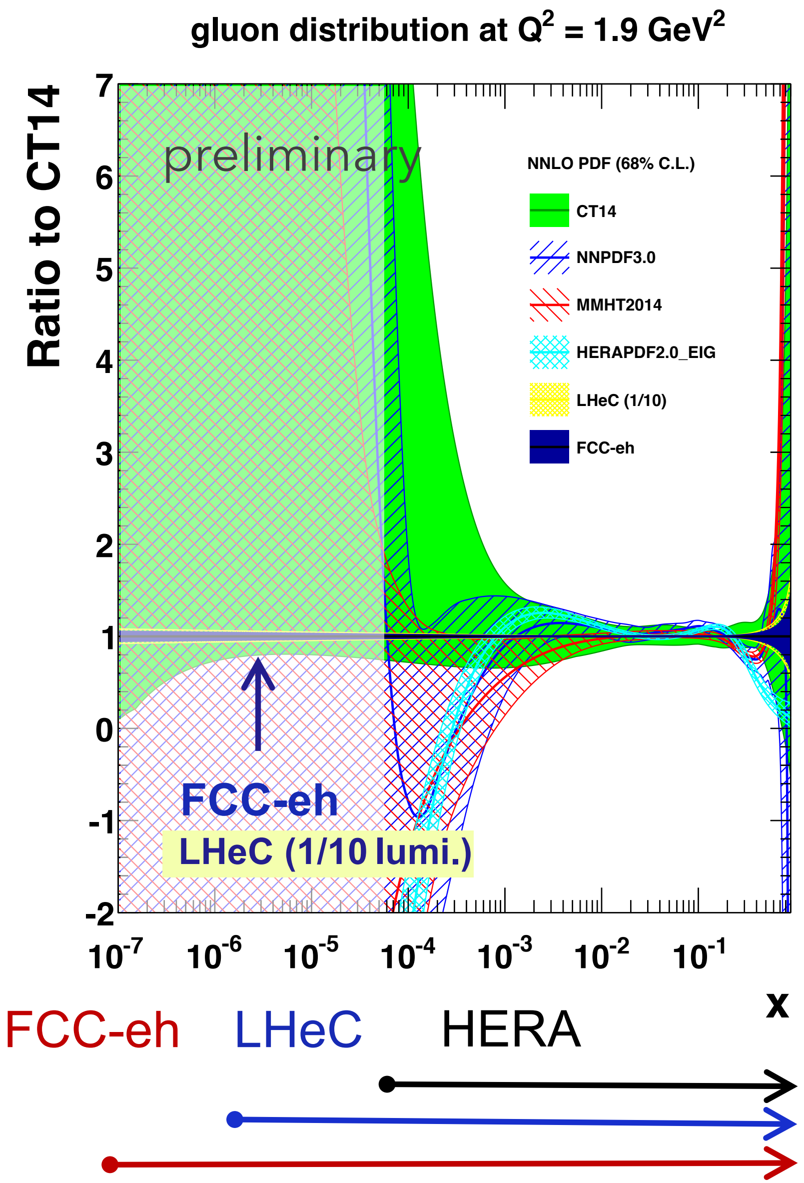
LHeC: direct sensitivity to strange via $W{+}s \rightarrow c$

(x,Q^2) mapping of (anti) strange quark for first time

also top pdf via CC DIS becomes possible!

†ATLAS arXiv:1203.4051, confirmed with high stats in 1612.03016; and by global fitters EG. NNPDF 1706.00428, MMHT 1708.00047

gluon at small x



no current data much below $x=5\times10^{-5}$

LHeC provides single, precise and unambiguous dataset down to $x=10^{-6}$

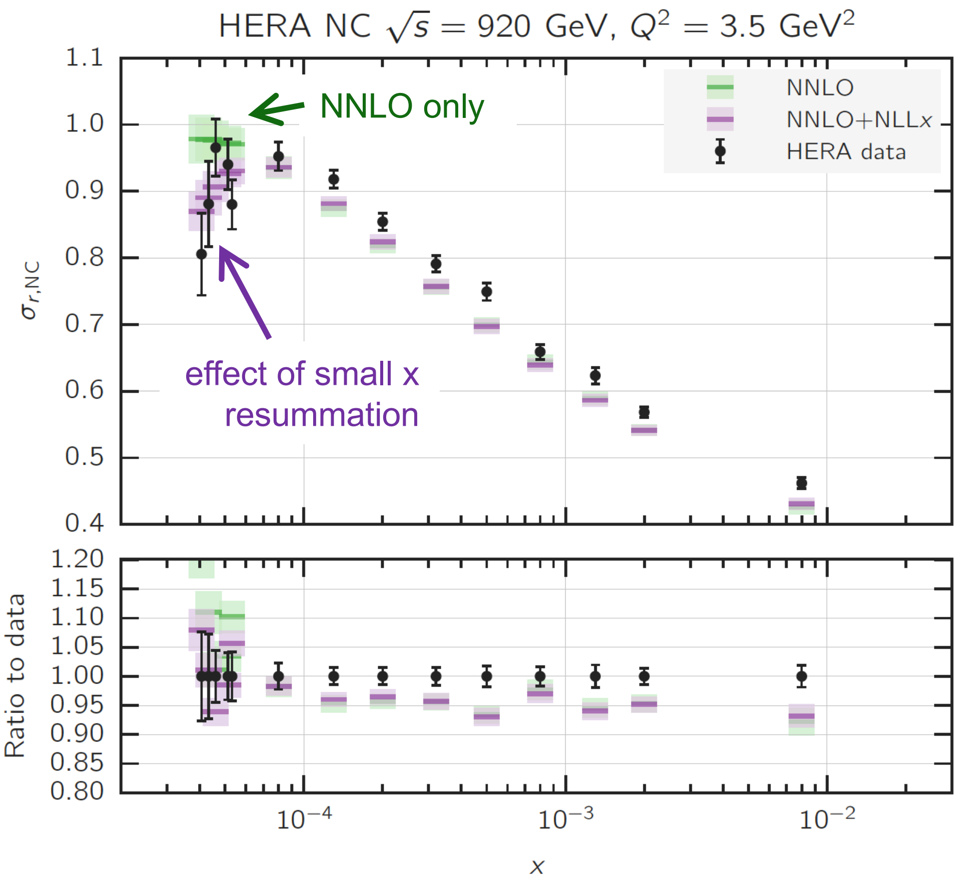
FCC-eh probes to even smaller $x=10^{-7}$

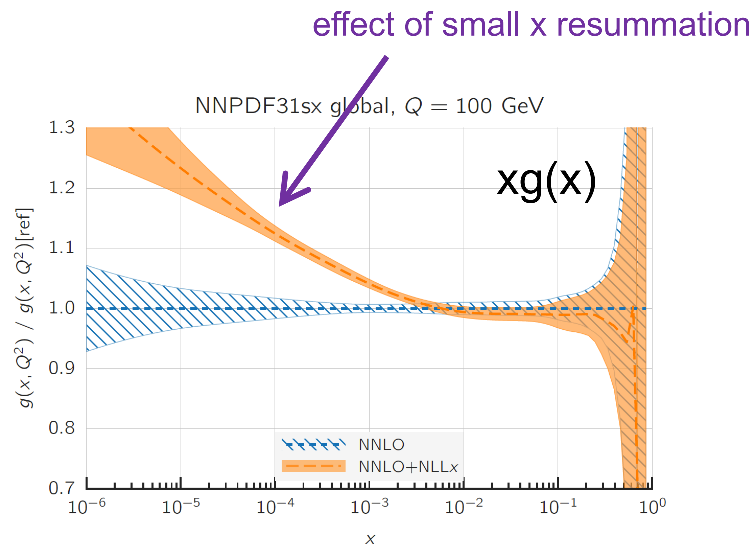
explore low x QCD:

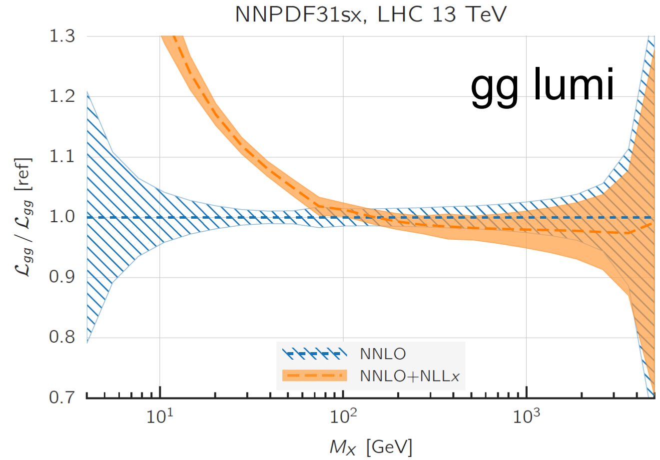
DGLAP vs BFKL; non-linear evolution; gluon saturation; implications for ultra high energy neutrino cross sections

gluon at small x

R. Ball et al, arXiv:1710.05935



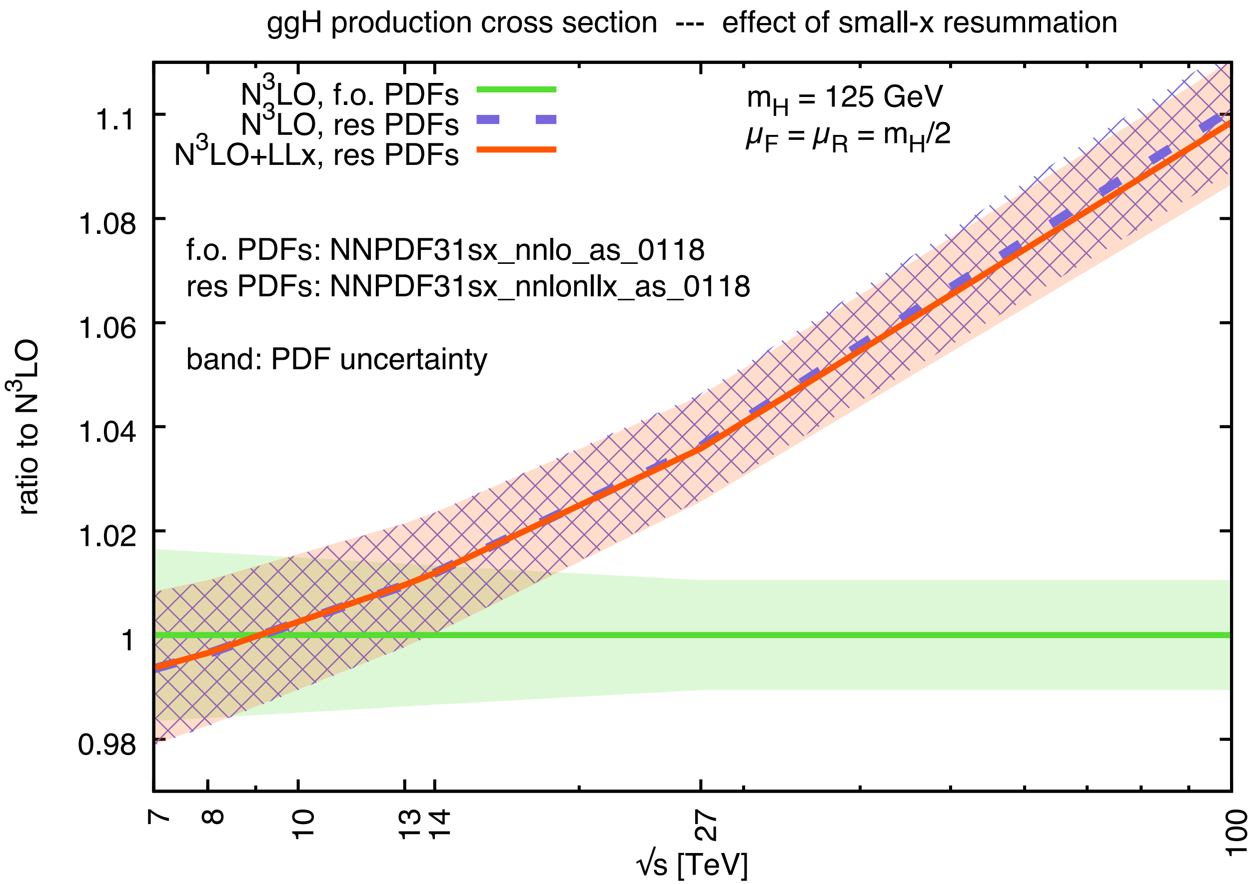




- recent evidence for onset of BFKL dynamics in HERA inclusive data
- **impact for LHC and most certainly at ultra low x values probed at FCC**

(see also xFitter study, arXiv:1802.00064)

gluon at small x



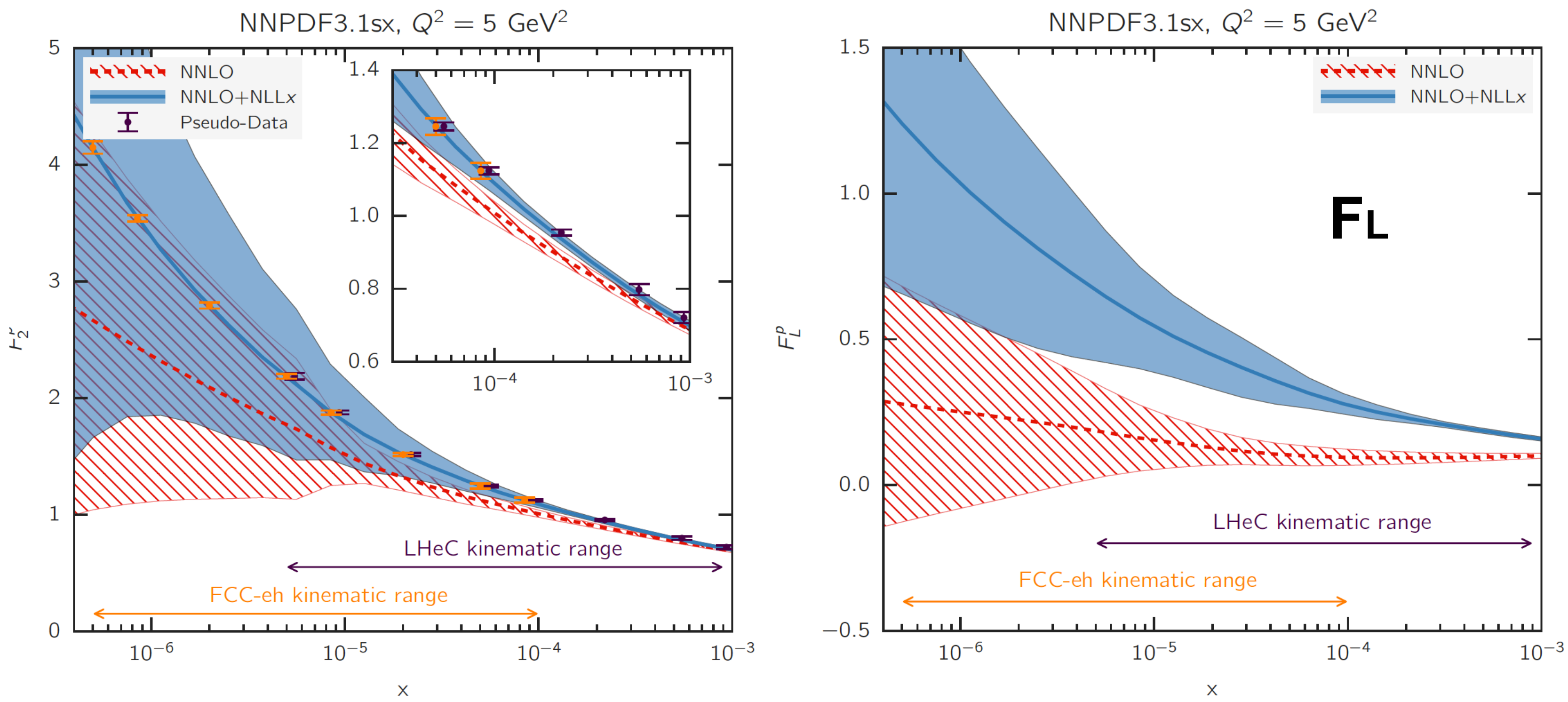
effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

impact on other EW observables could be of similar size

M. Bonvini and S. Marzani, arXiv:1802.07758

gluon at small x

arXiv:1710.05935



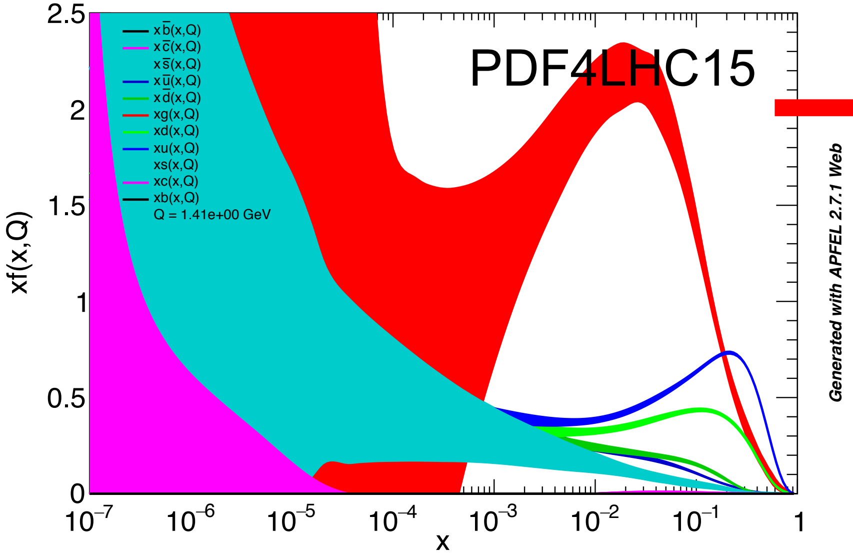
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

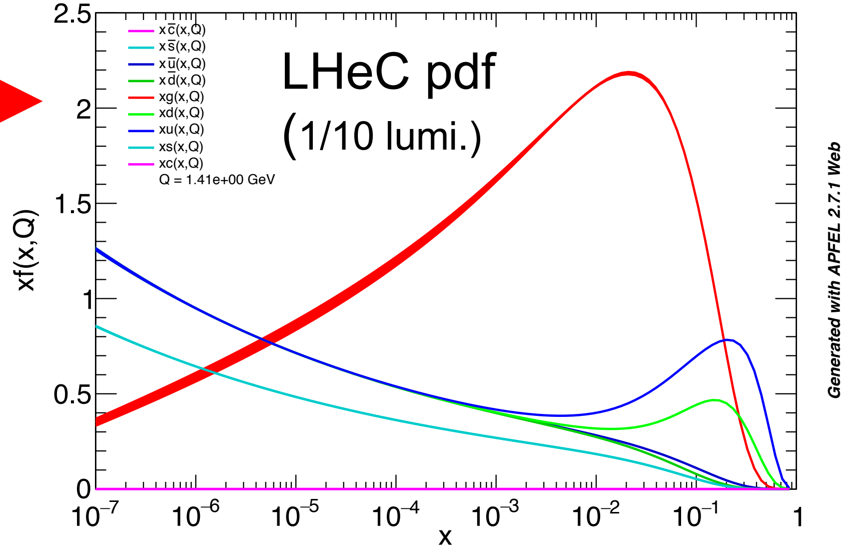
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

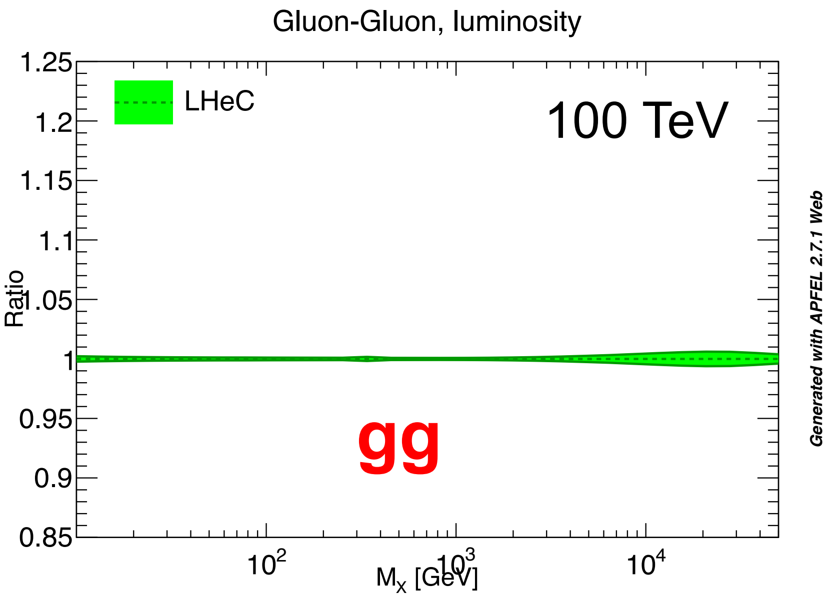
measurement of FL has a critical role to play

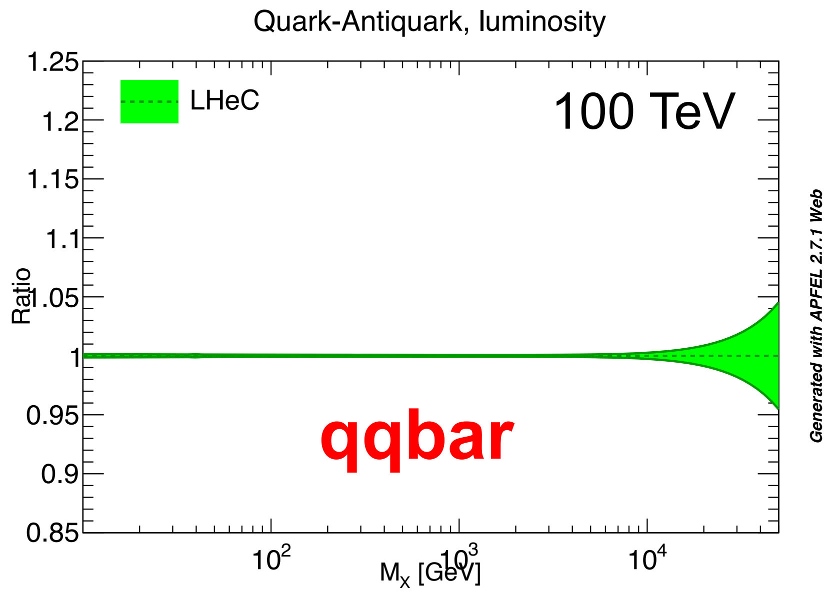
summary of LHeC pdfs

preliminary

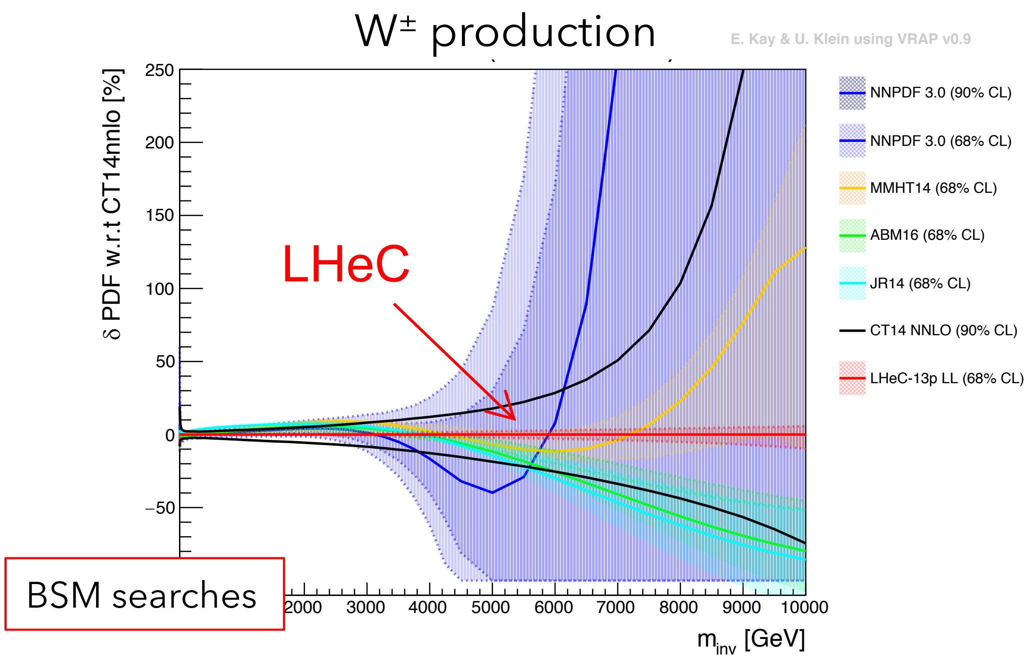


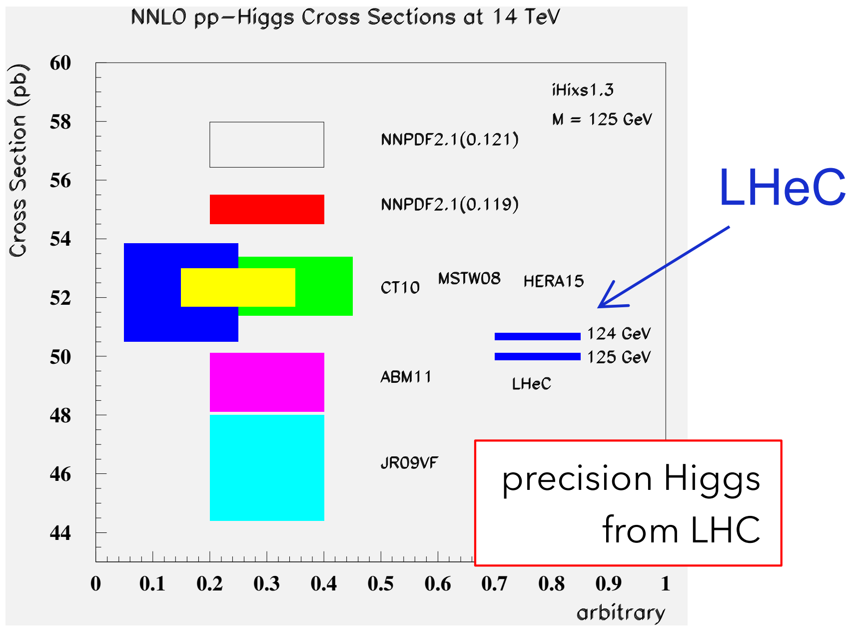


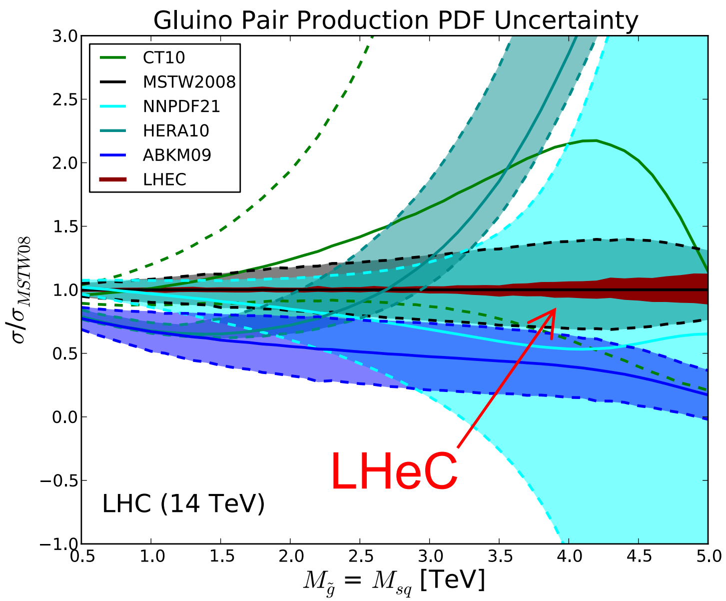


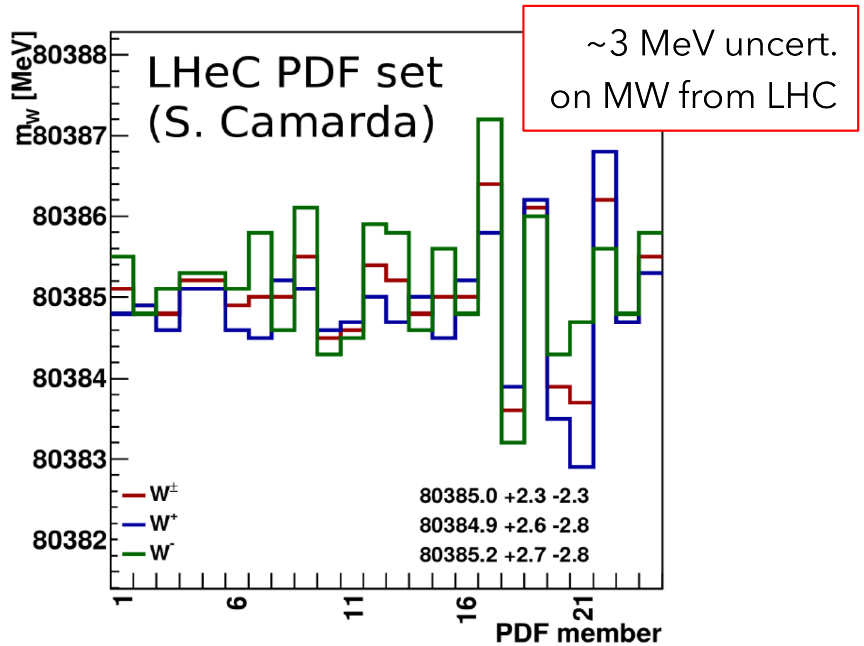


example impact for LHC



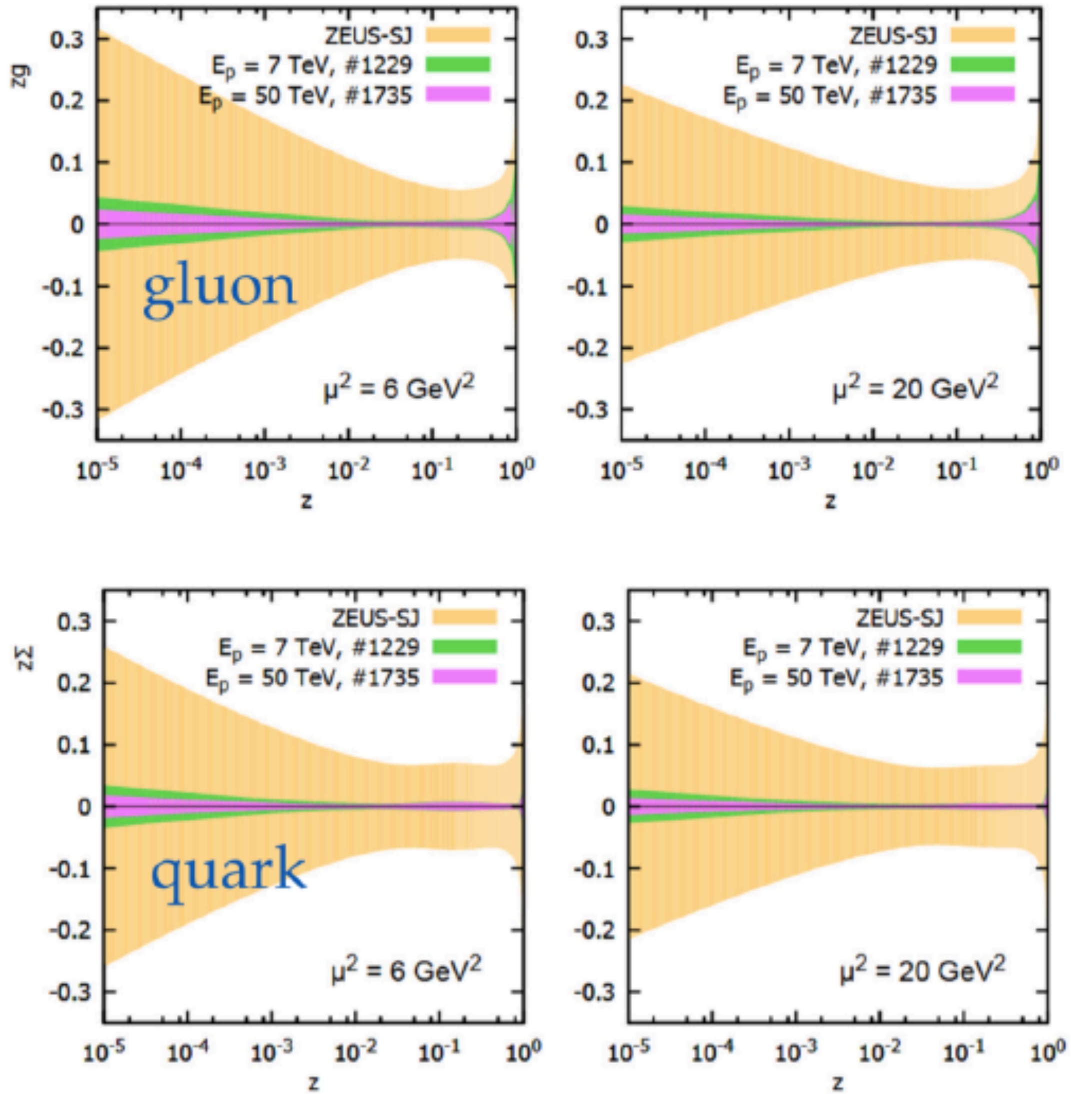




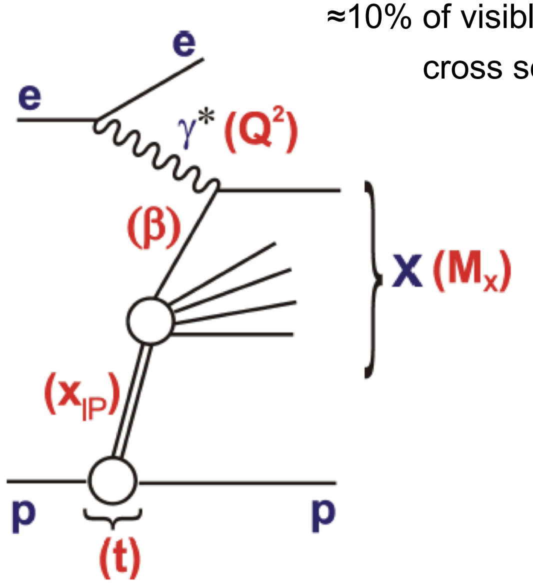


diffractive pdfs

$Q^2_{min} \approx 5$ GeV^2



HERA: diffractive processes constitute ≈10% of visible DIS cross section



simulation: extrapol. from ZEUS-SJ; 5% Gaussian noise (syst.) assumed

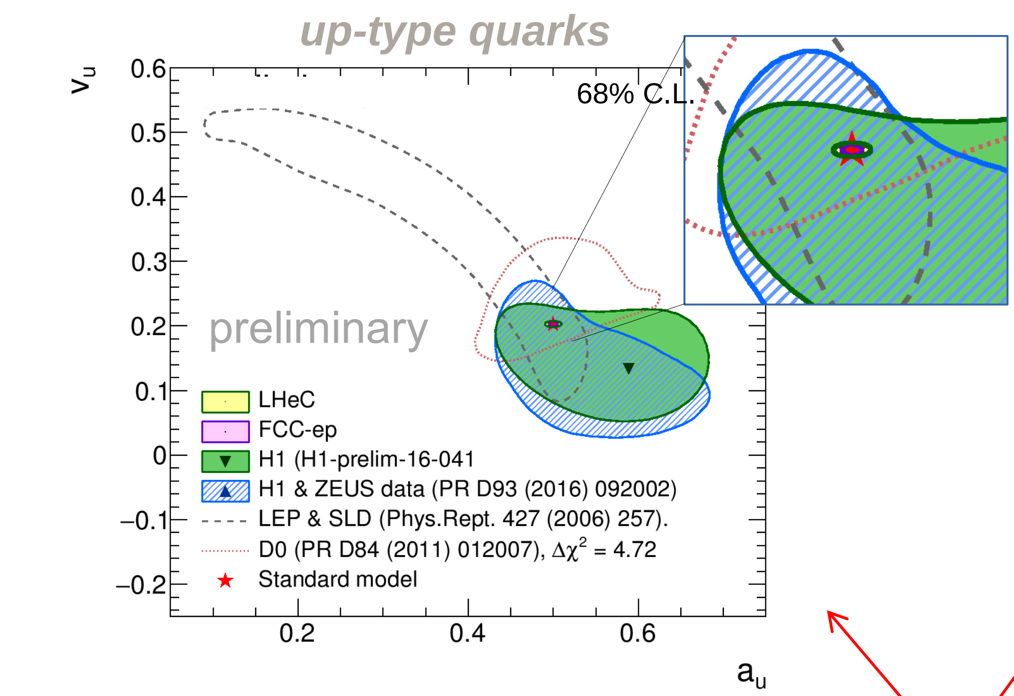
precision increased by about ×10 (20) at LHeC (FCC-eh)

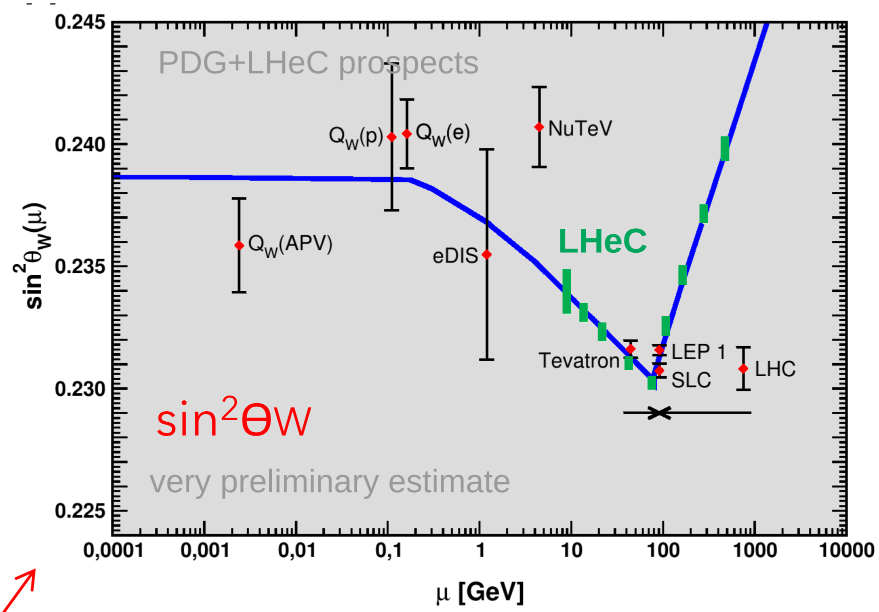
diffractive dijets could provide further gluon info.

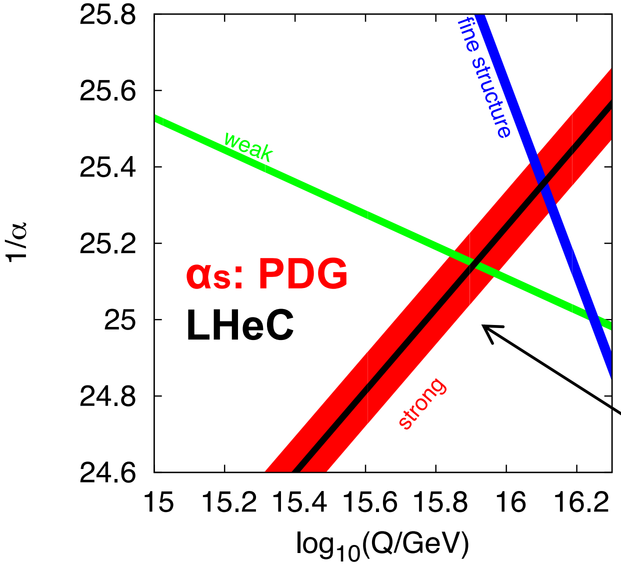
top quark PS also accessible

see also talk by A. Stasto, LHeC and PERLE workshop, LAL-Orsay, June 2018

electroweak physics, and α_s



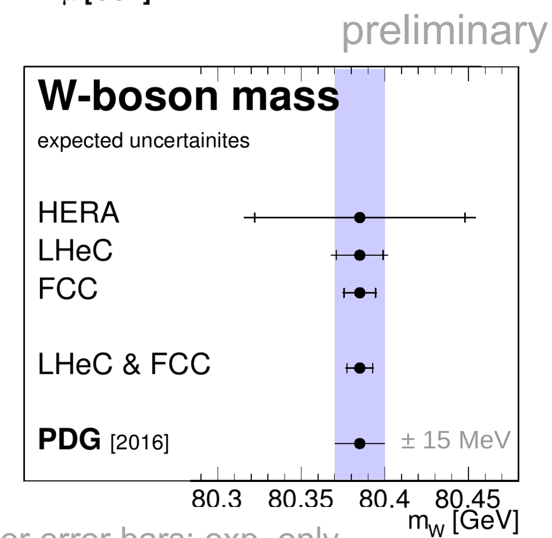




simultaneous pdf and EW fits

extraordinarily precise determinations of EW params.: **NC vector and axial-vector light quark couplings**, **Mz**, **Mw** and **$\sin^2\Theta_W$**

α_s to permille precision!



inner error bars: exp. only
outer: exp.+pdf

EW: see also talk by D. Britzger, LHeC and PERLE workshop, LAL-Orsay, June 2018

summary

much of LHC and FCC programme is or will become pdf or αs limited

LHC pdf-constraining measurements available; widely exploited in modern pdf fits

nevertheless, pp constrains, it does not precisely determine pdfs

electron-hadron colliders essential for future of high energy physics

LHC-eh and FCC-eh go beyond HERA in energy, luminosity (and eA)

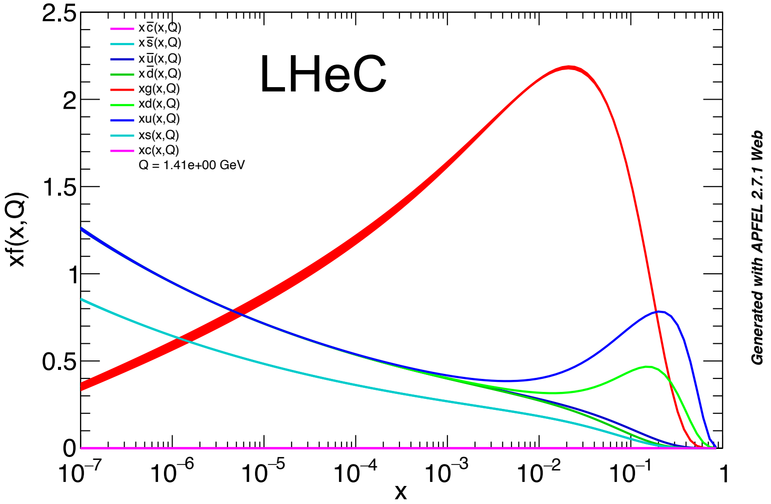
unprecedented kinematic reach;

accesses scales sensitive to BSM and Higgs;

precision electroweak;

precise determination of all pdfs,

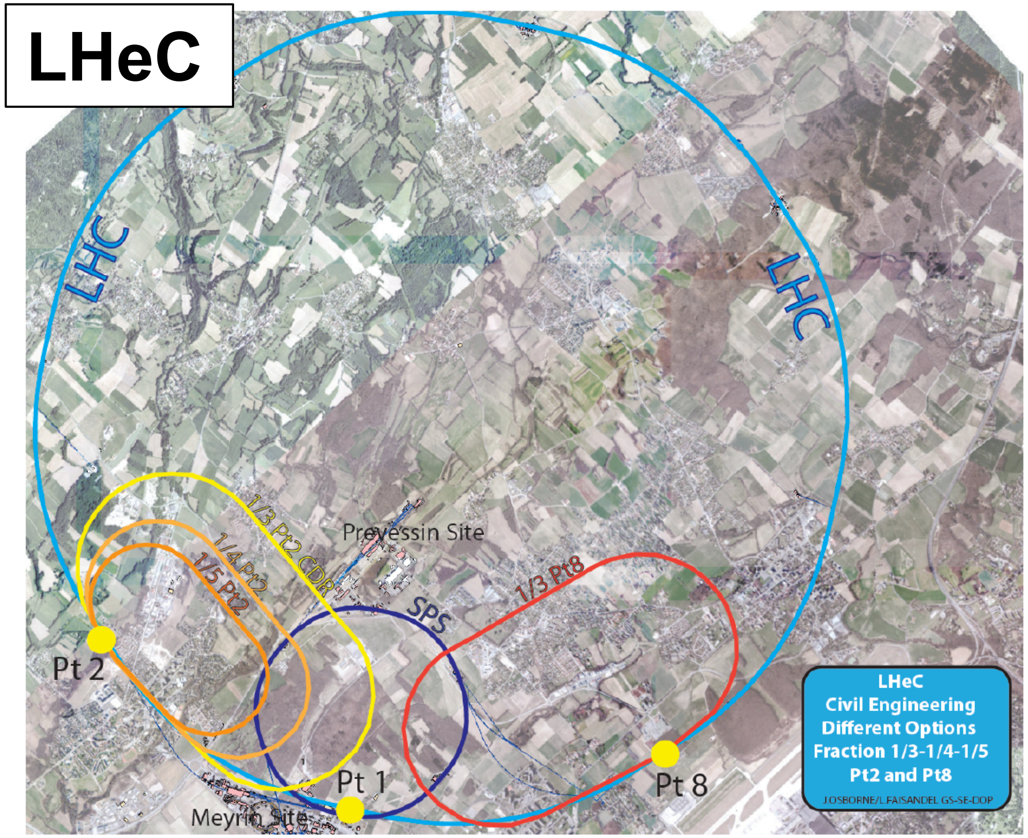
and αs to permille precision



more work ongoing…

extras

LHeC and FCC-eh



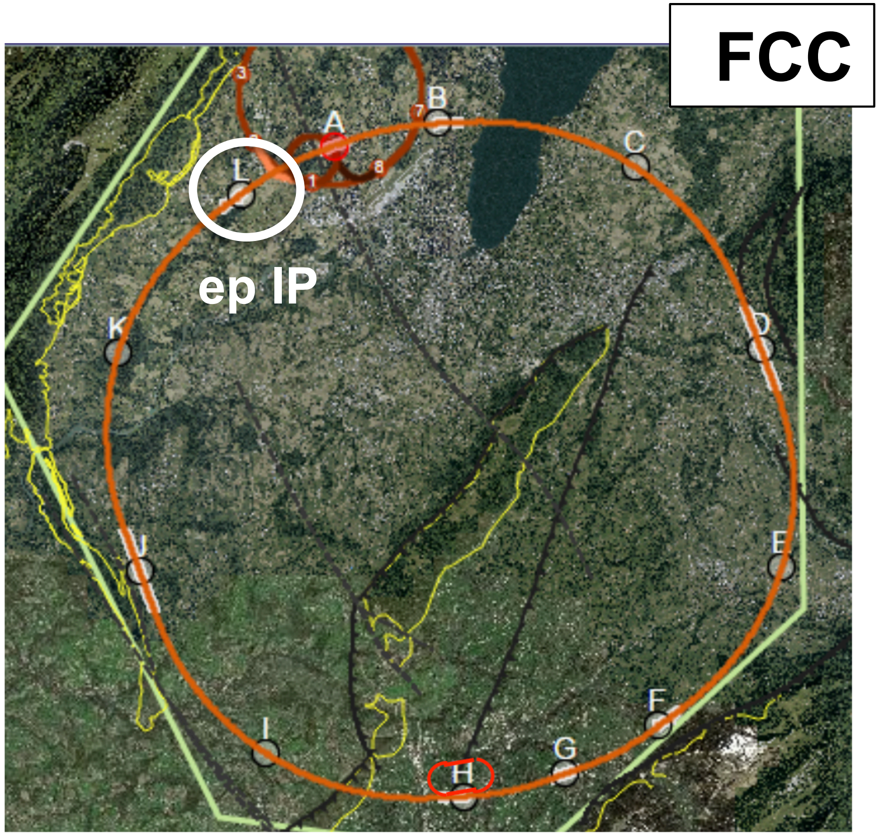
(M Klein, Rencontre du Vietnam, Sept 2017)

LHeC and **FCC-eh**

energy recovery LINAC

e-beam: 60 GeV

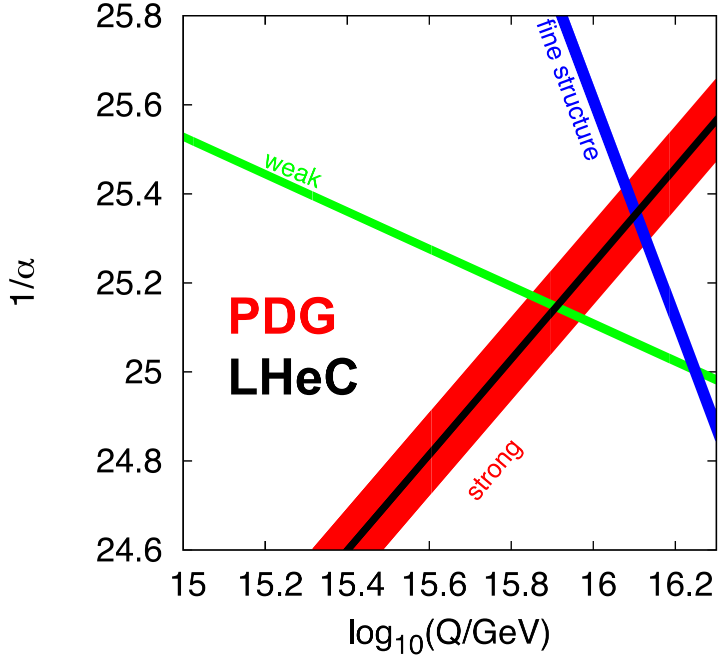
$L_{int} \rightarrow 1\ ab^{-1}$



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

strong coupling α_s from LHeC

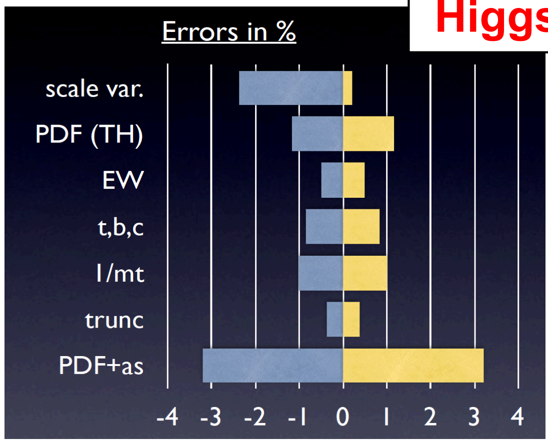
- α_s is least known coupling constant
  precise α_s needed to constrain GUT scenarios;
  for cross section predictions, including H; …
- measurements not all consistent
- what is true central value and uncertainty?
- α_s(DIS) smaller than world average?
- **LHeC**: **permille precision** from QCD fit of inclusive NC and CC DIS (α_s(DIS-jets)?)
- can challenge lattice QCD



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

(**LHeC**: NC+CC incl.; total exp. uncerts; independent of BCDMS)

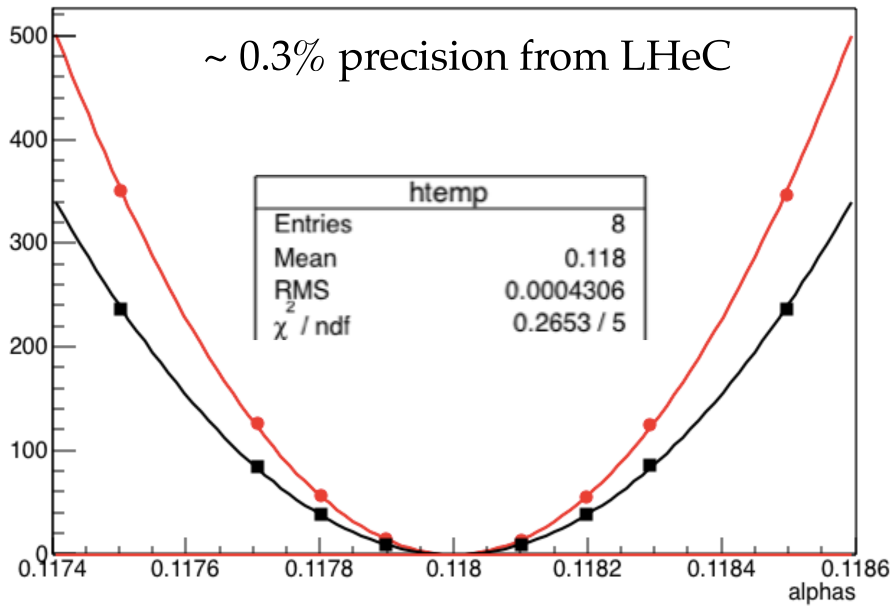
Higgs XS



(G. Zanderighi, Moriond16; from C. Anastasiou et al, arXiv:1602.00695)

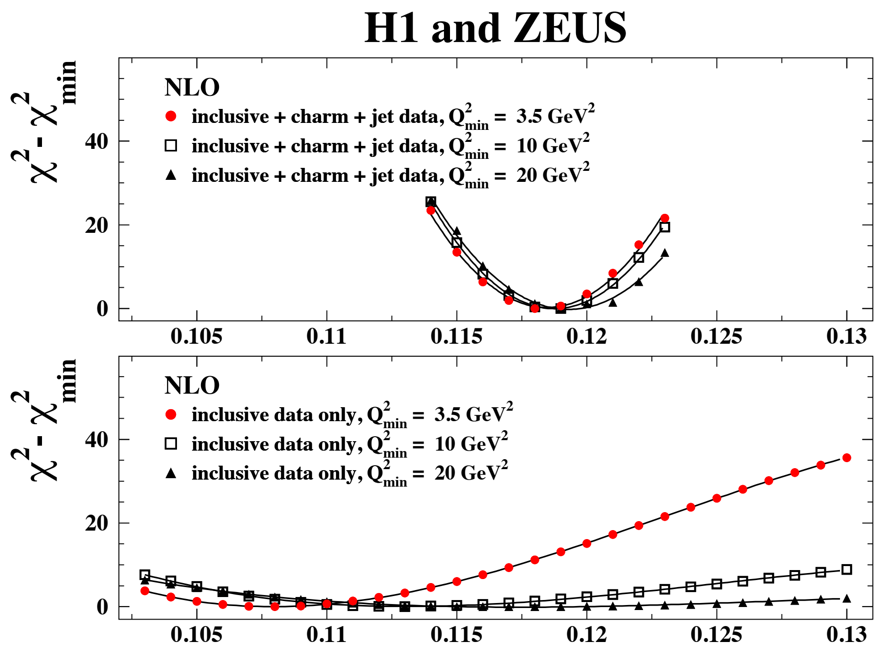
strong coupling from LHeC

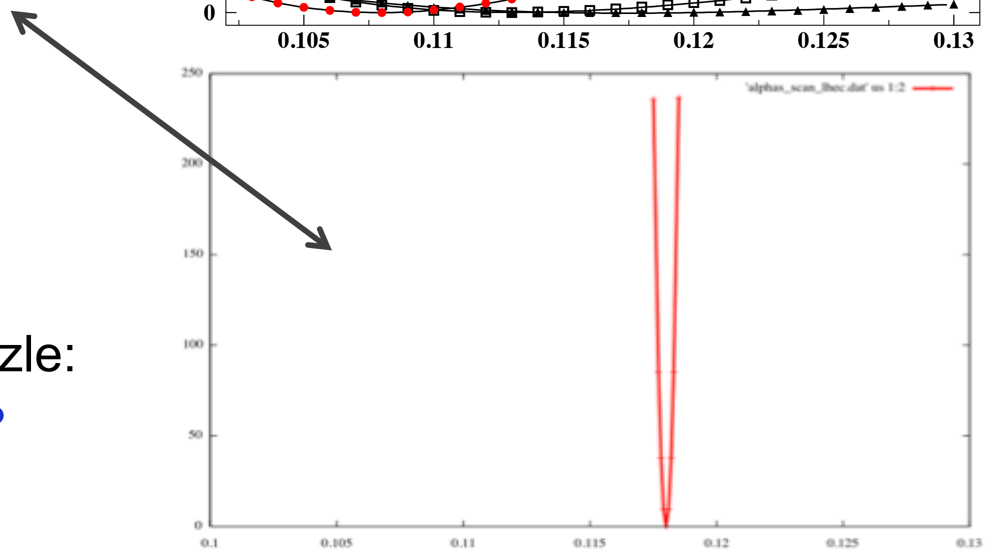
PDF+α_s fit using LHeC simulated data



(M Klein, V Radescu)

NC,CC
NC,CC+F2c





LHeC could resolve a > 30-year old puzzle:

α_s consistent in inclusive DIS, versus jets?

arXiv:1512.05194

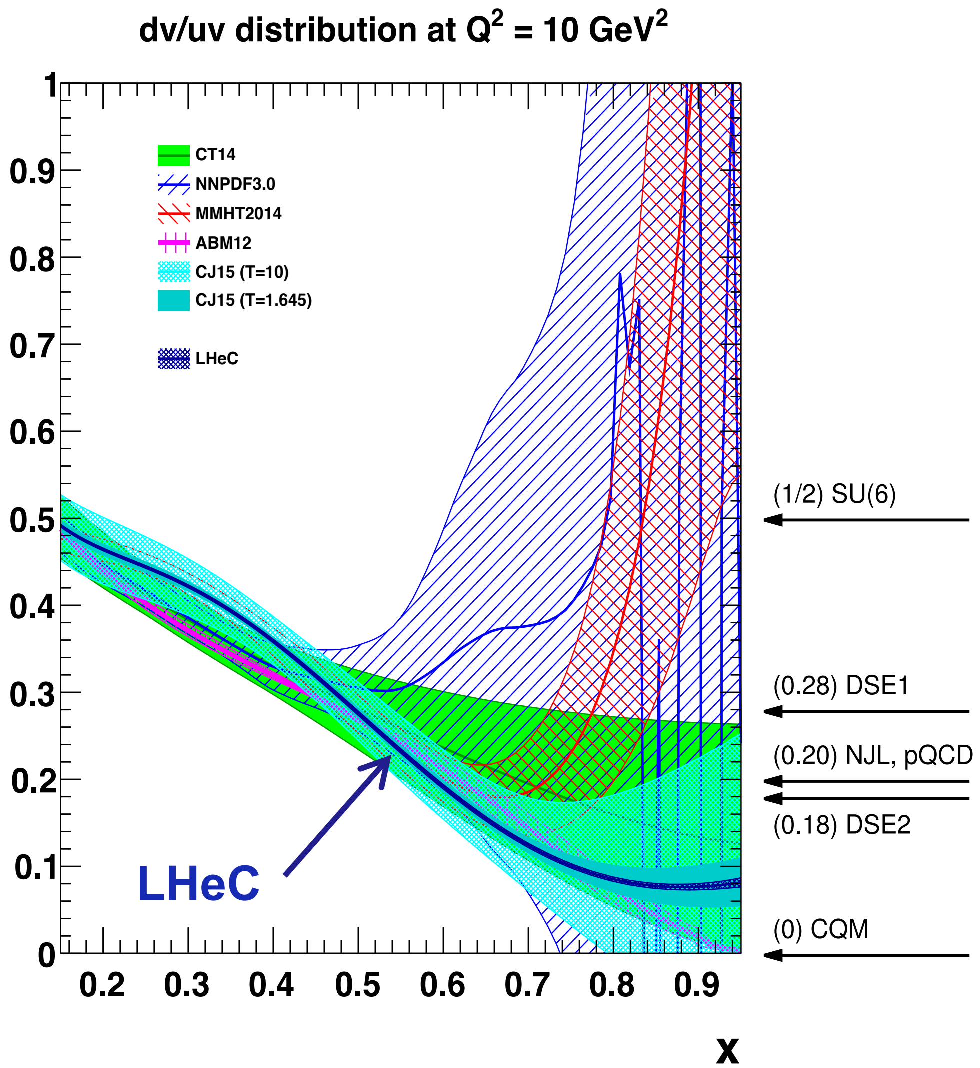
Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
lattice	$\approx$ 1% (latt. stats/spacing, N^{3}LO pQCD)	$\approx$ 0.1% ($\sim$10 yrs) (improved computing power, N^{4}LO pQCD)
π decay factor	$1.5\%_{th} \oplus 0.05\%_{exp} \approx$ 1.5% (N^{3}LO RGOPT)	$1\%_{th} \oplus 0.05\%_{exp} \approx$ 1% (few yrs) (N^{4}LO RGOPT, explicit $m_{u,d,s}$)
τ decays	$1.4\%_{th} \oplus 1.4\%_{exp} \approx$ 2% (N^{3}LO CIPT vs. FOPT)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx$ 1% (+B-factories), <1% (FCC-ee) (N^{4}LO, $\sim$10 yrs. Improved spectral function data)
$Q\overline{Q}$ decays	$4\%_{th} \oplus 4\%_{exp} \approx$ 6% (NLO only. Υ only)	$1.4\%_{th} \oplus 1.4\%_{exp} \approx$ 2% (few yrs) (NNLO. More precise LDME and R_γ^{exp})
soft FFs	$1.8\%_{th} \oplus 0.7\%_{exp} \approx$ 2% (NNLO* only (+NNLL), npQCD small)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx$ 1% ($\sim$2 yrs), <1% (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{th} \oplus 5\%_{exp} \approx$ 5% (NLO only. LEP data only)	$0.7\%_{th} \oplus 2\%_{exp} \approx$ 2% (+B-factories), <1% (FCC-ee) (NNLO. More precise e^+e^- data)
global PDF fits	$1.5\%_{th} \oplus 1\%_{exp} \approx$ 1.7% (Diff. NNLO PDF fits. DIS+DY data)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx$ 1% (few yrs), 0.15% (LHeC/FCC-eh) (N^{3}LO. Full DIS+hadronic data fit)
jets in $e^{\pm}$p, γ-p	$2\%_{th} \oplus 1.5\%_{exp} \approx$ 2.5% (NNLO* only)	$1\%_{th} \oplus 1\%_{exp} \approx$ 1.5% (few yrs), < 1% (FCC-eh) (NNLO. Combined DIS + (extra?) γ-p data)
F_2^γ in γ-γ	$3.5\%_{th} \oplus 3\%_{exp} \approx$ 4.5% (NLO only)	$1\%_{th} \oplus 2\%_{exp} \approx$ 2% ($\sim$2 yrs), <1% (FCC-ee) (NNLO. More precise new F_2^γ data)
e^+e^- evt shapes	$(1.5\text{–}4)\%_{th} \oplus 1\%_{exp} \approx$ (1.5–4)% (NNLO+N$^{(3)}$LL, npQCD significant)	$1\%_{th} \oplus 1\%_{exp} \approx$ 1.5% (+B-factories), < 1% (FCC-ee) (NNLO+N^{3}LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2\text{–}5)\%_{th} \oplus 1\%_{exp} \approx$ (2–5)% (NNLO+NLL, npQCD moderate)	$1\%_{th} \oplus 1\%_{exp} \approx$ 1.5% (few yrs), < 1% (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)
W decays	$0.7\%_{th} \oplus 37\%_{exp} \approx$ 37% (N^{3}LO, npQCD small. Low-stats data)	$(0.7\text{–}0.1)\%_{th} \oplus (10\text{–}0.1)\%_{exp} \approx$ (10–0.15)% (LHC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{th} \oplus 2.4\%_{exp} \approx$ 2.5% (N^{3}LO, npQCD small)	$0.1\%_{th} \oplus (0.5\text{–}0.1)\%_{exp} \approx$ (0.5–0.15)% (ILC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{p}$	$3.5\%_{th} \oplus (2\text{–}3)\%_{exp} \approx$ (4–5)% (NLO only. Combined exp. observables)	$1\%_{th} \oplus 1\%_{exp} \approx$ 1.5% (Tevatron+LHC, $\sim$2 yrs) (NNLO. Multiple datasets+observables)
$t\bar{t}$ in p-p, p-$\overline{p}$	$1.5\%_{th} \oplus 2\%_{exp} \approx$ 2.5% (NNLO+NNLL. CMS only)	$1\%_{th} \oplus 1\%_{exp} \approx$ 1.5% (Tevatron+LHC, $\sim$2 yrs) (Improved m_{top}^{pole} & PDFs. Multiple datasets)

lattice QCD

ep: per mille level
(LHeC/FCC-eh combined with HERA)

ee: order **per mille** with an FCC-ee

d/u at large x



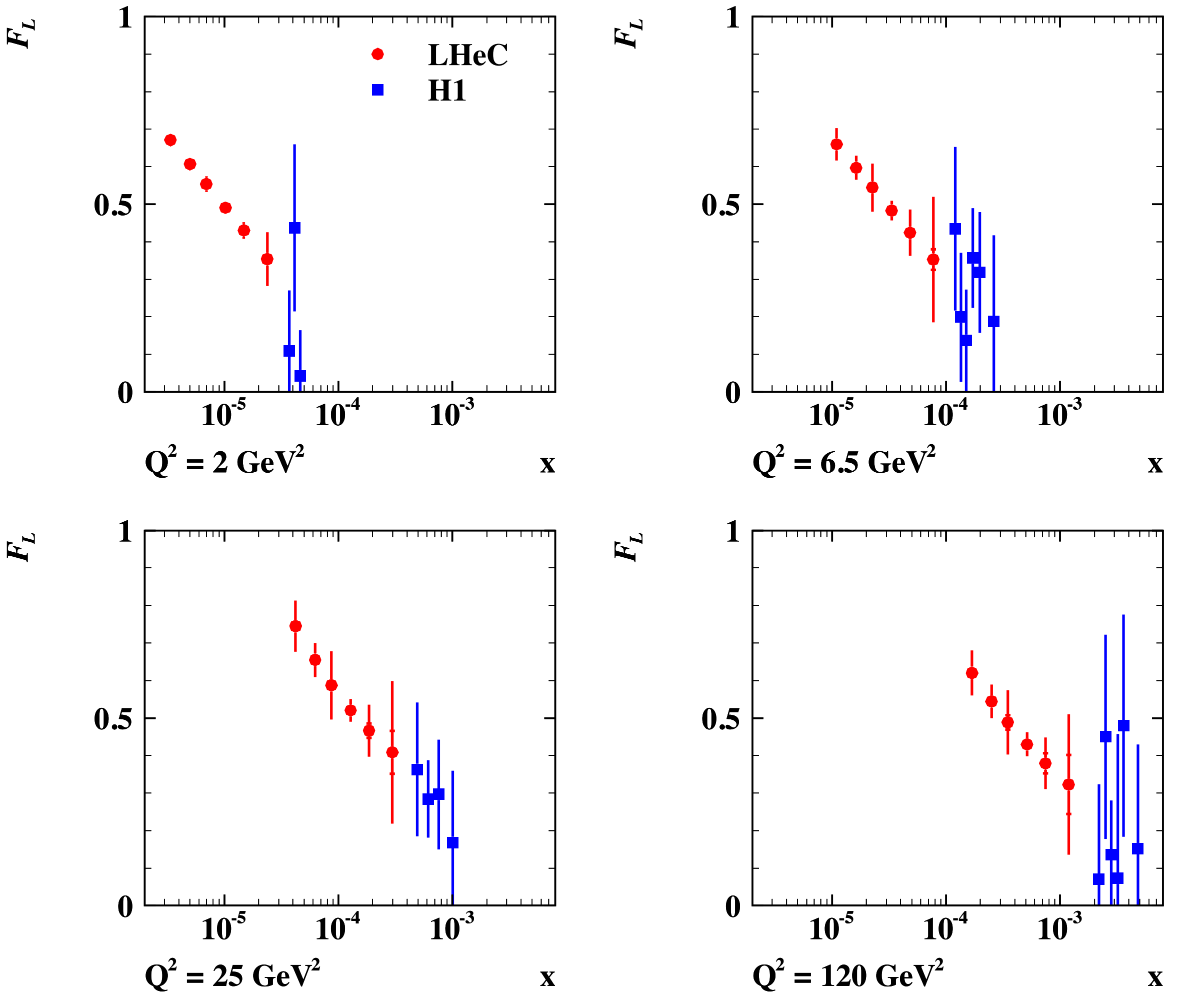
d/u essentially unknown at large x

no predictive power from current pdfs; conflicting theory pictures;
data inconclusive, large nuclear uncerts.

with precision ep(n) data to v. large x
no nuclear corrections; relax assumptions

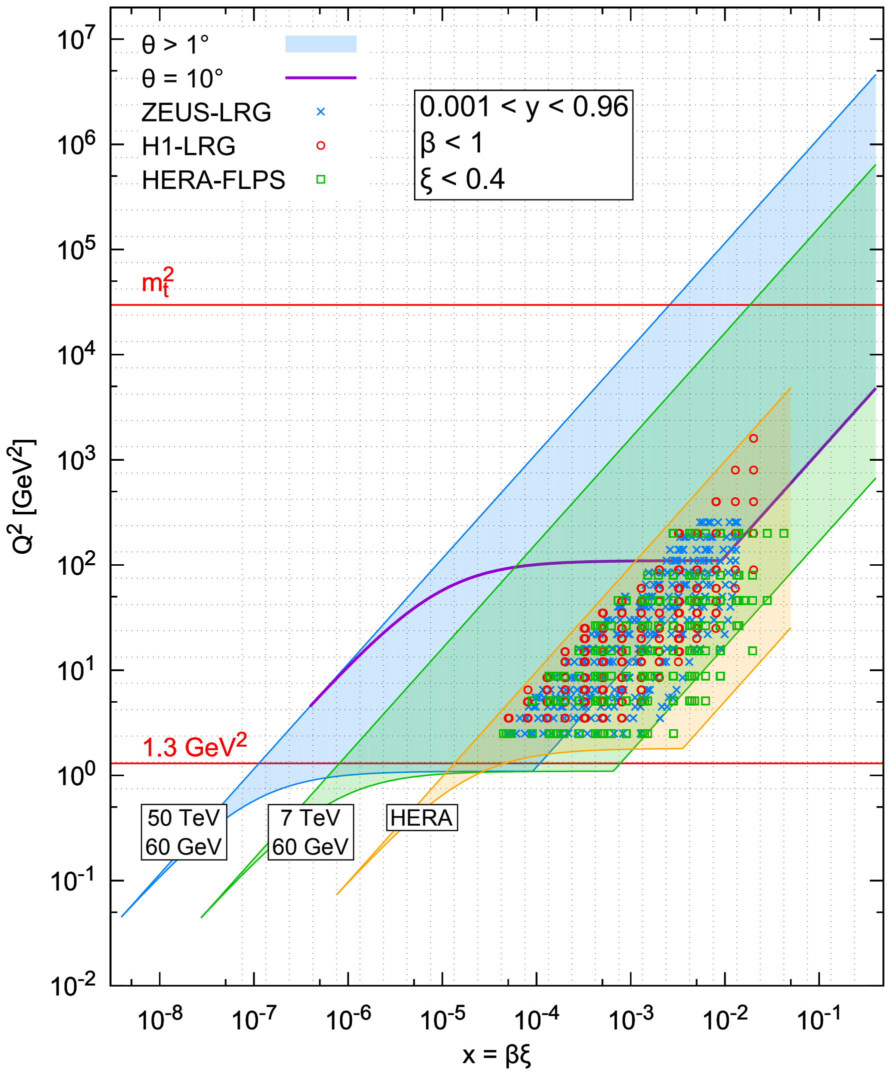
resolve long-standing mystery of d/u ratio at large x

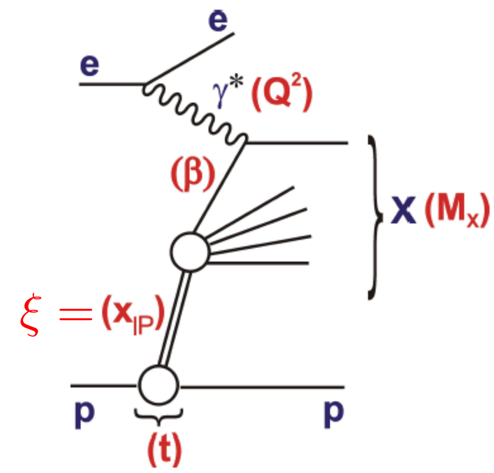
FL at the LHeC



M. Klein, arXiv:1802.04317

diffractive pdfs

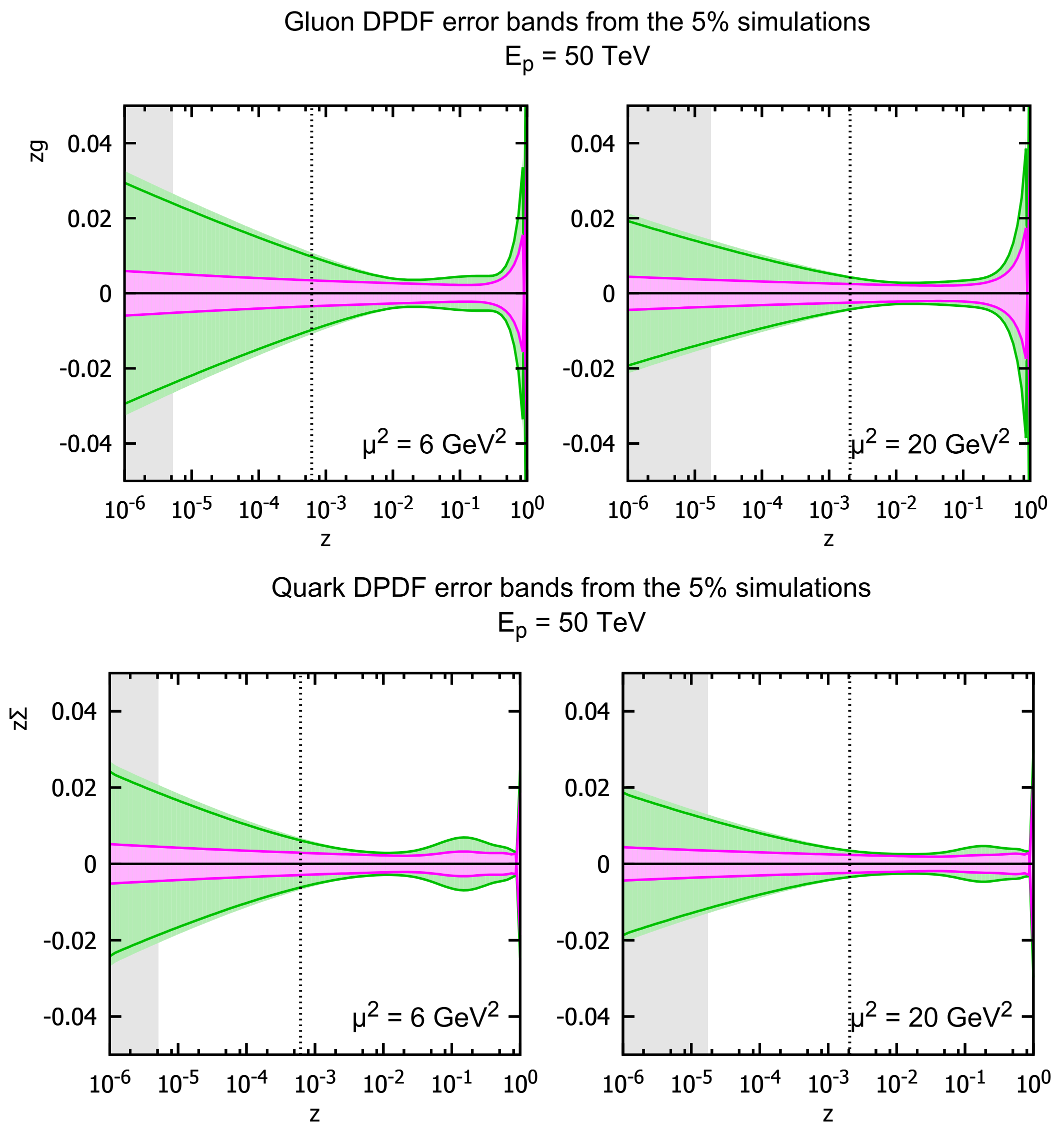




$E_e = 60$ GeV

- $E_p = 7$ TeV vs. HERA
  - $x_{\min}$ down by factor ~20
  - $Q^2_{\max}$ up by factor ~100
- $E_p = 50$ TeV vs. 7 TeV
  - $x_{\min}$ down by factor ~10
  - $Q^2_{\max}$ up by factor ~10

dpdfs: top contribution



top quark phase space region does not have a big effect on the dpdf extraction

LHC pdf prospects

A.M. Cooper-Sarkar
HL/HE-LHC WS, CERN, Nov. 2017

Summary: where can we improve in future?

- **W,Z and Drell-Yan distributions** – sensitivity to valence quarks, strangeness, photon PDF

ATLAS peak W,Z data has already reached systematic uncertainties of ~0.5%, experimental improvement unlikely and this is already challenging NNLO calculations
The reach to lower x at 13,14,27TeV brings more theoretical challenges- need for ln(1/x) resummation- see arXIV:1710.05935
Off-peak Drell-Yan can still improve BUT low-mass brings the same low-x challenges.
This also affects the LHCb data
And high-mass requires good understanding of the NLO-EW corrections and photon PDF

- **Inclusive, di-jet and tri-jet distributions**------sensitivity to gluon

Already challenging theoretical understanding -NNLO is needed but scale choice is still an issue

- **Top-antitop distributions** –sensitivity to gluon

NNLO calculations already required, data can also improve (data consistency?)

Combinations of types of data and different beam energies –accounting for their correlations- can help

For all of these below: precision of the data can improve

- **W,Z +jets** --------sensitivity to gluon- so far limited, can improve
- **W,Z/γ +heavy flavour** -sensitivity to strangeness and intrinsic charm- can improve
- **Direct photon**-------sensitivity to gluon—studies needed

… likely to bring incremental rather than dramatic improvements;
more concrete studies underway in context of ongoing HL/HE-LHC workshop