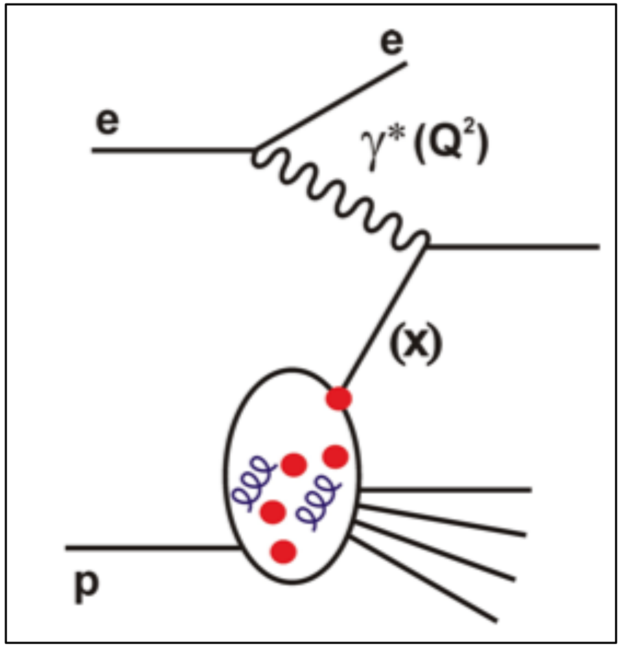
PDFs and α_s at future colliders

LHeC, EIC, HL/HE-LHC, FCC

Claire Gwenlan, Oxford

DIS18, Kobe, Japan, April 2018



with emphasis on precision (unpolarised) pdfs for current and future hadron colliders

with special thanks to A. Accardi, E.A. Aschenauer, M. Klein, R. Yoshida

importance of pdfs

current uncerts. in proton parton distribution functions (pdfs):

limit searches for new heavy particles; dominate (together with **αs**) theory uncertainties on Higgs production; limit precision of fundamental parameters EG. MW, and of backgrounds to BSM searches

with higher luminosity and higher energy pp machines on horizon, will need higher precision pdfs

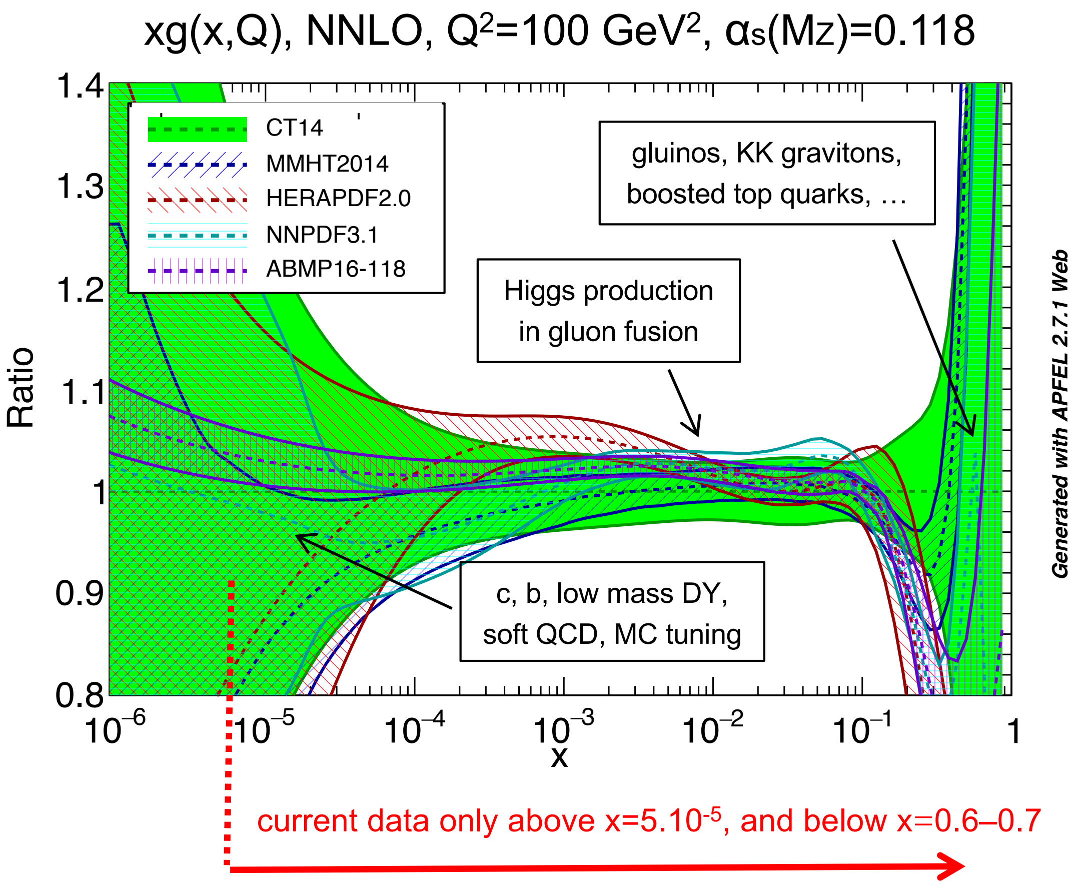
LHC measurements are providing useful pdf constraints;

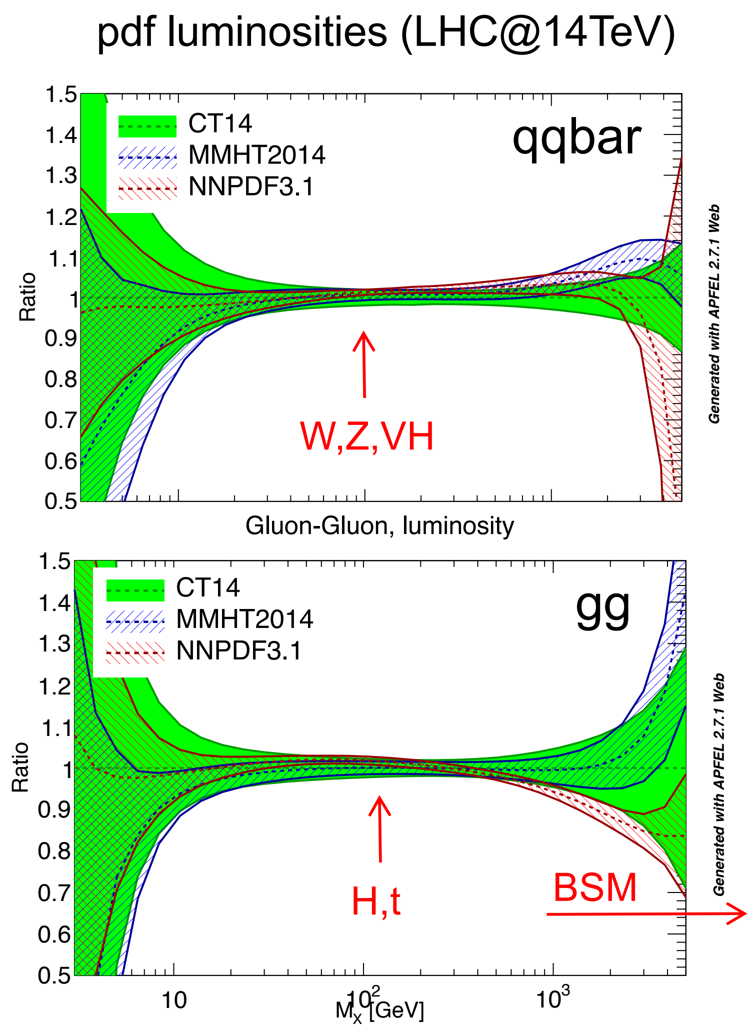
should certainly be exploited; currently we have nothing else …

is there a NEED for future ep collider for pdfs?

will we not improve the precision of pdfs sufficiently using LHC data?

situation today

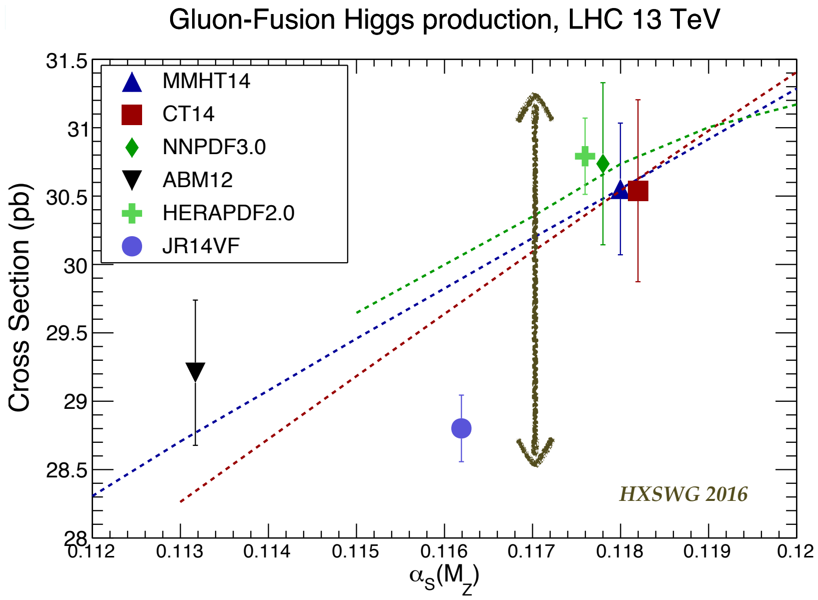




pdfs poorly known at large and small x

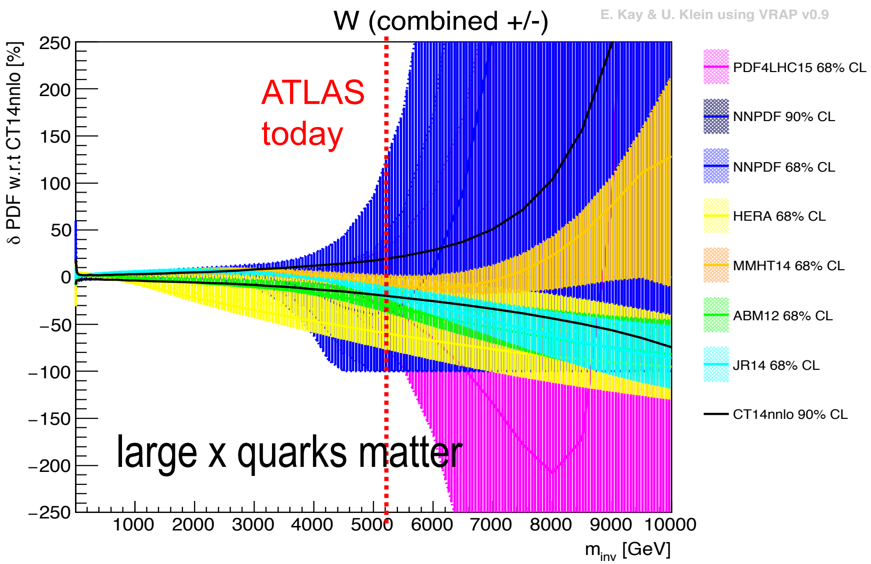
higher precision needed also for H, W, t

situation 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

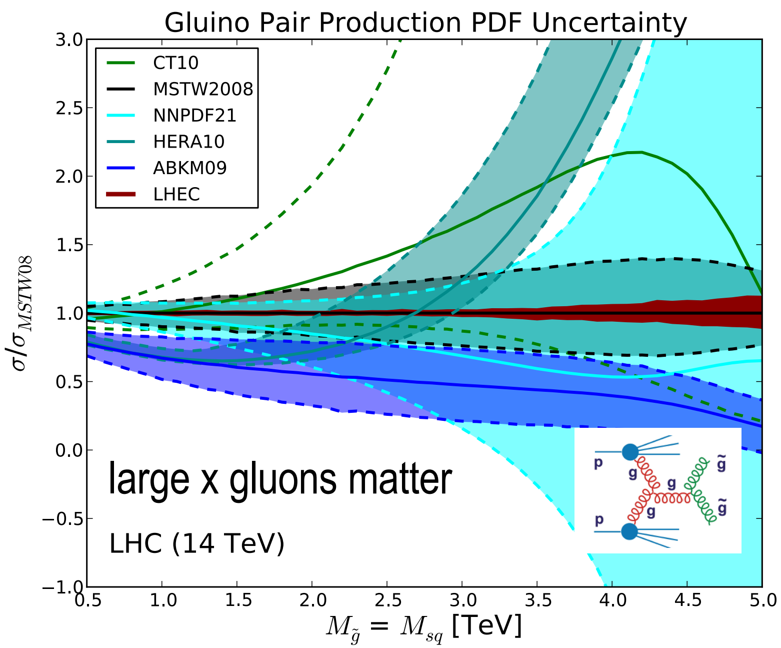


Mw

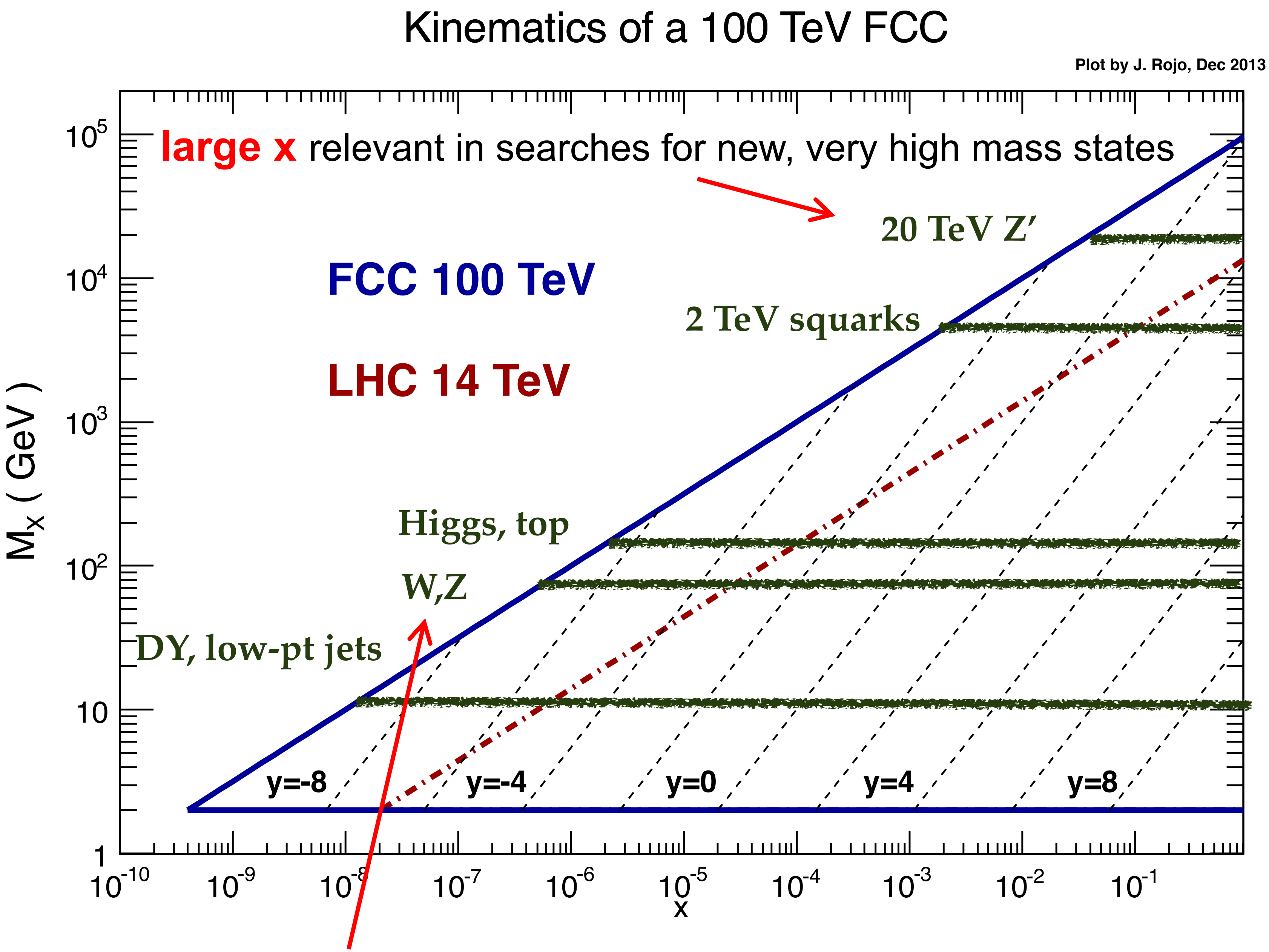
Higgs

BSM

...

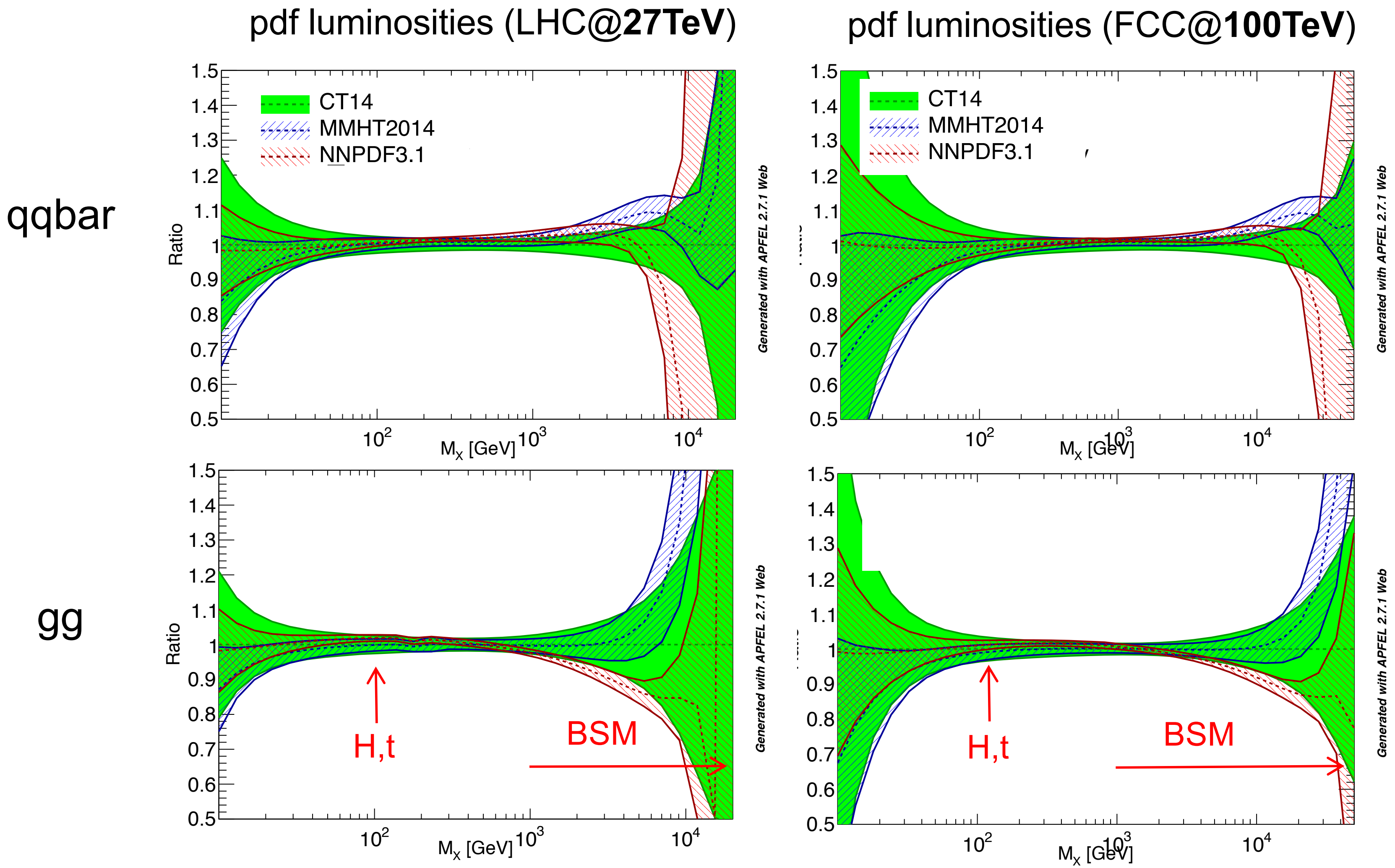


take home message: much of **LHC programme** will be **limited by pdf uncertainties** as we move towards ultimate LHC luminosity, **unless there is a transformation in precision**

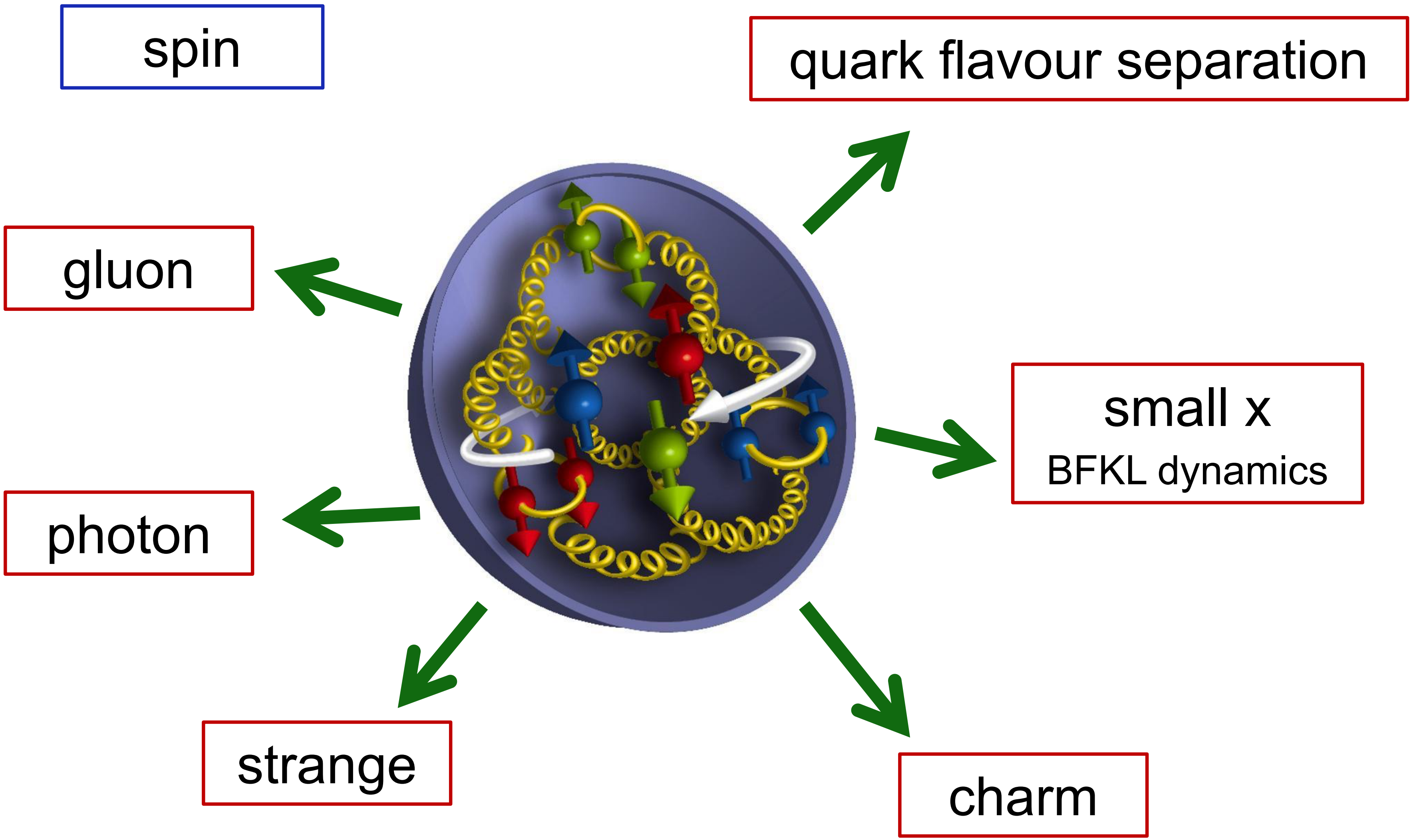


small x becomes relevant even for “common” physics (EG. W, Z, H, t)

pdf luminosities for HE-LHC and FCC

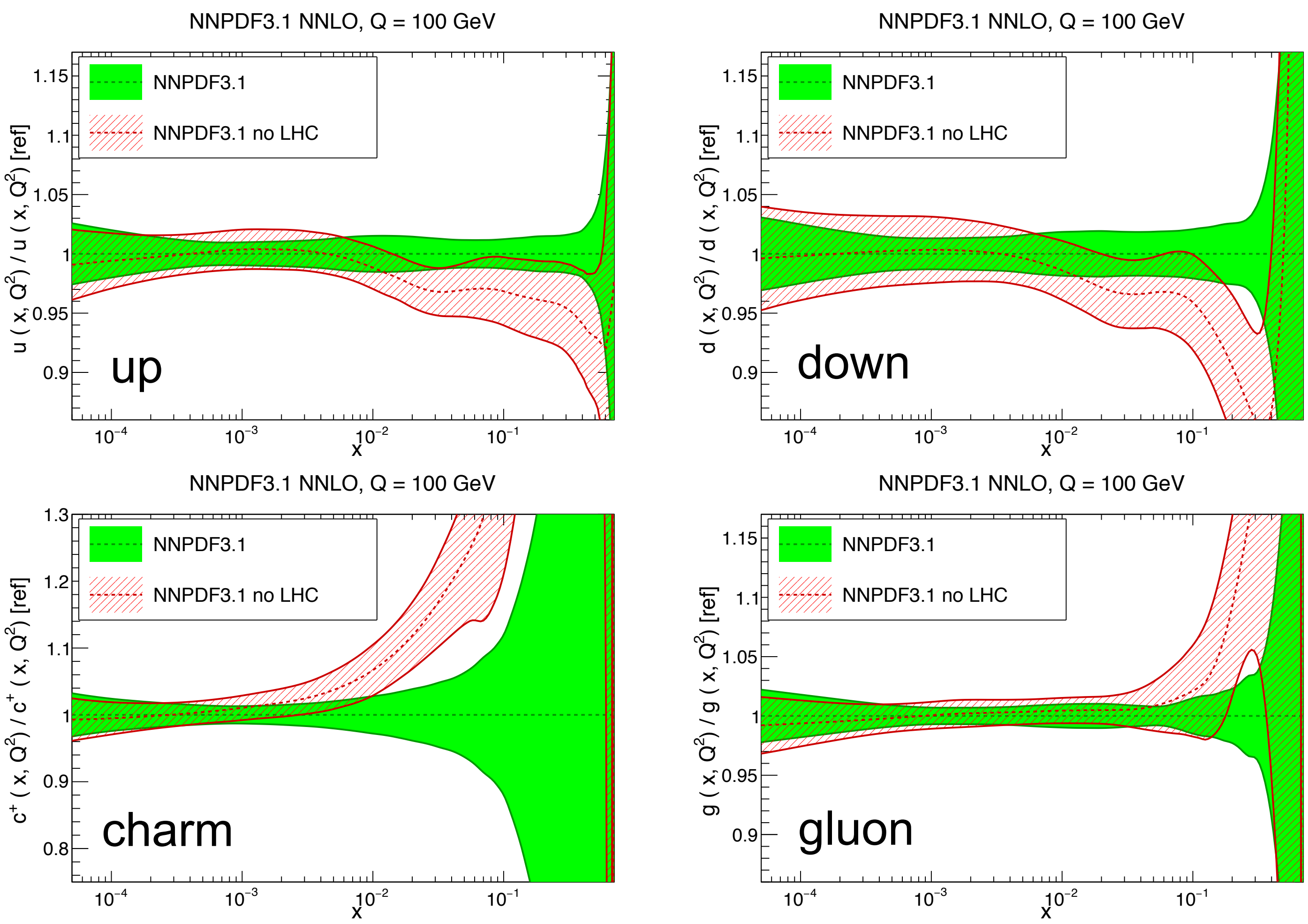


inside the proton



(based on slide from J. Rojo, POETIC8)

impact of LHC on today's pdfs



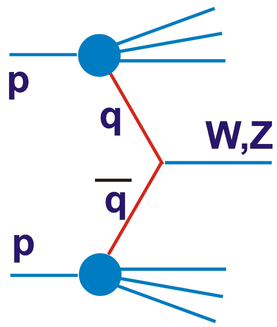
arXiv:1706.00428

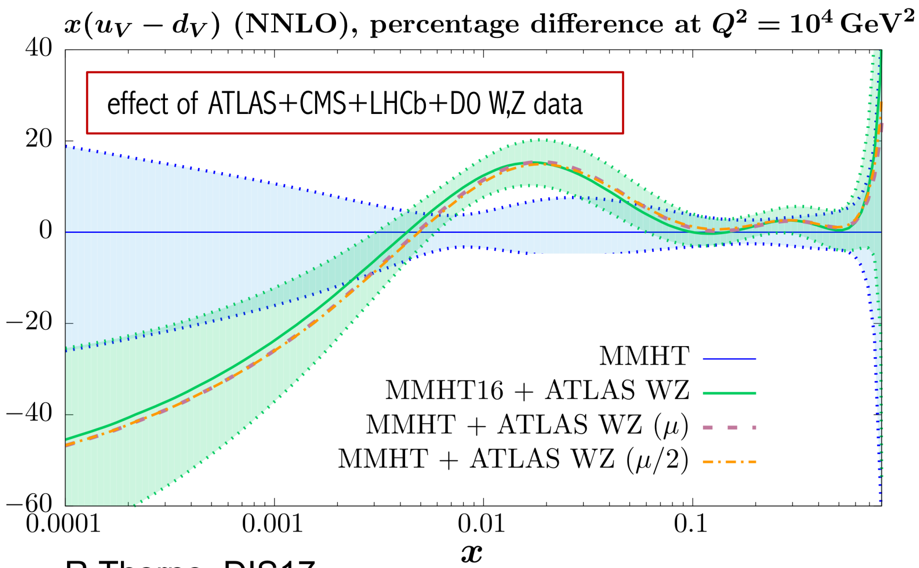
(**NNPDF3.1** includes modern LHC data on W,Z+top+jets+ZPt)

pp constrains pdfs, it does not precisely determine them …

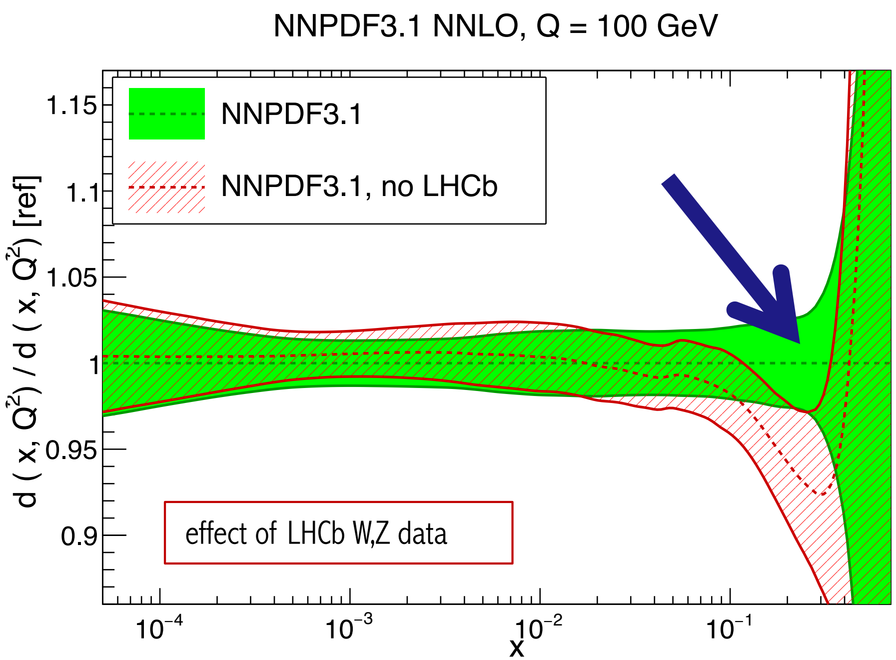
LHC: electroweak gauge bosons

- information on **quark** and **anti-quark flavour** separation
  LHCb measurements extend to forward region (impact at small & large x)
- ATLAS W,Z & W+c; **strange pdf** larger vs. dimuon data (see later)
- HM Drell Yan data also sensitive to **photon pdf** of proton (arXiv:1606.01736)





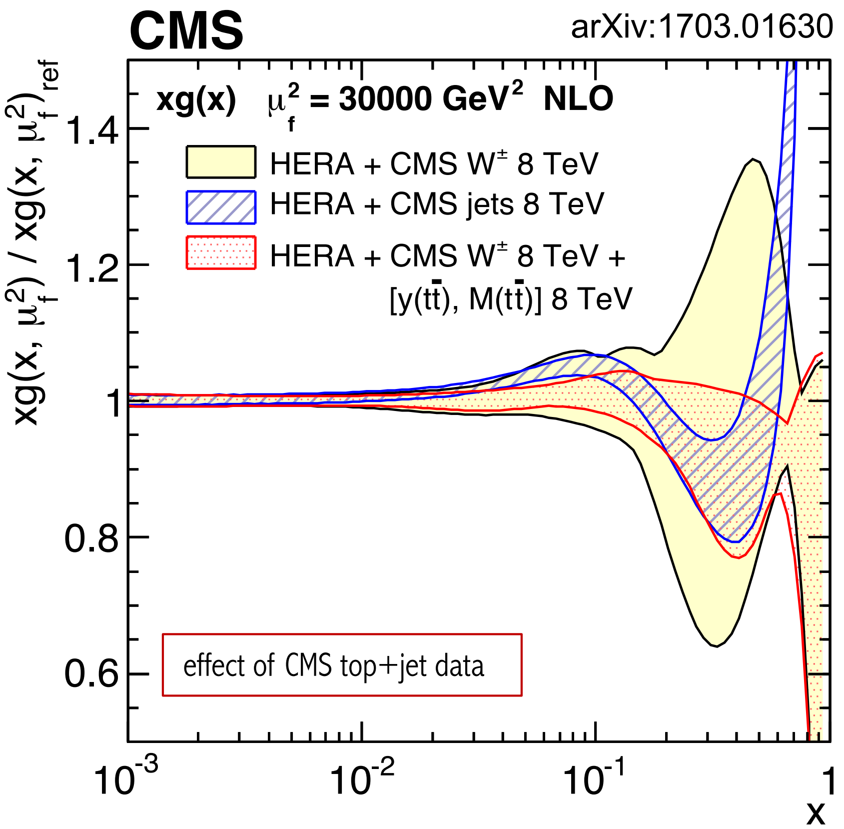
R.Thorne, DIS17

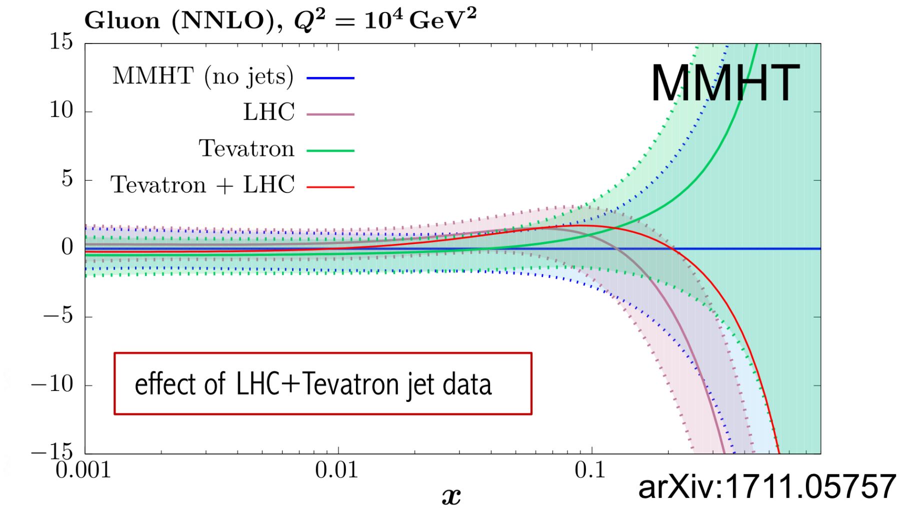


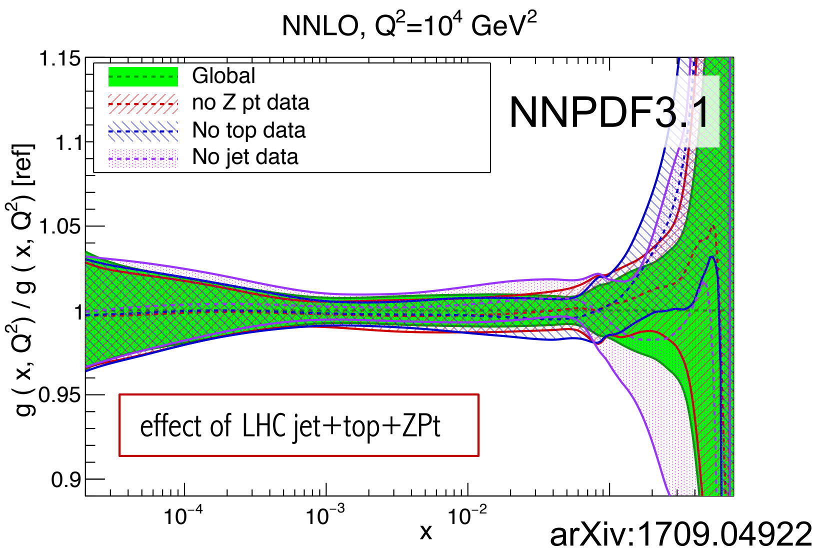
arXiv:1706.00428

state-of-the-art theory: NNLO(QCD)+NLO(EW)

LHC: gluon from jets, top, ZPt







jet, **top quark pair** and **ZPt** measurements constrain **gluon** at medium and high x

numerous studies from ATLAS, CMS, xFitter and global fitters

NNLO QCD calcs. now available in all cases

(**LHCb forward charm and beauty** measurements COULD also help at small x?)

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?)

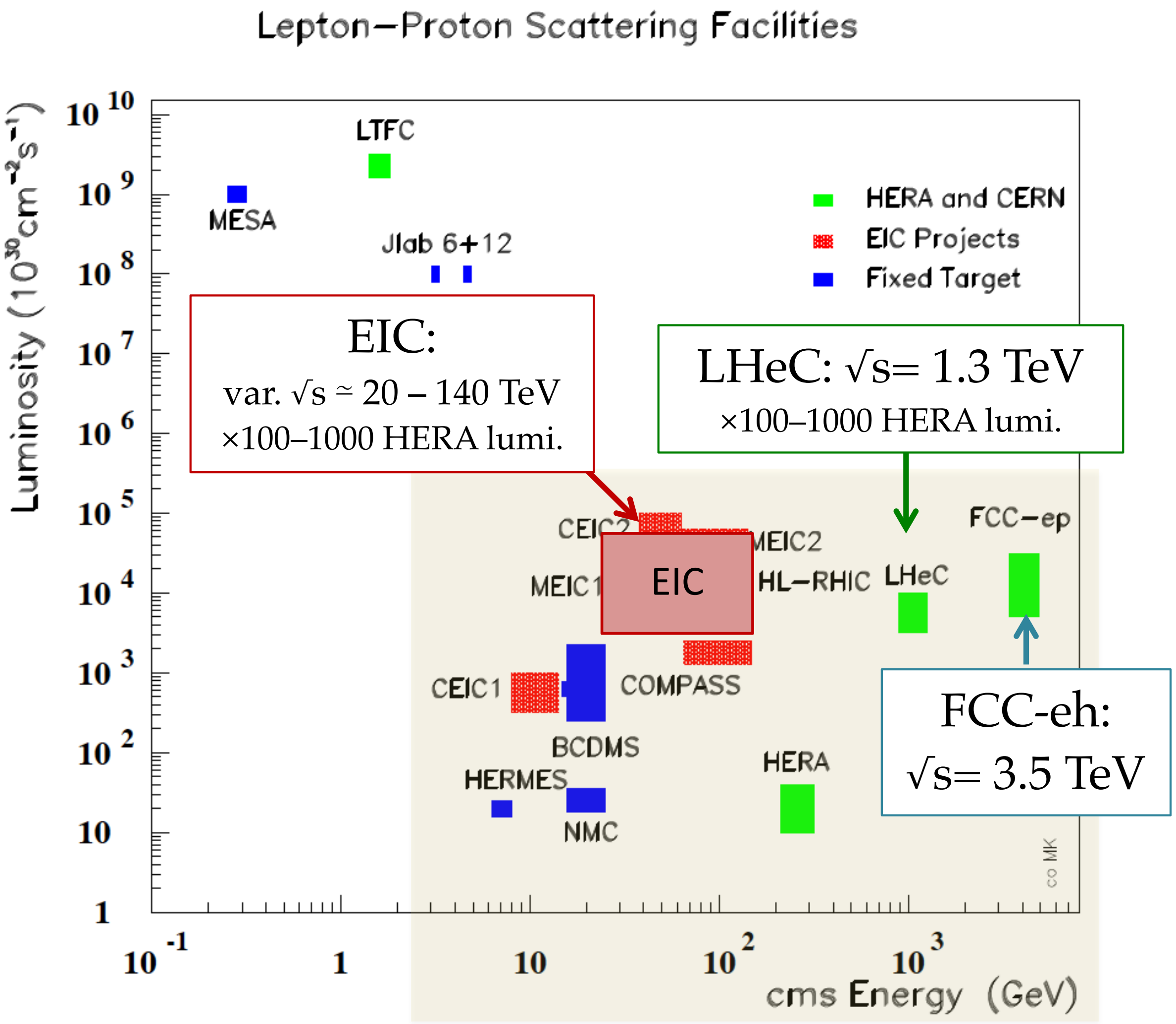
Combinations of types of data and different beam energies –accounting for their correlations- can help

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

ep colliders



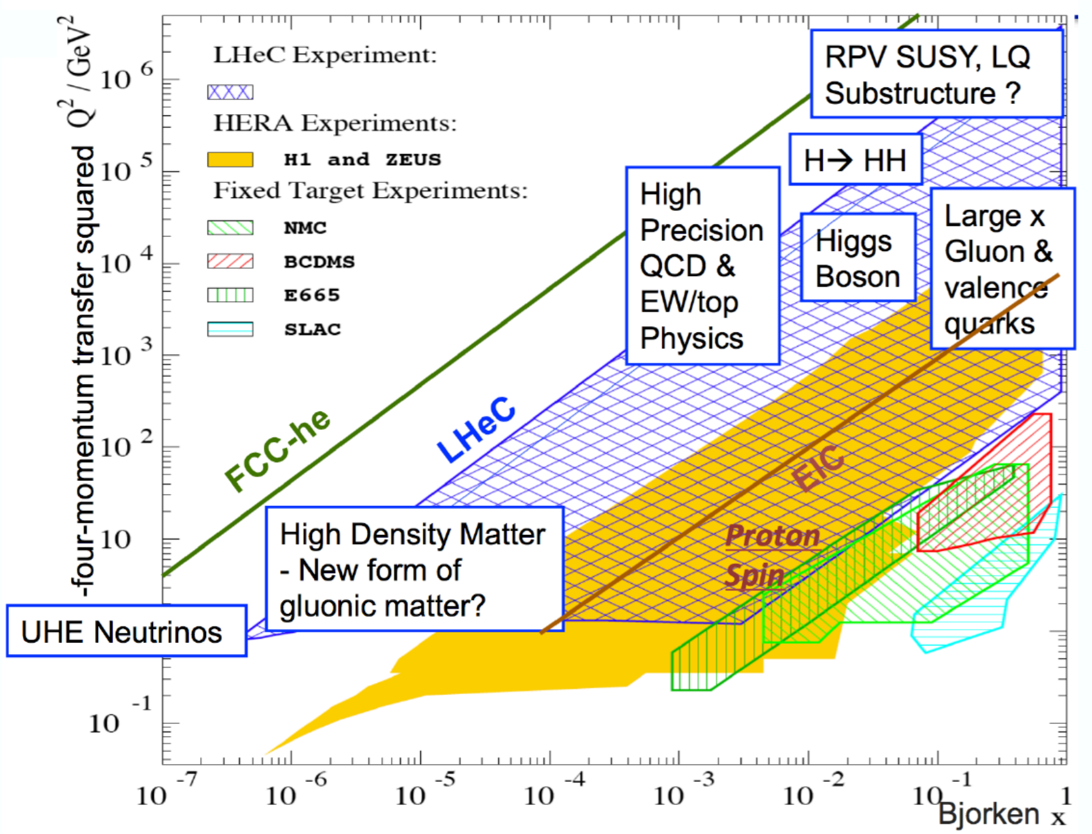
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

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**)

EIC: world's first <u>polarised</u> ep and eA future collider (image structure/interactions of nucleons and nuclei in multi-dimensions (x, bt, kt, spin)) EG. arXiv:1108.1713,1212.1701,1708.01527

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: $10^{-7} \longrightarrow 1$

(×100 extension in Q^2, 1/x reach vs HERA)

EIC:

Q^2 to 10^4 GeV^2, x: $10^{-4} \longrightarrow 1$

variable CM: $\sqrt{s} \approx$ 20–100 (140) GeV

(interpolates fixed target and HERA)

optimised for proton spin

LHeC/FCC-eh and **EIC** have hugely rich physics programmes

see also many other WG7 talks in this workshop

LHeC and EIC pdf programmes

LHeC / FCC-eh goal:

completely resolve <u>all</u> **proton pdfs**; and α_s to permille precision

no higher twist, no nuclear corrections, free of symmetry assumptions, N3LO theory (coming)

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

pdf fit studies:
M. Klein, V. Radescu

NC and CC data of high precision (stat.+syst.) over unprecedented (x,Q^2) kinematic range; tagging of c, b with high precision and coverage; ep (eD)

NB, fit studies mostly do not yet include simulated s, c, b, t or FL data (full details of sim. and fit in extras)

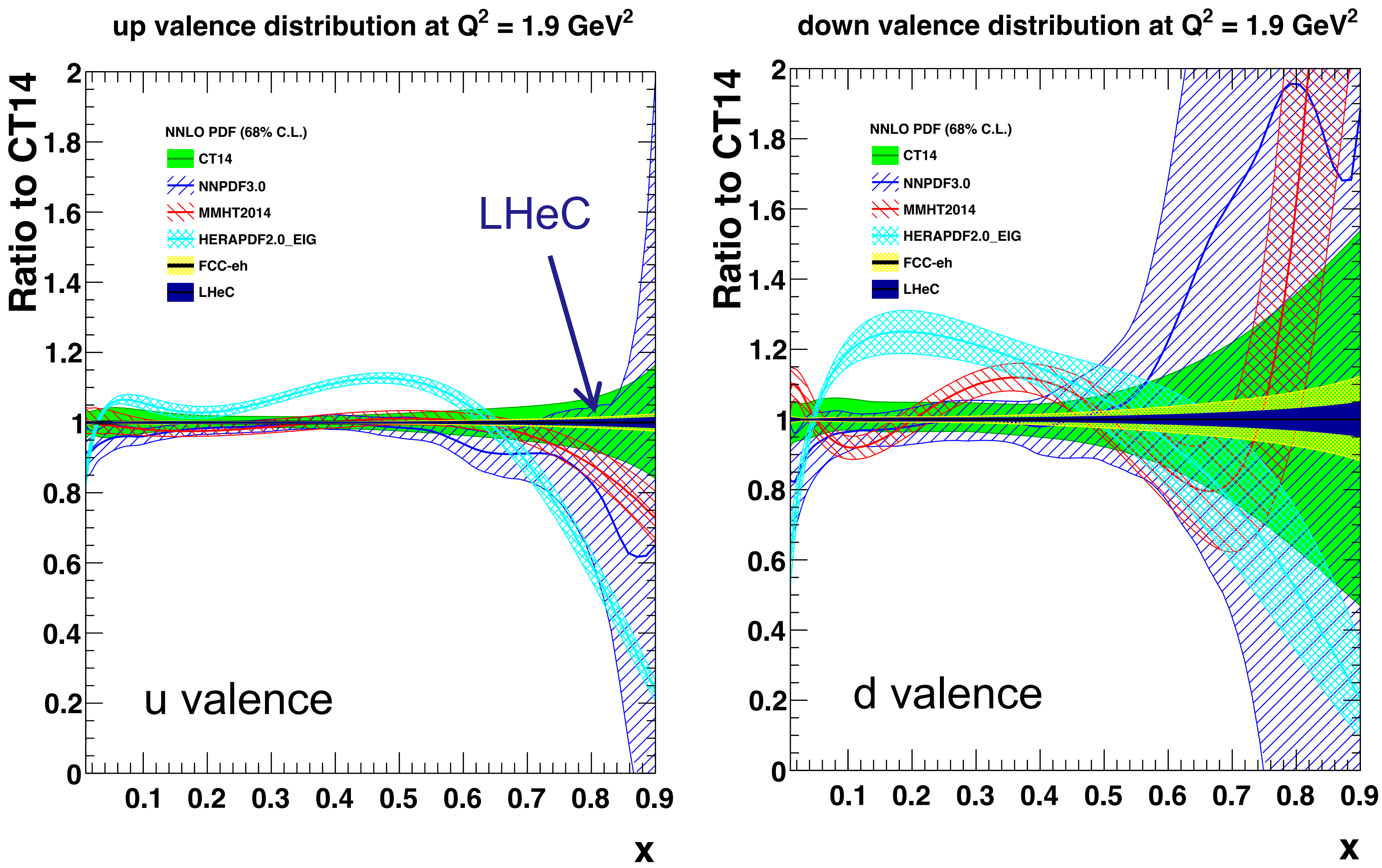
EIC: focus is on pdfs in nuclei and polarised pdfs in spin polarised protons†

pdf 4LHC programme being worked out; **EIC** likely to run alongside HL-LHC; important to establish what it can do for unpolarised pdfs for LHC and beyond

some questions to be addressed: d/u and **xg(x)** at **large x**; **s**; **c**; **FL**; EW contributions to proton pdfs; … (arXiv:1108.1713)

† **nuclear pdfs** (N. Armesto, WG7); **polarised pdfs** (in this talk, briefly, if time); **not covered: TMDs, GPDs**

valence quarks from LHeC



precision determination, free from higher twist corrections and nuclear uncertainties

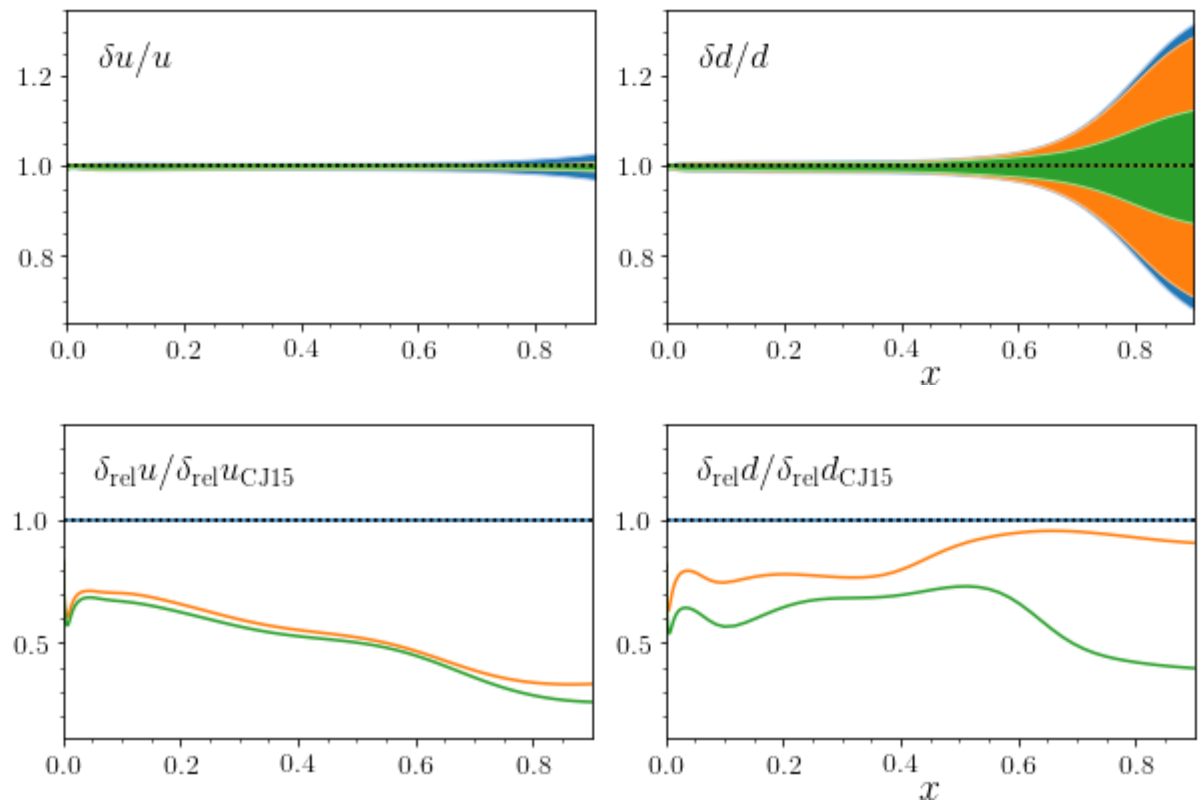
large x crucial for HL/HE–LHC and FCC searches; also relevant for DY, MW etc.

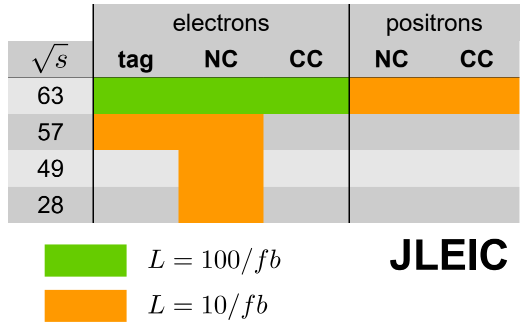
u, d quarks at large x from EIC

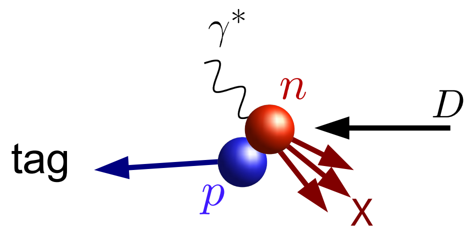
EIC: improvement on **u quark**; measurement of **F2n** (via proton spectator tagging) has significant impact on knowledge of **d quark**

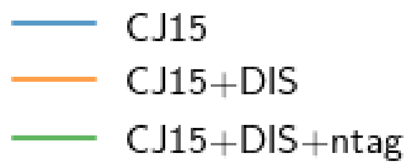
A. Accardi, R. Ent, J. Furletova, C. Keppel, K. Park, R. Yoshia, M. Wing

new sim. data since DIS17



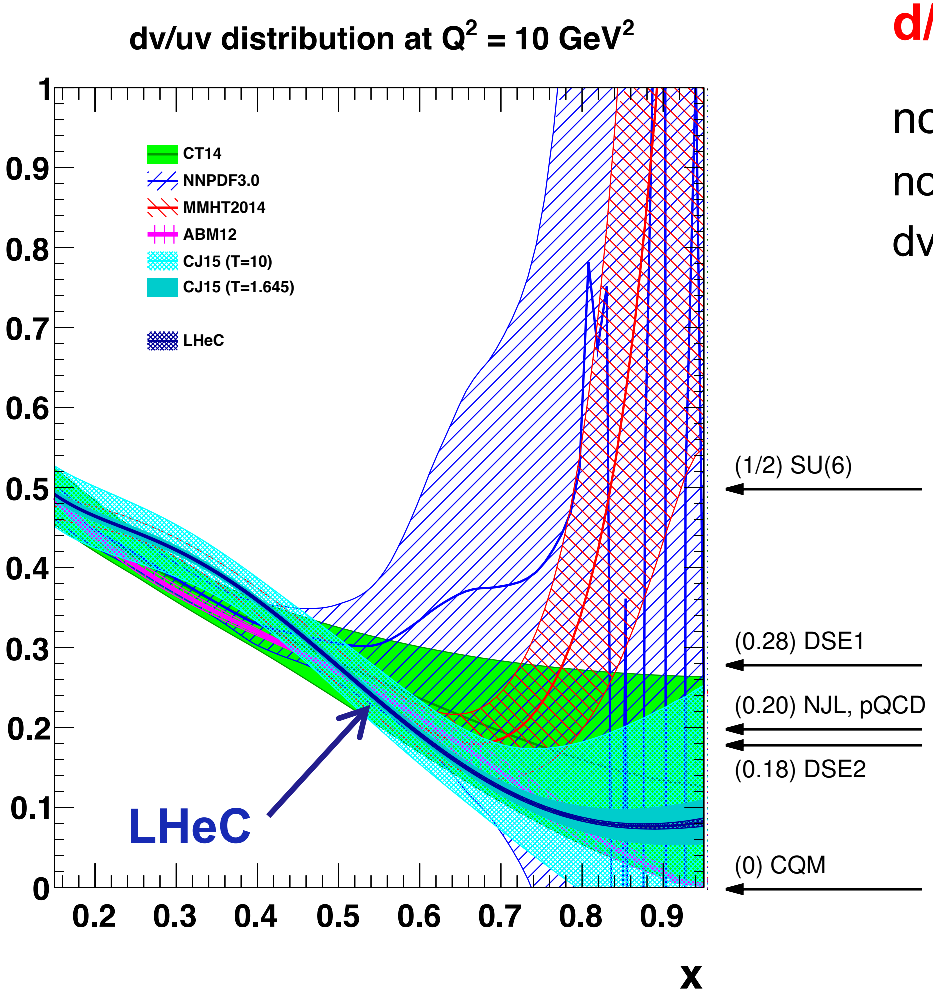






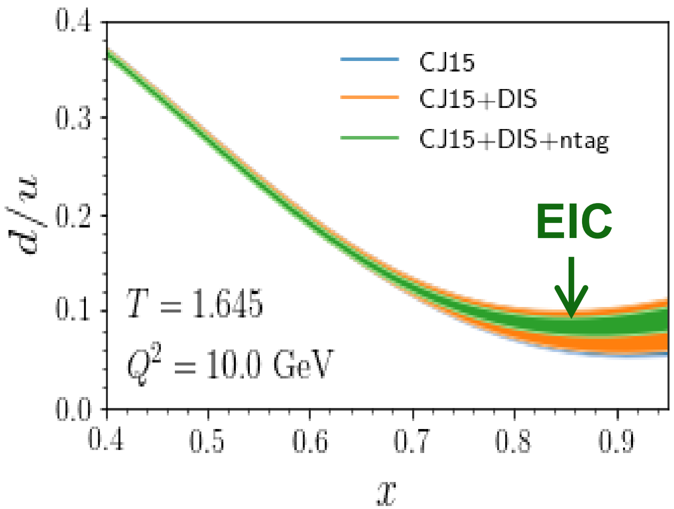
NB, also older **LHeC** study, showing symmetrised knowledge of u and d quarks with D running

dv/uv at large x



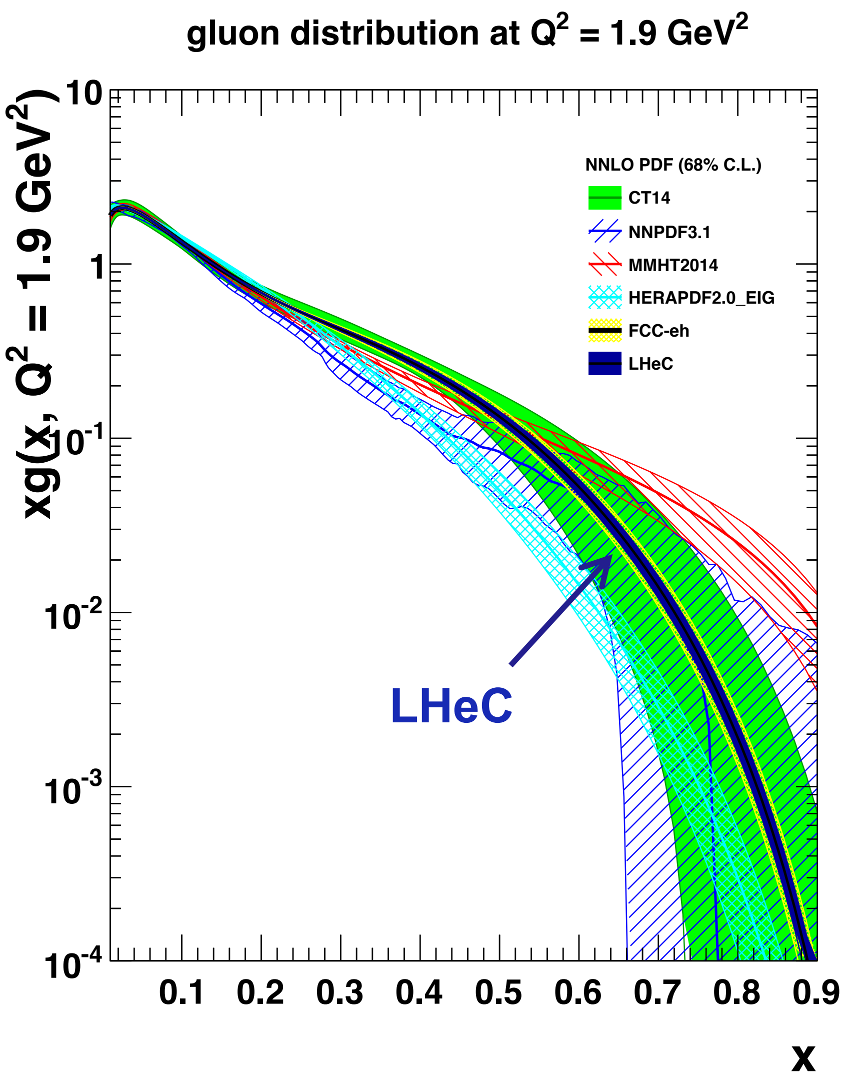
d/u essentially unknown at large x

no predictive power from current pdfs;
no discrimination among models, unless
dv/uv $\xrightarrow{x\to 1}$ k built into parameterisation



resolve long-standing mystery of d/u ratio 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

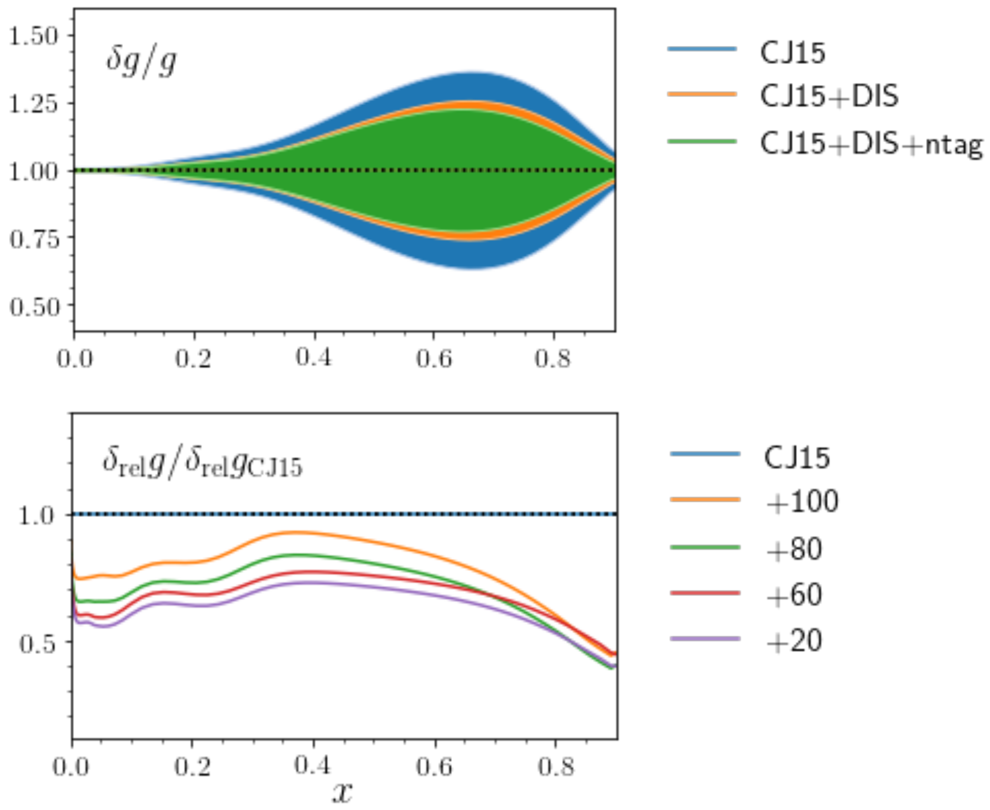
high luminosity (×100–1000 HERA); fully constrained quark pdfs; low x; momentum sum rule

gluon and sea intimately related

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

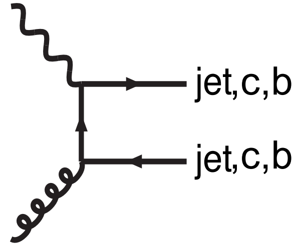
gluon at large x

A. Accardi, et al



EIC: large x gluon
gain from including inclusive
data at different CM energies
(increased Q2 lever arm)

impact as a function of proton energy

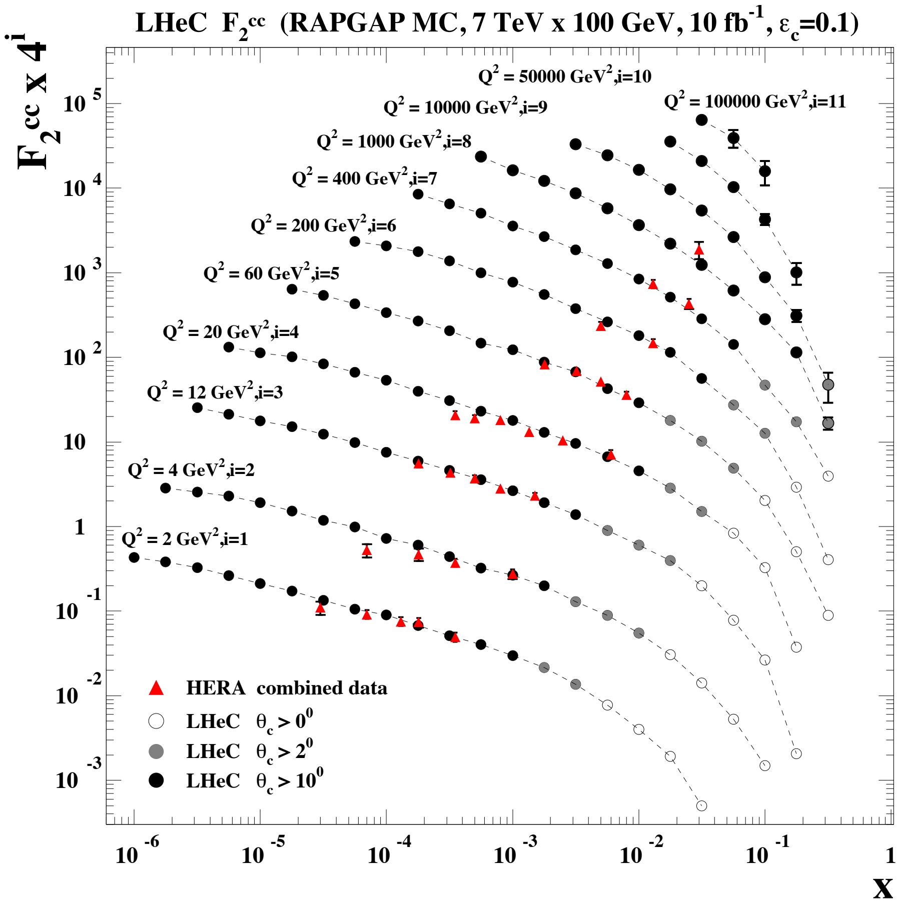


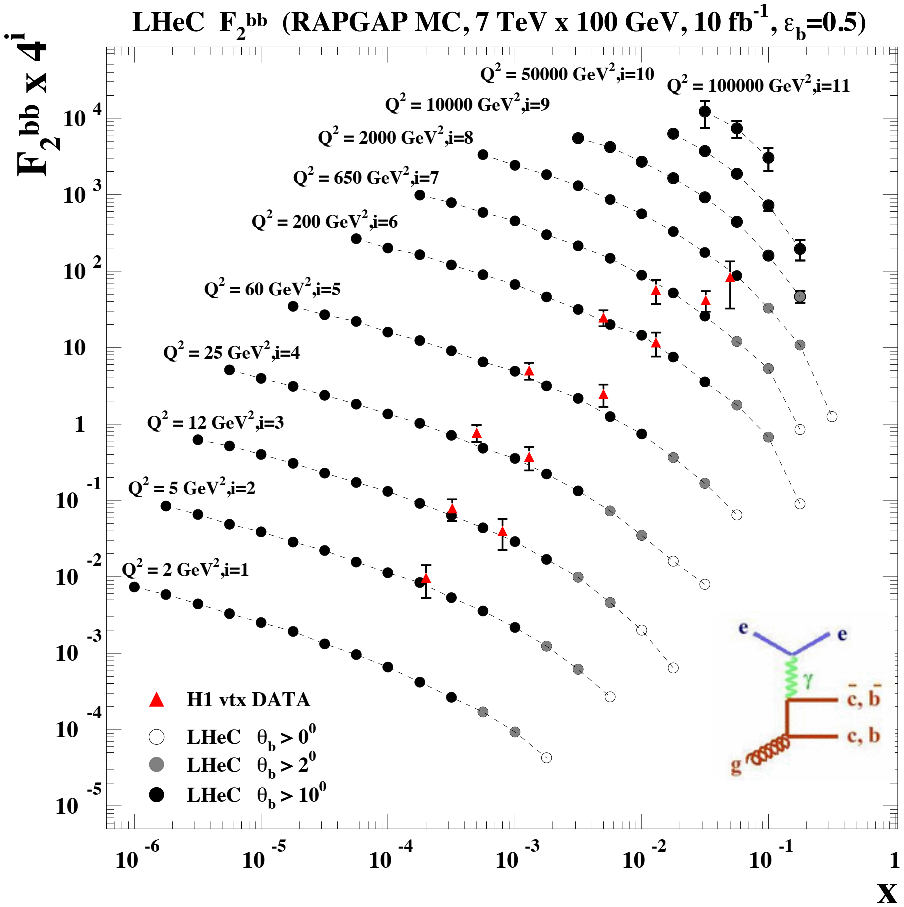
LHeC and **EIC**: extra direct information on gluon also from **c**, **b** and **jets**

not yet included in LHeC or EIC pdf projection studies

NB, ep incl. jet and dijet now available at NNLO QCD; Currie et al, arXiv:1606.03991,1703.05977; Abelof et al, 1607.04921

c, b quarks

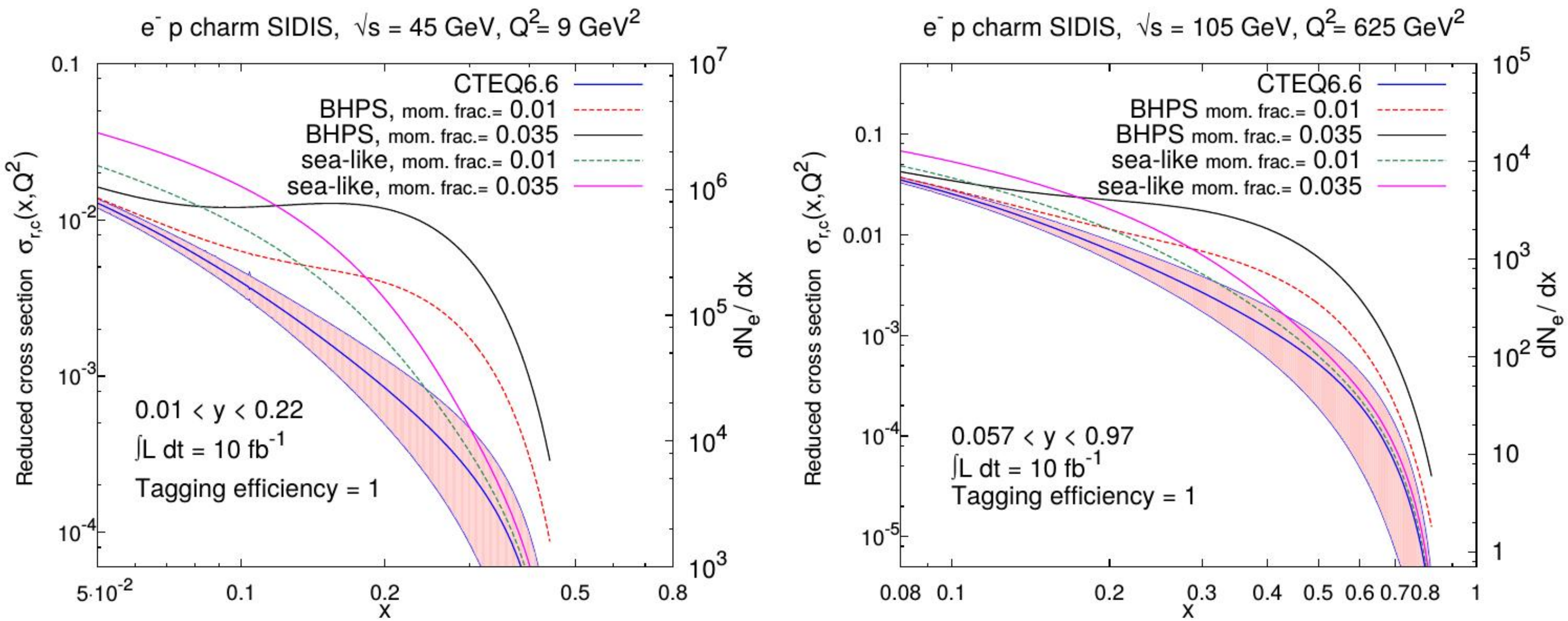




LHeC: enormously extended range and much improved precision c.f. HERA

- **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 $b\bar{b} \rightarrow A$

intrinsic charm



arXiv:1108.1713

EIC: intrinsic charm may be probed via charm contributions to DIS reduced cross section, $F_{L,c}$ or angular distributions

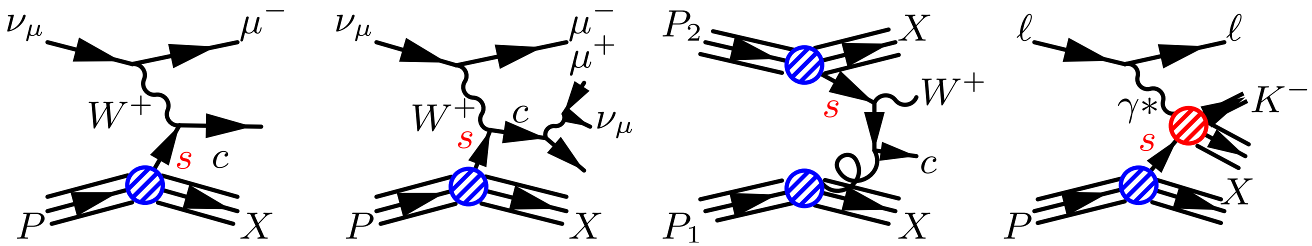
sensitivity to intrinsic vs perturbative charm; and to different shapes of intrinsic charm

LHeC: challenge – charm tagging in very forward direction to access large x values of interest; could be favourably done with dedicated lower proton beam energy runs (CDR study)

LHC: EG. Z+c, γ+c; most recent measurements not yet discriminating (see extras)

strange

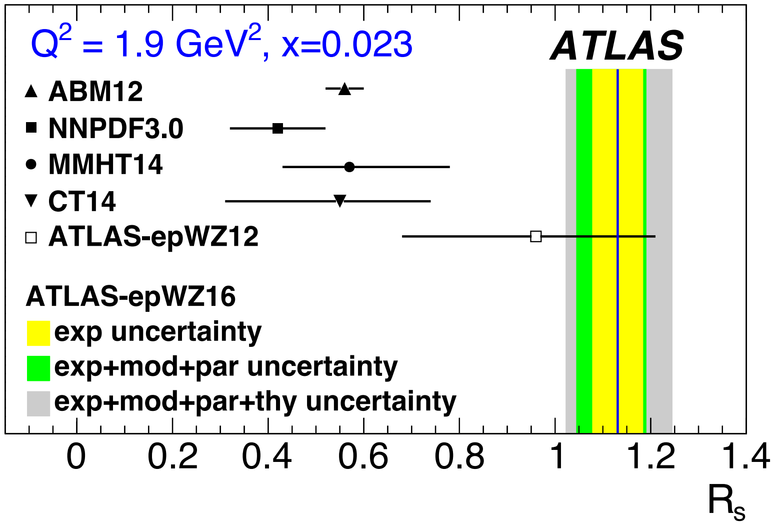
strange pdf poorly known; suppressed cf. other light quarks? strange valence?

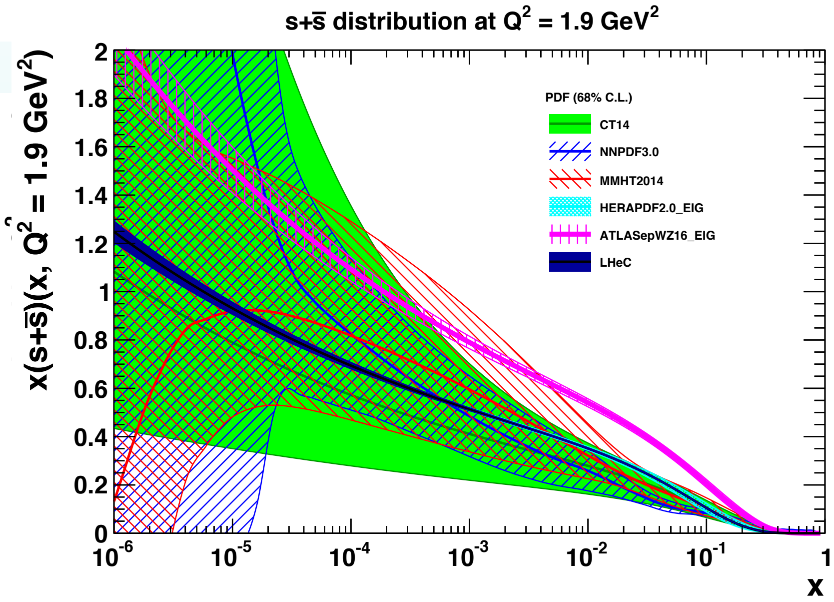


EG. CHORUS NuTeV ATLAS/CMS HERMES

ATLAS† observe large strange fraction at mean Bjorken x around 0.01

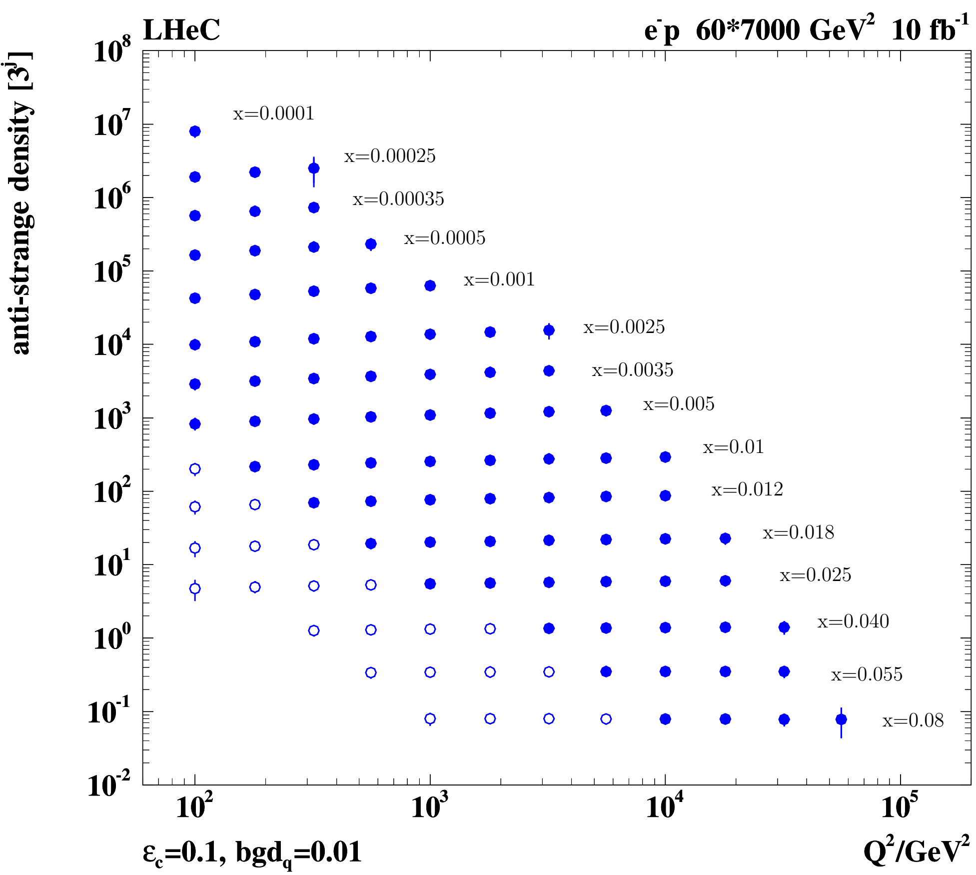
$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$



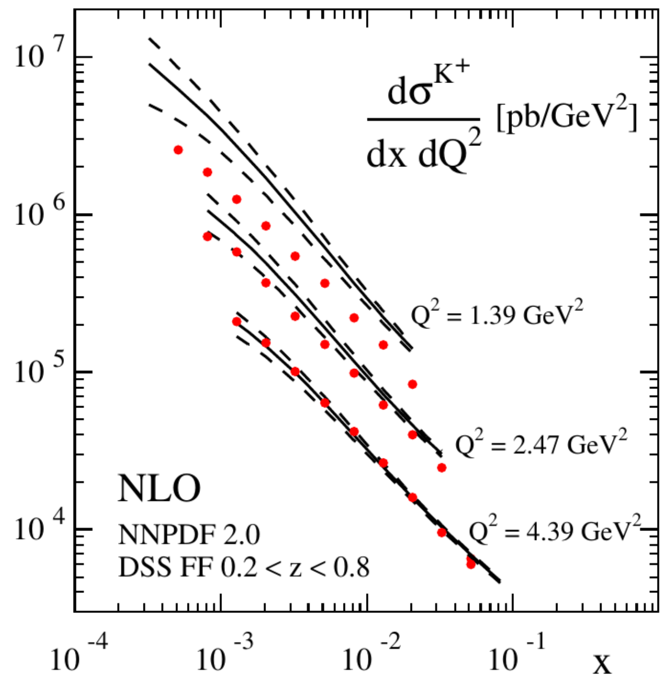


†ATLAS arXiv:1203.4051, confirmed with high stats in 1612.03016; and by global fitters EG. NNPDF 1706.00428, MMHT 1708.00047

strange



arXiv:1108.1713



LHeC: direct sensitivity to strange via W+s → c

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

also top pdf via CC DIS becomes possible!

EIC: $K^\pm$ prod. in semi-inclusive DIS;

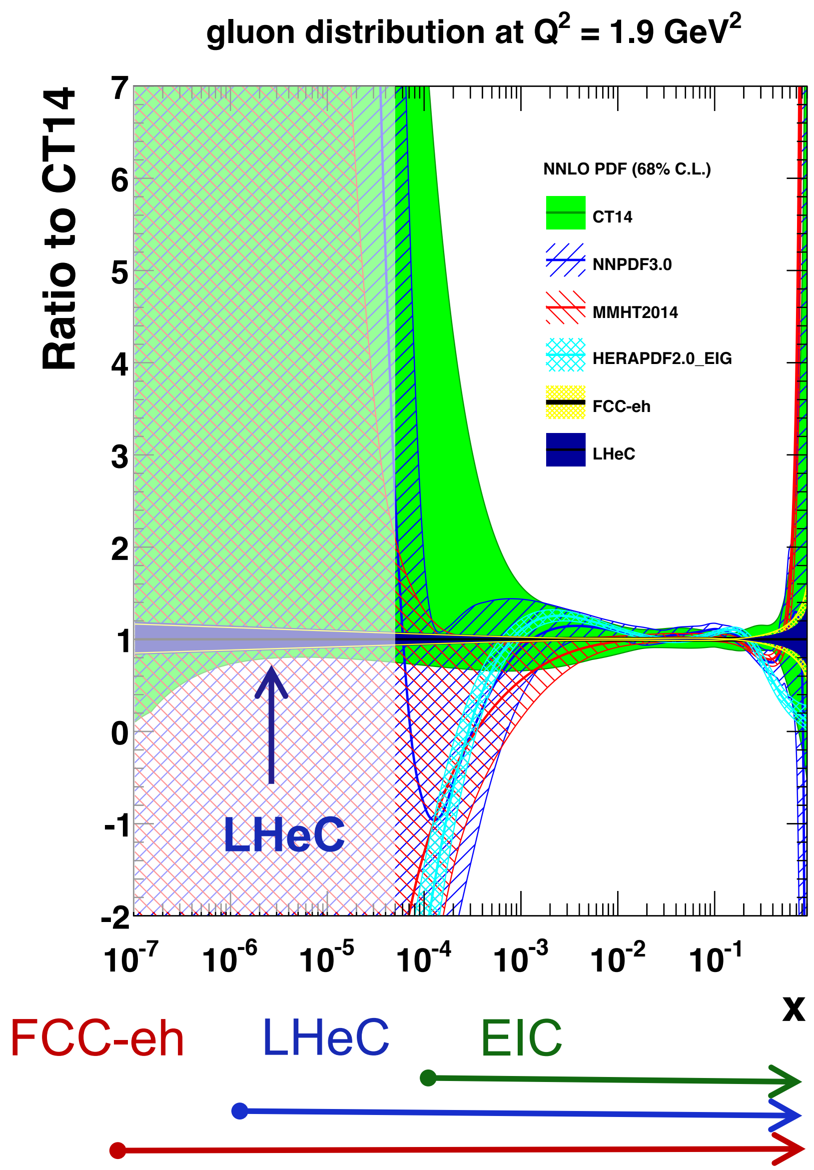
complication: $K^\pm$ fragmentation; could study FFs separately, or simult. analyse pdfs and FFs

also **strange** sensitivity in PV DIS;

W+s → c,

in complementary phase space to LHeC

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

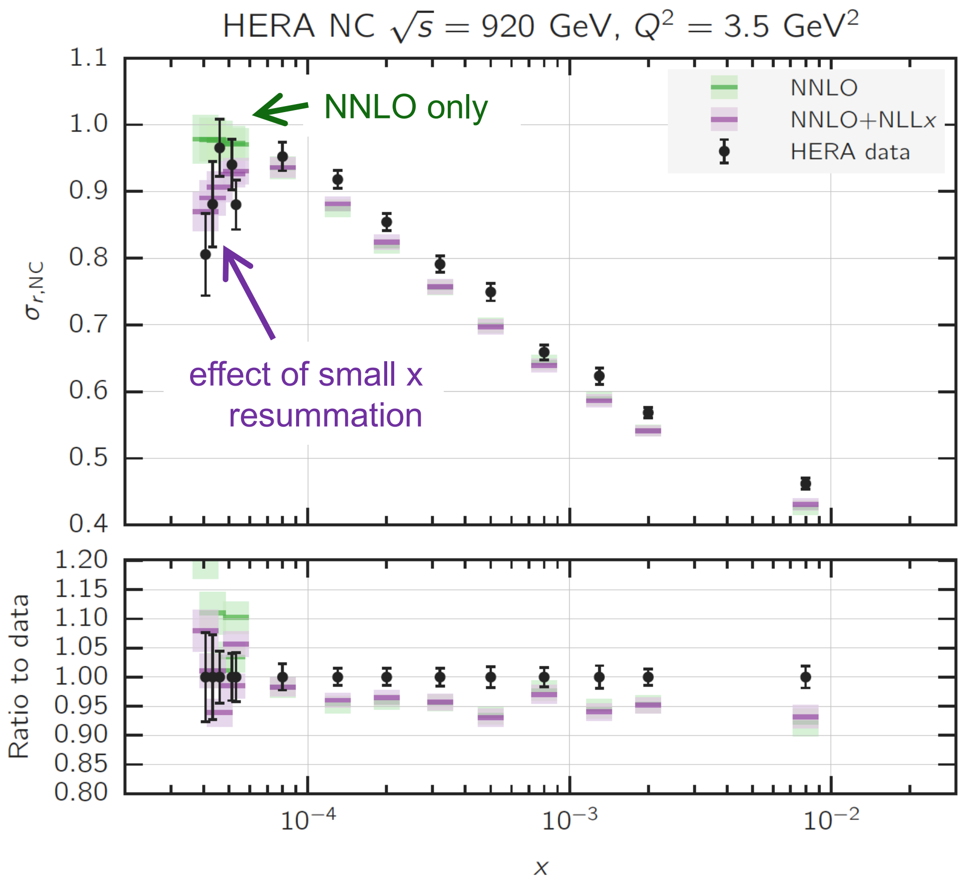
(**EIC**: study of gluon saturation in **eA** a key goal;

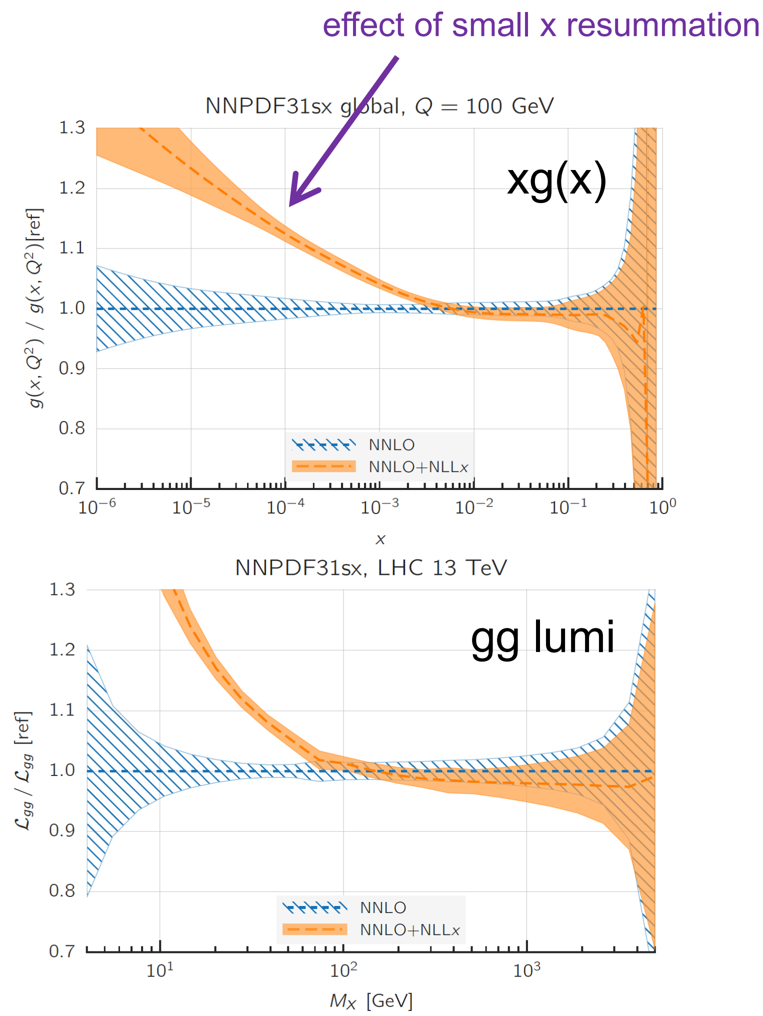
nuclear enhancement $Qs^2 \sim A^{1/3}$;

saturation effects expected at larger x for heavy nuclei cf. proton)

gluon at small x

R. Ball et al, arXiv:1710.05935

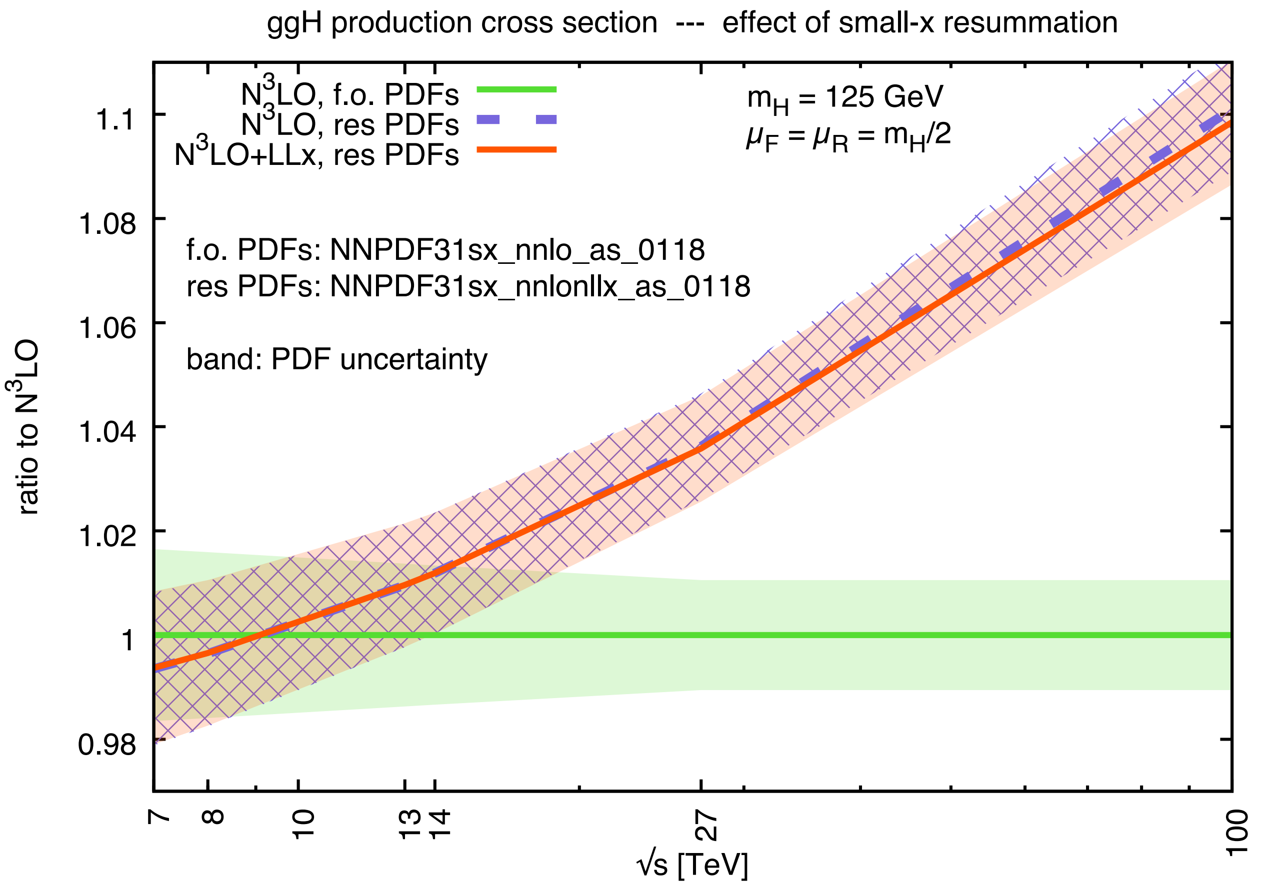




- recent evidence for onset of BFKL dynamics in HERA inclusive data
- **impact for LHC and most certainly at ultra low x values probed at FCC**

(see also xFitter study, arXiv:1802.00064)

gluon at small x



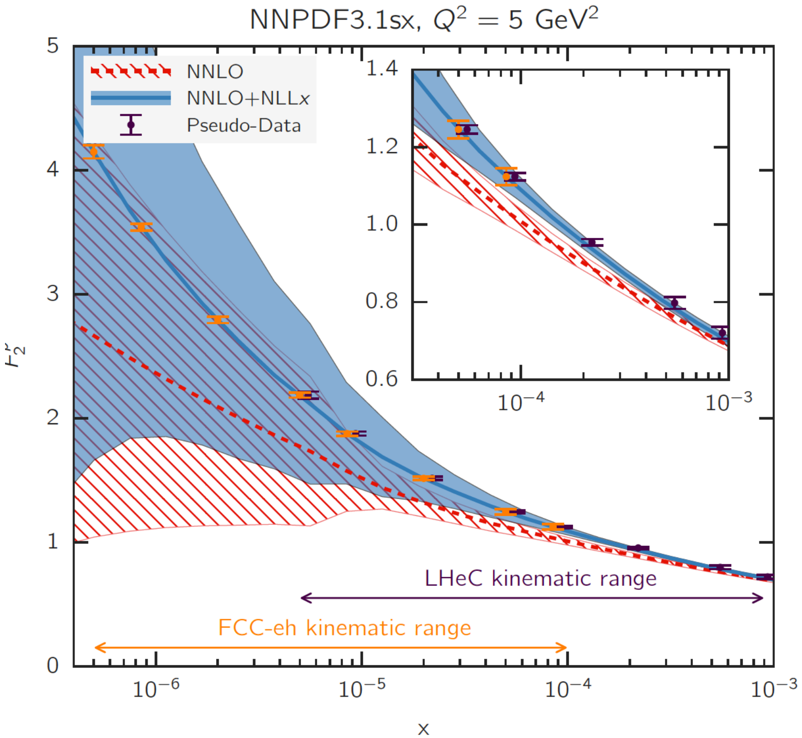
effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

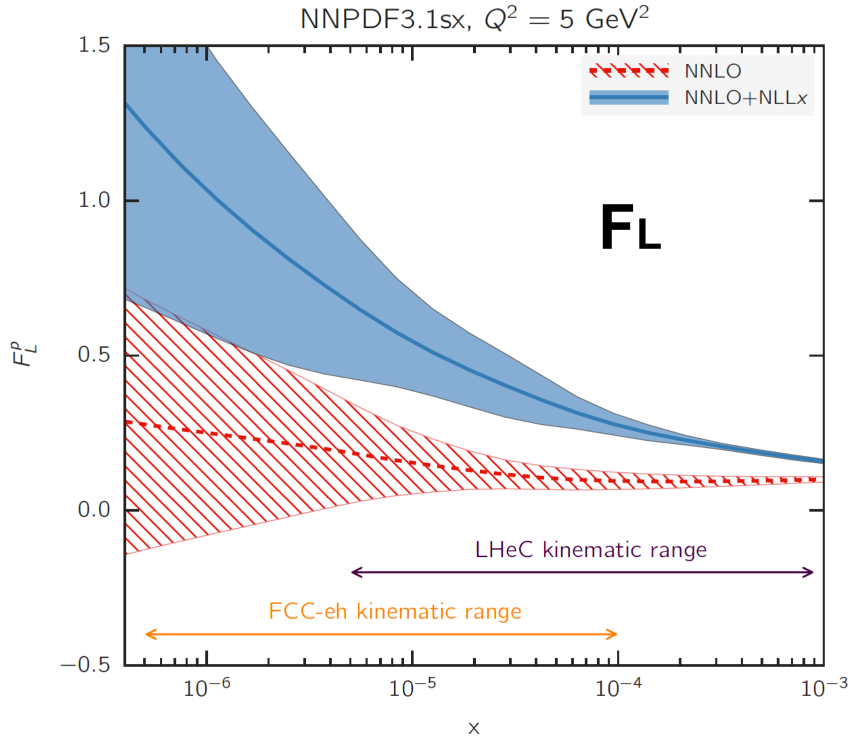
impact on other EW observables could be of similar size

M. Bonvini and S. Marzani, arXiv:1802.07758

gluon at small x

arXiv:1710.05935



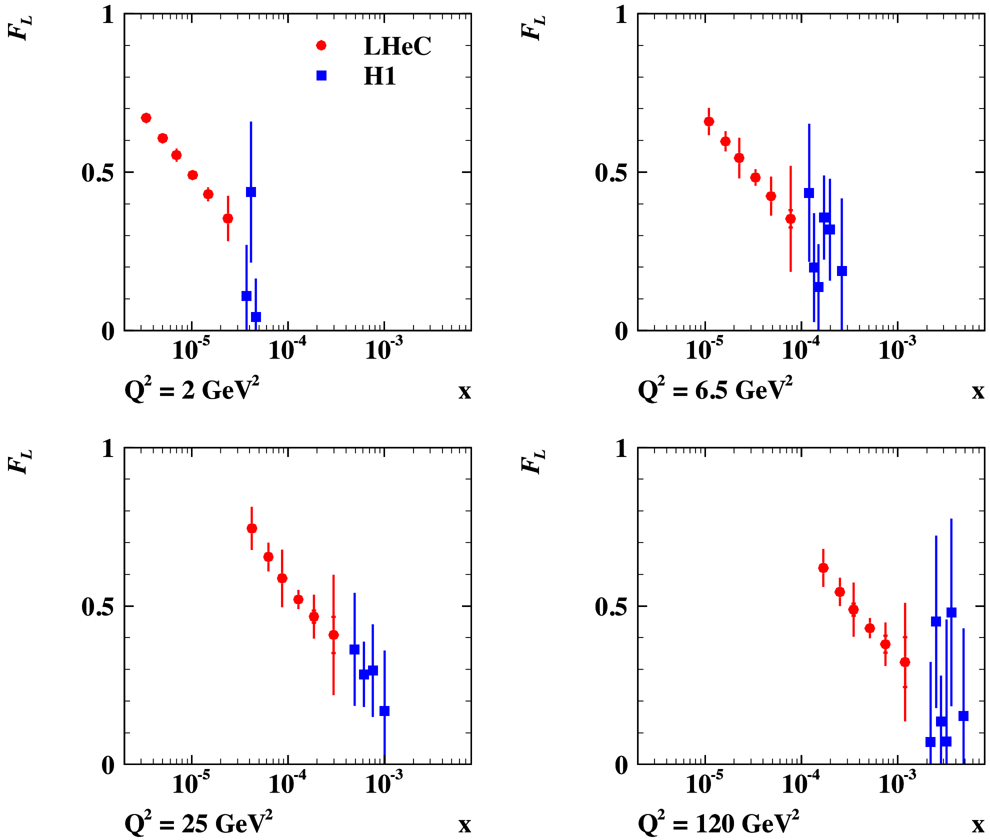


F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

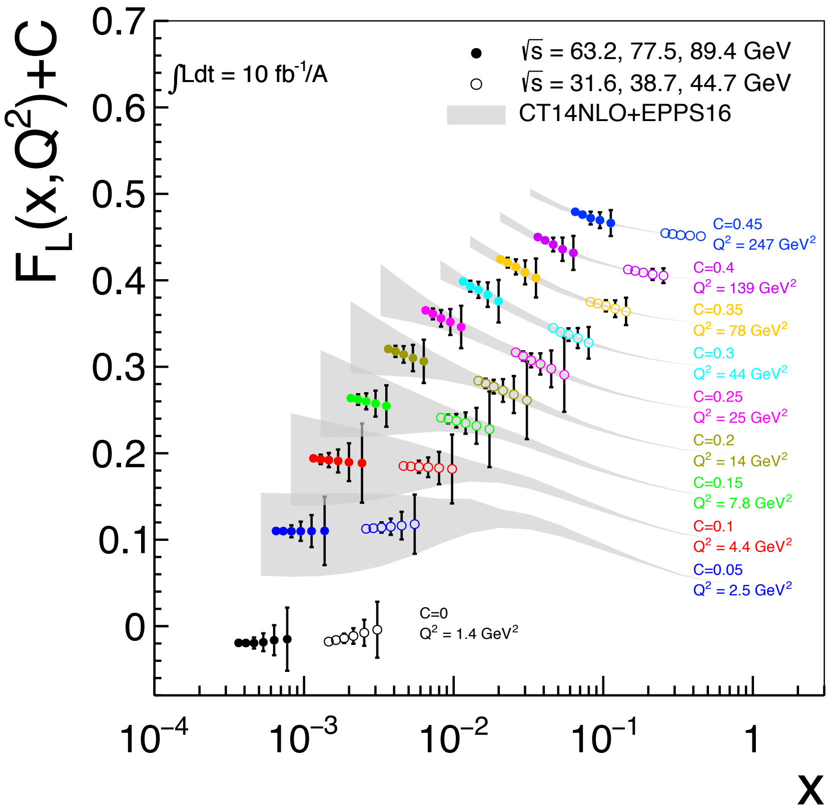
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play ⟶

FL at LHeC and EIC



M. Klein, arXiv:1802.04317

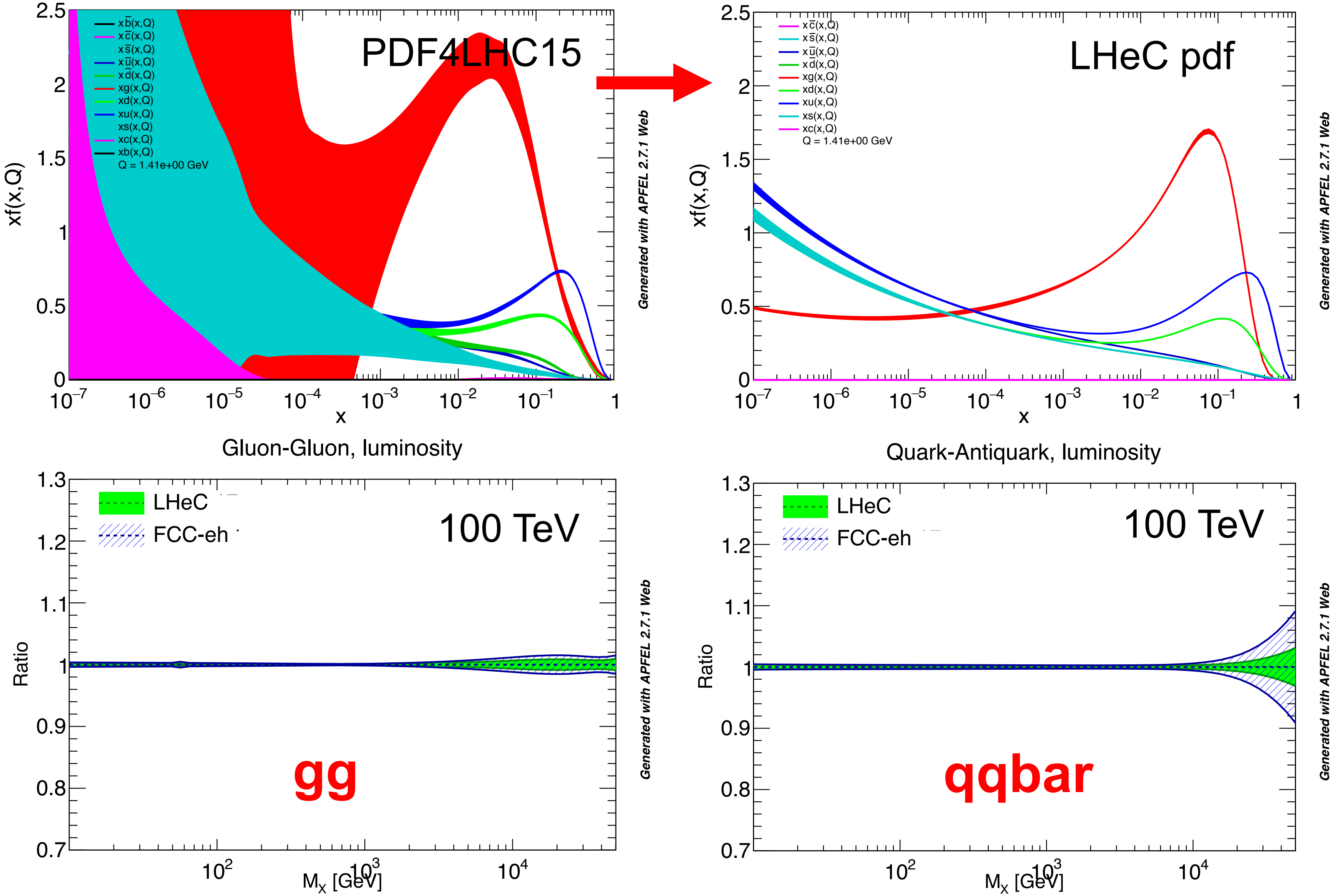


E.A. Aschenauer et al, arXiv:1708.05654

complementary FL measurements from LHeC and EIC

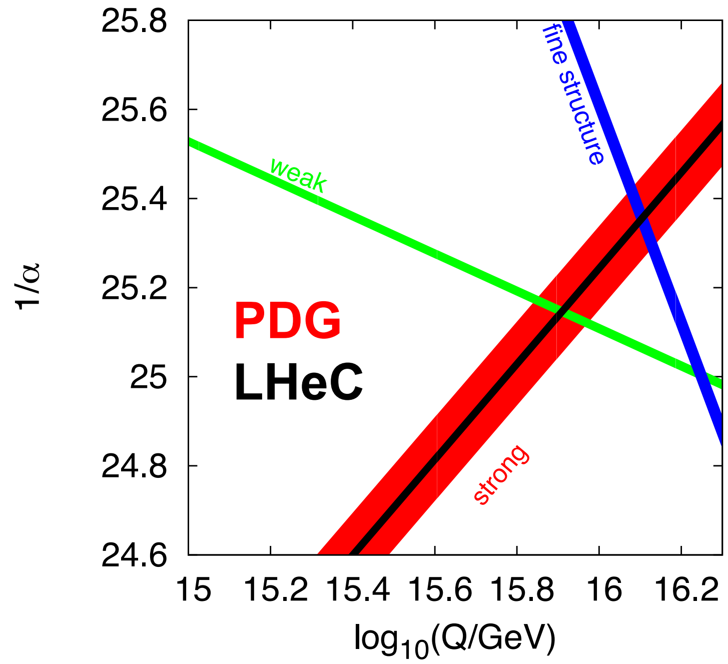
together ranging from very small to large x

summary of LHeC pdfs



strong coupling α_s from LHeC

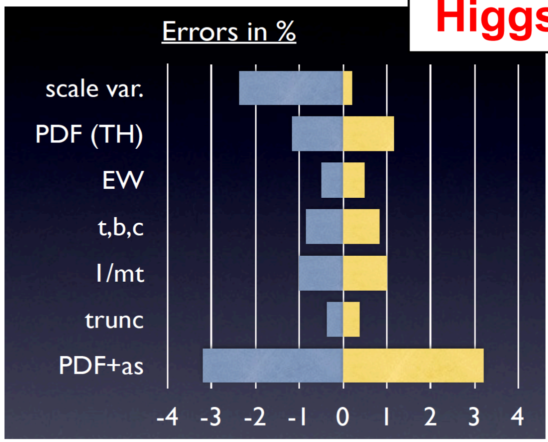
- α_s least known coupling constant
  precision α_s needed to constrain GUT scenarios;
  and cross section predictions, including H
- measurements not all consistent
- what is true central value and uncert.?
- α_s(DIS) smaller than world average?
- **LHeC**: **permille precision** from QCD fit of inclusive 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 α_s from FCC-ee

FCC-ee: comprehensive programme for α_s; many complementary processes

(event shapes, τ decays, FFs, $F2^{\gamma}$, jets in e^+e^-, W and Z decays)

arXiv:1512.05194

EG. most precise determinations from W and Z hadronic decays

N3LO theory; α_s enters in expressions for, EG: **decay widths Γ; $R = \Gamma_{had}/\Gamma_l$**

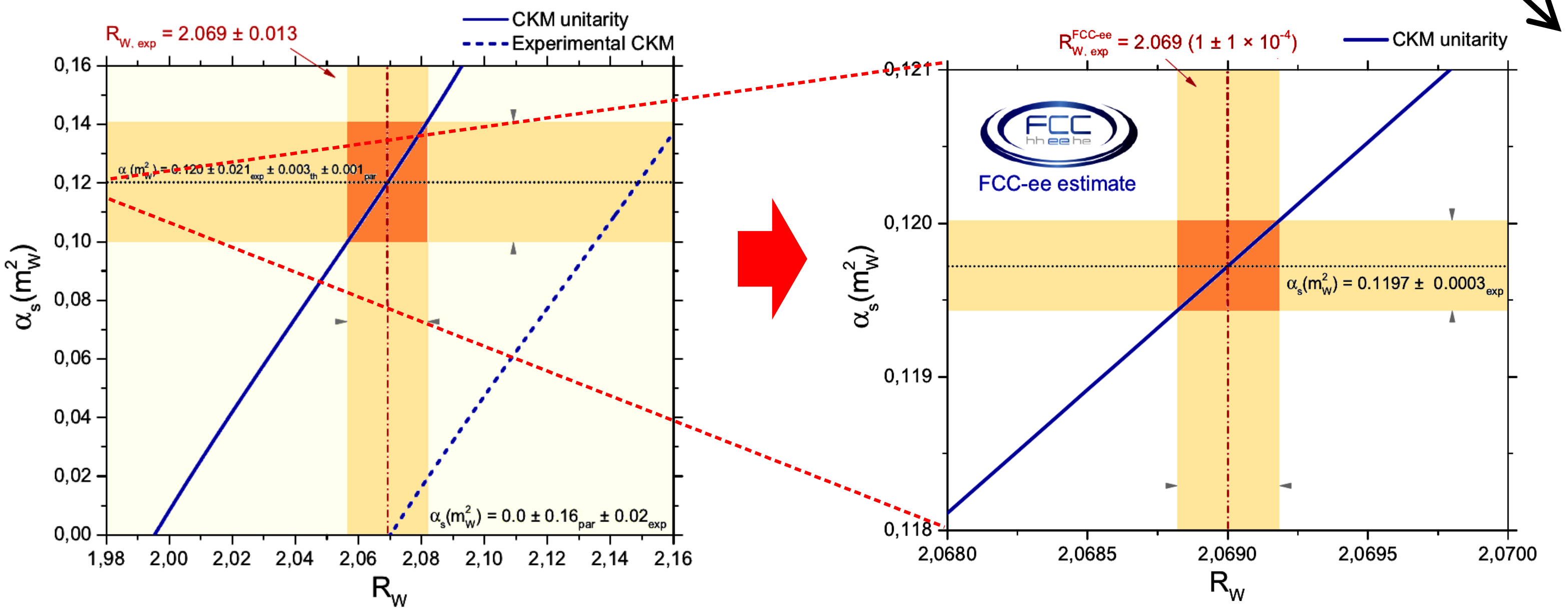
Z: LEP: $\alpha_s(M_Z)=0.1196\pm0.0030$ ($\pm2.5\%$) $\rightarrow$ $\delta\alpha_s < 0.2\%$ (**FCC-ee**) $\longrightarrow$ stats ($\times10^5$ LEP)

improved $\sin^2\theta_{eff}$, MW, Mt

W: LEP: $\alpha_s(M_Z)=0.117\pm0.040$ ($\pm35\%$) $\rightarrow$ $\delta\alpha_s < 0.3\%$ (**FCC-ee**) $\searrow$

stats ($\times10^4$ LEP)

improved δV_{cs}



see also talk by
D. d'Enterria
in WG4

D. d'Enterria et al, arXiv:1603.06501

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^3LO pQCD)	$\approx 0.1\%$ (∼10 yrs) (improved computing power, N^4LO pQCD)
π decay factor	$1.5\%_{th} \oplus 0.05\%_{exp} \approx 1.5\%$ (N^3LO RGOPT)	$1\%_{th} \oplus 0.05\%_{exp} \approx 1\%$ (few yrs) (N^4LO RGOPT, explicit $m_{u,d,s}$)
τ decays	$1.4\%_{th} \oplus 1.4\%_{exp} \approx 2\%$ (N^3LO CIPT vs. FOPT)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx 1\%$ (+B-factories), $<1\%$ (FCC-ee) (N^4LO, ∼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)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx 1\%$ (∼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^3LO. 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)	$1\%_{th} \oplus 2\%_{exp} \approx 2\%$ (∼2 yrs), $<1\%$ (FCC-ee) (NNLO. More precise new F_2^γ data)
e^+e^- evt shapes	$(1.5\text{–}4)\%_{th} \oplus 1\%_{exp} \approx (1.5\text{–}4)\%$ (NNLO+$N^{(3)}$LL, npQCD significant)	$1\%_{th} \oplus 1\%_{exp} \approx 1.5\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO+N^3LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2\text{–}5)\%_{th} \oplus 1\%_{exp} \approx (2\text{–}5)\%$ (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^3LO, npQCD small. Low-stats data)	$(0.7\text{–}0.1)\%_{th} \oplus (10\text{–}0.1)\%_{exp} \approx (10\text{–}0.15)\%$ (LHC,FCC-ee) (N^4LO, ∼10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{th} \oplus 2.4\%_{exp} \approx 2.5\%$ (N^3LO, npQCD small)	$0.1\%_{th} \oplus (0.5\text{–}0.1)\%_{exp} \approx (0.5\text{–}0.15)\%$ (ILC,FCC-ee) (N^4LO, ∼10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{p}$	$3.5\%_{th} \oplus (2\text{–}3)\%_{exp} \approx (4\text{–}5)\%$ (NLO only. Combined exp. observables)	$1\%_{th} \oplus 1\%_{exp} \approx 1.5\%$ (Tevatron+LHC, ∼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, ∼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

proton spin at EIC

what forms proton spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{G+q}$$

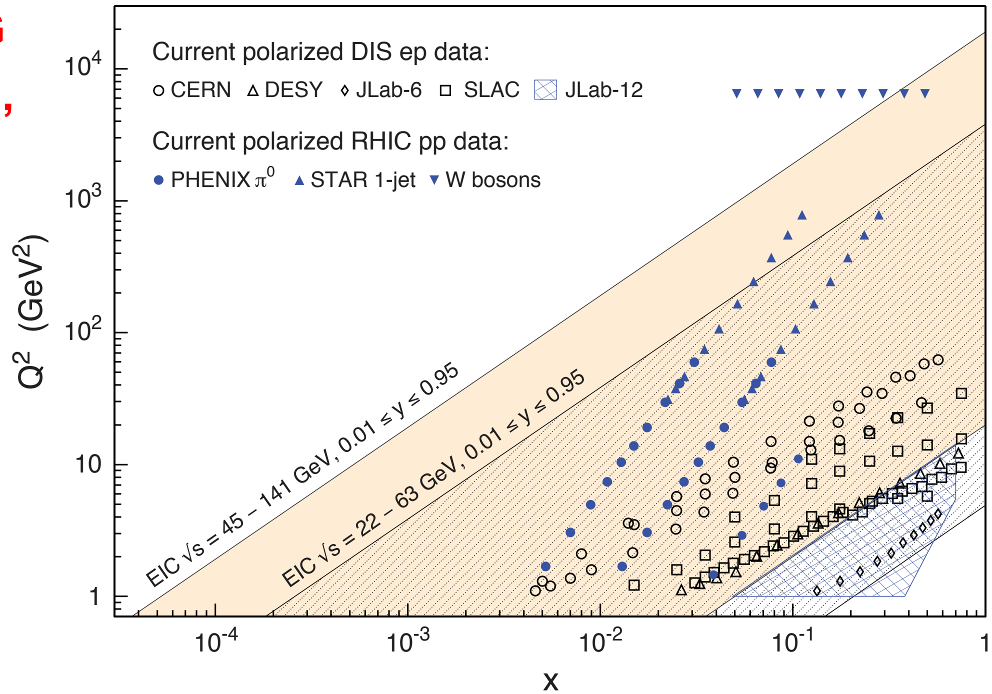
total quark   gluon   orbital AM

$\Delta\Sigma$, ΔG = integral over x of polarised pdfs;

encode extent to which q and g with momentum fraction x have spins aligned with spin direction of nucleon

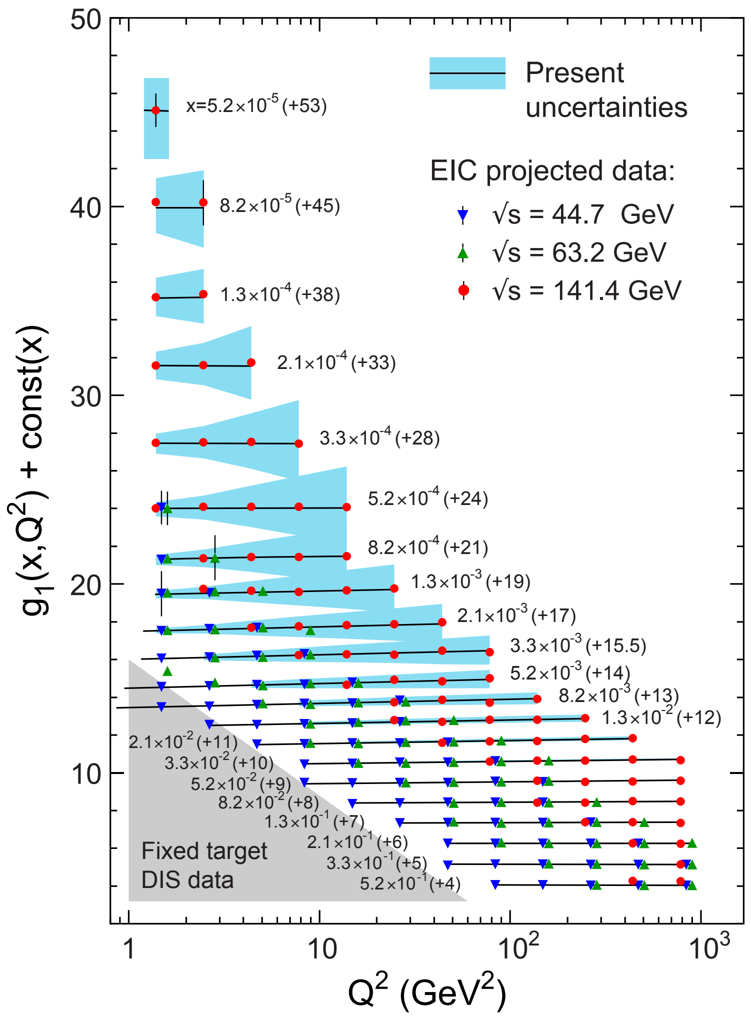
experimental access to ΔΣ and ΔG via polarised structure function g1,

$$g_1(x, Q^2) \sim \left[\frac{d^2\sigma^{\leftrightarrows}}{dx dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx dQ^2}\right]$$

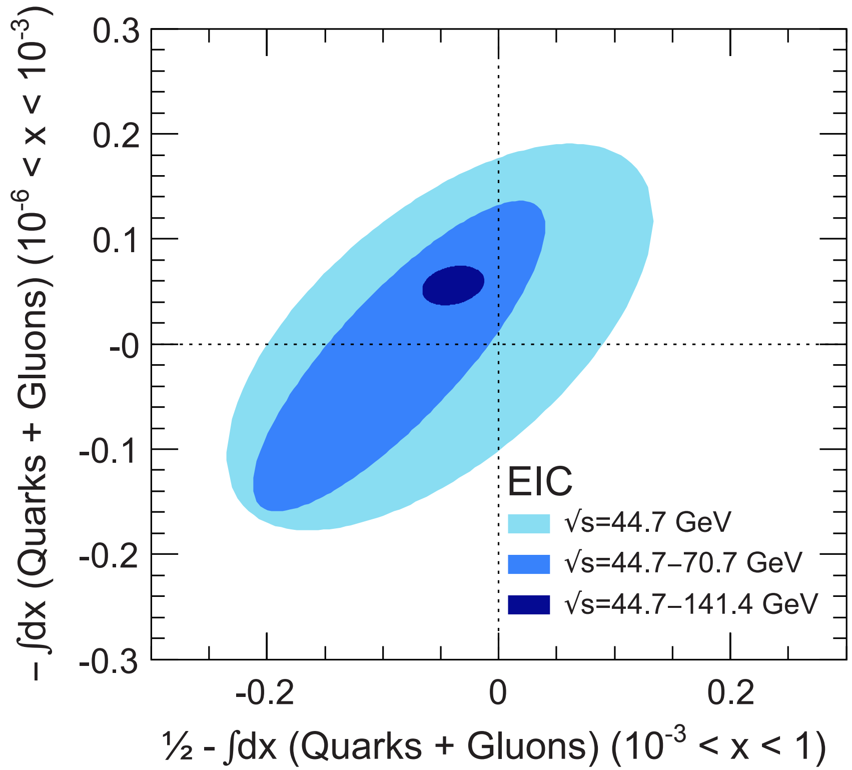


EIC: key asset for polarised pdfs is **kinematic coverage**

proton spin at EIC



quark contribution from integral of g1 over x;
gluon from scaling violations



EIC: for first time different contributions to spin of proton can be disentangled

(additional info, EG. quark flavour separation, from SIDIS)

E.A. Aschenauer et al, arXiv:1708.01527

summary

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

wealth of pdf-constraining measurements from LHC; widely exploited in modern pdf fits;
future LHC measurements likely to give incremental rather than dramatic improvements;
more concrete studies being performed in context of HL/HE-LHC workshop

electron-hadron colliders essential for future of particle & nuclear physics

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

unprecedented kinematic reach; accesses scales sensitive to BSM and Higgs physics;
precise determination of all pdfs, and αs to permille precision

EIC: goes beyond HERA in pol. for spin physics, luminosity, and eA

⟶ image structure/interactions of nucleons and nuclei in multi-dimensions (x, bt, kt, spin)
pdfs 4LHC not yet part of remit; studies in progress are establishing potential; NC/CC require detector redesign; **volunteers welcome**

extras