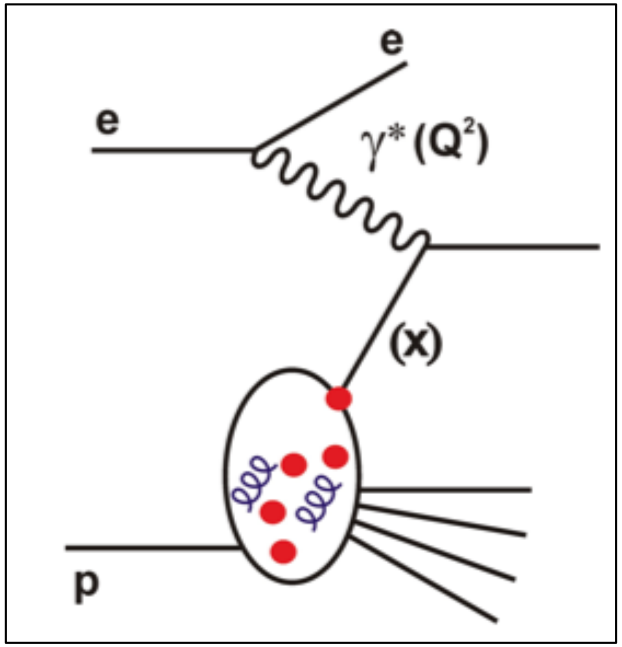
PDFs and α_s at future colliders

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 uncerts on Higgs production cross sections; 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

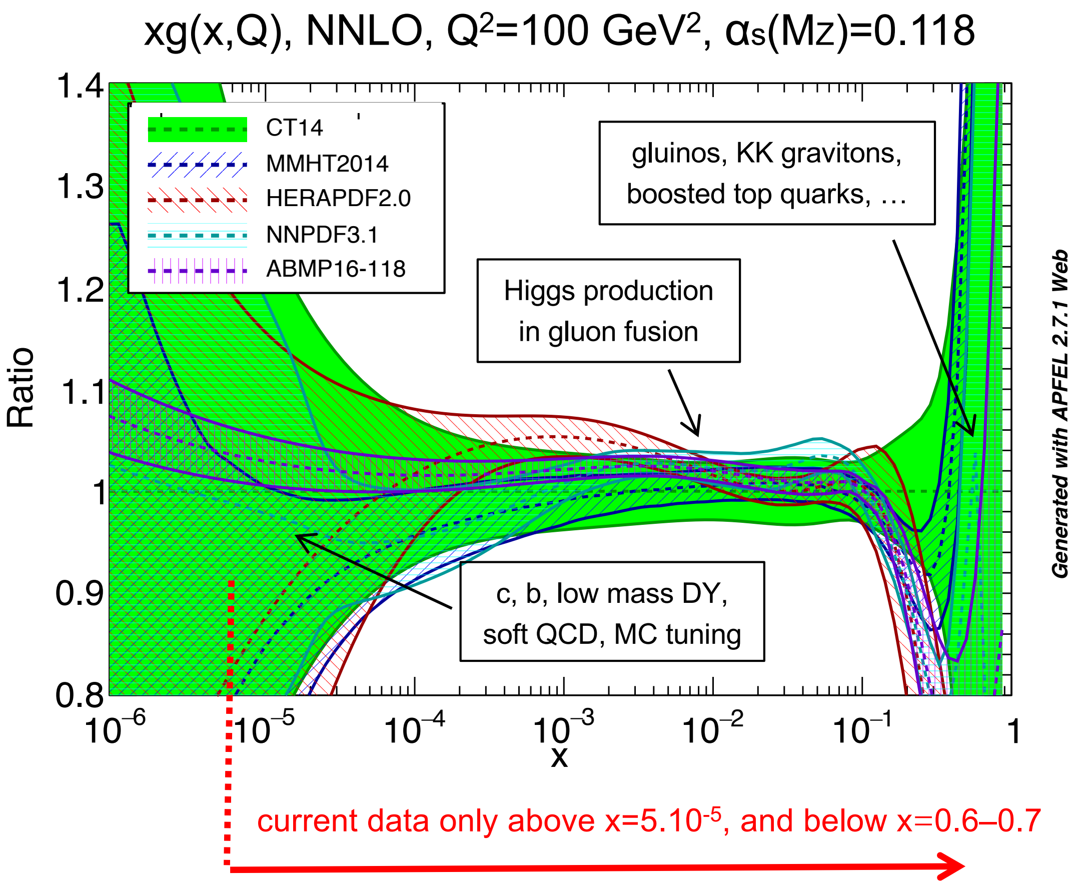
LHC measurements are providing useful pdf constraints;

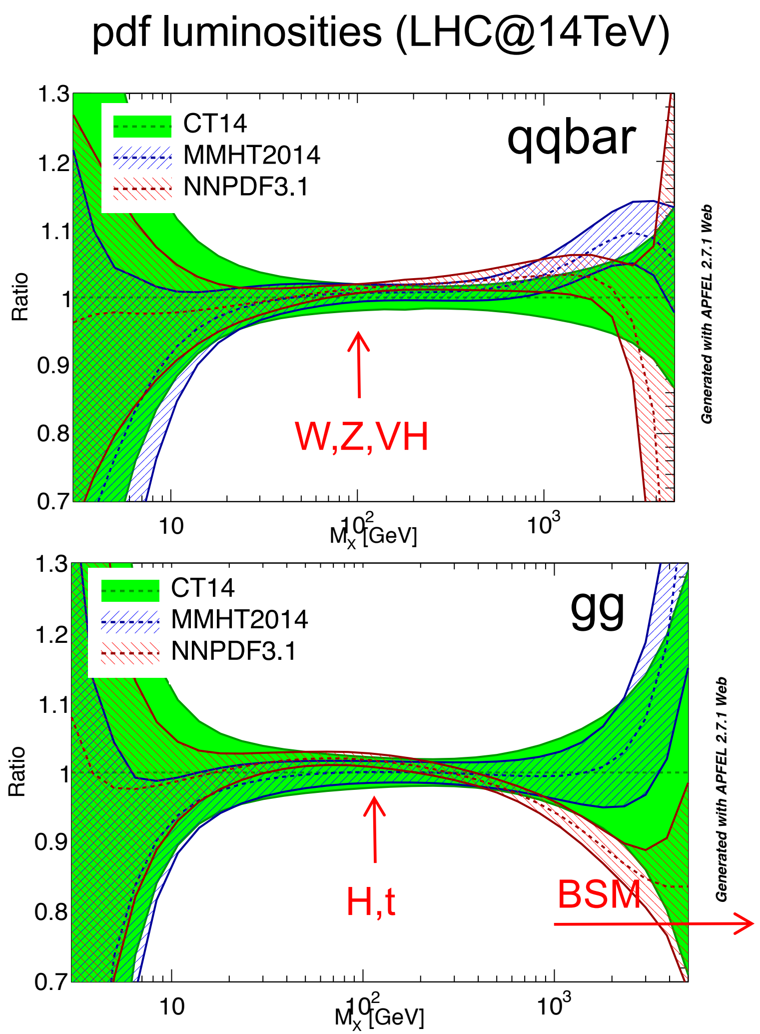
should certainly be exploited; and currently we have nothing else …

is there a NEED for future ep collider for pdfs?

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

situation today

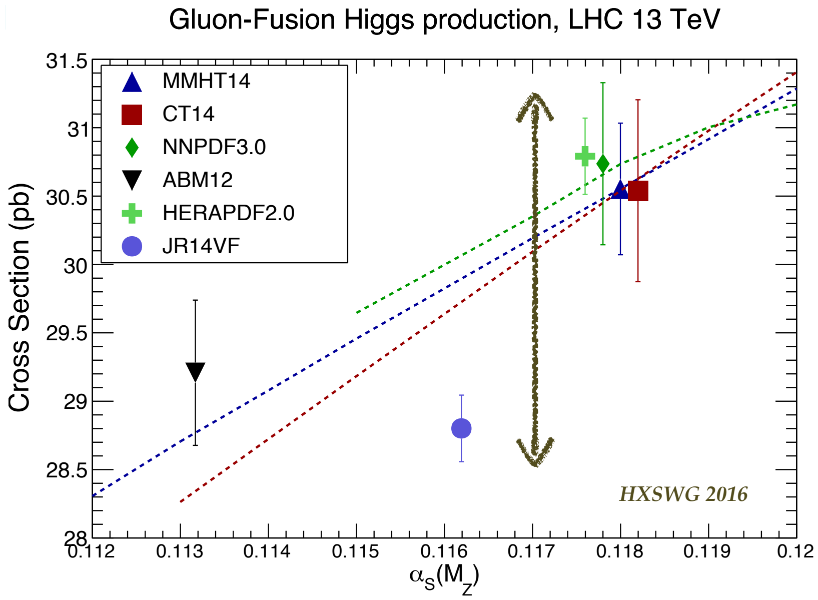




pdfs poorly known at large and small x

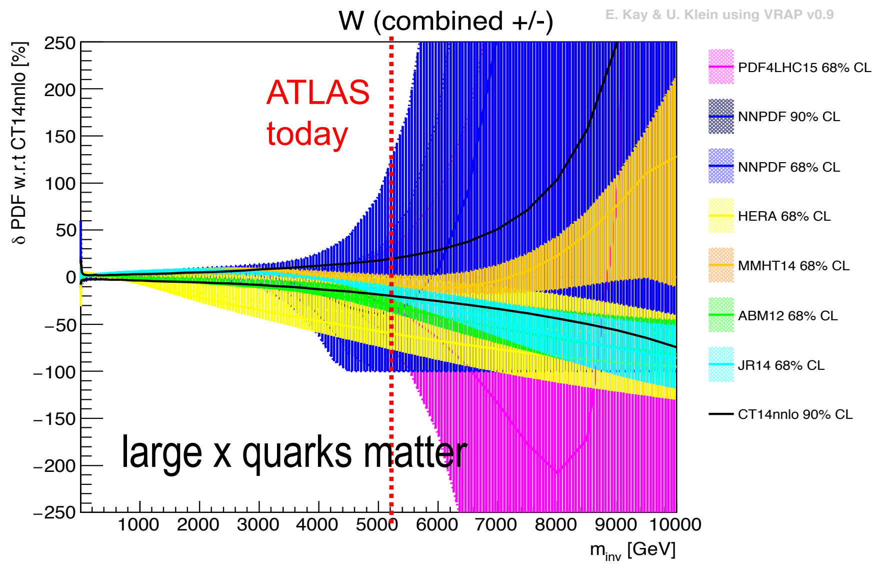
higher precision needed also for H, W, t

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

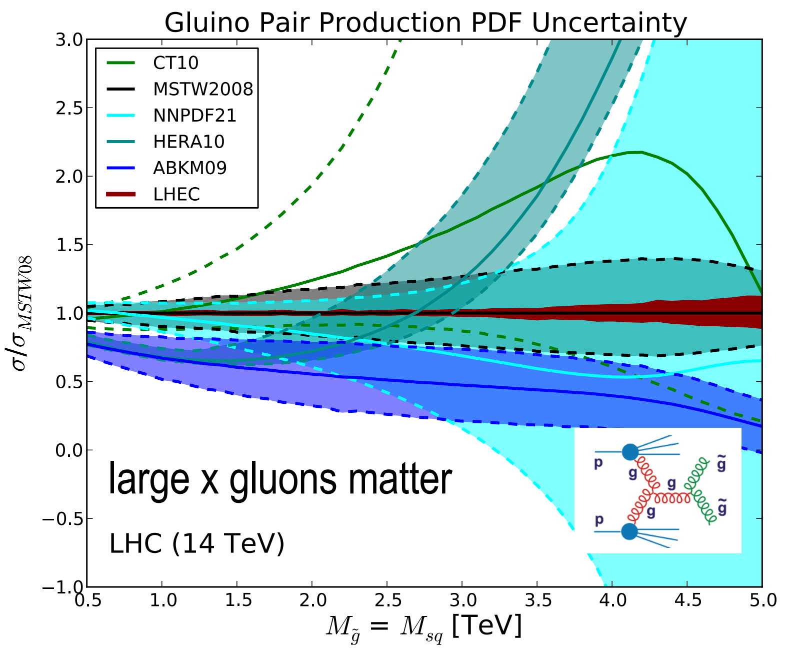


Mw

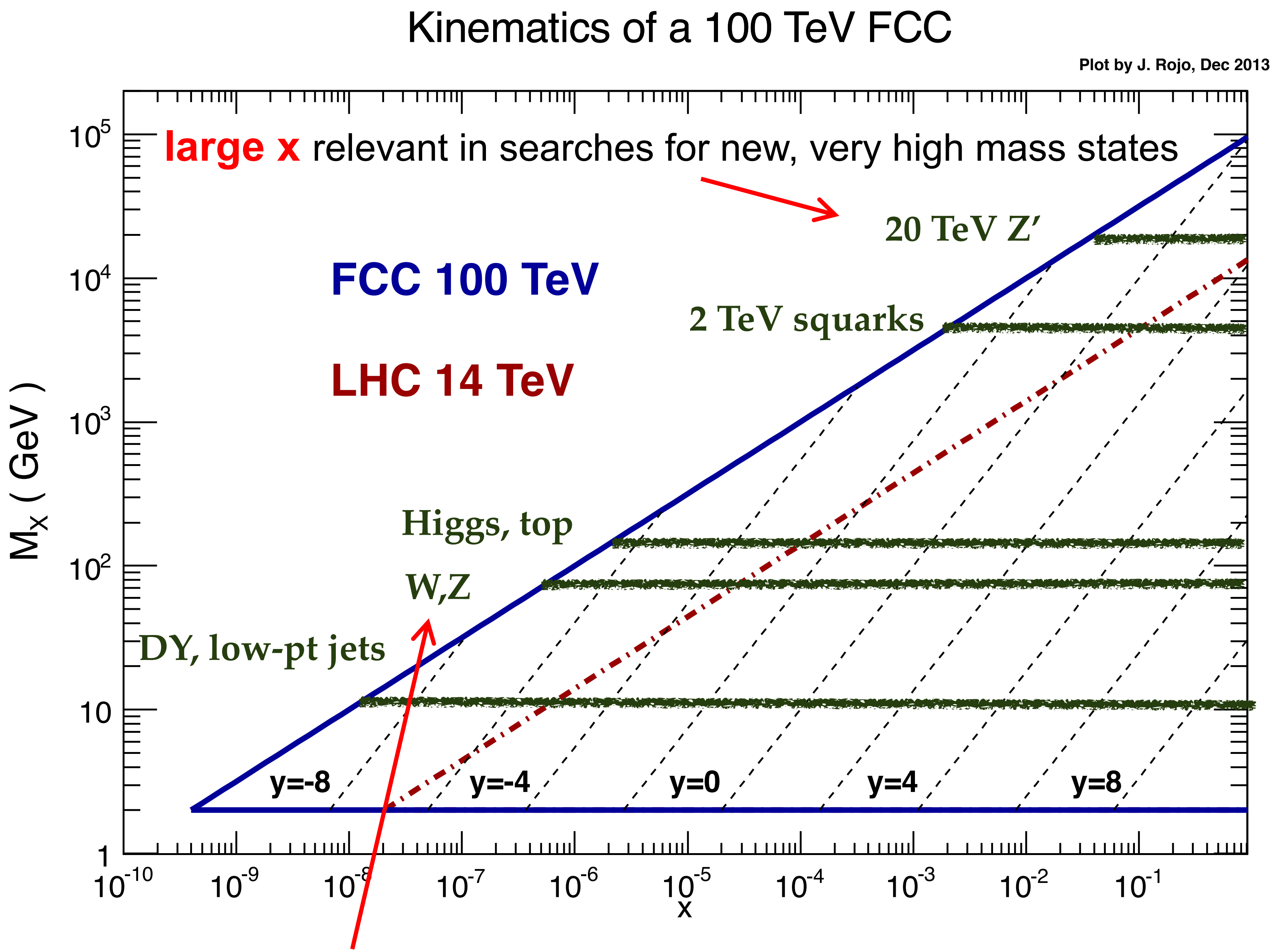
Higgs

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)

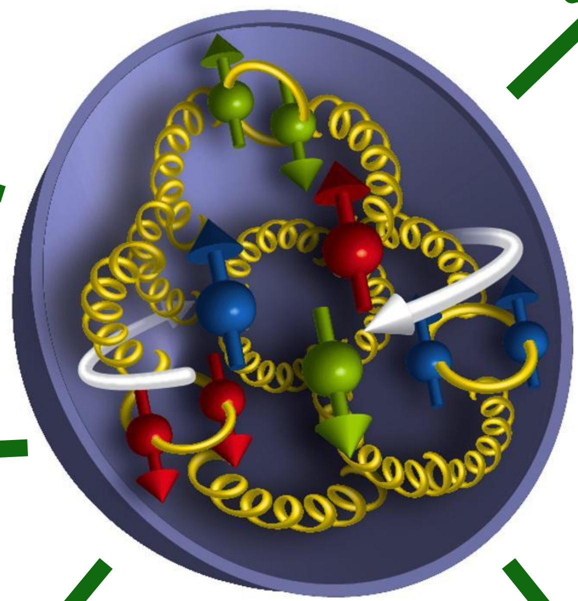
inside the proton

spin

see extras

quark flavour separation

gluon



small x

BFKL dynamics

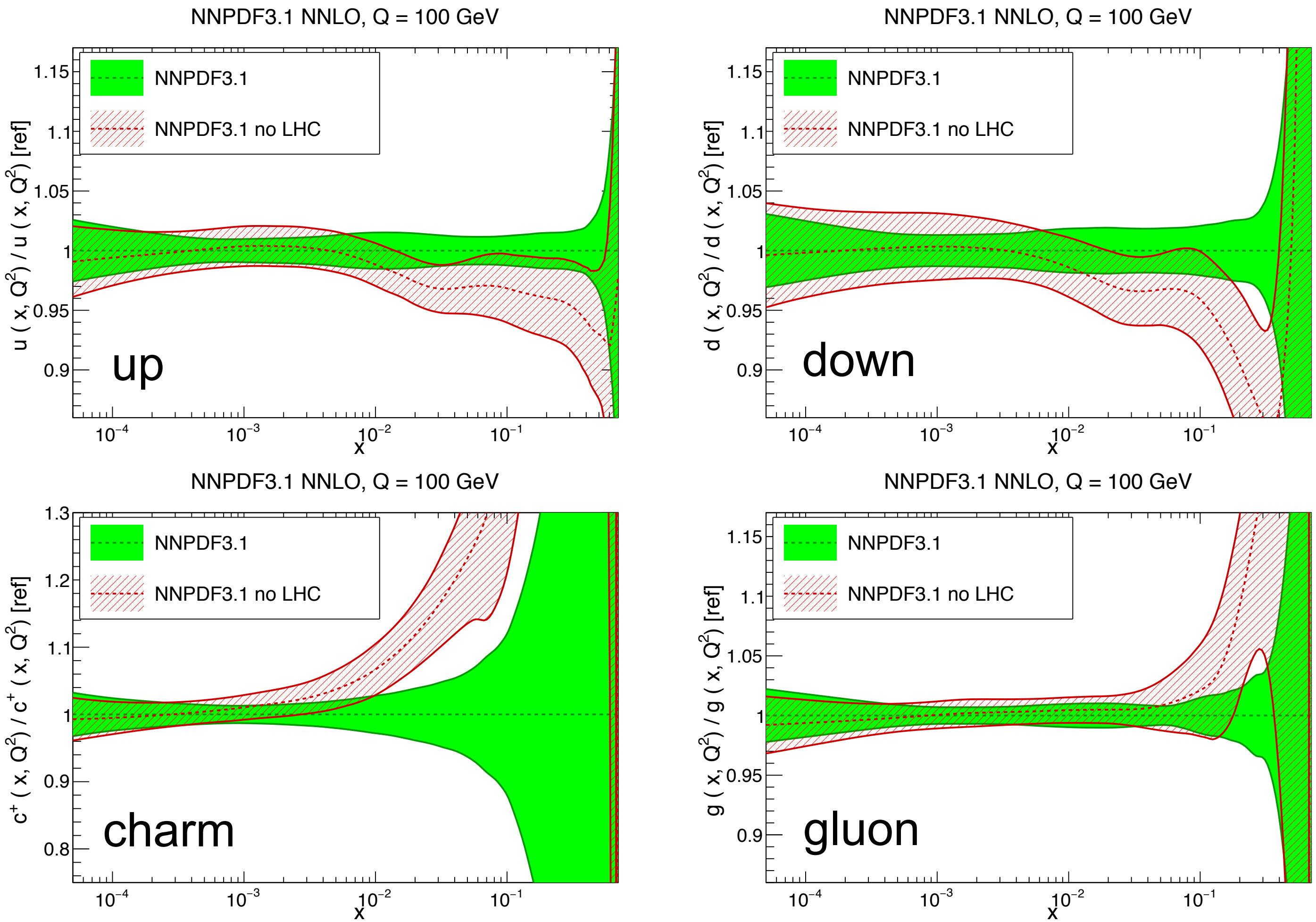
photon

strange

charm

(slide based on J. Rojo, POETIC8)

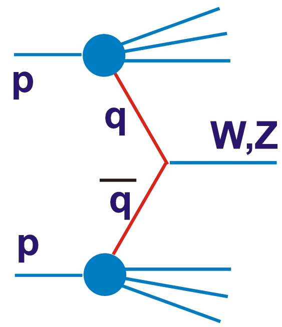
impact of LHC on today's pdfs



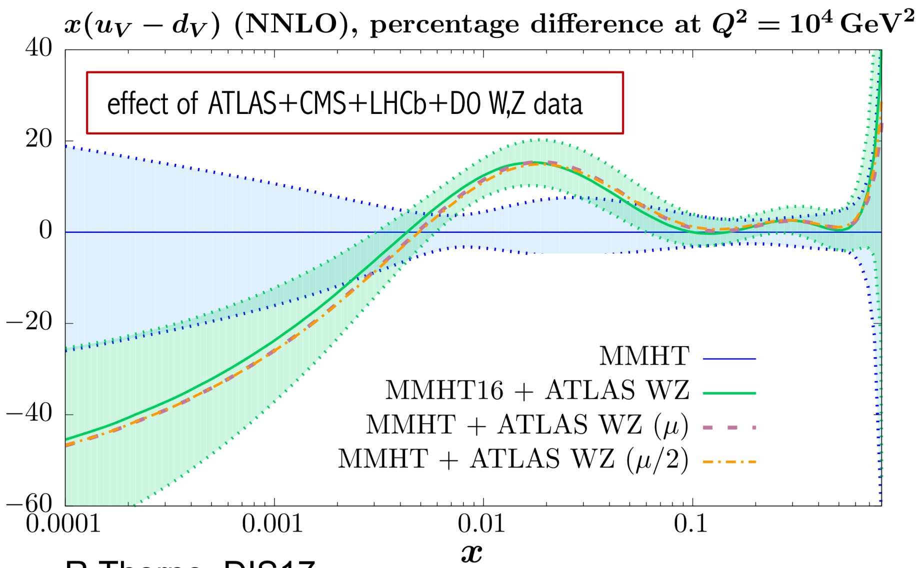
arXiv:1706.00428

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

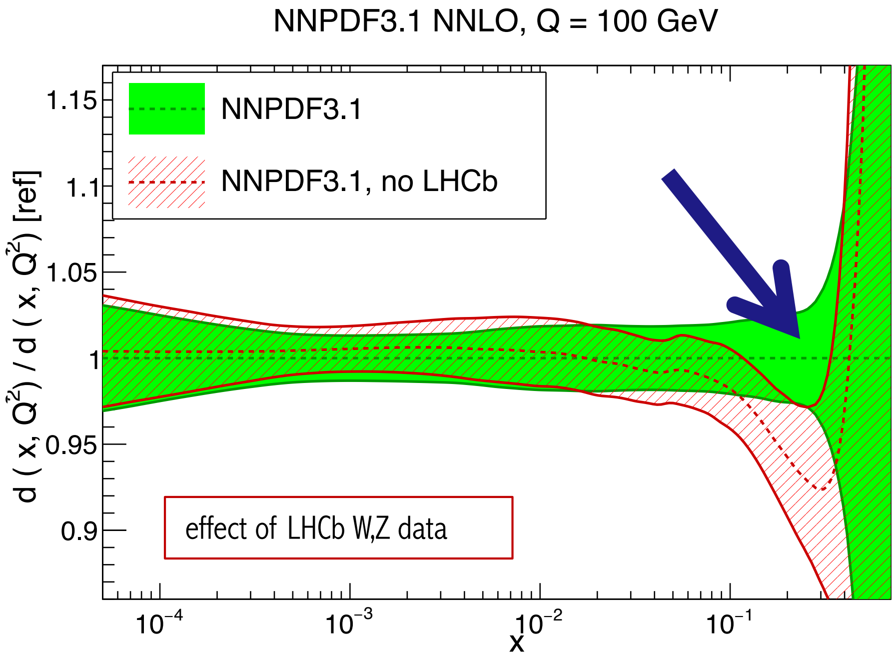
LHC: electroweak gauge bosons



- 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)



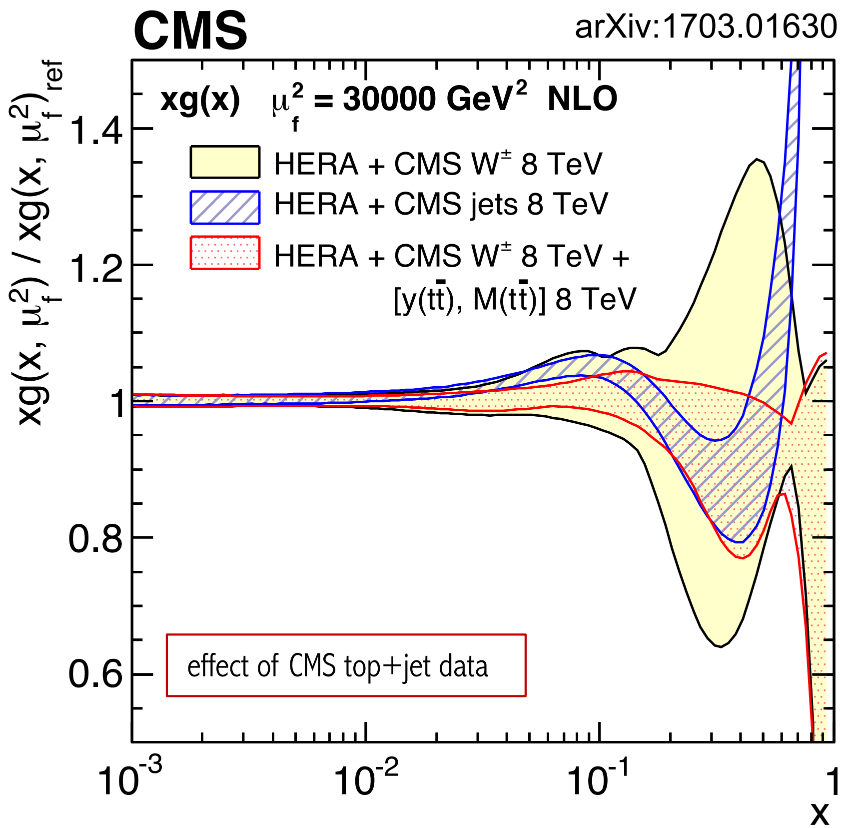
R.Thorne, DIS17

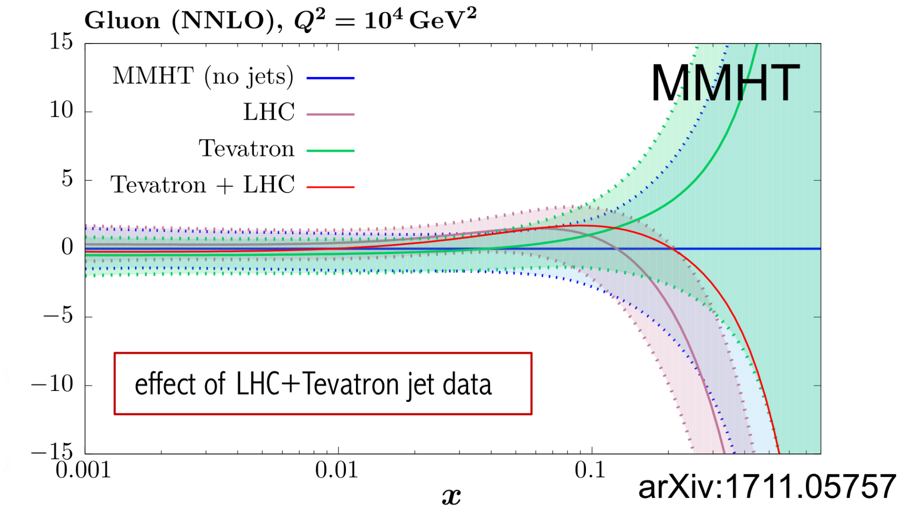


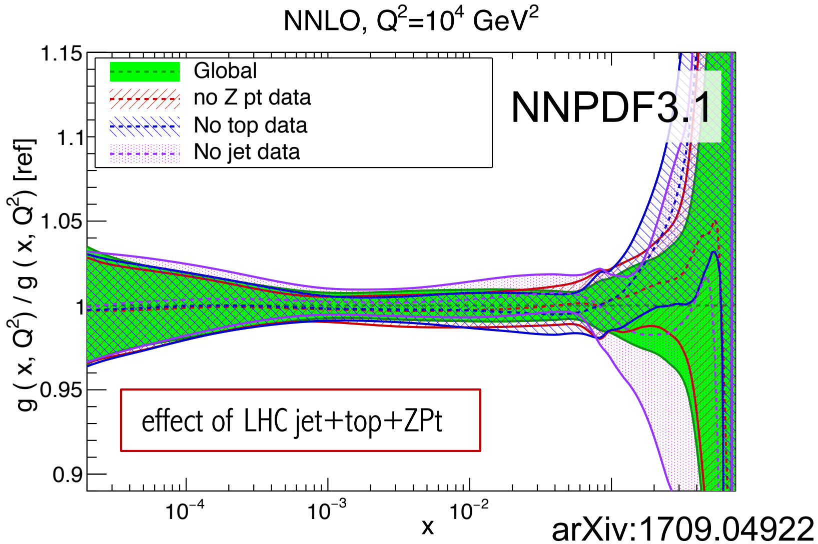
arXiv:1706.00428

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

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pp <u>constrains</u> pdfs, it does not precisely determine them … need ep

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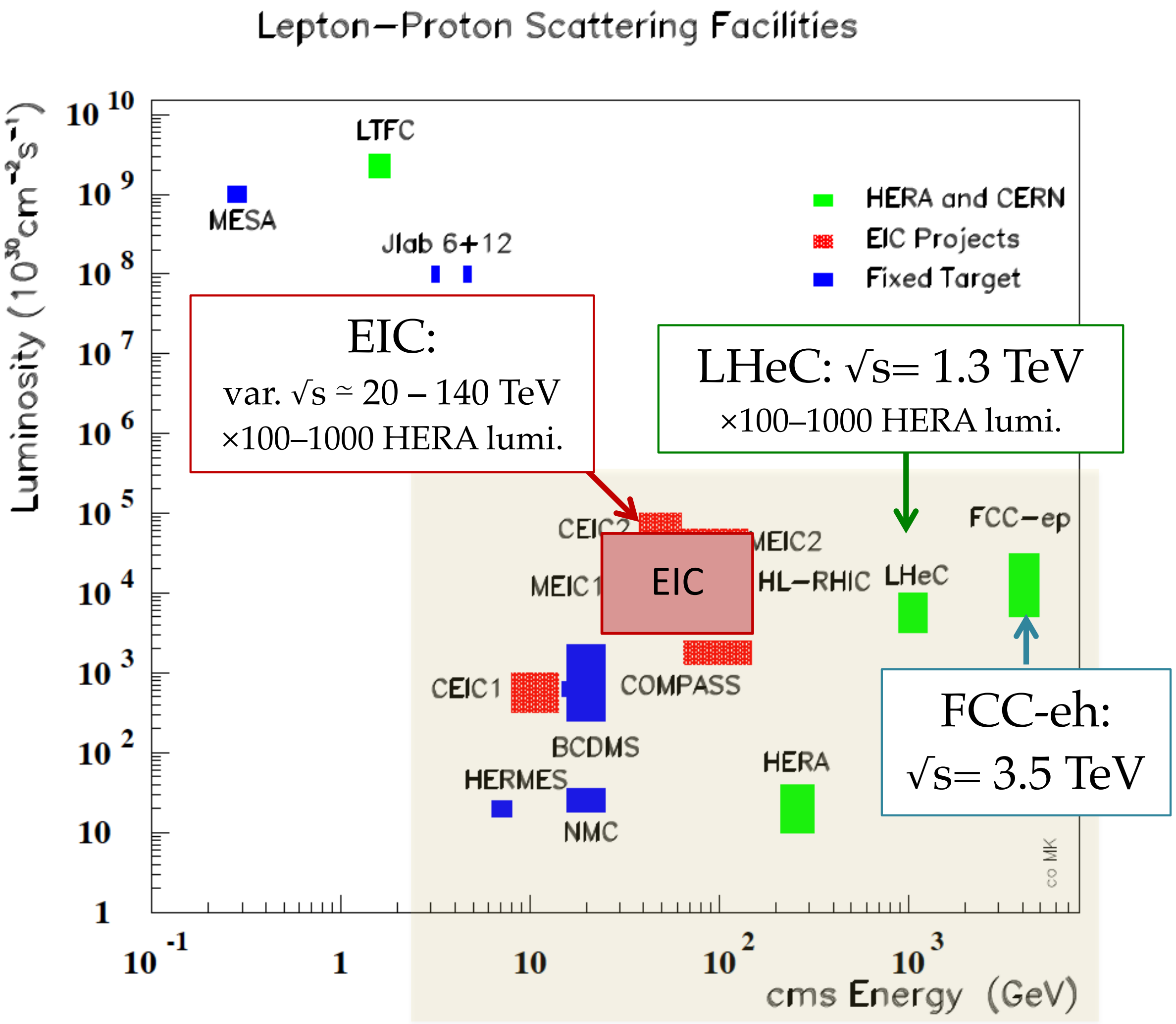
ep colliders



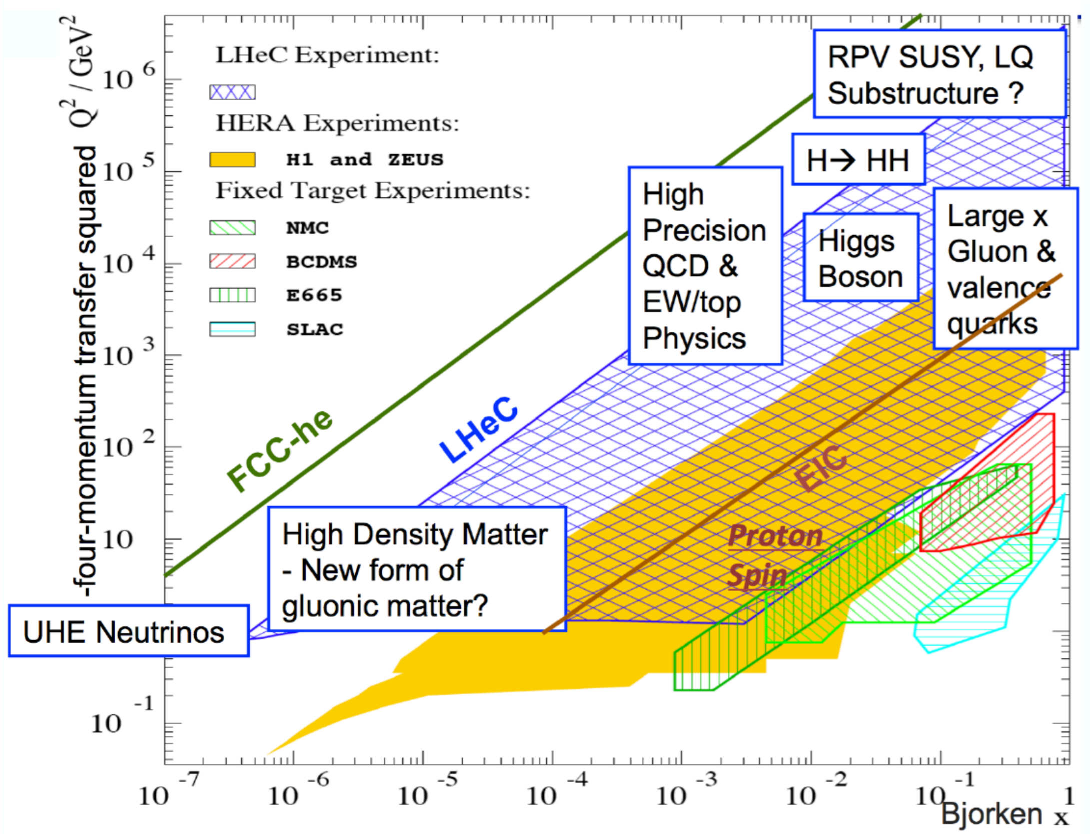
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

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

(×**15**/**120** 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)

ideal 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 goals:

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)

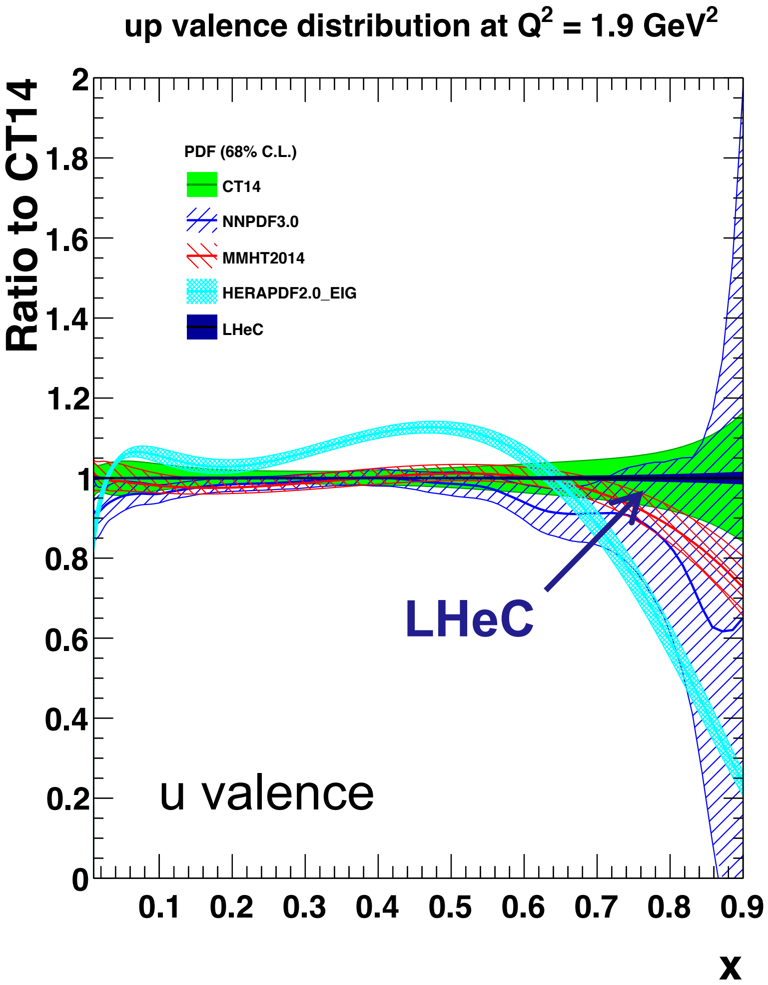
EIC: focus is on pdfs in nuclei and pdfs in spin polarised protons

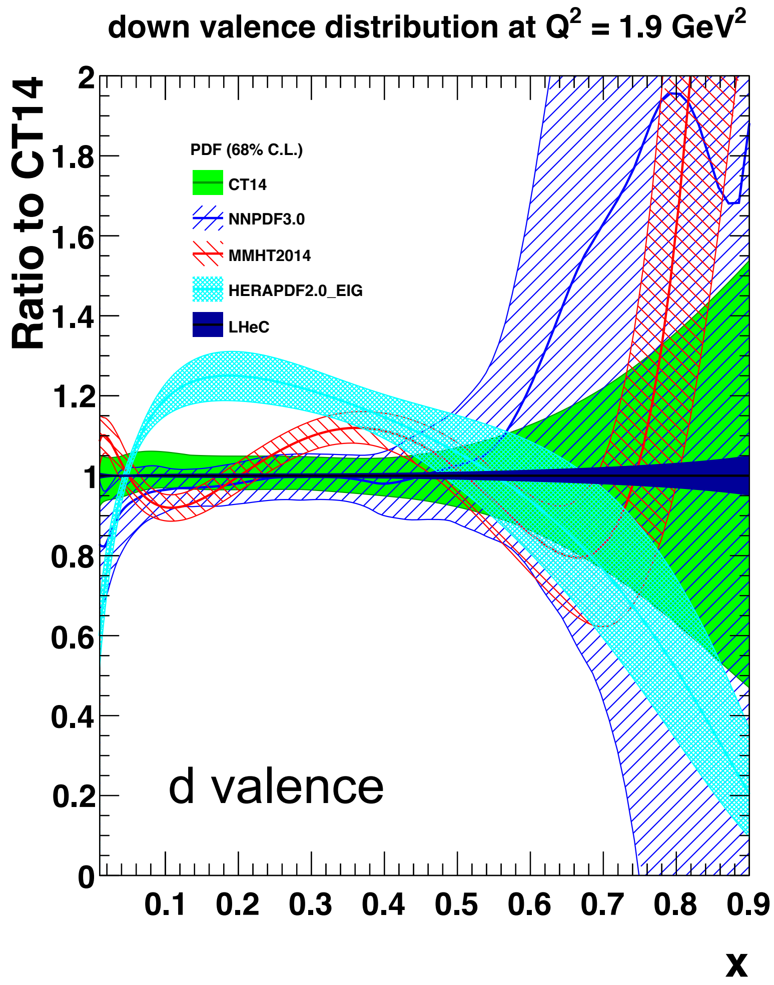
EIC likely to run alongside HL-LHC; important to establish what it can do for **pdfs** for the HL-LHC era and beyond

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

† not covered in this talk: **polarised pdfs** (EG. J. Qiu, WG7); **nuclear pdfs** (N. Armesto, WG7)

valence quarks from LHeC





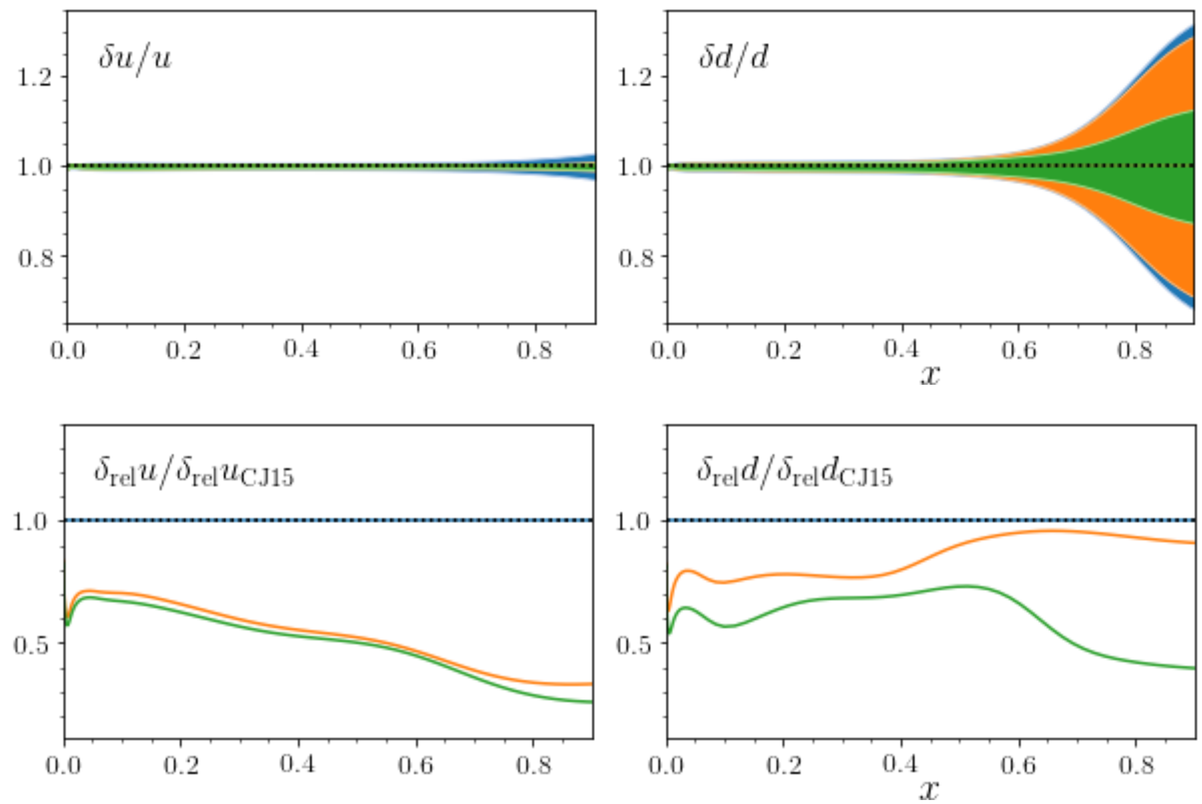
precision determination, free from higher twist corrections and nuclear uncertainties

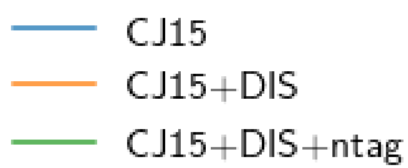
large x crucial for HL/HE–LHC and FCC searches; also relevant for DY, MW etc.

u, d quarks at large x from EIC

EIC: substantial improvement of **u**; 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





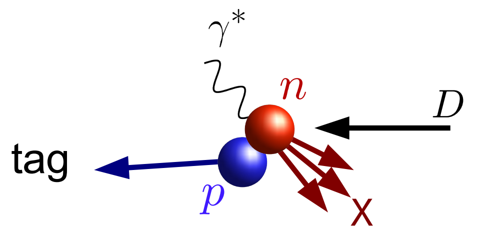
new sim. data since DIS17

JLEIC projection; x bins: 0.01 ⟶ 0.9

	electrons			positrons	
$\sqrt{s}$	tag	NC	CC	NC	CC
63					
57					
49					
28					

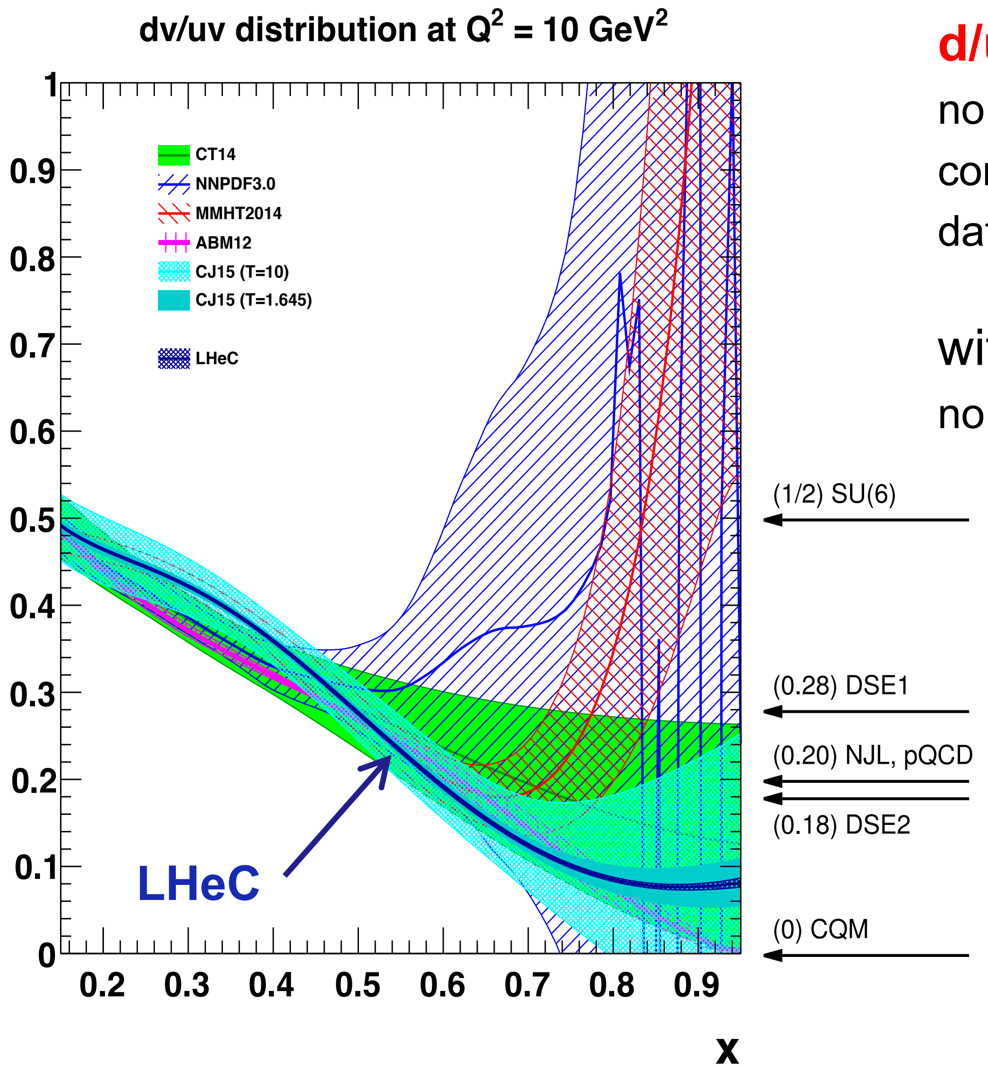
$L = 100/fb$

$L = 10/fb$



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

d/u at large x



d/u essentially unknown at large x

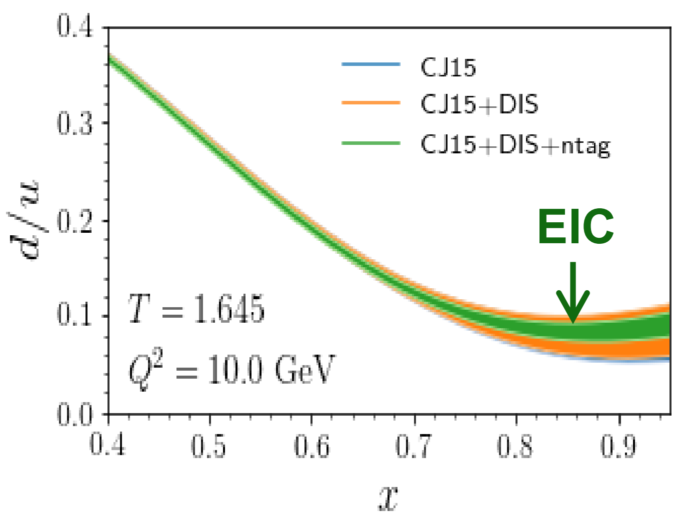
no predictive power from current pdfs;

conflicting theory pictures;

data inconclusive, large nuclear uncerts.

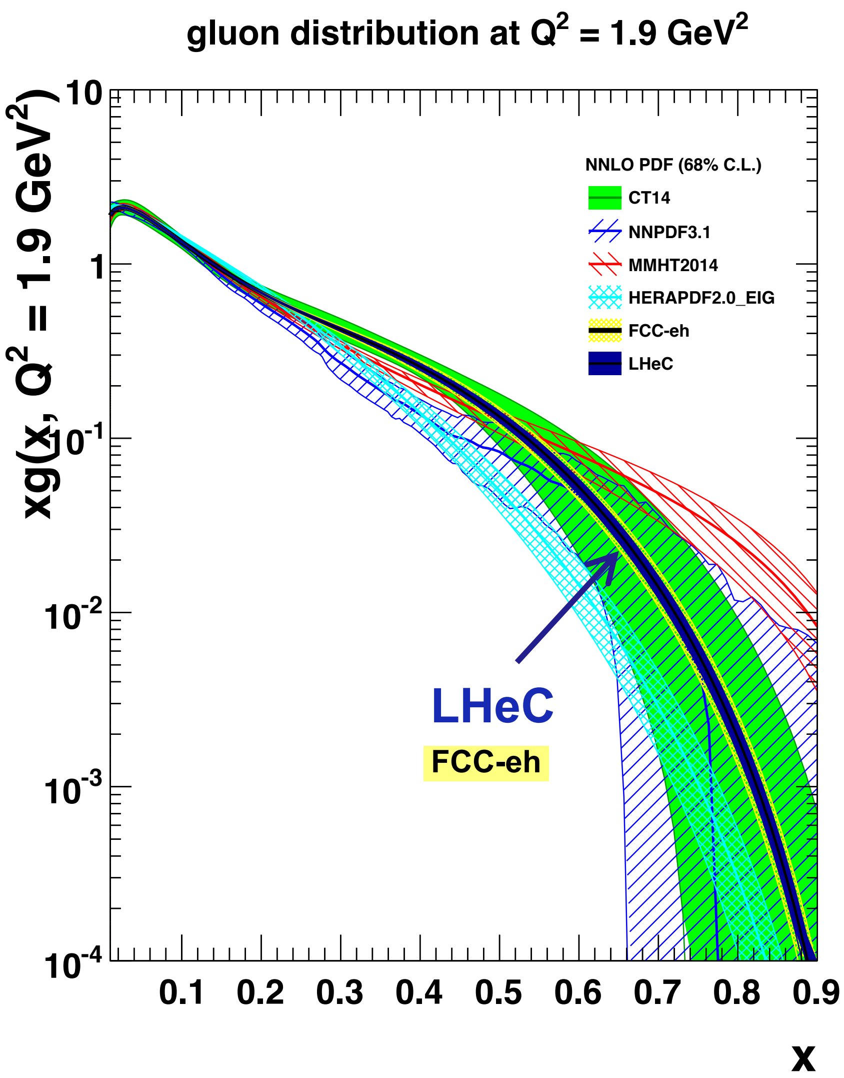
with precision ep (n) data to v. large x:

no nuclear corrections; relax assumptions



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

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

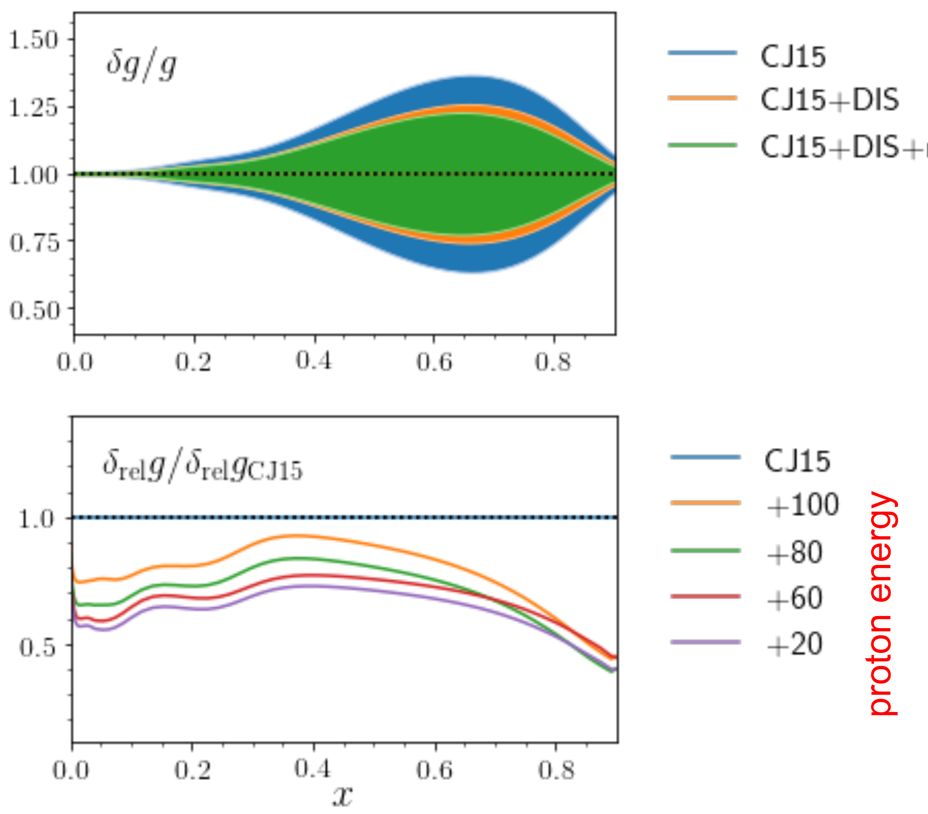
high luminosity (×100–1000 HERA);
fully constrained quark pdfs; low x;
momentum sum rule

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

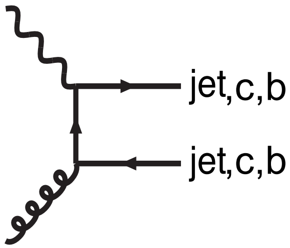
A. Accardi, et al



EIC: large x gluon

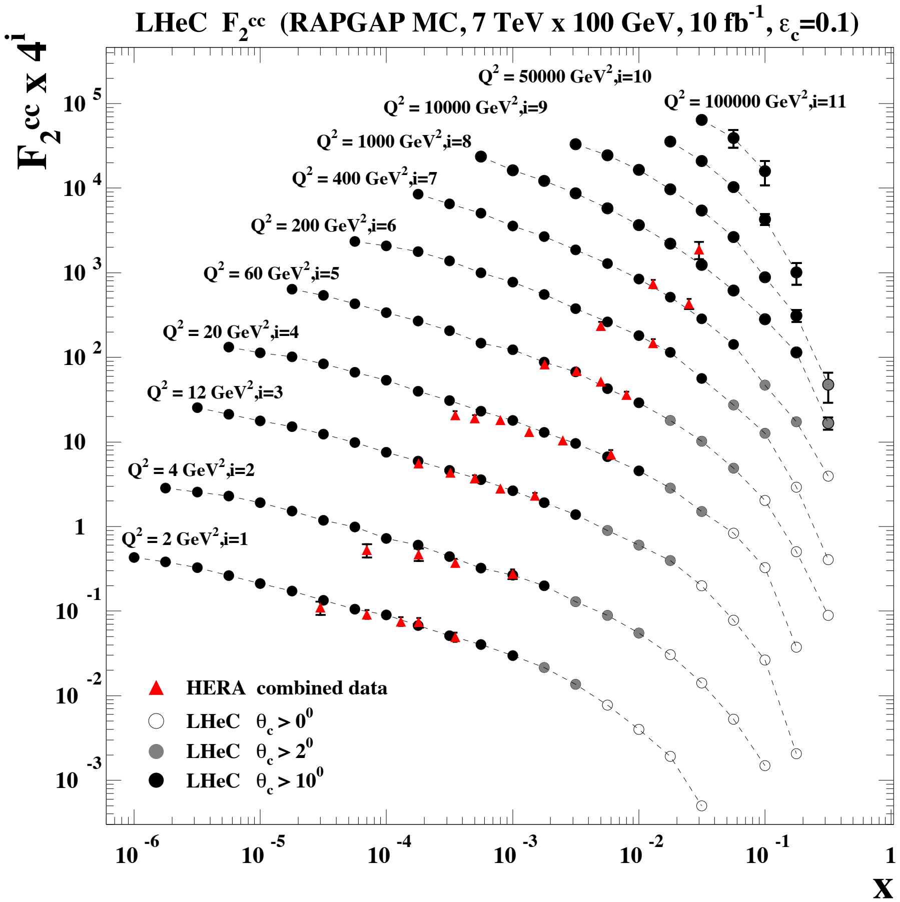
gain from inclusive data at multiple CM energies; increased Q2 lever arm

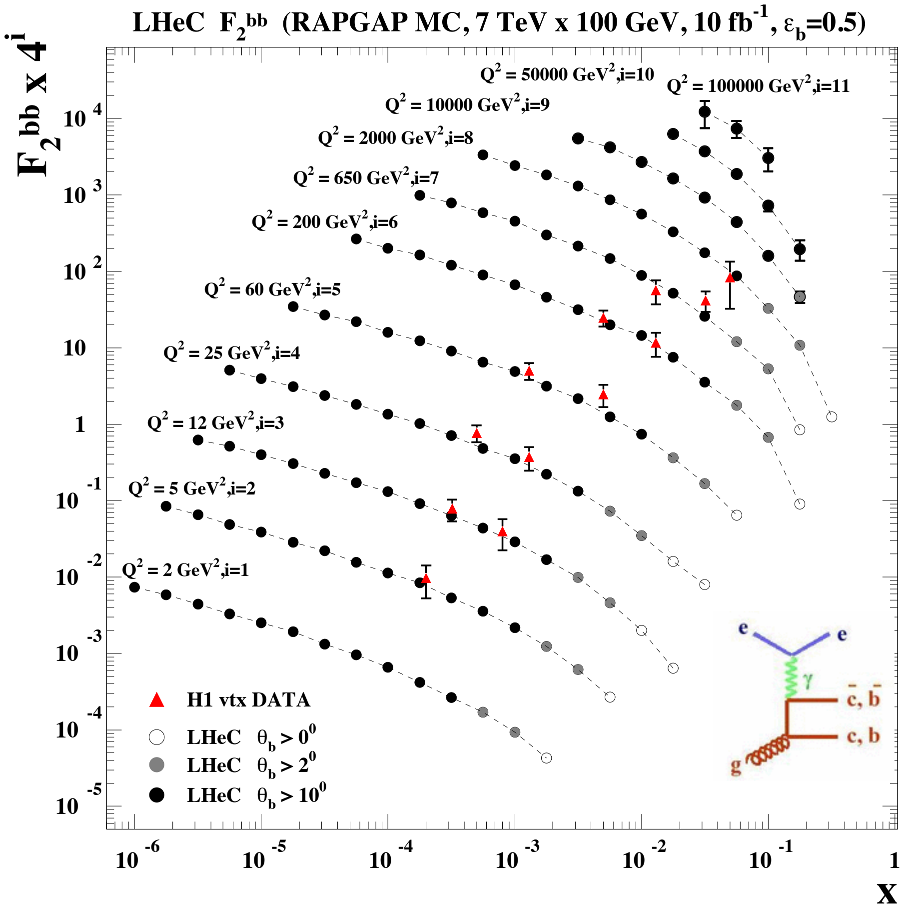
LHeC and **EIC**: extra direct information on gluon also from **c**, **b**, **jets**; **not yet included in LHeC or EIC pdf projection studies**



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

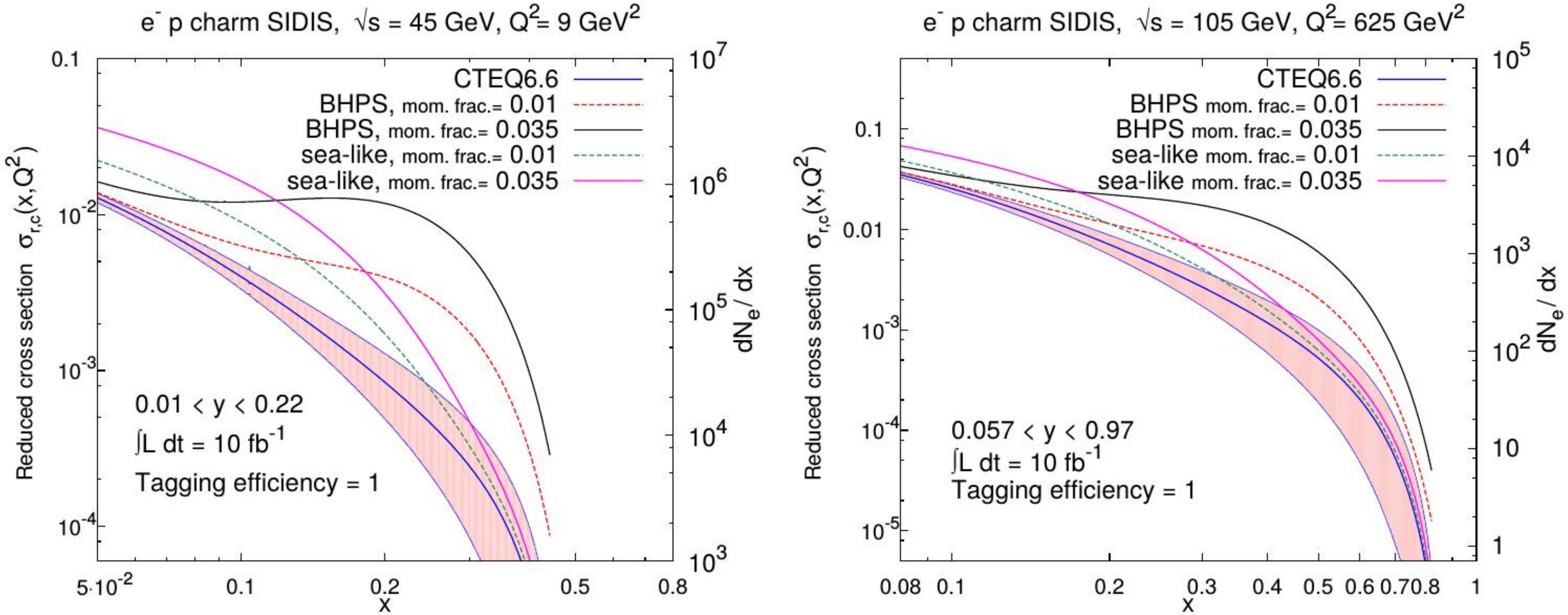




LHeC: enormously extended range and much improved precision c.f. HERA

- **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

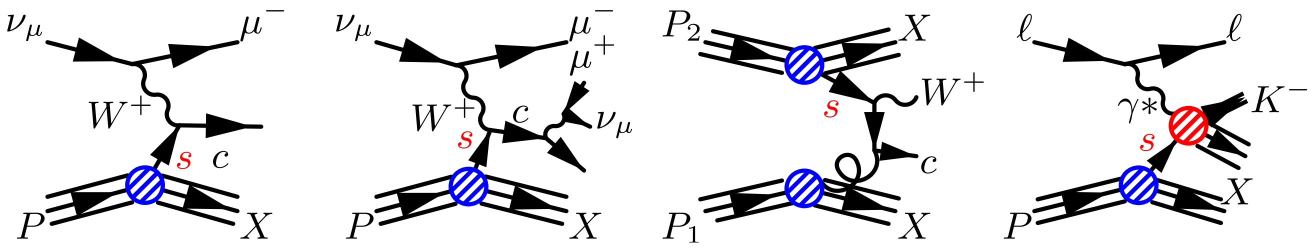
sensitivity to intrinsic vs perturbative charm; and to different shapes of intrinsic charm

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: Z+c, γ+c; most recent measurements not yet discriminating (EG. M. Stockton, WG1)

strange

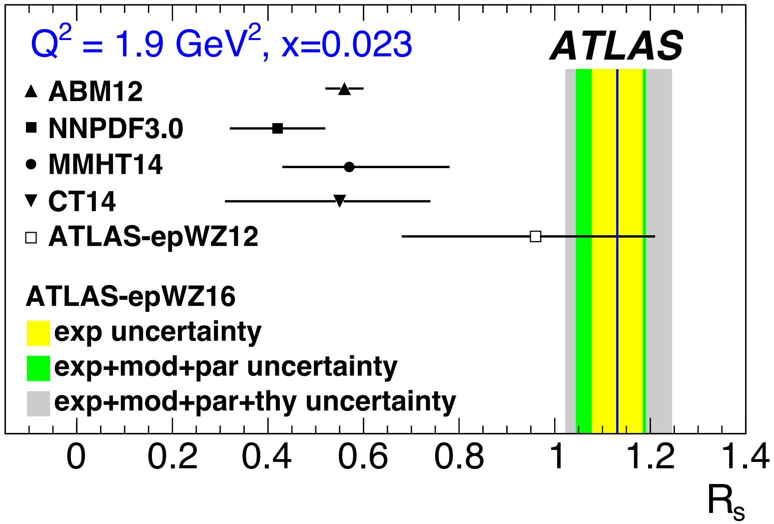
strange pdf poorly known; suppressed cf. other light quarks? strange valence?

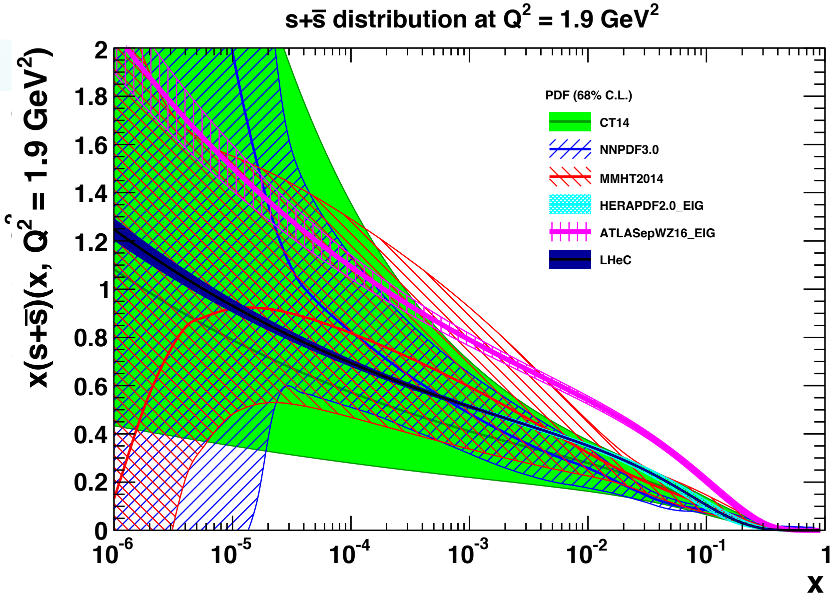


EG. CHORUS NuTeV ATLAS/CMS HERMES

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

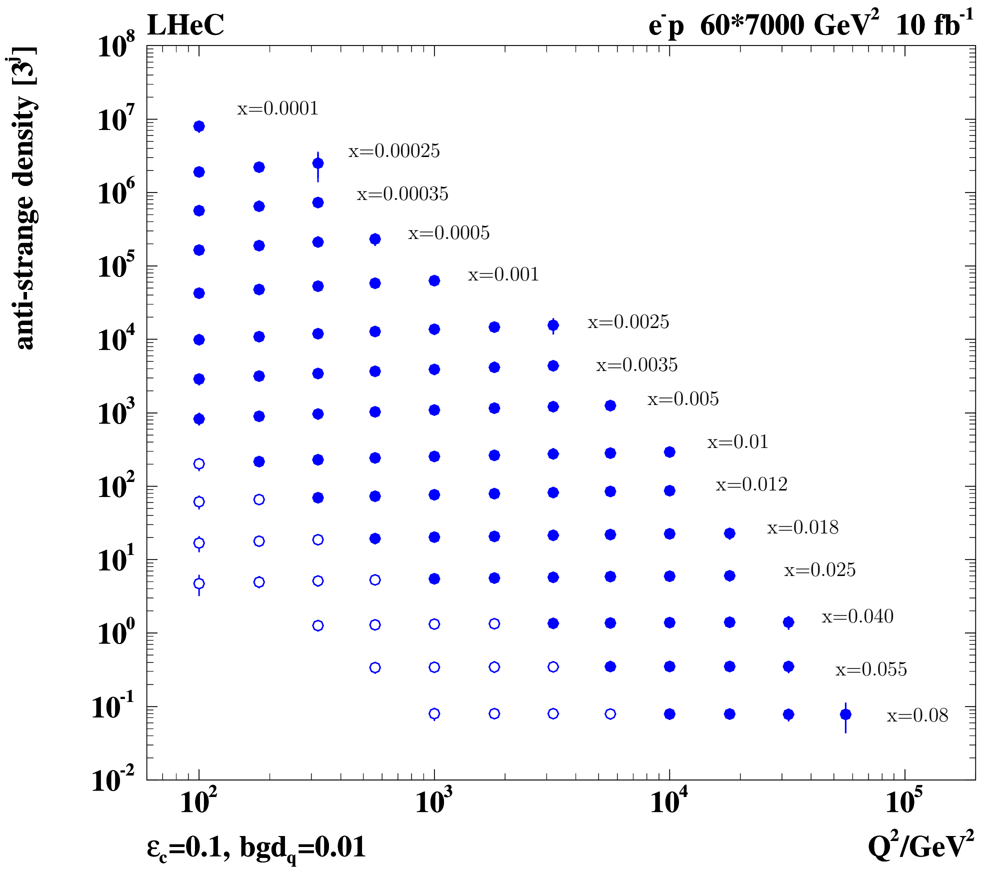
$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$



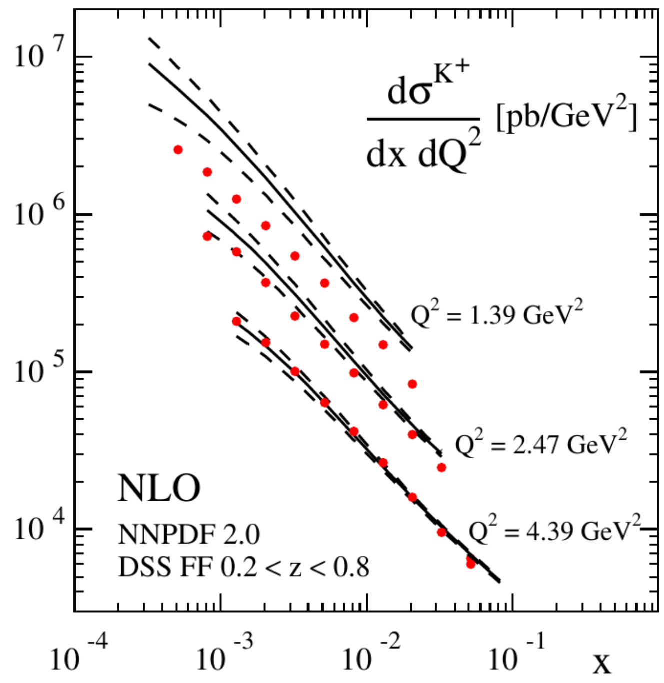


†ATLAS arXiv:1203.4051, confirmed with high stats in 1612.03016; and by global fitters EG. NNPDF 1706.00428, MMHT 1708.00047

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;

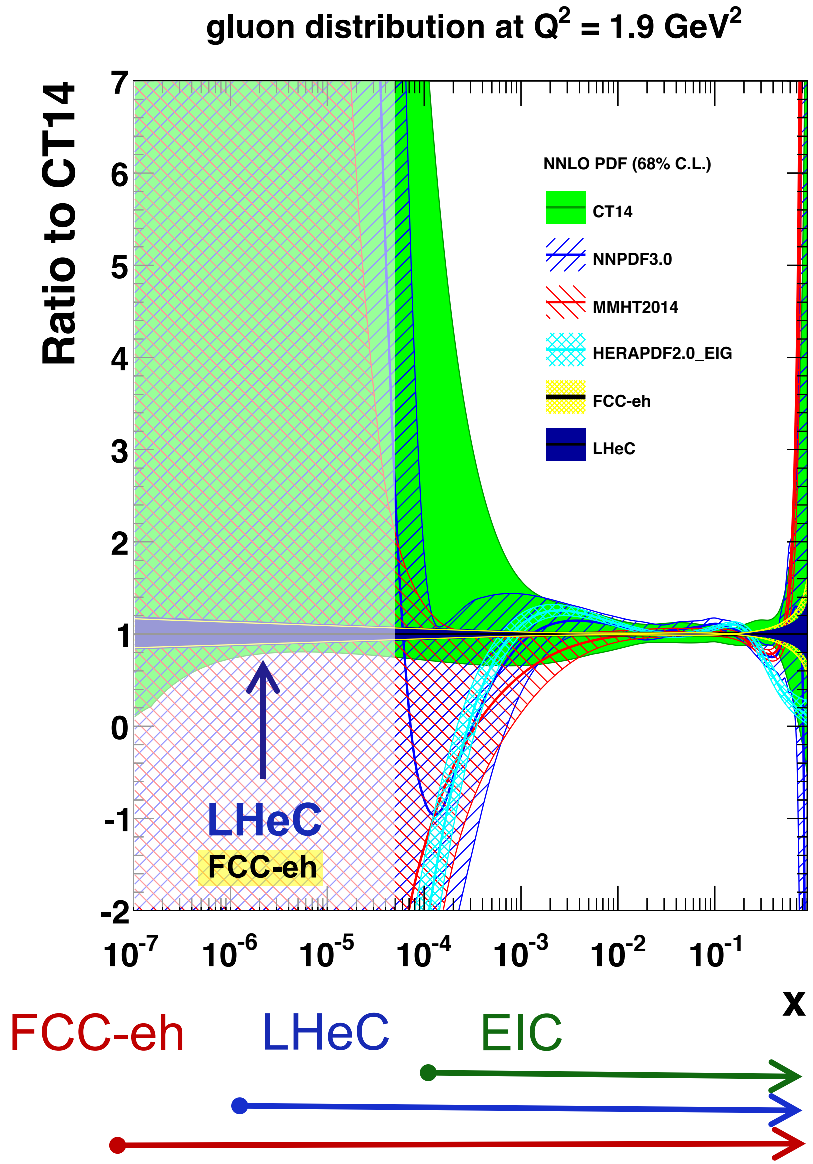
complication: $K^\pm$ fragmentation; could study FFs separately, or simult. analyse pdfs and FFs

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 $x=10^{-7}$

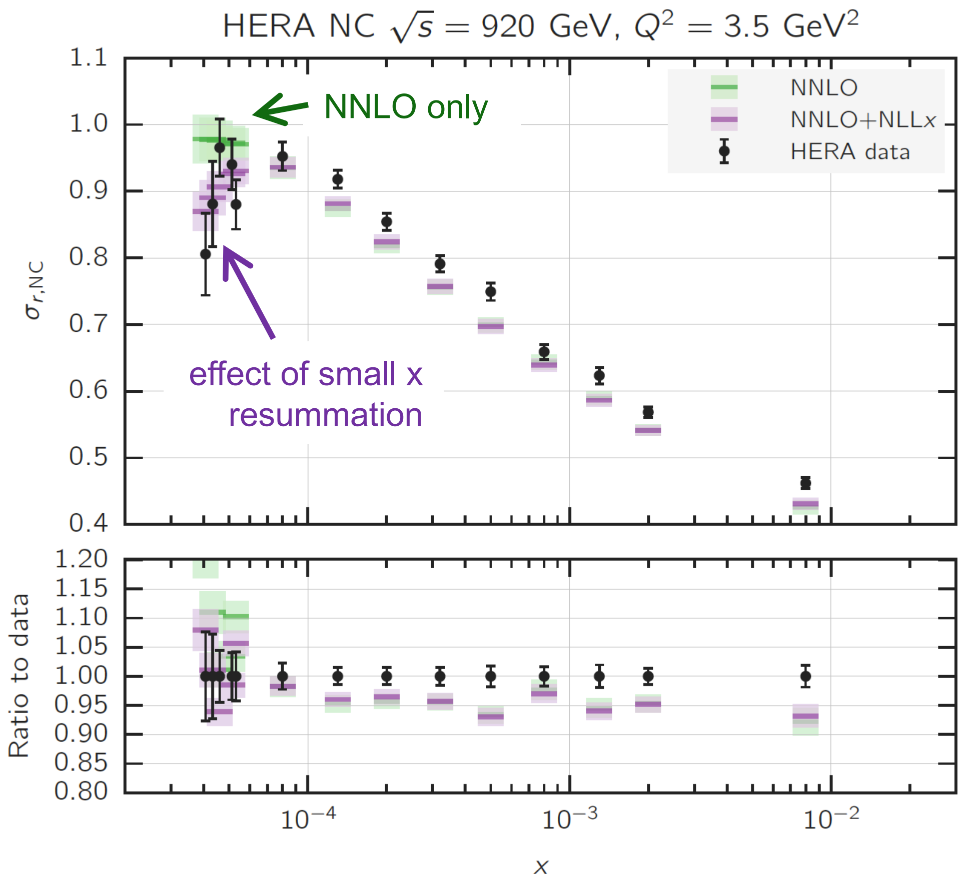
explore low x QCD:

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

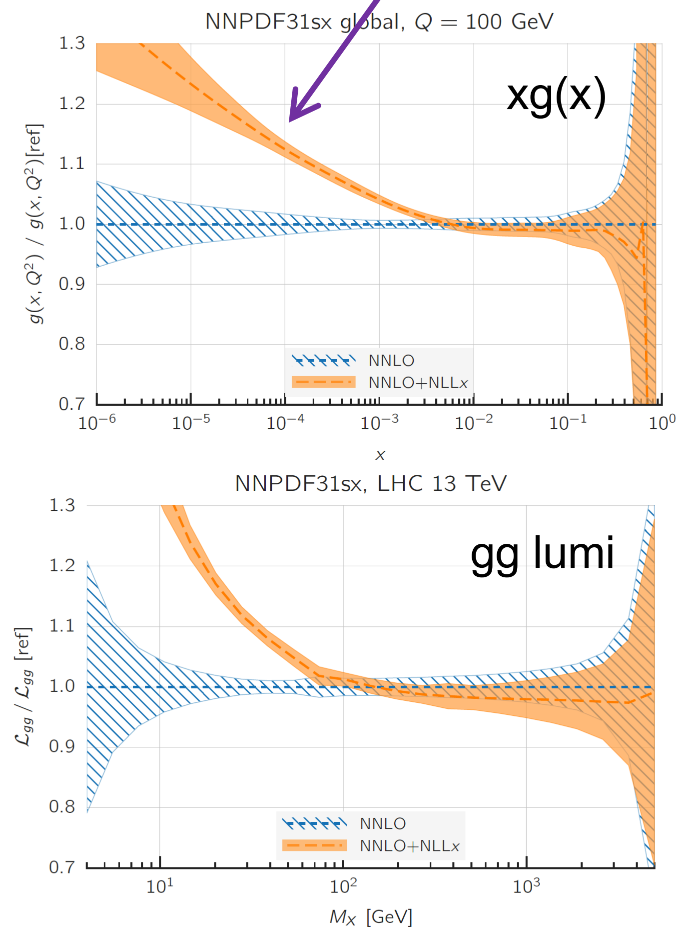
(**EIC**: study of gluon saturation in **eA** a key goal;
nuclear enhancement $Qs^2 \sim A^{1/3}$;
saturation effects expected at larger x for heavy nuclei cf. proton)

gluon at small x

R. Ball et al, arXiv:1710.05935



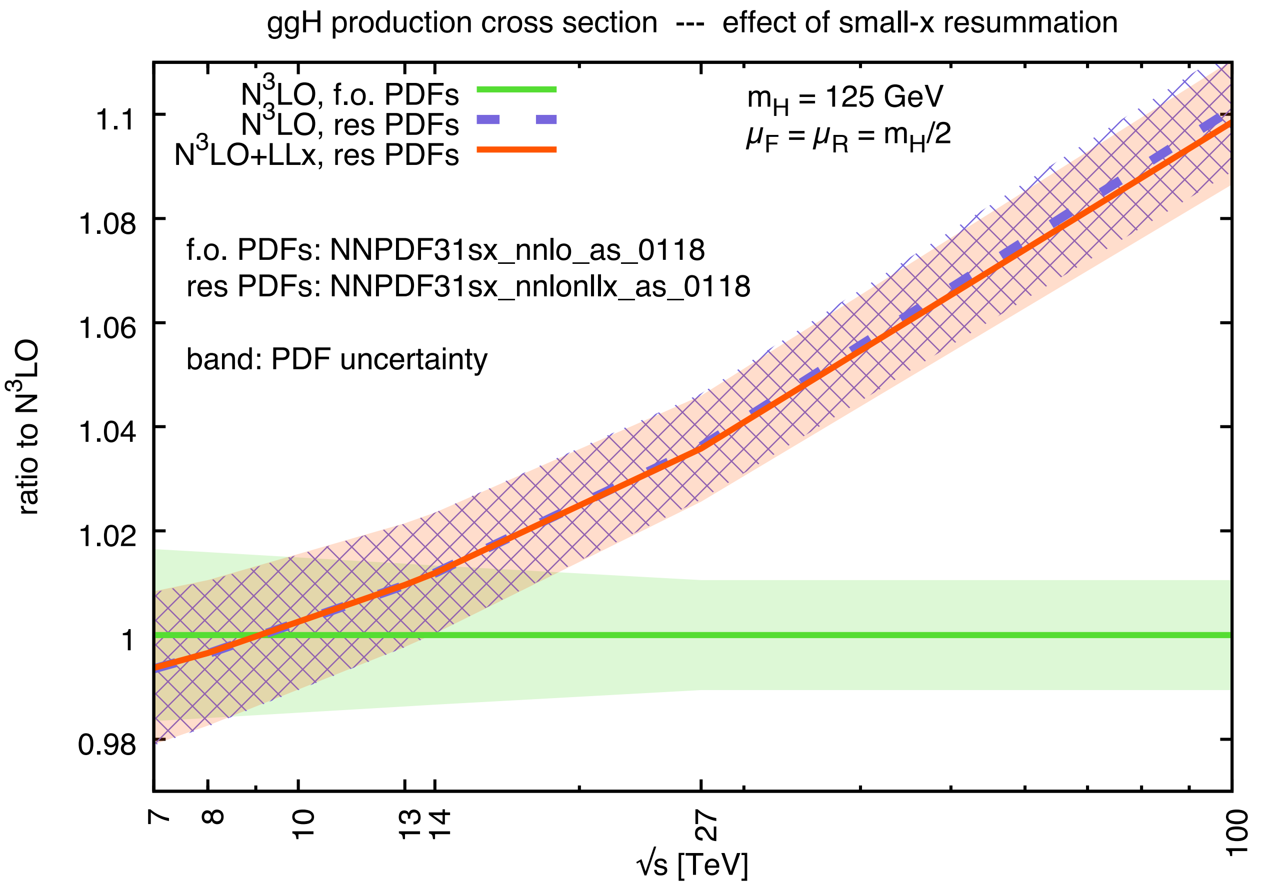
effect of small x resummation



- 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



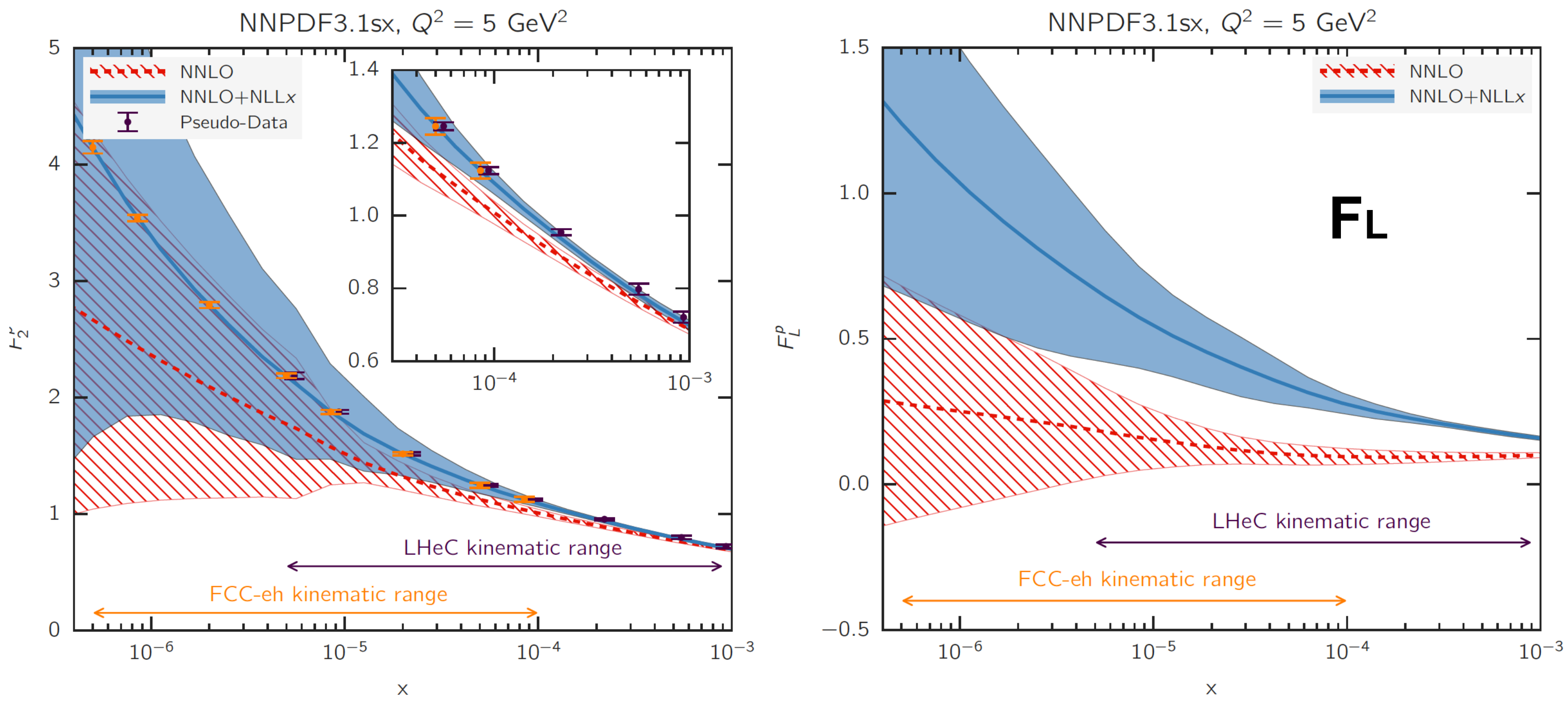
effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

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

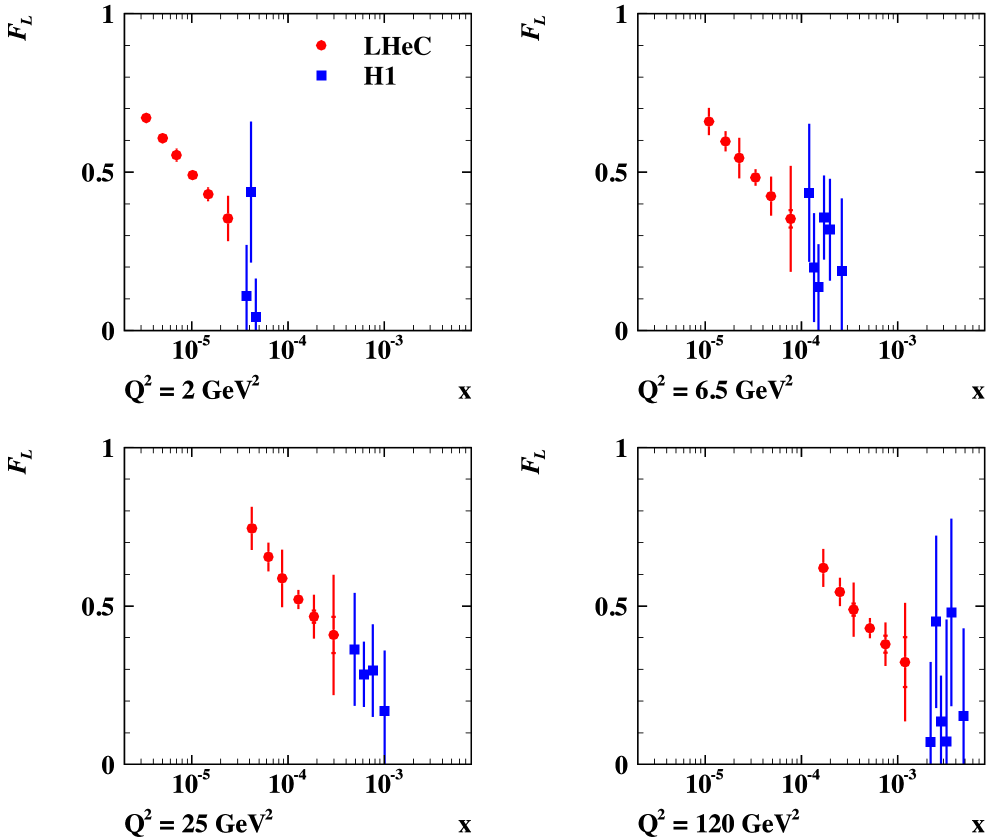


F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

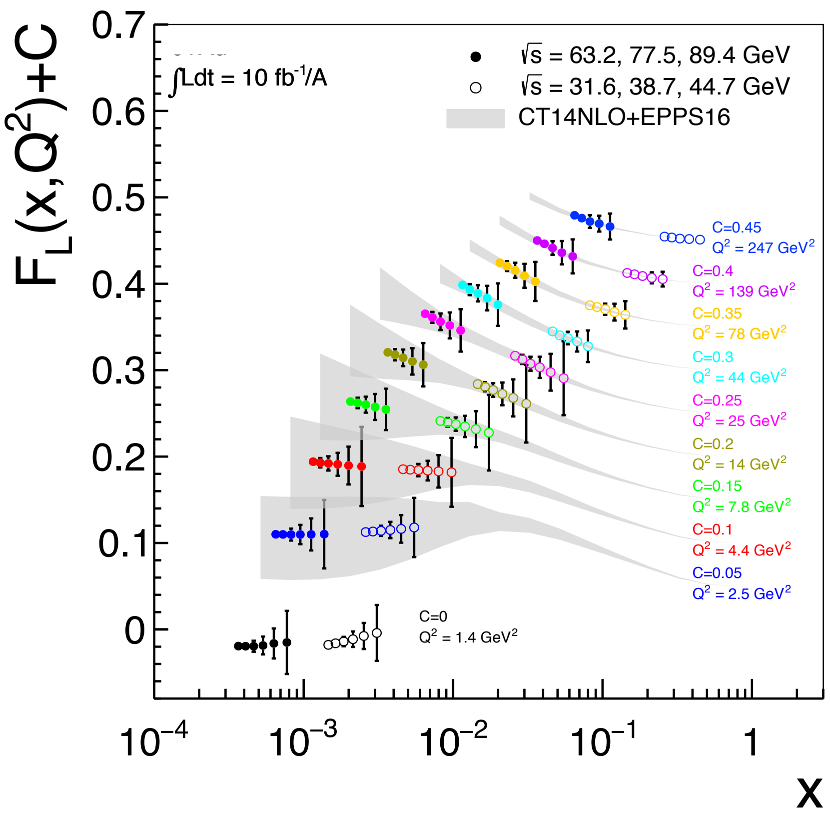
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play ⟶

FL at LHeC and EIC



M. Klein, arXiv:1802.04317



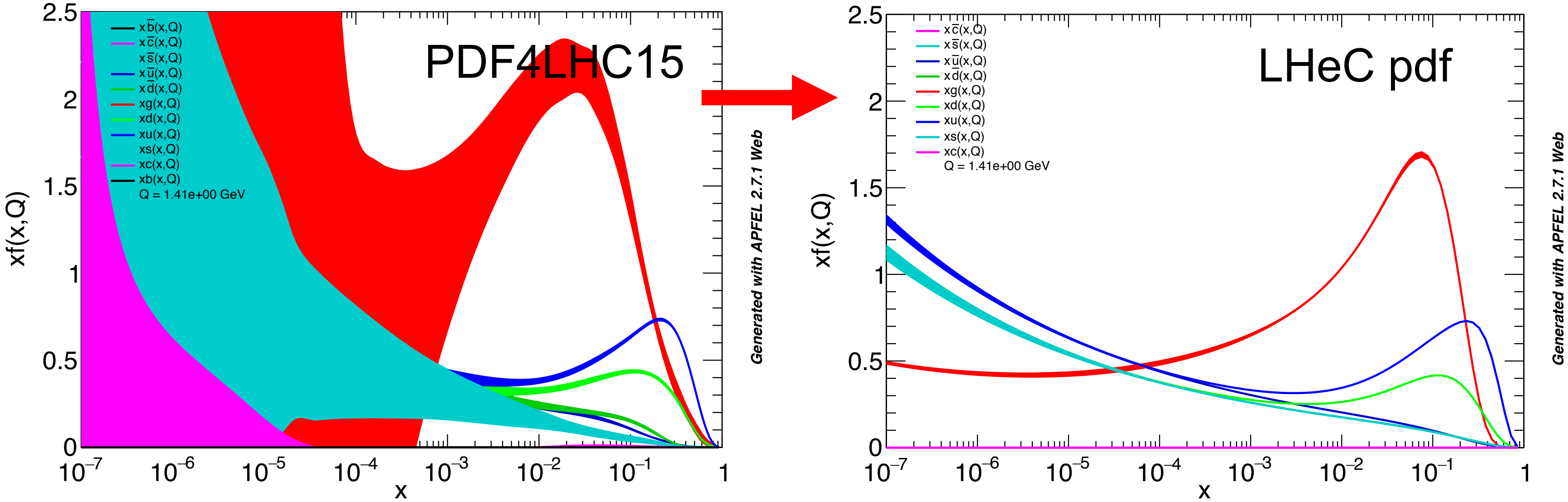
E.A. Aschenauer et al, arXiv:1708.05654

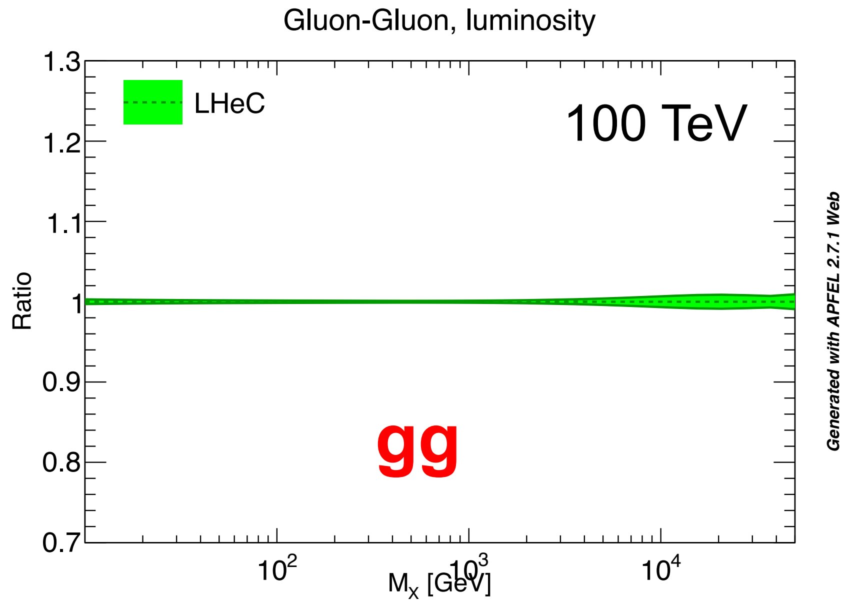
(eAu shown; similar precision expected in ep, and larger kinematic coverage with $\sqrt{s}$ up to 141 GeV)

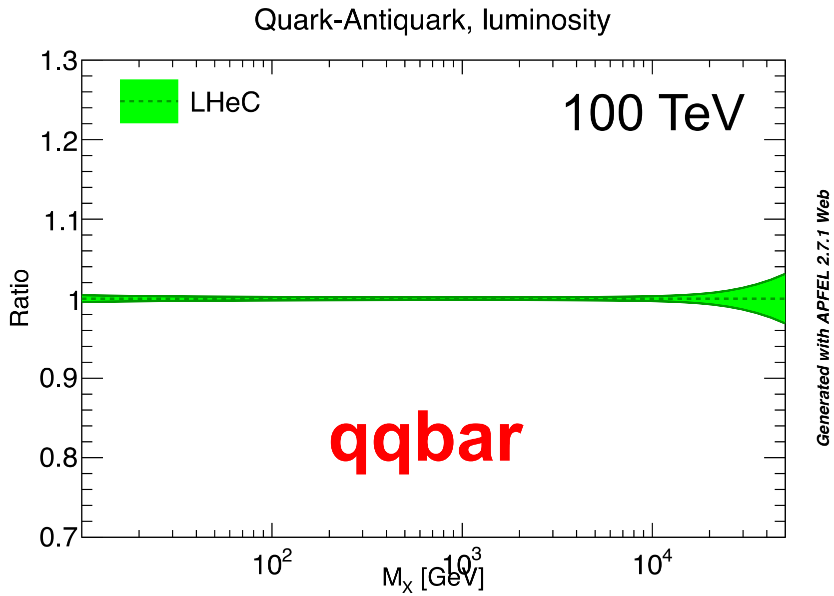
complementary FL measurements from LHeC and EIC

together ranging from very small to large x

summary of LHeC pdfs







EIC proton pdfs

+ ongoing studies presented here on impact of ep NC/CC + F2n on **large x pdfs**

	Measurement	Process	What we learn
Unpolarized	unpolarized structure functions F_L and F_L^c	scaling violations in inclusive DIS	unpolarized gluon distribution at small x
	heavy mesons J/ψ and Υ charm contribution to the cross section	heavy-quark production in (semi-inclusive) DIS	unpolarized gluon at large x intrinsic charm contribution in the proton
	kaon multiplicities	charged kaon production in semi-inclusive DIS	unpolarized strange and antistrange distributions
Polarized	polarized structure function g_1	scaling violations in inclusive DIS	gluon contribution to proton spin
	polarized structure function g_1^h	semi-inclusive DIS for pions and kaons	quark contribution to proton spin sea asymmetry $\Delta\bar{u} - \Delta\bar{d}$; Δs
	novel electroweak spin structure functions	inclusive DIS at high Q^2	flavor separation at medium x and large Q^2

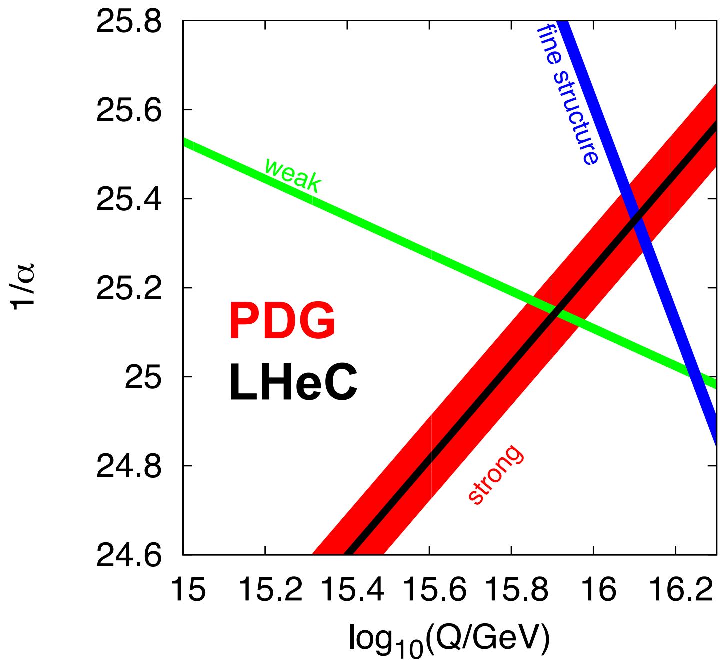
UNP Excellent complementarity with the LHC (discovery) and LHeC (ultra-precision)
training ground for future colliders as HERA has been for the EIC

POL Unique machine to address the spin structure of the proton
the EIC might save unexpected surprises, like the SPS-EMC did in the 80s

(taken from E. R. Nocera, POETIC7)

strong coupling α_s from LHeC (FCC-eh)

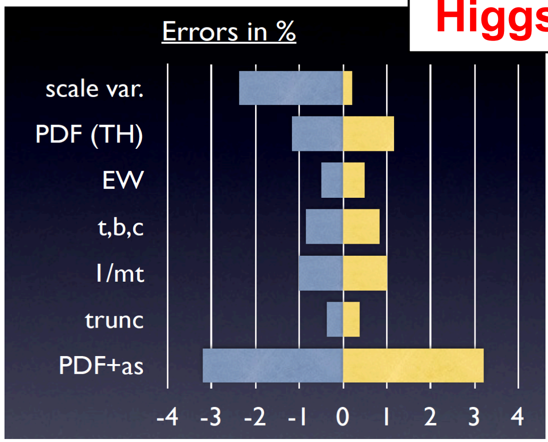
- α_s is least known coupling constant
  precise α_s needed to constrain GUT scenarios;
  for cross section predictions, including H; …
- measurements not all consistent
- what is true central value and uncertainty?
- α_s(DIS) smaller than world average?
- **LHeC**: **permille precision** from QCD fit 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. Zanderigi, Moriond16;
from C. Anastasiou et al, arXiv:1602.00695)

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	$(1.5\text{–}4)\%_{th} \oplus 1\%_{exp} \approx (1.5\text{–}4)\%$ (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^-	$(2\text{–}5)\%_{th} \oplus 1\%_{exp} \approx (2\text{–}5)\%$ (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^{3}LO, 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^{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)	$0.1\%_{th} \oplus (0.5\text{–}0.1)\%_{exp} \approx (0.5\text{–}0.15)\%$ (ILC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{\text{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, $\sim$2 yrs) (NNLO. Multiple datasets+observables)
$t\bar{t}$ in p-p, p-$\overline{\text{p}}$	$1.5\%_{th} \oplus 2\%_{exp} \approx 2.5\%$ (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

see also talk by D. d'Enterria in WG4

summary

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

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

LHC future measurements likely to give incremental rather than dramatic improvements;

also may have to worry about LHC feedback (BSM?) for SM pdfs

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 polarisation for spin physics, luminosity, and eA

wealth of NP & PP goals, beyond its use for unpolarised pdfs (see, EG. J. Yiu, WG7)

pdfs 4LHC not yet part of remit; studies in progress are establishing potential;

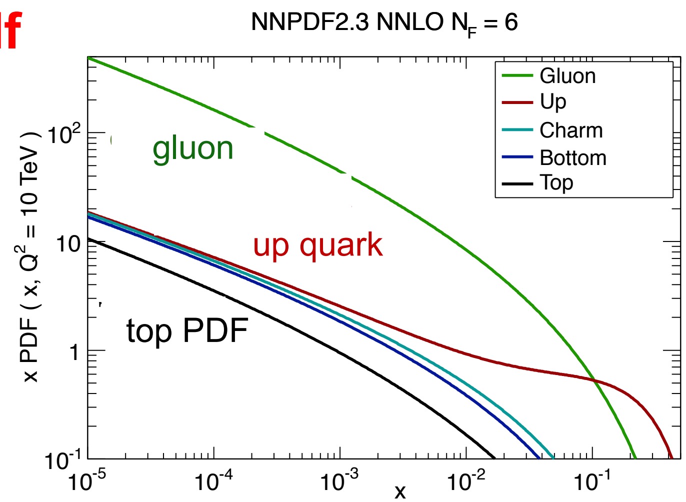
volunteers and further engagement with HEPP community welcome

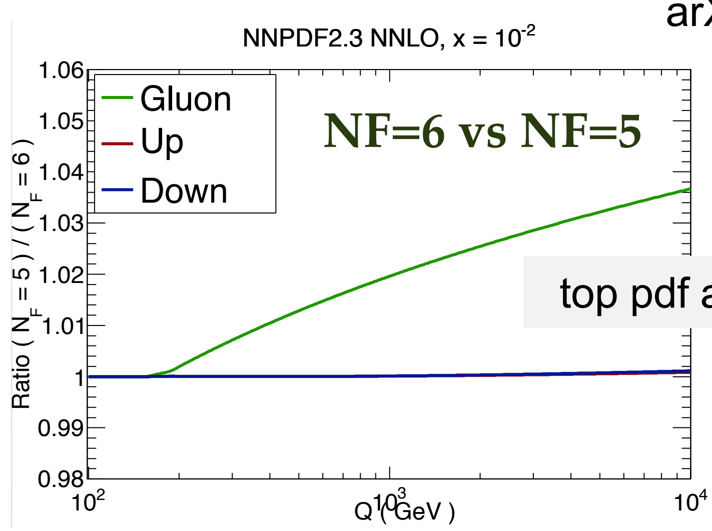
extras

some other considerations

arXiv:1607.01831

top pdf

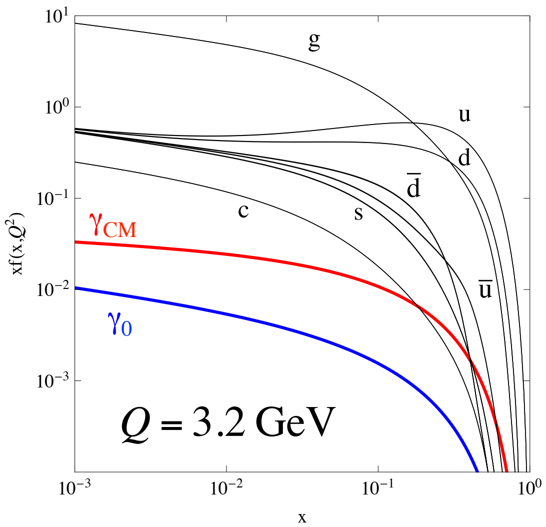


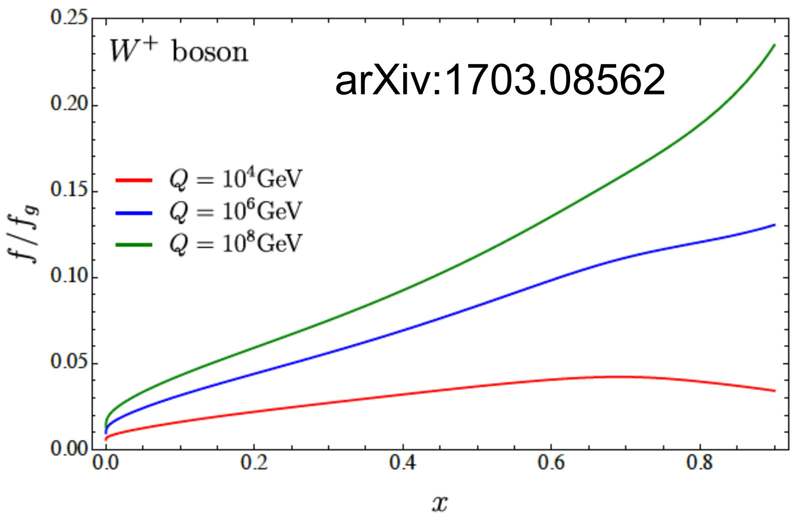


top pdf affects gluon

photon pdf

already visible impact on high scale LHC data





arXiv:1703.08562

EW pdfs

also contribute at FCC

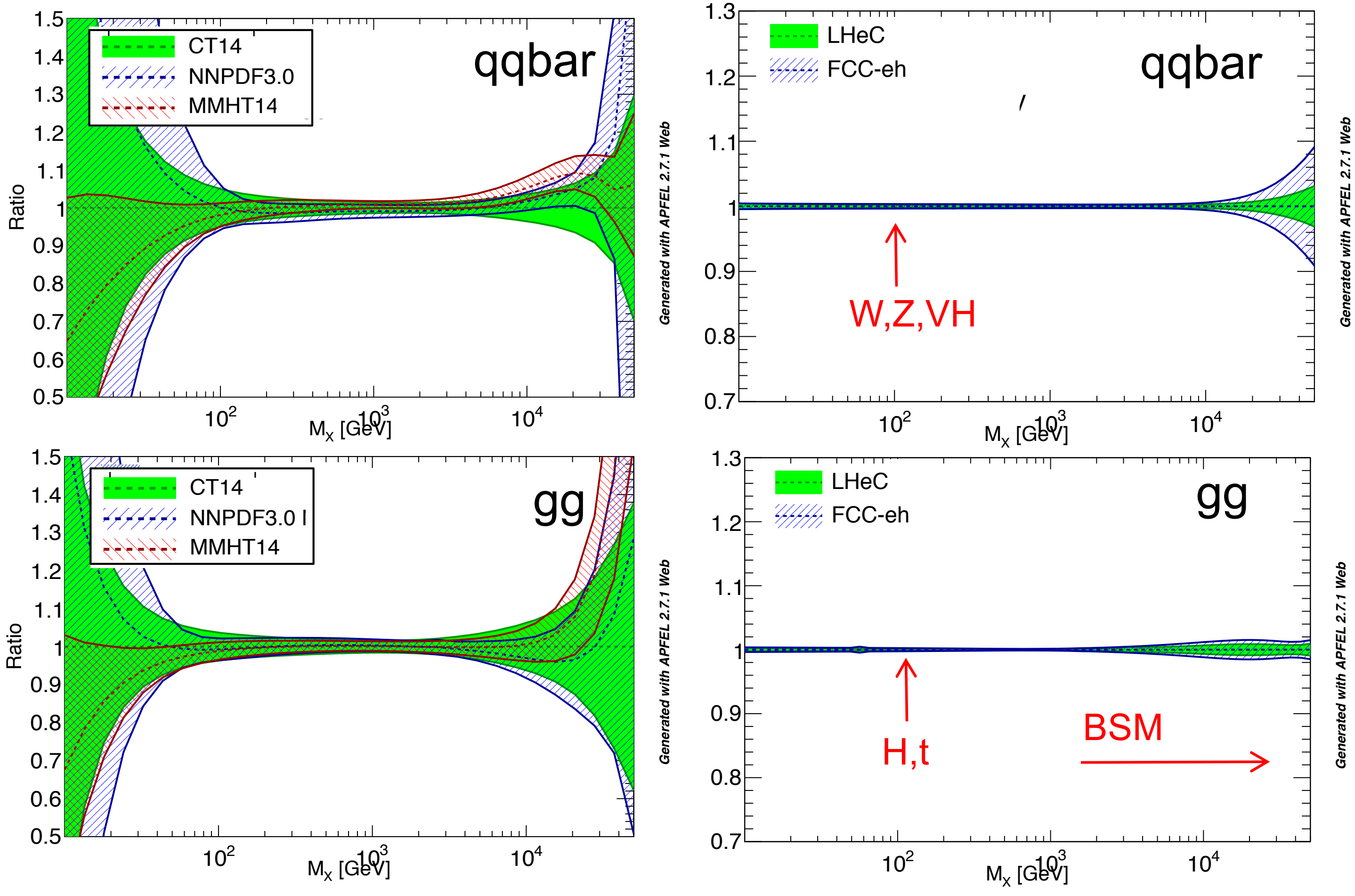
FCC not simply a scaled version of **LHC** (qualitatively new phenomena introduced)

FCC parton luminosities

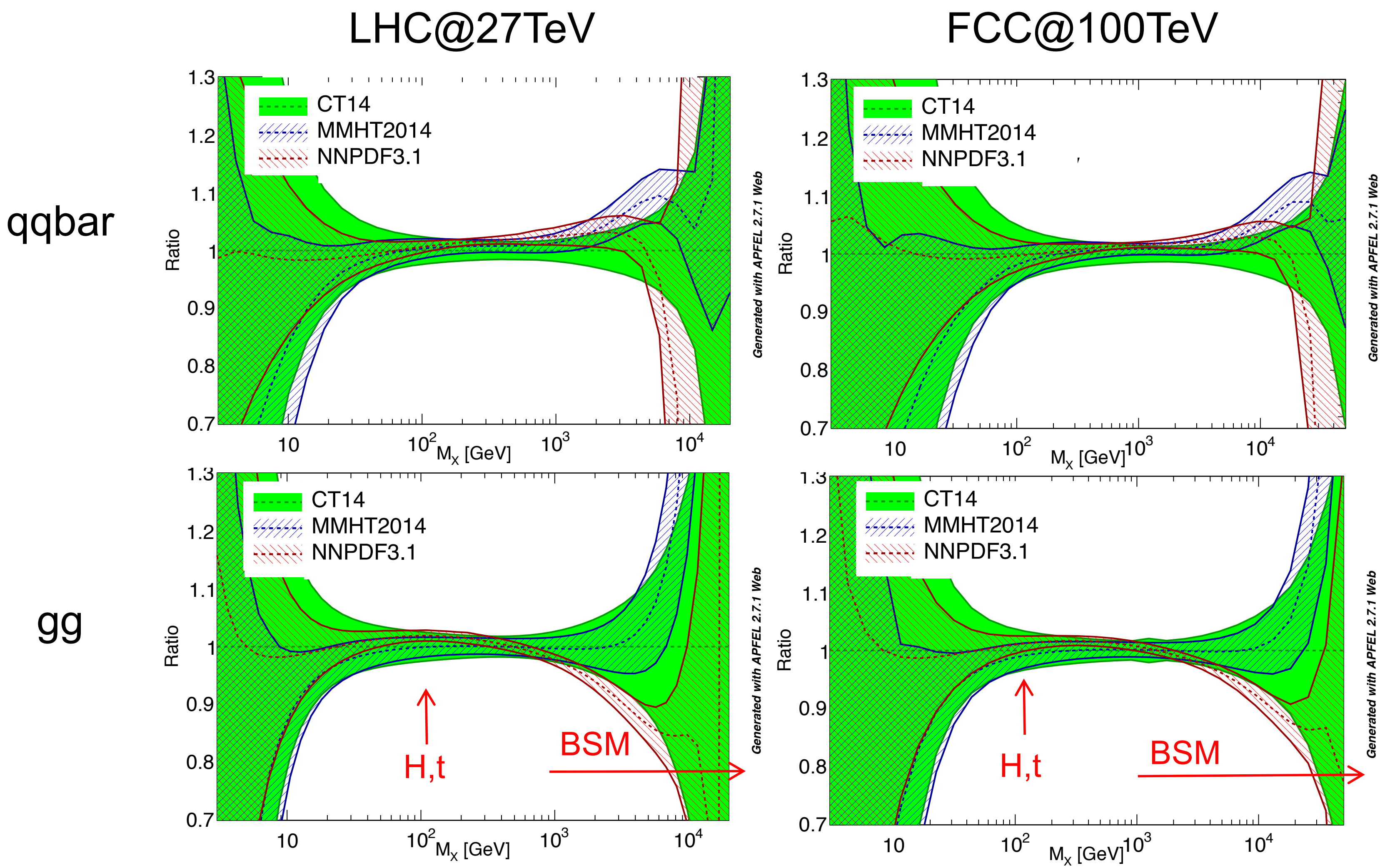
today…

FCC parton luminosities (100 TeV)

… then,
with LHeC
or FCC–eh



pdf luminosities for HE-LHC and FCC



proton spin at EIC

what forms proton spin?

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

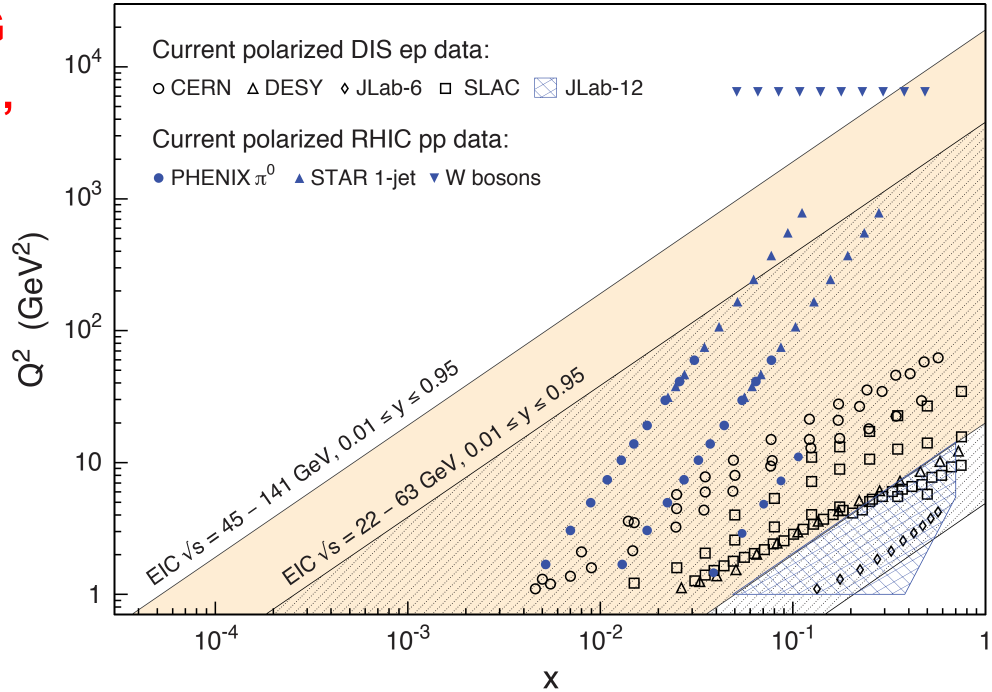
total quark — gluon — orbital AM

$\Delta\Sigma$, 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**

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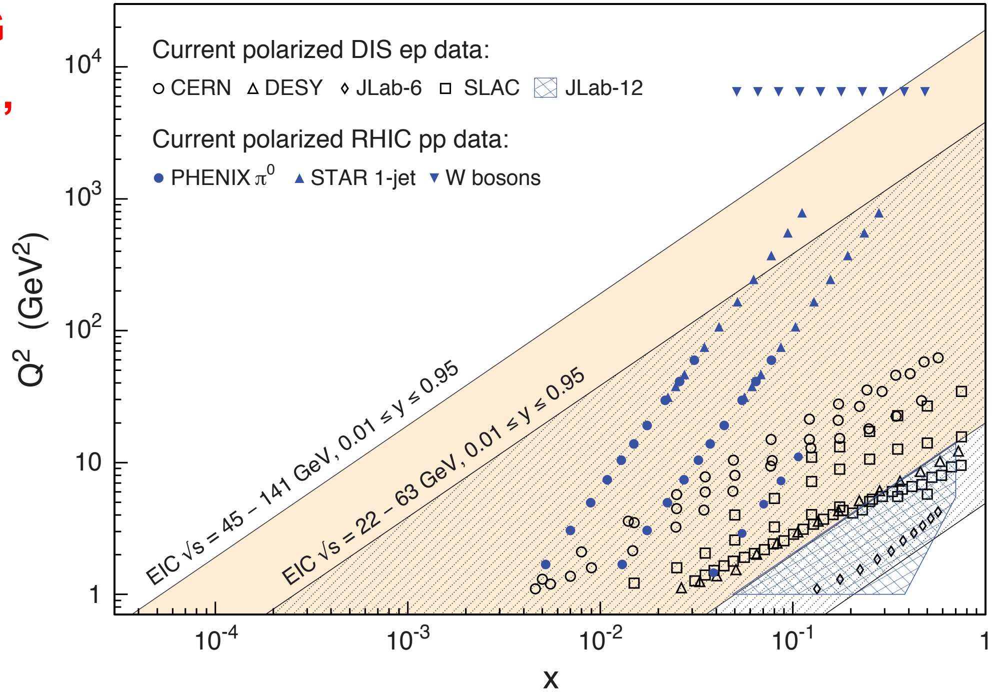

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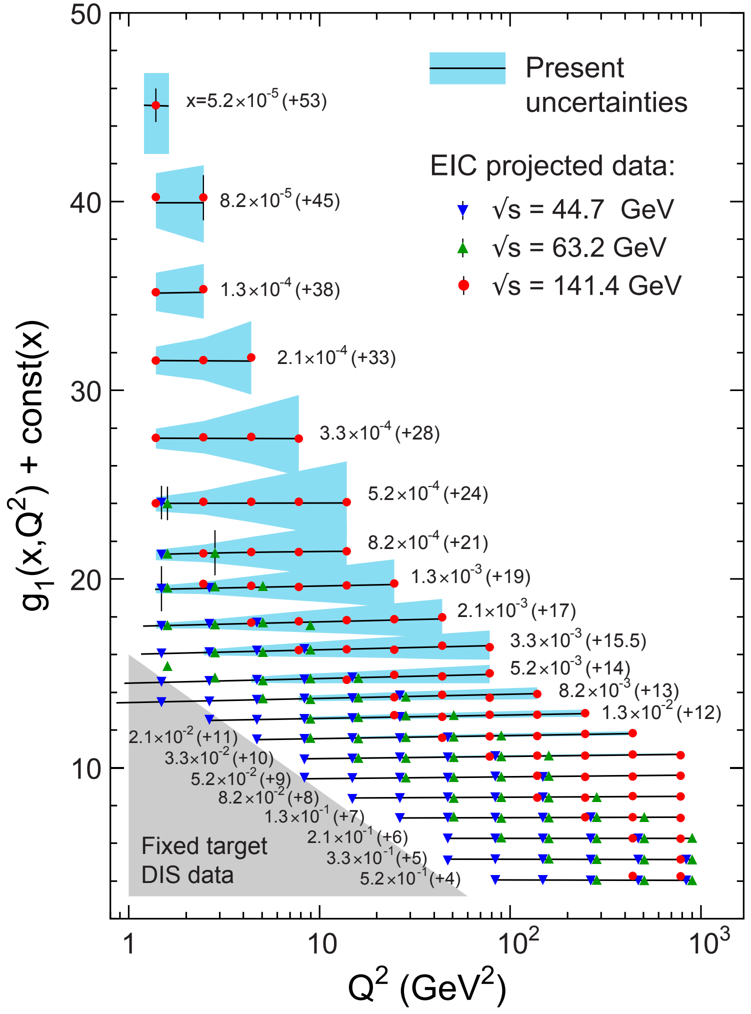
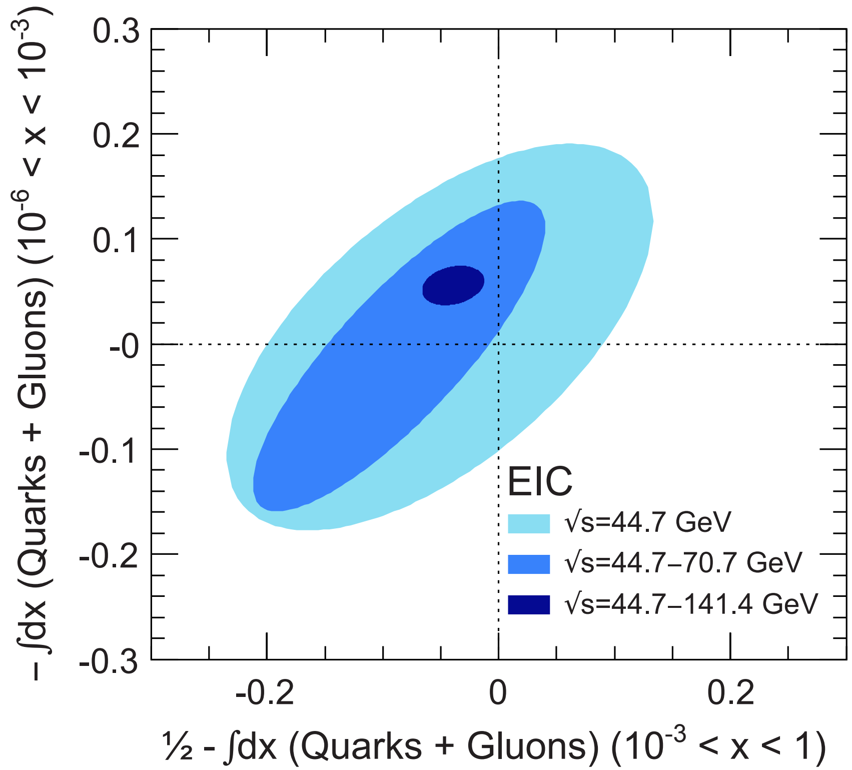


quark contribution from integral of g1 over x;
gluon from scaling violations

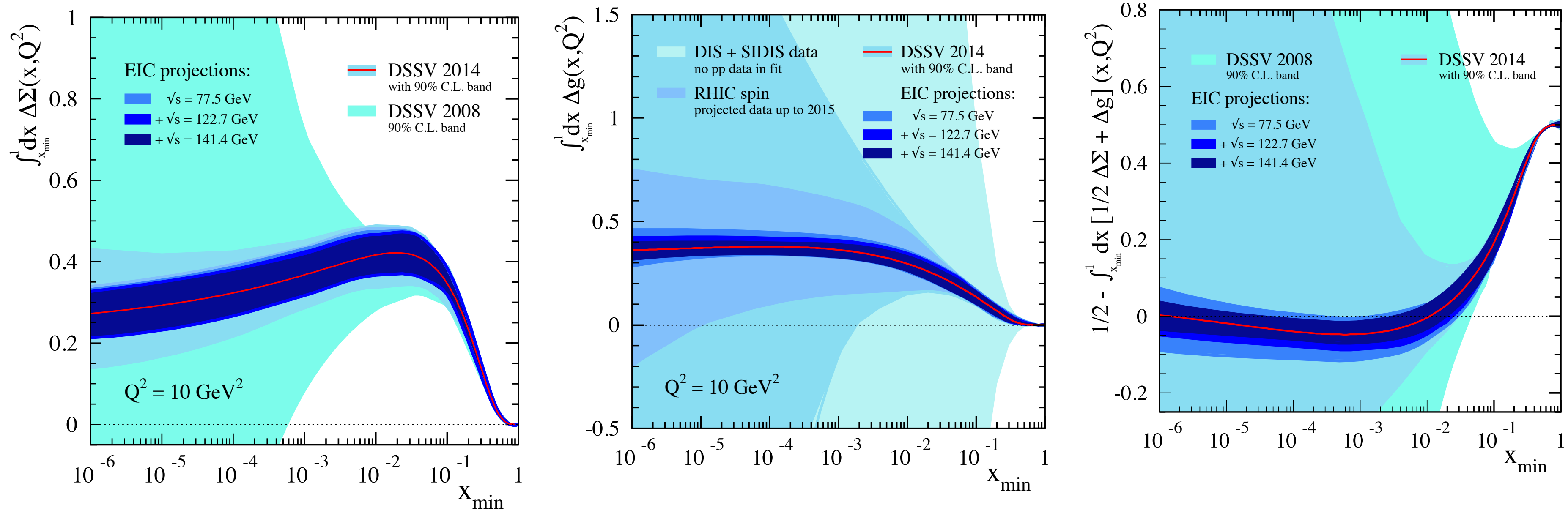


EIC: for first time different contributions to spin of proton can be disentangled

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

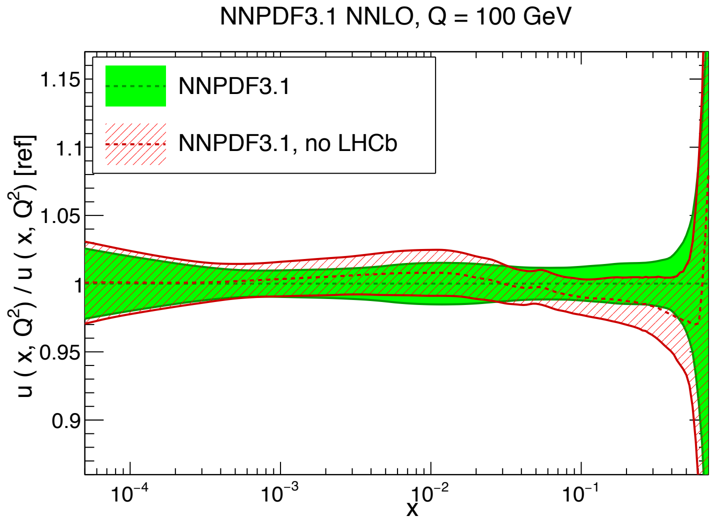
E.A. Aschenauer et al, arXiv:1708.01527

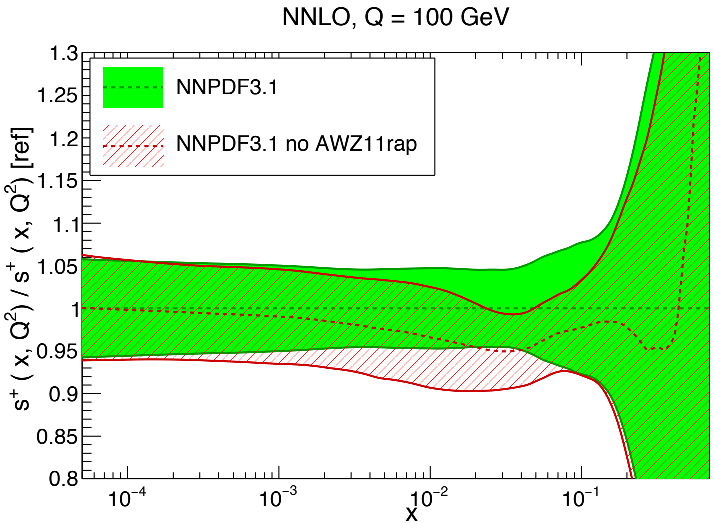
polarised pdfs at the EIC

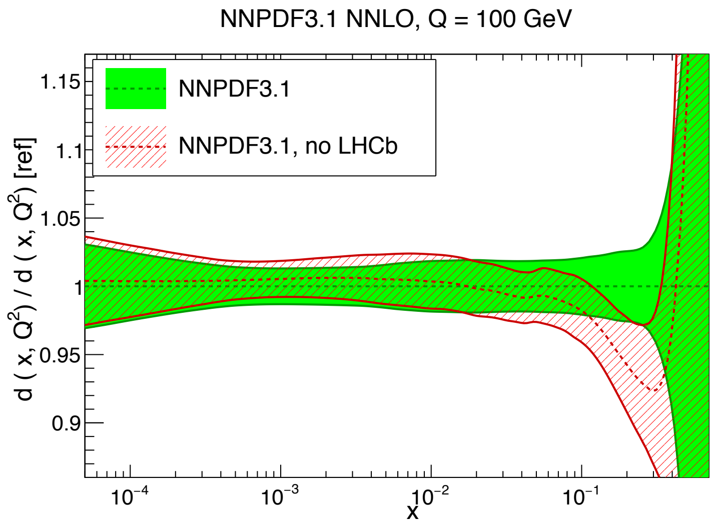


E.A. Aschenauer et al, arXiv:1509.06489

impact of LHC on today's PDFs





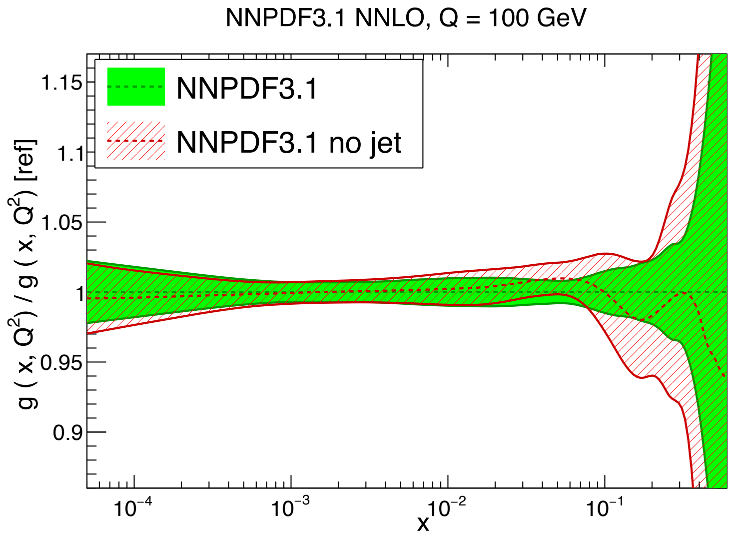


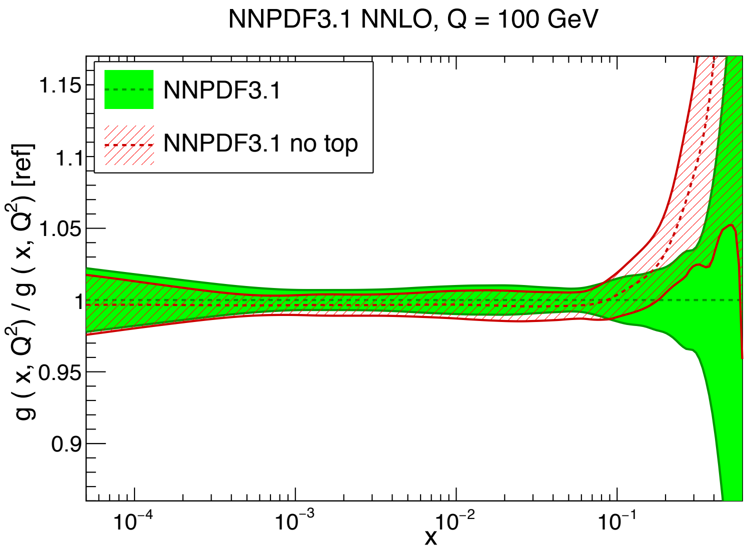
data sets that affect the quarks:

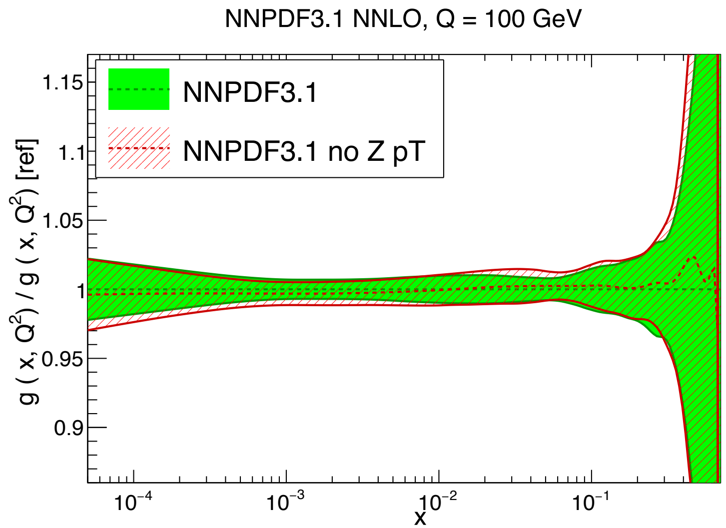
W^+, W^-, Z production from the Tevatron, ATLAS, CMS, LHCb

(arXiv:1706.00428)

impact of LHC on today’s PDFs







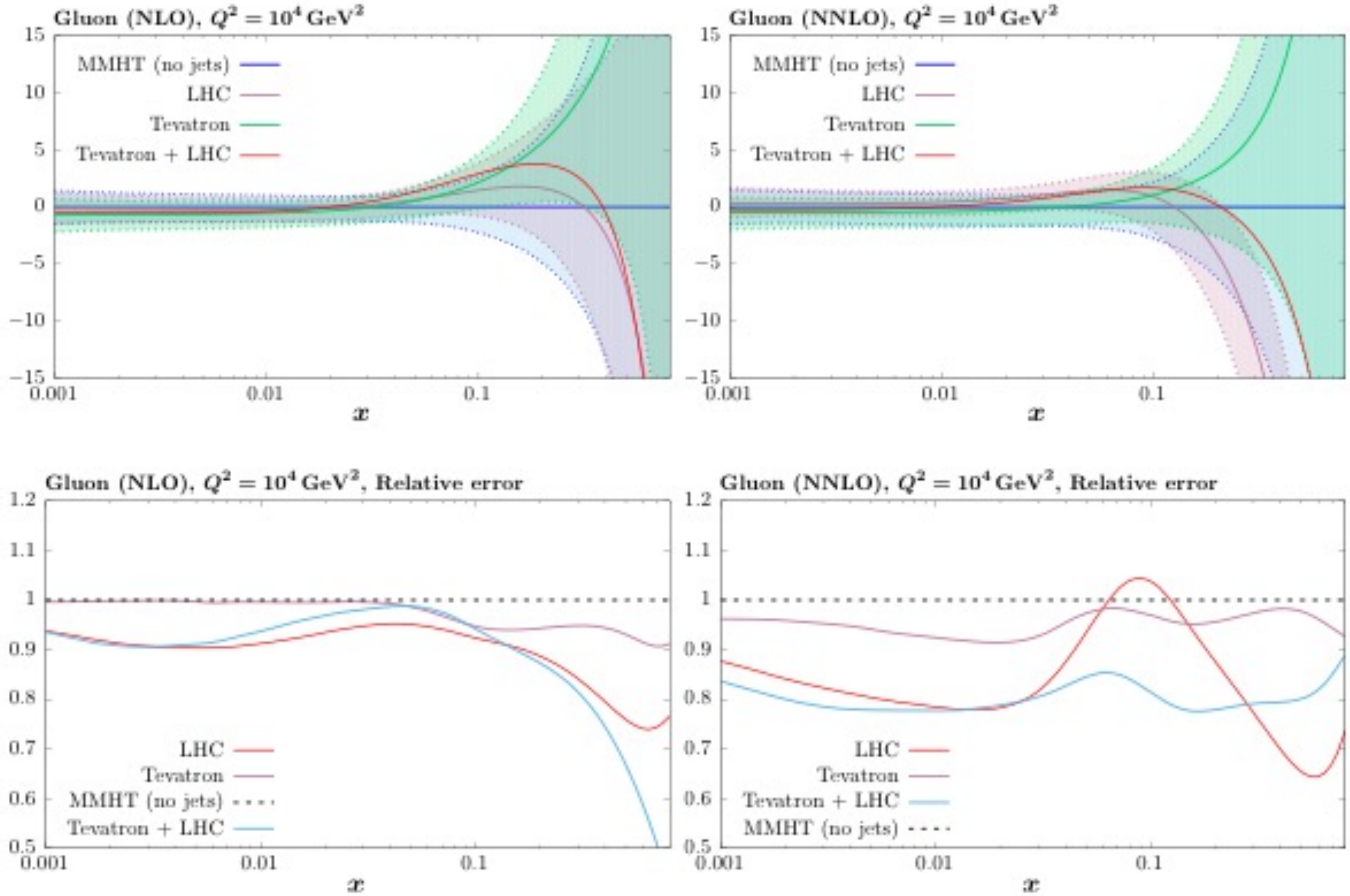
data sets that affect the gluon:

jet production

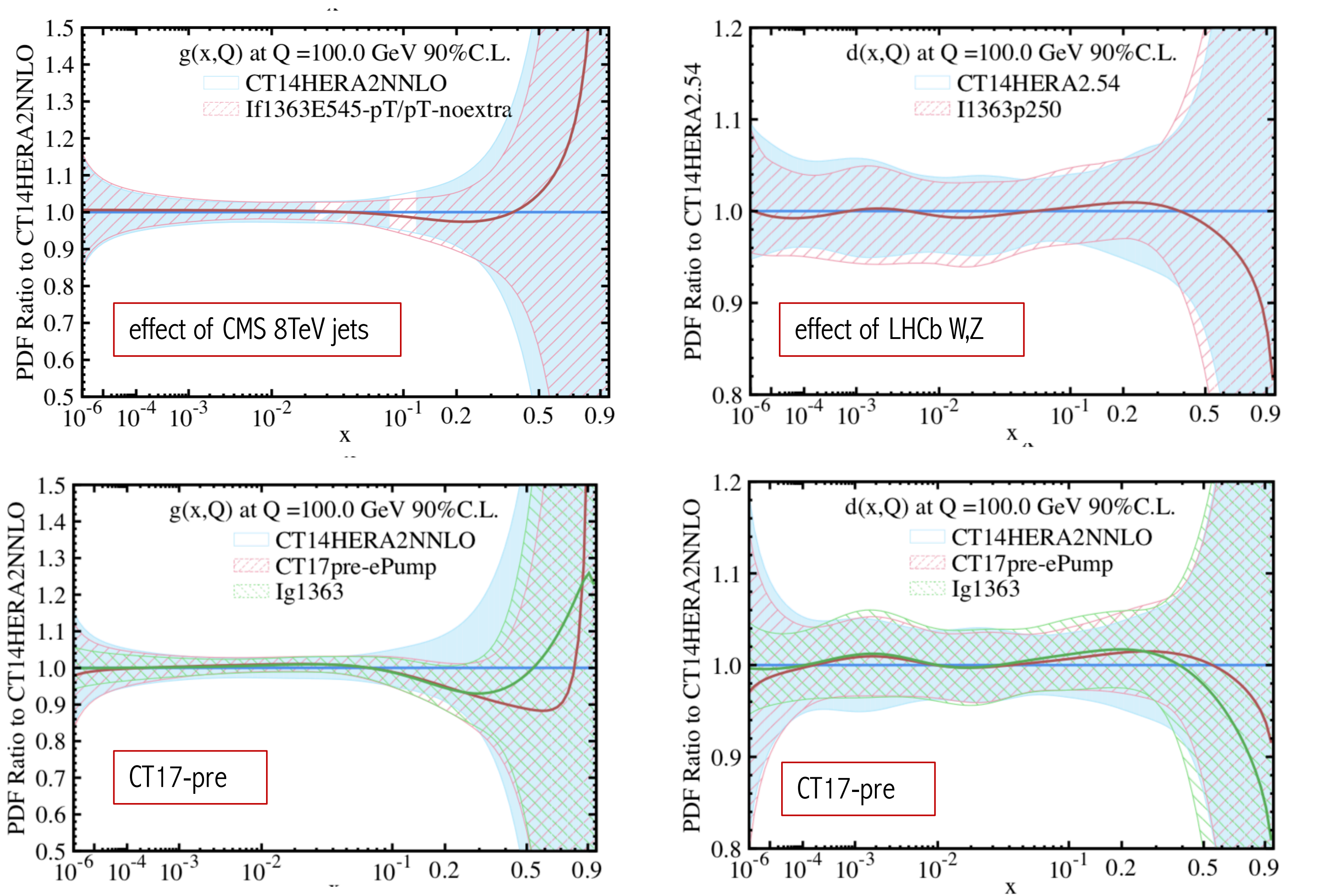
ttbar differential distributions

ZPt

(arXiv:1706.00428)



(R. Thorne, PDF4LHC March 2018)



(J. Huston, PDF4LHC March 2018)

LHC ultimate precision for W,Z

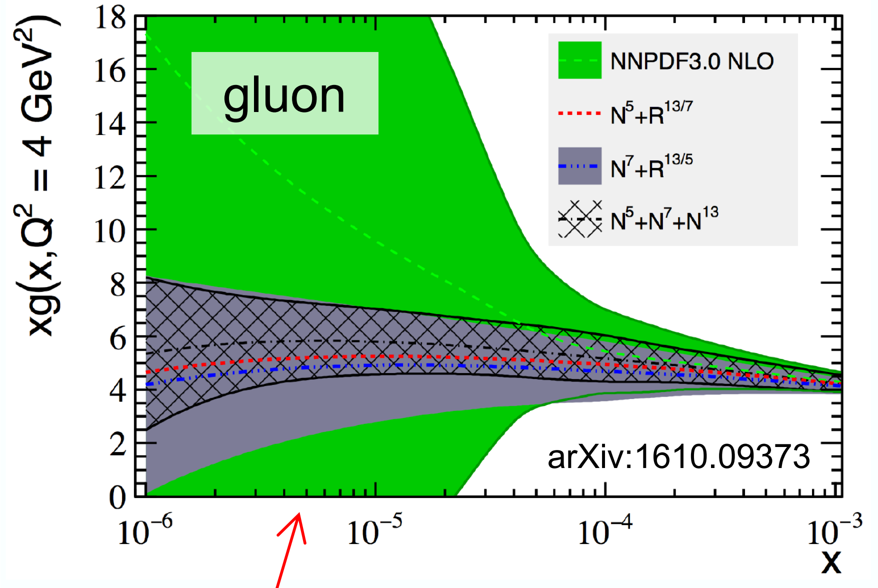
ATLAS coll., arXiv:1612.03016

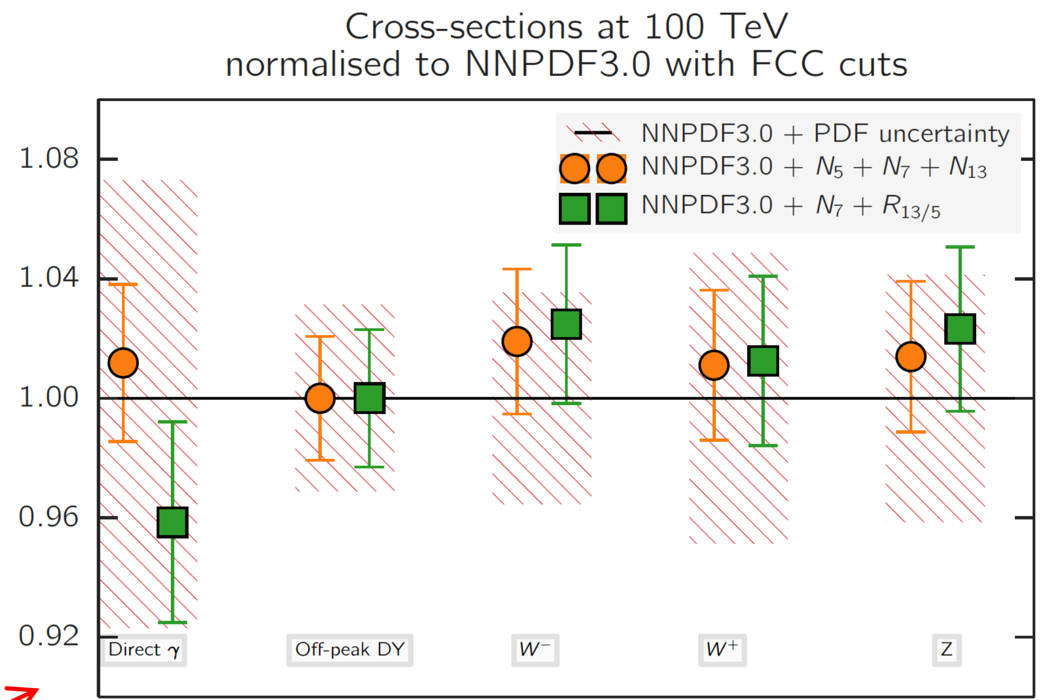
	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.19	0.19	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
Signal modelling (parton shower and hadronization)	0.14	0.17	0.22
PDF	0.09	0.12	0.07
Boson p_{T}	0.18	0.14	0.04
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

Table 6: Relative uncertainties $\delta\sigma$ in the measured integrated fiducial cross sections times branching ratios in the muon channels. The efficiency uncertainties are partially correlated between the trigger, reconstruction and isolation terms. This is taken into account in the computation of the total uncertainty quoted in the table.

LHC constraints for FCC?

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





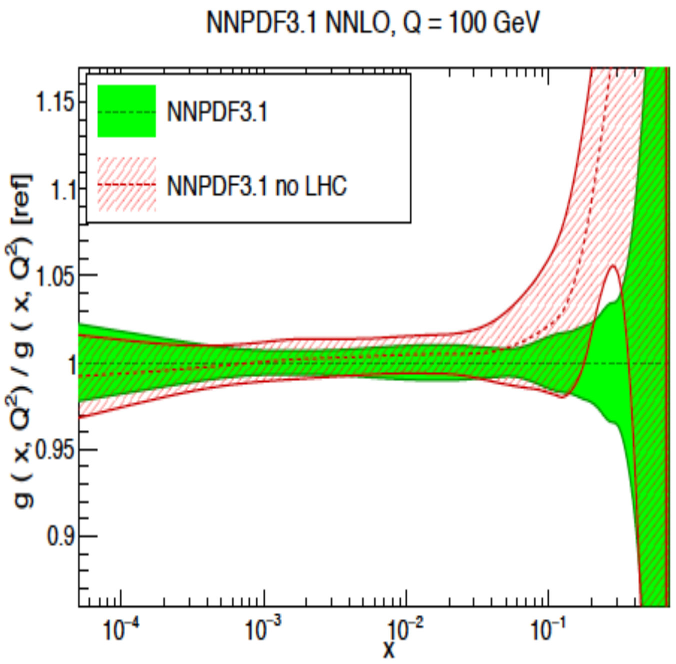
improved **small x gluon** using combinations of **LHCb forward charm** cross sections:– stabilises FCC predictions

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

though theoretically contentious region…

(also PROSA study, arXiv:1503.04581)

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

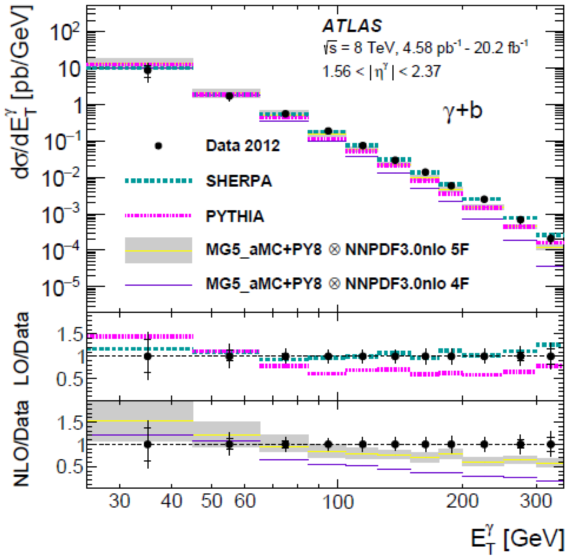
- Needs complete q_i,g unfolding (miss variety) at all x, as there are sumrules
- Needs strong coupling to permille precision, not in pp
- Needs stronger effects (miss Q^2 variation) cannot come from W,Z at $Q^2=10^4$ GeV^2
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t measured and VFNS fixed
- Needs verification of BFKL at low x (only F_2-F_L)
- Needs N^3LO (as for Higgs)
- Needs external input to find QCD subtleties such as factorisation, resummation…to not go wrong
- Needs external precise input for subtle discoveries
- Needs data which yet (W,Z) will hardly be better
- Needs agreement between the PDfs and χ^2+1 ..

PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at x ~ 0.01 (nonsuppressed s/dbar). Can take low pileup runs, mitigate PDF influence .. − but can't do what is sometimes stated.

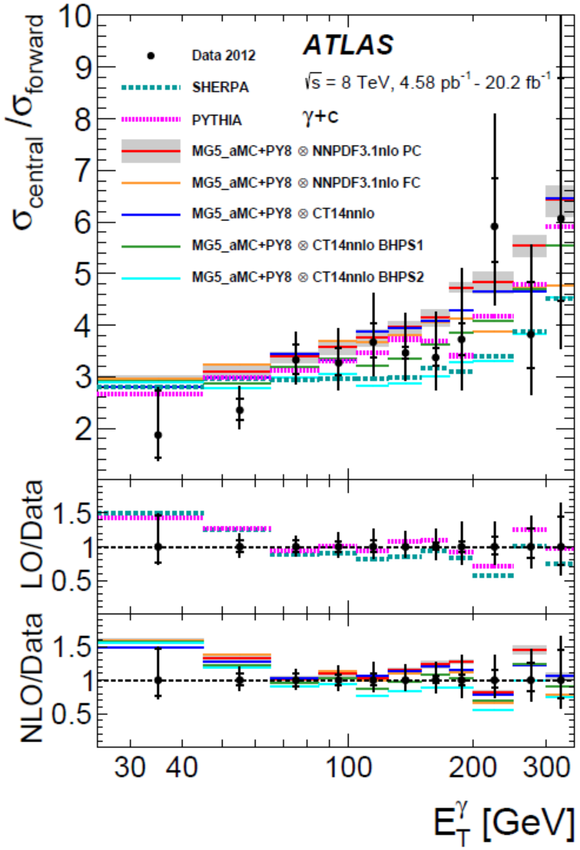
LHeC vs HERA: Higher Q^2: CC; higher s: small x/g saturation?; high lumi: x→ 1; s, c,b,t. …

(M. Klein)

arXiV:1710.09560 ATLAS γ+c and γ+b at 8 TeV

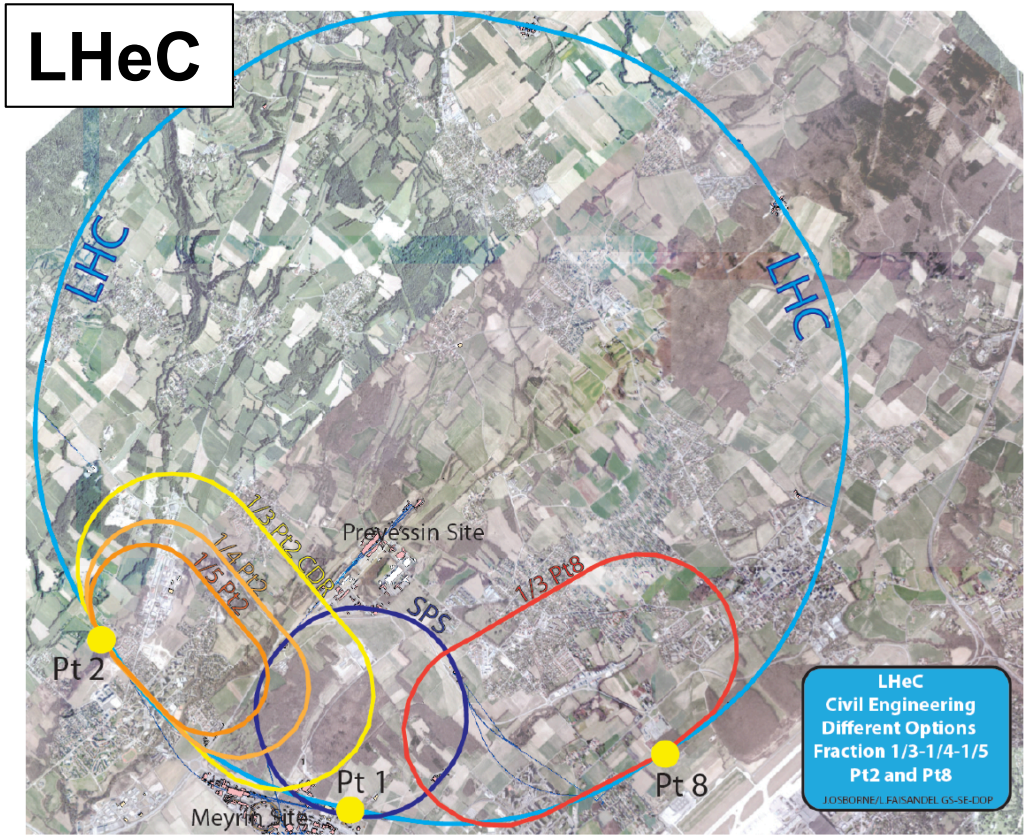


γ+b at high rapidity:
5-flavour scheme favoured over 4-flavout scheme



Central rapidity/forward rapidity for γ+c
No discrimination of intrinsic charm

LHeC and FCC-eh



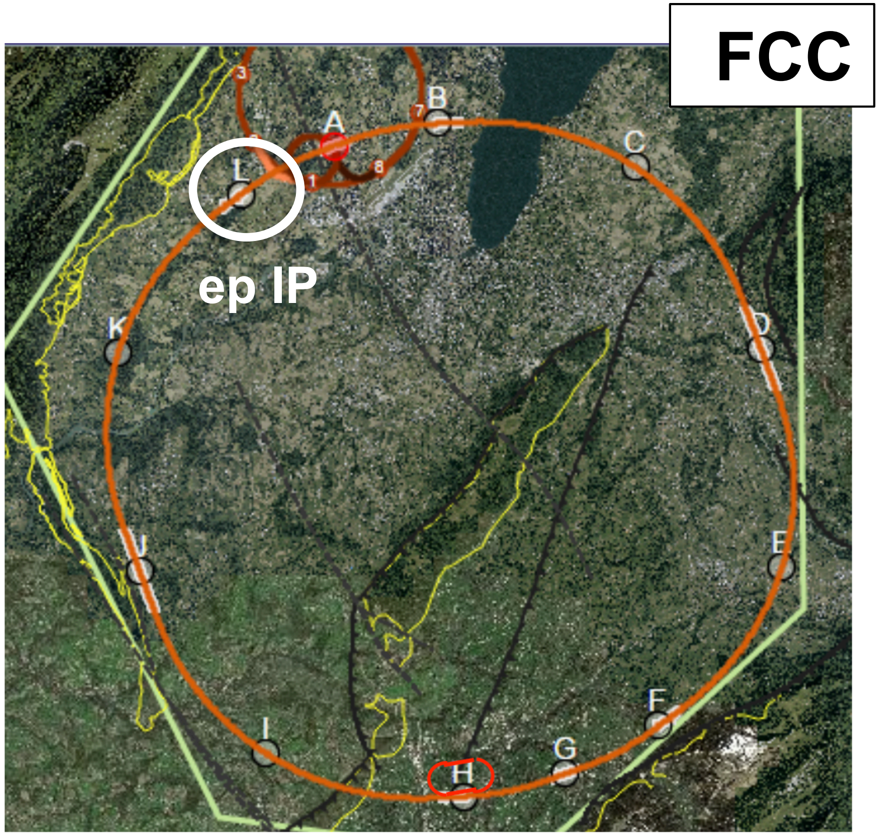
(M Klein, Rencontre du Vietnam, Sept 2017)

LHeC and **FCC-eh**

energy recovery LINAC

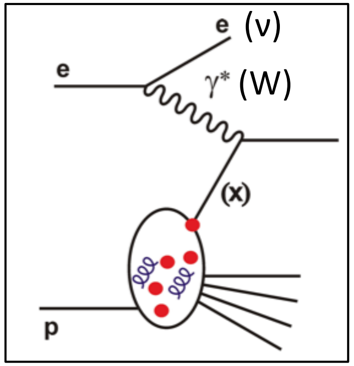
e-beam: 60 GeV

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



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

simulated LHeC/FCC-eh data



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
CC	60 (60)	50 (7)	-0.8	-1	1000
NC	60 (60)	50 (7)	$+0.8$	-1	300
CC	60 (60)	50 (7)	$+0.8$	-1	300
NC	60 (60)	50 (7)	0	$+1$	100
CC	60 (60)	50 (7)	0	$+1$	100
NC	20 (60)	7 (1)	0	-1	100
CC	20 (60)	7 (1)	0	-1	100

e–, neg. pol.

e–, pos. pol.

e+, unpol.

low energy

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

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

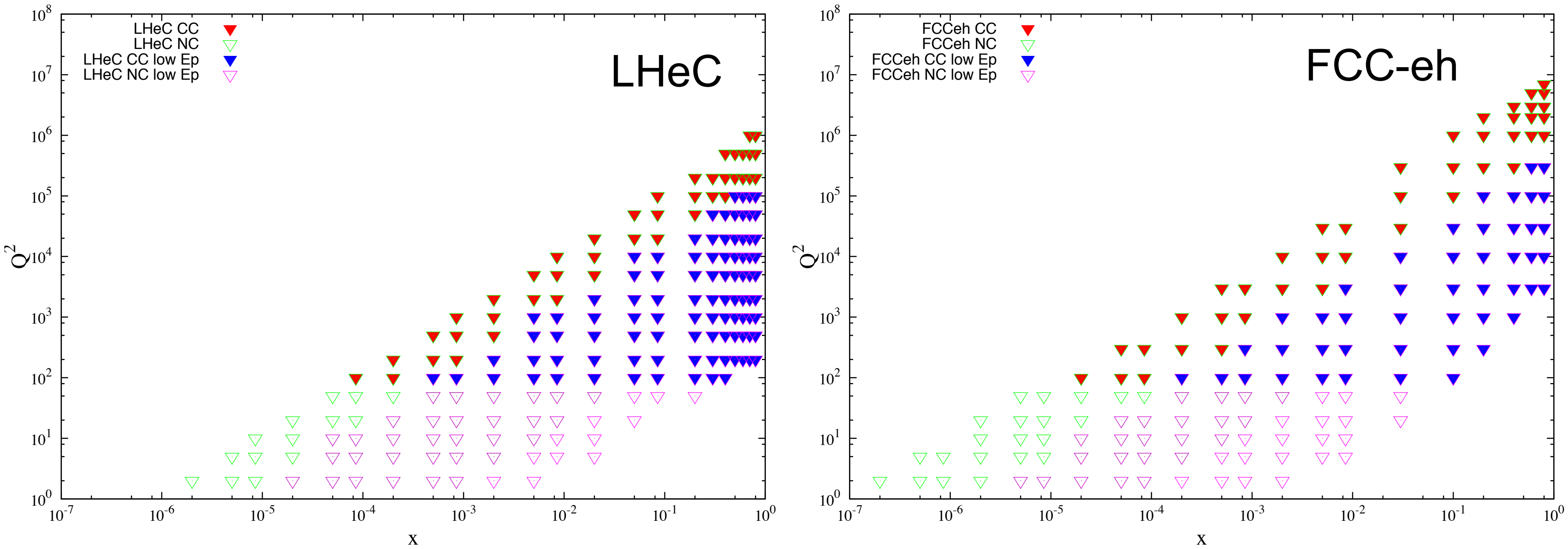
pseduo-data: M.Klein
QCD analysis: V. Radescu

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

work in progress

LHeC and FCC-eh kinematic coverage

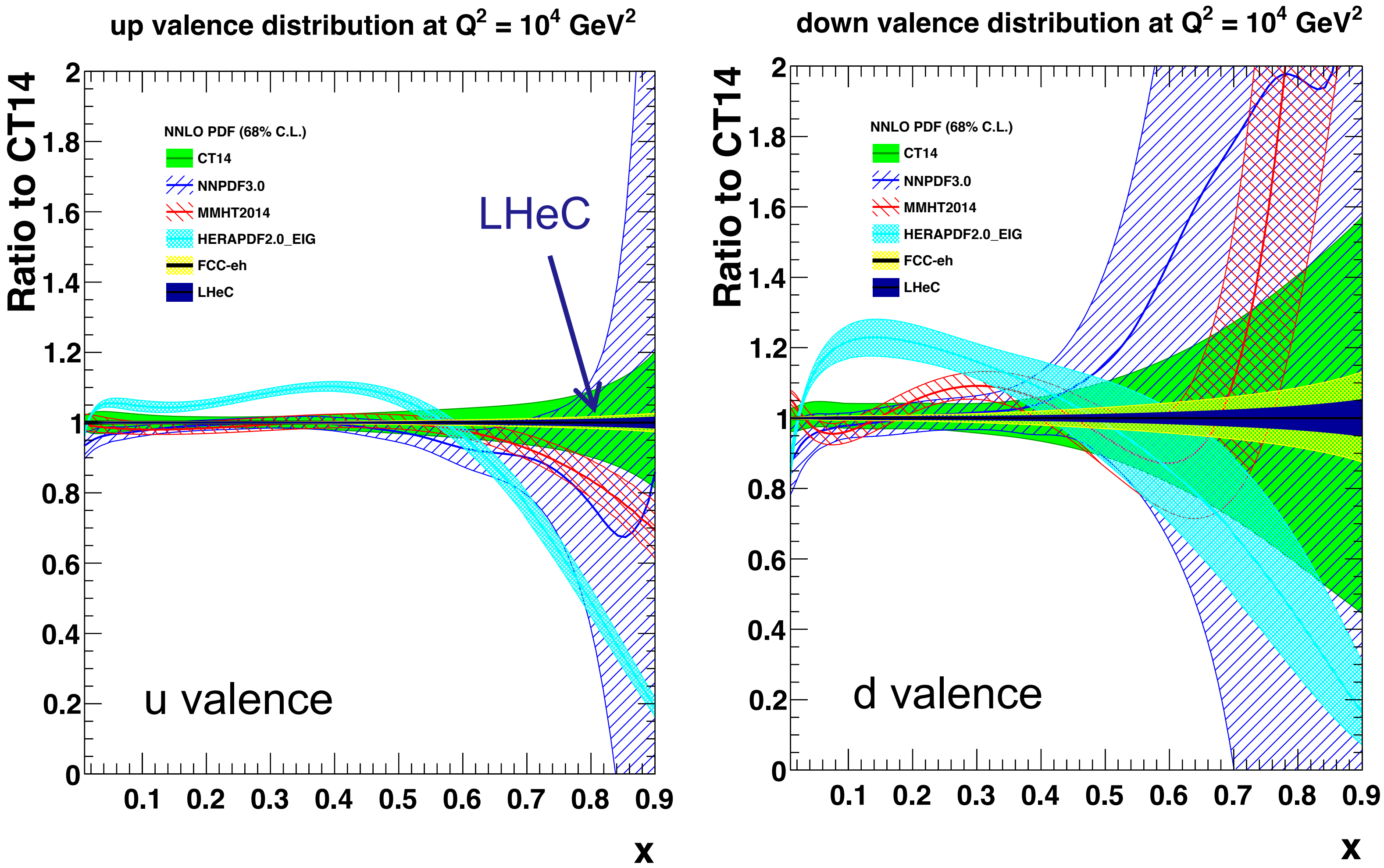
new simulated **inclusive NC** and **CC DIS data** for latest running scenarios



QCD fit parameterisation

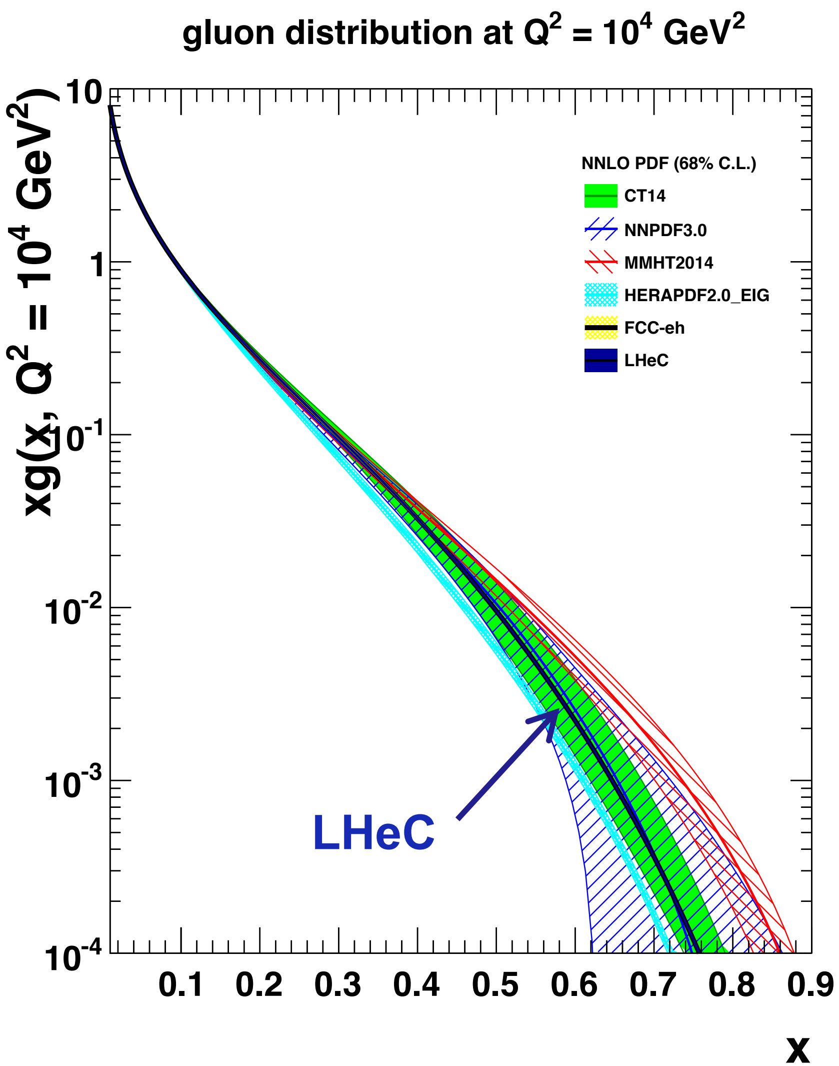
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v} x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}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

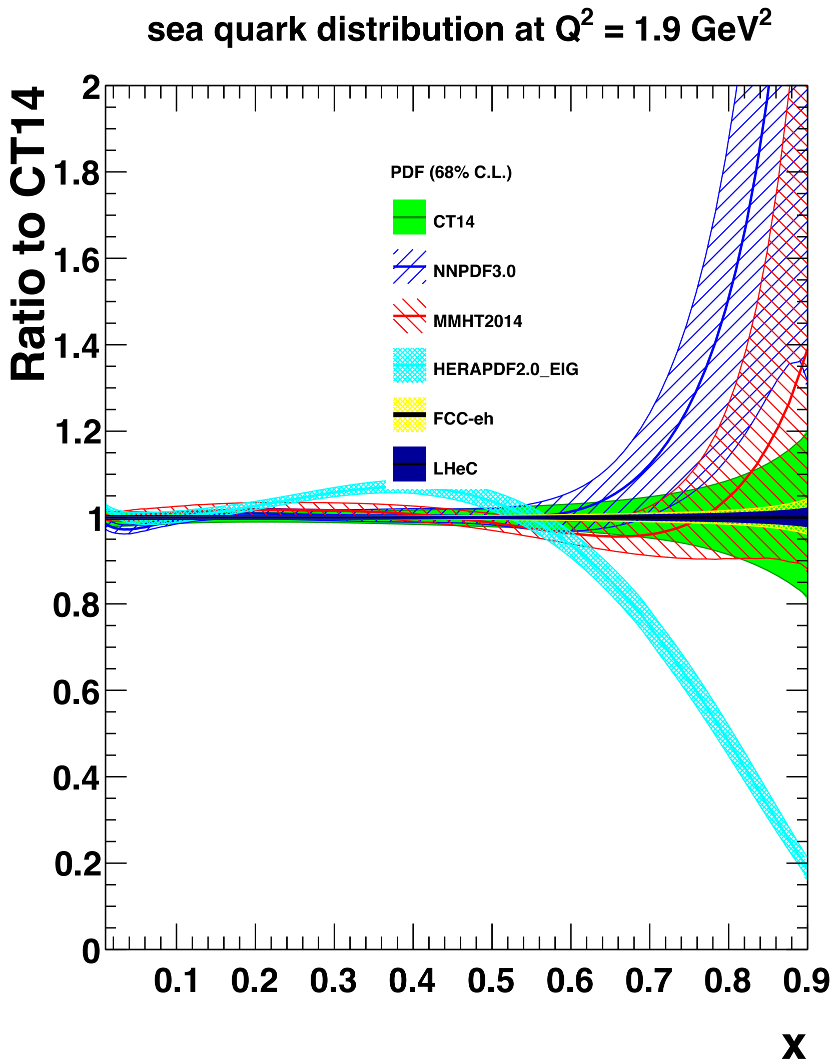
valence quarks from the LHeC



shown here at scale Q =100 GeV^2

gluon and sea at large x



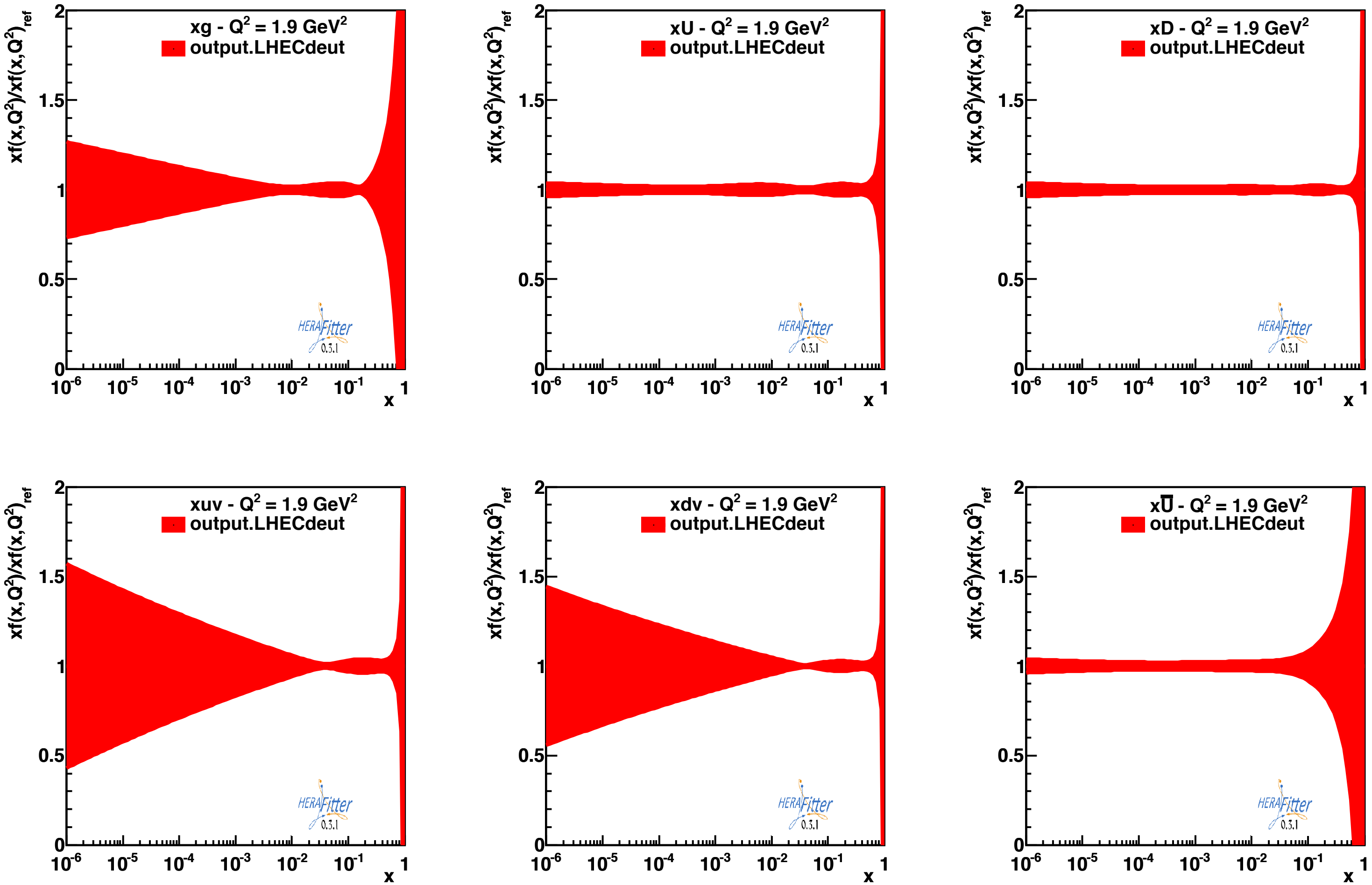


shown here at scale Q =100 GeV^2

LHeC deuteron data

older simulation

3.5TeV × 60GeV, $e^{-}p$, P= –80%, $1fb^{-1}$, NC and CC, experimental uncertainties



- symmetrised understanding of uv and dv
- future fits with ep+eD will lead to precise unfolding of u and d

strange

ATLAS coll.,
arXiv:1612.0301

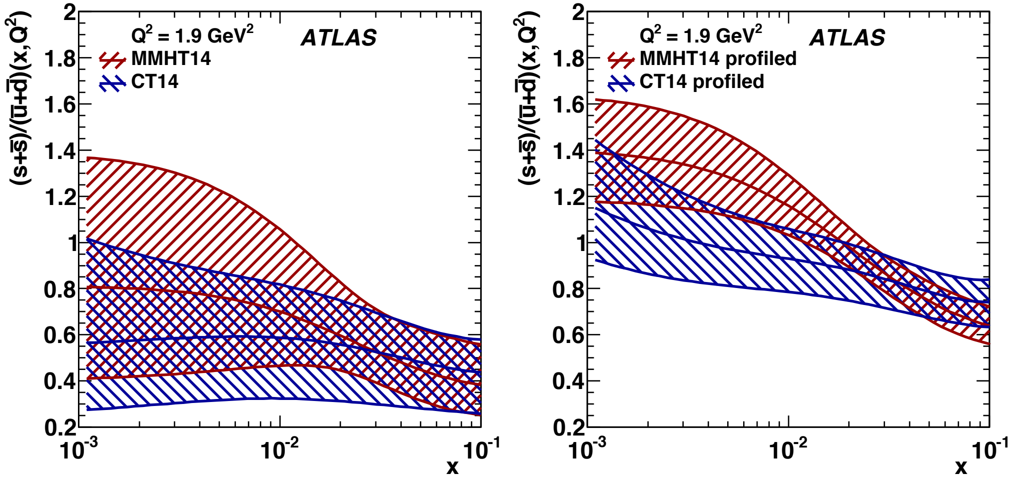


Figure 25: Ratio $R_s(x) = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$ as a function of Bjorken-x at a scale of $Q^2 = 1.9$ GeV^2 for the original MMHT14 and CT14 PDF sets (left) and for the MMHT14 and CT14 sets when profiled with the new W, Z differential cross-section data (right).

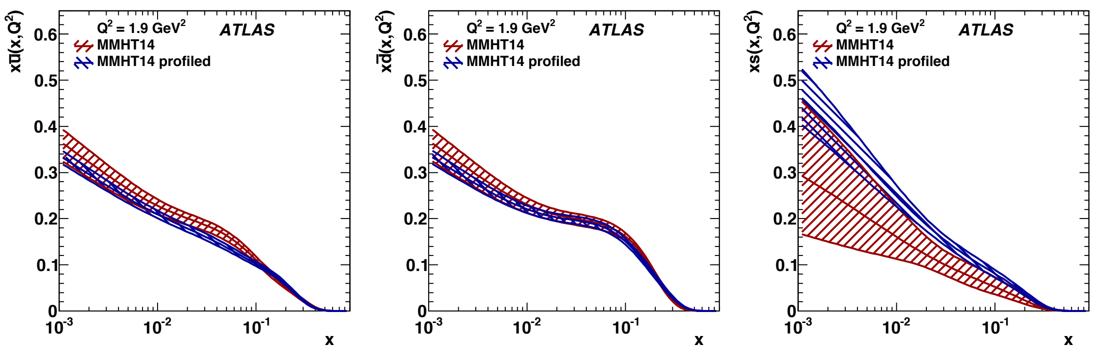
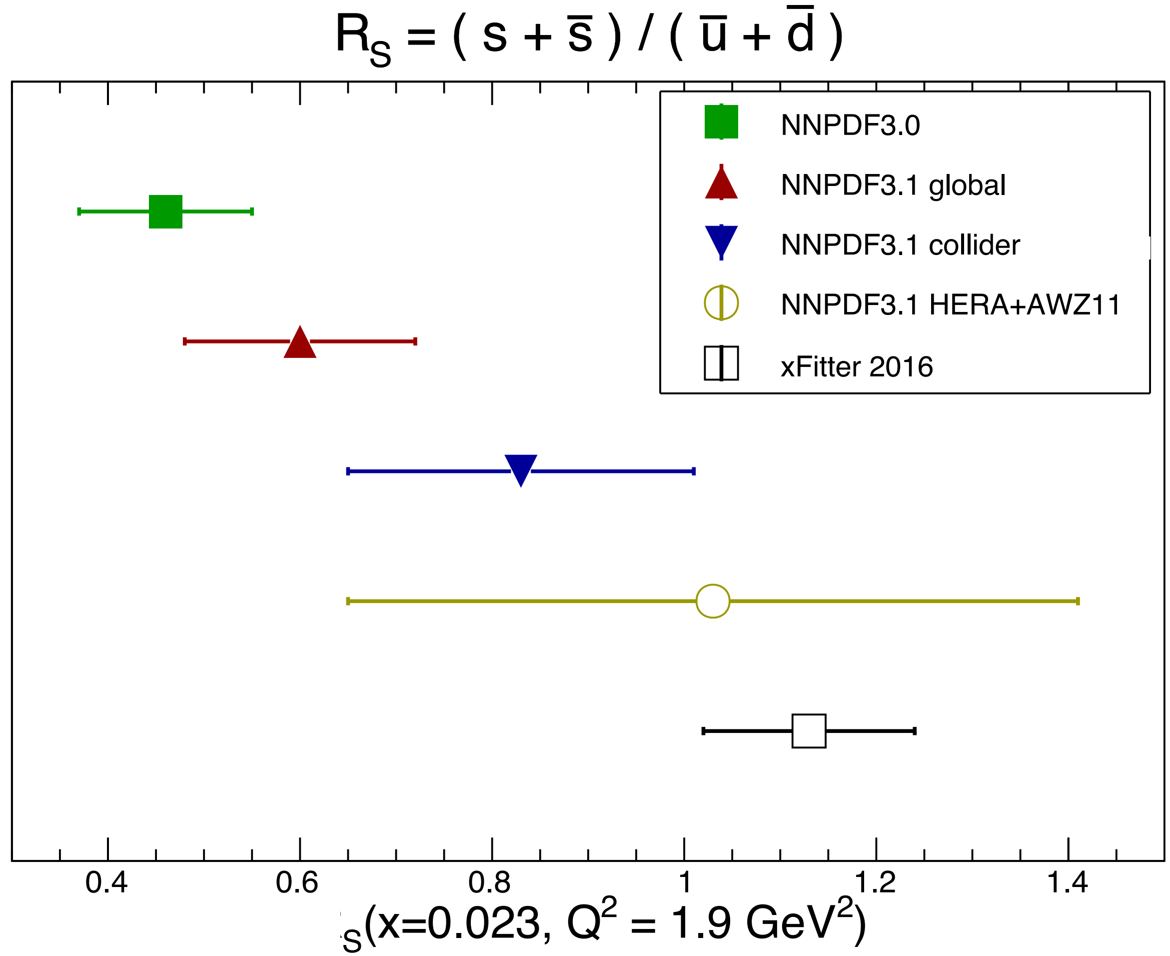


Figure 26: Distribution of $x\bar{u}$ (left), $x\bar{d}$ (middle) and xs (right) PDFs as a function of Bjorken-x at a scale of $Q^2 = 1.9$ GeV^2 for the MMHT14 PDF set before and after profiling.

strange

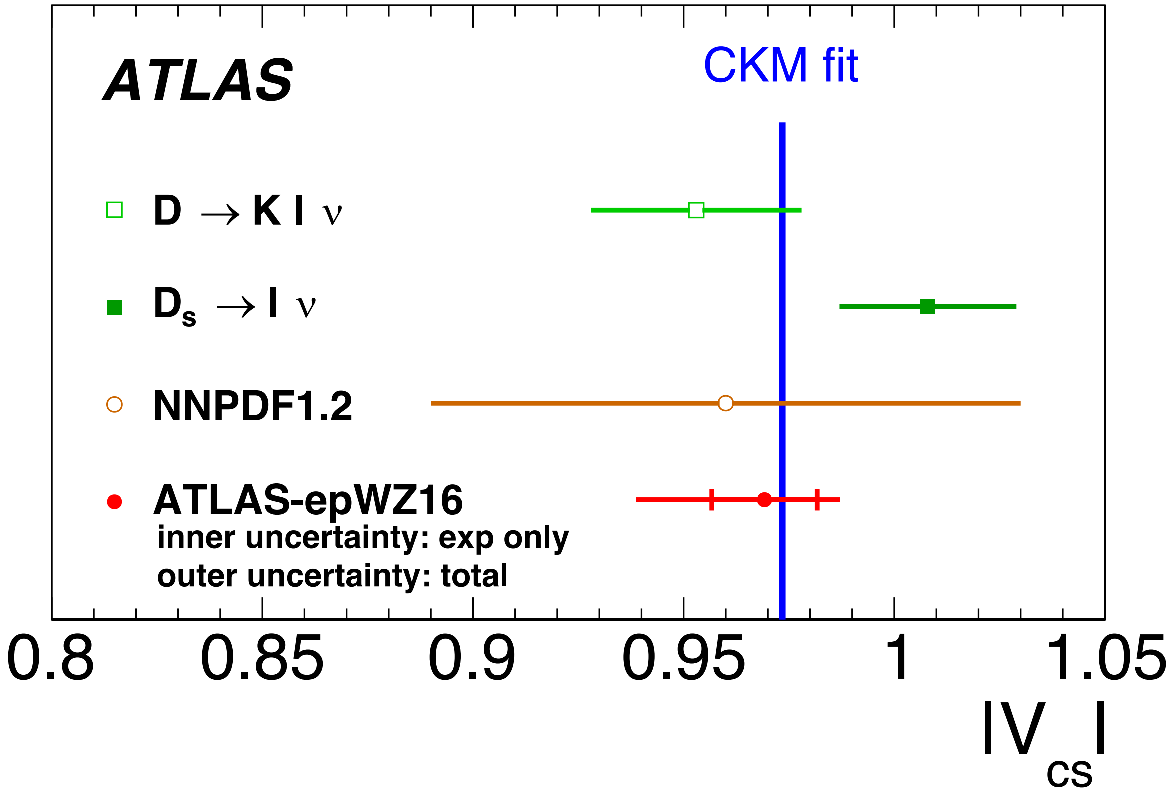
NNPDF3.1, arXiv:1706.00428



* “xFITTER16” = ATLAS arXiv:1612.0301

Vcs

ATLAS coll., arXiv:1612.03016



HERA+ATLAS ⟶ Vcs

expect much better precision from **LHeC** or **FCC-eh** (×10 or more)

FCC – x regions probed

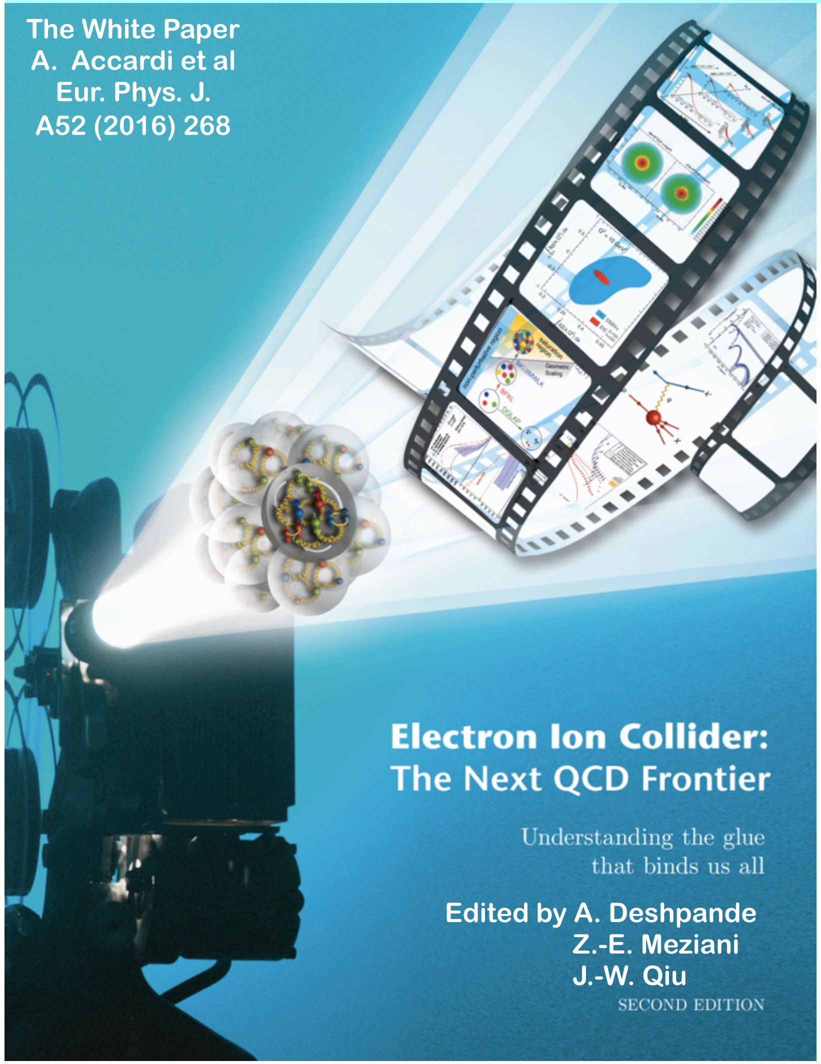
(arXiv:1607.01831)

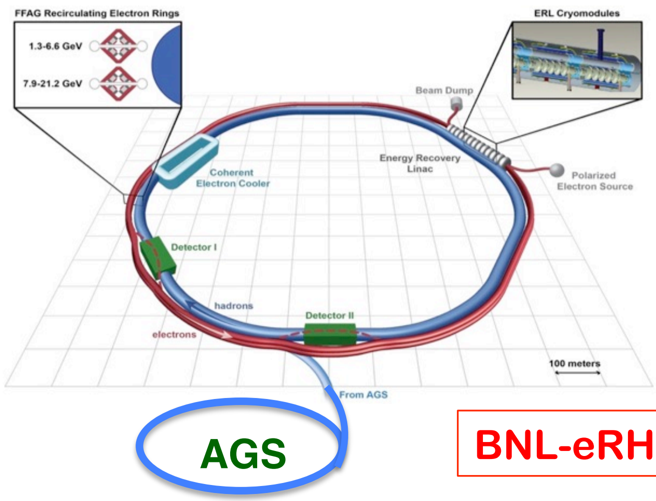
Process	M_X	x_{min}		
		$y = 0$	$\|y\| = 2$	$\|y\| = 4$
Soft QCD Charm pair production Low-mass Drell-Yan	1 (10) GeV	10^{-5} (10^{-4})	$1.4 \cdot 10^{-6}$ $(1.4 \cdot 10^{-5})$	$1.8 \cdot 10^{-7}$ $(1.8 \cdot 10^{-6})$
W and Z production Top pair production Inclusive Higgs	80 (400) GeV	$8 \cdot 10^{-4}$ $(4 \cdot 10^{-3})$	$1.1 \cdot 10^{-4}$ $(5.4 \cdot 10^{-4})$	$1.5 \cdot 10^{-5}$ $(7.3 \cdot 10^{-5})$
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, $x_{\text{min}} = (M_X/\sqrt{s})\exp(-|y|)$, for central ($y = 0$), intermediate ($|y| = 2$) and forward ($|y| = 4$) rapidities.

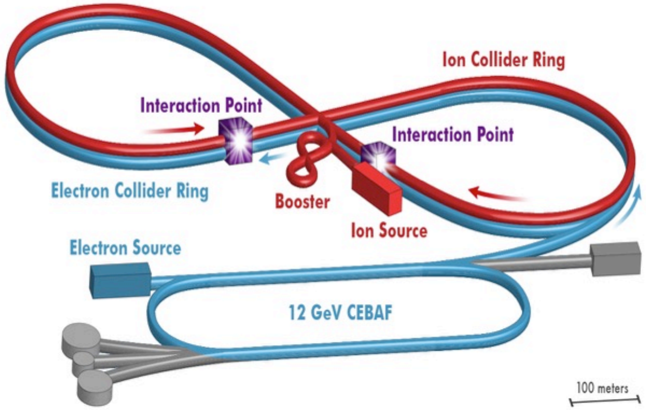
EIC

US EIC – Two Options of Realization



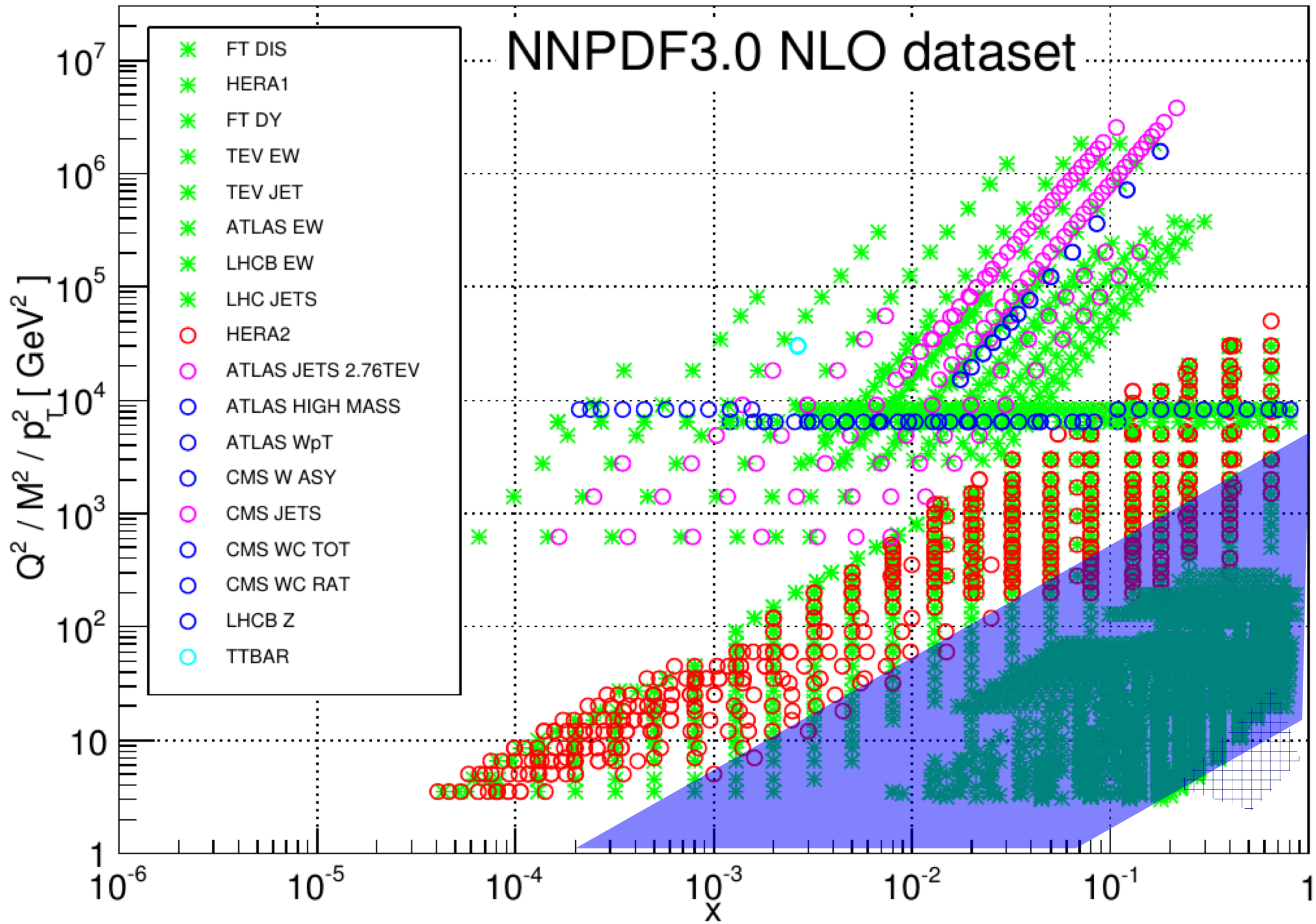


BNL-eRHIC



JLab-JLEIC

EIC kinematic coverage

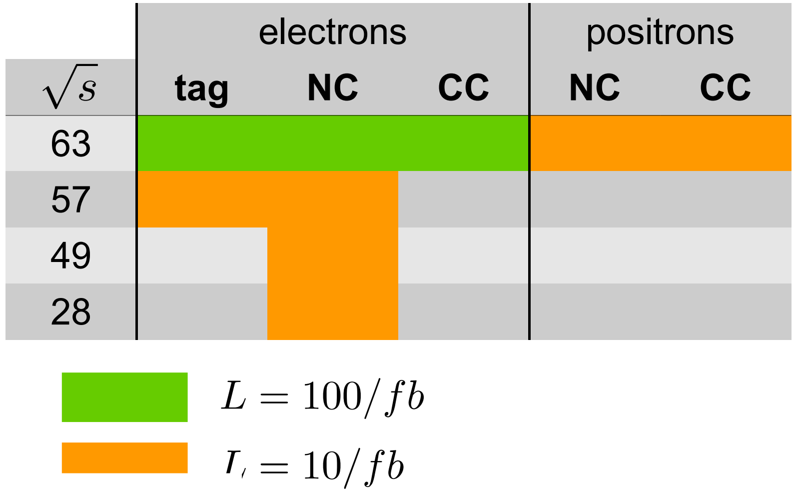


simulated EIC data

Projected data (so far)

This exercise: projections in 0.01 < x < 0.9 bins for:

- ✓ Cross sections on proton target: *(Y. Furletova)*
  - NC and CC; electrons and positrons
- ✓ F_2^n from deuterium with tagged proton spectator *(K. Park)*
- ✓ Max energy: 10x100 GeV^2 at 100/fb, energy scan at 10/fb



Finally,

- bootstrap projected data around CJ15 calculations
- fit along rest of CJ15 data sets
- examine impact on u, d, g

(Impact of deuteron target DIS was presented in Argonne, 2016)

Cuts

W^2 > 3.5 GeV^2 (standard CJ15 cut)
Q^2 > 2 GeV2 (NC) ; 100 GeV^2 (CC)
0.05 < y < 0.95

Systematics

Normalization: 1%
NC: 1.5% y>0.8 , 0.5% elsewhere
CC: 5% y>0.8 or Q^2<125 , 2% elsew.
Tag: 5% x>0.3 , 2% elsewhere

A. Accardi, EIC users group meeting, Trieste, July 2017

work in progress

gluon at large x

EIC dijet data for ep (top) and eA (bottom)

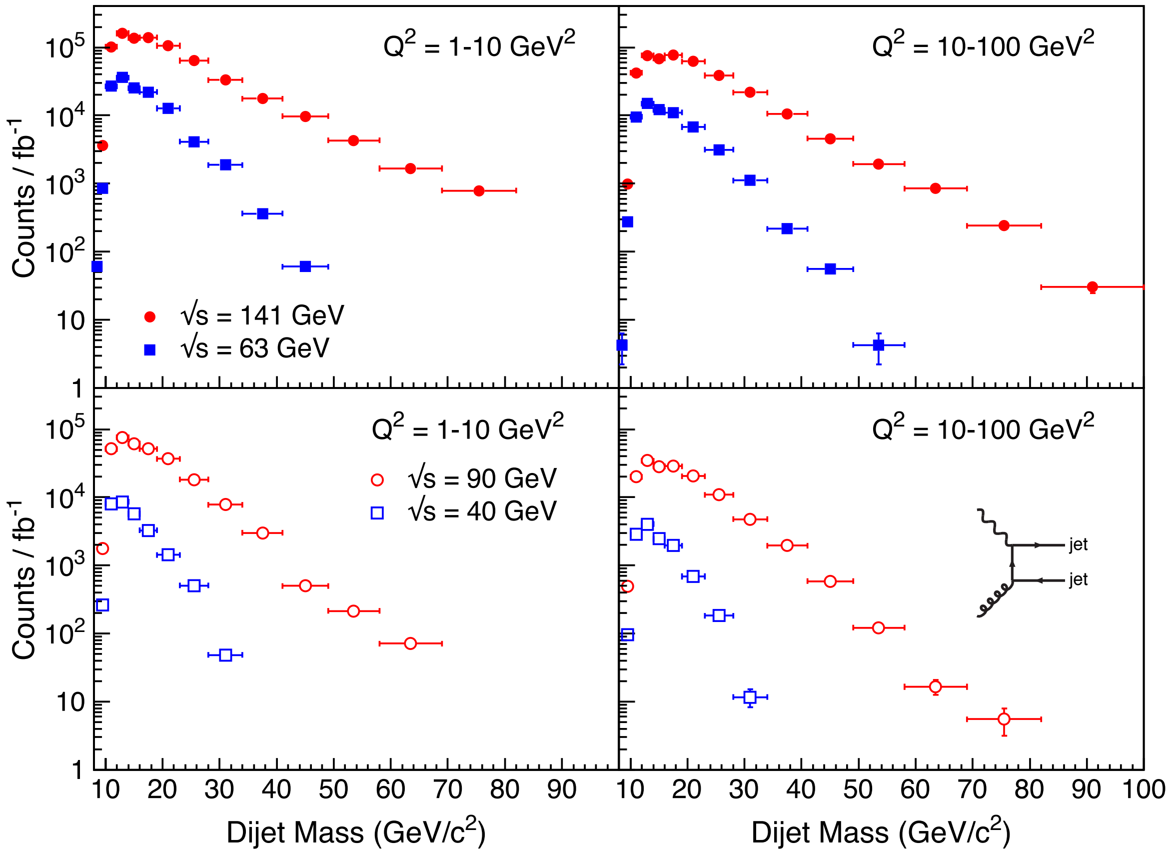
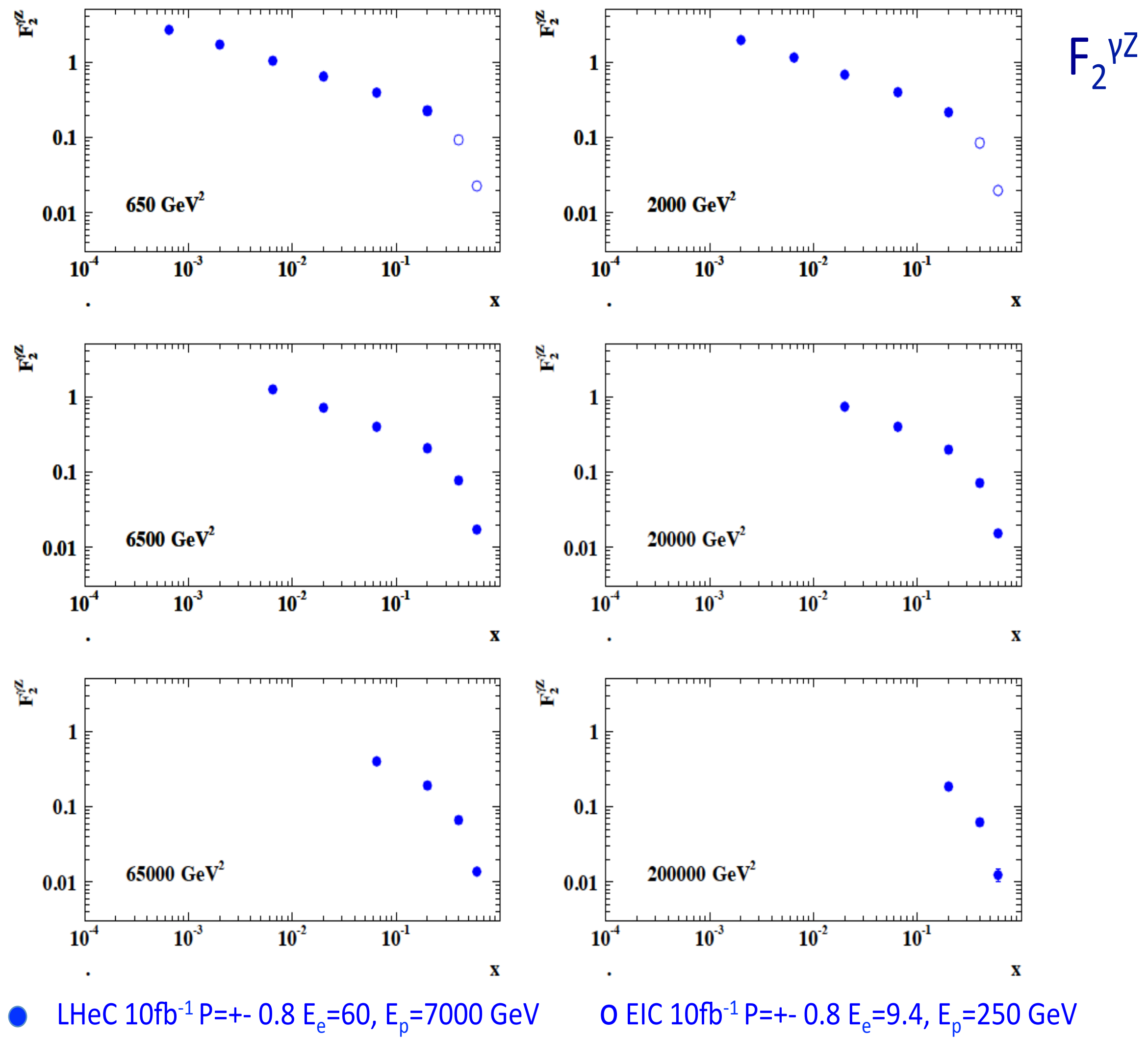


Figure 34: Dijet yields as a function of invariant mass scaled to a luminosity of 1 fb^{-1} for $Q^2 = 1 - 10$ GeV^2 (left column) and $Q^2 = 10 - 100$ GeV^2 (right column). The top row compares proposed e+p center-of-mass energies while the bottom row compares e+A energies.

arXiv:1708.01527

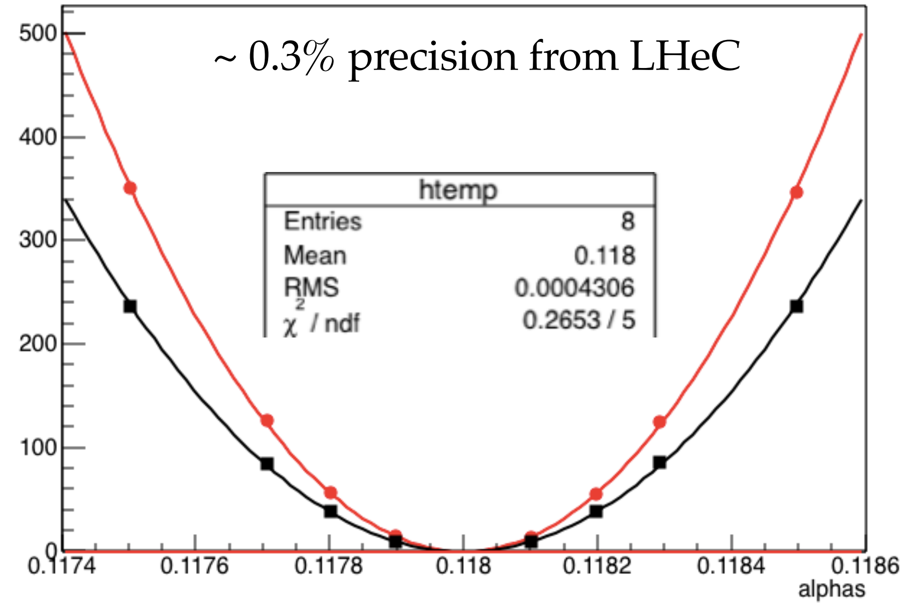
PV structure function $F_2^{\gamma Z}$



(M. Klein, POETIC7)

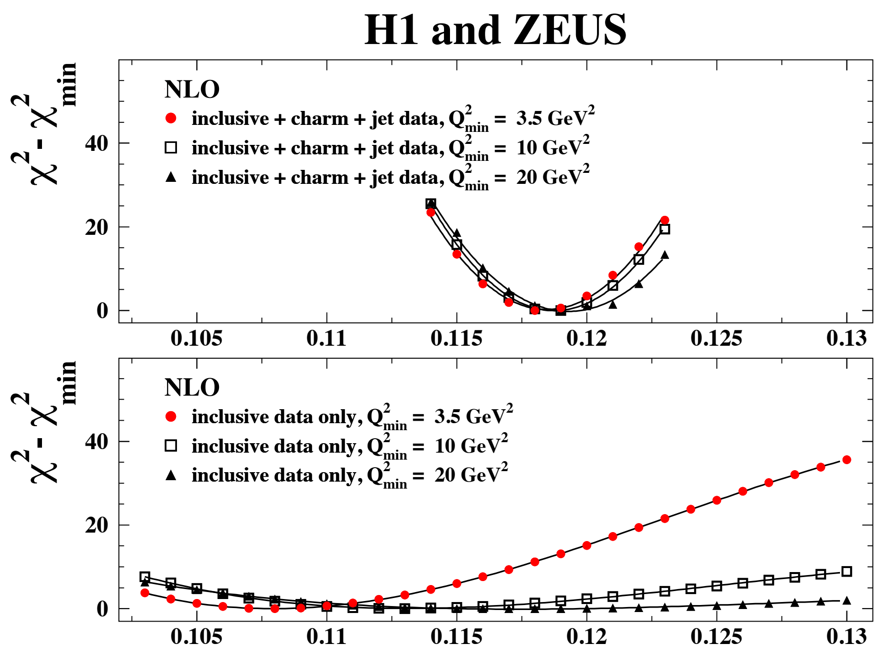
strong coupling from LHeC

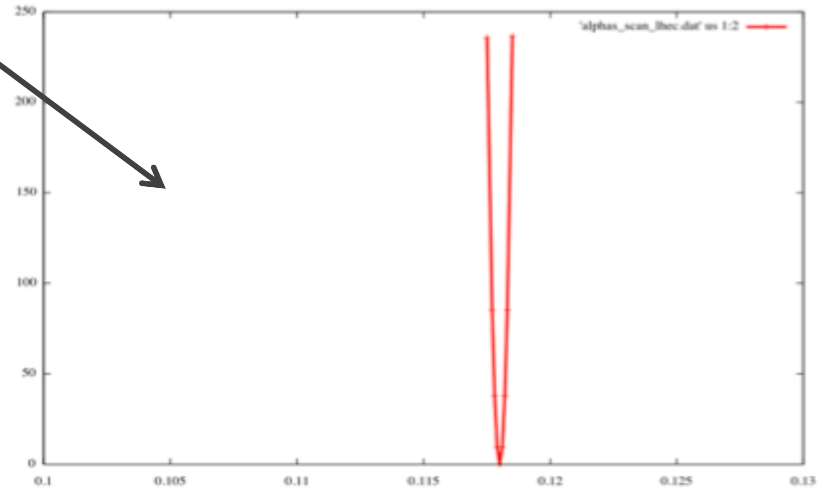
PDF+αs fit using **LHeC** simulated data



(M Klein, V Radescu)

NC,CC
NC,CC+F2c



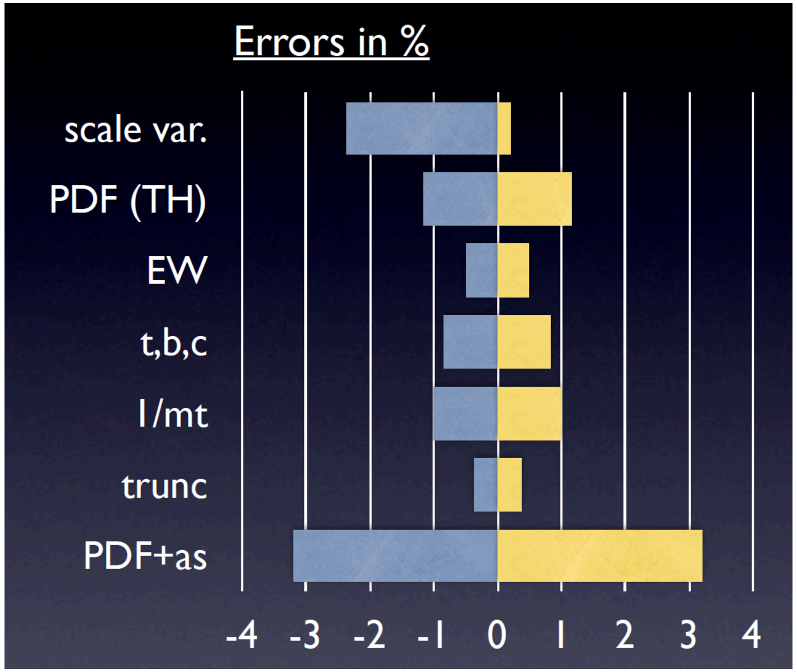


updated studies (also for **FCC-eh**) underway

could resolve a > 30-year old puzzle:

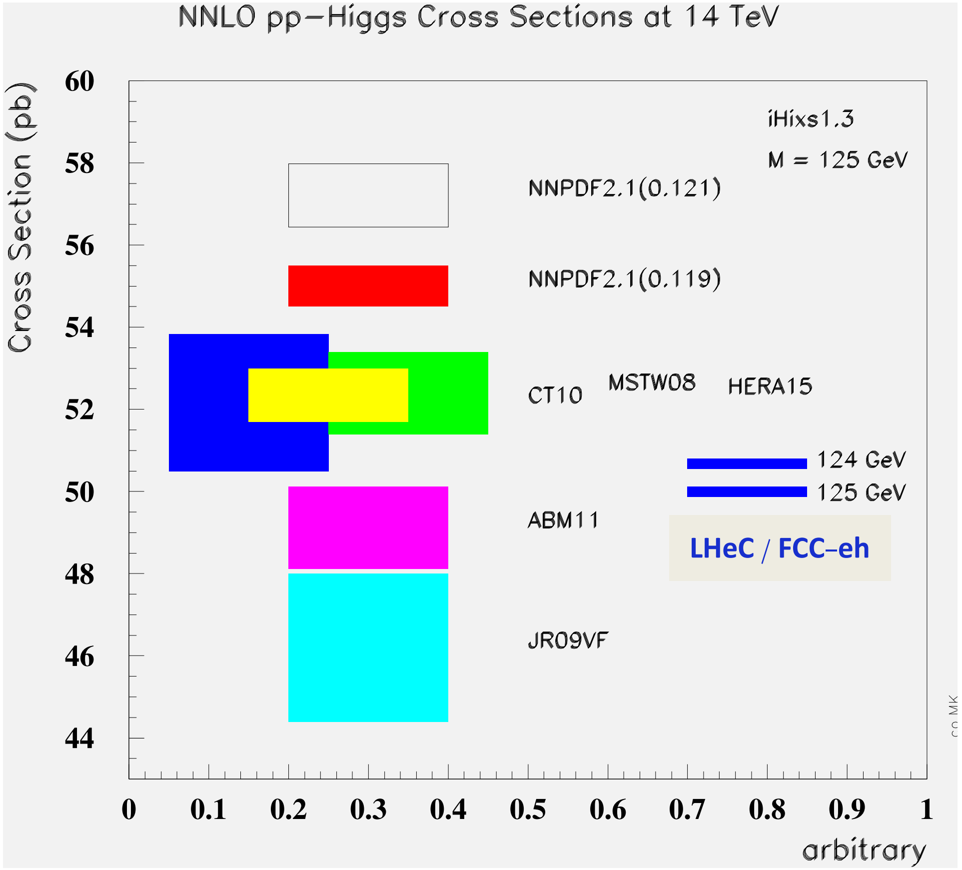
αs consistent in inclusive DIS, versus jets?

PDFs, α_s and Higgs



inclusive H production uncertainties

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



PDF+α_s dominates Higgs cross section uncertainty

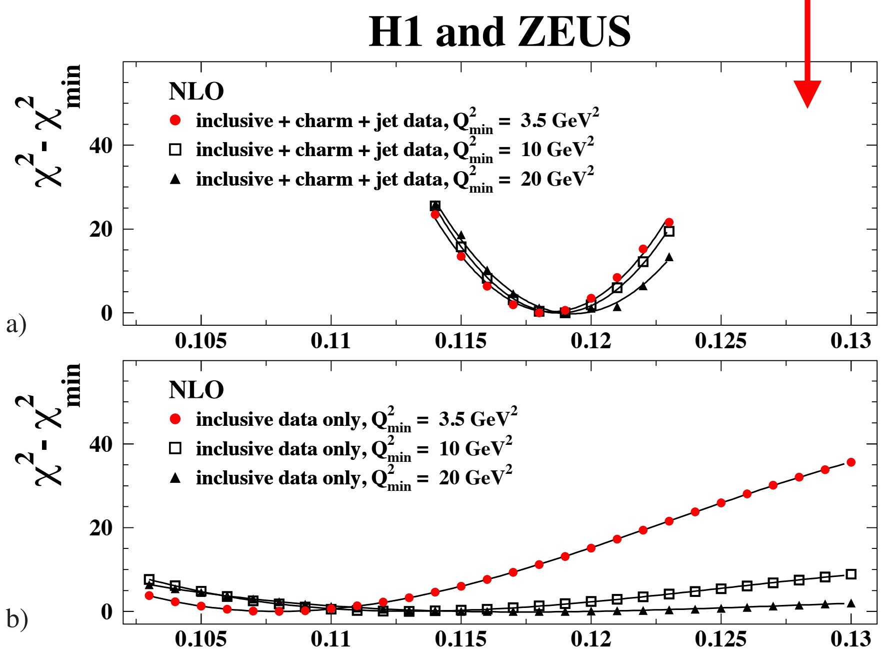
LHeC gives extraordinarily precise PDFs and can expect α_s to per mille experimental precision

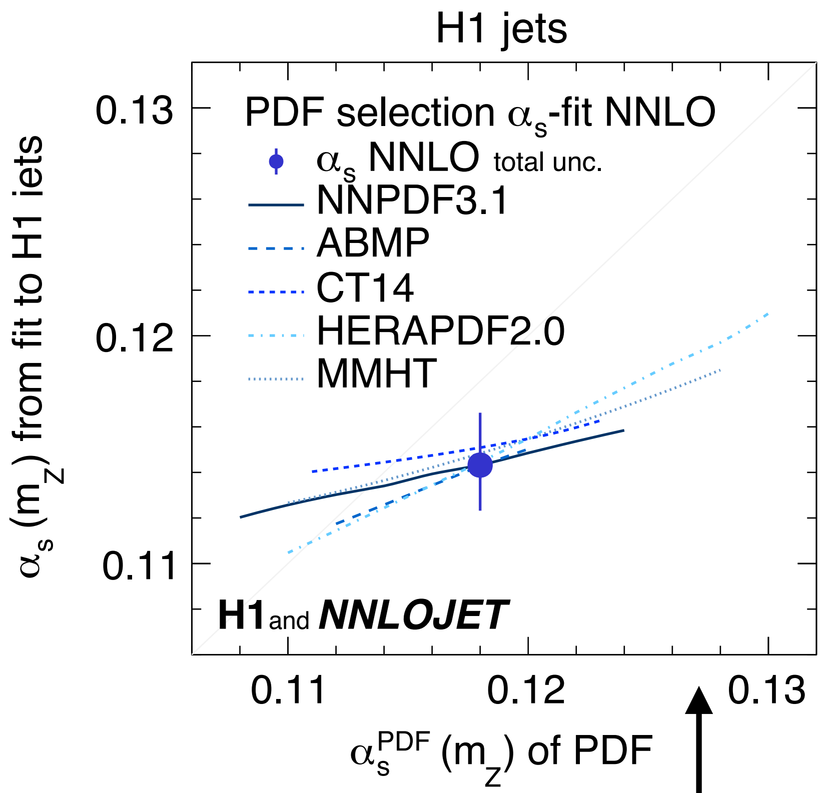
LHeC is also in itself a precision Higgs facility

strong coupling from jet data in ep

ep jet data can provide additional constraints

cf. inclusive DIS data alone



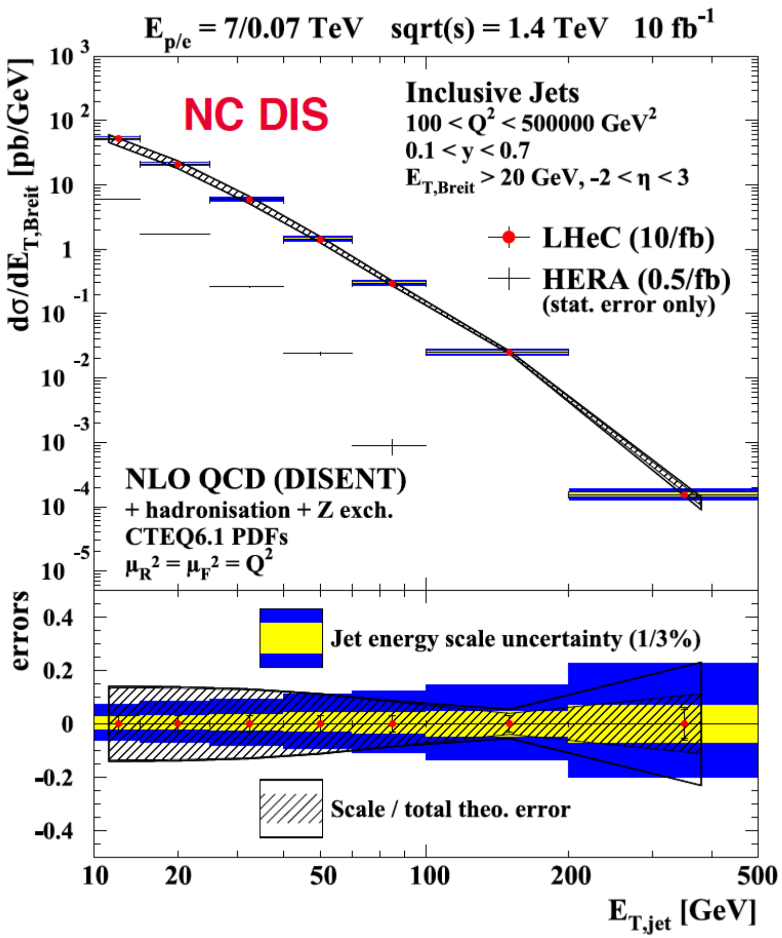


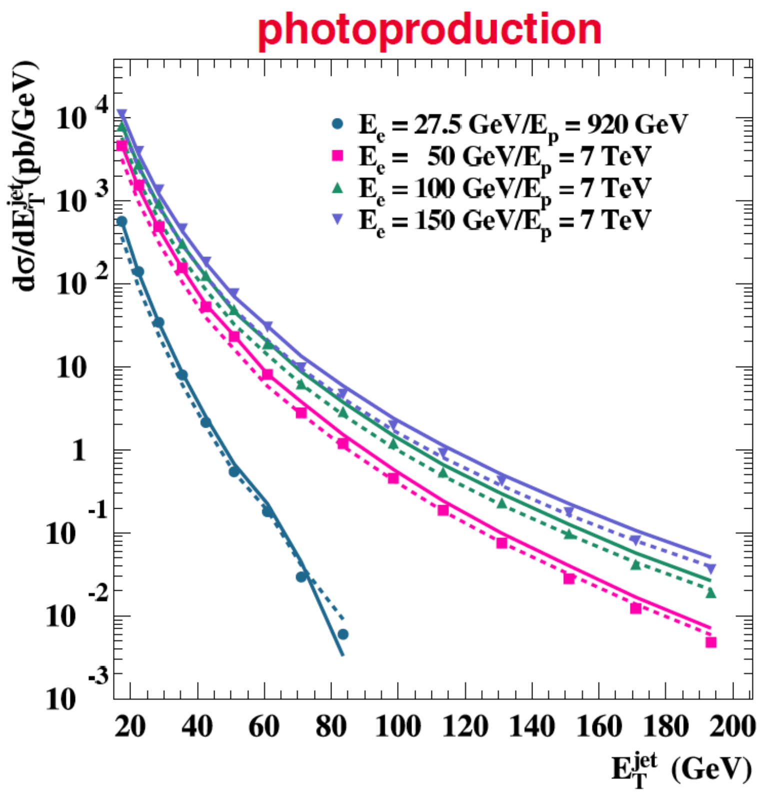
strong coupling from LHeC and FCC-he simulated **DIS jet data** to come…

NNLO fit now also possible

(H1 Coll., arXiv:1709.07251)

LHeC jet data





(plots from LHeC CDR – illustrative)

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

strong coupling α_s from FCC-ee

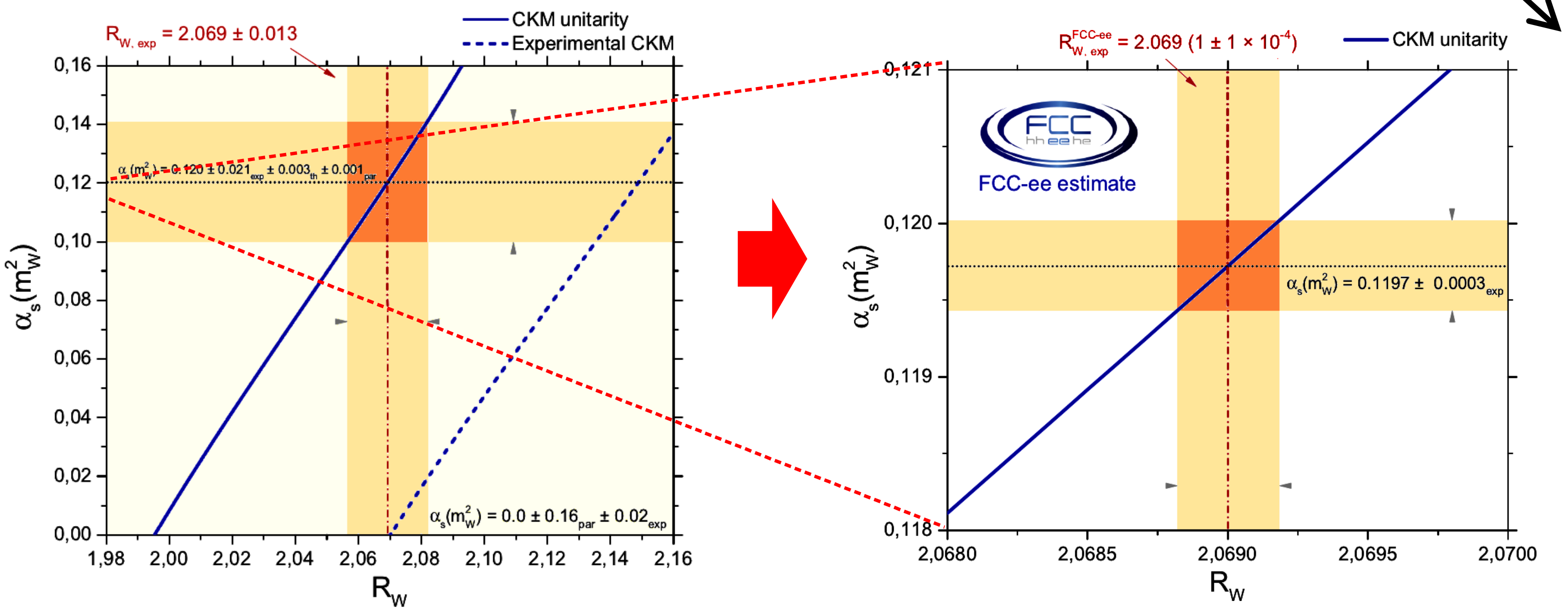
FCC-ee: comprehensive programme for α_s; many complementary processes
(event shapes, τ decays, FFs, F_2^γ, jets in e^+e^-, W and Z decays)

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 = Γ_{had}/Γ_l**

Z: LEP: $\alpha_s(M_Z)=0.1196\pm0.0030$ ($\pm2.5\%$) → $\delta\alpha_s < 0.2\%$ (**FCC-ee**) ⟶ stats (×10^5 LEP)
improved $\sin^2\theta_{eff}$, MW, Mt

W: LEP: $\alpha_s(M_Z)=0.117\pm0.040$ ($\pm35\%$) → $\delta\alpha_s < 0.3\%$ (**FCC-ee**) ↘ stats (×10^4 LEP)
improved δV_{cs}



see also talk by
D. d'Enterria
in WG4

D. d'Enterria et al, arXiv:1603.06501