PDFs and QCD with the LHeC

and BSM prospects for LHeC and FCC-he

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for the LHeC and FCC-eh study groups

DIS 2015, Dallas, Texas, April 2015

with special thanks to: George Azuelos, Monica D'Onofrio, Max Klein, Voica Radescu

some introductory words

now entering an exciting new era in high energy physics

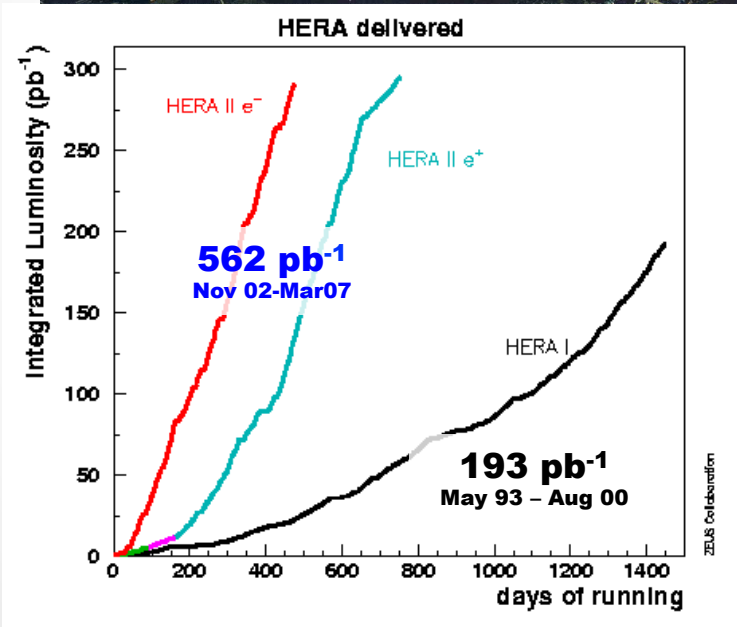
- LHC@13TeV about to begin – new opportunities in **searches** and **precision physics**
- higher luminosity and energy machines on the horizon, or being explored
  - HL-LHC: what can be learnt from 300 – 3000 fb^{-1} ?
  - energy: HE-LHC, FCC@100TeV, …
- **new physics discovery** and full **understanding of known physics** at energy frontier, relies on QCD at high orders and precise knowledge of **proton structure** (PDFs)
- current proton PDF uncertainties: limit searches for new, heavy particles; dominate theory uncertainty on Higgs production; limit precision of MW, αs, EW parameters

priorities for next generation: Higgs exploitation and BSM searches (and characterisation)
limitations on current knowledge **will restrict** physics extracted from current and future colliders

LHeC: future ep (and eA) collider proposed to run concurrently with HL-LHC – **precise extraction of all PDFs**, and wealth of physics opportunities in its own right (BSM, Higgs, top, small x, … – see also talks of Uta Klein, Anna Stasto, Christian Schwanenberger)

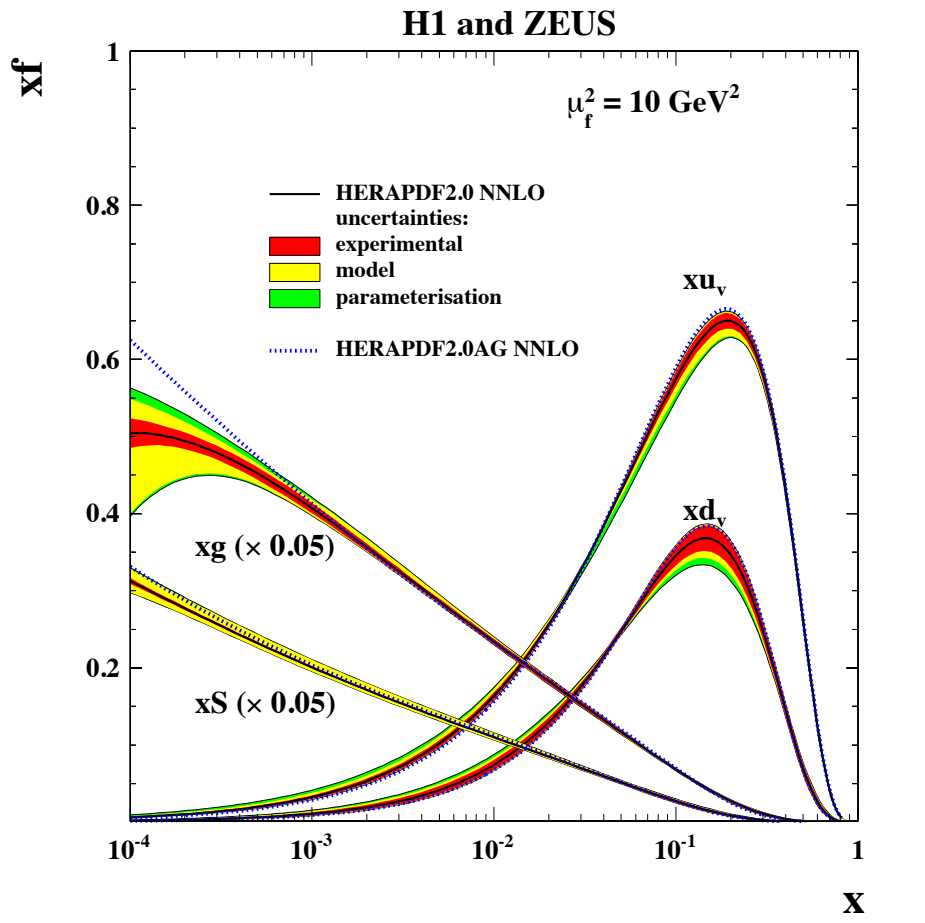
FCC-eh: further future ep collider; integrated with FCC-hh

DIS ep collider



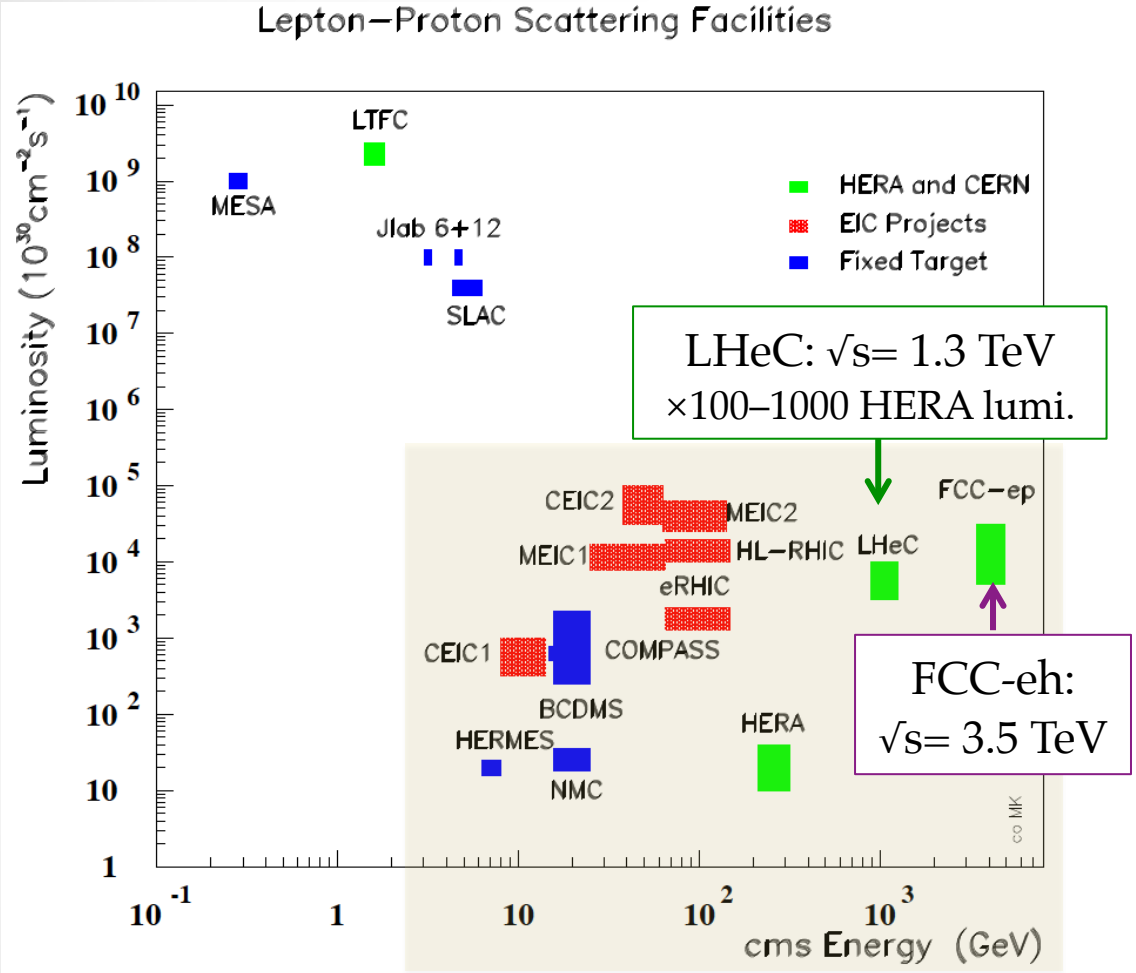
HERA: established detailed proton structure (PDFs)
– including strong rise of gluons at low x

quantitative Tevatron and LHC results of today
would not be possible without HERA

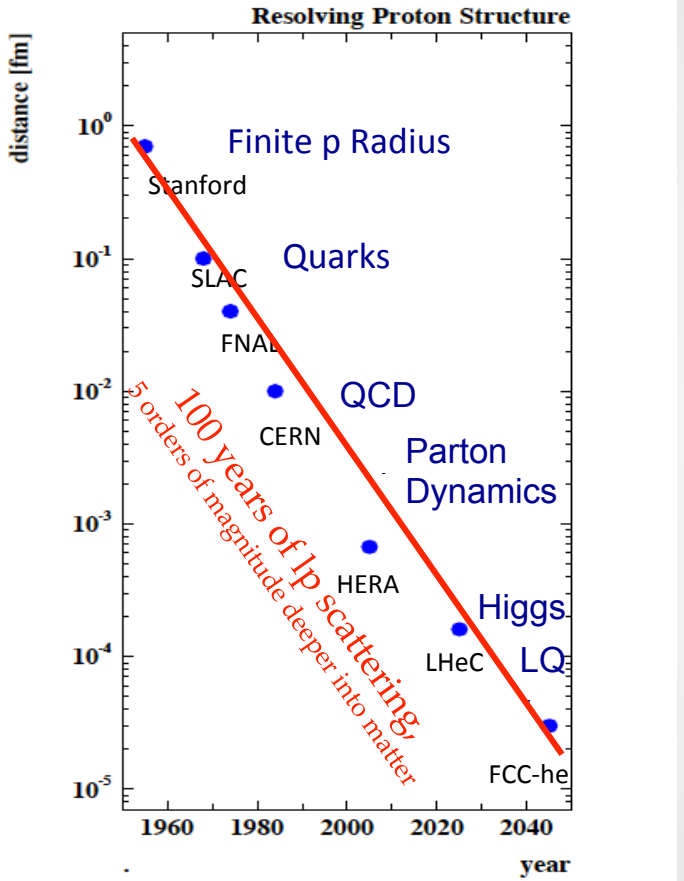


… and much more: α_s; jets; γ structure; diffraction (10%); c, b; BSM limits (leptoquarks), …

lepton-proton facilities



HERA–LHeC–FCC-eh:
finest microscopes, resolution as 1/Q

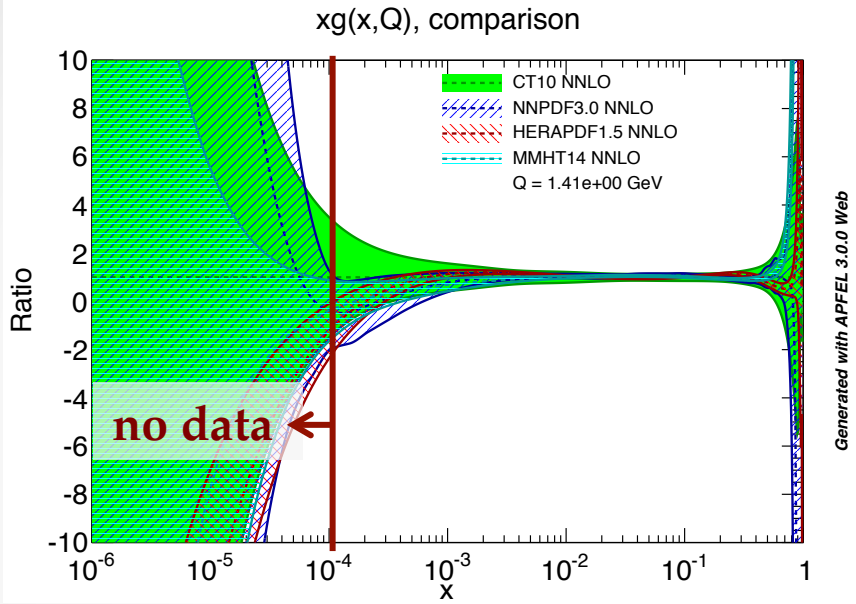


LHC (and other future machines eg. FCC-pp) is/will be main discovery machine

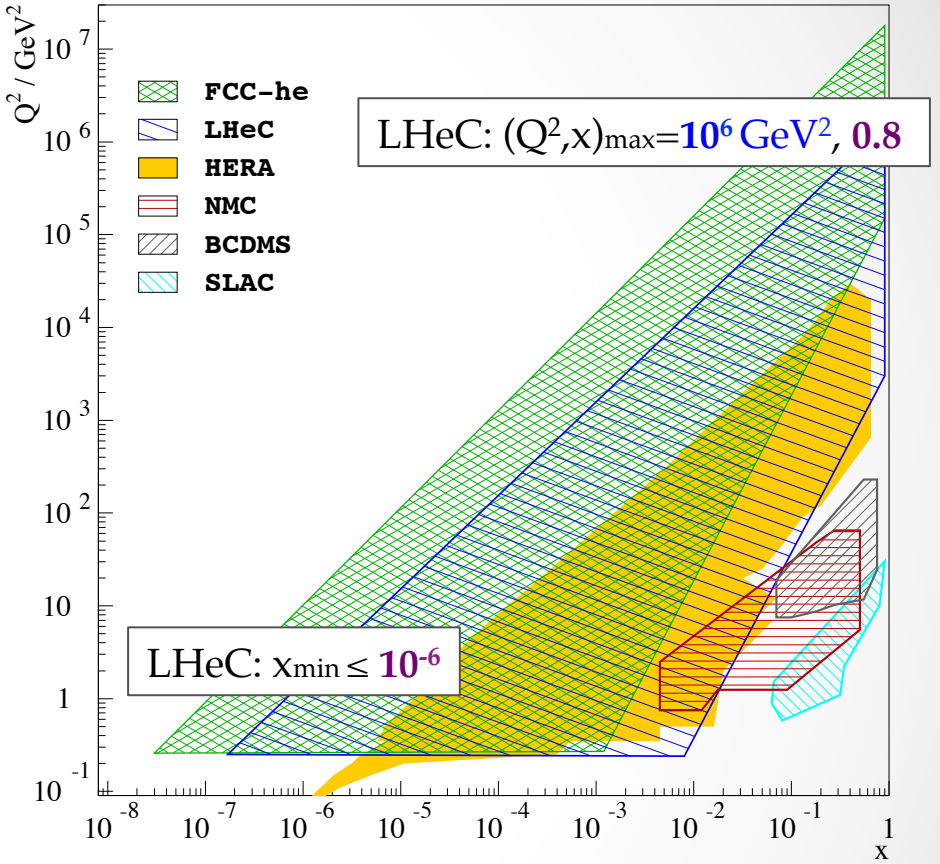
LHeC not a competitor to these; complementary; synchronous with HL-LHC; transforms them into high precision facilities

… and wealth of other physics in its own right

improving PDFs with the LHeC



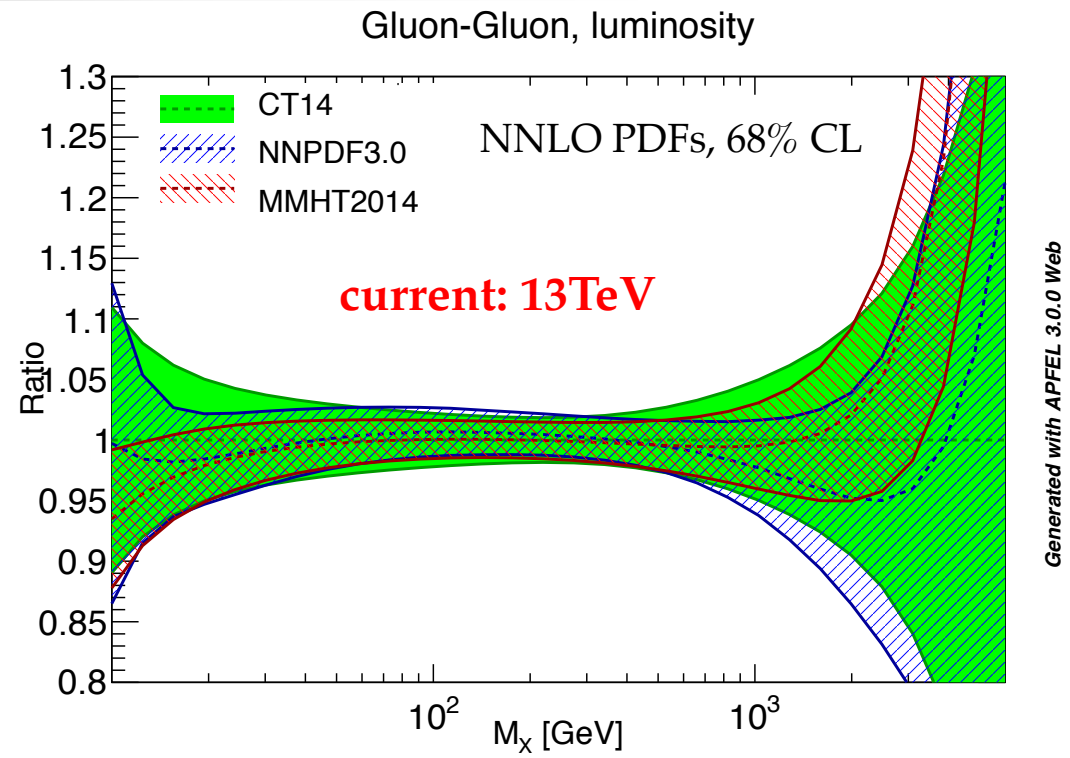
- **low-x**: no current data to constrain $x \leq 10^{-4}$; rely purely on extrapolation
  onset of BFKL effects, non-linear equations, gluon saturation?
- **mid-x**: need higher precision for Higgs
- **high-x**: very poorly constrained – limits searches for new, heavy particles

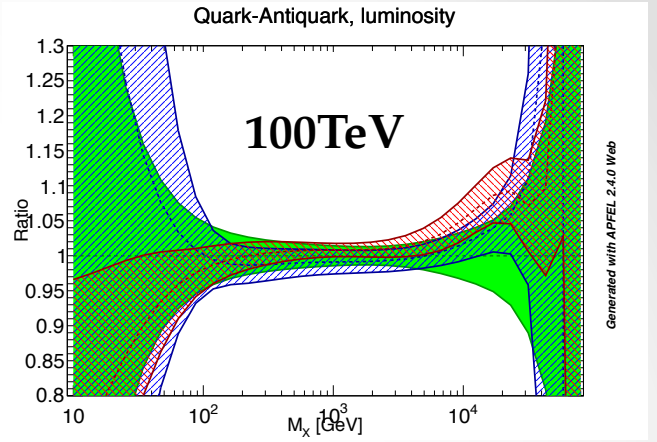


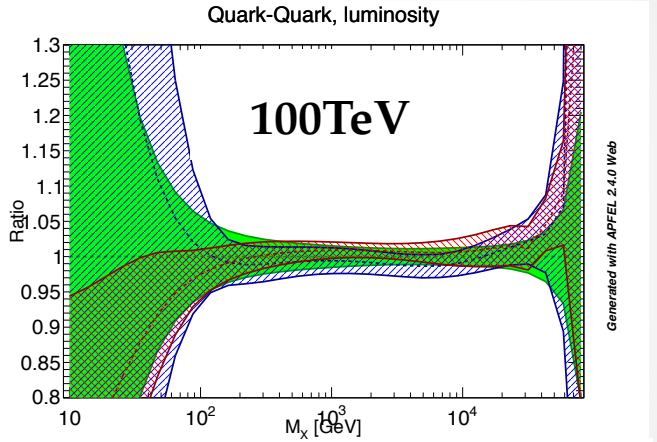
LHeC: access to much smaller x, larger Q^2 (1000× HERA luminosity); operation with ep, eD, eA

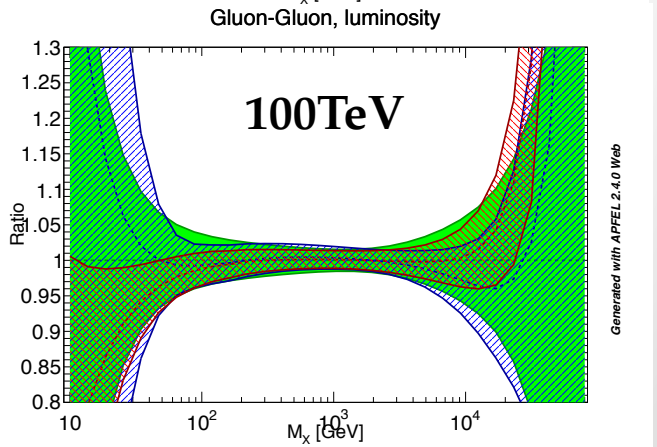
and FCC-he extends even further

proton PDFs, today





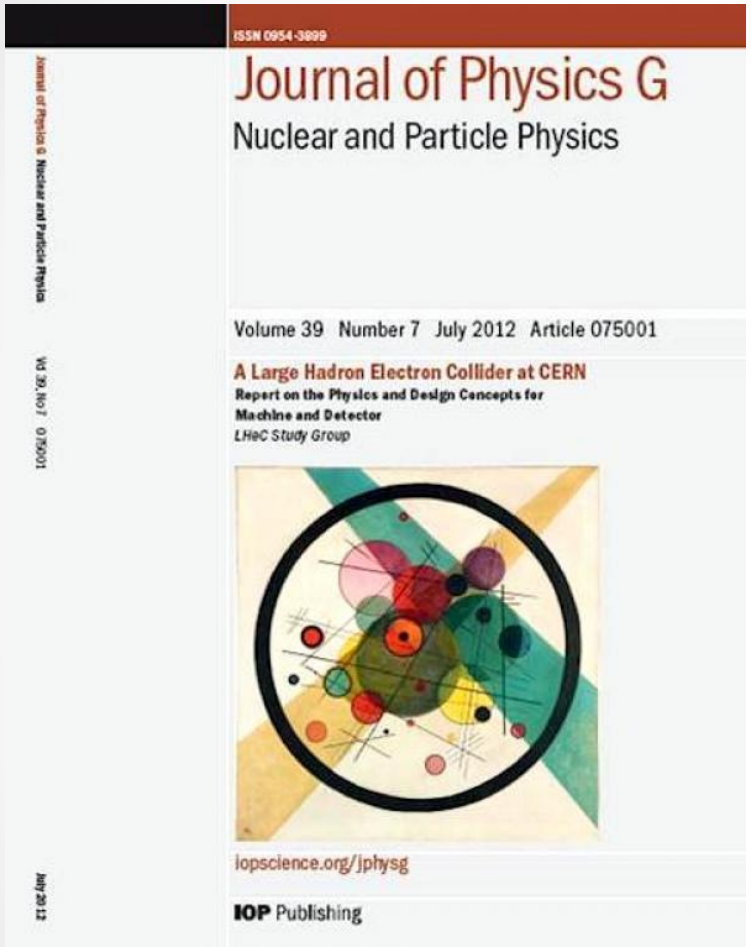




- **need to know PDFs much better than today, for:** nucleon structure; q-g dynamics; Higgs; BSM searches; future colliders, FCC-hh; and development of QCD
- LHC will provide further constraints, but cannot resolve precisely (shown are latest global PDFs, also including available LHC data)

… many thanks to Joey Huston

LHeC program



http://cern.ch/lhec

LHeC Study Group

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about 200 experimentalists and theorists from 76 institutes

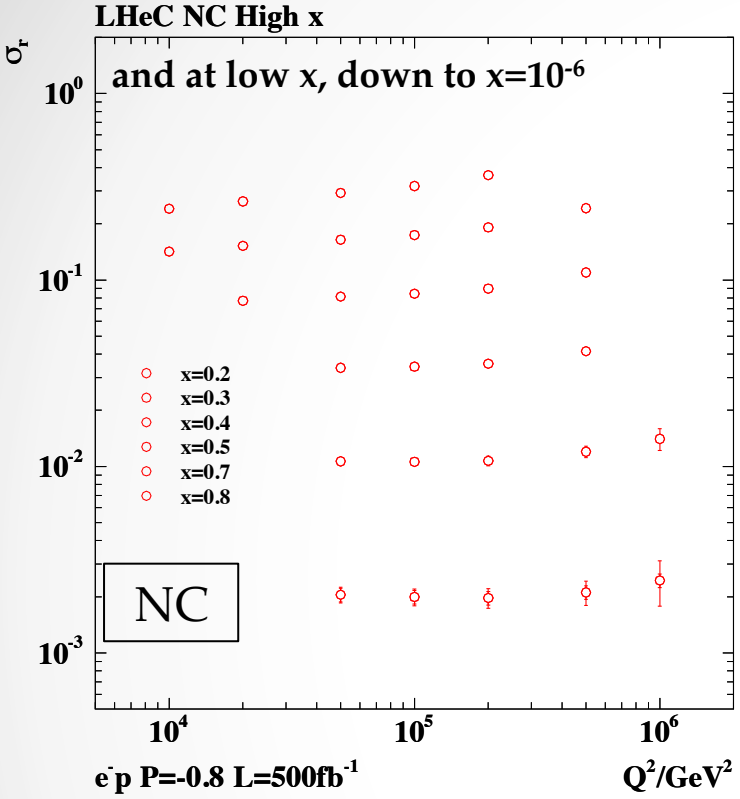
supported by CERN, ECFA, NuPECC

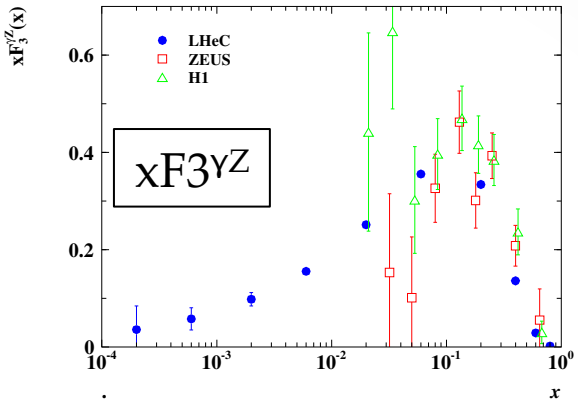
since then, proposal re-evaluated by CERN: new mandate, inviting IAC and coordination groups to **extend LHeC study**; also launched FCC design study in which ep integral part

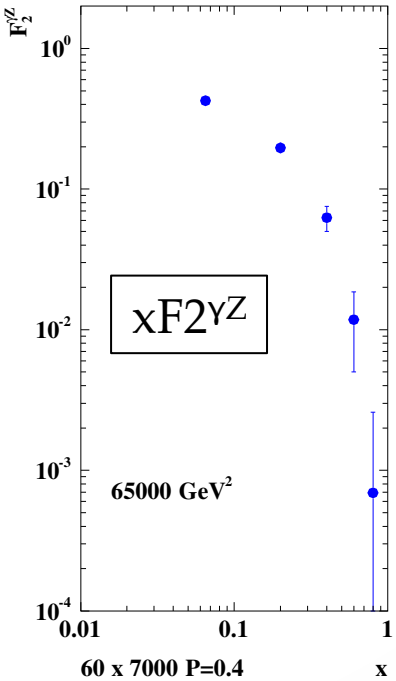
CDR: arXiv:1206.2913

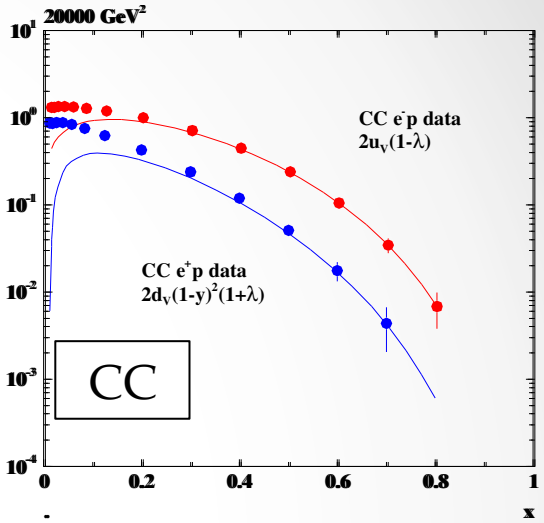
additional material: arXiv:1211.4831,1211.5102; arXiv:1305.2090; and recent, PDF+α_s studies, courtesy Voica Radescu (BSM part, many thanks to Monica D'Onofrio and Georges Azuelos)

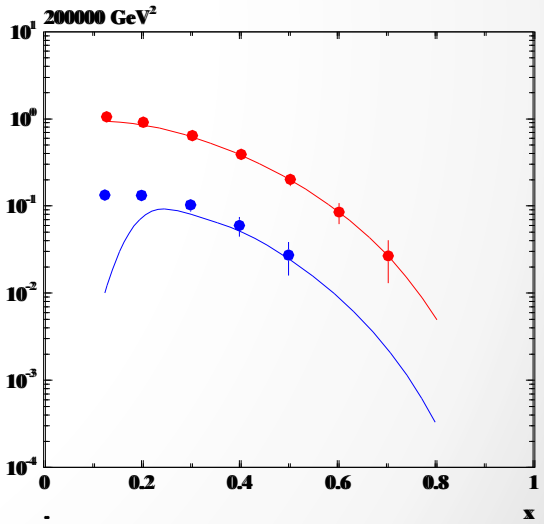
primary measurements – simulated – high Q^2











NC/CC cross sections to high precision

- structure functions, sensitive to quarks
- access high x, free from nuclear corrections (via high Q^2, high luminosity)
- different beam charge and polarisation: determination of all quark types

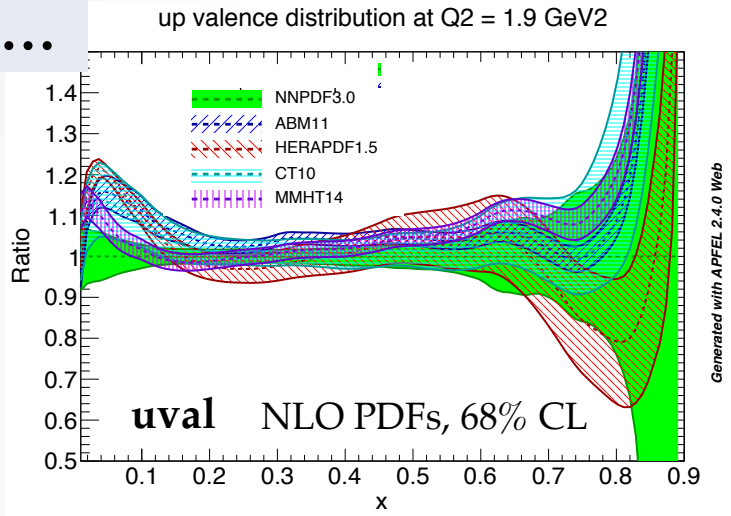
gluon via scaling violation (and F_L)

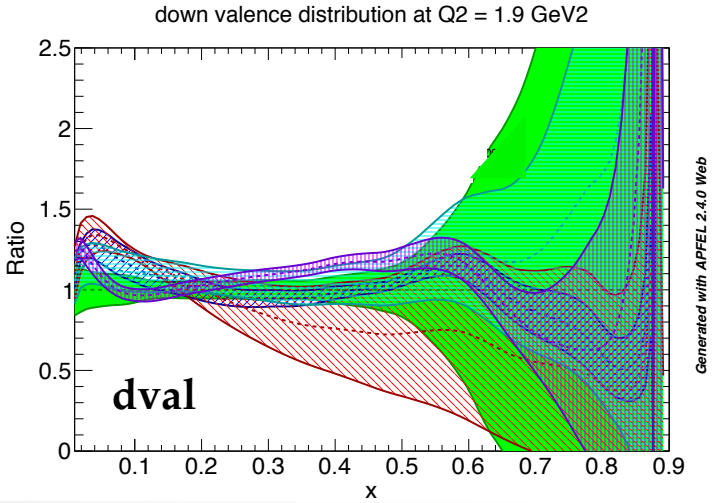
valence quarks

CDR study: LHeC simulated NC, CC e±p, P=±0.4, including projected systematics

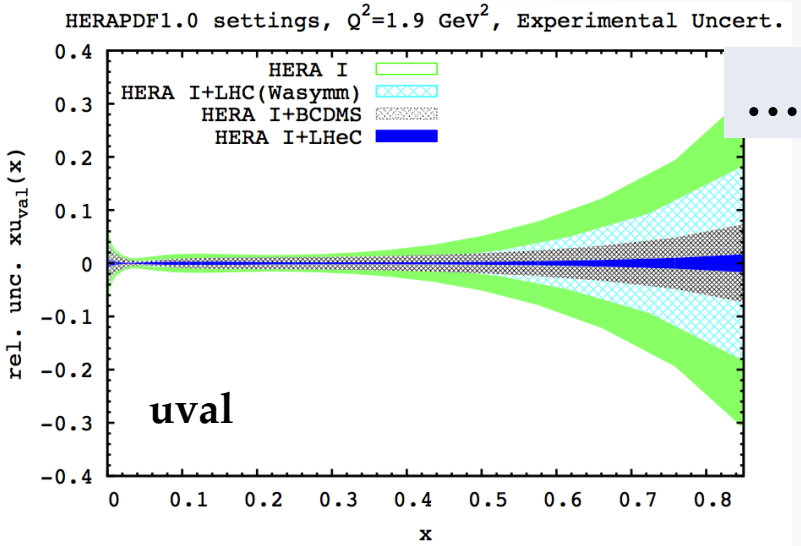
HERAfitter framework with HERAPDF1.0 NLO settings

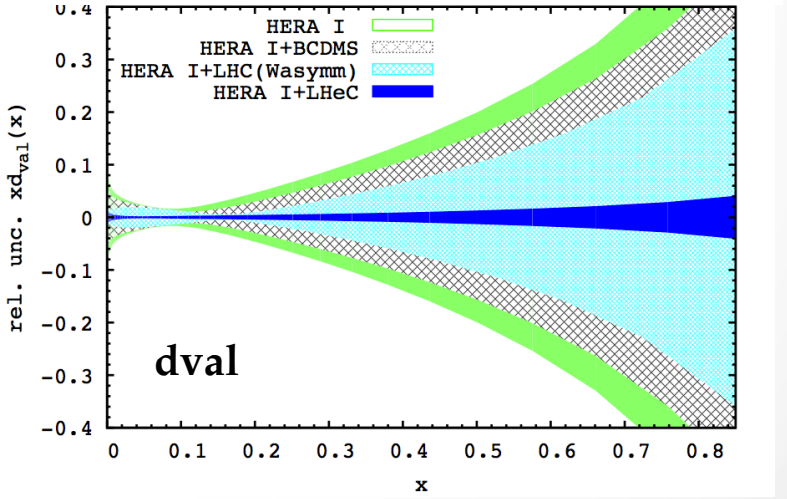
now…





…then

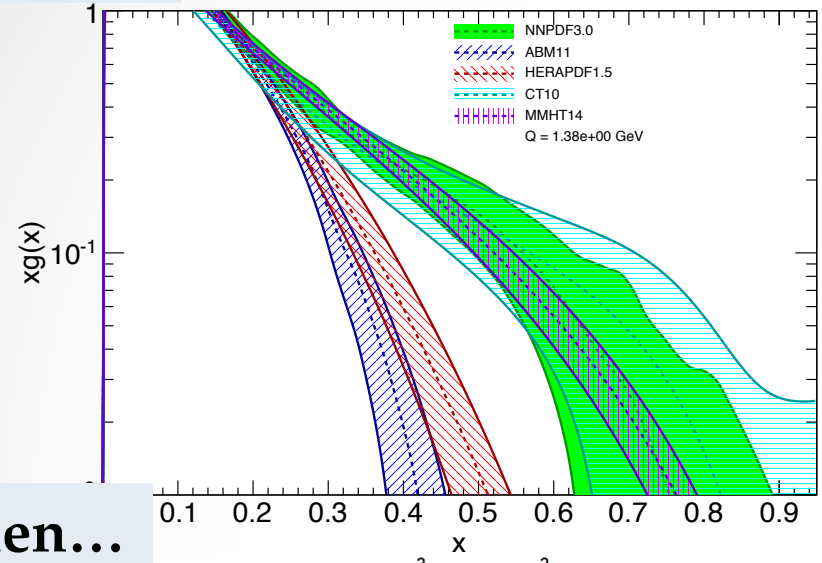




precision determination, free from higher twist corrections and nuclear uncertainties

gluon and sea at high x

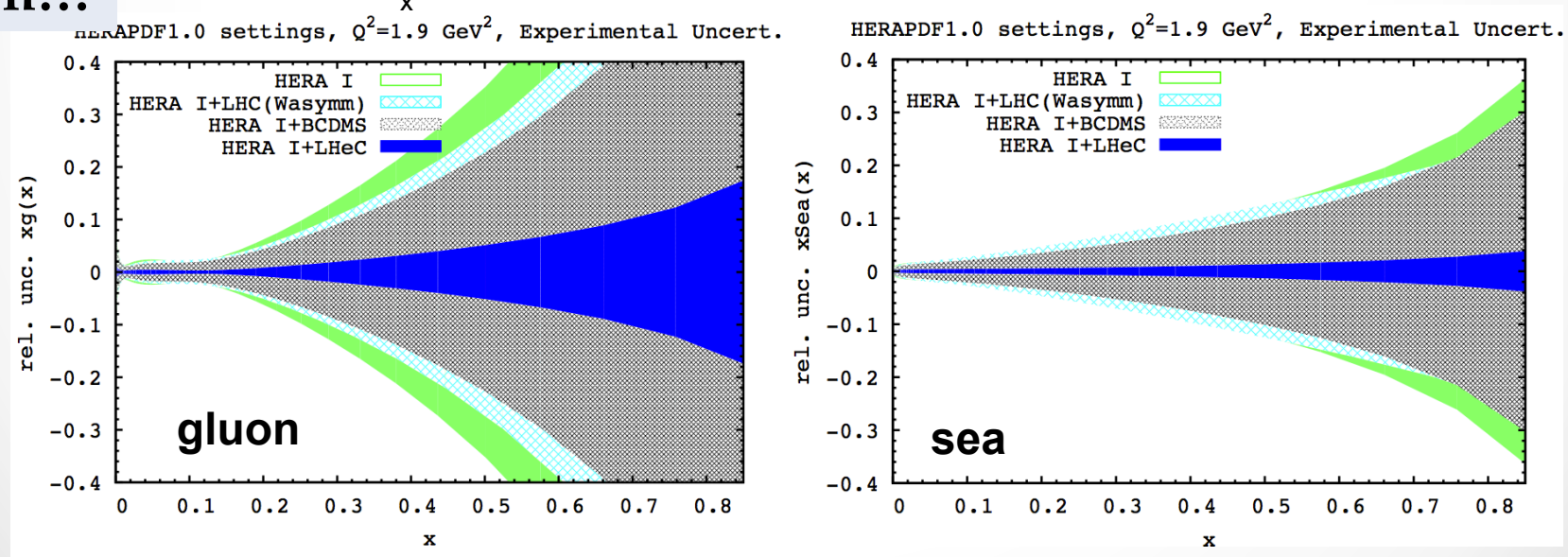
now…



gluon PDF at high x poorly known

- gluon and sea evolution intimately related
- important to disentangle sea from valence at large x – can be done with precise LHeC measurements of CC cross sections and NC $F2^{\gamma Z}$, $xF3^{\gamma Z}$

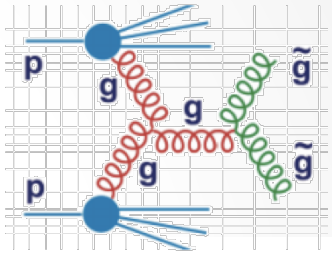
then…

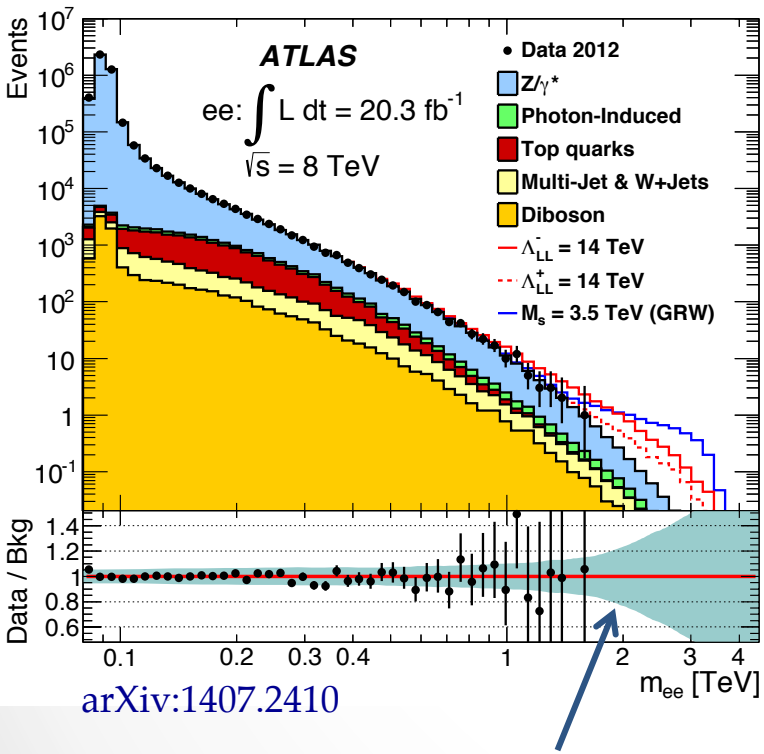


high x PDFs: link to LHC

- large uncertainties in high x PDFs limit searches for new physics at high scales

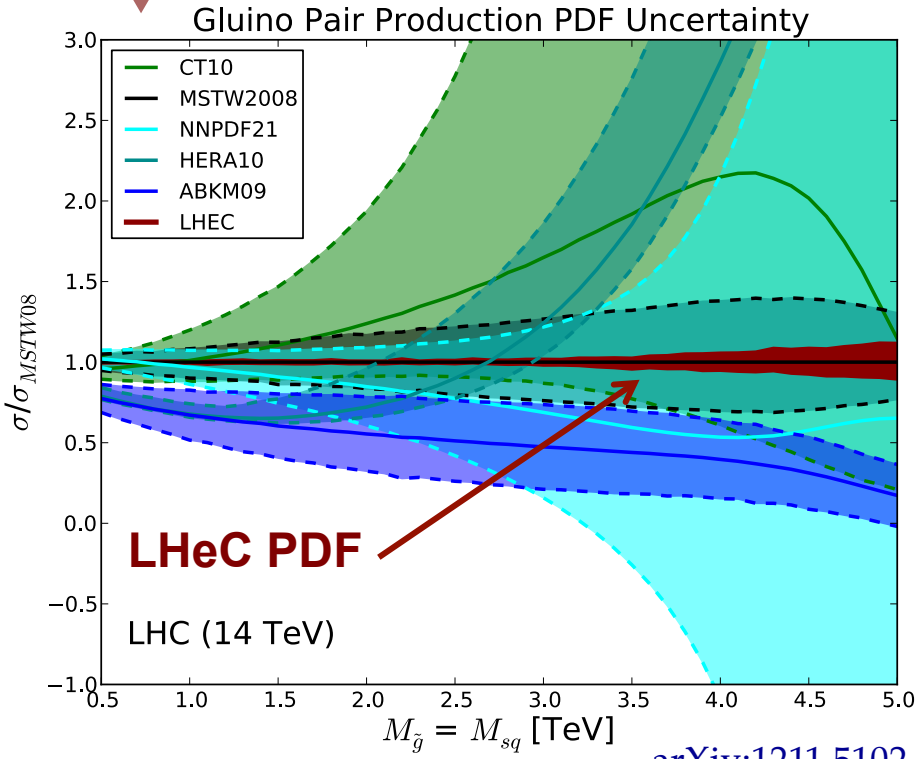
  many interesting processes at LHC are gluon-gluon initiated:
  top, Higgs, … and BSM processes, such as gluino pair production





arXiv:1407.2410

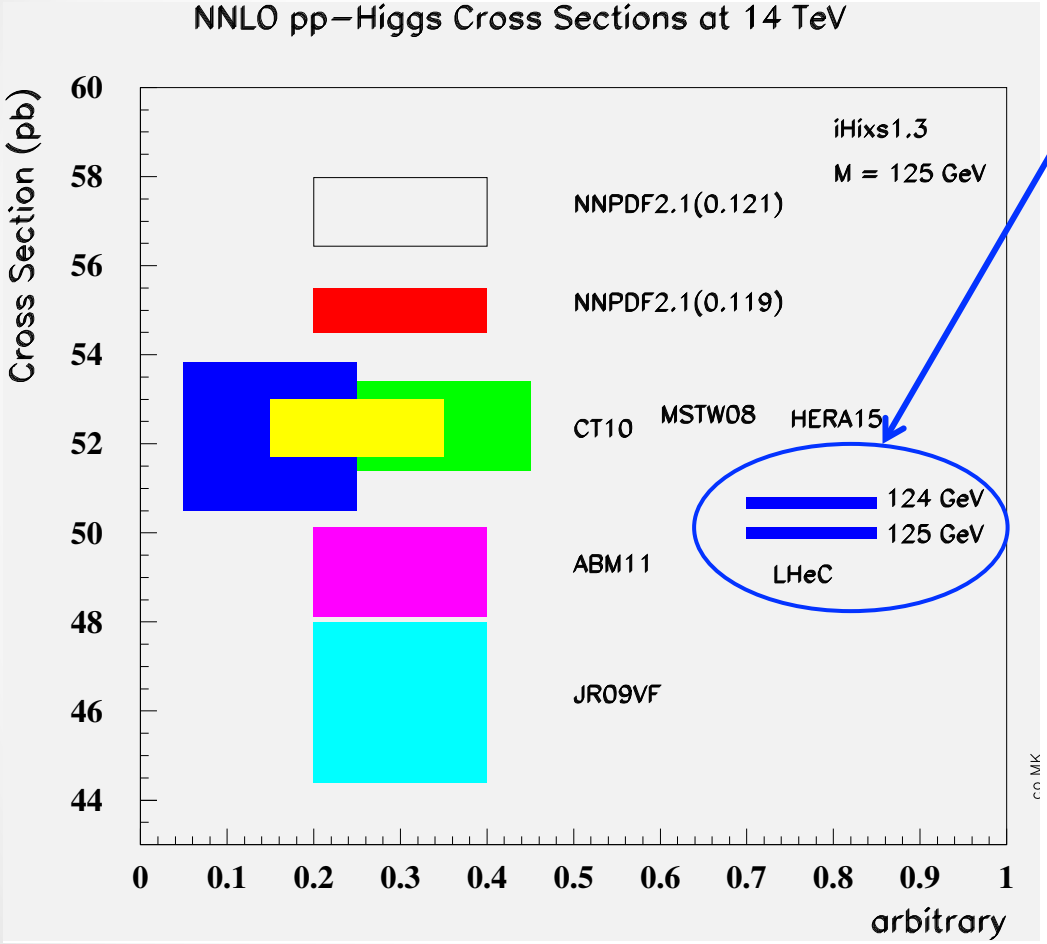
current BSM search in dilepton final state;
uncertainties on high-x (anti)quarks dominate



arXiv:1211.5102

LHeC PDFs for Higgs at the LHC

ggH is dominant Higgs production mechanism at LHC



LHeC PDF: 0.3% on cross section (experimental stat+syst)

sensitivity to Higgs mass

α_s is underlying parameter:
0.005 change ≅ 10% on cross section
LHeC: α_s to per mille (0.0002)!

N^{3}LO needed: available for ggH

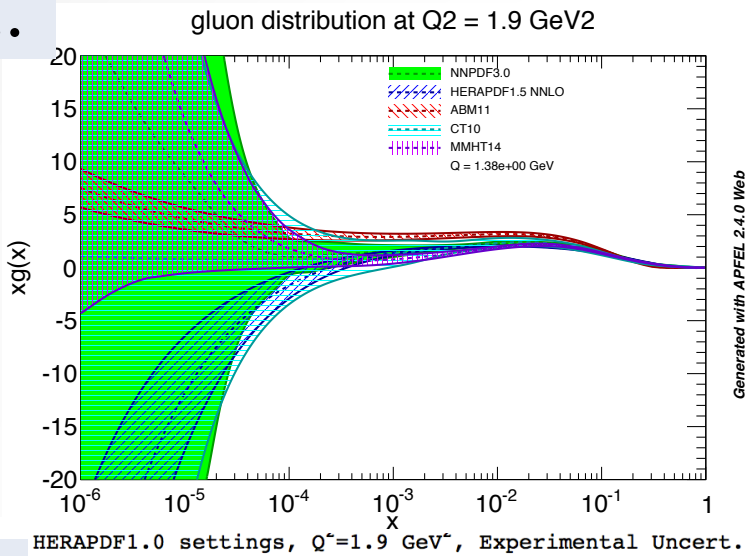
LHeC with high luminosity is in itself a precision Higgs facility

also see talk of Uta Klein

gluon saturation at low x?

see A. Stasto's talk for more

now…



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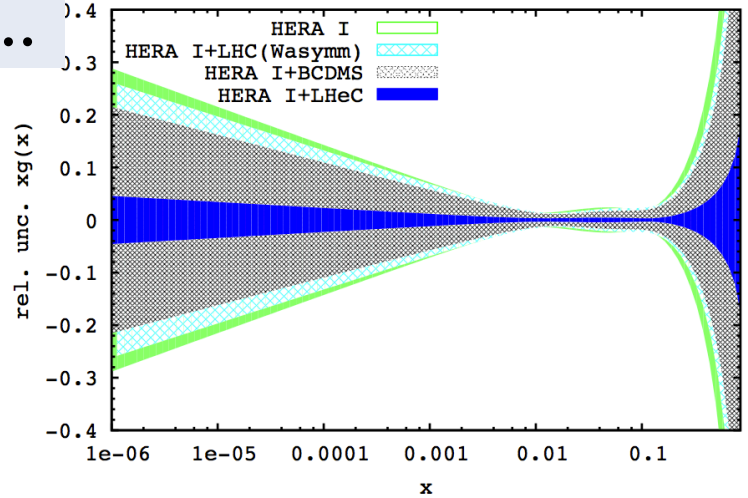
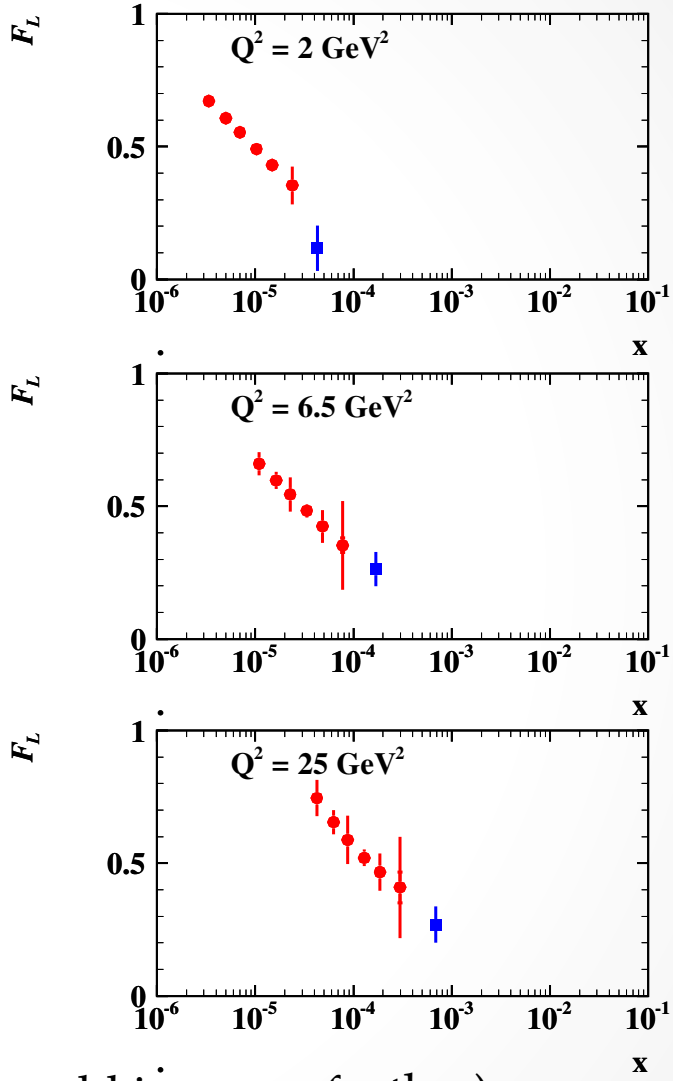


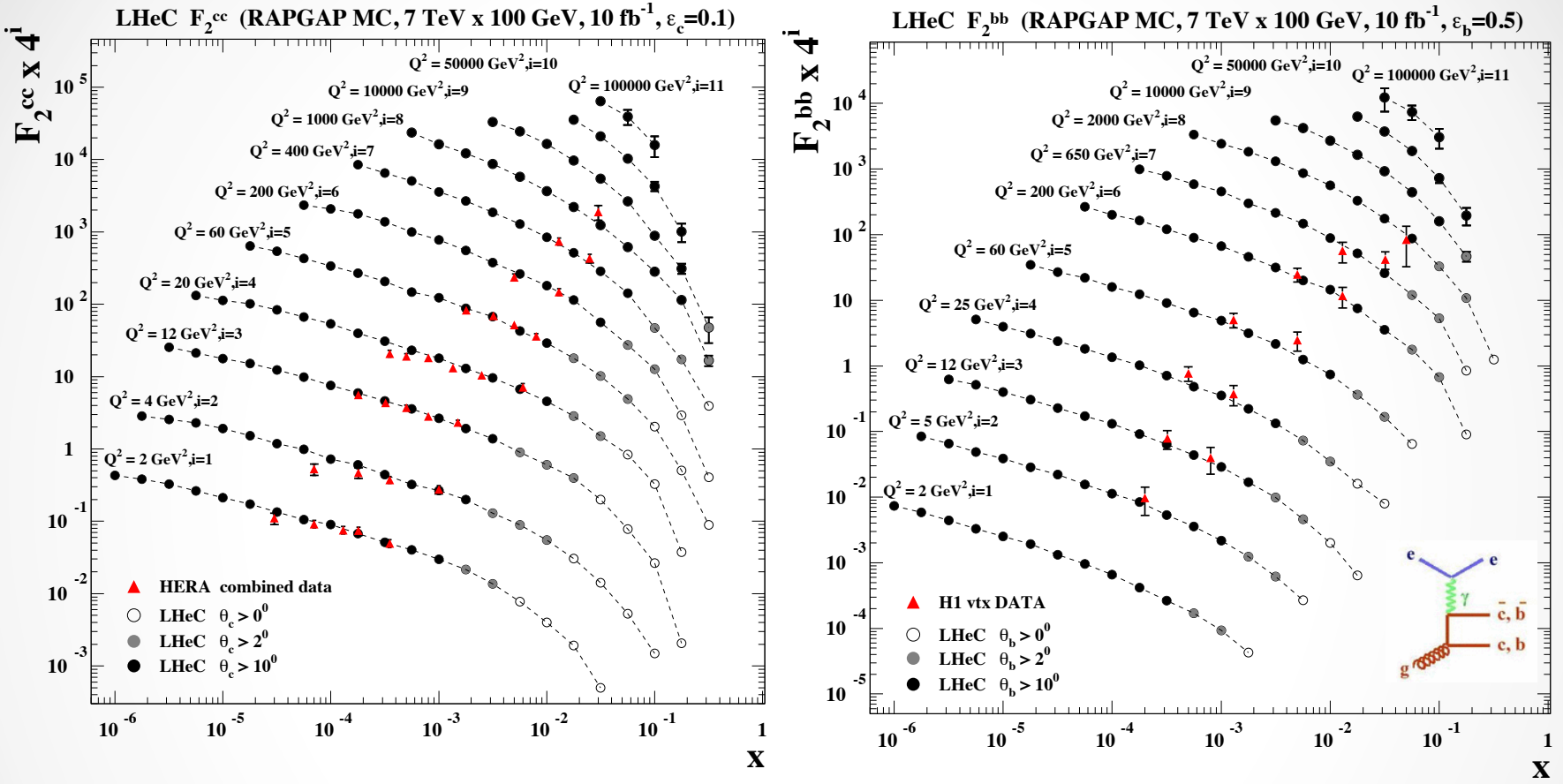


gluon measurement down to x=10^{-5}; (F_L would improve further)

explore low x QCD: DGLAP vs BFKL? non-linear evolution, saturation? F_2, and precise F_L

- important for high energy neutrino cross sections

flavour decomposition, charm and beauty



LHeC: much more precise and kinematically extended measurements

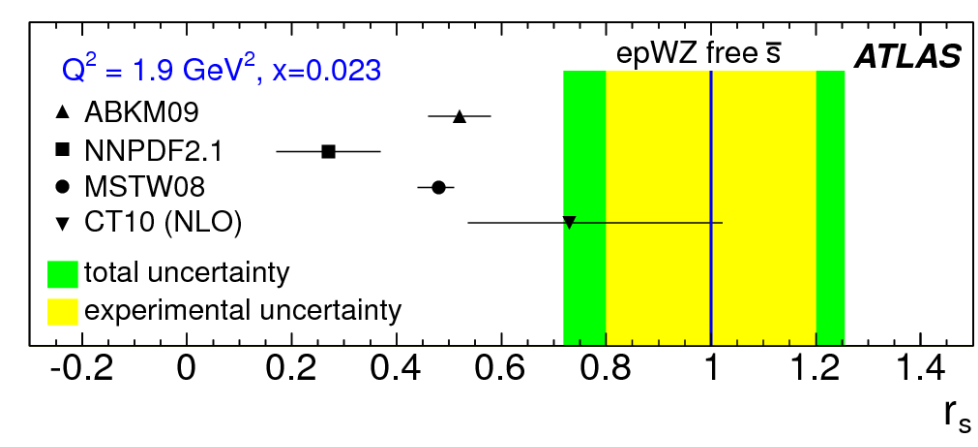
high Q^2/cross section, high luminosity, no pileup, small beam spot, new generation of Si detectors

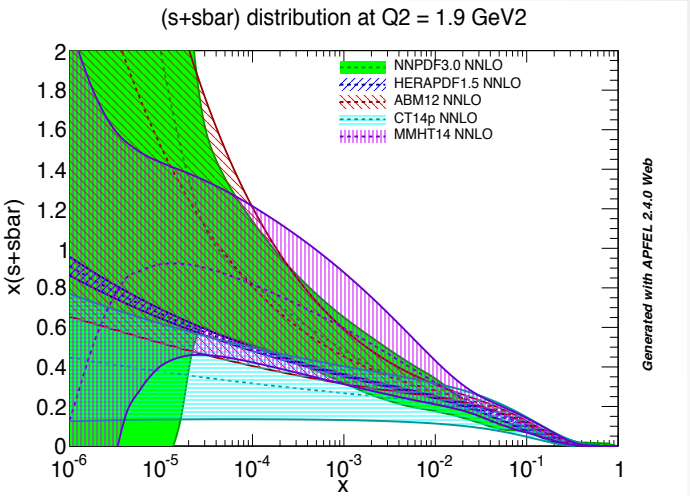
- $\delta Mc = 60$ (HERA) to 3MeV: impacts on αs, regulates ratio of charm to light, …
- MSSM: Higgs produced dominantly via $b\bar{b}$ ➔ A

strange

strange: largely unknown; suppressed compared to other light quarks? s=sbar?

e.g. ATLAS data suggest SU(3) symmetric sea





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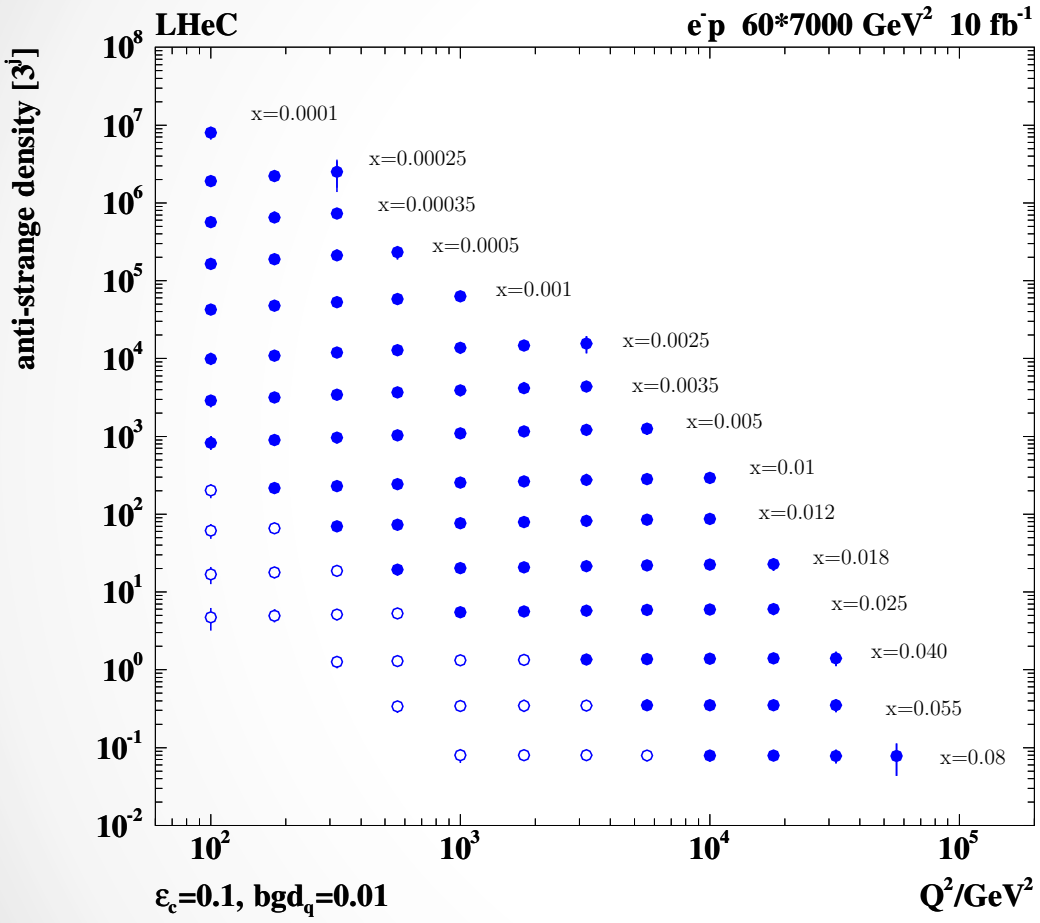
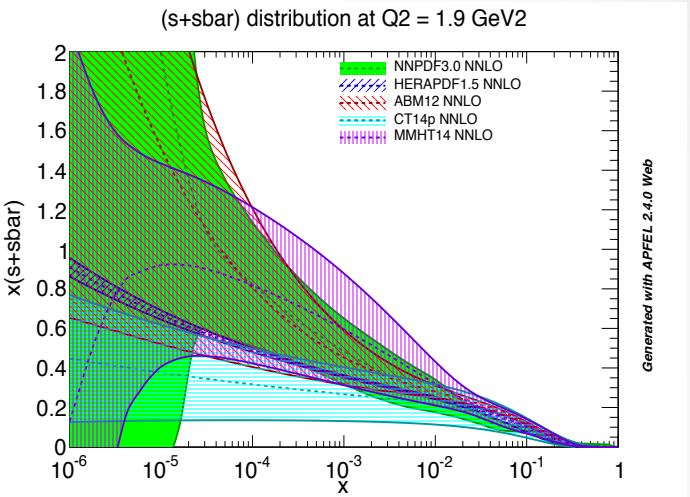




LHeC: direct sensitivity to strange, via charm tagging in CC

– first (x,Q2) measurement of (anti-) strange density

note, direct sensitivity to top (tPDF) also possible, for first time (Wb➔t)

(initial study (CDR): 10% charm tagging efficiency, 1% light quark background in impact parameter)

impact of different LHeC datasets

new since CDR

ERL scenario; interest in Higgs

prefers e-, high polarisation

Ep=7 TeV, E=60 GeV:

NC,CC:

	P	L (fb-1)
e+p	0	5
e-p	+80%	50
e-p	-80%	500

plus, dedicated measurements of strange, anti-strange, F2cc

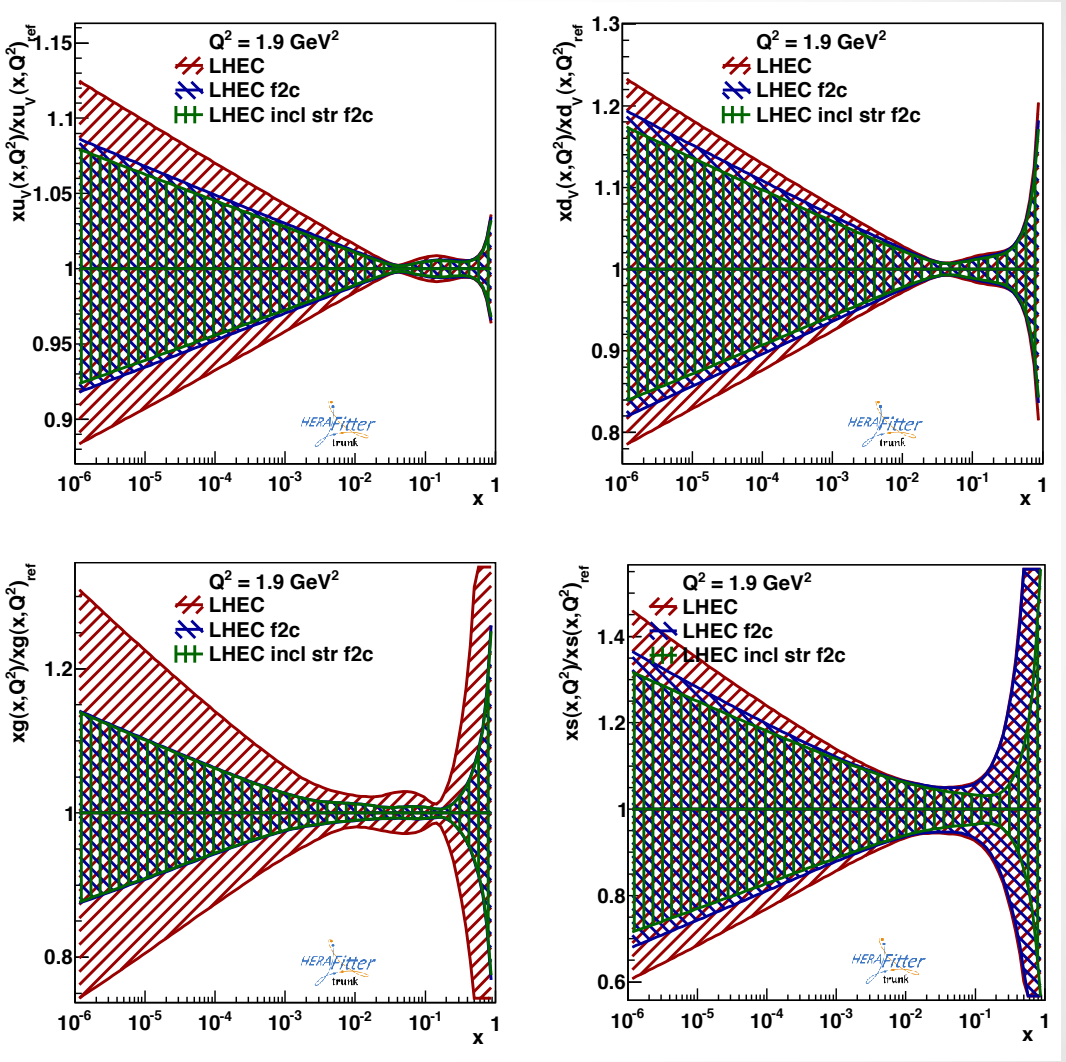
(not yet F2bb, low Ep data, F_L)

more flexible PDF fit:

xg, xuv, xdv, xub, xdb, **xstr**

$xf(x) = A\,x^B\,(1-x)^C\,(1+Dx+Ex2)$

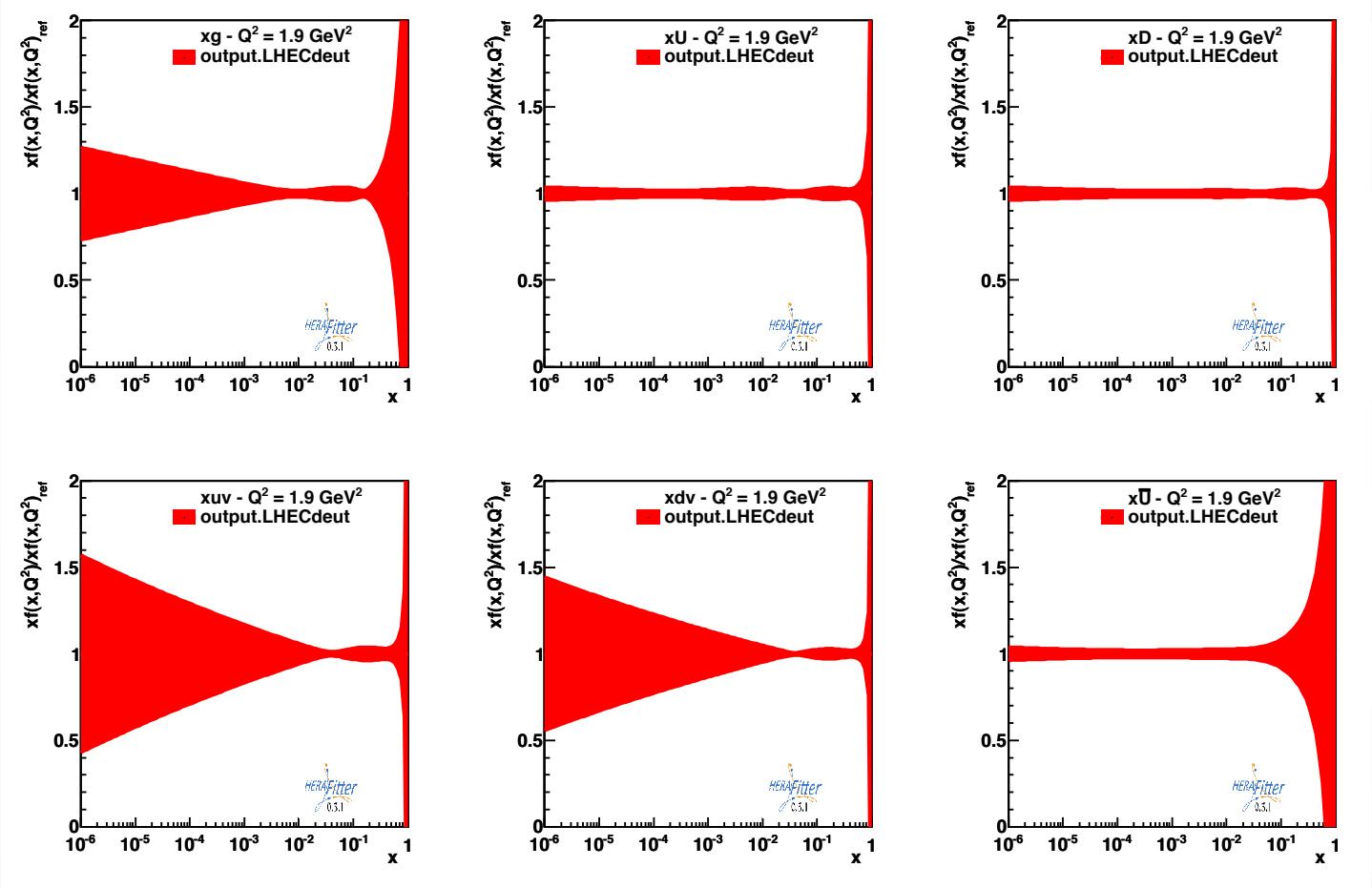
– 14 free parameters



can better constrain all PDFs

LHeC deuteron data

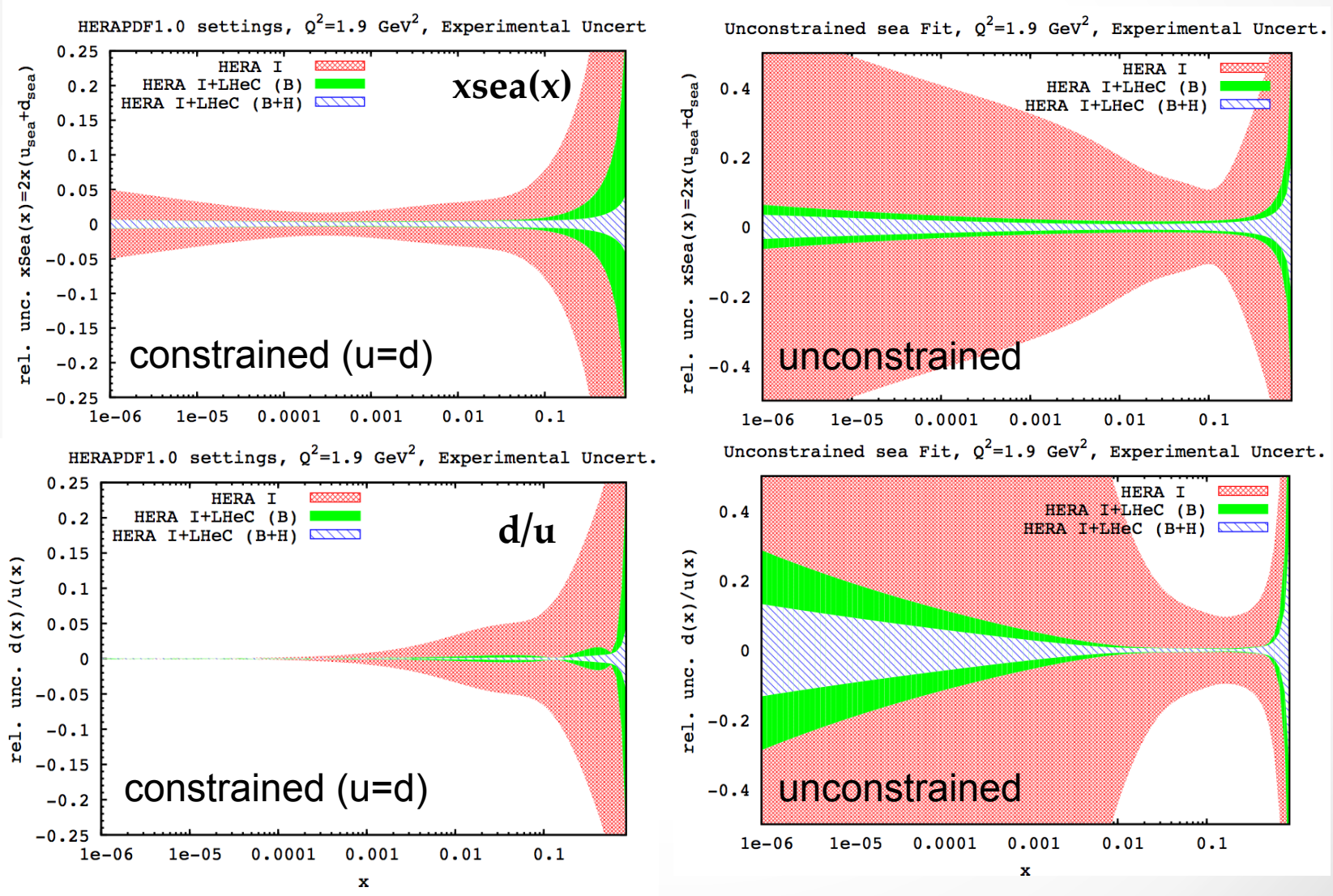
3.5TeV × 60GeV, e-p, P=-80%, 1fb-1, NC and CC, experimental uncertainties



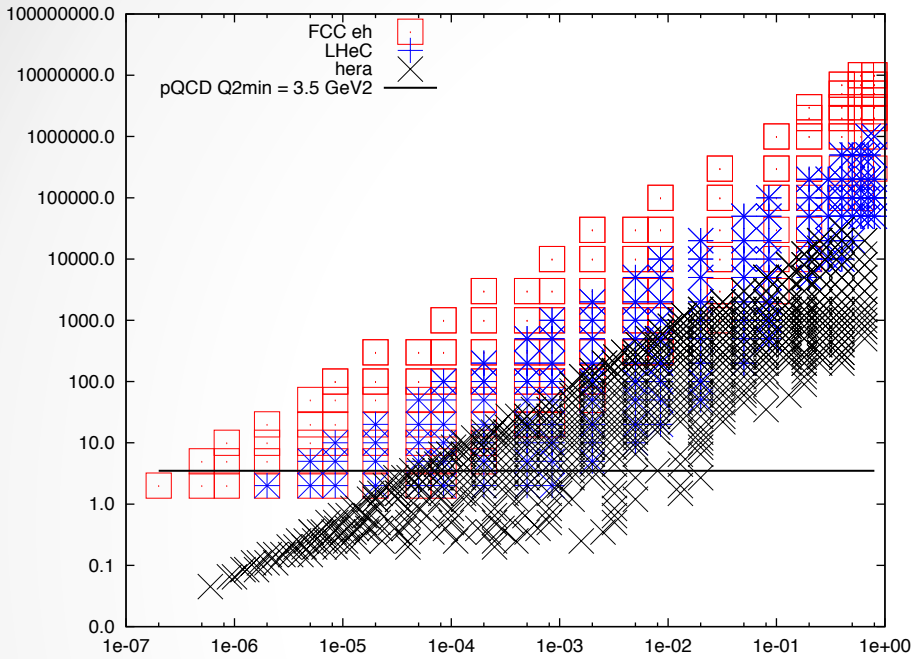
- symmetrised understanding of u-valence and d-valence
- future fits with ep+eD will lead to precise unfolding of u and d

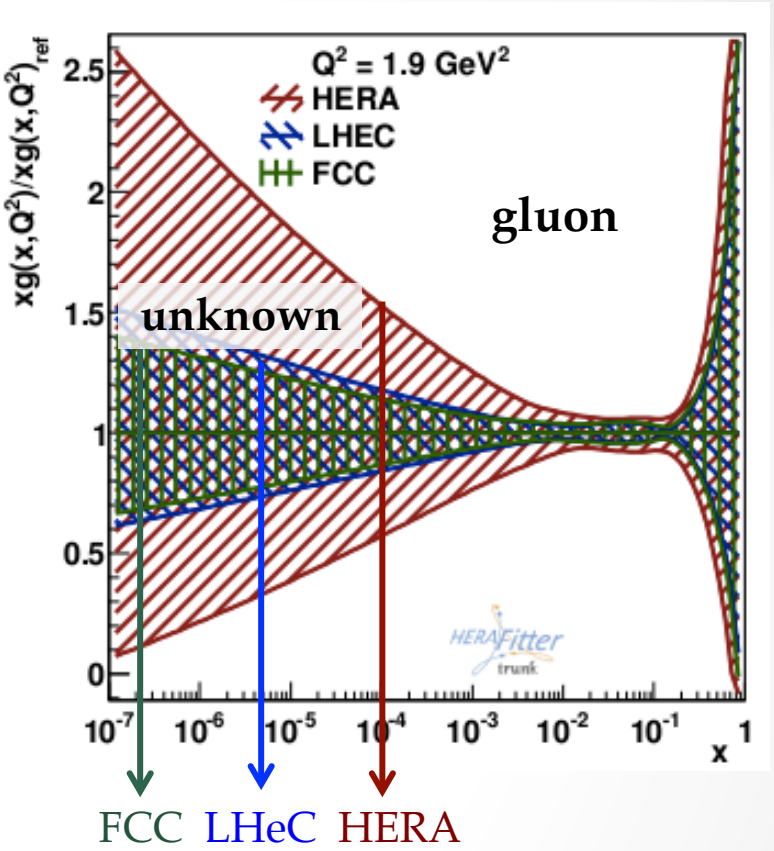
LHeC PDFs with released assumptions

- furthermore, LHeC does not need to rely on 'usual' constraint that u=d at low x, which **may not be valid**



FCC-eh vs LHeC vs HERA





FCC-eh: Ep=50 TeV, Ee=100 GeV

NC and CC: e-p, P=80%, 1000 fb^{-1}

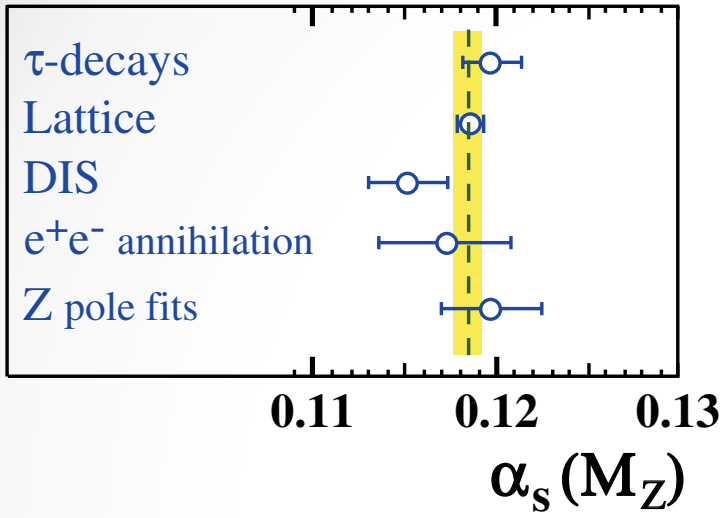
stat: 0.1 – 30%, uncor 0.7%, syst 1 – 5%

coverage down to x=2×10-7, up to $Q^2 = 10^7$ GeV^2

need FCC to constrain much below x=10^{-5}

FCC-eh can further improve, and explore low-x phenomenology

strong coupling



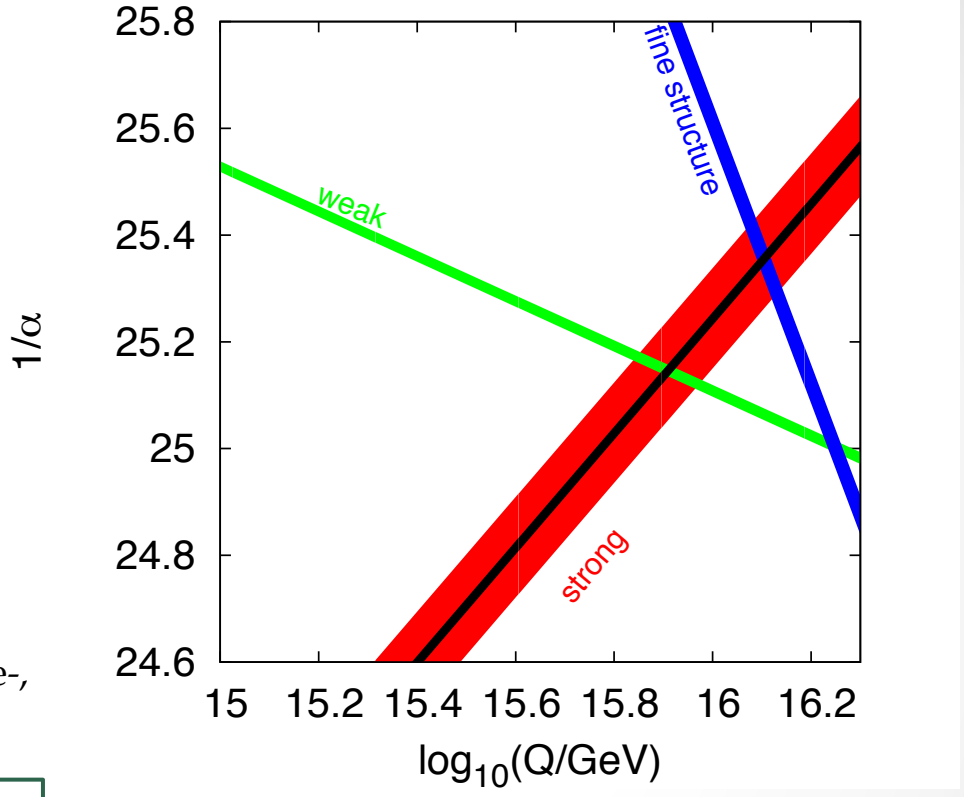
strong coupling αs is fundamental parameter, not given by theory

extracted from experimental measurements in e+e-, ep, pp, and from lattice QCD calculations

PDG world ave.: αs(Mz)=0.1184±0.0006

without lattice input: αs(Mz)=0.1183±0.0012

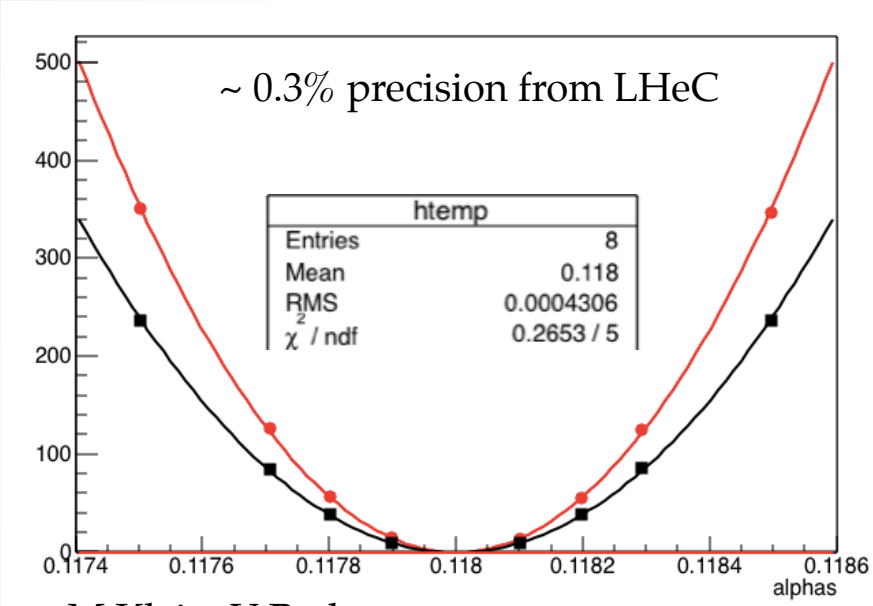
but, measurements not all consistent – what is true central value; true uncertainty; role of lattice calculations?

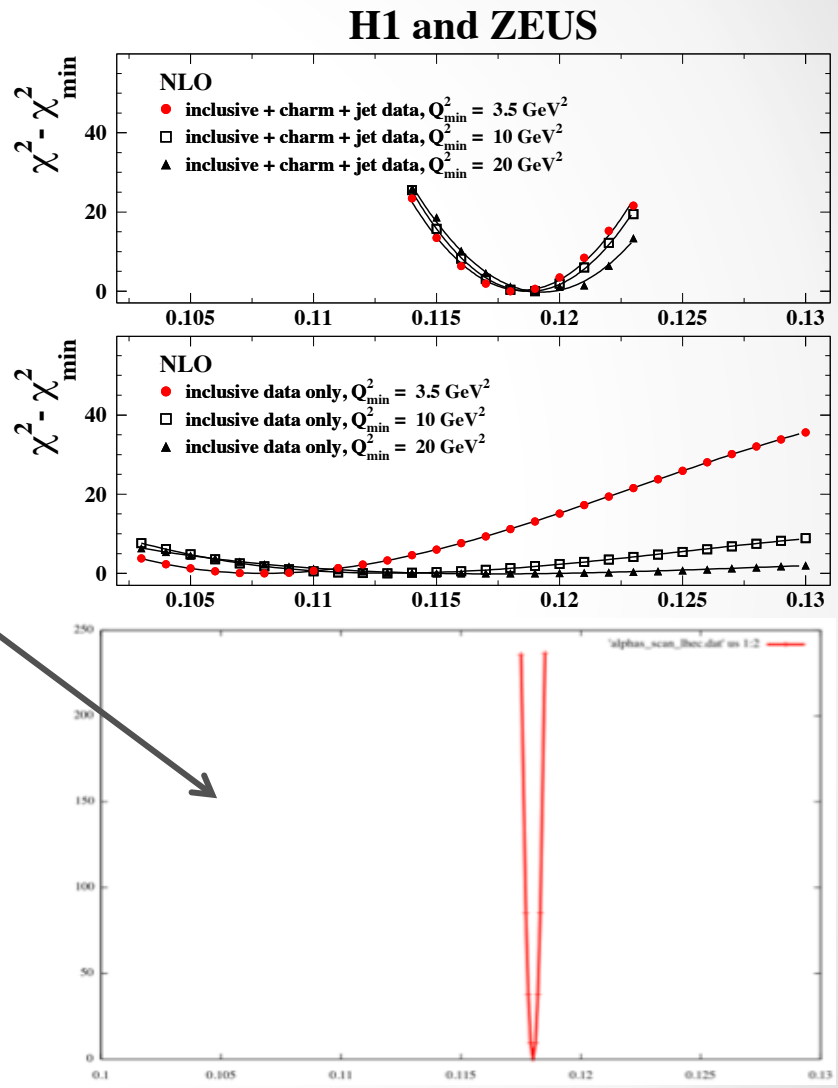


precise αs(Mz) important to constrain GUT scenarios, and for cross section predictions, such as Higgs

strong coupling from LHeC

combined fit to PDFs+αs using LHeC data





LHeC could resolve a > 30-year old puzzle:

αs consistent in inclusive DIS, versus jets?

expected 0.1% precision when combined with HERA

strong coupling

Snowmass13 report – arXiv:1310.5189

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry $\sim$ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	$\sim$ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

per mille

per mille

per mille accuracy can challenge QCD lattice calculations

TLEP = old name for FCC-ee

BSM prospects

LHC (FCC-pp, …) main discovery machine, at energy frontier

- **LHeC, FCC-eh: potential for improving, or possibly discovering, new physics**
- improved PDFs (esp. gluon), αs, … , transforms LHC into higher precision machine
- ... discovery also possible in own right: B and L quantum numbers in initial state, and very clean environment favourable for certain BSM scenarios

- since LHeC CDR, strong constraints on new physics from LHC, up to 1 TeV; window of discovery remains open only for specific channels
- FCC-eh offers more potential; detailed studies underway

<u>specific BSM phenomena:</u>
BSM, high Pt: **LQs**, **contact interactions**, compositeness, excited fermions, **anomalous coups.**
Higgs sector: **VBS – anomalous couplings, CP properties**

only very selected results shown here – more in backups – some results very preliminary, further studies underway, detector simulation in progress

slides: thanks to Georges Azuelos, Monica D'Onofrio, Christian Schwanenberger

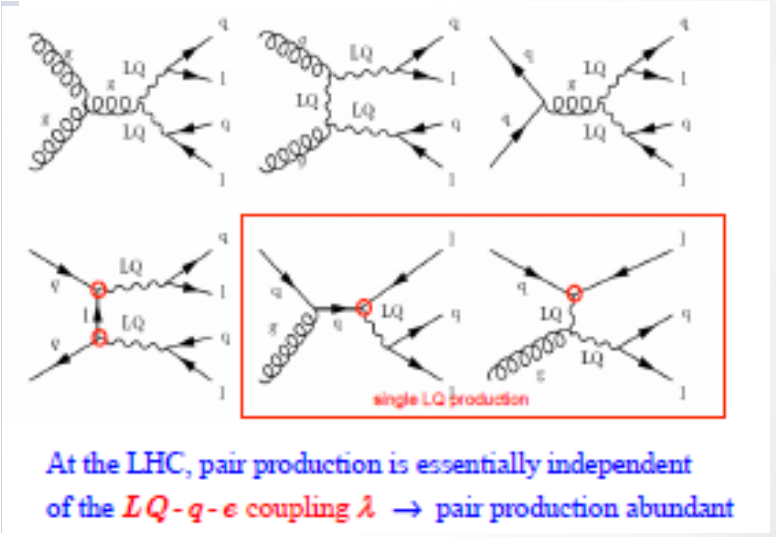
leptoquarks

- **LHeC**: both baryon and lepton quantum numbers – ideally suited to search for and study properties of new particles coupling to both leptons and quarks

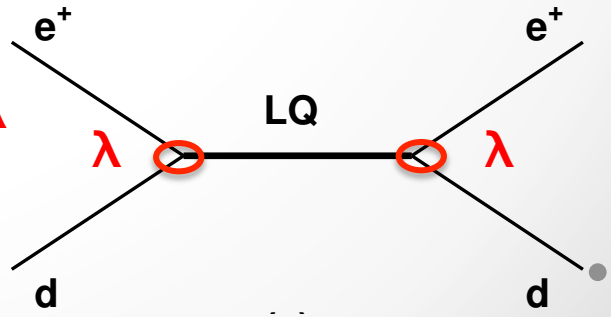
- **leptoquarks (LQs)** appear in several extensions to SM:
  E6 GUT, extended technicolour, Pati-Salam model, lepton-quark compositeness, …
  (also – squarks in R-parity violating SUSY (see later))

- can be **scalar** or **vector**, with fermion number 0 (e^-qbar) or 2 (e^-q)

- **LHC**: mainly pair-production via gg or qq – essentially insensitive to LQ q–e coupling, **λ**
- single LQ production at LHC suppressed by λ dependence

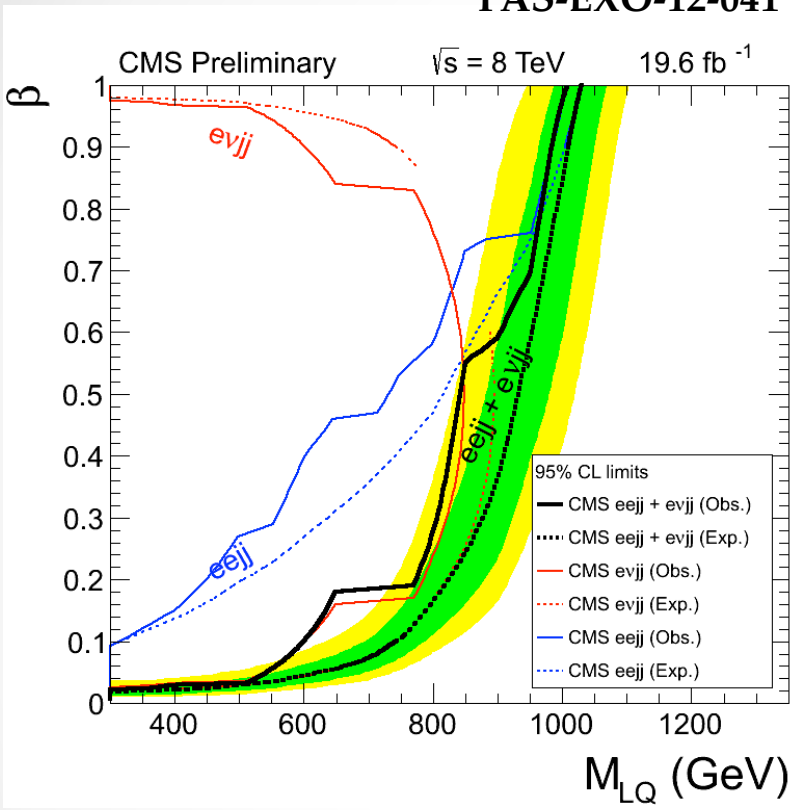


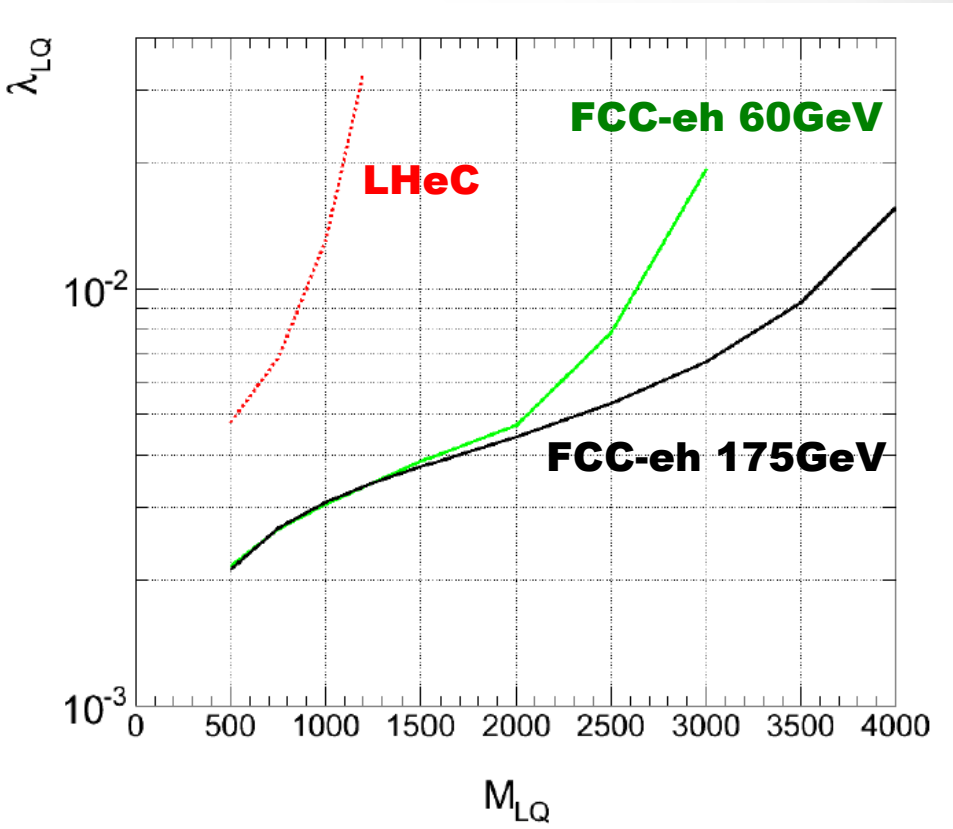
- **LHeC**: single, resonant production; sensitive to **λ**



LQs: comparison with current LHC bounds

PAS-EXO-12-041





1st generation LQs; β=BR(LQ→eq)=1

ATLAS+CMS (20fb^{-1}): $m_{LQ} \leq 1000$ GeV

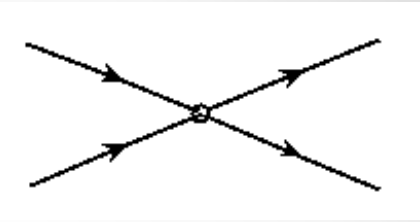
expect up to 1.2 (1.5)TeV (pair production) with 300fb^{-1} at LHC@14TeV for scalar (vector)

ep scenarios:

also sensitive to $\lambda << e=\sqrt{4\pi\alpha}=0.3$

preliminary study: in progress

contact interactions



- **if new physics enters at higher scales: Λ>> √s**
- such indirect signatures can be seen as effective 4-fermion interaction

$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)}; \quad j_\mu^{(f=e,q)} = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_R \bar{f}_R \gamma_\mu f_R + h.c.$$

$\Rightarrow$ all combinations of couplings $\eta_{ij} = \eta_i^{(e)} \eta_j^{(q)}; \quad q = u, d$

- may be applied very generally to new phenomena

Λ:
- LQ mass >> √s
- Planck scale (Ms) of extra dimensional models
- compositeness scale
- …

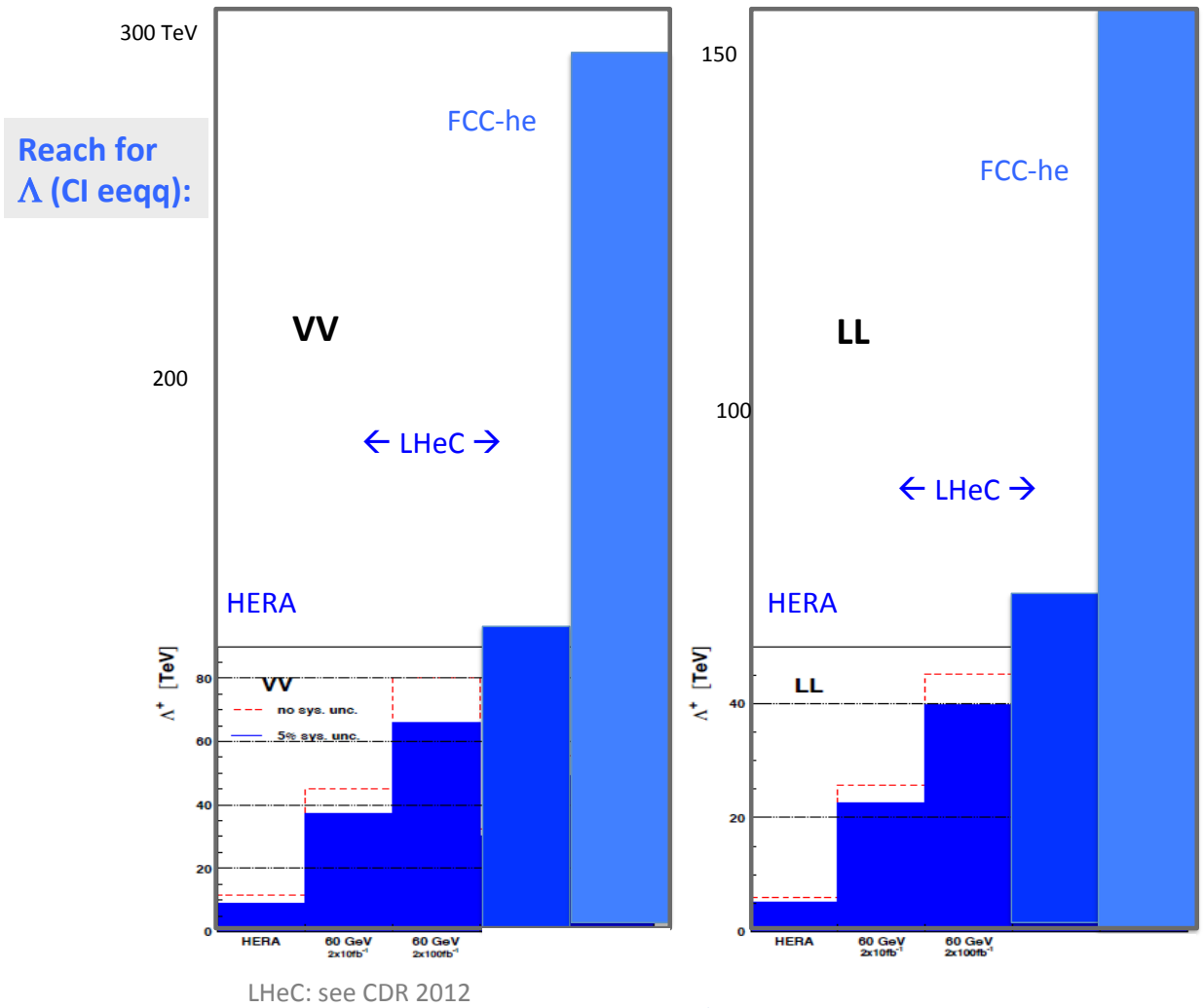
present LHC constraints on scale of qqll contact interactions: 15 – 26 TeV, depending on model (expected up to **40 TeV** at LHC@14TeV)

- sensitivity to fermion radius below 10^{-19}–10^{-20}m at LHeC (FCC-eh) $\frac{\hbar c}{1.3\,\text{TeV}} = 1.5 \times 10^{-4}\,\text{fm}$

form factor: $f(Q^2) = 1 - \frac{1}{6}\langle r^2 \rangle Q^2$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2)$$

scale of contact interactions at future colliders



LHeC: see CDR 2012

present LHC constraints on scale of qqll contact interactions: 15 – 26 TeV, depending on model (expected up to **40 TeV** at LHC@14TeV)

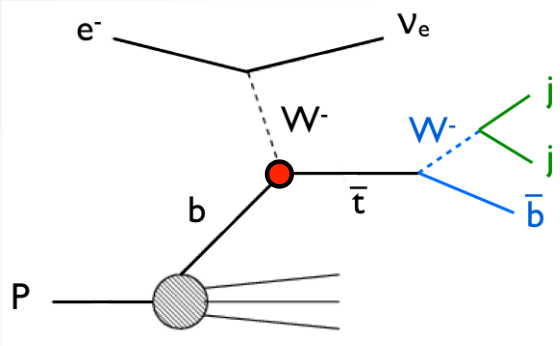
also advantages over, and complementarities with, pp (and e+e-) in characterising nature of new physics

FCC rough scaling only, very preliminary

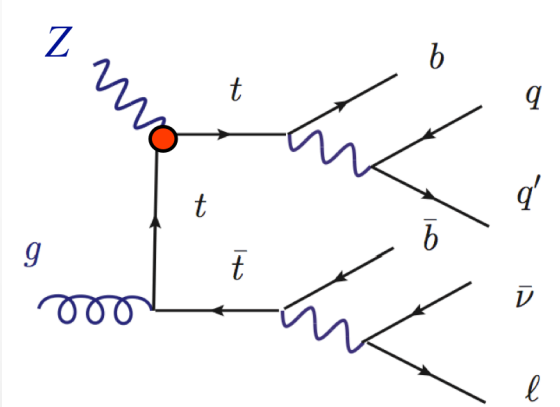
see Christian Schwanenberger's talk for more

top quark electroweak interactions

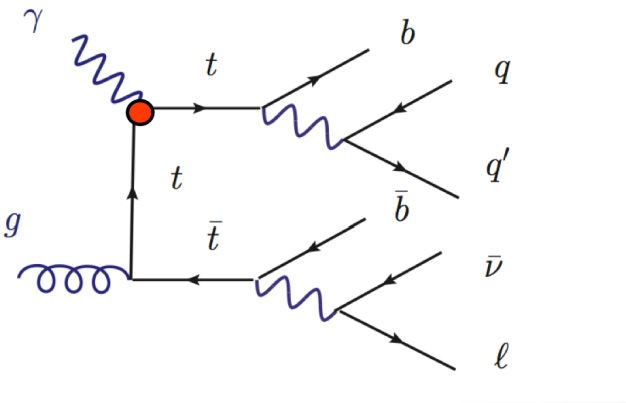
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



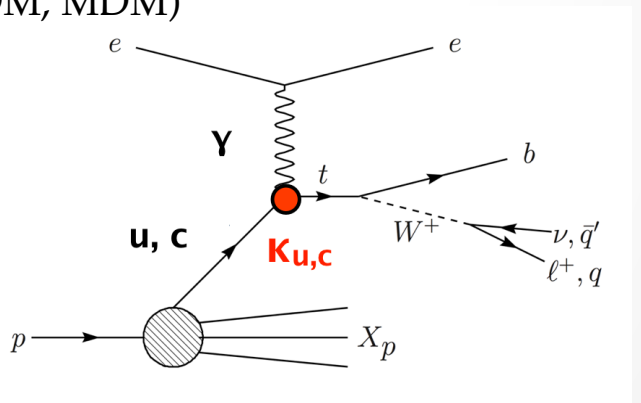
- high precision measurements of Vtb and search for anomalous Wtb couplings



- measurement of top isospin and search for anomalous ttbarZ couplings (eg. EDM, MDM)



- direct measurement of top quark charge and search for anomalous ttbarγ couplings (eg. EDM, MDM)



- sensitive search for FCNC couplings will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

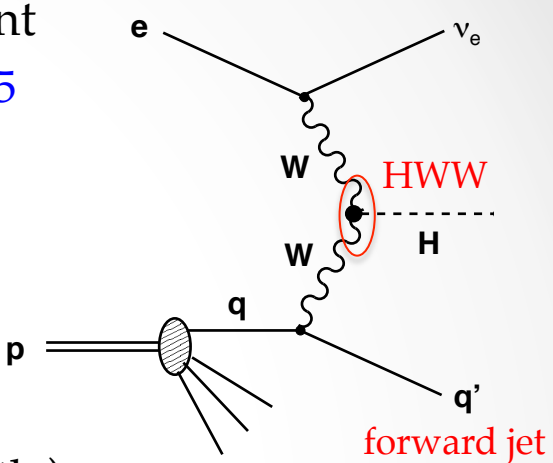
CP properties of Higgs

also see Uta Klein's talk

- LHC has shown that discovered Higgs boson consistent with 0+ state, but: are there small additional dimension-5 anomalous couplings to the HWW vertex?

$$i\Gamma^{\mu\nu}(p_-, p_+)\varepsilon_\mu(p_-)\varepsilon^*_\nu(p_+)$$

$$\Gamma^{\mu\nu} = g M_W \left(-g^{\mu\nu} + \frac{1}{M_W^2}\left[\lambda\left(p_- \cdot p_+ \, g^{\mu\nu} - p_-^\nu p_+^\mu \right) + i\lambda' \varepsilon^{\mu\nu\rho\sigma} p_{-\rho} p_{+\sigma} \right] \right)$$

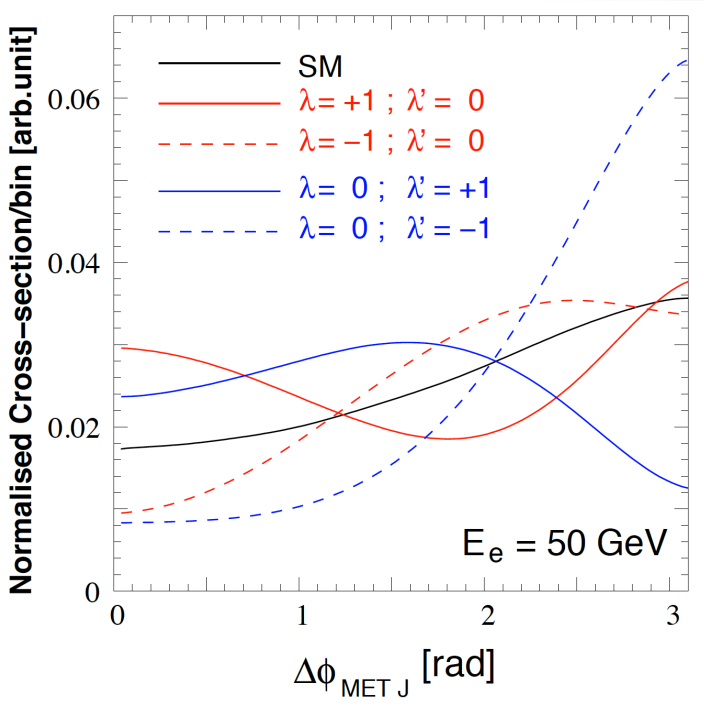


(BSM will modify CP even (λ) and odd (λ') states diffferently)

- measure **azimuthal angular distribution** between etmiss and forward jets
- sensitive probe of nature of **HWW vertex** and hence **CP properties**

LHeC CDR initial study of HWW vertex: sensitivity to λ 0.05 and λ' 0.2, with 50 fb^{-1}

(T. Plenh et al, hep-ph/0105325
S. Biswal et al, arXiv:1203.6285, and update)

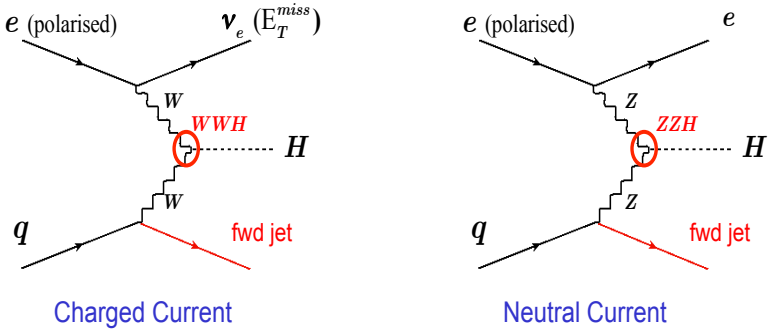


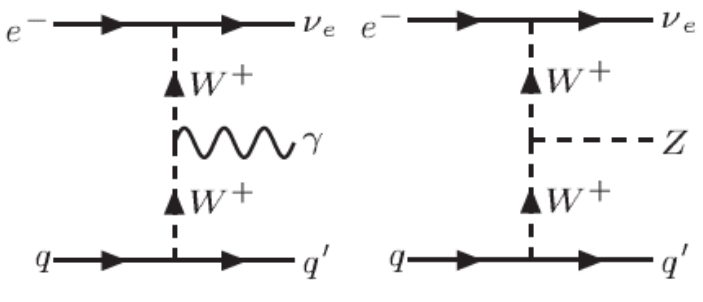
BSM in vector boson scattering (FCC-he)

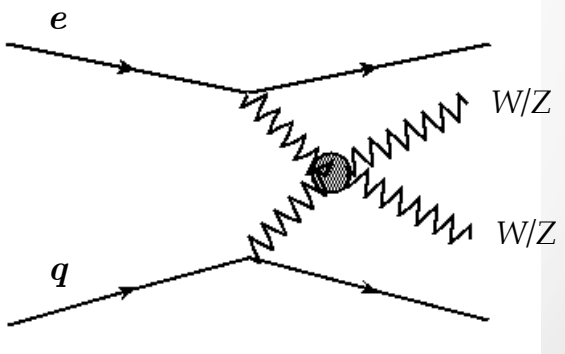
1. VBF Higgs production with BSM decays
   eg. RPV cases $H \rightarrow \chi_1^0 \chi_1^0 \rightarrow 3j\,3j$ (resonances)
   need to understand backgrounds

2. **vector boson scattering at high mass**
   mass dependence of cross section

- anomalous TGC, QGC couplings?
  I.T.Cakir et al., arXiv:1406.7697
  studies show sensitivity comparable to LHC
- is unitarity restored only by Higgs?
  are there new resonances (composite Higgs model)?
  expect below about 2 – 3 TeV:
  e-q ➔ e-qWZ, νqWZ
  search for deviations from SM predictions
- **LHC**: hadronic modes challenging (high QCD backgrounds not present in ep, pileup, difficult if no lepton triggers used, …)





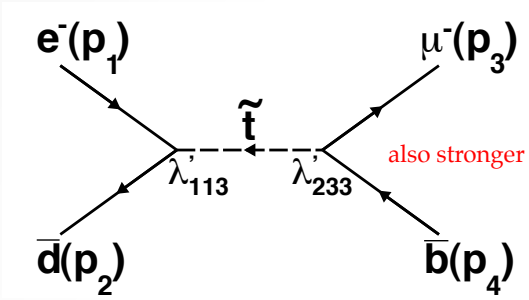


SUSY – RPV

Barbier hep-ph/0406039

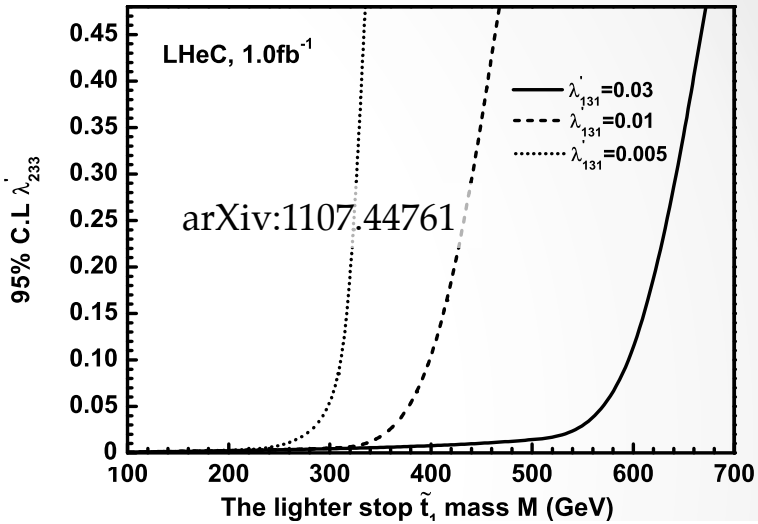
single squark production, in RPV SUSY (signal like leptoquarks, with generation mixing)

stop



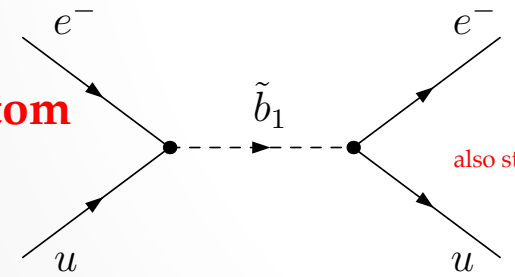
$\Lambda'_{131} < 0.03$

also stronger bounds from ββ0ν



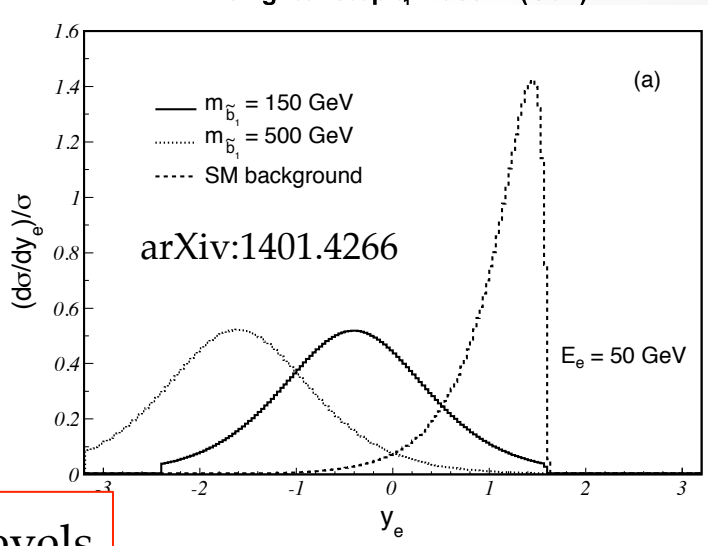
- sensitivity up to 700 – 800 GeV with only 1fb^{-1}
- LHC will also provide constraints
- very promising with high luminosity, 100 fb^{-1}
- requires good b-tagging

sbottom



$\Lambda'_{131} < 0.02$

also stronger bounds from ββ0ν



- < 100 fb^{-1} needed for 1TeV RPV sbottom discovery

RPV interaction can be probed at unprecedented levels

summary

LHeC: enormous increase in kinematic reach of DIS, and in luminosity

- **main goal, PDFs**: precise determination of proton (and nucleon) structure
- specifically, precise unfolding of **all** PDFs, not constrained by standard assumptions
  (not talked about: unintegrated, diffractive, generalised, polarised, photonic, nuclear PDFs)
- α_s to per mille level
- transforms discovery machines (LHC, HL-LHC, ..) to higher precision facilities for Higgs, BSM physics, …
- and exploration of low x; learn more about QCD beyond non-linear DGLAP

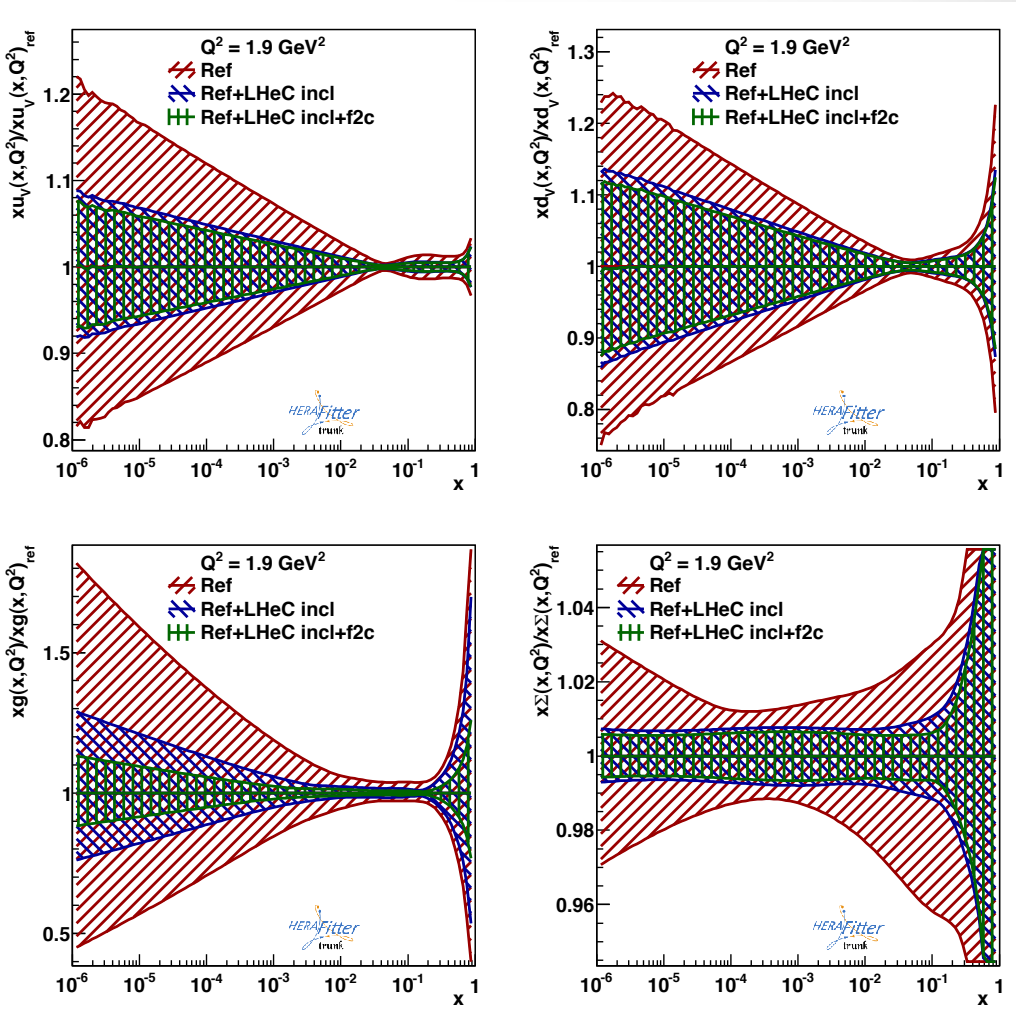
- **exotica and BSM**: improvements, and possibly discovery, of new physics
- leptoquarks, with sensitivity to coupling, compositeness, heavy and excited quarks, top anomalous couplings, Higgs (VBS, anomalous couplings, CP properties), SUSY (RPV, BSM Higgs decays)
- FCC-eh higher sensitivity (further studies ongoing)

extras

LHeC PDFs c.f. world data

Ref

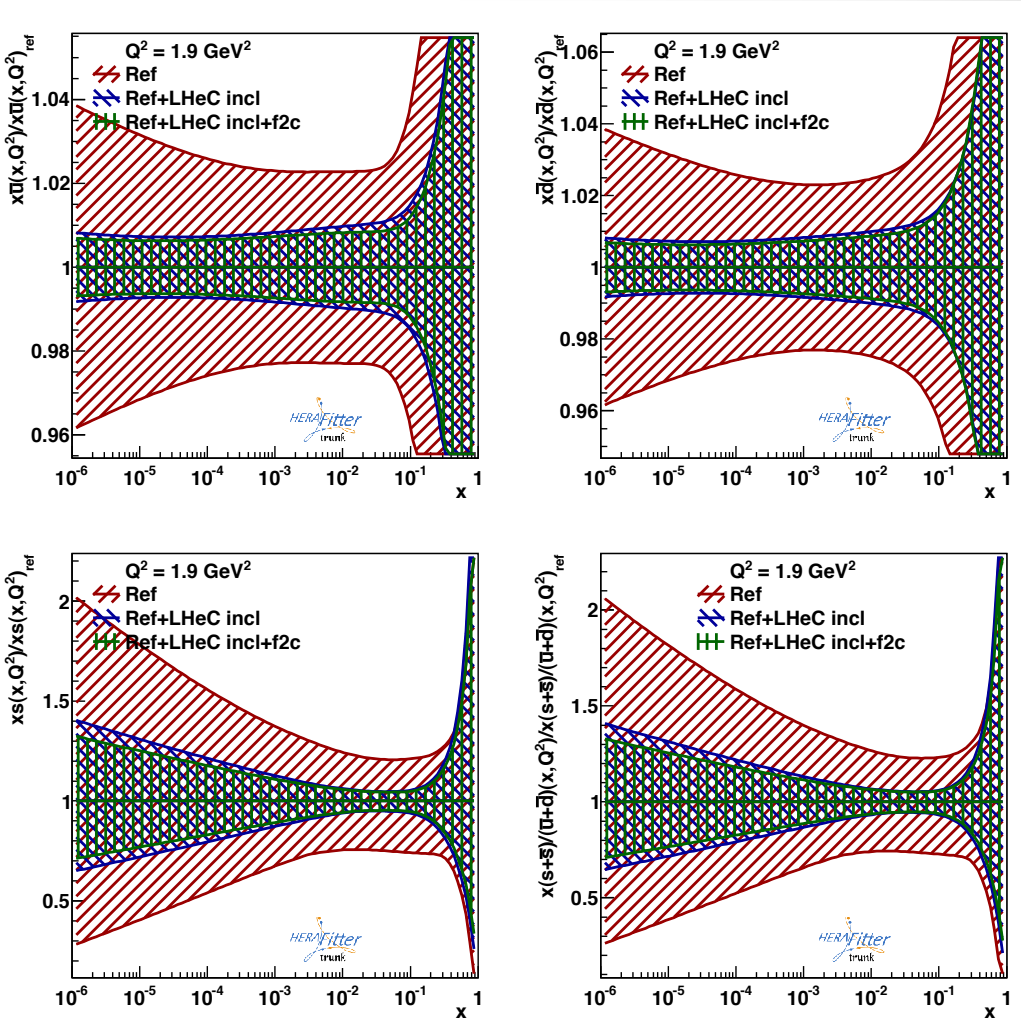
HERA	NC cross section HERA-I H1-ZEUS combined e-p.
	NC cross section HERA-I H1-ZEUS combined e+p.
	CC cross section HERA-I H1-ZEUS combined e-p.
	CC cross section HERA-I H1-ZEUS combined e+p.
	H1 Low Ep : 460, 575 GeV
Tevat.	CDF inclusive jets
	CDF Z rapidity 2010
	D0 pp jets
	D0 Z rapidity 2007
	D0 W asymmetry 2013
	D0 W-¿mu nu lepton asymmetry ptl ¿ 35 GeV
	CDF W asymmetry 2009
fixed target	BCDMS F2p 100GeV
	BCDMS F2p 120GeV
	BCDMS F2p 200GeV
	BCDMS F2p 280GeV
LHC	ATLAS Jet data 0 ¡= —y— ¡ 0.3
	ATLAS Jet data 0.3 ¡= —y— ¡ 0.8
	ATLAS Jet data 0.8 ¡= —y— ¡ 1.2
	ATLAS Jet data 1.2 ¡= —y— ¡ 2.1
	ATLAS Jet data 2.1 ¡= —y— ¡ 2.8
	ATLAS Jet data 2.8 ¡= —y— ¡ 3.6
	ATLAS Jet data 3.6 ¡= —y— ¡ 4.4
	ATLAS Z rapidity, 2010 data
	ATLAS W+ lepton pseudorapidity, 2010 data
	ATLAS W- lepton pseudorapidity, 2010 data



LHeC can precisely constrain all PDFs

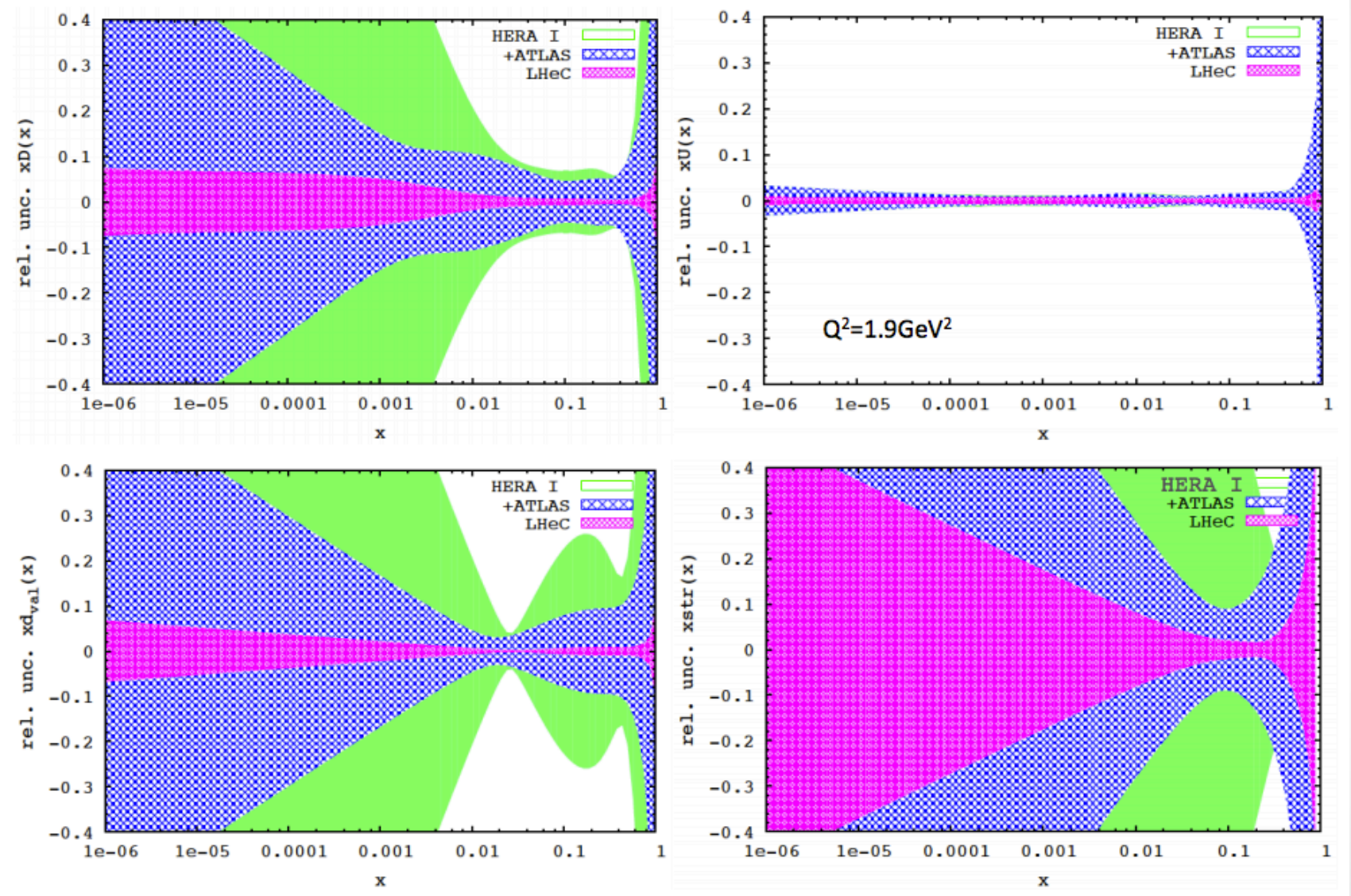
LHeC PDFs c.f. world data

	Ref
HERA	NC cross section HERA-I H1-ZEUS combined e-p.
	NC cross section HERA-I H1-ZEUS combined e+p.
	CC cross section HERA-I H1-ZEUS combined e-p.
	CC cross section HERA-I H1-ZEUS combined e+p.
	H1 Low Ep : 460, 575 GeV
Tevat.	CDF inclusive jets
	CDF Z rapidity 2010
	D0 pp jets
	D0 Z rapidity 2007
	D0 W asymmetry 2013
	D0 W-¿mu nu lepton asymmetry ptl ¿ 35 GeV
	CDF W asymmetry 2009
fixed target	BCDMS F2p 100GeV
	BCDMS F2p 120GeV
	BCDMS F2p 200GeV
	BCDMS F2p 280GeV
LHC	ATLAS Jet data 0 ¡= —y— ¡ 0.3
	ATLAS Jet data 0.3 ¡= —y— ¡ 0.8
	ATLAS Jet data 0.8 ¡= —y— ¡ 1.2
	ATLAS Jet data 1.2 ¡= —y— ¡ 2.1
	ATLAS Jet data 2.1 ¡= —y— ¡ 2.8
	ATLAS Jet data 2.8 ¡= —y— ¡ 3.6
	ATLAS Jet data 3.6 ¡= —y— ¡ 4.4
	ATLAS Z rapidity, 2010 data
	ATLAS W+ lepton pseudorapidity, 2010 data
	ATLAS W- lepton pseudorapidity, 2010 data

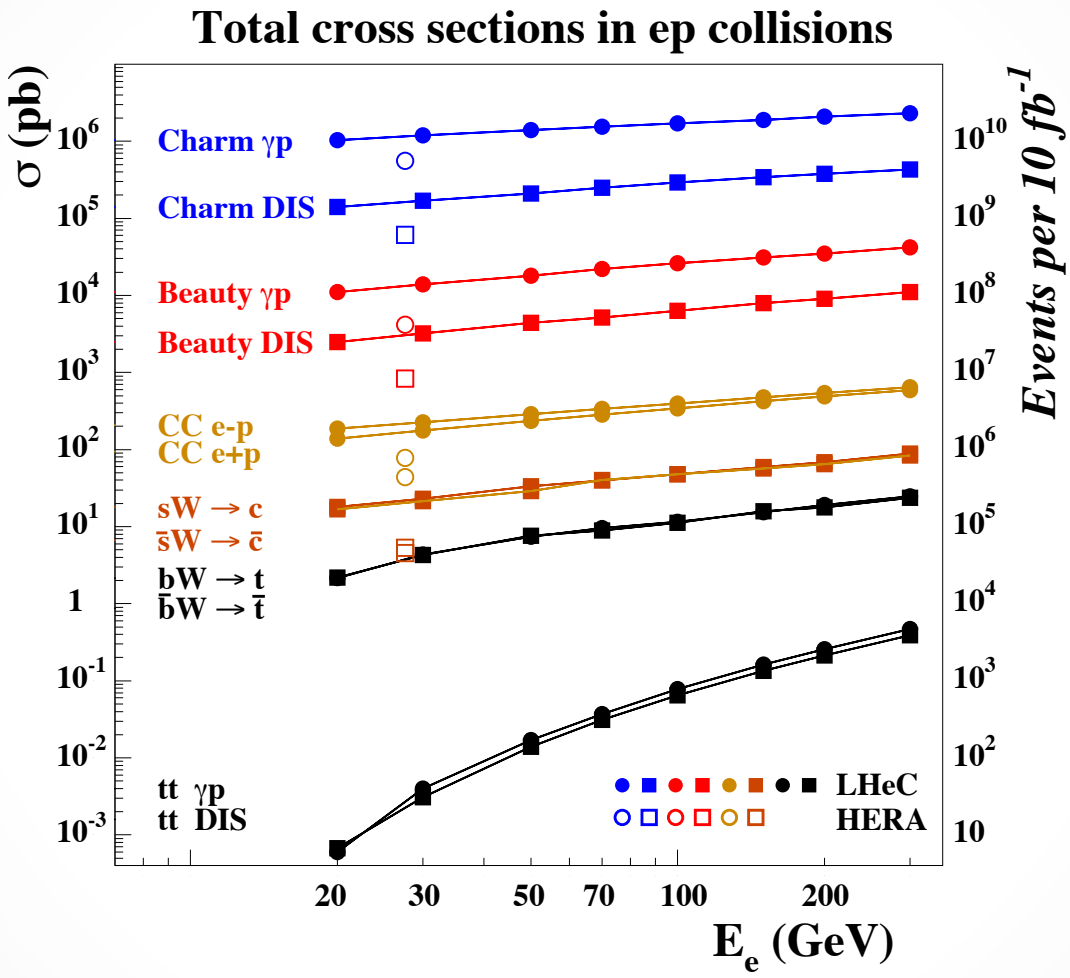


LHeC can precisely constrain all PDFs

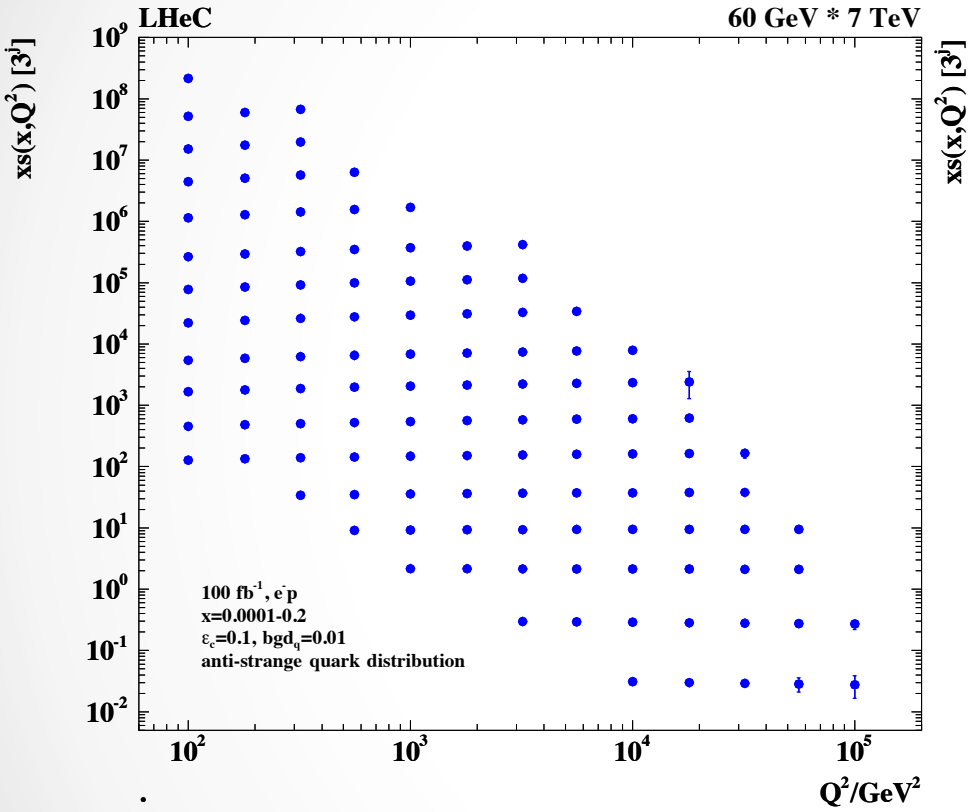
LHeC PDFs with released assumptions

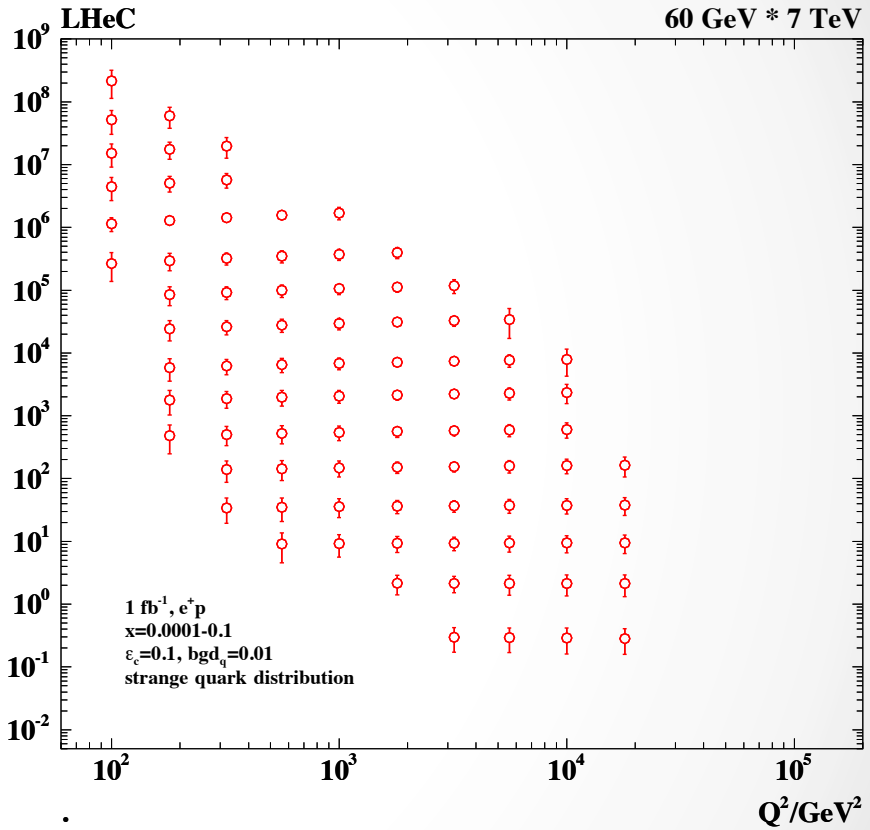


LHeC heavy flavour cross sections

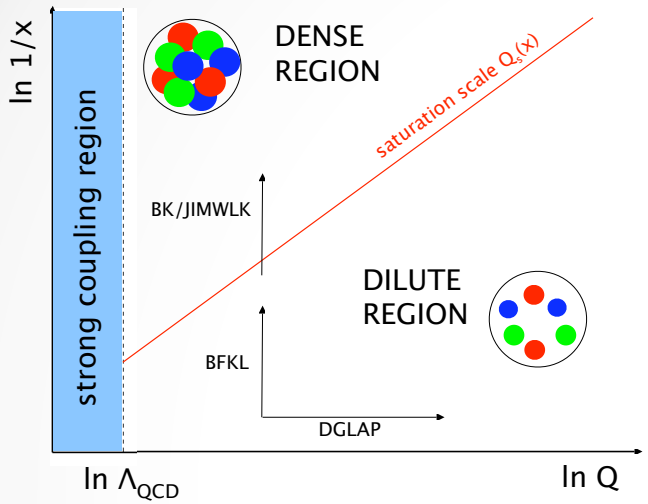


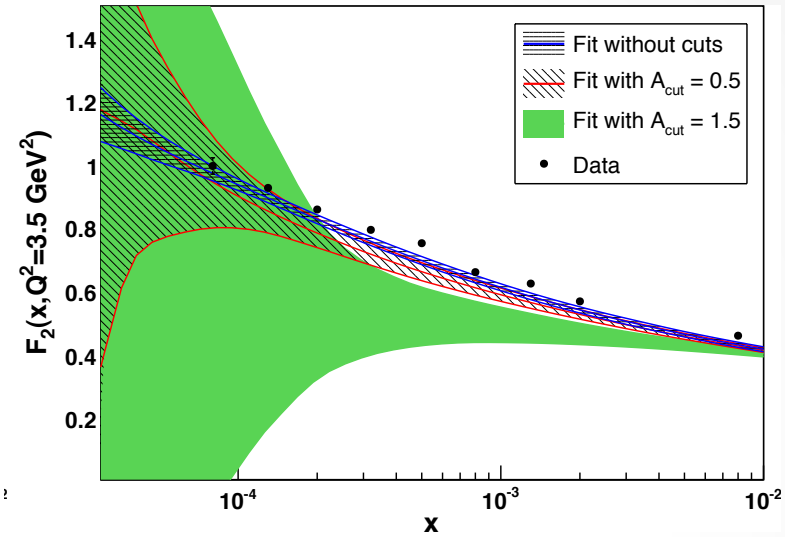
(anti-)strange – new LHeC scenario

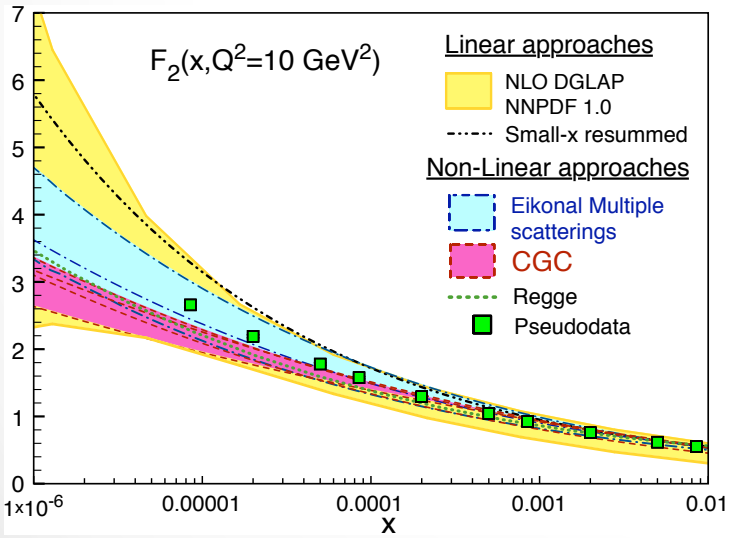


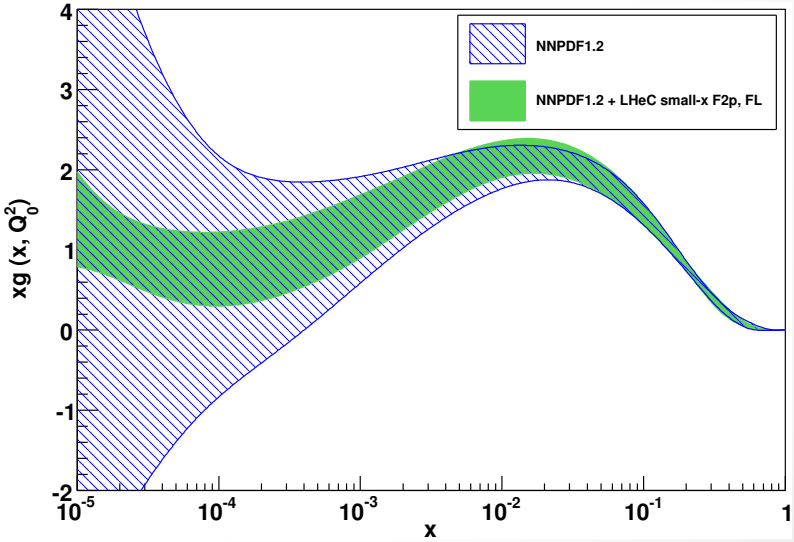


partons at low x





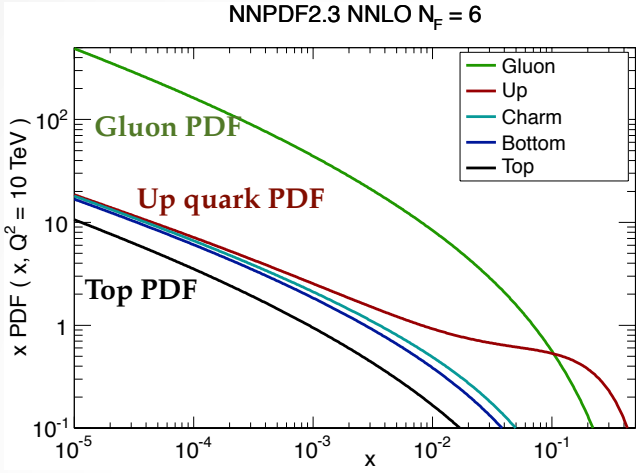


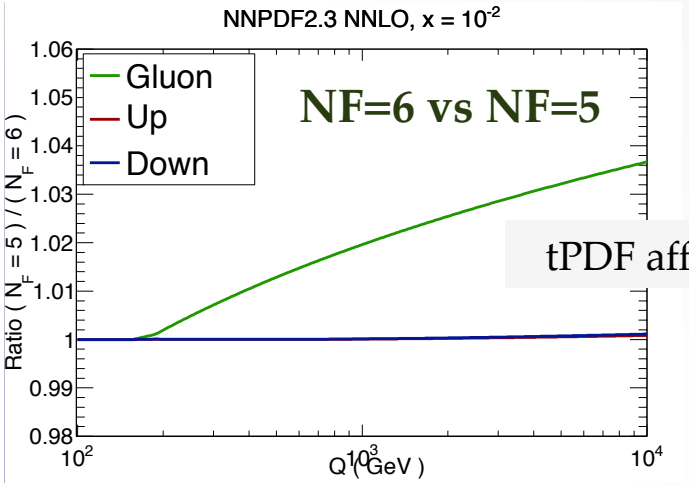


- also see talk of A. Sasto

some other considerations for the future

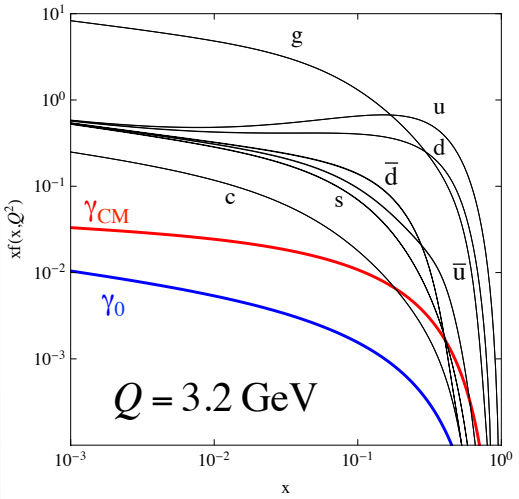
top PDF

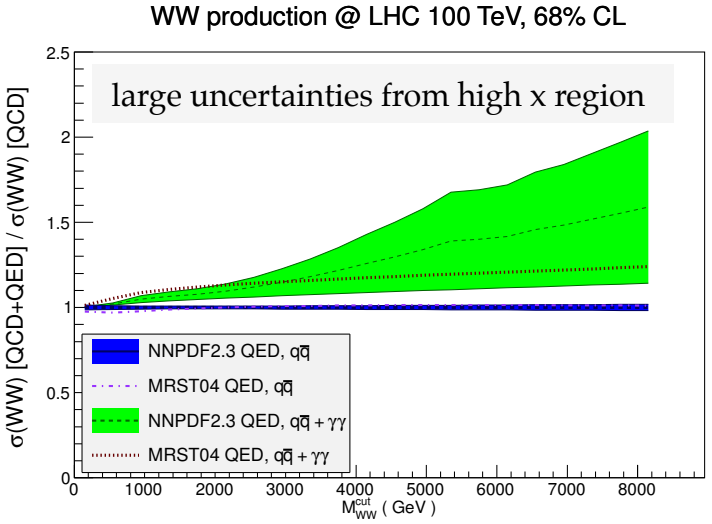




tPDF affects gluon

photon PDF



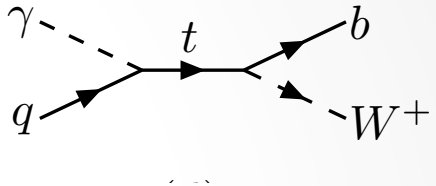


NNLO PDFs might also be needed, if scale not dominant uncertainty, and data highly precise

top quark FCNC

- **top quark expected to be most sensitive to BSM physics, due to large mass**
- precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations)

LHeC operating as γp collider: sensitive to anomalous tqγ vertices – can reach much better limits in κ/Λ than LHC

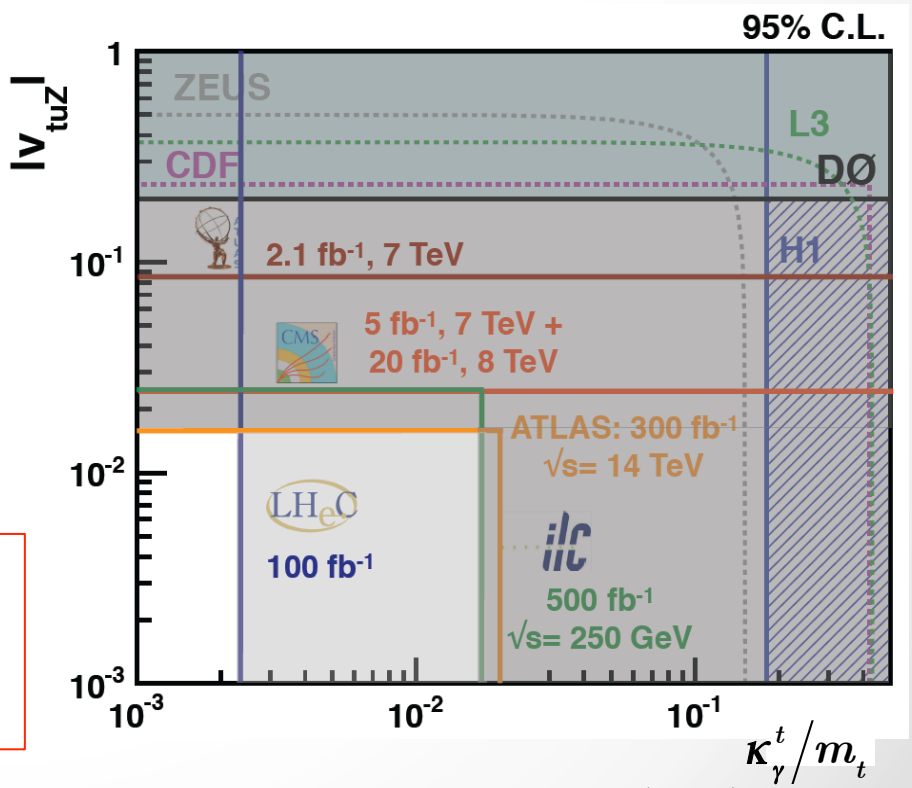


κ= anomolous FCNC coupling
Λ= new physics scale

κ/Λ= 0.01= BR 2×10^{-6} (two orders of magnitude better than LHC reach with 100fb^{-1})
(can also explore κu≠κc)

SS	$L = 2$ fb^{-1}	$L = 10$ fb^{-1}
$\kappa/\Lambda = 0.01$ TeV^{-1}	2.6 (2.9)	5.8 (6.5)
$\kappa/\Lambda = 0.02$ TeV^{-1}	5.3 (5.9)	11.8 (13.3)

new physics models: SUSY, technicolour, little Higgs, extra dimensions, … predict BR=O(10^{-5})



O. Cakir, S. Sultansoy, PL B685,170 (2010)