A Future for xFITTER

Energy Frontier DIS

Realisation of the LHeC

The PDF Programme

A Data Base for LHeC/FCCeh

Simulations and Needs

LHeC:
E_e=60 GeV
x E_p= 7 TeV

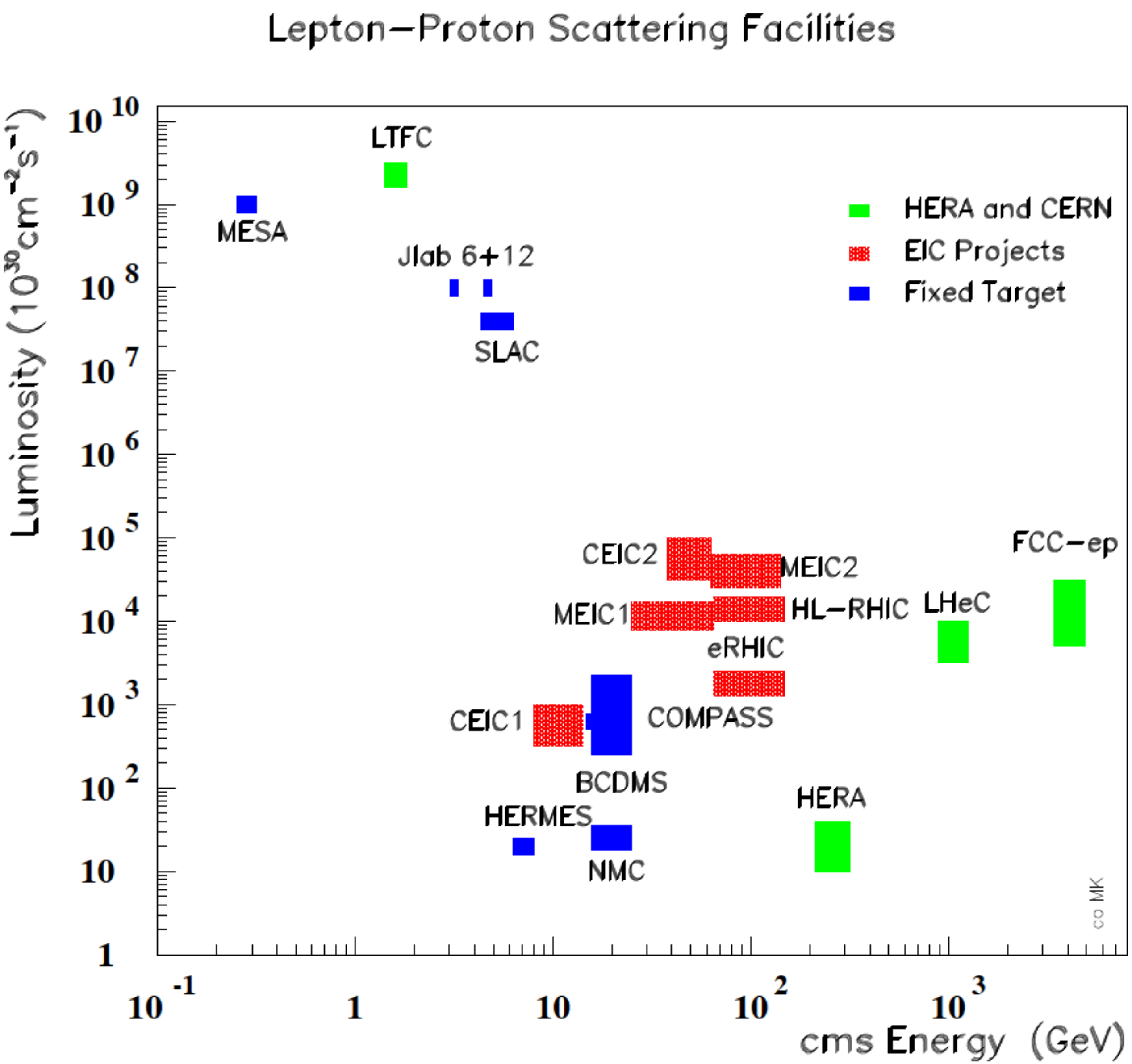
For references,
please consult
lhec.web.cern.ch
LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

Max Klein
University of Liverpool
for the LHeC Study Group

FCC_eh:
E_e=60 GeV
x E_p =50 TeV

xFITTER Meeting at Oxford, UK, 20.3.2017

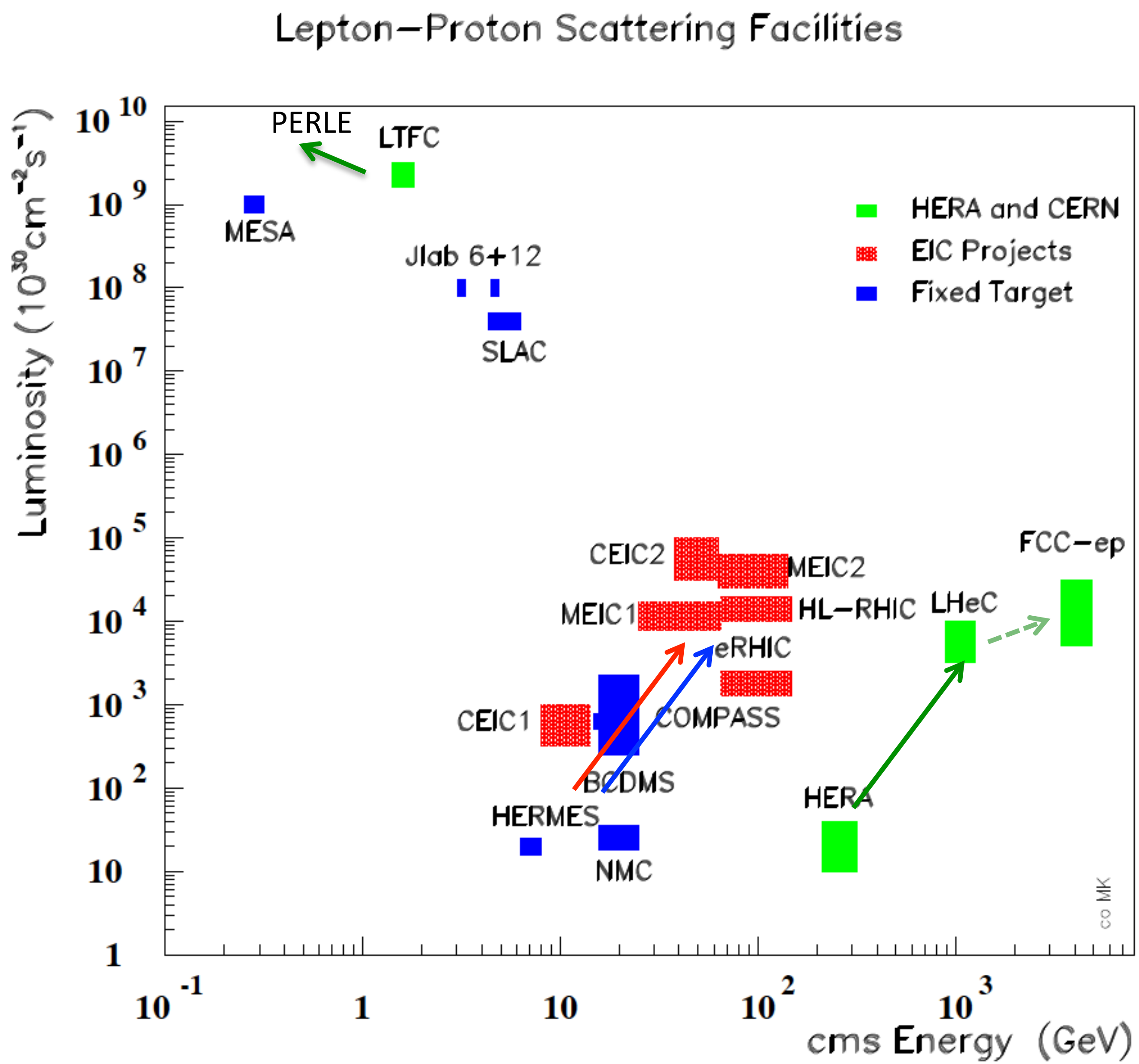
Intensity and Energy Frontier of Future DIS



From CERN Courier
MK, H.Schopper
June 2014

With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

Intensity and Energy Frontier of Future DIS



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With input from
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A new high energy, high luminosity ep collider?

High energy: $\sqrt{s}=2\sqrt{(E_e E_p)} \approx 1$ TeV or more, for

Higgs, BSM, top, high Q^2: charged currents, elweak, low x~1/E…

High Luminosity: $L = O(10^{34})\ cm^{-2}\ s^{-1}$ in order to *really* access

Higgs physics, high Q^2 to $10^6\ GeV^2$, high x up to 0.9 in NC and CC ep

Concurrently to pp and e^+e^- → operation in 2030+

Extra Motivations

A new accelerator for CERN, a new detector/experiment for HEP, a sustained HL-LHC, a bridge to the 10 TeV super colliders, a boost to technology (SCRF, ERL, Si…)

QCD - Developments and Discoveries

AdS/CFT

Instantons

Odderons

Non pQCD

QGP

N^kLO

Resummation

Saturation and BFKL

Non-conventional PDFs …

Breaking of Factorisation

Free Quarks

Unconfined Color

New kind of coloured matter

Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background. The contribution of the LHeC to that can not be overestimated.

Potential of ep Colliders at CERN

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

FCC Note April 2017, to appear

Baseline of ep at (HL+HE)-LHC and FCC-eh

.. a 3 turn, two fold, high current, 802 MHz energy recovery linac

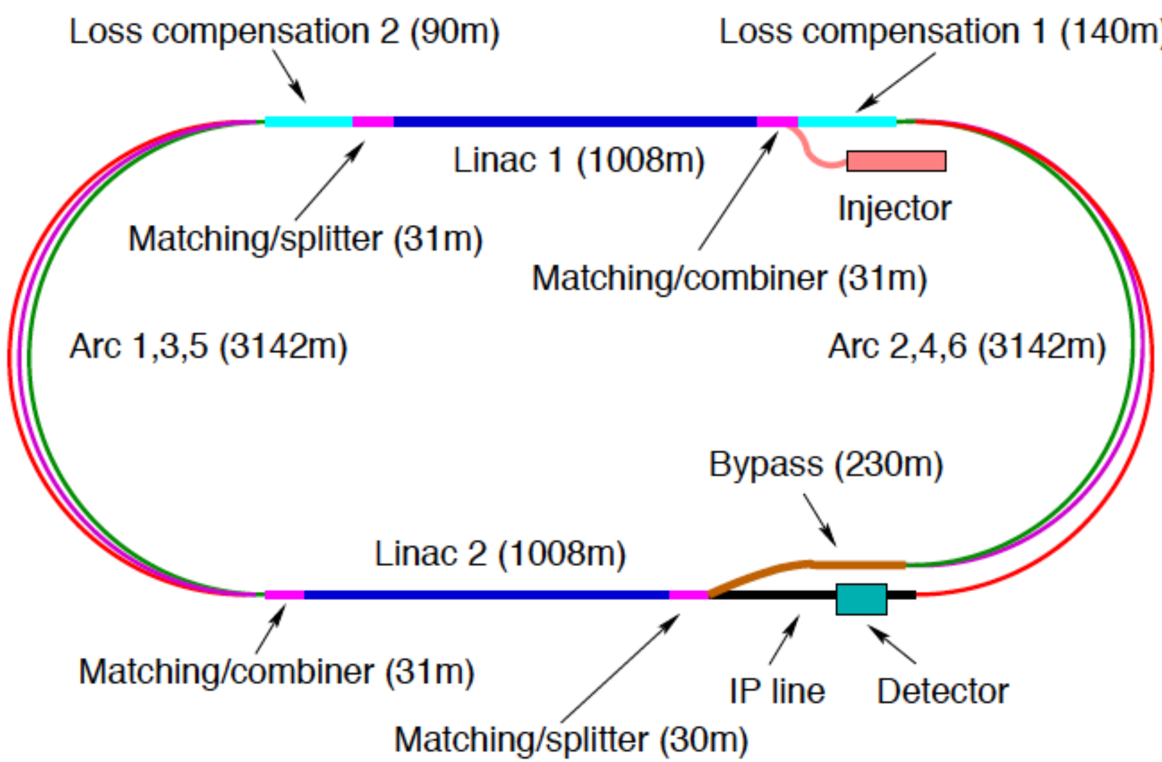
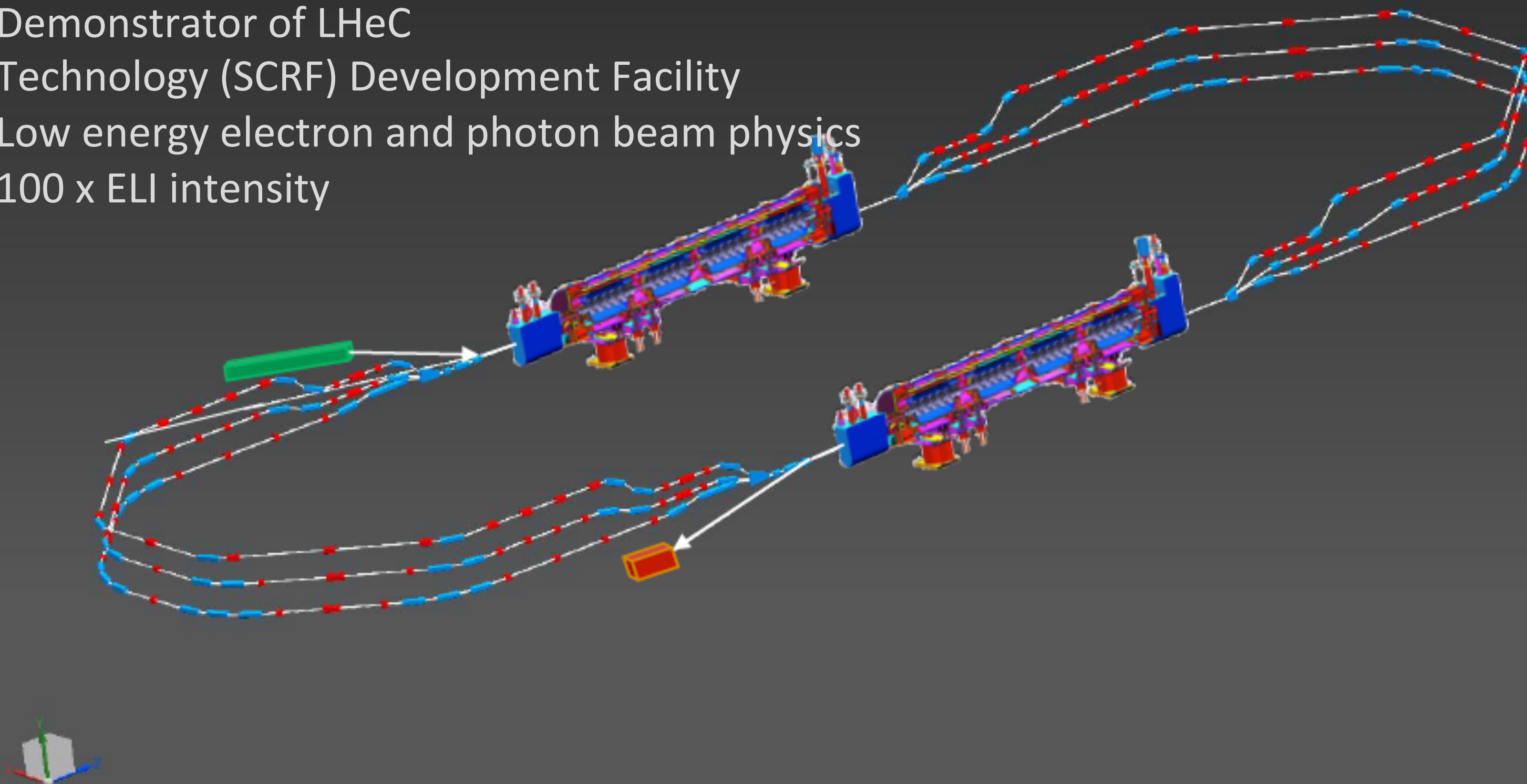


Figure 2: Schematic view of the default LHeC configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite lying linac structures made of 60 cavity-cryo modules each. The arc radius is about 1 km and the circumference chosen to be 1/3 of that of the LHC. The beam is decelerated for recovering the beam power after having passed the IP.

Powerful ERL for Experiments (ep.γp): PERLE at Orsay

PERLE at Orsay: New Collaboration of
BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +
CDR publication imminent.
3 turns, 2 Linacs, 15mA, 802 MHz ERL facility
Demonstrator of LHeC
Technology (SCRF) Development Facility
Low energy electron and photon beam physics
100 x ELI intensity



See https://indico.lal.in2p3.fr/event/3428/

Location and E-Cost Scaling for e ERL

U(LHeC)=1/3U(LHC), 60 GeV -→ 1/5(LHC) 51 GeV at much reduced cost. SPS: 1/4(LHC)

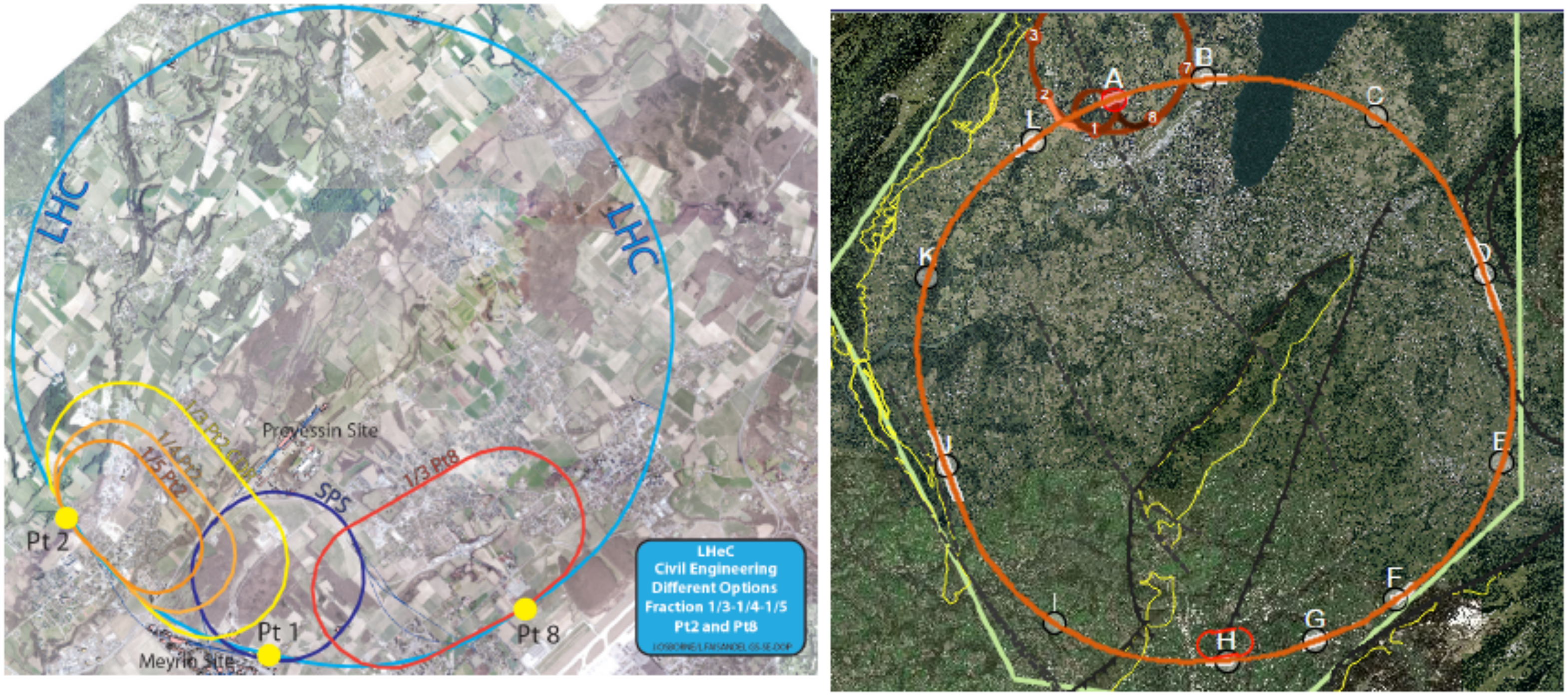


Figure 3: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\mathrm{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\mathrm{GeV}$) and 1/5 (most inner track, $E_e = 52\,\mathrm{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Geological considerations suggest a preference for Point H, left from Point G housing one of the large GPDs conceptually while location L may be a possibility too.

Now to PDFs

Physics of Parton Distributions

There are many, some fundamental, problems with the collinear, classic PDFs:

- Poor data base (HERA limited in range and luminosity), data inconsistent though "tolerated"
- Dependence on parametrisations, α_s, and theory assumption (heavy flavour, intrinsic s,c,b)
- Many assumptions/distortions: nuclear corrections, higher twists, poor hi x, isospin, HQ (s)
- Unpleasant mix of lp and pp data input and fits: may hide QCD issues (factorisation, resummation, hadronisation) and screen subtle occurrence of new physics as at large x

And there are many more parton distributions known to a much lesser extent such as

- Generalised Parton Distributions [DVCS] – "proton in 3D – tomography"
- Unintegrated Parton Distributions [Final State] – DGLAP/BFKL?
- Diffractive Parton Distributions [Diffraction] – pomeron, confinement??
- Photon Parton Distribution [Photoproduction Dijets,QQ; $F_{2,L}$] - fashionable..
- Neutron Parton Distributions [Tagged en (eD) Scattering] – ignored at HERA

→ New ep collider(s) have a fundamental task in understanding the substructure of matter
→ Much but far from all of this we discussed in the LHeC Conceptual Design Report

Simulation of inclusive NC and CC ep Cross Sections

- Determination of PDFs using only inclusive NC and CC simulated data
- Numerical treatment of correlated and uncorrelated systematic and statistical errors
  [based on PHE-1990-02 (J.Blümlein, M.K.), cross checked with H1 Monte Carlo]

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Initial assumptions, realistic for H1

- Data input to QCD analysis using **xFITTER,** Hessian Errors cross-checked MC replica used for various sets, assumptions, targets: p also A (Armestor, Paukuuen)
- see LHeC CDR and description in: Voica Radescu, MK

Contribution to Snowmass 2013, LHeC-Note-2013-002. PDF set available on LHAPDF5.1 →6

NC Cross Section Correlated Uncertainties (Q^2=2 GeV^2)

Angular and energy calibration errors keep uncertainties to (much) below 1%

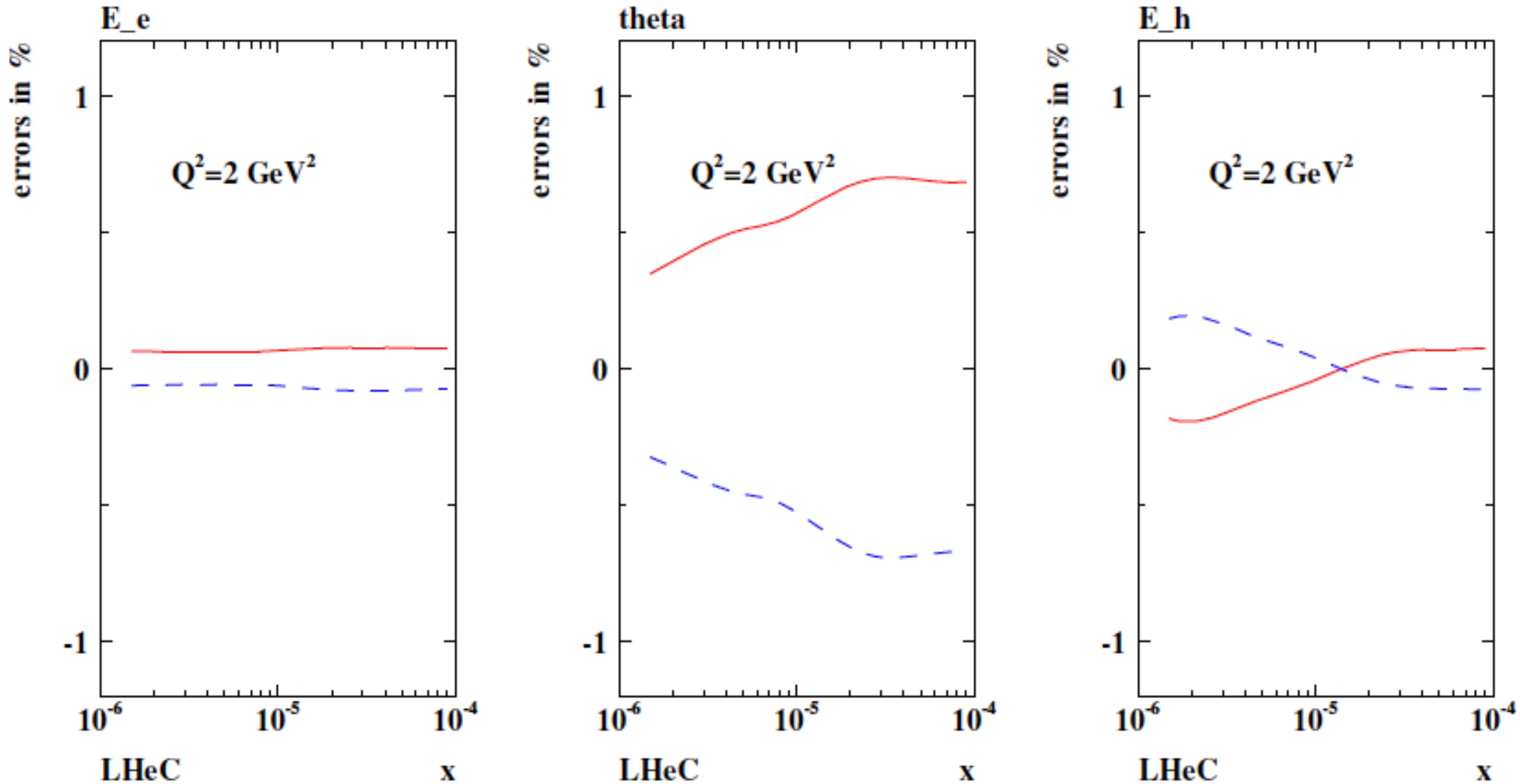


Figure 3.2: Neutral current cross section errors, calculated for $60 \times 7000\,\text{GeV}^2$, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\text{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at low $Q^2 = 2\,\text{GeV}^2$ and correspondingly low x.

From LHeC CDR

NC Cross Section Correlated Uncertainties (Q^2=20000 GeV^2)

Angular and energy calibration errors keep uncertainties to (much) below 1% - but high x is hard

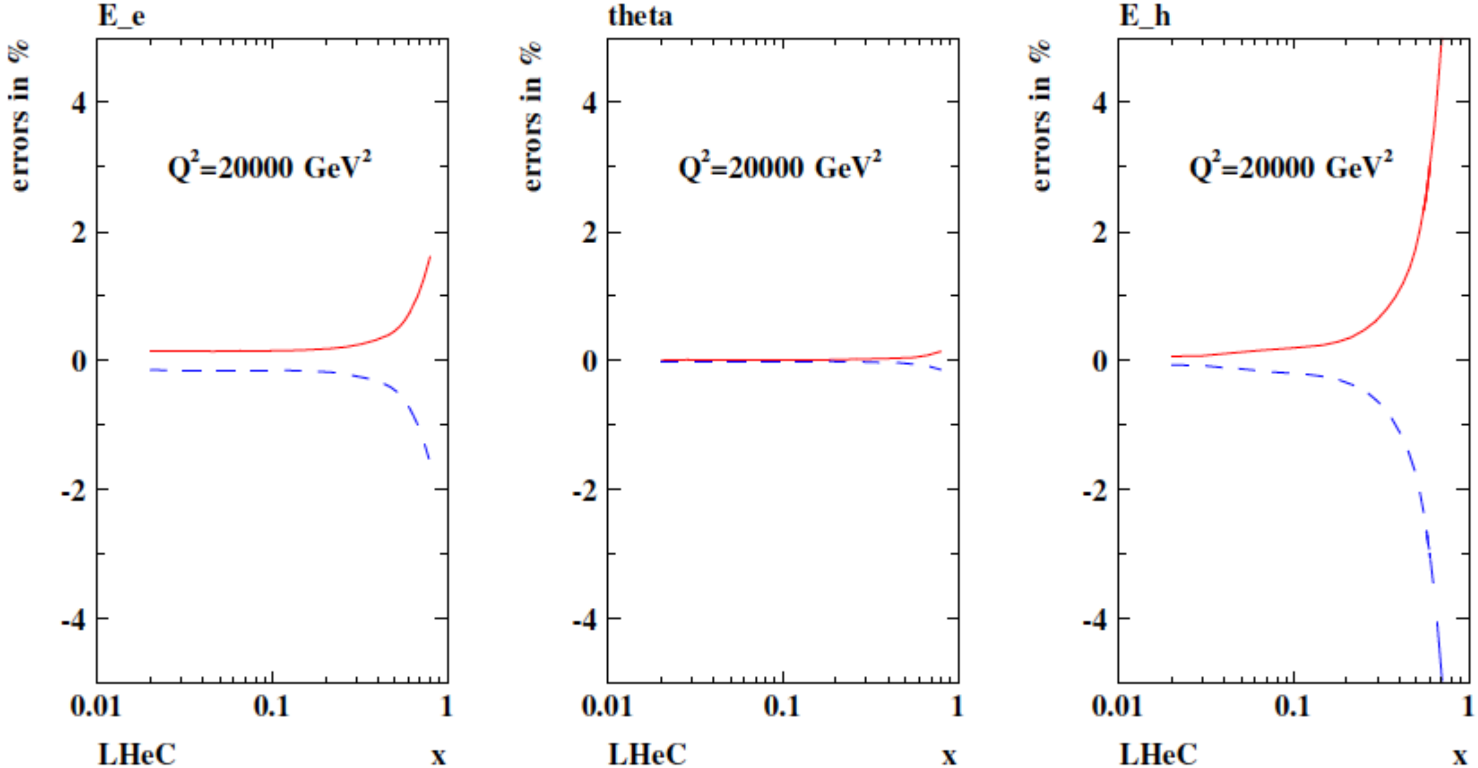
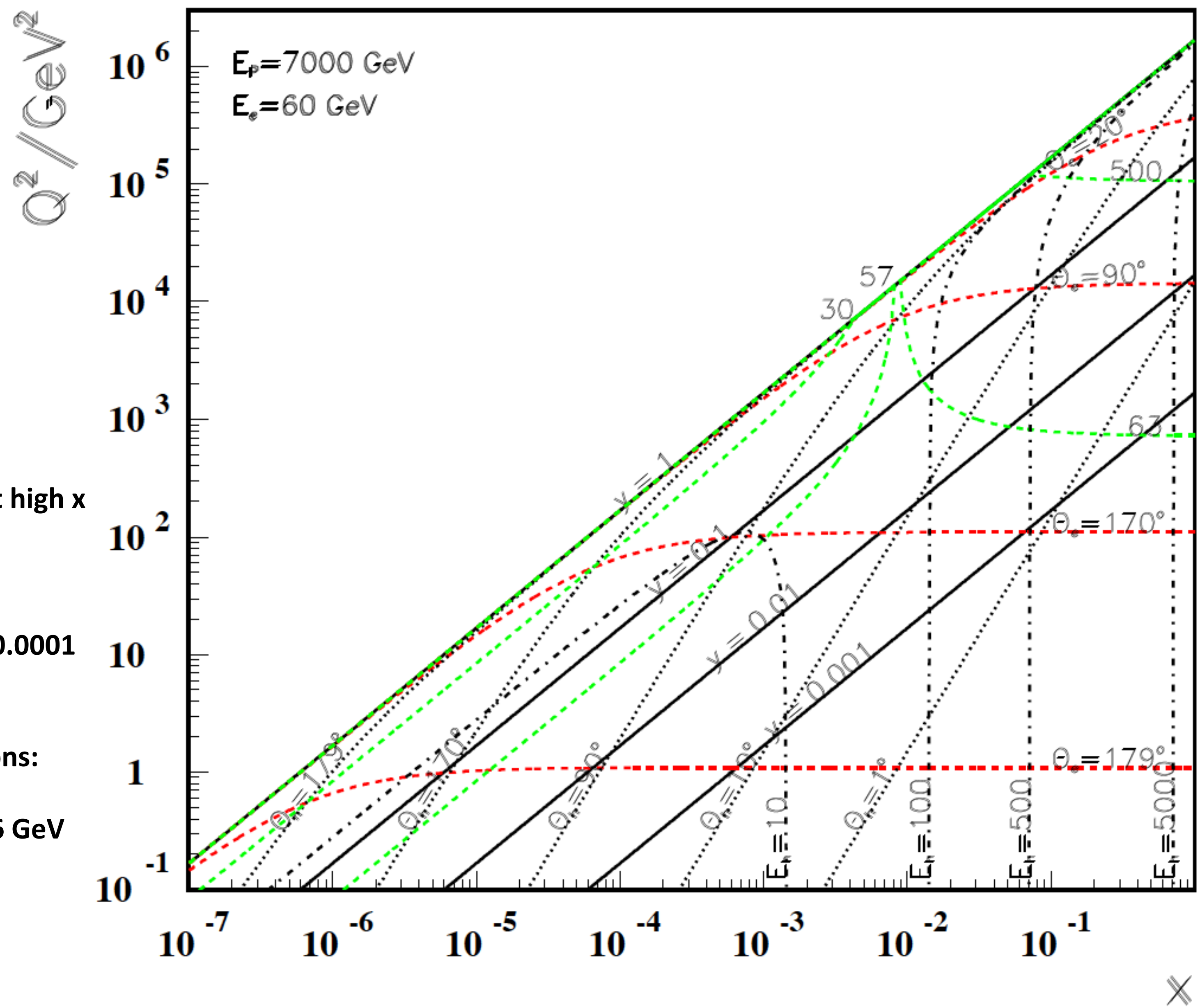


Figure 3.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised e^-p scattering, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at large $Q^2 = 20000\,\mathrm{GeV}^2$ and correspondingly large x. Note that the characteristic behaviour of the relative uncertainty at large x, i.e. to diverge $\propto 1/(1-x)$, is independent of Q^2, i.e. persistently observed at $Q^2 = 200000\,\mathrm{GeV}^2$ for example too.

From LHeC CDR

Kinematics at LHeC Nominal energies



Observations

Good angular coverage but at high x low Q2

High Q^2 to 10^6
CC at large x > 0.0001

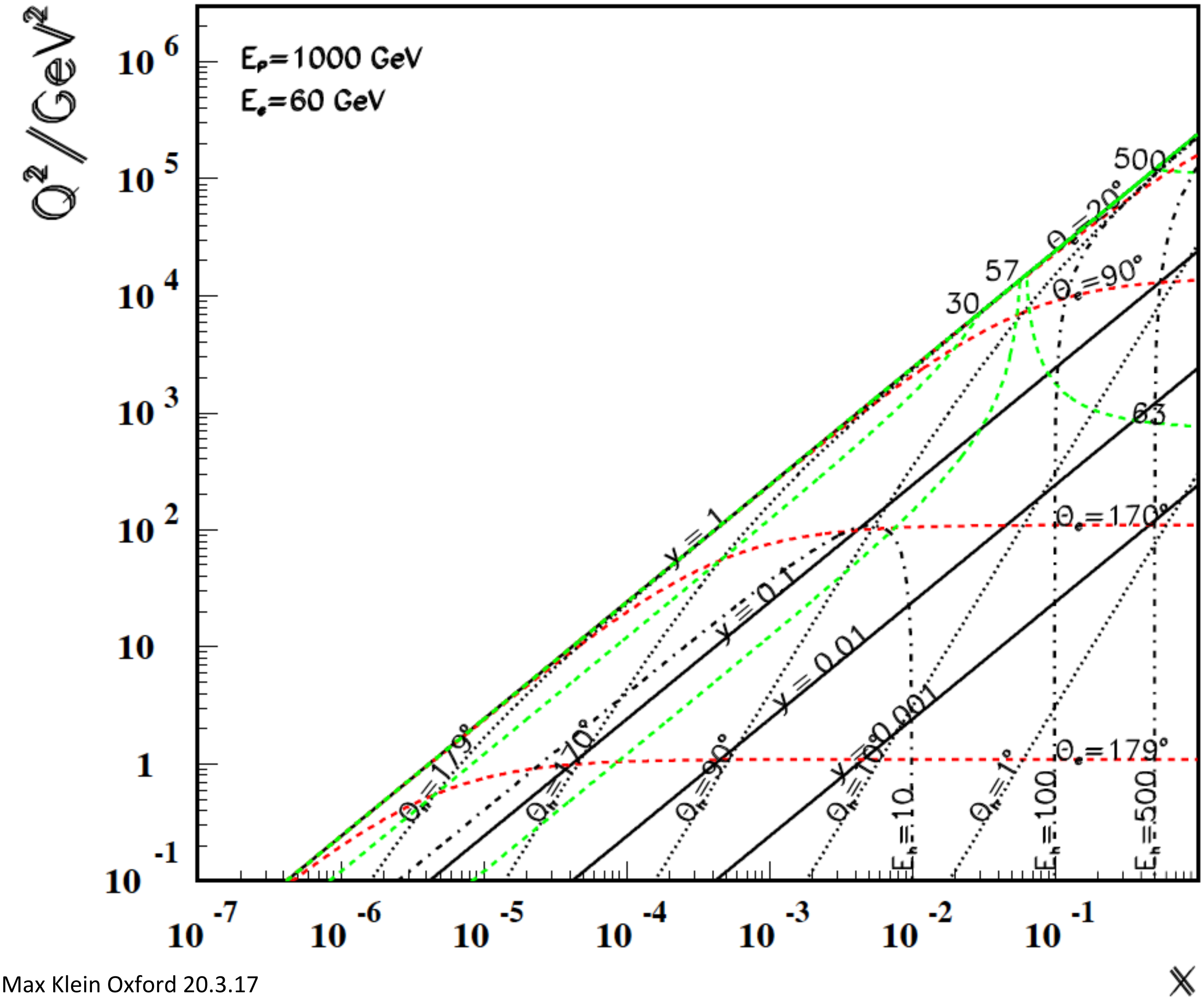
Low Q^2 High x
Very fwd hadrons:

High y =0.9 → 6 GeV
F_L "easy"

Kinematics at LHeC

Lowered proton energies

$$Q^2\ (x, \theta_{h,min}) \simeq [2E_p x \tan^2(\theta_{h,min}/2)]^2$$



← B EIC

Lower E_p to access high x at lower Q^2

Modest Luminosity required

Max Klein Oxford 20.3.17

Data Sets

see: http://lhec.web.cern.ch and http://xfitter/hepforge.org/data/hml

LHeC (to be updated wrt CDR and intermediate studies)

[this should be “doubled” for HE LHC, 12.5 TeV x 60 GeV]

$L=1ab^{-1}$ electrons $P=-0.8$: maximum CC cross section for Higgs
$L=0.3ab^{-1}$ electrons $P=+0.8$ for electroweak physics
$L=0.1\ ab^{-1}$ low $E_p= 1TeV$ to access high x, medium Q^2
$L=0.1\ ab^{-1}$ positrons
$L=0.0015\ ab^{-1}$ low E_e sets for F_L and the transition to γp

FCC-eh (50 TeV x 60 GeV)

simulated 16.3.17 (MK)

$L=1ab^{-1}$ electrons $P=-0.8$: maximum CC cross section for Higgs
$L=0.3ab^{-1}$ electrons $P=+0.8$ for electroweak physics
$L=0.1\ ab^{-1}$ low $E_p= 7$ TeV to access high x, medium Q^2
$L=0.1\ ab^{-1}$ positrons

Remember: HERA is $0.001ab^{-1}$ and $0.00001ab^{-1}$ for F_L

Prior to Some Results:

Often shown. Time for

Extensions: release assumptions, integrate HQ into fits, top?, consider ep+eA

Updates: new data sets, modified assumptions, HE LHC and FCC-eh, electroweak..

Deeper analyses: joint study with pp: pp precision, theory limitations/tests; **jets in ep**

Enlarged circle of analysers

welcome to LHeC/FCC-eh study: Physics Working Groups (LHeC+FCC-eh):

-Higgs: Uta Klein and Masahiro Kuze

-Top: Olaf Behnke and Christian Schwanenberger joint bi-weekly meetings

-QCD+PDFs: Fred Olness and Voica Radescu: meeting later today

-Low x: Paul Newman and Anna Stasto

-Nuclear Dynamics: Nestor Armesto joint bi-weekly meetings

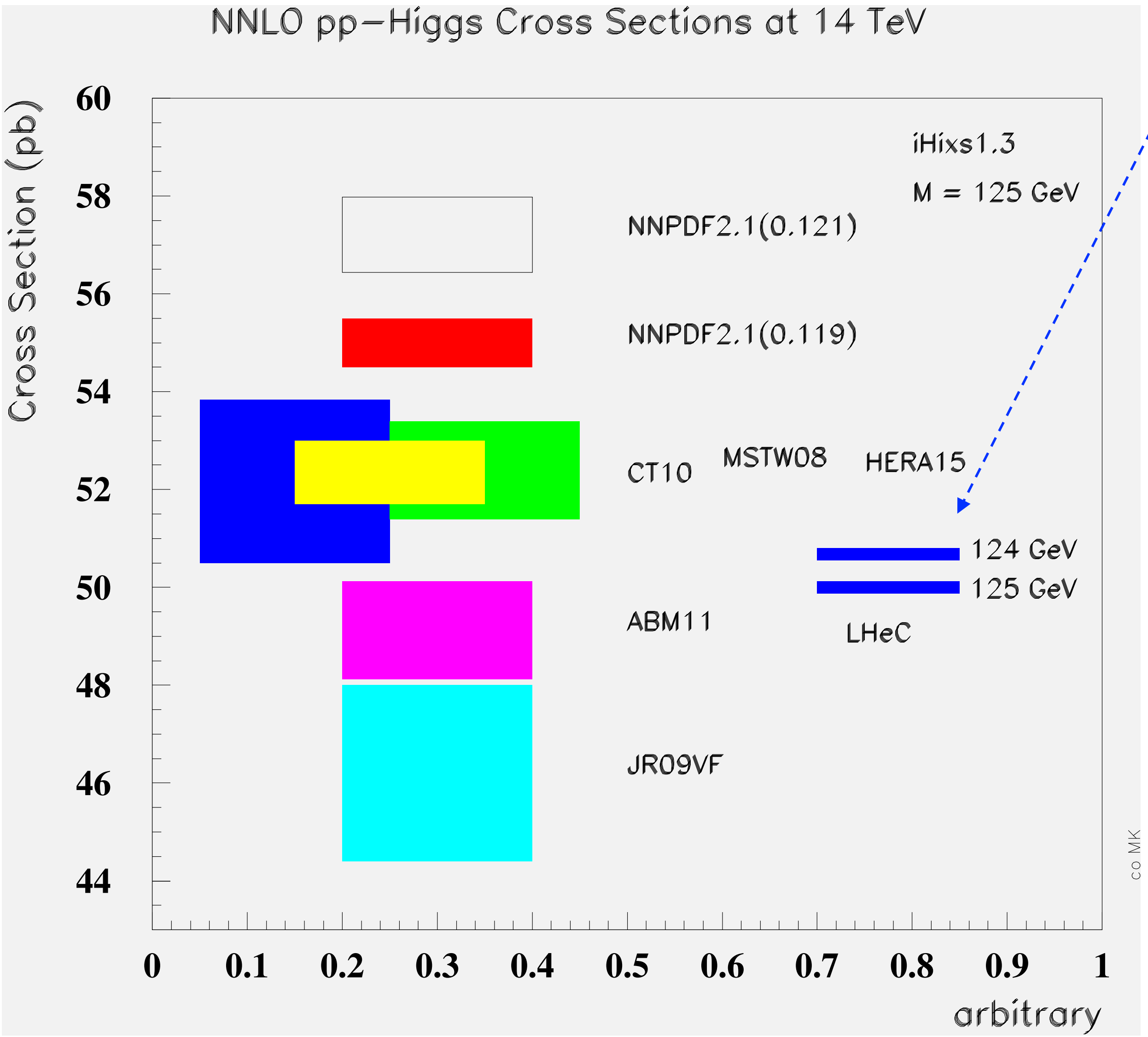
-BSM: Monica D'Onofrio and Georges Azuelos bi-weekly meetings

-Detector and Software: Alessandro Polini and Peter Kostka

FCC Physics: Monica D'Onofrio

LHeC Physics: Stefano Forte **LHeC Workshop: September 17. CDR's 2018**

Precision PDFs for Higgs at the LHC



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%). LHeC: 0.0002 !

Needs N^3LO

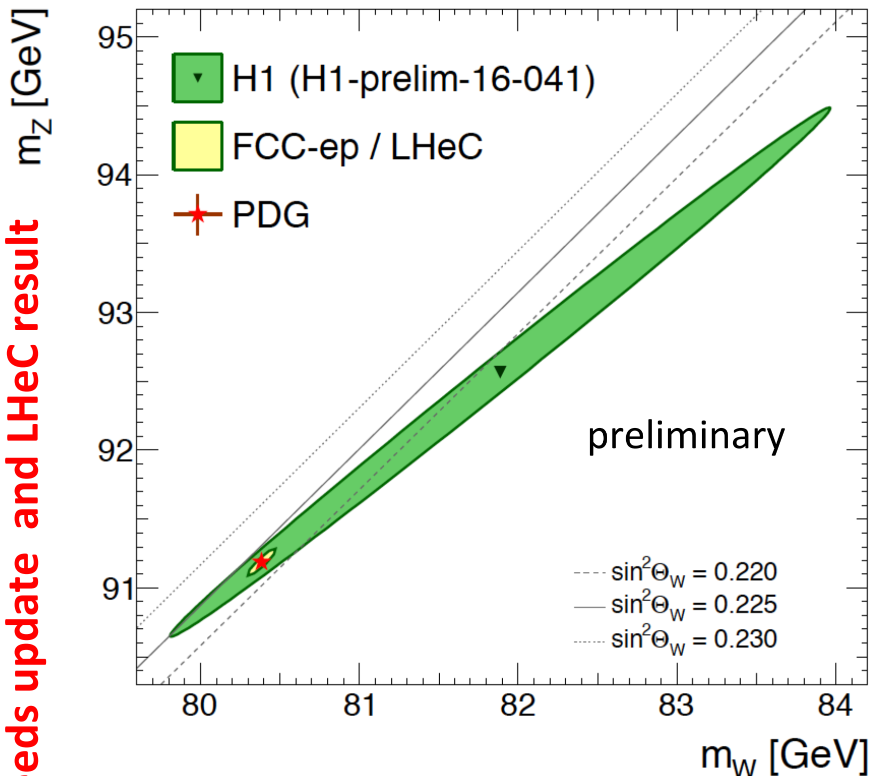
HQ treatment important …

Needs update

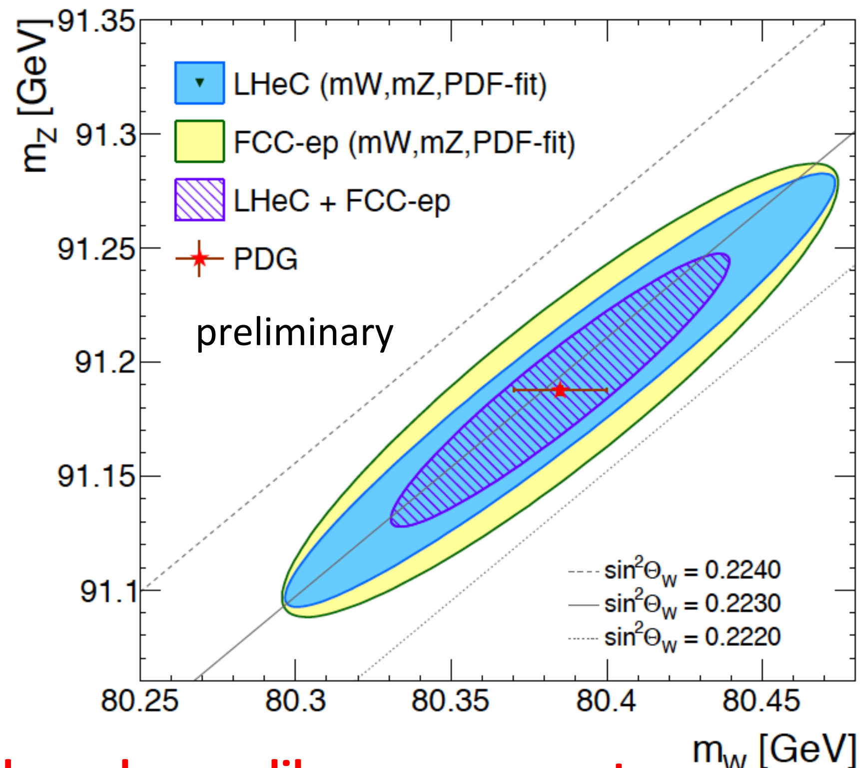
Determination of W,Z Masses in Deep Inelastic Scattering with FCC-eh

D.Britzger, MK
ALPOS (xFITTER)

Needs update and LHeC result



An example study for how LHeC and FCC-eh would improve measurement precision



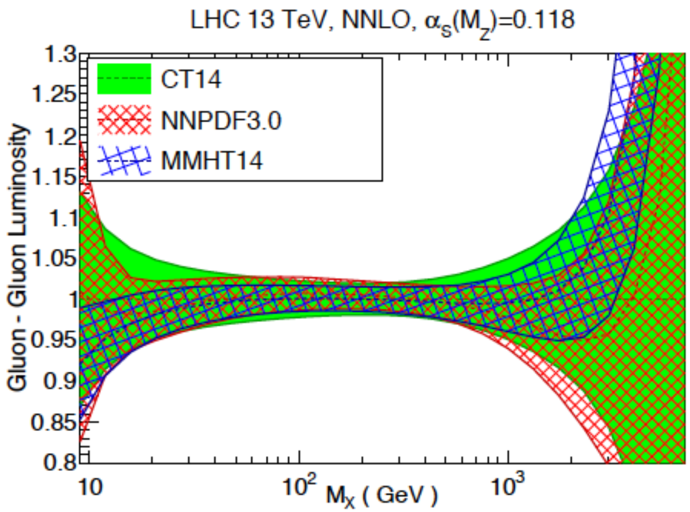
Huge improvement wrt HERA due to higher energy and luminosity

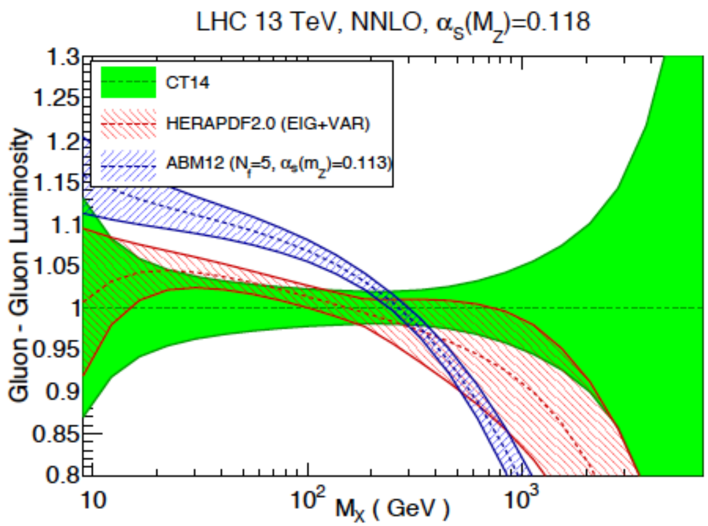
10 MeV MW error important cross check through spacelike measurement
comparable to pp but inferior precision to dedicated timelike ee measurement.

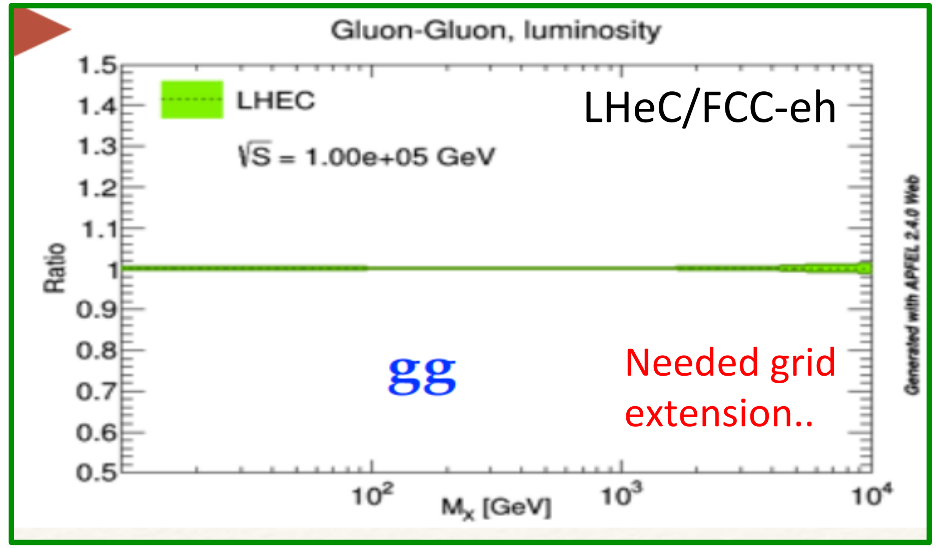
Also: get 3 MeV error on MW in pp from LHeC PDFs (S.Camarda)

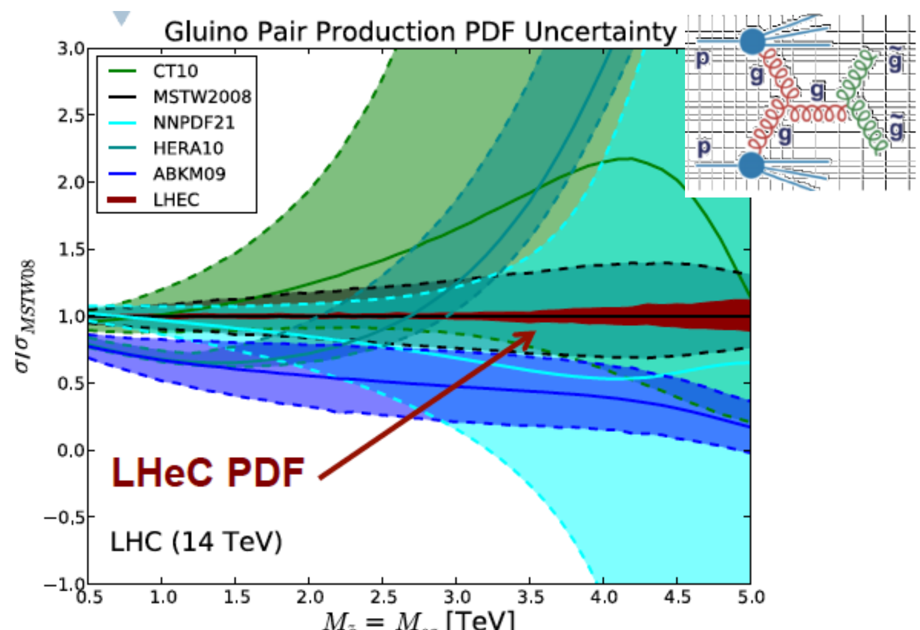
Gluon (gg) Luminosity

Present status





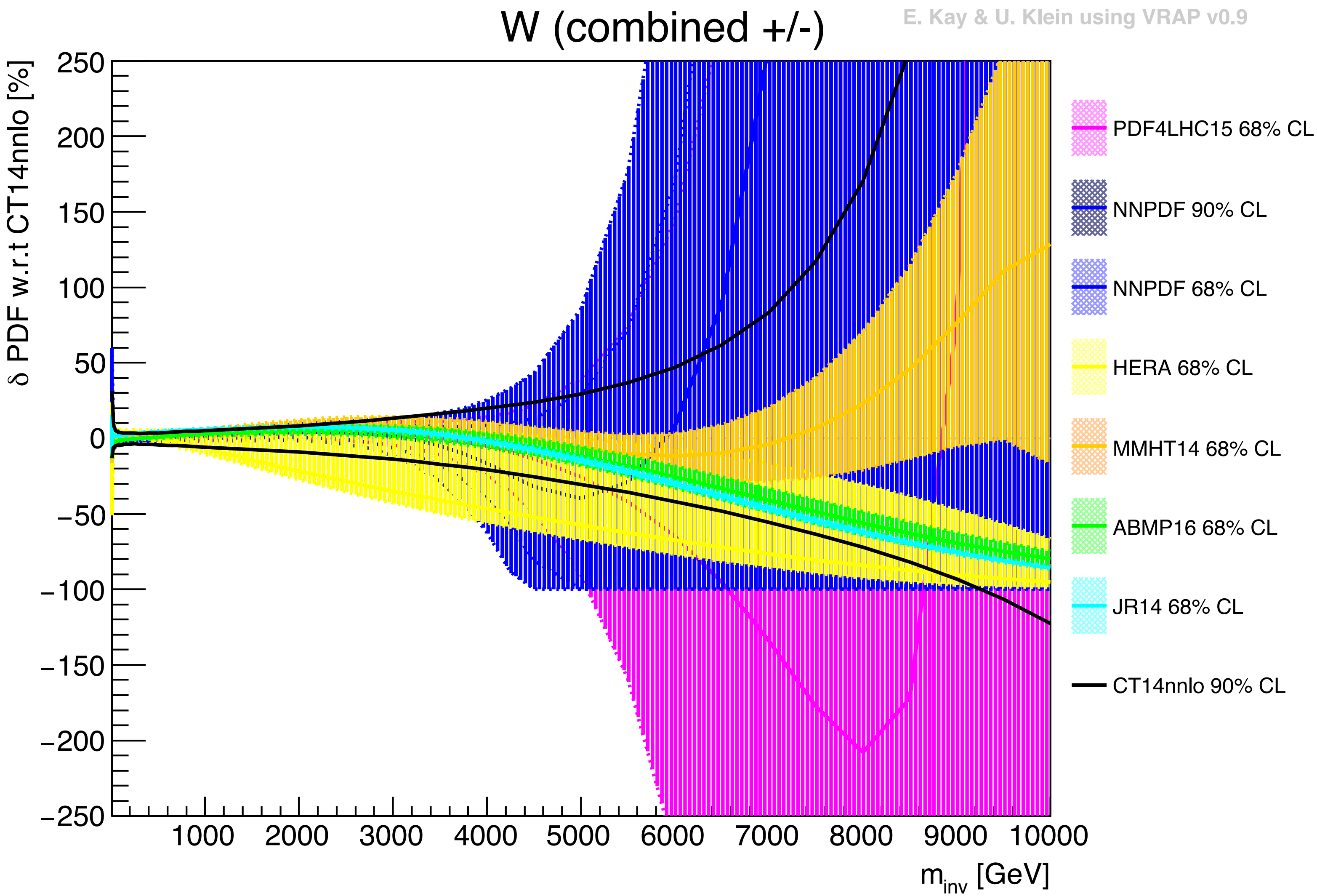




arXiv:1211.5102

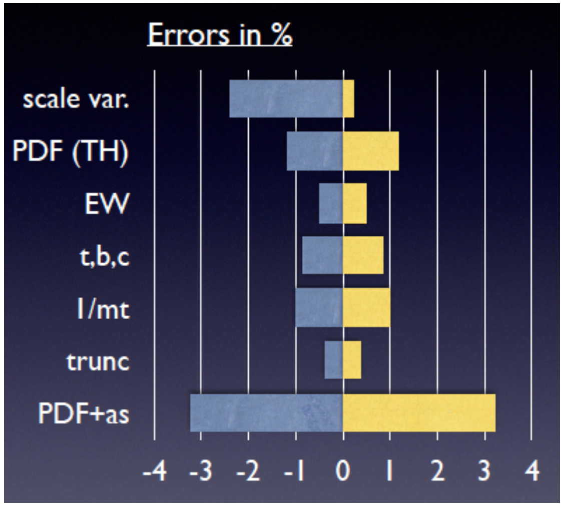
Needs deeper study of relation of ep prospects to search potential at LHC

Searches at LHC, for example W'



Estimated limit with 1% of LHC luminosity

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, this conference,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..

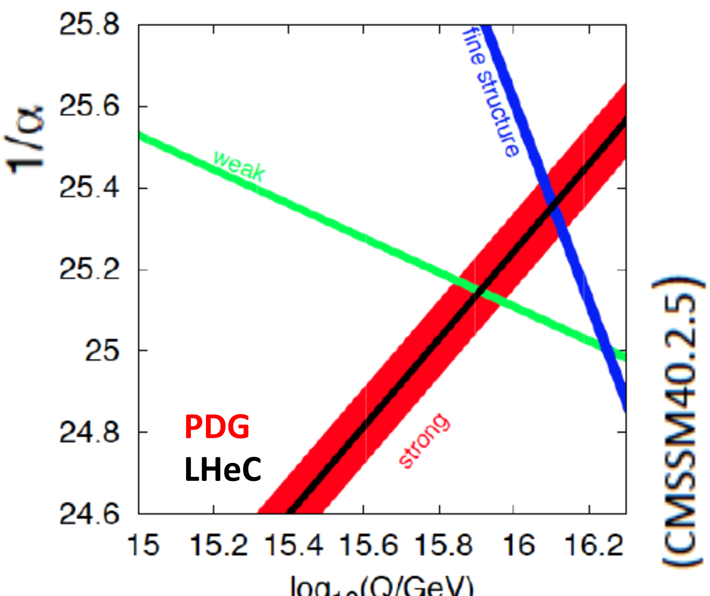
- **α_s least known of coupling constants**
  Grand Unification predictions need smaller $\delta\alpha_s$

- **Is α_s(DIS) lower than world average (?)**

- **LHeC: per mille - independent of BCDMS!**

- **High precision from inclusive data – α_s(jets)??**

- **Challenge lattice QCD** [cf L Del Debbio, this conf]



LHeC simulation, NC+CC inclusive, total exp error

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

Two independent QCD analyses using LHeC+HERA/BCDMS

Needs feedback to Higgs groups + update for FCC-eh

The measurement of α_s is another issue where DIS is essential

Hadron collider processes most often start with powers of α_s: for example the Higgs g-g crossection starts with α_s^2.

The existing averages of α_s measurements are based on a list of different sources, typically computed at NNLO or even beyond.

However for some entries the stated error is taken directly from the original works and is not transparent from the outside (a typical example is the lattice determination).

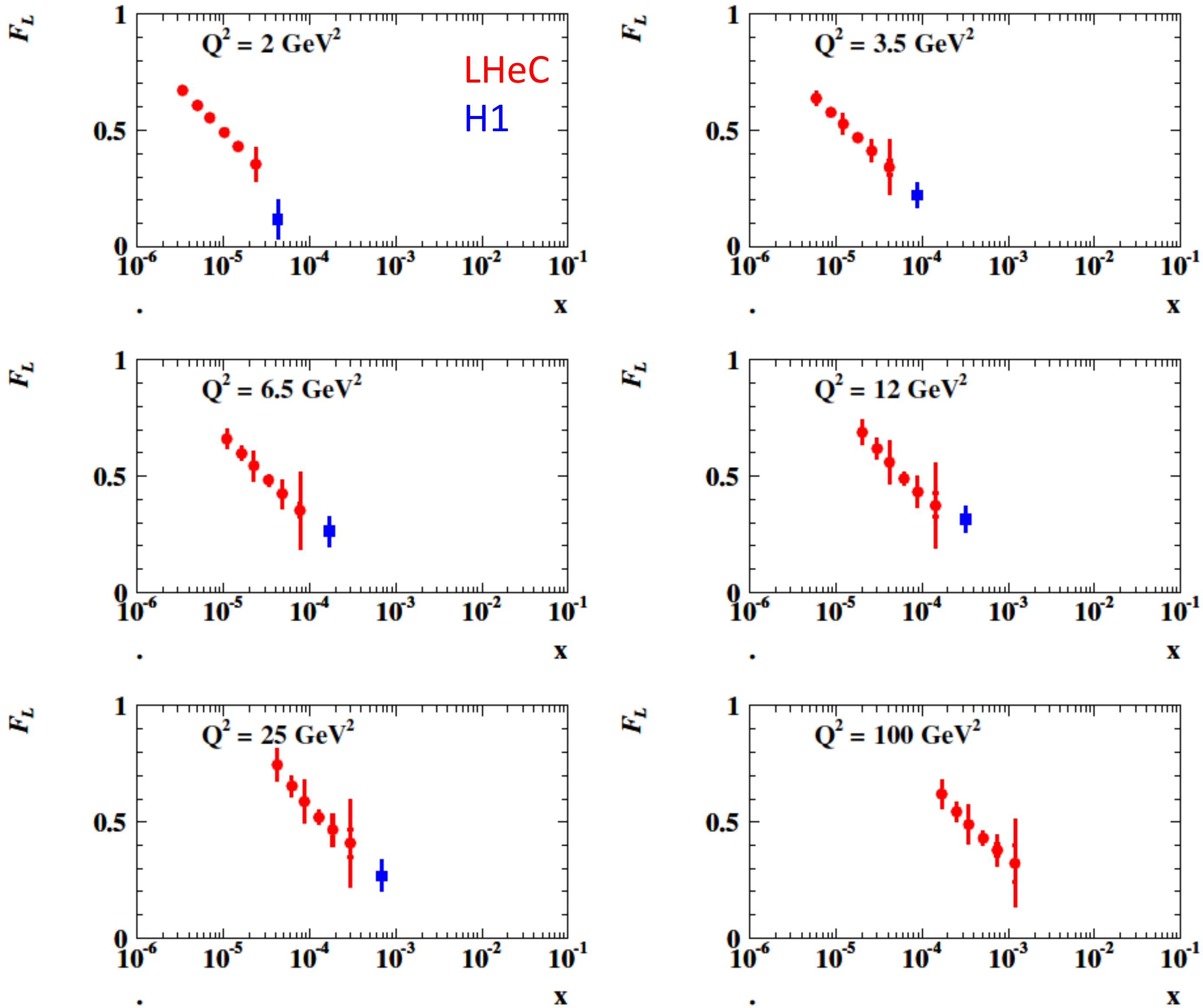
In my opinion one should select few theoretically simplest and cleanest processes for measuring α_s

Note that this is what is done in QED where α is measured from one single very precise and theoretically reliable observable (one possible calibration process is at present the electron g-2)

From the last talk of Guido Altarelli, 24th of June, 2015 at the LHeC Workshop

F_L LHeC

+ H1 data



E_e/L[fb^{-1}] 60/1 30/0.3 20/0.1 10/0.05

Stat+syst Errors.

See CDR

Needs update for Lx10

Nine Quark Distributions and xg

u_v, d_v, $\bar{u}$, $\bar{d}$, s, $\bar{s}$, c, b, t

Various important features of the NC and CC and F_L and HQ Structure Function DIS Data:

- high precision (e-h redundancy, clean final state, no pile-up..)

- high statistics (1000 times HERA) – much increased precision at high x, recall: $xq_v \sim (1-x)^3$

- much extended kinematic range: at high $Q^2 < 1$ TeV^2: CC becomes precise, unlike at HERA

- charged current: hugely important for: Higgs, strange, top and flavour separation

- low x ~ 1/s : DGLAP may fail, long expected BFKL? xg damping "saturation"

- beam spot extension ~7µm in x and y. with modern Silicon trackers → precision HQdfs
- ...

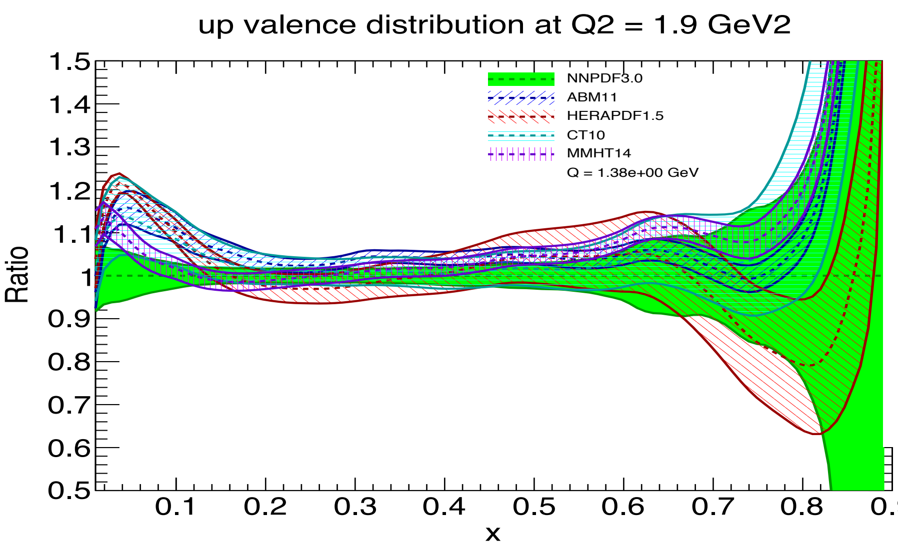
Theory: clean, light cone. In 10 years time: provide N^{3}LO PDFs - for precision Higgs at LHC
Phenomenology: no more symmetry assumptions, HQ known, no HT, no nuclear corrections, parameterisation uncertainties 'gone', model errors also (mc, α_s, ...)

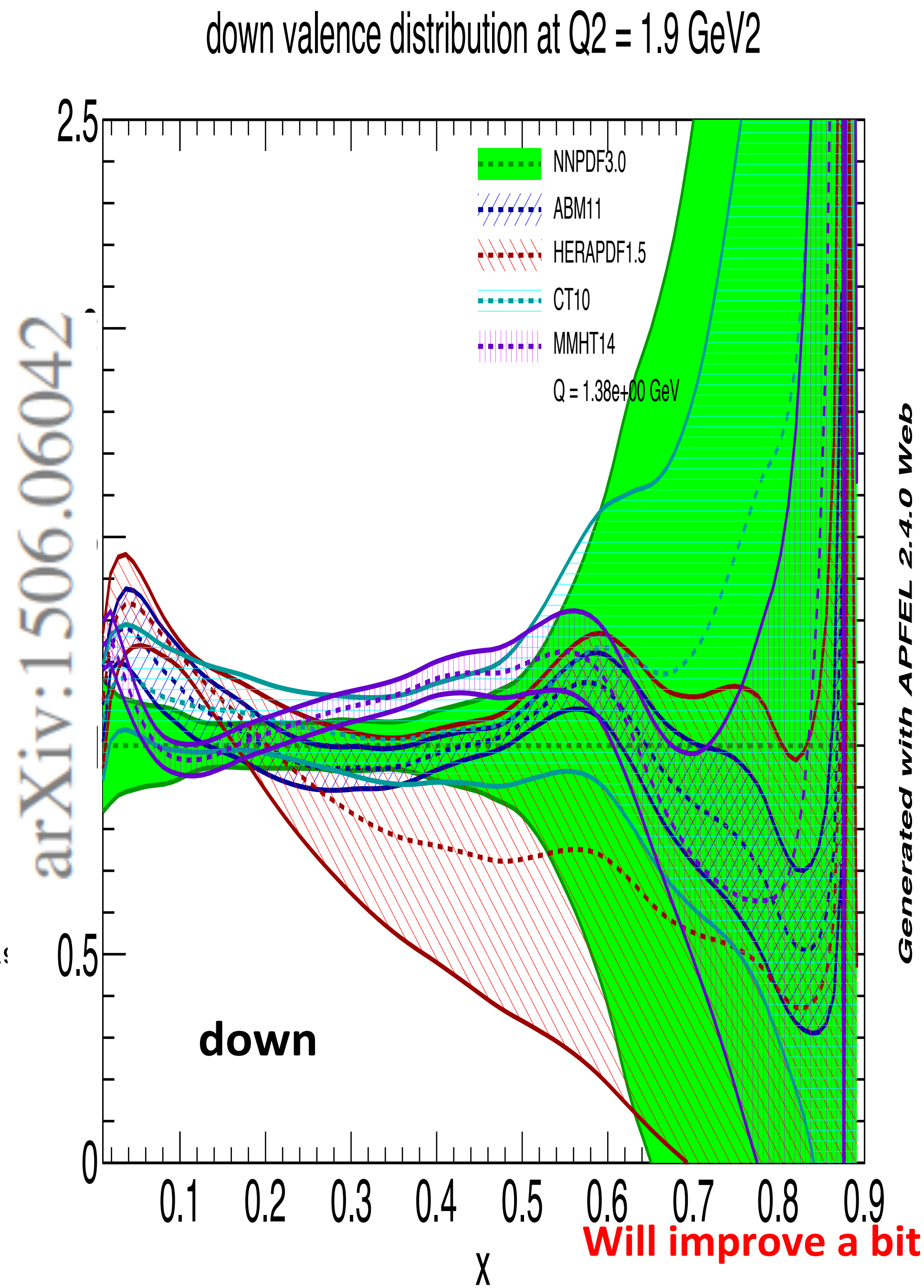
Needs to be made understood

Valence quarks

High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up





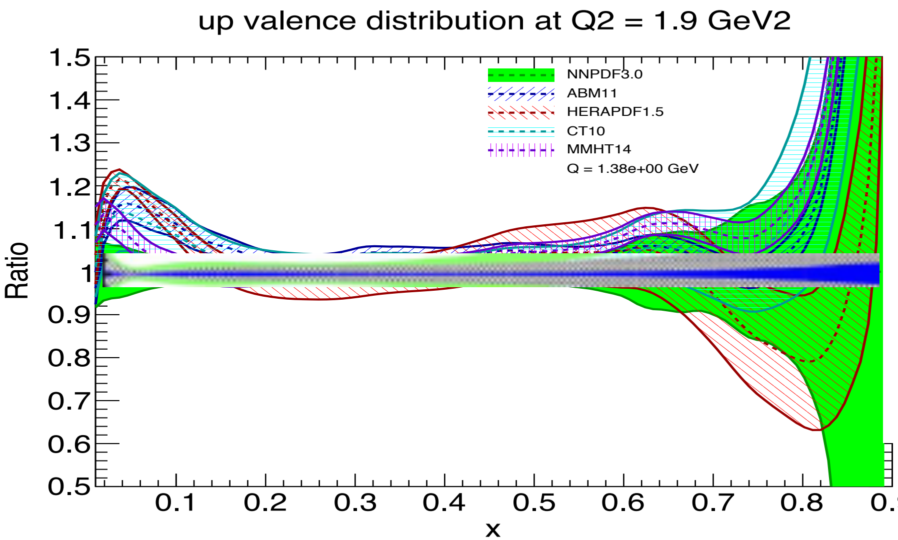
down

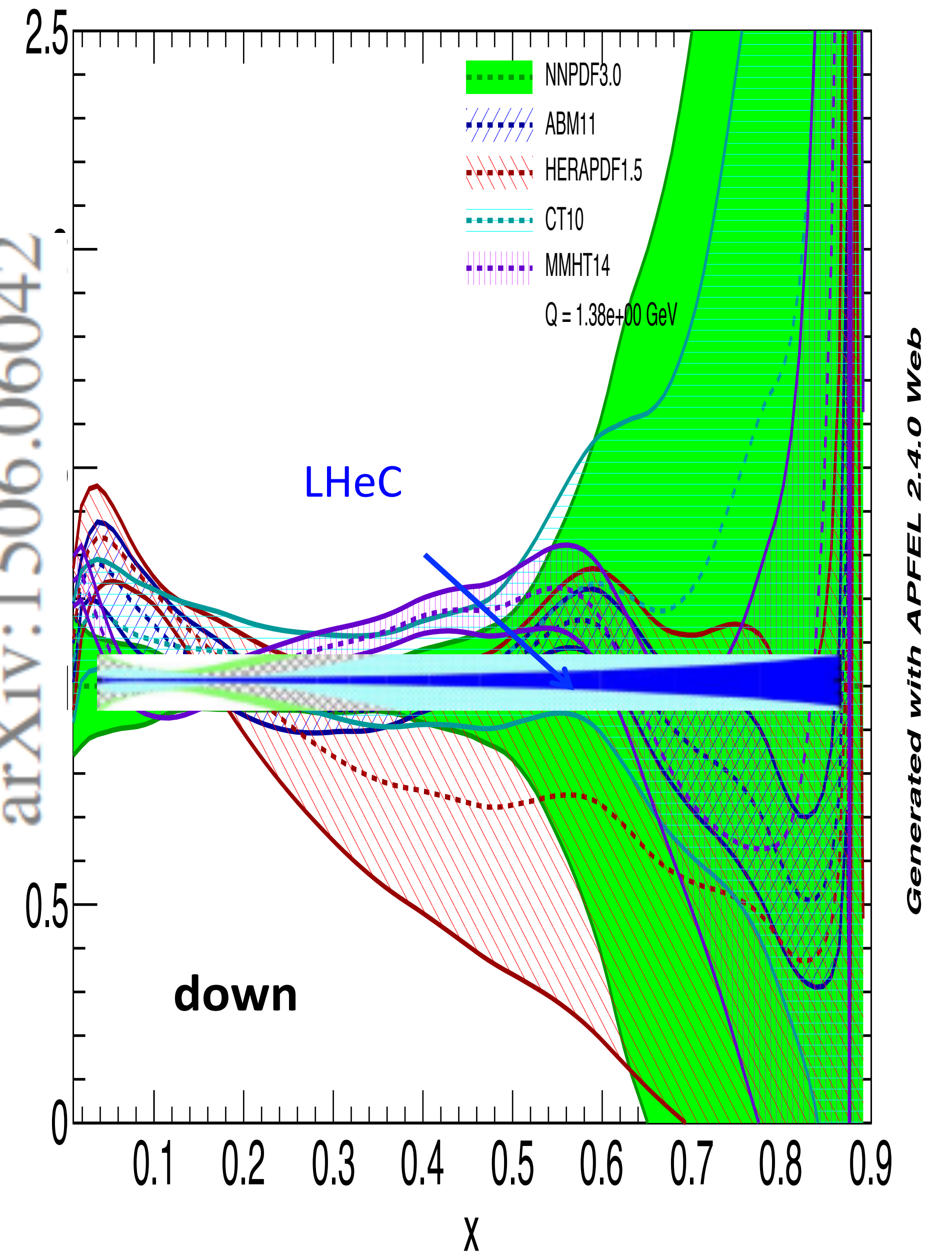
Will improve a bit

Valence quarks

High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up





Needs update + LHAPDF6

Gluon from the LHeC

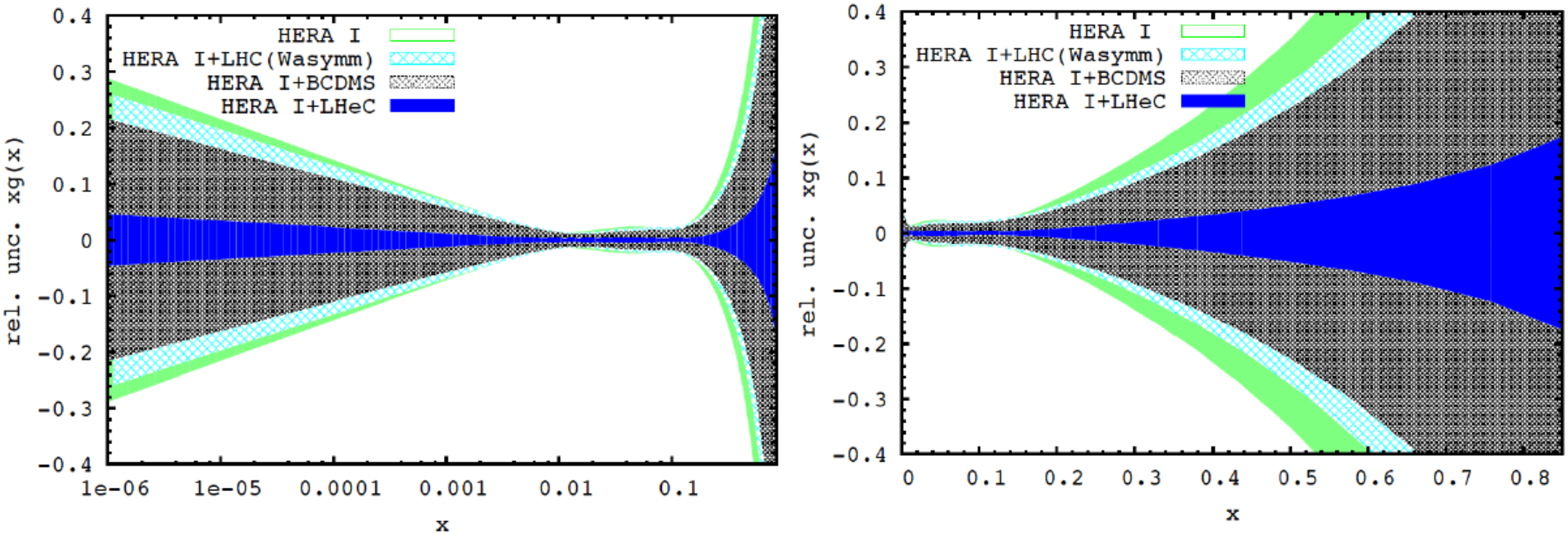


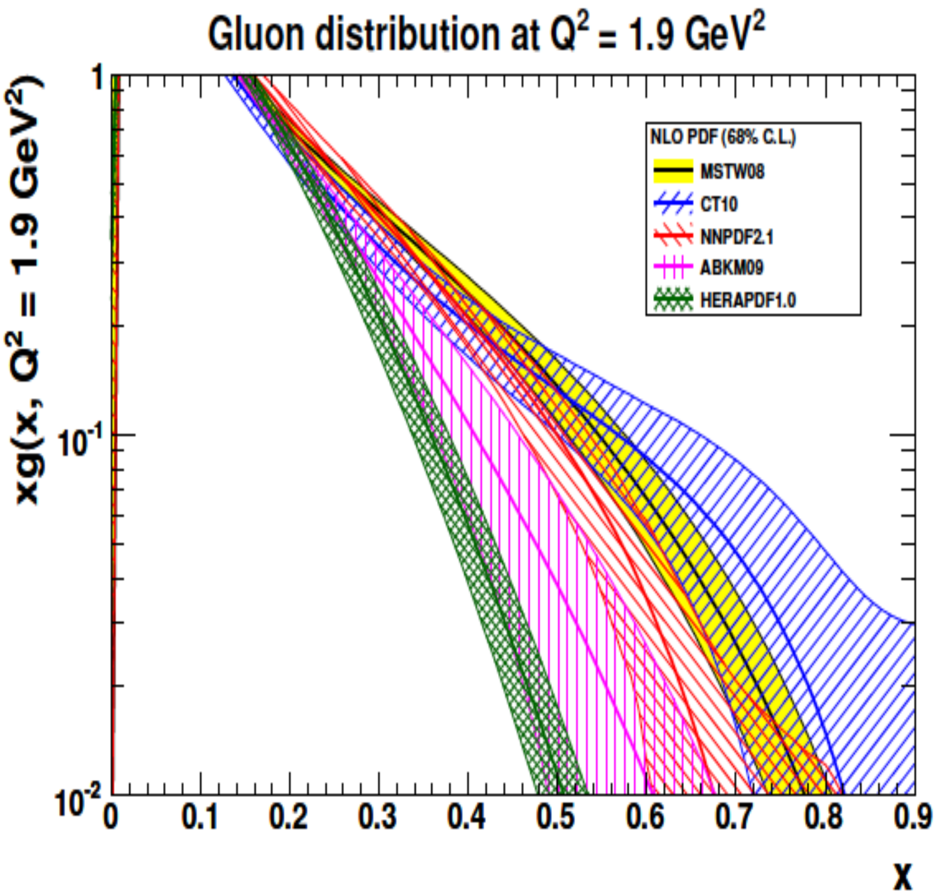
Figure 3.19: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

From the LHeC Conceptual Design Report

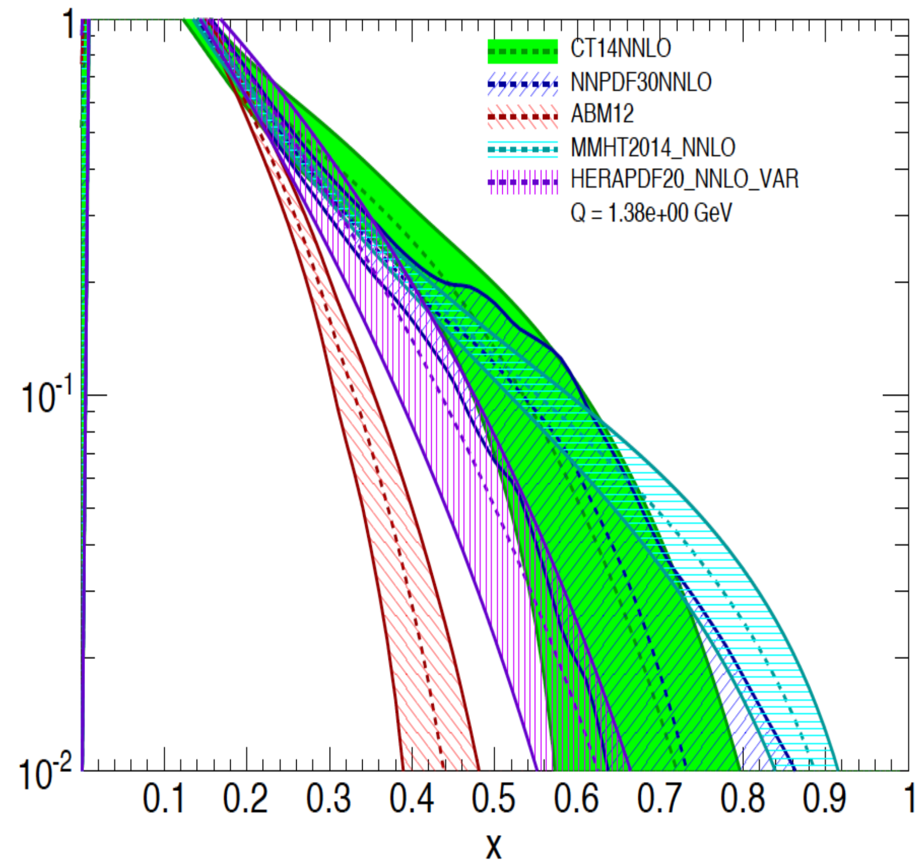
Hopefully correct

Gluon Density

High x



Gluon prior to LHC data (2011)

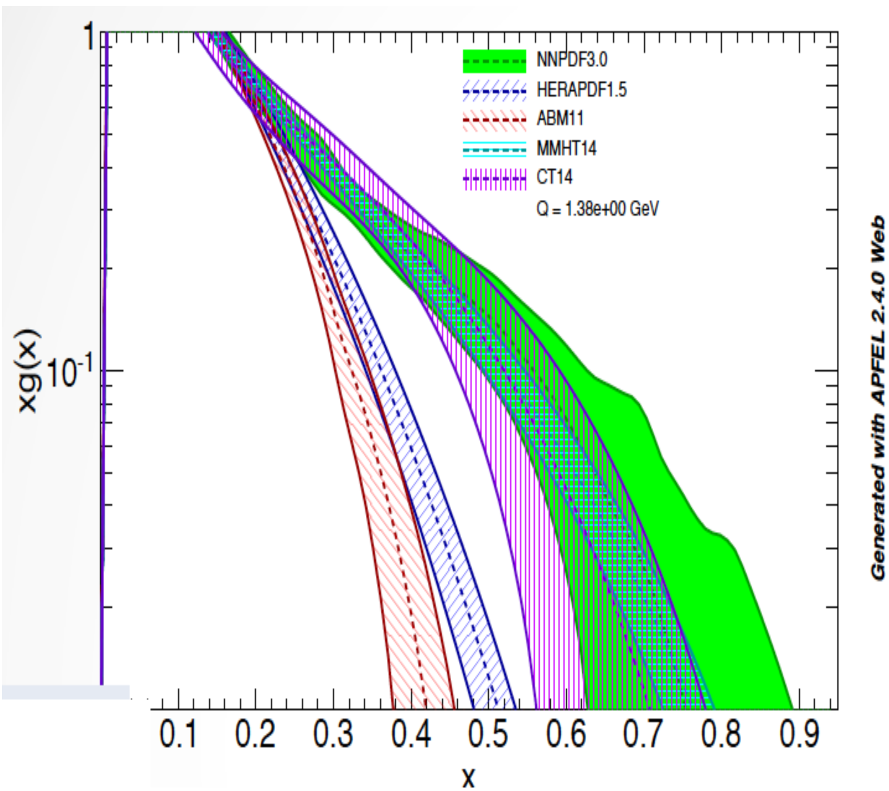


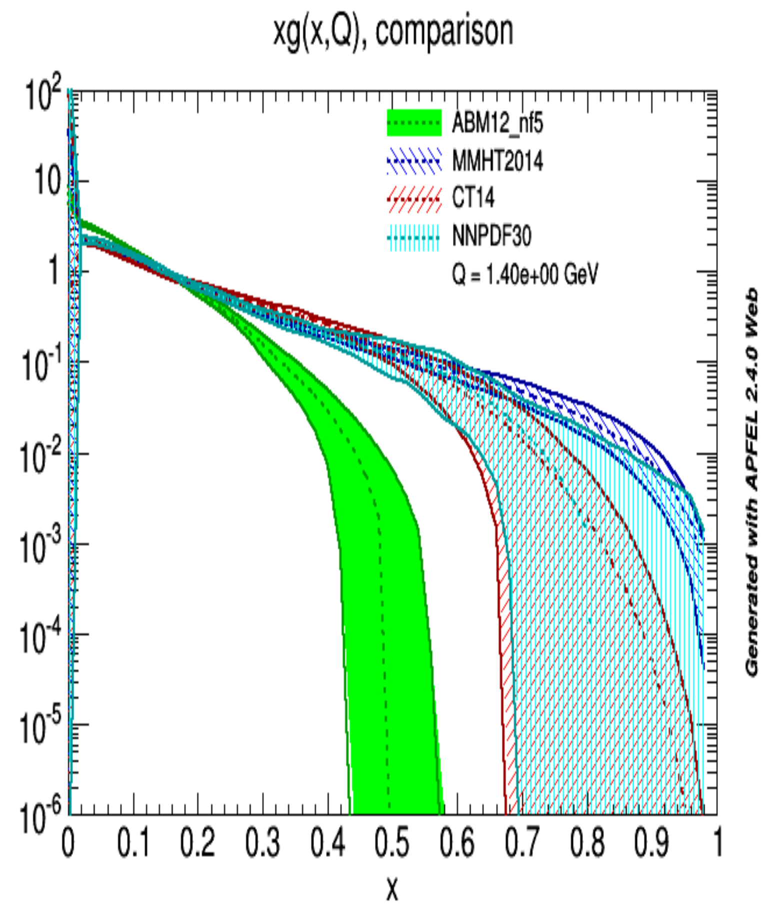
Gluon with (first) LHC data (2015)

used by CT14,NNPDF,MMHT

Needs update

Gluon Distribution at High x



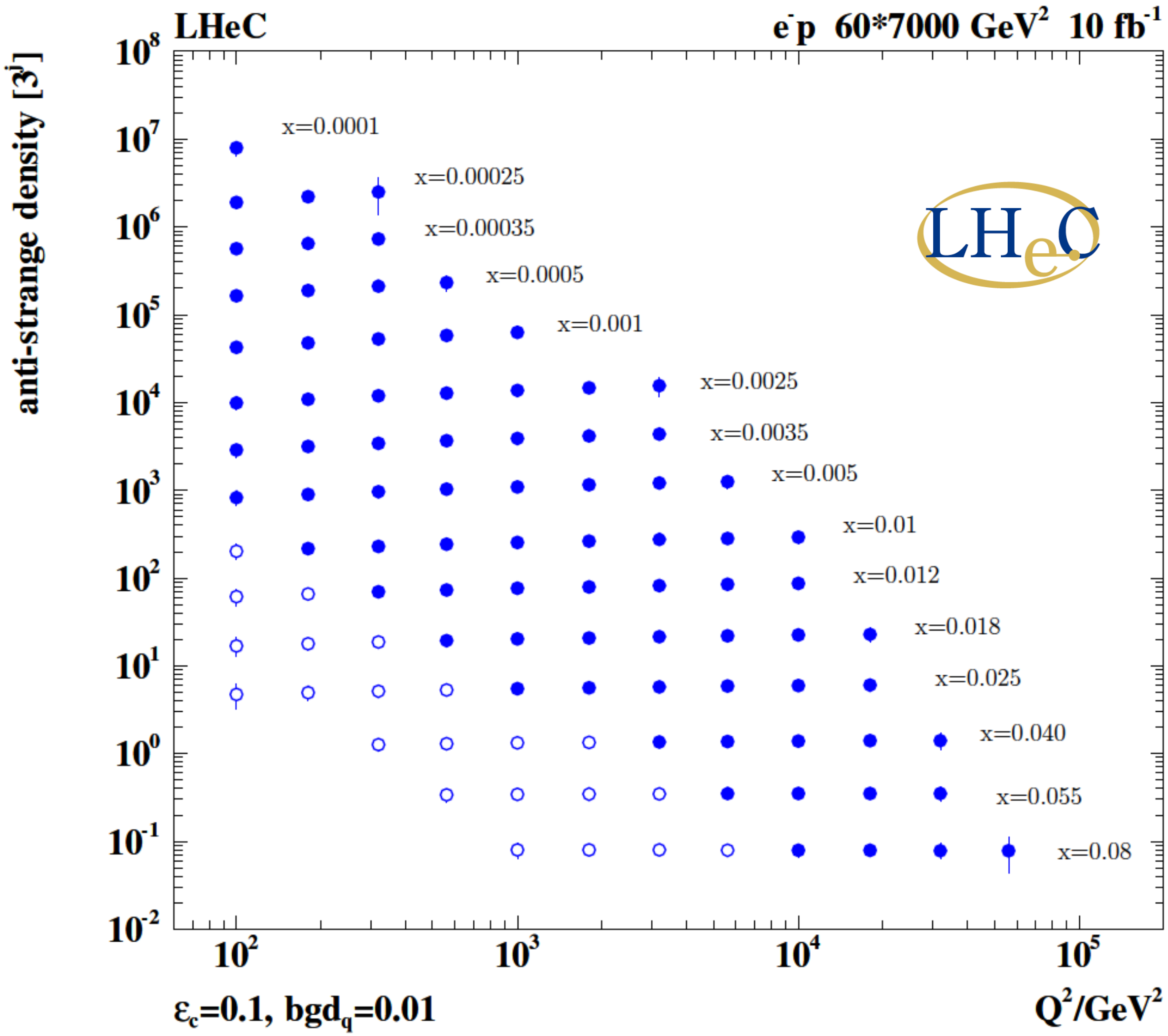


Needs not be forgotten how xg disappears with rising x

HERA and ABM gluons are much steeper at large x than those of MMHT,CT,NNPDF
→ Can we trust factorisation, how do we test it. Jets vs inclusive DIS

The determination of xg at large x is a severe challenge + not just for one channel

Strange Quark Distribution from LHeC



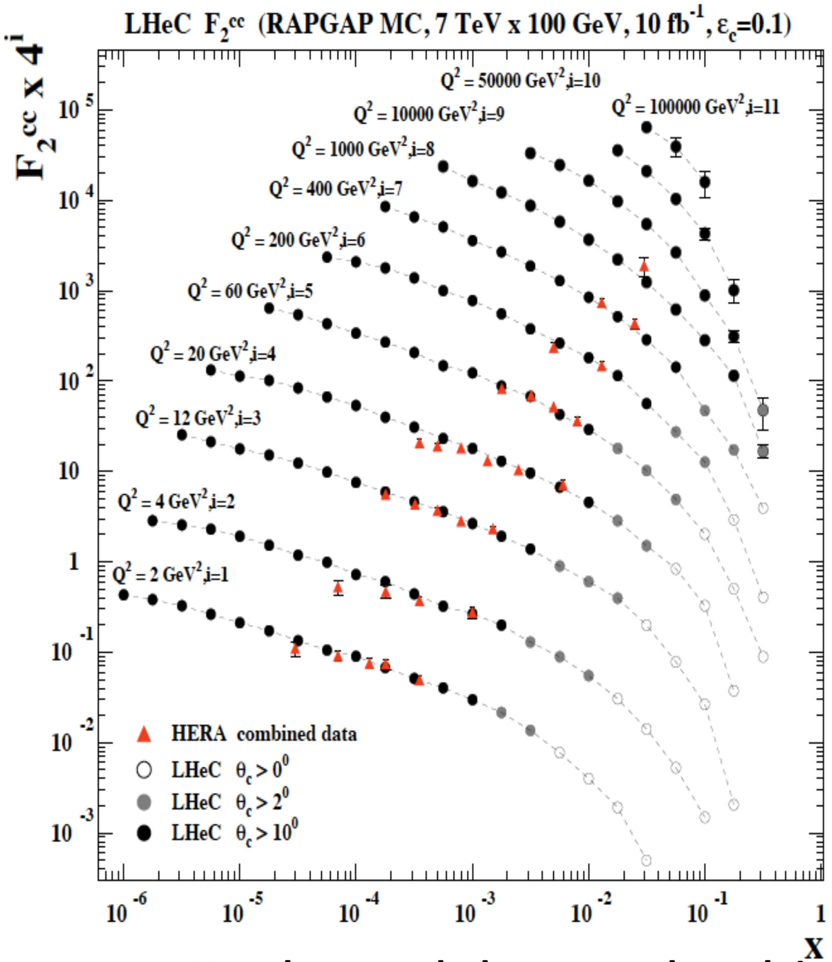
→ First (x,Q²) measurement of the (anti-)strange density, HQ valence?

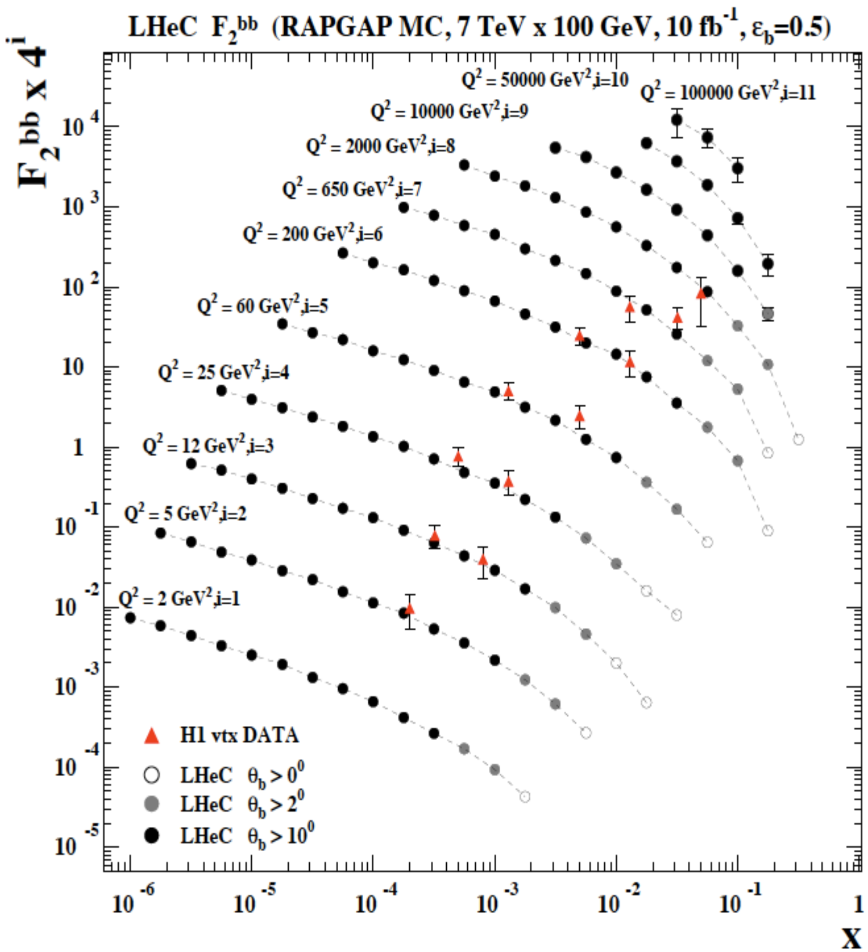
$x = 10^{-4}$ .. 0.05
$Q^2 = 100 – 10^5\ GeV^2$

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

Needs to be integrated in QCD fit

F_2^{charm} and F_2^{beauty} from LHeC

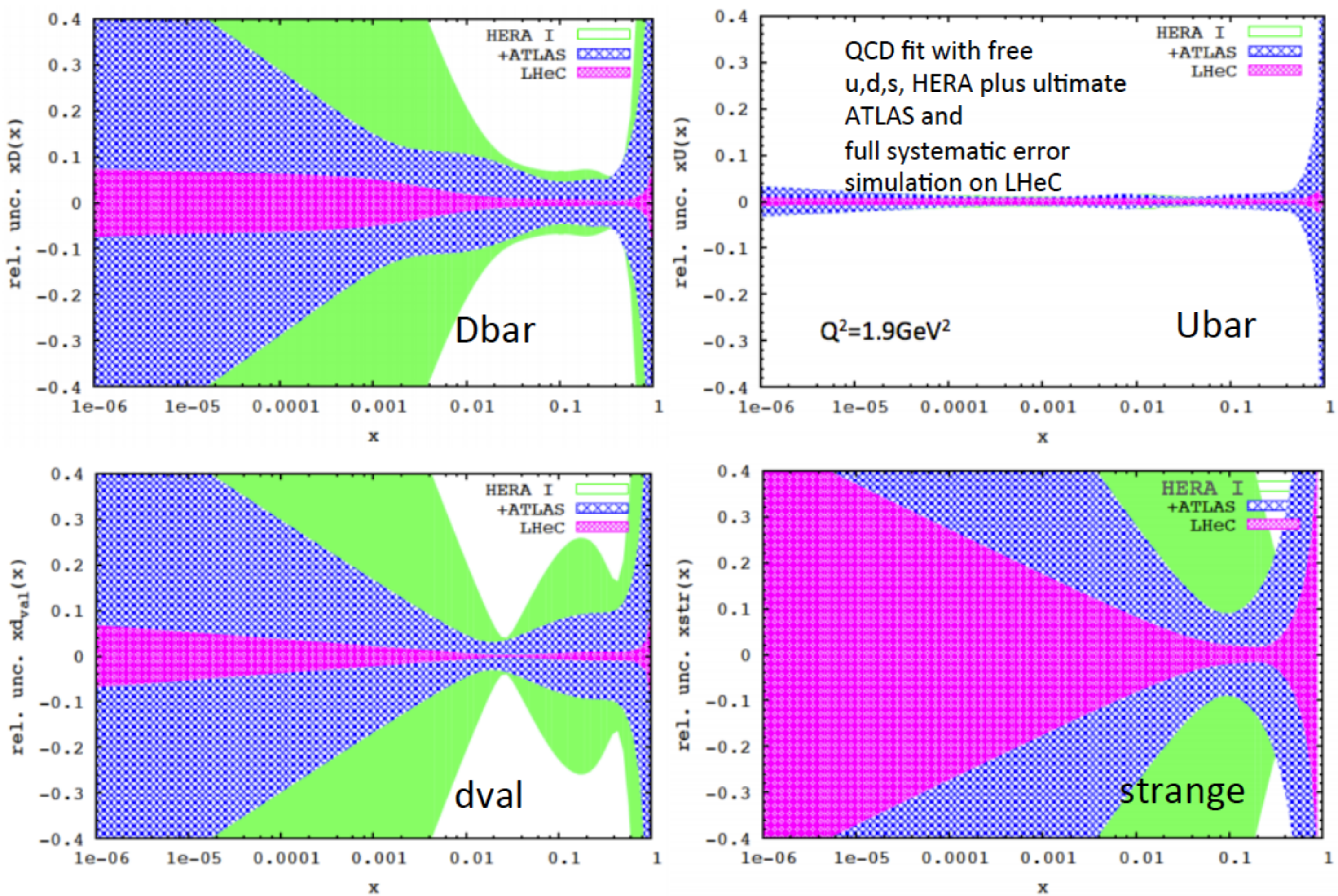




Hugely extended range and much improved precision (δM_c=50 HERA → 3 MeV)

Needs to show recent HERA data and be integrated in QCD fit

ep + pp and free fit to ū,d̄,s

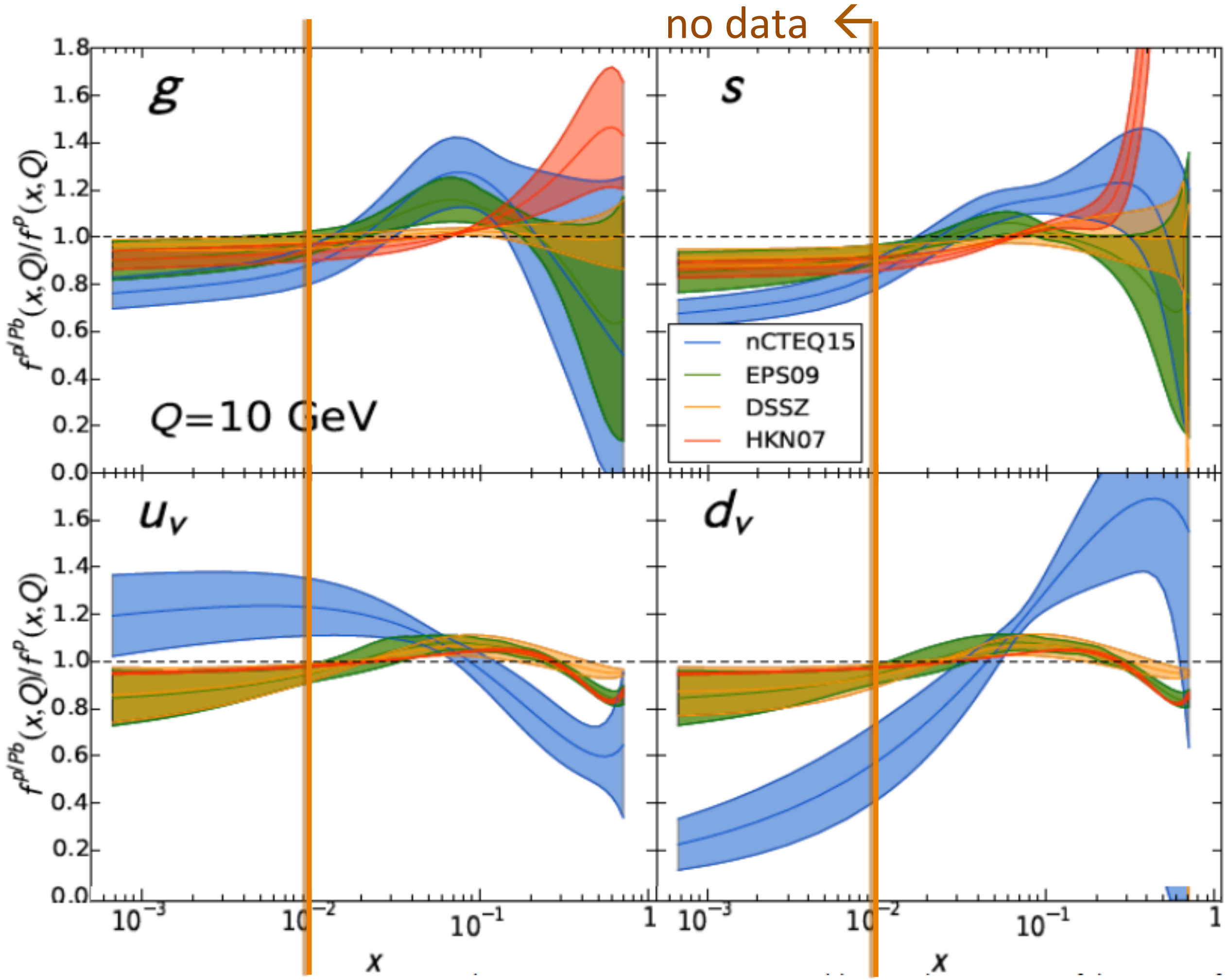


HERA: assume ubar=dbar and no sensitivity to s. LHC (W,Z) helps. LHeC provides independent determination

MK, V.Radescu at 2014 LHeC Workshop, Chavannes, January 2014

Needs more thorough +extended analysis

Nuclear Parton Distributions



[Nuclear Parton Distributions with the LHeC]()

MK, POETIC 2015, **EPJ Web Conf. 112 (2016) 03002**

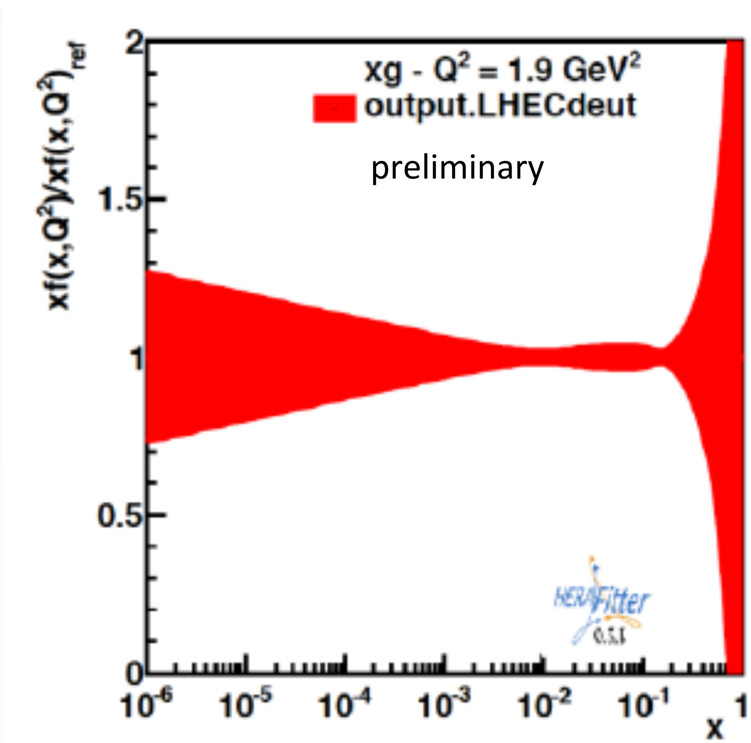
Collaboration with H.Paukkuunen, N.Armesto, V.Radescu

nPDFs are in infant state,
Needs the LHeC

Future Nuclear PDFs with LHeC

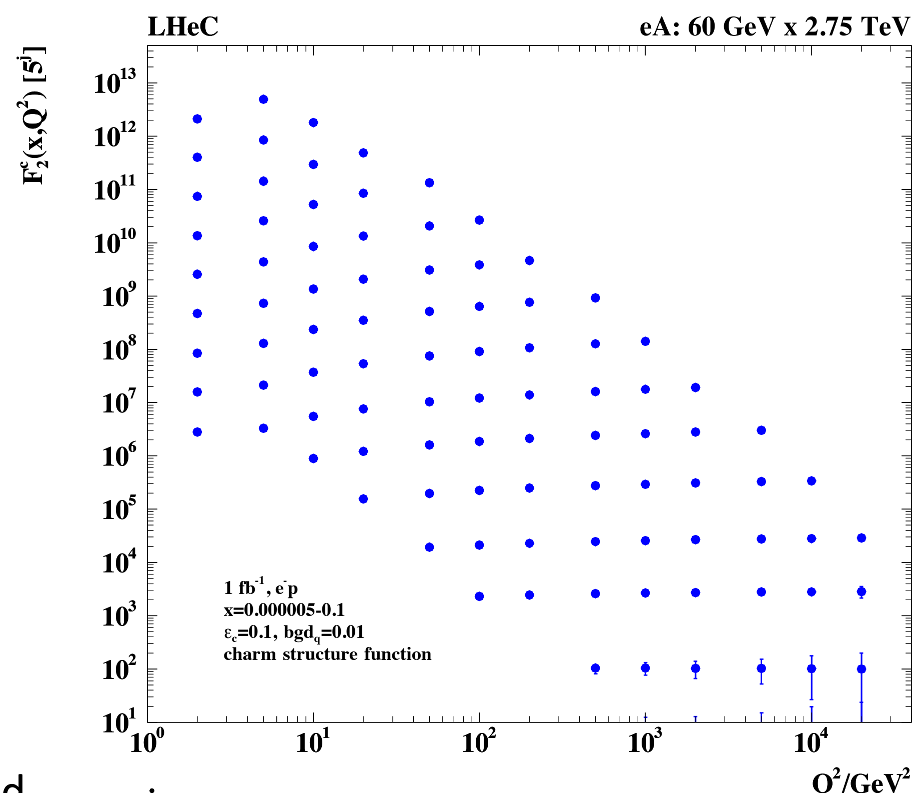
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA



1fb^{-1} of sole eA isoscalar data fitted

Charm density in nuclei

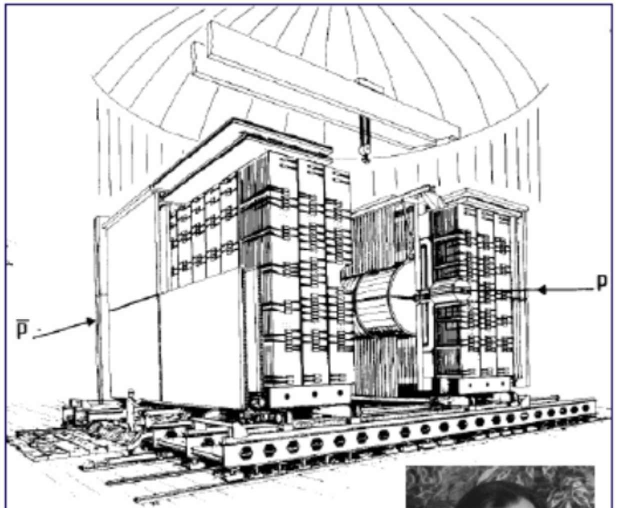


Needs update, extension to CC and joint ep+pp study

Can CERN host pp and DIS at once?

Needs a courageous answer

.. in the 80ies it successfully did



UA1

“ We have two tasks: kill Weinberg Salam, kill QCD”
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

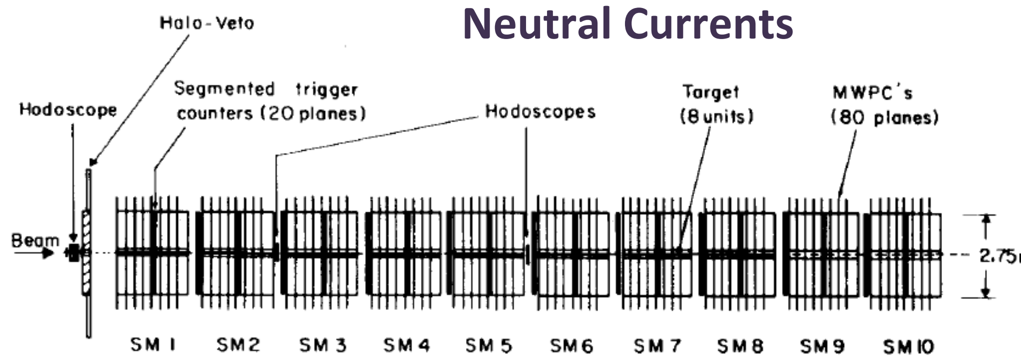
UA2

Pierre Darriulat
now in Vietnam

Charged Currents

BEBC, **CDHS(W)**, CHARM, CHORUS

Neutral Currents



BCDMS, EMC, SMC, COMPASS

"The future belongs to those who believe in the beauty of their dreams."

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

Needs Trump to go to (his) tower

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

An Invitation

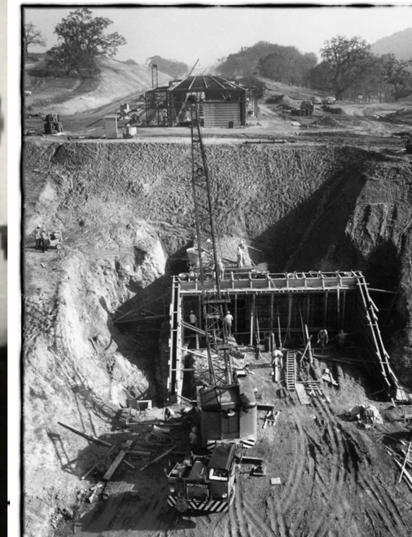
We would be glad to welcome many of you in the pursuit of the studies ahead and in also critical discussions such that the right way may be determined for a next energy frontier ep and eA collider.

This requires to convince (parts of) the HEP community and the public about the high value of building a first precision Higgs facility and a new microscope to the substructure of matter of unprecedented resolution power, from 0.0001-0.1 fm.

CERN has a unique potential, through DIS, to deepen the exploration of nature significantly. Adding an ERL electron machine to the LHC is adding to its value, it may turn the LHC into a precision Higgs facility.

We ought to go beyond our areas of comfort and genuine expertise, as well as develop that further, if we want to succeed, as previous generations indeed mastered to do. →

can one build a 2 km long linac?



it has been done before

Courtesy F.Zimmermann

backup

We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision

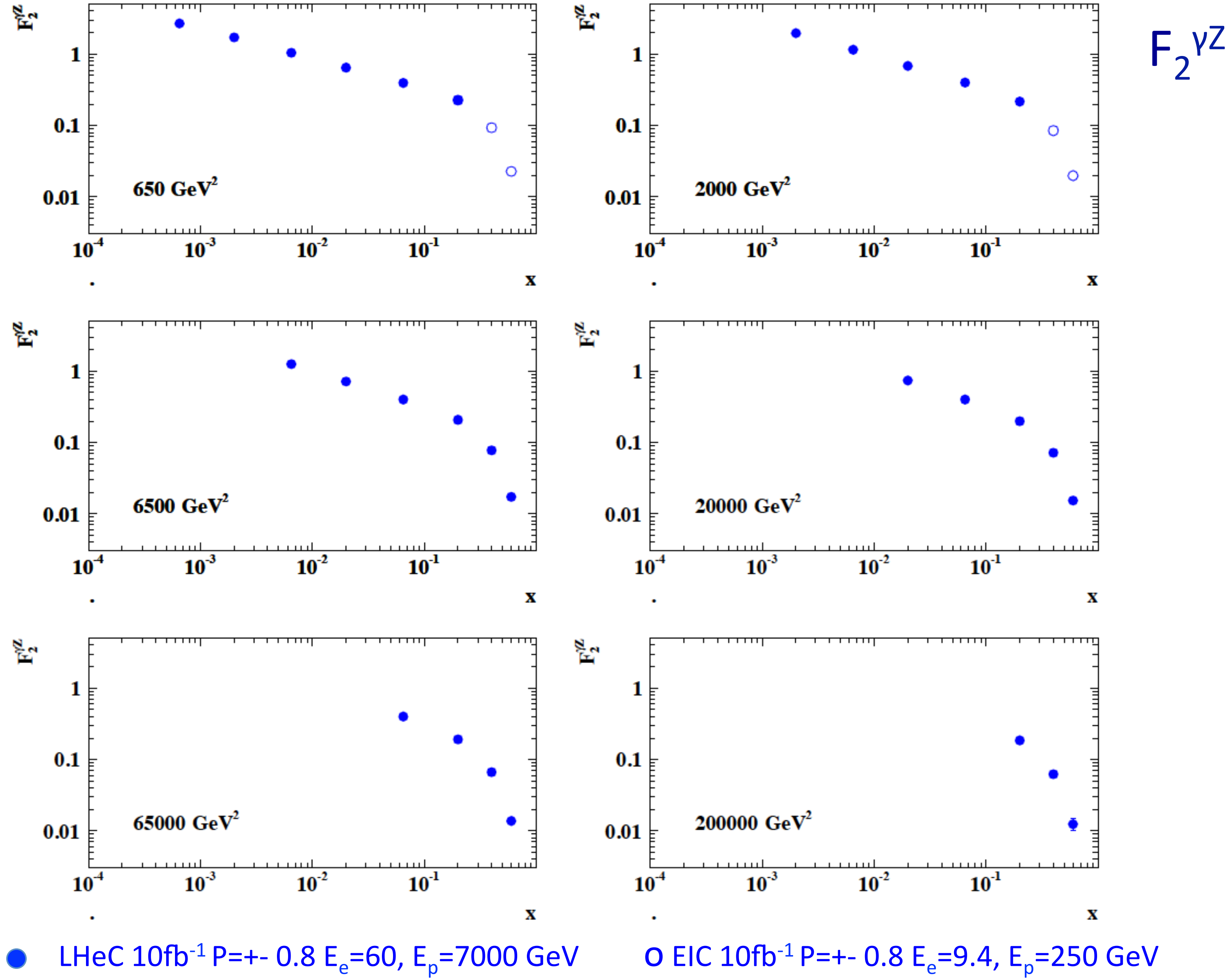
x times density of parton A

$$\sigma(s) = \sum_{A,B} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} p_A(x_1, Q^2) p_B(x_2, Q^2) \hat{\sigma}_{AB}(x_1 x_2 s, Q^2)$$

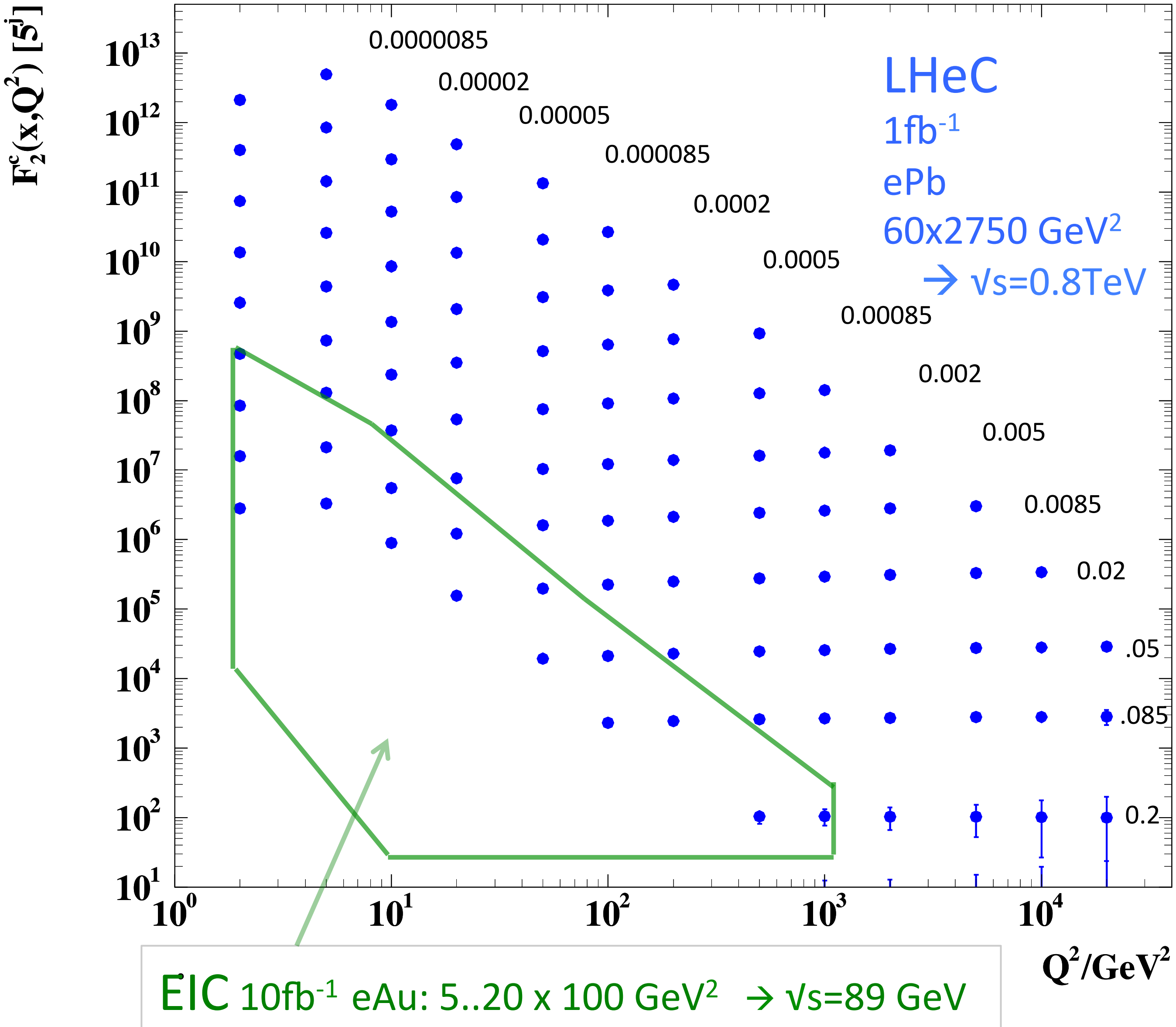
reduced X-section

One way: precisely measure gluons and quarks at large x in DIS, evolve in Q^2, and predict the jet rates at large p_T at the LHC

From the last talk of Guido Altarelli 24th of June, 2015 at the LHeC Workshop

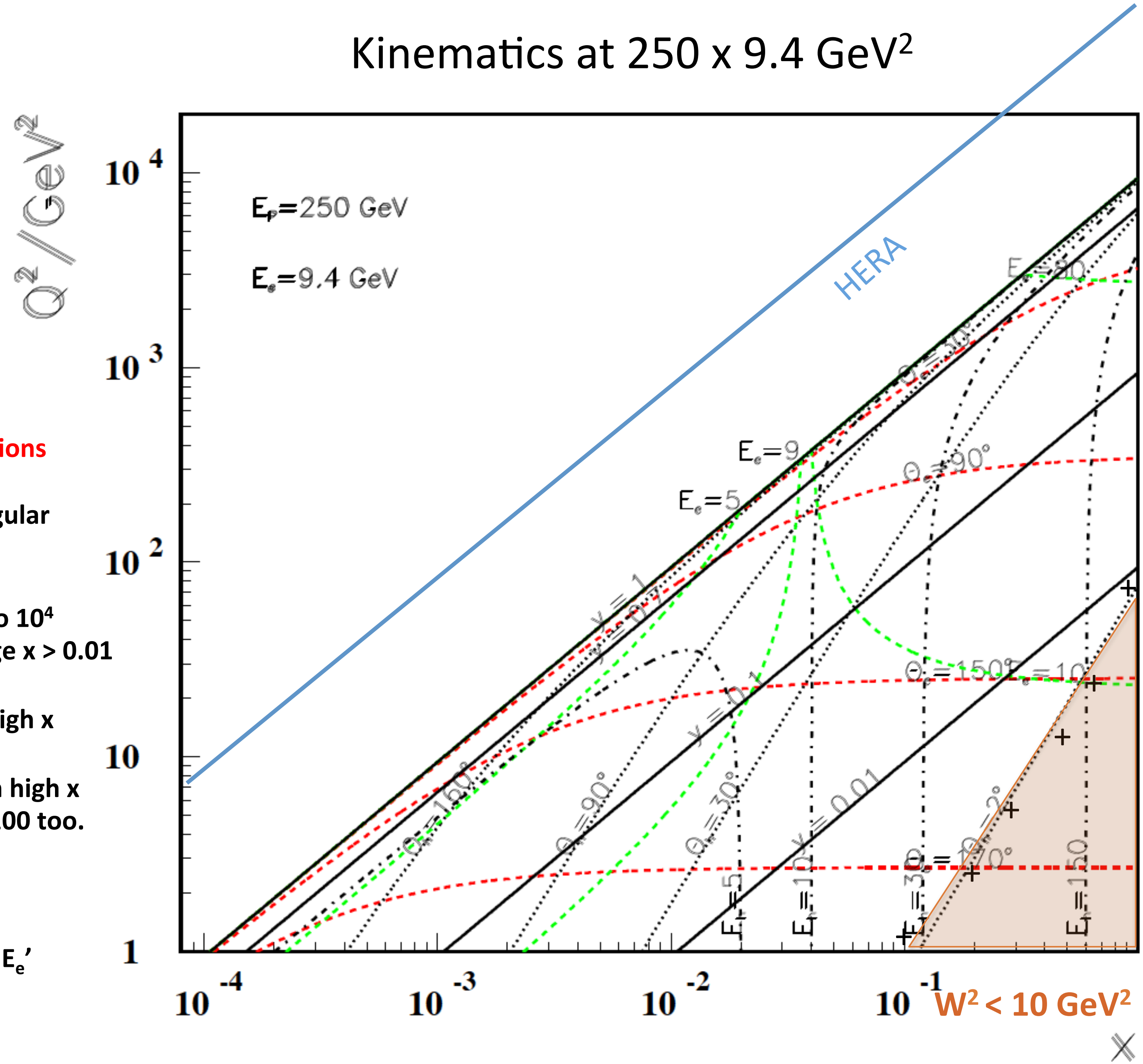

$F_2^{\gamma Z}$
650 GeV²
2000 GeV²
6500 GeV²
20000 GeV²
65000 GeV²
200000 GeV²
x
LHeC 10fb⁻¹ P=+- 0.8 Eₑ=60, Eₚ=7000 GeV
o EIC 10fb⁻¹ P=+- 0.8 Eₑ=9.4, Eₚ=250 GeV

Charm Structure Function in Nuclei



Also F_Lc and b

Kinematics at 250 x 9.4 GeV^2



Observations

Good angular coverage

High Q^2 to 10^4
CC at large x > 0.01

Low Q^2 High x
HT area,
but reach high x for Q^2 > 100 too.

High y
Very low E_e'

Kinematics at 61 x 5 GeV^2

Observations

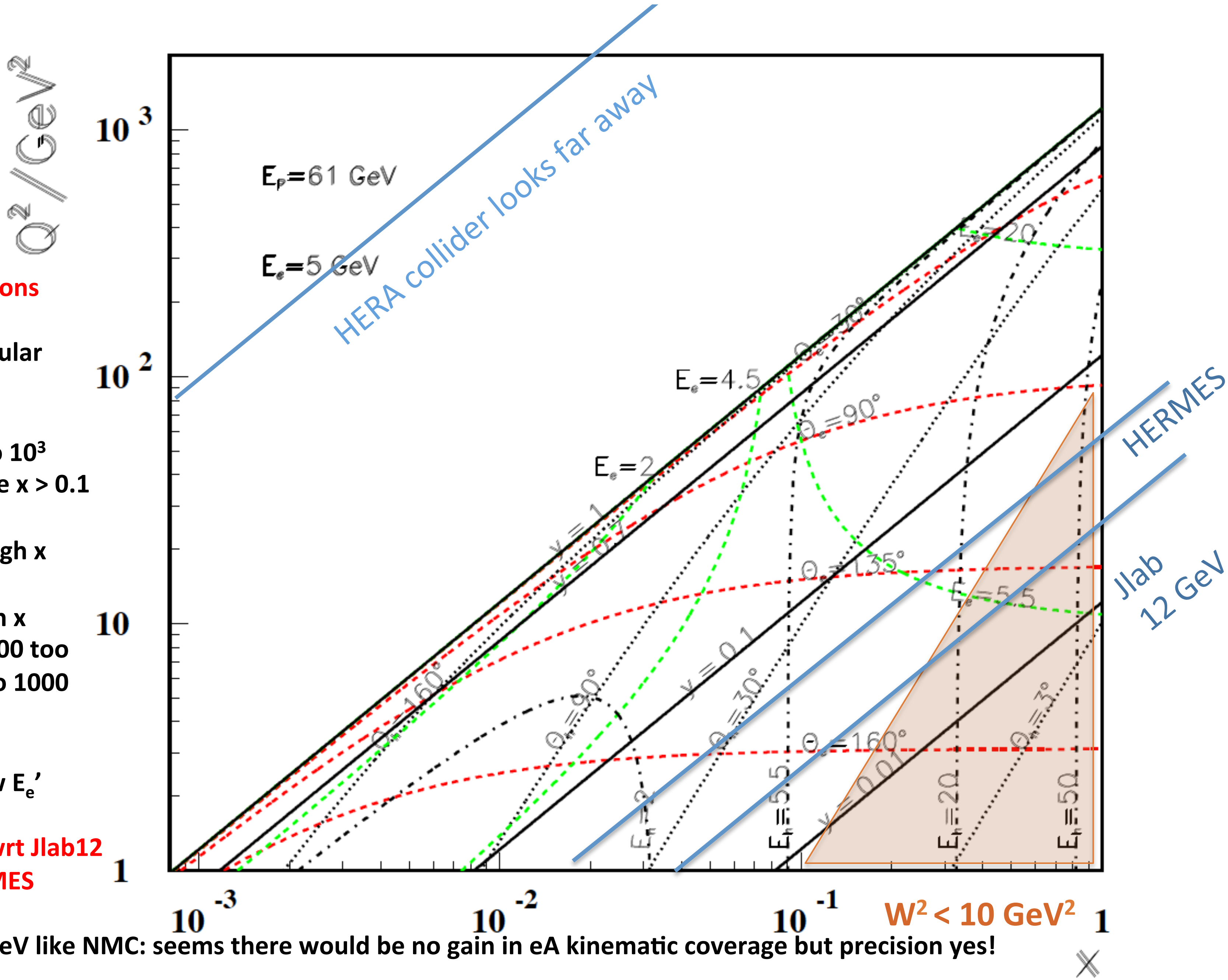
Good angular coverage

High Q^2 to 10^3
CC at large x > 0.1

Low Q^2 High x
HT area,
reach high x
for Q^2 > 100 too
But just to 1000

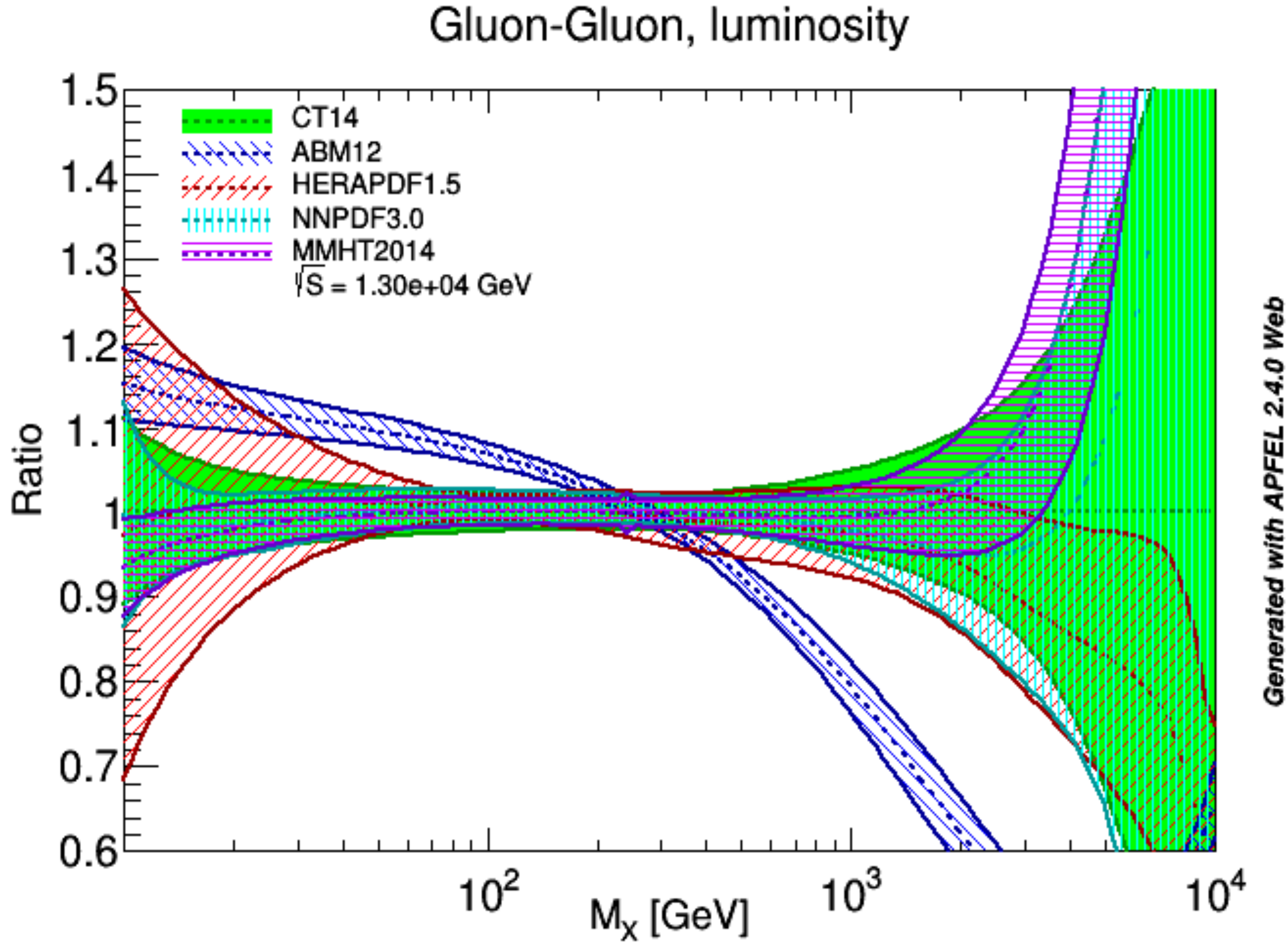
High y
Really low E_e'

Big step wrt Jlab12
and HERMES



eAu: 18 GeV like NMC: seems there would be no gain in eA kinematic coverage but precision yes!

Parton-Parton "Luminosities"



0.00077 0.1 0.77 1

x →

Note: ABM and HERA do not use LHC jets – is that relevant?. qq luminosity isn't solved either