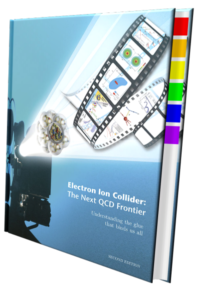
EIC and LHeC side by side

in the CTEQ context of unpolarised parton distribution functions PDFs

"Side by Side"
Physics Programs
Detector Choices + Kinematics
The PDF Vision of the LHeC
PDFs with the EIC
An Initial Comparative Study
Longitudinal Structure Function
PDFs in Nuclei



For references, please consult
EIC web page

EIC White Paper
arXiv:1212.1701
unpublished

Max Klein
University of Liverpool
with
Voica Radescu
CERN

Contributions to a Discussion

LHeC:
E_e=60 GeV
E_p= 7 TeV

For references, please consult
lhec.web.cern.ch

LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

POETIC7 with CTEQ, Philadelphia, 17th of November 2016

Side by Side

In time: - The EIC and the LHeC will not be operational before 2030

[cf B. Mueller on eRHIC Monday and LH(e)C time schedule (LS4),
HERA took 8 years to build: approval in 1984 data 1992 → 2007. XFEL ~9 years]

- They should be considered to be operational together, not sequential *)
- EIC needs decades for spin, ep and eA data, much beyond the Trump time
- LHeC will be terminated with the LHC but may reappear with HE LHC (FCC)

In their technology choice:

- currently (BNL?) both the two US EICs and the LHeC use ERLs for the e beam
- they have similar challenges (multi-turn, high current ERL)
- all luminosity goals are very ambitious and need R+D:
  a common problem is a high current polarised e^- source (LHeC 15, BNL 50mA)
- they almost certainly will have 100 times less or no positrons, P=0

In their kinematics: $Q^2_{max} = s = 10^4$ GeV^2 (EIC) 10^6 GeV^2 (LHeC), $x > 1$ GeV^2 /s in DIS

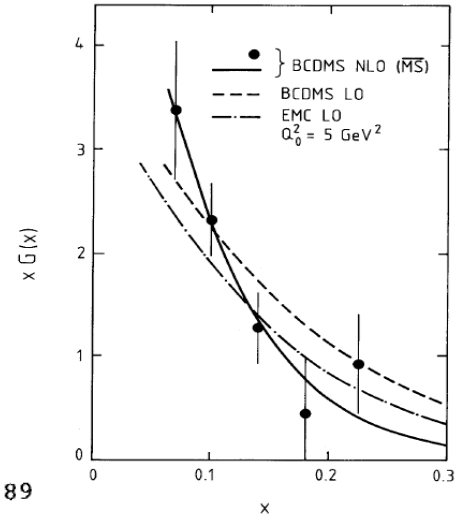
In their role: seen from the perspective of genuine deep inelastic scattering:

- EIC will "replace BCDMS/NMC (suspicious at high x) and HERMES/COMPASS"
- LHeC will "replace HERA (uncertain at high x and no CC x > 0.5)"

*) Predicting is difficult, in particular if it concerns the future (V. Weisskopf)

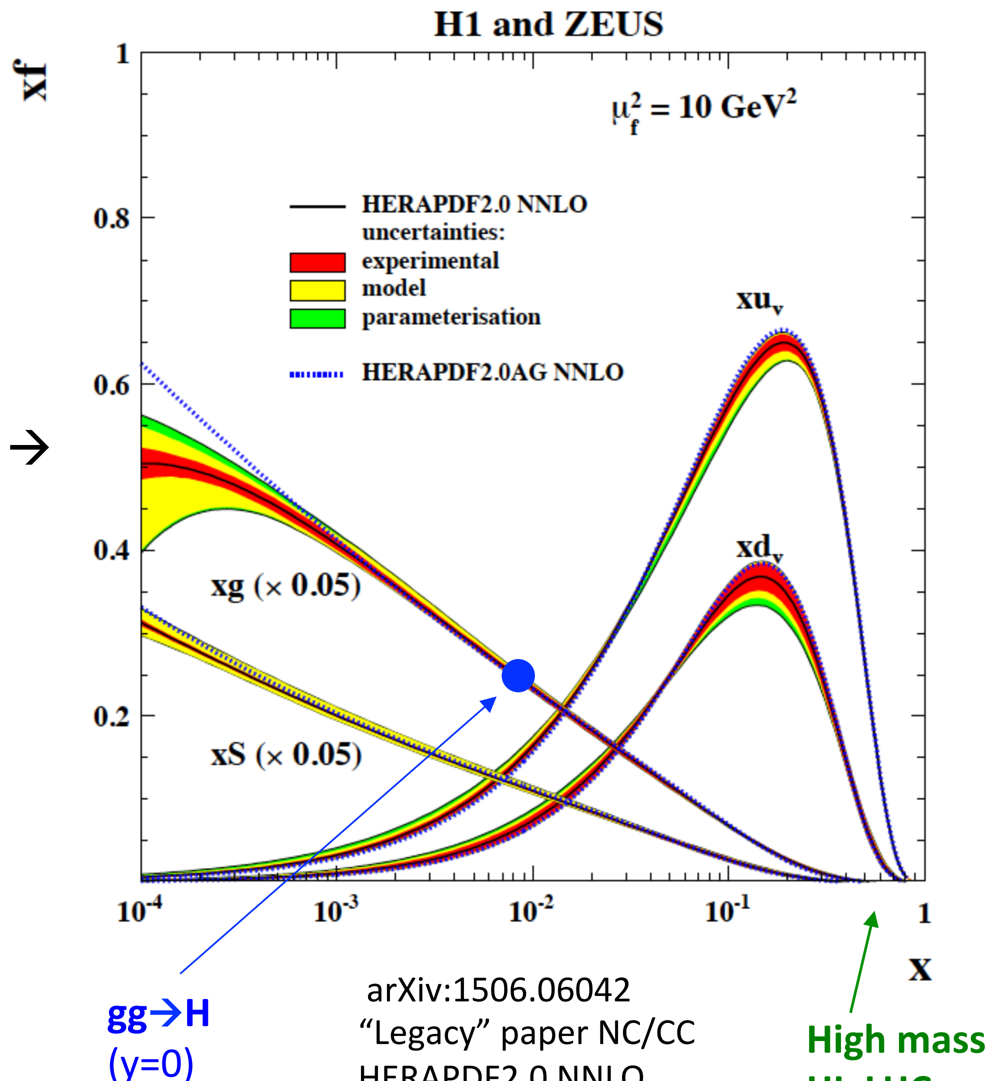
Gluons and Quarks 1989 → 2015

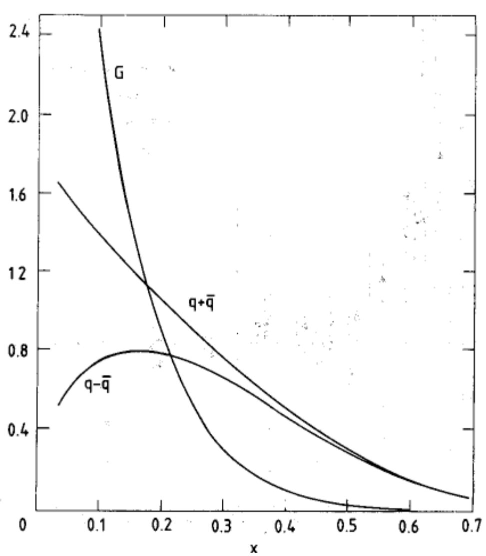
BCDMS



CERN-EP/89-07
January 17th, 1989

fixed target lN to ep collider →





CDHS

CERN-EP/89-103
15 August 1989

arXiv:1506.06042
"Legacy" paper NC/CC
HERAPDF2.0 NNLO

Motivation for a 100 TeV pp Collider

N. Arkani-Hamed
@SUSY2013

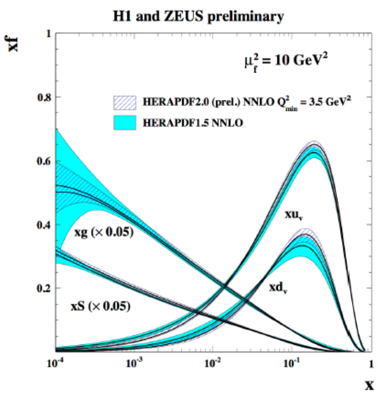
* It's the OBVIOUS FUTURE
* BIG physics ideas, BIG ambitions and BIG machines are the lifeblood of our field. It's how we've attracted the best minds on the planet to work on the hardest, most fundamental, most long-term problems in all of Science.

M. Mangano
@UKForum2014

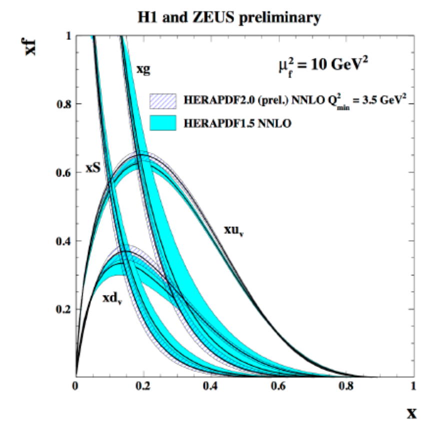
'The "physics case" will emerge at the end, when confronting the potential against the explicit circumstances arising from the future 10 years of LHC running, DM searches, Belle2, etc., and in view of the overall synergy/complementarity with the other components of the project (ee and eh).'

The Physics Programme of the EIC

1409.1633



Experimental results suggest that both nucleons (see Figure 2-1) and nuclei, when viewed at high energies, appear as dense systems of gluons, dominating not only the hadronic structure but also creating fields whose intensity may be the strongest known in nature. The quest to probe this universal gluonic regime drives the development of eRHIC.



How are the sea quarks and gluons and their spins distributed in space and momentum inside the nucleon?

eRHIC Design Study

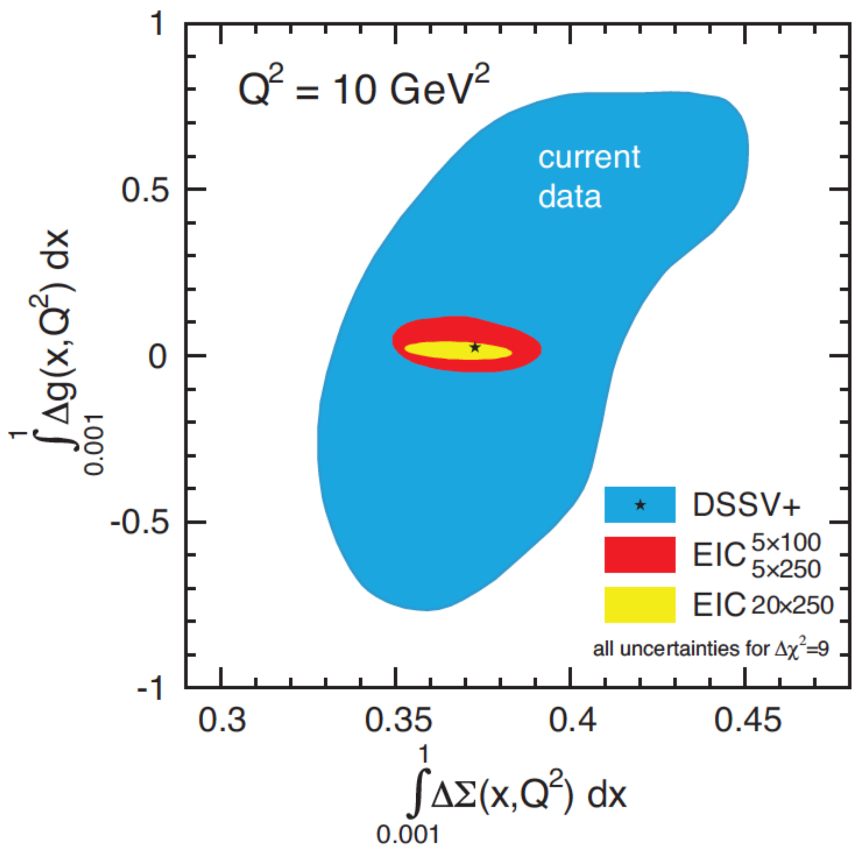
An Electron-Ion Collider at BNL

Where does the saturation of gluons set in?

How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

See talks of Berndt Mueller, Rik Yoshida, Elke Aschenauer and many others at this workshop

The Proton Spin - A Unique Focus of the EIC wrt LHeC



White Paper
why $\Delta g=0$?

Figure 2.9: Accuracies for the correlated truncated integrals of $\Delta\Sigma$ and Δg over $0.001 \leq x \leq 1$, on the basis of the "DSSV+" analysis (outer area) and projected for an EIC (inner areas) [73].

Simulations of g_1 based on $10 fb^{-1}$ at different energies, in polarised-polarised state

The Physics Programme of the LHeC

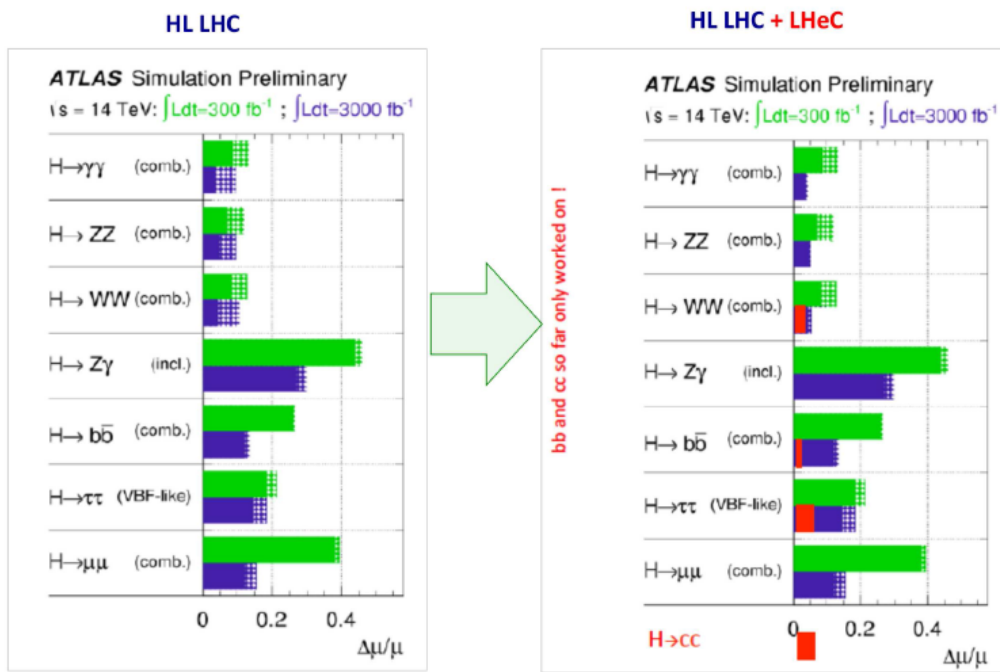
arXiv:1206.2913 (CDR) 1211.4831 and 5102

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s top PDF, $xt = x\bar{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top $\mathrm{N^3LO}$, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

See introductory talk on Tuesday 15.11. and special presentations at this workshop

Precision Higgs – A Unique Focus of the LHeC wrt EIC + LHC

HIGGS PHYSICS AT THE LHEC
SUMMARY



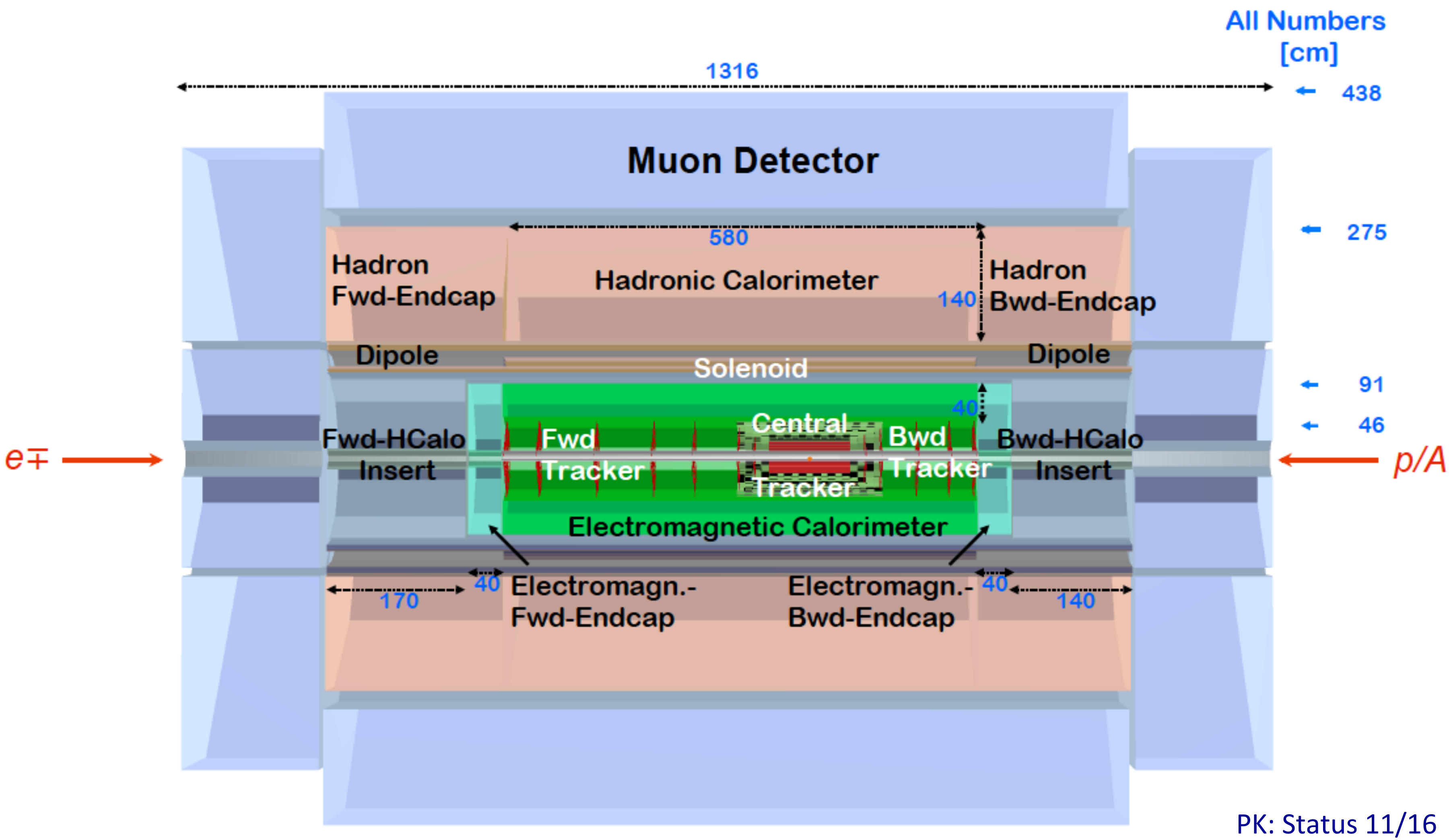
- GLUON FUSION AND W FUSION ⇒ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

Stefano Forte ECFA 11/15

BSM Higgs physics, C Zhang at this workshop

H cross section is largest in e^-p, P=-0.8 → predominantly operate in this configuration, O(1)ab^{-1}

LHeC Detector



PK: Status 11/16

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =13x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e), 100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

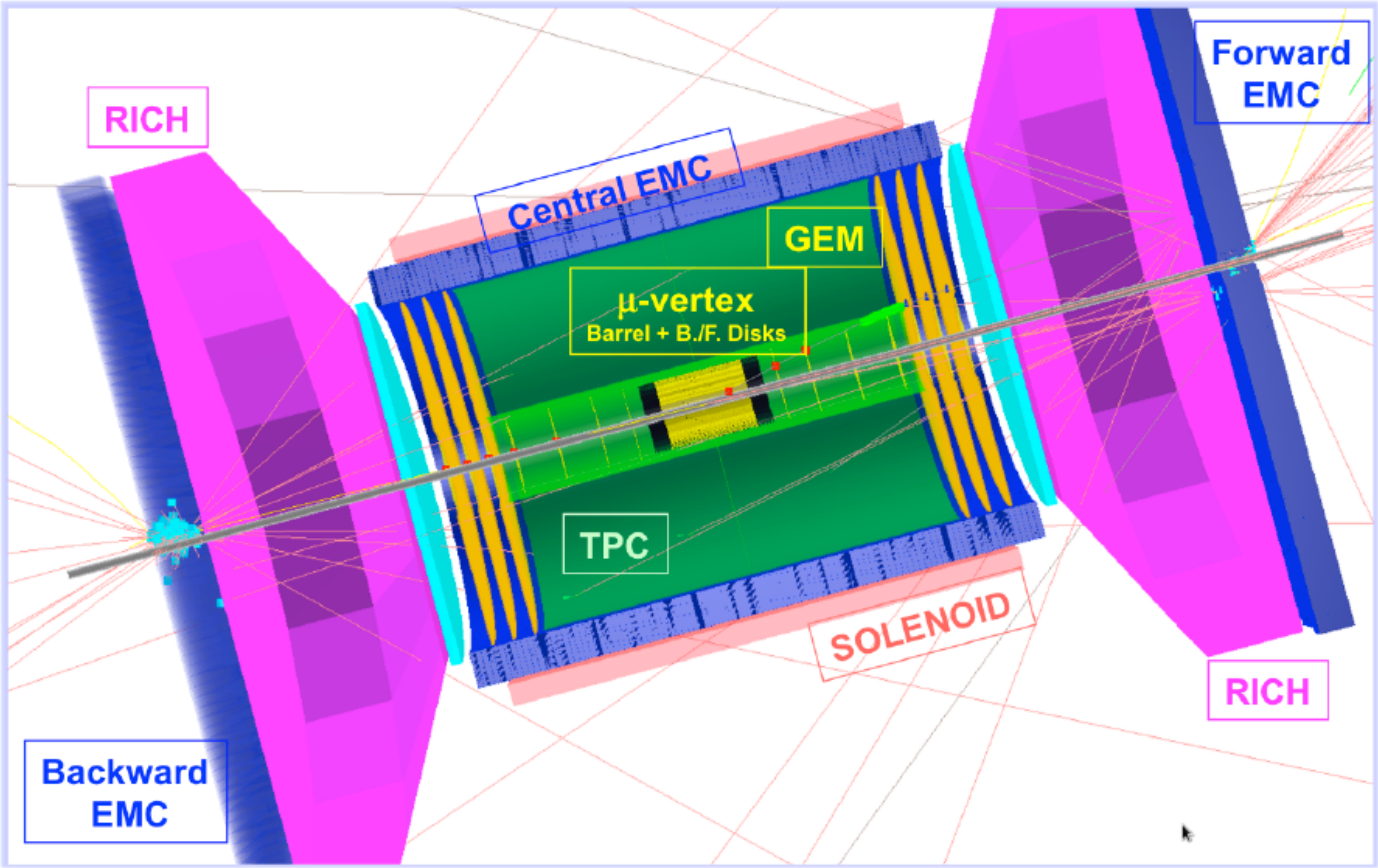
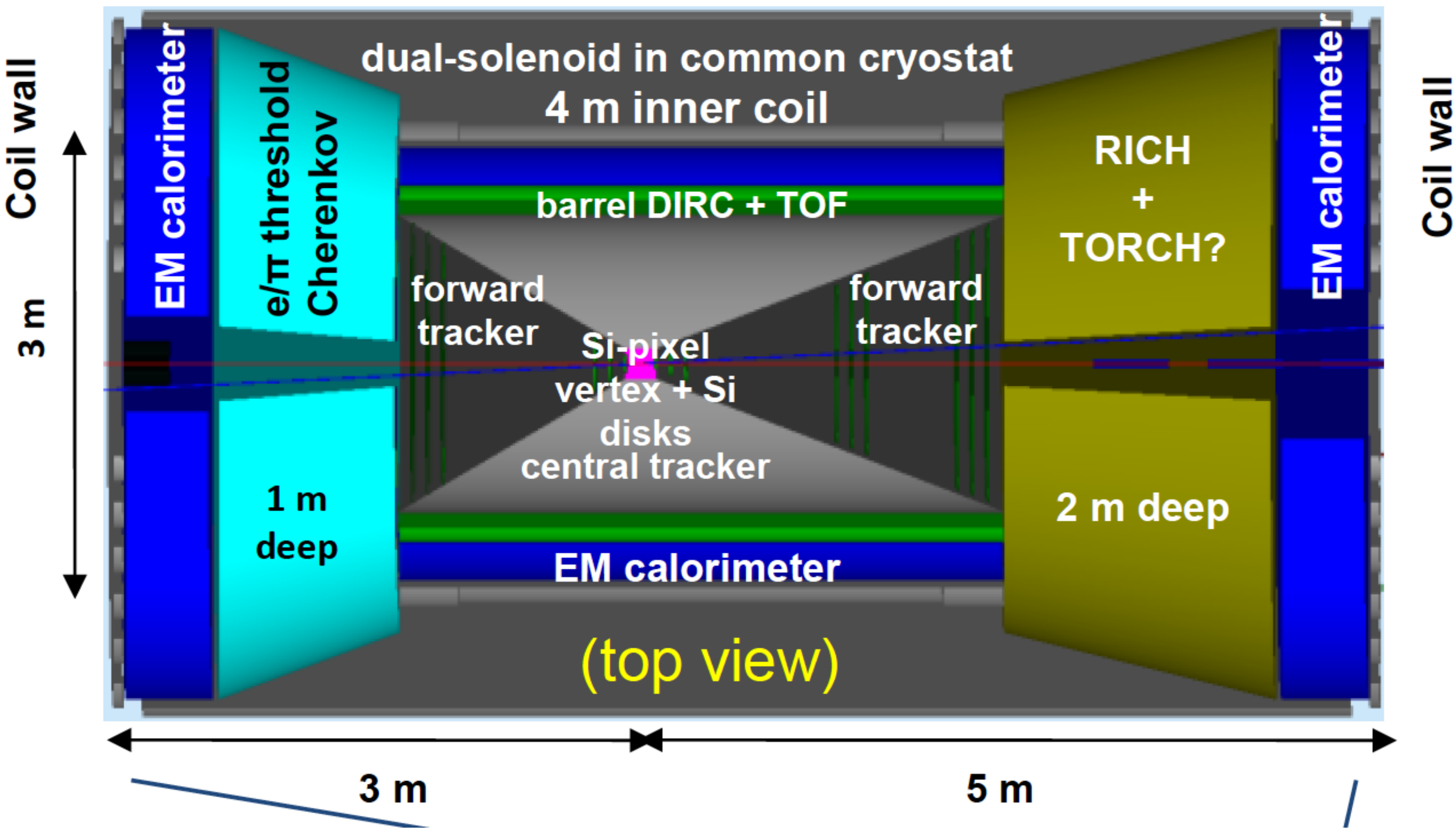


Figure 6.6: The eRHIC model detector implementation (BeAST = Brookhaven eA Solenoidal Tracker) with tracker and calorimeter components implemented in the EicRoot GEANT simulation framework [342]

From white paper



From the white paper

The importance of hadron calorimetry for DIS

-Coverage of low y, since the electron measurement precision diverges as $1/y_e$

-Cross calibration of hadronic and elm energy scales (needs 0.5% on $\delta E_h/E_h$ scale)

-High resolution for disentangling the final state (LHeC: H → bb as an example)

-Charged current measurement needs missing energy reconstruction (γp background)

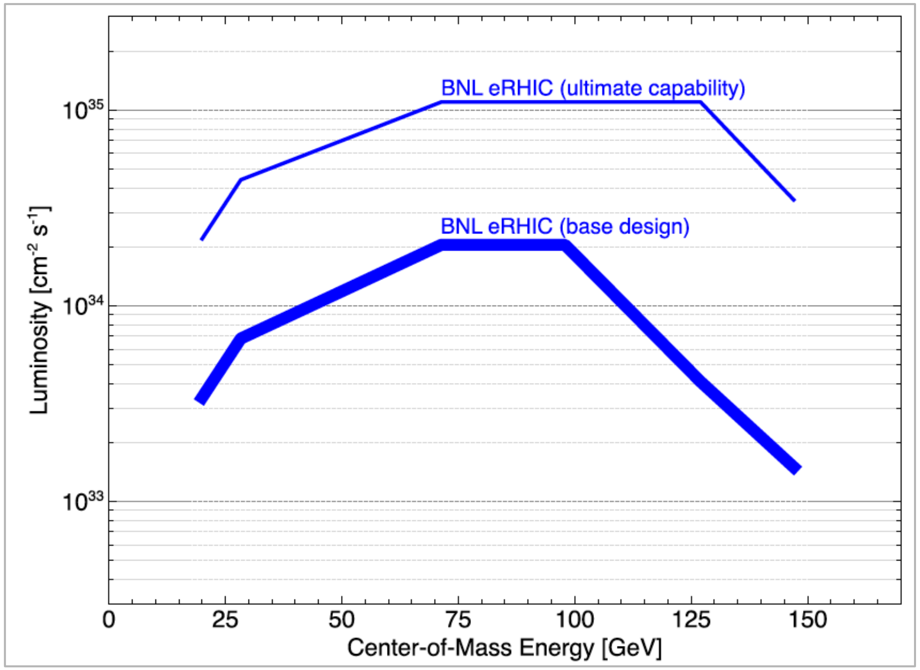
-Momentum balance ("E-p_z") required to cope with RC and background from photoprod.

LHeC thus has classic ep collider detector configuration ("H1 + ATLAS")
innovative in technology eventually but conservative in its design concept

EIC (white paper) focus has been different: semi-inclusive DIS, particle ID
it probably is being studied how precise NC and CC may be measured then
and it would be only logical to design two complementary EIC apparatus
(simulation study presented below assumes a high precision "classic" detector)

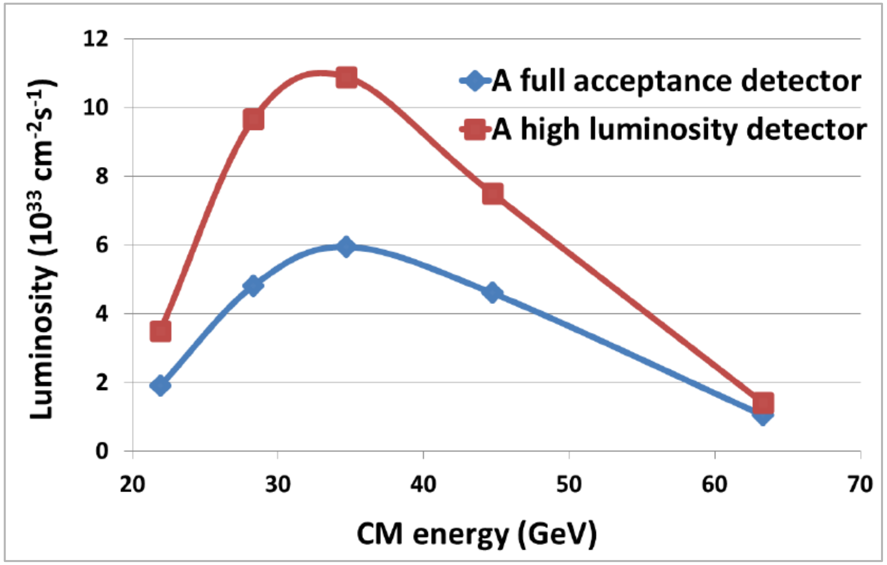
Luminosity ($e^- p$) and Energy ($\sqrt{s}=2\sqrt{E_e E_p}$)

These are projections which
depend on $, trust, R+D and time..
BNL: RR? (BM) Jlab: no PEP? (RY)
Baseline: 100 GeV cms and 10^{34}
Notice strong L dependence on energy



1409.1633 eRHIC design report, 2014

note logarithmic scale for luminosity

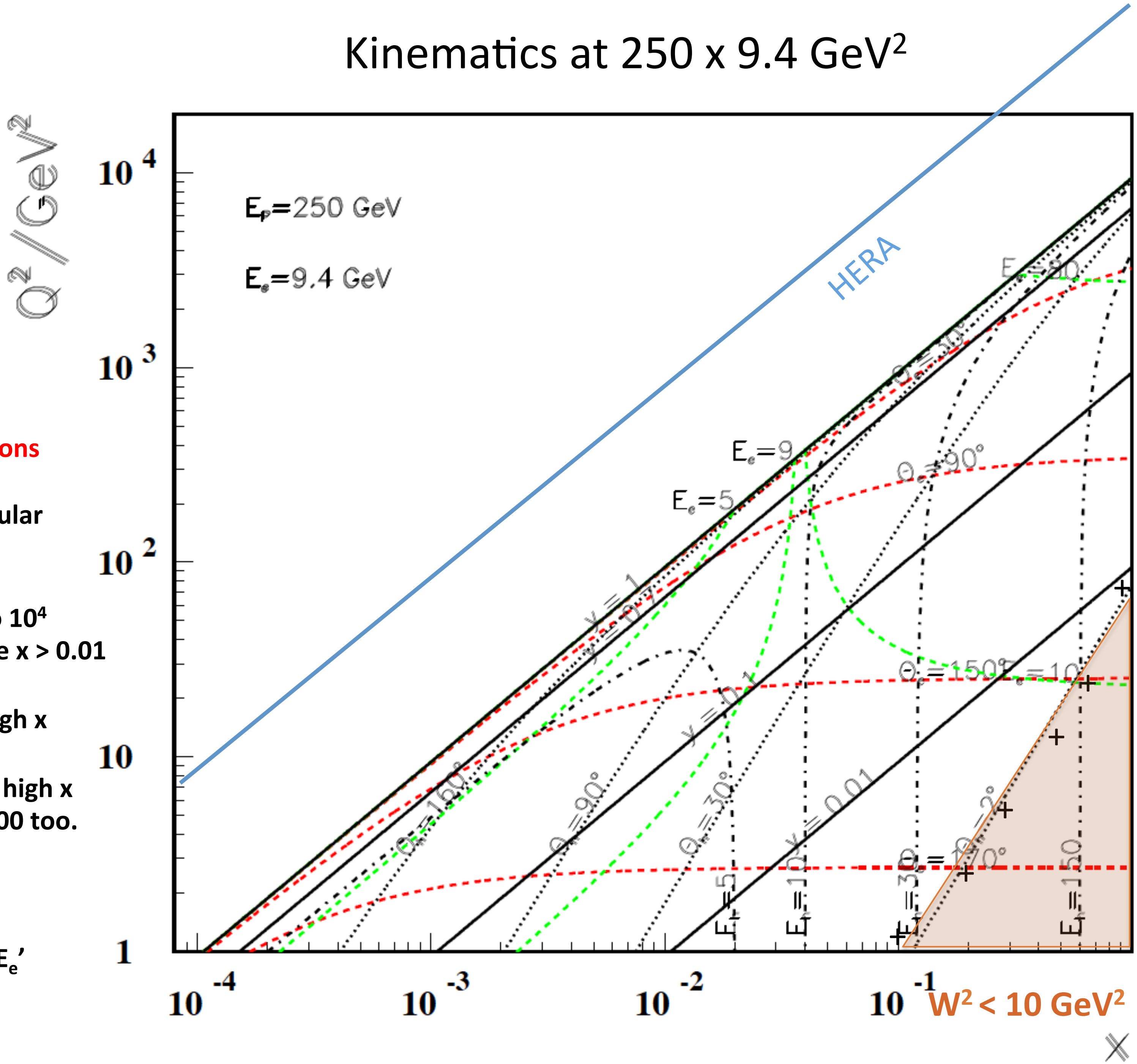


1504.07961 MEIC design report 2015

note linear scale for luminosity

Subsequently considered two energy settings: 100 GeV and 30 GeV cms energy

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

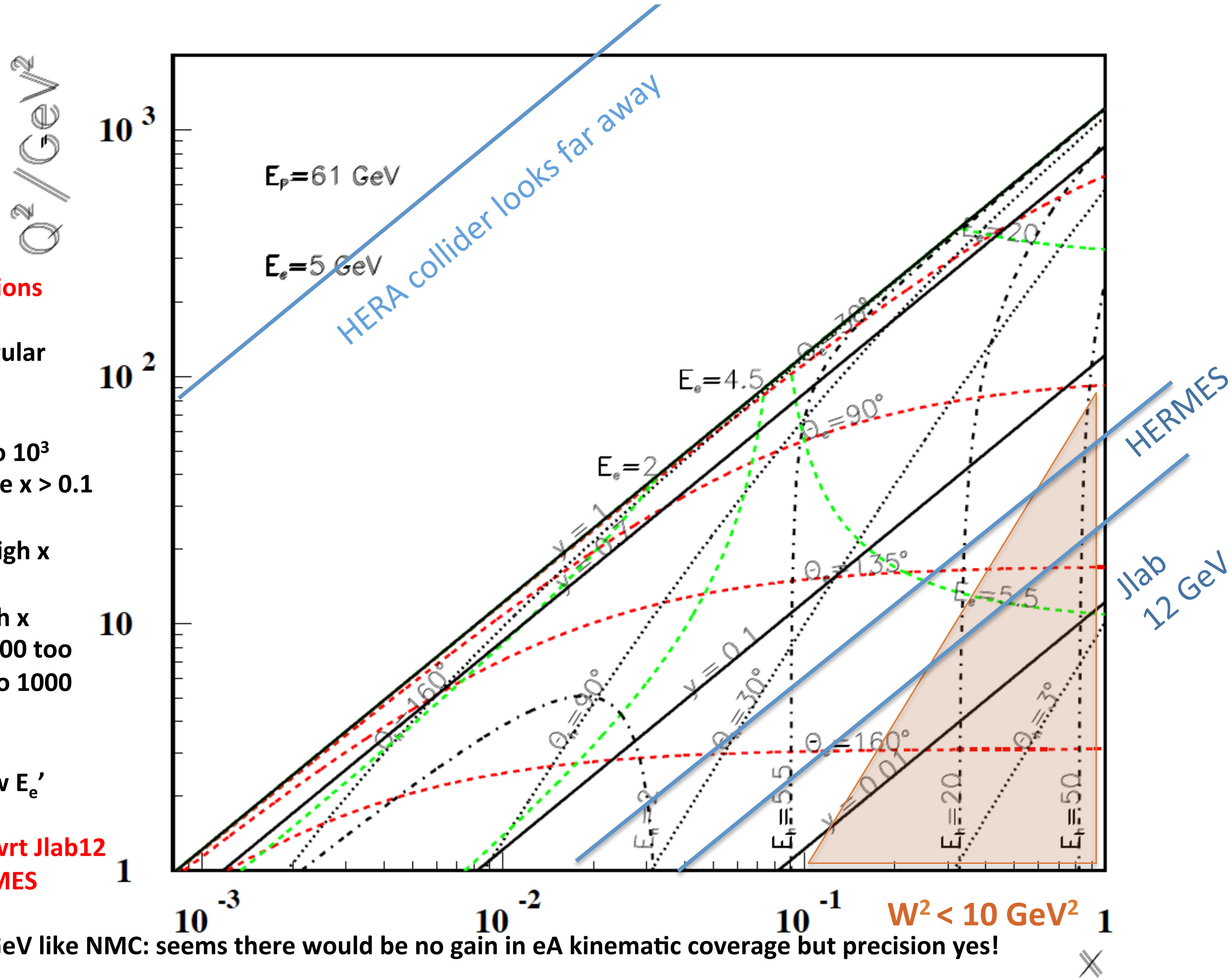
Good angular coverage

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

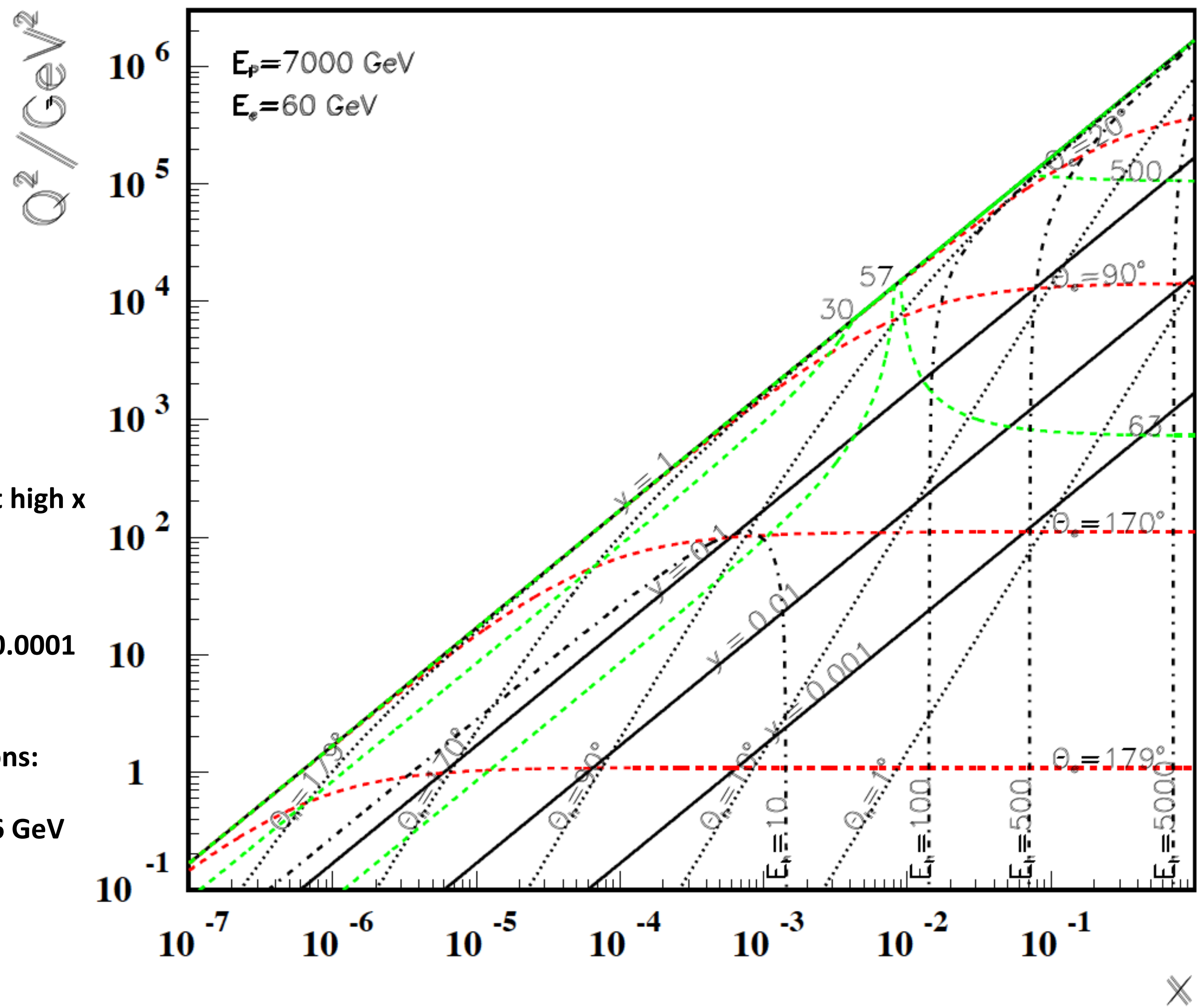
High y
Really low E$_e$'

Big step wrt Jlab12 and HERMES



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

Kinematics at LHeC



Observations

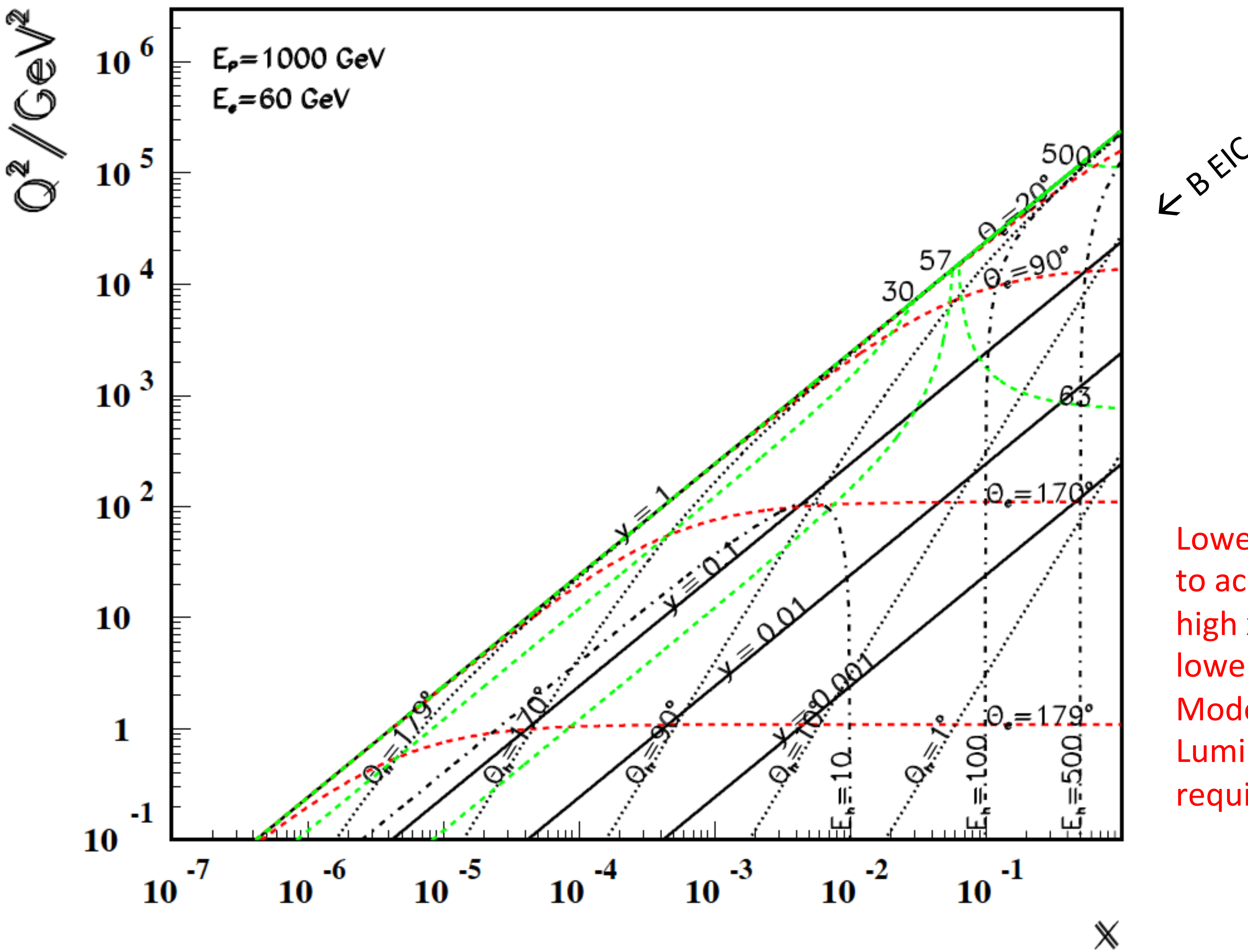
Good angular coverage but at high x low Q2

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"

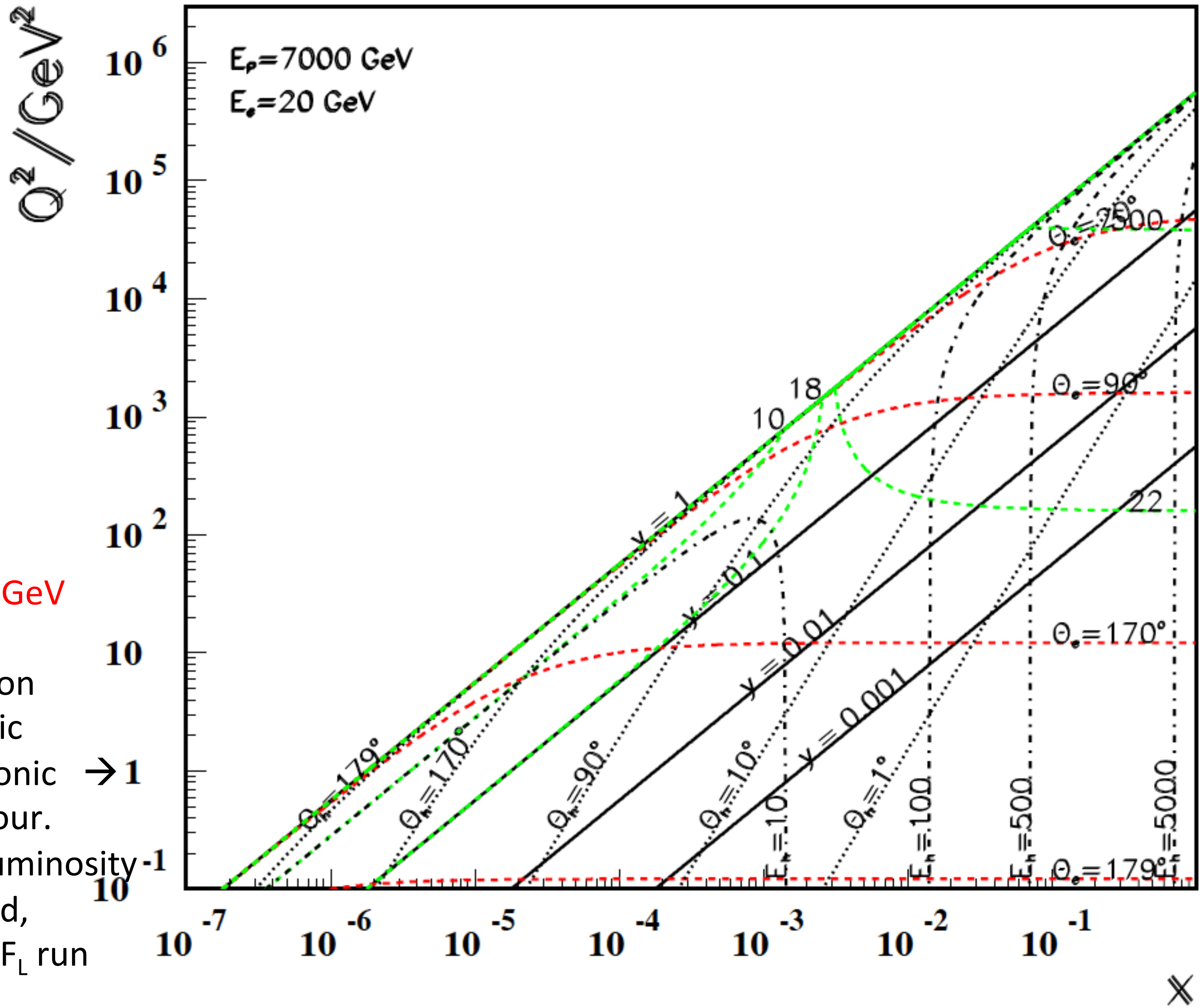
Kinematics at LHeC



Lower E_p to access high x at lower Q^2

Modest Luminosity required

Kinematics at LHeC



E_e = 20 GeV

Covers transition hadronic to partonic → 1 behaviour.

"NO" luminosity required, part of F_L run

Unpolarized parton distribution functions: questions to be addressed at an EIC

Marco Guzzi, Pavel Nadolsky, Fredrick Olness

Nuclear PDFs

In 1108.1713
EIC Science Case

Better constraints on the strangeness PDF

The d/u ratio at large x

Gluon PF in the proton and charm production at large x

Inclusive charm production

Transition to the high density regime.. particularly using heavy ion beams

Perturbative-nonperturbative QCD boundary

The longitudinal structure function

Electroweak contributions to proton PDFs [photon PDF, isospin violation, weak NC+CC]

The LHeC PDF Programme

Input: high precision (stat+syst) data on

Neutral Current (x: 10^{-6}-1; Q^2:1-10^6) Charged Current (10^{-4}-1; 100-10^6)

Tagging of Charm and Beauty with high precision and coverage. ep (eD)

Goal

Determine ALL pdfs in a coherent way + the strong coupling to 0.1% accuracy

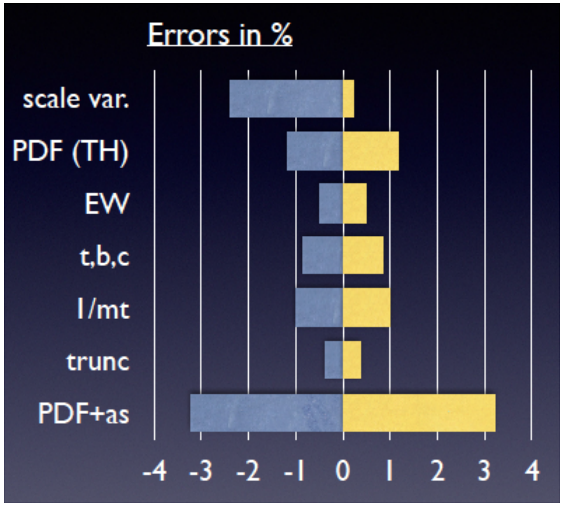
No higher twists, no nuclear corrections, no symmetry assumptions, N^3LO

→ ubar, uv, dbar, dv, s, c, b, t, xg and $alpha_s$

See talks by Mandy Cooper-Sarkar and Claire Gwenlan on ALL pdfs simulated

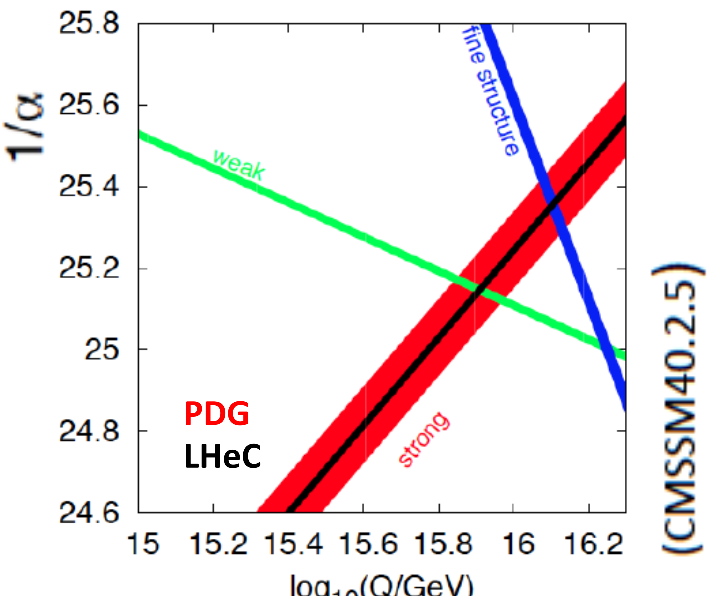
Note that the fit studies mostly do not use the simulated s,c,b nor t data, yet.

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
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**

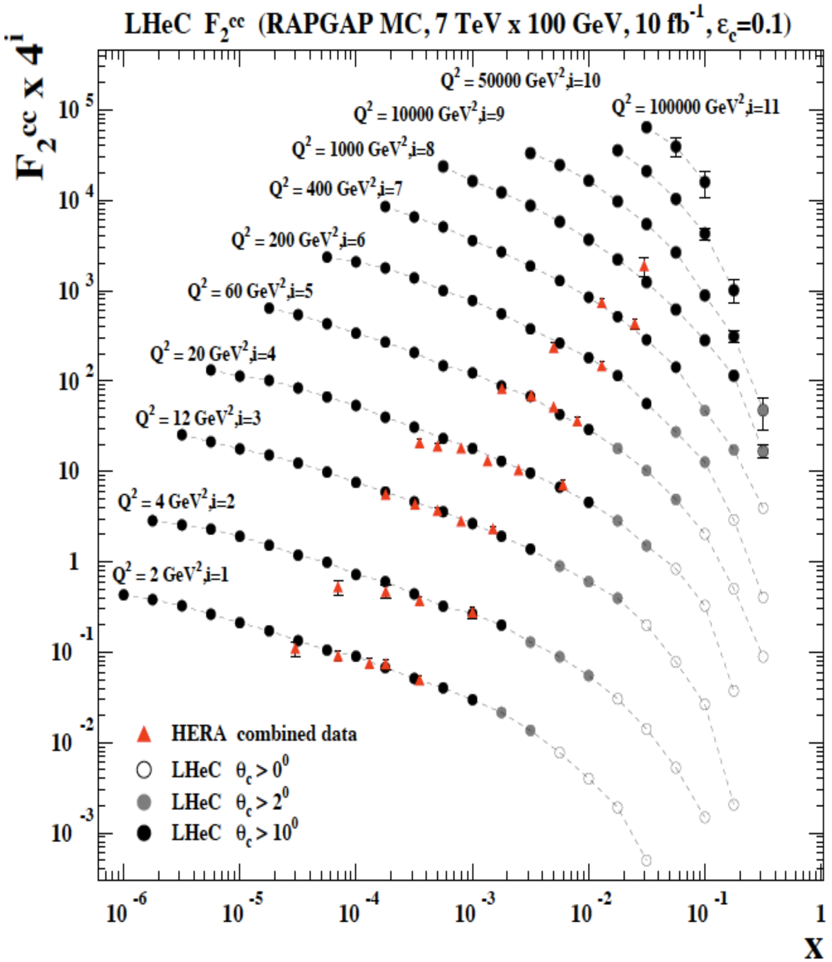


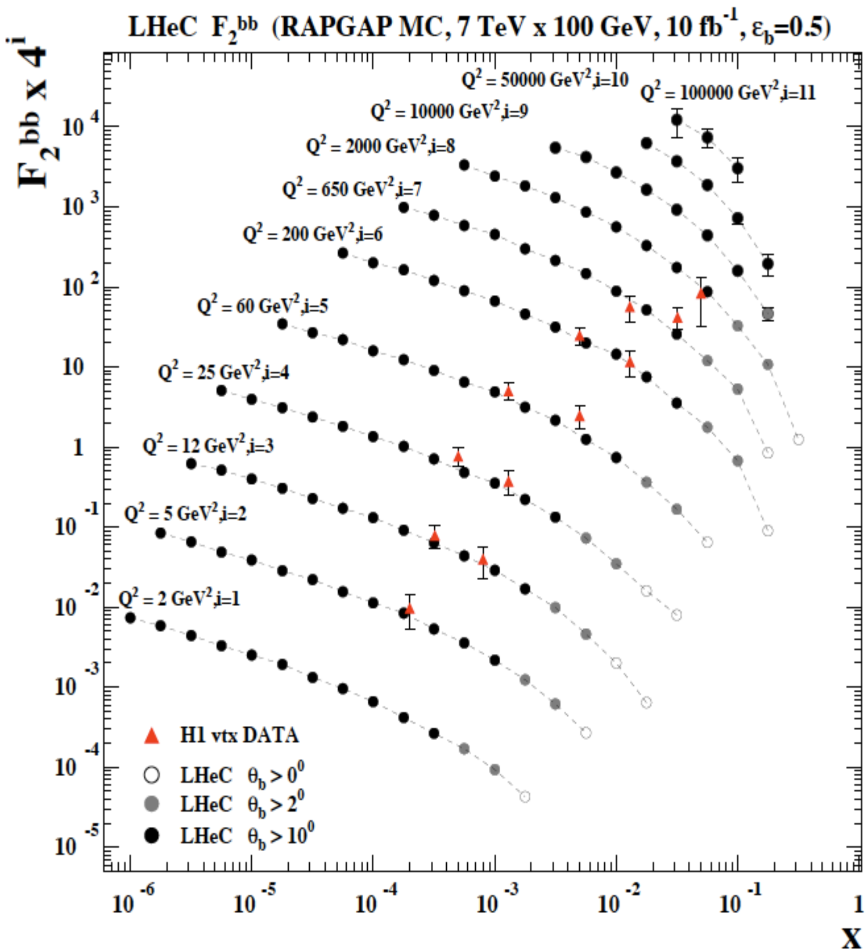
LHeC simulation, NC+CC inclusive, total exp error

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

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





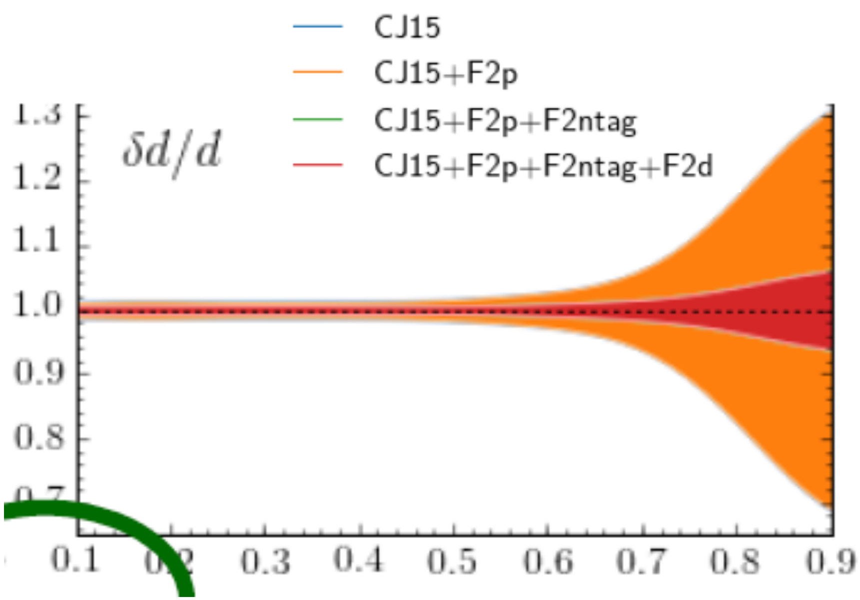
Hugely extended range and much improved precision (δM_c=60 HERA → 3 MeV)
will pin down heavy quark behaviour at and far away from thresholds, crucial for precision t,H..
In MSSM, Higgs is produced dominantly via bb → H (Pumplin et al) , but where is the MSSM..

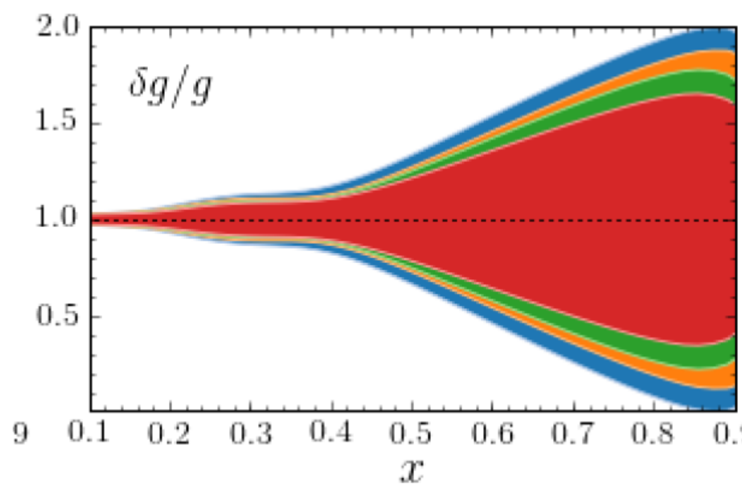
The EIC PDF Programme

Being worked out in detail (AA today) Depends on the energy chosen,
Especially: 100 GeV and 30 GeV are different: CC and low x

Presentations by Elke Aschenauer, see also Jlab High x Workshop 10/16

Alberto Accardi





Novel Simulation Study and QCD Evaluation

Perhaps too optimistic (det, 100fb^{-1}) and surely **very preliminary** (days old) and not thorough (E's fixed)

- 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]
- **Here also applied to EIC for 100 GeV CM energy NO W^2 cut made, no thy uncertainties**
  [Note: this assumes high EIC detector performance at lower energies, e-h 4π calorimetry..]

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 %

- followed by QCD analysis using HERA fit framework, XFITTER, Hessian Errors
  used for various sets, assumptions, targets. Here for a first comparison with EIC too

see LHeC CDR and description in: Voica Radescu, MK

Contribution to Snowmass 2013, LHeC-Note-2013-002. PDF set available on LHAPDF

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

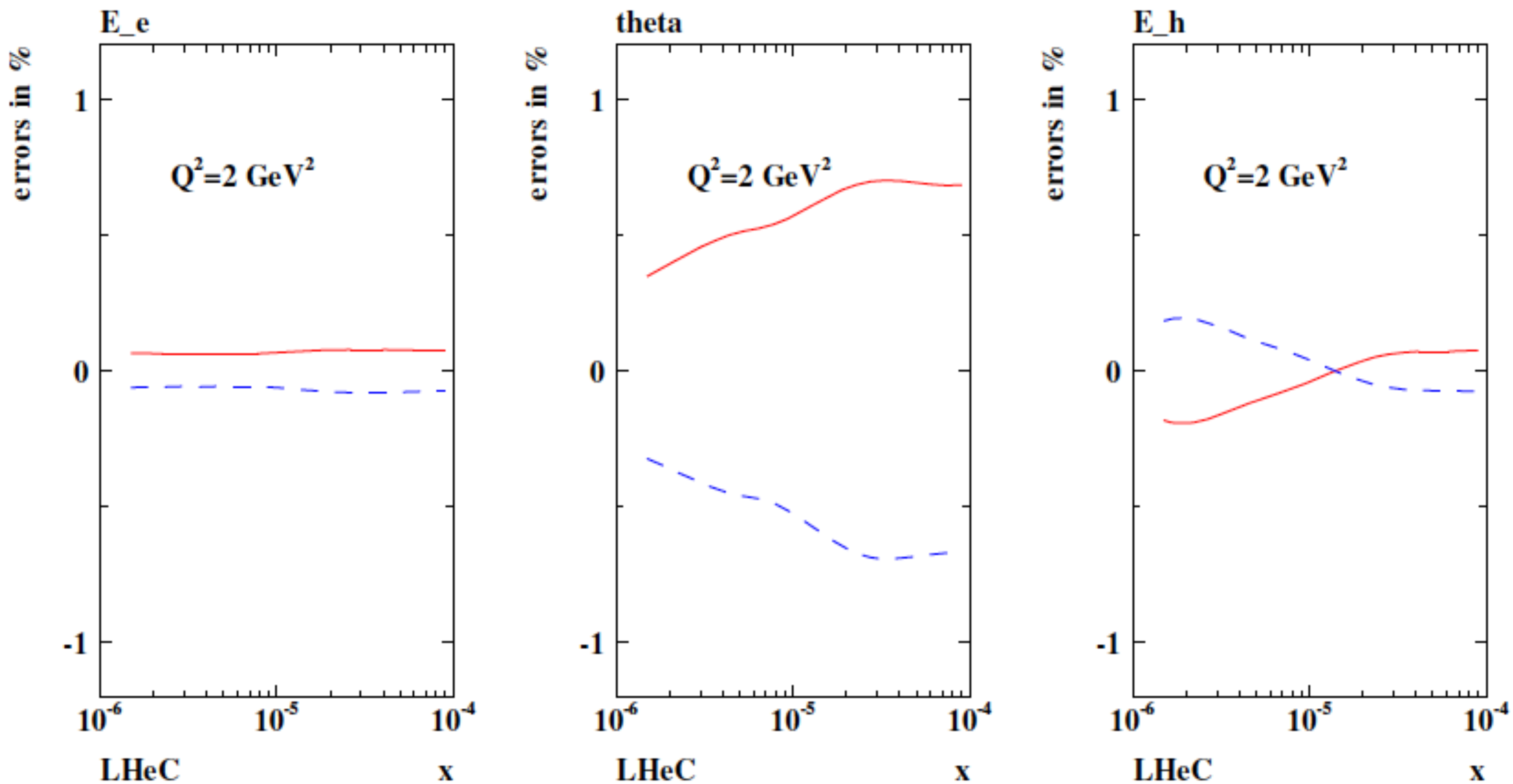


Figure 3.2: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h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

From LHeC CDR

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

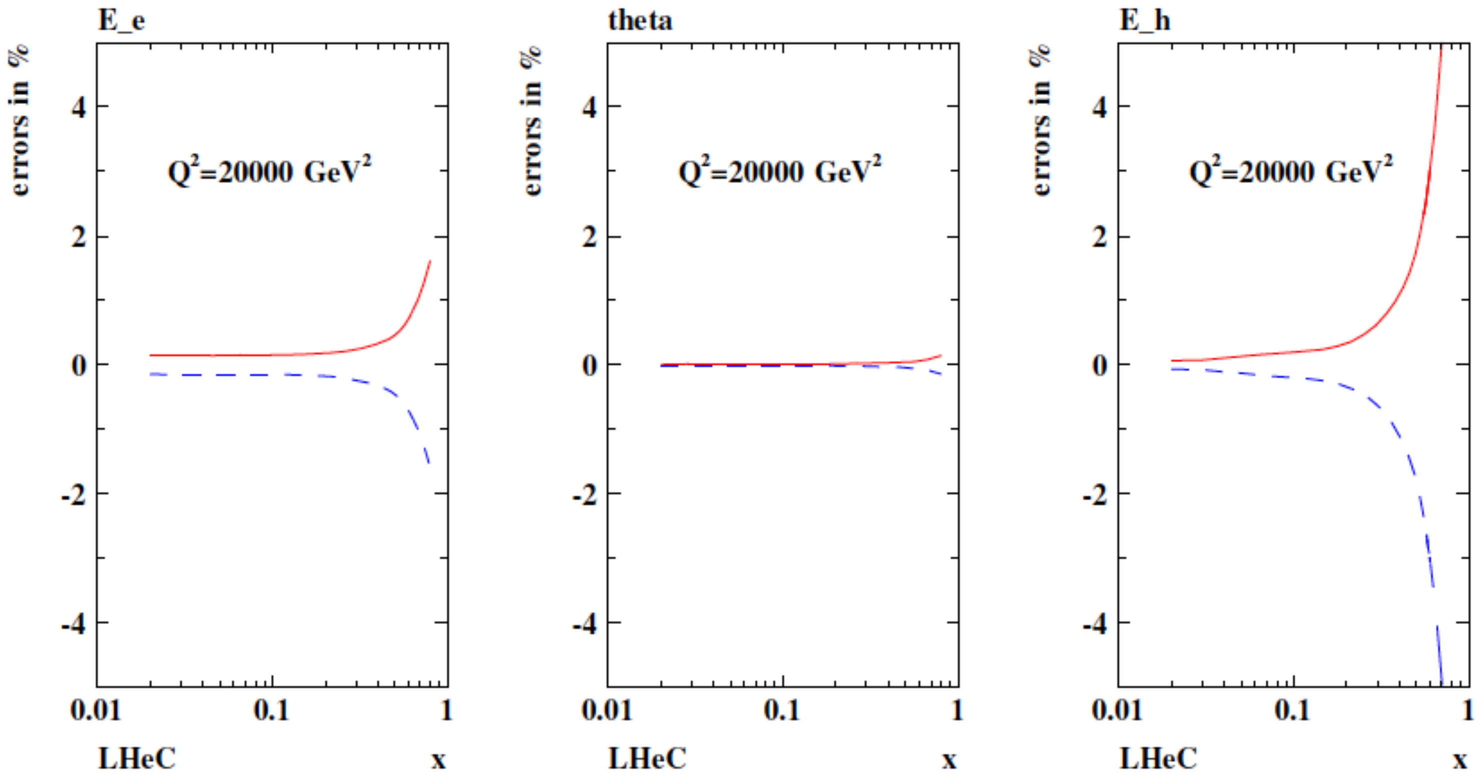


Figure 3.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised e^-p scattering, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final 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.

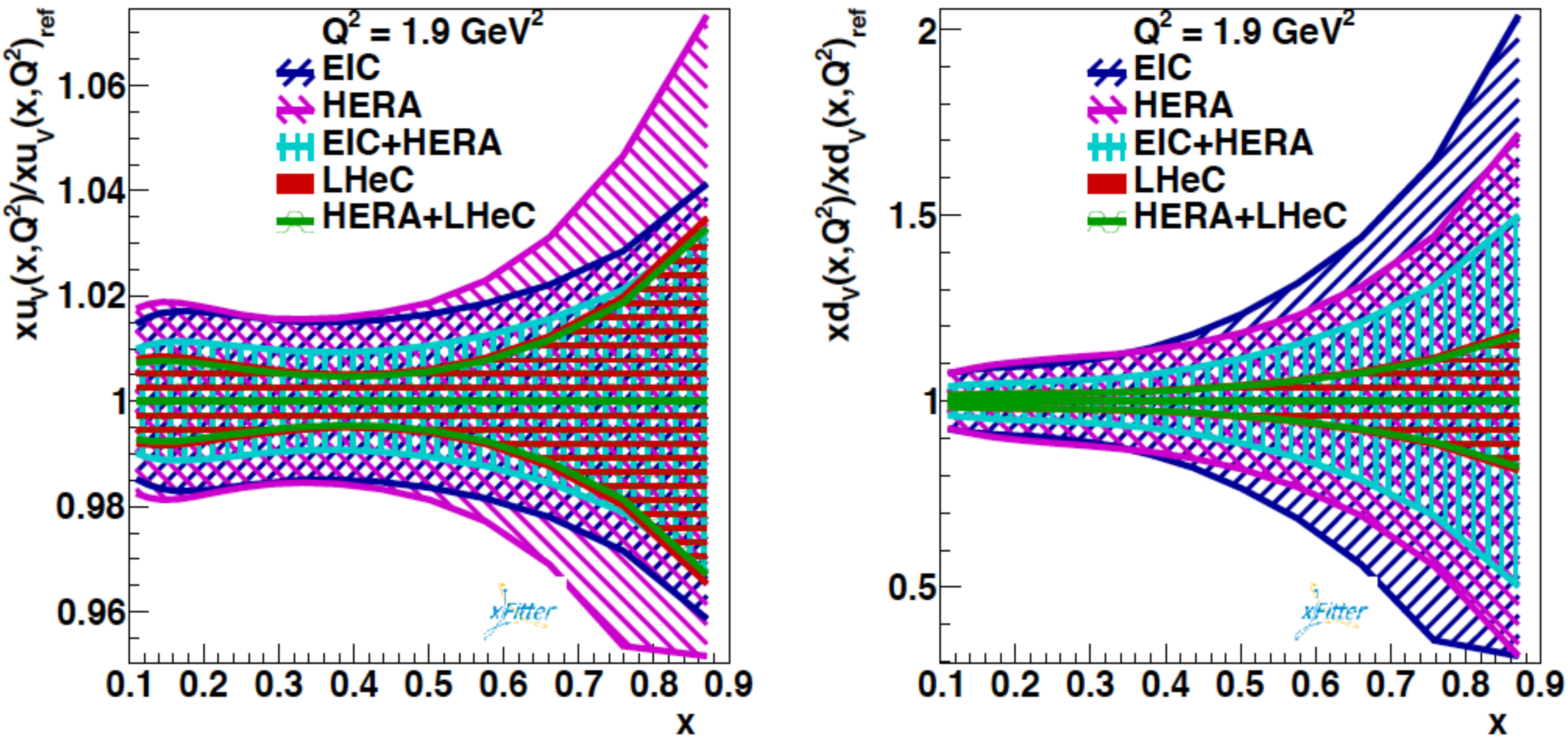
From LHeC CDR

Valence Quarks

Very preliminary

u valence

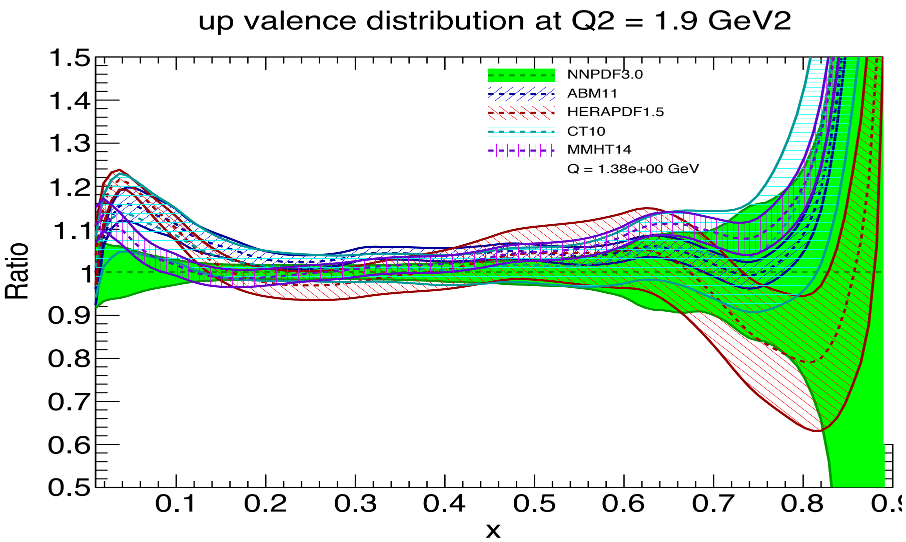
d valence

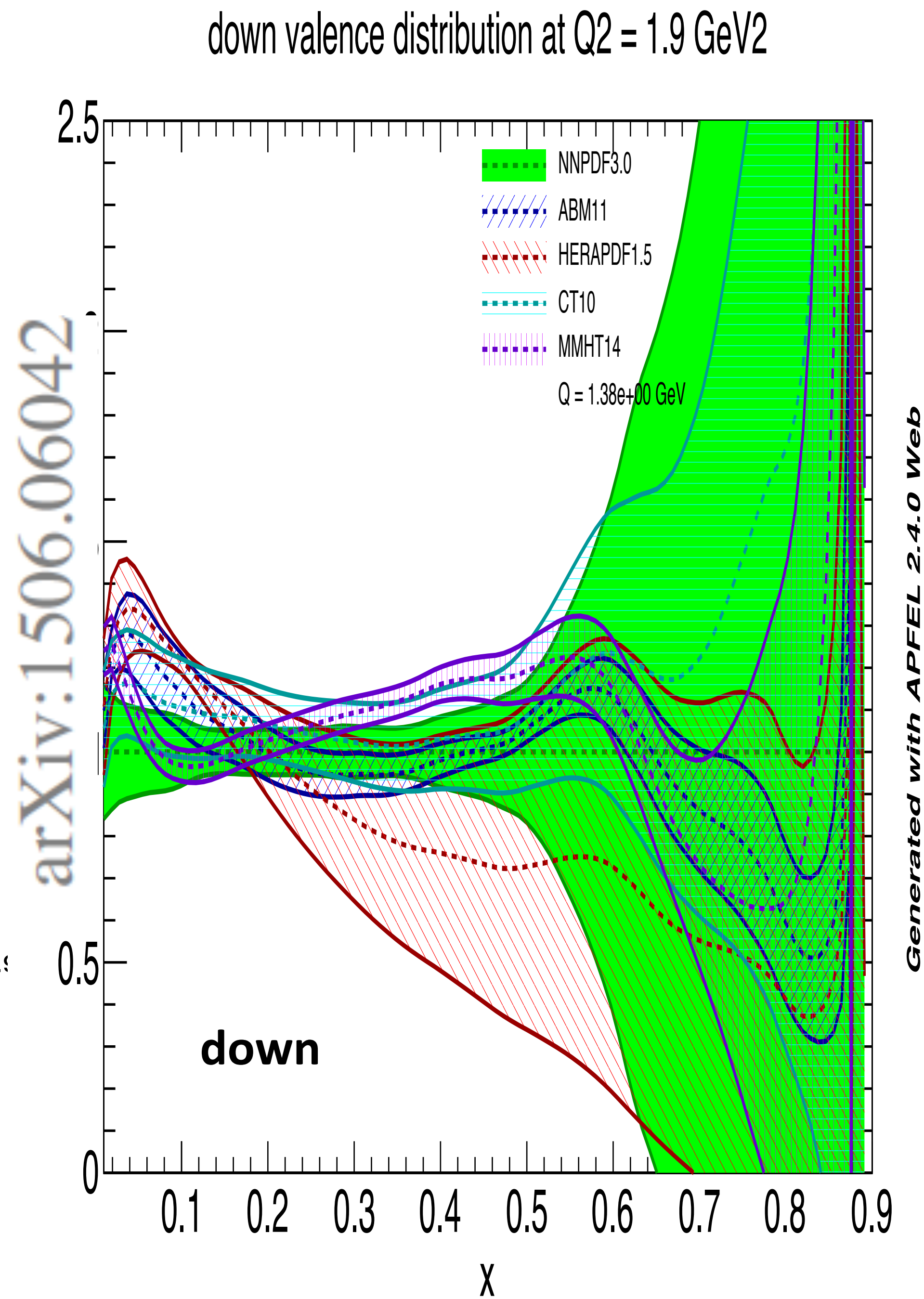


Valence quarks

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

up



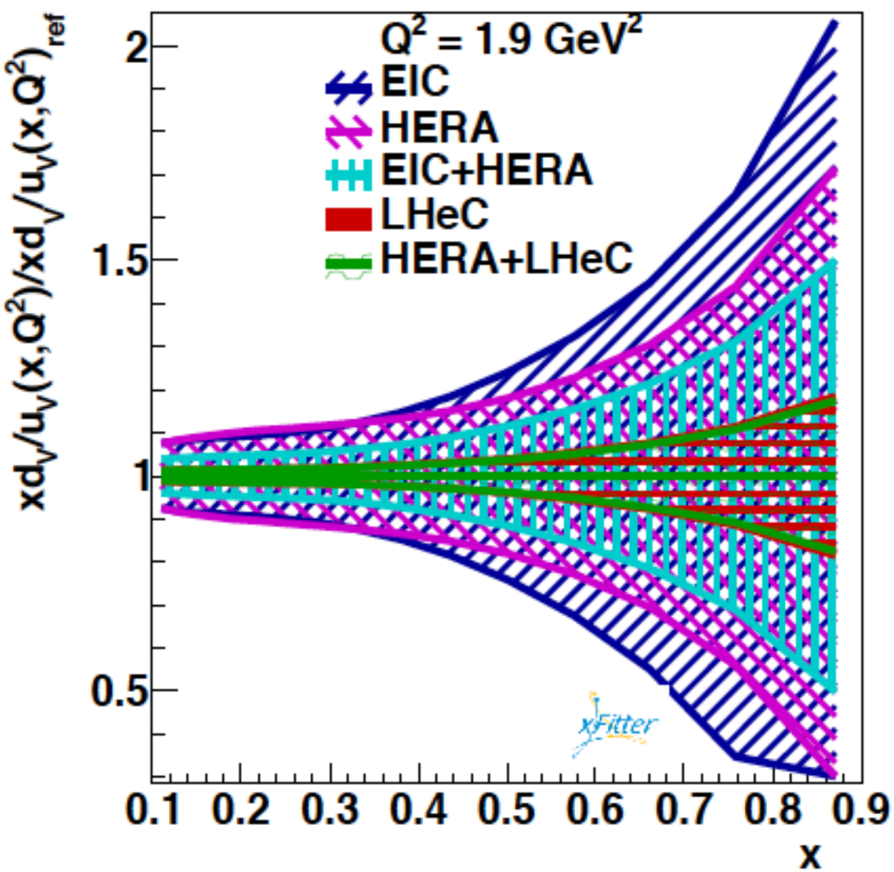


Need to be very careful about error estimates and central values also! Study only indicative.

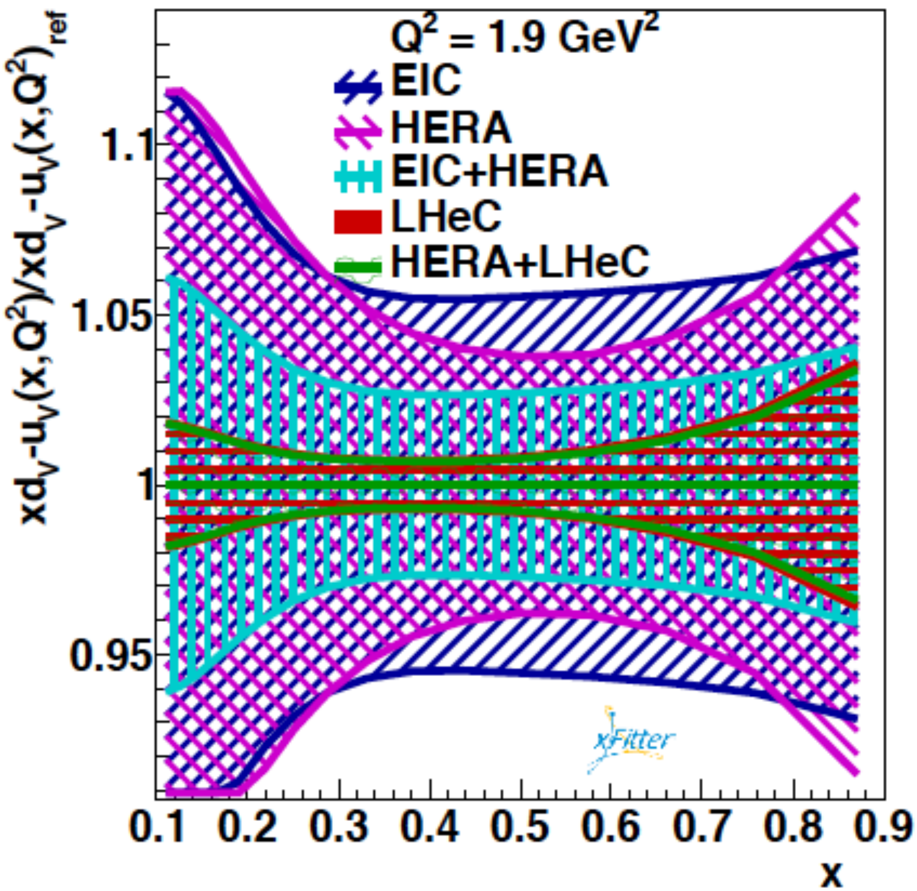
Light Quarks at Large x

Very preliminary

d_v/u_v



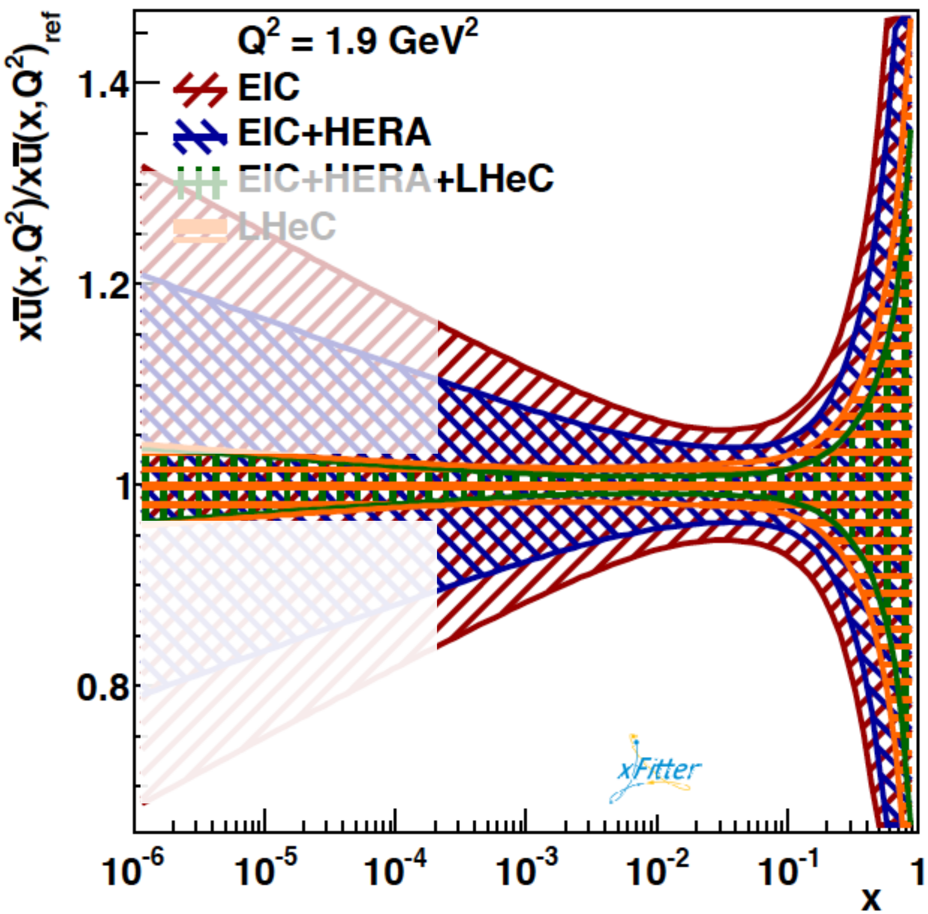
d_v-u_v



Light Sea at small x

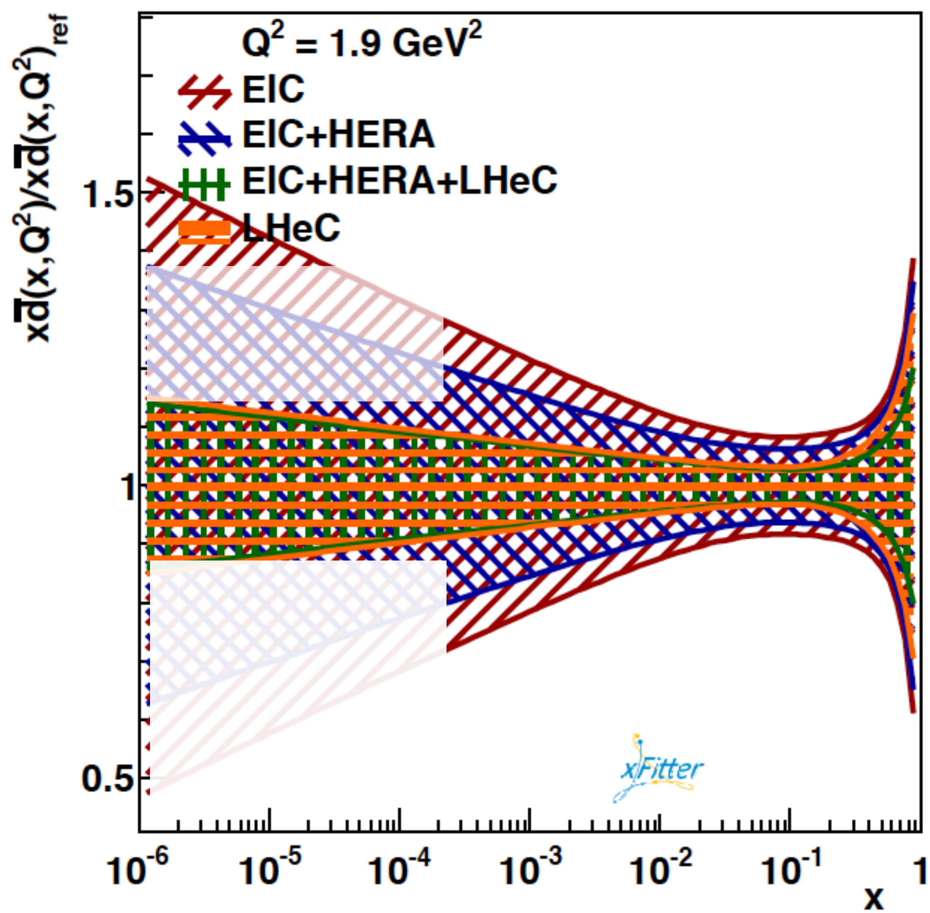
Very preliminary

anti-up



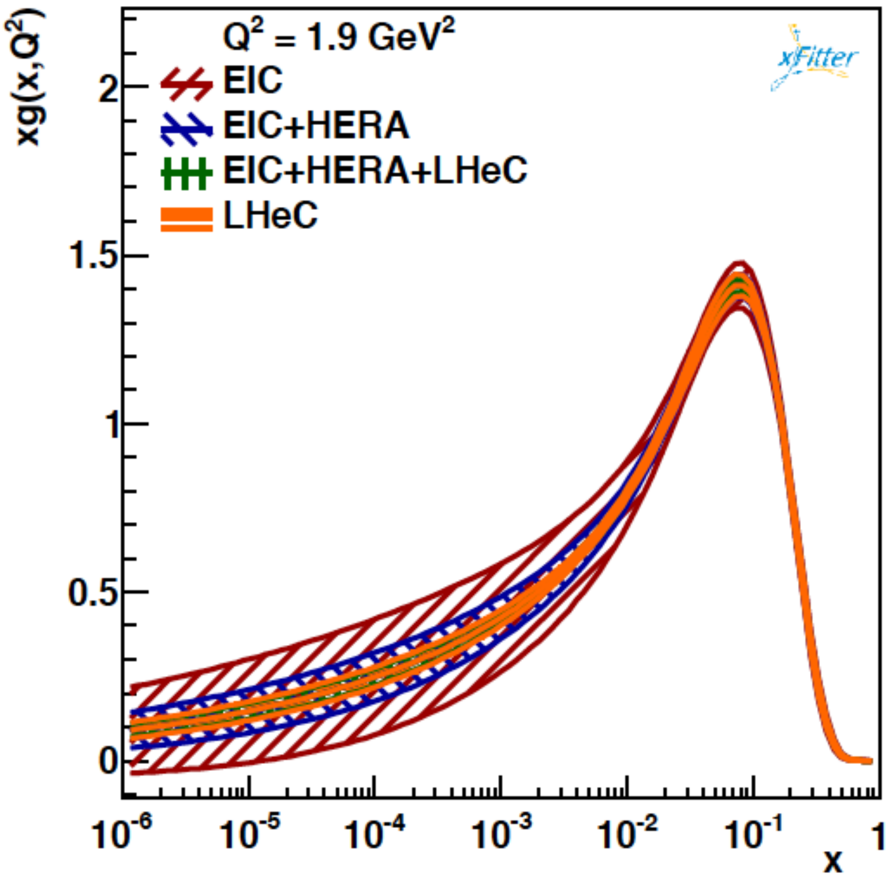
Kine coverage NC B-EIC

anti-down

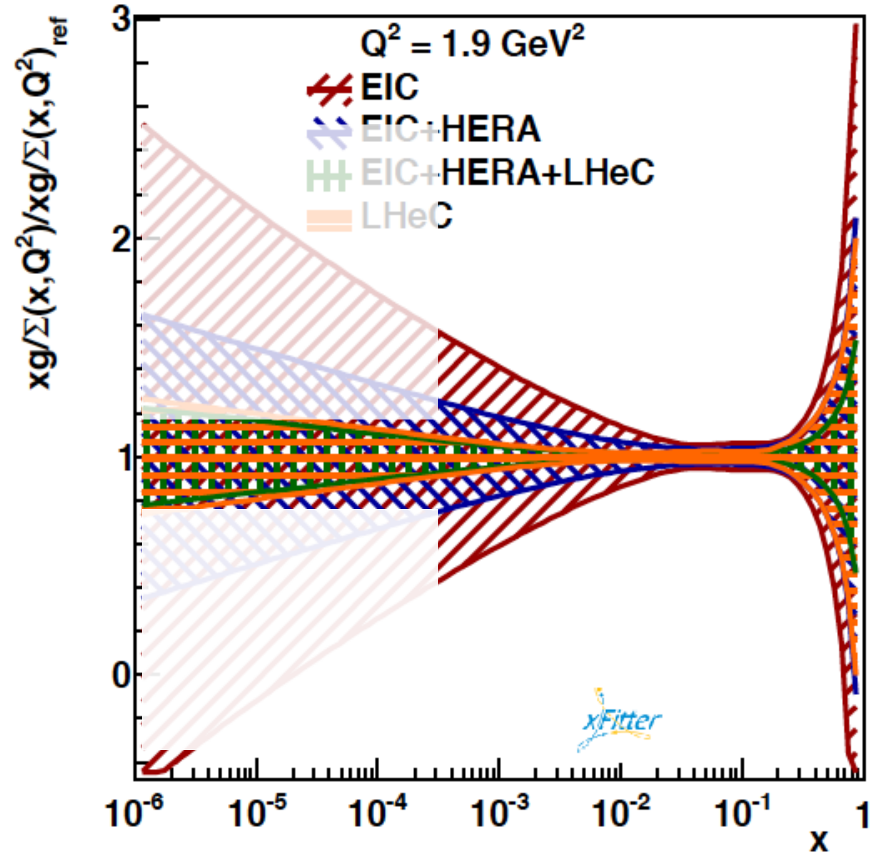


Gluon distribution

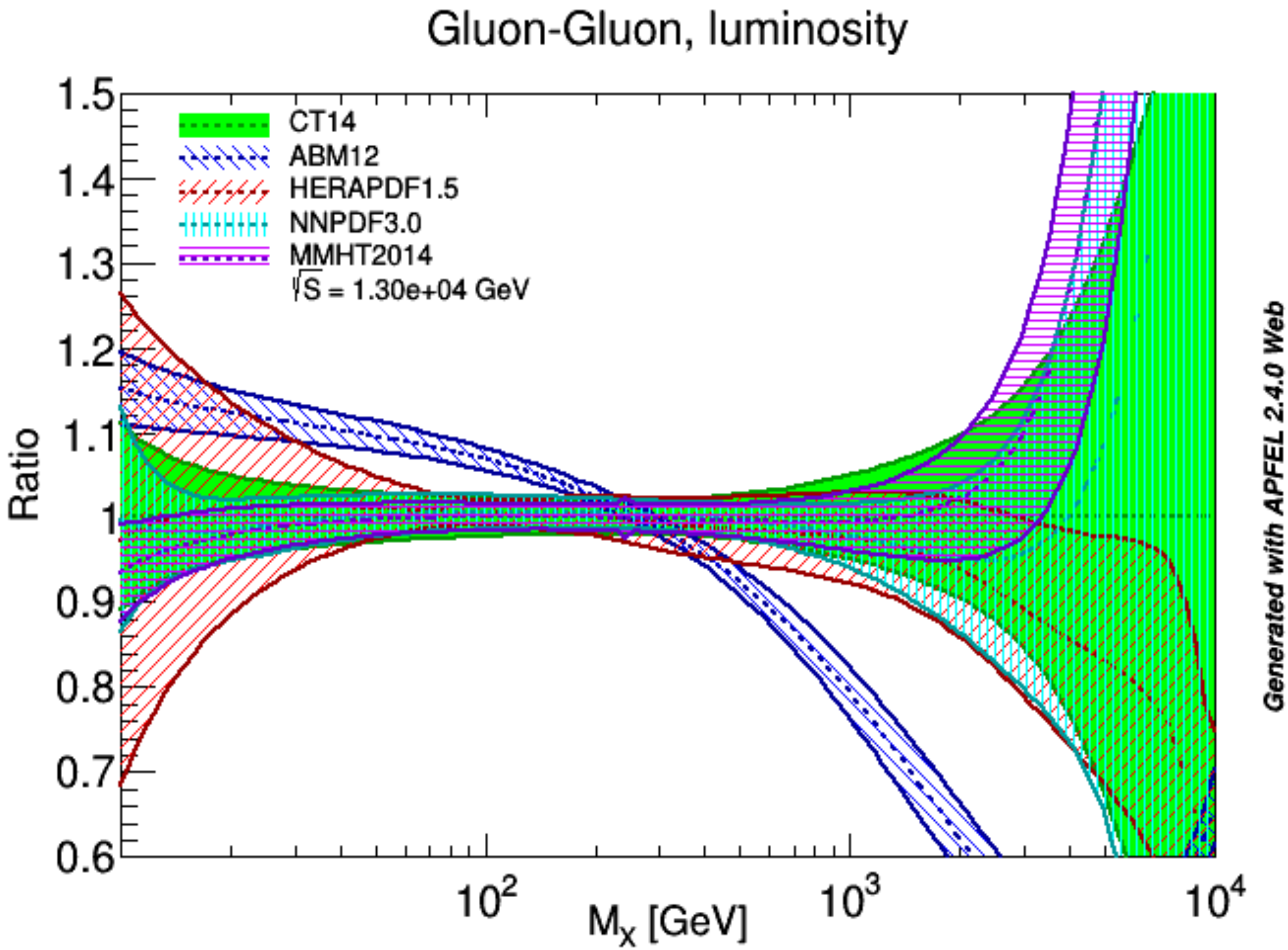
Very preliminary



Kine coverage NC B-EIC



Parton-Parton "Luminosities"

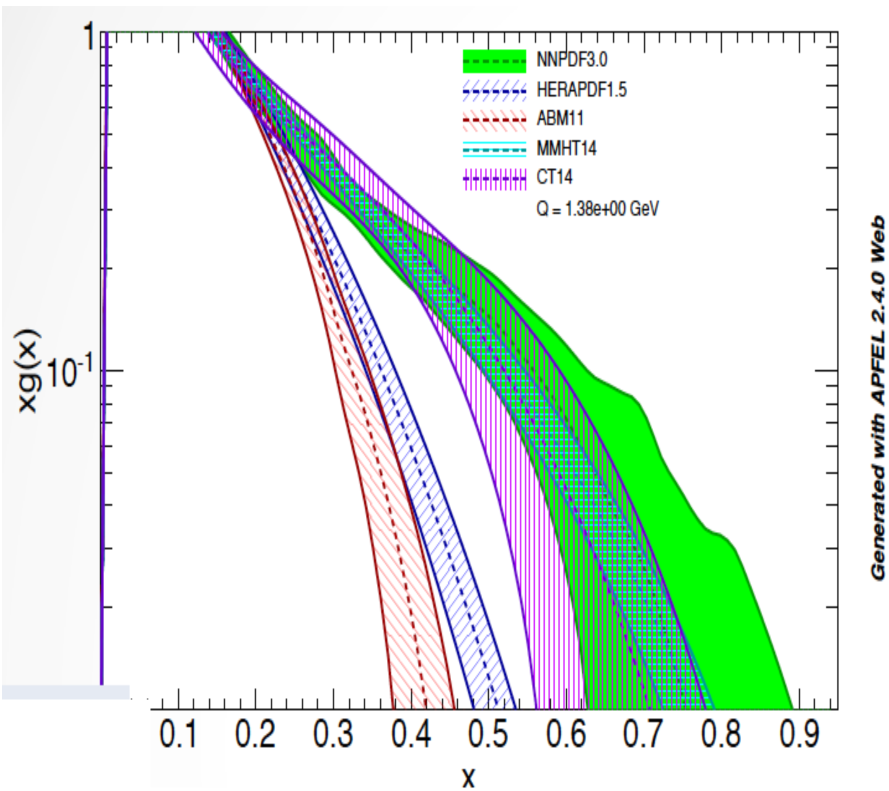


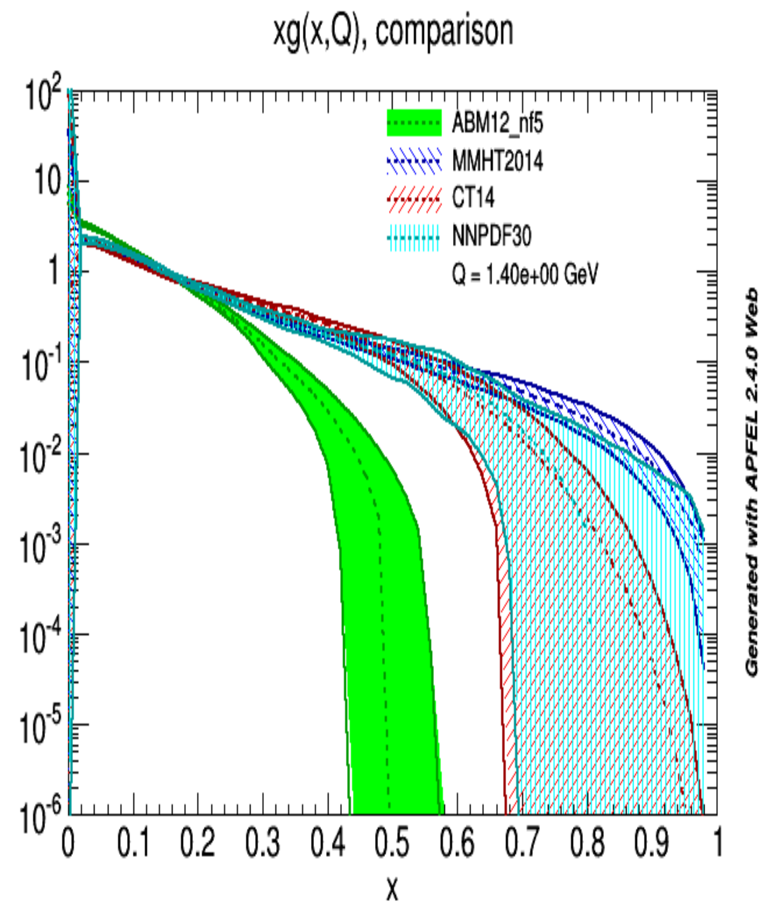
0.00077 0.1 0.77 1

x →

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

Gluon Distribution at High 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

Gluon at large x becomes very small and is hugely uncertain while $M_X^2=sx_1x_2$ ..

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

PV Structure Function $F_2^{\gamma Z}$

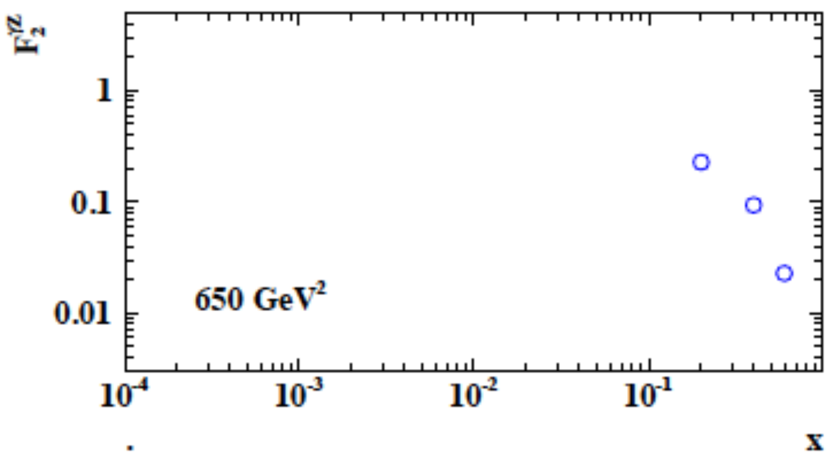
$$\mathbf{F_2^{\pm}} = F_2 + \kappa_Z(-v_e \mp P a_e)\cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e)\cdot F_2^Z$$
$$\mathbf{xF_3^{\pm}} = \kappa_Z(\pm a_e + P v_e)\cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2))\cdot xF_3^Z.$$

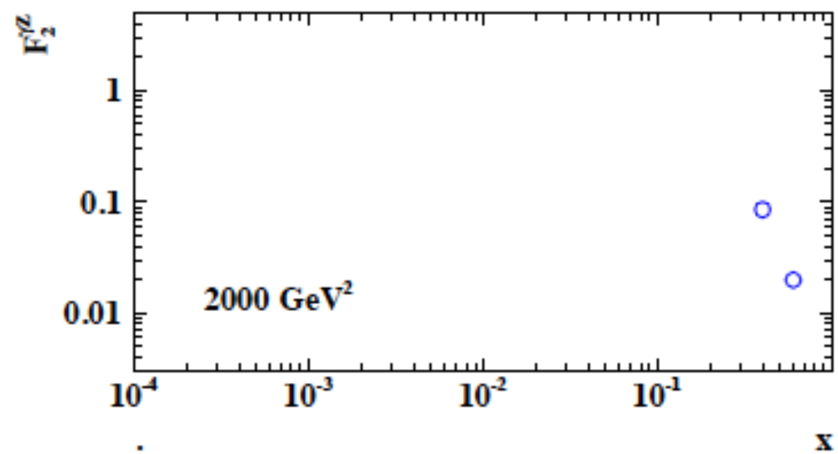
$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2}\cdot\frac{1}{4\sin^2\Theta\cos^2\Theta} \qquad v_f = i_f - e_f 2\sin^2\Theta \qquad a_f = i_f$$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q})$$
$$(xF_3^{\gamma Z}, xF_3^Z) = 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}),$$

	e^2	2ev
u	4/9	2/9
d	1/9	2/9

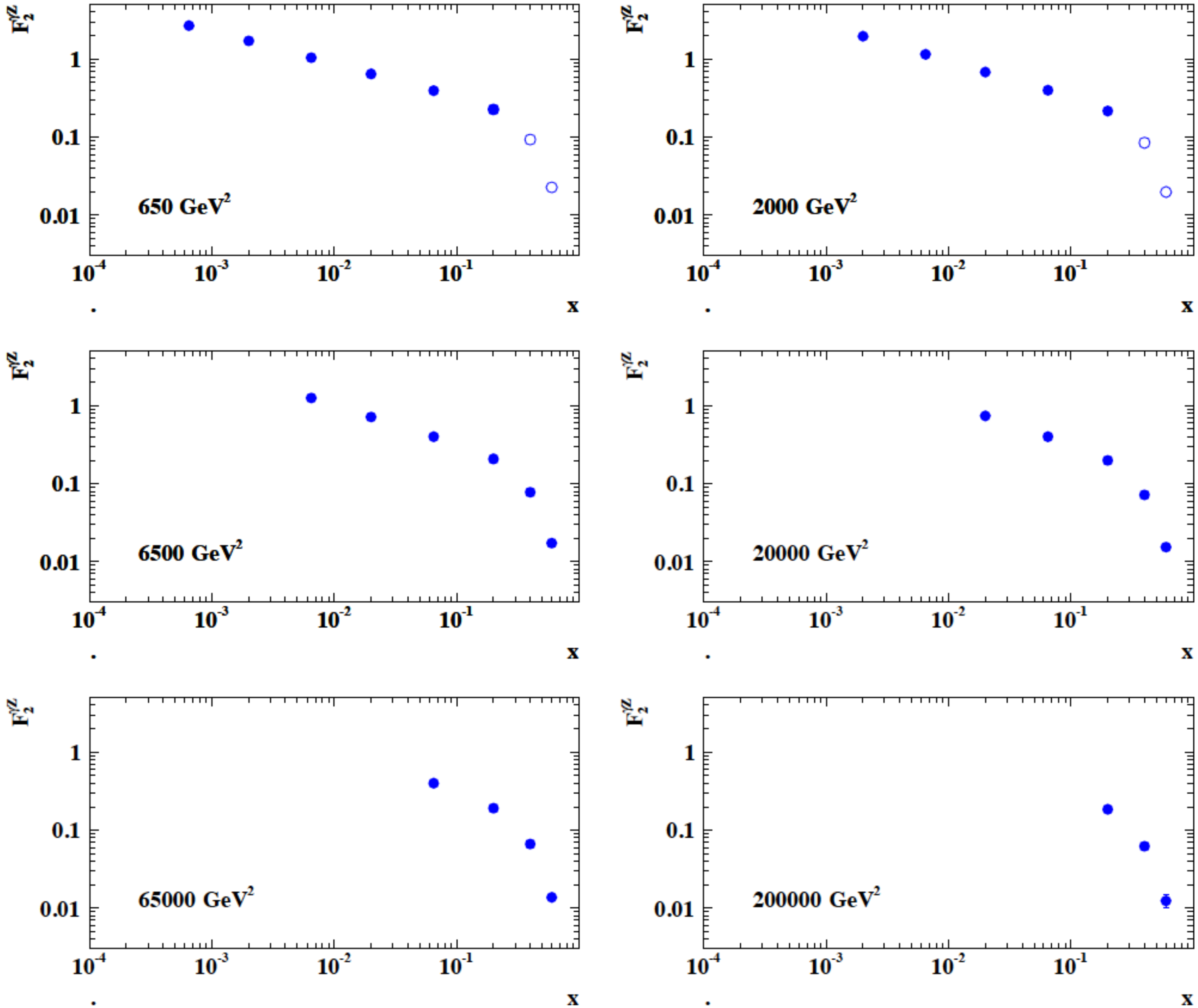
EIC $10\,fb^{-1}$ P=+- 0.8 E_e=9.4, E_p=250 GeV





Z exchange may be seen at large x at the EIC to measure PV effects with polarisation flip

$F_2^{\gamma Z}$



● LHeC 10fb^{-1} P=+- 0.8 E_e=60, E_p=7000 GeV   o EIC 10fb^{-1} P=+- 0.8 E_e=9.4, E_p=250 GeV

Remarks on Saturation

cf talk by Anna Stasto

"BFKL evolution and Saturation in DIS"

"Critical gravitational collapse"

Circles in a circle
V. Kandinsky, 1923
Philadelphia Museum of Art

5d tiny black holes and perturbative saturation
Talk by A.S.Vera at LHeC Workshop 2008

Neutrino-Nucleon Cross Section at UHE

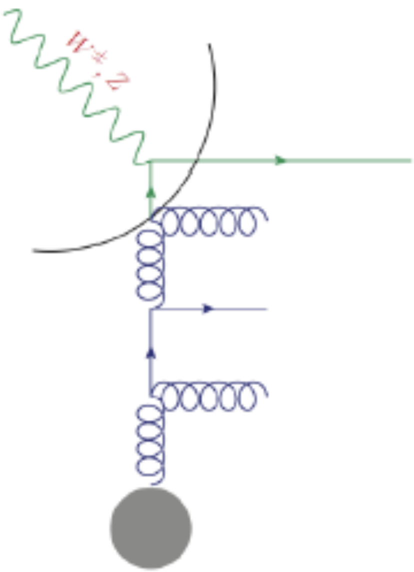
& its *astrophysical* Implications

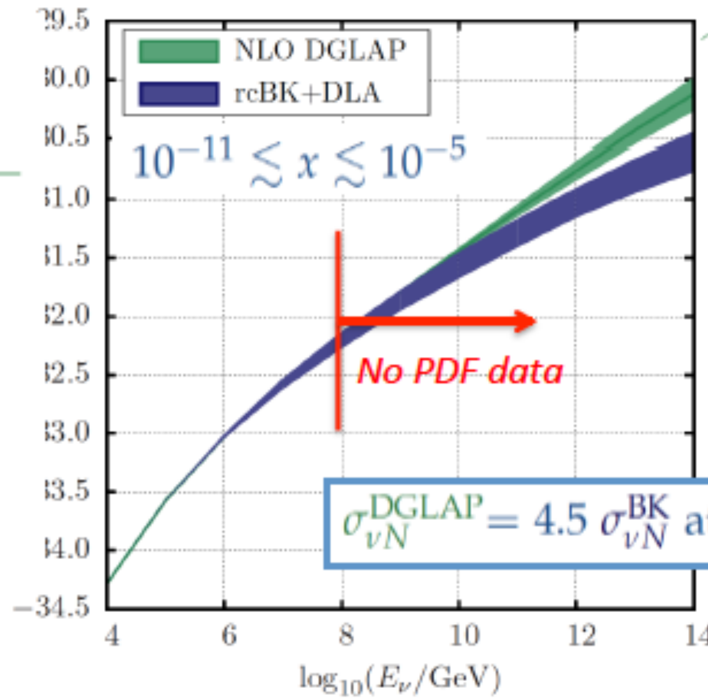
Alba SOTO ONTOSO,
@POETIC VI
PRD 92, 014027 (2015)

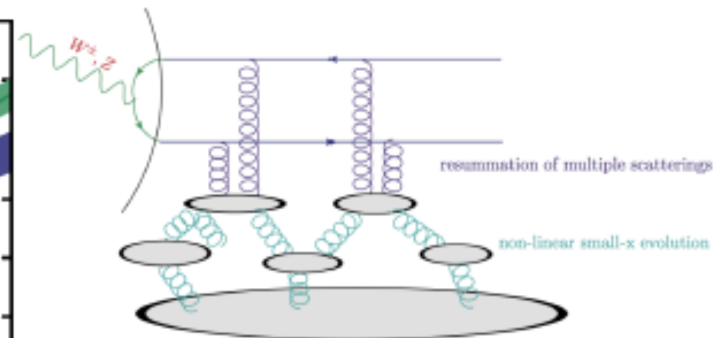
$$\sigma_{\nu N} \sim \underbrace{\begin{pmatrix}\text{Probability of} \\ \text{finding a quark/gluon} \\ \text{in nucleon}\end{pmatrix}}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

DGLAP approach $(\alpha_s \ln(Q^2/Q_0^2) \sim 1)$

À la BK $(\alpha_s \ln(x_0/x) \sim 1)$







$\sigma_{\nu N}^{\text{DGLAP}} = 4.5\ \sigma_{\nu N}^{\text{BK}}$ at $E_\nu = 10^{14}$ GeV.

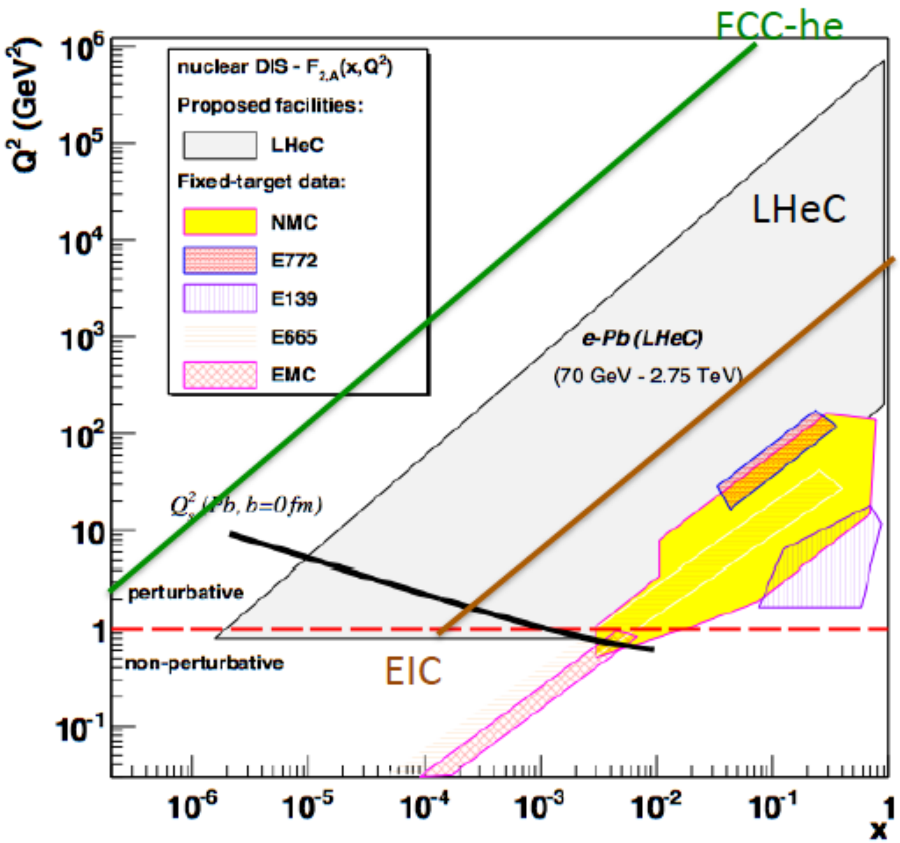
cf Anna Stasto at Chavannes

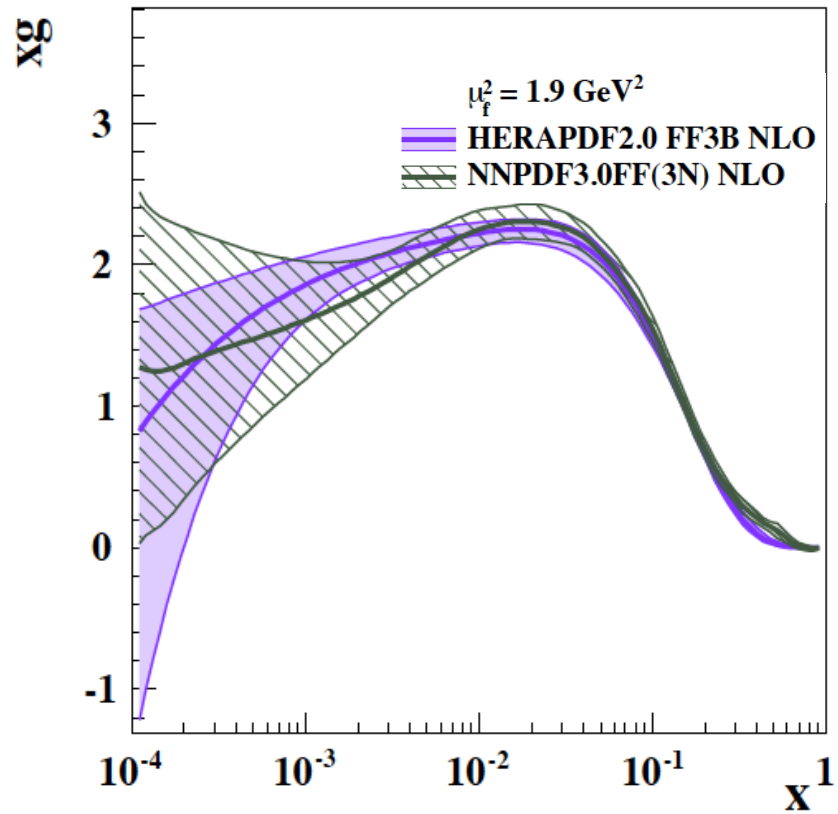
Limits on astrophysical ν fluxes

… **have a much larger uncertainties than currently assumed :**

factors 1.4 to 4.5 for $10^9 < E_\nu < 10^{14}$ GeV.

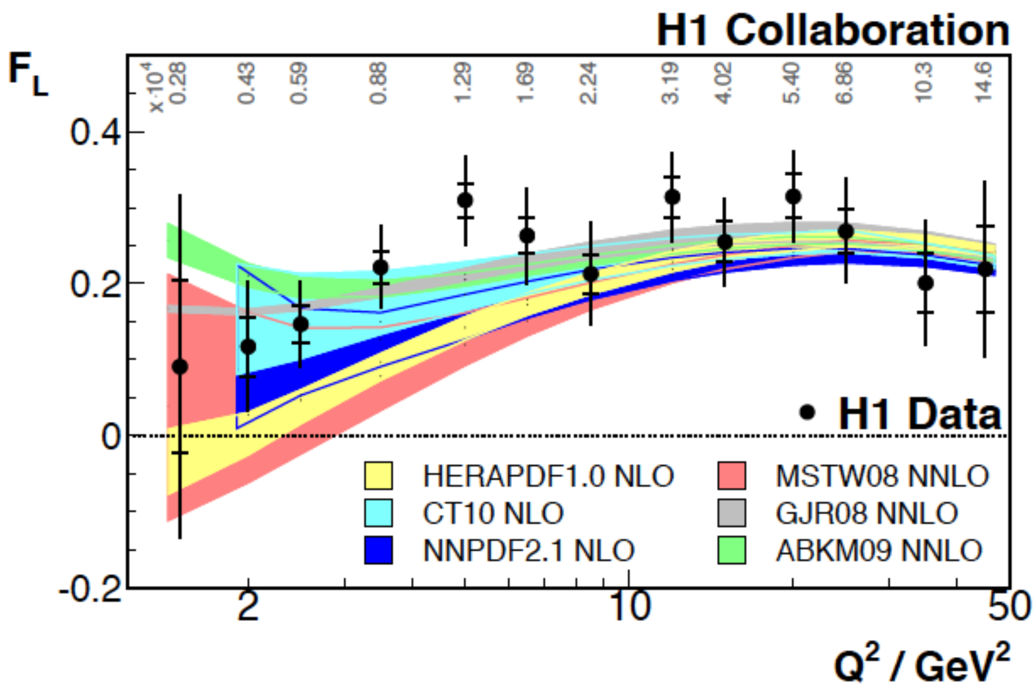
eA Kinematics and xg near the Saturation Line

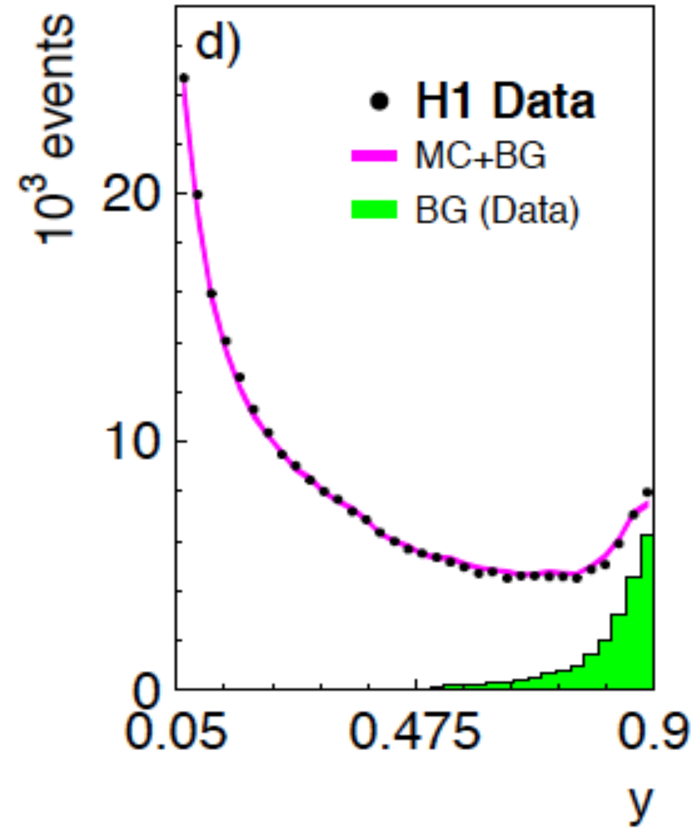




To see saturation you need xg to be large, the strong coupling small, ep and eA. To discover subtleties such as log(1/x) terms one needs high precision data of $\delta F_2/\delta \ln Q^2$ which requires to include data to Q^2 ~ 10 GeV^2 [x_{min}=10/s] and of F_L. This has been demonstrated for the LHeC kinematic range in the CDR (cf MCS talk).

HERA - Lessons on F_L





Large backgrounds at high $y=1-E'/E_e$

Subtraction with opposite beam charge data, corrected for background charge asymmetry

→ Need very high luminosity at minimal three energy settings

→ Need some e^+ data

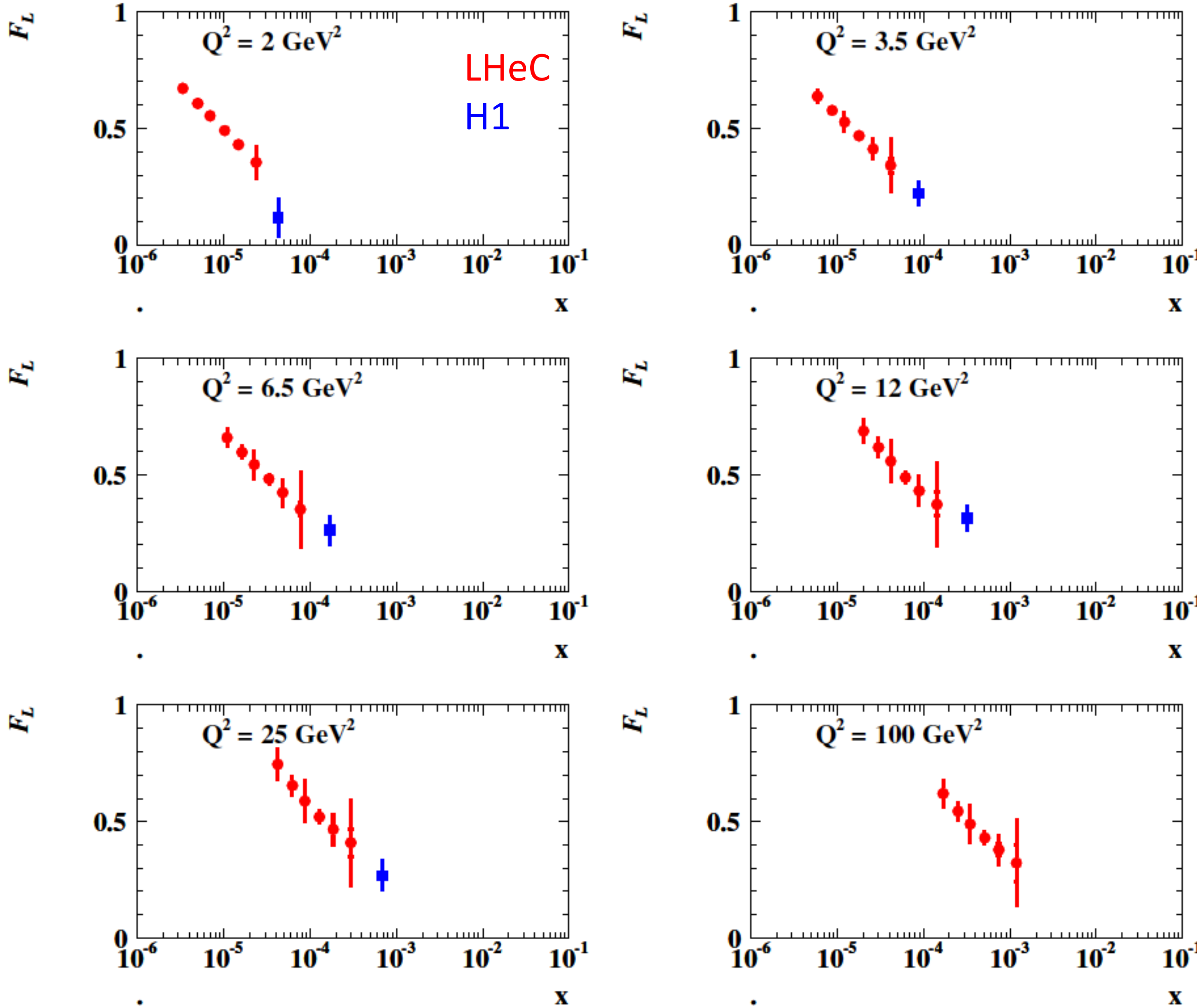
→ Need $E_e \rightarrow E'$ as large as possible (y=0.9 is E'=1 GeV for 10 GeV electron beam energy)

→ Need tracker in front of backward calorimeter, charge measurement [H1 BST..]

→ Need efficient photoproduction tagger

F_L LHeC

+ H1 data



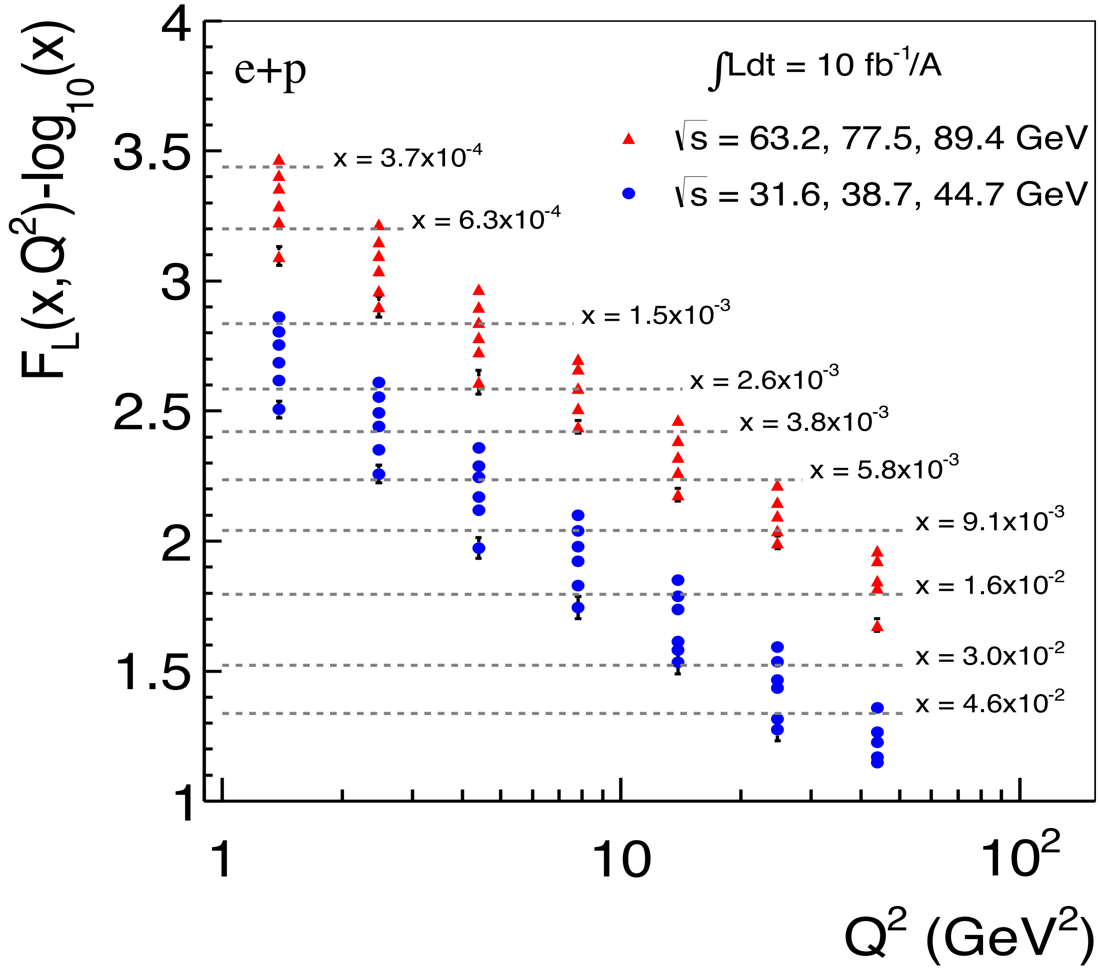
Stat+syst Errors.

See CDR

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

Much increased range and precision vs H1. Luminosities chosen for 10^{33} design. Lower E_e

F_L at the EIC in ep



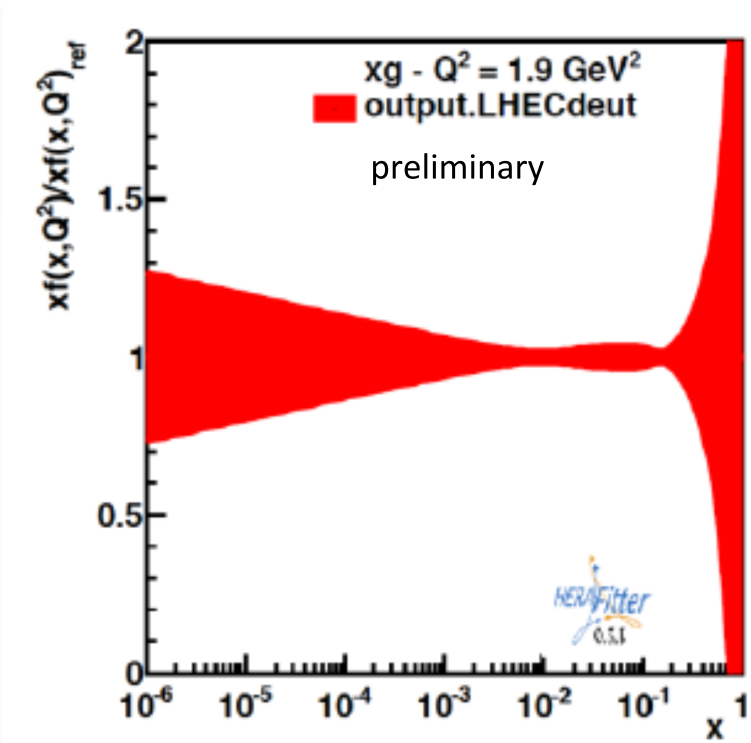
Complementary F_L measurements of EIC and LHeC - will be "side by side"

Future Nuclear PDFs with LHeC

cf talk by Nestor Armesto at this workshop

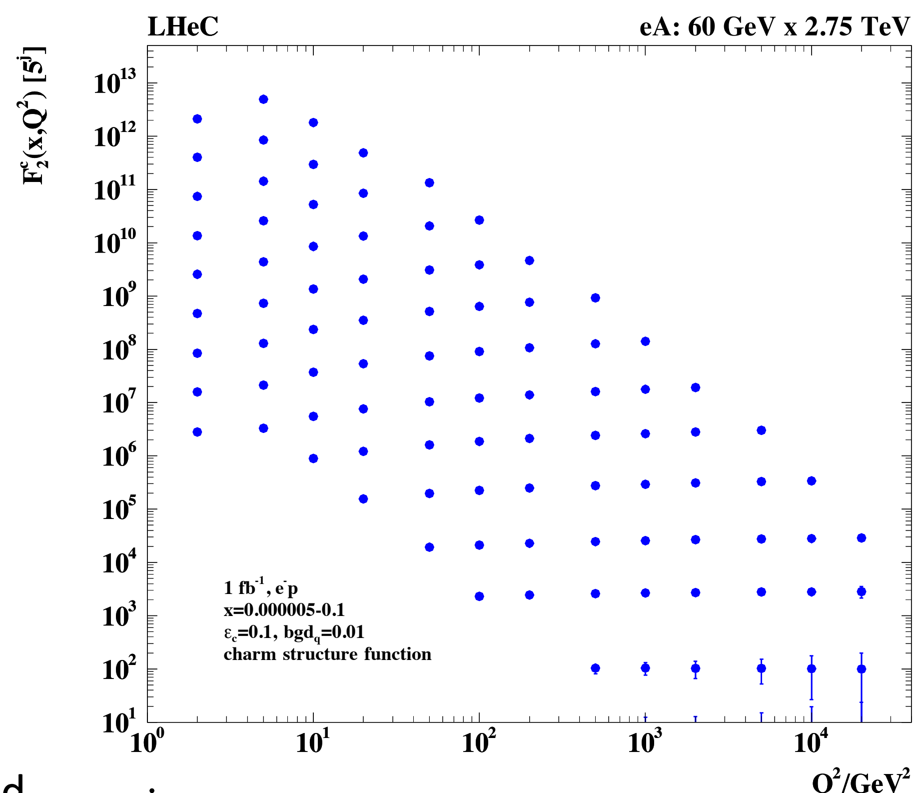
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA



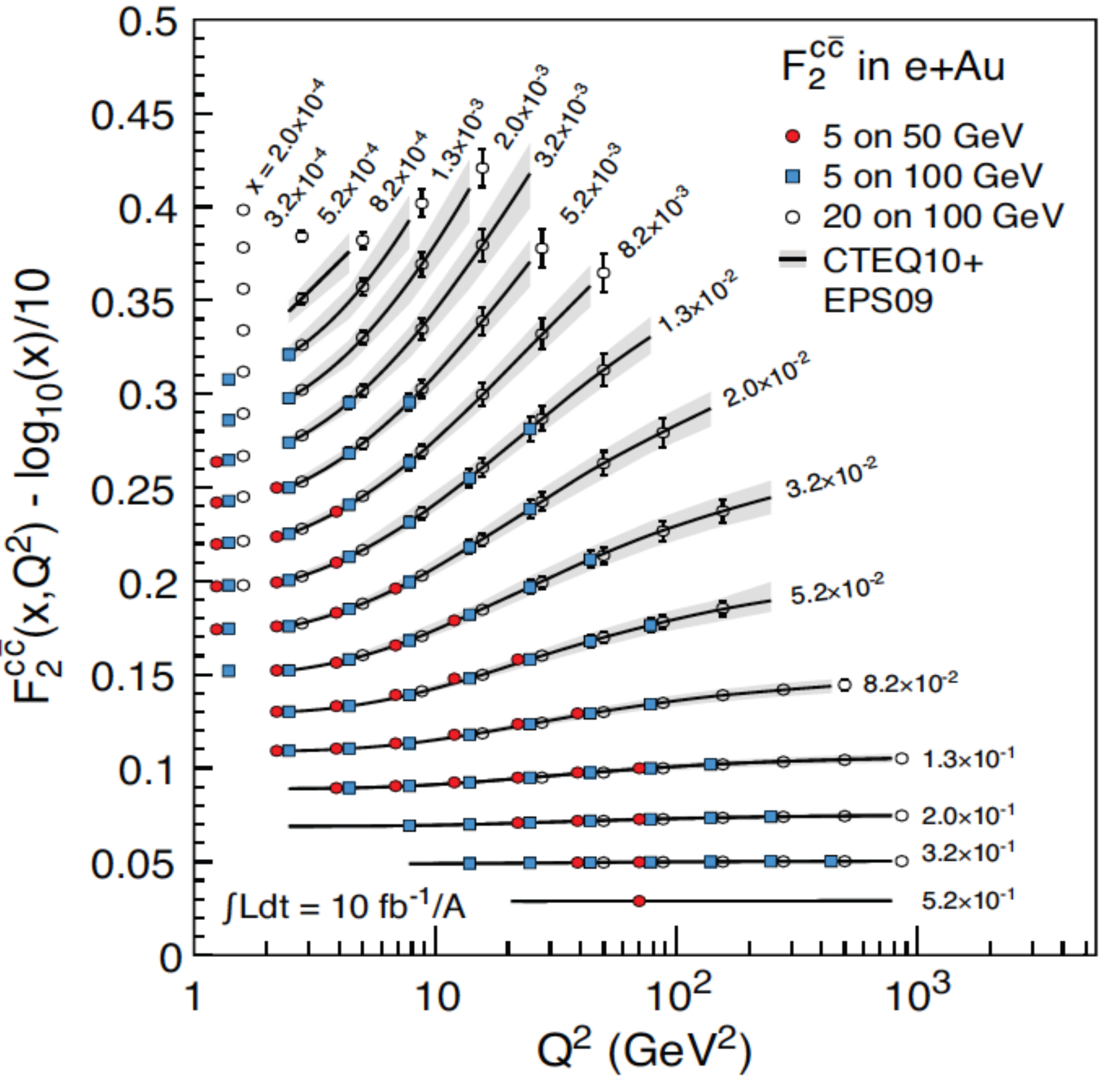
1fb^{-1} of sole eA isoscalar data fitted

Charm density in nuclei



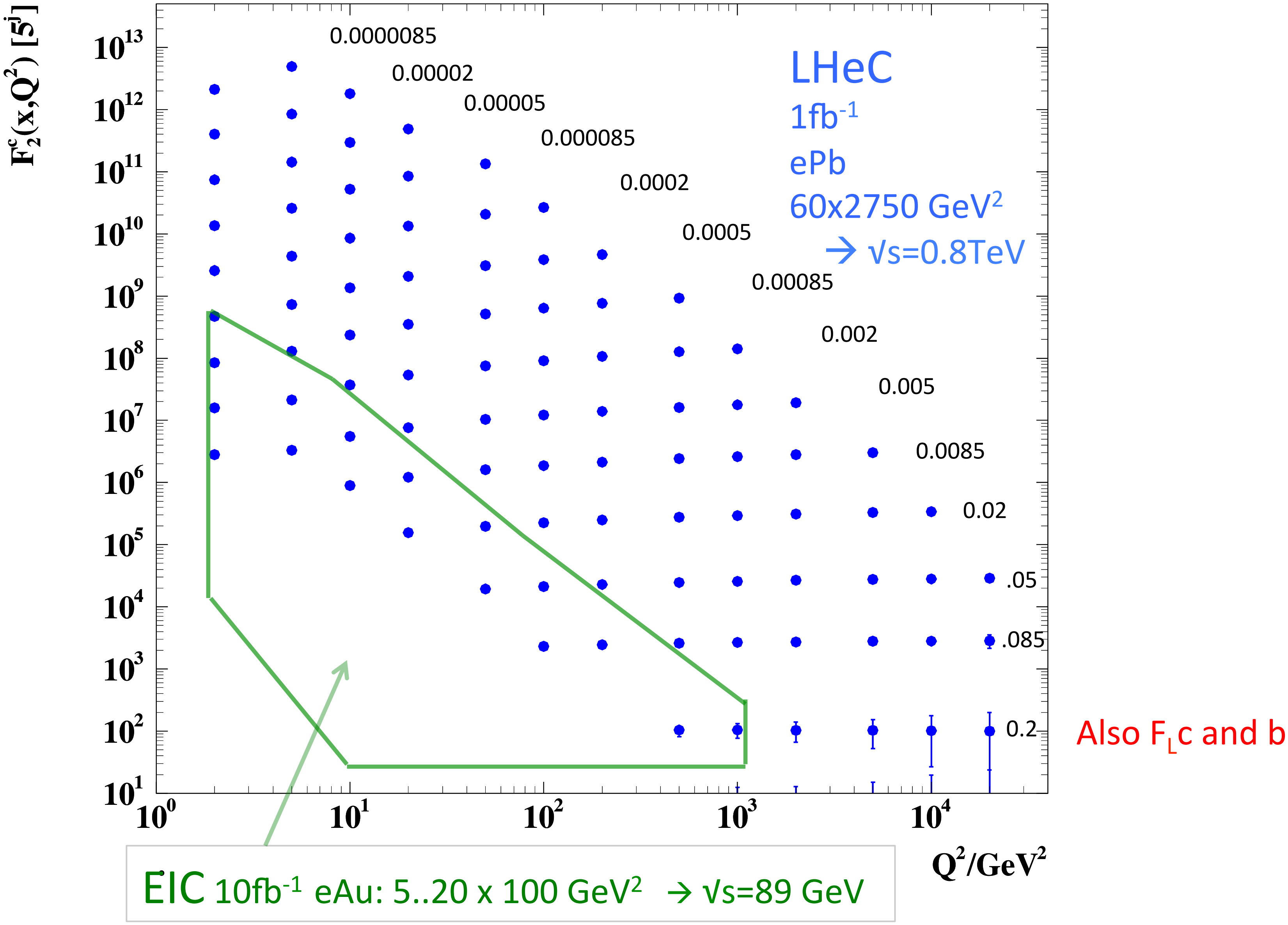
Impact parameter measurement in eA

$F_2^{c,Au}(x,Q^2)$ with the EIC

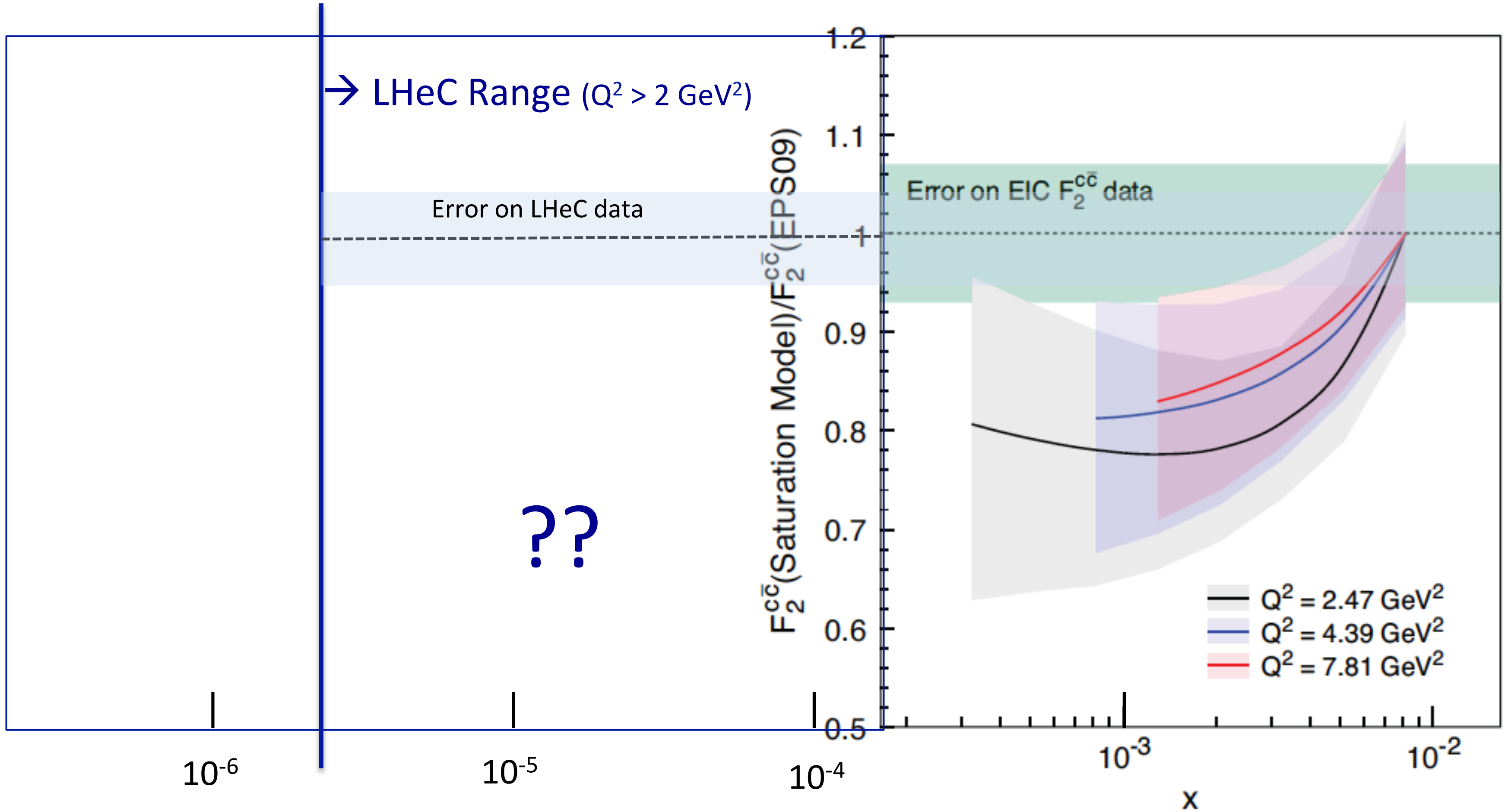


eRHIC
Design Study
1409.1633

Charm Structure Function in Nuclei



Nuclear and Non-Linear Effects in $F_2^{c,A}$



The interesting quantity may be F_2^{cA}/F_2^{cp} which should be measurable at both EIC and LHeC

Fig2.21 in eRHIC Design Study 1409.1633

Remarks

Electron-hadron colliders, following HERA, are essential for the future of PP and NP.

The LHeC goes beyond HERA in the energy, luminosity and with eA. It accesses scales sensitive to new and Higgs physics. Its QCD program has an unrivalled scope and range.

The EIC goes beyond HERA in the energy for spin physics, luminosity and with eA.
It chooses a kinematic coverage which is ideal for spin and interesting for QCD.

The EIC's shall not be judged upon by 'just' their PDF abilities, because of BSM + the unexplored richness of QCD, nucleon structure and dynamics. The US EIC yet needed a 4π detector for NC and CC and desirably ~100 GeV cms energy to be of major PDF use.

Particle and nuclear physics in former times had accelerators with even exactly the same energy, with SLC and LEP or PETRA,PEP (and TRISTAN) as prominent examples. In this context, the complementarity of the LHeC and an EIC is striking and we should wish us mutually good luck. Future high precision PDFs may not fit to pp, *was dann*?

EIC in the NSAC context and LHeC in the LHC context are most impressive options for future nuclear and particle physics. Both communities ought to be strong enough to realize both. In this country the new president elect has a unique chance to build a universally acceptable, long term legacy which unites people..