Precision DIS Physics at High Energy

Max Klein
University of Liverpool

Kinematics
PDFs
Low x
Higgs(pp) and ep
Electroweak Physics

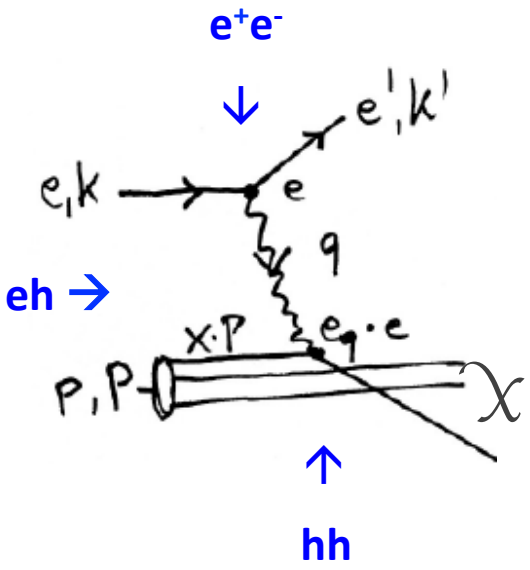
for the ep Study Group

FCC Meeting. 14.2.2014
University of Geneva

60 GeV x 7 TeV (LHC)

60 … 175 GeV x 50 TeV (FCC-h)

Deep Inelastic Scattering [eh → e'X]



$$x = \frac{Q^2}{sy}$$

$$Q^2 = -(k - k')^2$$

$$y_{lab} = 1 - \frac{E_e'}{E_e}$$

$$s = 4E_eE_p$$

Parton momentum fixed by electron kinematics

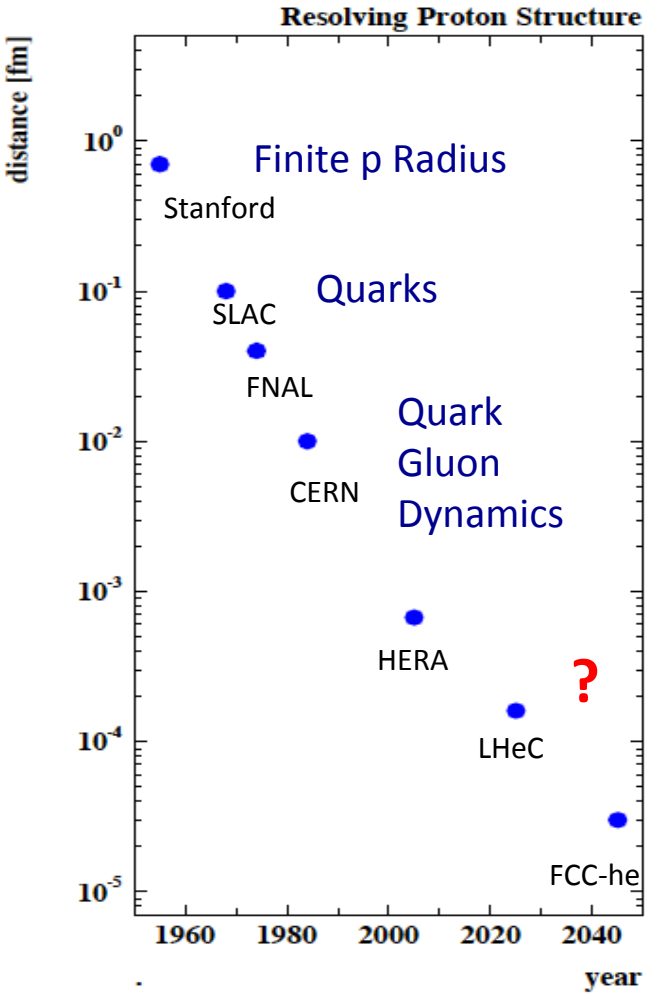
Incl. NC (γ,Z) and CC ($W^{\pm}$) independent of hadronisation

Rigorous theory: Operator expansion (lightcone)

Parton momentum distributions to be measured in DIS

Collider- HERA: $y_h = y_e$: Redundant kinematics

HERA-LHeC-FCC-eh: finest microscopes with resolution varying like $1/\sqrt{Q^2}$



electromagnetic radius

Possible 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

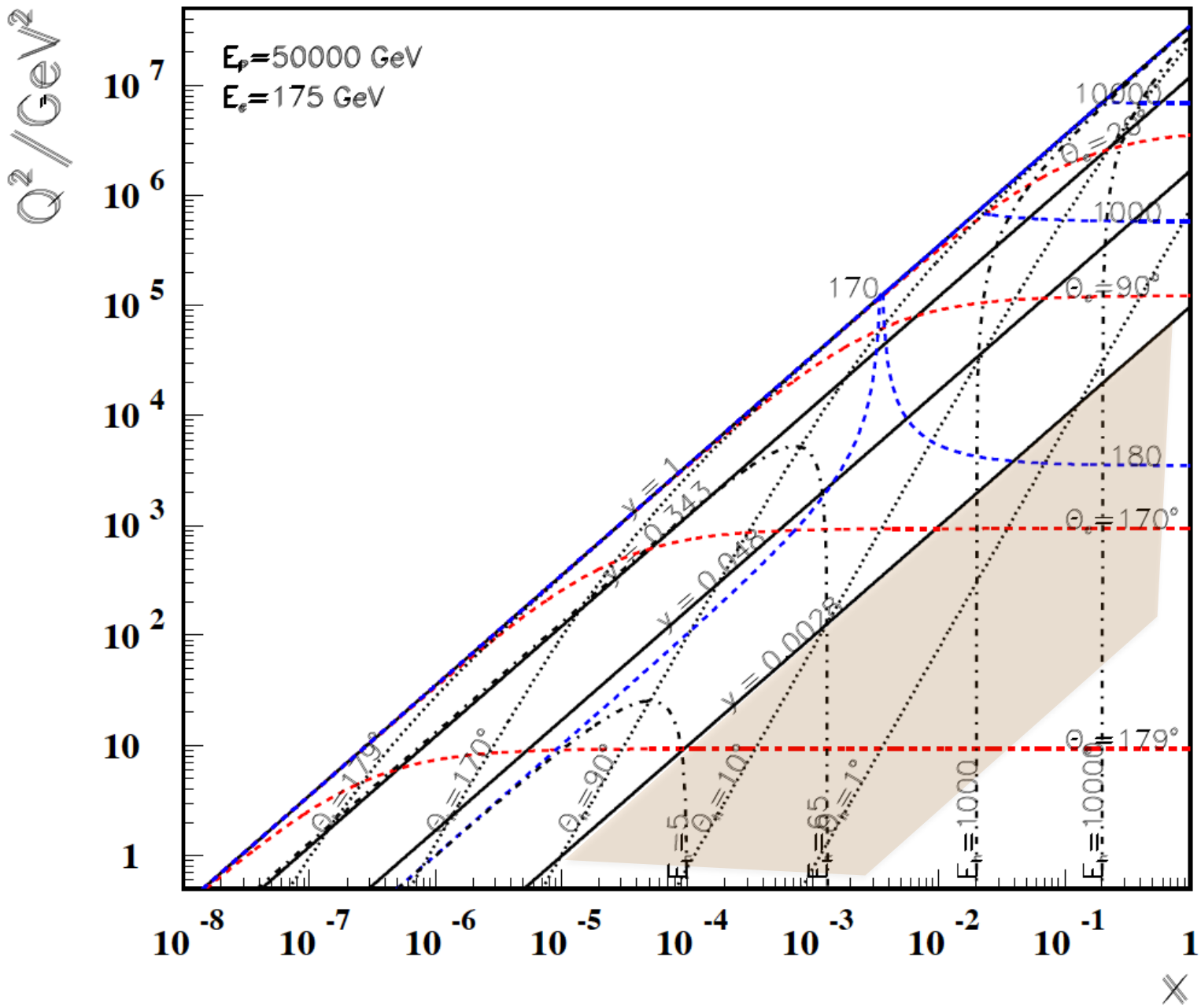
Quark substructure

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

FCC–he Kinematic Range



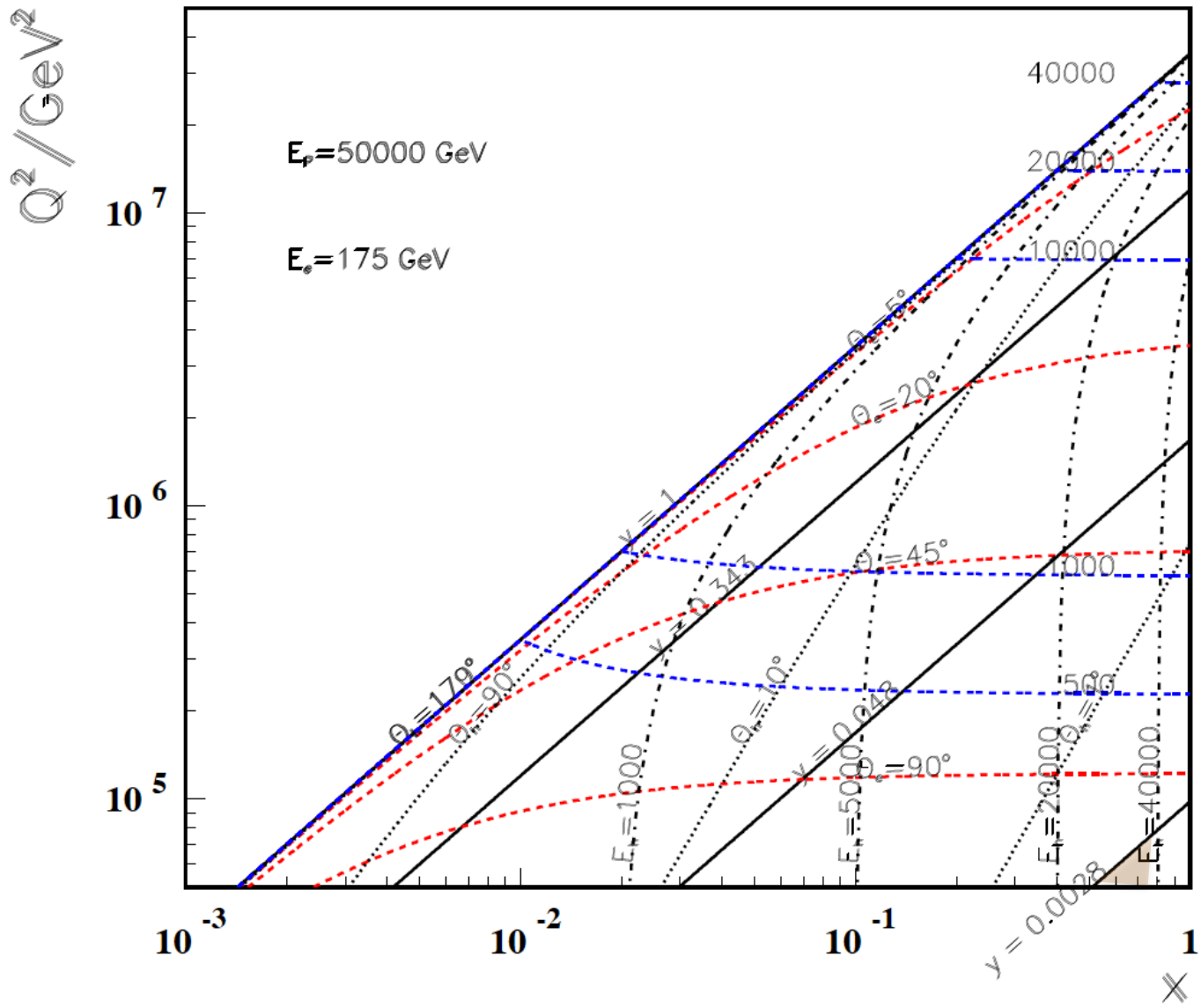
FCC-he

LHeC

HERA

High Q^2

Rutherford backscattering
of dozens of TeV e- energy



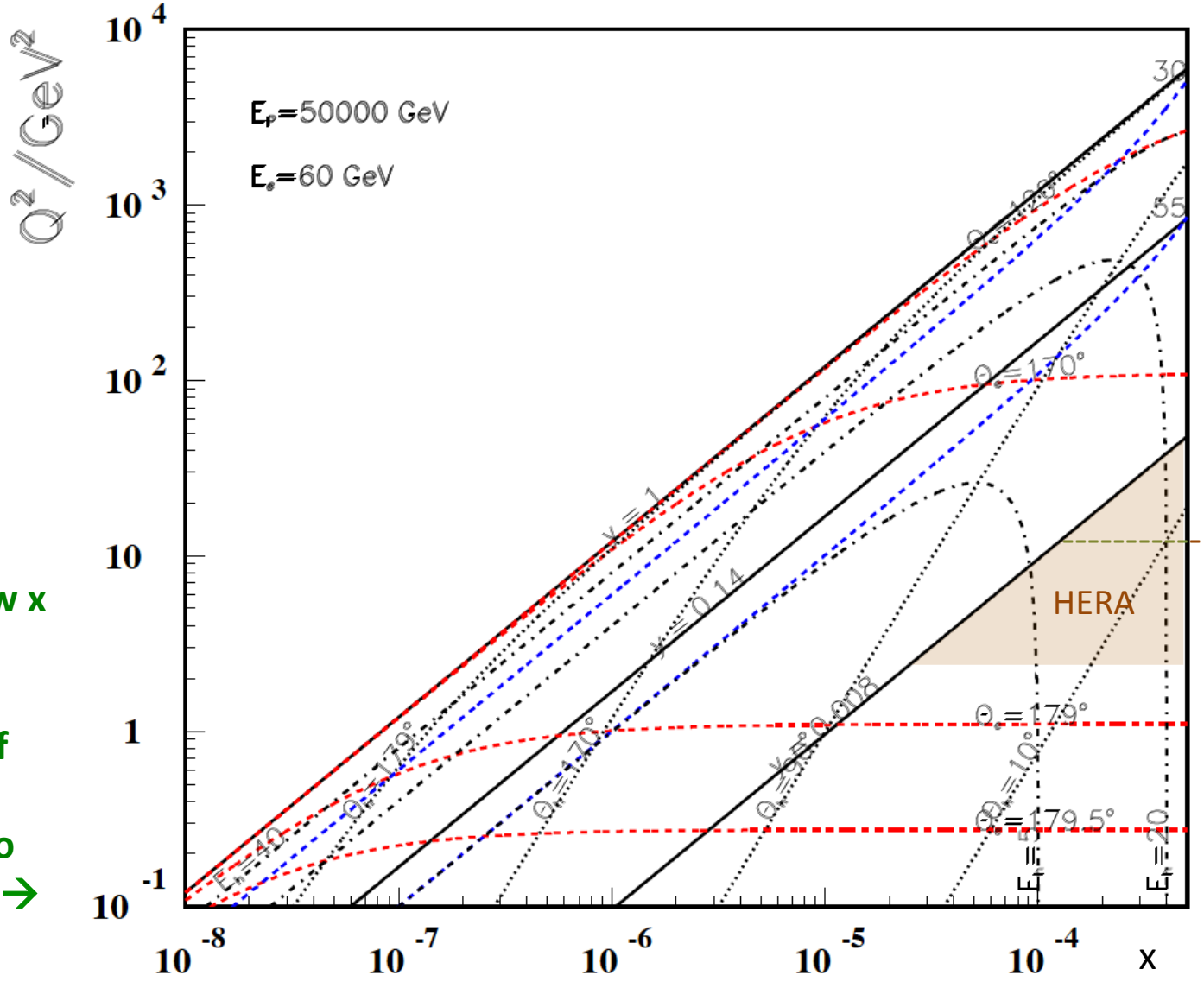
FCC-he

LHeC

← ϑ_h=1°

← HERA

Low x



FHeC

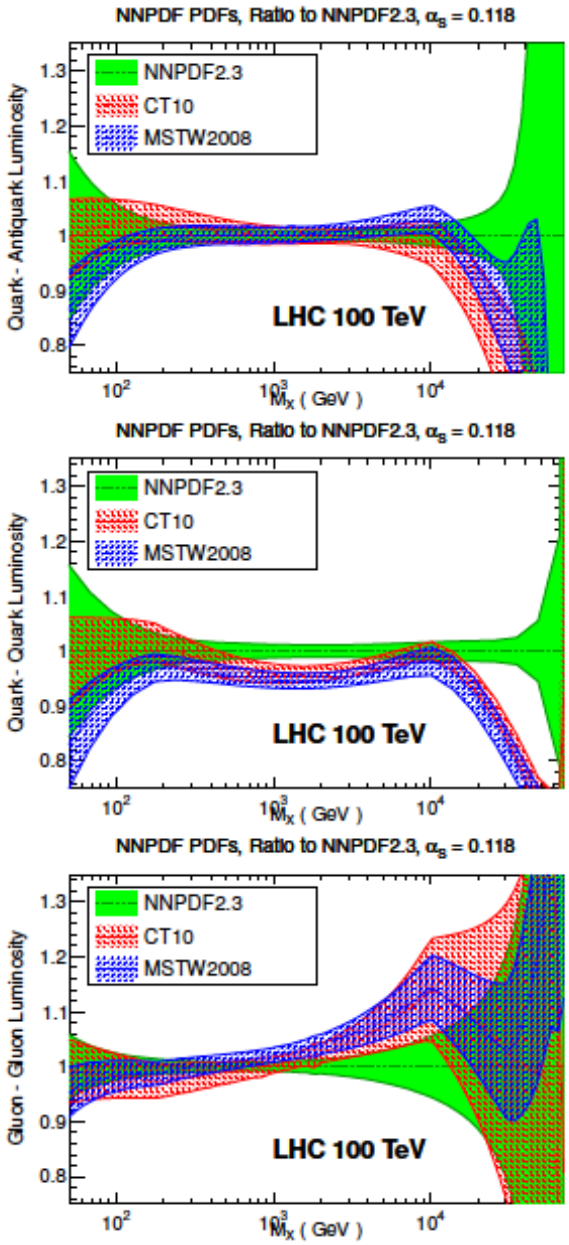
LHeC

← 179°
@ 180 GeV
.. very low x requires not the maximum of E_e

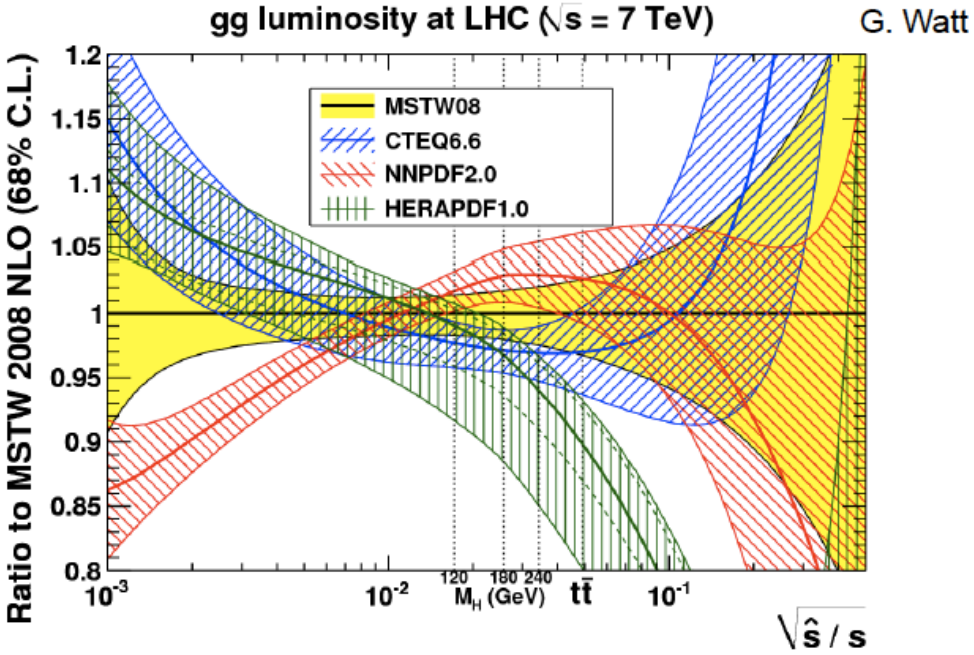
Very low x reaches direct range of UHE neutrino physics →

For $x < 10^{-3}$ no (average) energy deposition exceeding the electron beam energy

Parton Distributions

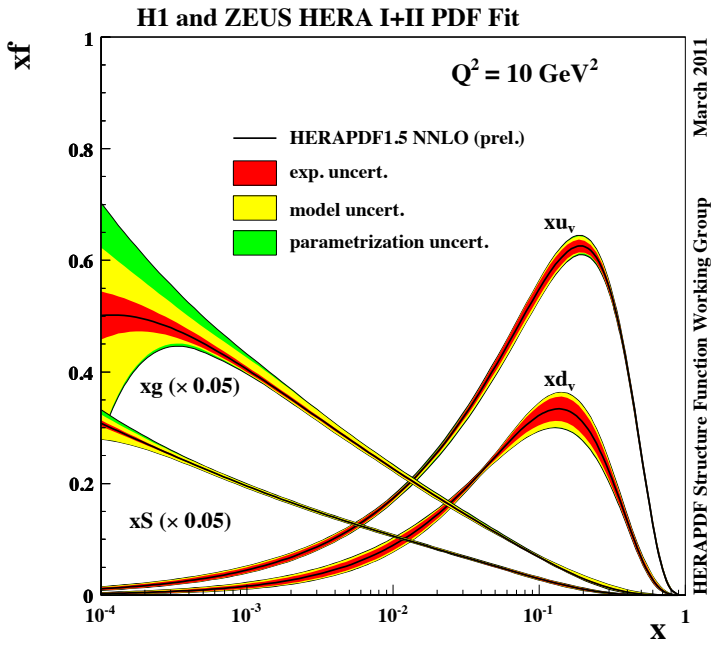


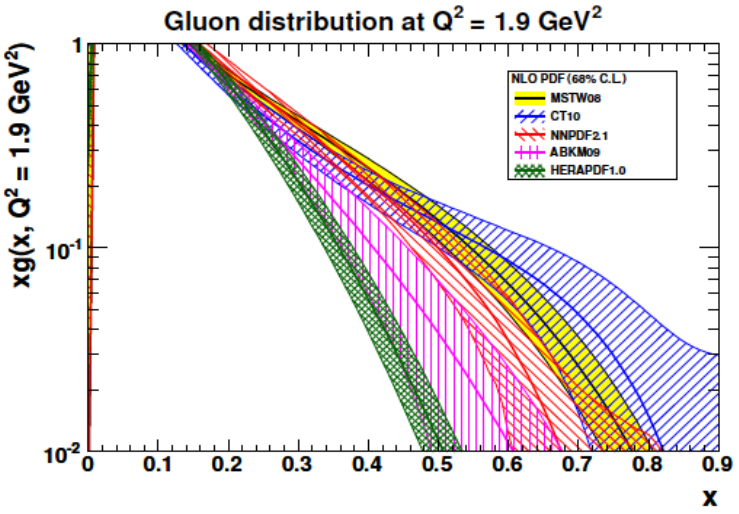
Snowmass13 QCD WG report



Need to know the PDFs much better than so far, for nucleon structure, q-g dynamics, Higgs, searches, future colliders, and for the development of QCD.

PDFs are much more/deeper than a “tool”





(Un)certainty on PDFs

Light Quarks:
valence $x < 0.01$, u_v $x > 0.8$, d_v $x>0.6$
light sea (related to strange) -8% ATLAS/F_2,
light sea quark asymmetry, d/u=?
Isospin relations (en!) ??

Strange: unknown, =dbar? strange valence?

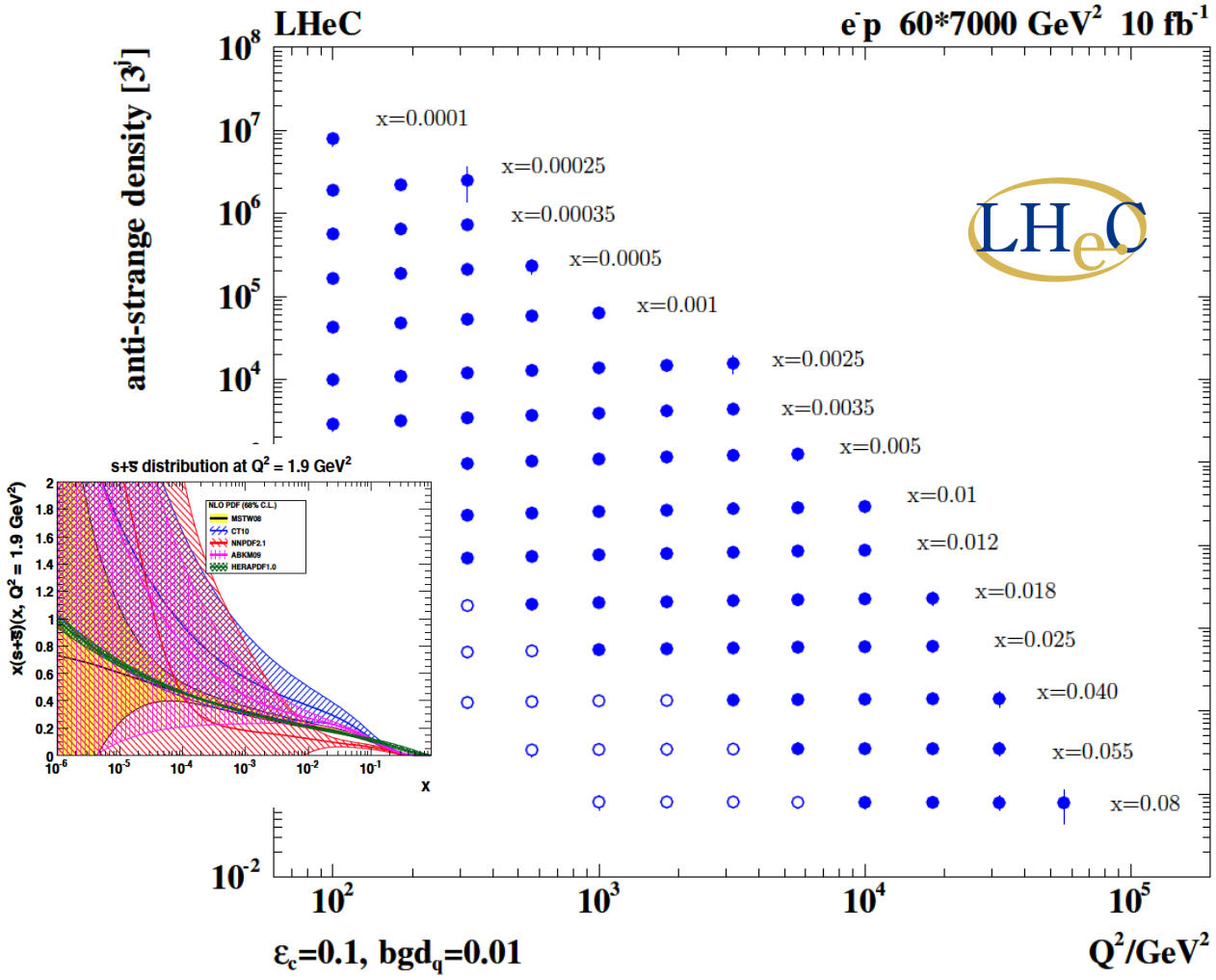
Charm: need high precision to % for α_s
(recent HERA 5%)
Beauty: HERA 10-20%, bb → A?
Top: tPDF at high Q^2 $>M_t^2$ - unknown

Gluon: low x, saturation?, high x - unknown
medium x: preciser for Higgs!
Recent review: cf E.Perez, E.Rizvi 1208.1178, in RPP

..unintegrated, diffractive, generalised, polarised, photonic, nuclear PDFs ???

A new, required level of determination of PDFs can only be achieved with the LHeC.

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

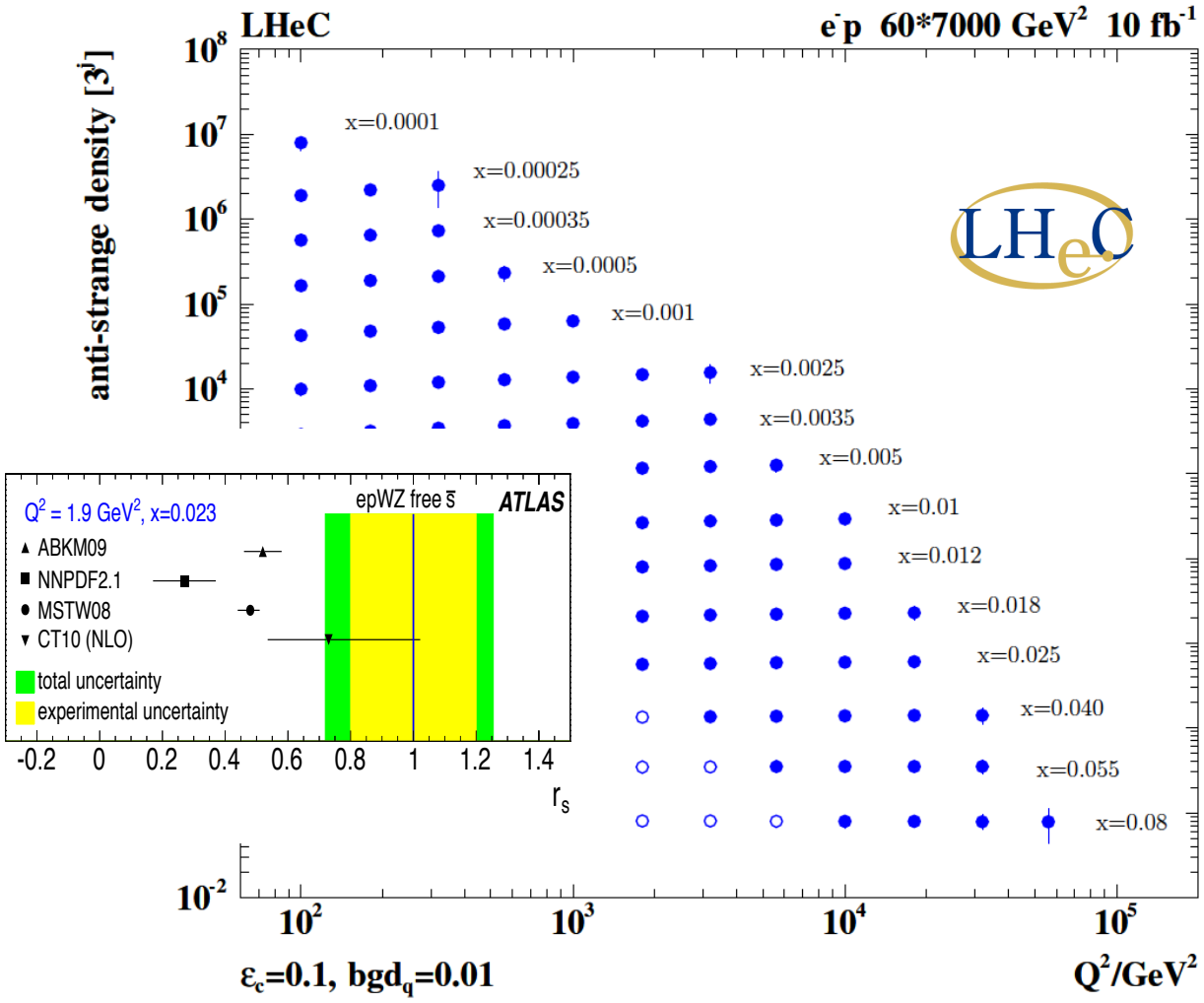
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} .. 0.05$

$Q^2 = 100 – 10^5\ GeV^2$

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

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

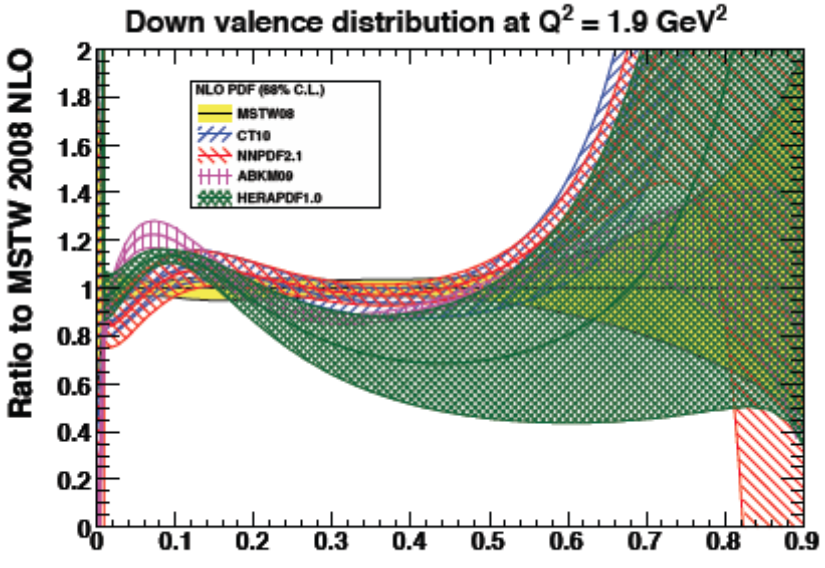
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

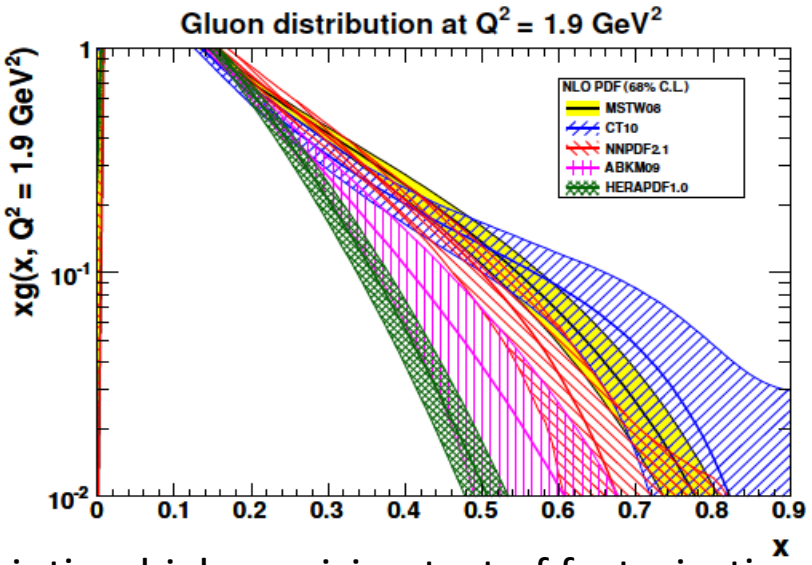
$x = 10^{-4} .. 0.05$

$Q^2 = 100 – 10^5\ GeV^2$

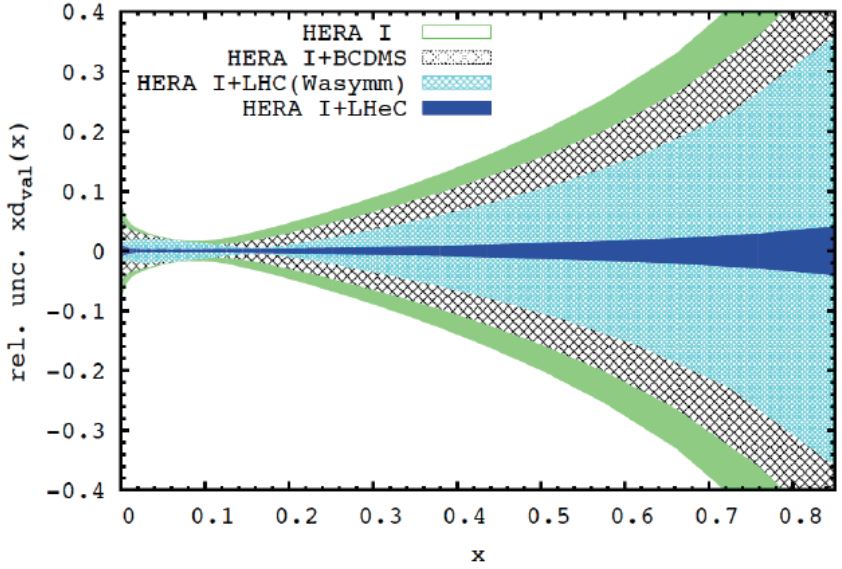
Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

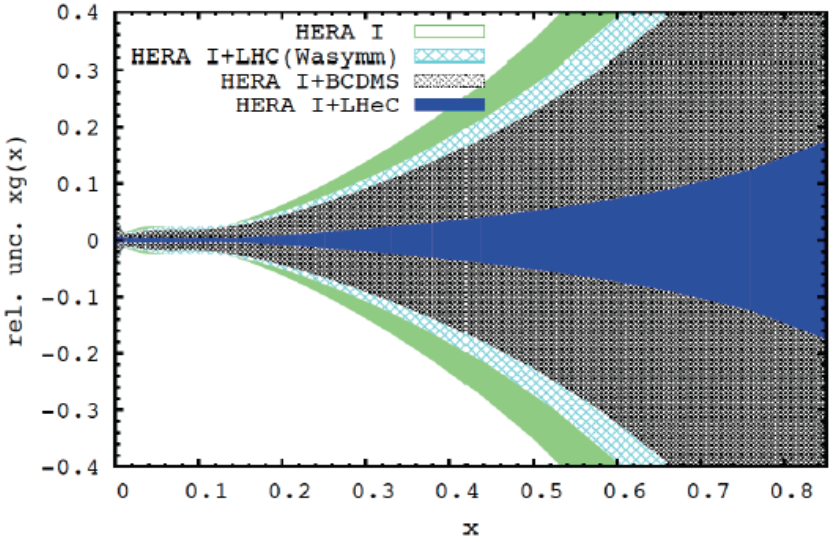
PDFs at Large x





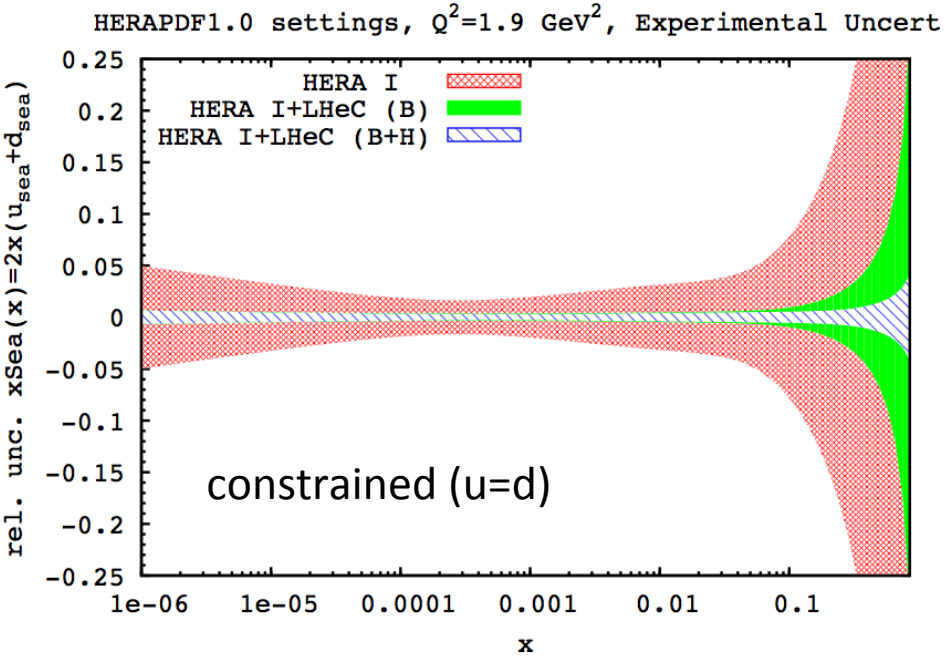
No higher twist corrections, free of nuclear uncertainties, high precision test of factorisation

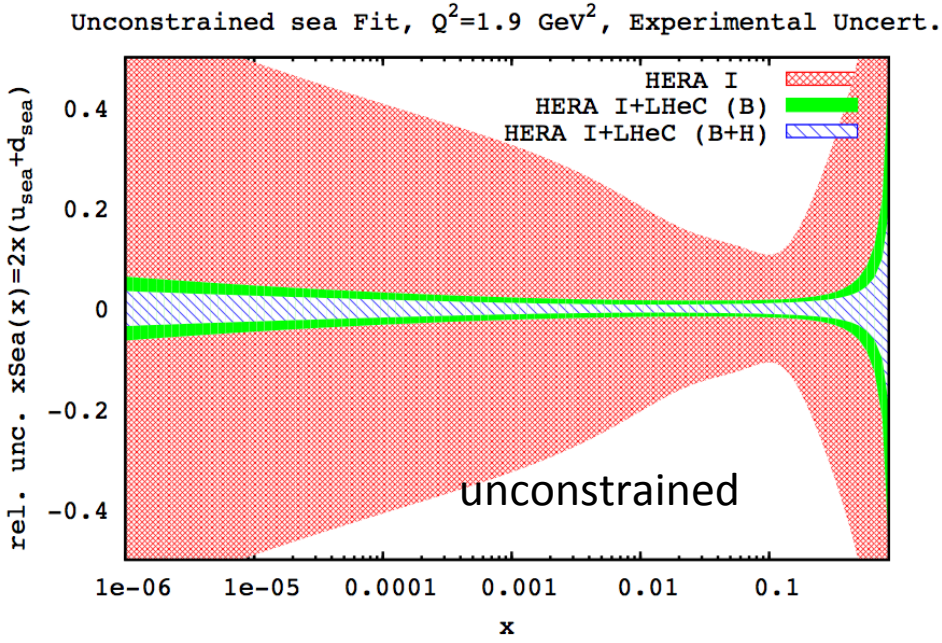




Unconstrained setting at low x

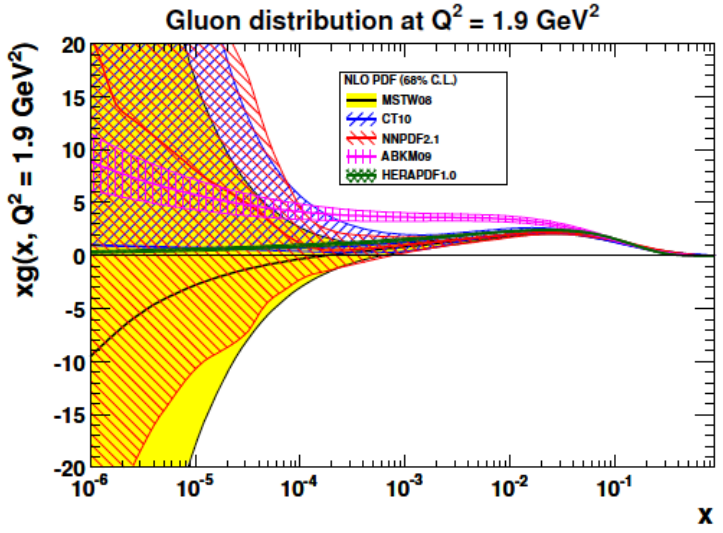
- Usual assumptions for light quark decomposition at low x may not necessary hold.
- Relaxing the assumption at low x that **u=d** , we observe that uncertainties escalate:

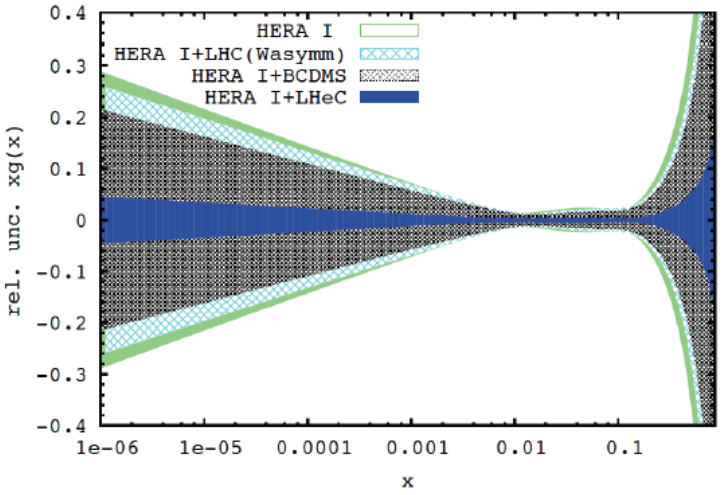


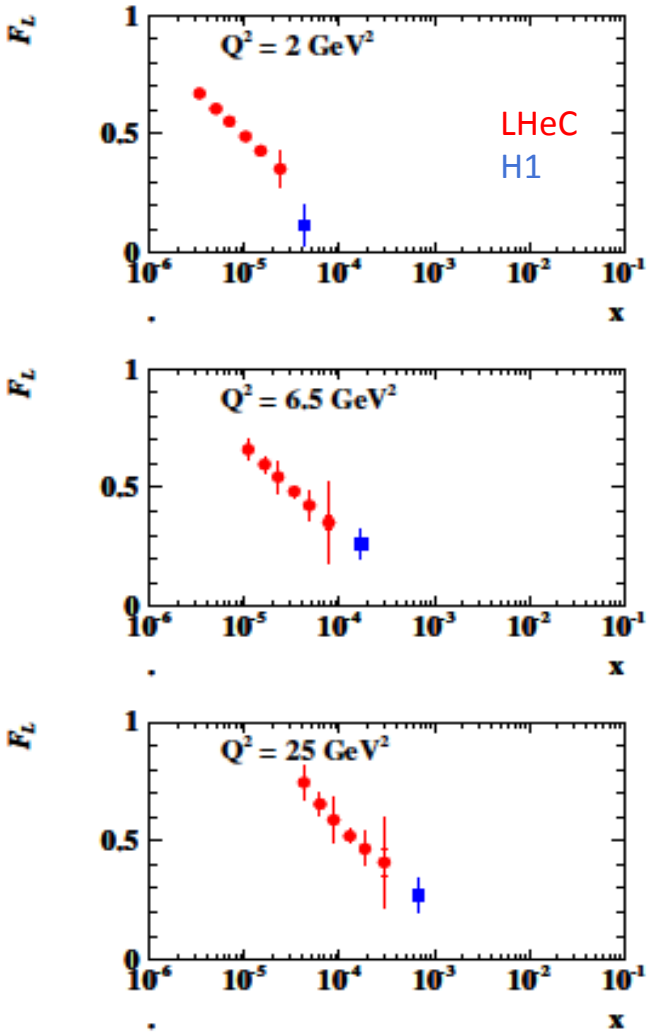


- One can see that for HERA data, if we relax the low x constraint on u and d,the errors are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing with diffraction…

Gluon Saturation at Low x?



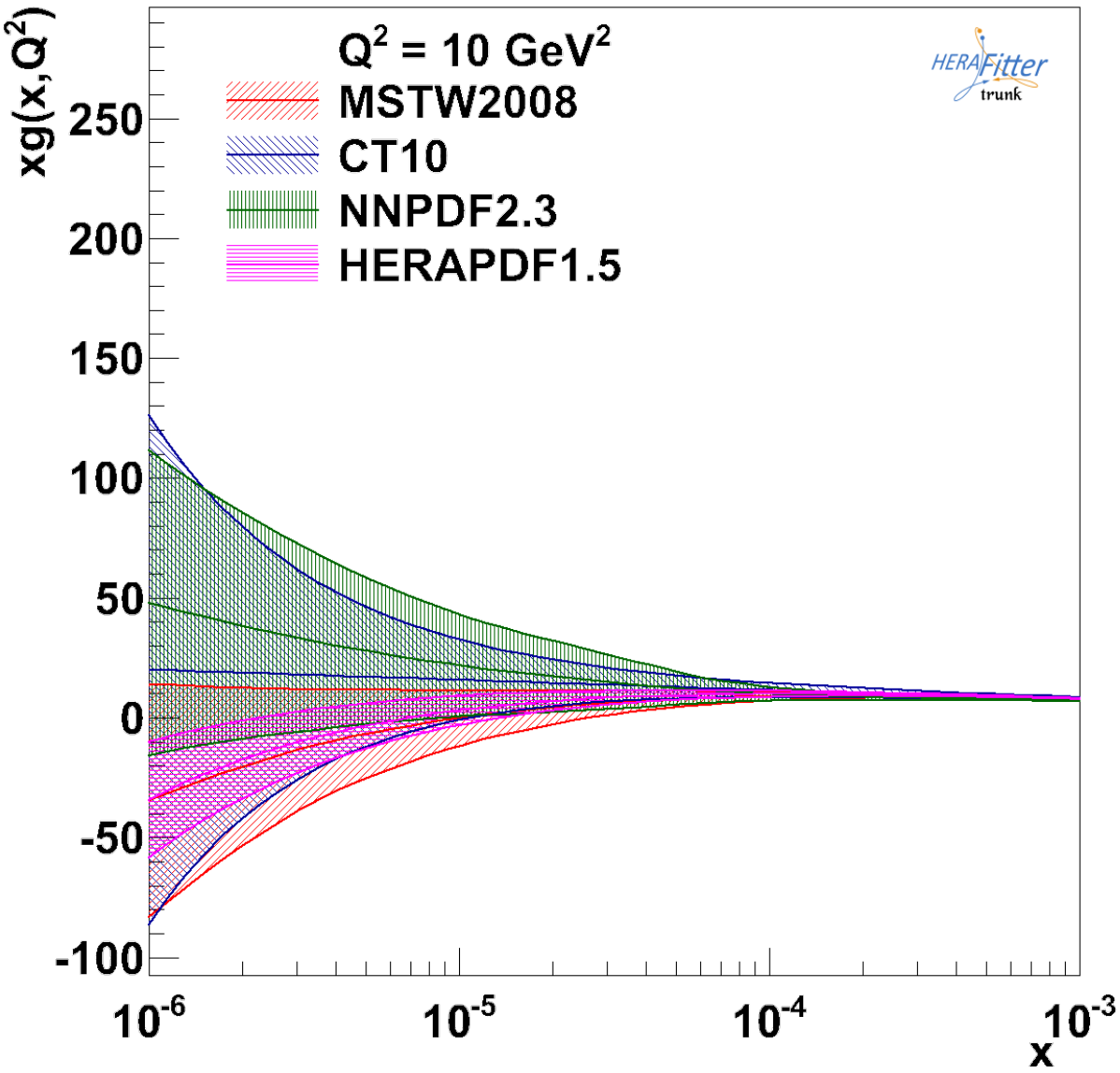




Gluon measurement down to x=10^{-5}, **Saturation or no saturation** (F_2 and precise F_L)
Non-linear evolution equations? Relations to string theory, and **SUSY at ~10 TeV**?

cf H.Kowalski, L.Lipatov, D.Ross, arXiv:1205.6713

xg at low x

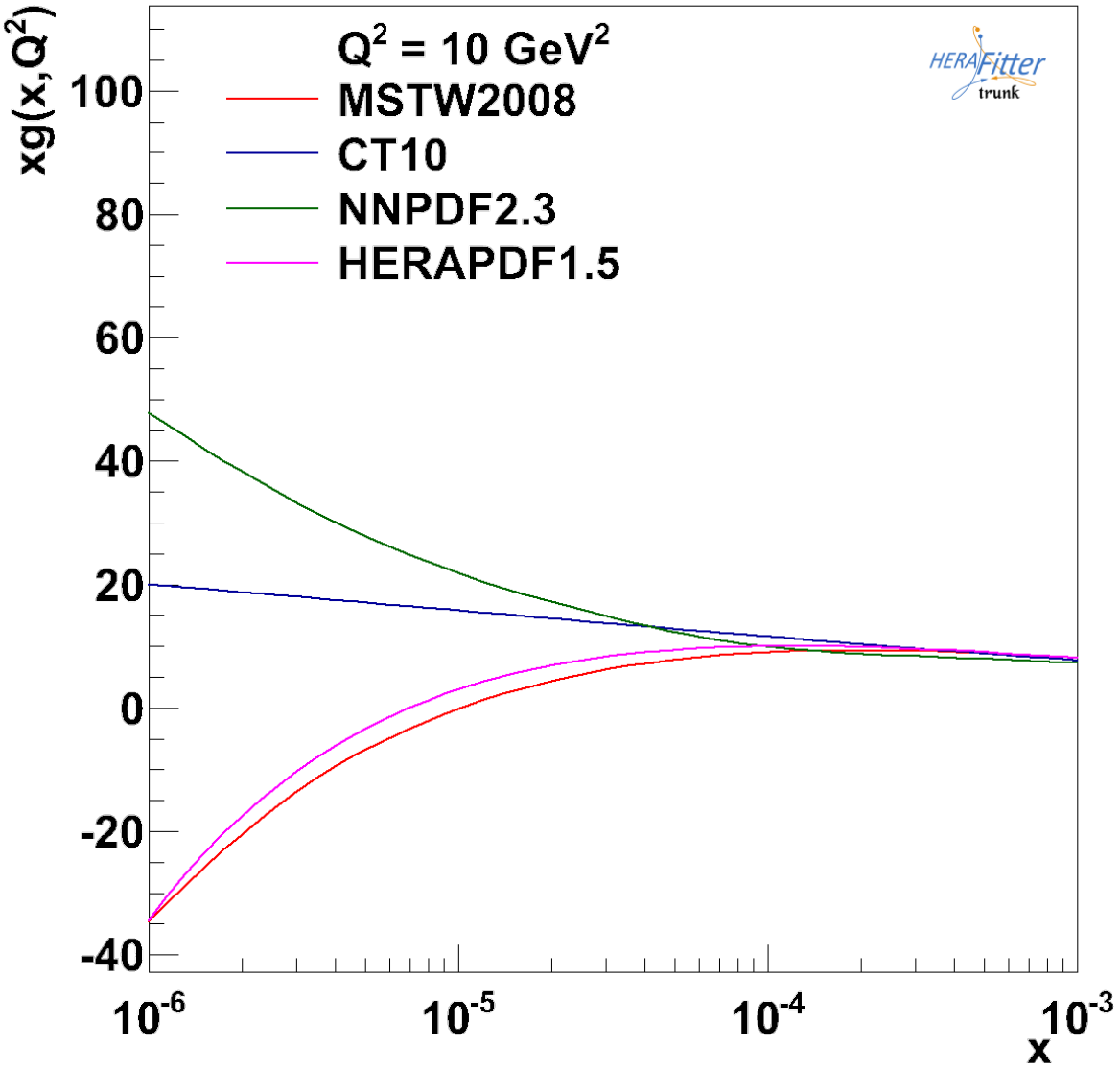

Q^2 = 10 GeV^2
MSTW2008
CT10
NNPDF2.3
HERAPDF1.5
HERAFitter trunk
xg(x,Q^2)
250
200
150
100
50
0
-50
-100
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x

xg at low x

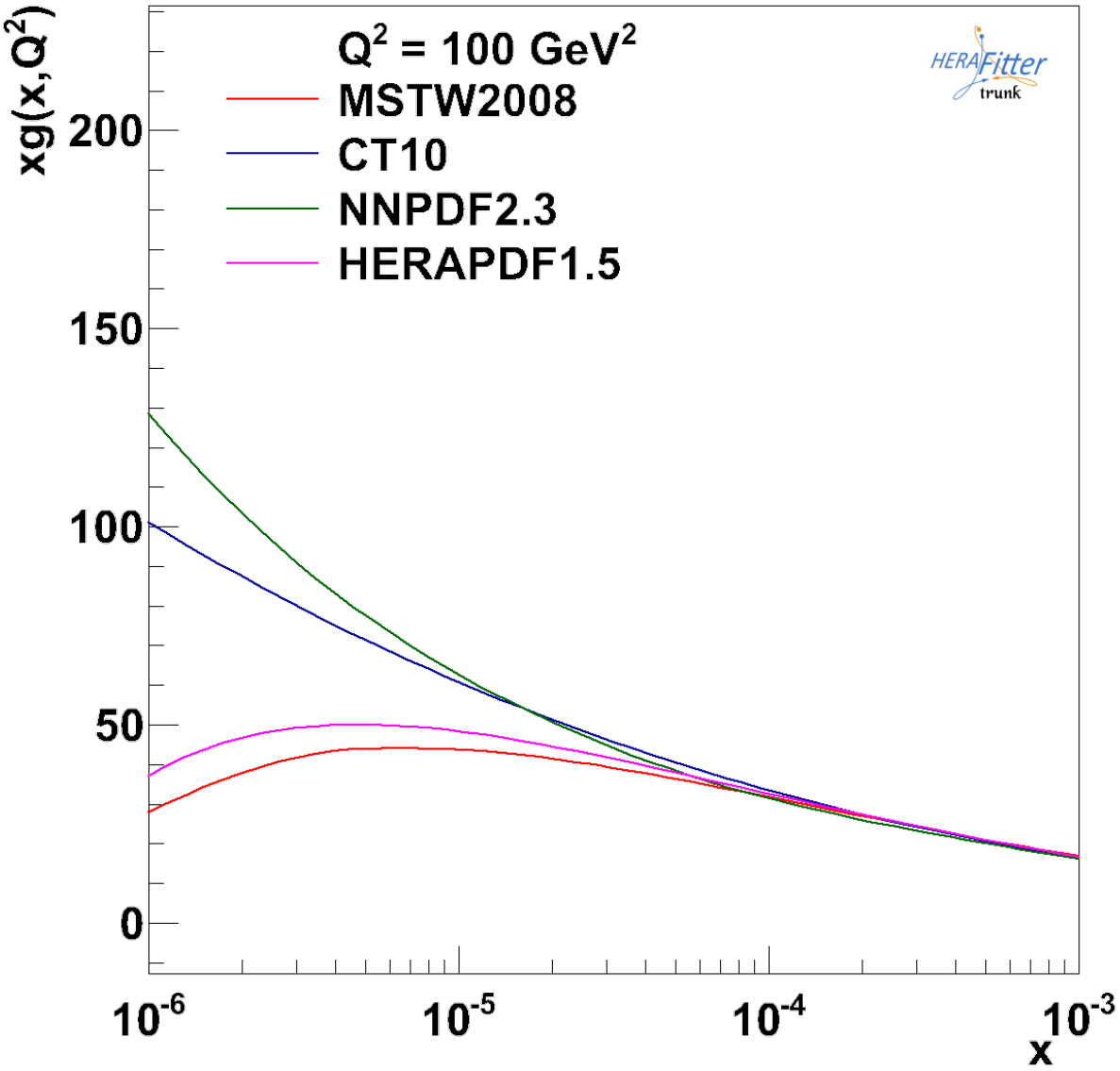
No clue about xg for $x < 10^{-4}$

Evolution law may not be DGLAP

Affects FCC-pp rates because x=M/sqrt(s) exp(+-y)



xg at low x

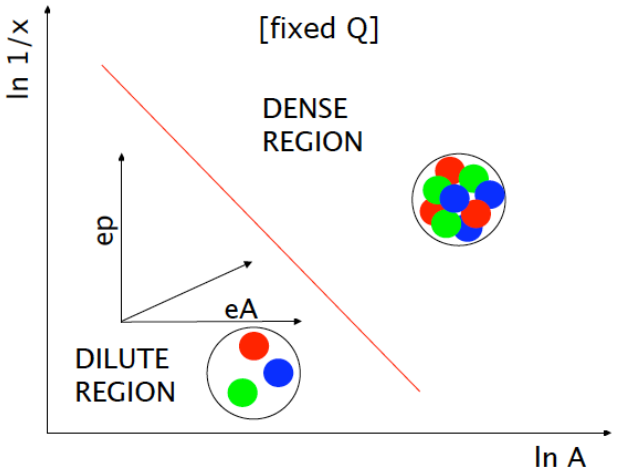


Uncertainty holds to high Q2 and the evolution will not be DGLAP

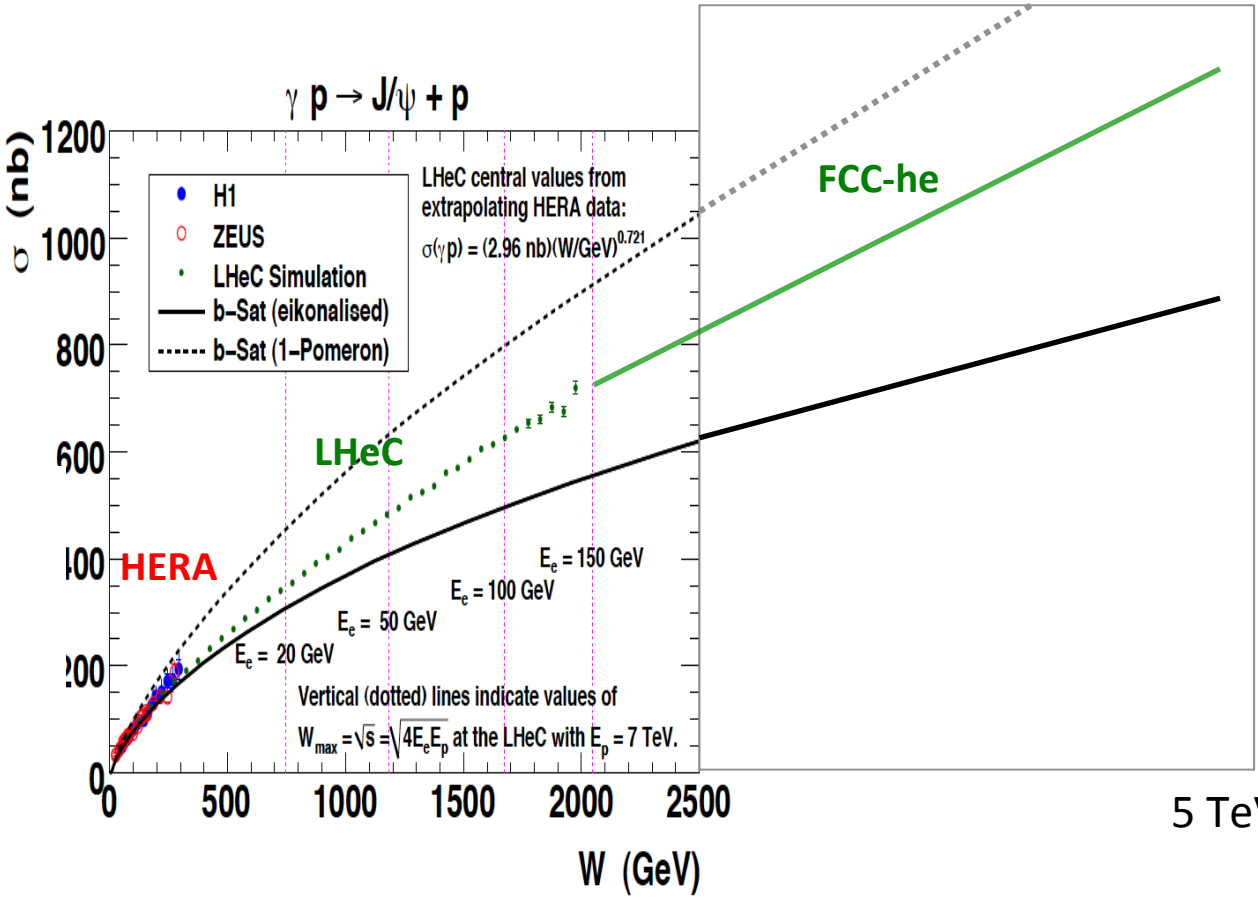
- **It needs ep to resolve this**

Vector Mesons

Precision Measurements of vector mesons and diffraction to very high $M_X \sim xg^2$



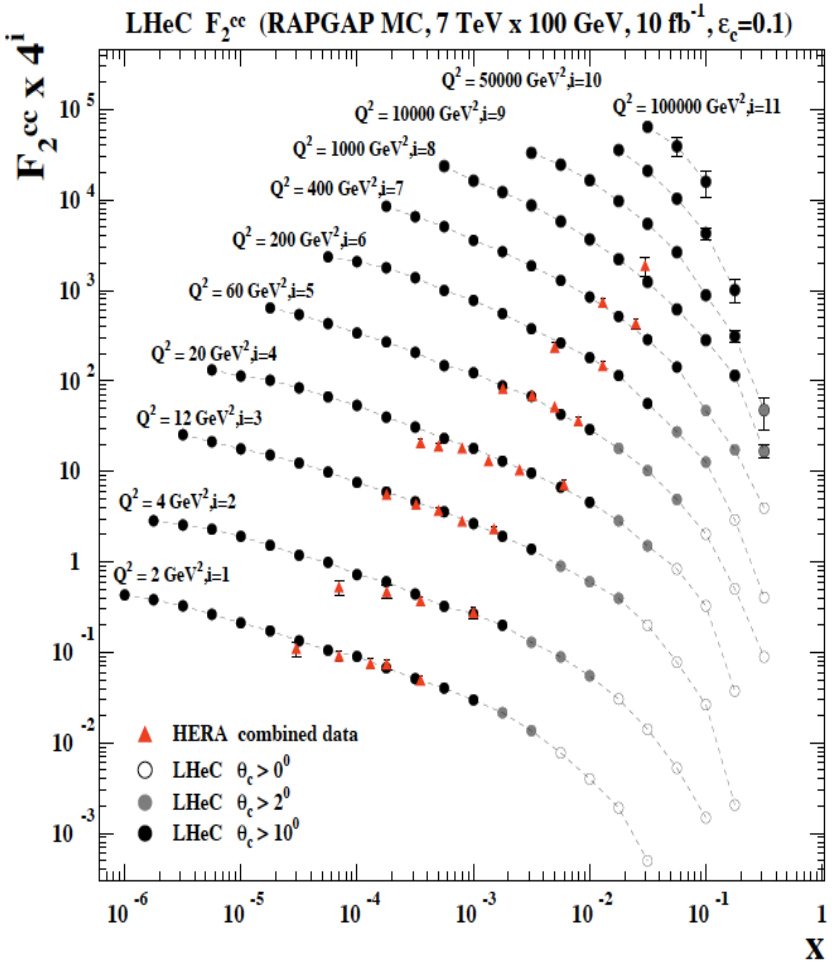
Higher energy (1/x), higher A

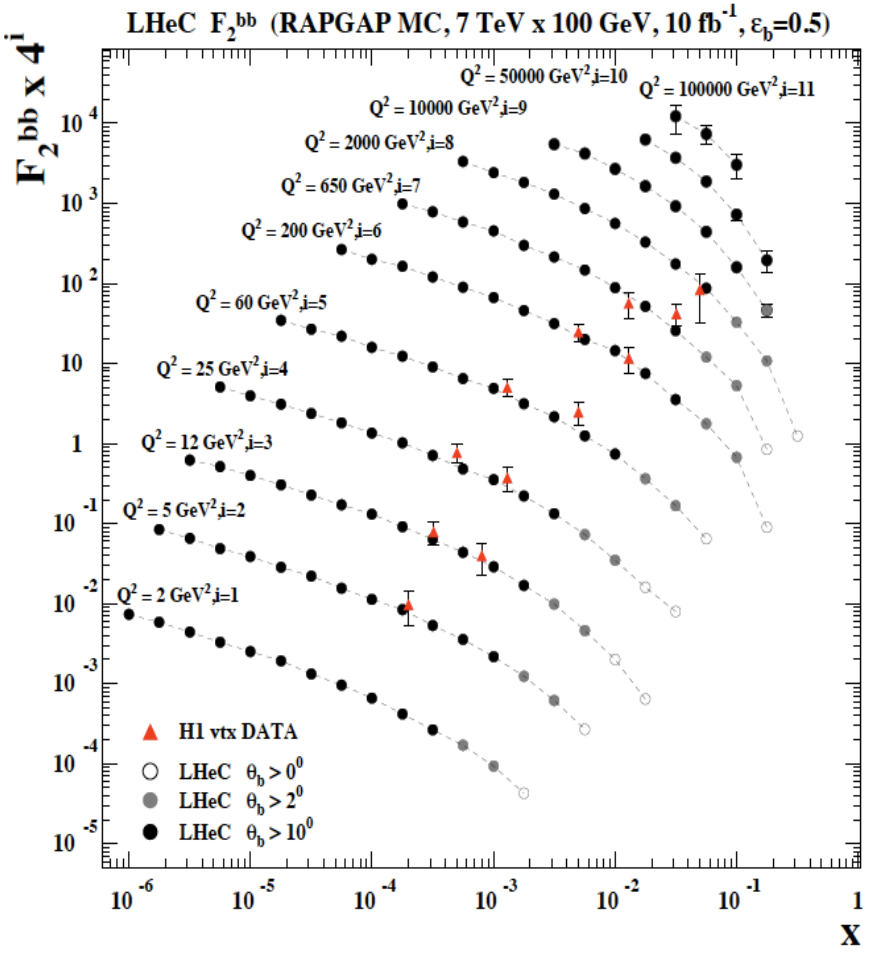


W = √ (ys) extends to ~ 5 TeV at FCC-he

Black body limit, interference pattern of σ

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



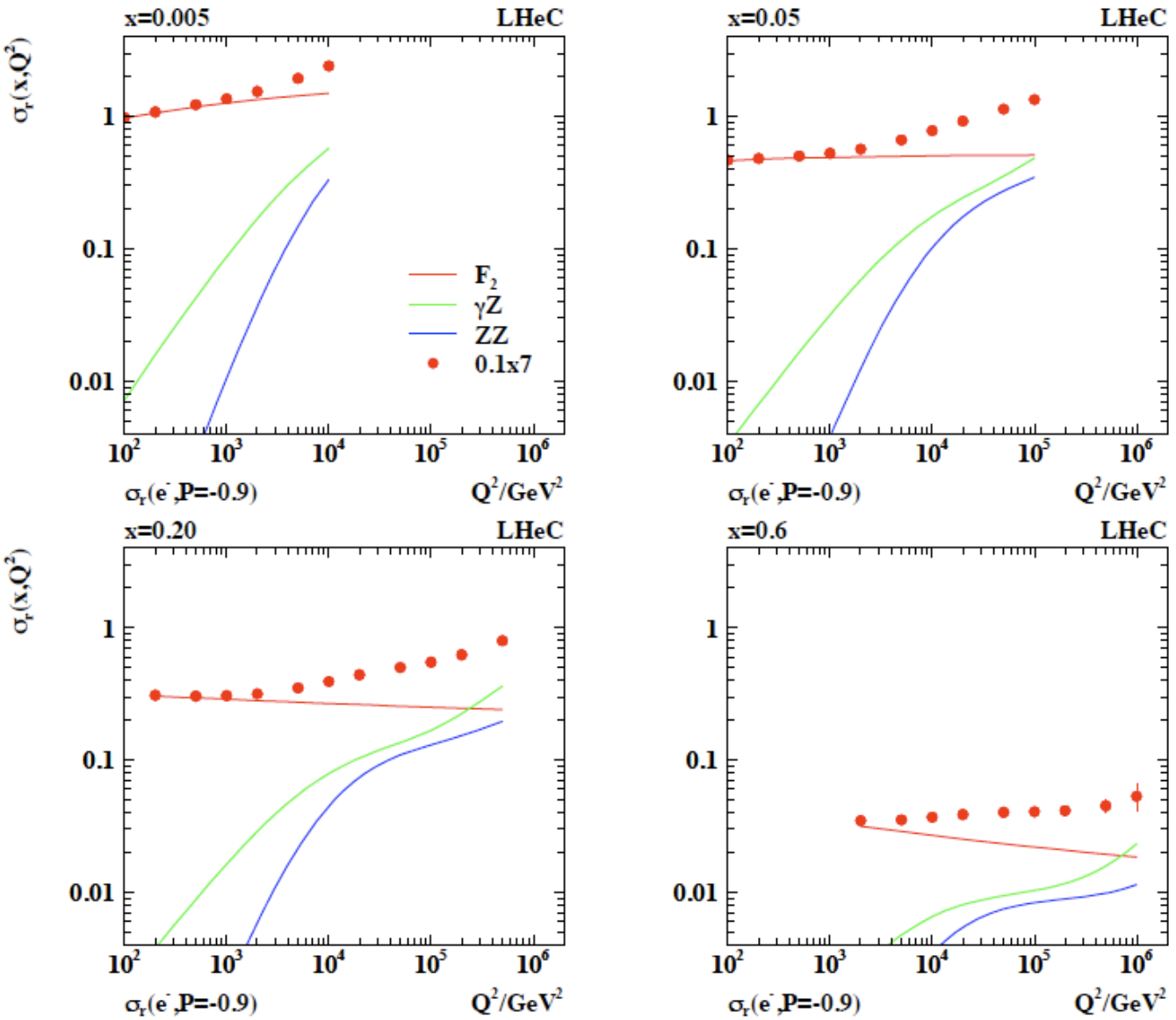


Hugely extended range and much improved precision (δM_c=60 HERA → 3 MeV)

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..

Electroweak Cross Section Measurements

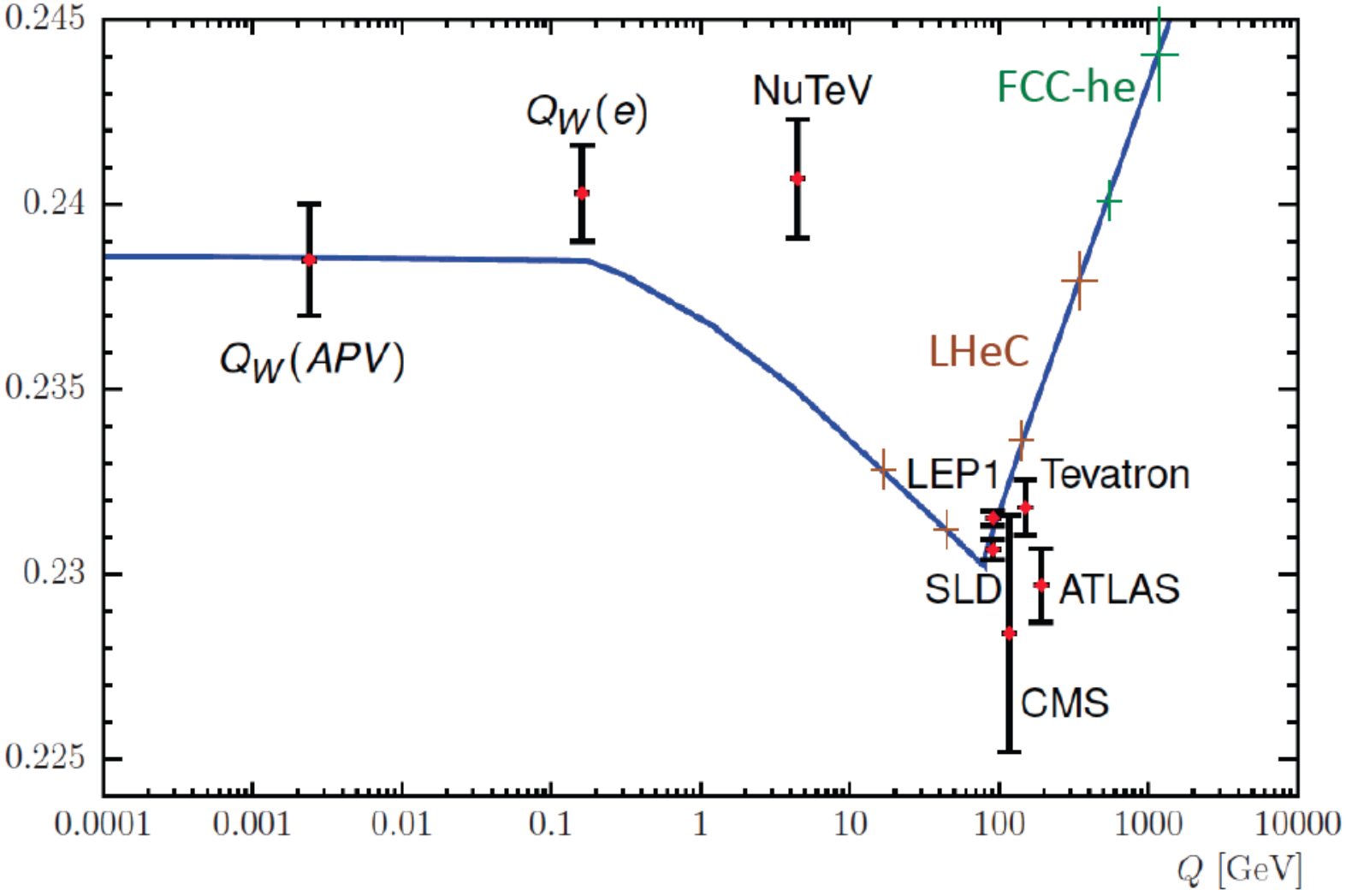


Huge
Z exchange part

→

high precision
Electroweak
measurements
with unique
scale variation
due to Q^2
dependence!

Scale dependence of $\sin^2\theta_W$



Preliminary illustration

Electroweak Physics in ep

In Deep Inelastic Scattering:

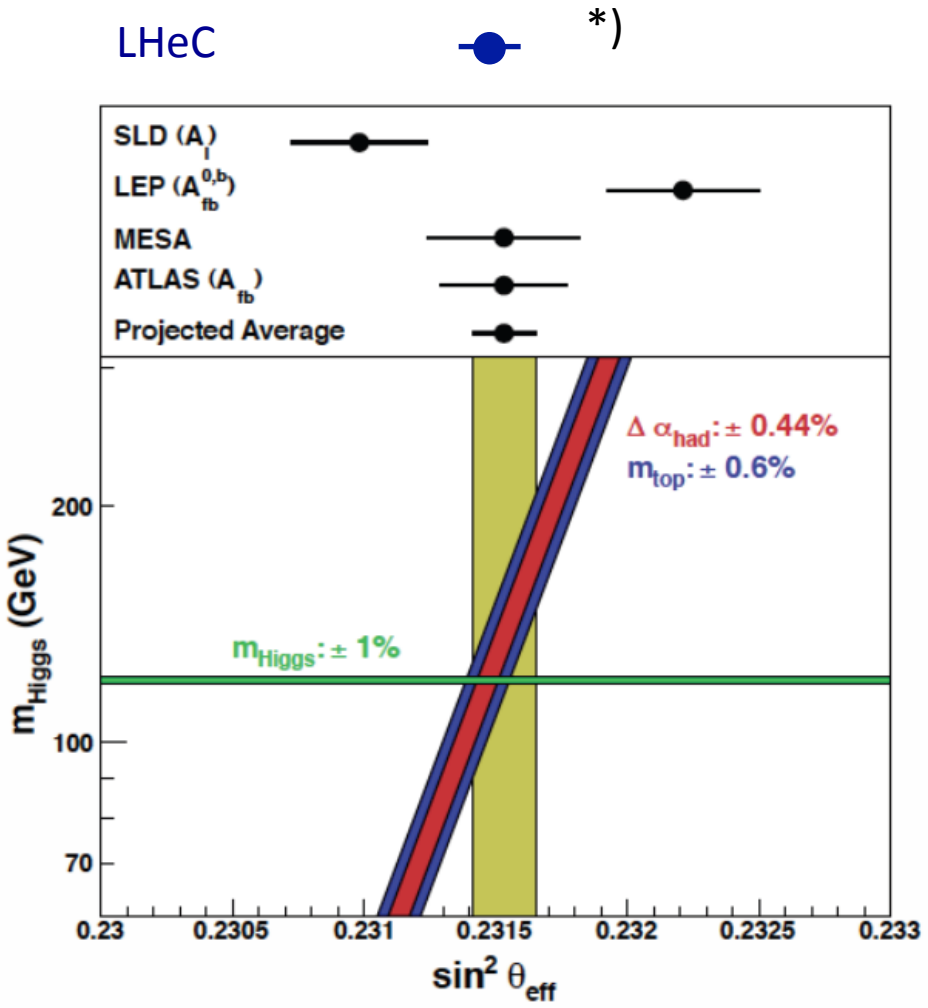
Polarisation Asymmetry $A^{-}(Q)$

NC-to-CC Ratio R- for P=±0.8

Measure weak mixing angle redundantly with very high precision of about 0.0001 as a function of the scale.

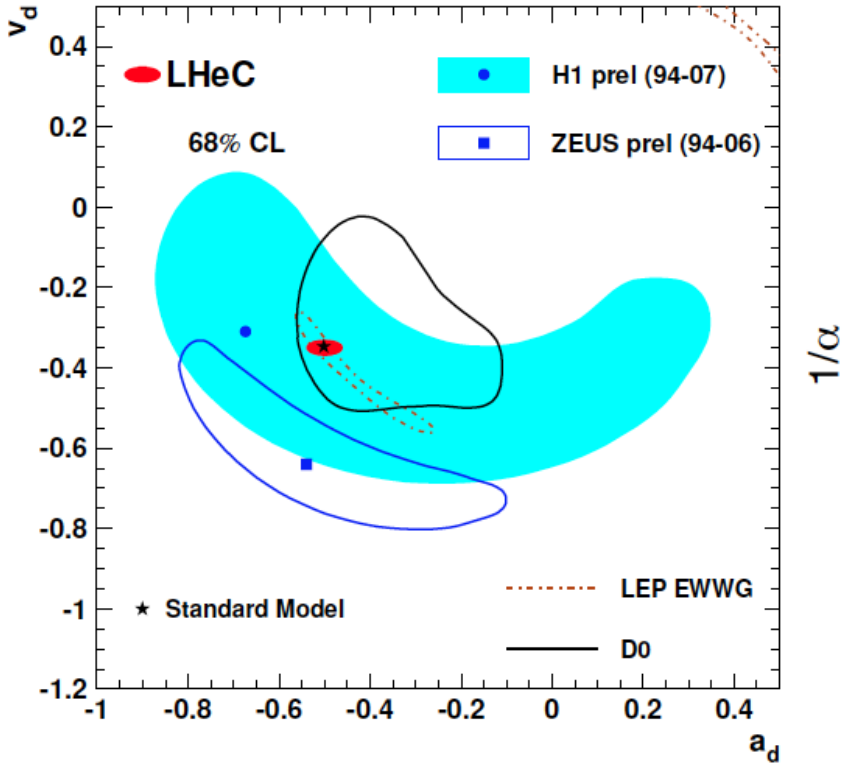
1% δM_{top} is about $\delta = 0.0001$

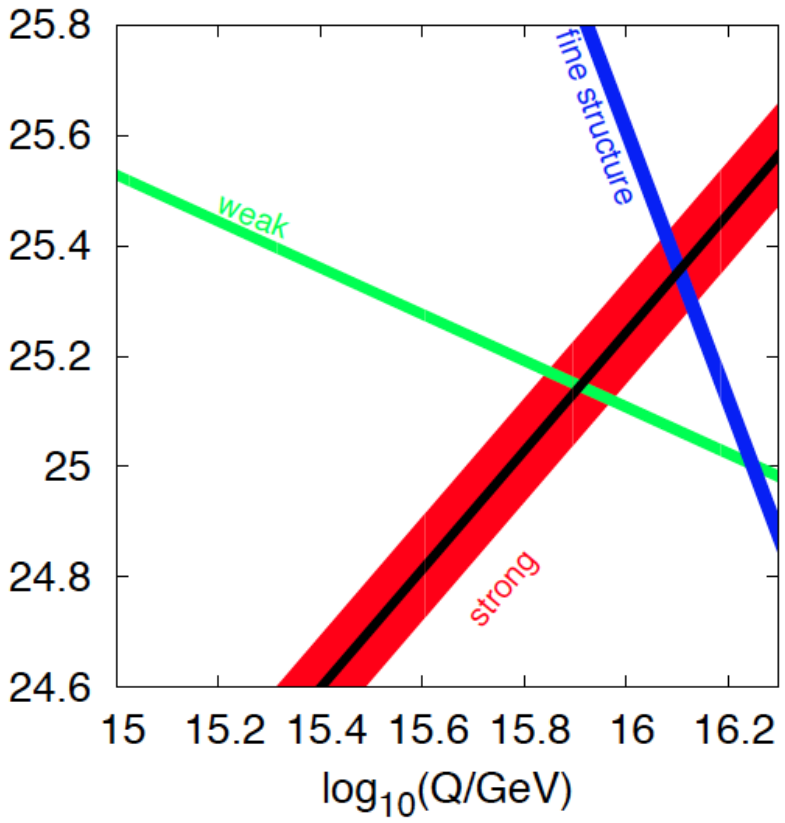
PDF uncertainty comes in at second order and ep provides very precise PDFs



*) first rough estimate, scheme dependent, syst+thy errors..

High Precision DIS



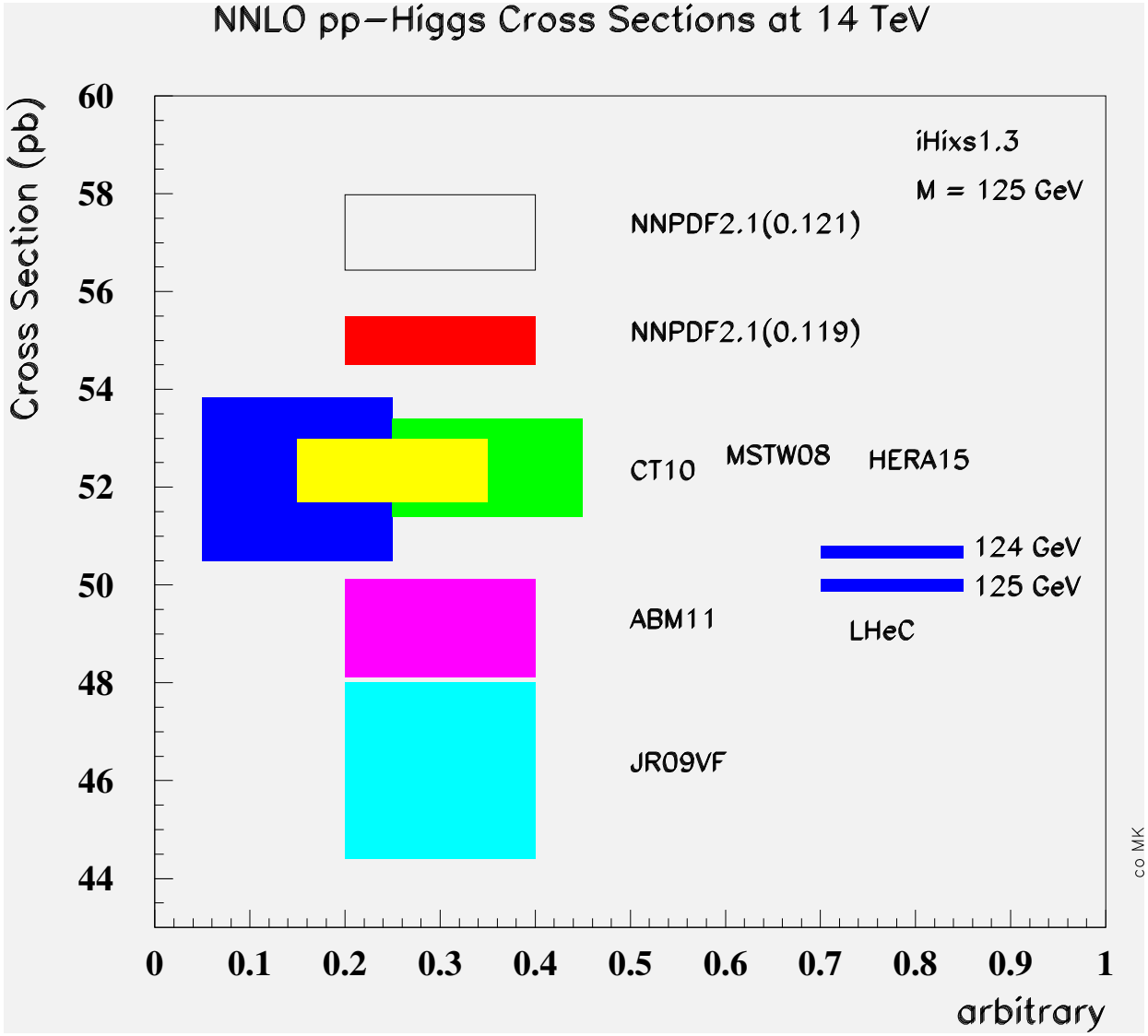


$Q^2 >> M_{Z,W}^2$, high luminosity, large acceptance
Unprecedented precision in NC and CC
Contact interactions probed to 50 TeV
Scale dependence of $\sin^2\theta$ left and right to LEP

→ **A renaissance of deep inelastic scattering** ←

Solving a 30 year old puzzle:
α_s small in DIS or high with jets?
Per mille measurement accuracy
Testing QCD lattice calculations
Constraining GUT (CMSSM40.2.5)
Charm mass to 3MeV, N^3LO

Precision for Higgs at the LHC



O.Brüning and M.Klein 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 …

Summary

LHeC and FCC-he are designed for 10^3 the luminosity of HERA

The kinematic range is extended to Q^2 of 10 TeV^2 and $x < 10^{-6}$

For PDFs for the first time ALL parton distributions will be measured and disentangled, unlike now!!. There is a huge, much wider PDF program: Unintegrated (parton emission?), generalised (amplitudes, DVCS), neutron (need deuteron beam), photon, pomeron, nuclear PDFs

The gluon distribution at large x will be measured for the first time so accurate that possible discoveries at the LHC (and later FCC) can be reliably interpreted and the gg → Higgs cross section be predicted

The strong coupling constant can be measured 10 times better than hitherto: unification of forces? Lattice? Resolving puzzles

The access to low x will be of crucial importance: DGLAP-BFKL, saturation of xg, UHE-neutrino scattering, decomposition of the light sea.. [important to have deuterons, and ions..]

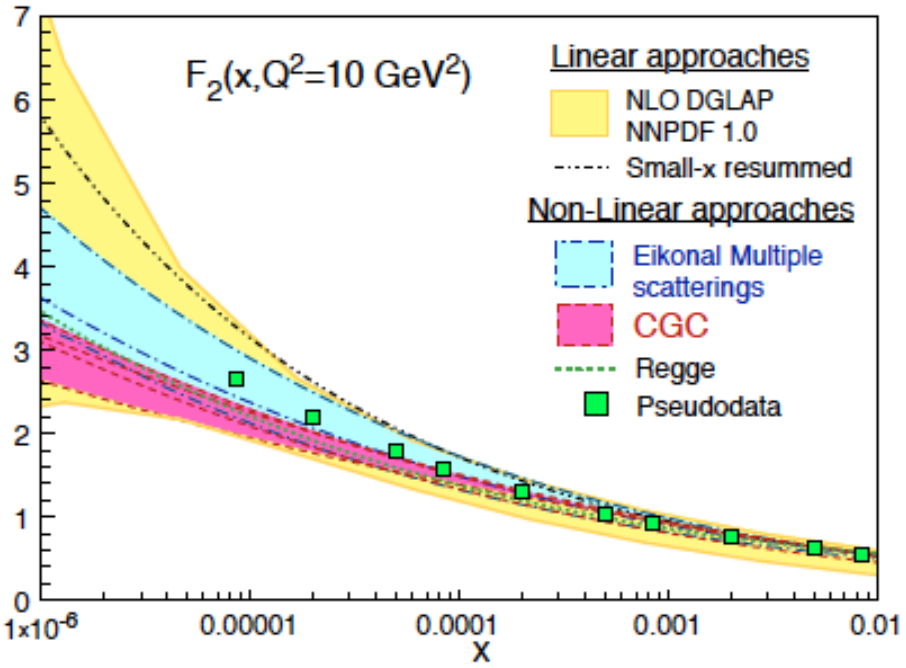
The LHeC-FCC-he has a unique program for electroweak precision physics ($s^2\theta$)

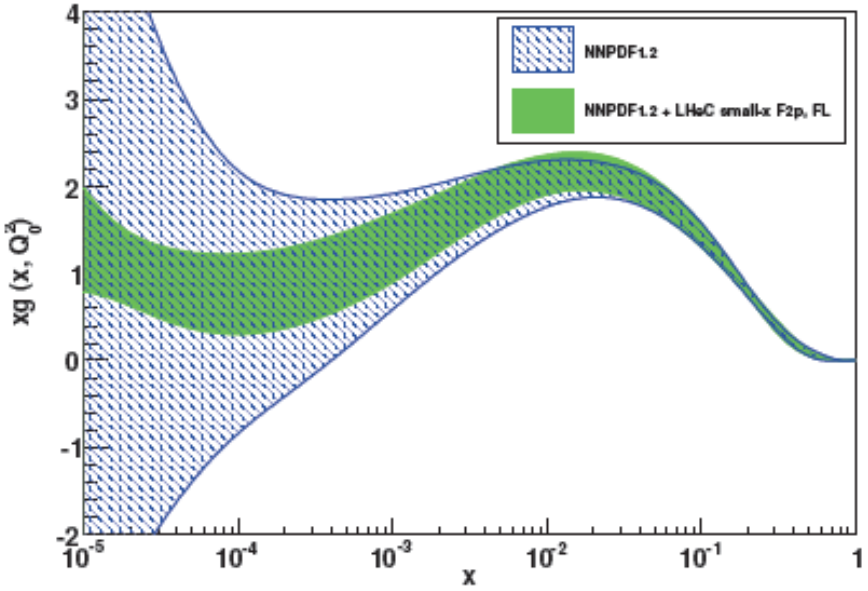
This program will be a MAJOR stimulus for h.o. theory, may lead to discoveries and is a NECESSITY for the exploration of the TeV and multi-TeV scale phenomena

backup

Partons at low x

Studies within NNPDF (CDR 8/12)





High precision F_2 and F_L pin down low x phenomenology and determine the gluon distribution down to $x \sim 10^{-5}$

Electroweak Physics in ep [$\sin^2\theta_W$]

Present situation

- $\sin^2\hat{\theta}_w(m_Z) = 0.23070 \pm 0.00026$ from A_{LR}, SLD
- $\sin^2\hat{\theta}_w(m_Z) = 0.23193 \pm 0.00029$ from $A_{FB}^{b\bar{b}}$, LEP1

  ➜ 3σ difference !
- $\sin^2\hat{\theta}_w(m_Z) = 0.23125 \pm 0.00016$ world average
- $\sin^2\hat{\theta}_w(m_Z) = 0.23104 \pm 0.00015$ from α, G_μ, m_Z and m_W

Very different implications for new physics:
look at S, T, U parameters, e.g.,

- from A_{LR} ➜ $S = -0.18 \pm 0.15$ ➜ Susy?
- from $A_{FB}^{b\bar{b}}$ ➜ $S = +0.46 \pm 0.17$ ➜ heavy Higgs? KK at 1 - 2 TeV?
- from average ➜ $S = +0.11 \pm 0.11$ ➜ new heavy doublets? KK above 3 TeV?

The strong coupling constant

	$\alpha_s(M_Z)$	
BBG	$0.1134\ ^{+\ 0.0019}_{-\ 0.0021}$	valence analysis, NNLO [235, 236]
BB	0.1132 ± 0.0022	valence analysis, NNLO [237]
GRS	0.112	valence analysis, NNLO [238]
ABKM	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$ [228]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [228]
JR	0.1124 ± 0.0020	dynamical approach [231]
JR	0.1158 ± 0.0035	standard fit [231]
ABM11	0.1134 ± 0.0011	[229]
MSTW	0.1171 ± 0.0014	[239]
NN21	0.1173 ± 0.0007	[233]
CT10	0.118 ± 0.005	[240]
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust [241]
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust [242]
3 jet rate	0.1175 ± 0.0025	Dissertori et al. 2009 [243]
Z-decay	0.1189 ± 0.0026	BCK 2008/12 (N^3LO) [121, 244]
τ decay	0.1212 ± 0.0019	BCK 2008 [244]
τ decay	0.1204 ± 0.0016	Pich 2011 [20]
τ decay	0.1180 ± 0.0008	Beneke, Jamin 2008 [245]
lattice	0.1205 ± 0.0010	PACS-CS 2009 (2+1 fl.) [246]
lattice	0.1184 ± 0.0006	HPQCD 2010 [247]
lattice	0.1200 ± 0.0014	ETM 2012 (2+1+1 fl.) [248]
BBG	$0.1141\ ^{+\ 0.0020}_{-\ 0.0022}$	valence analysis, $N^3LO(^*)$ [235]
BB	0.1137 ± 0.0022	valence analysis, $N^3LO(^*)$ [237]
world average	0.1184 ± 0.0007	[249] (2009)
	0.1183 ± 0.0010	[20] (2011)

α_s is the worst measured fundamental coupling constant. Is there grand unification?

In DIS, values (NNLO) range from 0.113 to 0.118.

τ leads to about 0.120

Lattice predictions seem to determine the world average.

The LHeC has the potential to measure αs to permille accuracy (0.0002) from a consistent data set. This leads to high precision understanding of all related effects (low x, δM_c=3MeV) and pQCD at N^3LO

J.Bluemlein, Why Precision, arXiv:1205.4991

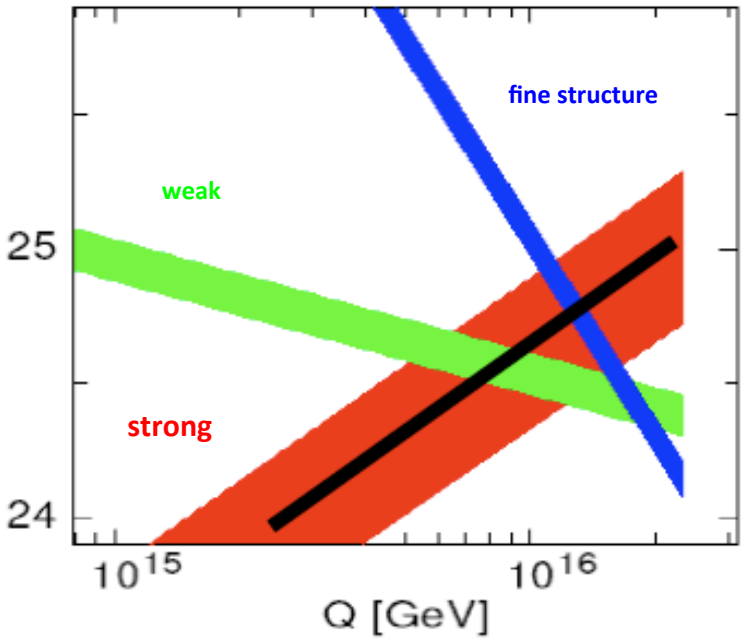
Strong Coupling Constant

α_s least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average (?)

LHeC: per mille - independent of BCDMS.

Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than one outstanding measurement only.



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

DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) γ_h>5°	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%