Precision QCD and electroweak physics at

DIS 2012, Bonn, Germany
29th march 2012

Olaf Behnke (DESY)

Need for LHeC

27.5 GeV x 920 GeV ep HERA

with integrated L~0.5 fb^{-1} was a

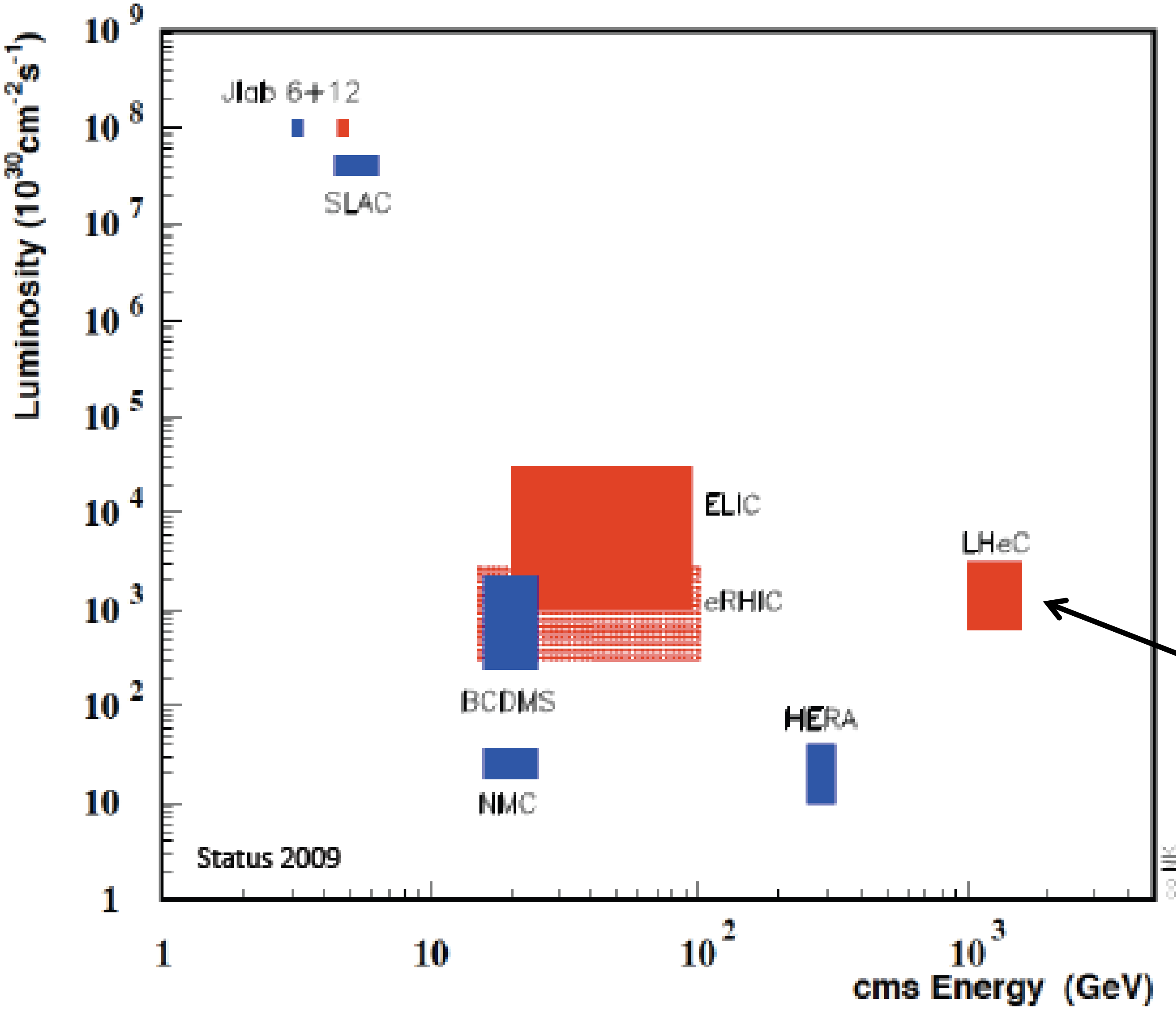
- high precision machine for QCD
- modest precision machine for electroweak physics

Where could we go with a

60 GeV x 7 TeV $e^{\pm}p$, also eA collider

with integrated L~1-100 fb^{-1} ?

Lepton proton scattering experiments

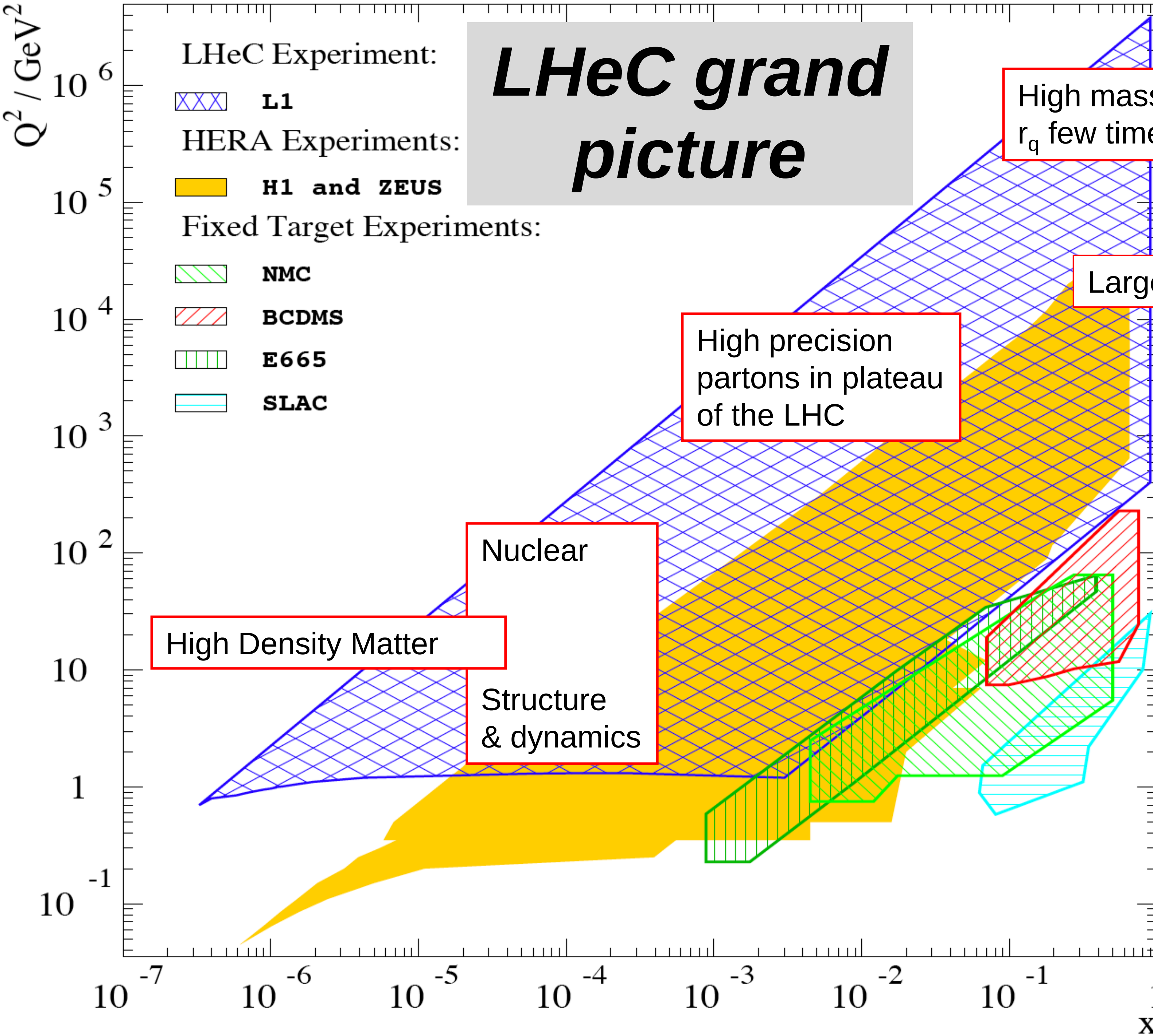


done

planned

LHeC = highest energy and high lumi

LHeC grand picture



Talk Content:

Accelerator

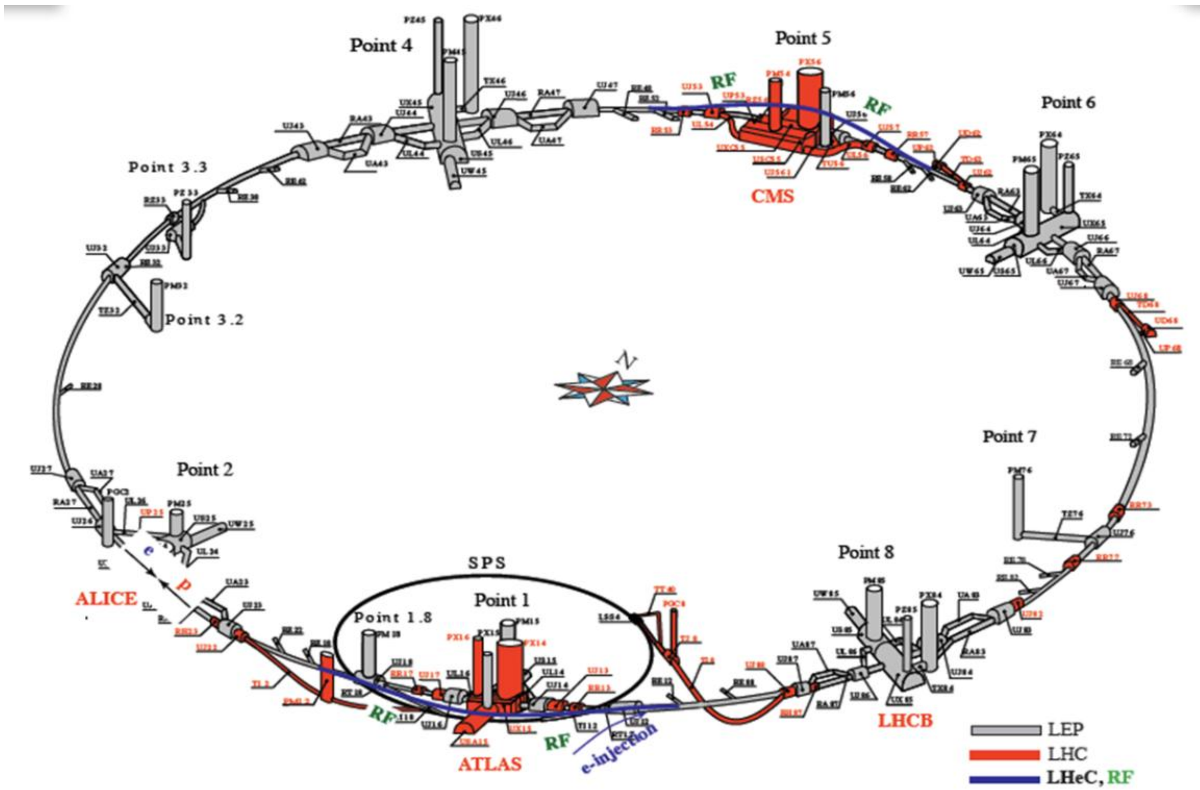
1. Inclusive DIS & PDFs
2. Jets & Heavy flavours
3. Electroweak physics

LHeC Accelerator options

Ring-Ring

Power Limit of 100 MW wall plug
with “ultimate” LHC proton and
60 GeV $e^{\pm}$ beam

→ $L = 2\ 10^{33}\ cm^{-2}s^{-1}$ → $O(100)\ fb^{-1}$

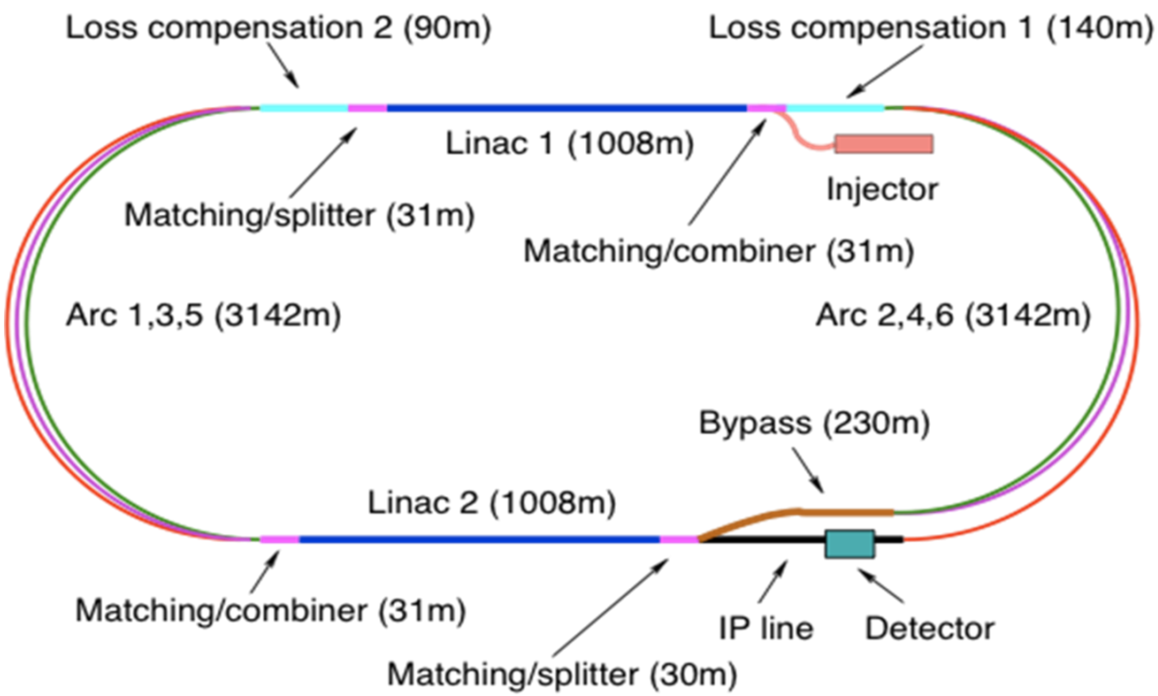


LHeC Accelerator options

LINAC Ring

60 GeV "Circus Maximus" with Energy recovery

L = 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}



140 GeV pulsed LINAC L = 0.4 10^{32} $cm^{-2}s^{-1}$ → O(4) fb^{-1}

1. Inclusive NC & CC DIS: simulated Default Scenarios

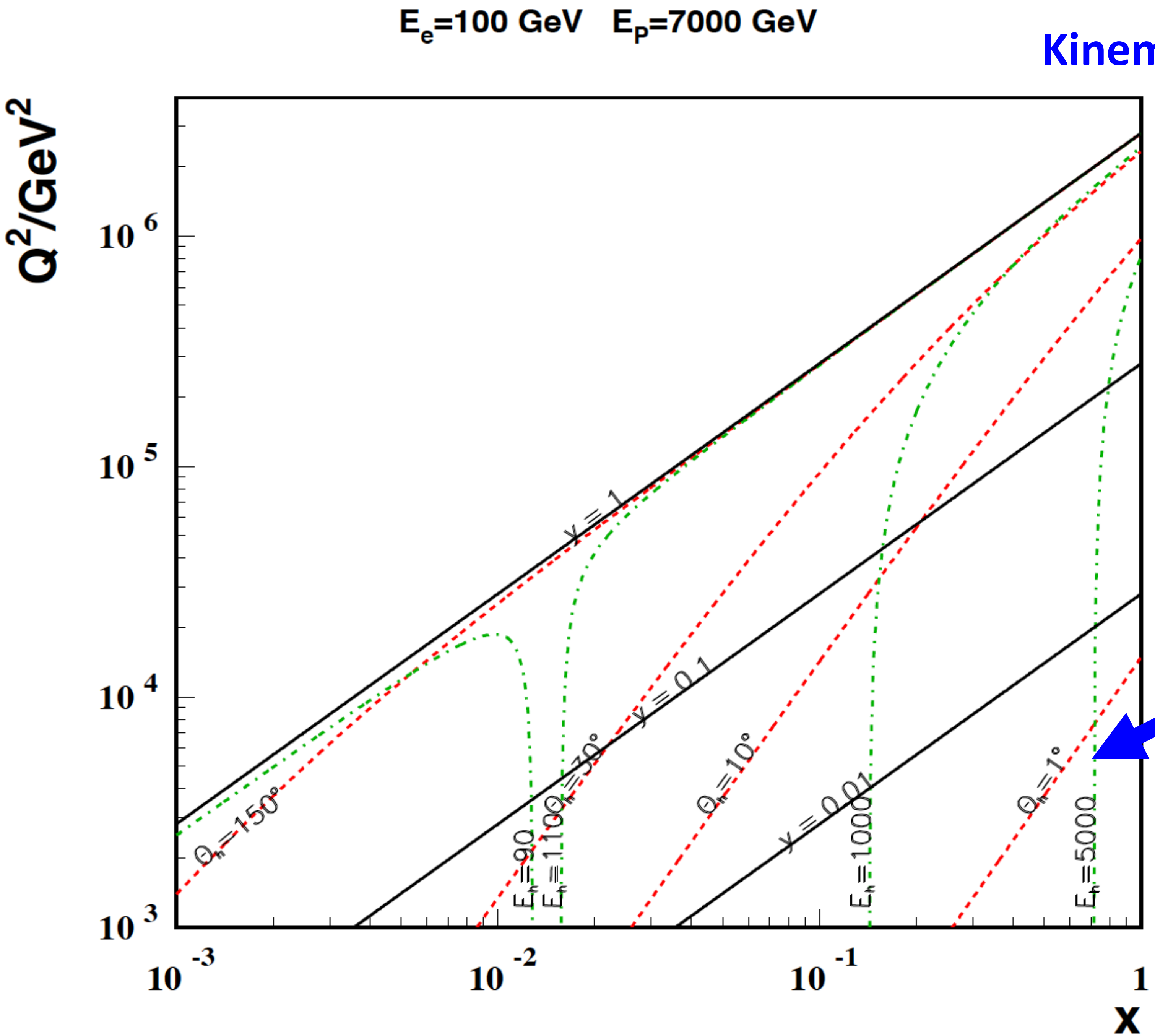
http://hep.ph.liv.ac.uk/~mklein/simdis09/lhecsim.Dmp.CC, readfirst

Max Klein, LHeC

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp

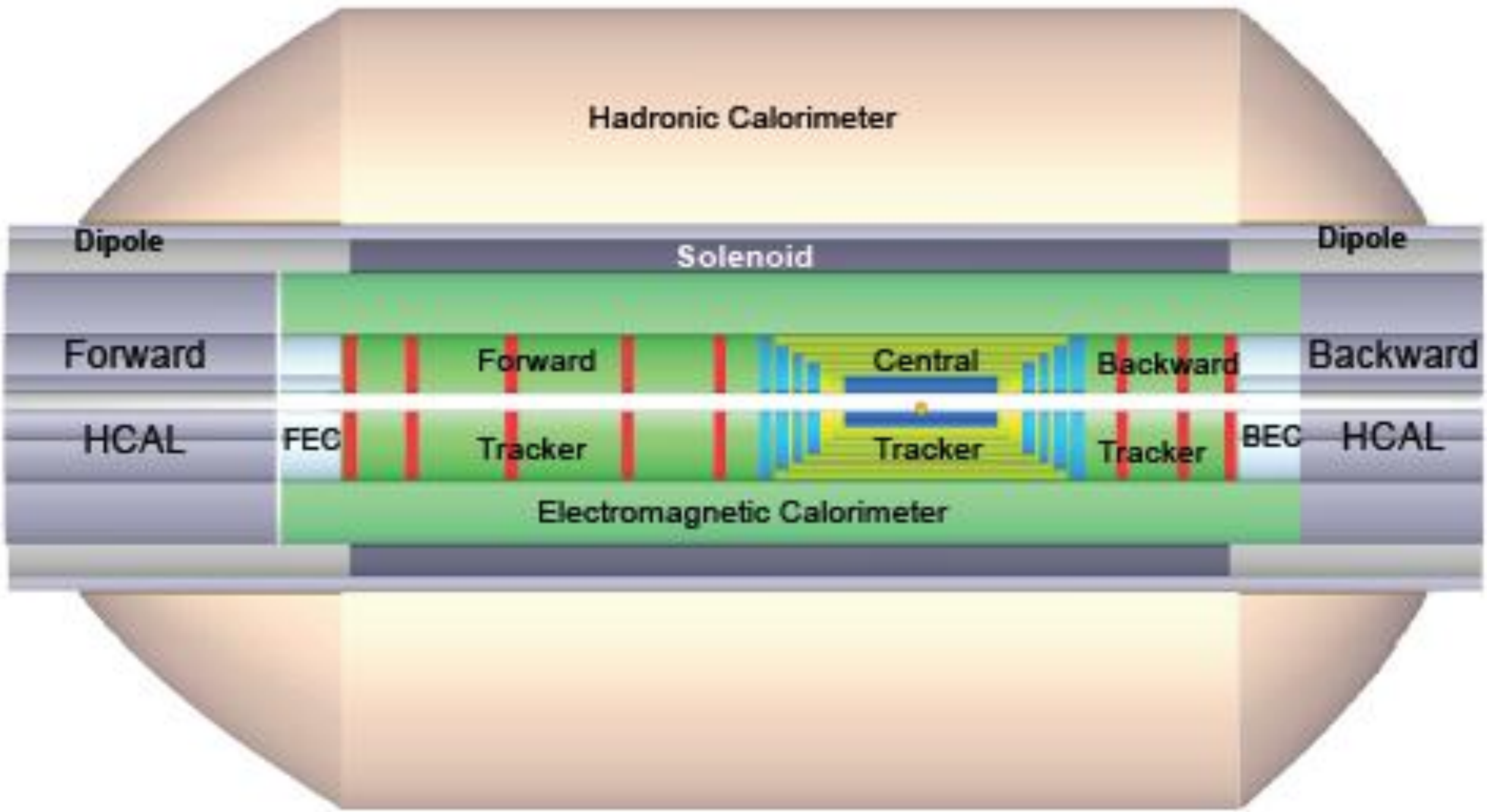
Not simulated

Kinematics – high Q^2



Need excellent forward hadron calorimetry & calibration

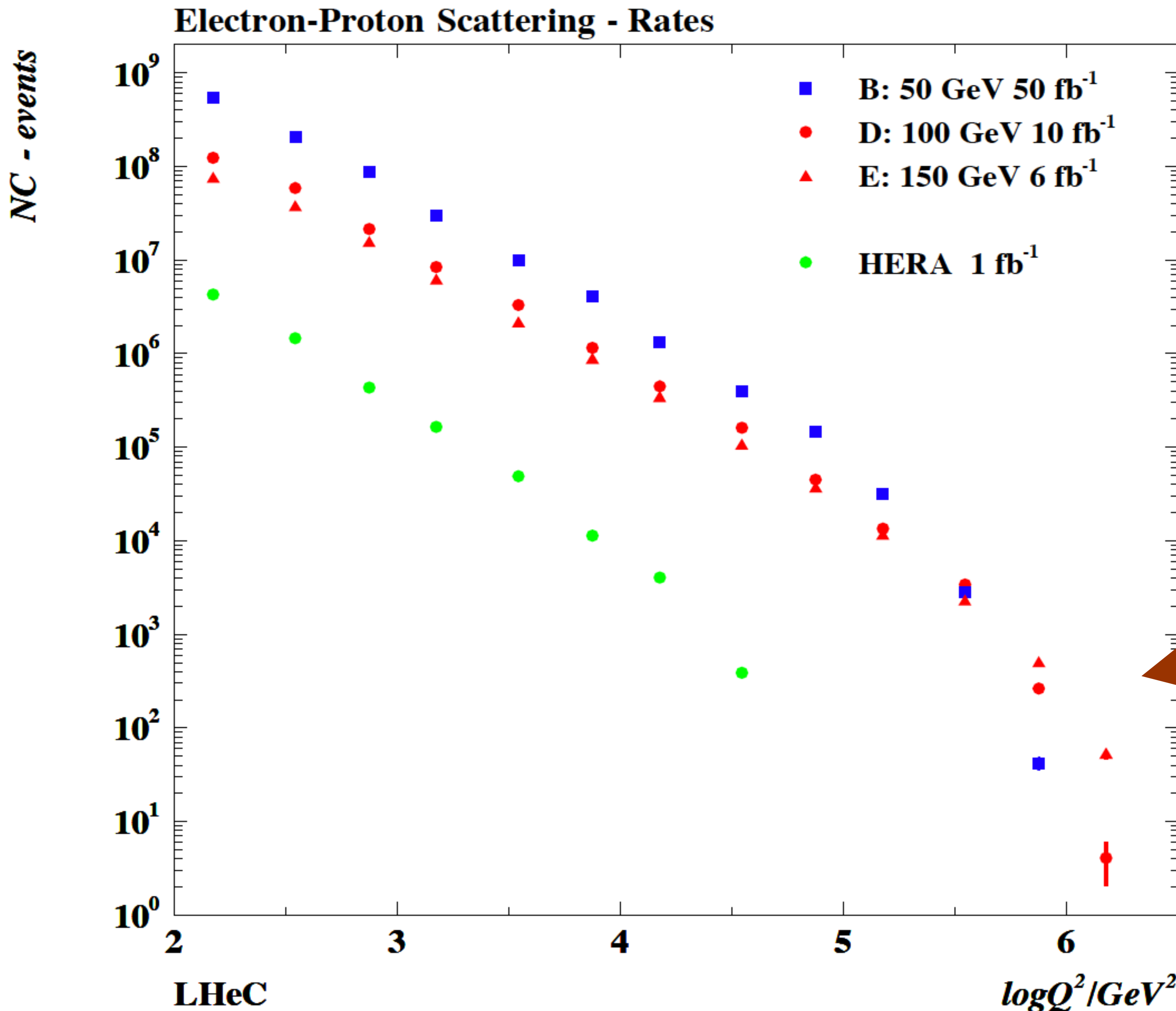
The Detector 'that should do it': Ring-Linac scenario

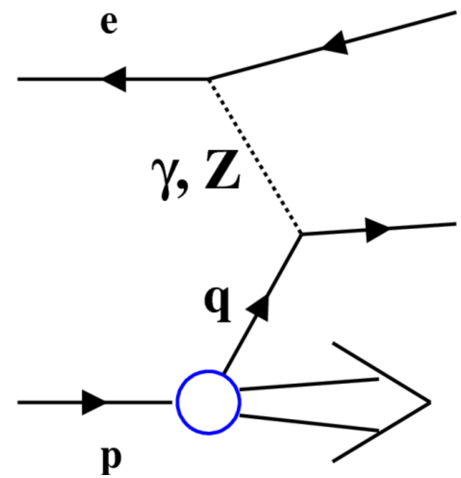


Outer detectors (HAC tailcatcher/muon detectors not shown)

also not shown: forward proton taggers, backward lumi monitors

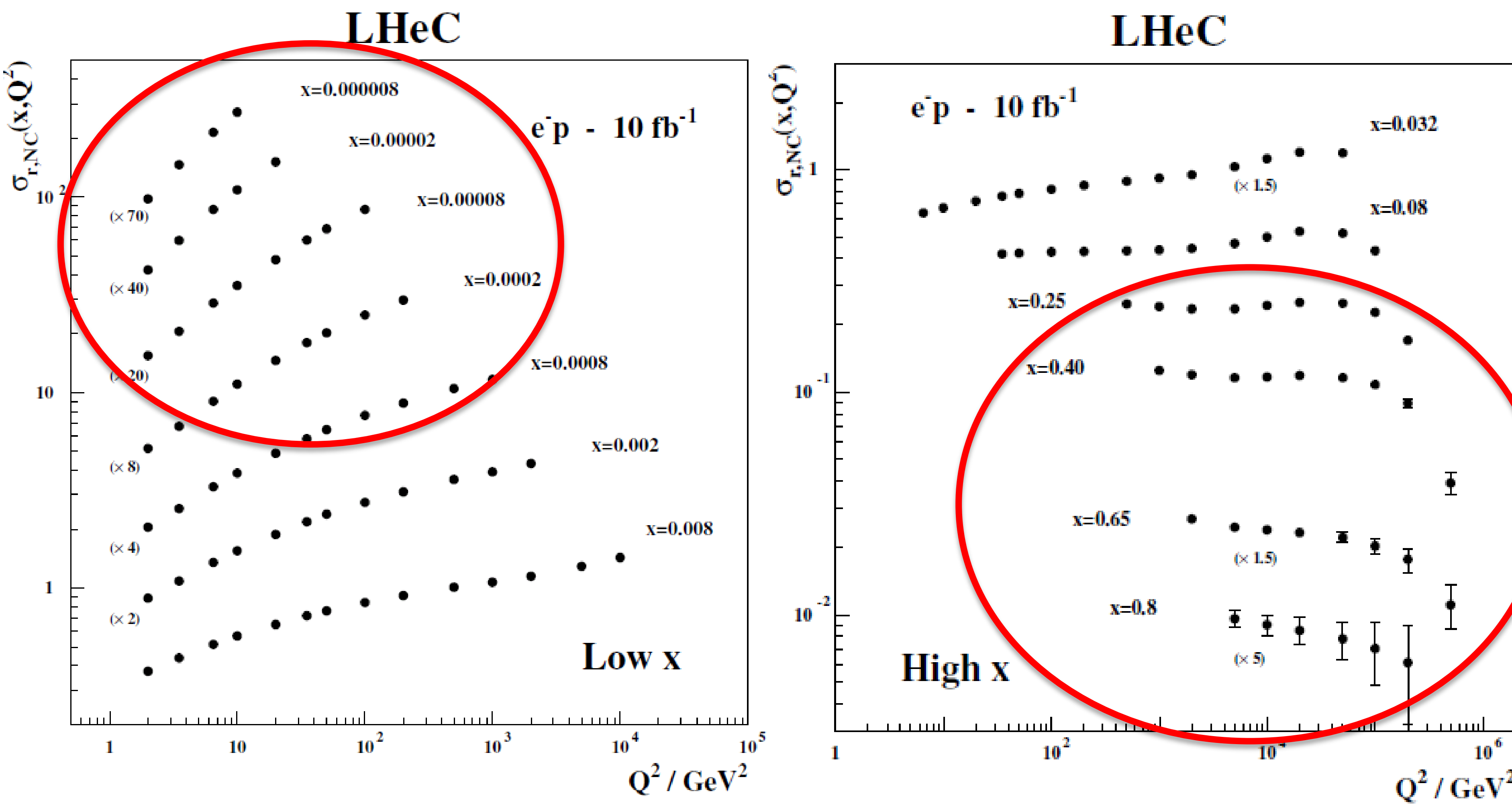
Pseudodata: Neutral Current Event Rates





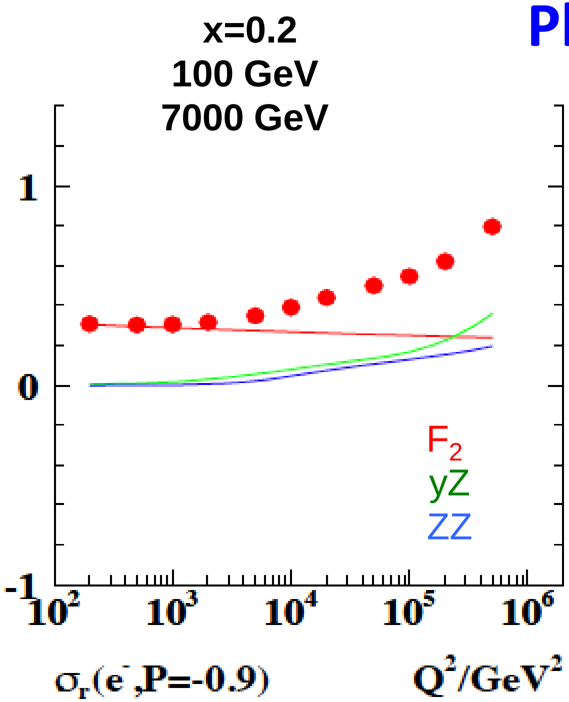
Trivial, but important: largest E_{lep} allows highest Q^2 scales

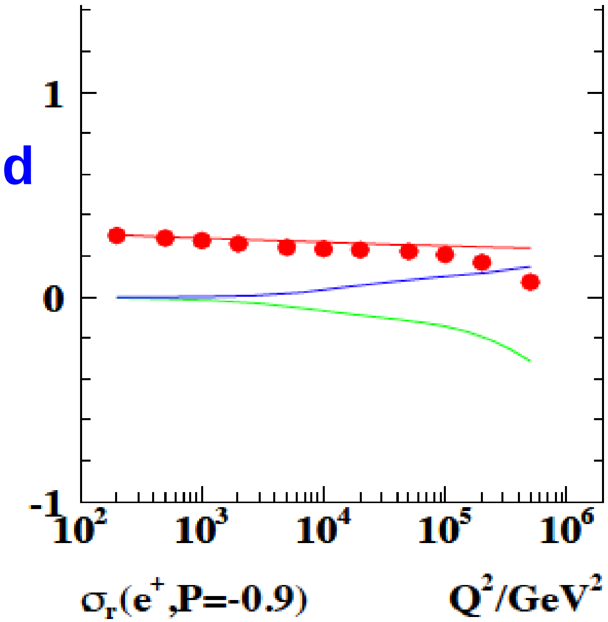
Neutral Current reduced σ



→ *Precise data from smallest to high x*

Photon and Z exchanges are 1:1

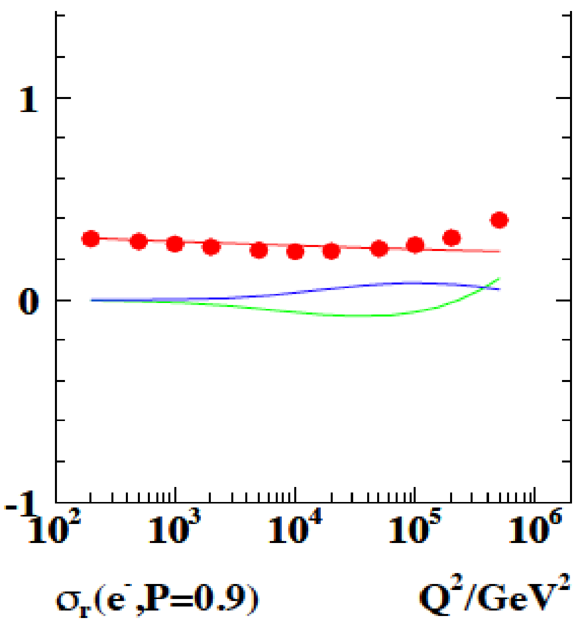


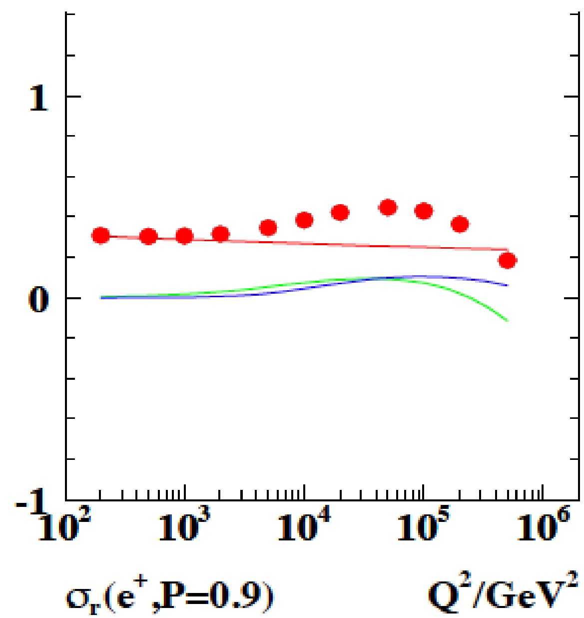


Z effects depend on lepton charge and polarisation.

2 charges and 2 polarisations very desirable

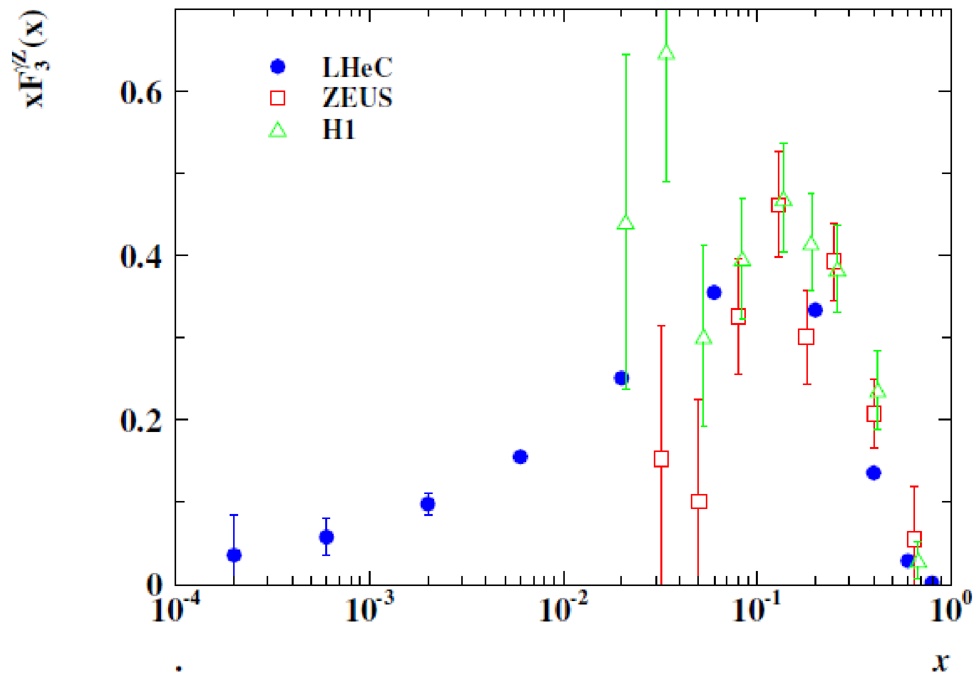
for electroweak precision physics and a new spectroscopy should that appear.

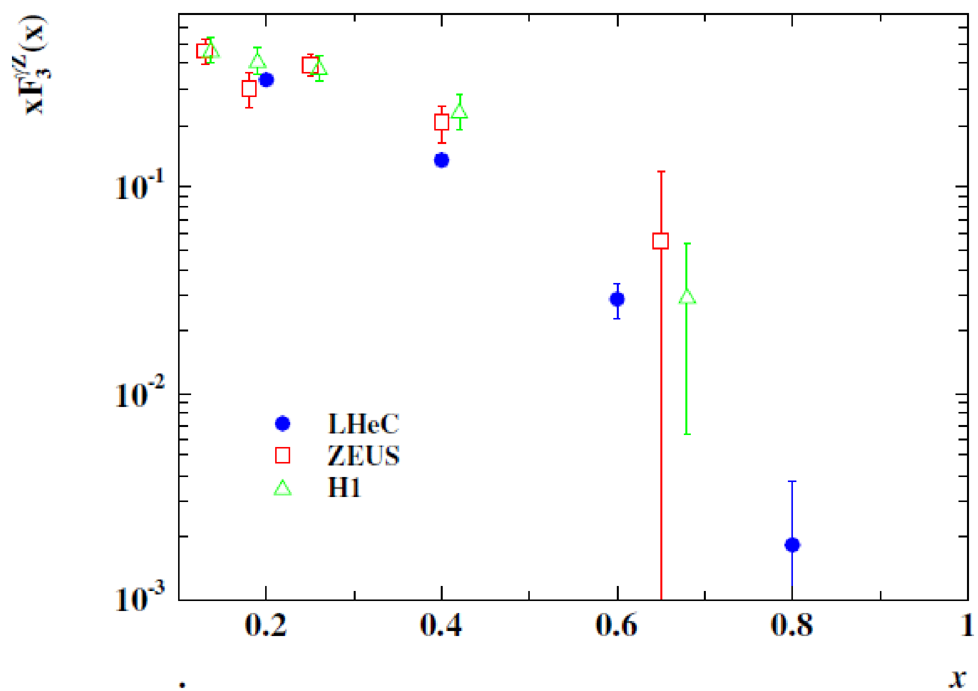




General Remark: LHeC can uniquely reach/exploit electroweak sector:

- Z and W exchanges assist γ exchange for complete quark flavour decomposition of proton structure (next slides)
- precision electroweak tests, e.g. $\sin^2\theta_W(\mu)$ (end of talk)





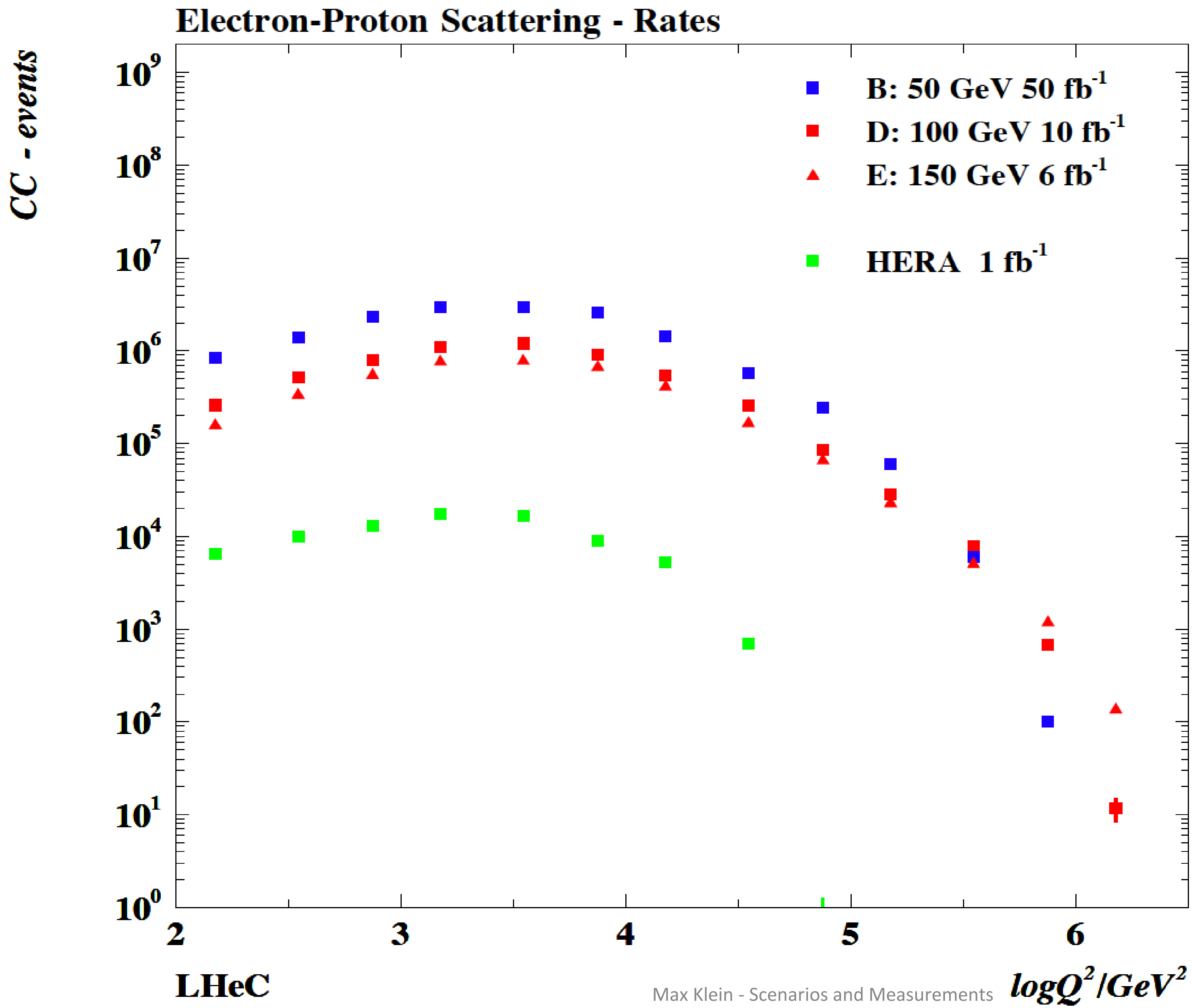
Charge Asymmetry $xF_3^{\gamma Z}$

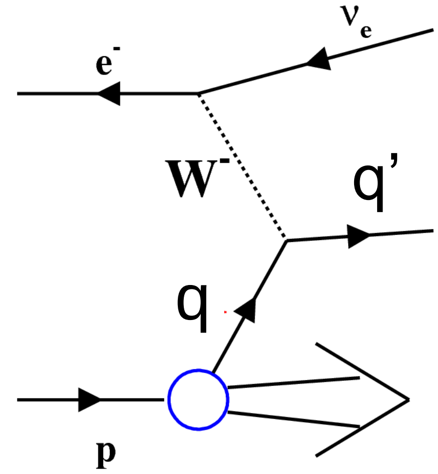
60x7000 GeV^2
P=0
10fb^{-1}

$$xF_3^{\gamma Z} = 2x[e_u a_u(u_v + \Delta_u) + e_d a_d(d_v + \Delta_d)]$$

Get handle on valence quarks from x~0.001 to x~0.8

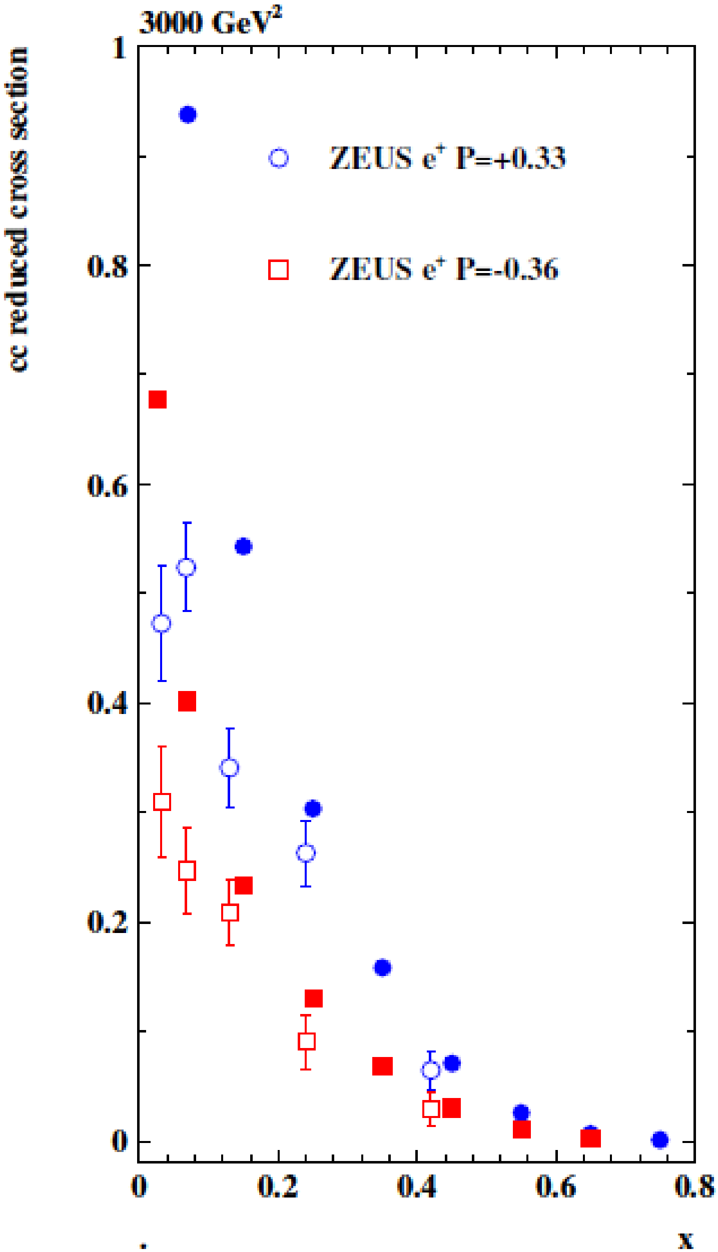
Pseudodata: Charged Current Event Rates

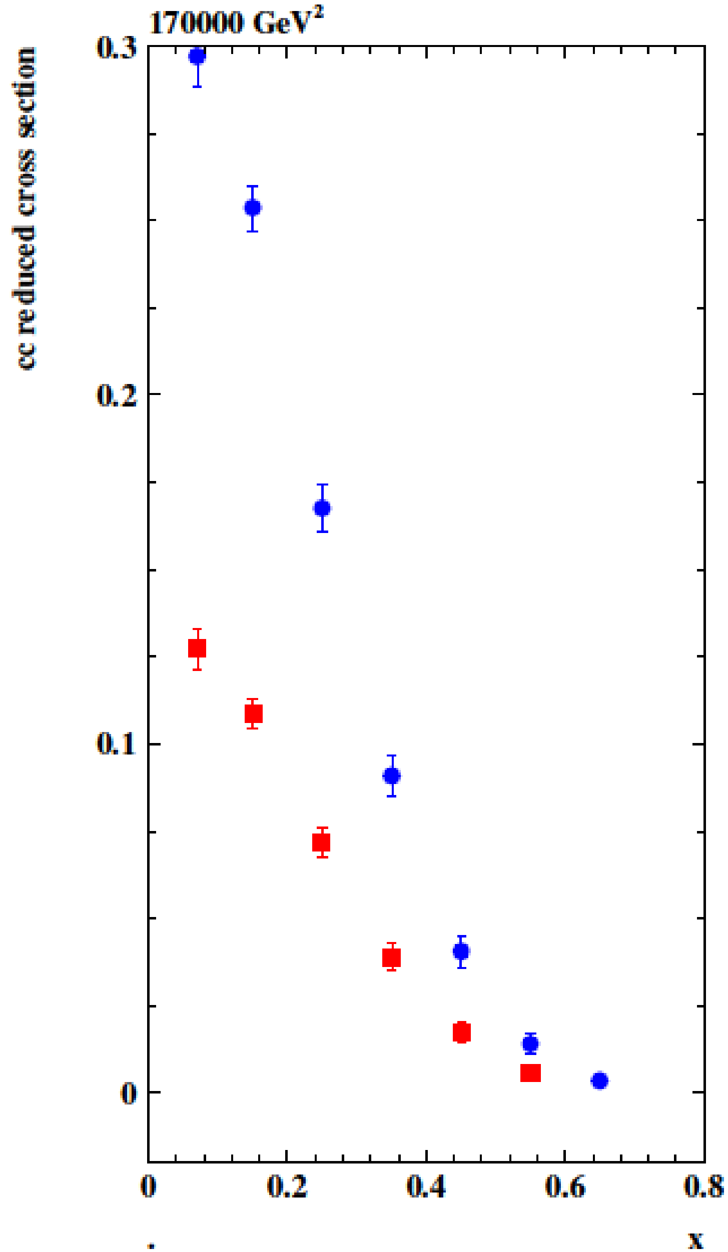


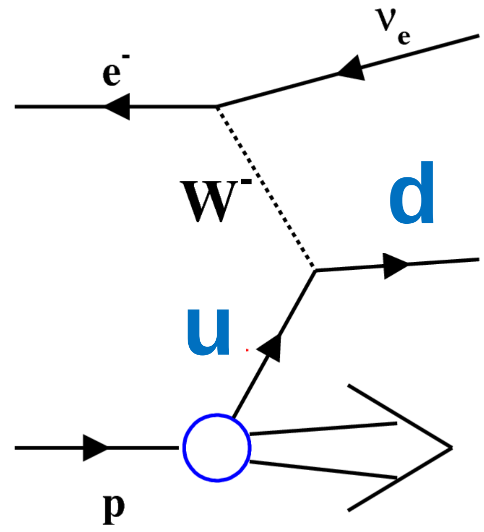


LHeC: expect ~ two orders of magnitude **more events** + better coverage for x>0.5

Charged Currents



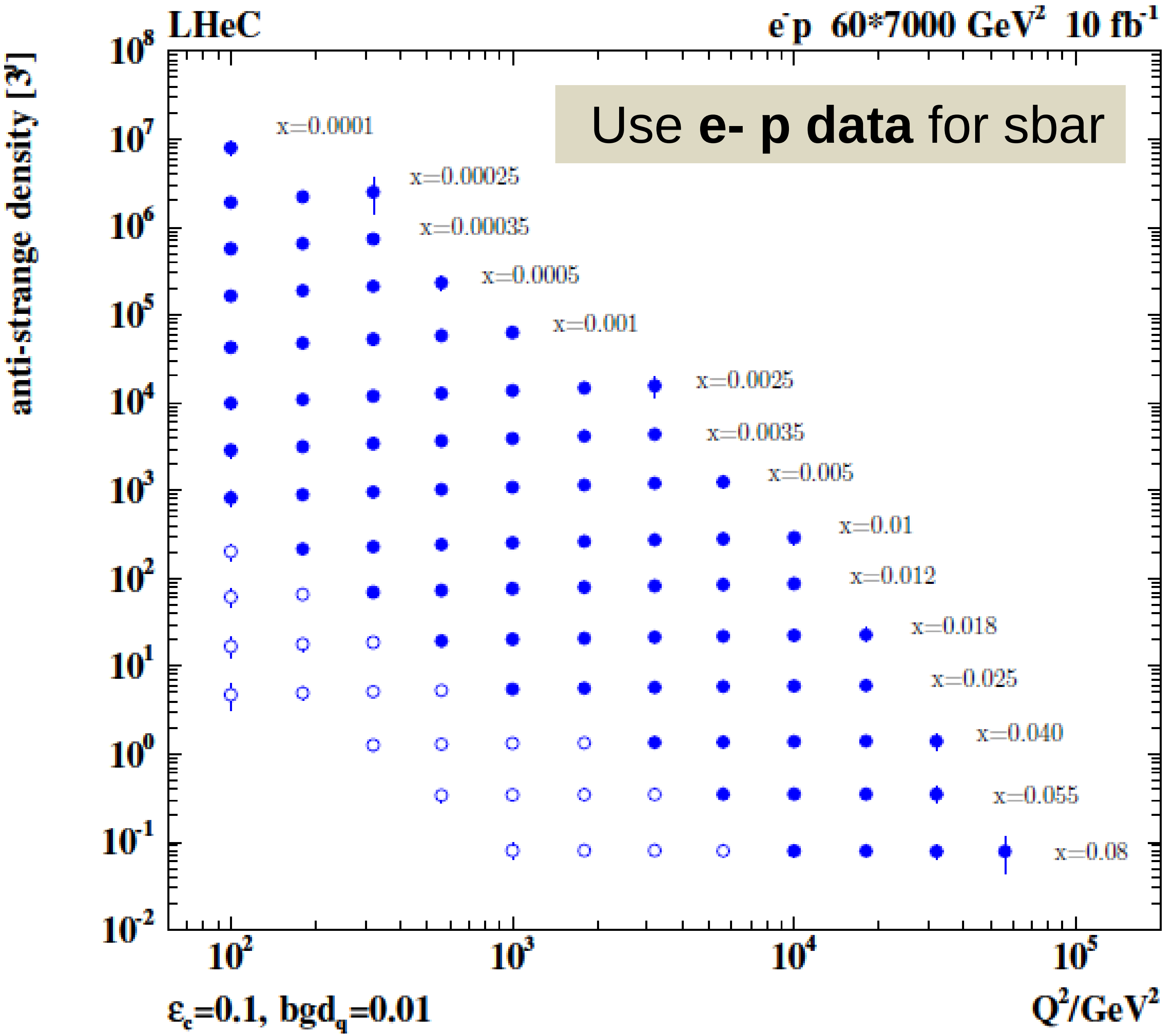


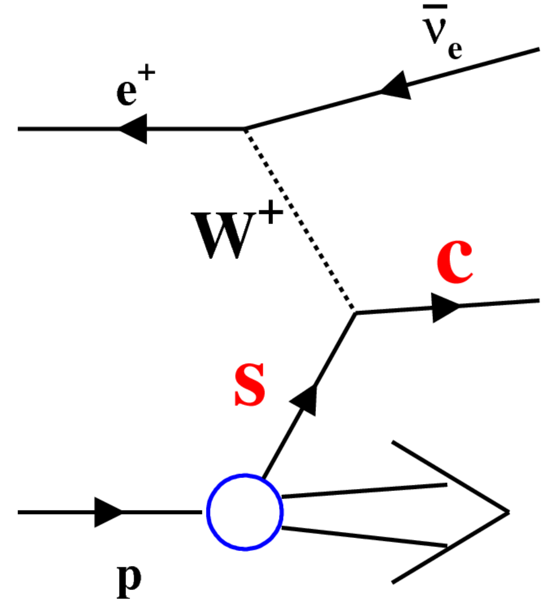


Valence quarks up to x=0.8

Unfold U,D and anti U,D

Strange =? Anti-strange quark density

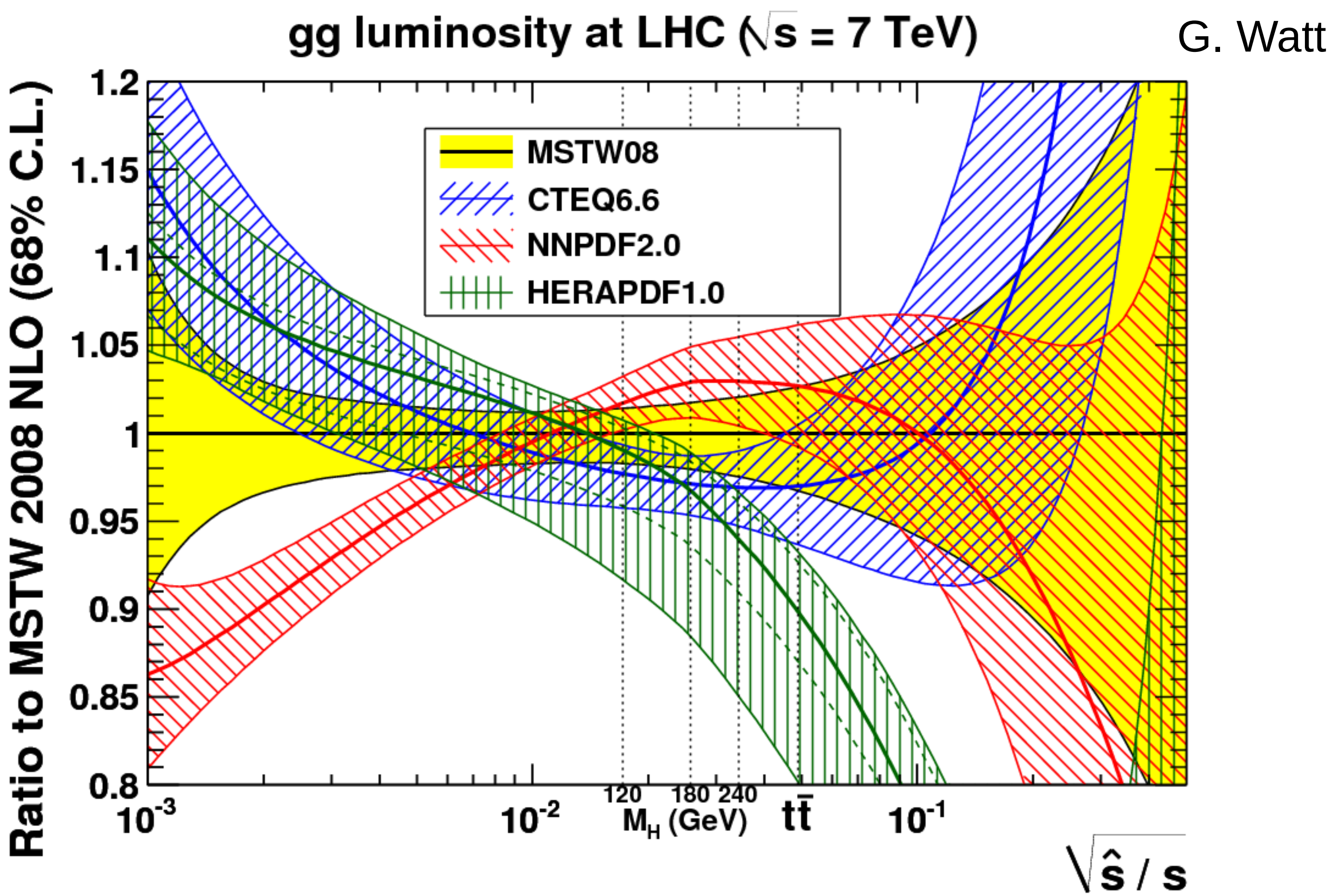




Some dimuon and K data, but never properly measured

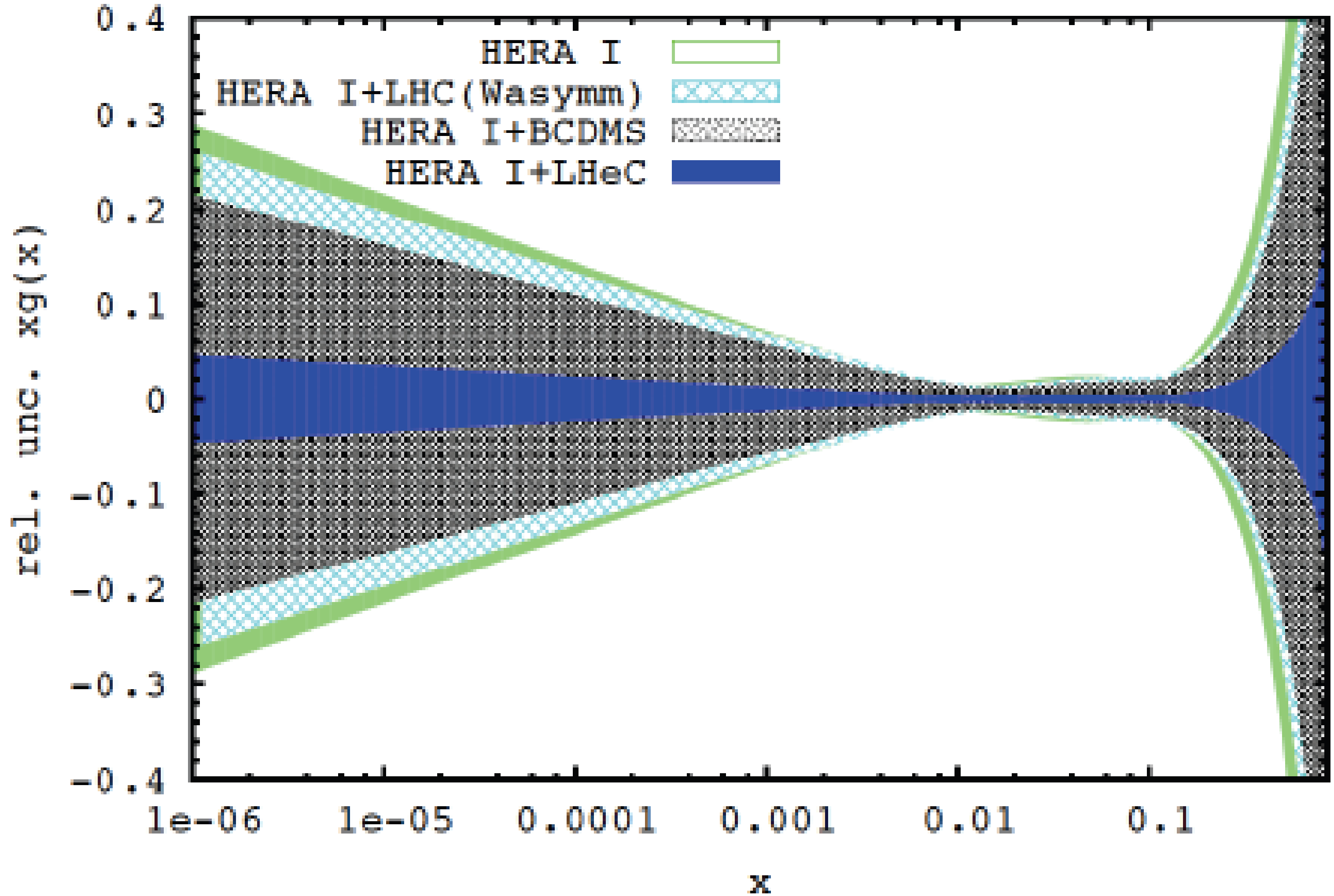
→ Pin down s & sbar

How well do we know PDFs today? gg parton luminosities



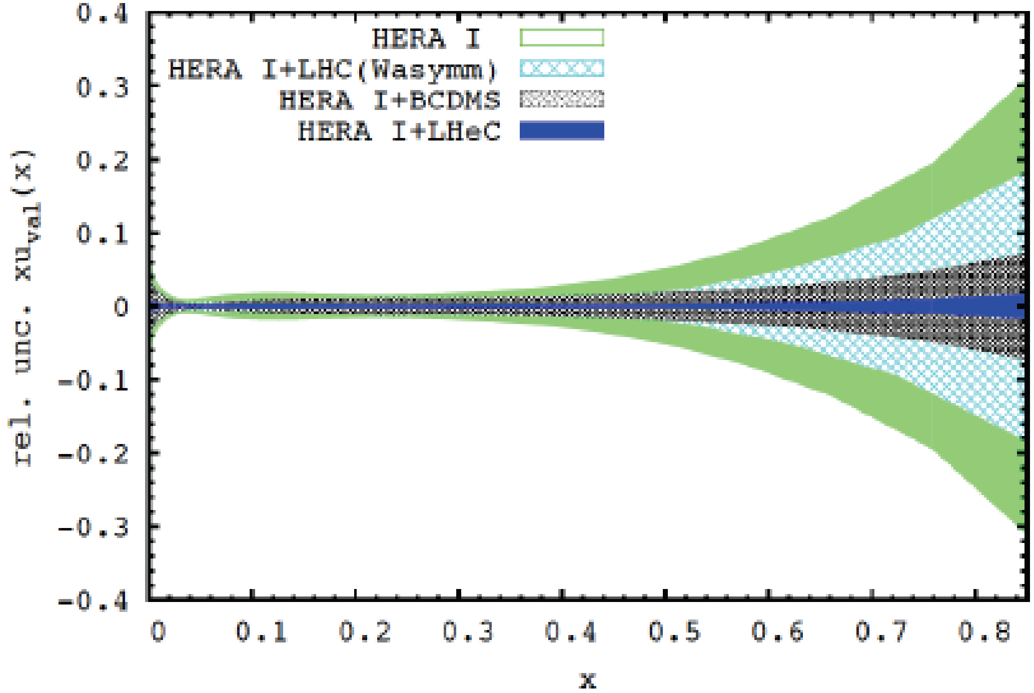
Agree in region relevant for Higgs at LHC, but diverge towards smaller/largest shat

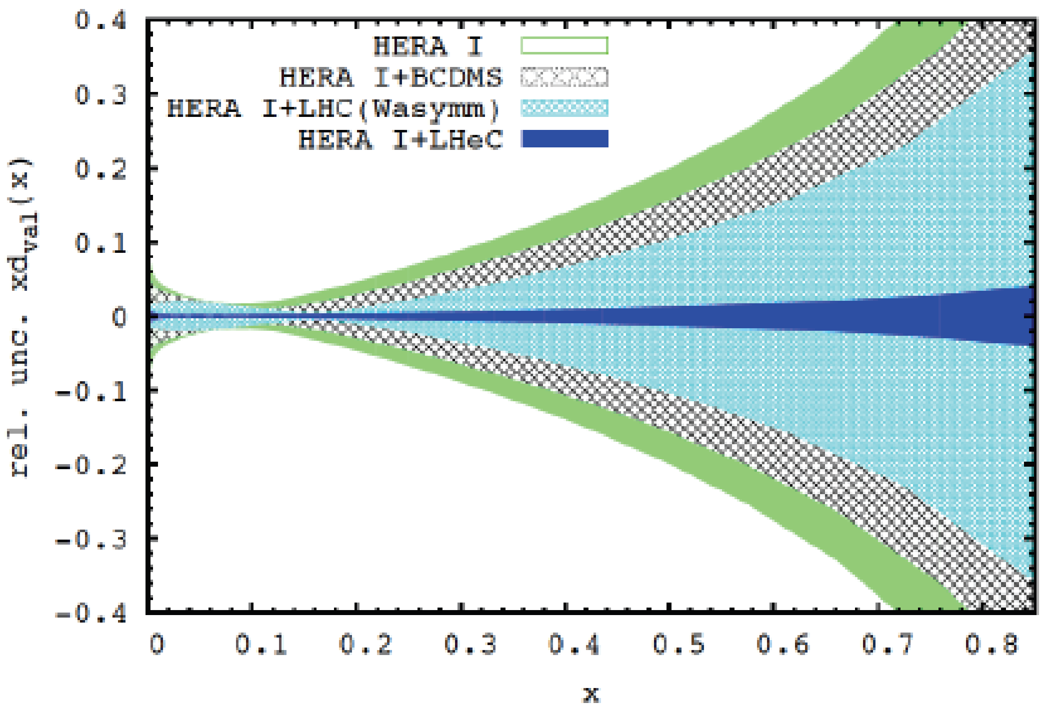
Impact of LHeC **incl. NC & CC** on PDFs: gluon



Unique improvement over huge x range

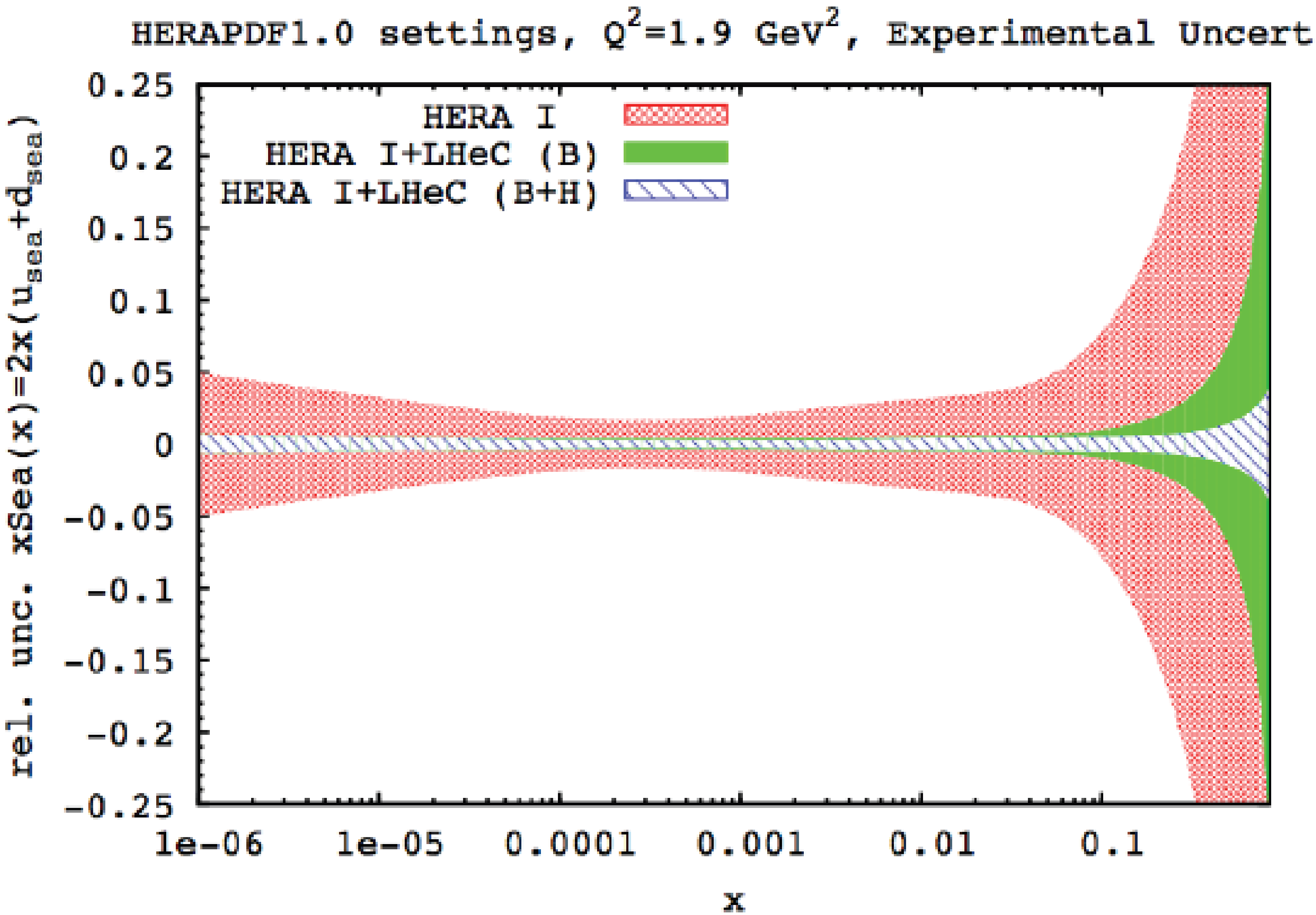
Impact of LHeC **incl. NC & CC** on PDFs: u_v, d_v





Also helpful to pin down u/d for $x \longrightarrow 1$

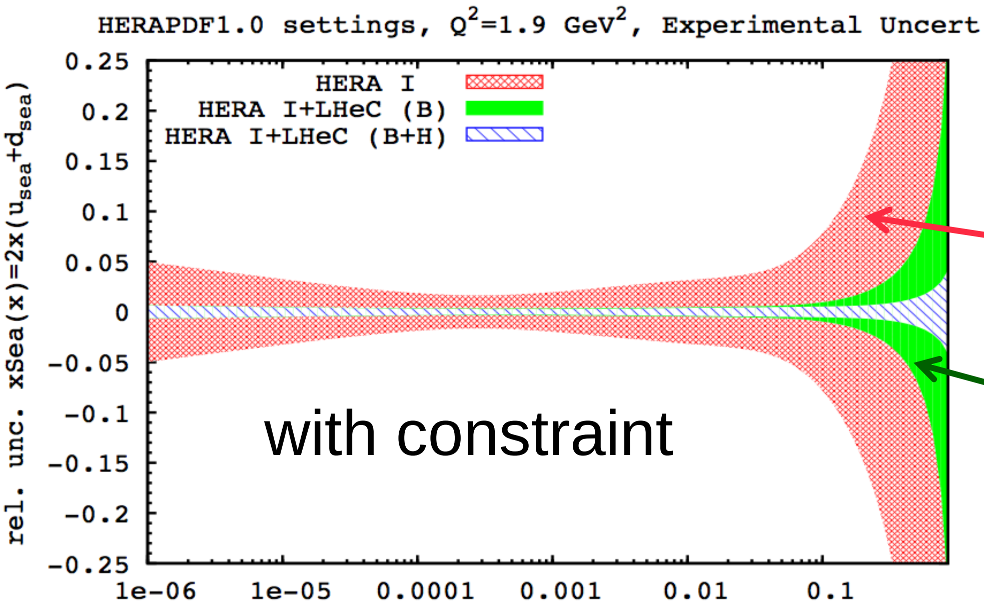
Impact of LHeC **incl. NC & CC** on PDFs: sea



Unique improvement over huge x range

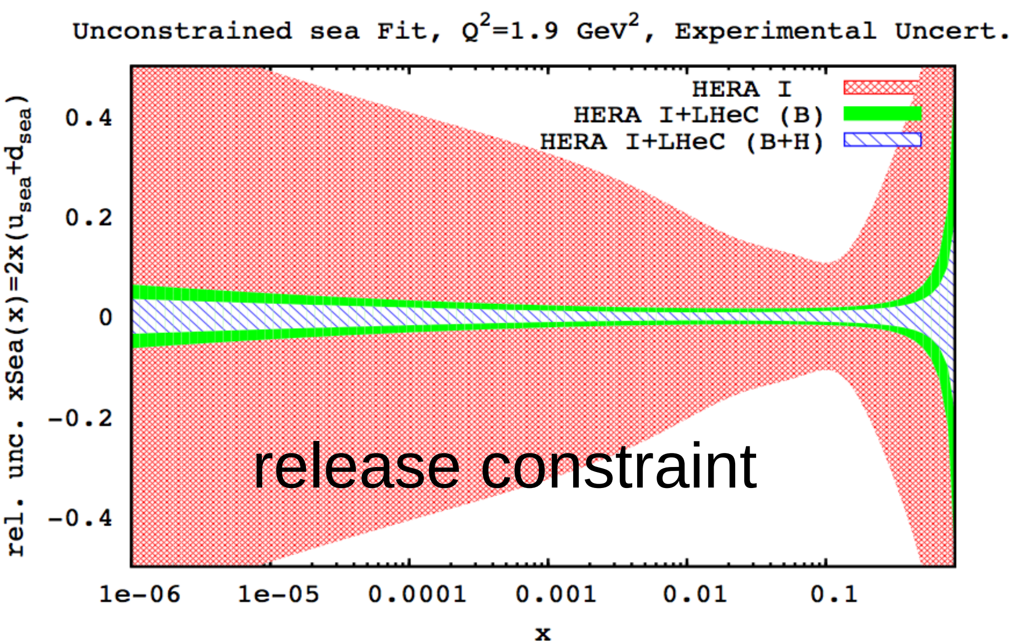
Sea quark uncertainties and usual constraint ubar=dbar for x→0

Voica Radescu



HERA only

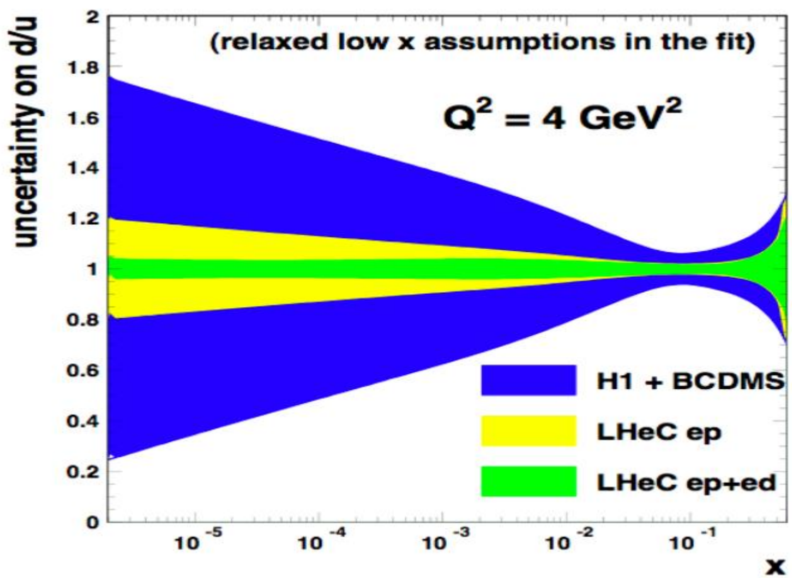
Adding LHeC



With LHeC can get rid of such assumptions

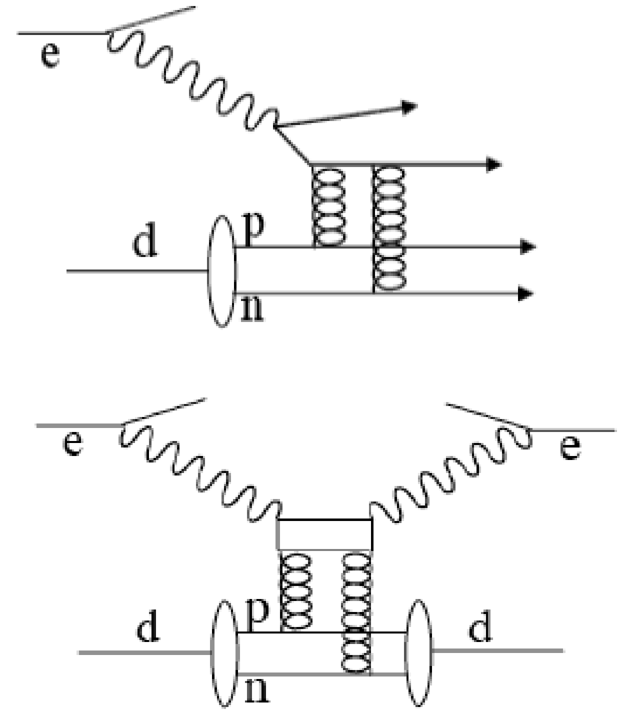
Further PDF improvements at LHeC with ep + eD

d/u at low x from deuterons



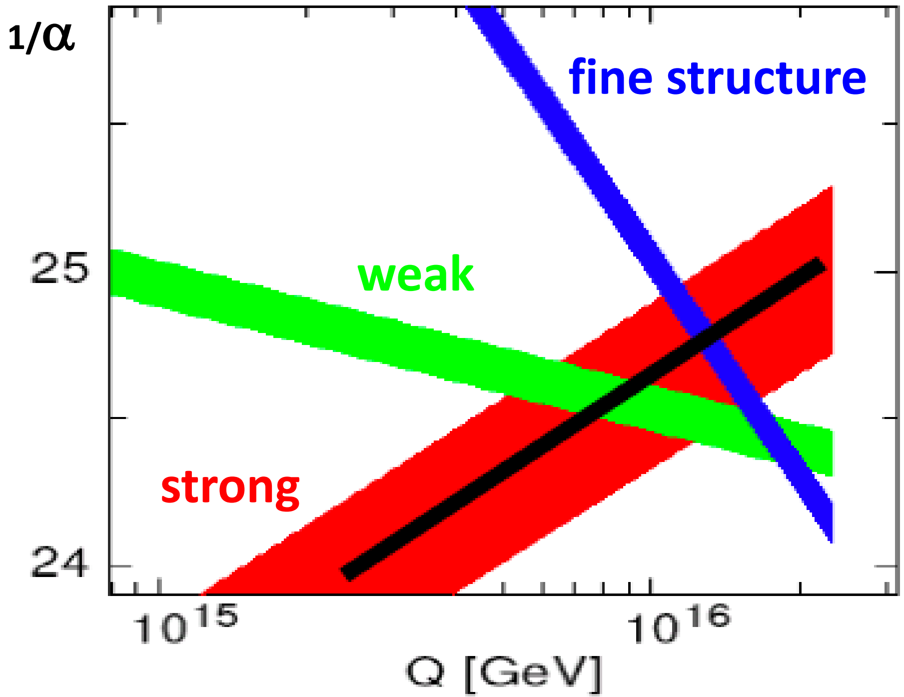
(13) There are five color-singlet combinations of the deuteron wavefunction in QCD, only one of which is the standard proton-neutron state. The "hidden color" [13] components will lead to high multiplicity final states in deep inelastic electron-deuteron scattering.

crucial constraint on evolution (S-NS), improved α_s



In eA at the collider, test Gribovs relation between shadowing and diffraction, control nuclear effects at low Bjorken x to high accuracy

Strong Coupling Constant from inclusive DIS



(sensitivity mainly from dF2/dln(Q2))

Existing NNLO results

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO [80]
GRS	0.112	valence analysis, NNLO [81]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [82]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [82]
JR	0.1124 ± 0.0020	dynamical approach [83]
JR	0.1158 ± 0.0035	standard fit [83]
MSTW	0.1171 ± 0.0014	[84]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [85]
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^{3}LO [80]
world average	0.1184 ± 0.0007	[86]

~1% prec.

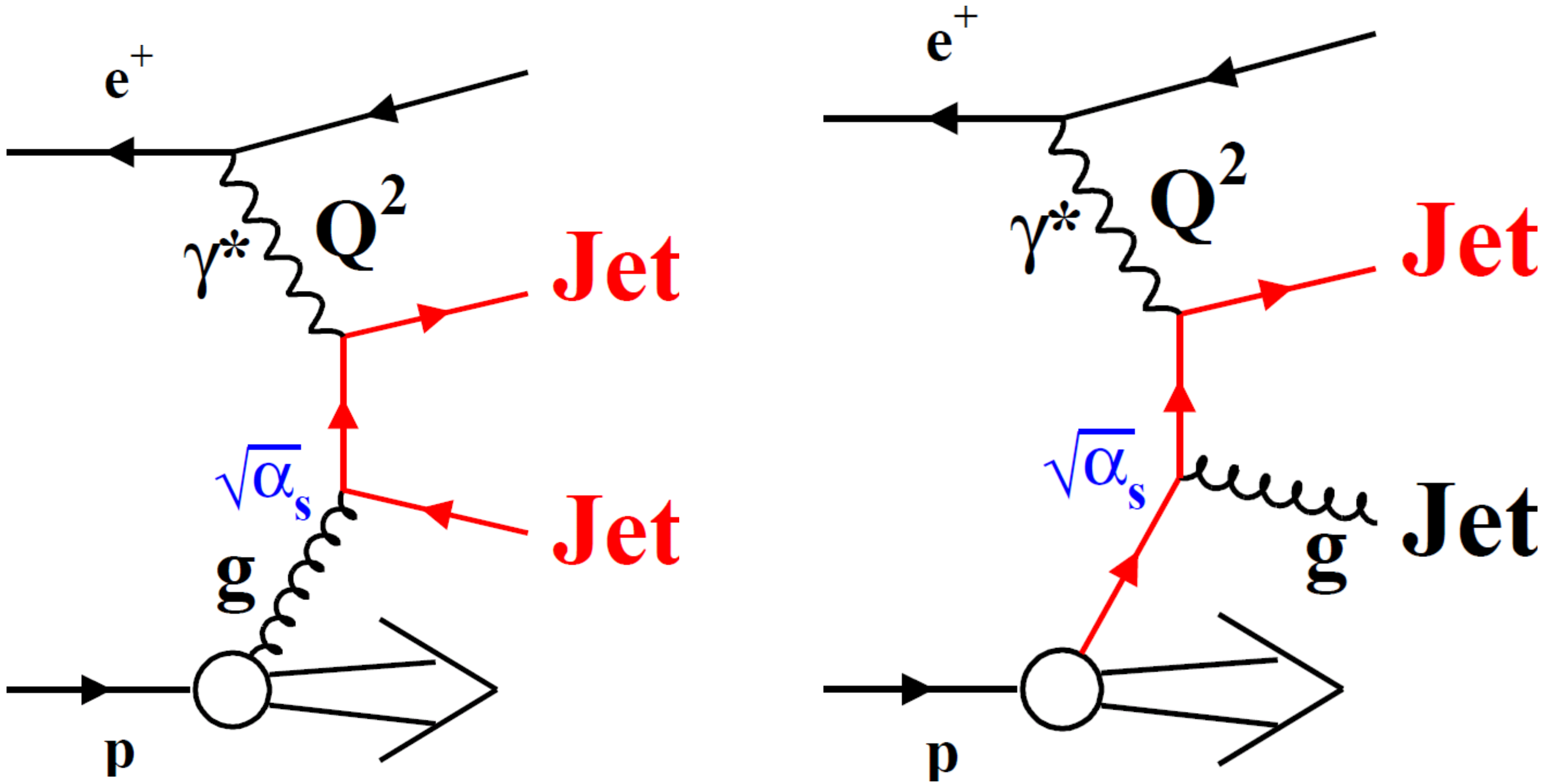
HERA + LHeC

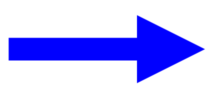
case	cut [Q^2 in GeV^2]	α_S	±uncertainty	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

~0.1% precision

2. Measurements @LHeC with hadronic final states: Jets and Heavy flavours

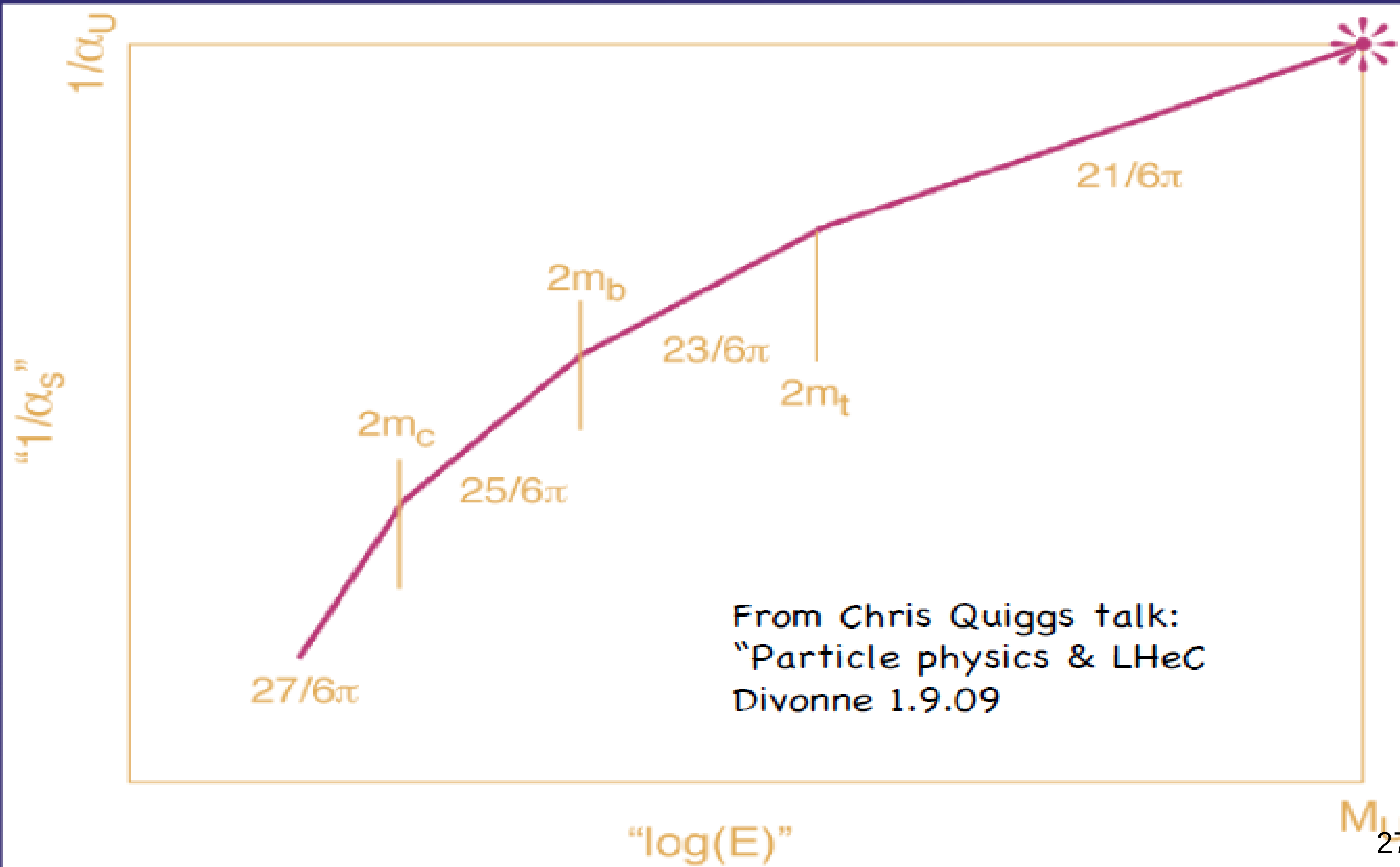
High pt Jets



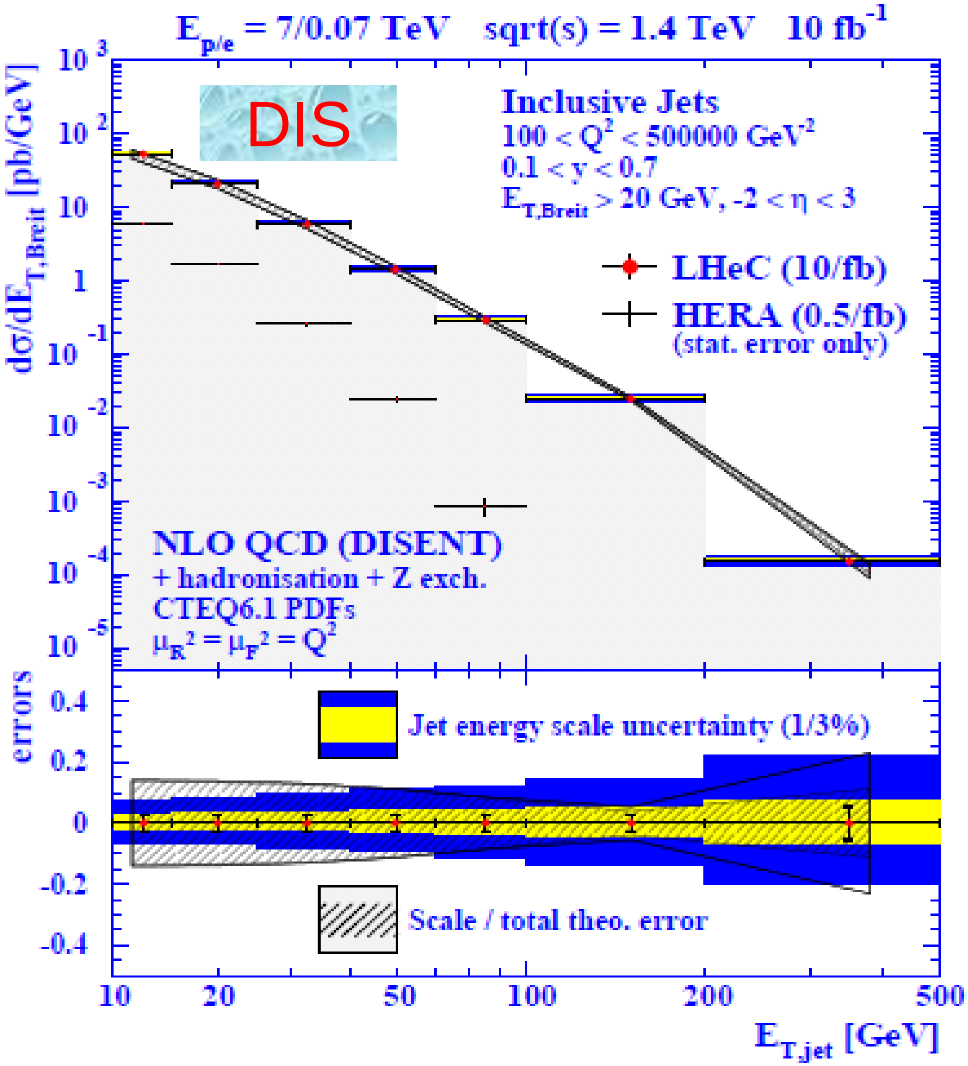


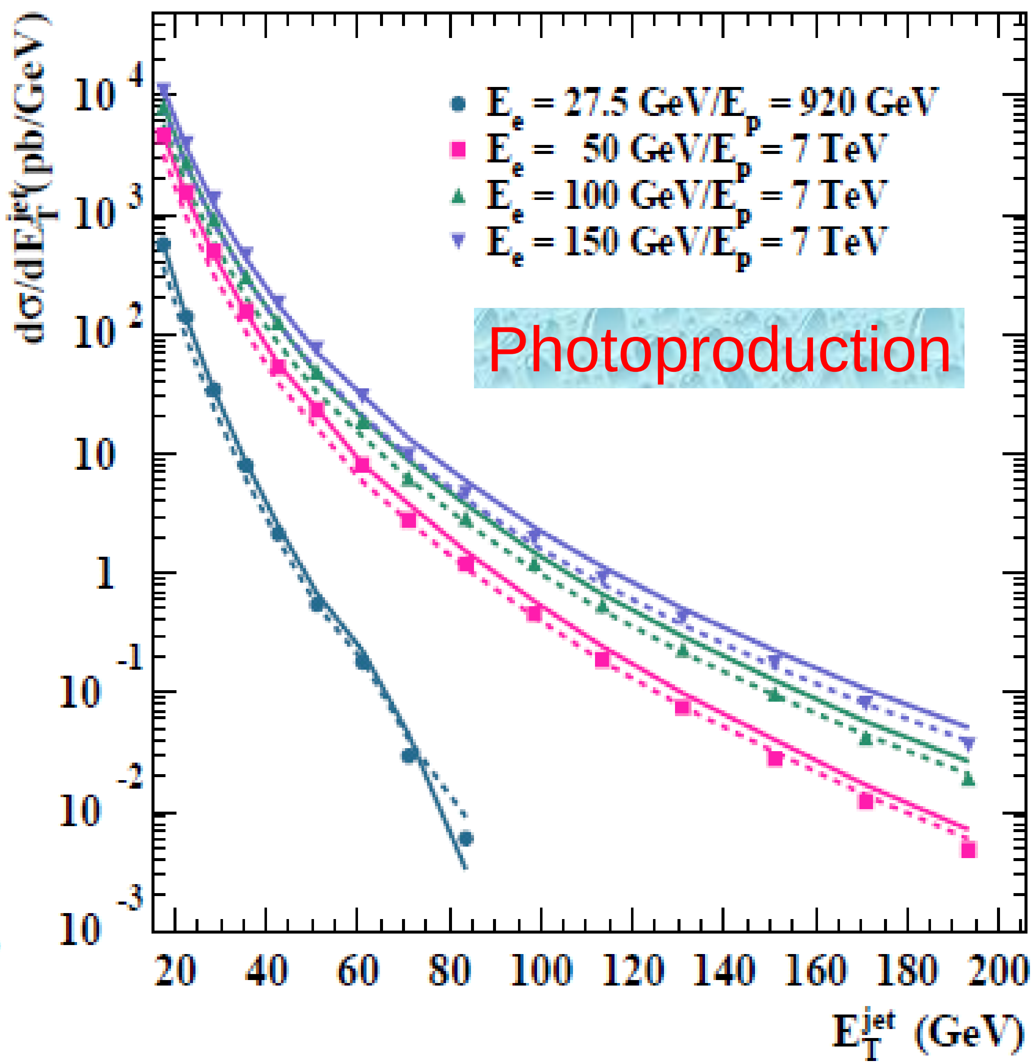
Different processes allow to disentangle g(x) and α_s

Measure change in slope at top threshold?



Jet production





→ study running of α_s up to 500 GeV

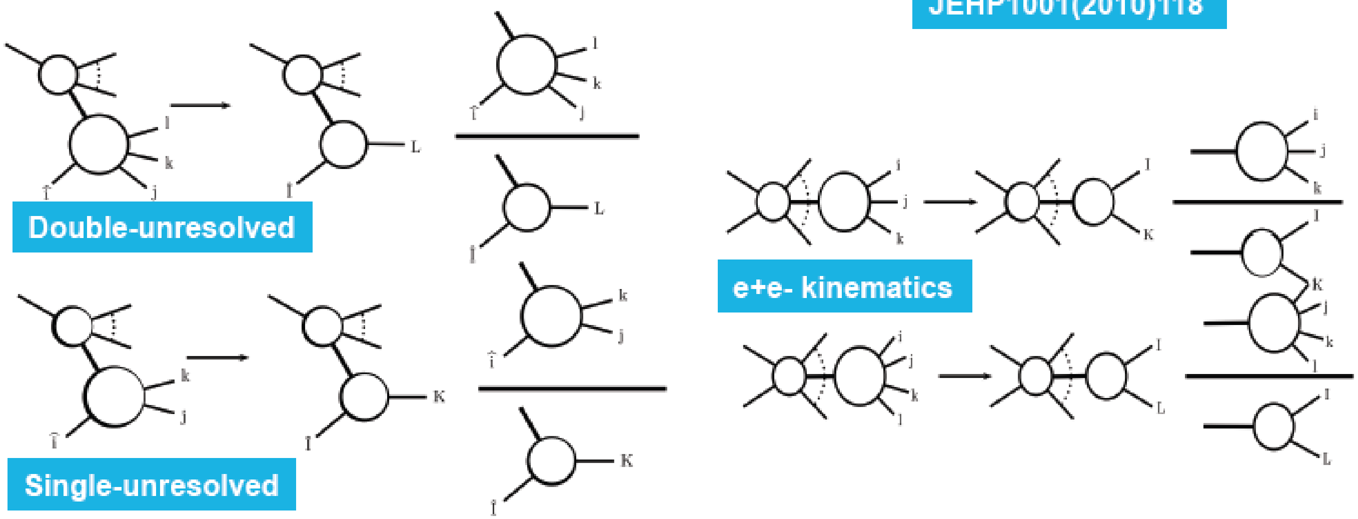
NNLO THEORY (T. Gehrmann et al.) $O(\alpha_s^3)$

- NNLO calculations are ongoing. Matrix elements are either
  - already derived (NLO corrections to 3-jet production in DIS, Z. Nagy, NLOJET++) or
  - Contained in work by Gehrmann/Glover (for the two-loop 2-parton final state).

PLB676(2009)146

- Required: subtraction method!
  - Gehrmann et al.: antenna subtraction method (for DIS).

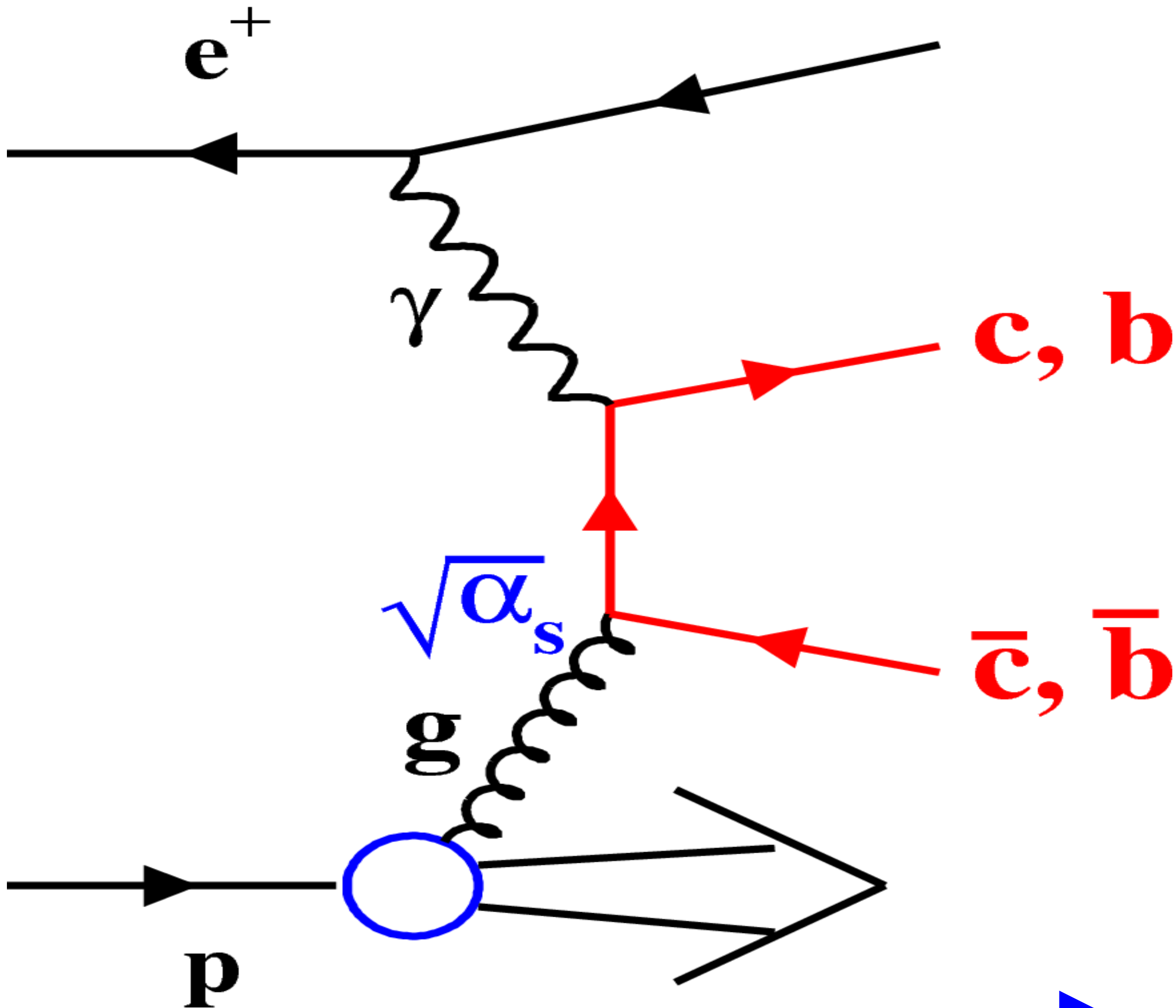
JHEP0704*2007)016
JEHP1001(2010)118



- Currently implementing method into program for DIS jet production.

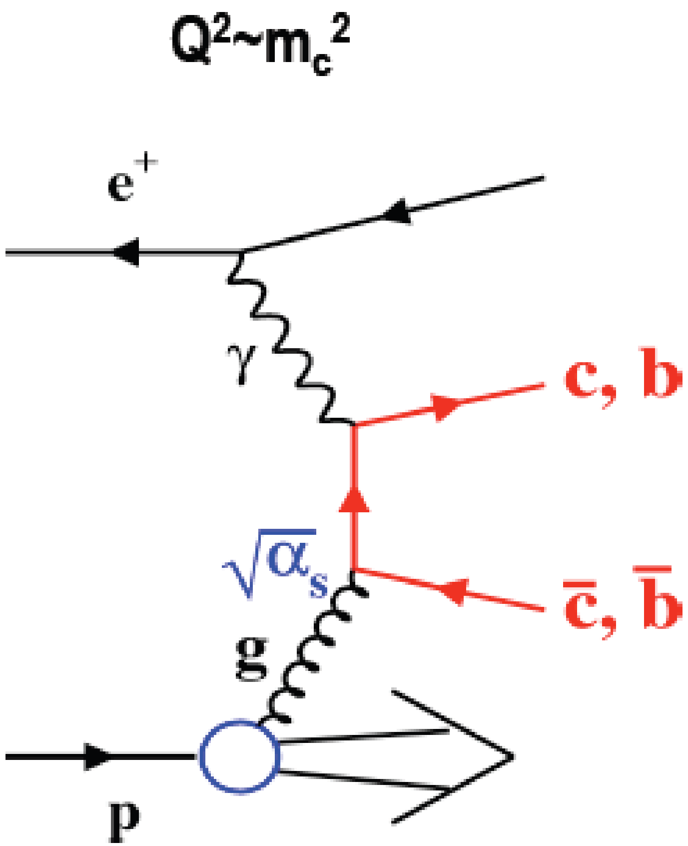
Will reduce significantly theory (higher order) uncertainty for α_s extraction from jet data

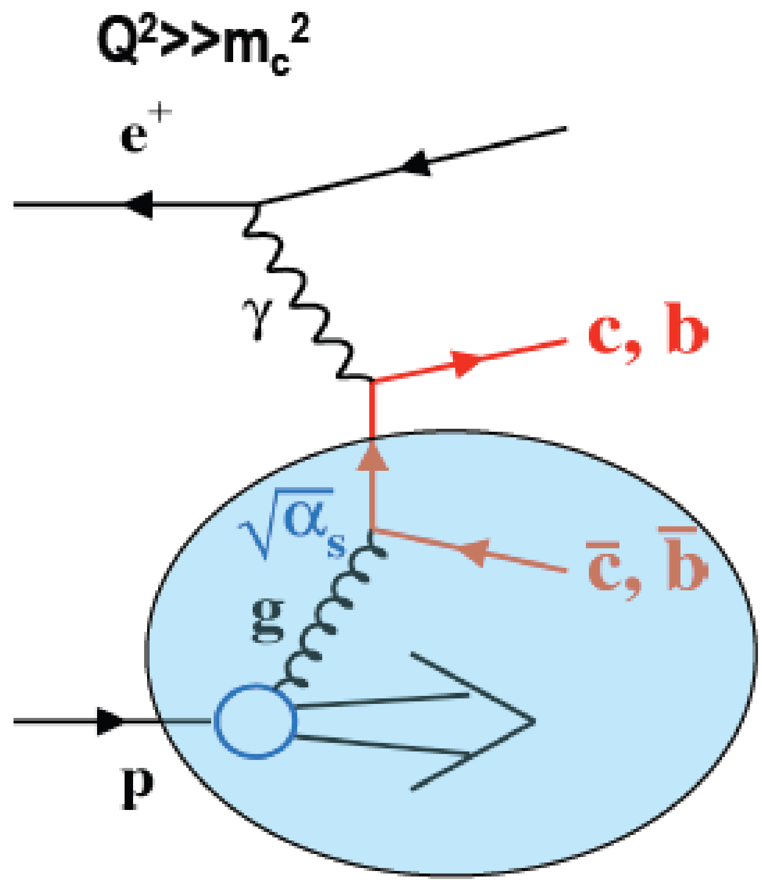
Charm and Beauty



sensitive to g(x)

Subtle topic: heavy quark mass dependent terms in pQCD

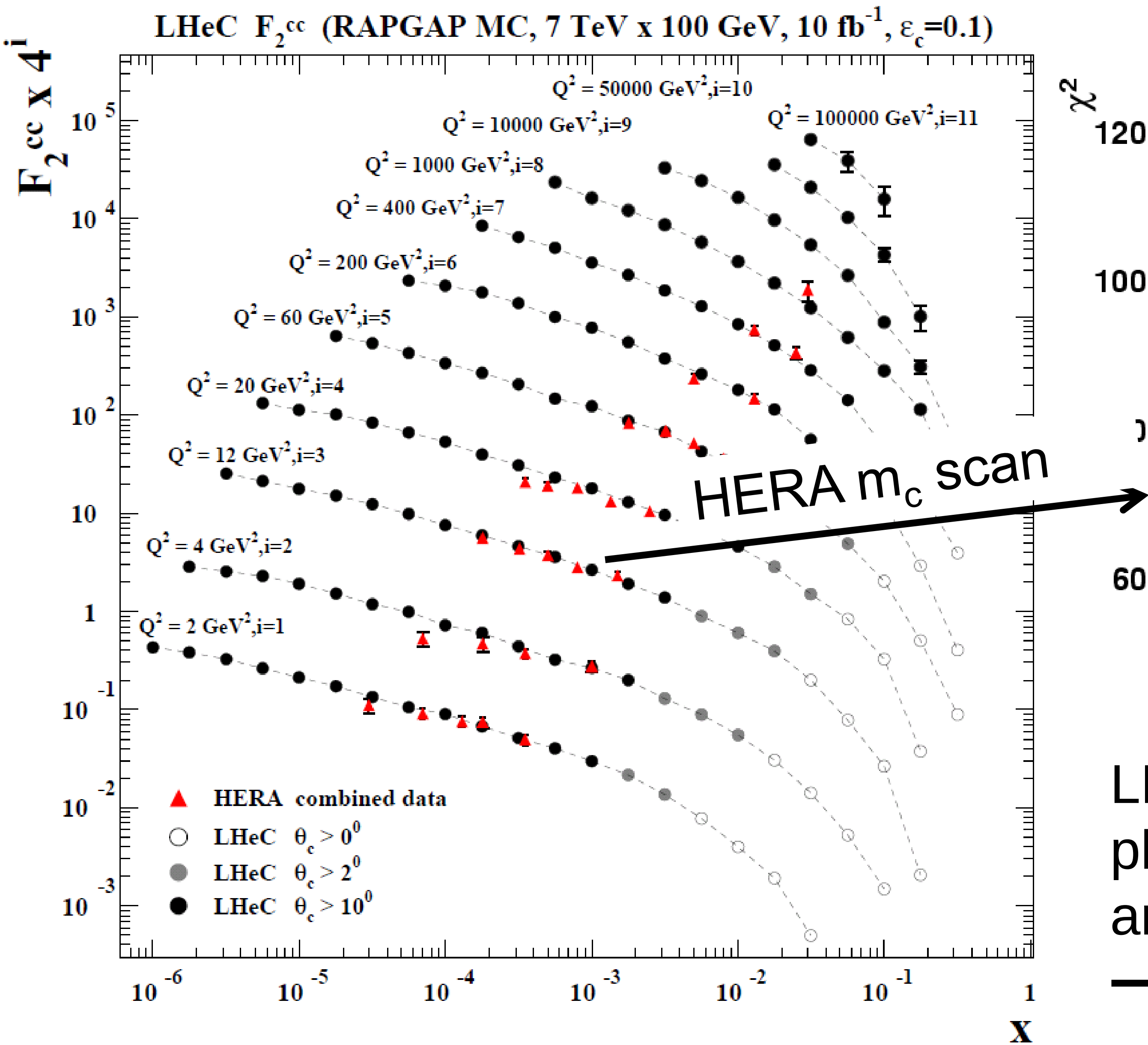


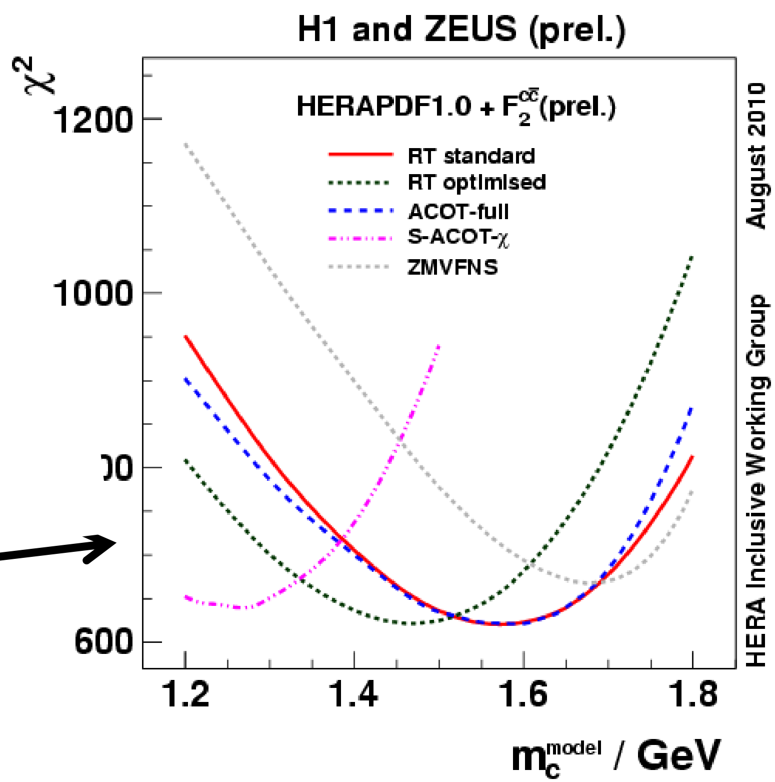


c,b = massless seaquarks

→ How to make properly the transition from left to right picture is a longstanding problem **for PDF fits**

Charm production contribution to $F_2 = F_2^{cc}$

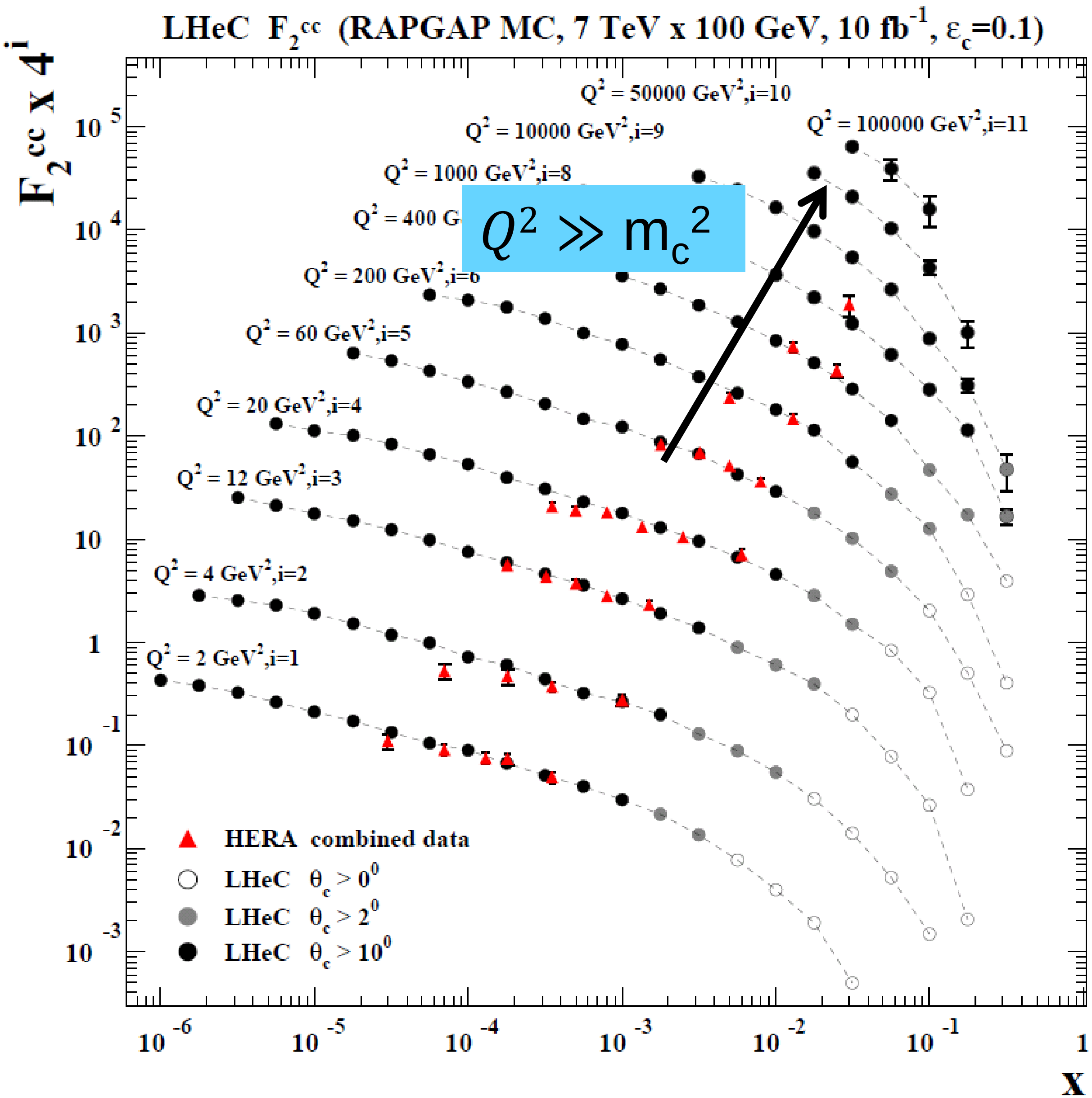




LHeC: Huge phasespace extension and high precision

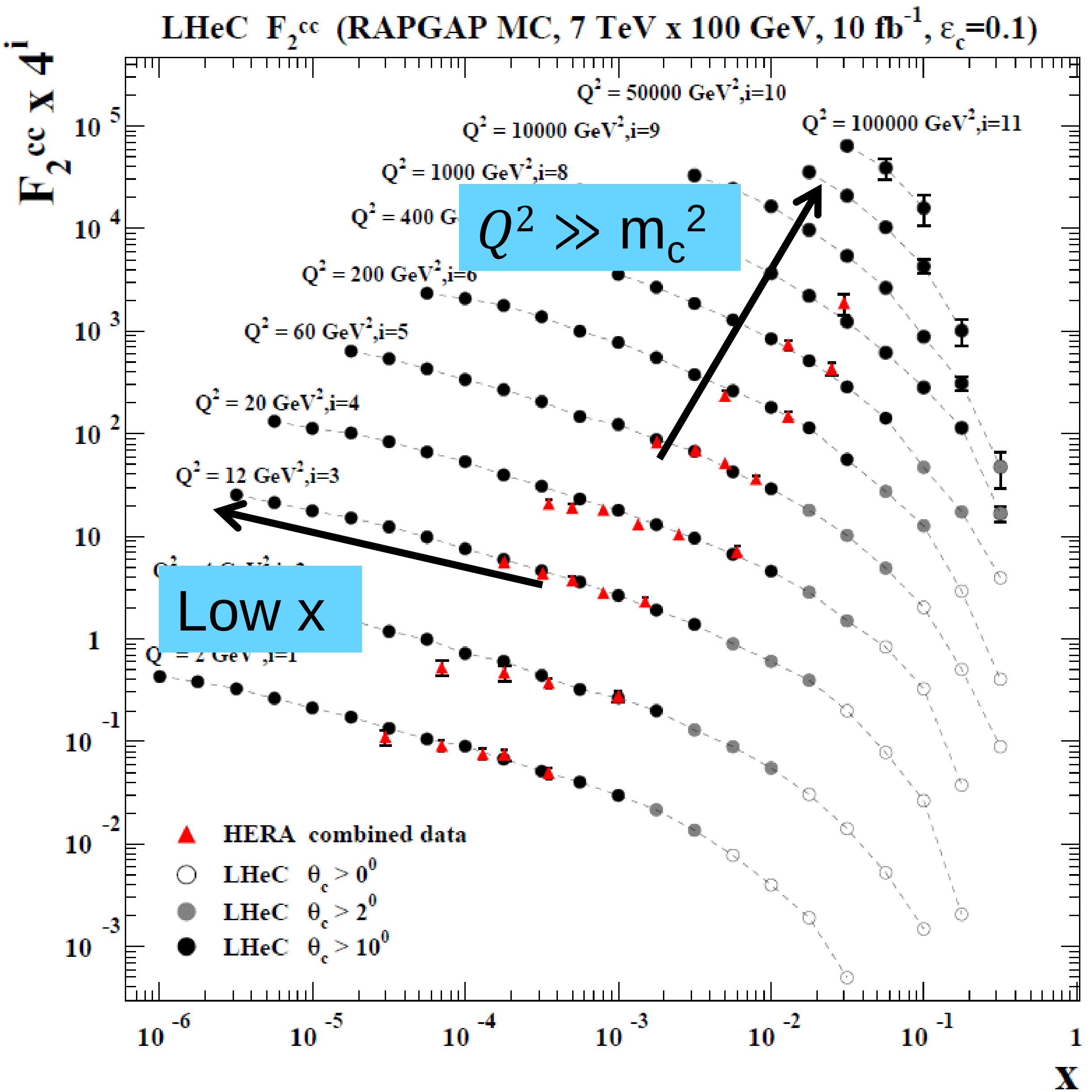
⟶ ultraprecise m_c

Charm production contribution to $F_2 = F_2^{cc}$



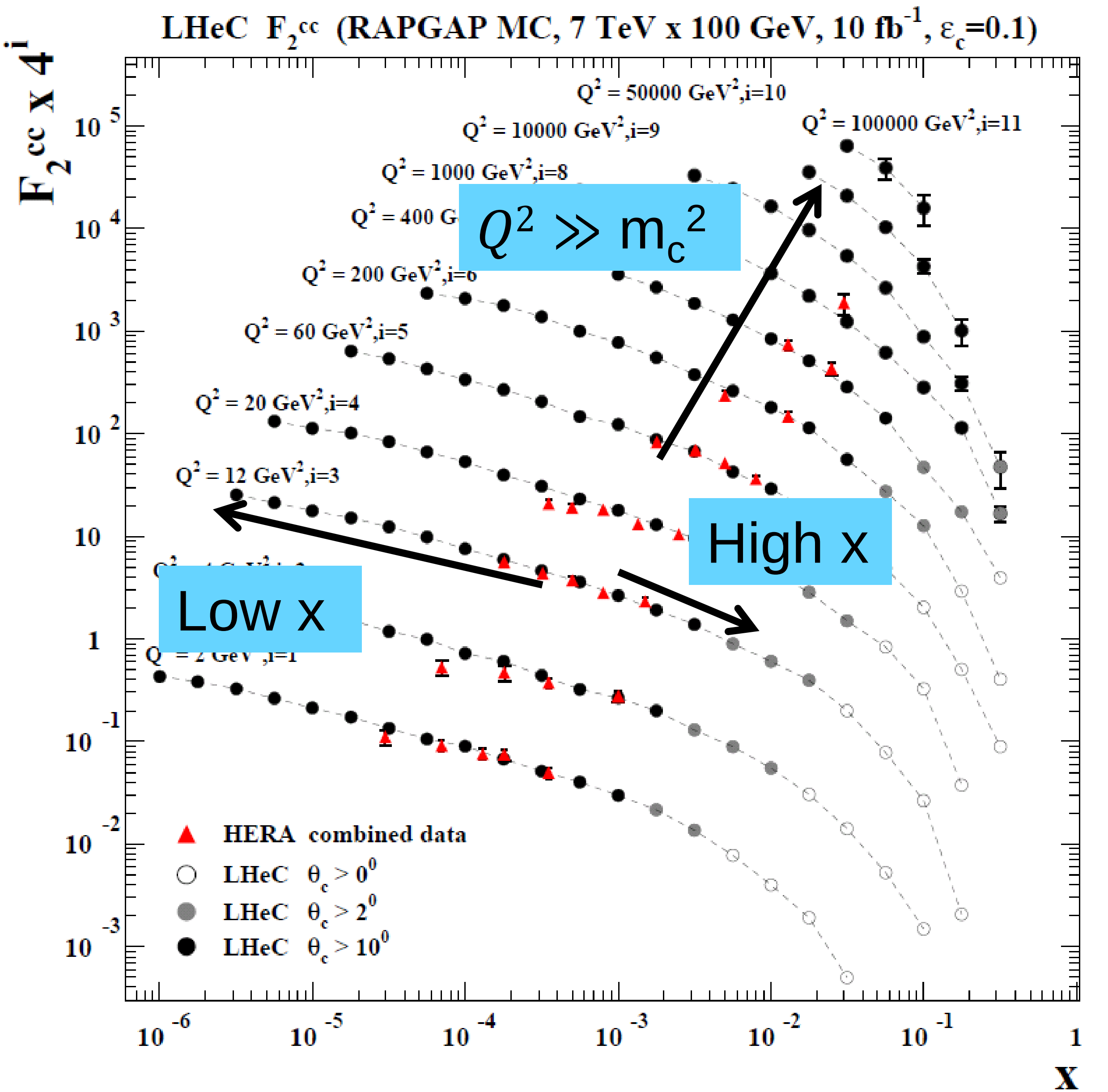
LHeC: Huge phasespace extension and high precision

Charm production contribution to $F_2 = F_2^{cc}$



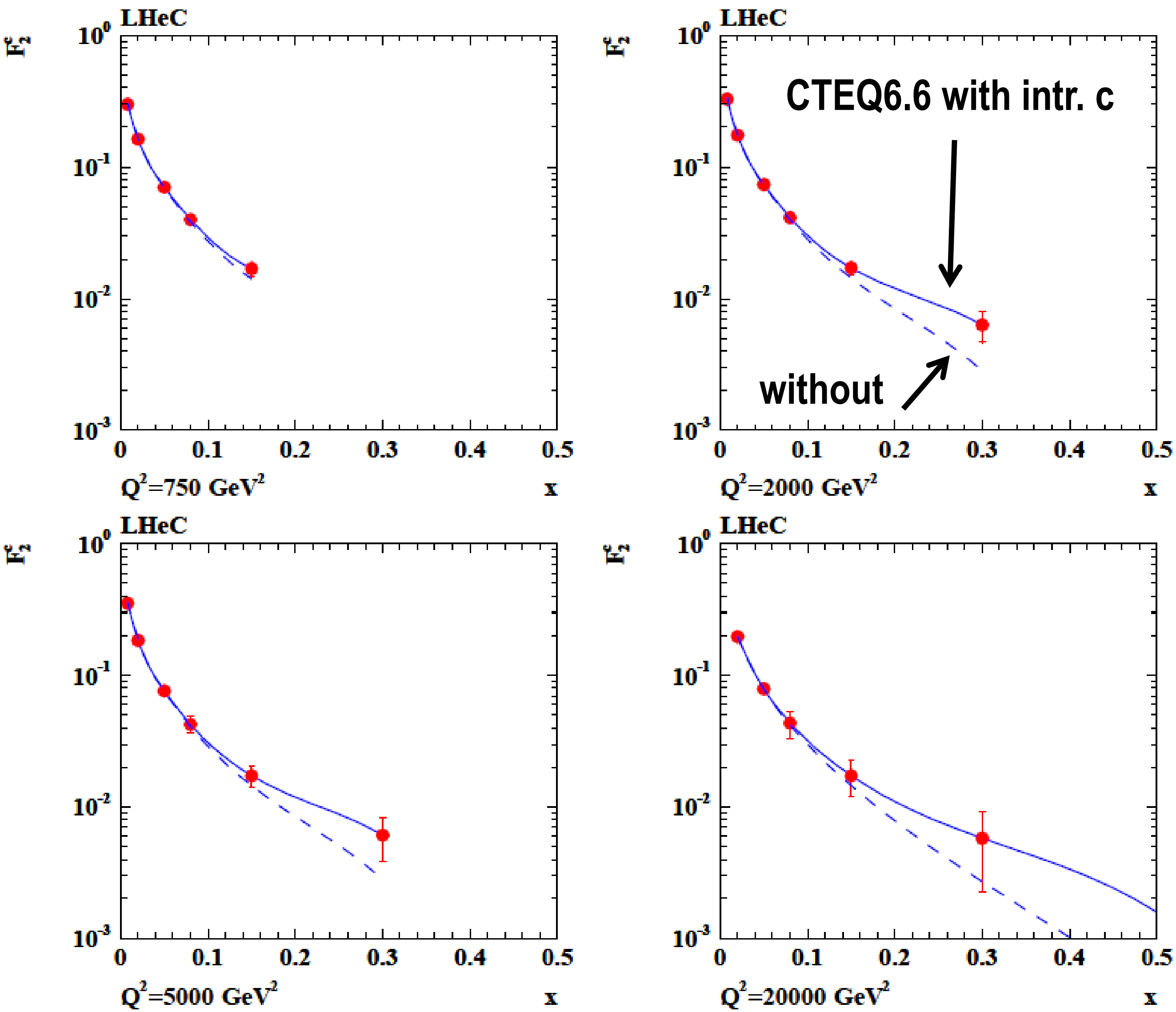
LHeC: Huge phasespace extension and high precision

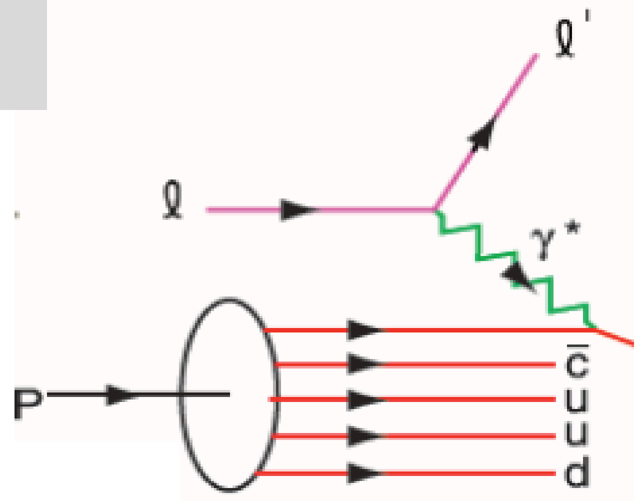
Charm production contribution to $F_2 = F_2^{cc}$



LHeC: Huge phasespace extension and high precision

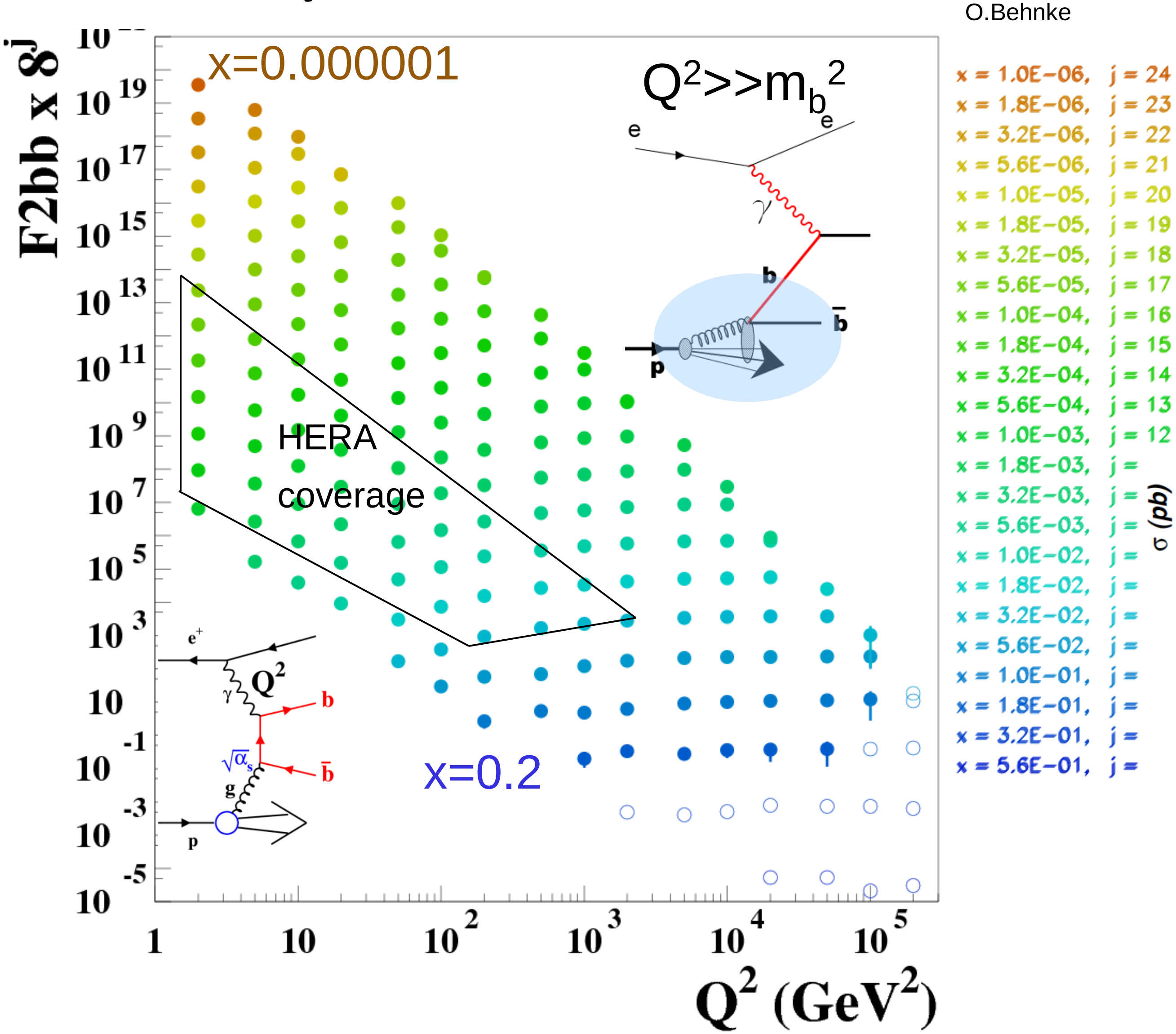
Test intrinsic charm in proton



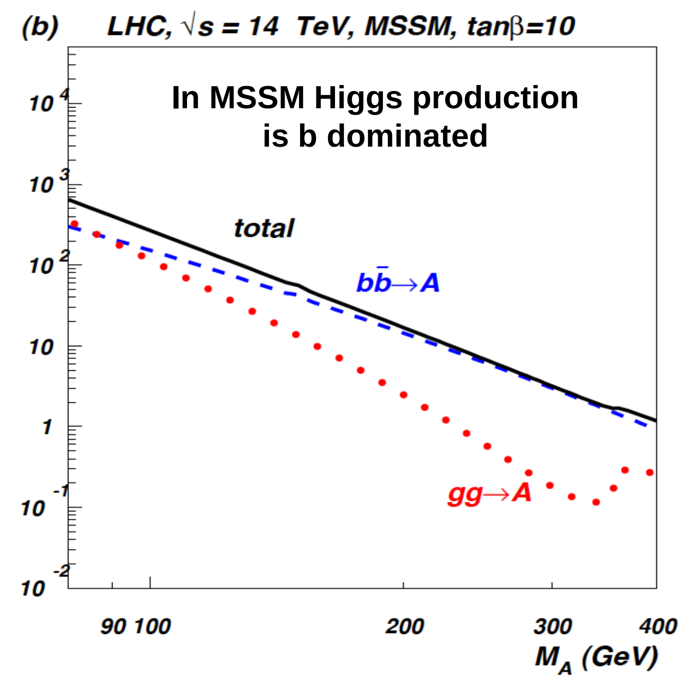


➡ Have some sensitiviy (with excellent forward c-tagging)

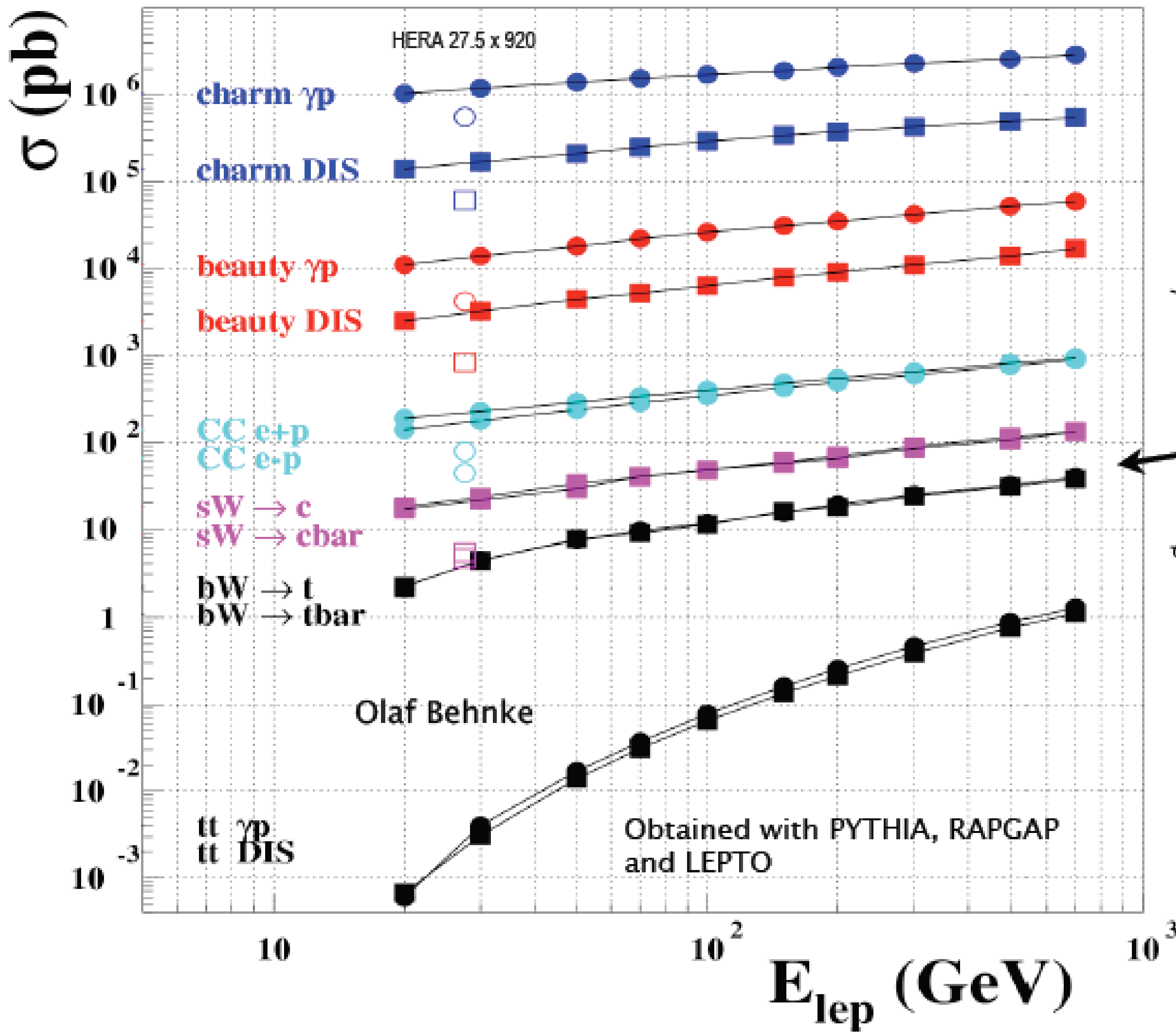
Beauty in DIS: → determine b-density in proton

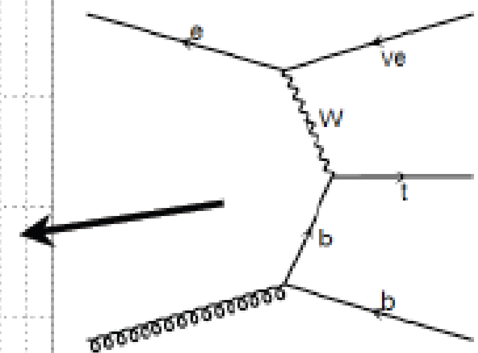


Use for LHC predictions



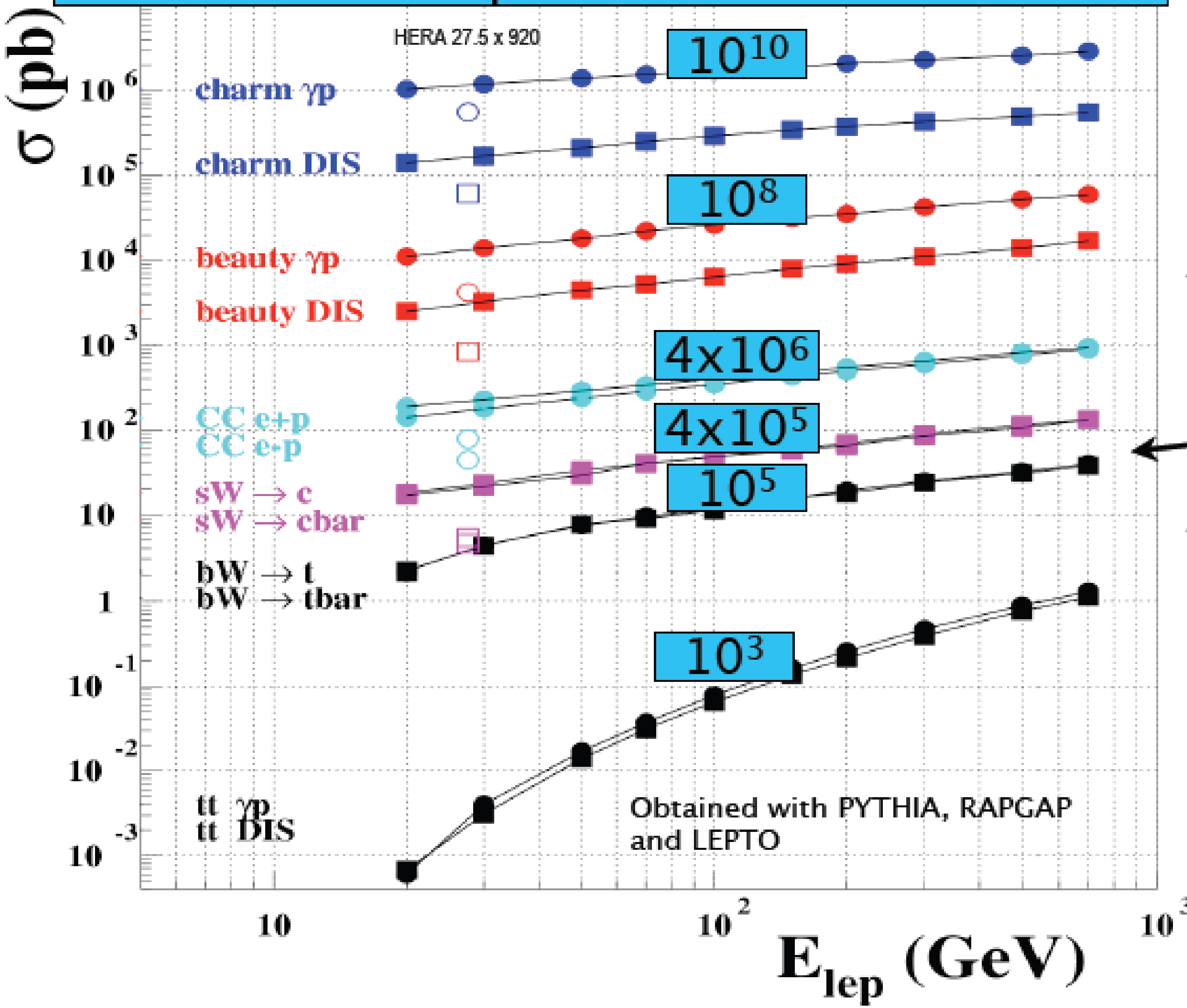
LHeC total cross sections (MC simulated)

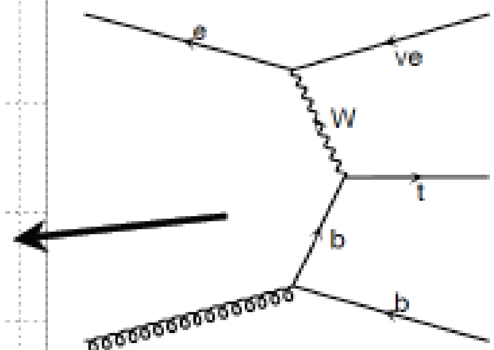




LHeC is a flavour factory

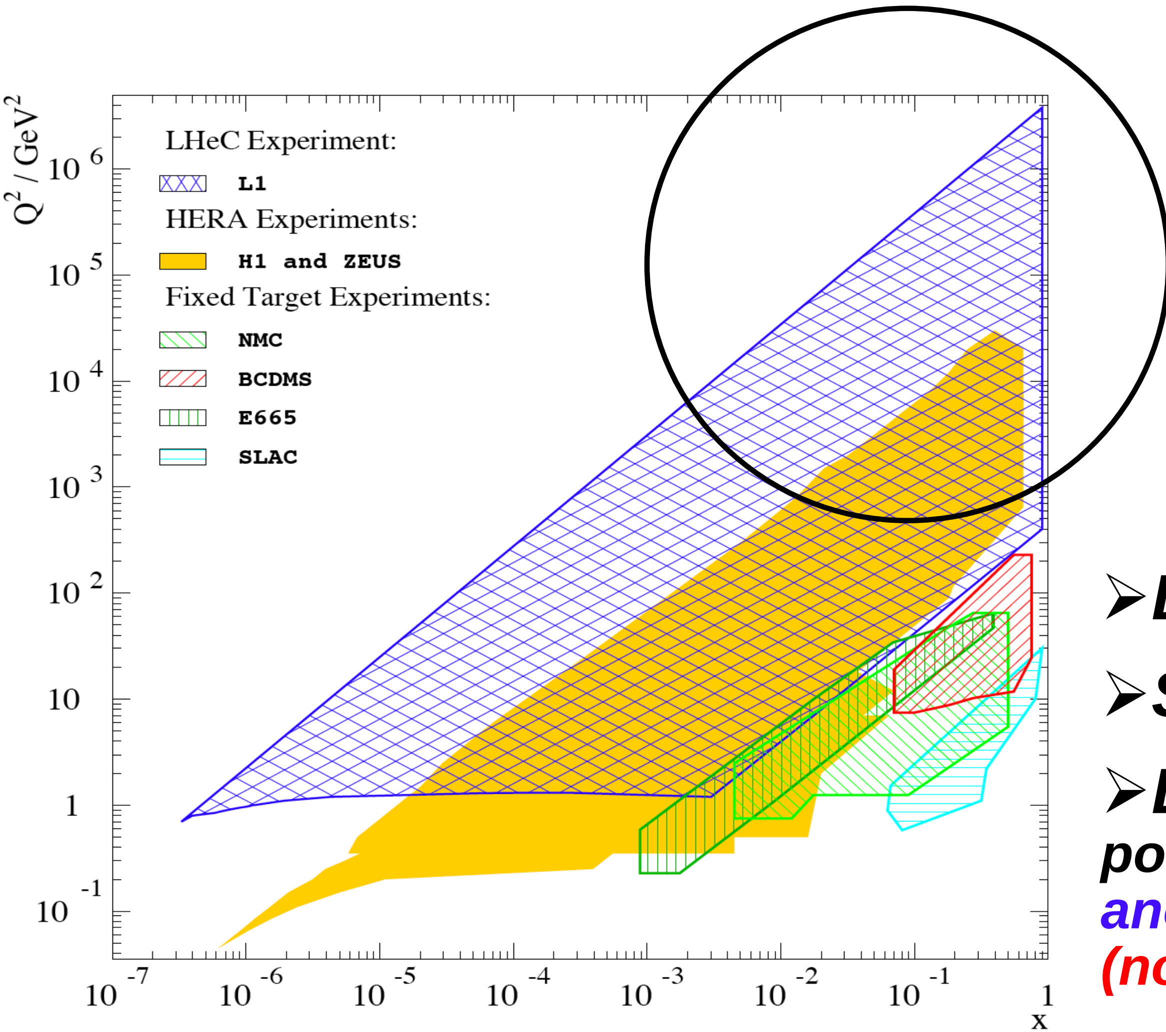
Events per 10 fb-1 Lumi





LHeC is a flavour factory

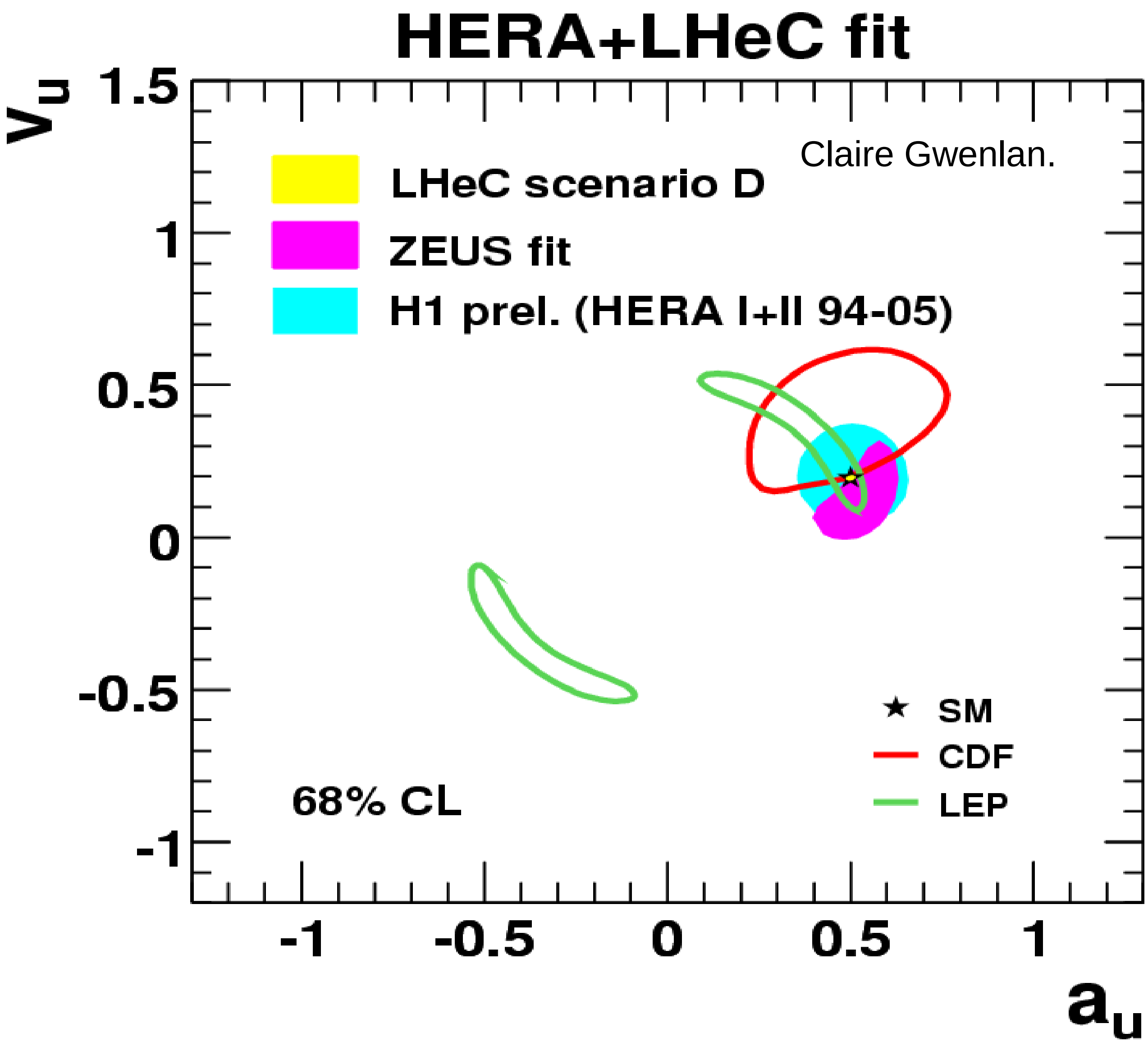
3. SM electroweak and new physics at the high energy frontier

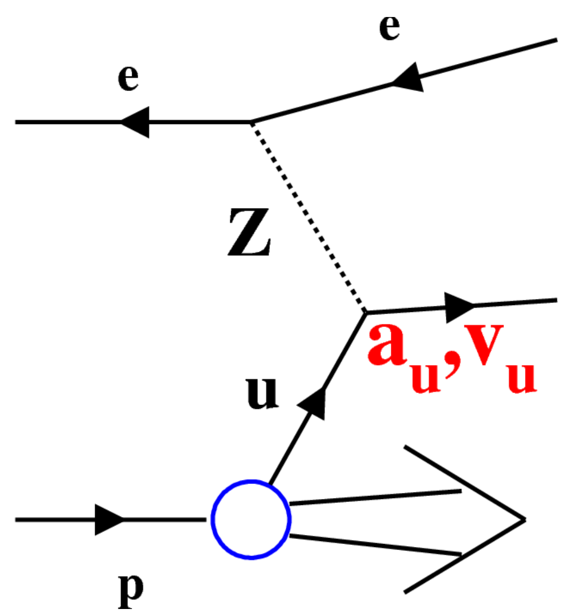


- ***Light quark couplings to Z***
- ***SM Higgs production***
- ***Leptoquarks** + many other possibilities, e.g. excited leptons, anomalous single top production, etc.*

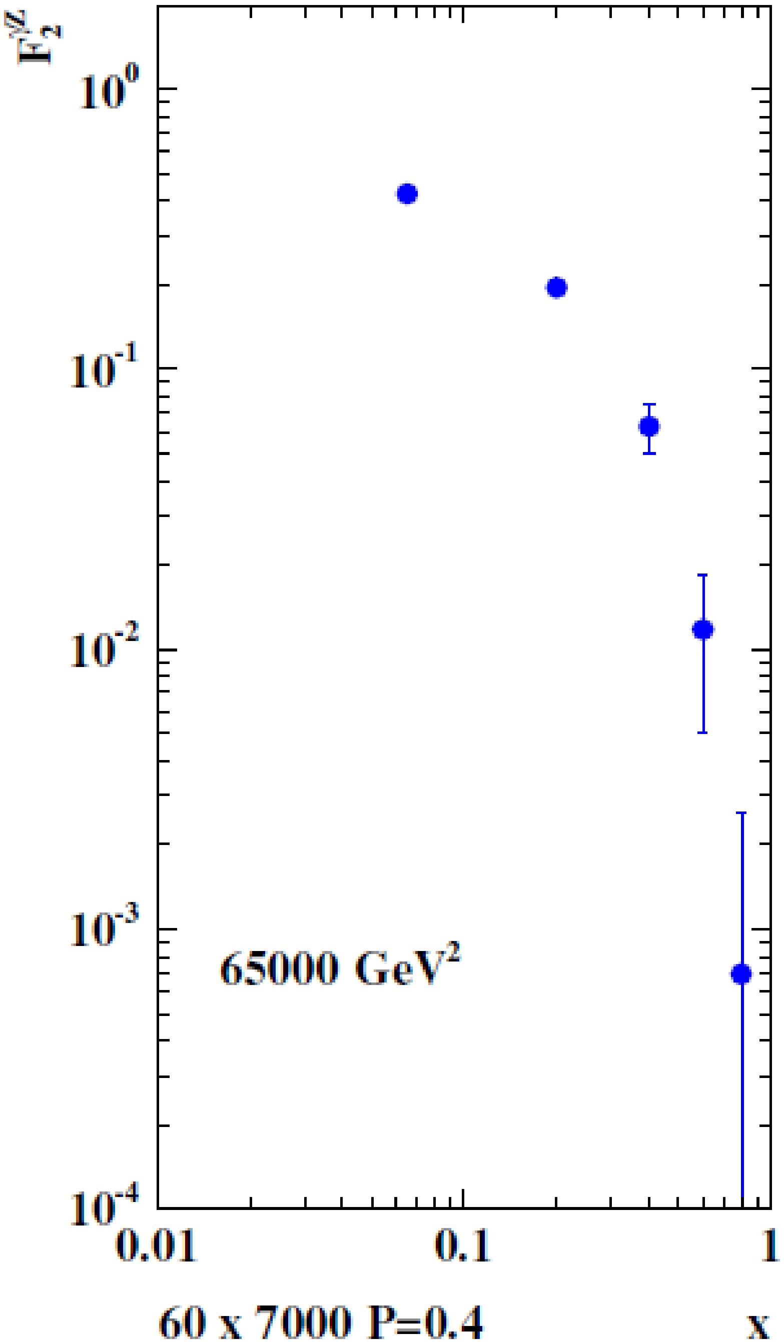
(not further discussed in this talk)

Fermion couplings to Z boson





LHeC could measure u and d couplings with ~1% precision



Parity violating Neutral Current **polarisation** asymmetries

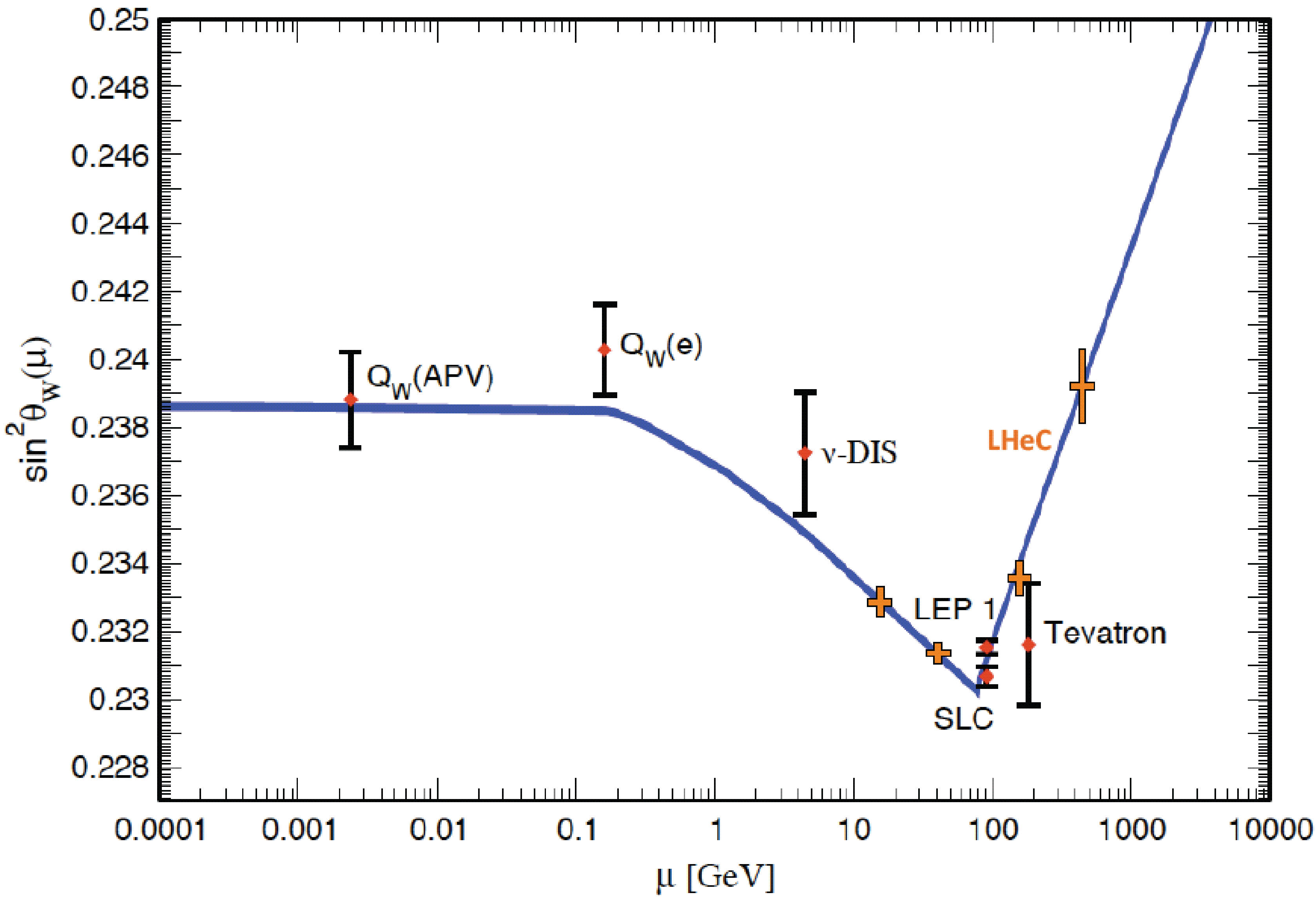
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2} \cdot \frac{1}{4 \sin^2 \Theta \cos^2 \Theta}$$

→ Determine $\sin^2 \theta_W$

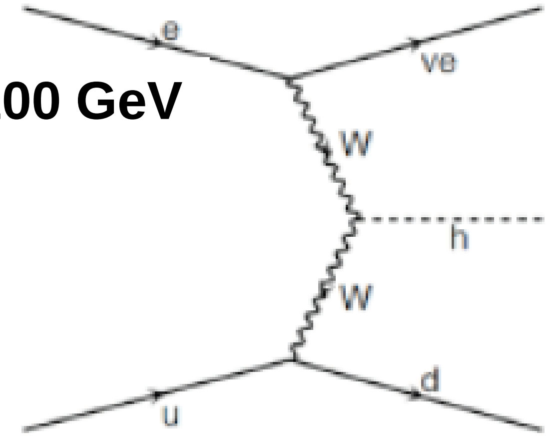
Running $\sin^2\theta_W(\mu)$



Higgs production at LHeC

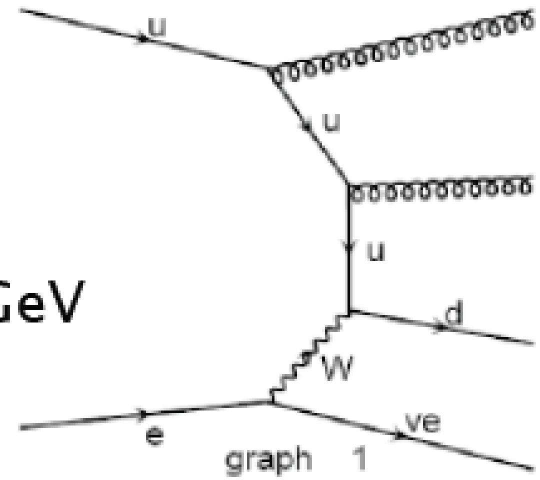
Dominating process

100 GeV



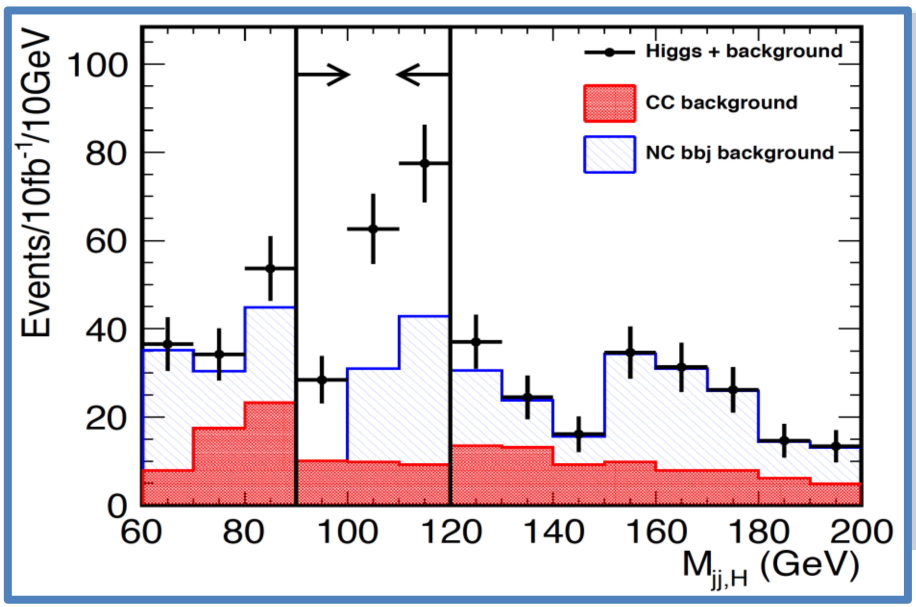
σ~160 pb
for mH=120 GeV

Beware of backgrounds



+ many many others

Motivation: Measure H→bb coupling



+ Unambigious HWW coupling

Excellent b tagging needed to suppress large backgrounds

Summary

The LHeC has potential to completely unfold the partonic content of the proton: u,d, c,s, t,b for the first time and in an unprecedent kinematic range. This is based on inclusive NC, CC cross sections complemented by heavy quark identification.

Puzzles as strange-antistrange asymmetry or u/d at large x will be solved.

Precision measurements are possible of xg (up to large x) and the beauty density which are of particular relevance for the LHC. The (almost) whole p structure which the LHC assumes to know will become accurately known.

Determine α_s with permille level precision

Wealth of QCD tests with final states: Jets (running α_s, test of higher orders, proton and photon structure), heavy flavours (mass terms in PQCD) , not discussed here: prompt photons, other identified particles

Low x and diffractive physics with ep and eA: See following talk by Anna Stasto

Electroweak and new physics
- **Light quark couplings to Z at ~1% level**
- **SM Higgs production for H-> bb coupling**
- **New physics: Leptoquarks and quantum numbers, quark radius, leptons* and more!**

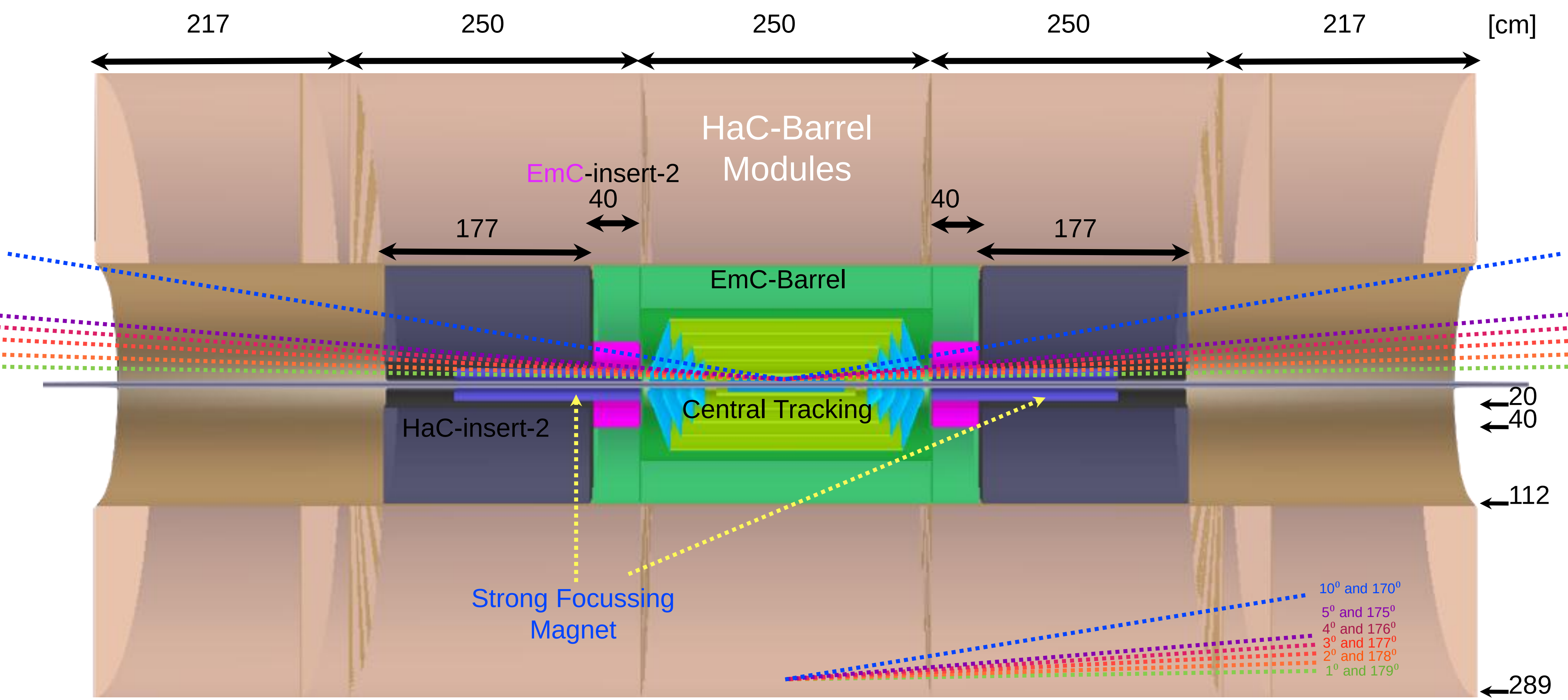
Physics summary - artistic view

Title plot from Conceptional Design Report

Backup slides

The High Lumi (High Q²) Setup

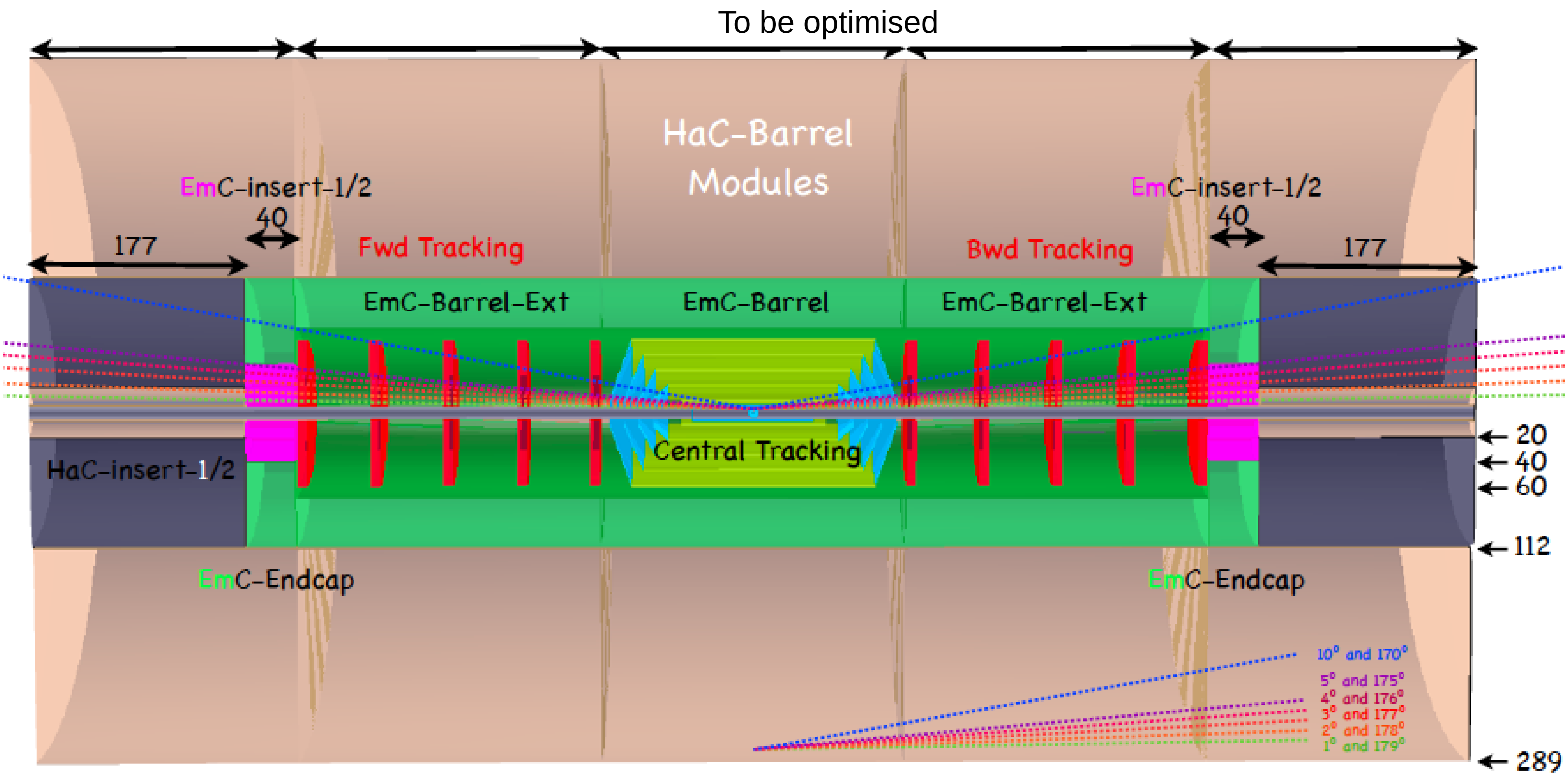
(to be optimised)



L1 Low Q² SetUp → High Q² SetUp

- Fwd/Bwd Tracking & EmC-Extensions, HaC-Insert-1 removed
- Calo-Inserts in position
- Strong Focussing Magnet installed

The Detector ‘that should do it’: - Low Lumi (Low Q^2) Setup

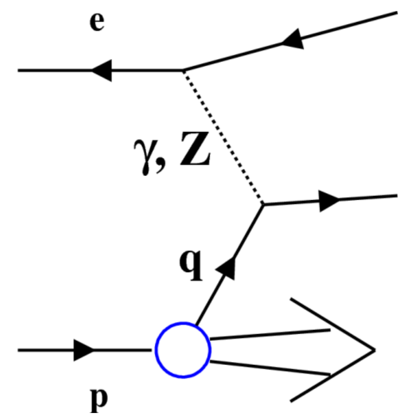


- Solenoid surrounding the HAC modules

-Outer detectors (HAC tailcatcher/muon detectors not shown)

to be discussed: very forward detector setup (proton taggers)

Master formulae for NC DIS



$$\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dx dQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_-}\mathbf{F_L}$$

$$\begin{aligned}
\mathbf{F_2^\pm} &= F_2 + \kappa_Z(-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z \\
\mathbf{xF_3^\pm} &= \kappa_Z(\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z
\end{aligned}$$

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

$$F_L(x) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3} F_2(z) + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) zg(z),\right]$$

Vary charge and polarisation and beam energy to disentangle contributions

Charged Currents

$$\sigma_{r,CC} = \frac{2\pi x}{Y_+ G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

$$\sigma_{r,CC}^{\pm} = \frac{1 \pm P}{2}\left(W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm}\right)$$

$$W_2^+ = x(\overline{U} + D),\, xW_3^+ = x(D - \overline{U}),\, W_2^- = x(U + \overline{D}),\, xW_3^- = x(U - \overline{D})$$

$$U = u + c \qquad \overline{U} = \overline{u} + \overline{c} \qquad D = d + s \qquad \overline{D} = \overline{d} + \overline{s}$$

$$\sigma_{r,CC}^{+} \sim x\overline{U} + (1-y)^2 xD,$$
$$\sigma_{r,CC}^{-} \sim xU + (1-y)^2 x\overline{D}$$

$$\sigma_{r,NC}^{\pm} \simeq [c_u(U + \overline{U}) + c_d(D + \overline{D})] + \kappa_Z[d_u(U - \overline{U}) + d_d(D - \overline{D})]$$

with $c_{u,d} = e_{u,d}^2 + \kappa_Z(-v_e \mp P a_e) e_{u,d} v_{u,d}$ and $d_{u,d} = \pm a_e a_{u,d} e_{u,d}$,

Complete unfolding of all parton distributions to unprecedented accuracy

Neutral current cross section **errors** at LHeC:

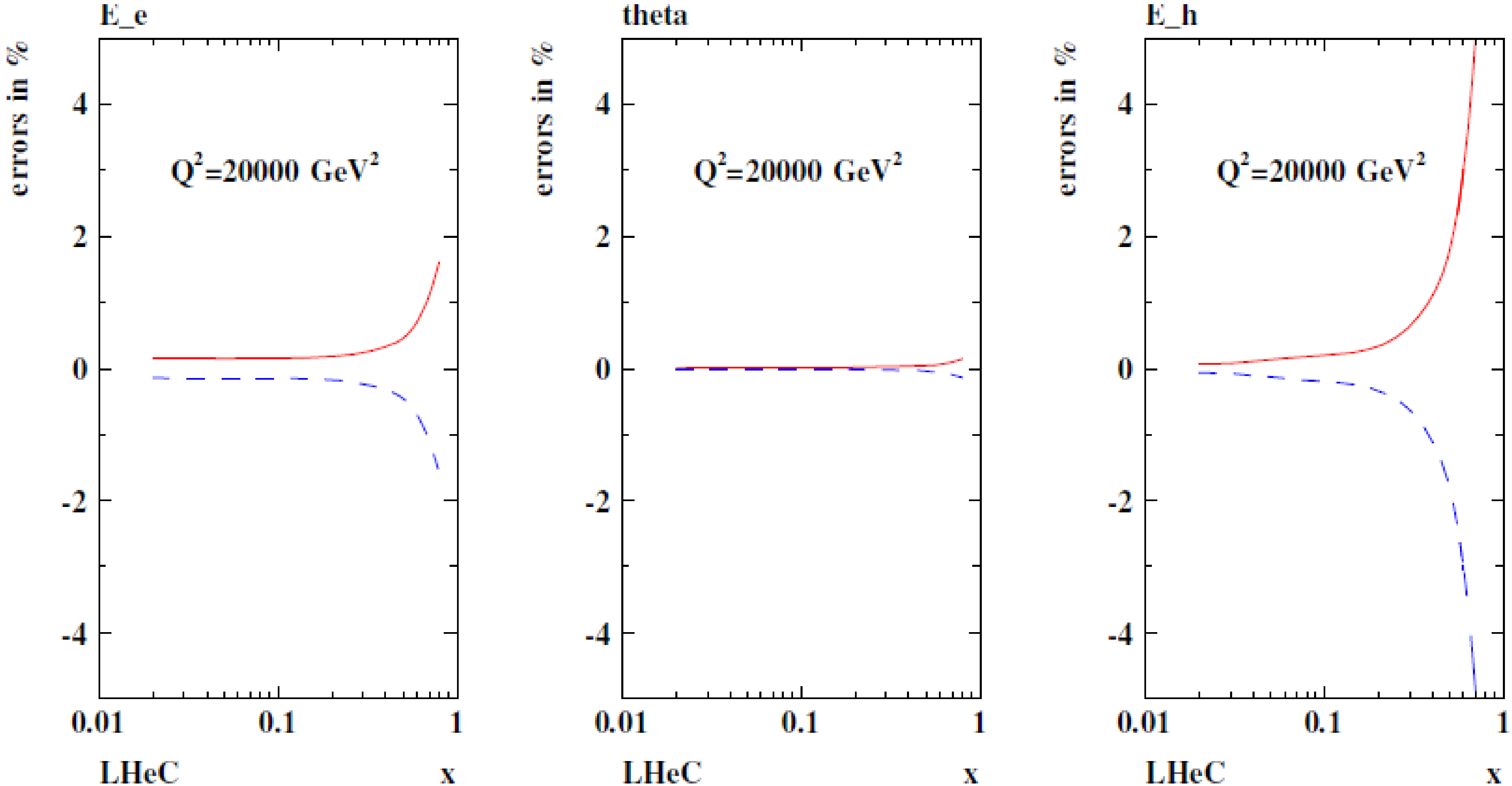
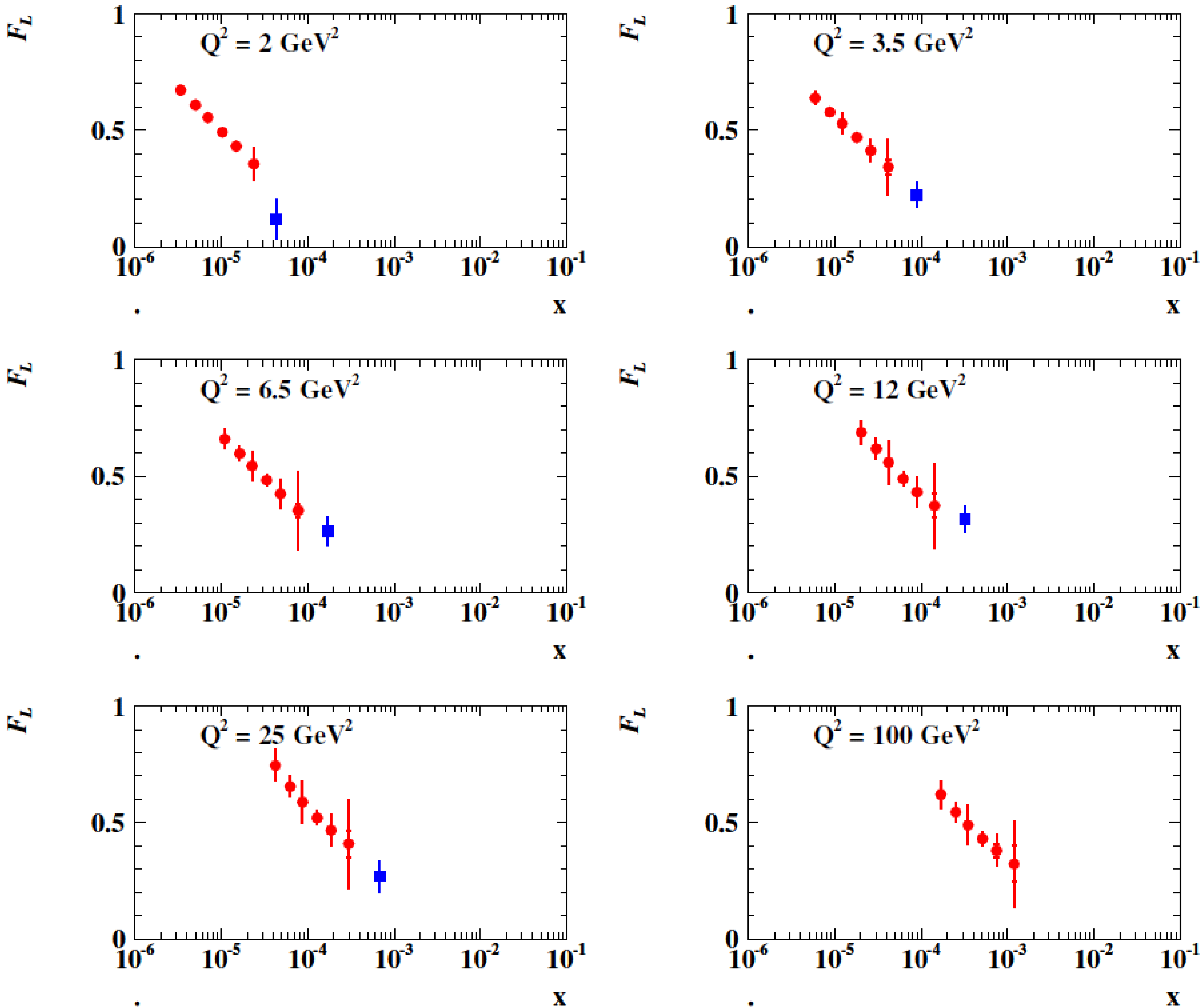
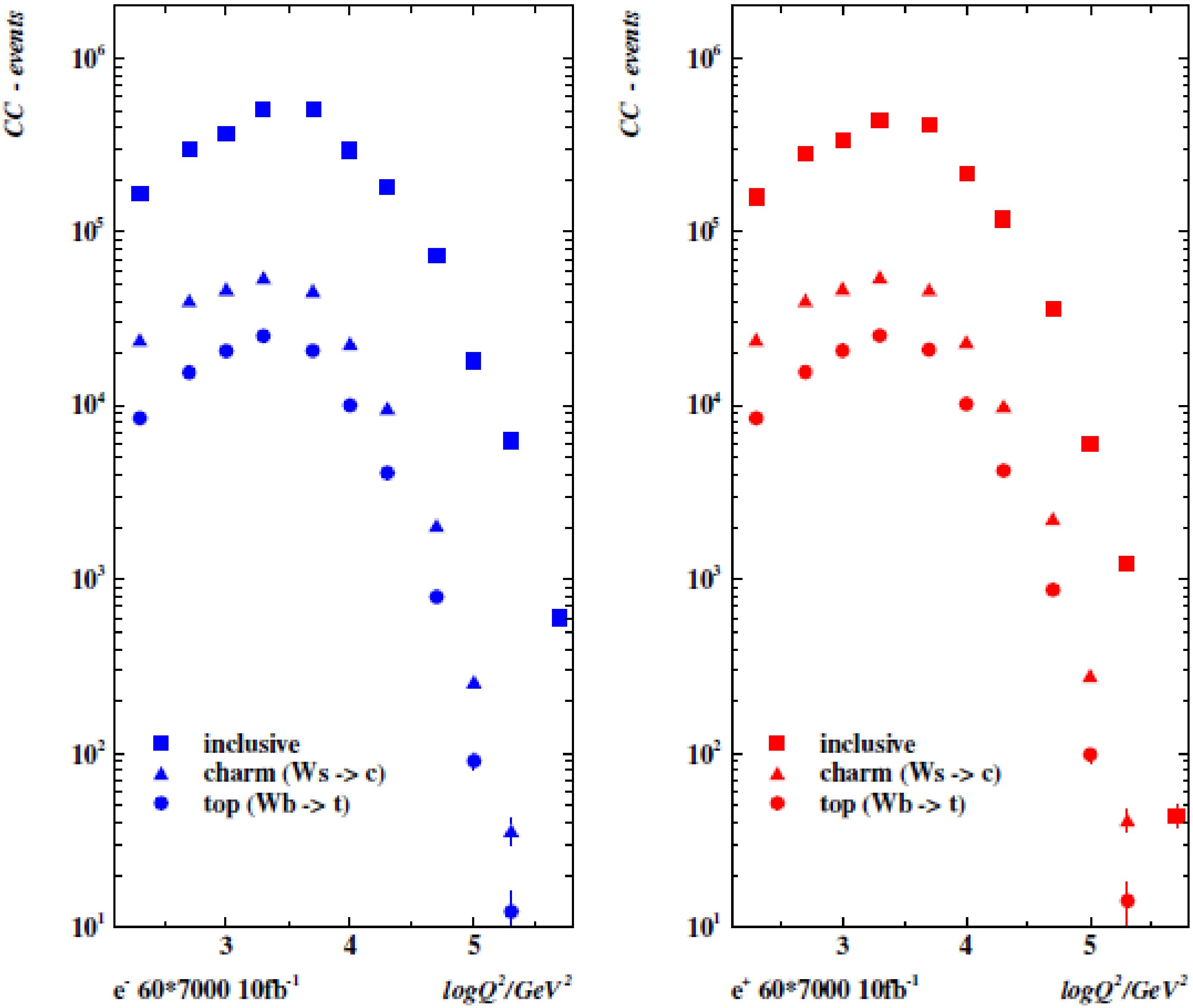


Figure 4.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised $e^- p$ scattering, as result from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic 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.

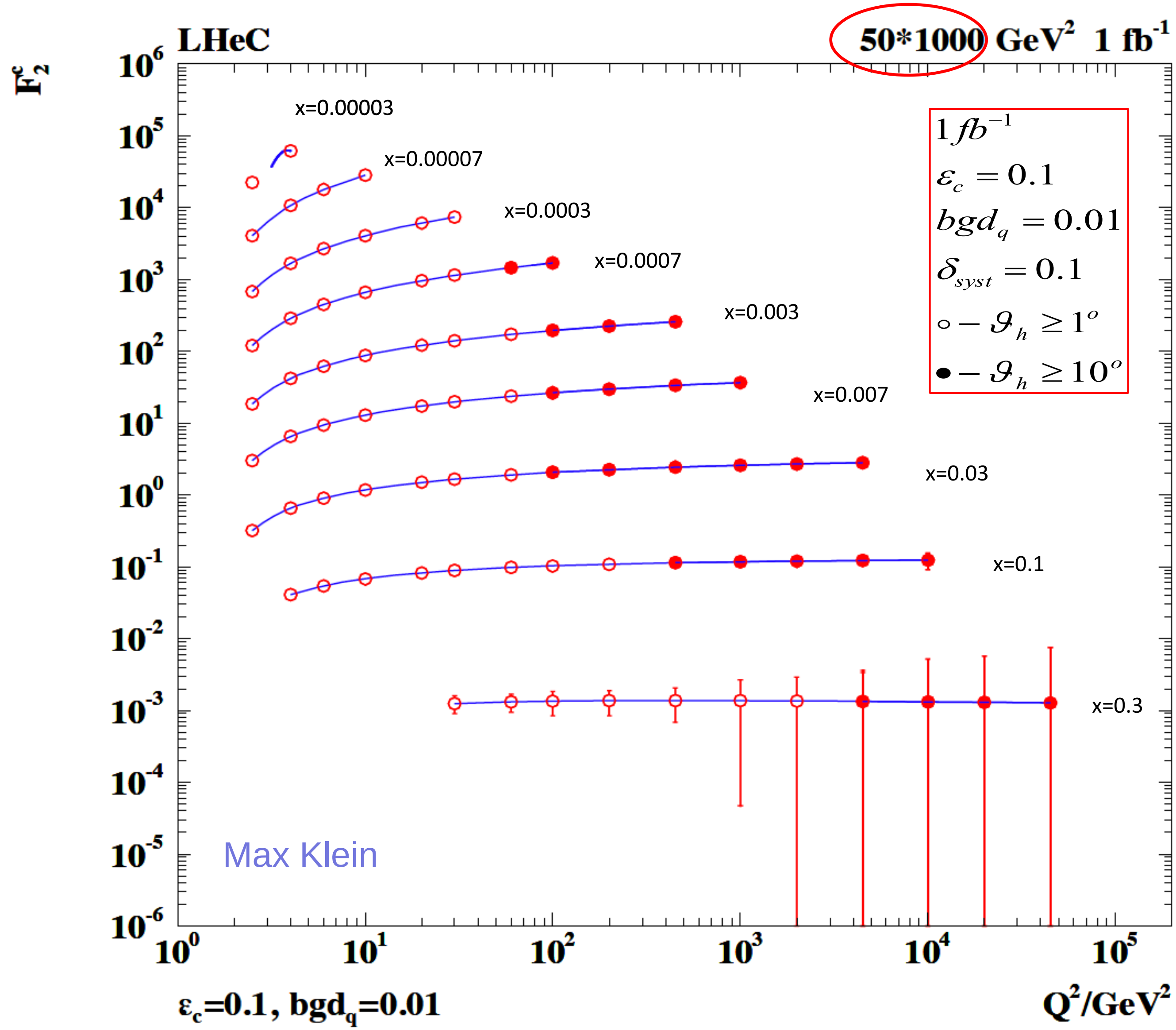
F_L at LHeC

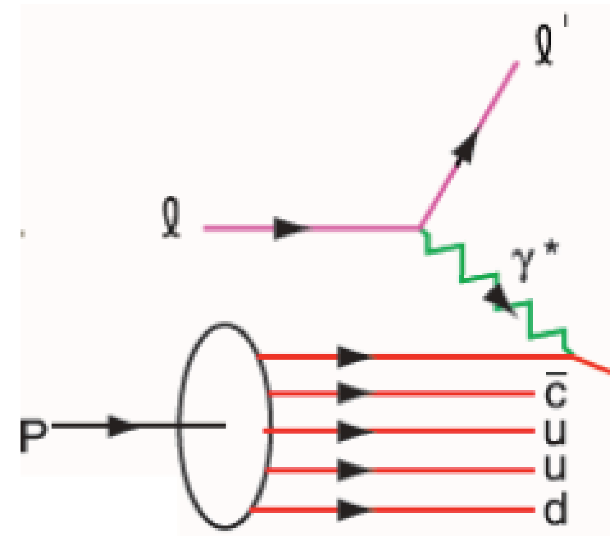

F_L
Q^2 = 2 GeV^2
Q^2 = 3.5 GeV^2
Q^2 = 6.5 GeV^2
Q^2 = 12 GeV^2
Q^2 = 25 GeV^2
Q^2 = 100 GeV^2
x

Charged current processes at LHeC



Charm in DIS: test intrinsic charm in p

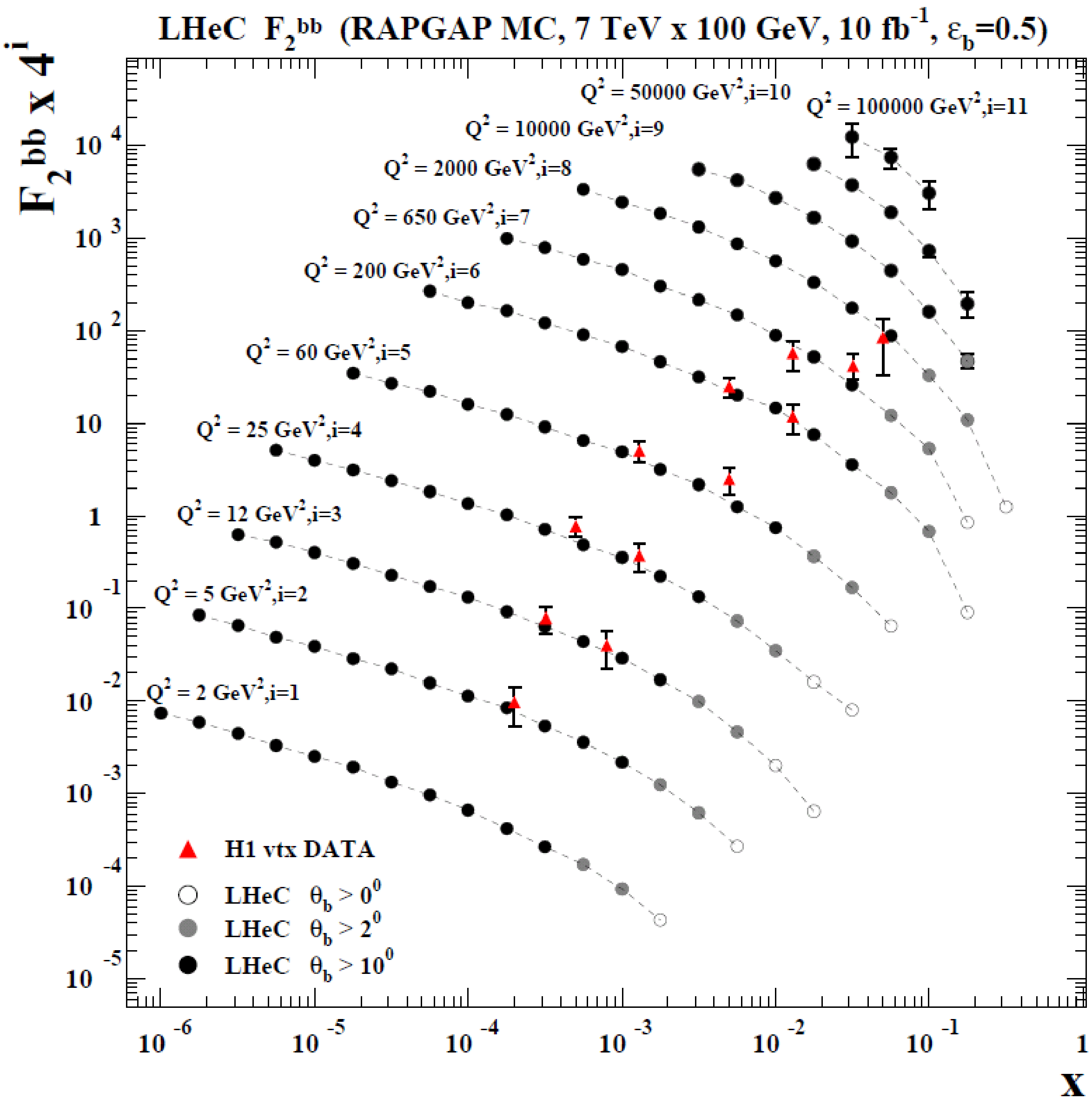




Expected to show up at $x_b > 0.1$

→ Requires c-tagging in very foward direction (θ~1 deg.)

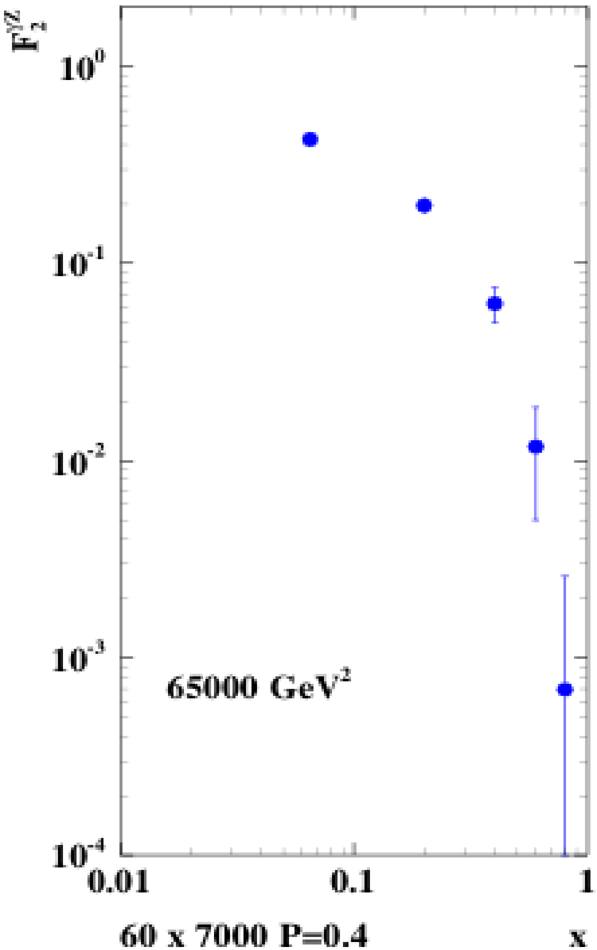
Beauty production contribution to $F_2 = F_2^{bb}$

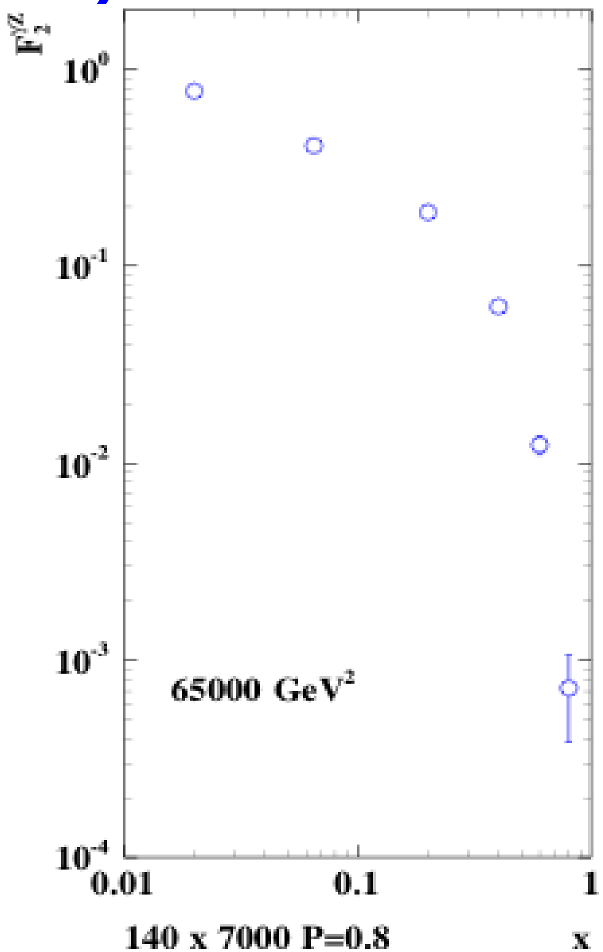


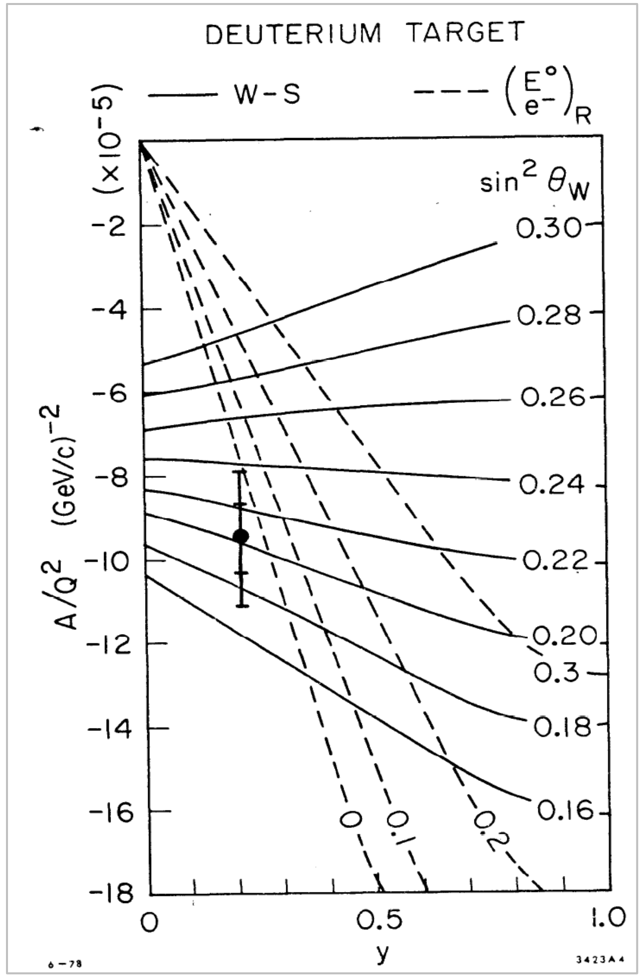
Parity violating polarisation asymmetries (for 60 GeV and 140 GeV lepton beams)

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$



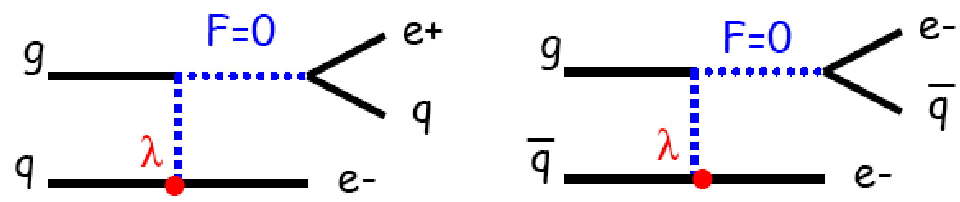


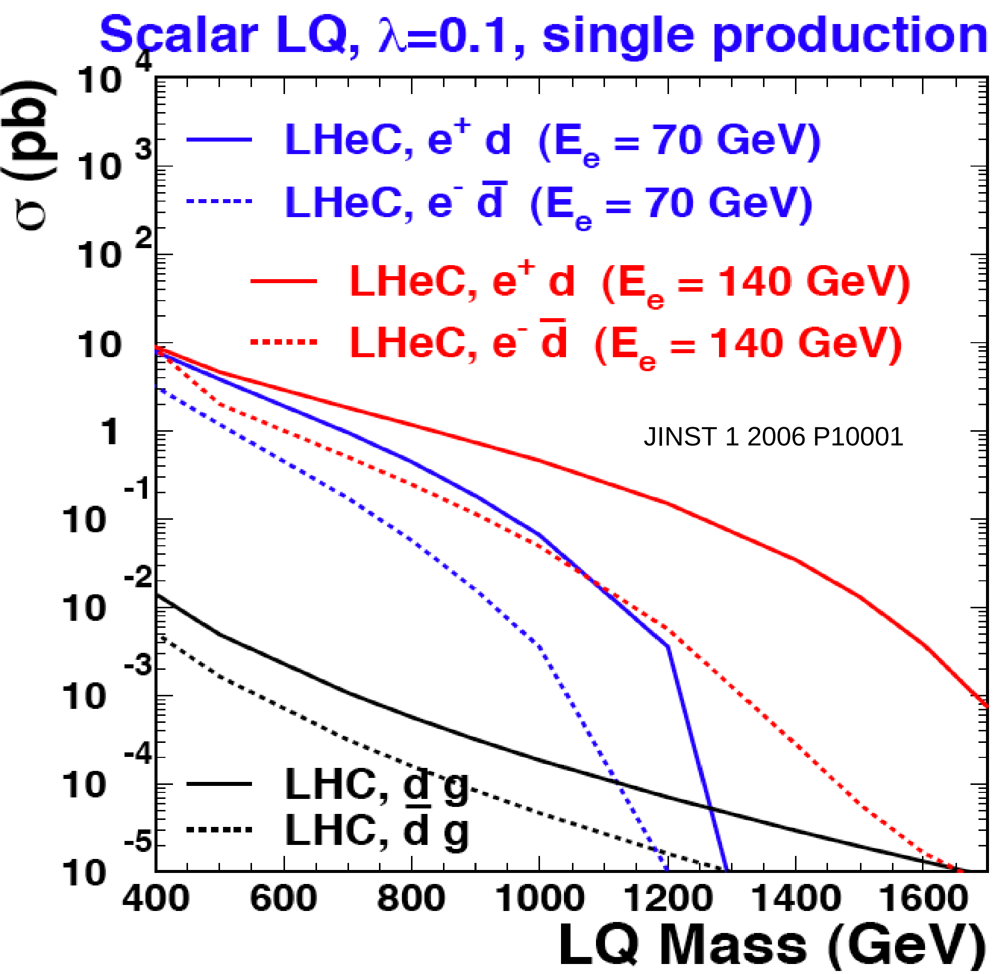


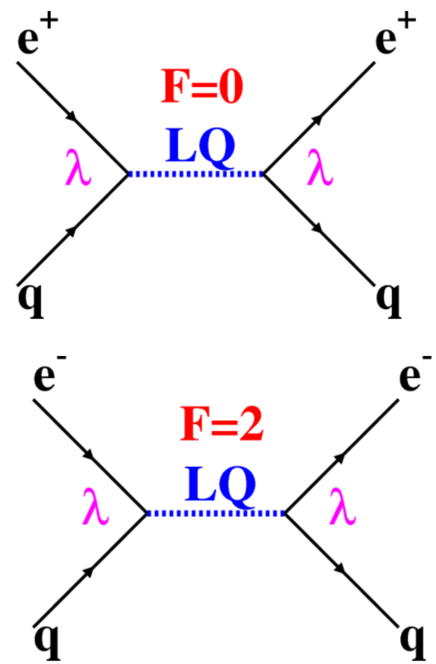
SLAC 1978

New physics example
Leptoquarks: determine quantum Numbers at LHeC

Single LQ production at LHC







Single LQ production at LHeC

e-p vs e+p asymmetries at LHeC will reveal the Fermion number F