Physics prospects at the LHeC

EINN09 workshop, 29 Sep 2009, Milos

Olaf Behnke (DESY)

Need for LHeC

27.5 GeV x 920 GeV ep HERA

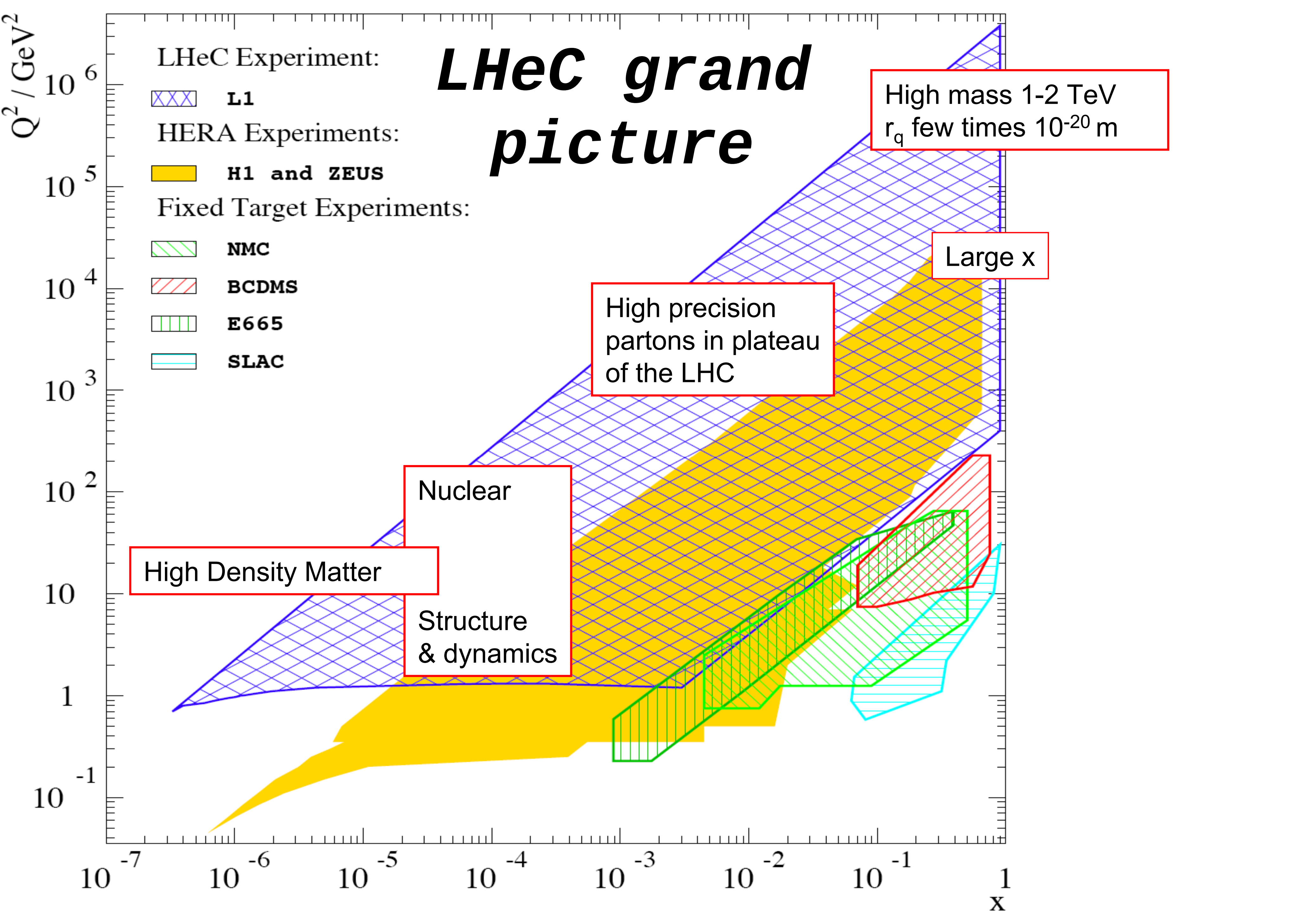
with integrated L~0.5 fb^{-1} was a

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

Where could we go with a

20-150 GeV x 7 TeV $e^{\pm}p$, also eA collider

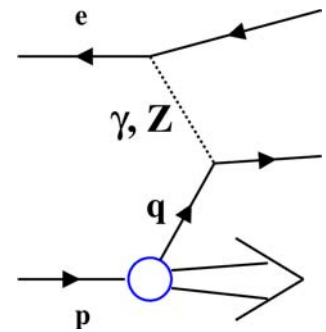
with integrated L~1-10 fb^{-1} ?

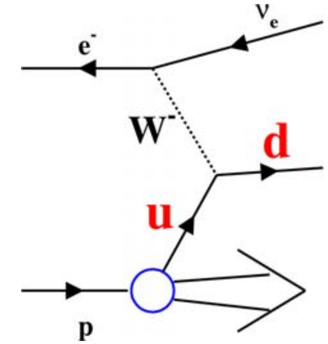


LHeC grand picture
LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
High mass 1-2 TeV
r_q few times 10^{-20} m
Large x
High precision partons in plateau of the LHC
Nuclear
Structure & dynamics
High Density Matter
Q^2 / GeV^2
x

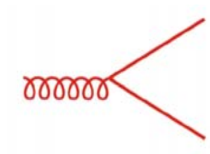
Content of this talk

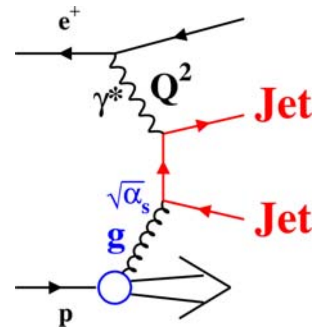
- Inclusive neutral (NC) and charged currents (CC) for electroweak physics and PDFs

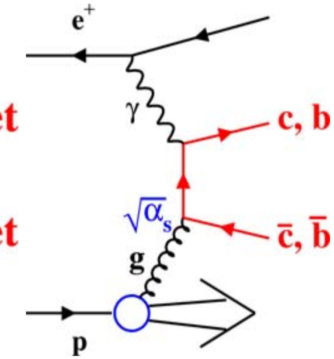




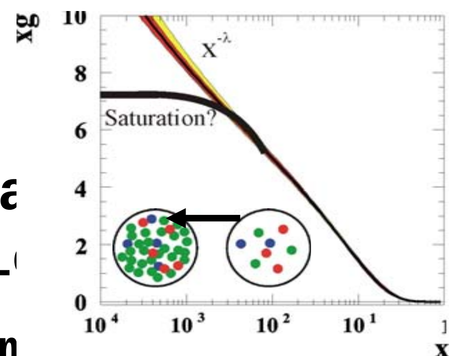
- o(α_s) processes, F_2 scaling violations, jets, charm, beauty -> precision α_s and g(x)

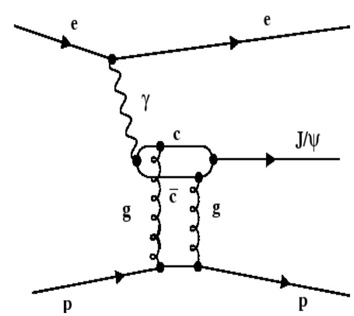


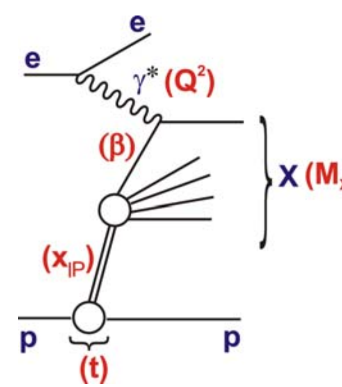




- low x domain:
  - Inclusive DIS in ep a… nuclear PDFs, saturati…
  - Diffraction: Vector mesons, inclusive processes

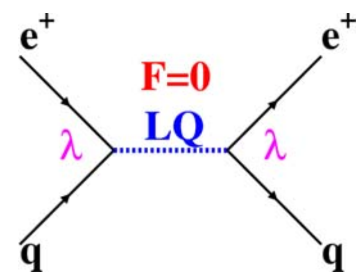






- High energies frontier:
  - SM Higgs production
  - New physics: Leptoquarks

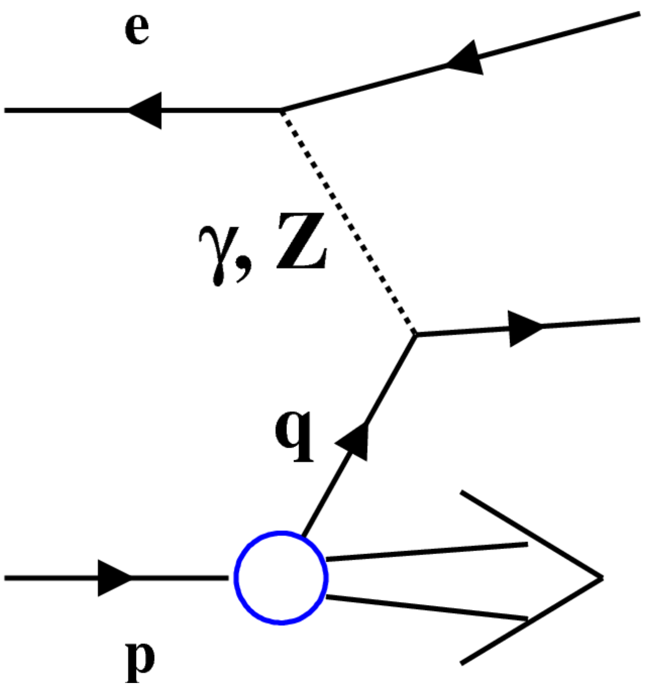
QuickTime™ and a decompressor are needed to see this picture.

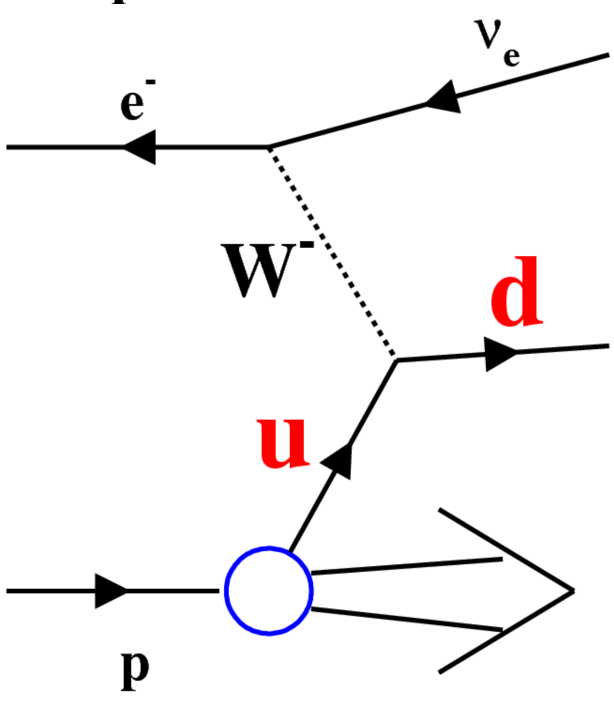


Thanks especially to the following persons for providing talk material such as slides:

- **Max Klein** (General)
- **Alessandro Pollini** (Detector)
- **Claire Gwenlan** (Pdf and electroweak fit)
- **Paul Newman** (Low x and diffraction)
- **Uta Klein** (Higgs)
- **Emmanuelle Perez** (Leptoquarks)

Inclusive NC and CC





Classical working horses in DIS

New since spring 2009:
LHeC Pseudodata
available (M. Klein)

Simulated Default Scenarios, April 2009

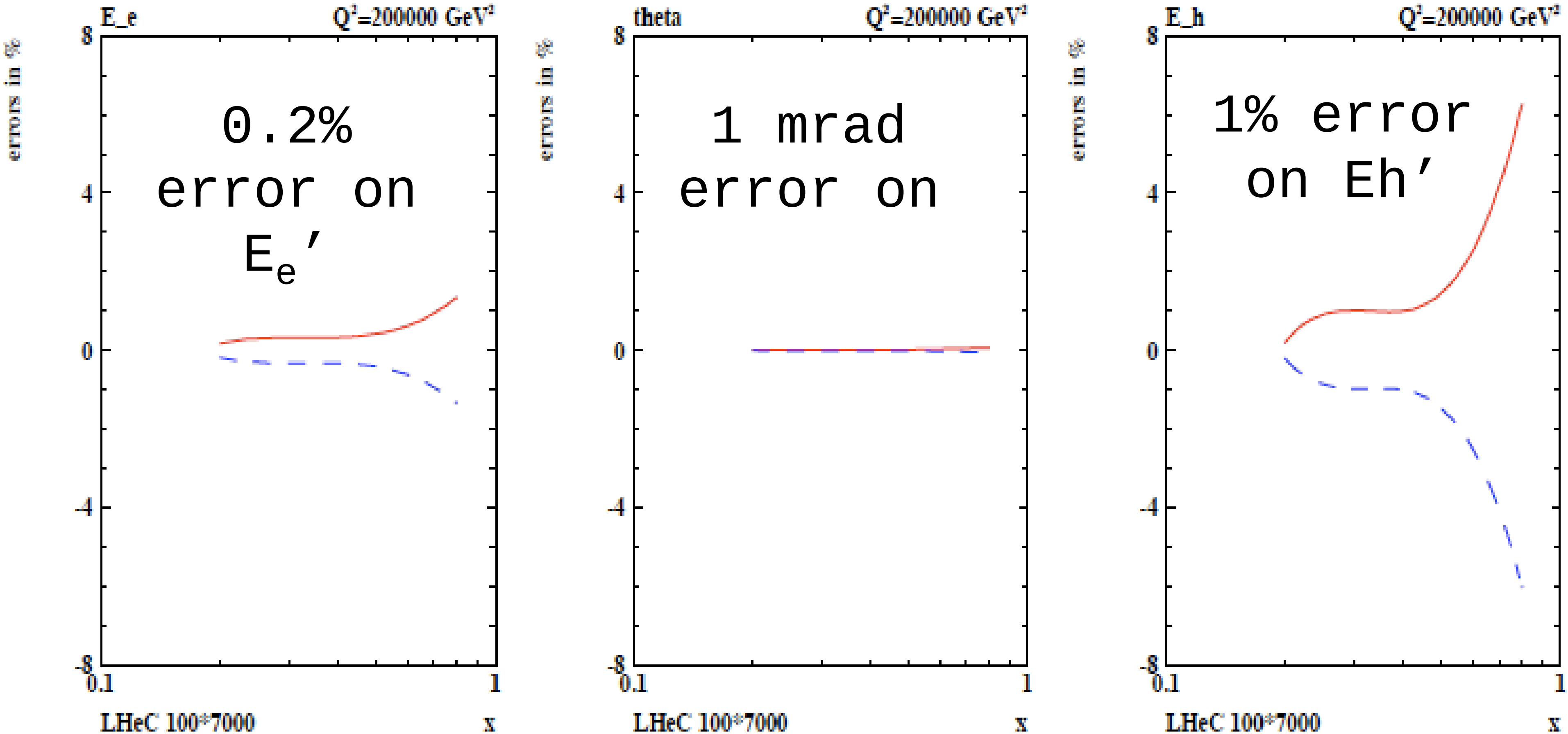
http://hep.ph.liv.ac.uk/~mklein/simdis09/lhecsim.Dmp.CC, readfirst

Max Klein, LHeC

config.	E(e)	E(N)	N	∫L(e⁺)	∫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

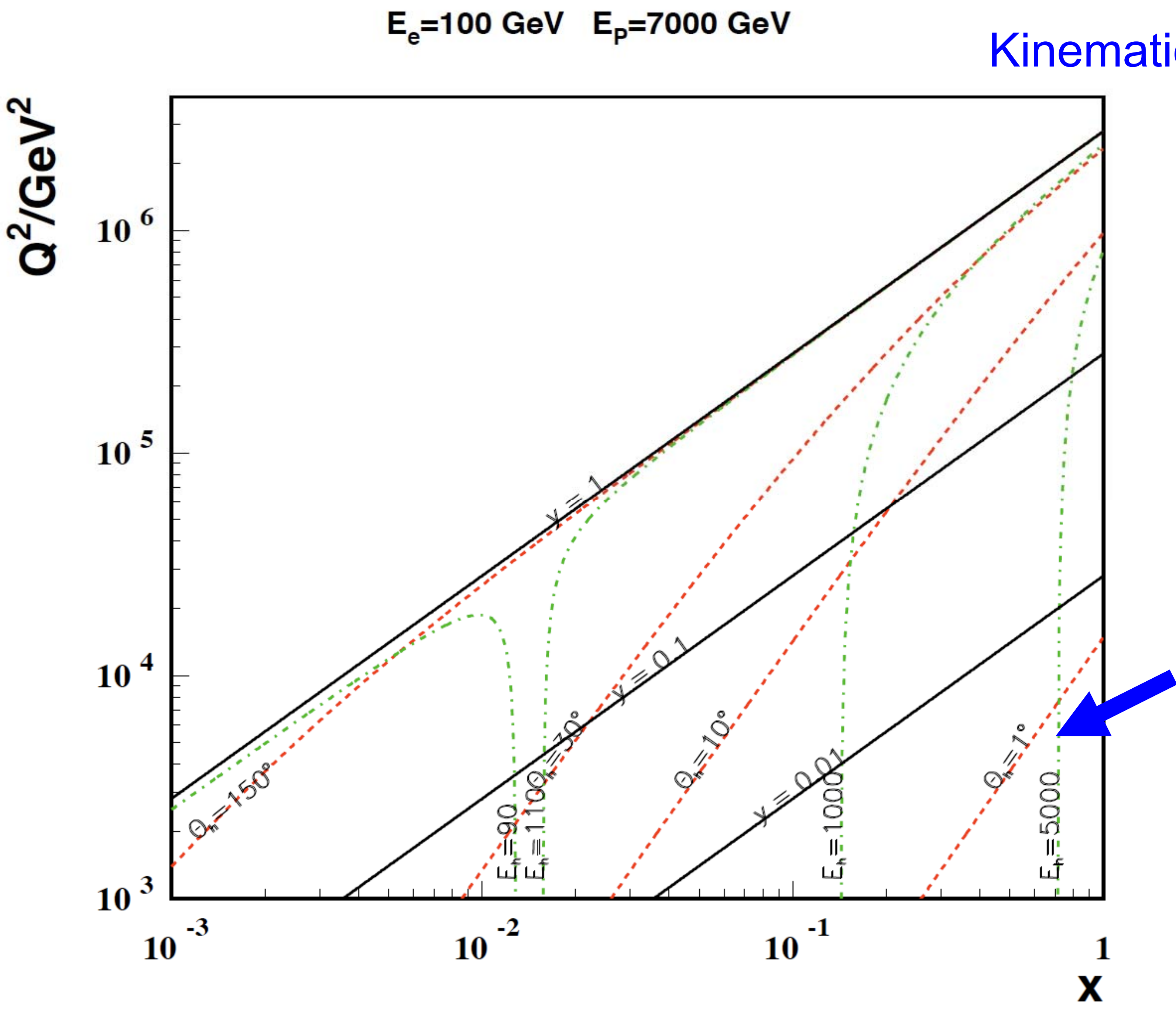
Not simulated

Systematic error calculation for inclusive NC & CC pseudodata: assumed uncertainties and effects on xsecs



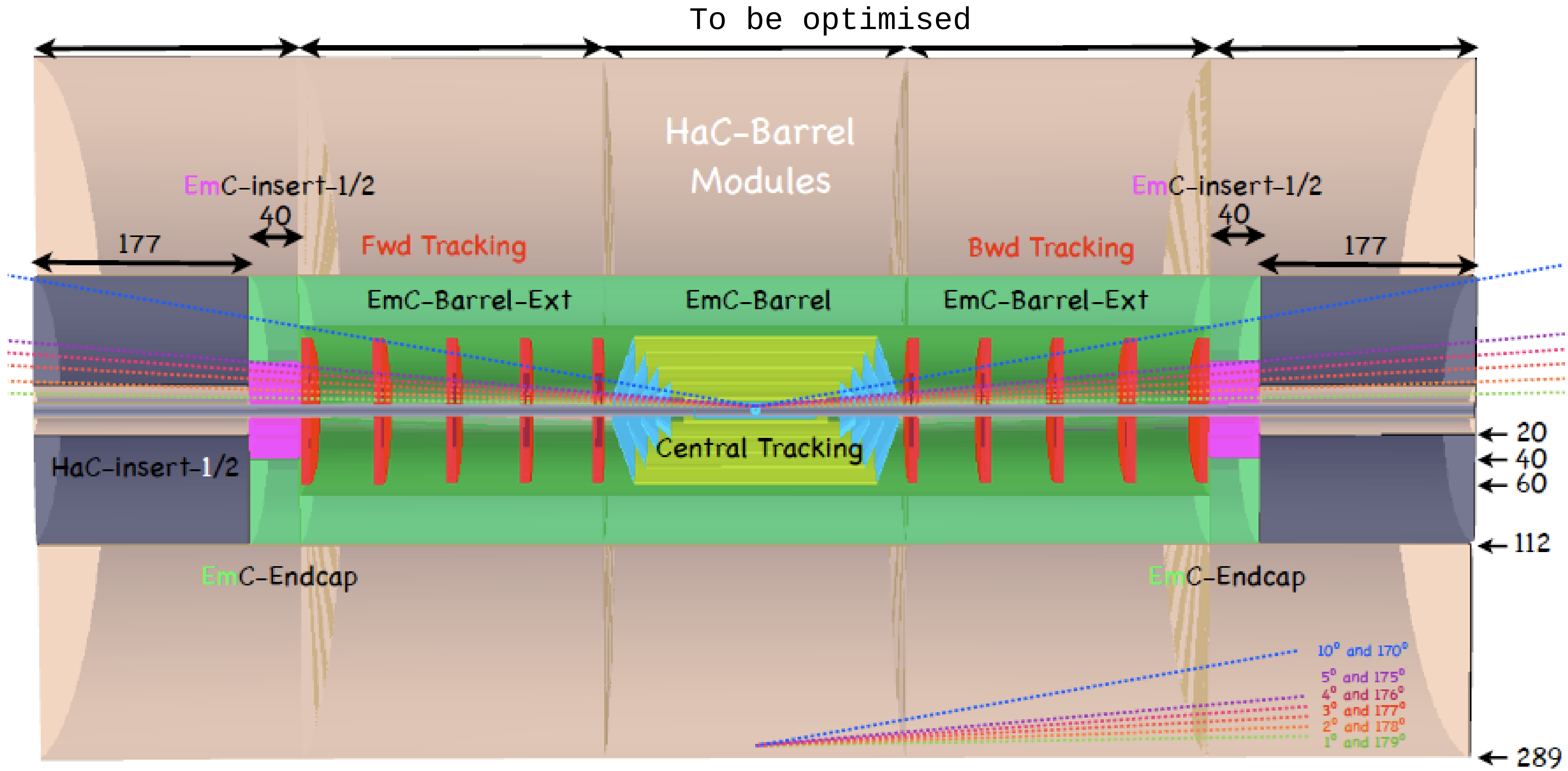
➡ At high Q^2: Need <=1% hadronic energy scale uncertainty at very large E_h

Kinematics – high Q^2



Need excellent forward hadron calorimetry & calibratio

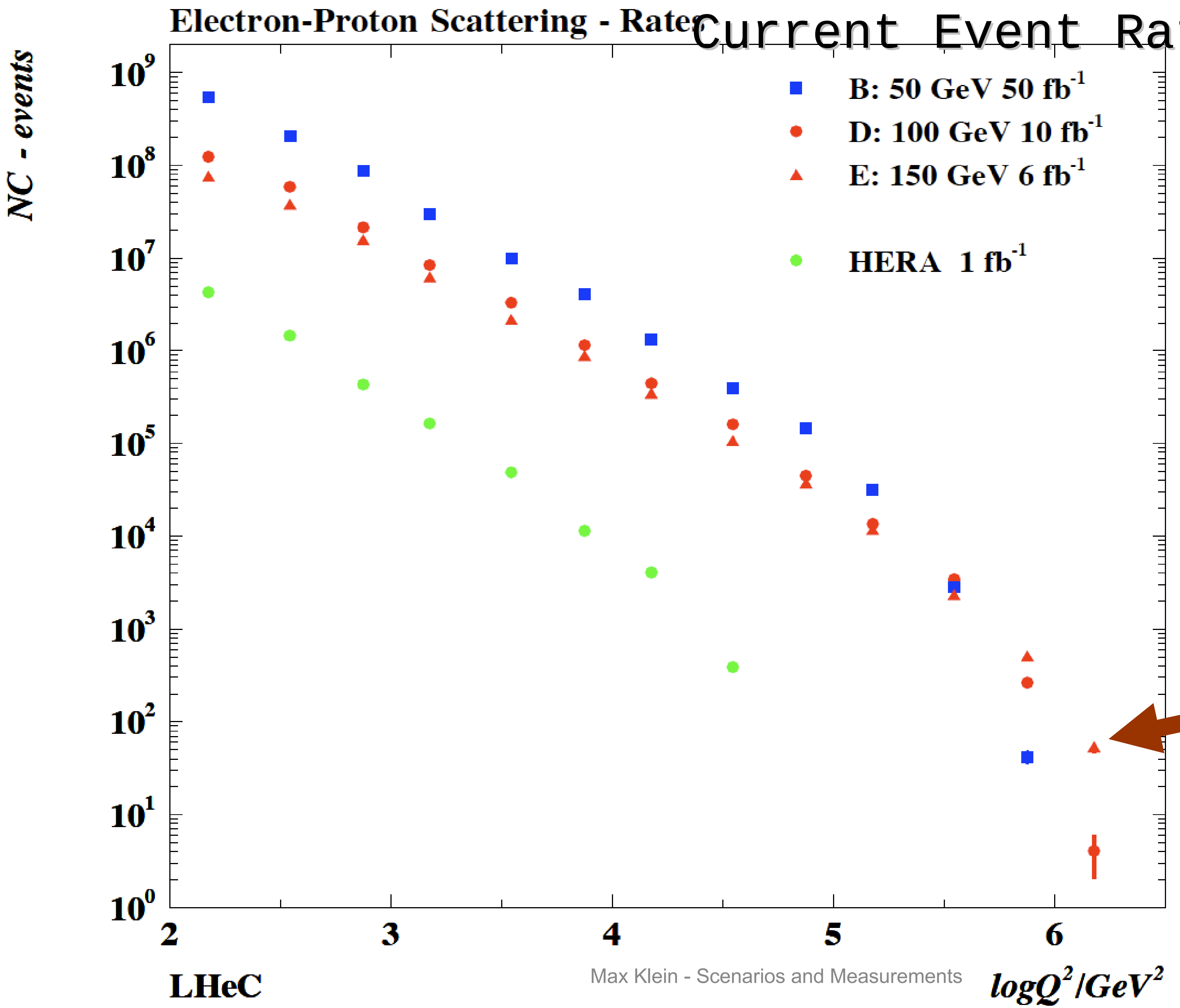
The Detector 'that should do it': - Low Lumi (Low Q^2) Setup

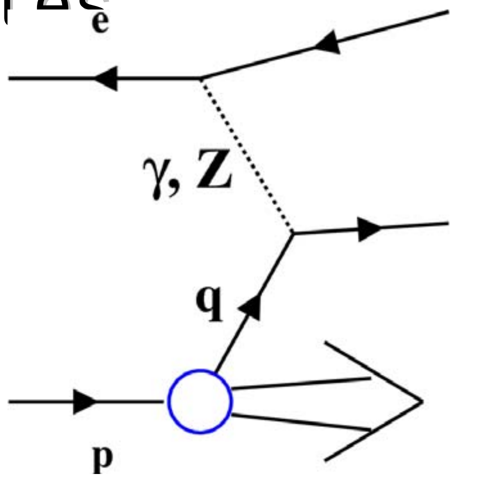


- Solenoid surrounding the HAC modules
- Outer detectors (HAC tailcatcher/muon detectors not shown)

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

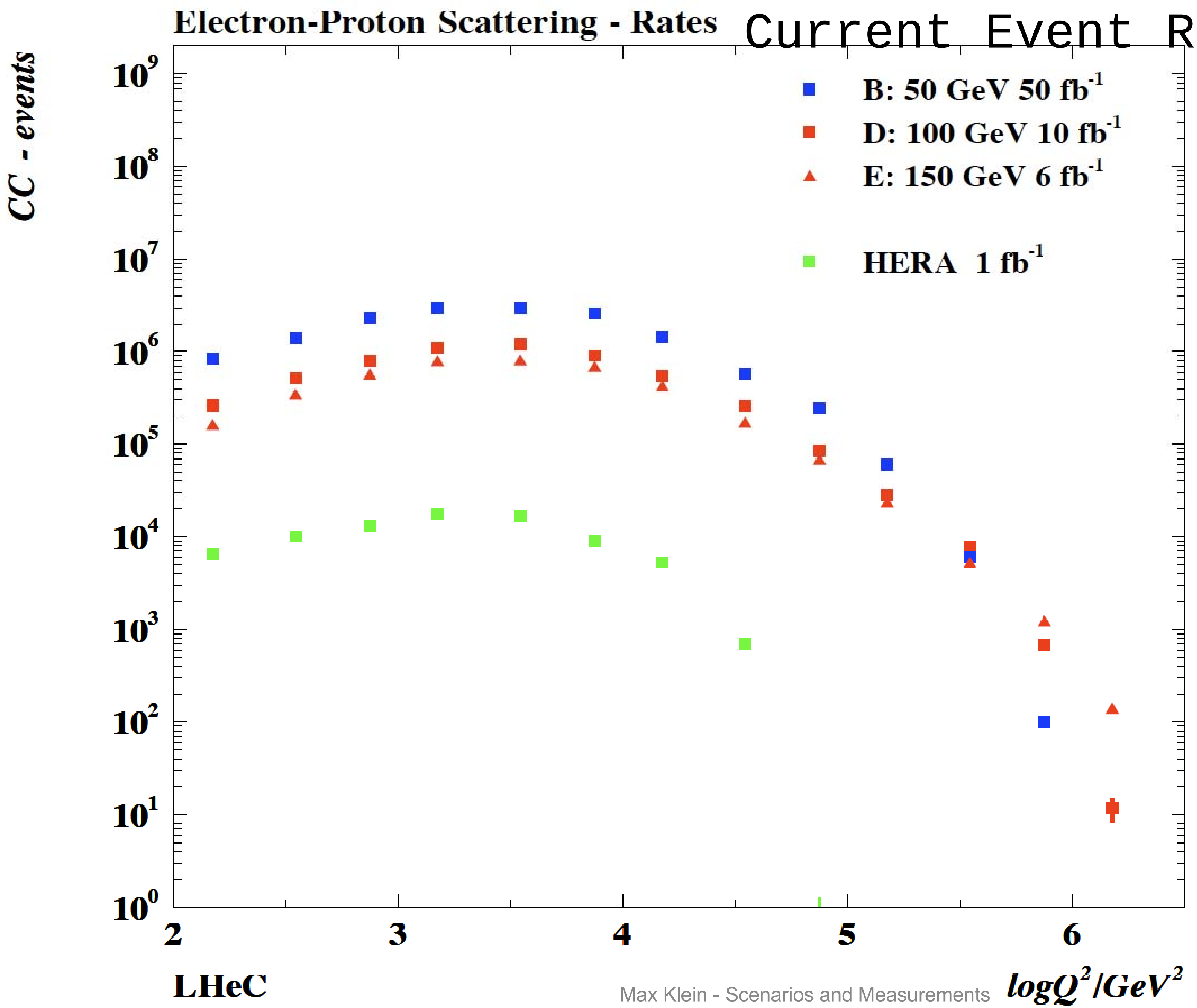
Pseudodata: Neutral Current Event Rates

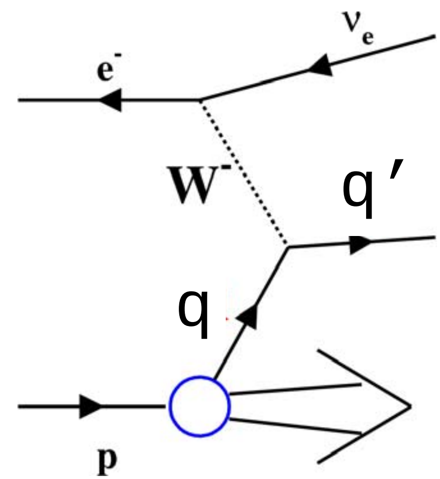




Trivial, but important: largest E_{lep} allows highest Q^2 scales

Pseudodata: Charged Current Event Rates





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

NLO QCD and electroweak fit

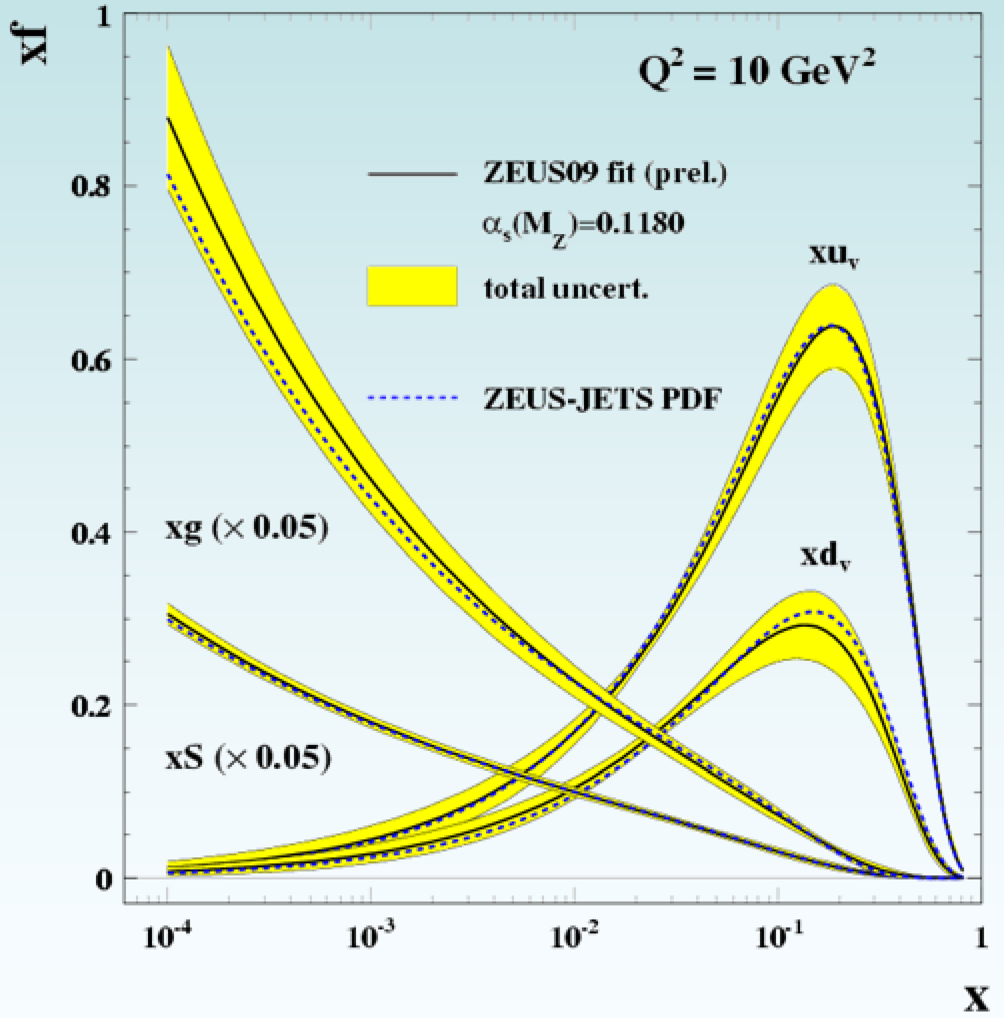
Claire Gwenlan

Study presented here is based on new **ZEUS NLO QCD fit** to HERA-I and HERA-II data

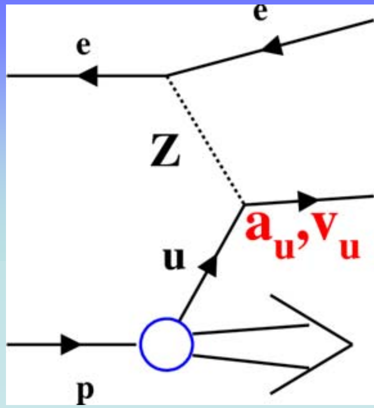
LHeC NC/CC simulated data added to this in a **combined fit** for the PDFs and electroweak parameters

Making use of Max pseudodata

ZEUS09 fit (c.f. central values of HERA-I fit)



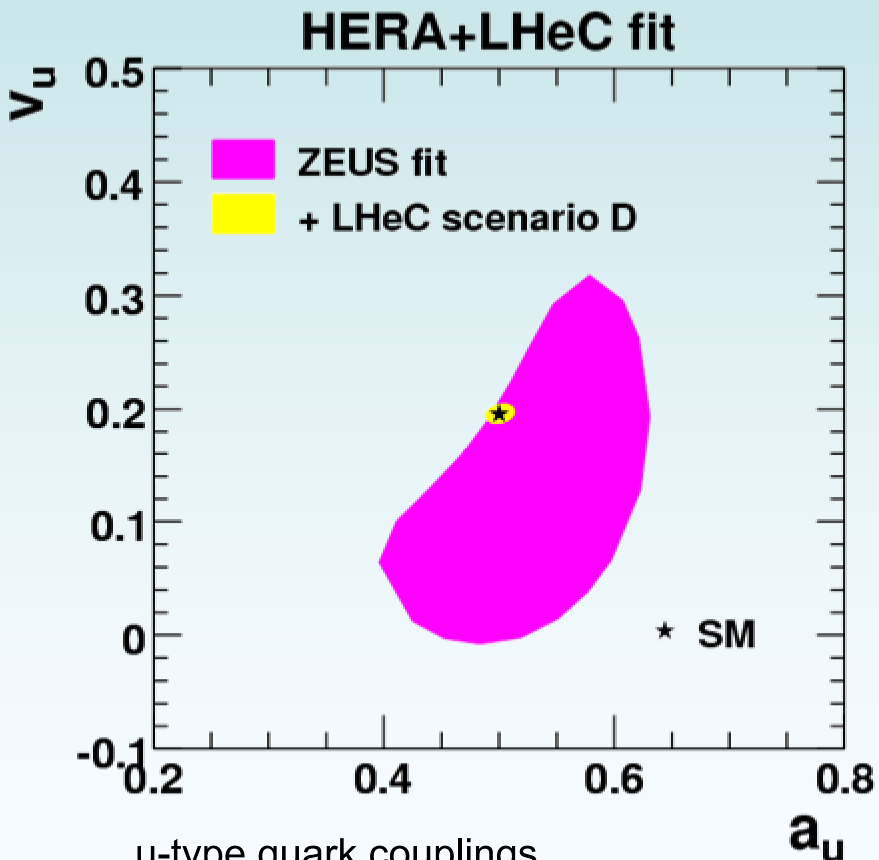
NC quark couplings



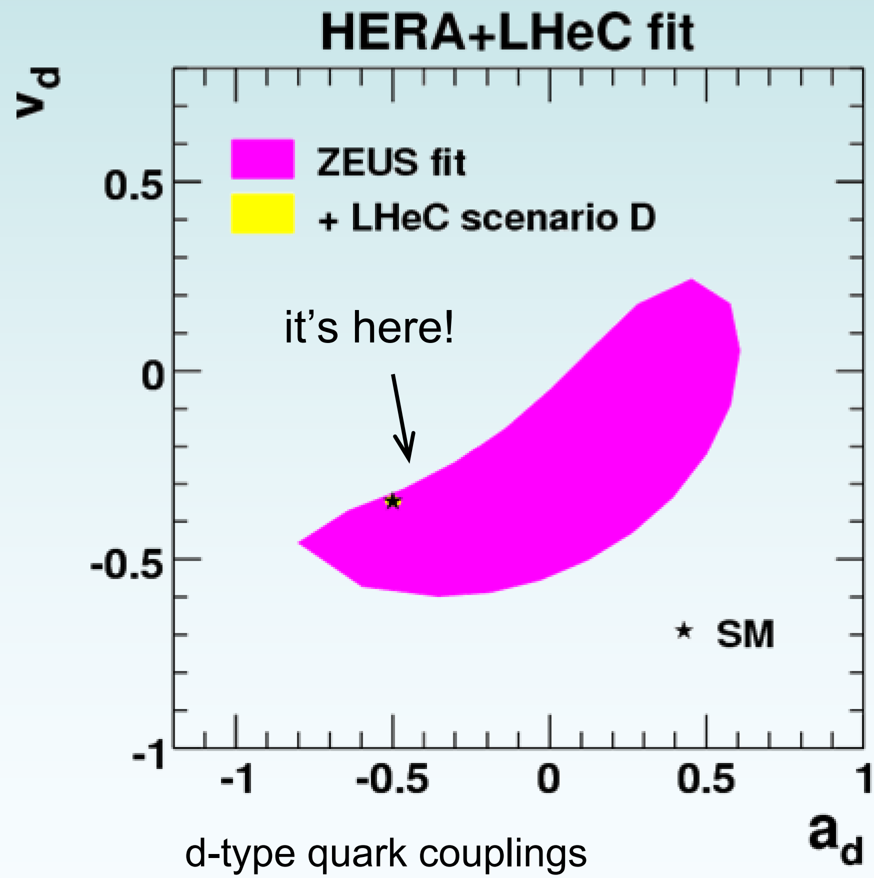
scenario D:
$P_e = \pm 0.9$

comparison with **ZEUS fit**

(base to which LHeC pseudo-data added)

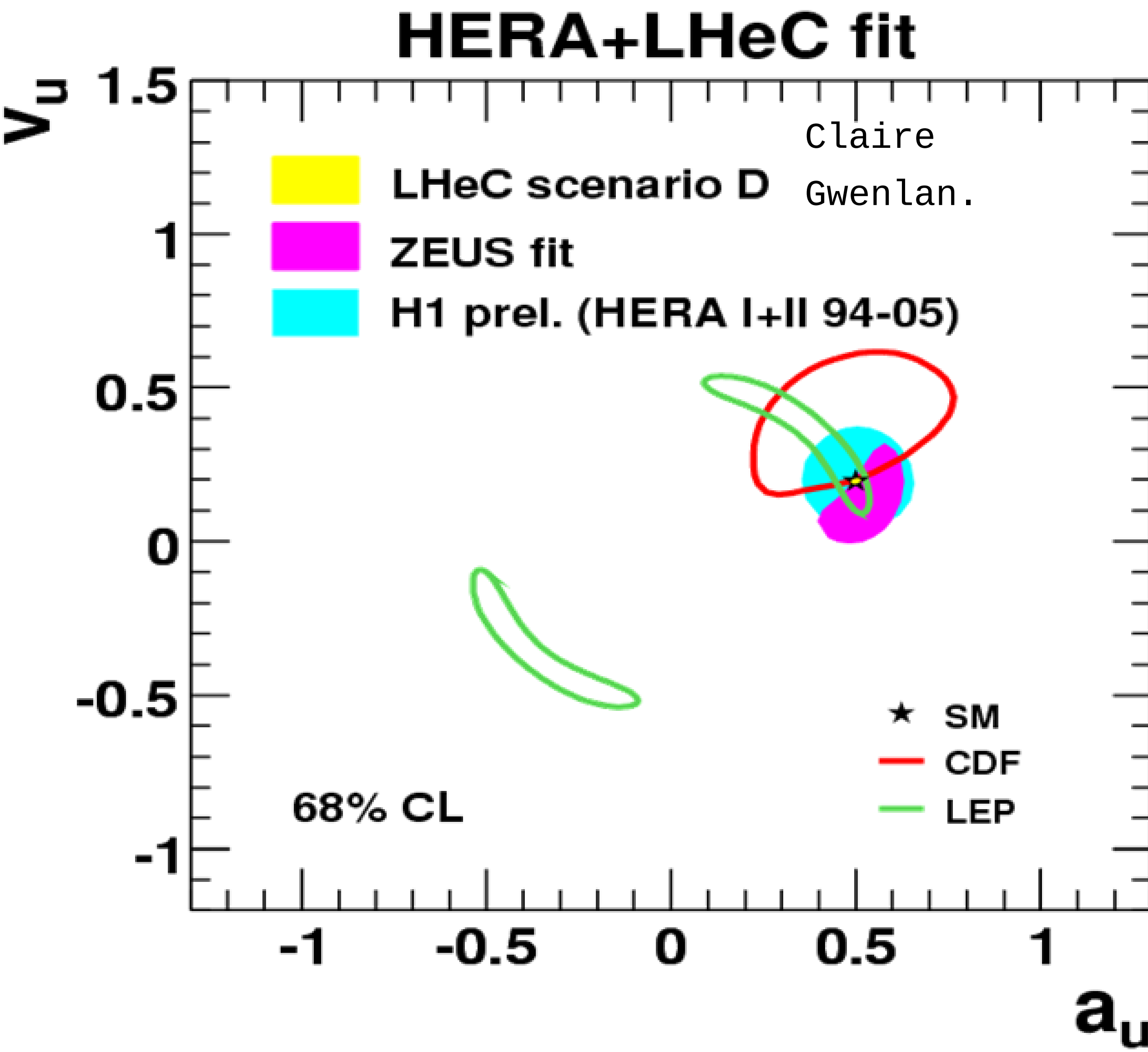


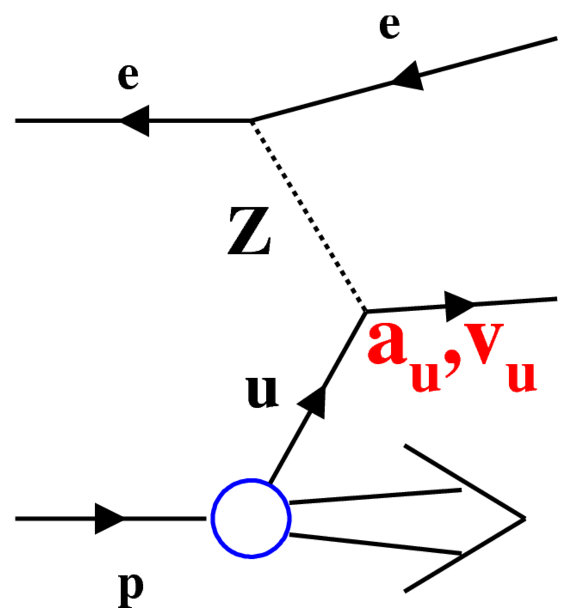
u-type quark couplings



d-type quark couplings

Fermion couplings to Z boson





LHeC (and HERA) especially sensitive u and d couplings

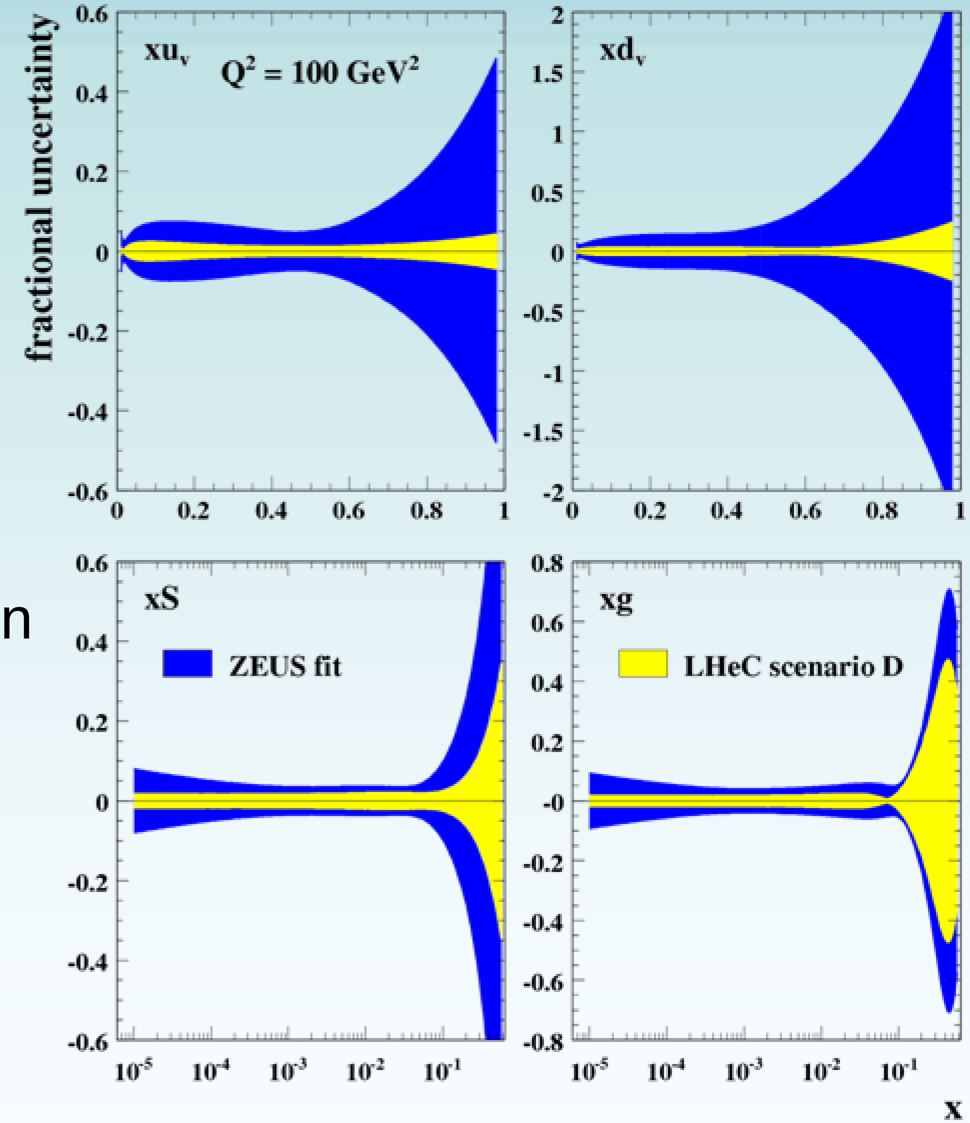
Proton PDFs

Claire Gwenlan

Q^2 = 100 GeV^2

scenario D

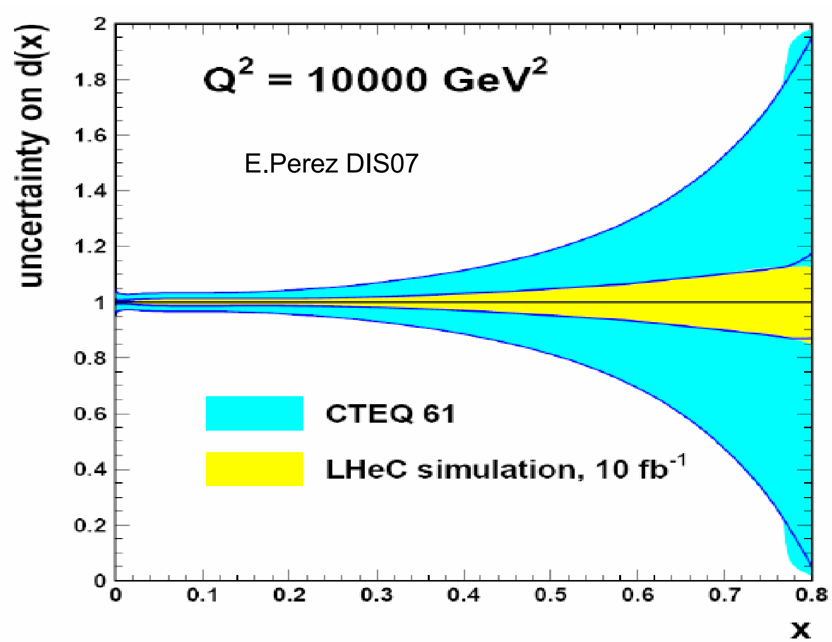
» <u>only</u> PDF parameters free (LHeC **NC** and **CC** $e^{\pm}p$ included)



Looks very promising, model and parameterisation uncertainties to be studied

☺ ☺ ☺

Light Quark Distributions

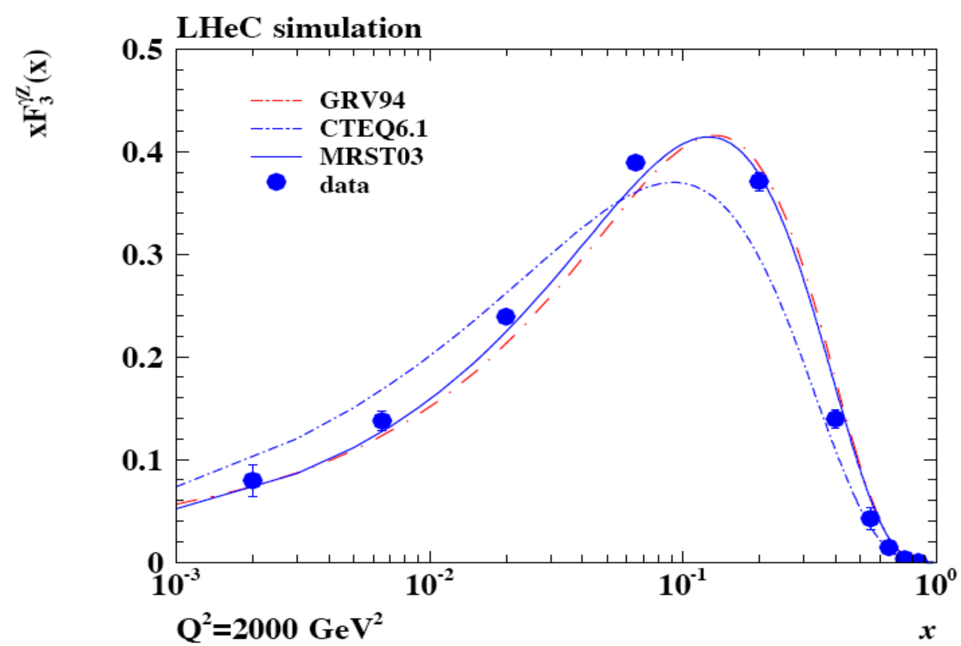


d and u at high x: a longstanding puzzle
NC/CC: free of HT, nuclear corrections.
Essential for predictions at high x

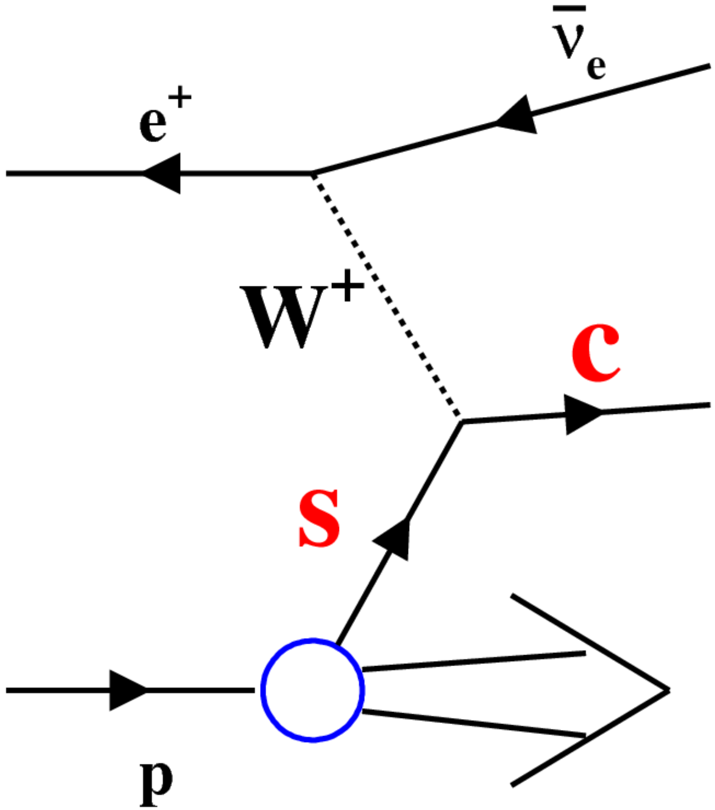
LHeC is an electroweak machine.
e.g.: Charge asymmetry in NC measures valence quarks down to x ~10^{-3} at high Q^2

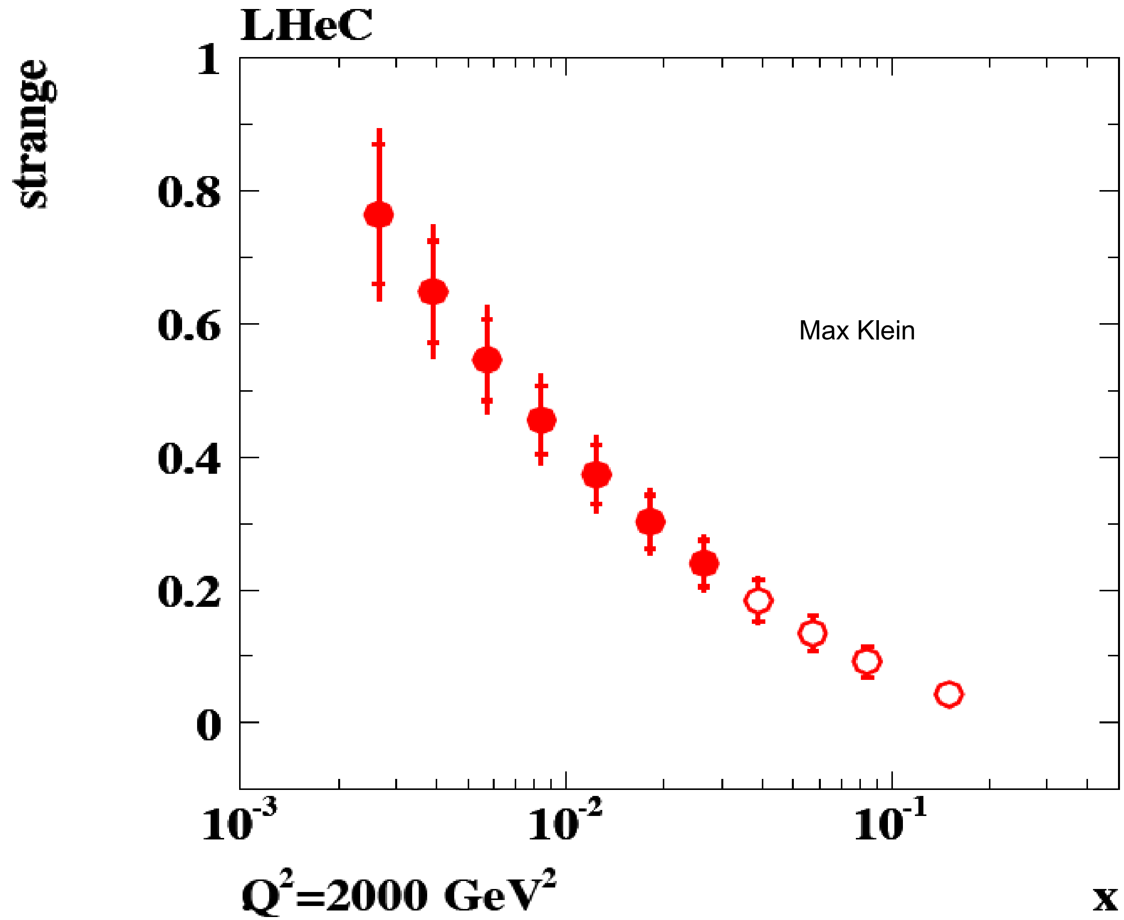
$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v)$$

QuickTime™ and a
decompressor
are needed to see this picture.



Single c Quark Production in CC -> measure s(x,Q2)

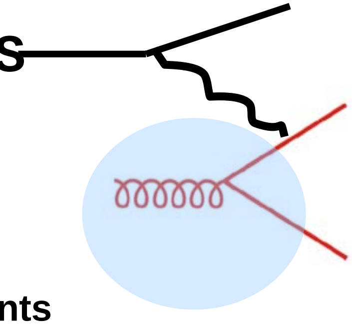




direct measurements of s and sbar densities in the pro

Strong Coupling Constant from inclusive DIS

(sensitivity mainly from dF2/dln(Q2))



Simulation of $_s$ measurement at LHeC

1/

fine structure

weak

strong

QuickTime™ and a
decompressor
are needed to see this picture.

MSSM - B.Allnach et al, hep-ex/0403133

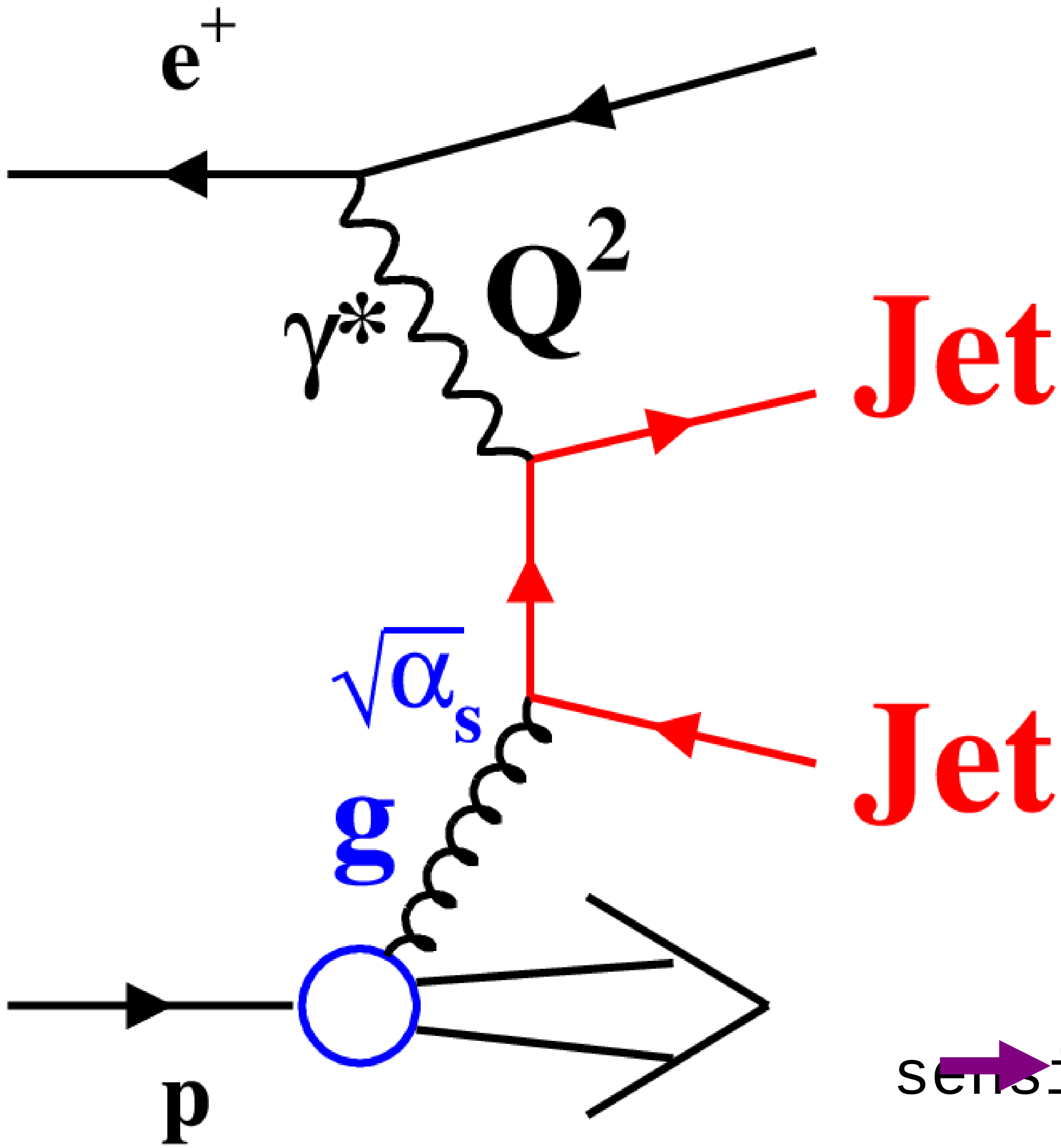
$_s$ least known of coupling constants
Grand Unification predictions suffer from $_s$

DIS tends to be lower than world average

LHeC: per mille accuracy indep. of BCDMS.
Challenge to experiment and to h.o. QCD

QuickTime™ and a
decompressor
are needed to see this picture.

O(α_s) processes: Jets



sensitive to g(x) and α_s

Jet production

DIS Joerg Behr

Photoproduction Claudia Glasman

QuickTime™ and a
decompressor
are needed to see this picture.

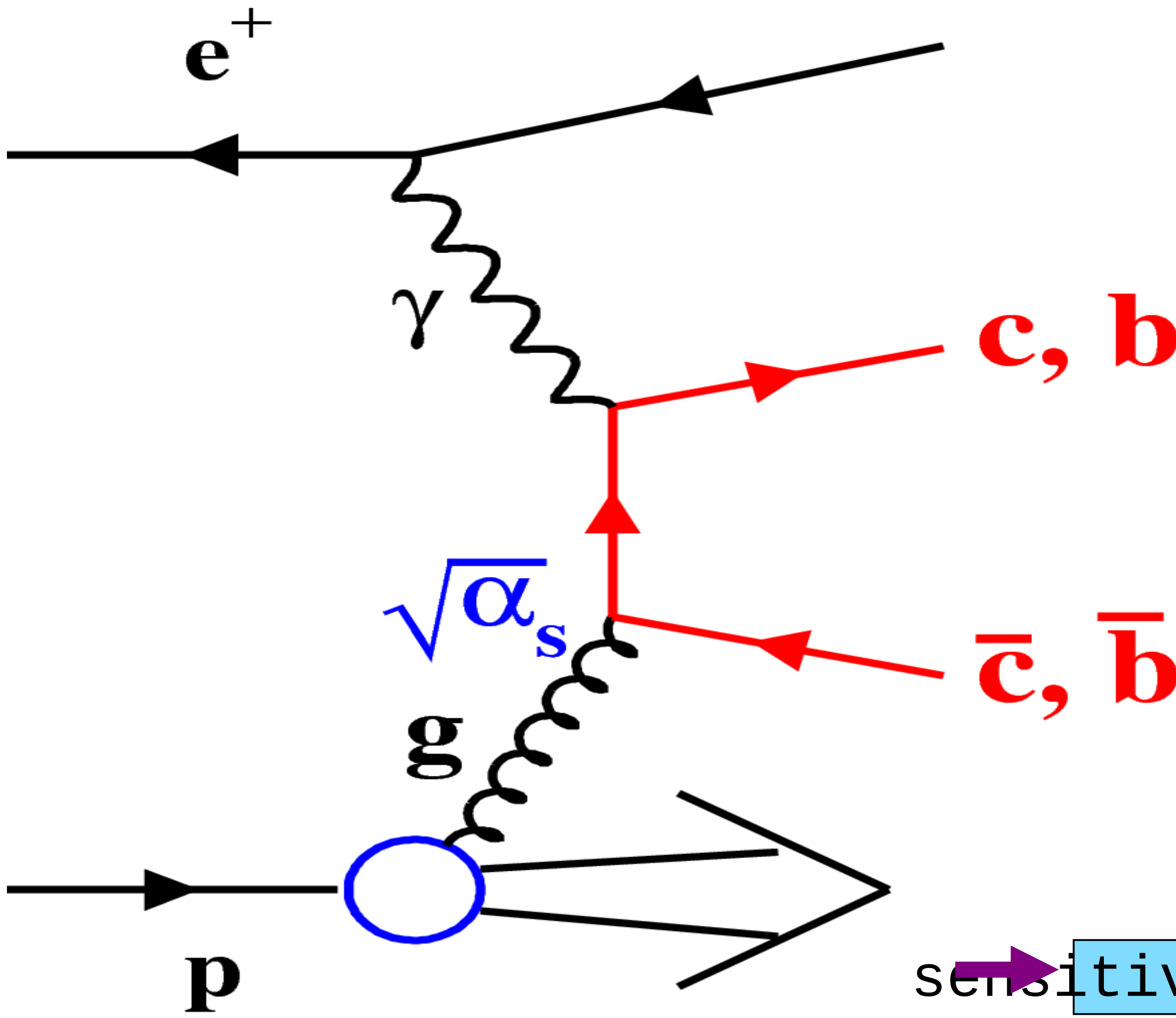
QuickTime™ and a
decompressor
are needed to see this picture.

Reach → scales up to 2m_top where change of $1/\alpha_s$ slope is e

QuickTime™ and a
decompressor
are needed to see this picture.

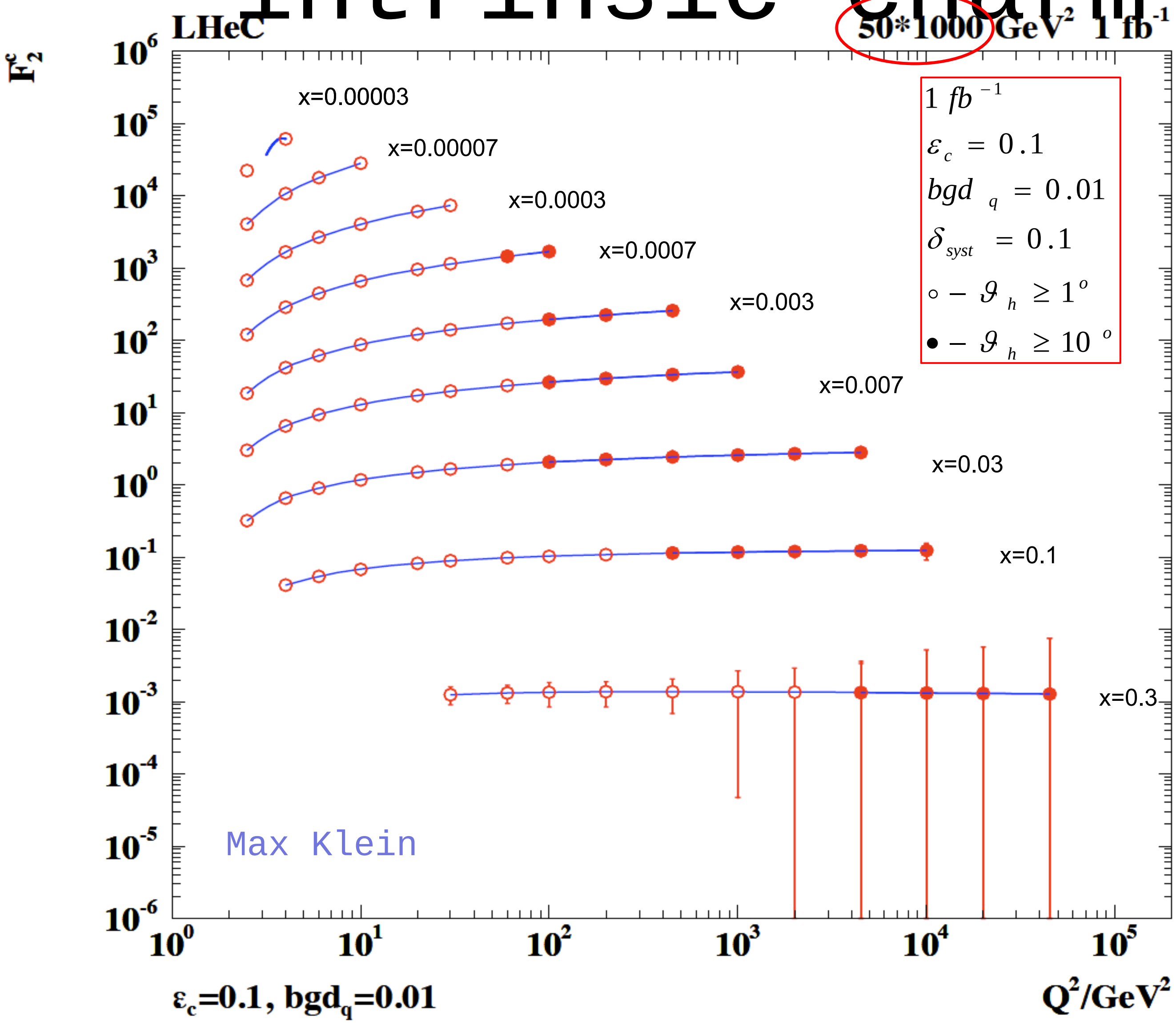
From Chris Quiggs talk:
“Particle physics & LHeC
Divonne 1.9.09

O(α_s) processes: charm & beauty



sensitive to g(x) and α_s

charm in DIS: try to test intrinsic charm in p



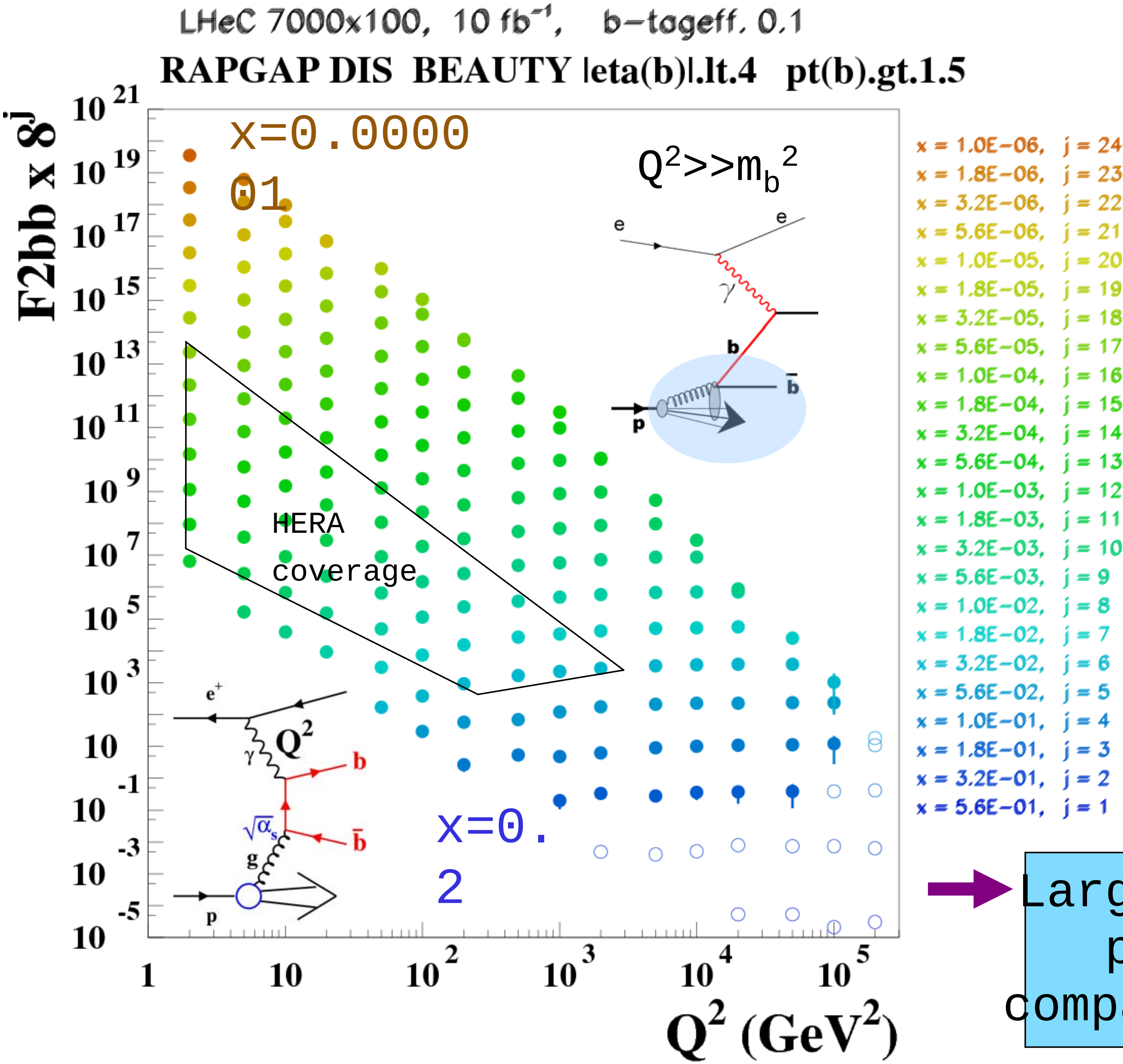
QuickTime™ and a decompressor are needed to see this picture.

Expected to show up at x_b >0.1

formidable challenge!

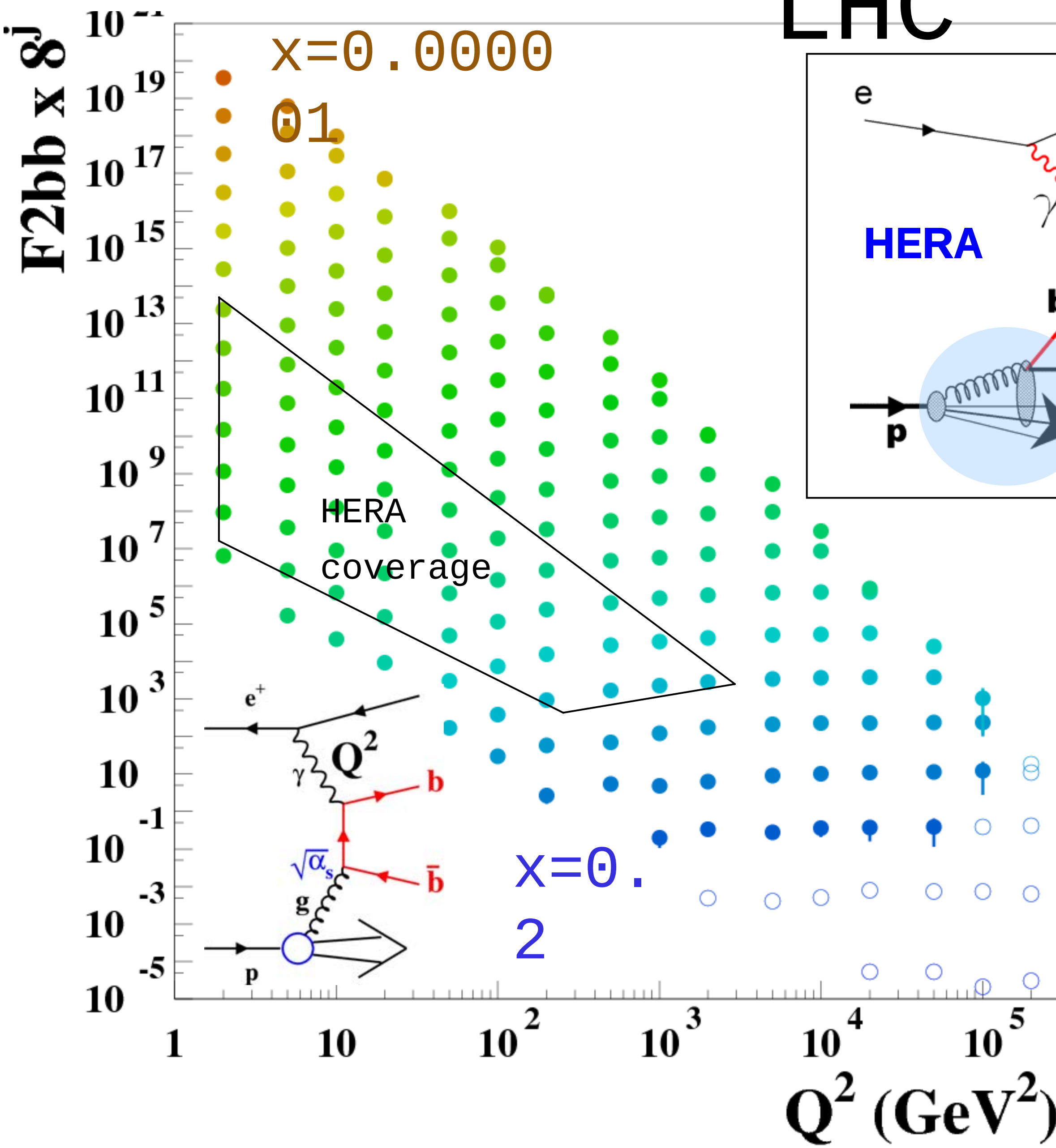
Beauty in DIS

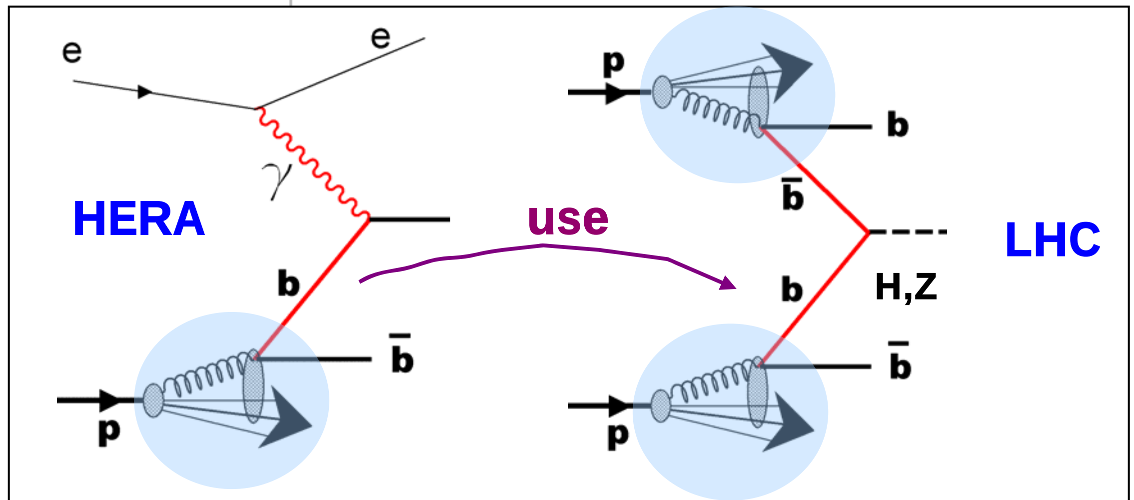
O.Behnke



→ Largely extended phasespace compared to HERA

b(x,Q²) from LHeC goes to LHC

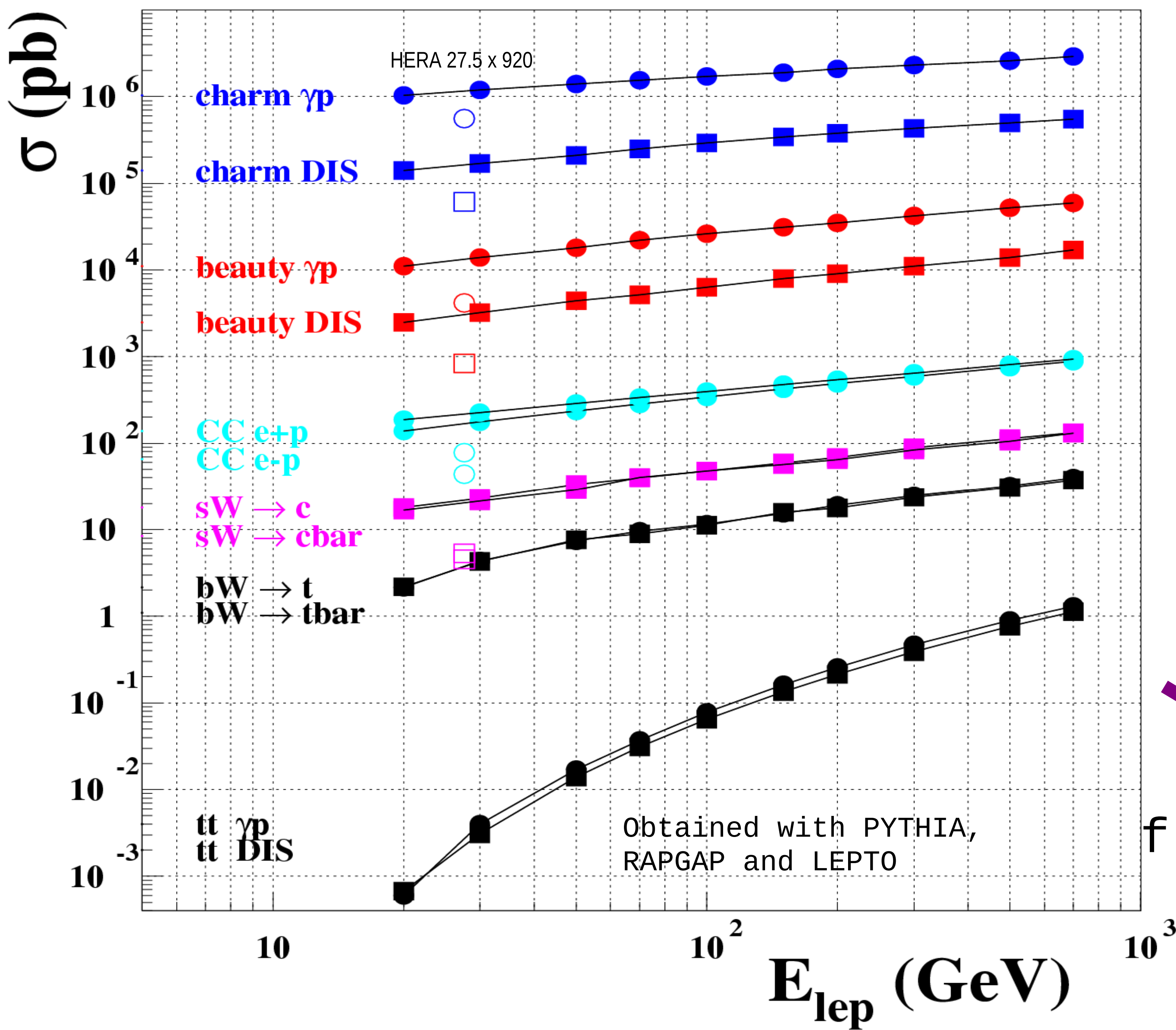




Competition from LHC: b+Z production also sensitive to b(x,Q2)

LHeC total cross sections (MC simulated)

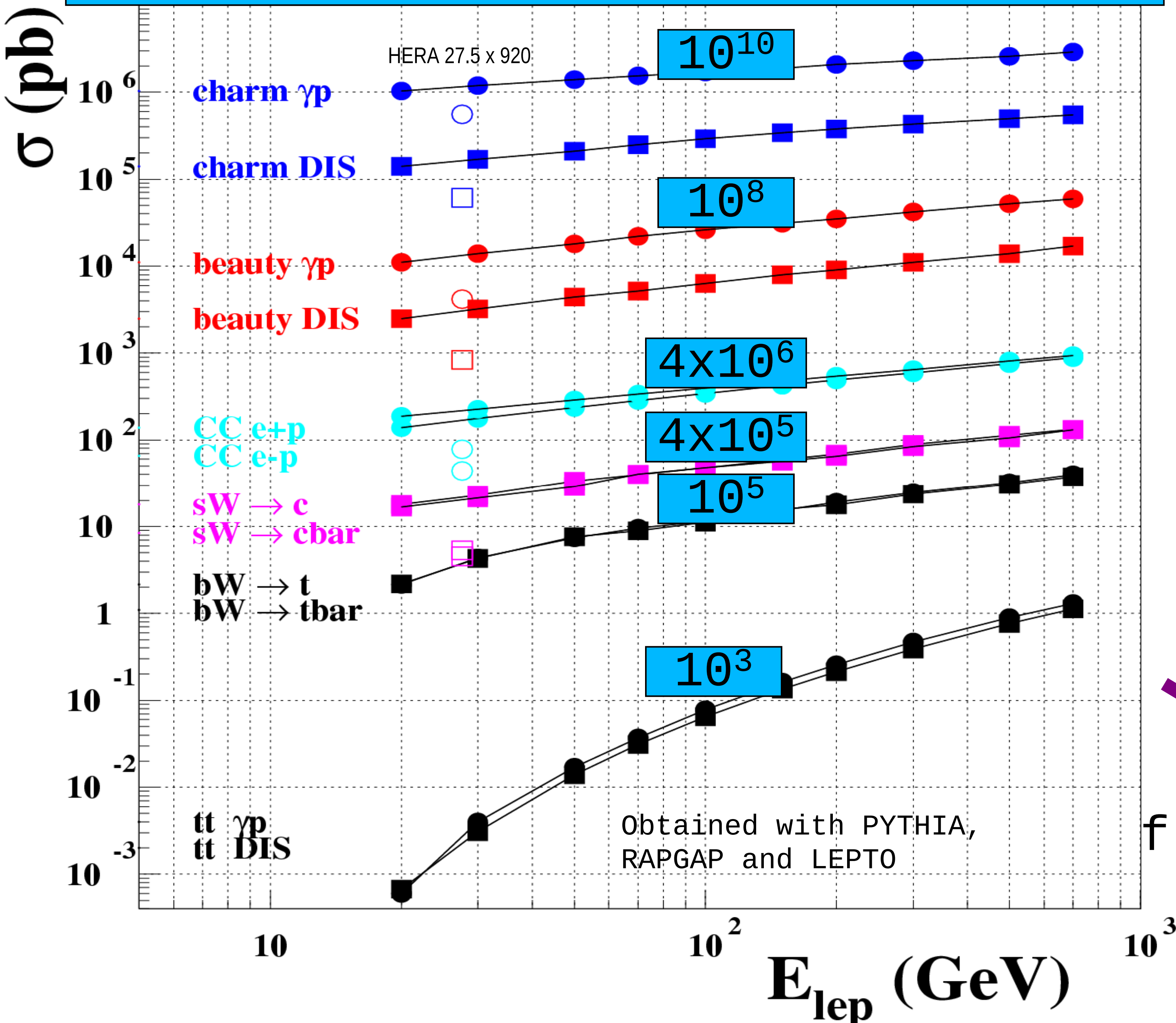
O.B.



LHeC is a flavour factory

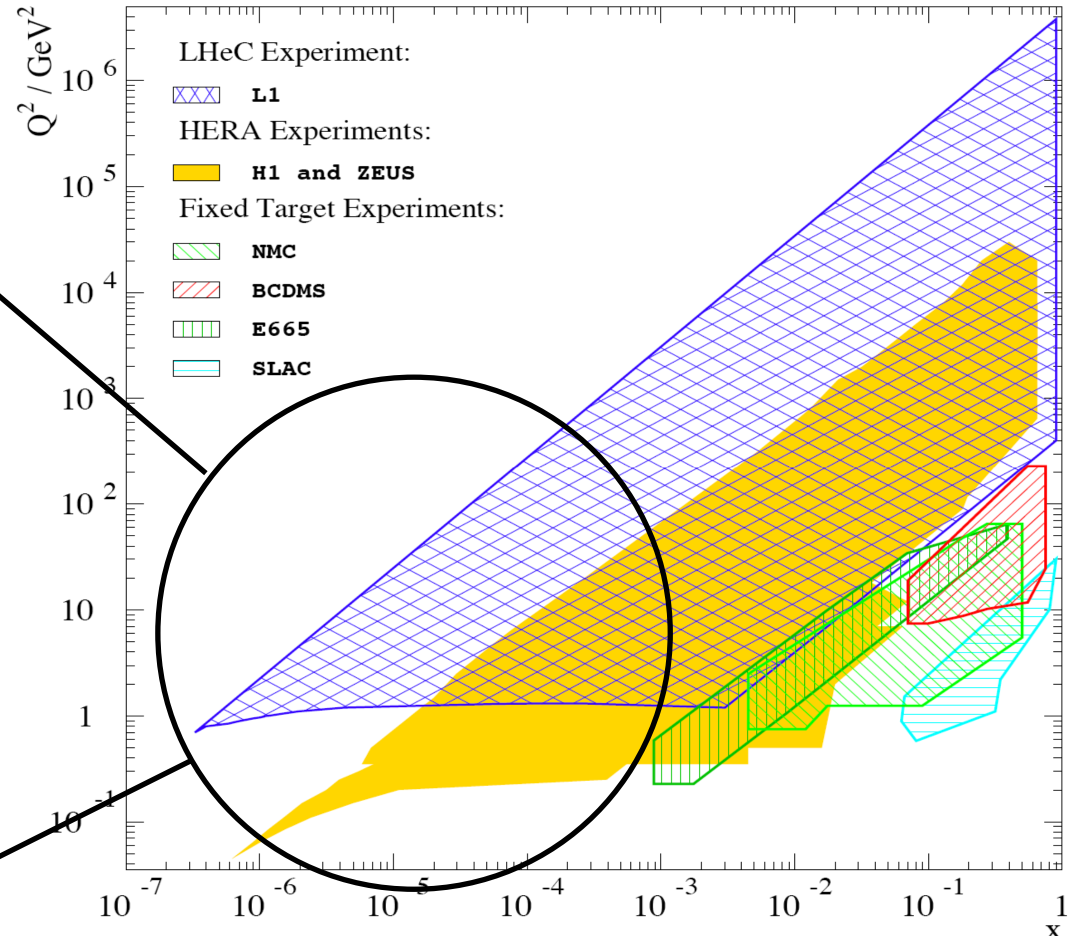
Events per 10 fb-1 Lumi

O.B.

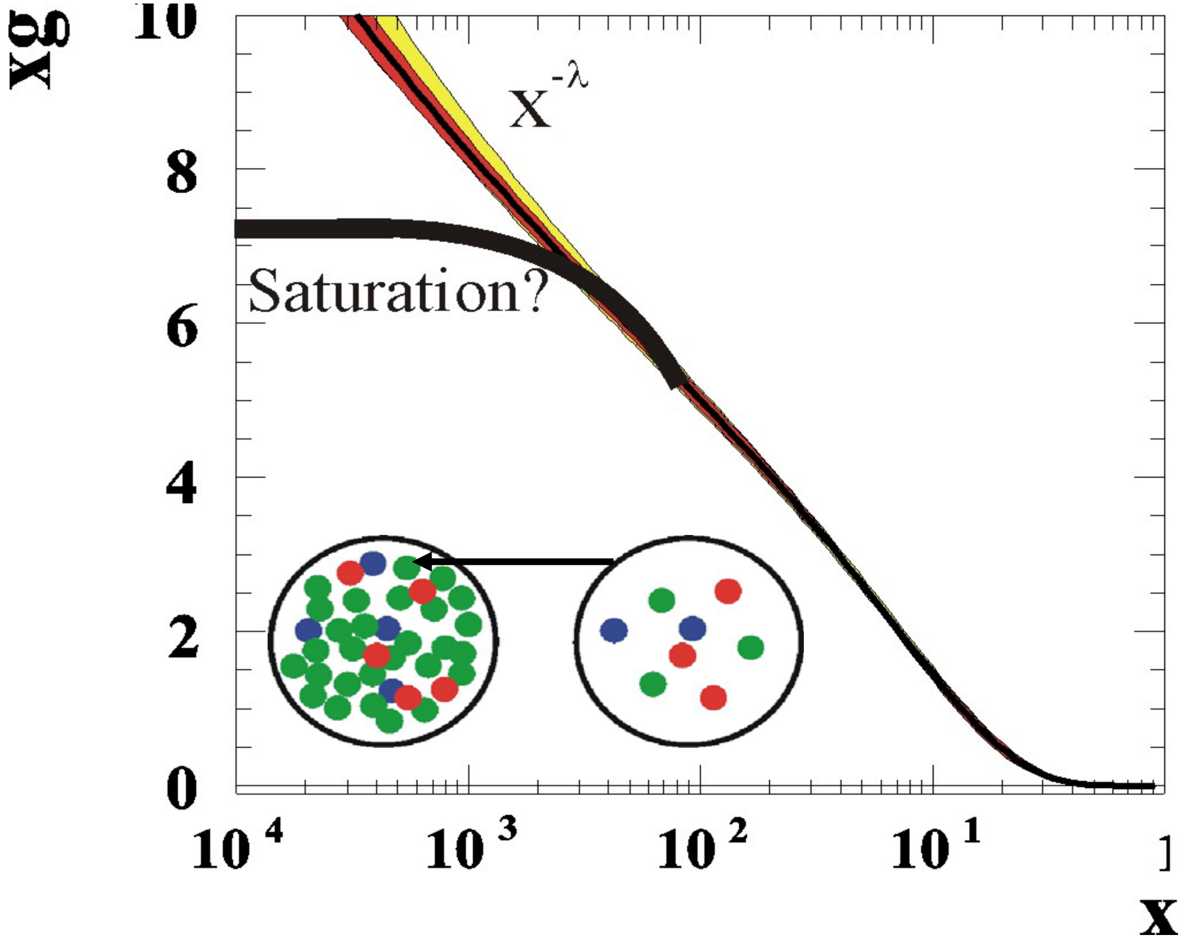


LHeC is a flavour factory

Entering the mysterious world of low x physics



Low-x Physics and Non-linear Evolution



Note: This and following slides taken from talk by Paul Newman, LHeC Workshop Divonne, 3 sep 09

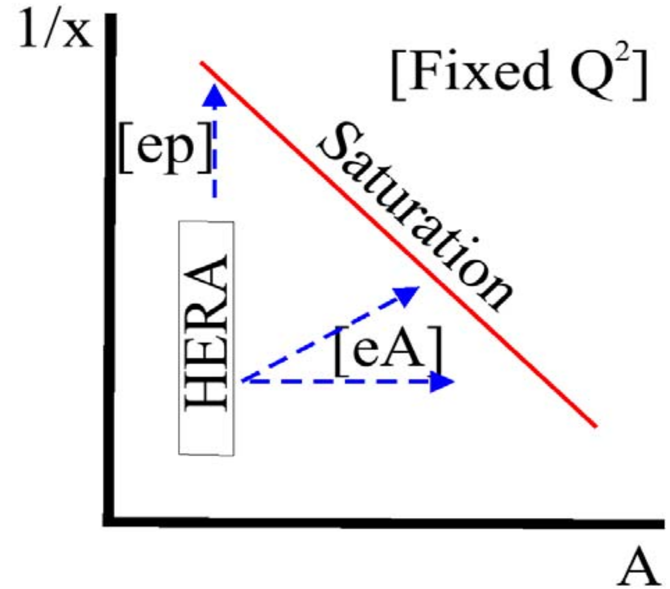
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Usually characterised in terms of an x dependent "saturation scale", $Q^2_s(x)$, to be determined experimentally

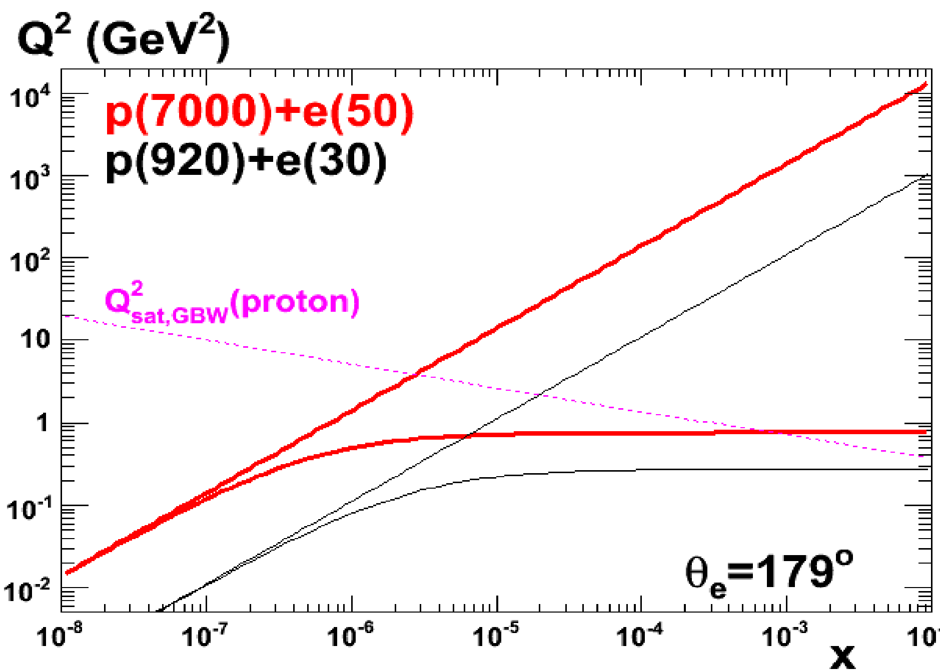
Going beyond HERA with Inclusive LHeC Data

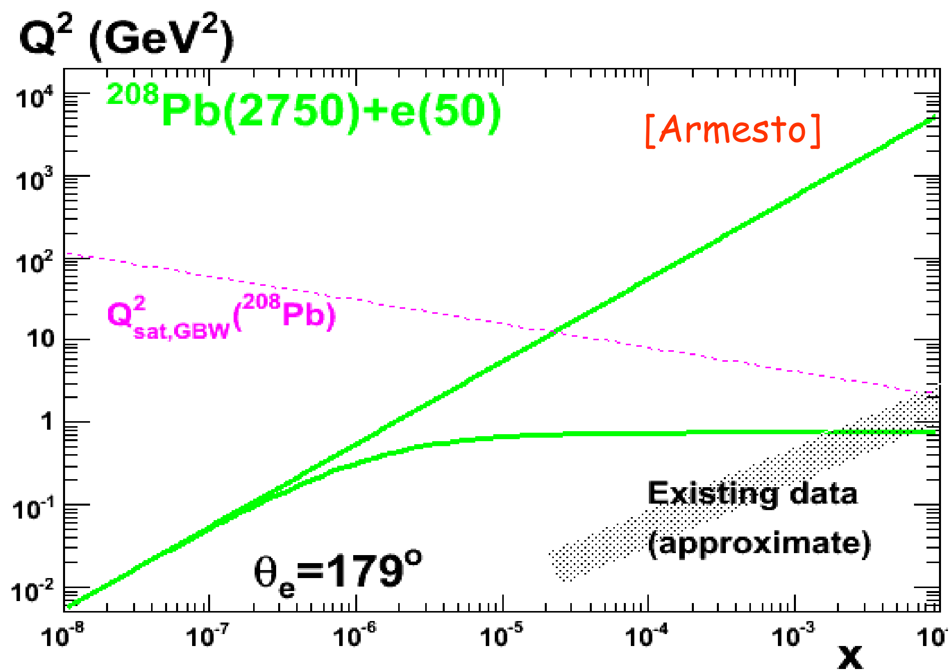
Enhance target `blackness' by:

1) Probing lower x at fixed Q^2 in ep

2) Increasing target matter in eA
… target density ~ $A^{1/3}$ ~ 6 for Pb



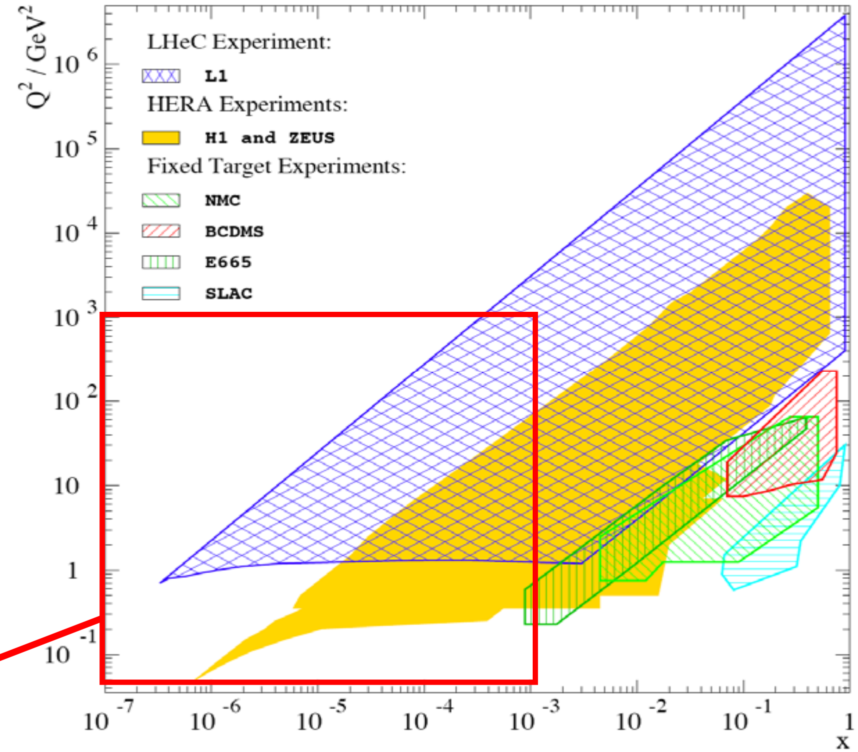


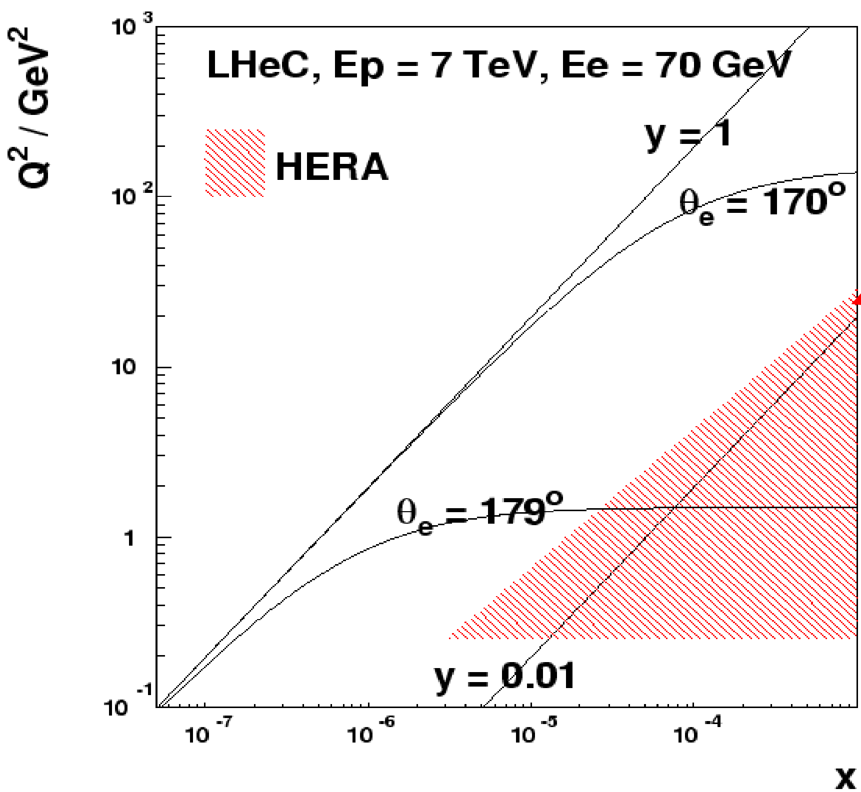


Basic Inclusive Kinematics / Acceptance

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} IF we have acceptance to 179° (and @ low E_e')

Nothing fundamentally new in LHeC low x physics with θ_e<170°





... luminosity in all scenarios ample for most low x processes

? Nothing sacred about 1° or 10°
... beyond 1° would be great!
... in between would need study

Deep Inelastic Scattering off Nuclei (D,A)

QuickTime™ and a
decompressor
are needed to see this picture.

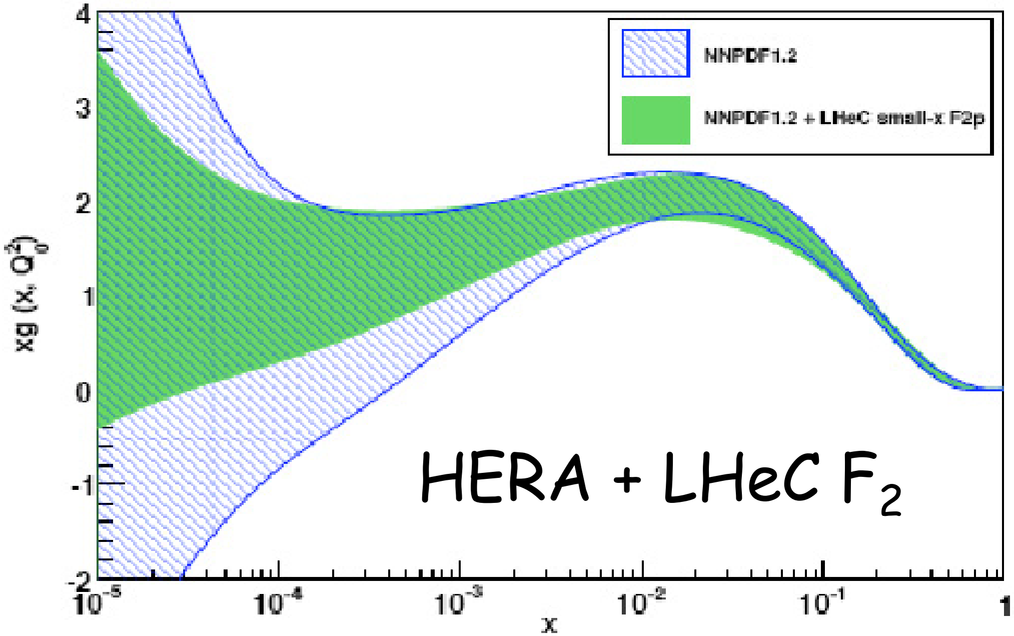
LHeC extends kinematic range of partonic structure of nuclei by 3-4 orders of magnitude.

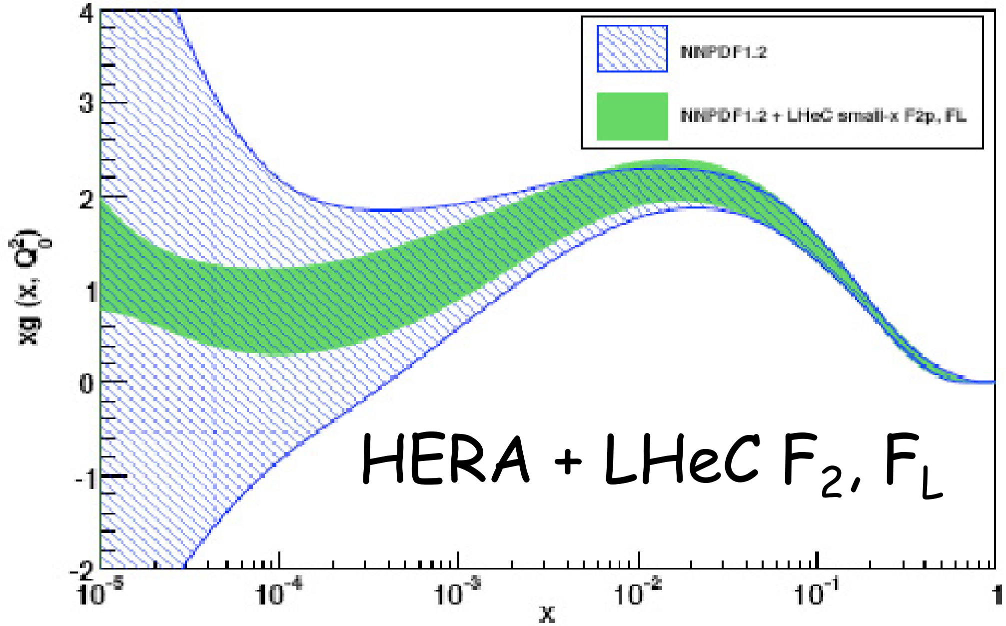
It accesses saturation effects at low x in DIS region (“beyond unitarity”)

eRHIC with nuclei could be complementary.

LHeC-A appears as natural complement and possible extension of ALICE physics programme.

Fitting for the Gluon with LHeC F_2 and F_L (Gufanti, Rojo ...)





($Q^2 = 2\ GeV^2$)

Including LHeC data in NNPDF DGLAP fit approach ...

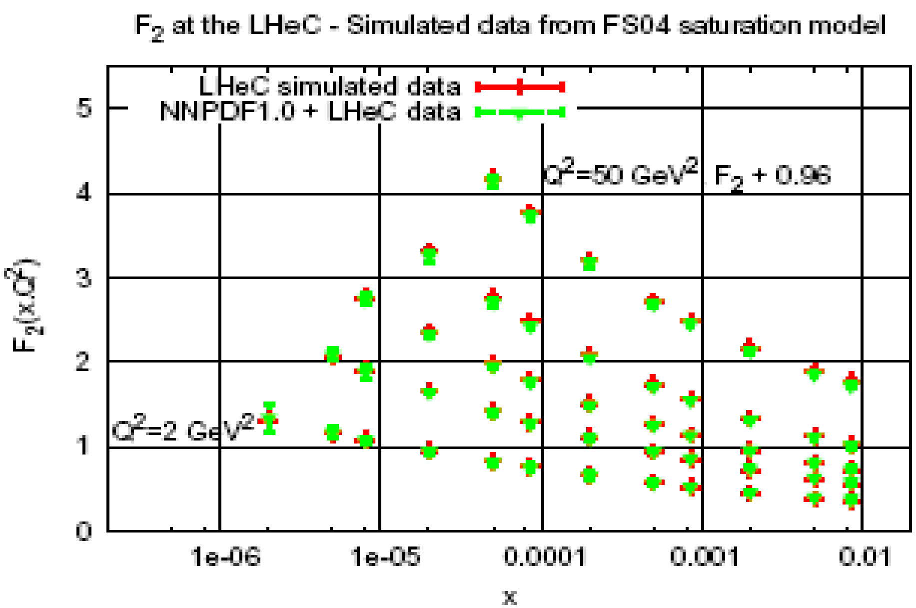
... sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

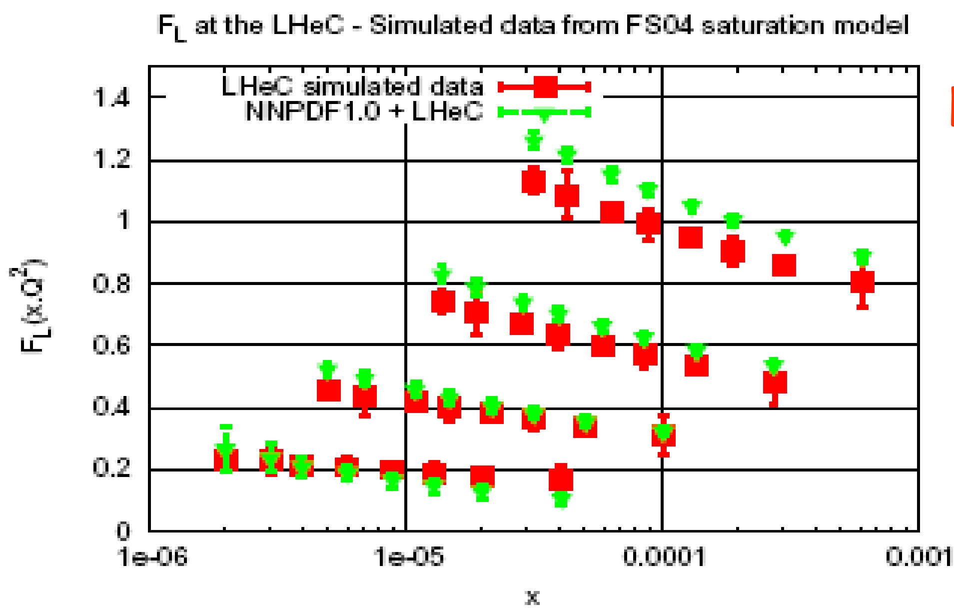
... but would DGLAP fits fail if non-linear effects present?

Can Parton Saturation be Established @ LHeC?

Simulated LHeC F_2 and F_L data based on a dipole model containing low x saturation (FS04-sat)…

… NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if F_2 and F_L both fitted





[Rojo]

Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>next try F_2^c in place of F_L</u> …

What about eA?

Common misconception: Final states in DIS from nuclei are not significantly more complicated than in DIS from protons

→ scattered electron, current jet essentially identical

→ target remnant more complicated, but very forward

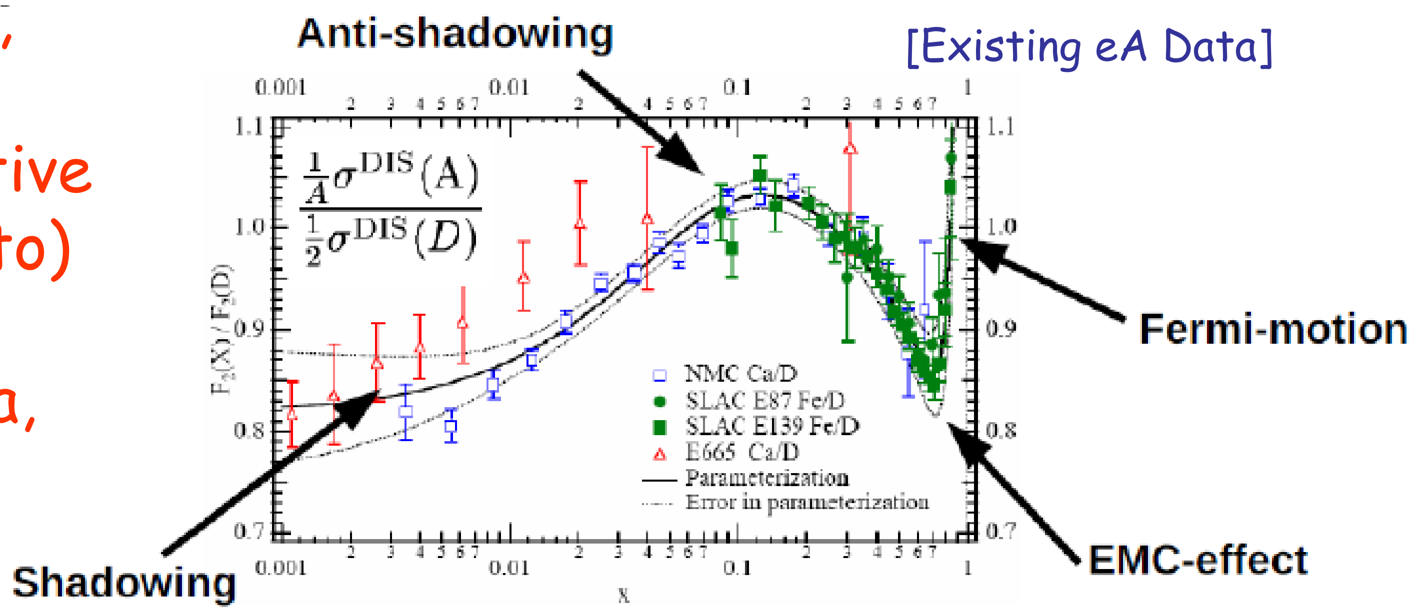
A recent highlight: quantified impact of LHeC data on nuclear parton densities:

→ pseudo-data → precision and kinematic range (Klein)

→ dipole based model, including shadowing derived from diffractive ep scattering (Armesto)

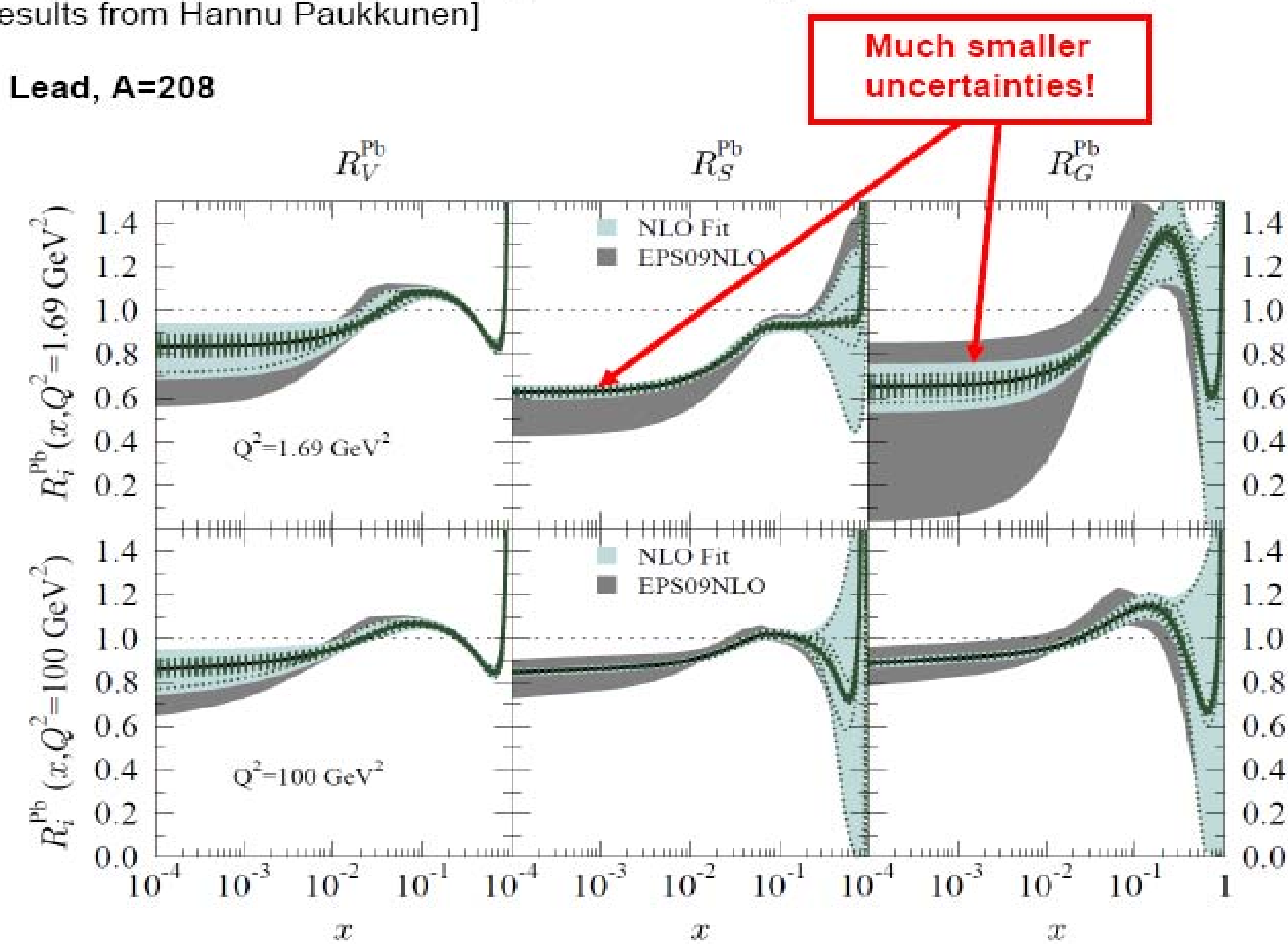
→ fits for nuclear PDFs in EPS09 (Eskola, Paukkunen)

[Existing eA Data]

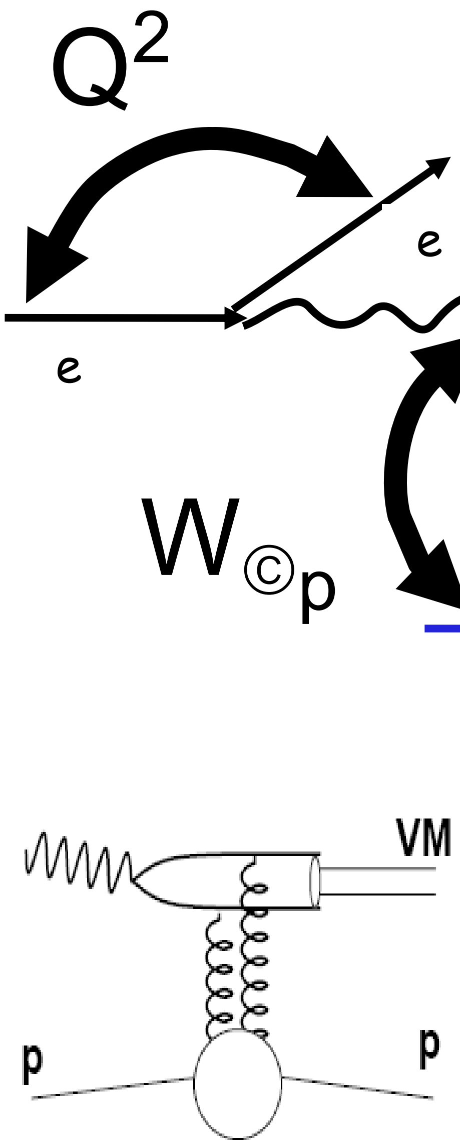


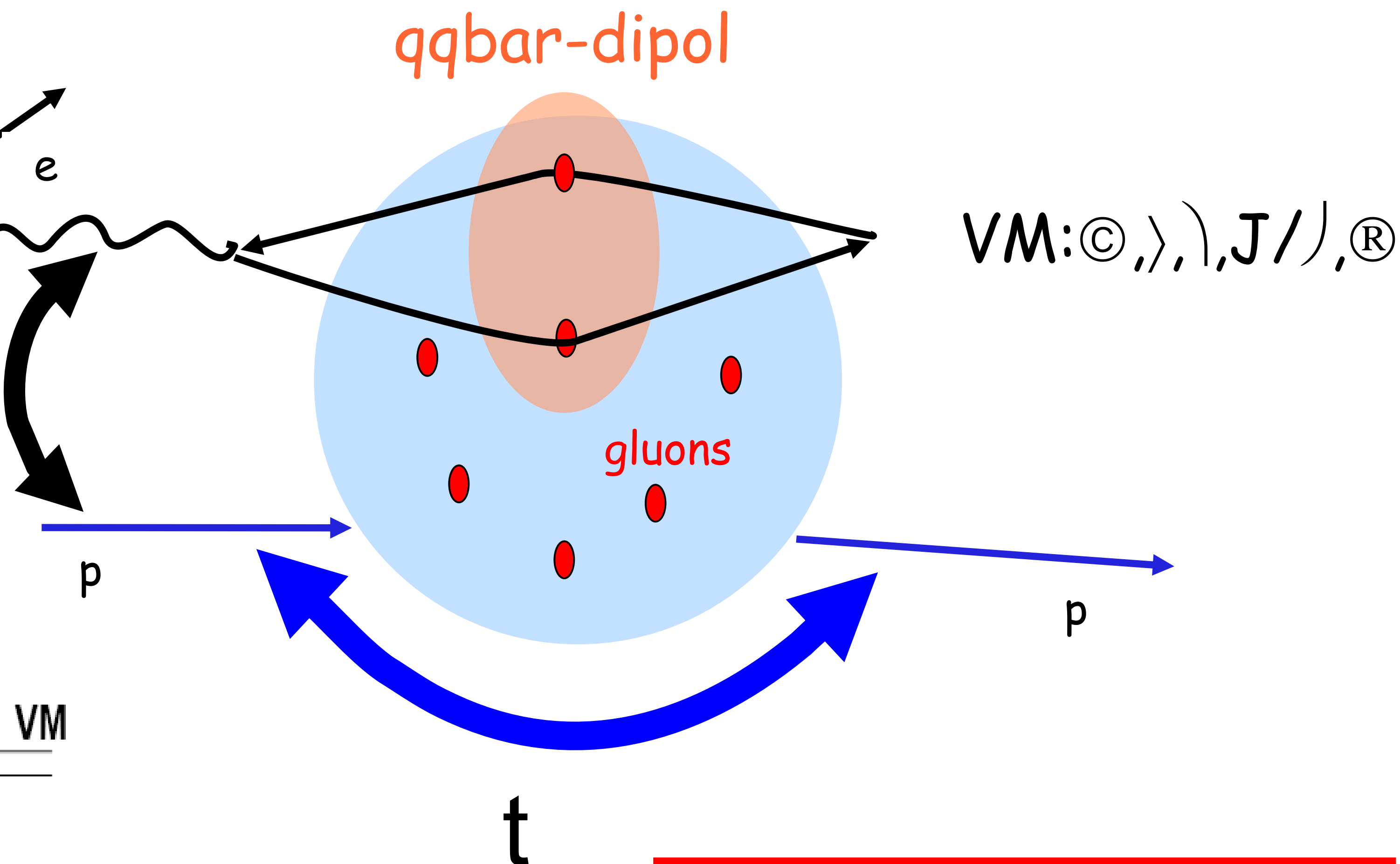
Global NLO fit with LHeC pseudodata [from N. Armesto] included

[results from Hannu Paukkunen]



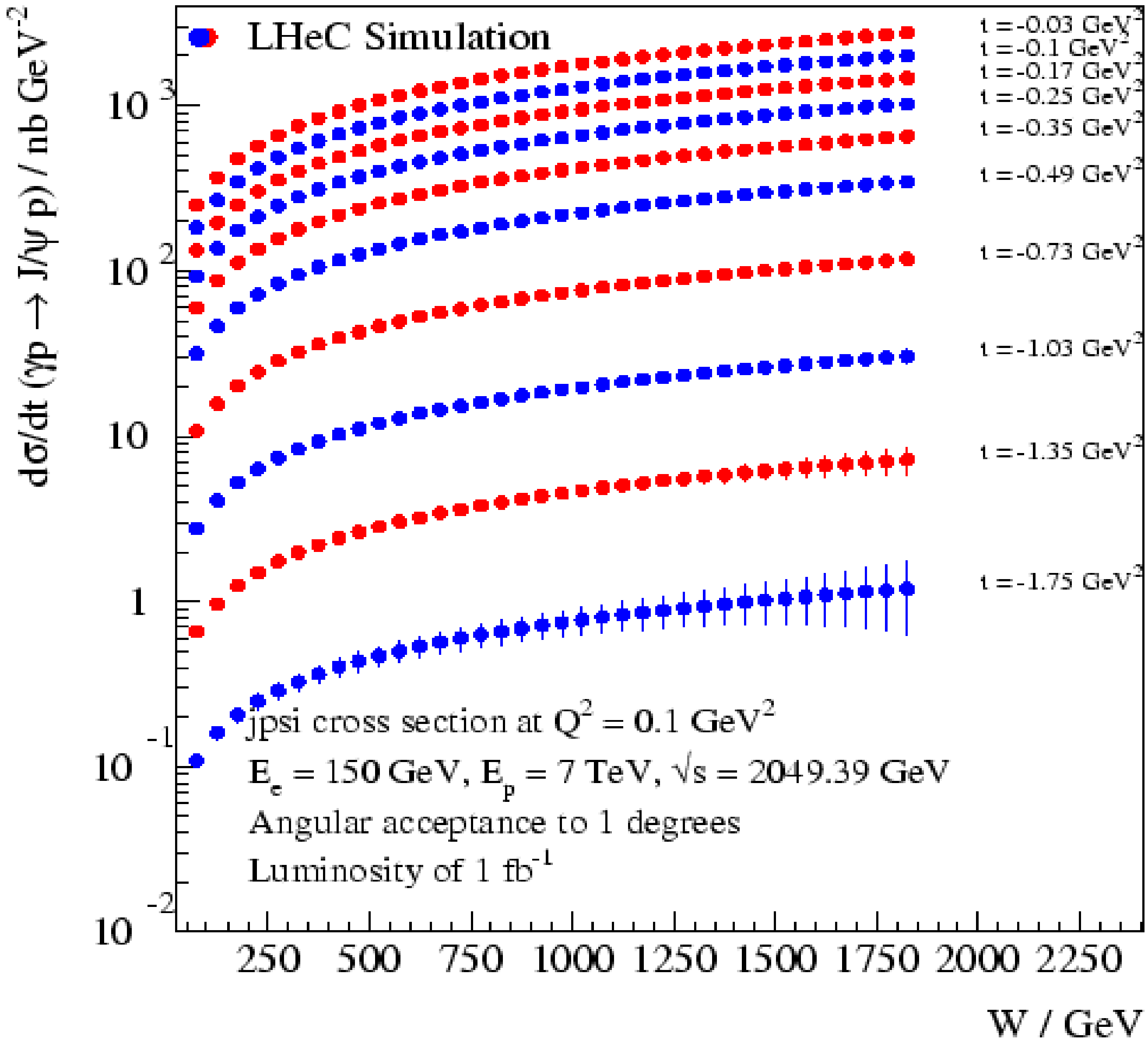
Elastic Vector meson production in ep scattering





→ Obtain 3d-picture of proton

Dedicated Low x Linac-Ring Scenario



Dream scenario!!!

J/ψ photoproduction double differentially in W and t,
E_e=150 GeV
1° acceptance

Probing x ~ 3.10^{-6}
at eff Q^2 ~ 2.5 GeV^2

c.f. GB-W model
x_s ~ 7.10^{-6} at
Q^2 ~ 2.5 GeV^2

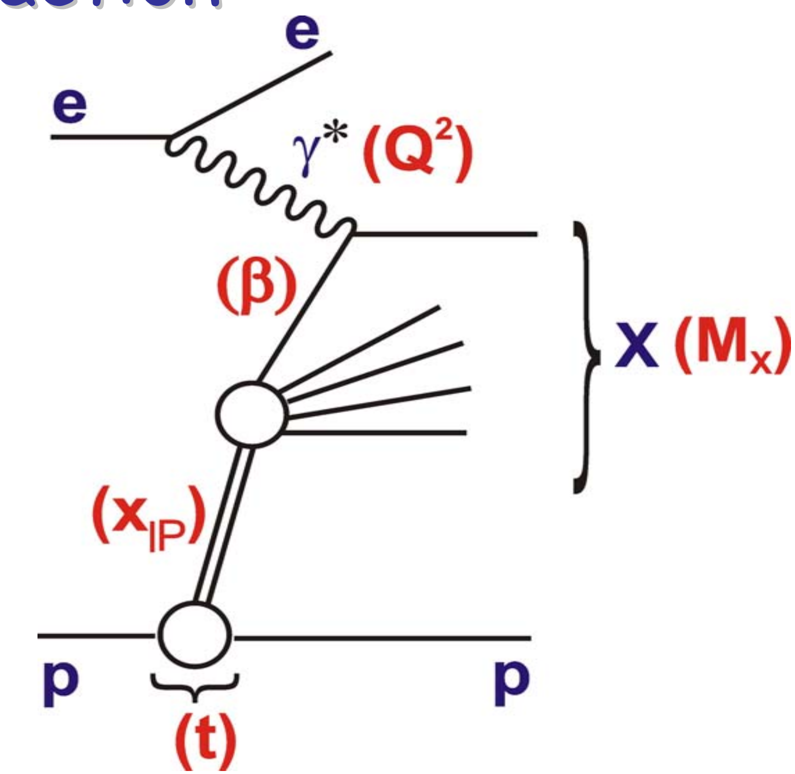
☺

Inclusive Diffraction

Additional variables …

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

b = x / x_{IP} (momentum fraction q / IP)



→ Further sensitivity to saturation phenomena

→ Diffractive parton densities in much increased range

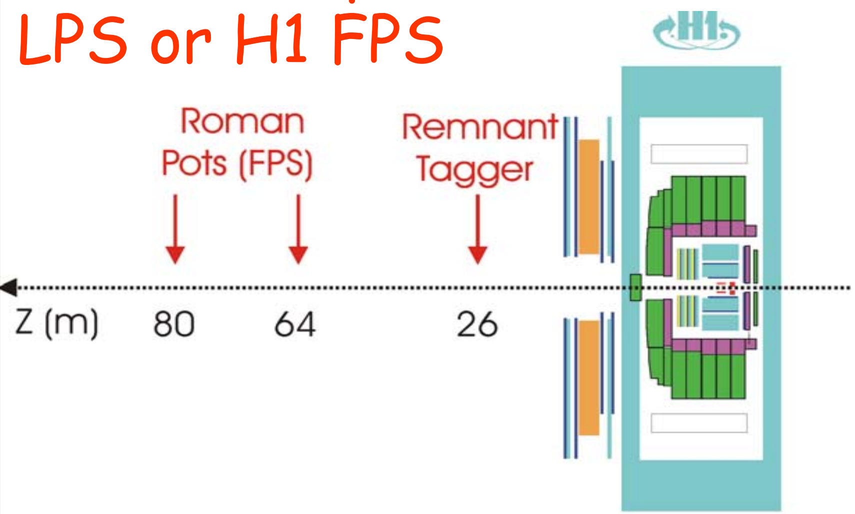
→ Sensitivity to rapidity gap survival issues

→ Can relate ep diffraction to eA shadowing

… Link between ep and eA for interpreting inclusive data

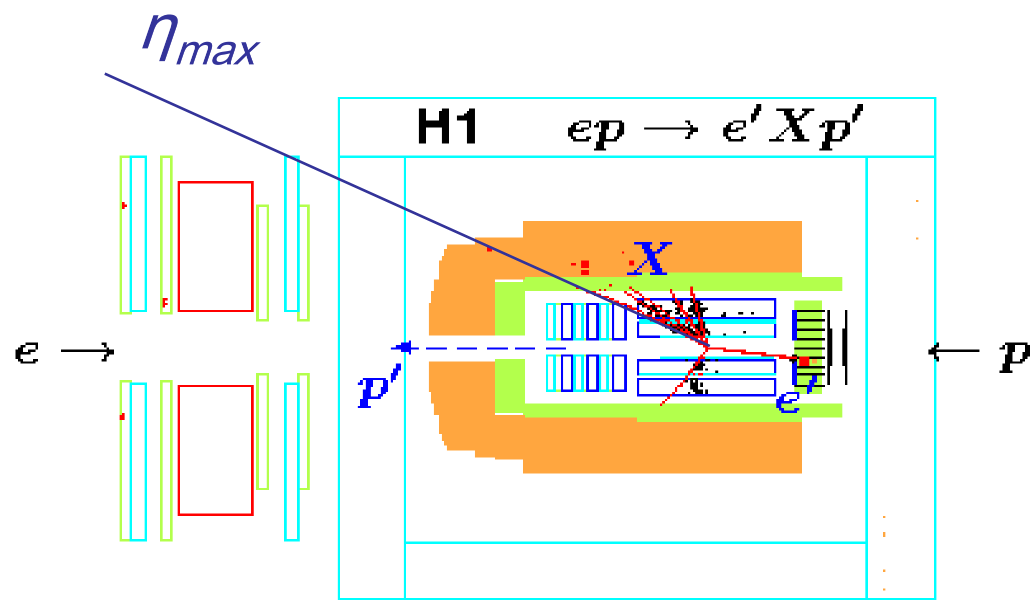
Signatures and Selection Methods at HERA

Scattered proton in ZEUS LPS or H1 FPS



- Allows t measurement
- Limited by stats and p-tagging systs

'Large Rapidity Gap' adjacent to outgoing (untagged) proton

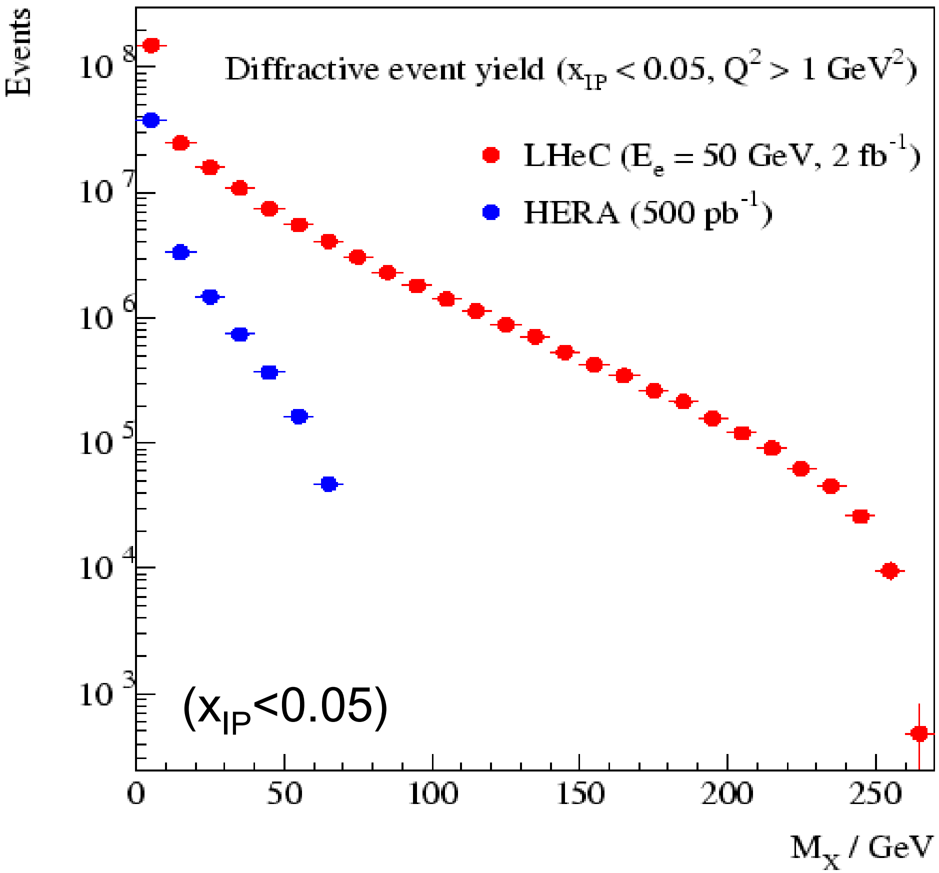


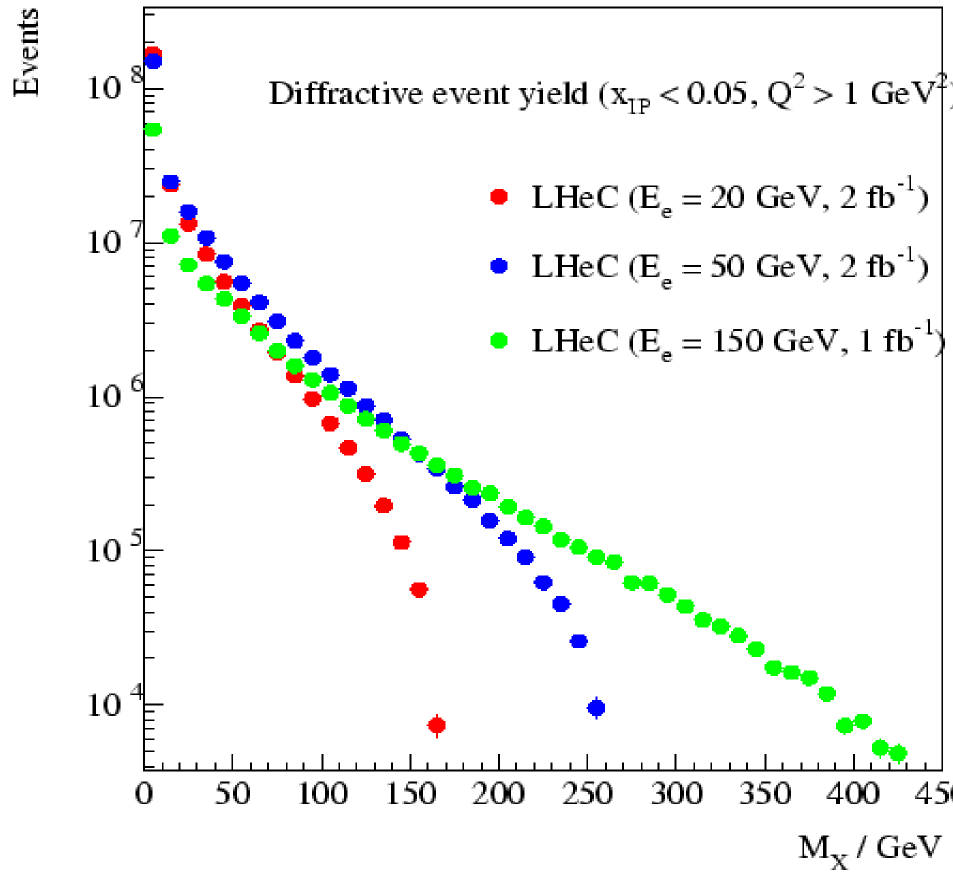
Limited by p-diss systs

Worked well: The methods have very different systs!
What is possible at LHeC?...

New region of Diffractive Masses

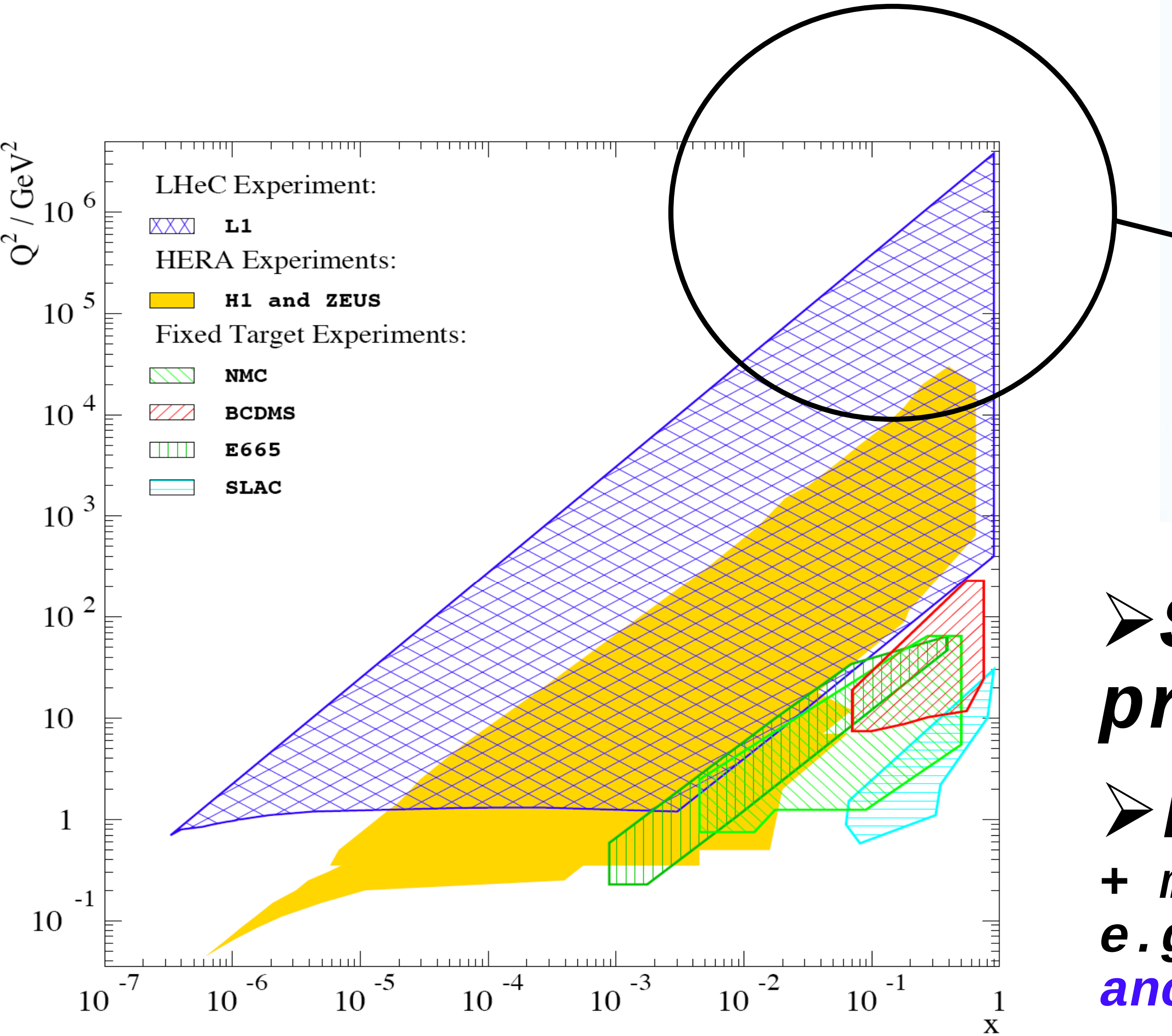
No alternative to proton spectrometer to select high M_x





- `Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z / H(?) bosons
- Unfold quantum numbers / precisely measure new 1^{--} states

SM and new physics at the high energy frontier



- ***SM Higgs production***
- ***Leptoquarks***

+ many other possibilities, e.g. excited leptons, anomalous single top production, etc.

Higgs production at LHeC

Dominating process

Beware of backgrounds

150 GeV

QuickTime™ and a decompressor are needed to see this picture.

σ~160 pb
for mH=120 GeV

QuickTime™ and a decompressor are needed to see this picture.

+ many many others

Motivation: Measure H→bb coupling

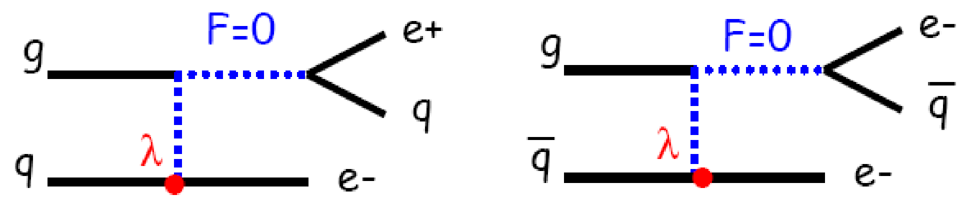
Expected reconstr. dijet mass spectrum of signal process only

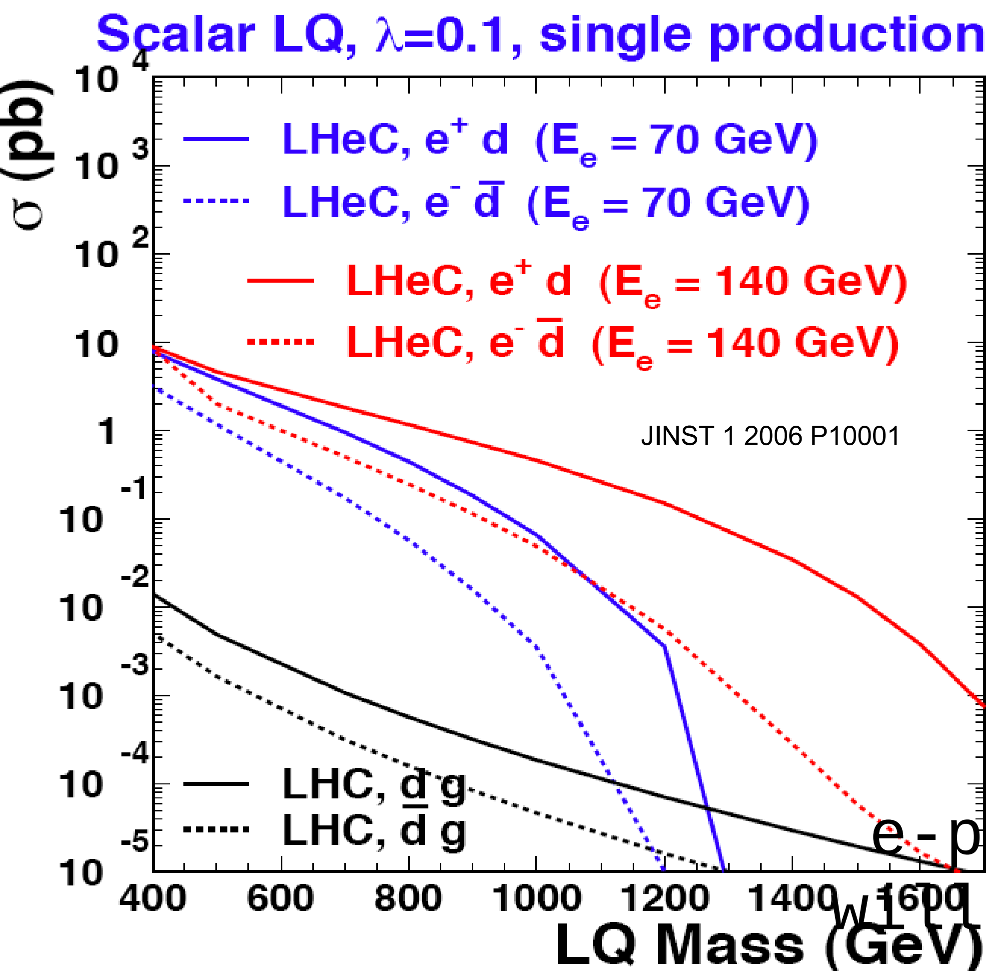
QuickTime™ and a decompressor are needed to see this picture.

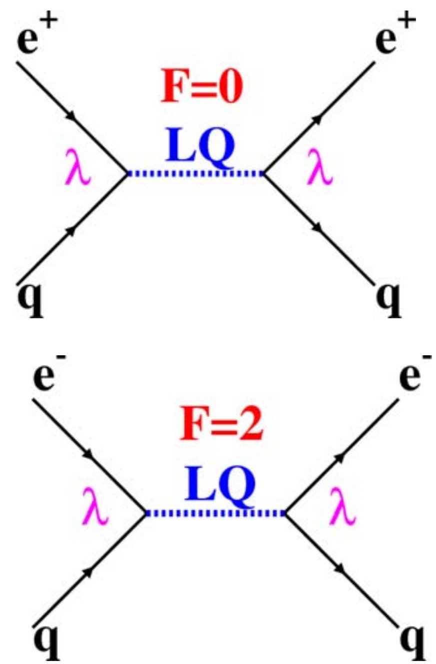
Excellent b tagging needed to suppress large backgrounds

Single LQ production at LHC

New physics example
Leptoquarks: determine quantum Numbers at LHeC







Single LQ production at LHeC

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

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 u/d at large x or a strange-antistrange asymmetry 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.

Determination of fundamental SM constants: light quark axial and vector couplings to Z boson, W propagator mass, strong coupling constant α_s with permille level precision

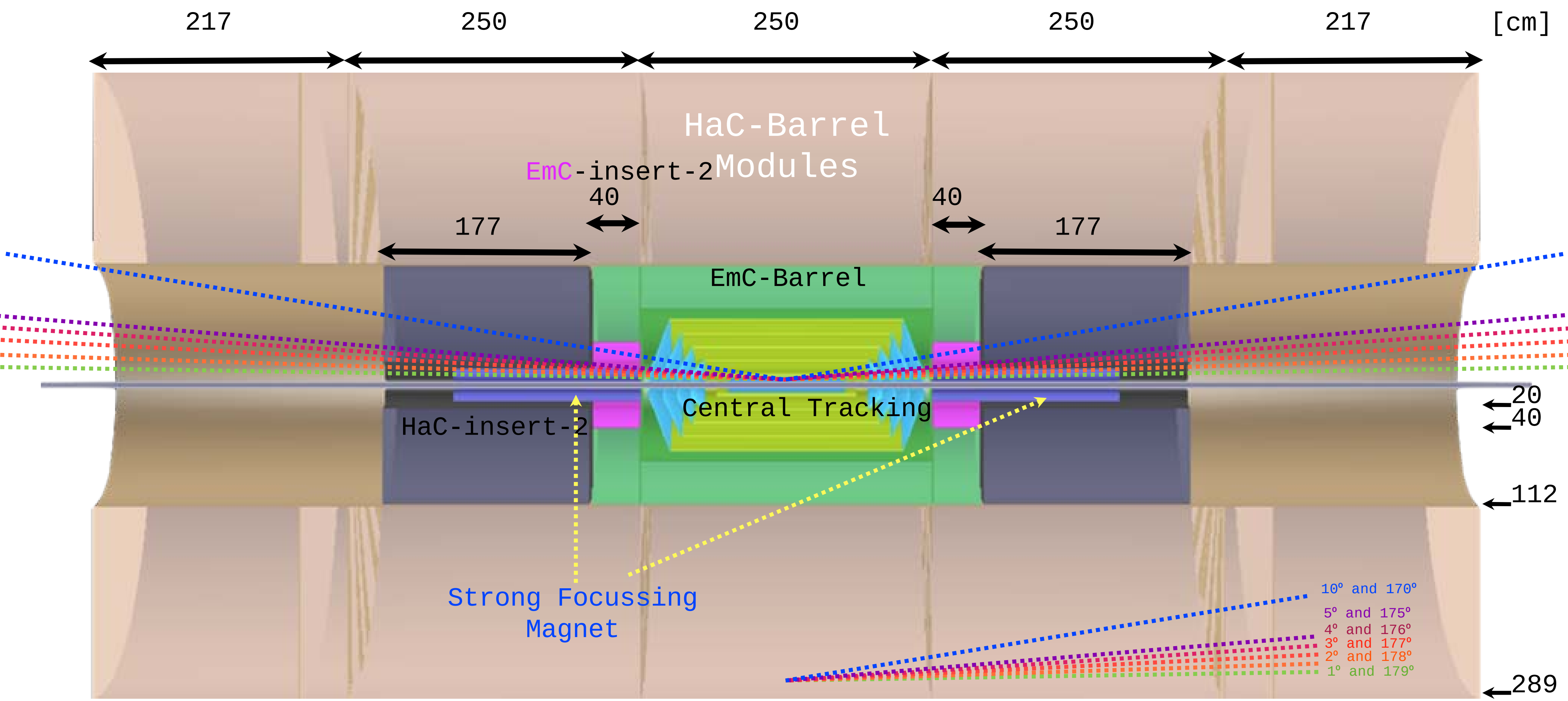
Wealth of QCD tests with final states (not much discussed in this talk : Jets (study also photon structure), heavy flavours, prompt photons, other identified particles

Low x and diffractive physics with ep and eA: Measuring multiple observables (F2, Fl, F2c, F2D, Vector mesons…) in ep and eA can lead to a microscopic understanding of non-linear evolution, unitarity

Backup slides

The High Lumi (High Q²) Setup

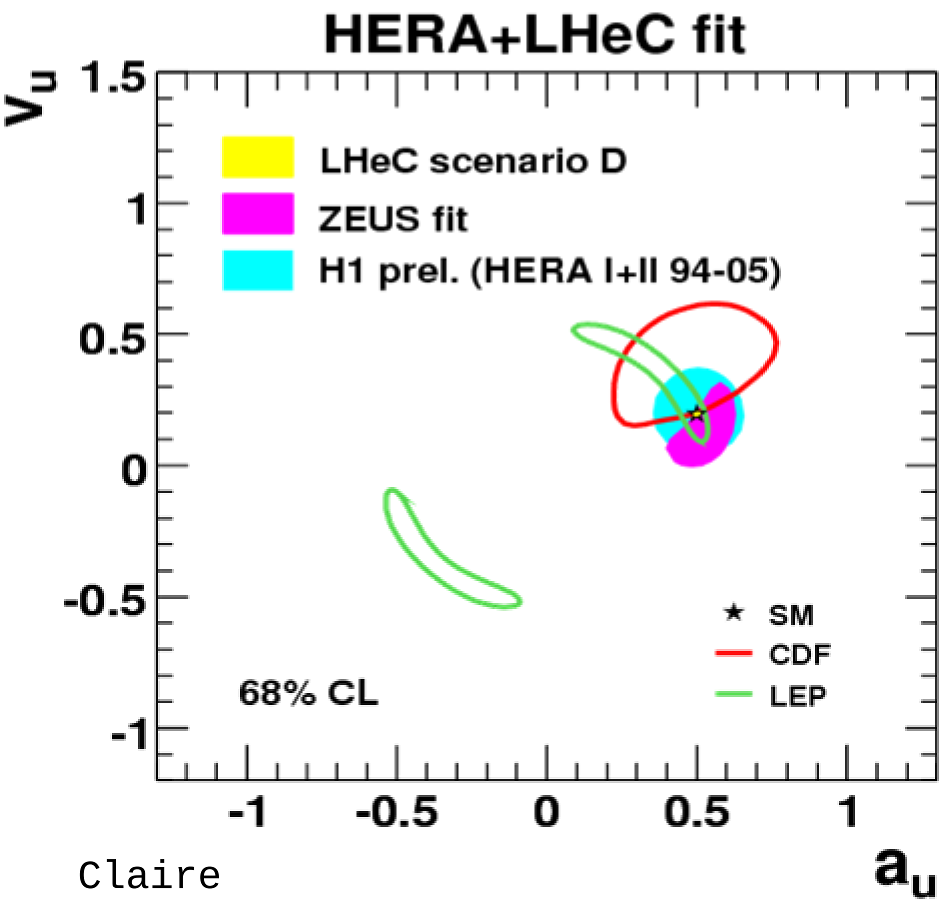
(to be optimised)



L1 Low Q² SetUp → High Q² SetUp

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

Fermion couplings to Z boson



QuickTime™ and a decompressor are needed to see this picture.

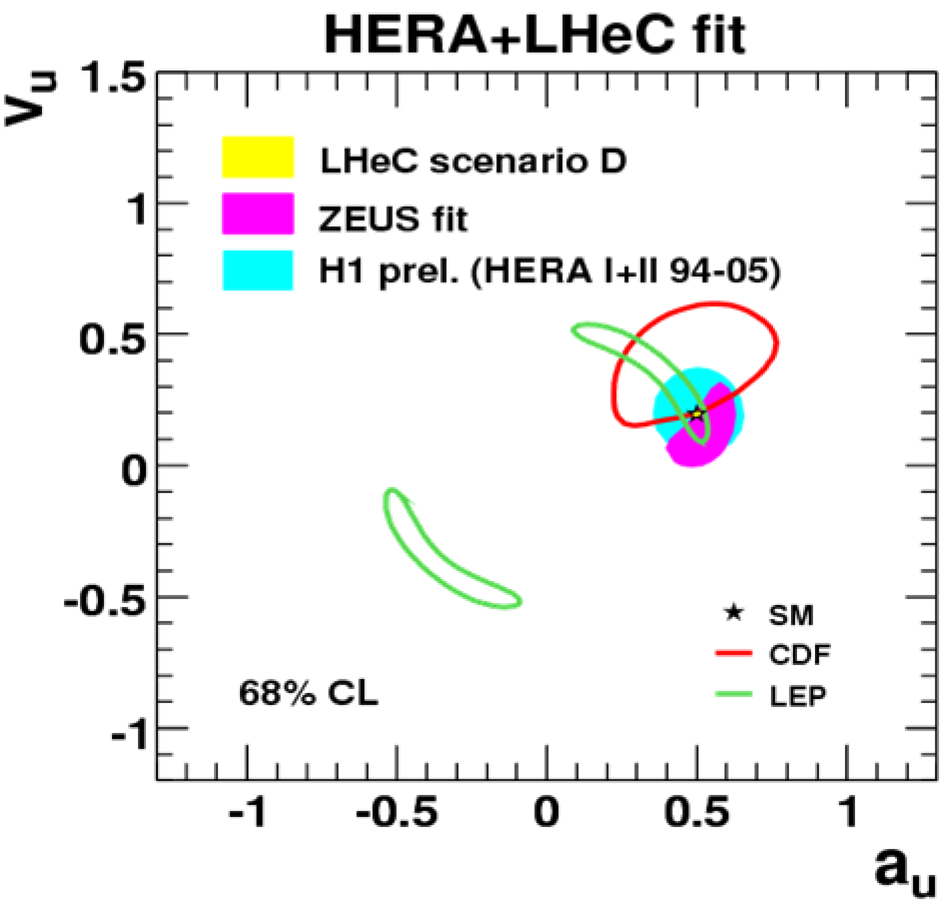
QuickTime™ and a decompressor are needed to see this picture.

Claire Gwenlan.

Reported by Soumitra Nandi.

(and HERA) especially sensitive to u and d couplings:
expect deviations from SM for these couplings
e.g in Leptophobic Z′ models

Fermion couplings to Z boson



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ral suggestion (Paolo Gambino) for LHeC electroweak stu
y fit with sin^2($_w$) as only free parameter; determinat
as function of hard scale also interesting

W boson mass

M_W enters the fit through the **propagator** in the CC cross sections:

$$\frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2}$$

➔ also performed fit including LHeC CC, **with M_W free**, together with the PDFs (NC quark couplings fixed to SM)

M_W (= 80.4 SM)

Scenario D

M_W = 80.40 ± 0.04 (uncorr.) ± 0.15 (corr.) GeV (total exp. 0.2%)

Improved (wrt HERA) but not competitive

(although still interesting as a cross-check; space-like regime)

current world average (PDG 2008): M_W = 80.398 ± 0.025 GeV **(0.03% total)**

Proton PDFs

Claire Gwenlan

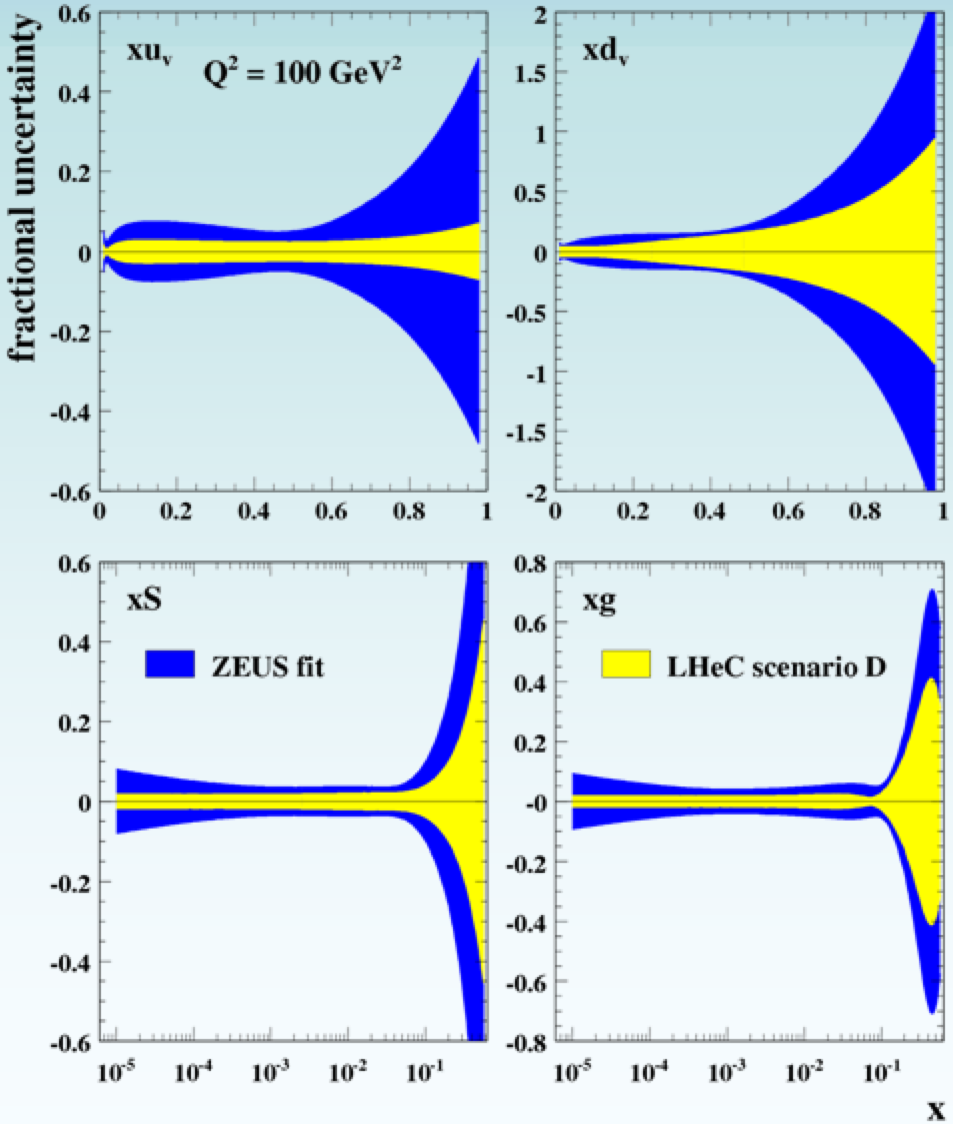
Q^2 = 100 GeV^2

scenario D

» <u>only</u> PDF parameters free
(LHeC **NC** $e^{\pm}p$ included)

<u>PDF uncertainties:</u>

- **NC $e^{\pm}p$**: direct constraints on **quark densities**; indirect on **gluon** via scaling violations



Proton PDFs

Claire Gwenlan

$Q^2 = 100$ GeV^2

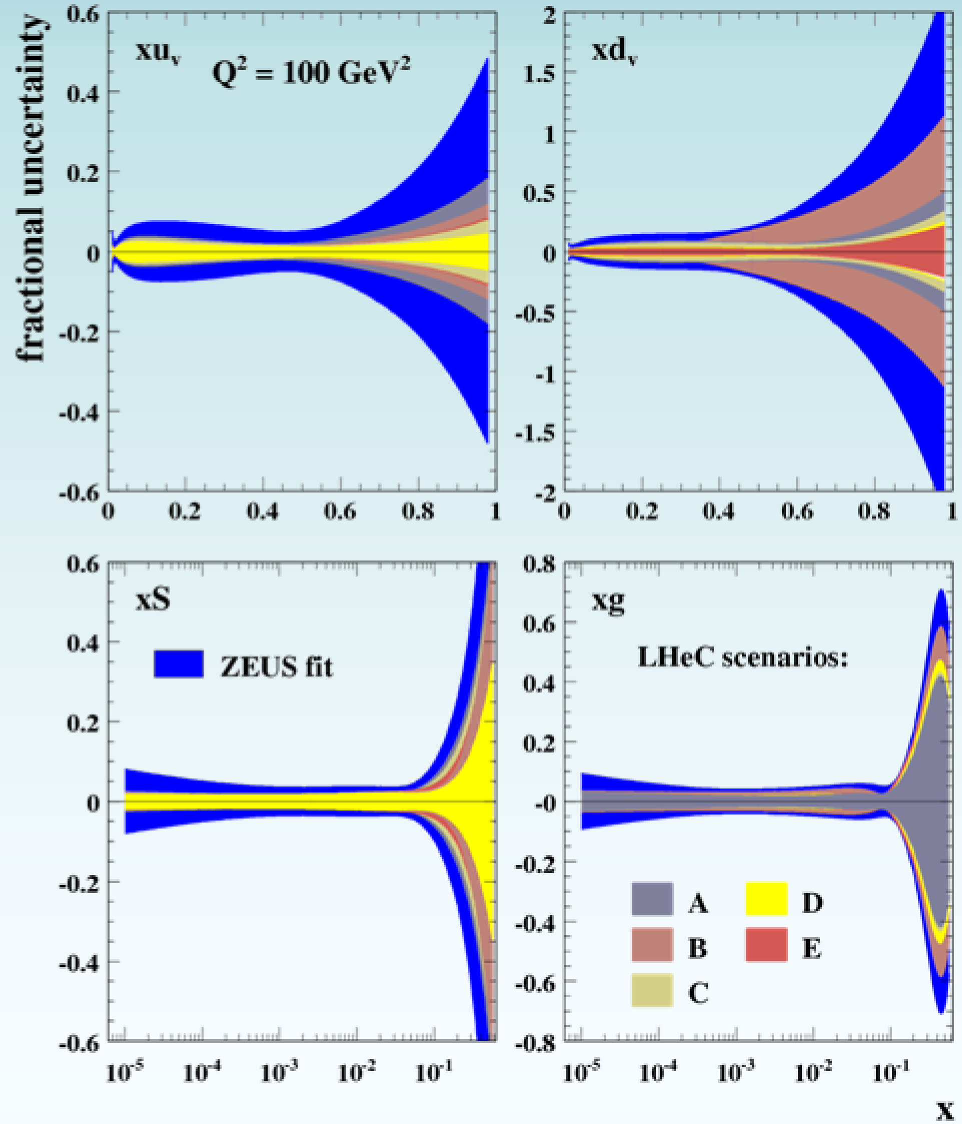
scenario D

» <u>only</u> PDF parameters free
(LHeC **NC** and **CC** $e^{\pm}p$ included)

scenarios: **A**, **B**, **C, D** and **E**

	E_e (GeV)	P	L (e-:e+)
A	20	0	2 (1:1)
B	50	0.4	200 (1:1)
C	50	0.4	4 (1:1)
D	100	0.9	30 (2:1)
E	150	0.9	18 (2:1)

(examples with several different Q^2 values are shown in backups)



* acceptance for scenario B has been taken to be: $10 < \theta < 170^o$

Higgs production and improvement due to LHeC pdfs

Alessandro Vicini

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are needed to see this picture.

Alessandro Vicini

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decompressor
are needed to see this picture.

Gluon - SM Higgs

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decompressor
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QuickTime™ and a
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are needed to see this picture.

E.Perez, DIS07

CTEQ Belyayev et al. JHEP 0601:069,2006

In SM Higgs production is gluon dominated

LHeC: huge x,Q^2 range for xg determination

WW to Higgs fusion has sizeable ep xsection

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decompressor
are needed to see this picture.

U.Klein
B.Kniehl
M.Kuze
E.Perez

Cross section is half at 70 GeV. NLO is about 2

Beauty - MSSM Higgs

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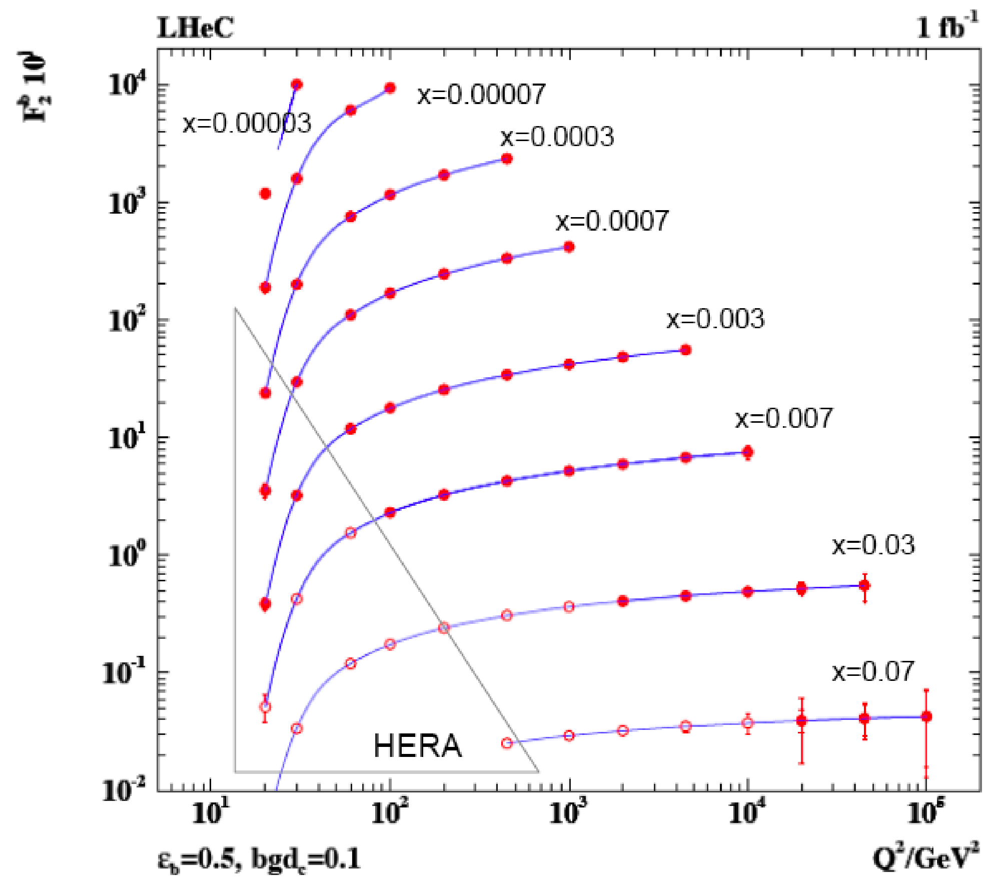

CTEQ Belyayev et al. JHEP 0601:069,2006

In MSSM Higgs production is b dominated

First measurements of b at HERA can be turned to precision measurement of b-df.

LHeC: higher fraction of b, larger range, smaller beam spot, better Si detectors

MK, A.Mehta (DIS07)

SHERPA

Stefan Hoeche

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QuickTime™ and a decompressor are needed to see this picture.

Lets make use of it for LHeC predictions, e.g. for bW-> t

Quark-Gluon Dynamics - Diffraction and HFS (fwd jets)

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decompressor
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QuickTime™ and a
decompressor
are needed to see this picture.

HERA

QuickTime™ and a
decompressor
are needed to see this picture.

H.Jung, L.Loennblad, THERA study

Diffraction to accompany (SUSY) Higgs fwd physics at LHC

P.Newman, DIS07

Understand multi-jet emission (unintegr. pdf's), tune MC's
At HERA resolved effects mimic non-kt ordered emission
Crucial measurements for QCD, and for QCD at the LHC

Quark-Gluon Dynamics (saturation, GPDs)

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decompressor
are needed to see this picture.

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QuickTime™ and a
decompressor
are needed to see this picture.

P.Newman, L.Favart, DIS08

J.Forshaw et al, DIS08

QuickTime™ and a
decompressor
are needed to see this picture.

Divonne

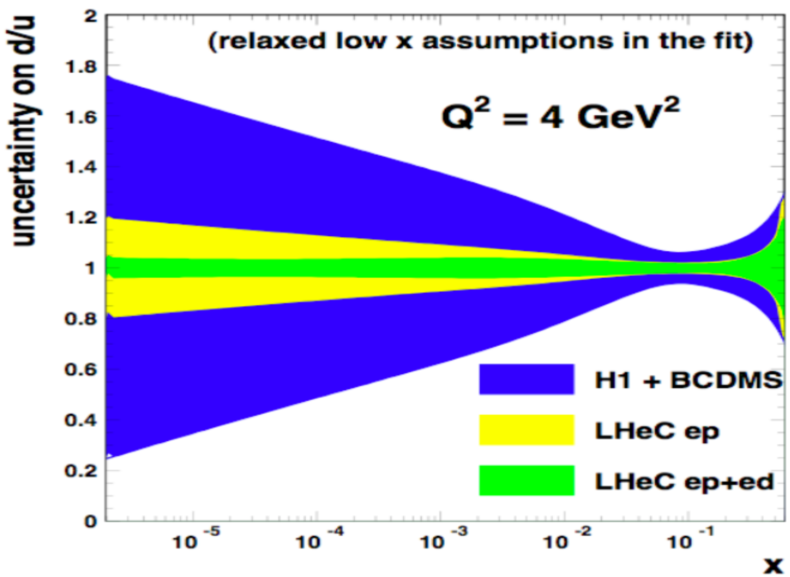
LHeC opens phase space to discover saturation in DIS

J.Bartels at Divonne on low x theory

High luminosity, polarisation, accuracy for GPD's (DVCS)

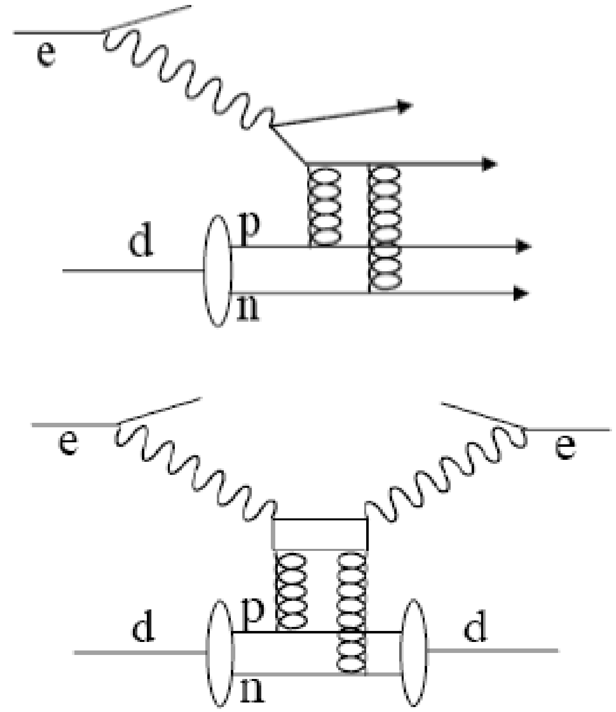
Neutron Structure (ed   eX)

d/u at low x from deuterons



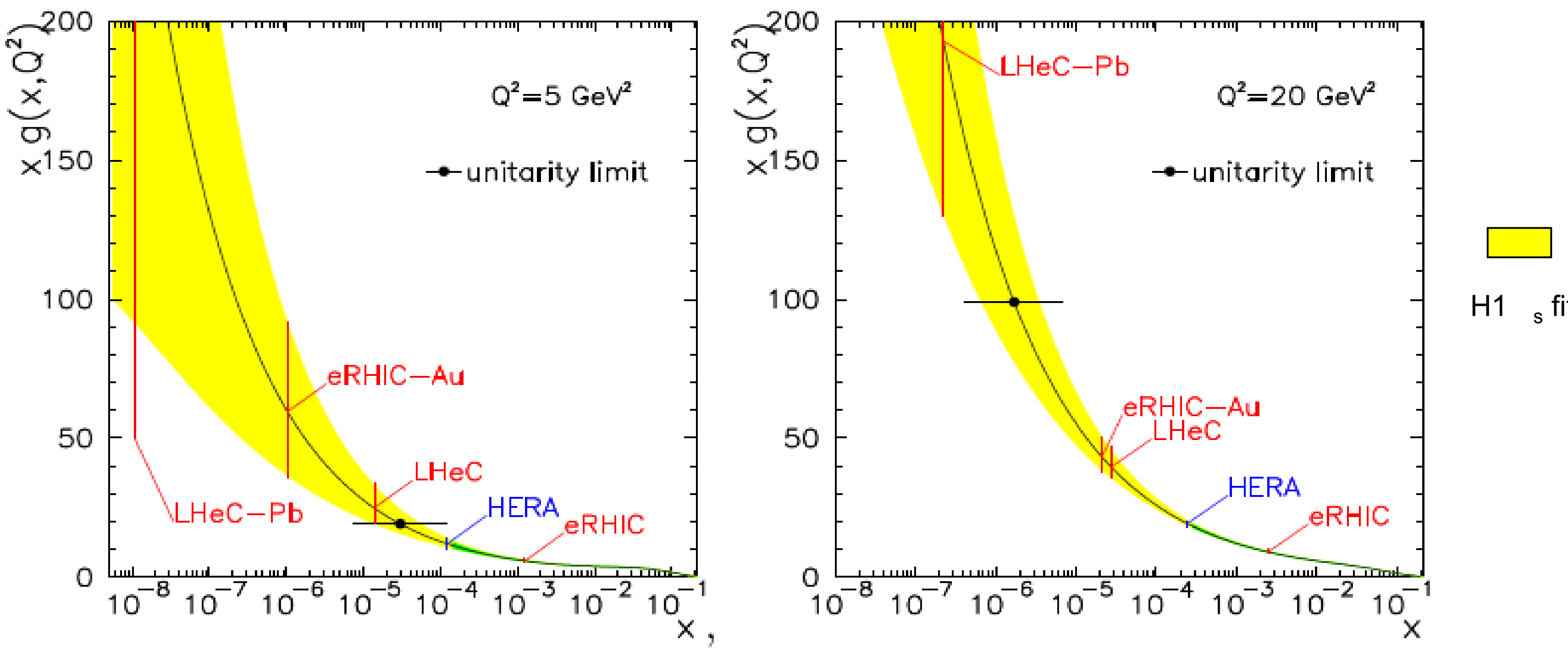
(13) There are five color-singlet combinations of the deuteron wavefunction in QCD, only one of which is the standard proton-neutron state. The "hidden color" [13] components will lead to high multiplicity final states in deep inelastic electron-deuteron scattering.

crucial constraint on evolution (S-NS), improved $_s$



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

Density Amplification and Unitarity Limit



High density $$\frac{g_A / \pi r_A^2}{g_p / \pi r_p^2} = A^{1/3} \frac{g_A}{A g_p}$$

Unitarity $$xg(x,Q^2) \le \frac{1}{\pi N_c \alpha_s(Q^2)} Q^2 R^2 \simeq \frac{Q^2}{\alpha_s}$$

Striking effects predicted:

Bj black disc limit $F_2 \sim Q^2 \ln(1/x)$

~50% diffraction

colour opacity, change of J/ (A) …

Need eA collider data to determine nuclear parton distributions in the kinematic range of pA/AA collisions at the LHC

NuPECC EIC-LHeC Study group

Tullio Bressani, INFN, Torino Univ.
Jens Jørgen Gaardhøje, Niels Bohr Inst.
Günther Rosner, Glasgow Univ.
Hans Ströher, FZ Juelich

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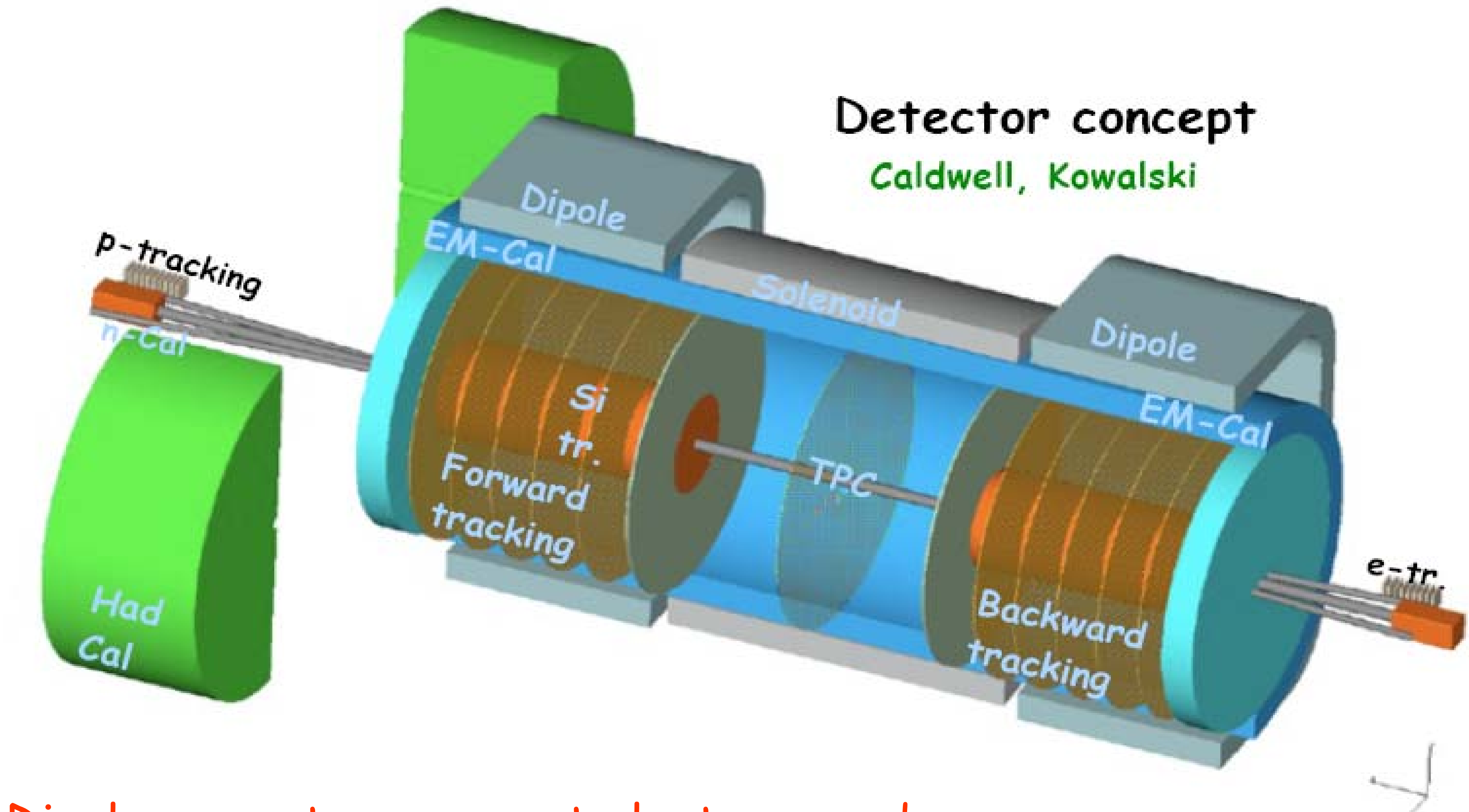
Another Low x Detector Concept



Dipole magnets sweep out electrons and forward going hadrons scattered at very low angles