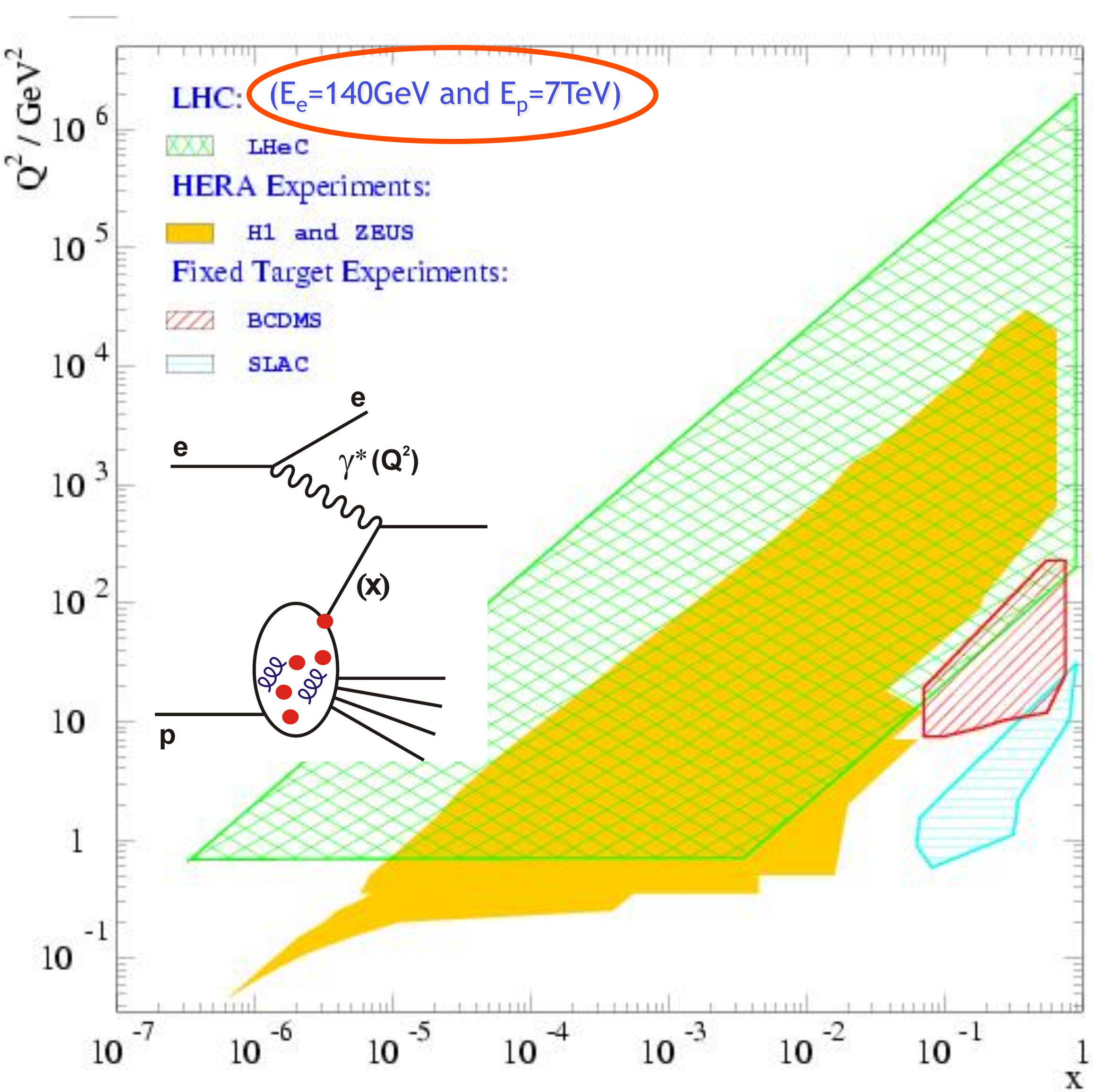
High Energy DIS after HERA?… The LHeC Project

Paul Newman
Birmingham University,
(for the LHeC study group)



Oxford Seminar
14 June 2011

… work in progress from ECFA/CERN/NuPECC workshop on ep/eA physics possibilities at the LHC

http://cern.ch/lhec

Material Taken from Draft Conceptual Design Report

DRAFT 0.5
CERN, June 1st, 2011

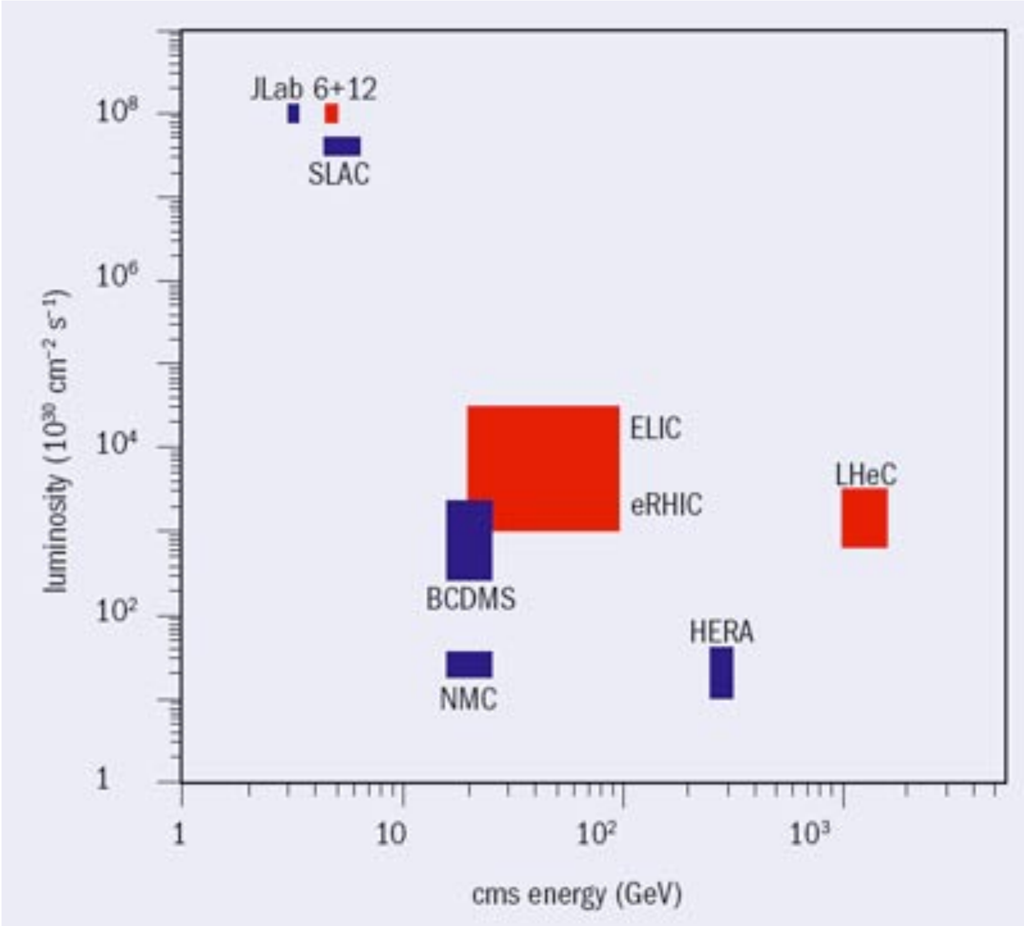
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

- Around 500 pages
- Summarising work of ~200 participants over 5 years
- Nobody works full time on LHeC yet
- Due for release in Autumn 2011

LHeC is the latest & most promising idea to take ep physics to the TeV centre-of-mass scale …
… at high luminosity



Contents

- A brief history of ep Physics
- How to build an ep Collider using the LHC
- Detector considerations
- Physics motivation
  - BSM physics
  - Precision QCD / EW
  - Low x / high parton densities
  - Electron – ion collisions
- Timeline and outlook

Electron Scattering Experiments

"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle."
[Ernest Rutherford, Royal Society, London, (as PRS) 30 Nov 1927]

1950s
Hoffstadter

First observation of **finite proton size** using 2 MeV e beam

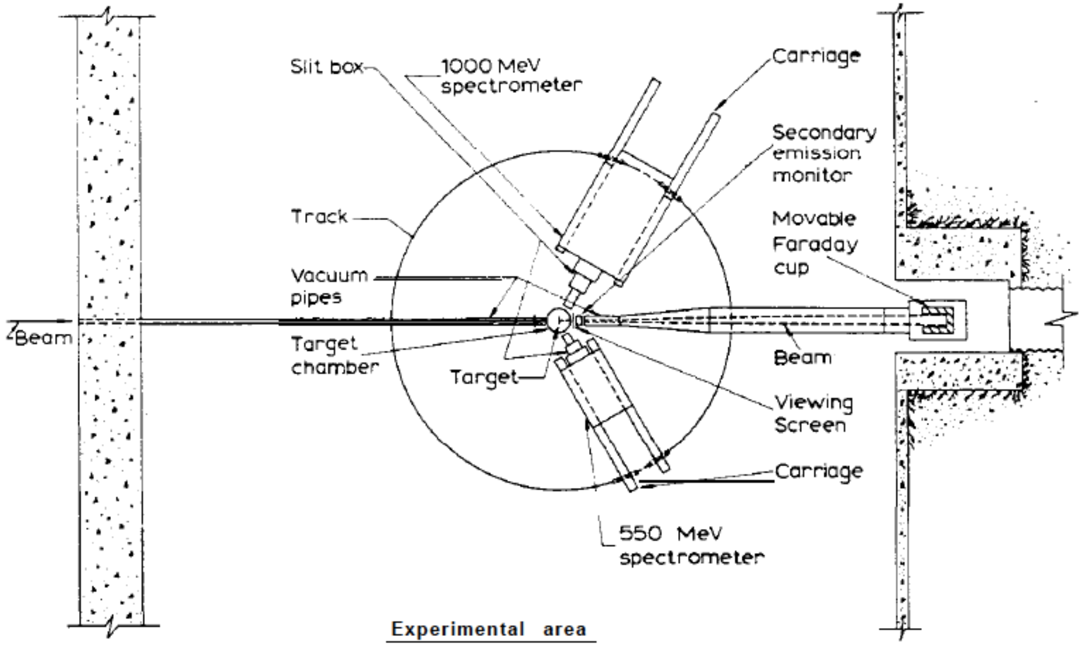
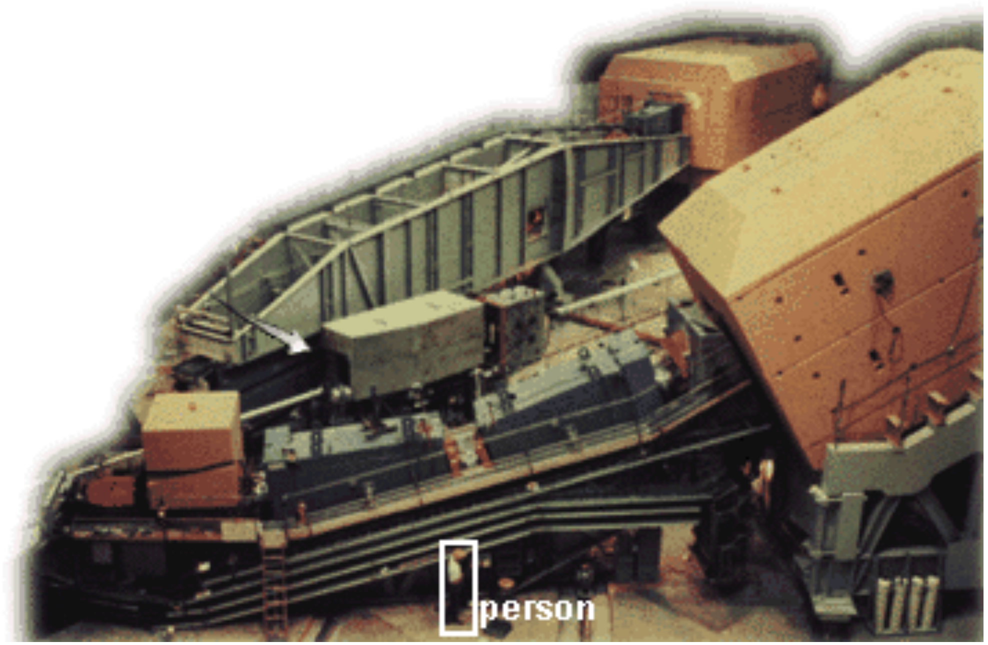


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

SLAC 1969: Electron Energies 20 GeV



Proposal:
"A general survey of the basic cross sections which will be useful for future proposals"

First Observation Of Proton Structure

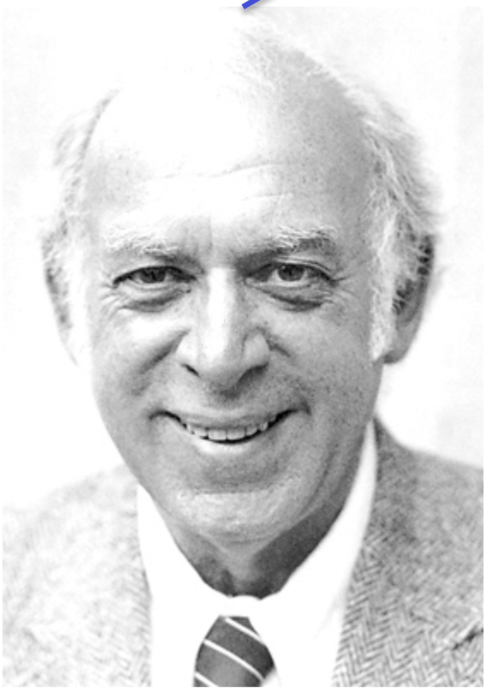
VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

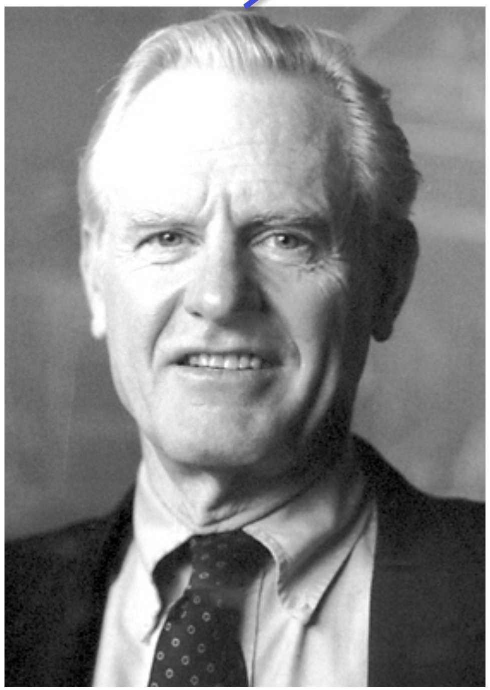
OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

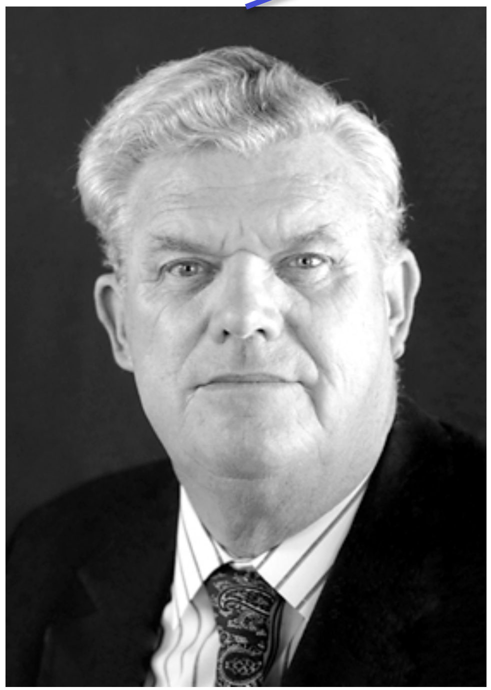
M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)





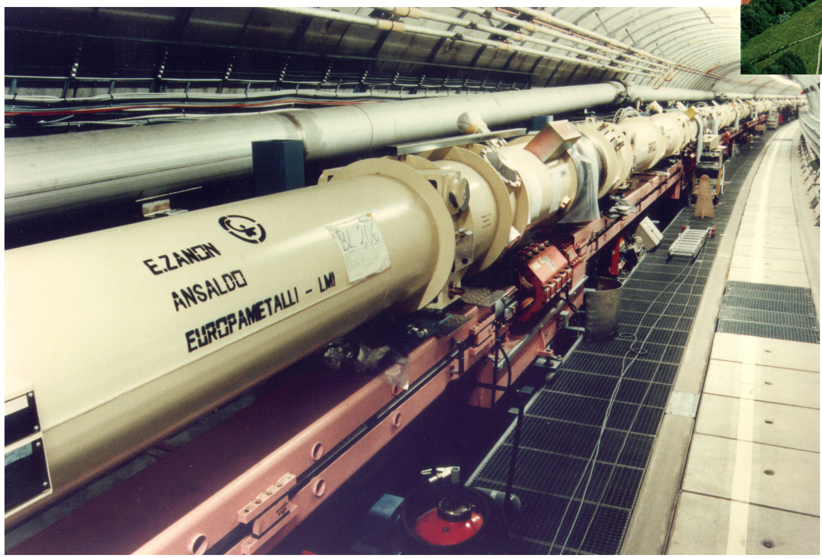


Nobel Prize 1990

DESY, Hamburg

HERA (1992-2007)

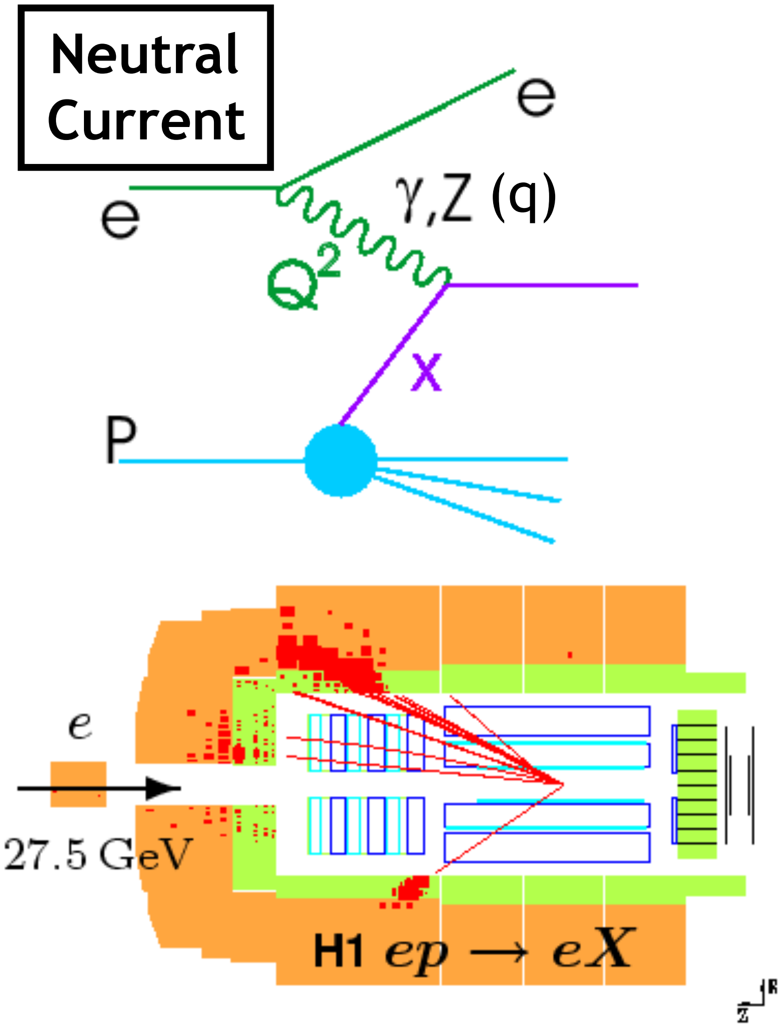
… the only ever collider of electron beams with proton beams

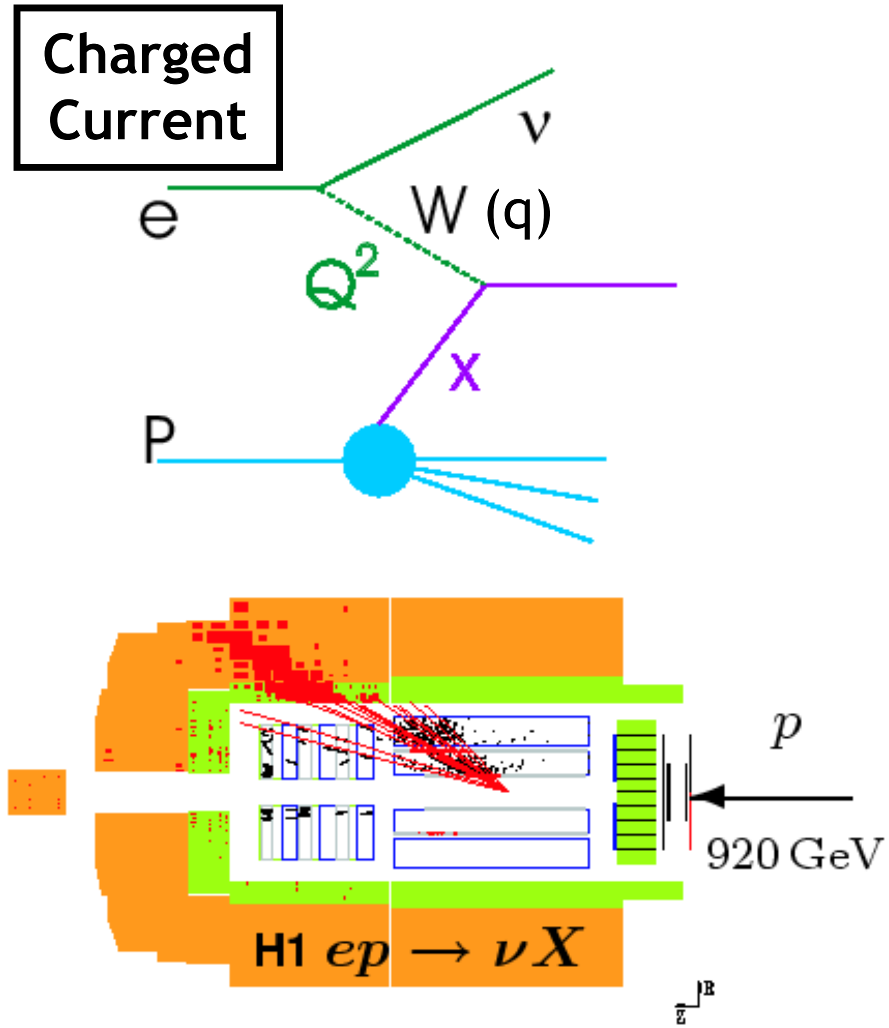


Equivalent to a 50 TeV beam on a fixed target proton
~2500 times more than SLAC!

Around 500 pb^{-1} per experiment

Basic Deep Inelastic Scattering Processes





$Q^2 = -q^2$:resolving power of interaction

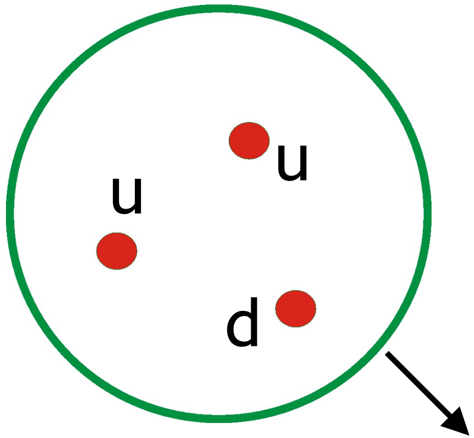
$x = Q^2 / 2q.p$: fraction of struck quark / proton momentum

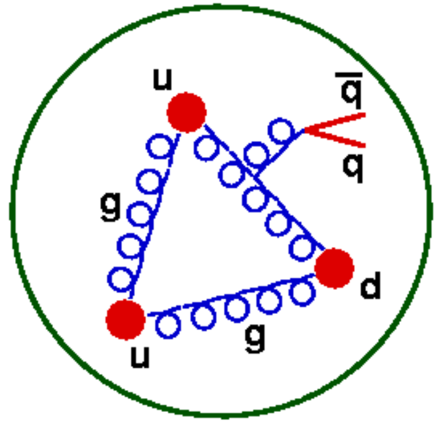
Proton "Structure"?

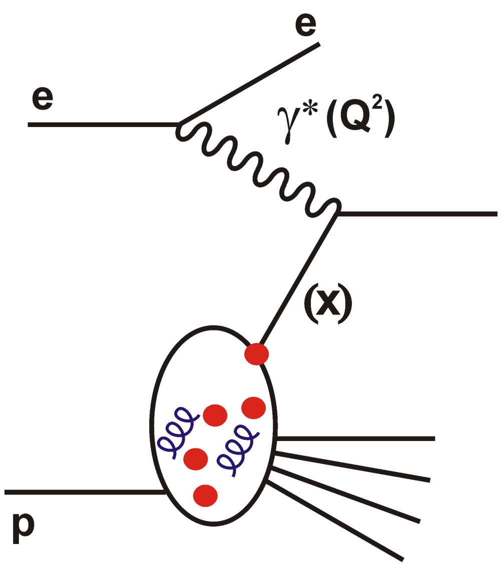
Proton constituents …

- 2 up and 1 down **valence quarks**
- … and some **gluons**
- … and some **sea quarks**
- … and lots more gluons and sea quarks …

→ strong interactions induce rich and complex \`structure' of high energy proton interactions!

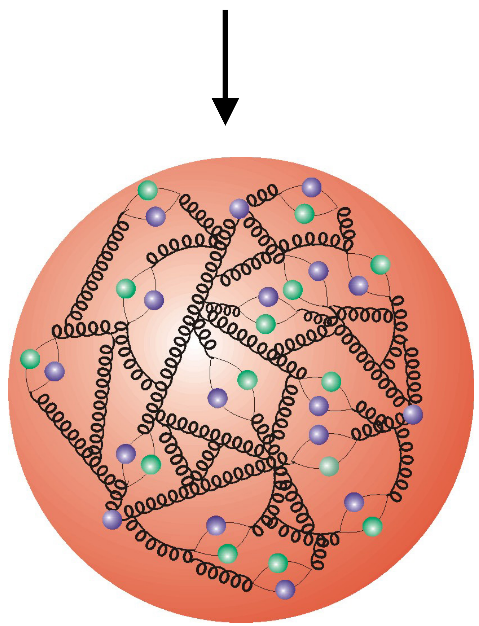




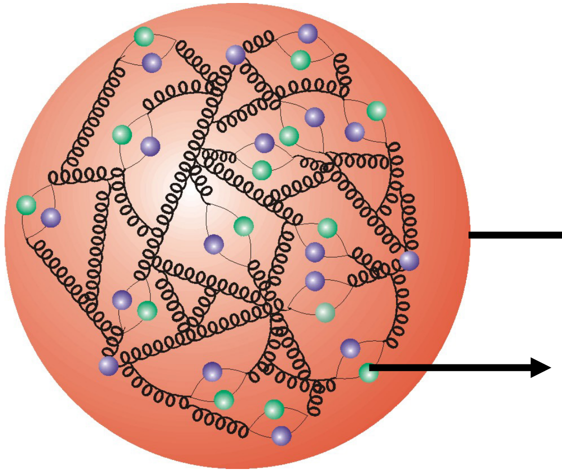


Scattering electrons from protons at √s > 300GeV at HERA has established detailed proton structure & provided a testing ground for QCD over a huge kinematic range

… **parton density functions**



How is the Proton's Energy Shared out?

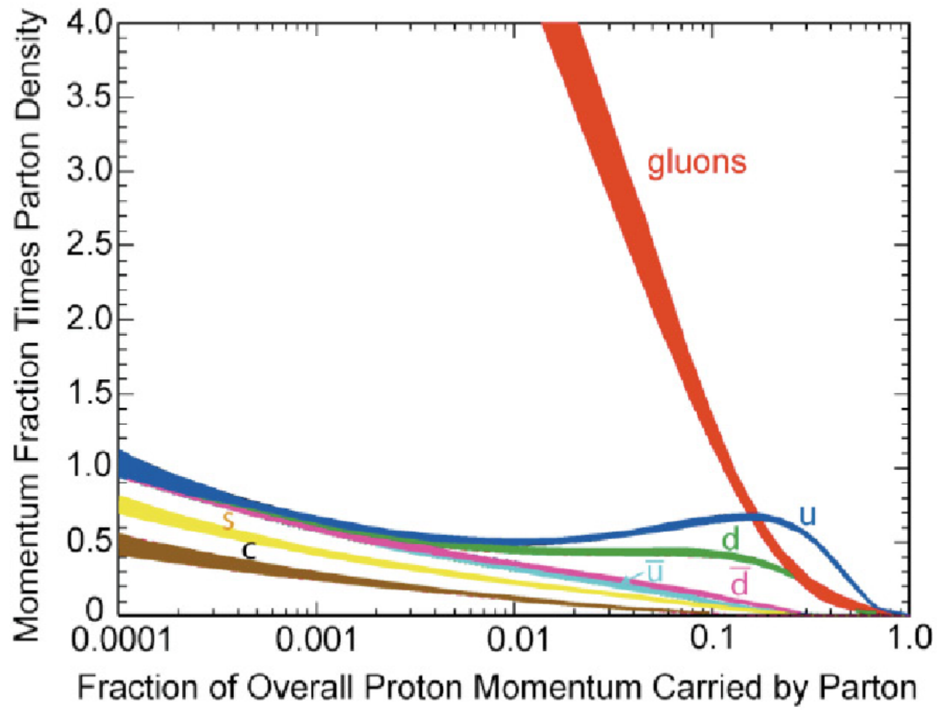


A proton with high energy

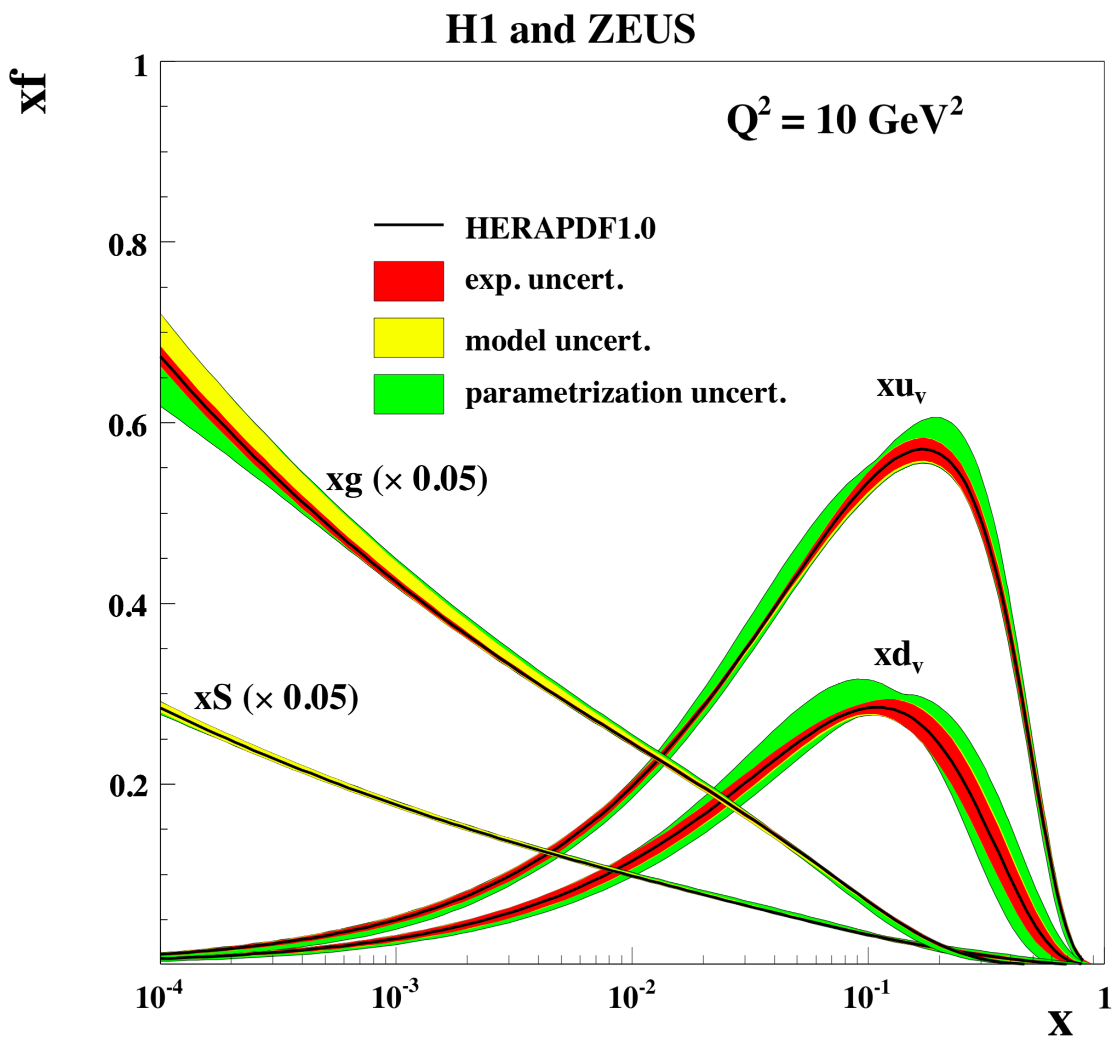
A quark carrying energy fraction, x

Energy carried by quarks and gluons as a function of x →

At TeV / LHC energies, a proton looks like a lot of gluons



HERA's greatest legacy



Parton densities of proton in a large x range

Some limitations:

- Insufficient lumi for high x precision

- Assumptions on quark Flavour decomposition

- No deuterons … u and d not separated

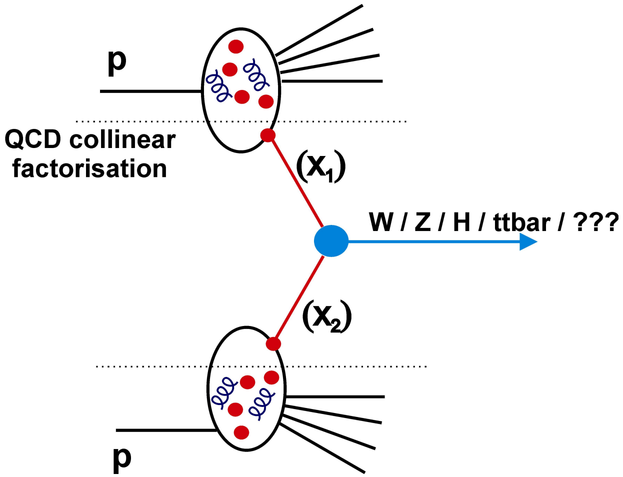
- No heavy ions

- H1/ZEUS/joint publications still coming for 1-2 years
- Further progress requires higher energy and luminosity …

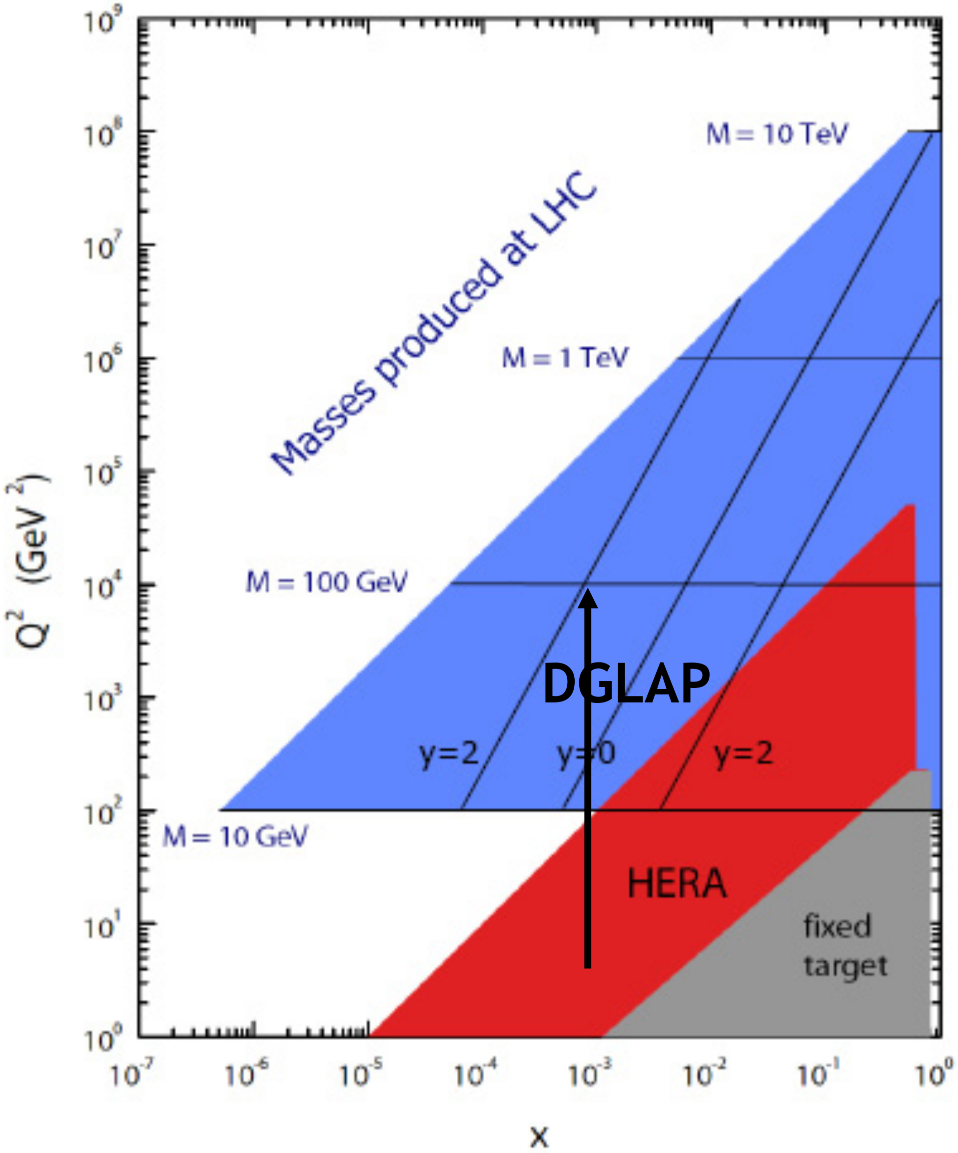
HERA kinematic range

- Unprecedented low x and high Q^2 coverage in DIS!

- HERA + **QCD factorisation** → parton densities in full x range of LHC rapidity plateau



- Well established **`DGLAP' evolution** equations generalise to any scale (for not too small x)

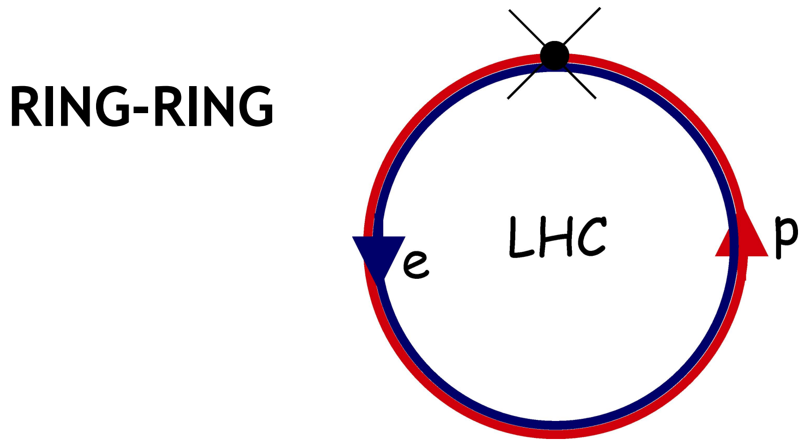


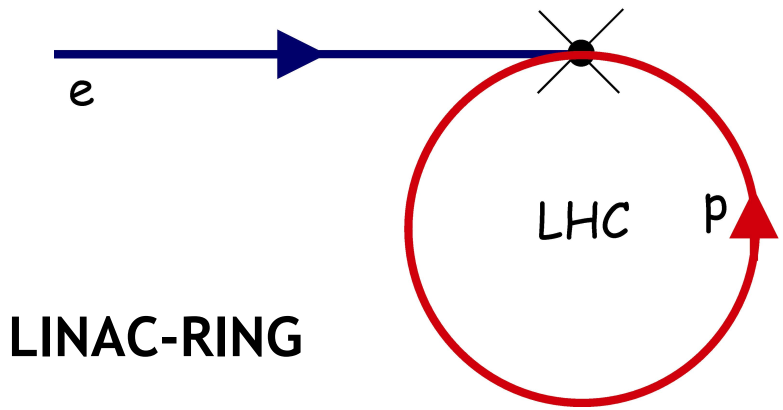
e.g. pp dijets at central rapidity: $x_1 = x_2 = 2p_t / \sqrt{s}$

Currently Approved Future of High Energy DIS

How Could ep be Done using LHC?

… whilst allowing simultaneous ep and pp running …





- First considered (as LEPxLHC) in 1984 ECFA workshop
- Main advantage: high peak lumi obtainable (~2.10^{33} cm^{-2} s^{-1})
- Main difficulties: building round existing LHC, e beam energy (60GeV?) and lifetime limited by synchrotron radiation

- Previously considered as `QCD explorer' (also THERA)
- Main advantages: low interference with LHC, high E_e (→ 150 GeV?) and lepton polarisation, LC relation
- Main difficulties: lower luminosity <10^{33} cm^{-2} s^{-1}? at reasonable power, no previous experience exists

Accelerator Design

Main design constraint: power consumption < 100 MW

Multi-Lab Involvement Novosibirsk, BNL, CERN, Cockcroft, Cornell, DESY, EPFL Lausanne, Jlab, KEK, Liverpool, SLAC, TAC Turkey, NTFU Norway, INFN ...

Ring-Ring Design

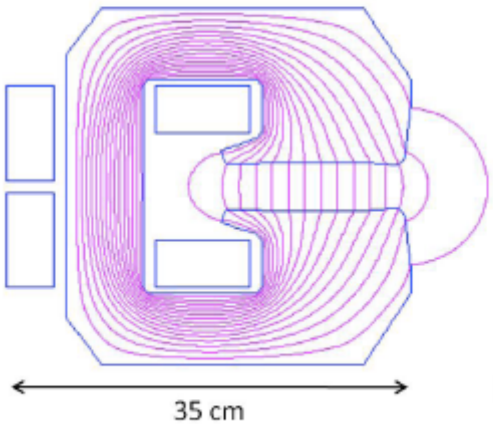
Installation 1m above LHC and 60cm inside

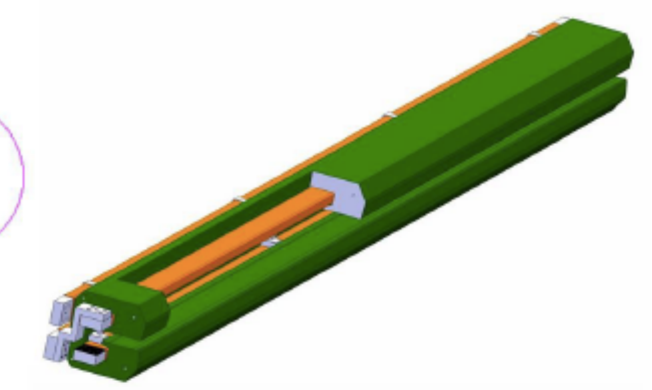
By-passes of existing experiments containing RF

Challenging, but no show stopper yet

Magnets for Electron Ring (CERN, Novisibirsk)

3040 bending dipole magnets



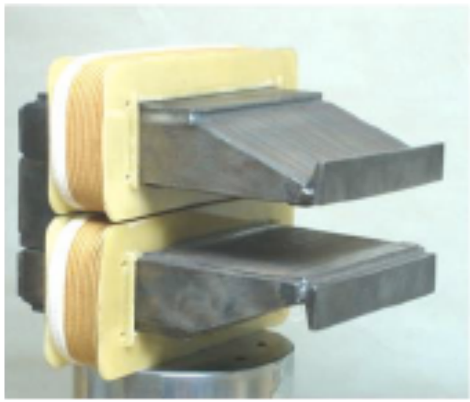


5m long
$(35cm)^2$ transverse

127 T/m gradient

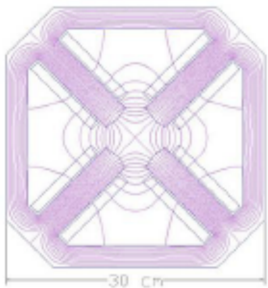
Compact and light

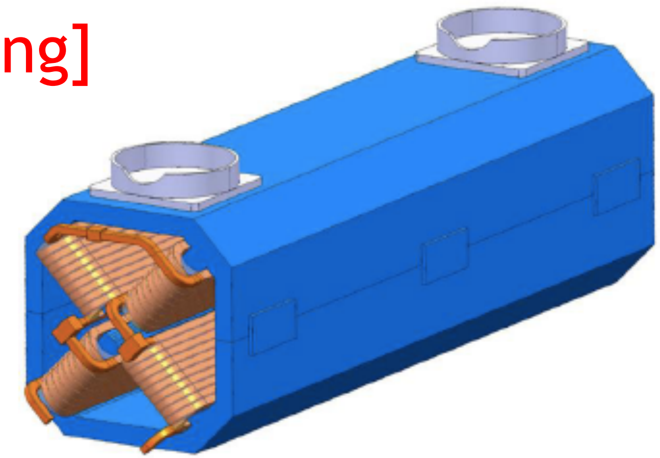
First prototypes



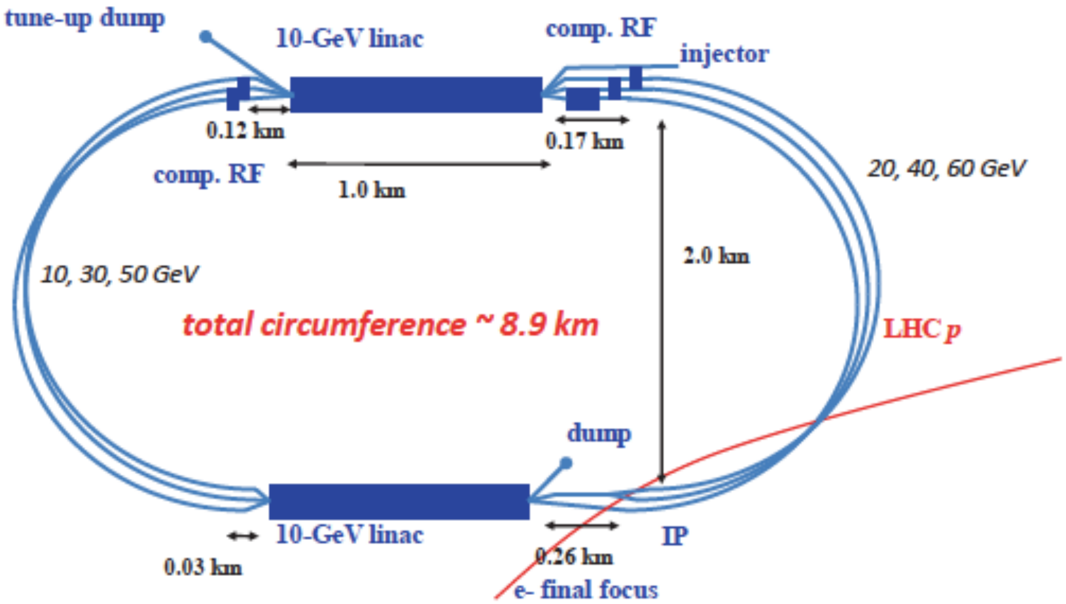
736 arc quadrupole magnets

[1.2m long]





Accelerator Design in Linac-Ring Configuration



4 separate designs for 60 GeV electron beam (CERN, Jlab, BNL)

- 500 MeV injection
- Two 10 GeV linacs,
- 3 returns
- Energy recovery in same structures (94%)?

More ambitious:
Pulsed single 140 GeV Linac 31.5 MV/m (ILC)

Design Parameter Summary

RR= Ring - Ring
LR =Linac -Ring

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

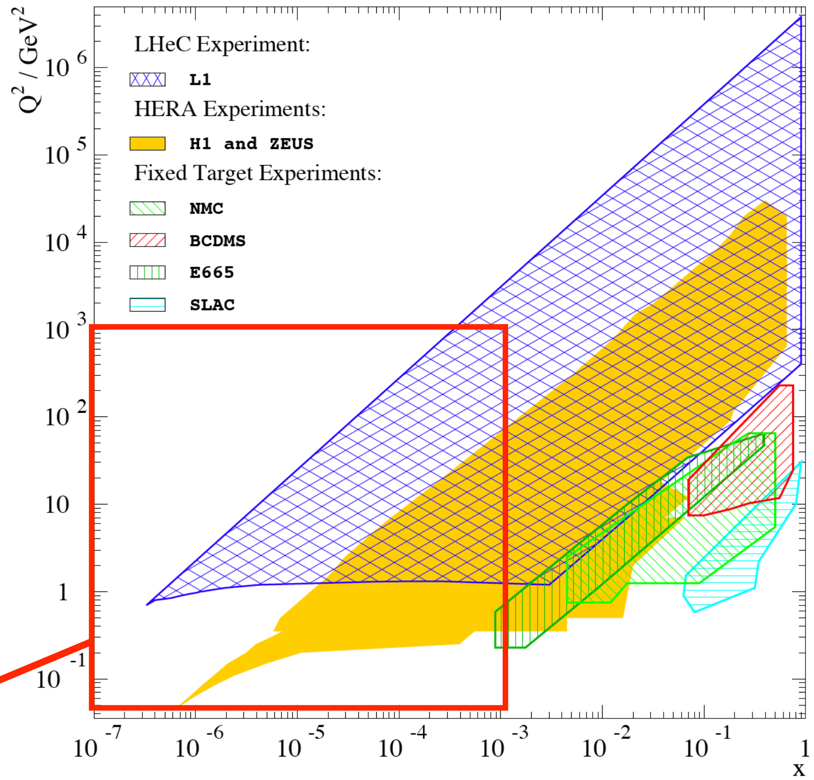
proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

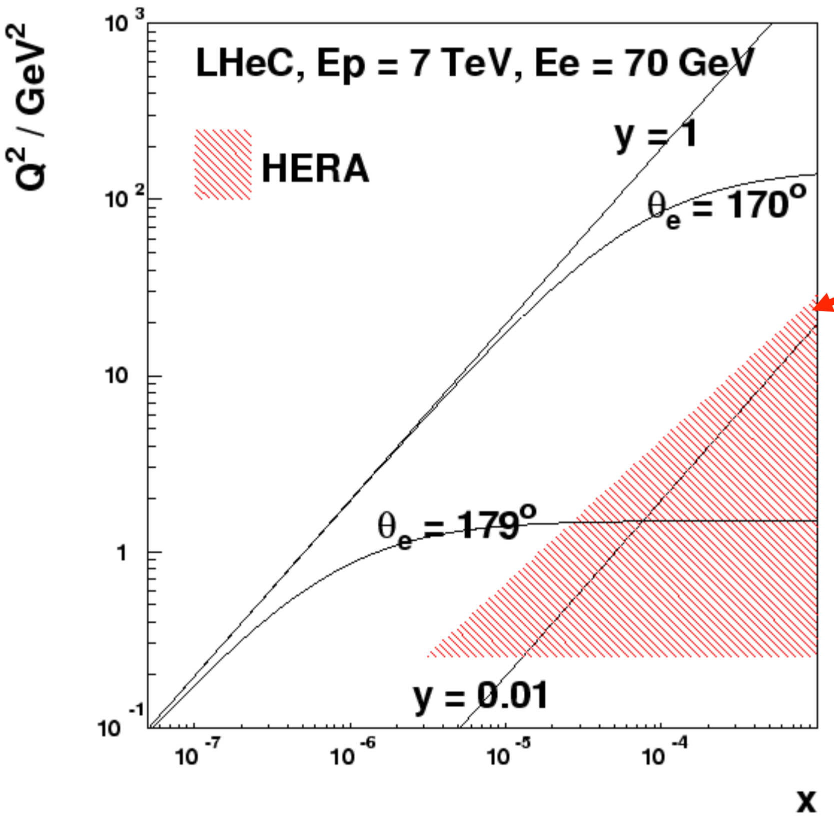
Include deuterons (new) and lead (exists)

10 fb^{-1} per year looks possible

Detector Acceptance Requirements

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°





Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

Experimental Precision Aims

Requirements to reach a per-mille α_s (c.f. 1-2% now) …

The new collider …

- should be ~100 times more luminous than HERA

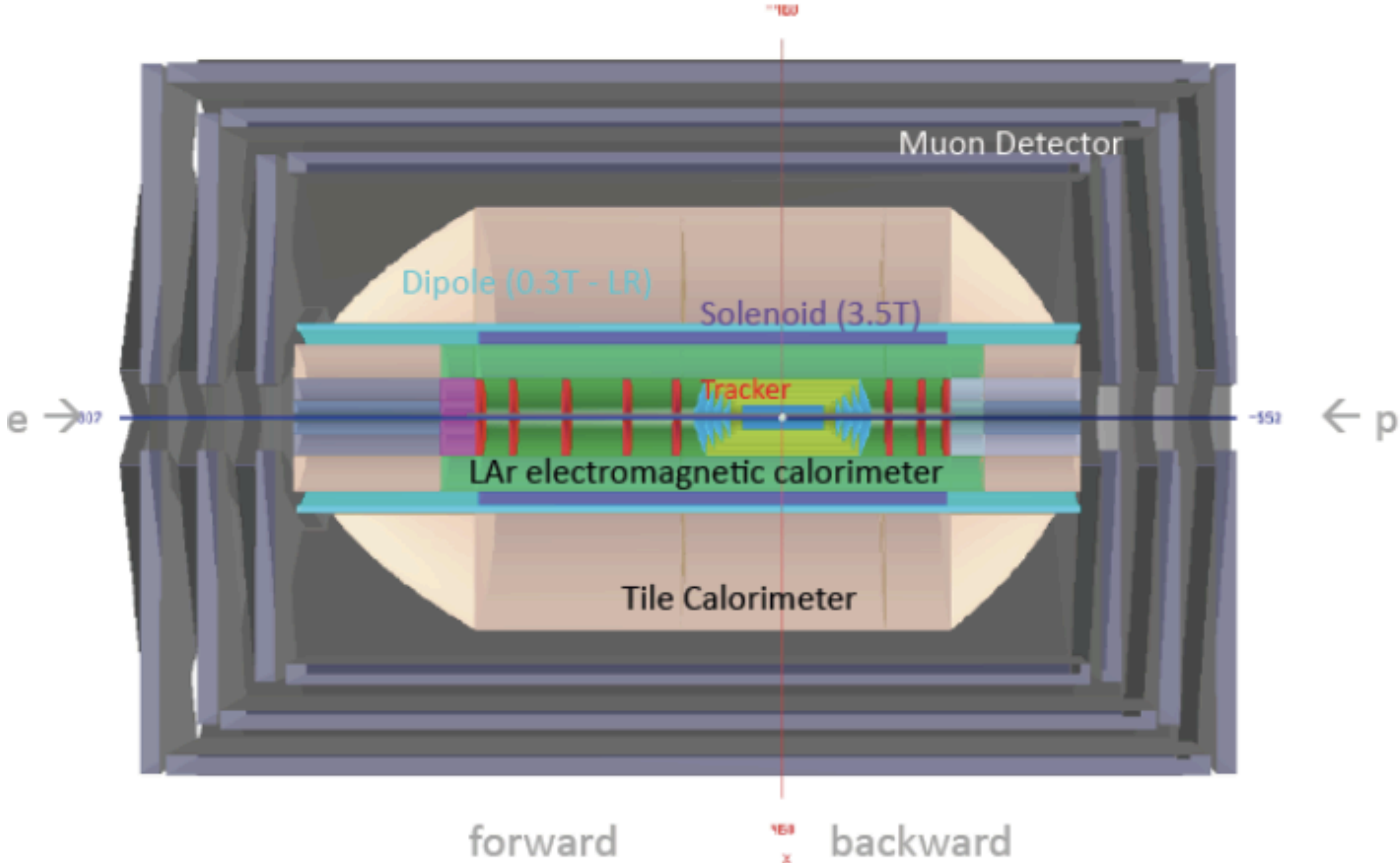
The new detector

- should be at least 2 times better than H1 / ZEUS

	LHeC	HERA
Lumi [$cm^{-2}s^{-1}$]	10^{33}	$1\text{-}5*10^{31}$
Acceptance [º]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

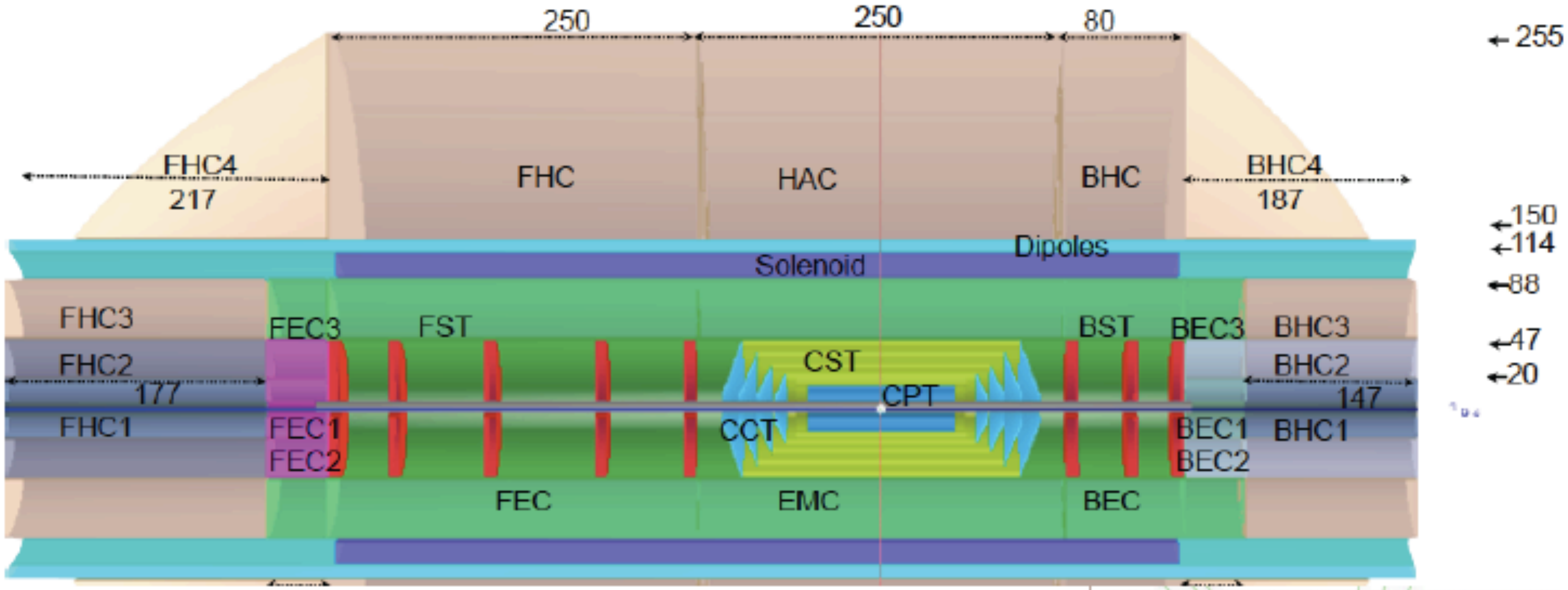
Simulated `pseudo-data' for F_2, F_L, F_2^D …produced on this basis

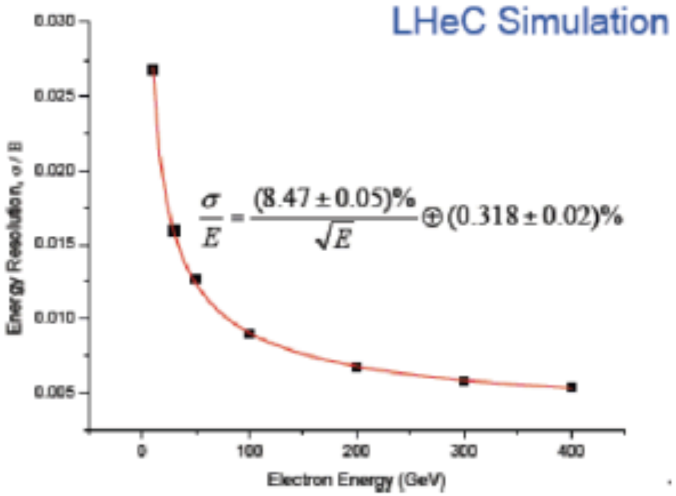
Detector Overview

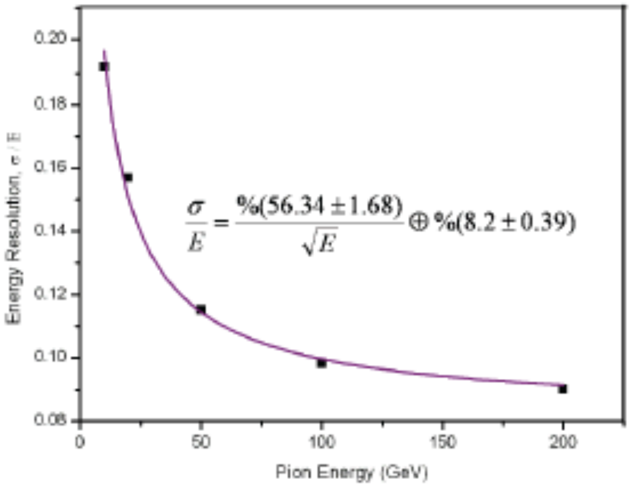


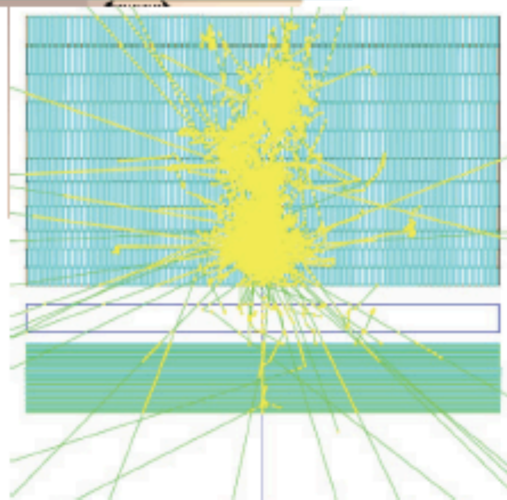
- Present dimensions: LxD =14x9m² [CMS 21x15m², ATLAS 45x25 m²]
- Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)
- General point: Lumi versus acceptance!

Calorimeters



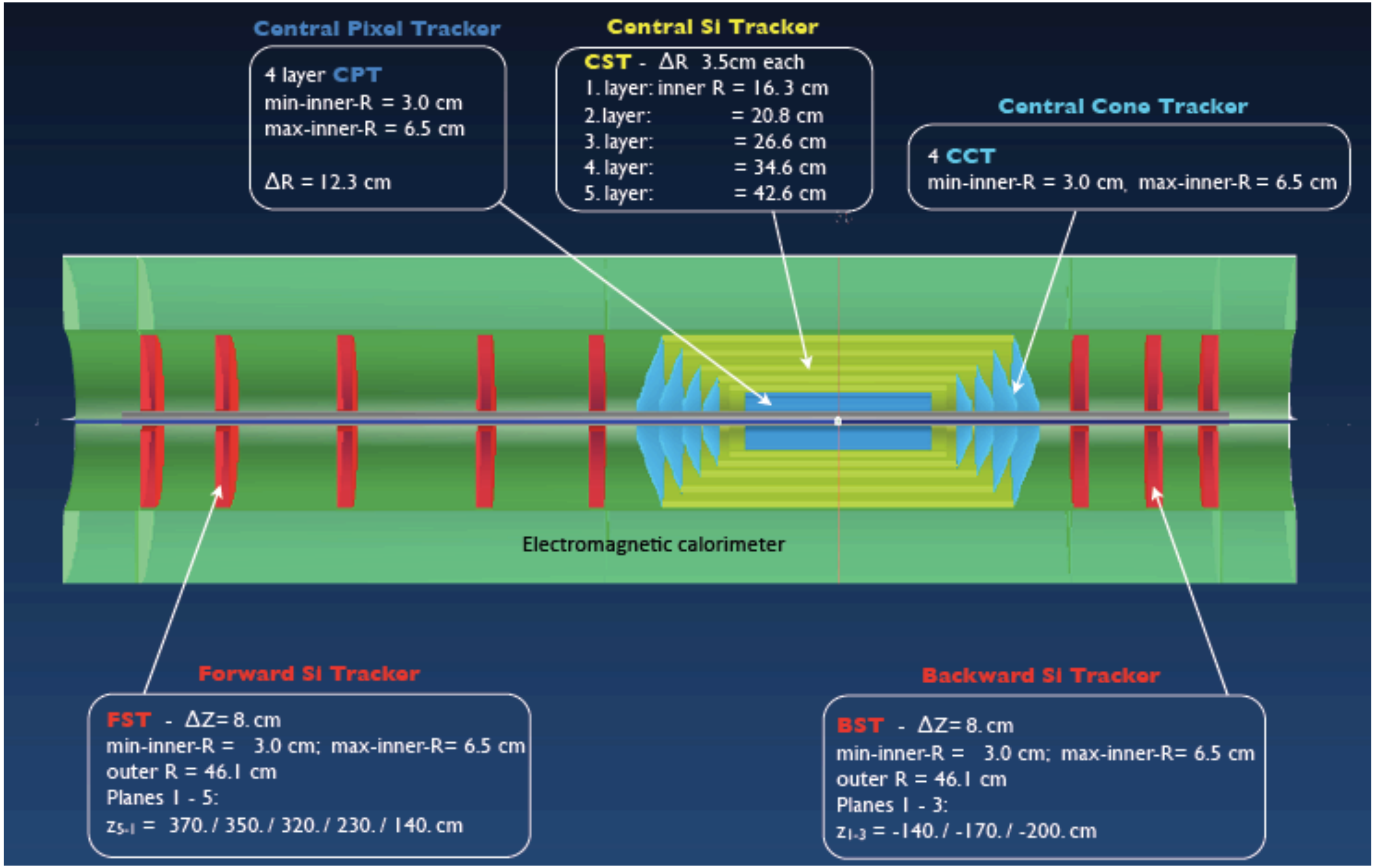






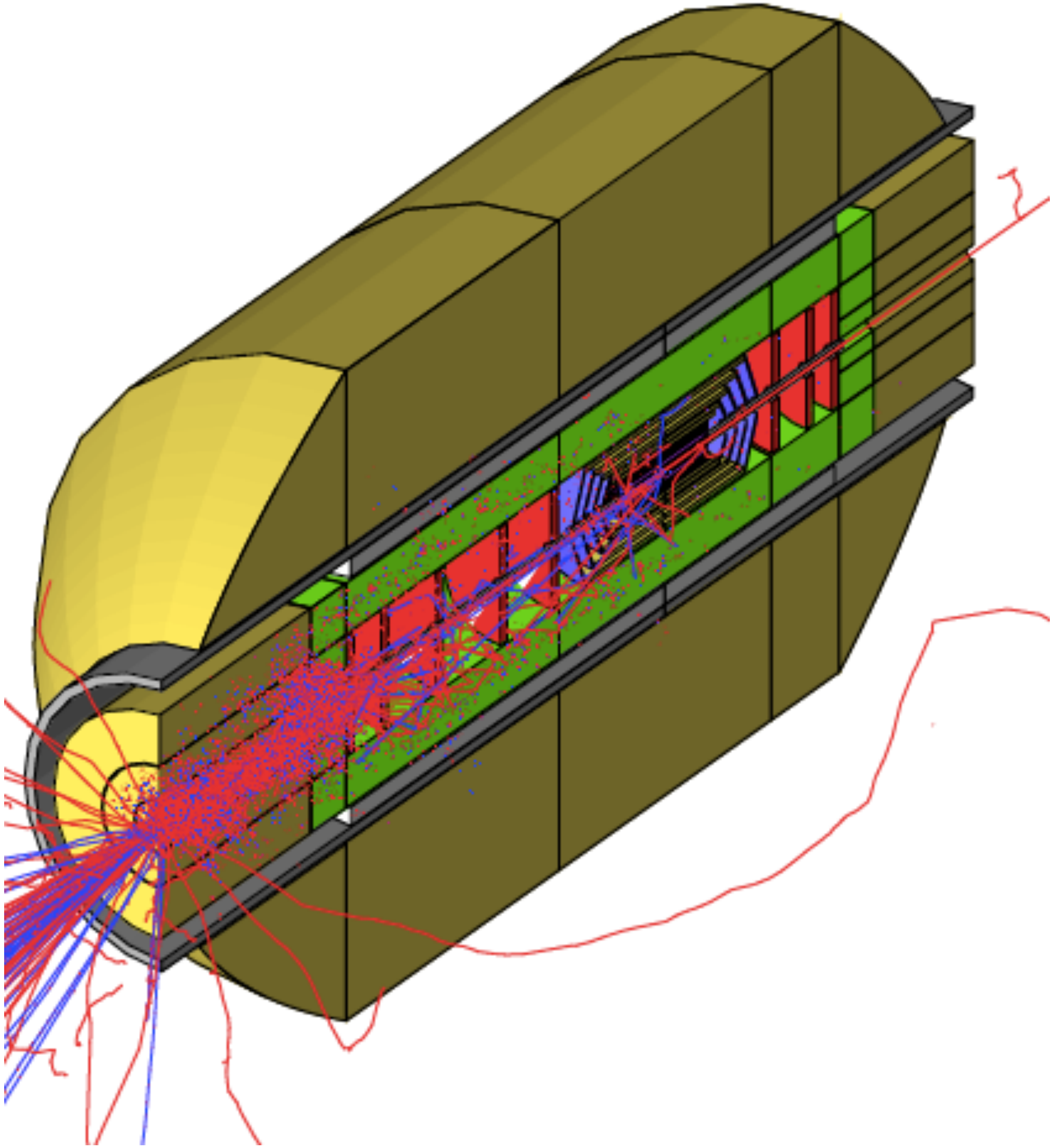
Liquid Argon / Tile technologies under study

Tracking Region



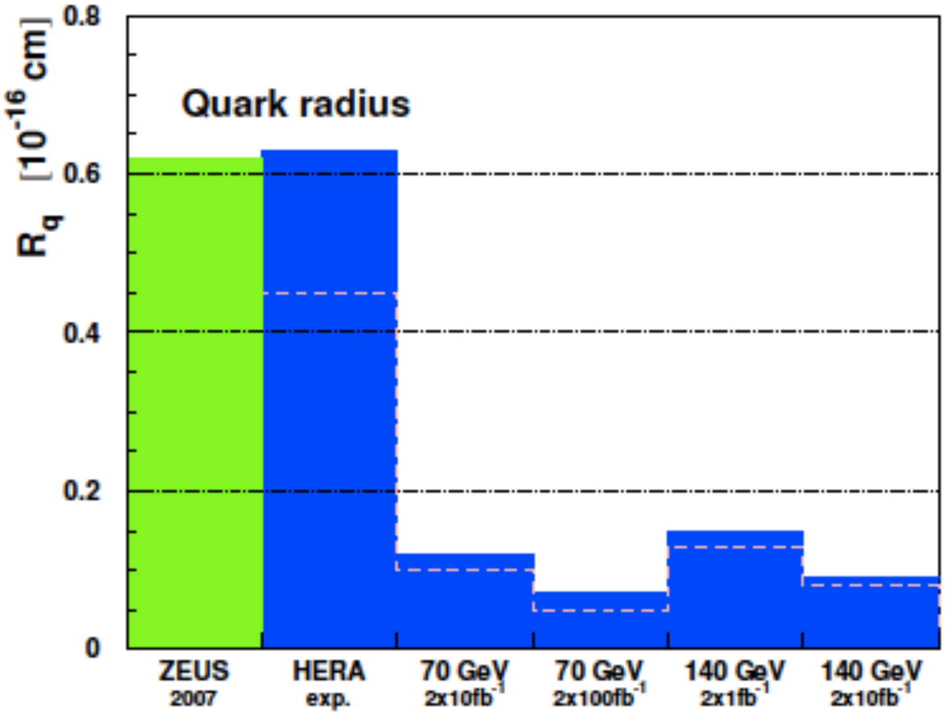
- Full angular coverage, long tracking region → 1° acceptance
- Technologies under discussion (lots of ideas!)

A GEANT4 Simulated Low x Event



Searches For New Physics

• The (pp) LHC has much better discovery potential than the LHeC (unless electron beam energy can increase to > 500 GeV)



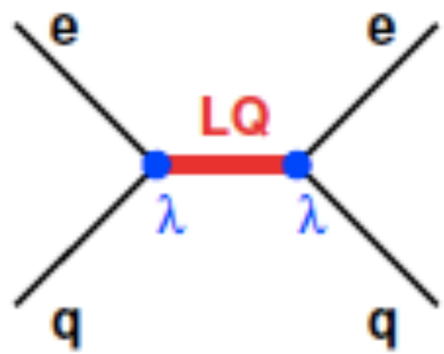
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

… big improvement on HERA, but already beaten by LHC in its first year

• However, LHeC is competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states

• Combined LHC / LHeC info can confirm and clarify new physics

Lepton-quark Resonances



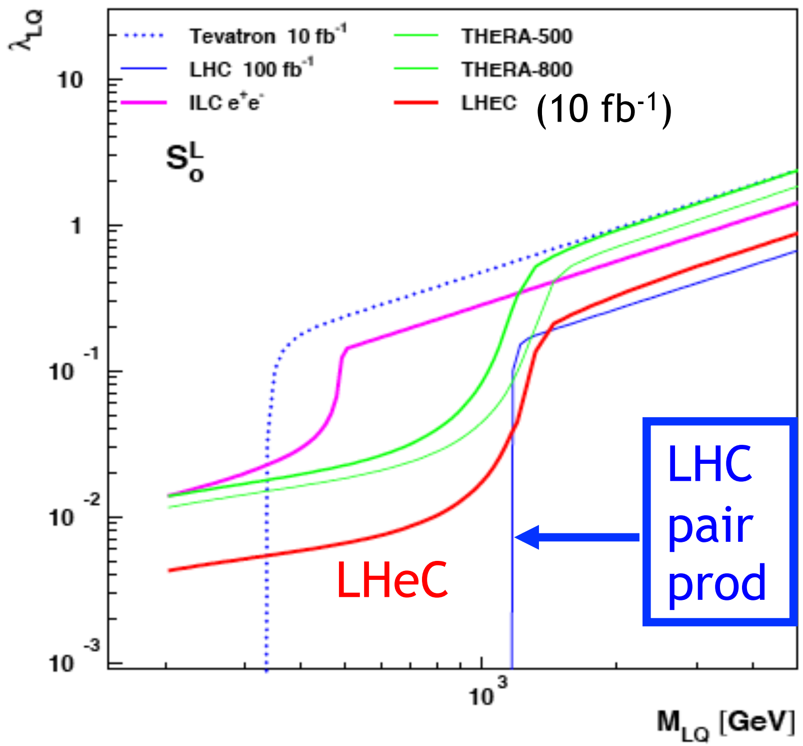
Yukawa coupling, λ

- Leptoquarks appear in many extensions to SM… explain apparent symmetry between lepton and quark sectors.

- Scalar or Vector color triplet bosons Carrying L, B and fractional Q, complex spectroscopy?

- (Mostly) pair produced in pp, single production in ep.

- LHeC discovery potential for masses <1.0 - 1.5 TeV for 10 fb^{-1} – Comparable to LHC, but cleaner final states

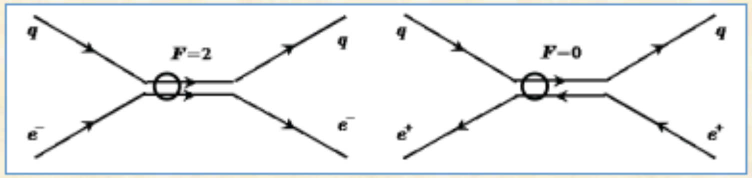


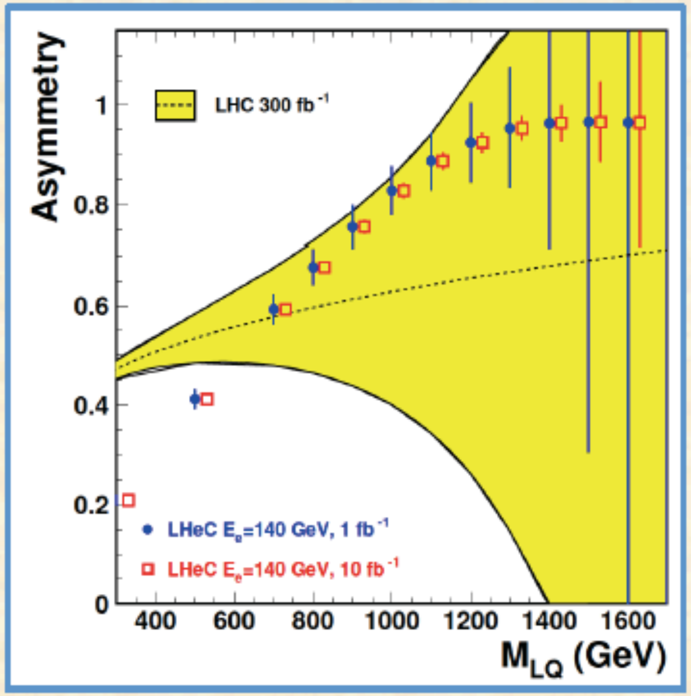
Determining Leptoquark Quantum Numbers

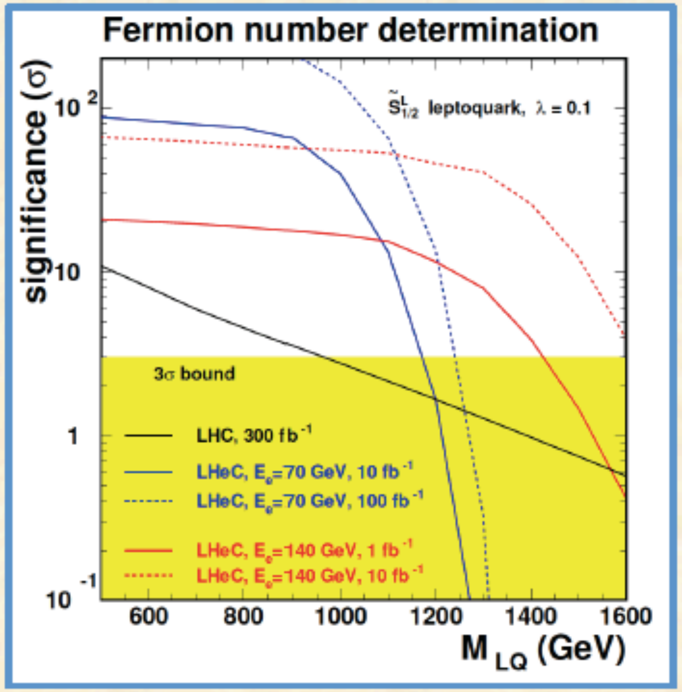
Single production gives access to quantum numbers:
- fermion number (below) - spin (decay angular distributions)
- chiral couplings (beam lepton polarisation asymmetry)

- Fermion number *F* from asymmetry in e+/e-p cross sections
- Much cleaner accessible in DIS

$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} > 0 \text{ for } F=2 \\ < 0 \text{ for } F=0 \end{cases}$$



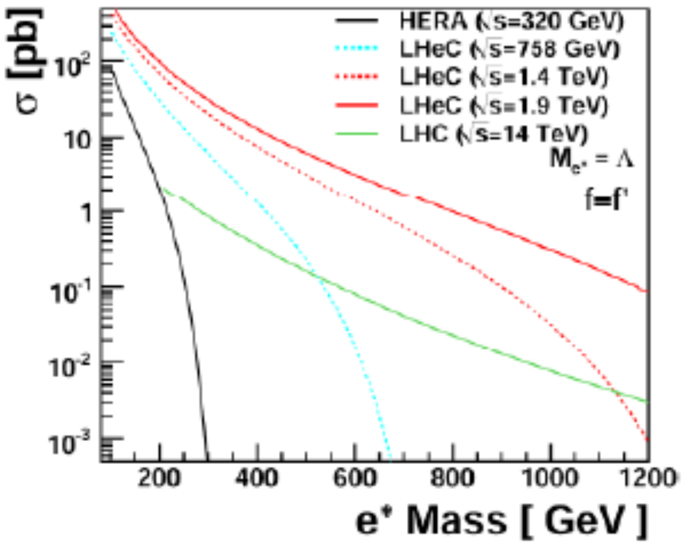


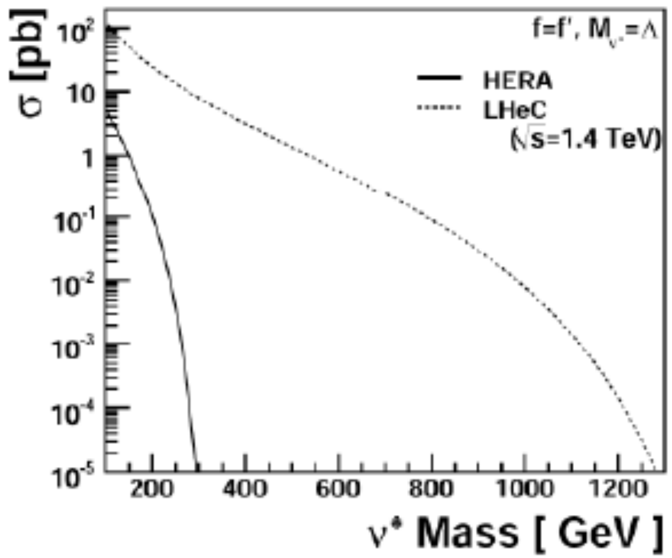


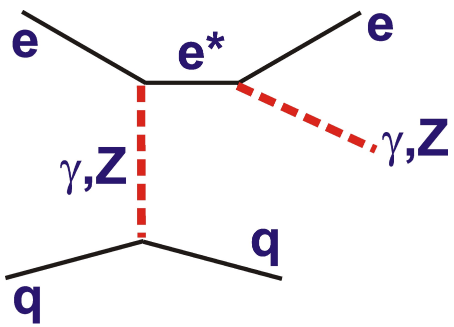
Studies for "low`` lumi assumptions for pp and ep

Excited Leptons

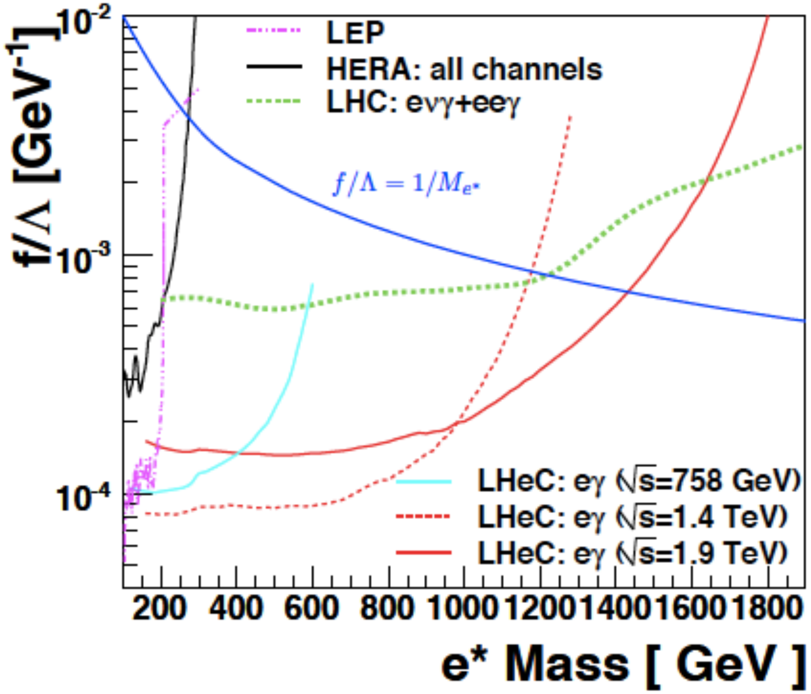
- Total cross section for l* productions through GM interaction at LHeC, assuming M*=Λ
  - comparison with HERA and LHC







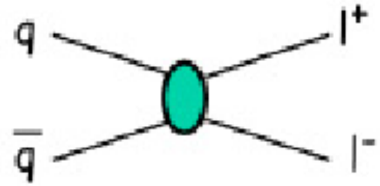
LHeC gives best sensitivity in this scenario ...

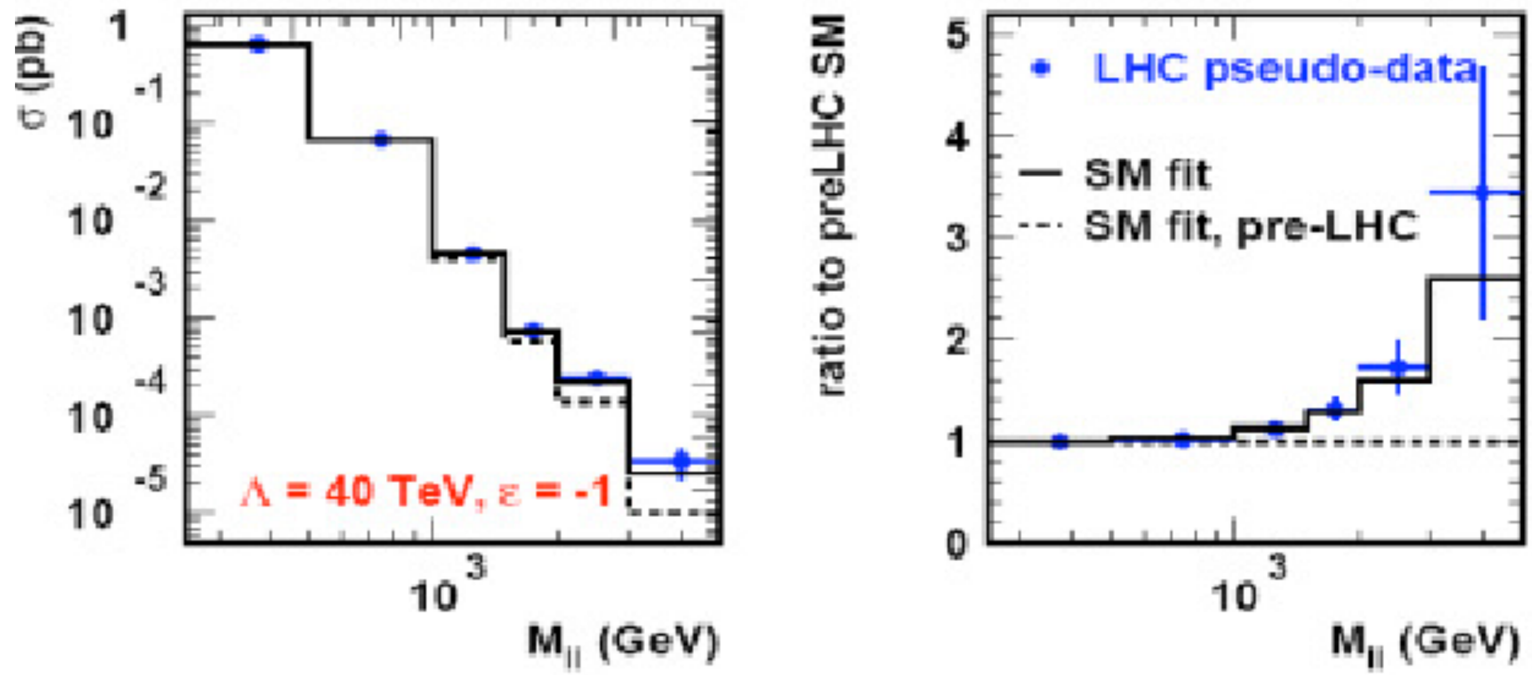


LHeC sensitivity with 1-10 fb-1 depending on E_e

Complementarity between LHC and LHeC

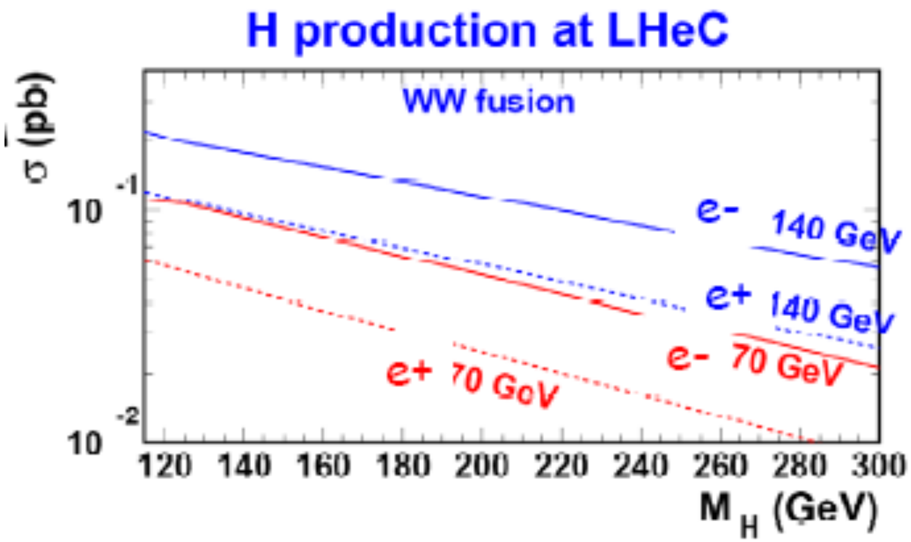
Contact interaction term introduced in LHC pseudo-data for high mass Drell-Yan

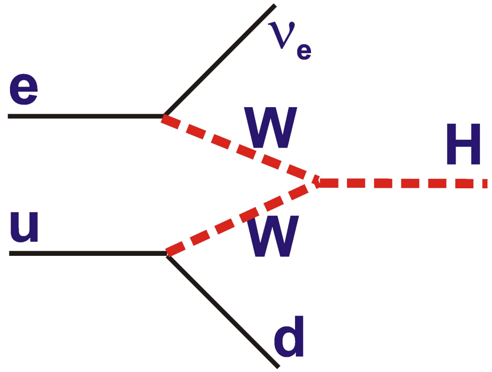




- Even if new physics looks rather different from SM, wide range of high x BSM effects can be accomodated in DGLAP fits due to poor current high x PDF constraints
- Better high x precision at high lumi LHeC could disentangle …

Higgs → bbbar Coupling

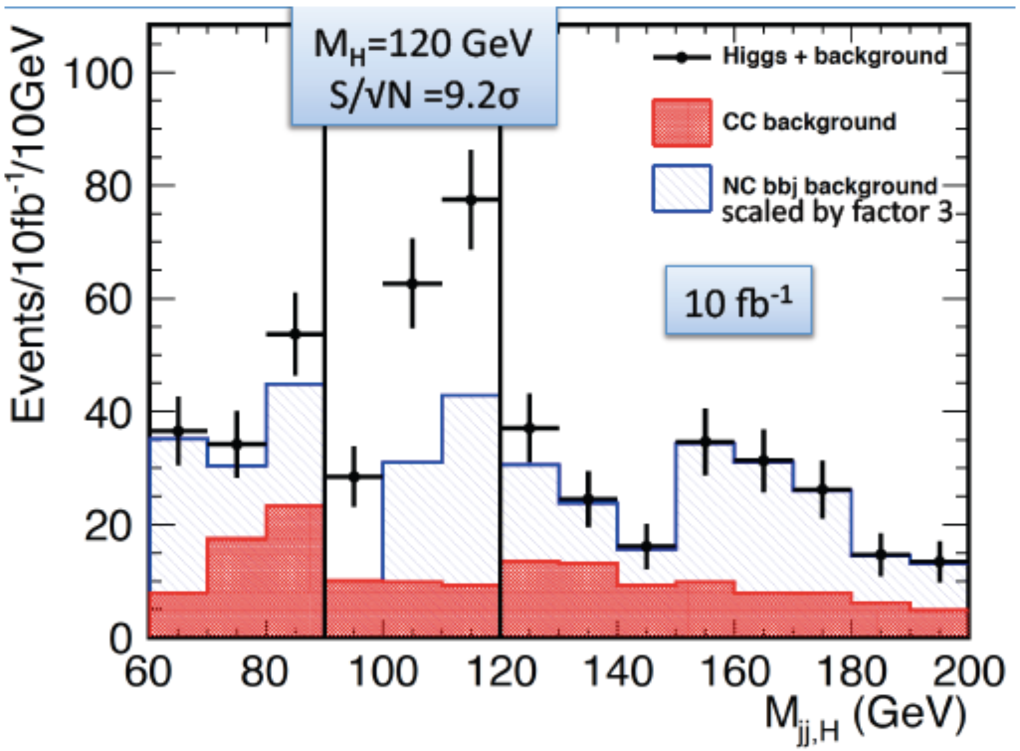




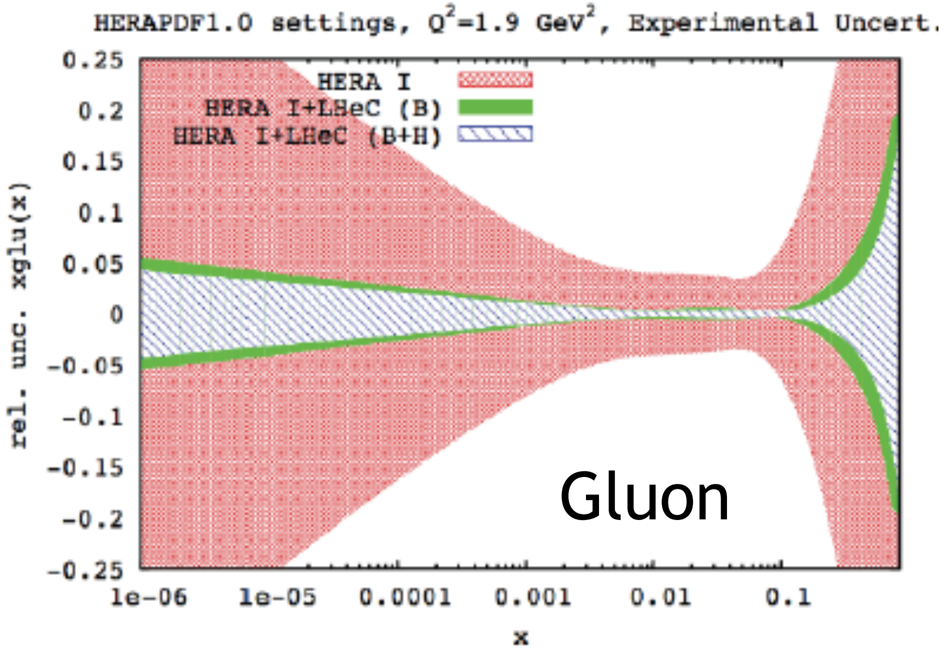
Sizeable CC (WW) x-section →
Few1000 events / year before cuts
Strongly dependent on m_H

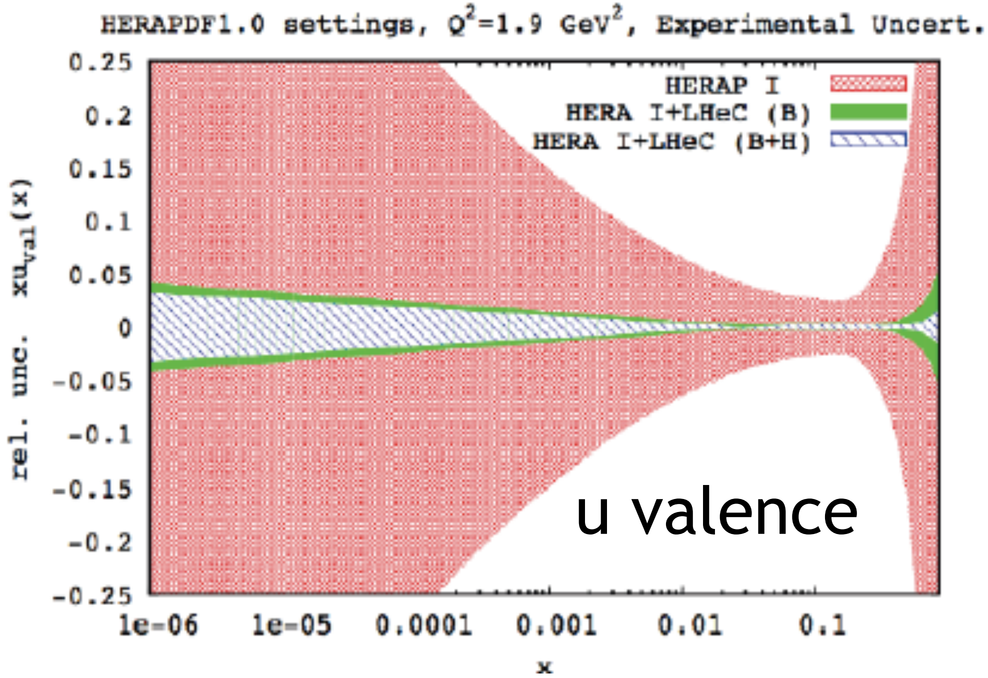
→ Novel production mechanism
→ Clean signal: H + j + p_t^{miss}

First study with 2 b-tags
Backgrounds (jets in NC, CC, top) suppressed with cuts on jet multiplicity, total E_t, event kinematics, missing p_t
~ 100 events / year after cuts?



LHeC Impact on Parton Densities



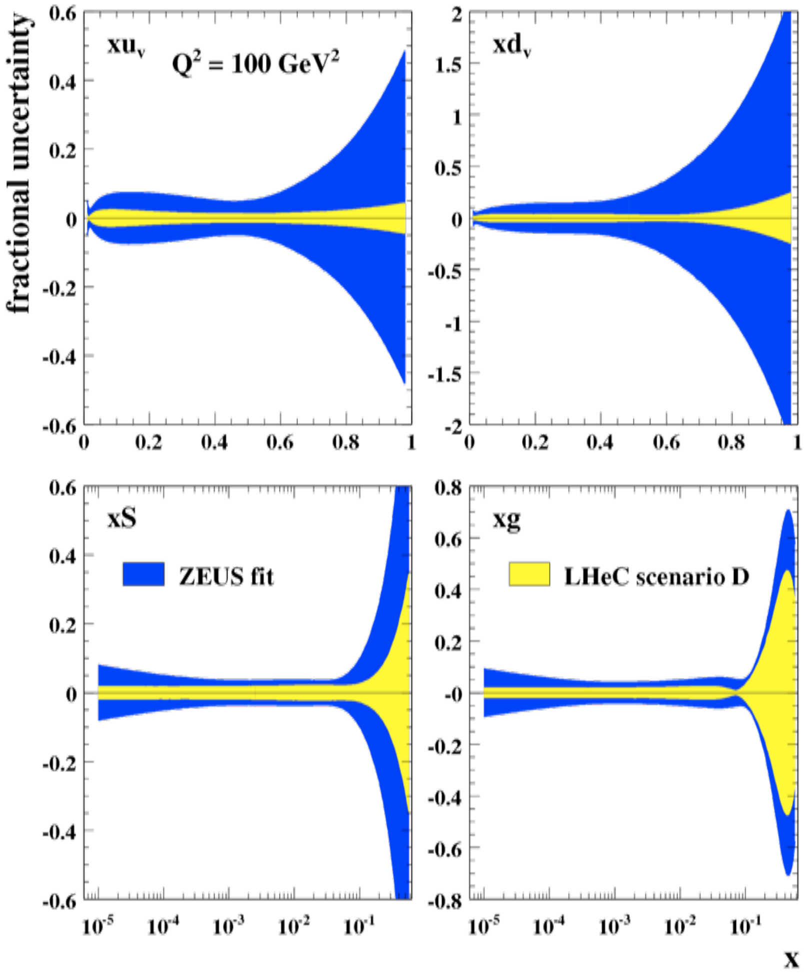


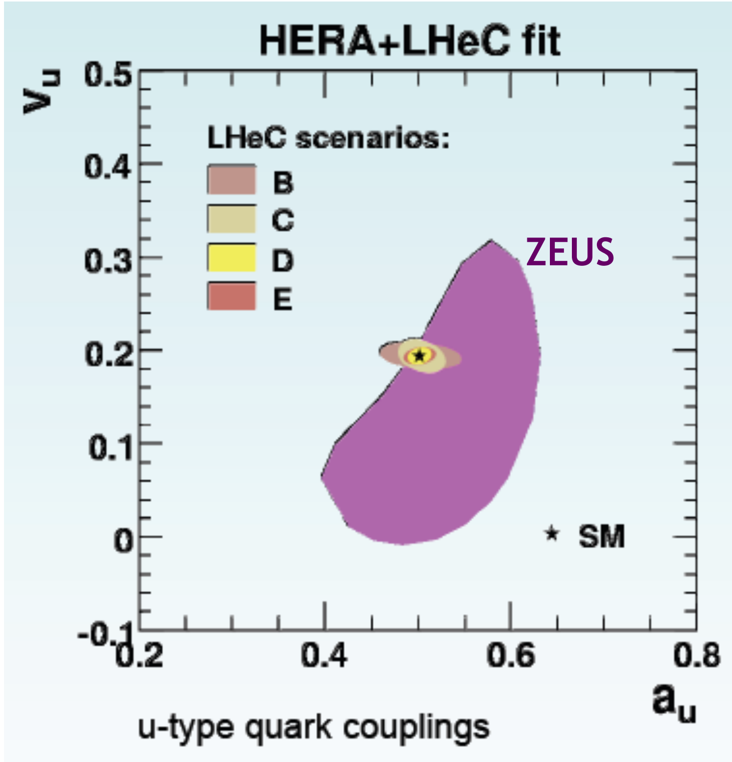
Full NC/CC sim (with systs giving per mille α_s) & NLO DGLAP fit using HERA technology…

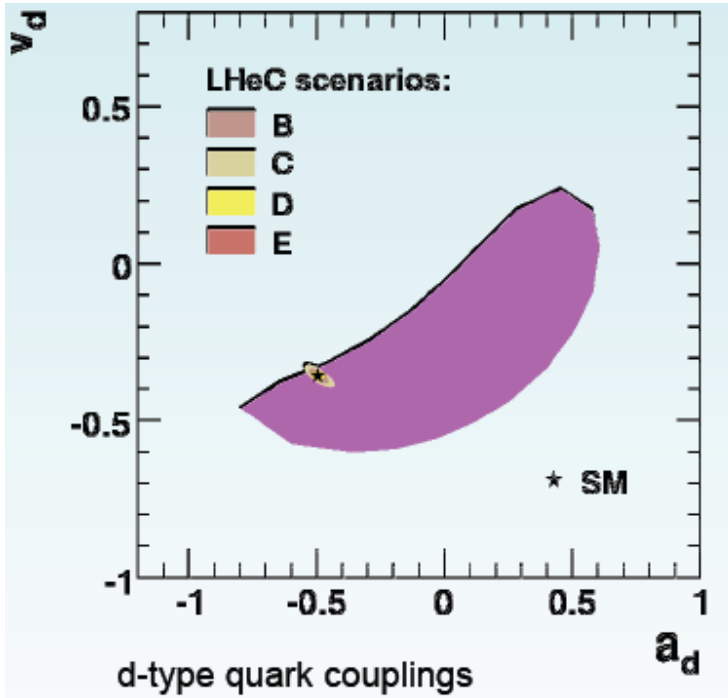
… big impact for both low x (kinematic range) and high x (luminosity)

… full flavour decomposition possible

PDFs & EW Couplings





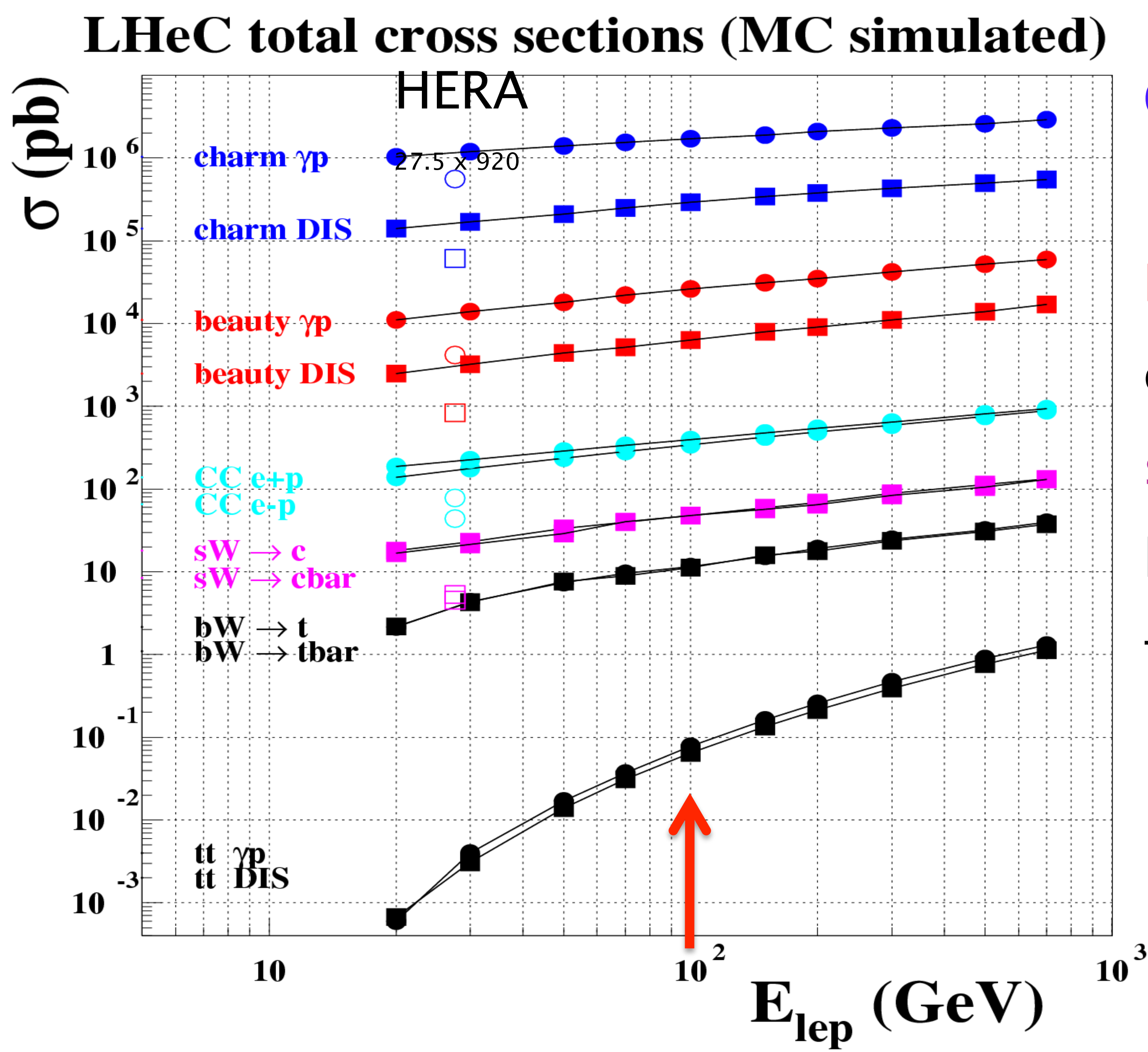


Using ZEUS fitting code, HERA + LHeC data … EW couplings free

E_e = 100 GeV, L = 10+5 fb^{-1}, P = +/- 0.9

Weak mixing angle can also be obtained

Cross Sections and Rates for Heavy Flavours



Charm $[10^{10} / 10\ fb^{-1}]$

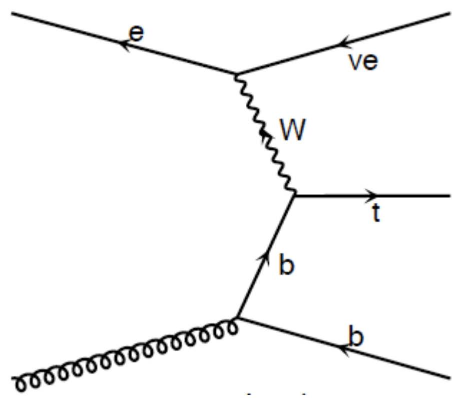
Beauty $[10^{8} / 10\ fb^{-1}]$

cc

sW → c $[4.10^{5} / 10\ fb^{-1}]$

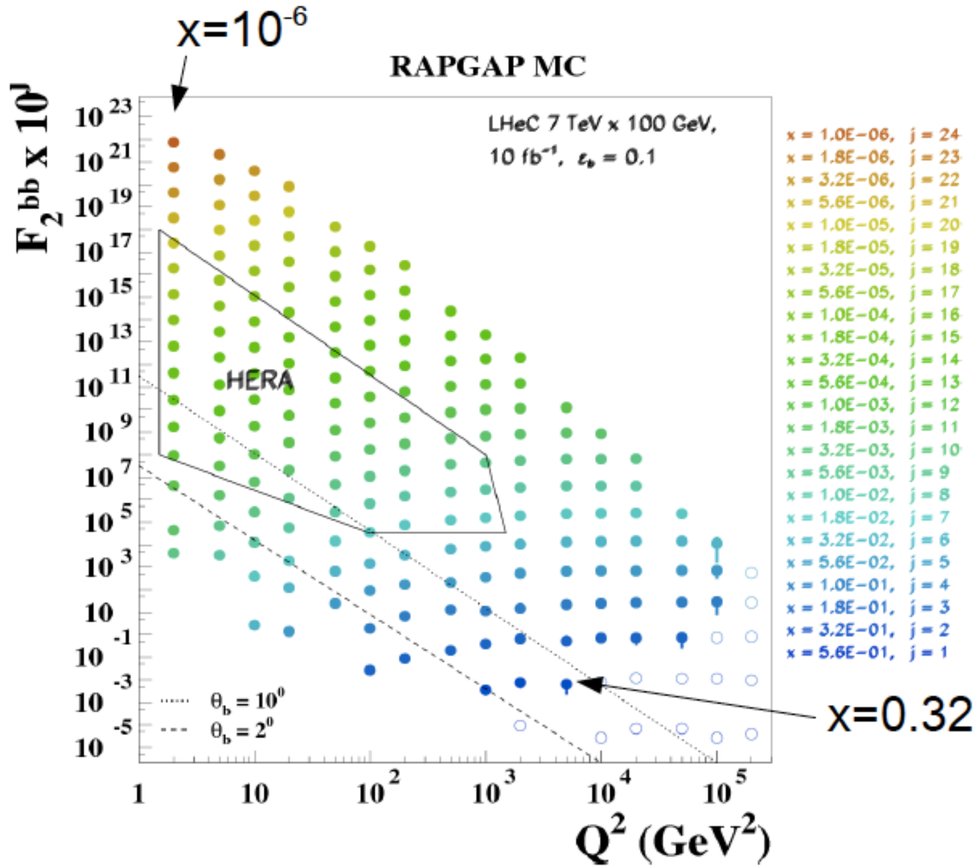
bW → t $[10^{5} / 10\ fb^{-1}]$

ttbar $[10^{3} / 10\ fb^{-1}]$



c.f. luminosity of ~10 fb^{-1} per year …

Flavour Decomposition



Precision c, b measurements

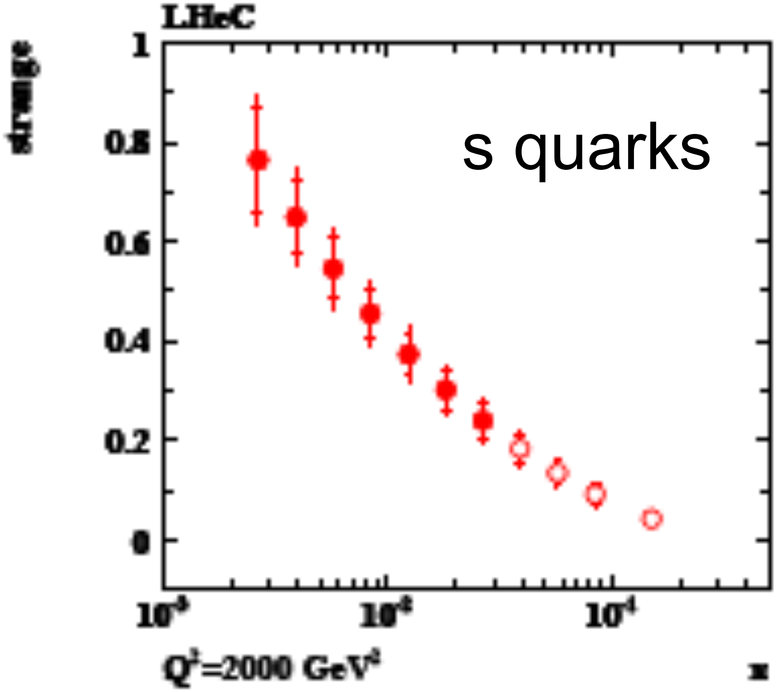
(modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

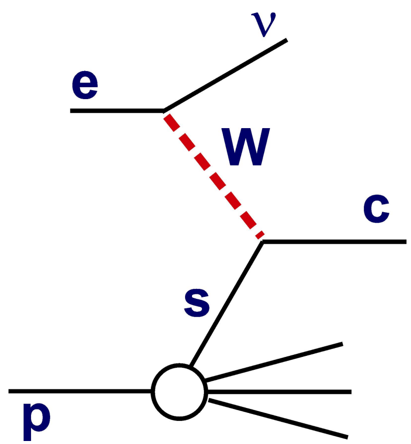
Systematics at 10% level

→beauty is a low x observable!

→s, sbar from charged current

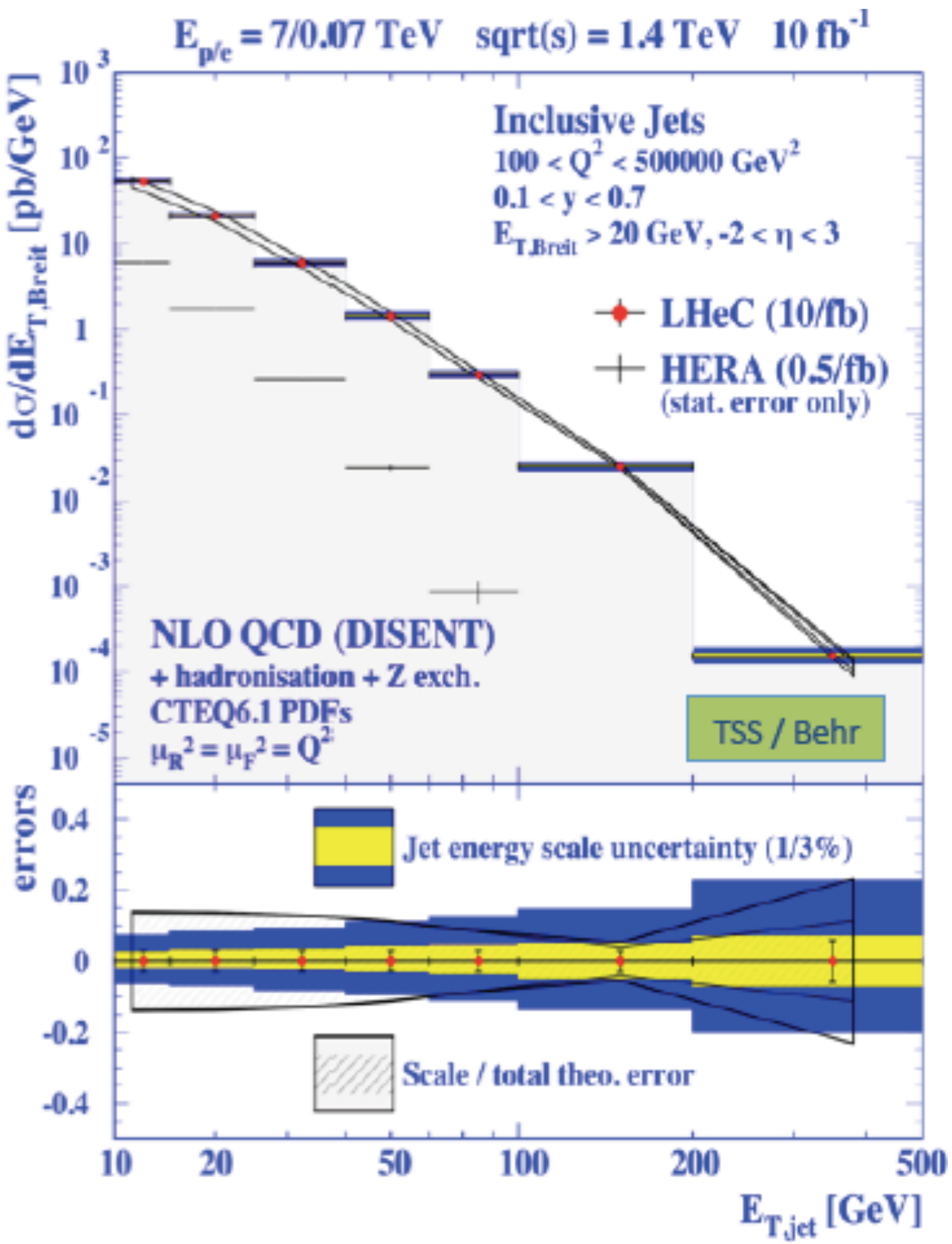
→ Similarly Wb → t





(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

Inclusive Jets & QCD Dynamics

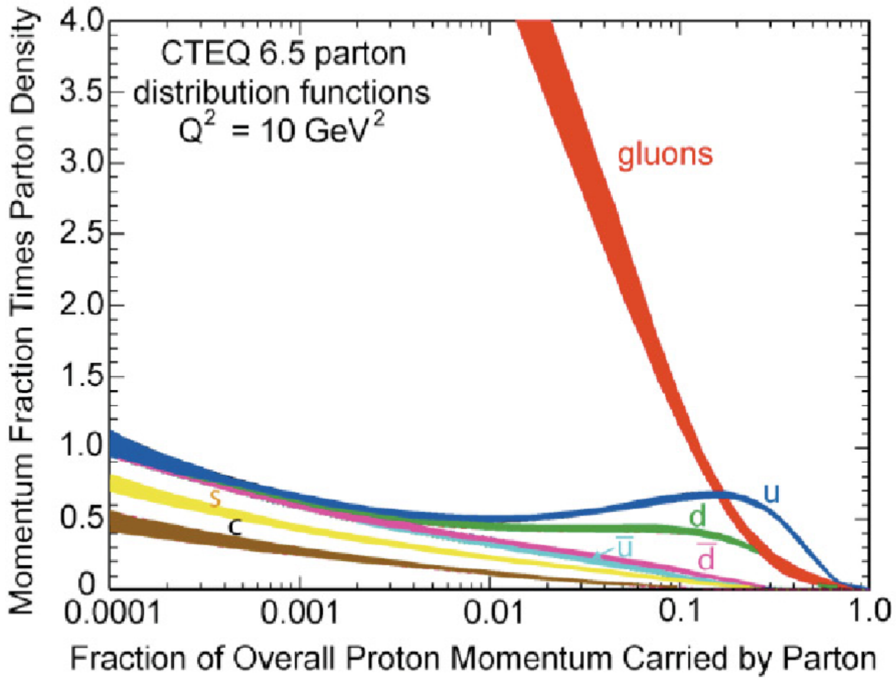


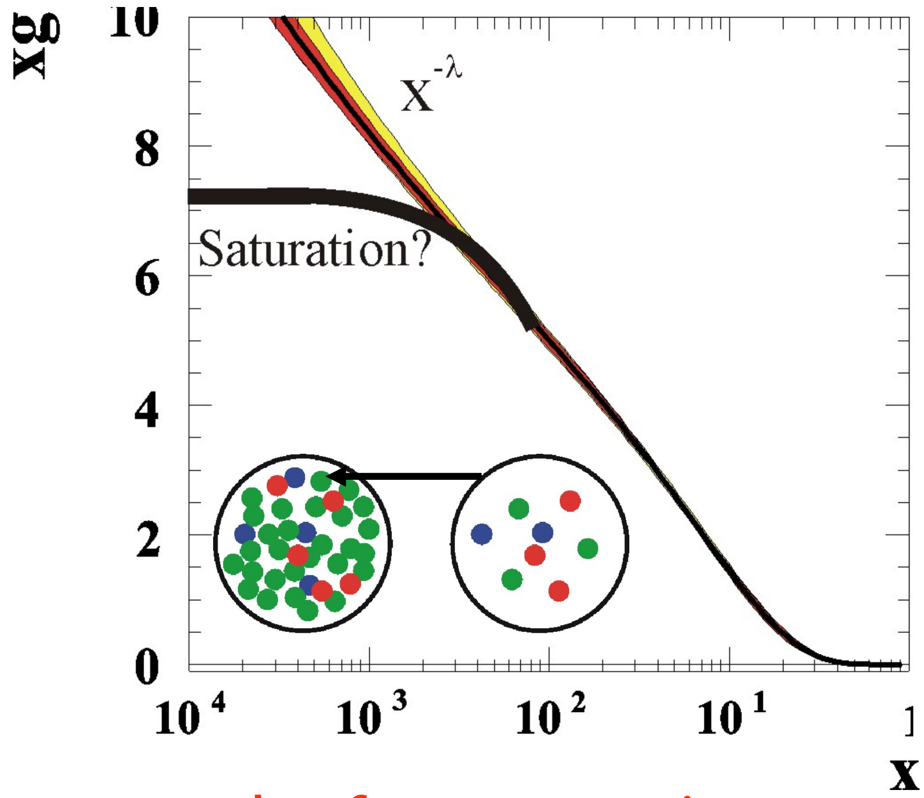
Also differential in Q^2 with high precision to beyond $Q^2 = 10^5$ GeV^2

α_s up to scale ~ 400 GeV

Detailed studies of QCD dynamics, including novel low x effects in regions not probed at HERA and (probably) not at LHC

Low-x Physics and Parton Saturation





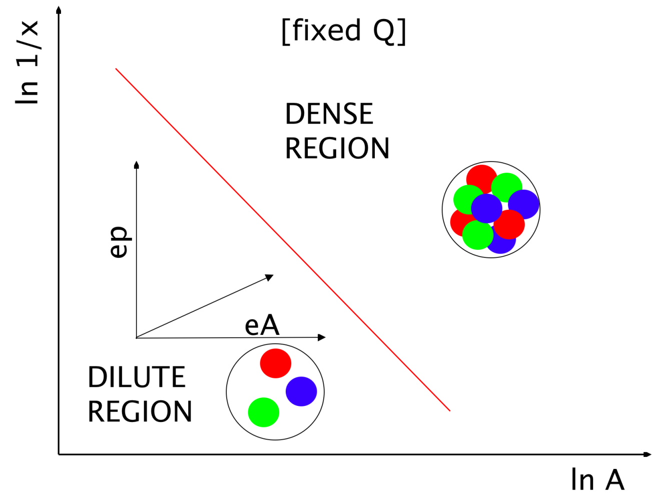
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Parton level language → **recombination gg → g**
- Saturation effects beyond x dependent saturation scale

$$Q_s^2 \sim xg(x)\alpha_s \sim cx^{-\lambda}A^{1/3}$$

- Weak hints at saturation effects @ HERA (but at very low Q^2)

Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



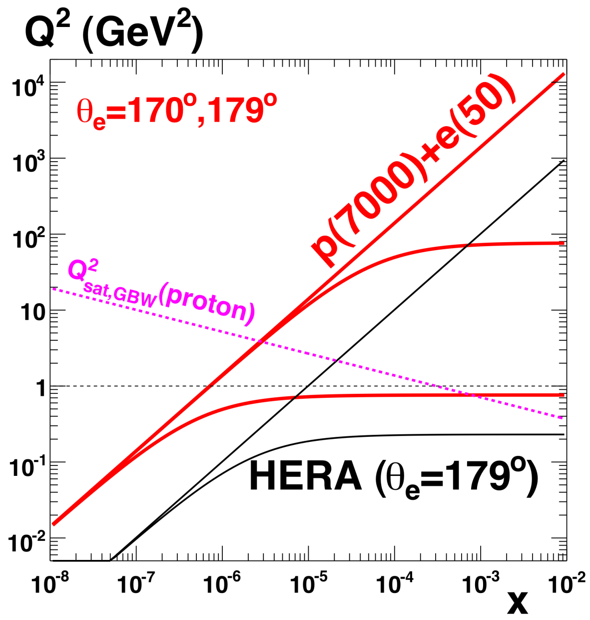
Enhance target `blackness' by:

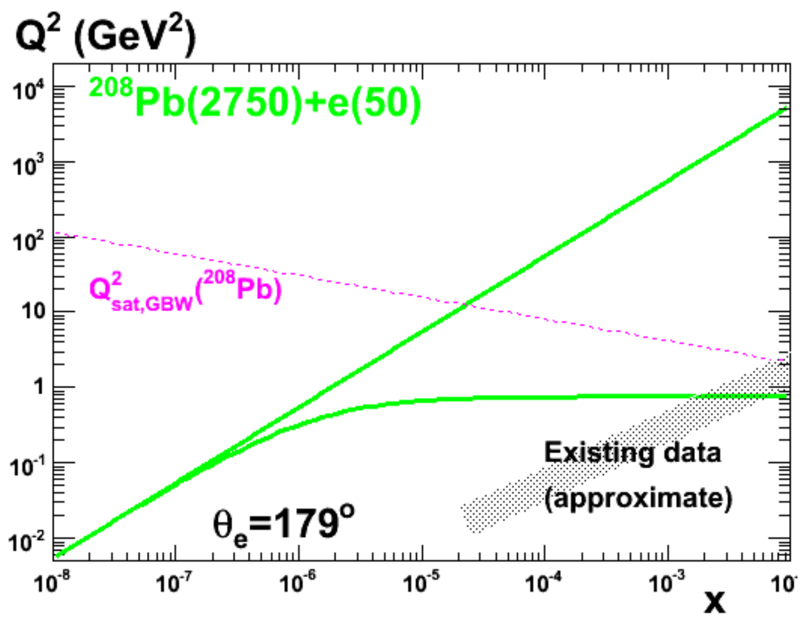
1) Probing lower x at fixed Q^2 in ep

[evolution of a single source]

2) Increasing target matter in eA

[overlapping many sources at fixed kinematics … density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]

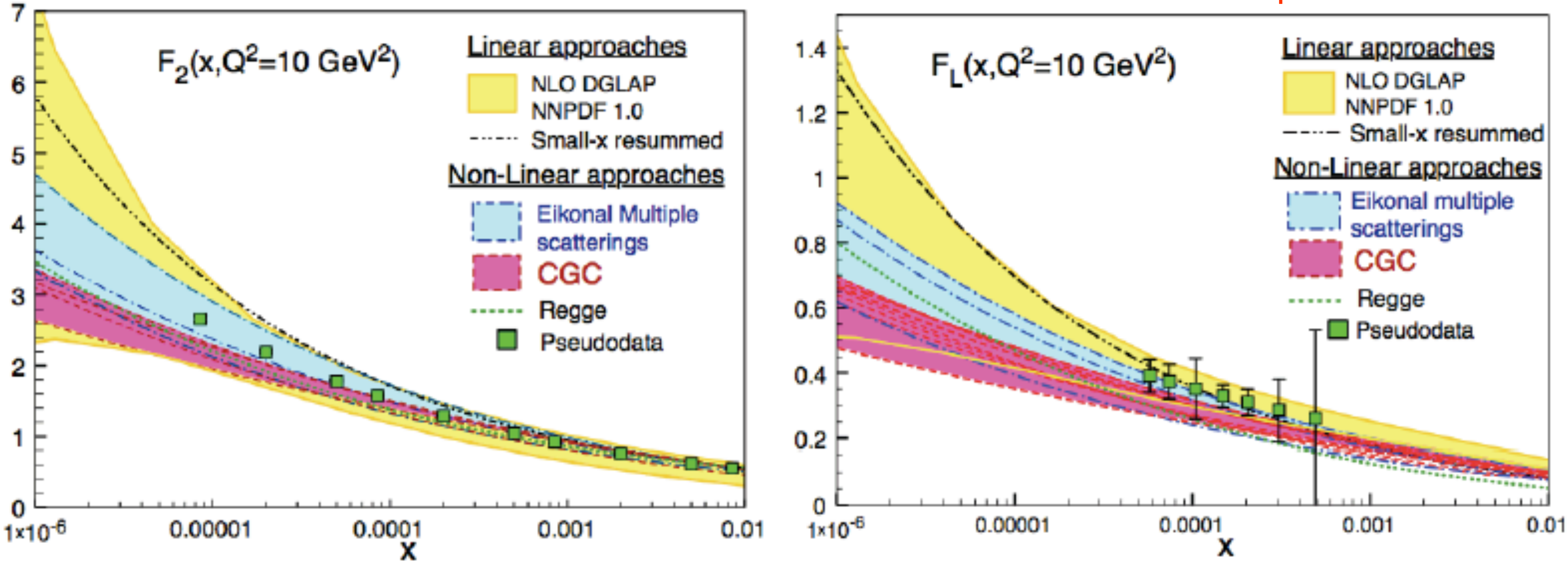




Extrapolating HERA models of F_2

With 1 fb^{-1} (1 year at 10^{32} cm^{-2} s^{-1}), F_2 stat. < 0.1%, syst, 1-3%

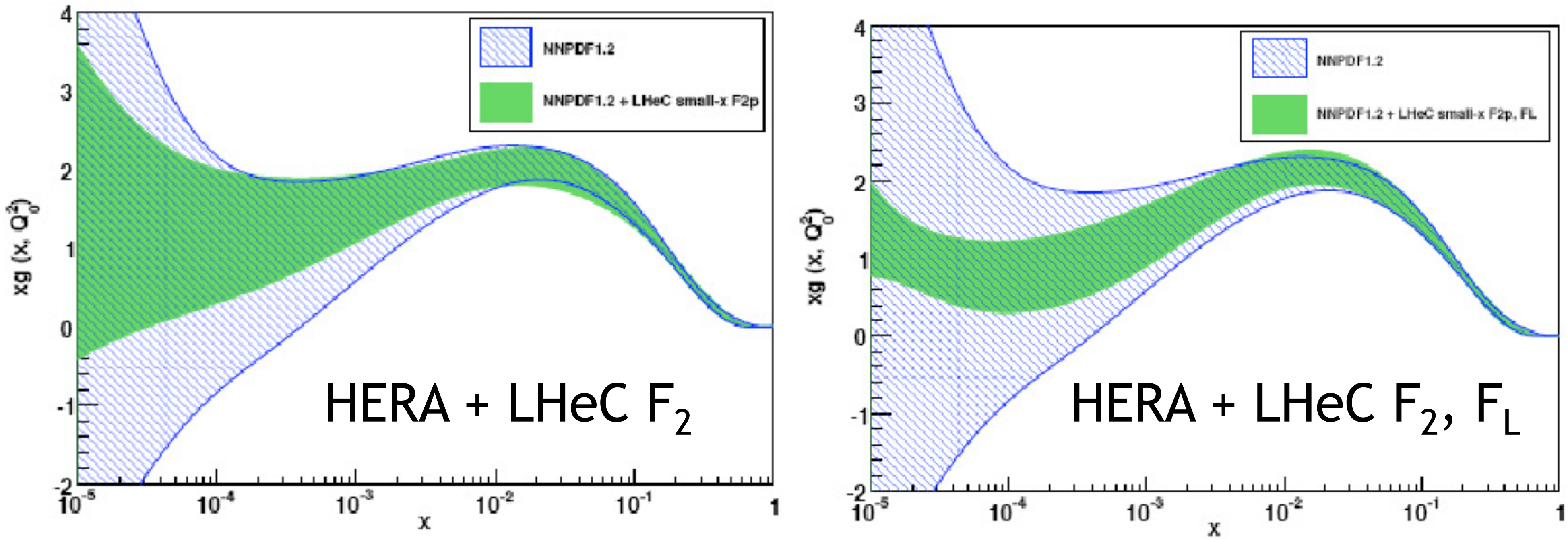
F_L measurement to 8% with 1 year of varying E_e or E_p



NLO DGLAP uncertainties explode @ low x and Q^2

- 'Modern' dipole models, containing saturation effects & low x behaviour derived from QCD give a much narrower range
- … we should be able to distinguish between different models for the onset of saturation effects

Fitting for the Gluon with LHeC F_2 and F_L



(Q^2 = 2 GeV^2)

Including LHeC data in NNPDF DGLAP fit approach …

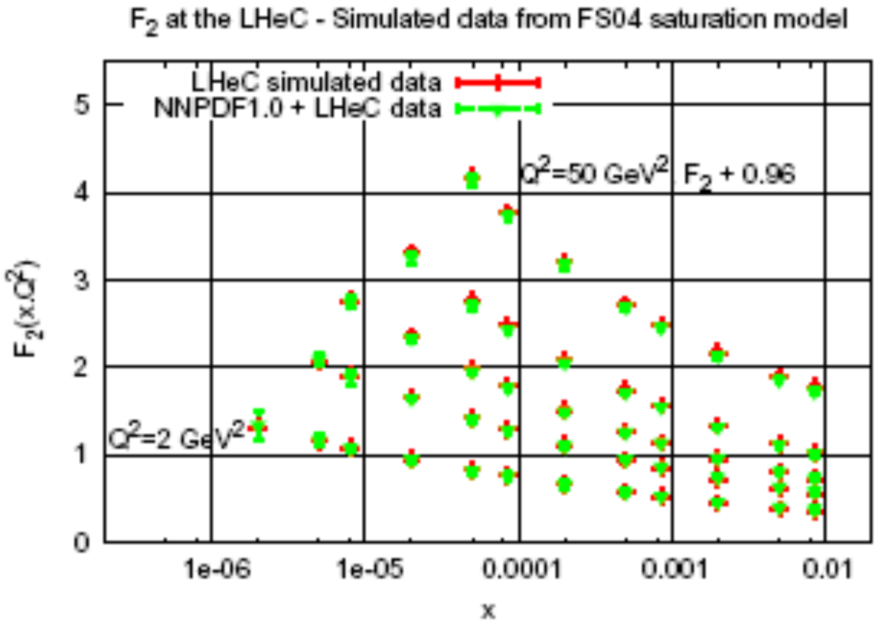
… sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

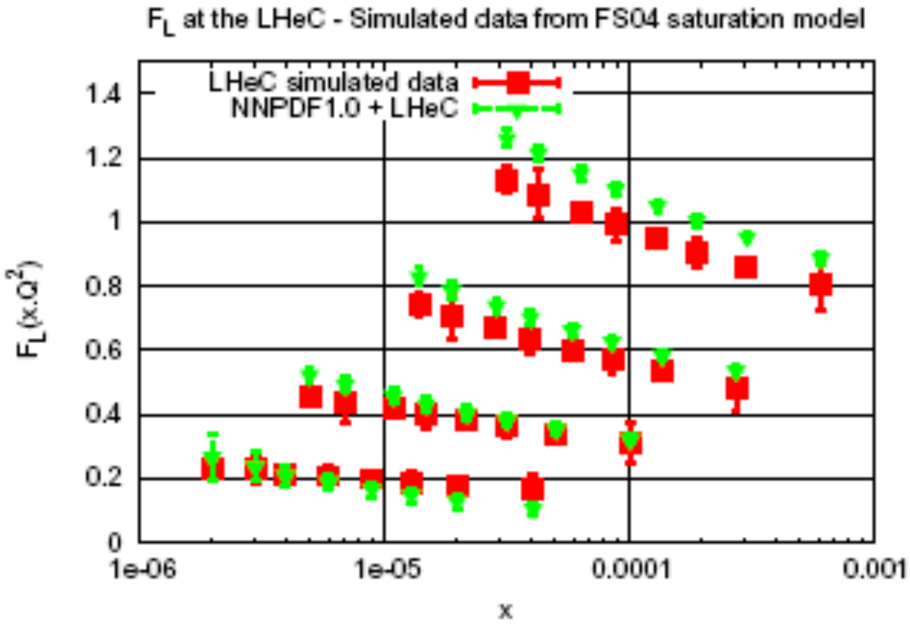
… but would DGLAP fits fail if non-linear effects present?

Can Parton Saturation be Established in ep @ 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

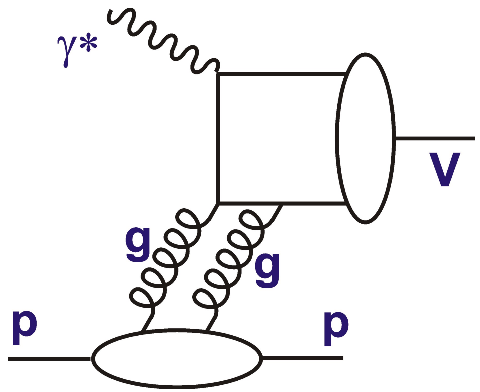




Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>(F_2^c may work in place of F_L)</u>…

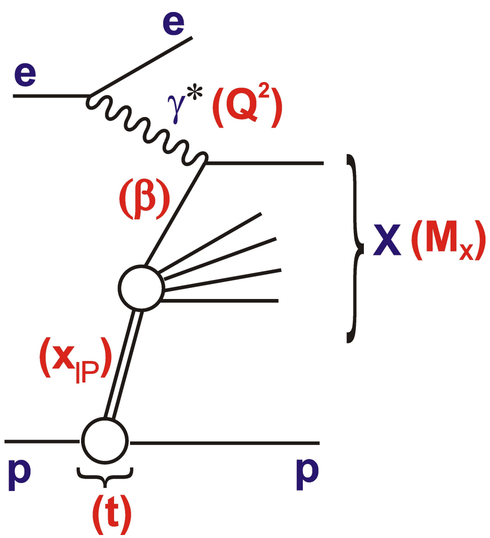
Exclusive / Diffractive Channels and Saturation

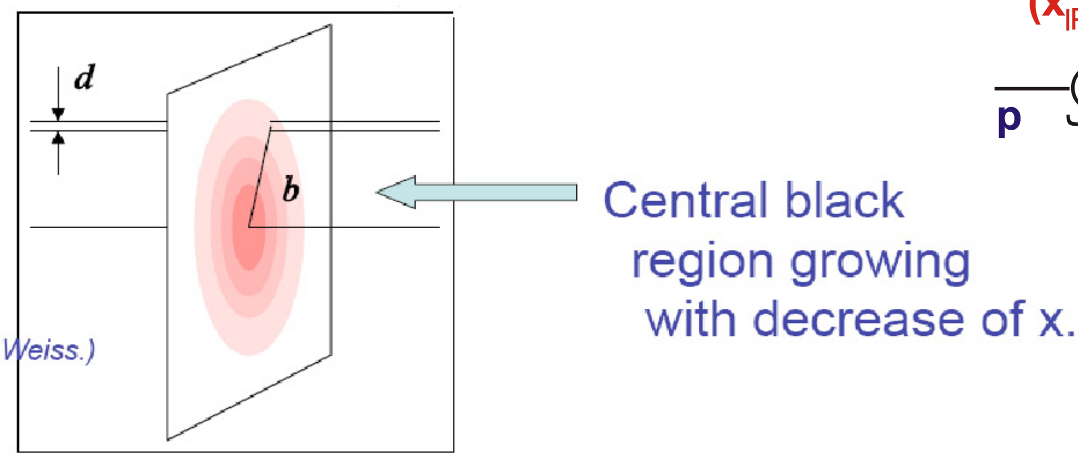
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon



2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?

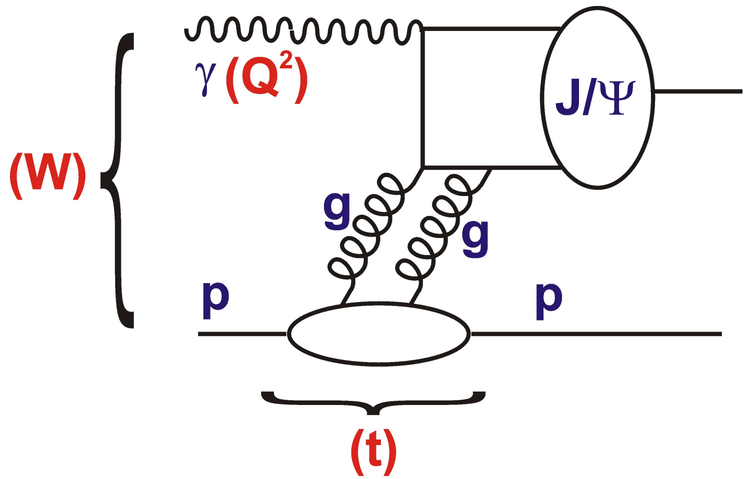




(figure from C. Weiss.)

Elastic J/Ψ Photoproduction: Golden Channel?

• `Cleanly' interpreted as hard 2g exchange coupling to qqbar dipole … enhanced sensitivity to low x gluon



• c and c-bar share energy equally, simplifying VM wavefunction

• Clean experimental signature (just 2 leptons)

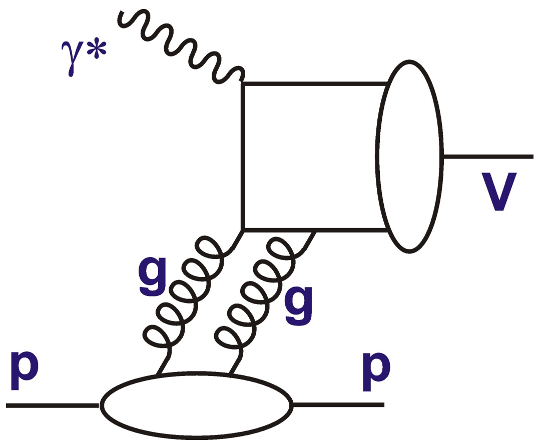
… LHeC reach extends to $x_g \sim 6.10^{-6}$ at $\overline{Q^2} \sim 3$ GeV^2

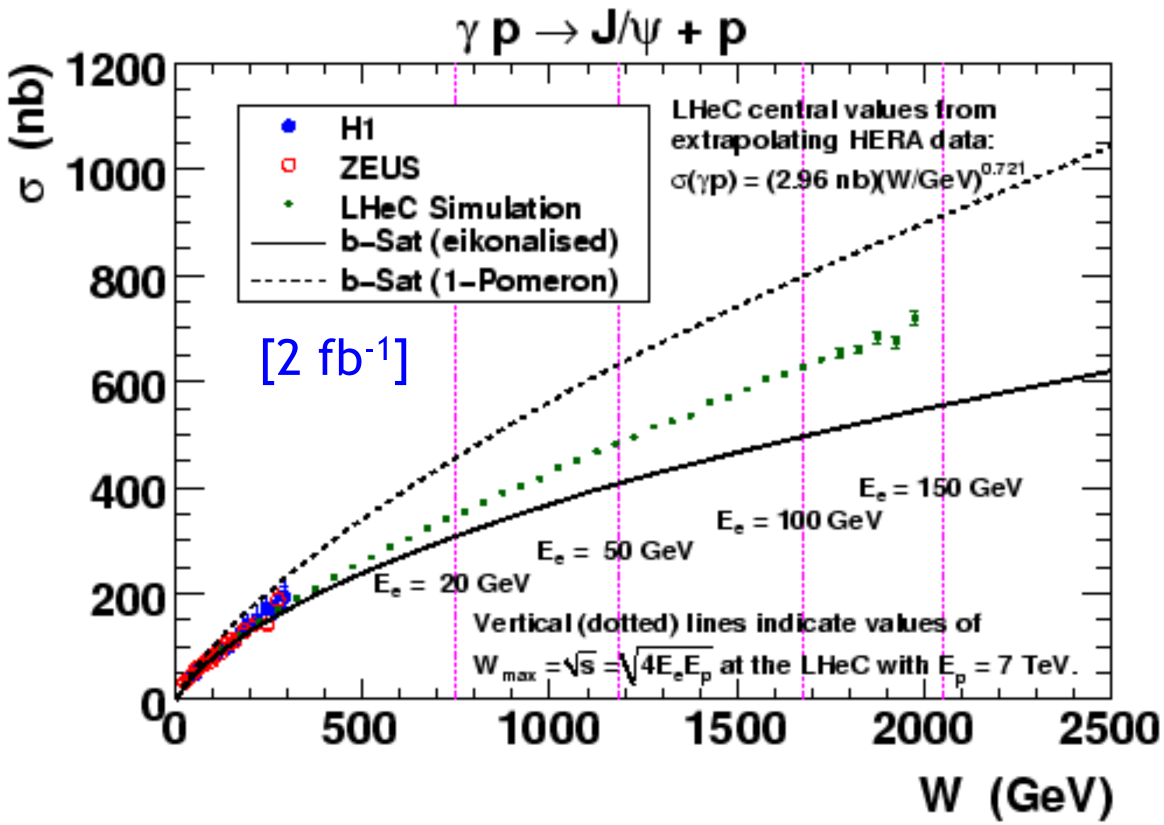
(MNRT etc) $X_g \sim (Q^2 + M_V^2) \,/\, (Q^2 + W^2)$ $\overline{Q^2} = (Q^2 + M_V^2) \,/\, 4$

• Simulations of elastic J/Ψ → μμ photoproduction
→ scattered electron untagged, 1° acceptance for muons
(similar method to H1 and ZEUS)

Simulation of J/ψ Photoproduction

e.g. "b-Sat" Dipole model
- "eikonalised": with impact-parameter dependent saturation
- "1 Pomeron": non-saturating

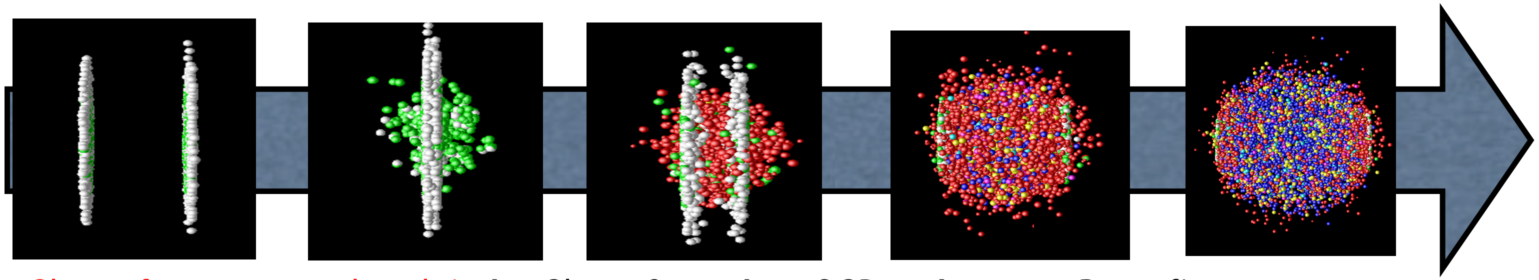




- Significant non-linear effects expected in LHeC kinematic range.

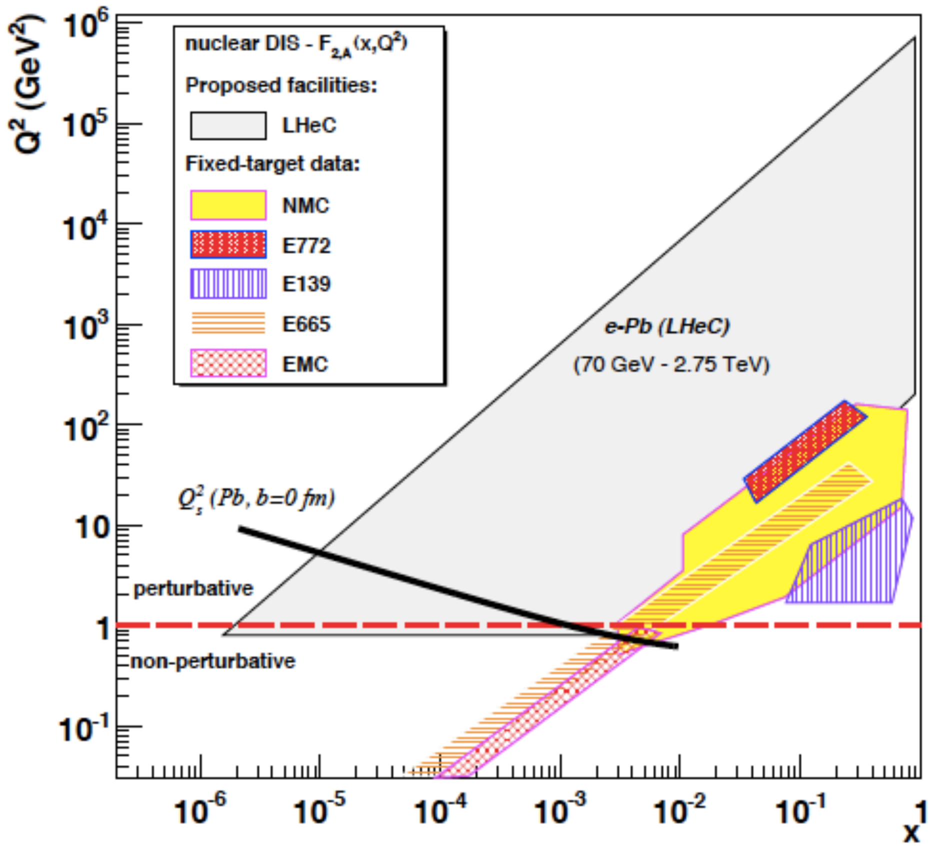
- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…
  → Sat^n smoking gun?

What is Initial State of LHC AA Collisions?

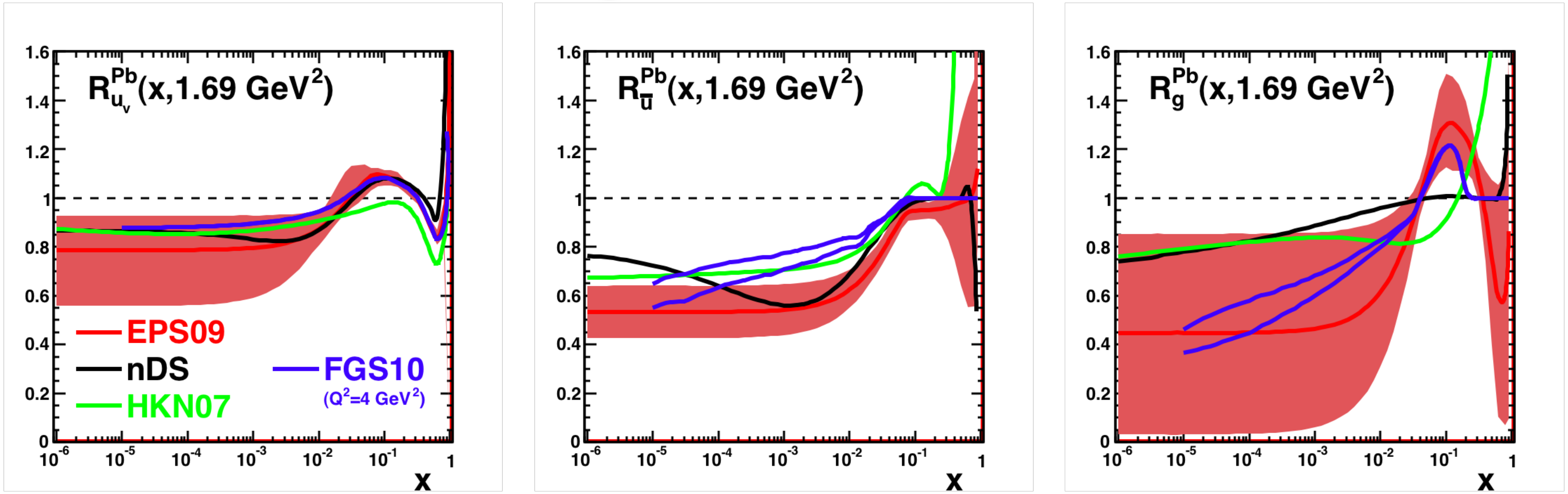


- Very limited x, Q^2 and A range for F_2^A so far (fixed target experiments covered x >~ 10^{-2})

- LHeC extends kinematic range by 3-4 orders of magnitude with very large A



Current Knowledge: Nuclear Parton Densities



R_i = Nuclear PDF i / (A * proton PDF i)

- Nuclear parton densities don't scale with A due to Fermi motion, shadowing corrections …

- All parton types poorly constrained for $x < 10^{-2}$

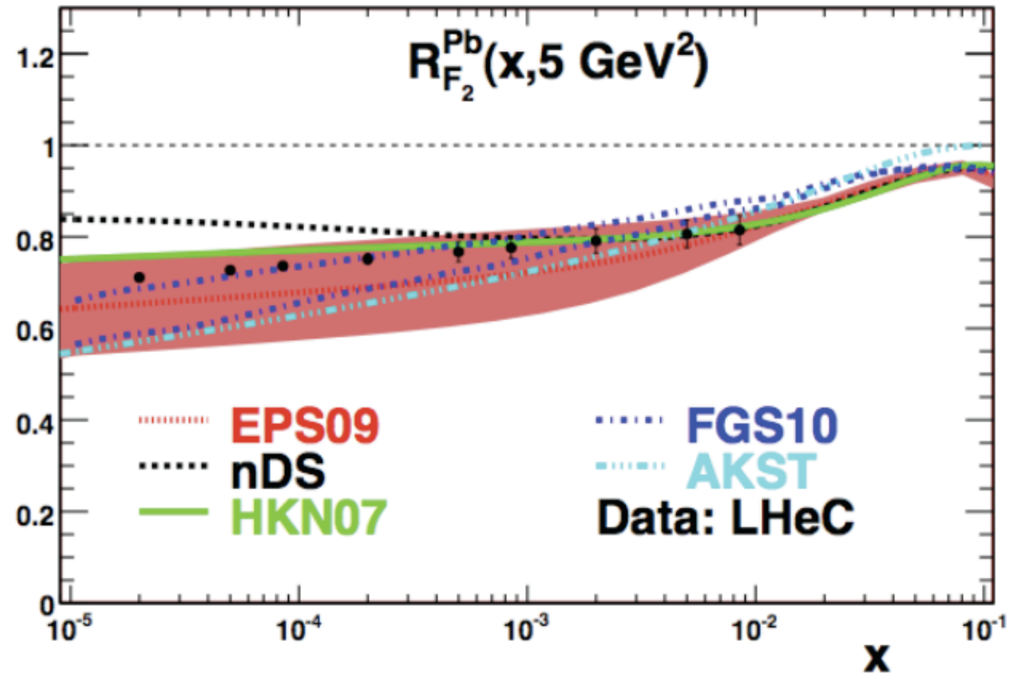
- Gluon density essentially unknown

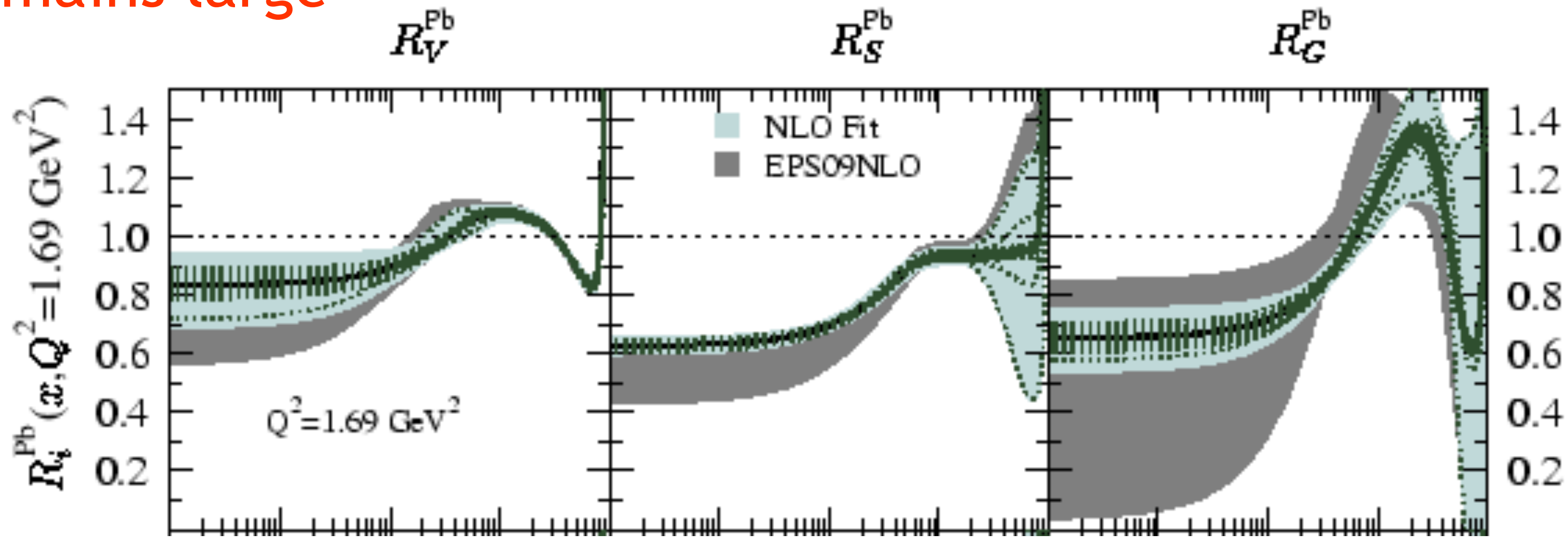
Study of Impact of e-Pb LHC data

- LHeC ePb F_2 measurement has huge impact relative to current uncertainties

- Striking effect on quark sea and gluons in particular

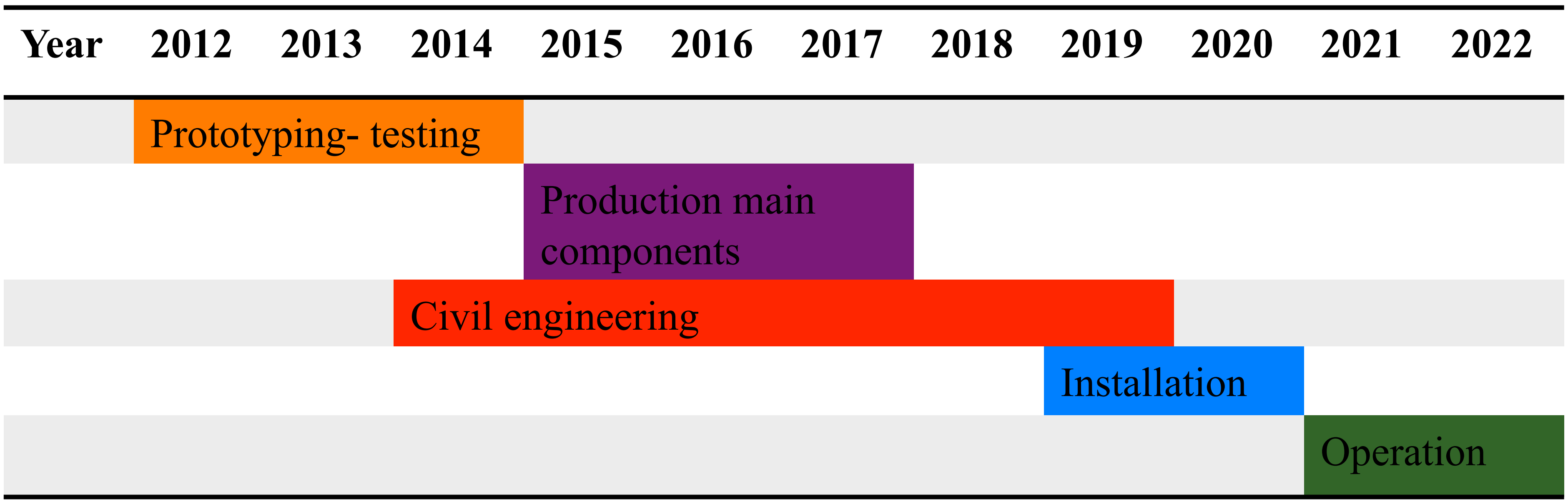
- High x gluon uncertainty remains large





Schedule and Remarks

- Aim to start operation by 2022 [new phase of LHC]
  → cf HERA: Proposal 1984 – Operation 1992. LEP: Proposal 1983 – Operation 1989
- The major accelerator and detector technologies exist
- Cost is modest in major HEP project terms
- Steps: Conceptual Design Report, 2011
  Evaluation within CERN / European PP/NP strategy
  If positive, move towards a TDR 2013/14



Summary

• LHC is a totally new world of energy and luminosity! LHeC proposal aims to exploit it for lepton-hadron scattering
… ep complementing LHC and next generation ee facility for full Terascale exploration

• Ongoing ECFA/CERN/NuPECC workshop has gathered many accelerator, theory & experimental colleagues
→ Conceptual Design Report

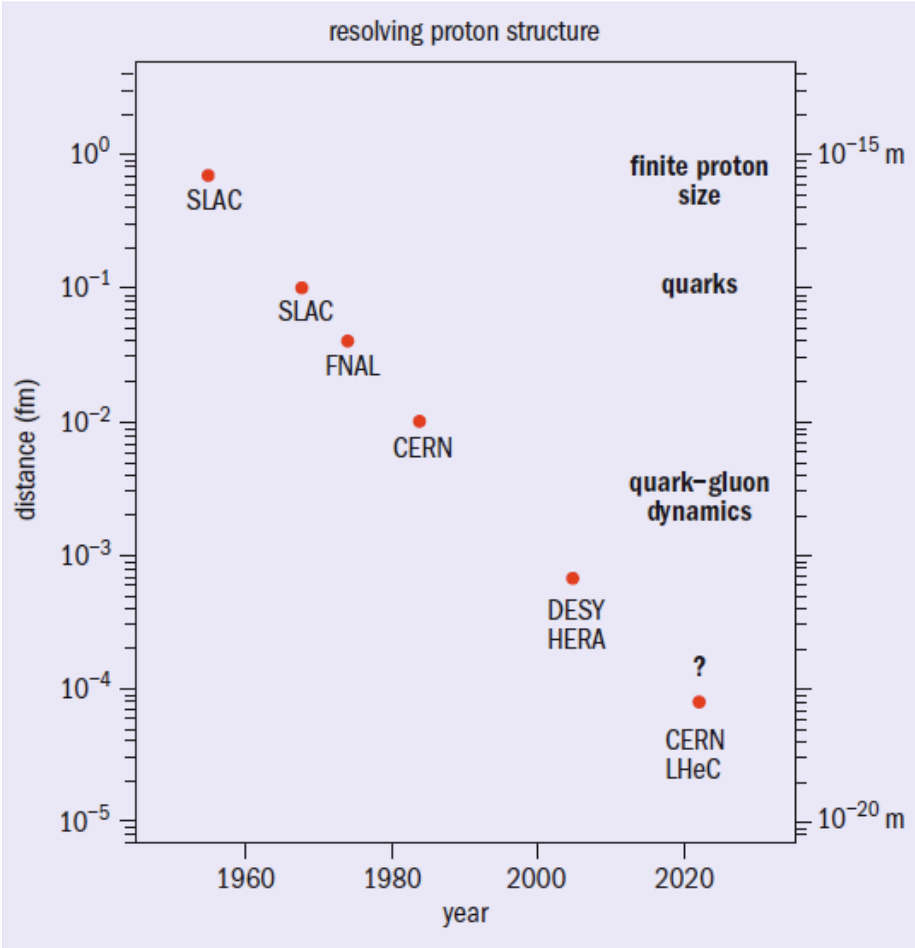


Fig. 1. Distance scales resolved in successive lepton–hadron scattering experiments since the 1950s, and some of the new physics revealed.

• CDR being finalised. Will be available by Autumn

[More at http://cern.ch/lhec]