Future High Energy Electron Proton Scattering … The LHeC Project

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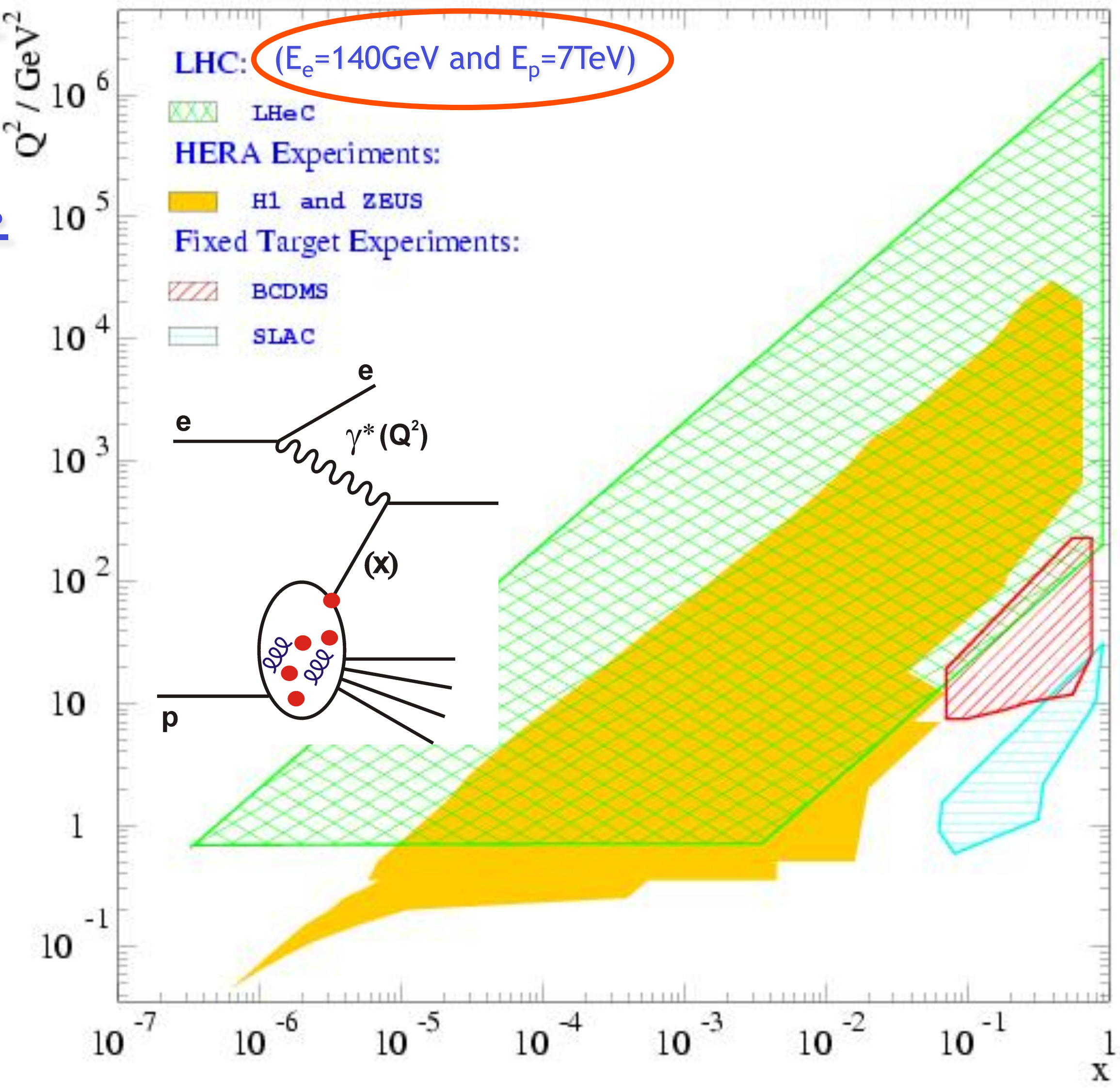
(for LHeC study group)



Manchester Seminar
7 March 2012

… 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

- 525 pages, summarising work of ~150 participants over 5 years

- Currently under review by CERN-appointed referees → final version expected April / May 2012

- Nobody works full time on LHeC yet

DRAFT 1.0
Geneva, August 5, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

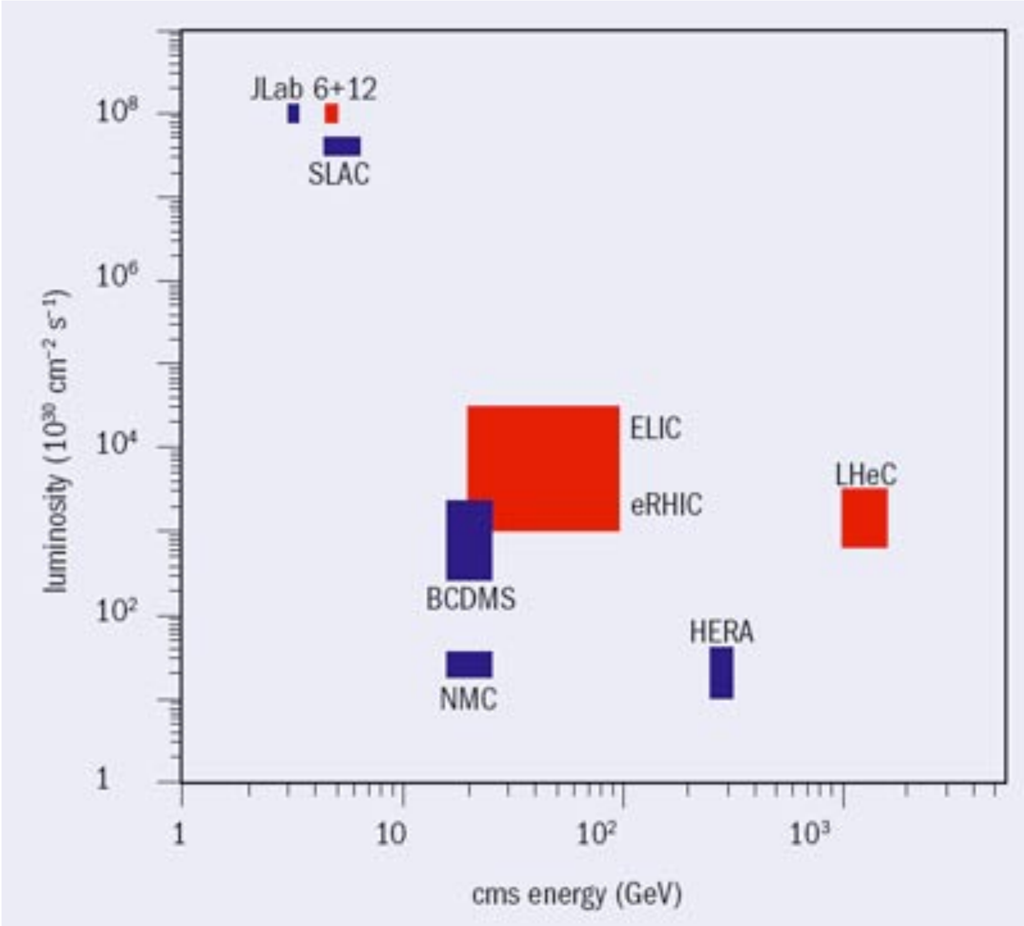
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

To be submitted for publication

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 based on the LHC
- Detector considerations
- Physics motivation
  - Proton structure / PDFs at low & high x
  - Precision QCD and electroweak physics
  - Electron – ion collisions
  - BSM physics
- 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

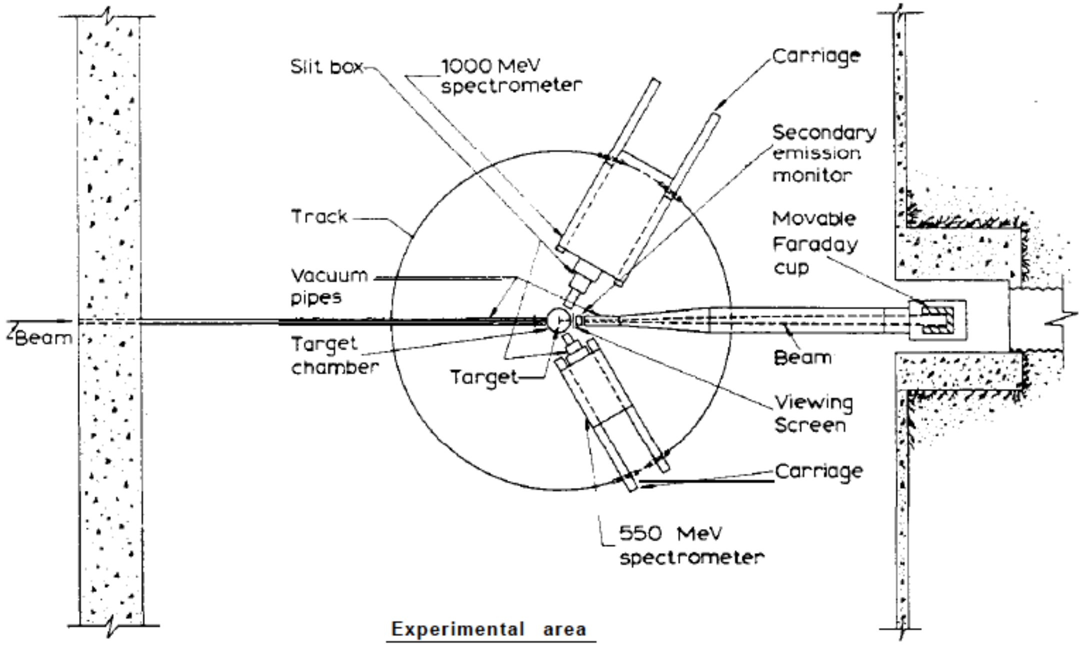
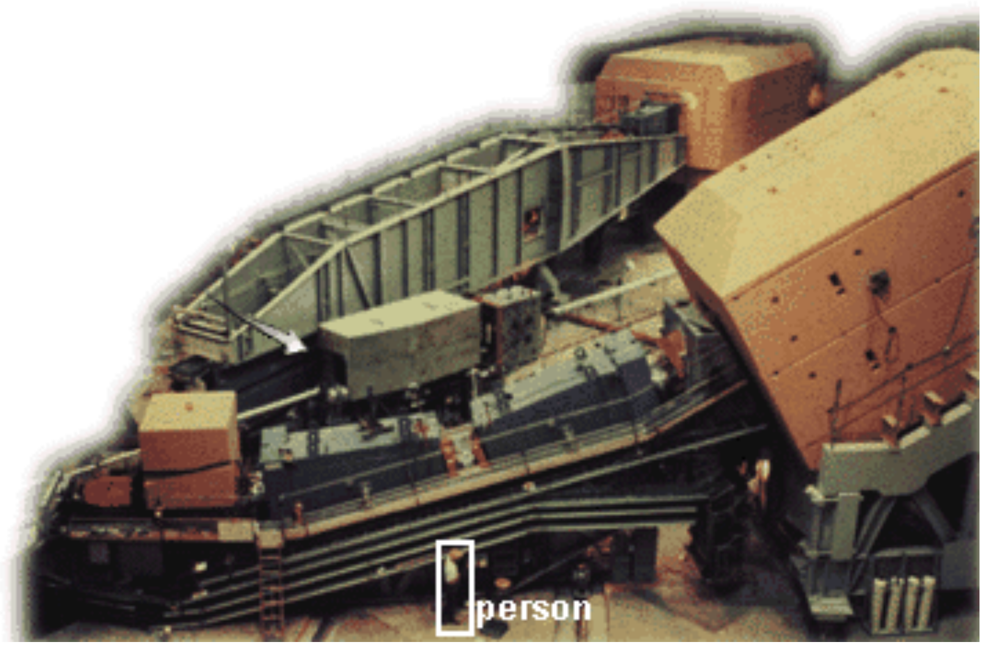


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

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

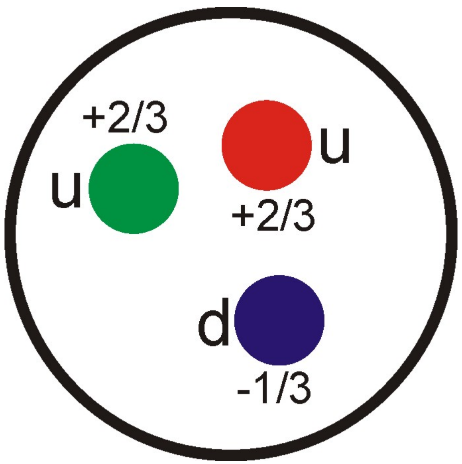
VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

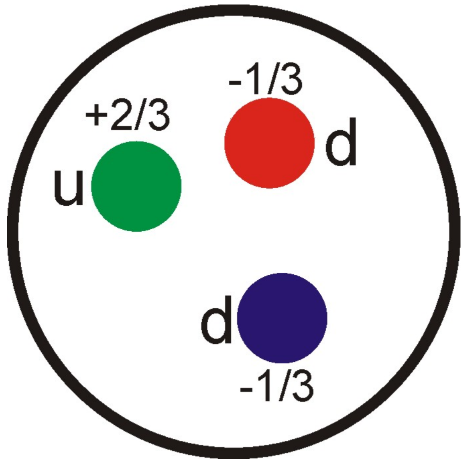
M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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)



proton



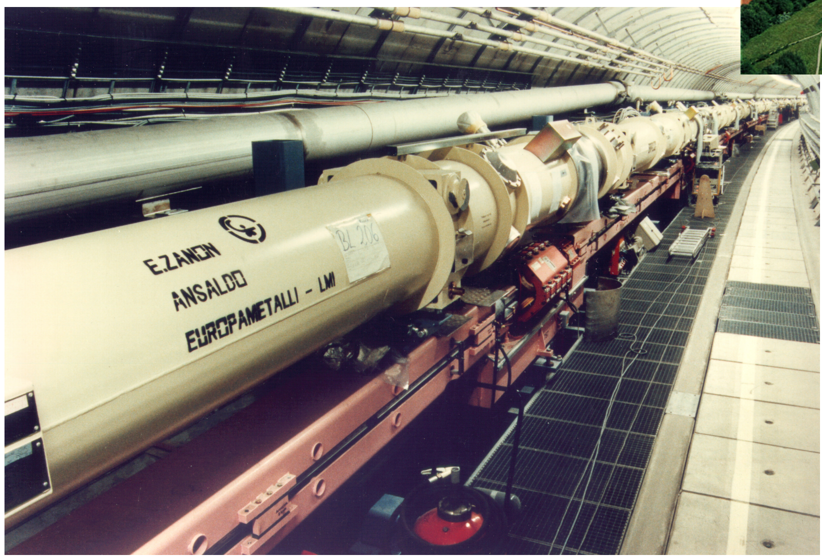
neutron

... and so on ...

DESY, Hamburg

HERA (1992-2007)

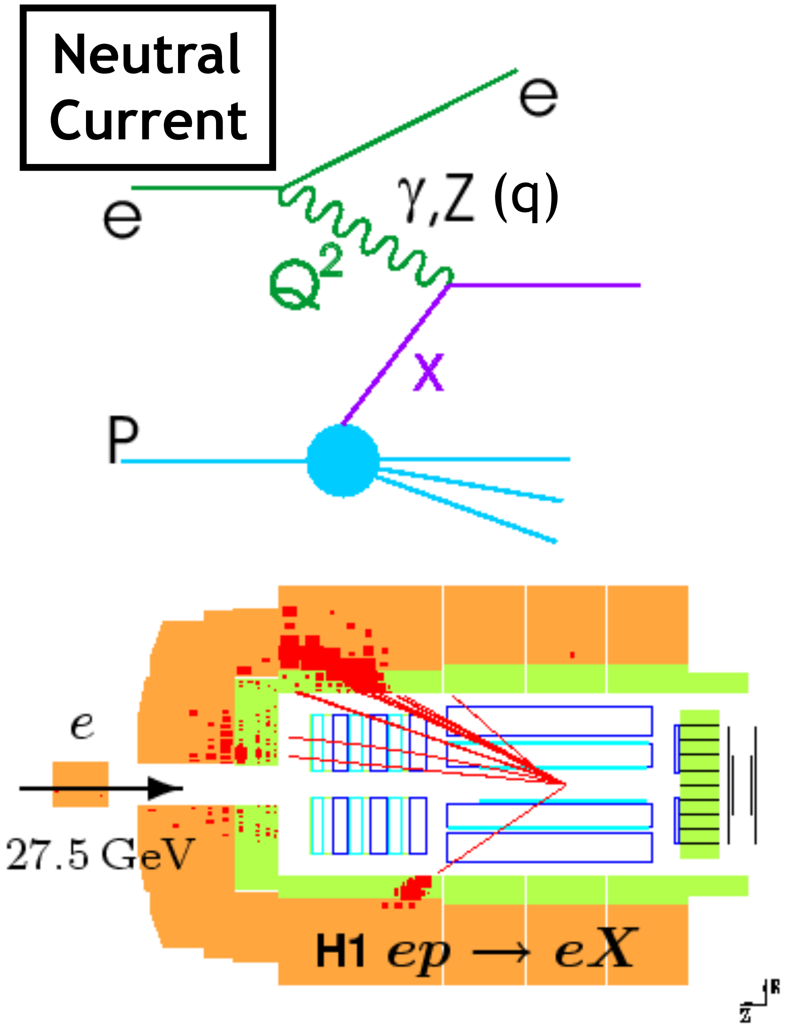
… the only ever collider of electron beams with proton beams

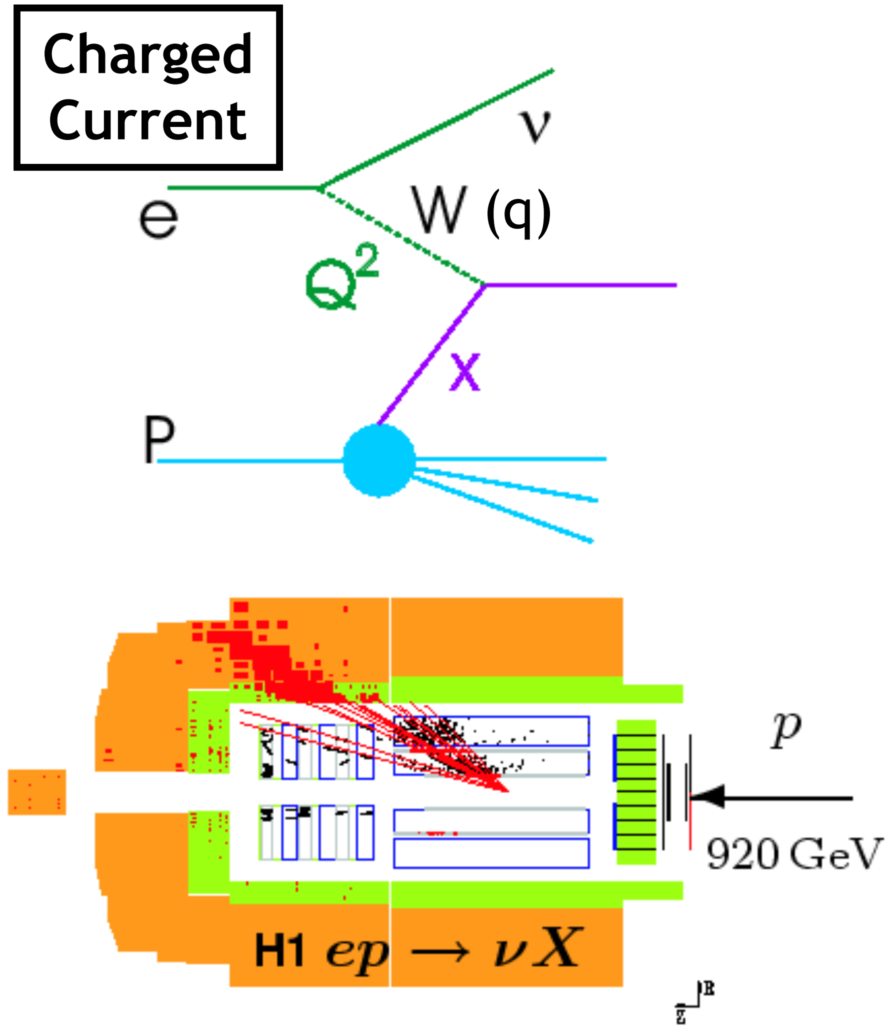


Equivalent to a 50 TeV beam on a fixed target proton
~2500 times more than SLAC!

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 …

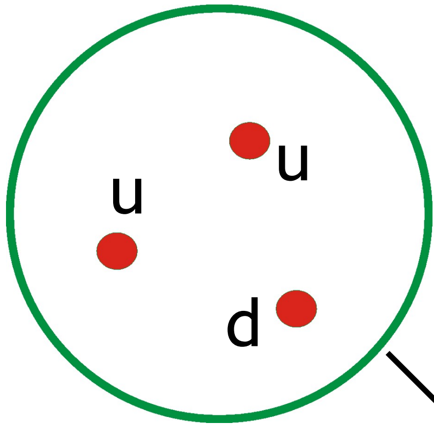
2 up and 1 down **valence quarks**

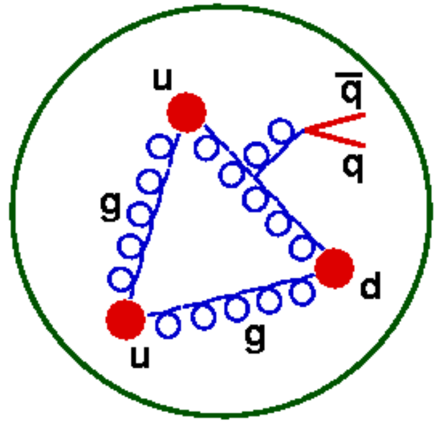
… and some **gluons**

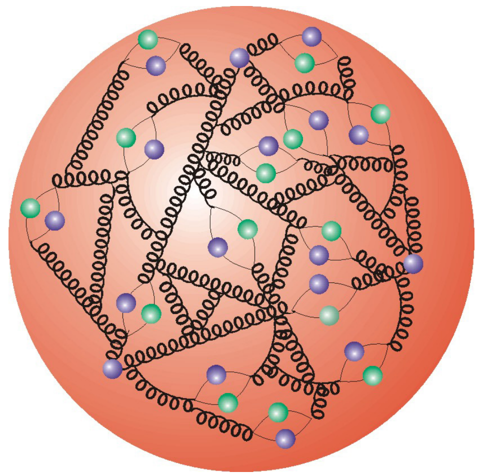
… and some **sea quarks**

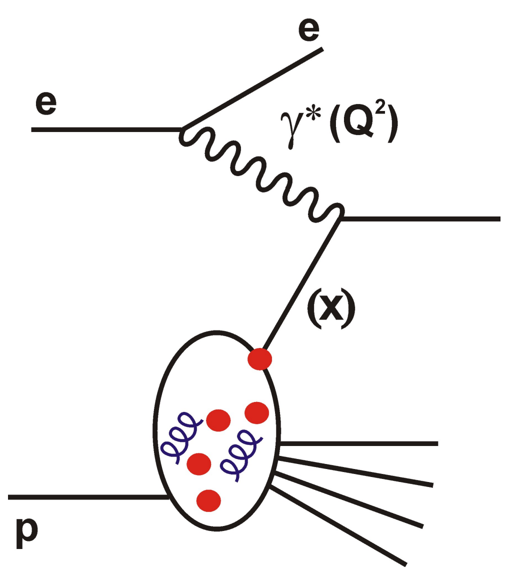
… and lots more gluons and sea quarks …

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





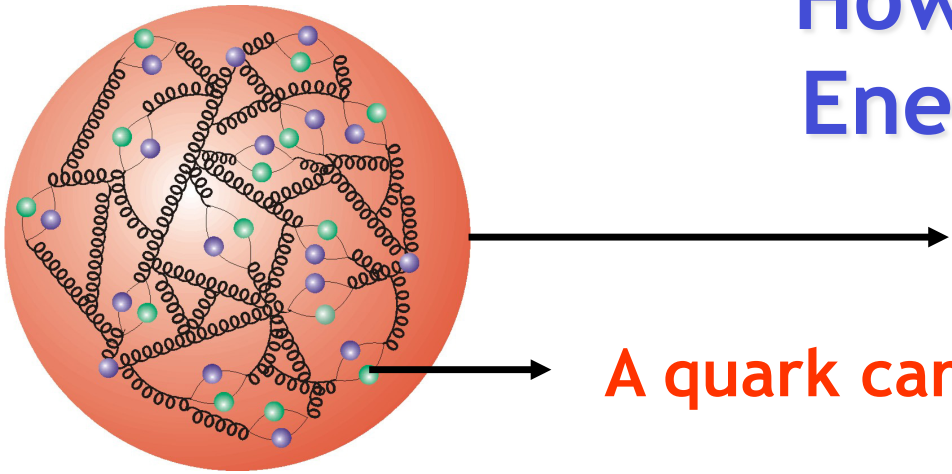




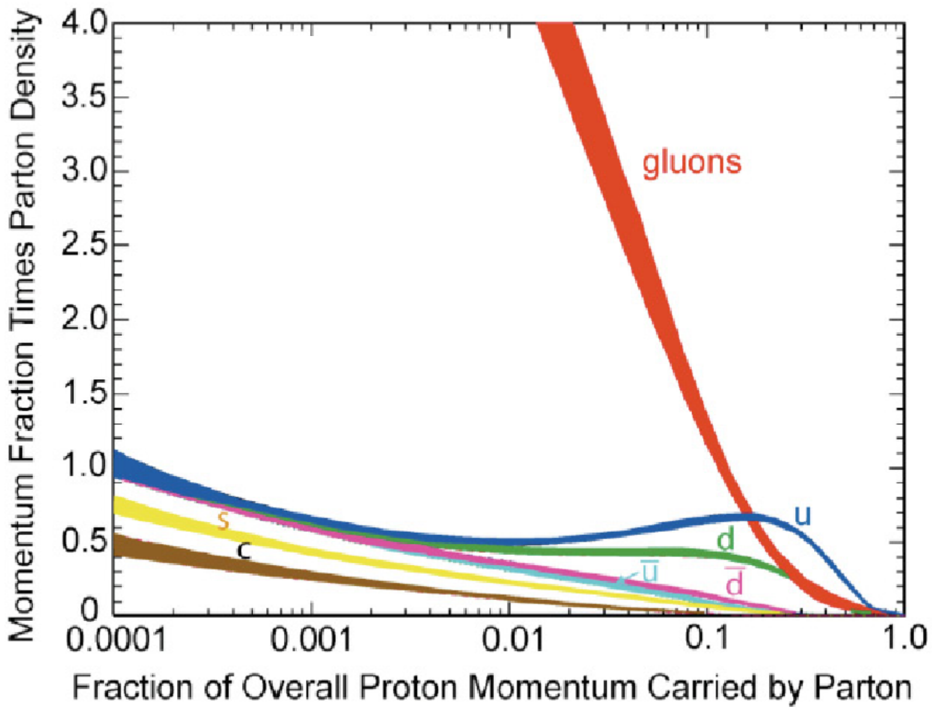
Scattering electrons from protons at $\sqrt{s}$ > 300GeV at HERA established detailed proton structure & provided a testing ground for QCD over a huge kinematic range

… **parton density functions**

How is the Proton's Energy Shared out?



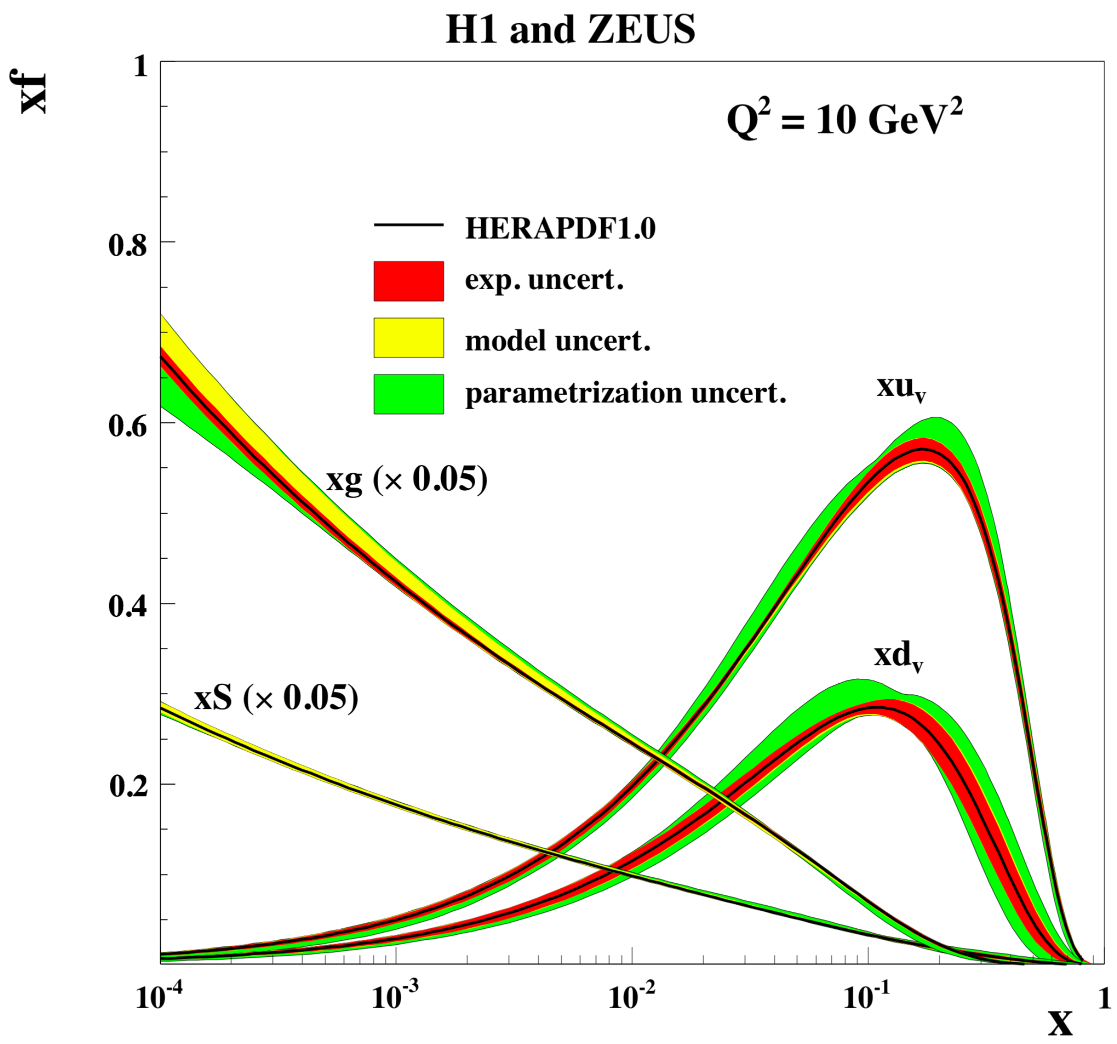
Energy carried by quarks and gluons as a function of x →



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

The measured x range at HERA matches that required on the LHC rapidity plateau

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

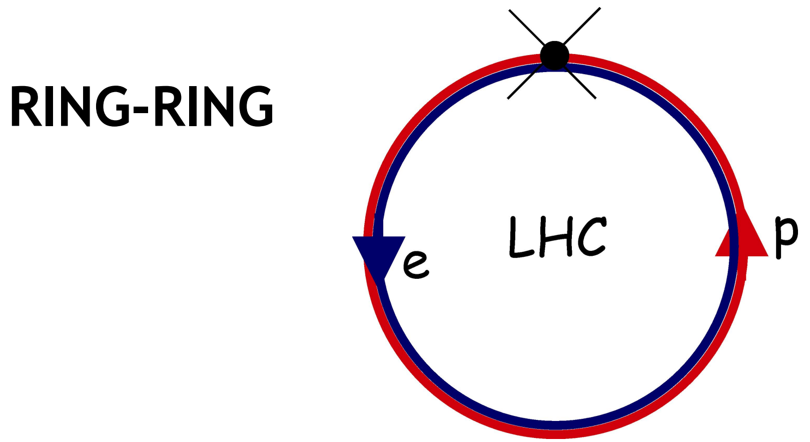
- No heavy ions

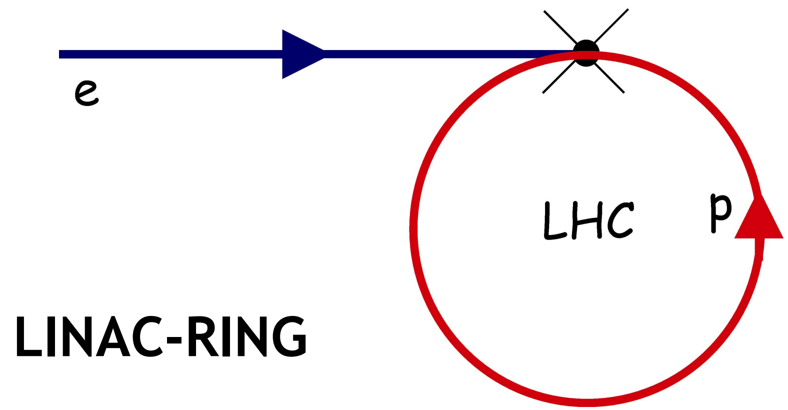
- H1/ZEUS/joint publications still coming for 1-2 years
- Further progress requires higher energy and luminosity …

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

<u>Multi-Lab Involvement</u> CERN, BNL, Cockcroft, Novosibirsk, Cornell, DESY, EPFL Lausanne, Jlab, KEK, SLAC, <u>MANCHESTER</u> …

Design constraint: power consumption < 100 MW

→ E_e = 60 GeV in ring-ring mode

Ring-Ring Design

Installation 1m above LHC and 60cm inside

By-passes of existing experiments containing RF

Challenging, but no show stopper yet

e Ring- p/A Ring

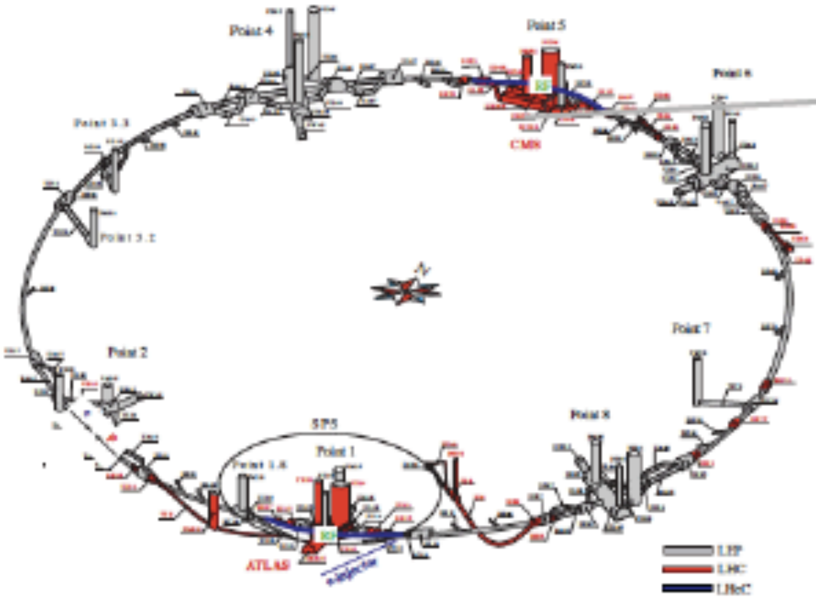
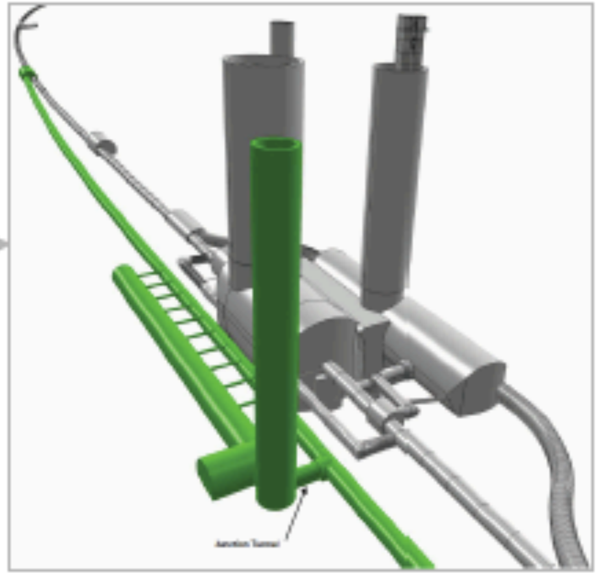
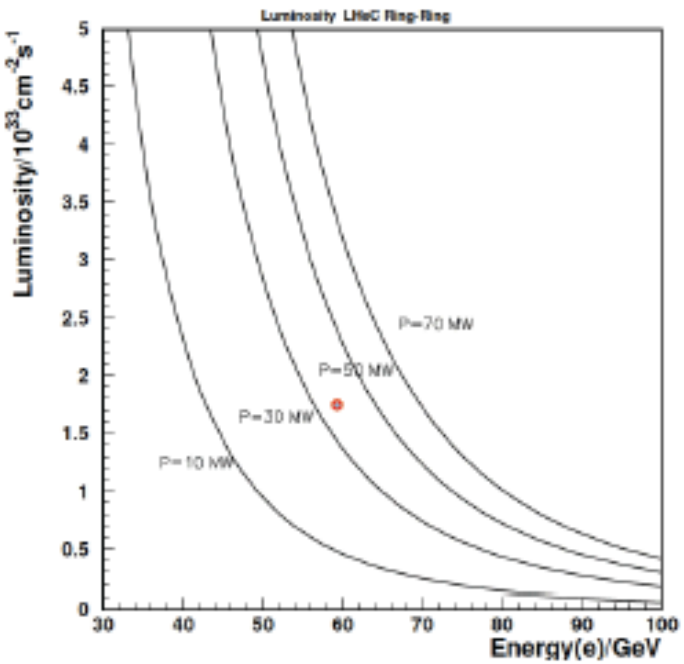


Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV superconducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.



10 GeV injector



Magnets for Electron Ring (CERN, Novisibirsk)

3080 bending dipole magnets

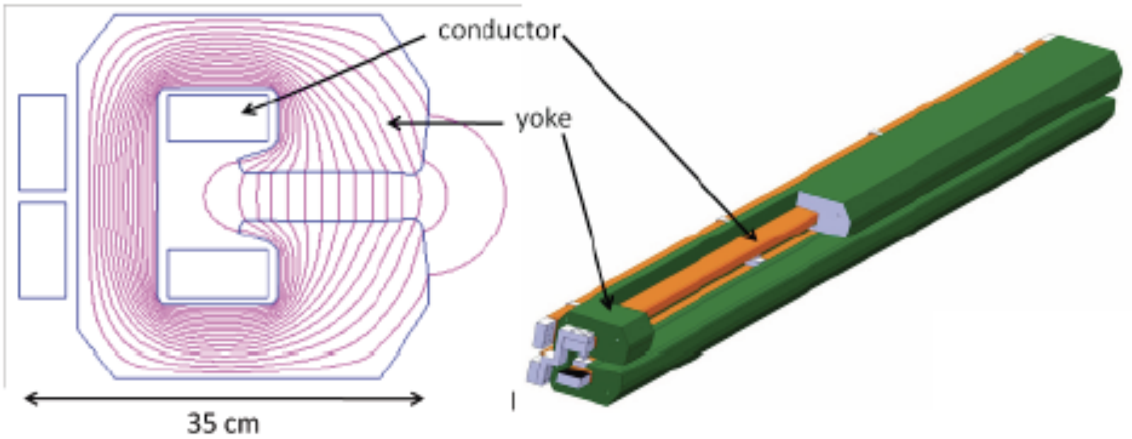


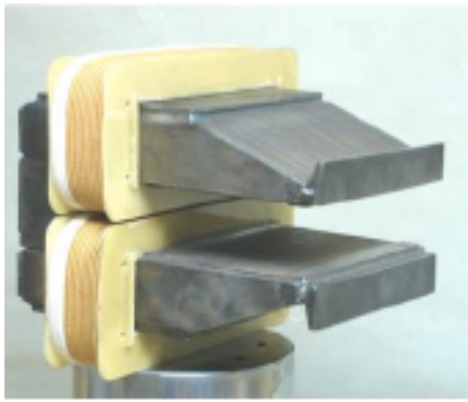
Fig. 2. Field lines and artistic view of a LHeC arc dipole.

5m long
(35cm)^2 transverse

0.013 – 0.08 T

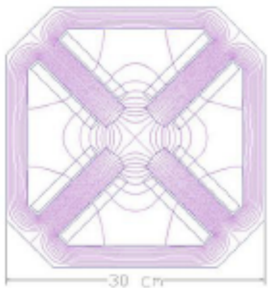
~ 200 kg / m

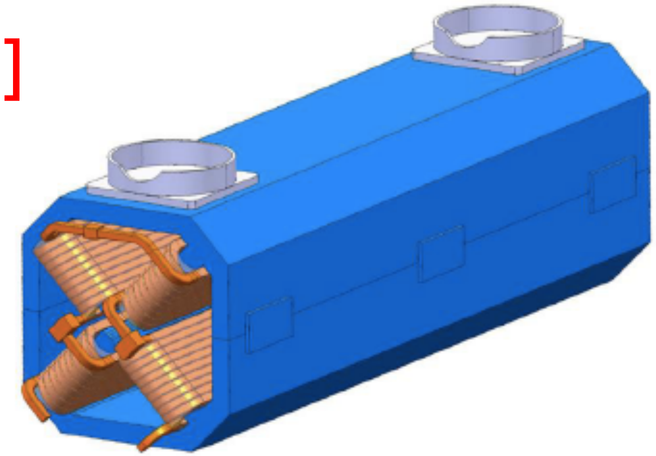
First prototypes (BINP/CERN) function to spec.



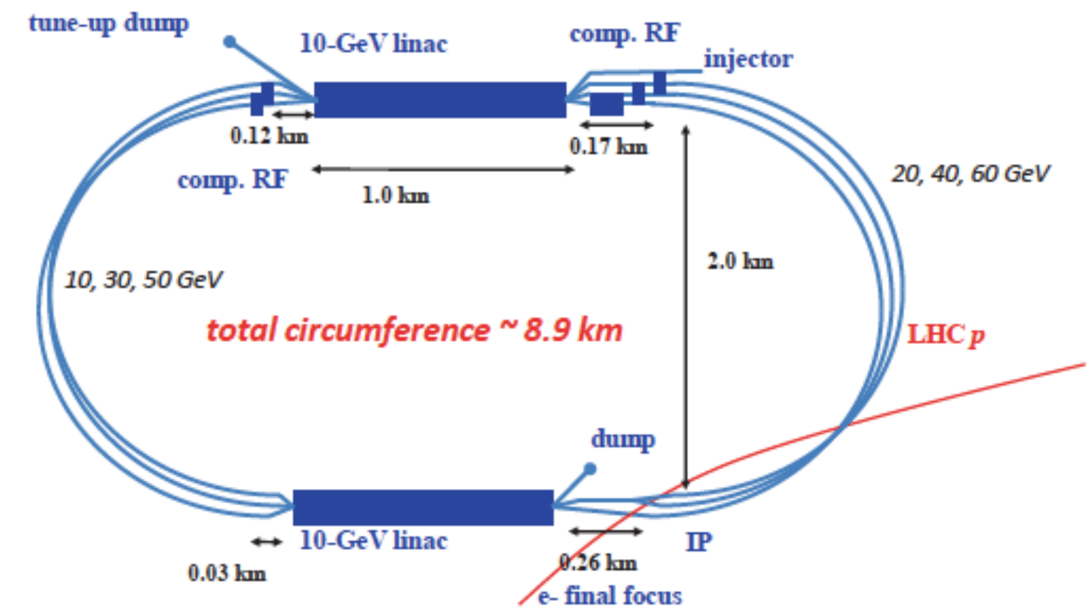
866 arc quadrupole magnets

[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, 20 MV/m CW
- Energy recovery in same structures

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

Civil Engineering Studies for Major Projects after LHC

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

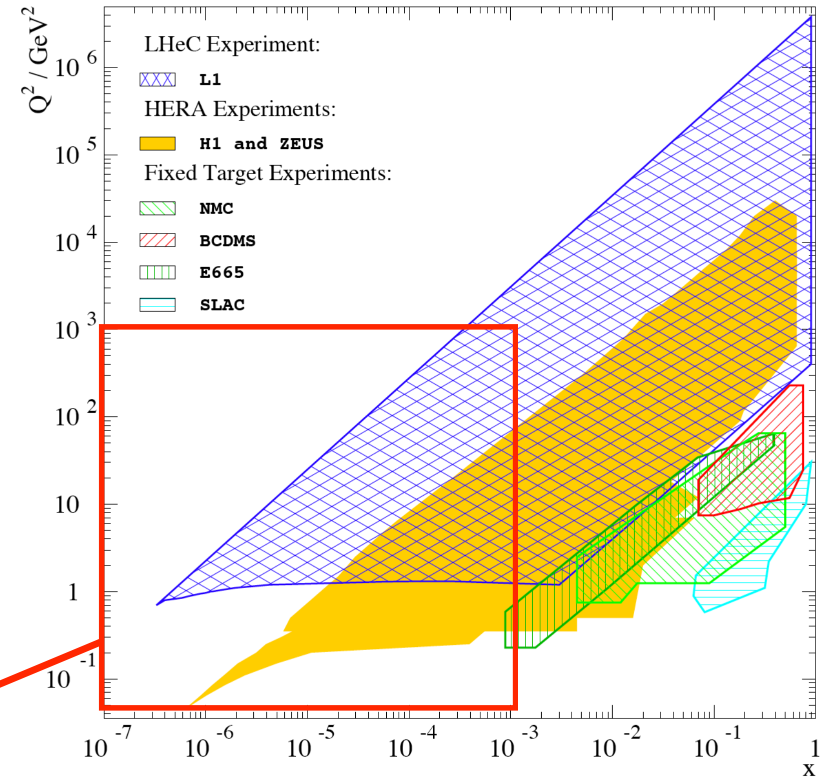
proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit. $\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

Include deuterons (new) and lead (exists)

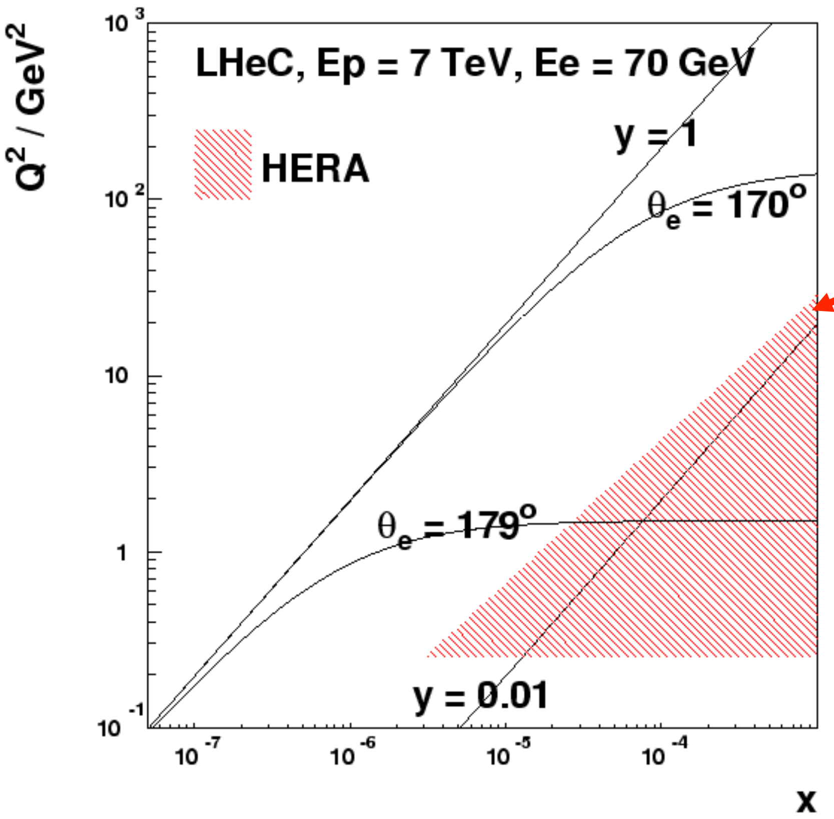
10 fb^{-1} per year looks possible

… ~ 100 fb^{-1} total

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)

Target Acceptance & Systematic Precision

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

The new collider …

- should be ~100 times more luminous than HERA

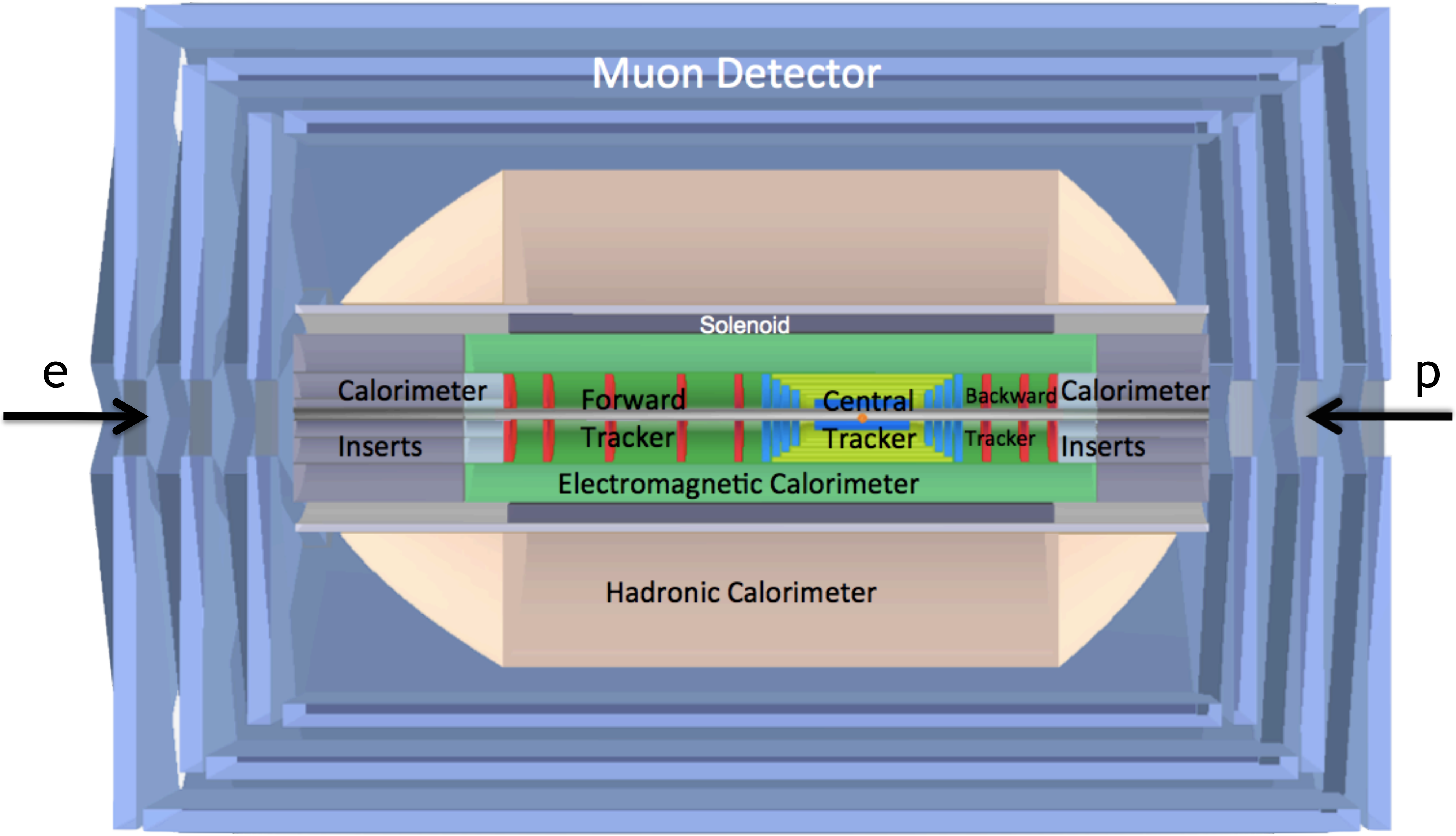
The new detector

- 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' produced on this basis

Detector Overview: LR full acceptance version

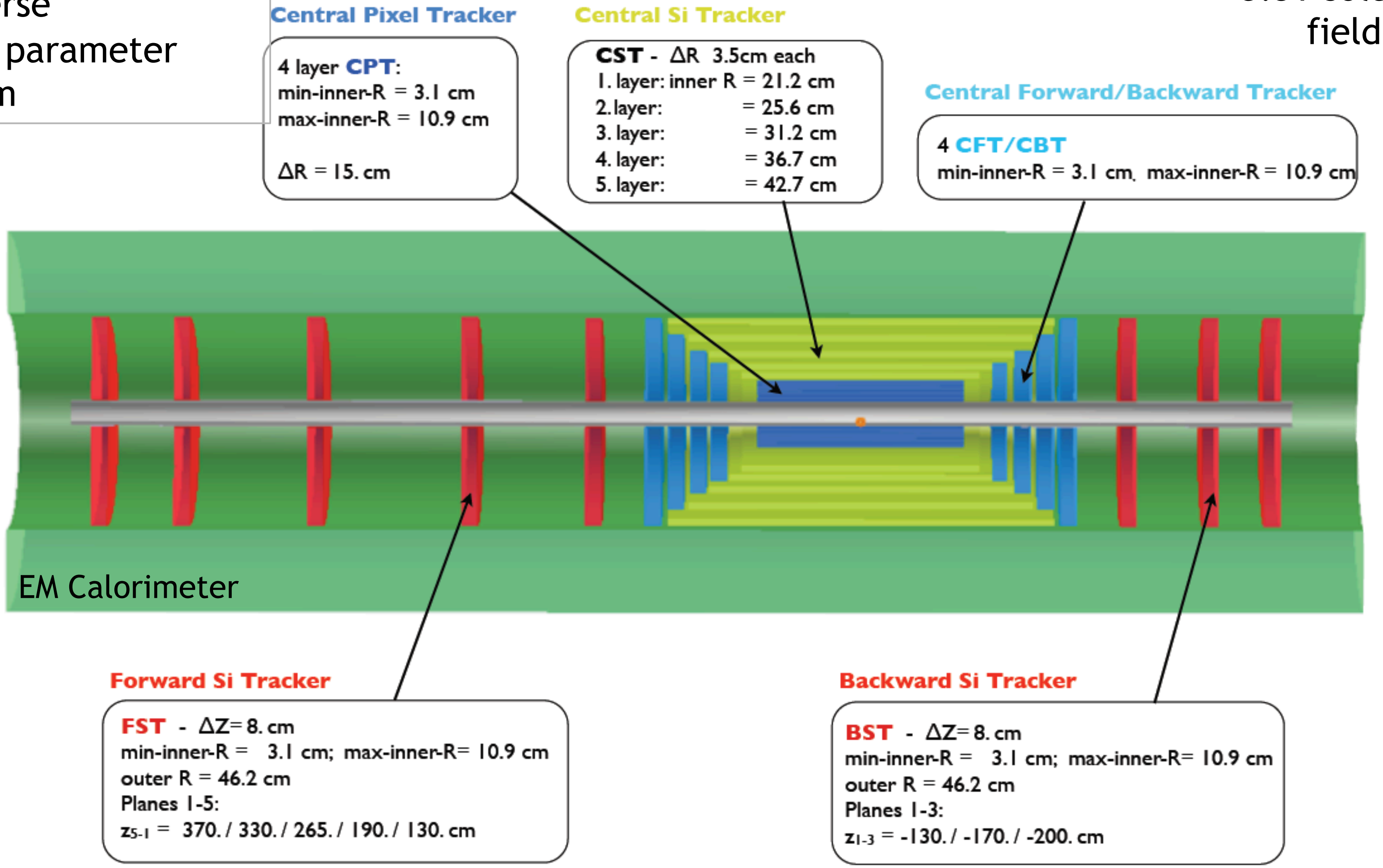


Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m² [CMS 21 x 15m², ATLAS 45 x 25 m²]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

Transverse momentum $\Delta p_t/p_t^2 \rightarrow 6\ 10^{-4}\ GeV^{-1}$
transverse
impact parameter
→ 10µm

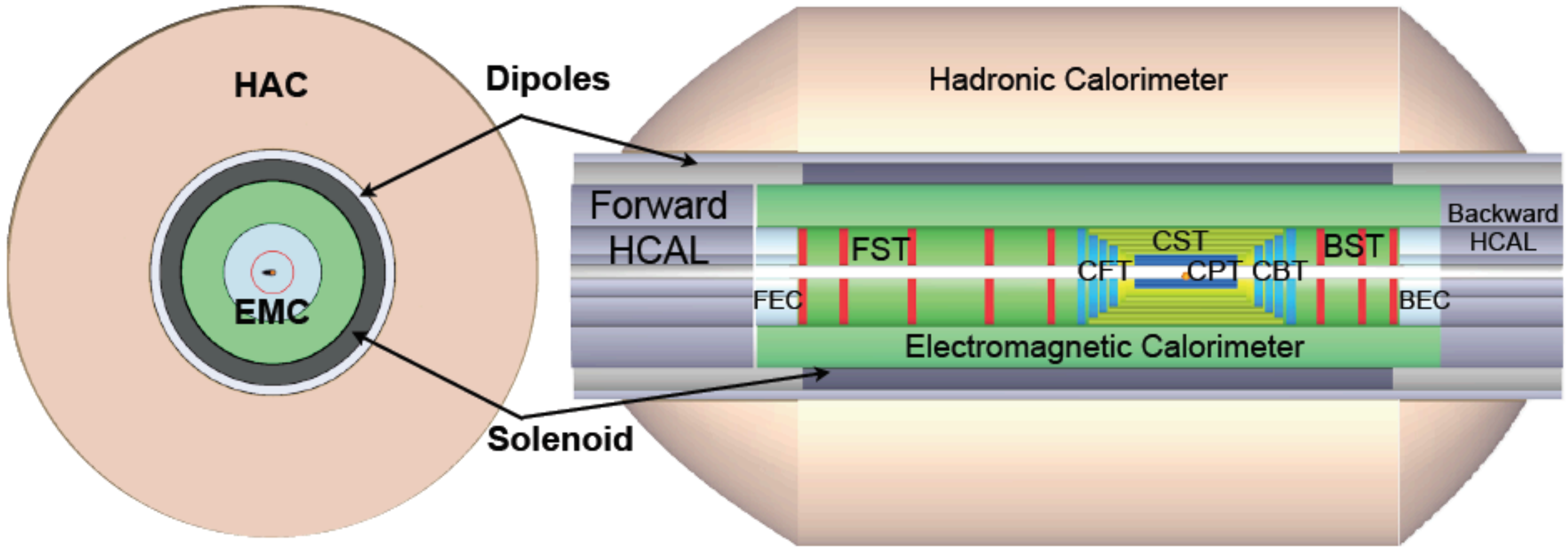
Tracking Region

[encased in 3.5T solenoid field]



- Full angular coverage, long tracking region → 1° acceptance
- Several technologies under discussion

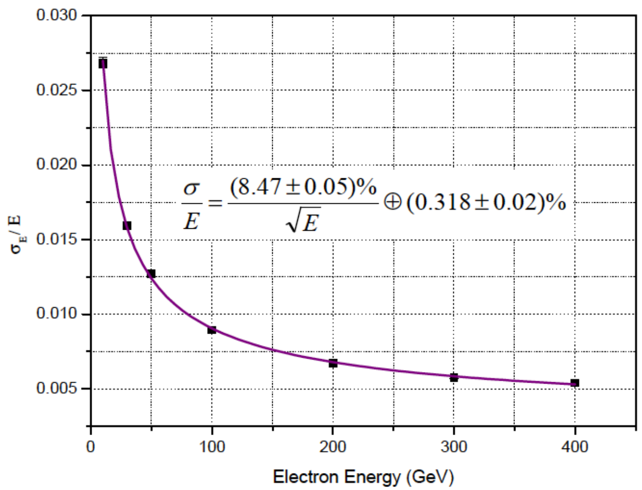
Calorimeters

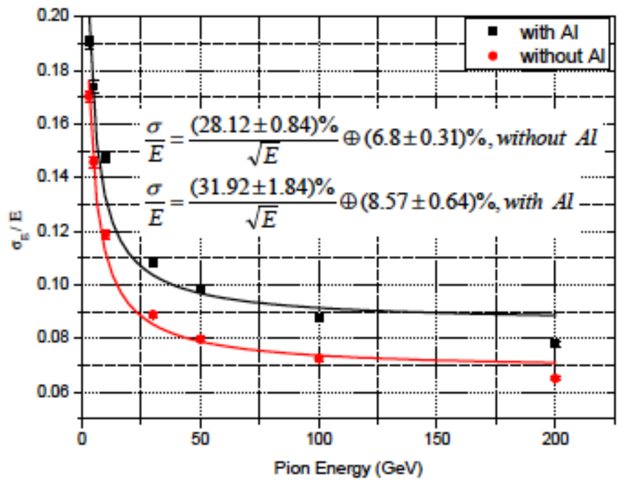


Liquid Argon EM Calorimeter [accordion geometry, inside coil]

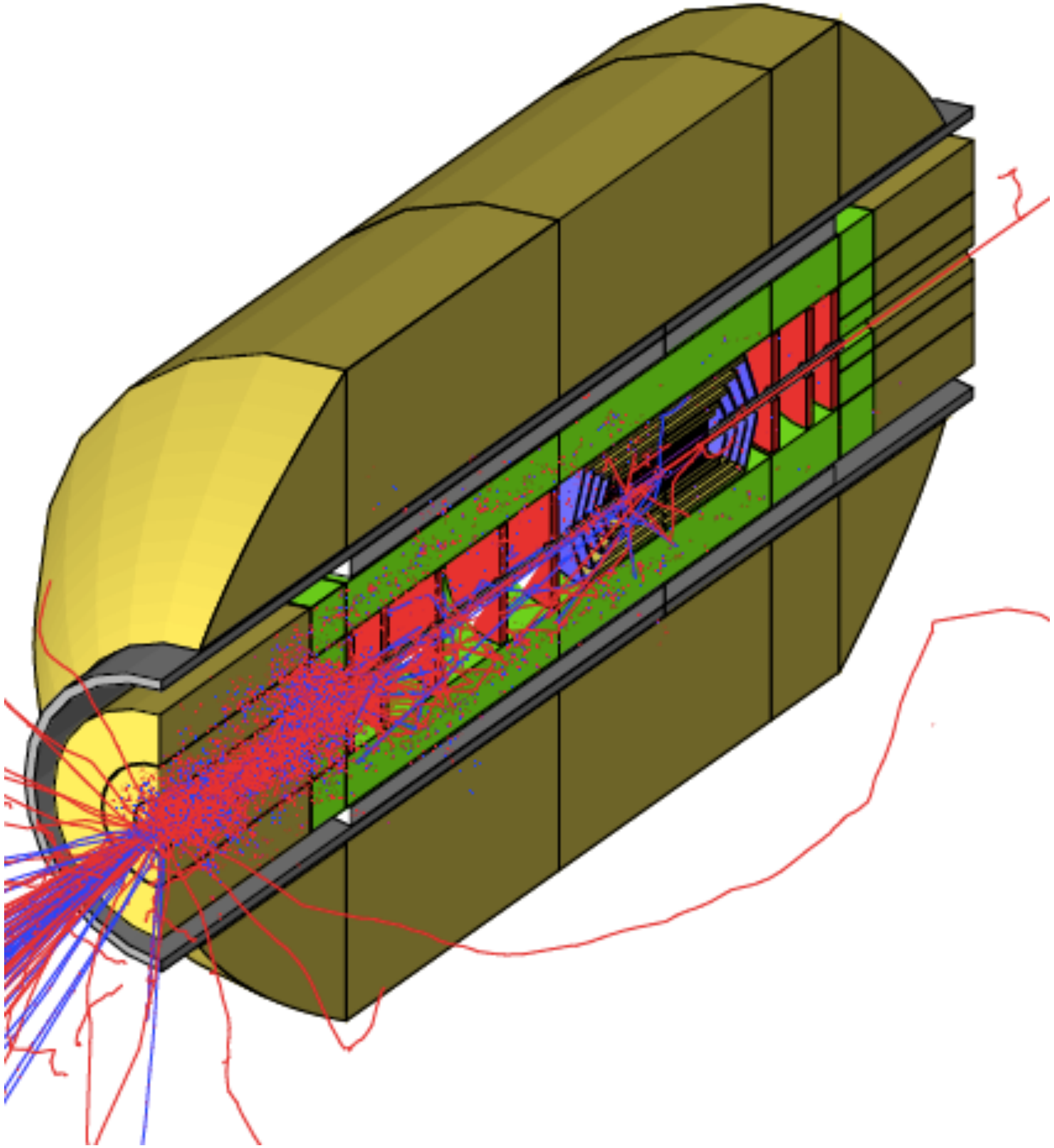
Barrel: Pb, 20 X_0 , 11m^3 FEC: Si -W, 30 X_0 BEC: Si -Pb, 25 X

Hadronic Tile Calorimeter [modular, outside coil: flux return]



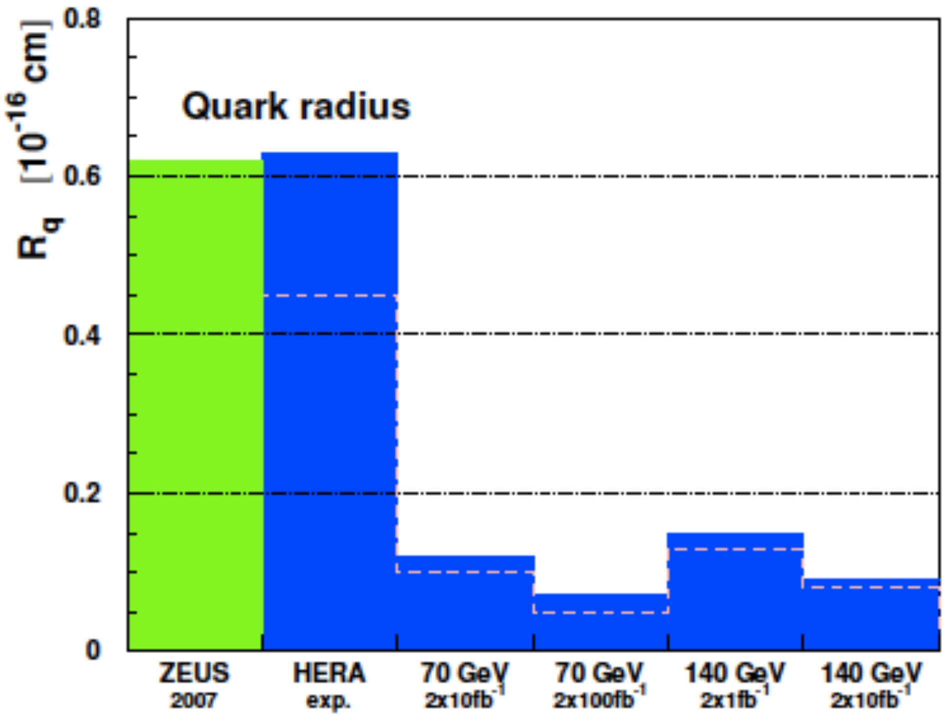


A GEANT4 Simulated High x Event



Sensitivity to New Physics

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

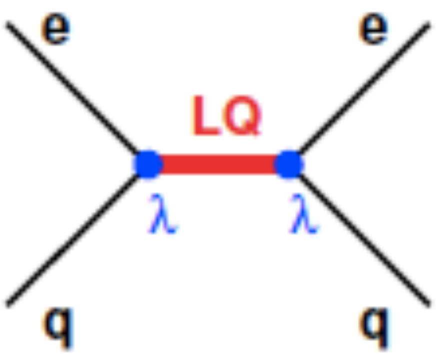


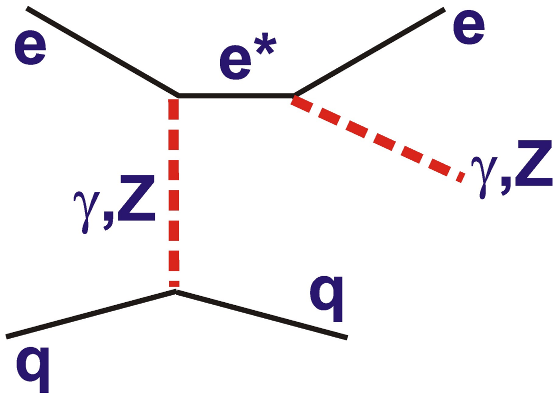
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

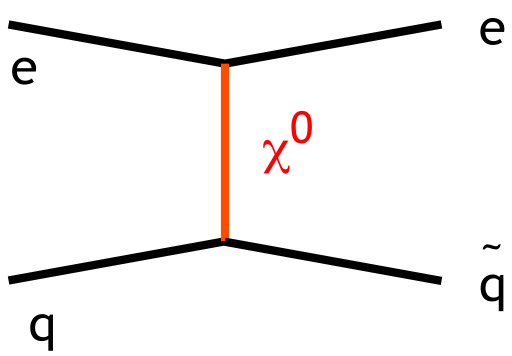
… big improvement on HERA, but already beaten by LHC

Sensitivity to New Physics

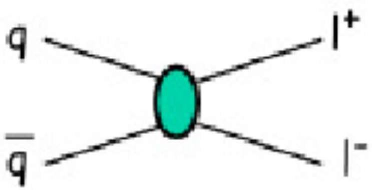
- LHeC is competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states

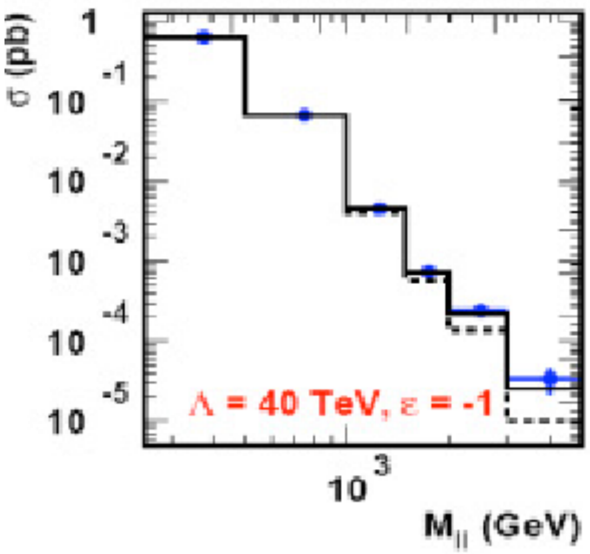


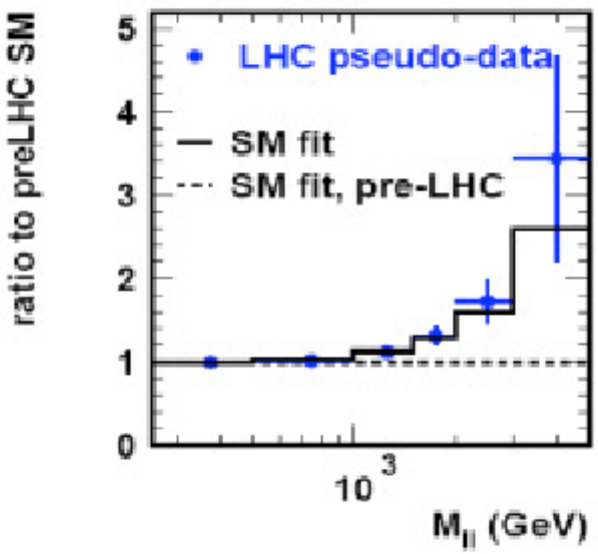




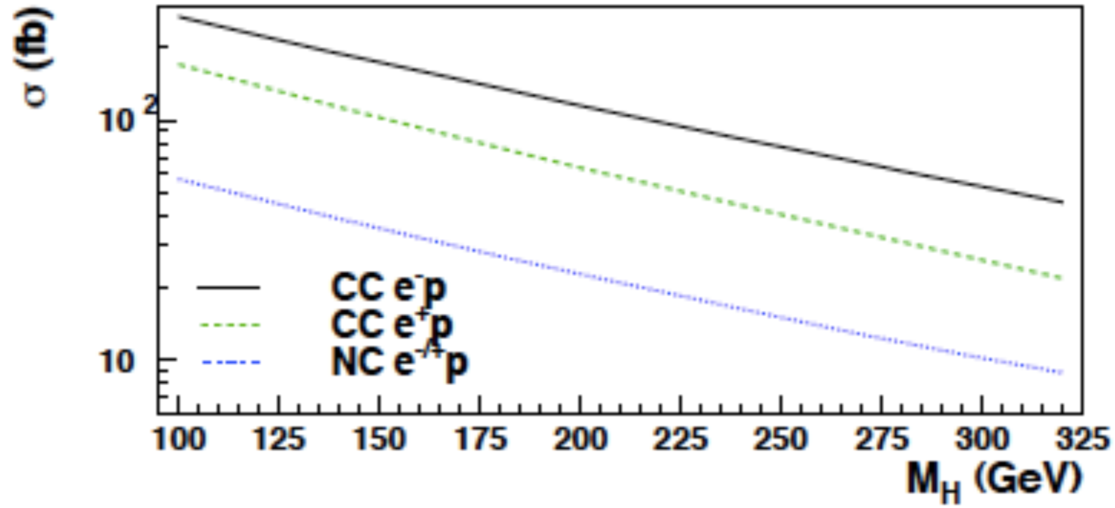
- LHeC info can confirm / clarify unexpected LHC effects, especially near the x → 1 kinematic limit

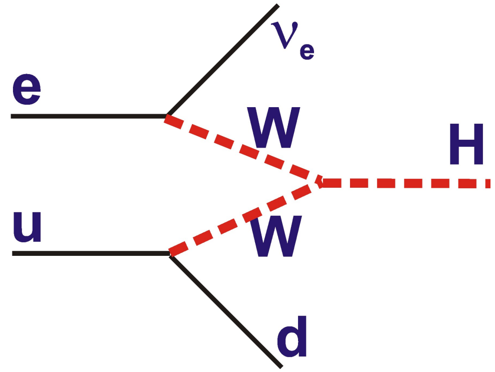






Anomalous Higgs Couplings





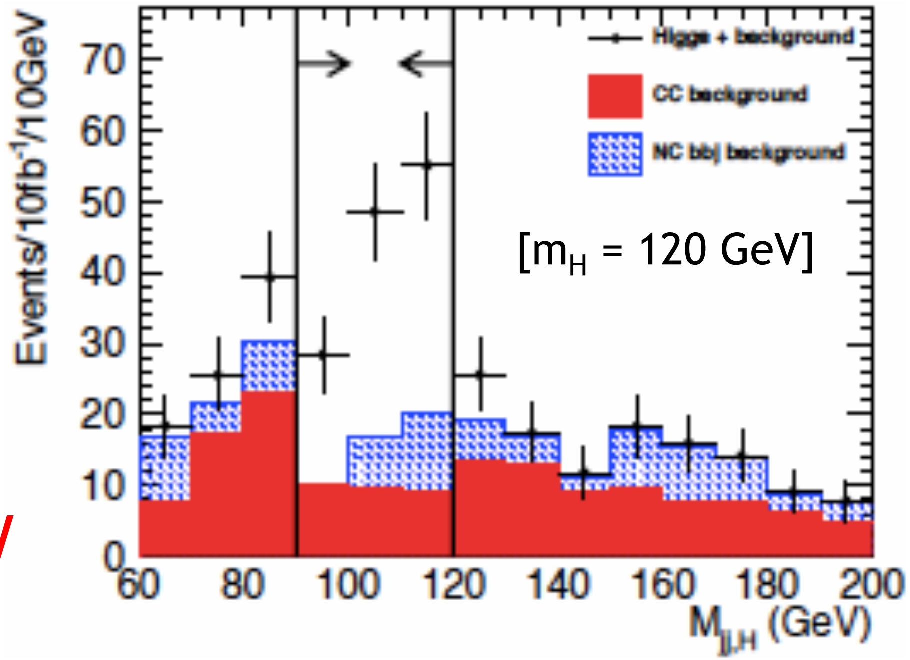
Clean signal: $H + j + p_t^{miss}$

First study with 2 b-tags

Backgrounds (jets in NC, CC, top) suppressed with cuts on jet multiplicity, b-tags, event kinematics, missing p_t

~ 100 events / year after cuts (S/B = 1.8)

→ Sensitive to anomalous H→WW and H→ bbbar couplings



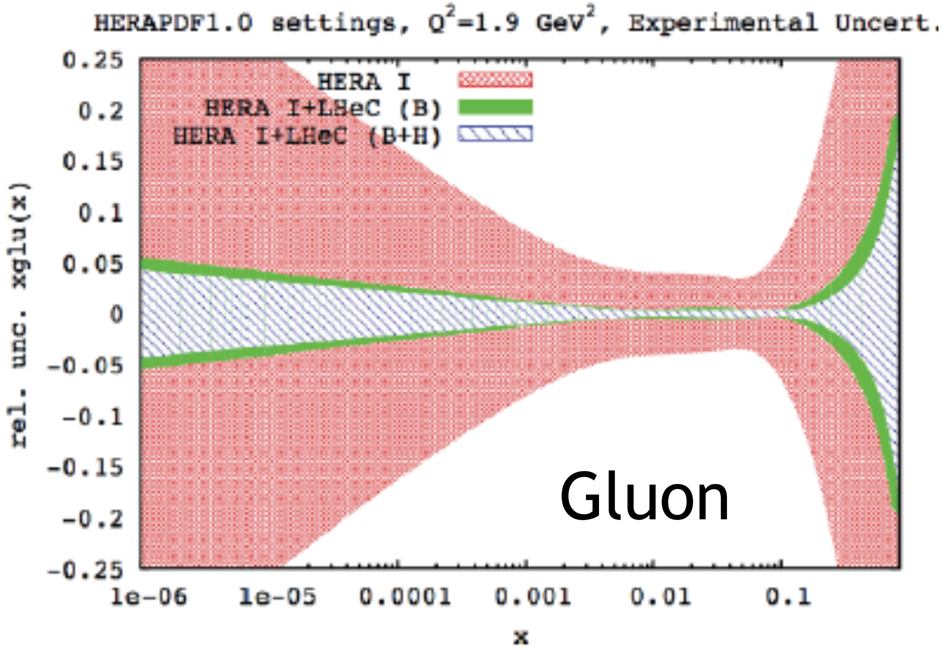
LHeC Impact on Parton Densities

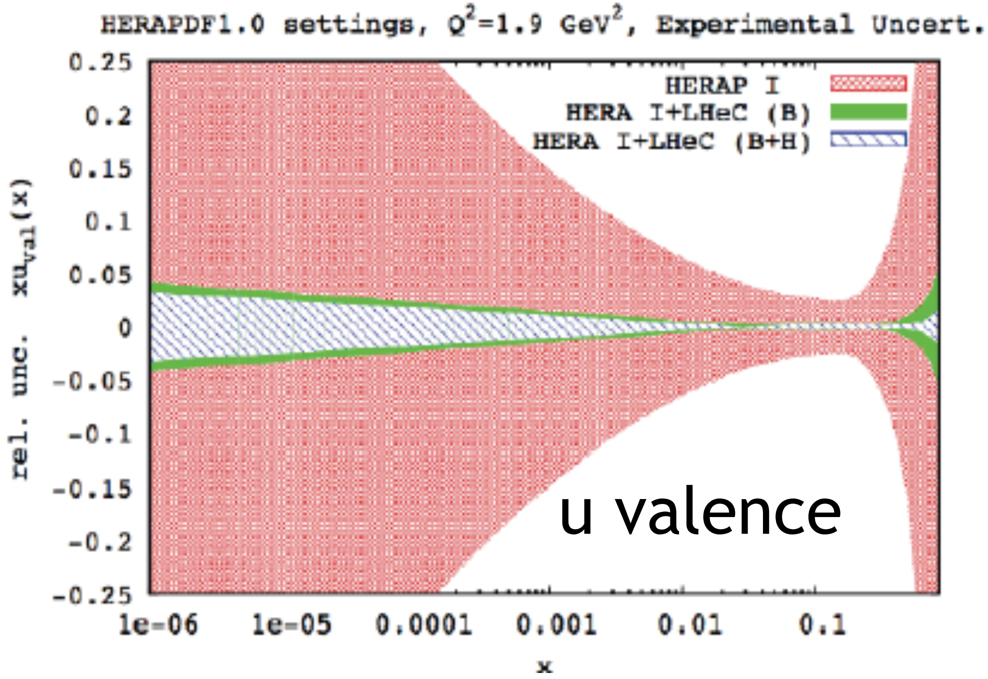
Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

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

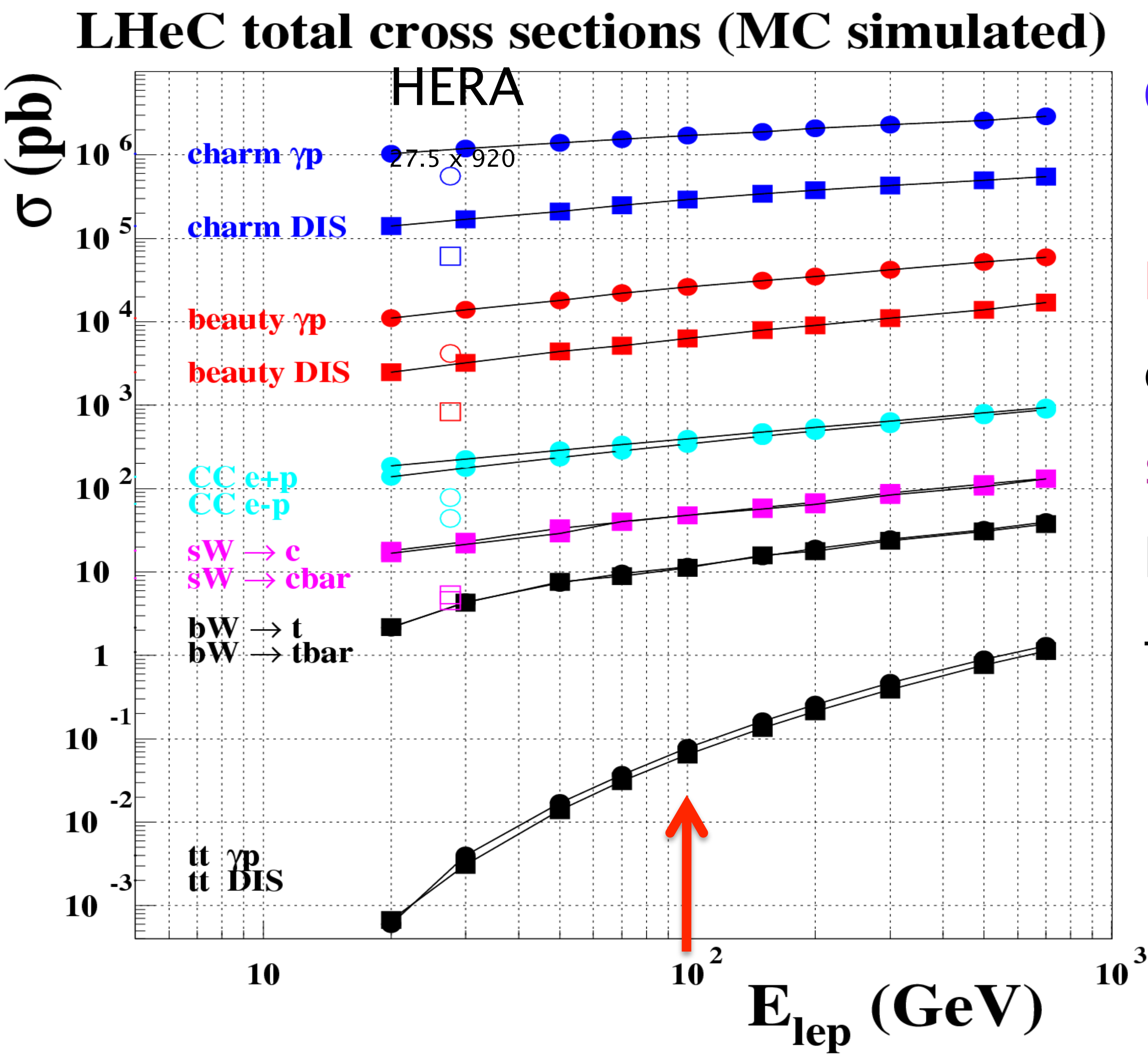
… precise light quark vector, axial couplings, weak mixing angle

… full flavour decomposition possible





Cross Sections and Rates for Heavy Flavours



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

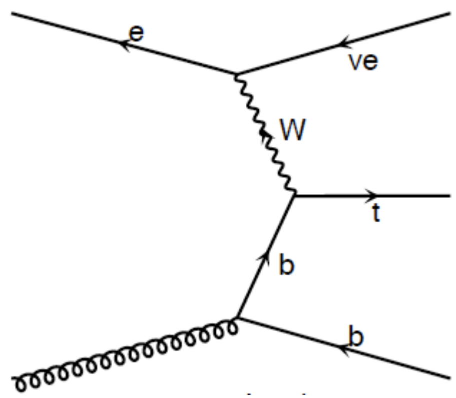
Beauty [10^{8} / 10 fb^{-1}]

cc

sW → c [4.10^{5} / 10 fb^{-1}]

bW → t [10^{5} / 10 fb^{-1}]

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

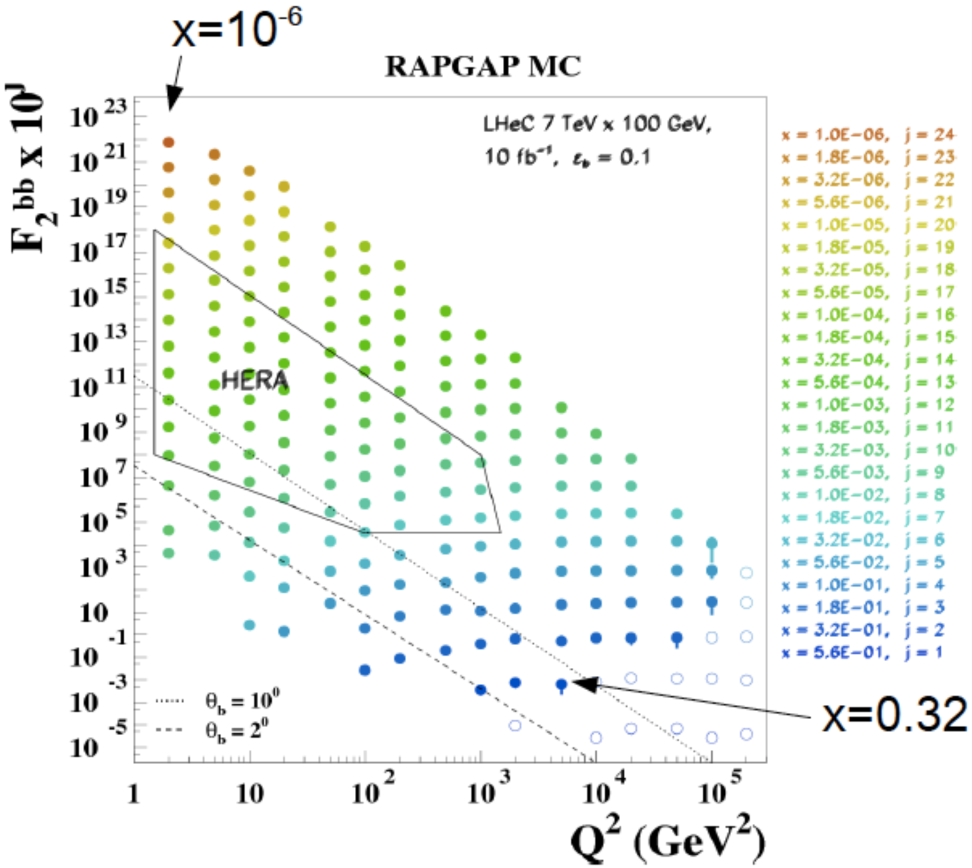


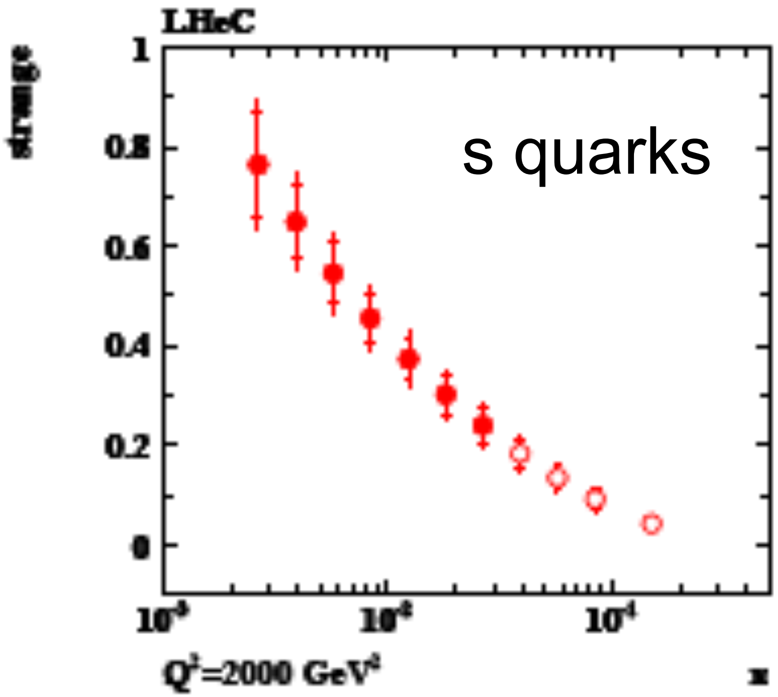
c.f. luminosity of ~10 fb^{-1} per year …

Flavour Decomposition

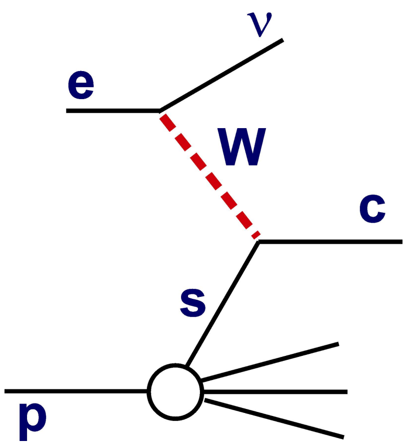
Precision c, b measurements
(modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).
Systematics at 10% level

→beauty is a low x observable!
→s, sbar from charged current



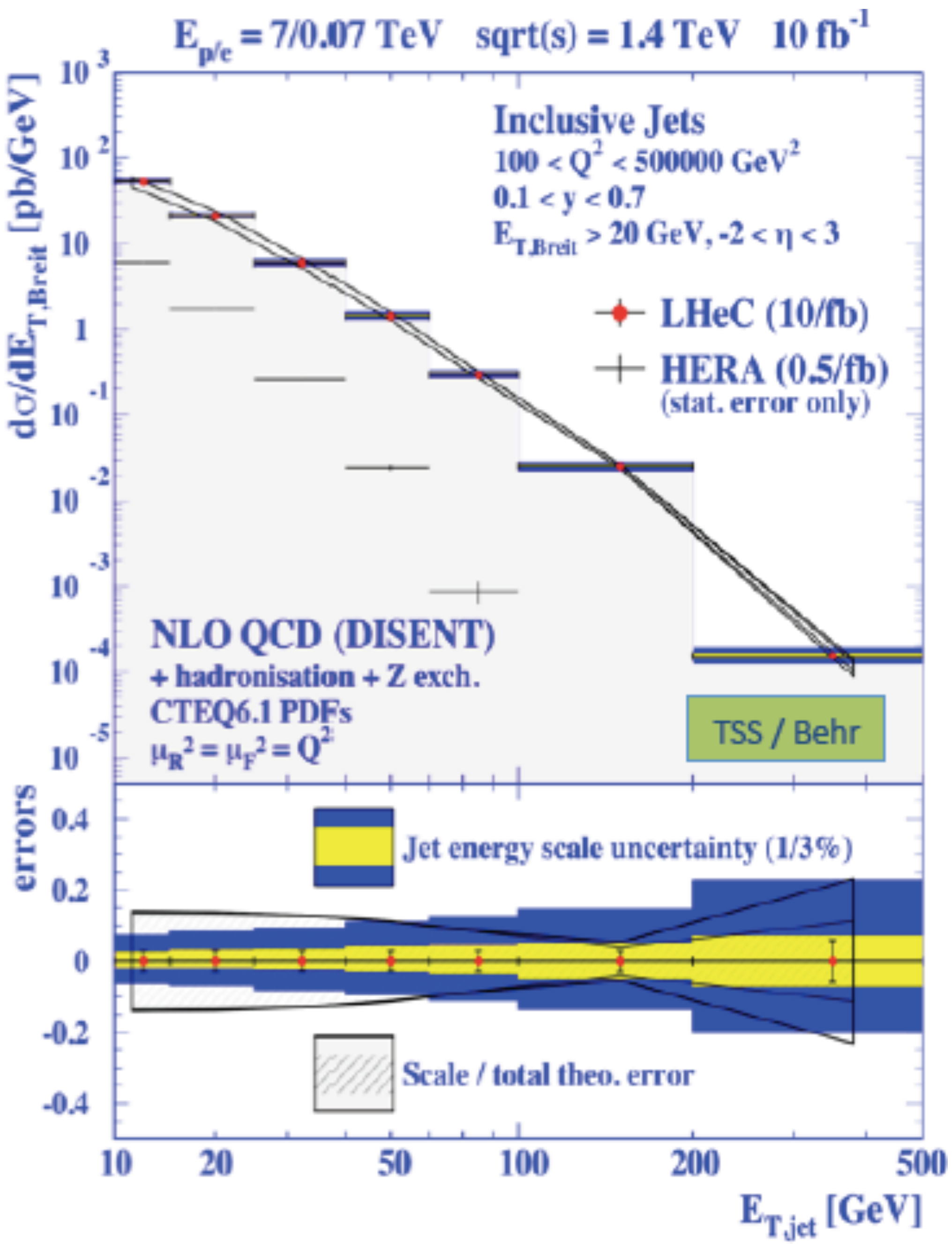


● LHeC 10° acceptance
○ LHEC 1° acceptance



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

Inclusive Jets & QCD Dynamics

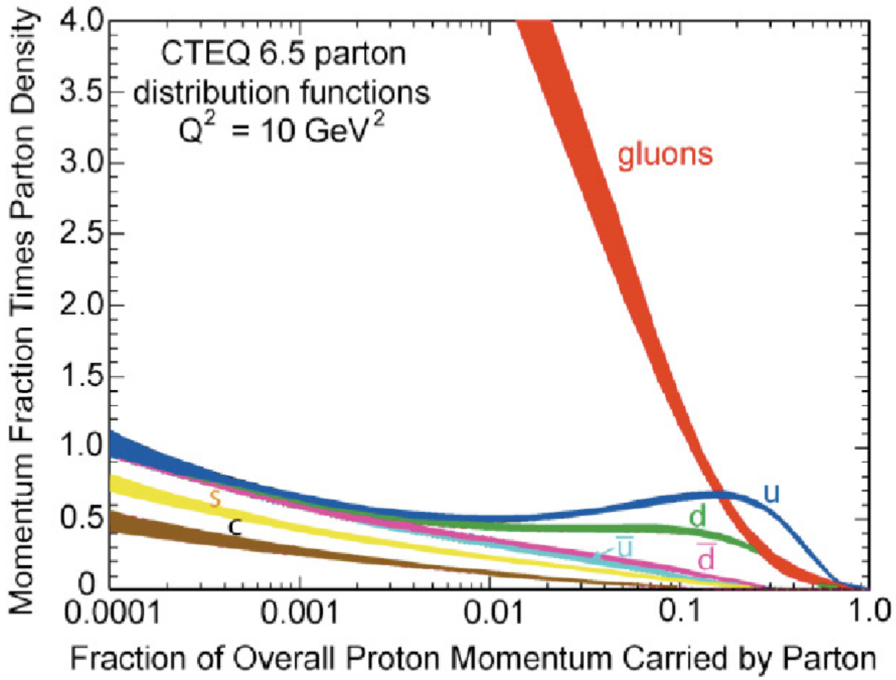


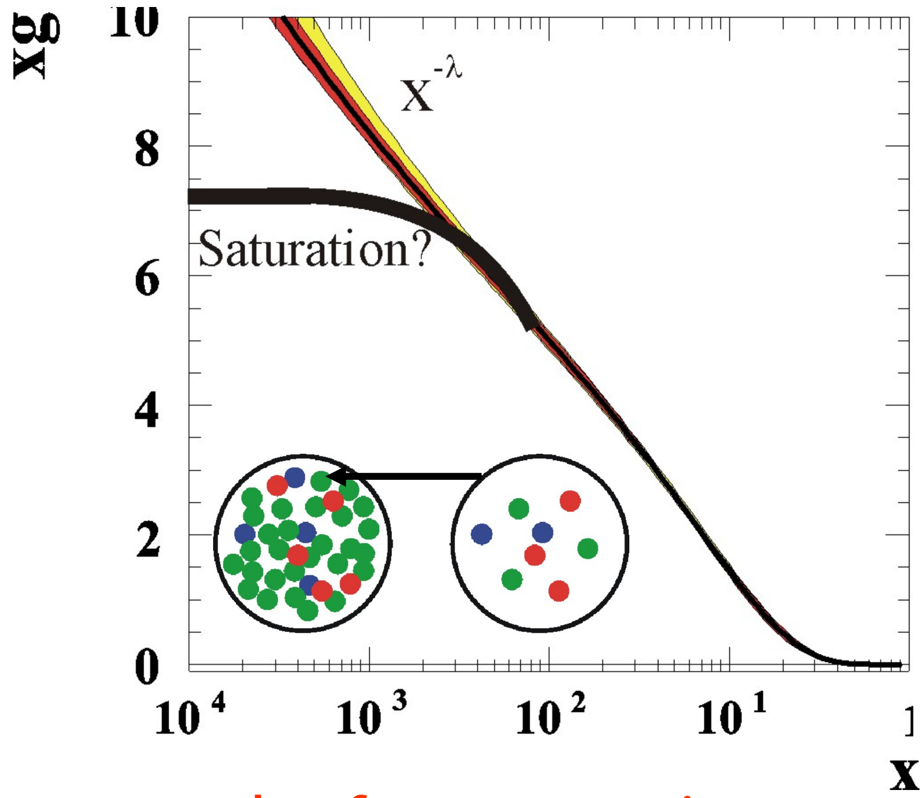
Also differential in Q^2 with high precision to beyond $Q^2 = 10^5$ GeV^2

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





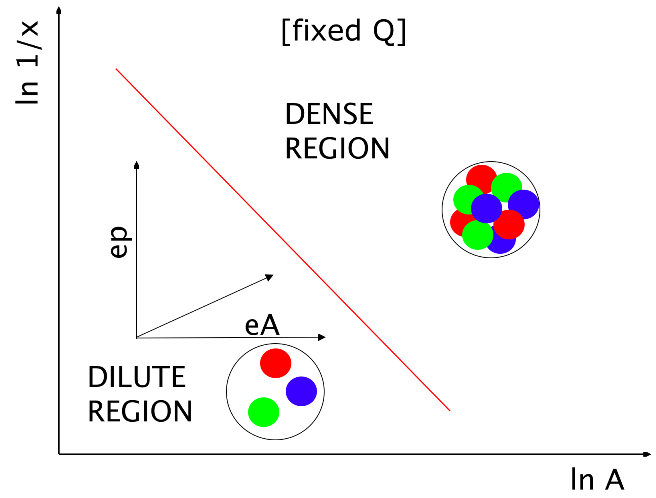
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Parton level language → **recombination gg → g**
- Saturation effects occur beyond x, A dependent saturation scale

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

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

Strategy for making the target blacker

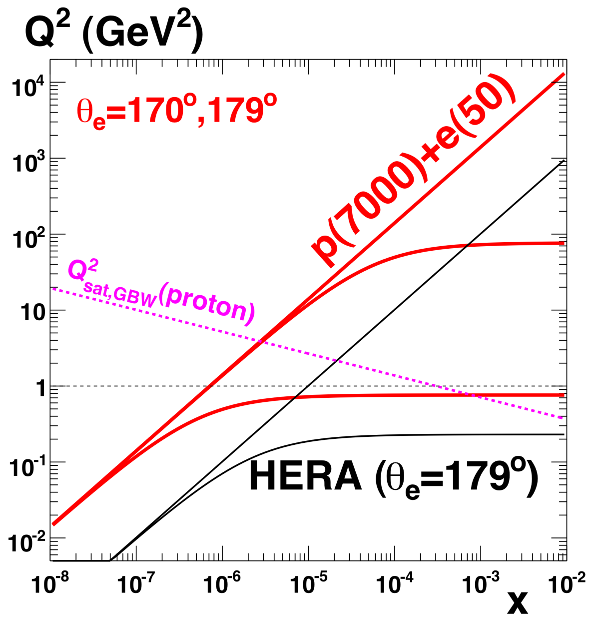
LHeC delivers a 2-pronged approach:

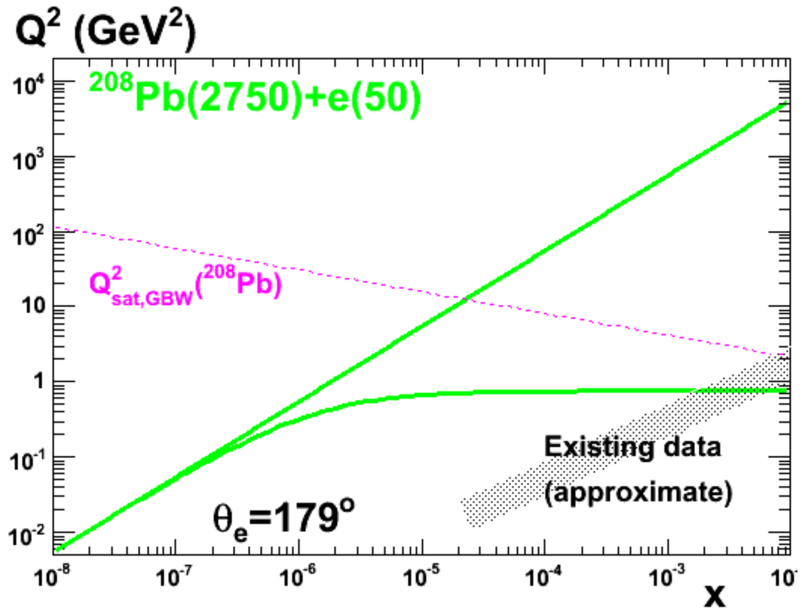


Enhance target `blackness' by:

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]

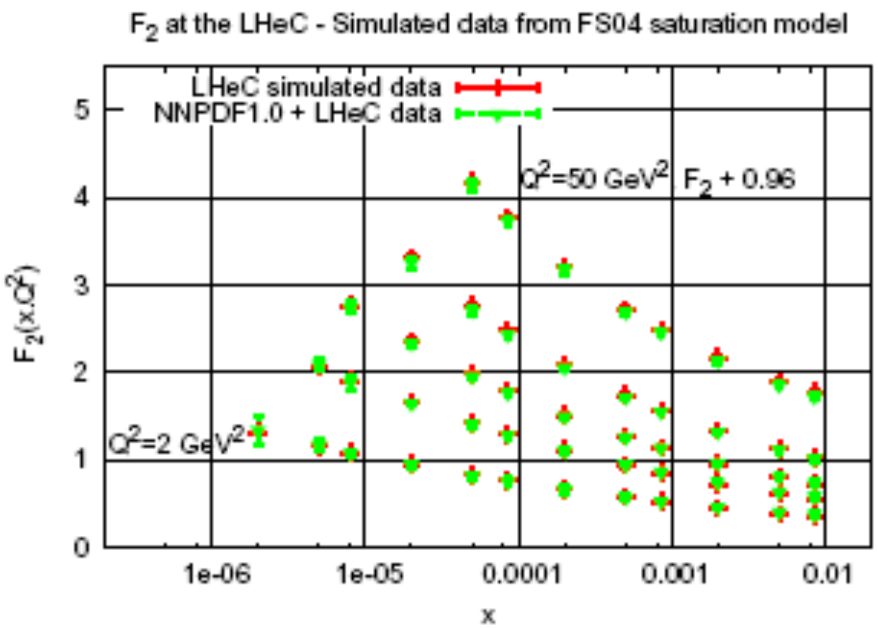


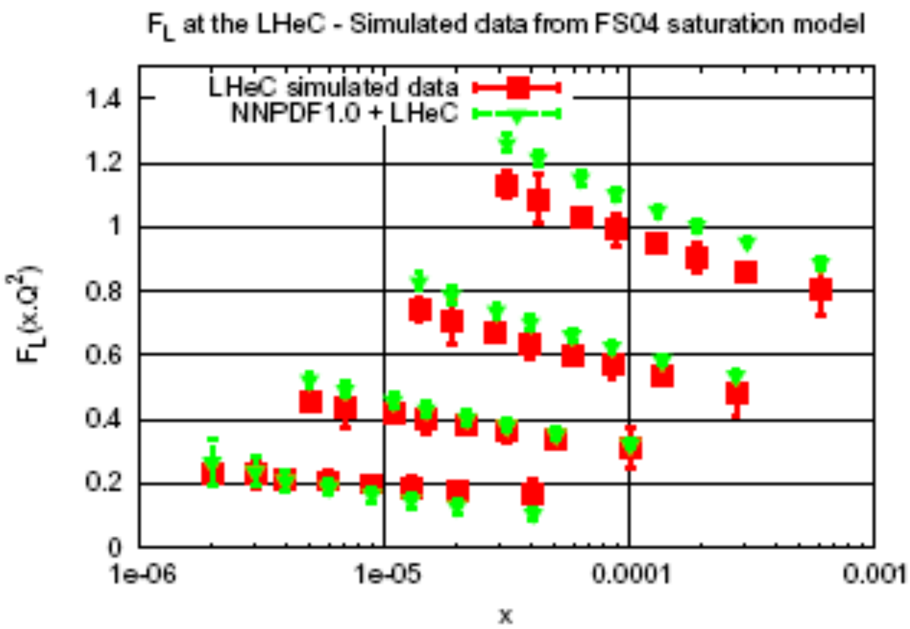


Can Parton Saturation be Established in ep @ LHeC?

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





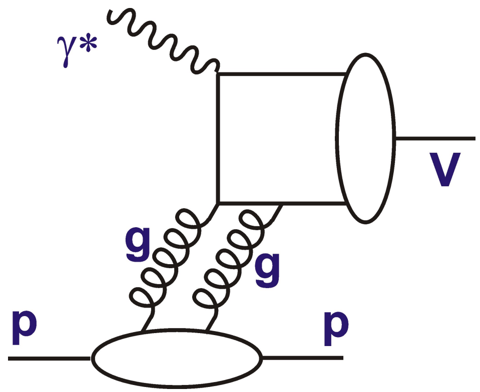
Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>(F_2^c may work in place of F_L)</u>…

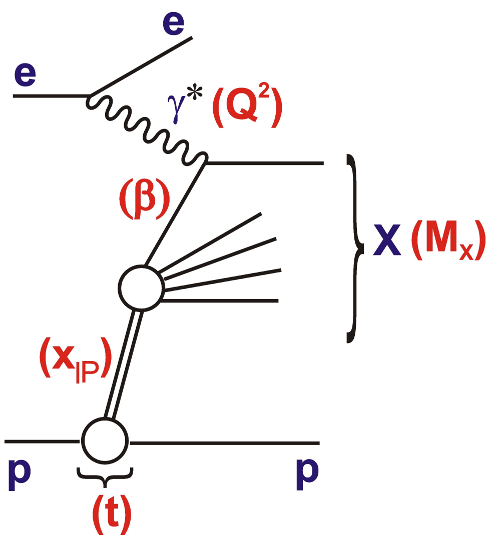
Exclusive / Diffractive Channels and Saturation

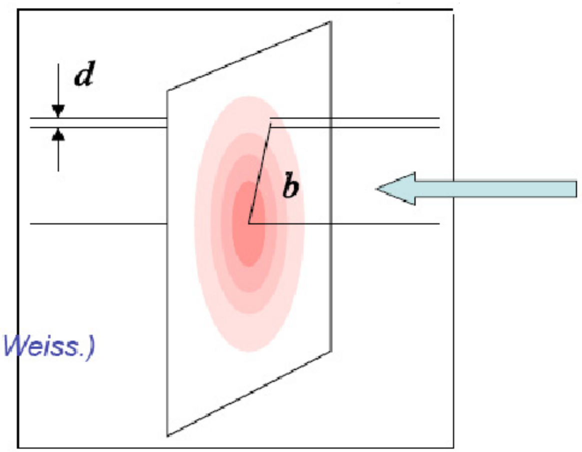
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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





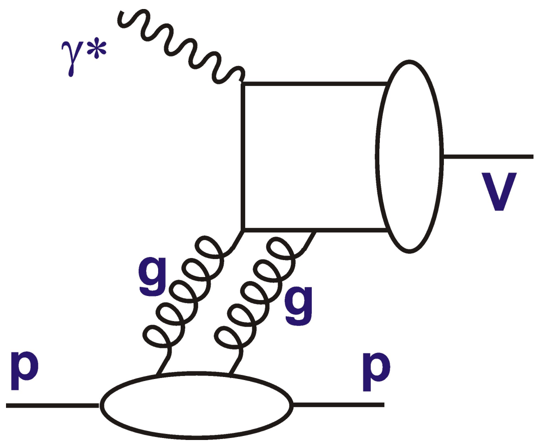


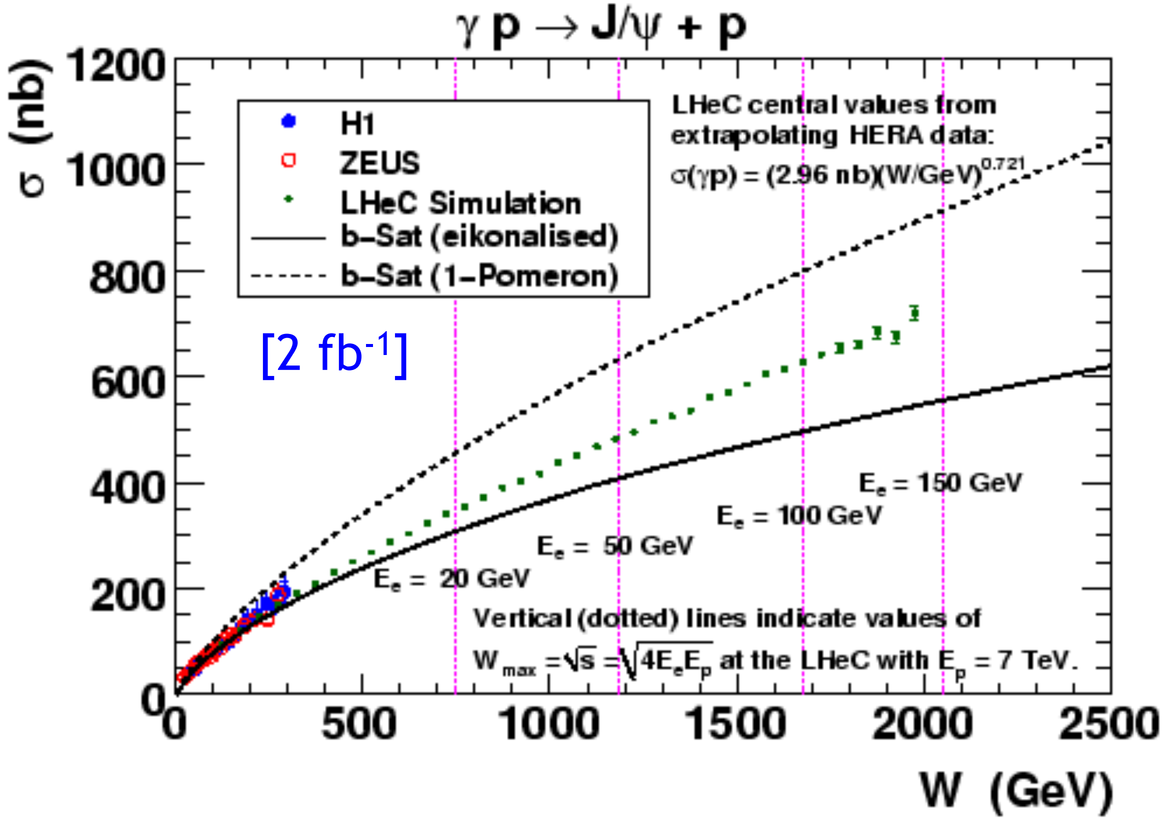
(figure from C. Weiss.)

Central black region growing with decrease of x.

Simulation of J/ψ Photoproduction

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

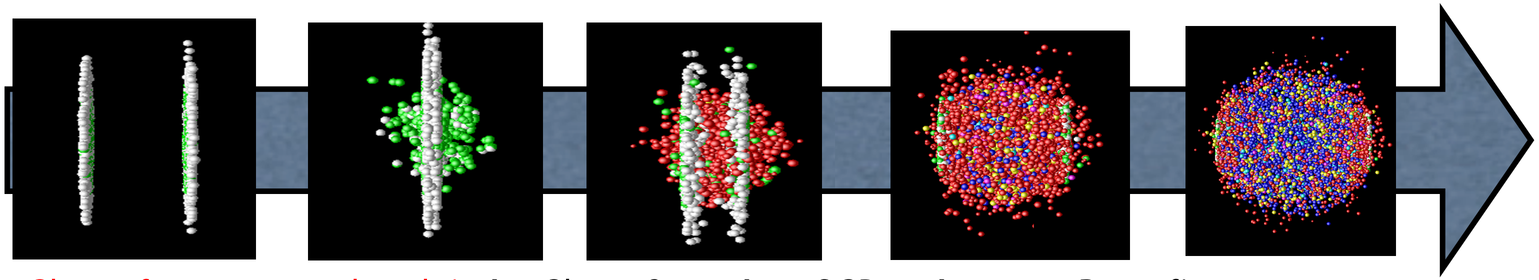




- Significant non-linear effects expected in LHeC kinematic range.
- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

  → Sat^n smoking gun?

What is Initial State of LHC AA Collisions?

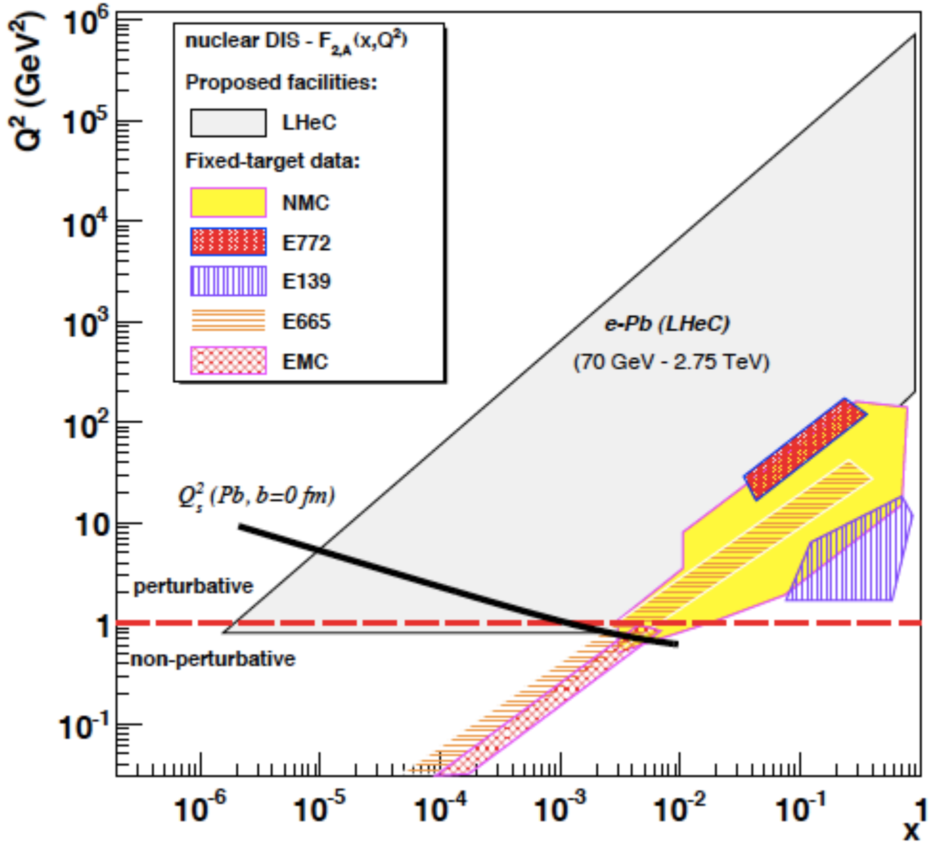


Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

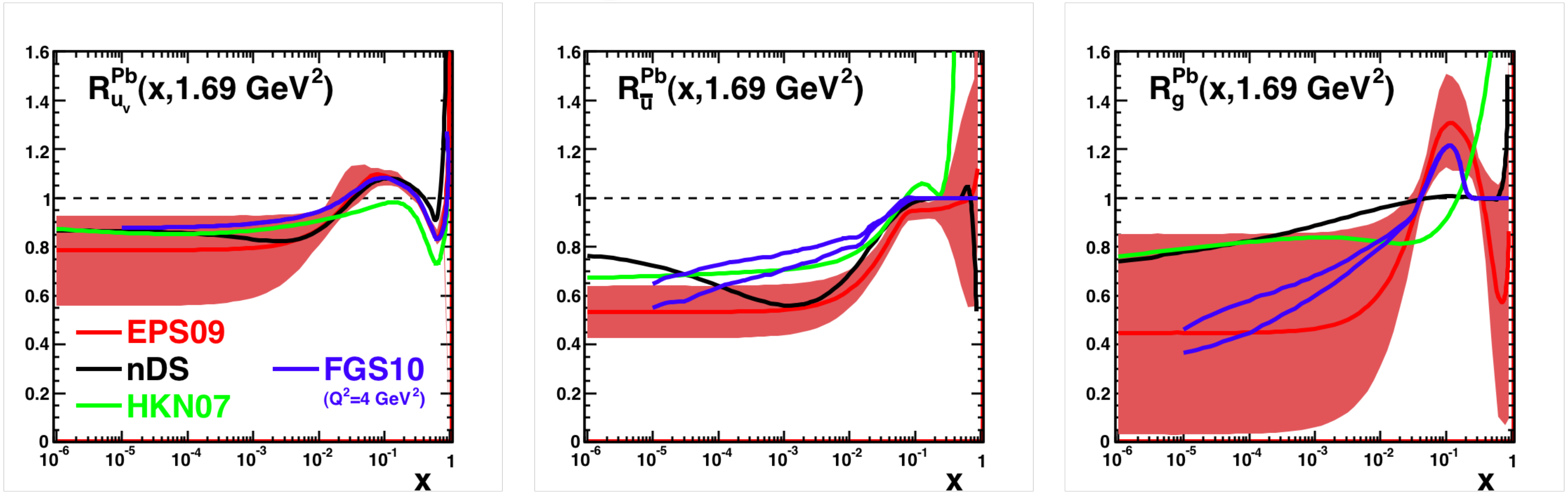
- Very limited x, Q^2 and A range for F_2^A so far (fixed target experiments covered x >~ 10^{-2})

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

[and eA potentially provides control for AA QGP signatures]



Current Knowledge: Nuclear Parton Densities



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

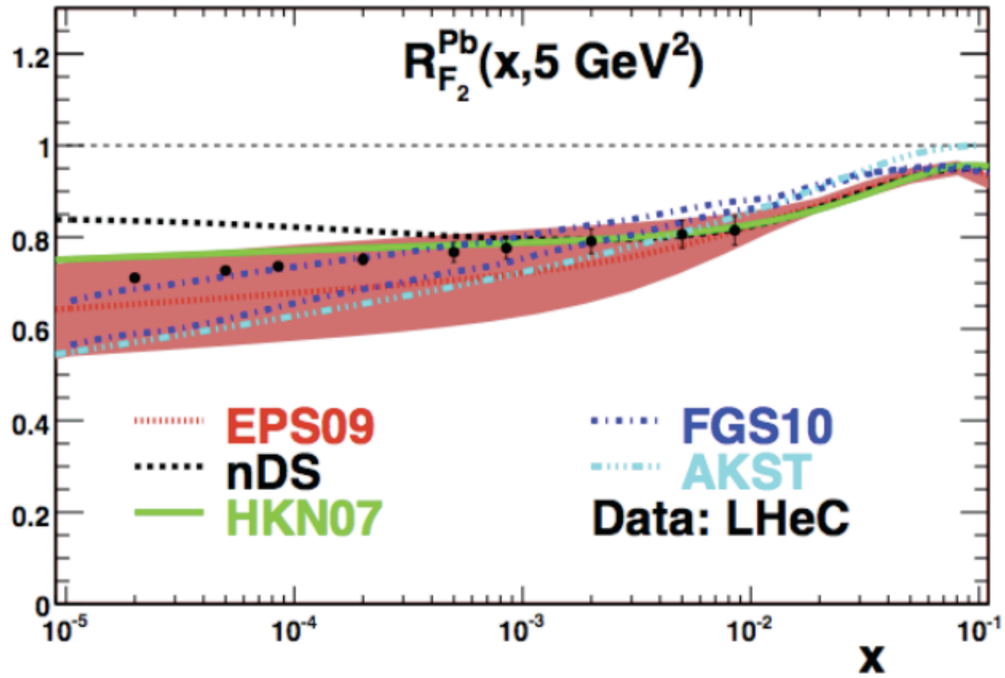
- Nuclear parton densities don't scale with A due to Fermi motion, shadowing corrections …

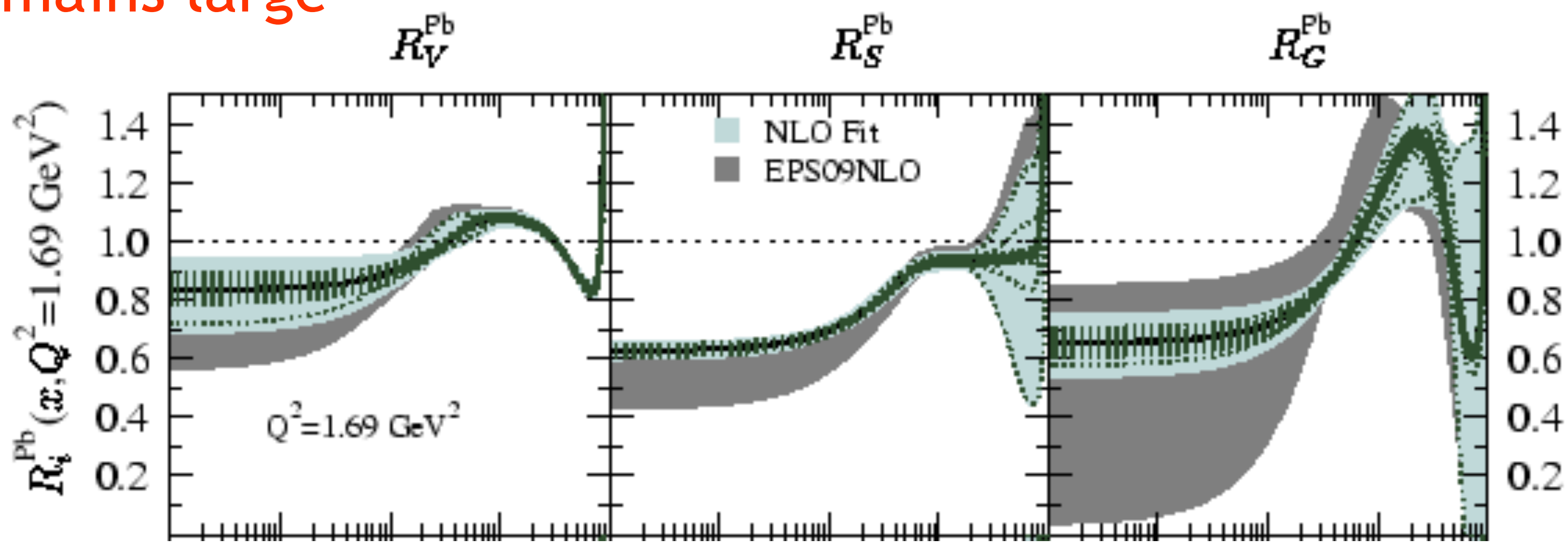
- All parton types poorly constrained for $x < 10^{-2}$

- Gluon density essentially unknown

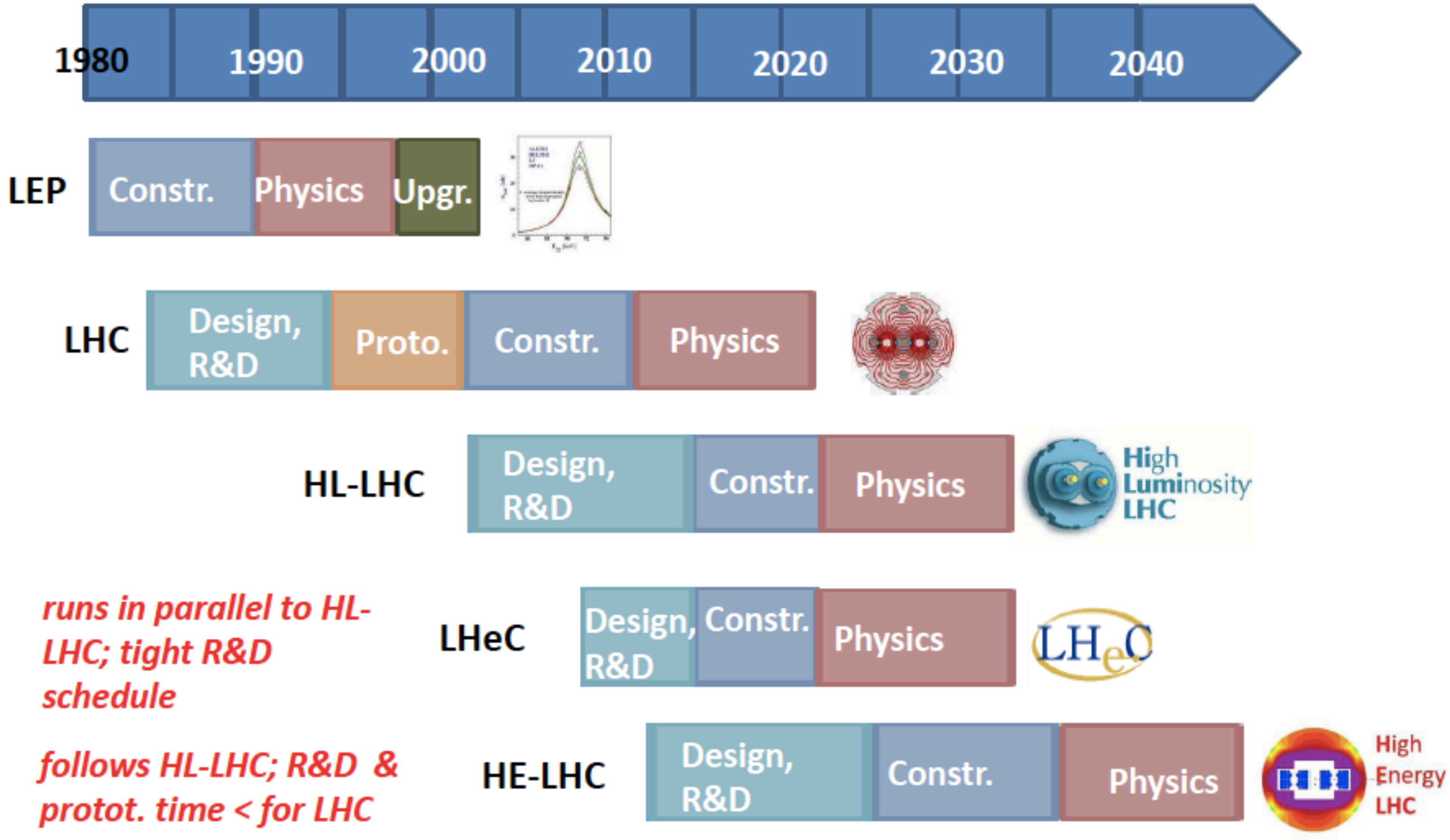
Study of Impact of e-Pb LHC data

- 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





time line of CERN HEP projects

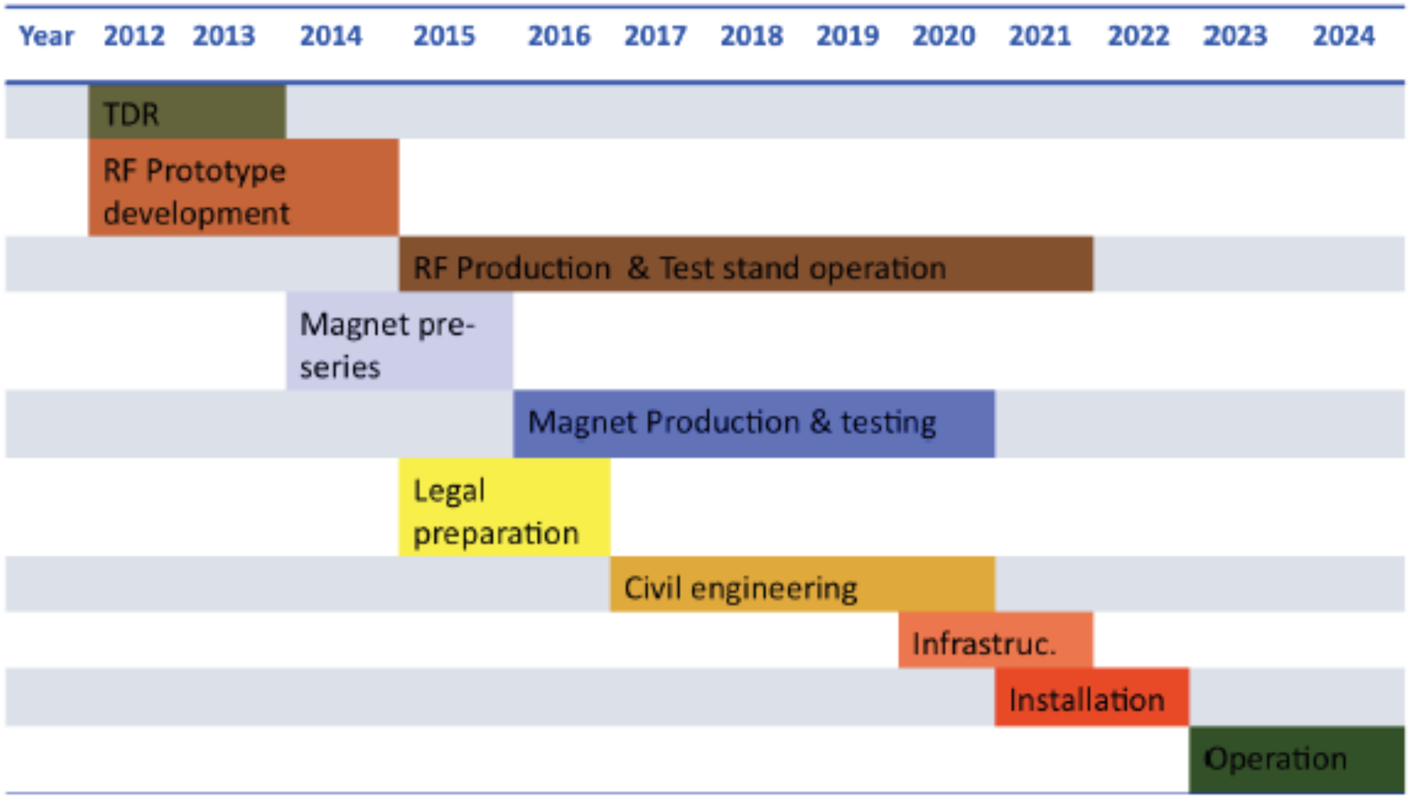


From 2012 Chamonix LHC Performance workshop summary (Rossi)

See also NuPeCC long range plan

Schedule and Remarks

- Aim to start operation by 2023 [high lumi phase of LHC]
- The major accelerator and detector technologies exist
- Cost is modest in major HEP project terms
- Steps: Conceptual Design Report, 2012
  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

• ECFA/CERN/NuPECC workshop has gathered many accelerator, theory & experimental colleagues

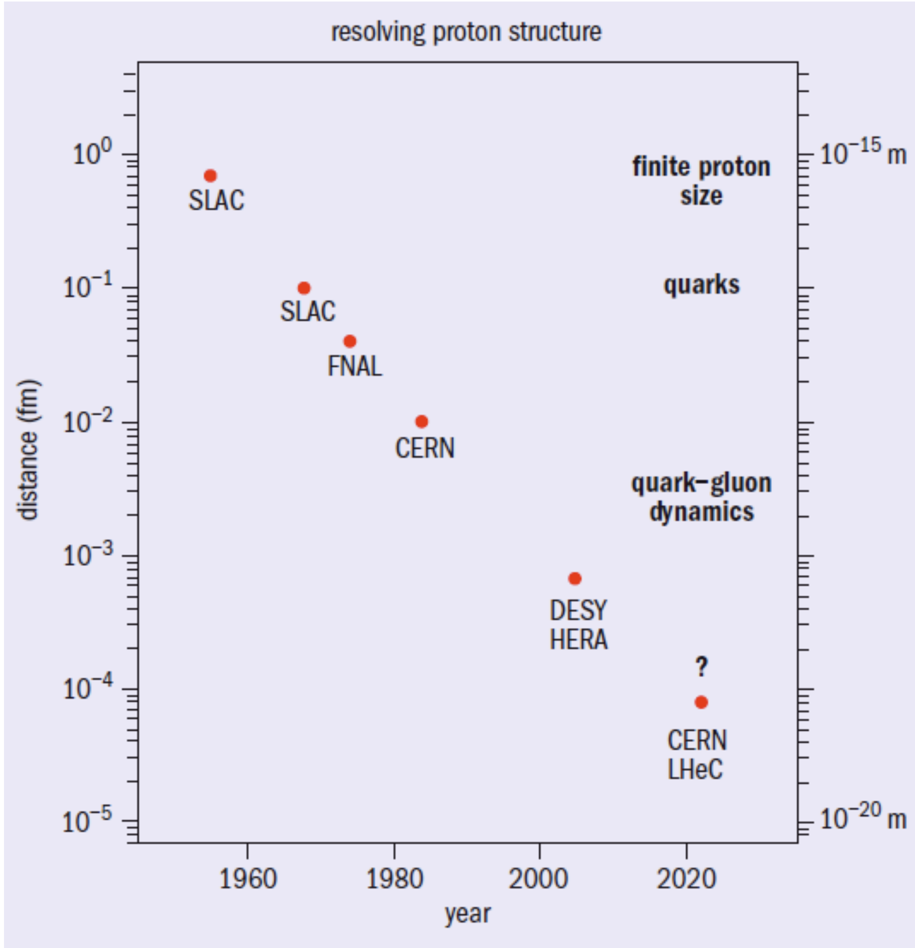


Fig. 1. Distance scales resolved in successive lepton–hadron scattering experiments since the 1950s, and some of the new physics revealed.

→ Conceptual Design Report available soon
→ Build collaboration for detector development

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

… with thanks to many colleagues working on LHeC …

http://cern.ch/lhec

LHeC Study Group

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