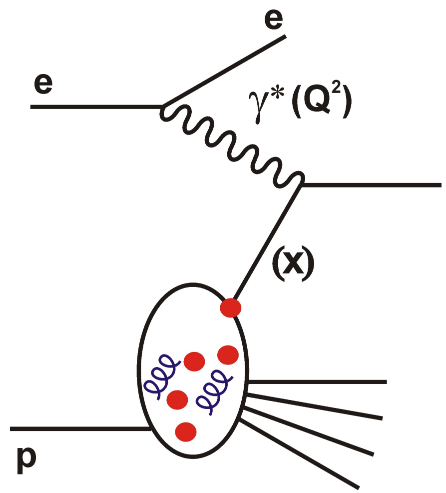
Future High Energy Electron - Hadron Scattering: The LHeC Project



Paul Newman
Birmingham University
QMUL seminar, 28 Nov 2014

- *Lepton-hadron collider based on the high lumi LHC*
- *Can we add ep and eA collisions to the existing LHC pp, AA and pA programme?*

- A brief history of ep Physics
- How to build an ep Collider based on the LHC
- Detector considerations
- Physics motivation
- 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]

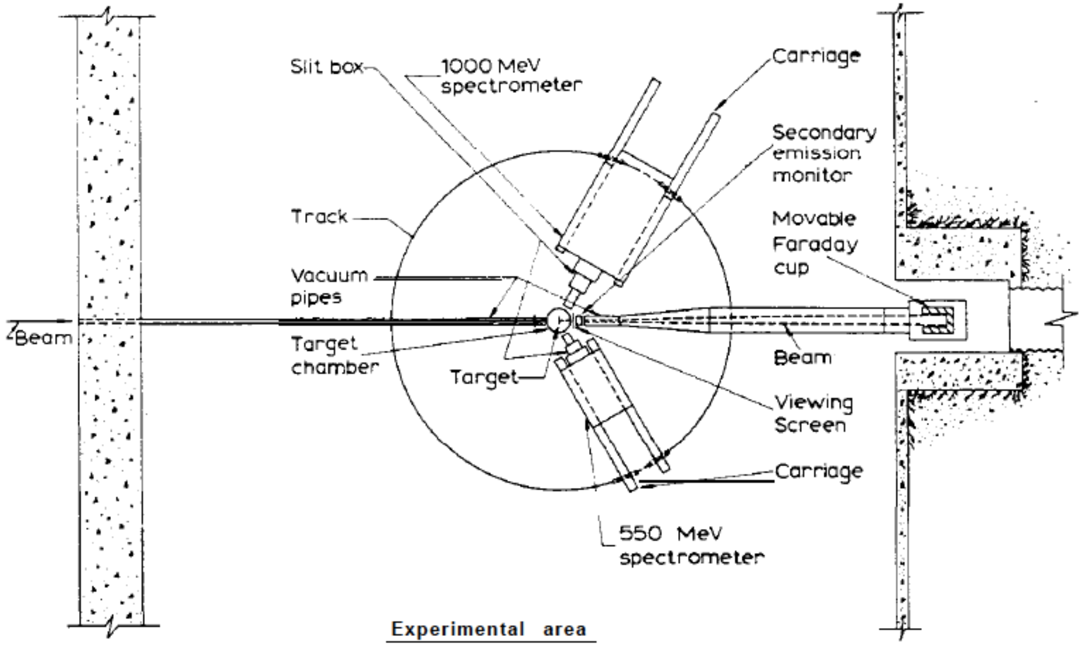
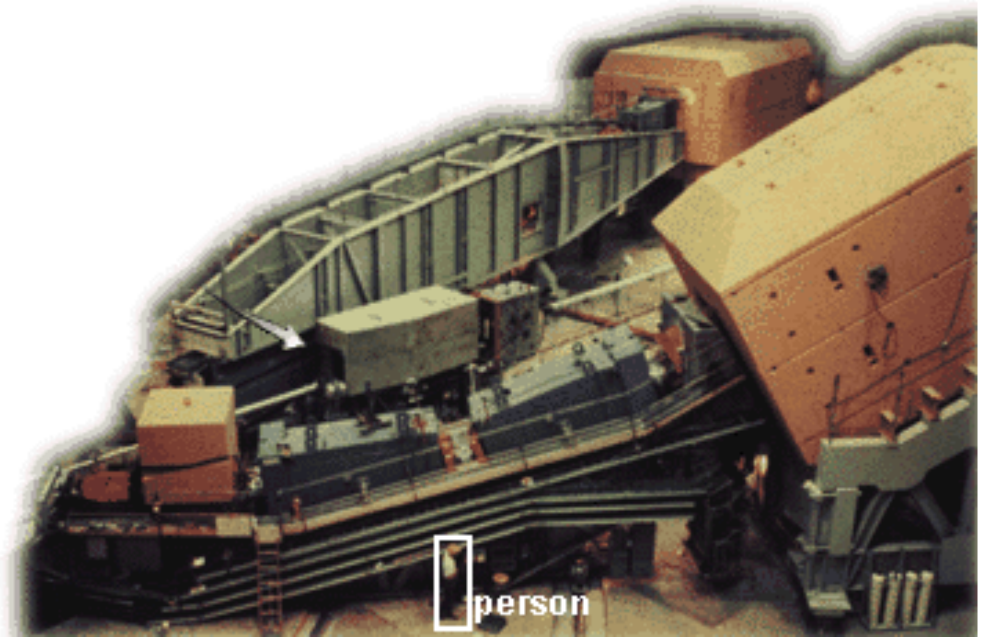


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

1950s
Hoffstadter

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

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

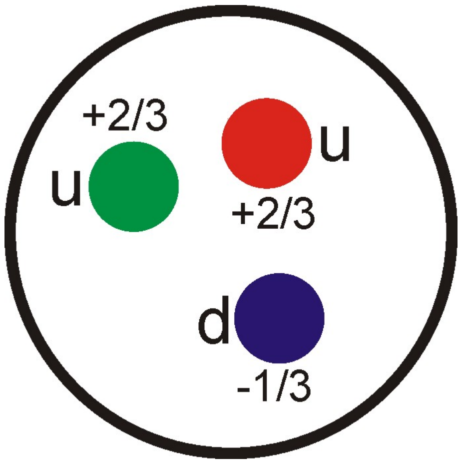
VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

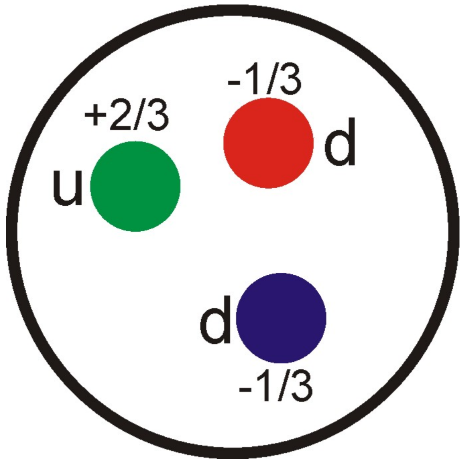
M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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

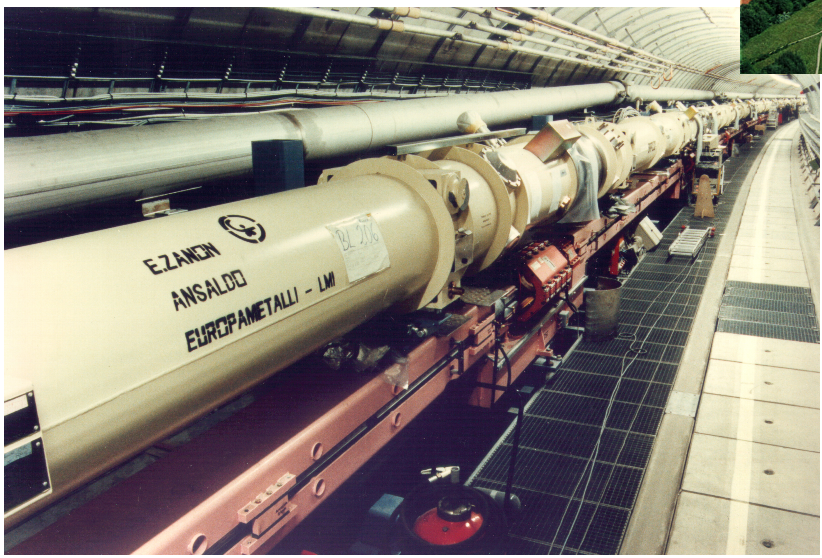
... and so on ...

DESY, Hamburg

HERA (1992-2007)

… the only ever collider of electron beams with proton beams:

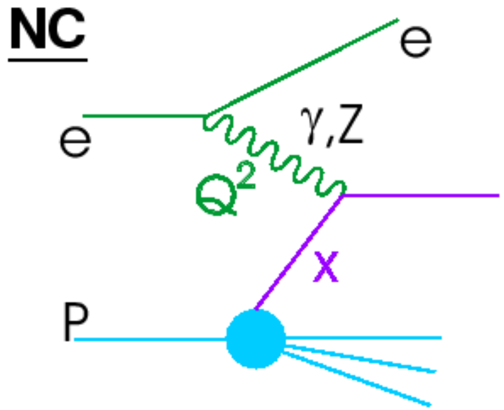
$\sqrt{s_{ep}} \sim 300$ GeV



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

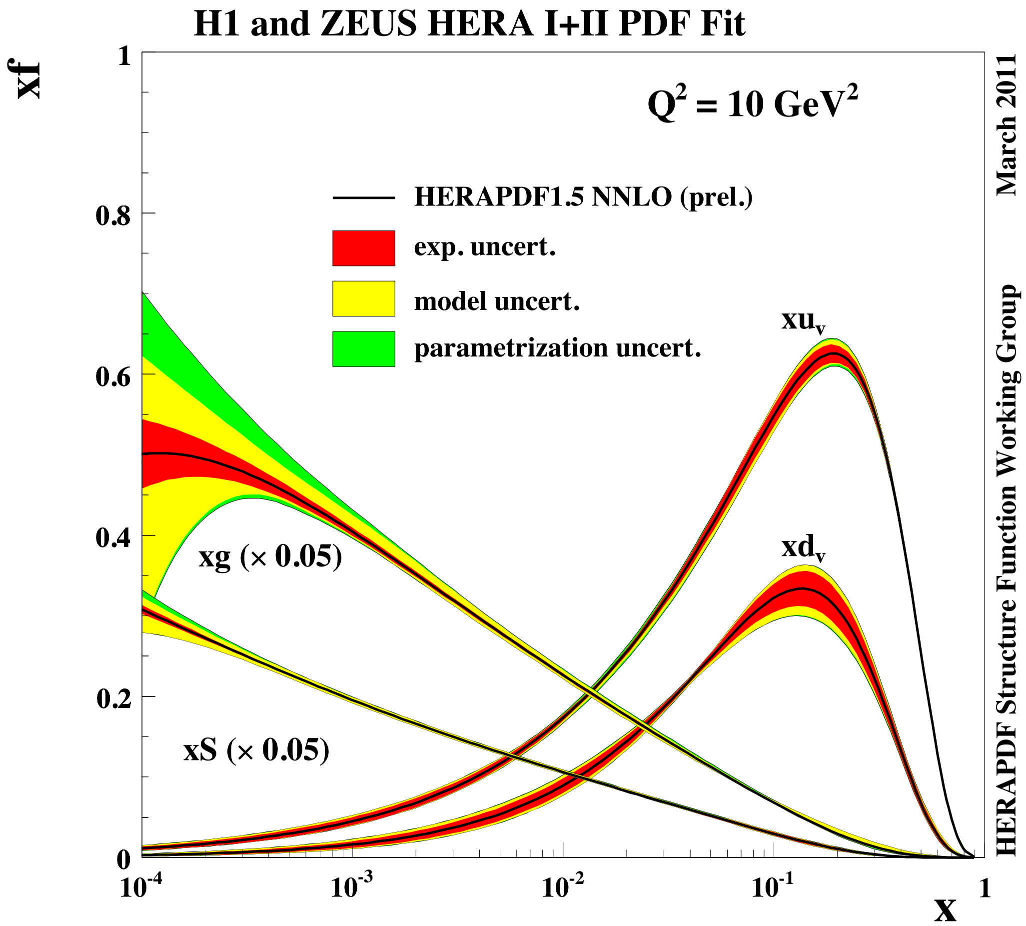
Around 500 pb^{-1} per experiment

DIS and HERA



Q^2: exchanged boson resolving power

x: fractional momentum of struck quark



HERA Proton parton densities in x range well matched to LHC rapidity plateau … BUT…

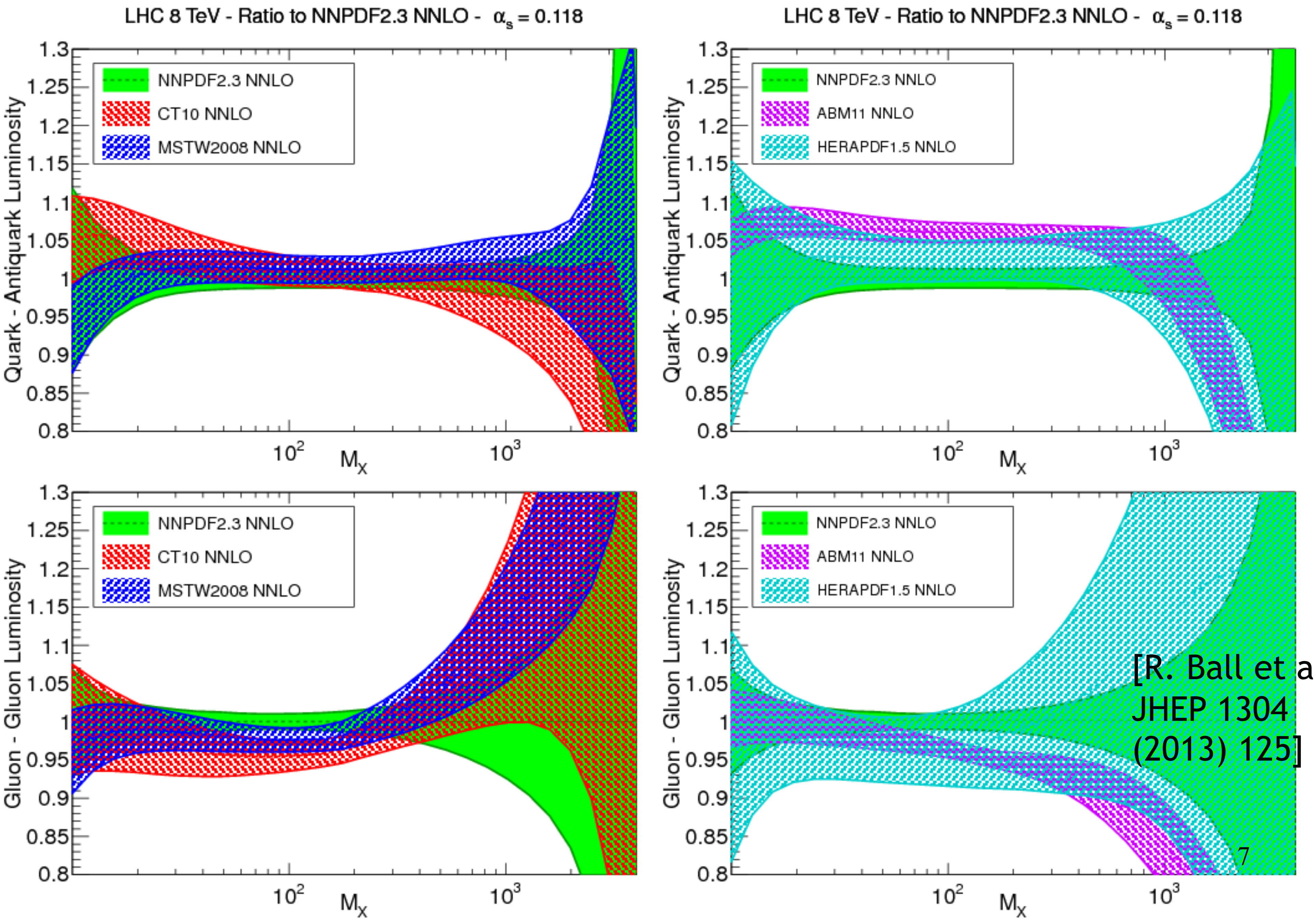
- Insufficient lumi for high x

- Lack of Q^2 lever-arm for low x gluon

- Assumptions on quark flavour decomposition

- No deuterons or heavy ions

Current PDF Uncertainties at LHC



[R. Ball et al., JHEP 1304 (2013) 125]

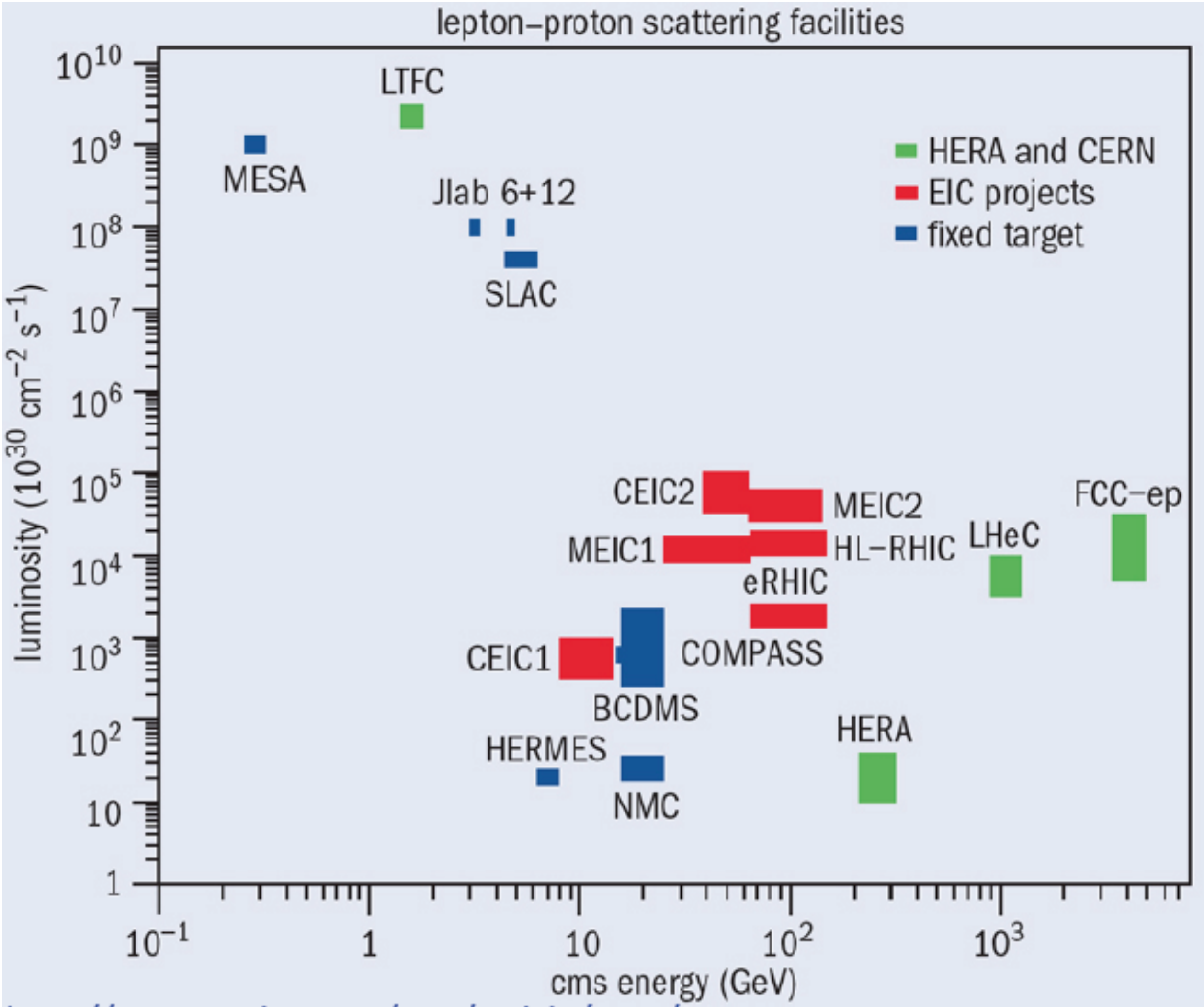
ep Physics Beyond HERA

- LHeC is latest and most promising idea to take lepton-hadron physics to the TeV centre of mass scale

- High luminosity: 10^{33} - 10^{34} cm^{-2} s^{-1}

- Runs simultaneously with ATLAS / CMS in post-LS3 HL-LHC period

- FCC-based ep facility takes this still further in the distant future



http://cerncourier.com/cws/article/cern/57304

LHeC Conceptual Design Report (July 2012)

630 pages, summarising 5 year workshop commissioned by CERN, ECFA and NuPECC

~200 participants, 69 institutes

Additional material in subsequent updates:

"A Large Hadron Electron Collider at CERN" [arXiv:1211.4831]

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

Journal of Physics G

Nuclear and Particle Physics

[arXiv:1206.2913]

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

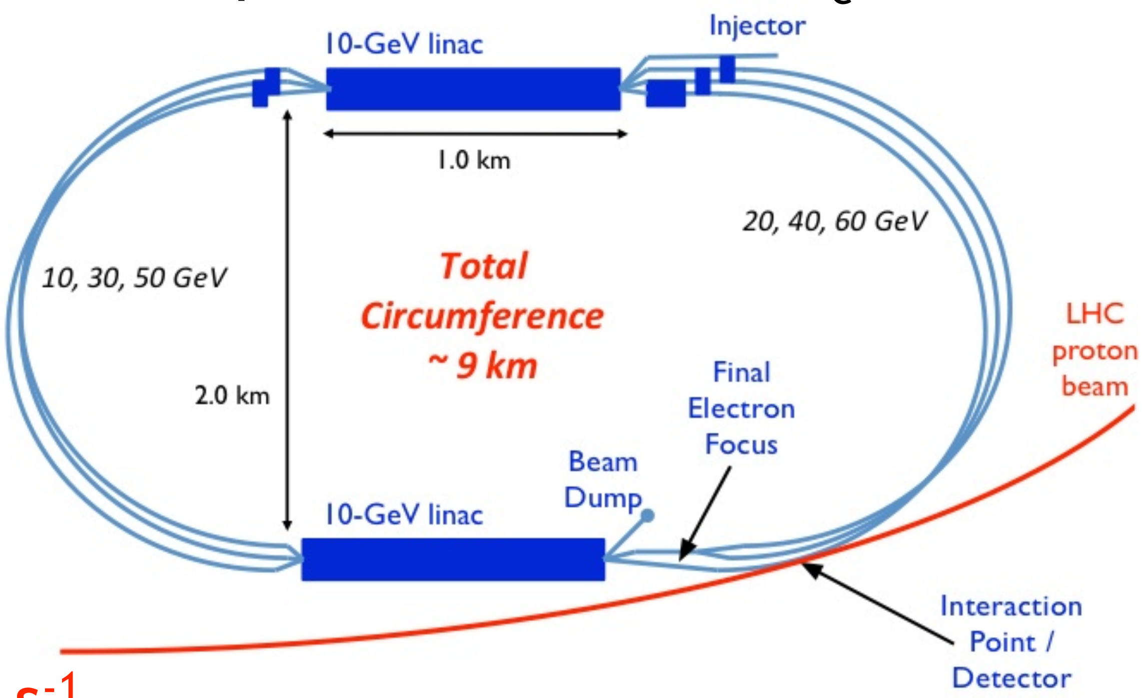
IOP Publishing

Baseline# Design (Electron "Linac")

Design constraint: power consumption < 100 MW → E_e = 60 GeV

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

[CERN plans energy recovery prototype]



- ep Lumi 10^{33} – 10^{34} cm^{-2} s^{-1}

→ 10 - 100 fb^{-1} per year

→ 100 fb^{-1} – 1 ab^{-1} total

- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

Machine Parameters

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}$$cm^{-2}$$s^{-1}$]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Beam Current [mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

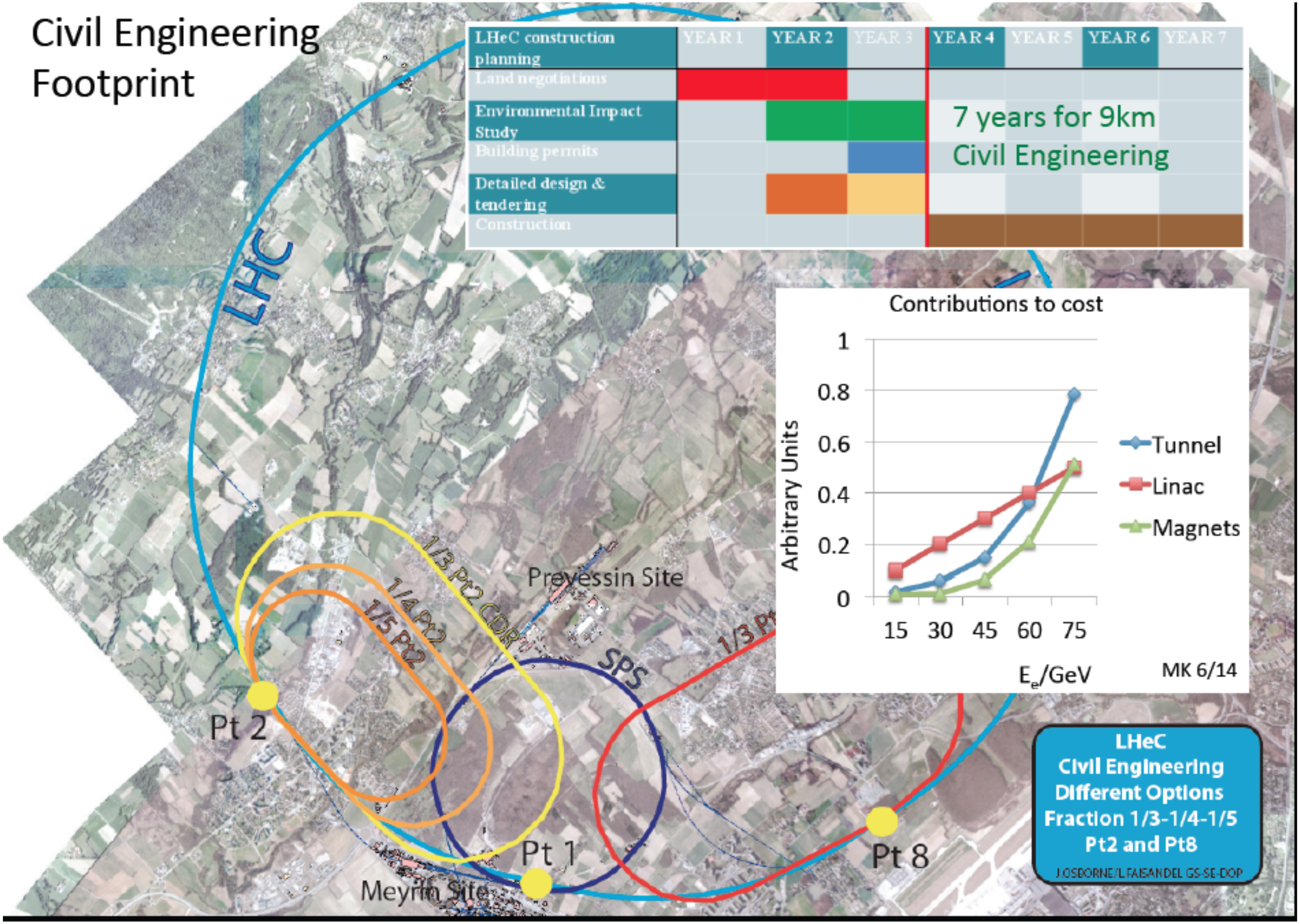
HL-LHC proton beam parameters

1000 times HERA Luminosity and 4 times cms Energy

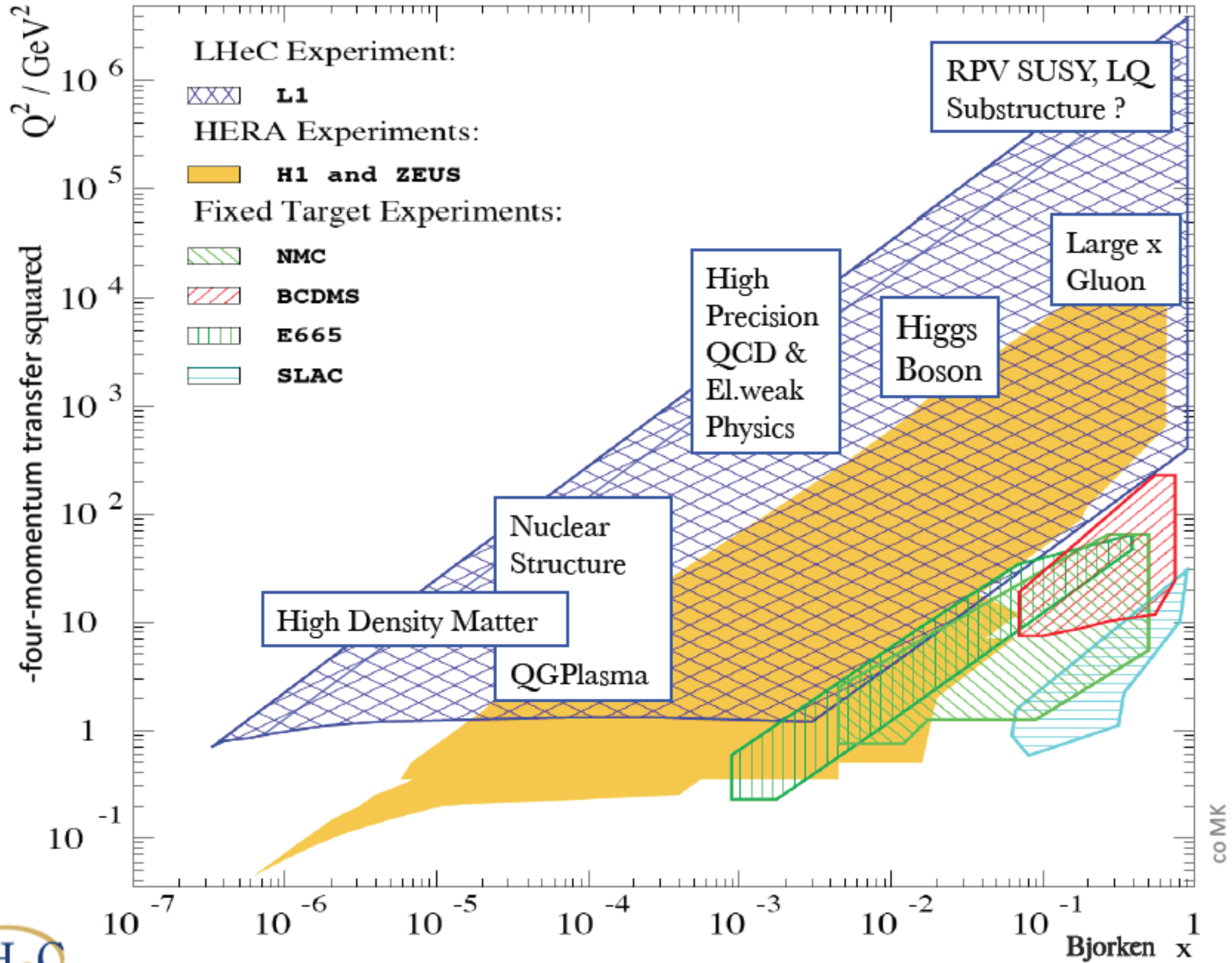
Civil Engineering Footprint

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km Civil Engineering

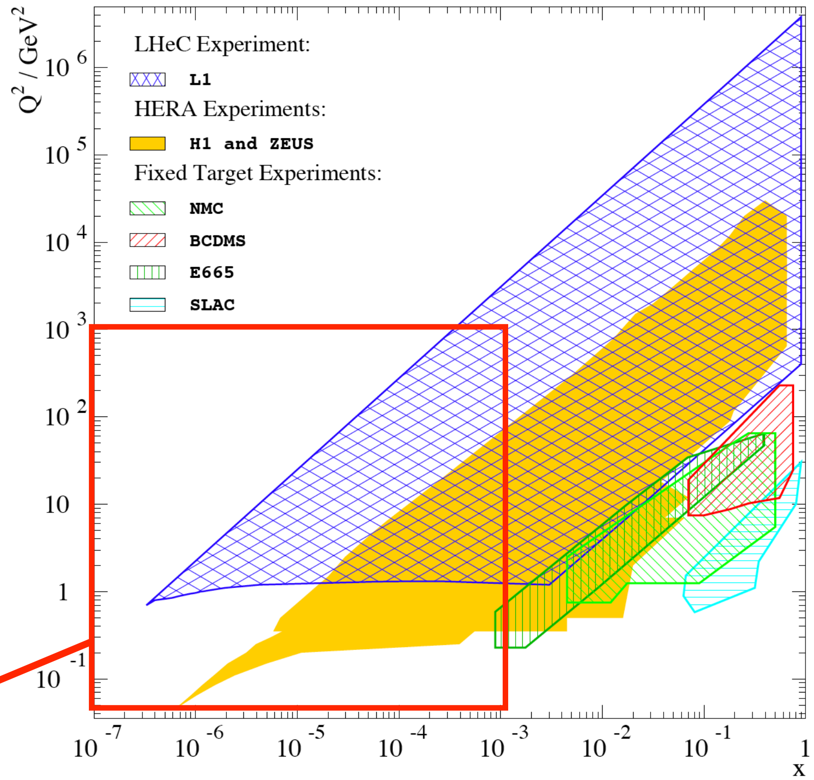


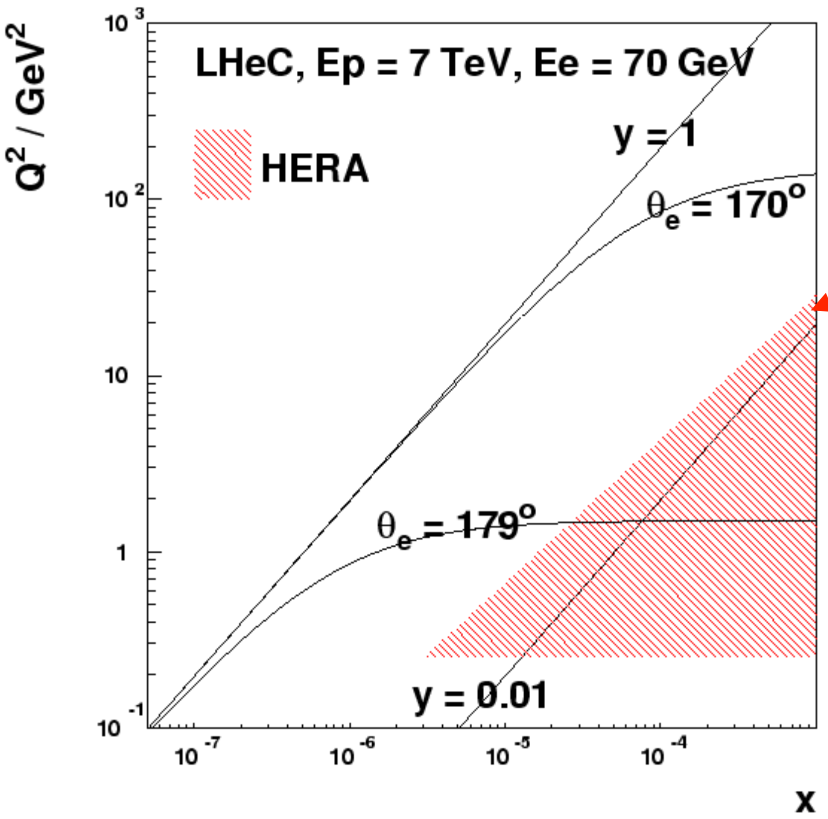
Physics Overview



LHeC Detector Acceptance Requirements

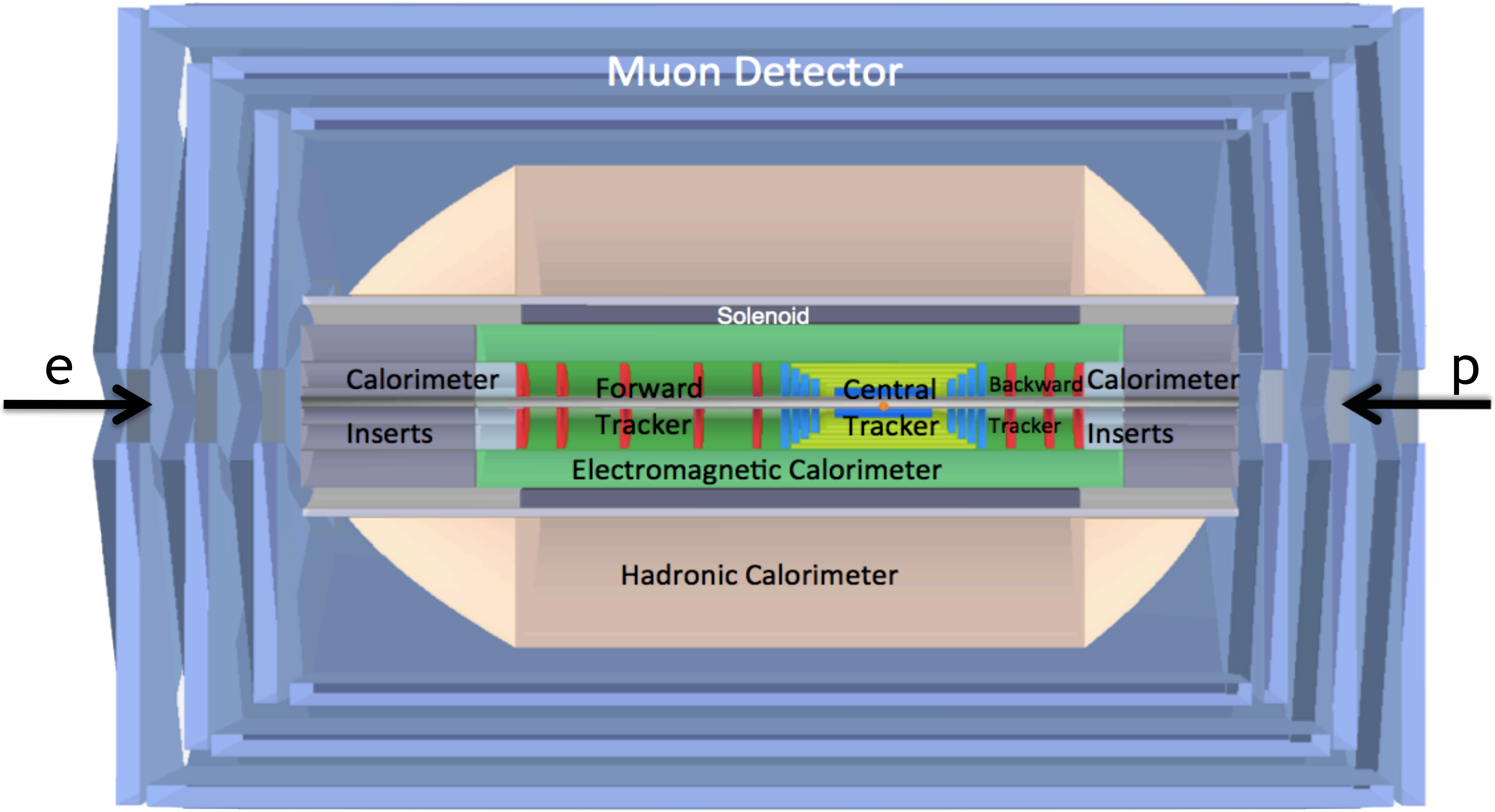
Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°





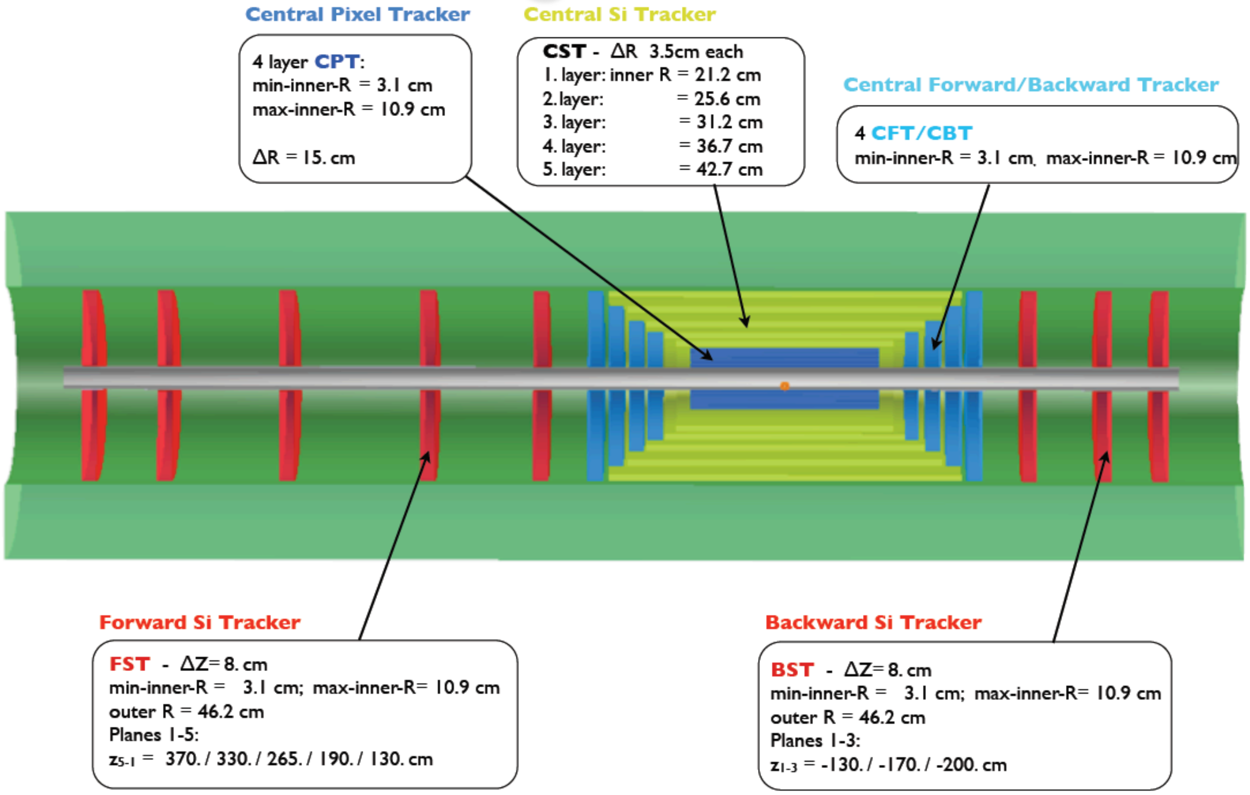
Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

Detector Design Overview



- Forward / backward asymmetry reflecting beam energies
- 1º electron hits two tracker planes
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

Tracking Overview



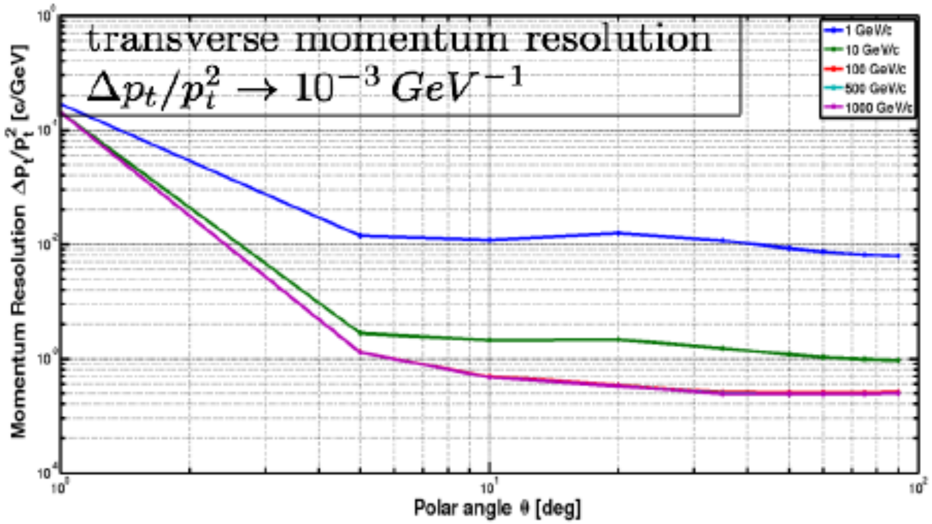
Pixels (CPT) + strips; several technologies under discussion

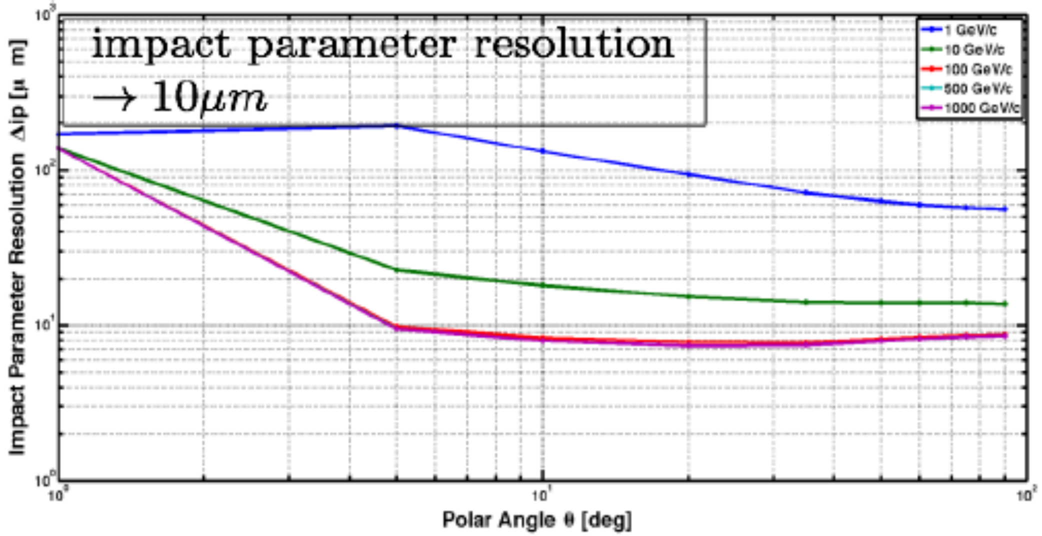
Performance evaluated using LicToy 2.0

For central tracks:

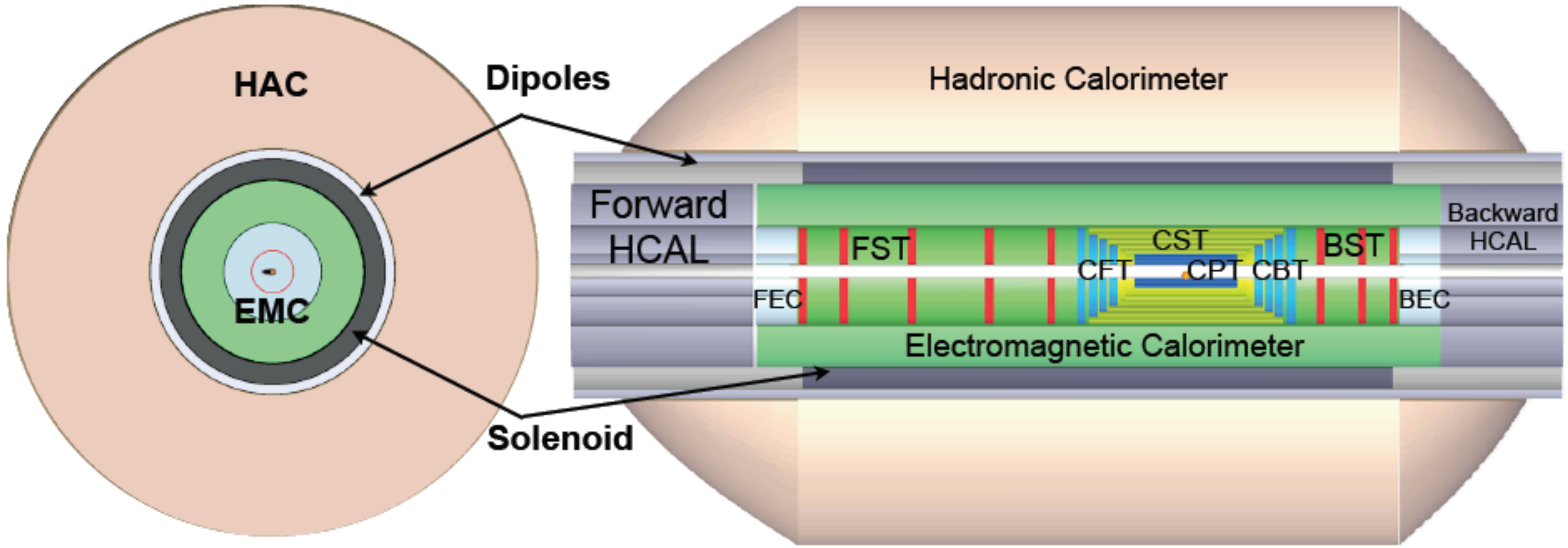
$\Delta p_t/p^2_t \rightarrow 6\ 10^{-4}\ GeV^{-1}$

10μm impact param resolution





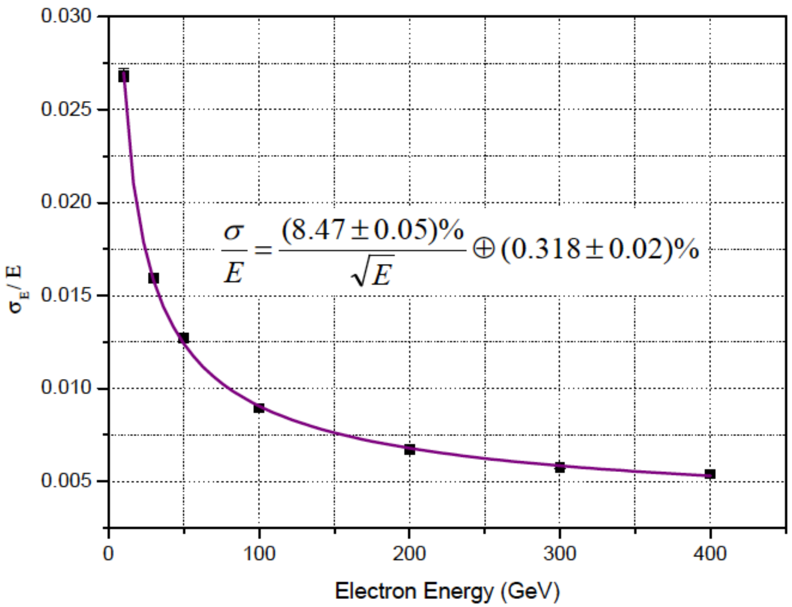
Calorimeter Overview



Current design based on (experience with) ATLAS (and H1), re-using existing technologies

- Liquid Argon EM calo, possibly
-accordion geometry (inside coil)

- Scintilating Tile HAD calorimeter (outside coil)



Systematic Precision for Simulated Data

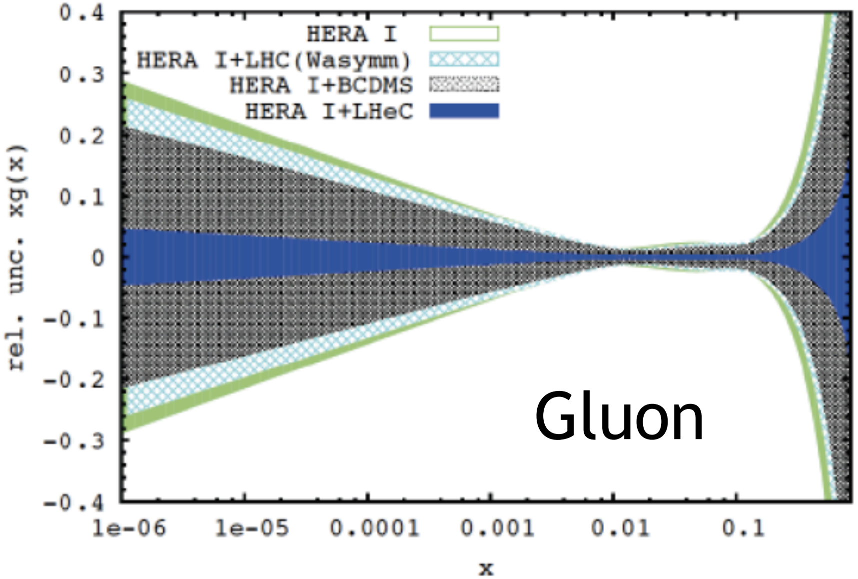
- First generation simulated `pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

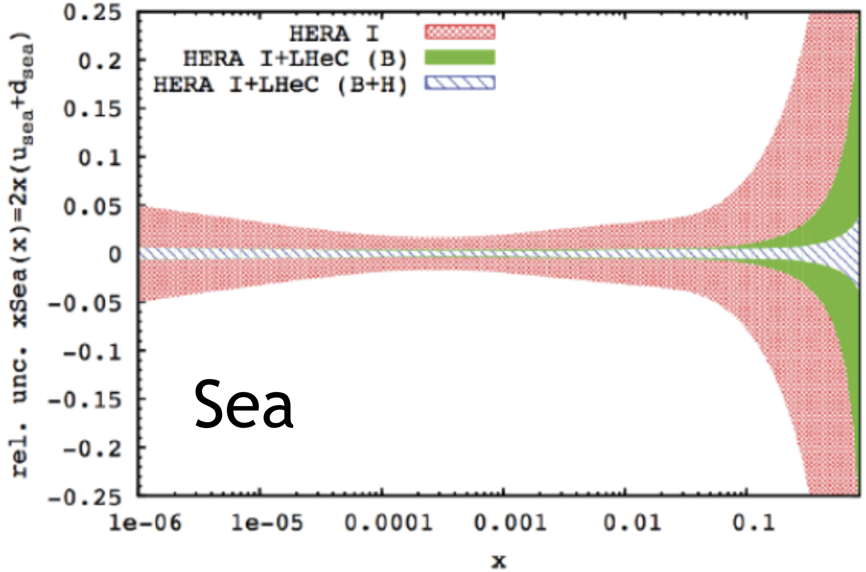
	LHeC	HERA
Lumi [$cm^{-2}s^{-1}$]	10^{33}	$1\text{-}5*10^{31}$
Acceptance [º]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

- Second generation pseudo-data (with full detector simulation) in progress

PDF Constraints at LHeC

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

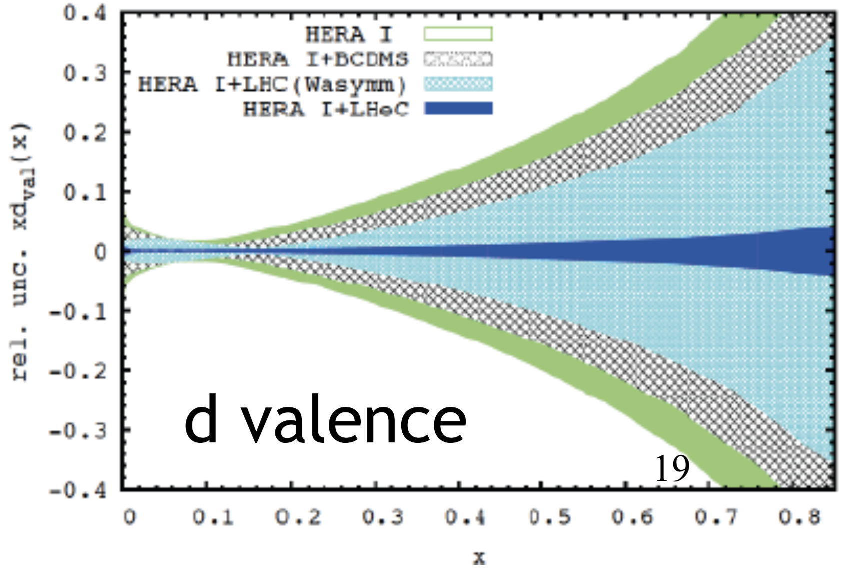




… impact at low x (kinematic range) and high x (luminosity)

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

… full flavour decomposition



Flavour Decomposition

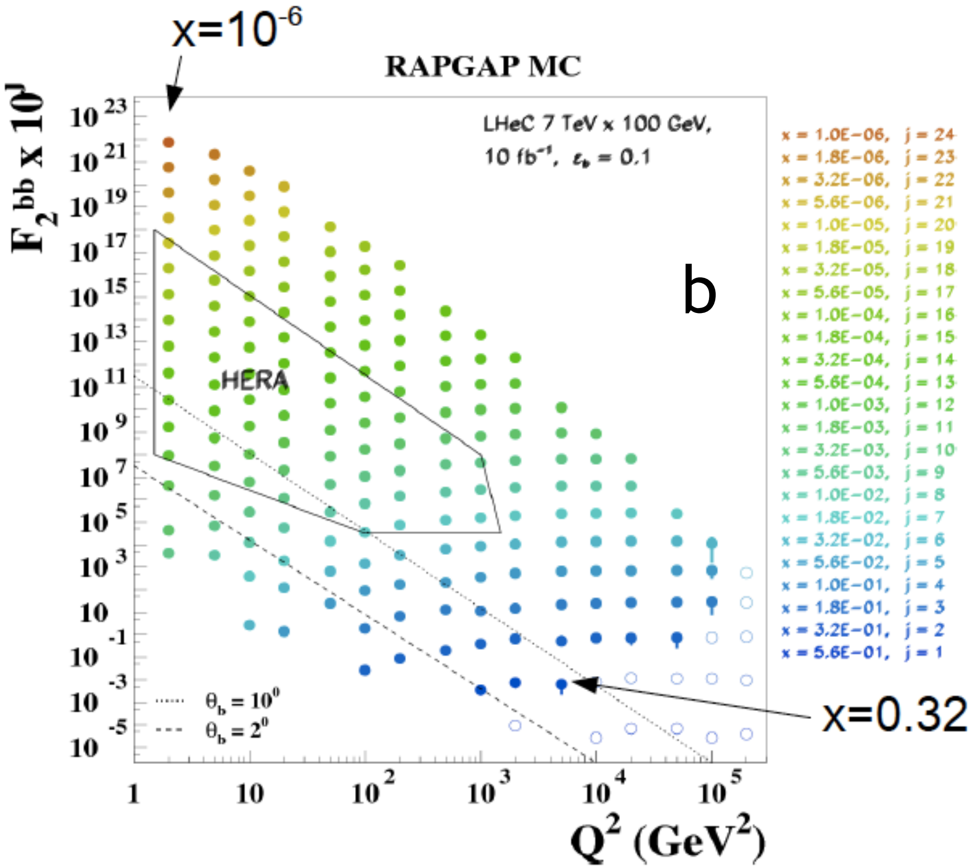
Precision c, b measurements

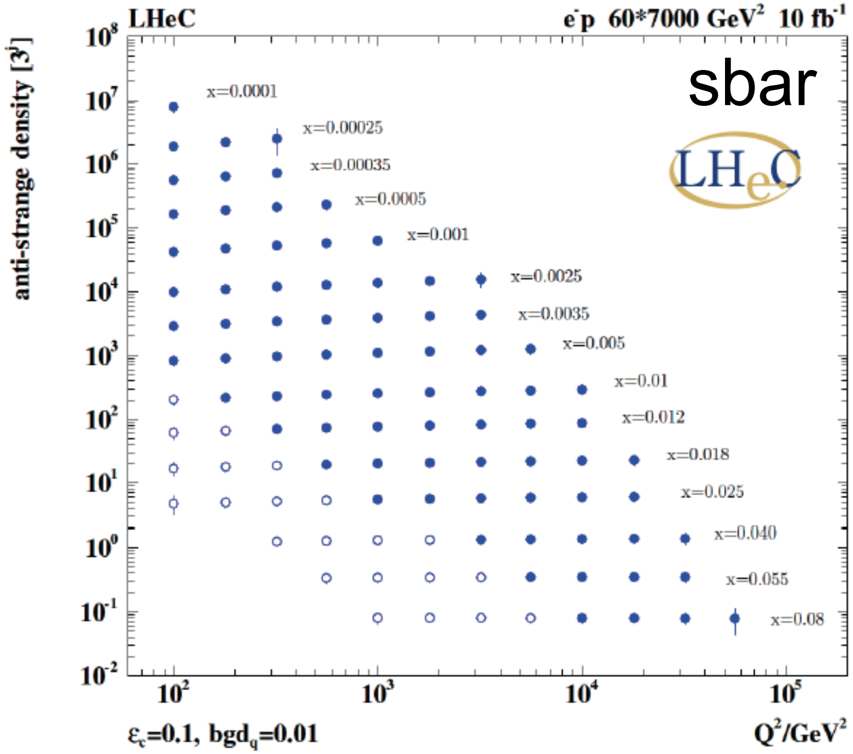
(modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

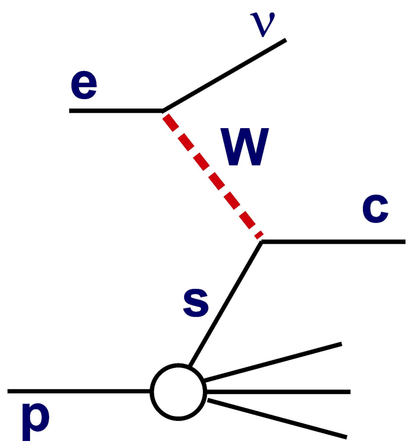
Systematics at 10% level

→beauty as a low x observable

→s, sbar from charged current







(Assumes 1 fb^{-1} and

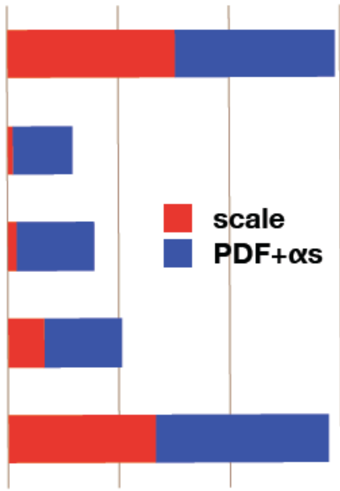
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

Should we care? PDF Unc's for LHC Higgs

Theory Cross Section Uncertainties

(125 GeV Higgs
J Campbell, ICHEP'12)

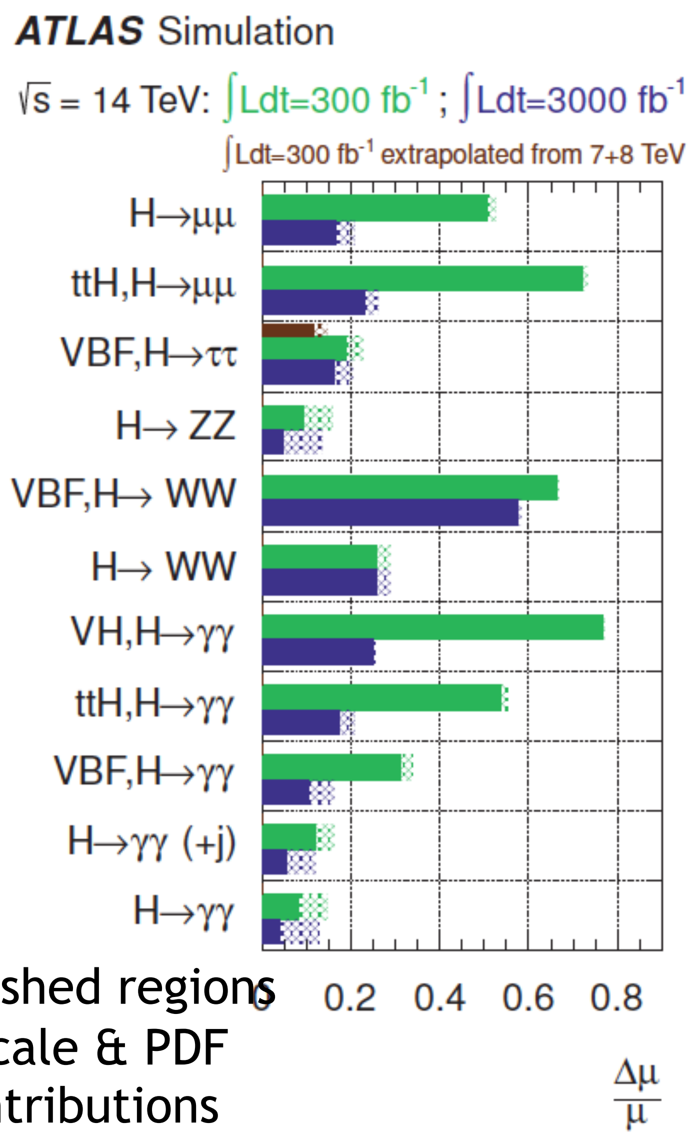
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Similarly fermionic modes (bbbar, ccbar)

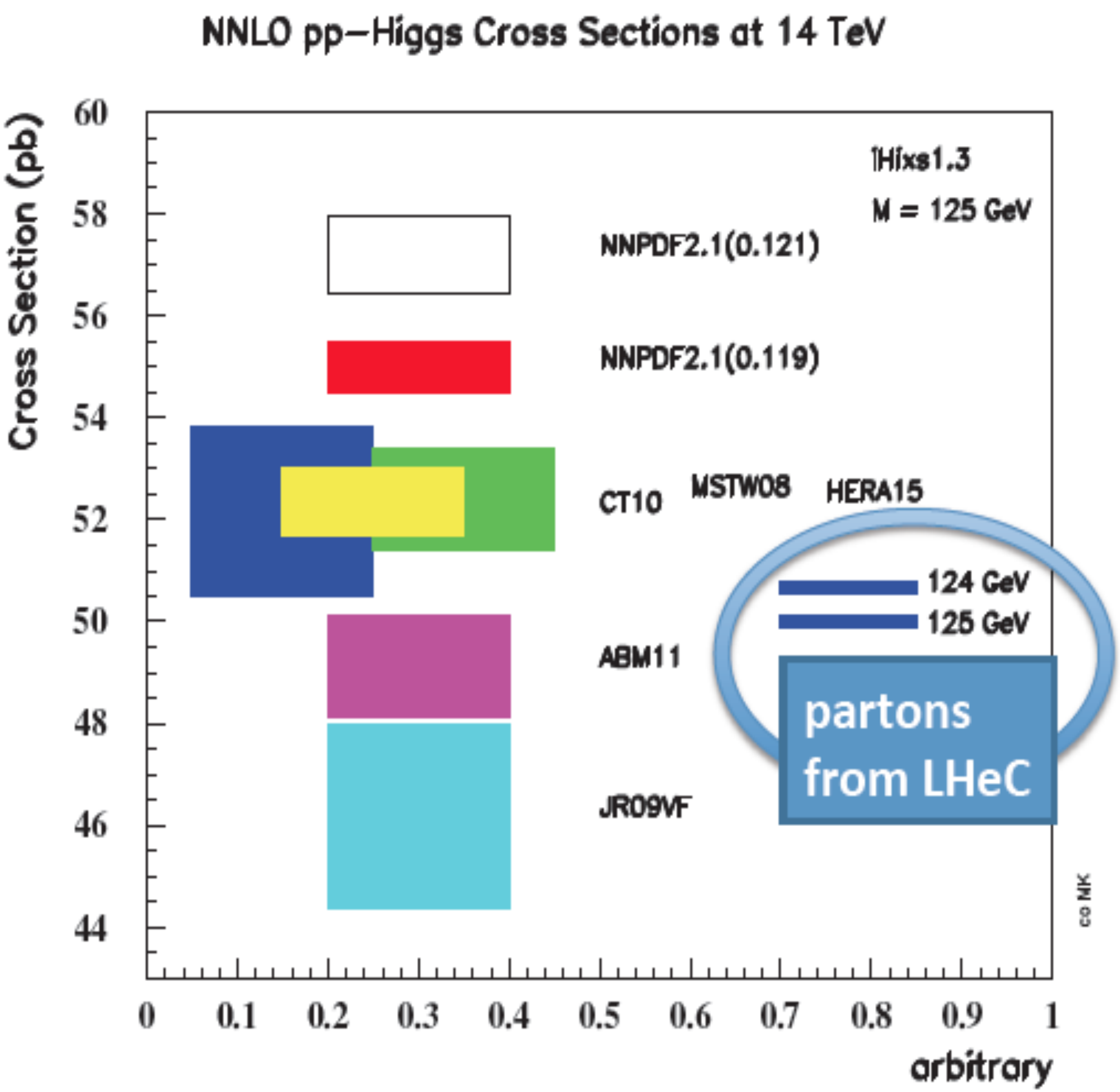
… tests of Standard Model in Higgs sector may become limited by knowledge of PDFs in HL-LHC era

Projected Experimental Uncertainties



[Dashed regions = scale & PDF contributions]

LHeC Impact on LHC Higgs PDF Unc'ty



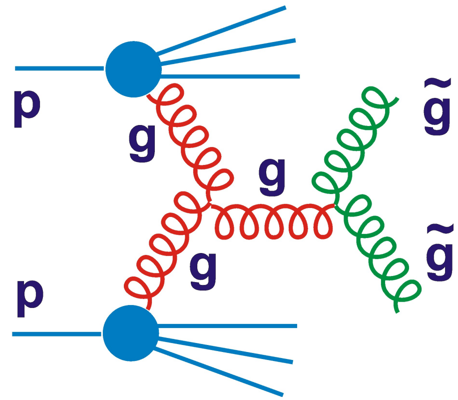
... needs N^3LO Higgs calculation

... needs improved α_s measurement (also @ LHeC)

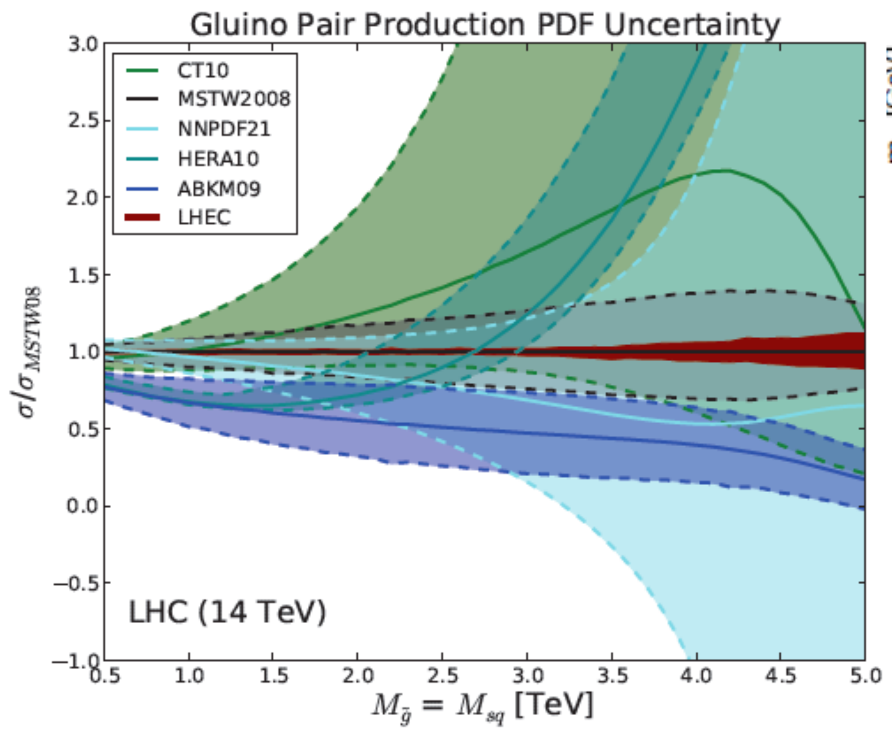
c.f. experimental uncertainty of 0.25%

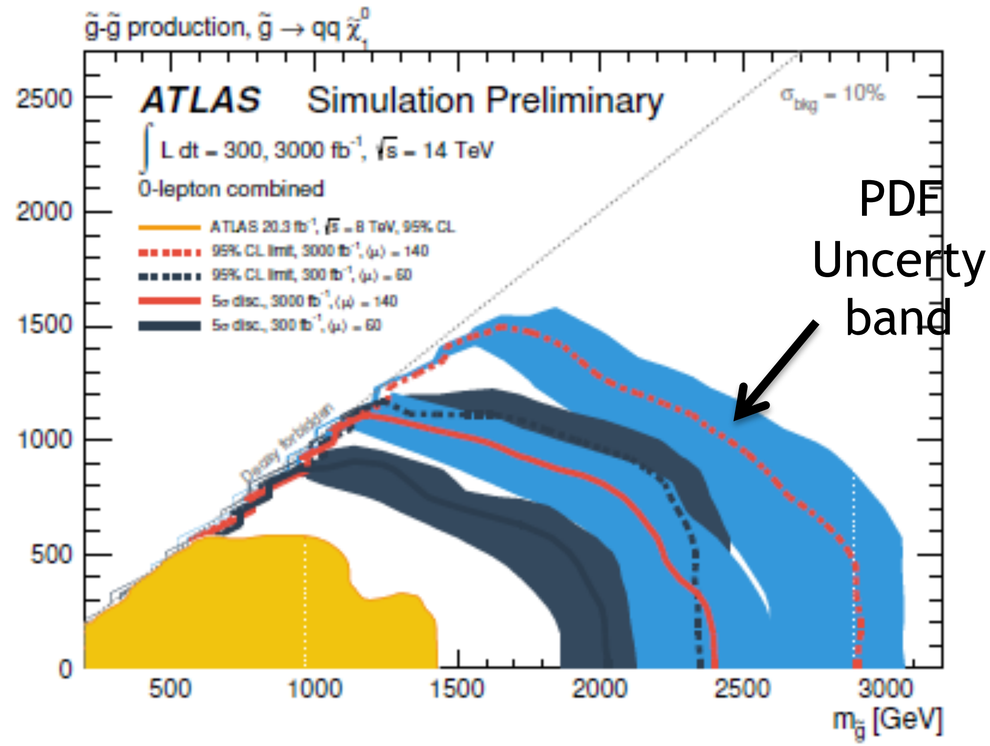
e.g. High Mass 2 Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg) poorly known for s-hat > 1 TeV.

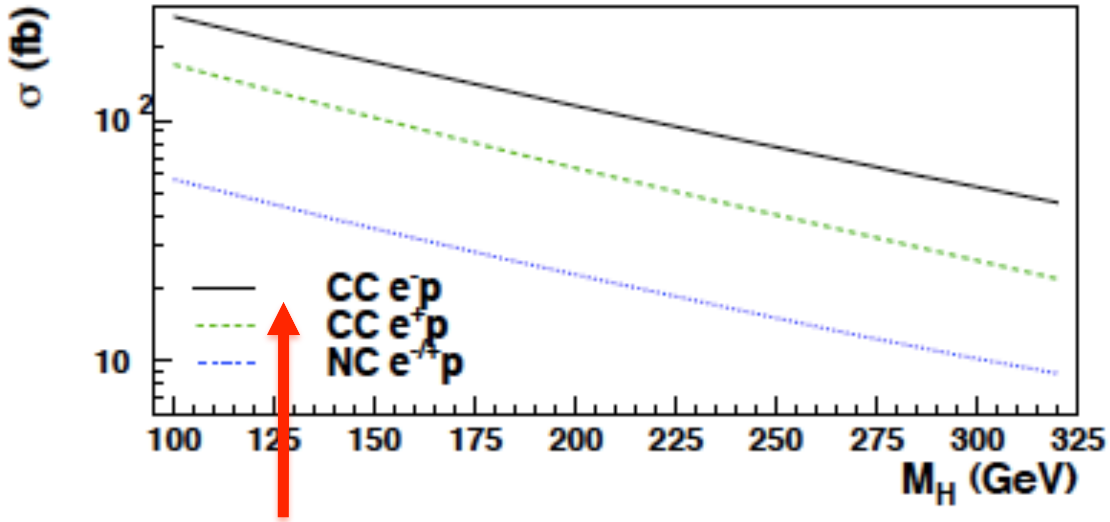


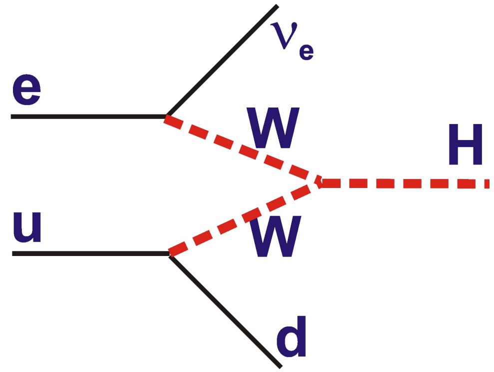
- Both signal & background uncertainties driven by error on gluon density … essentially unknown for masses much beyond 2 TeV





ep Higgs Production at LHeC





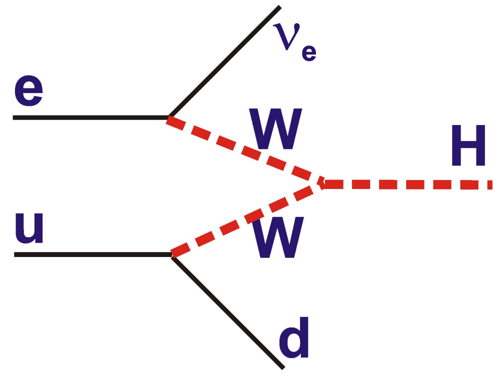
Clean signature:
H (→bbbar) + j + p_t^{miss}

Cross section similar to e^+e^- linear collider

Dominant charged current process probes product of WW → H and H → bbbar couplings

Sensitive to anomalous couplings and (via azimuthal degree of freedom) anomalous CP structure

A Direct Higgs Study

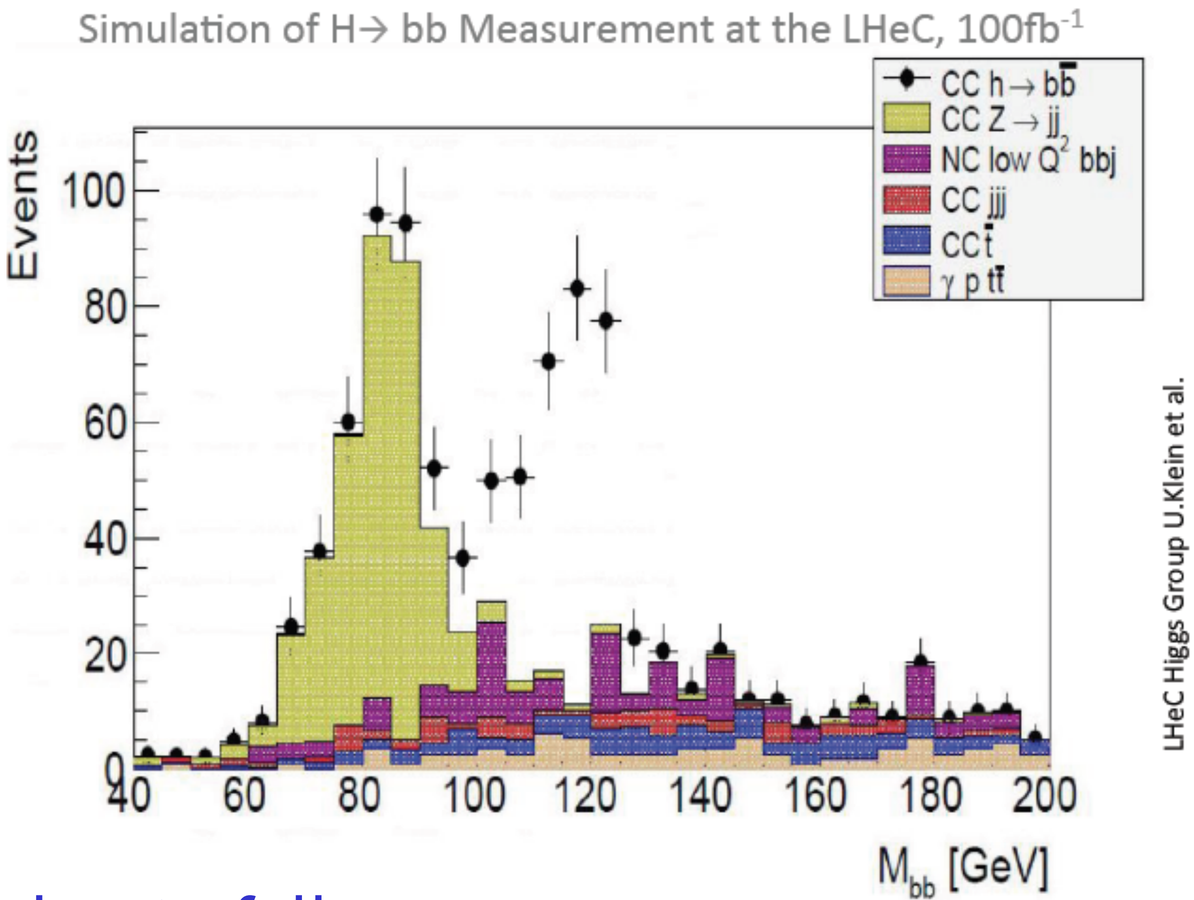


Study of H → bbbar in generic simulated LHC detector

- 80% lepton polarisation enhances signal by factor 1.7

- Signal/Background ~ 1-2

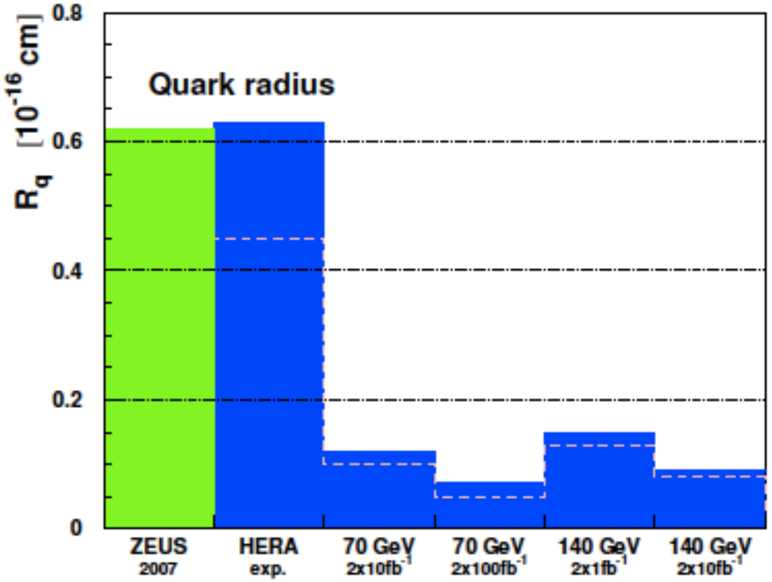
- With 10^{34} luminosity, x10 more data
  →~5000 events,
  → ~1% H→bbbar coupling



... ongoing studies of H→ccbar to follow.

Direct Sensitivity to New Physics

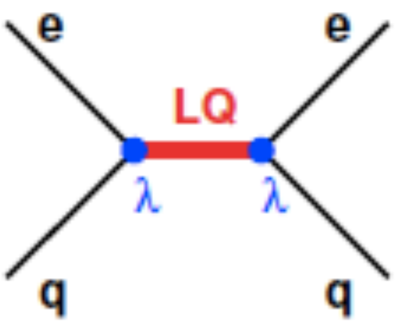
- The (pp) LHC has much better discovery potential than LHeC (unless E_e increases to >~500 GeV and 10^{34} lumi achieved)

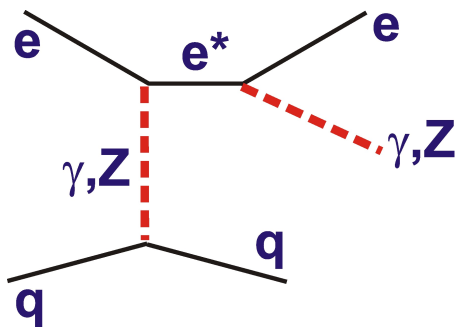


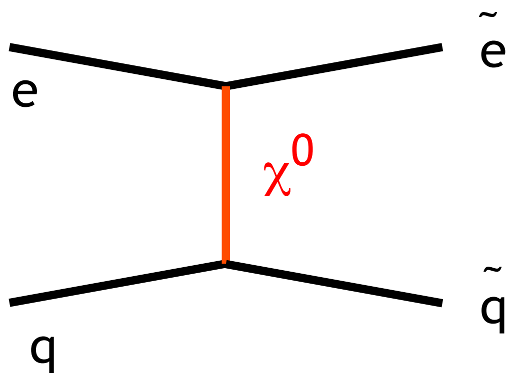
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

… big improvement on HERA, but already beaten by LHC

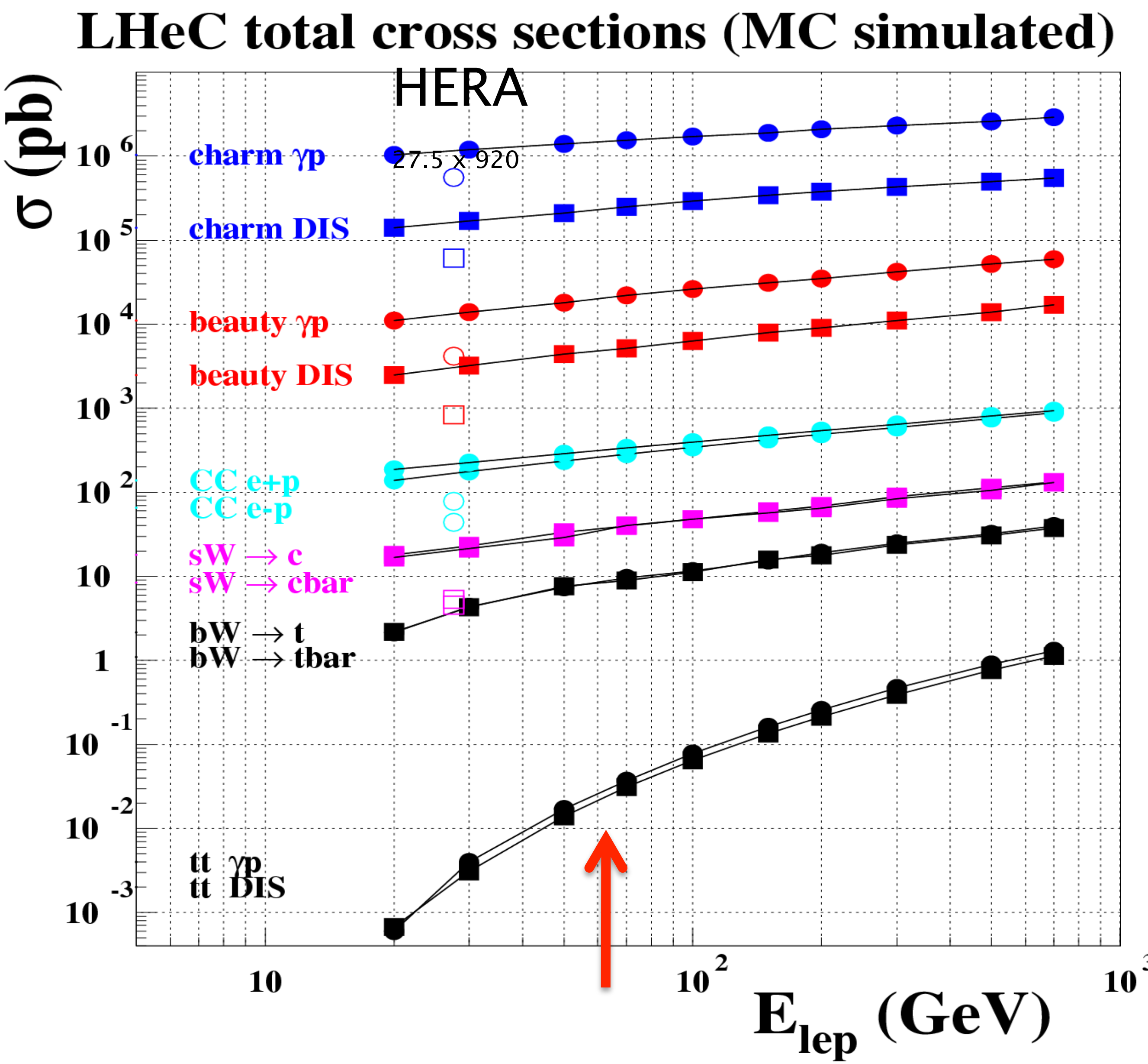
- LHeC *is* competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states







Cross Sections and Rates for Heavy Flavours



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

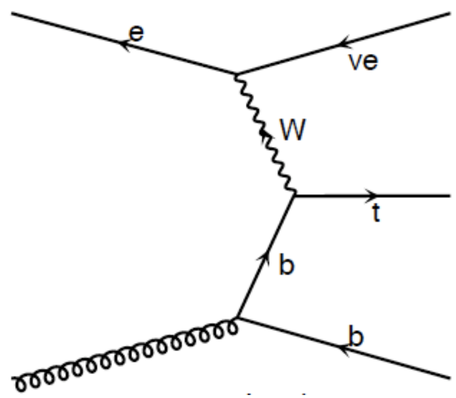
Beauty $[10^{8} / 10\ \mathrm{fb}^{-1}]$

cc

sW → c $[4.10^{5} / 10\ \mathrm{fb}^{-1}]$

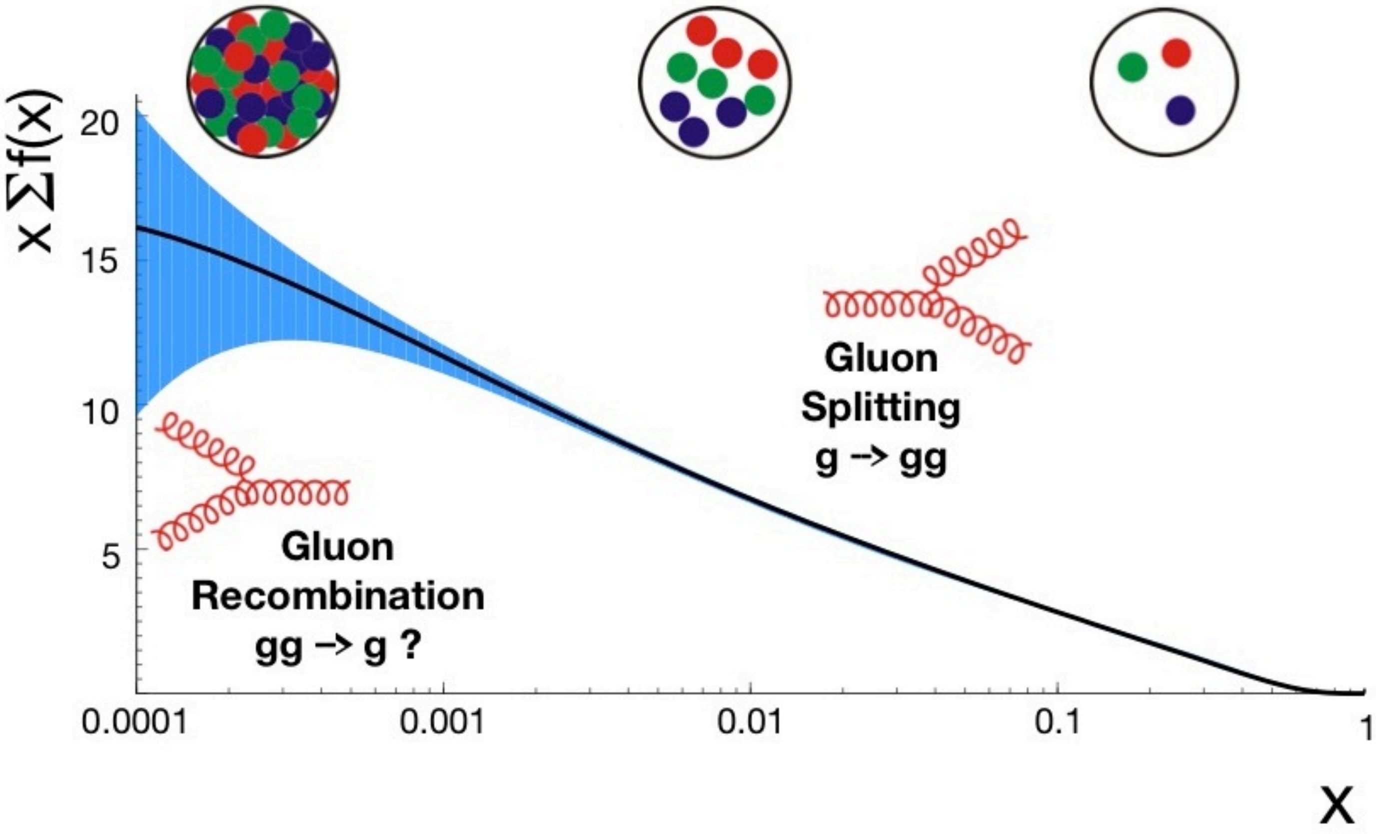
bW → t $[10^{5} / 10\ \mathrm{fb}^{-1}]$

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



c.f. luminosity of ~10-100 fb^{-1} per year

Low-x Physics and Parton Saturation



[HERAPDF 1.6 NNLO]

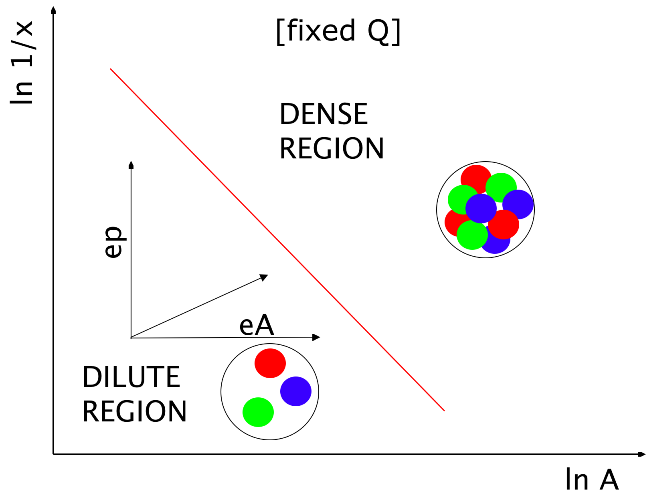
• Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects

… new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …

… gluon dynamics → confinement and hadronic mass generation

LHeC Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



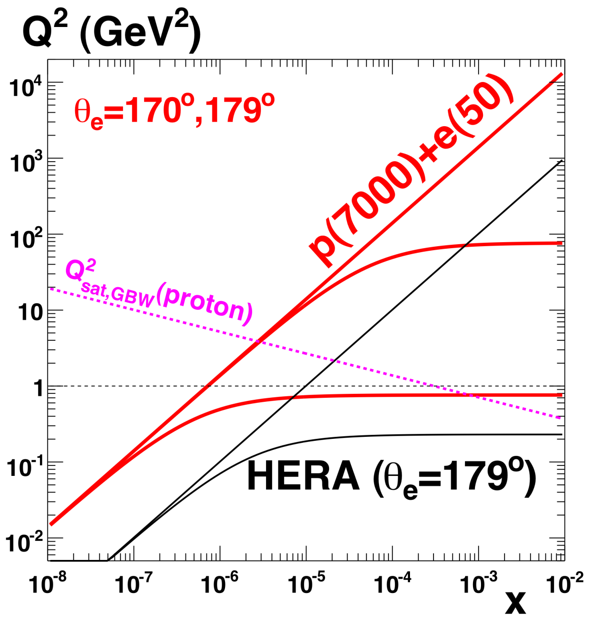
Enhance target `blackness' by:

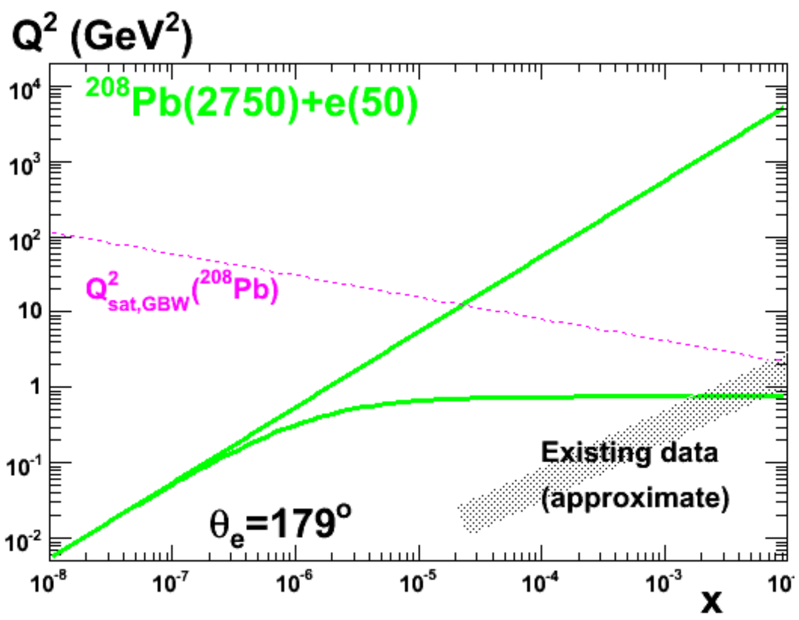
1) Probing lower x at fixed Q^2 in ep

    [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]



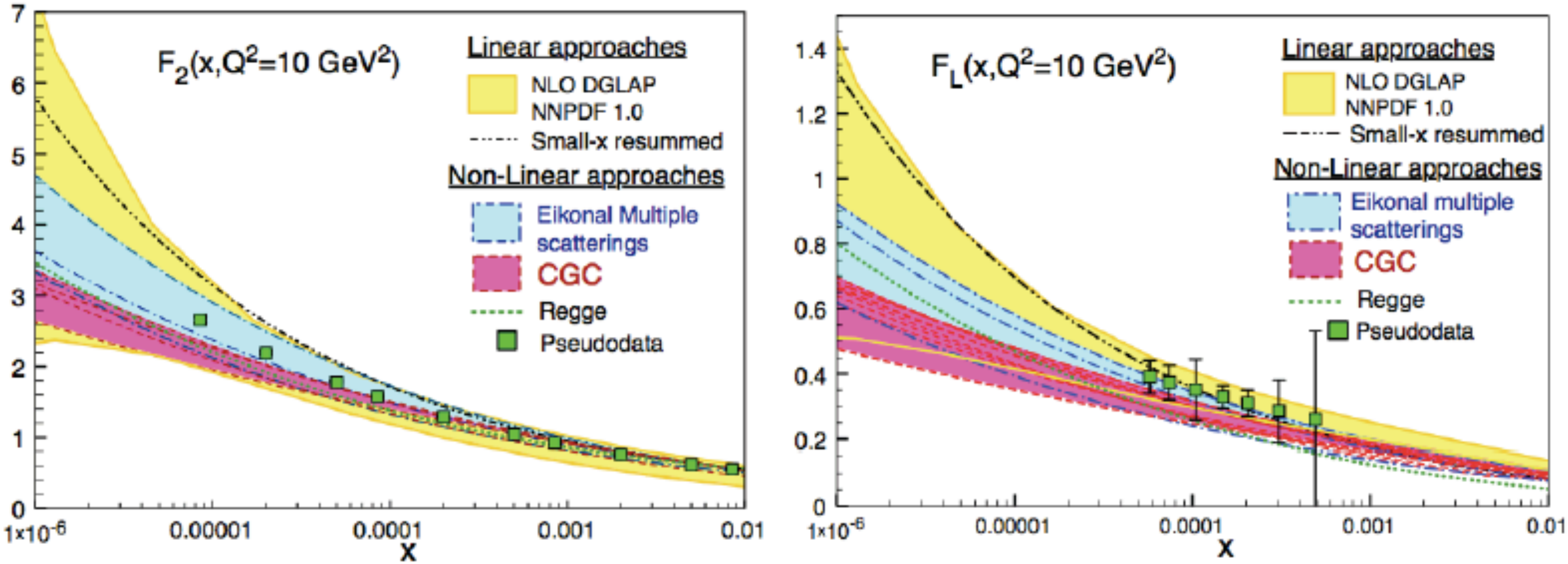


… Reaching saturated region in both ep & eA according to current models

Establishing and Characterising Saturation

With 1 fb^{-1} (1 month at 10^{33} 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

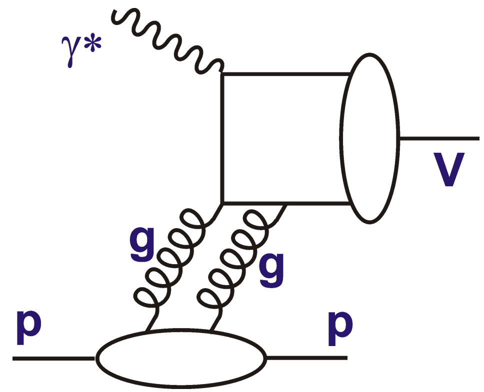


• LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

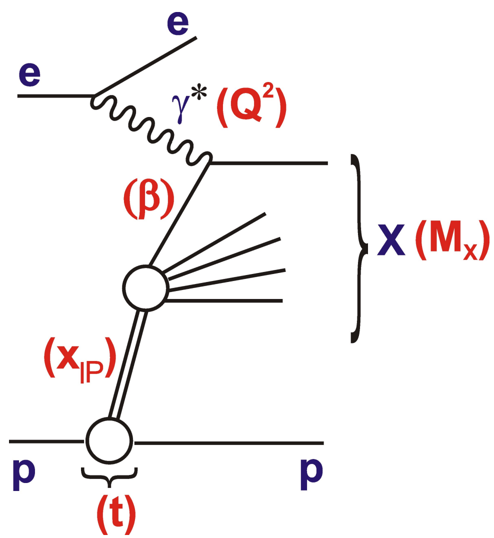
• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

Exclusive / Diffractive Channels and Saturation

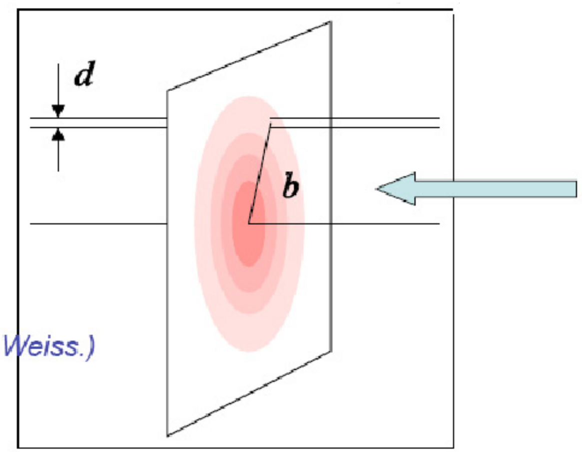
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon



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



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

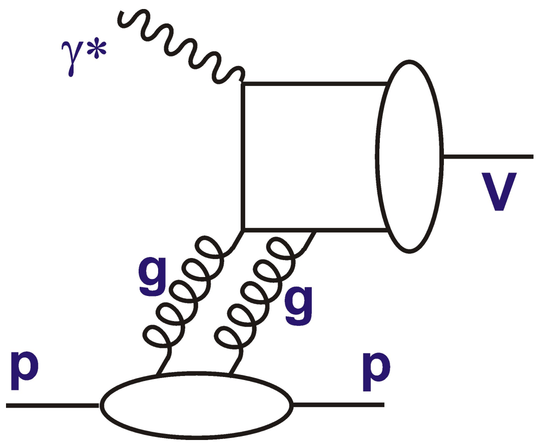


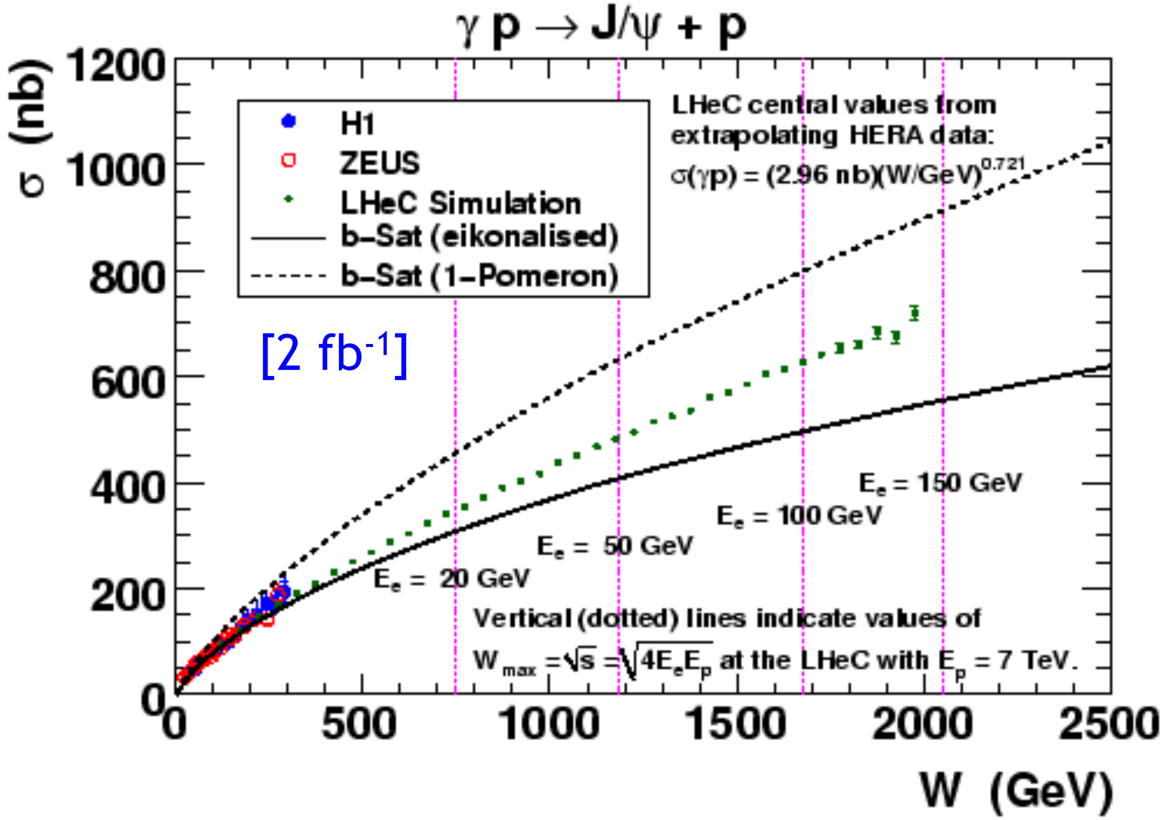
(figure from C. Weiss.)

Central black region growing with decrease of x.

e.g. J/ψ Photoproduction

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





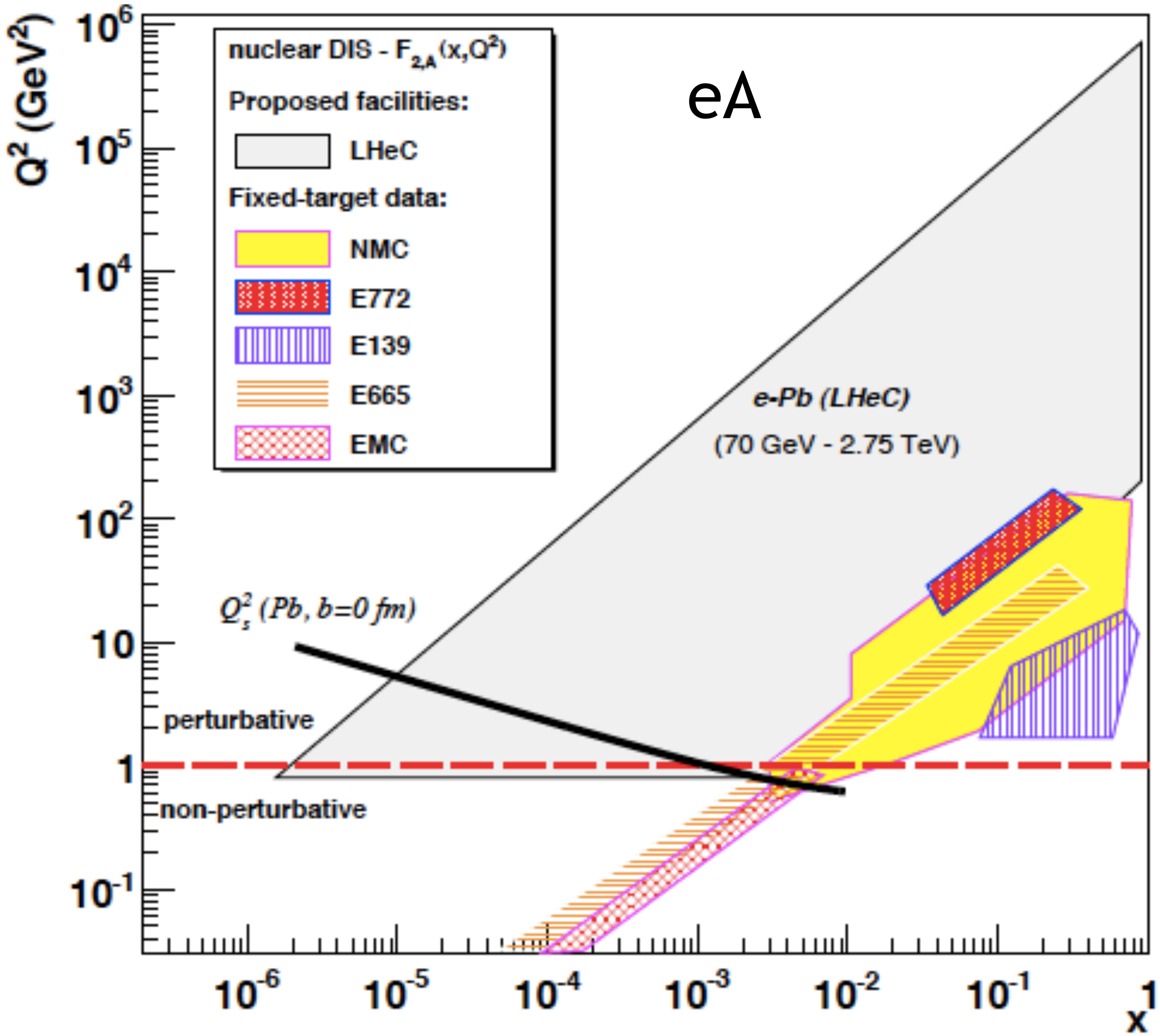
- Significant non-linear effects expected in LHeC kinematic range.

- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

  → Sat^n smoking gun?

LHeC as an Electron-ion Collider

Four orders of magnitude increase in kinematic range over previous DIS experiments.



Current knowledge for $x <\sim 10^{-2}$ almost zero.

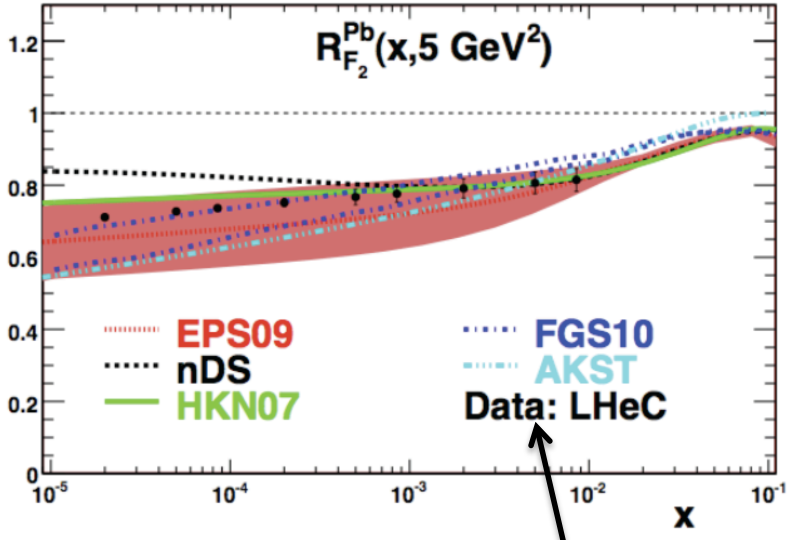
→LHeC revolutionises our view of partonic structure of nuclei.

→ Study interactions of densely packed, but weakly coupled, partons

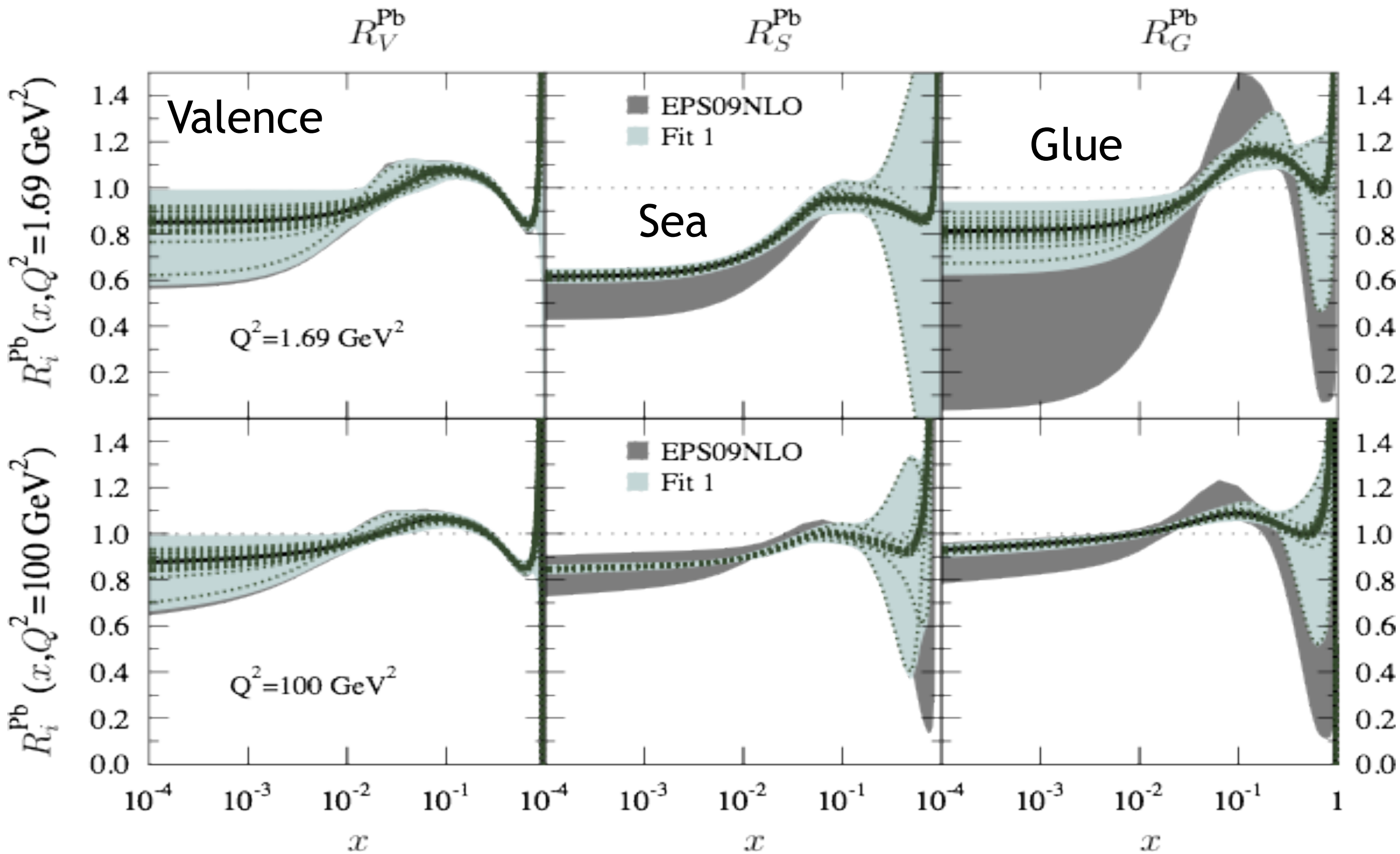
→Ultra-clean probe of passage of `struck' partons through cold nuclear matter

Impact of eA F_2 LHeC data

- Simulated LHeC ePb F_2 measurement has huge impact on uncertainties
- Most striking effect for sea & gluons
- High x gluon uncertainty still large



[Example pseudo-data from single Q^2 Value]



[Effects on EPS09 nPDF fit]

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

International collaboration :

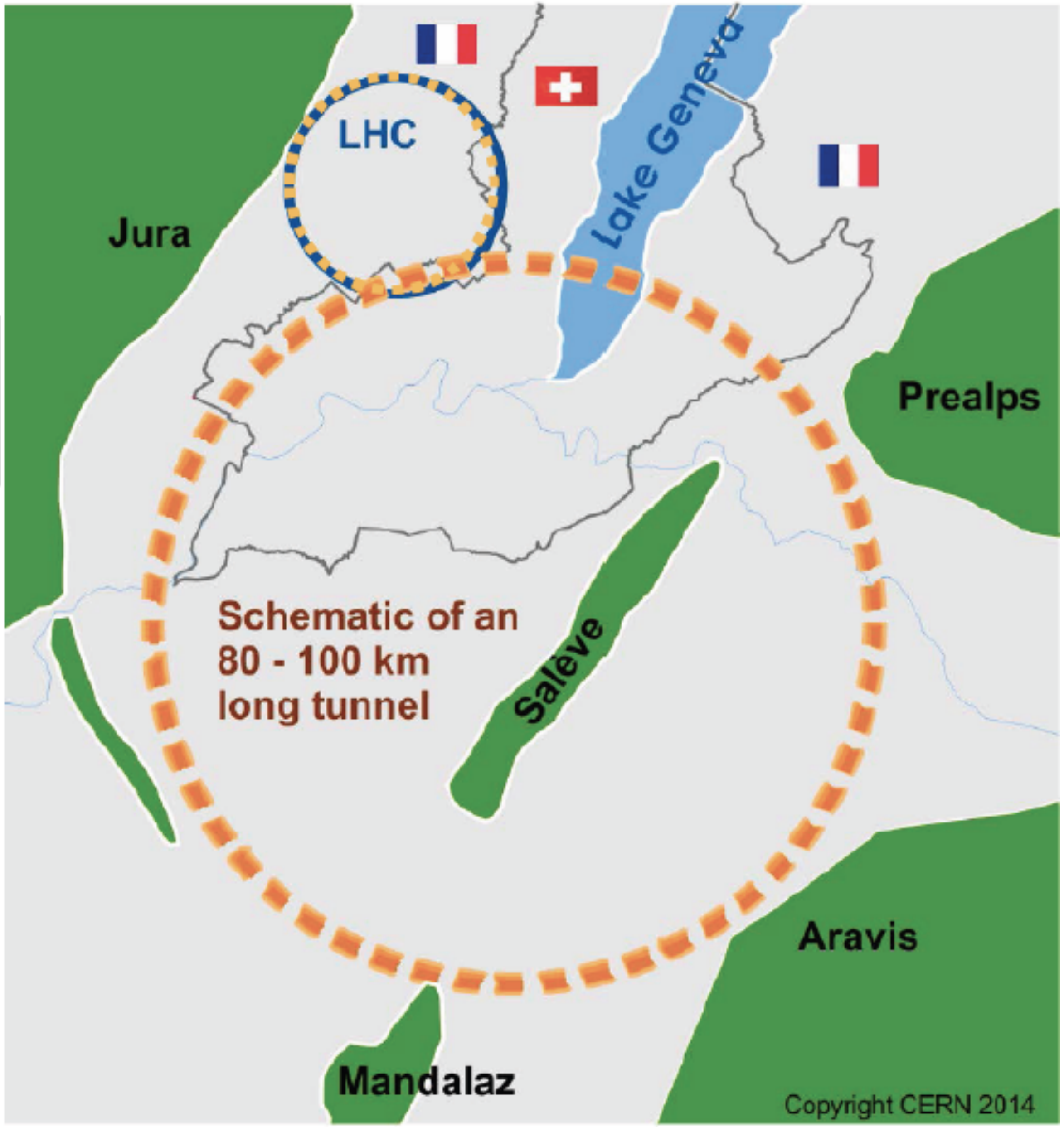
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV in 100 km

~20 T ⇒ 100 TeV in 80 km

- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e⁺e⁻* collider (*FCC-ee/TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

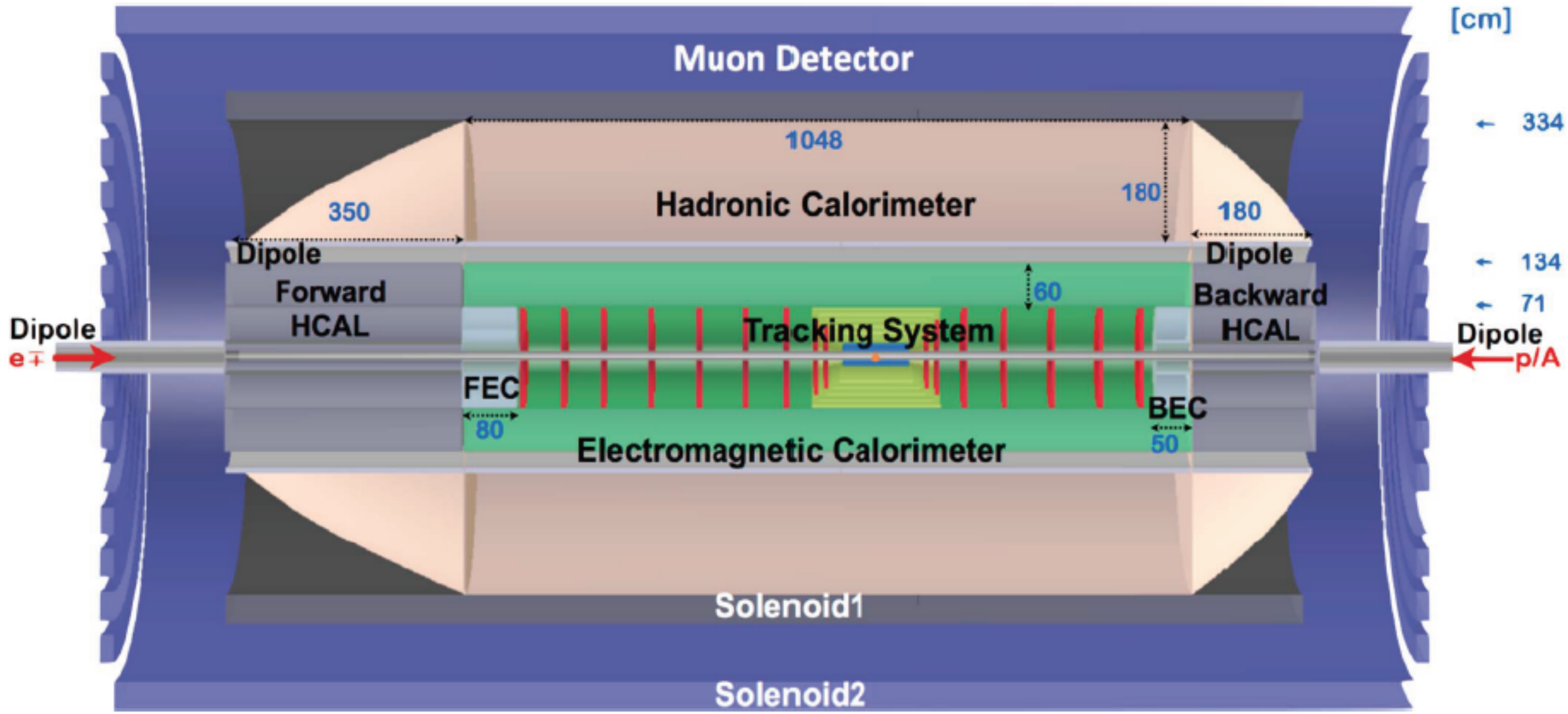
M. Benedikt



The Distant Future: ep at a CERN Future Circular Collider

First studies with current electron design, (E_e = 60 GeV) enhanced with crab cavities, and E_p=50 TeV.
Detector, scaled by up to ln(50/7) ~ 2

$\rightarrow \sqrt{s_{ep}}$ = 3.5 TeV, Lumi = few.10^{34} cm^{-2}s^{-1}



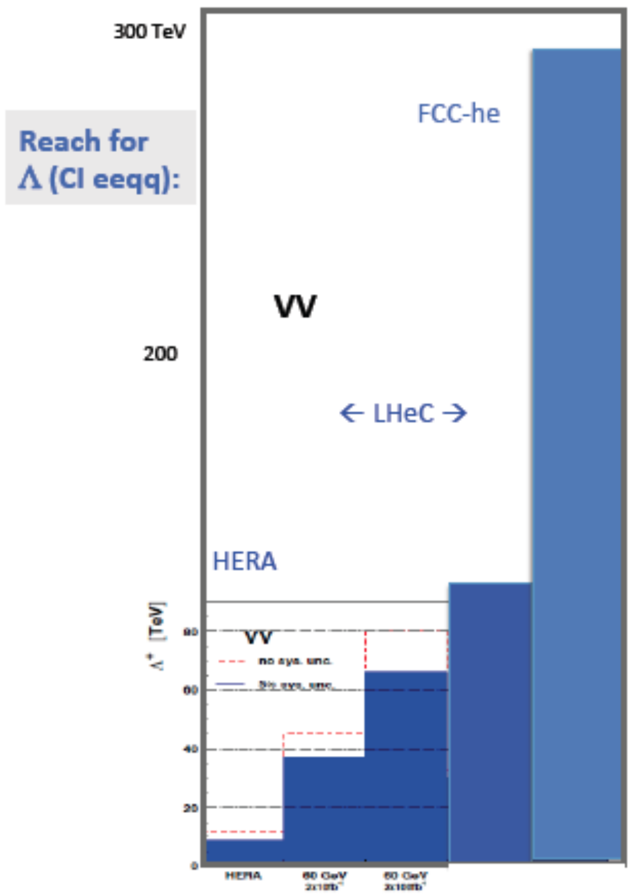
Summary of Higgs Yields at LHeC and FCC-he

Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

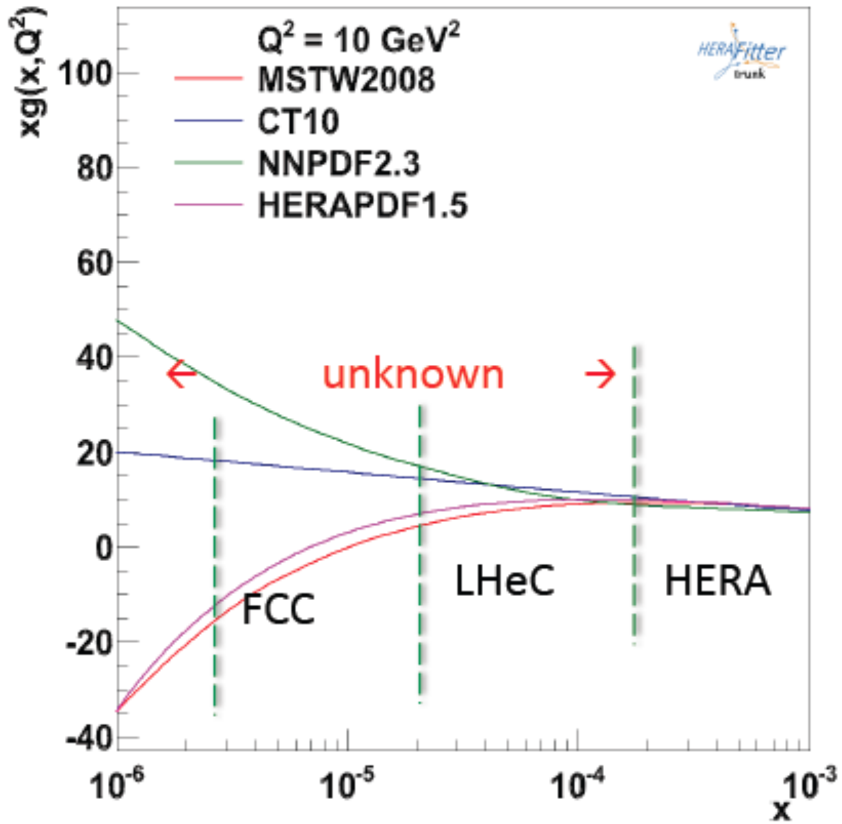
- Total FCC-he H cross section ~ 1 pb (cf lumi ~ 10^{34} cm^{-2}s^{-1})
- H→HH cross section ~0.5 fb within range?... Studies ongoing

First thoughts on Physics at FCC-he

High mass and Q^2 region



Low x Physics



- Leptoquark reach to ~ 4 TeV
- Sensitive to gluon density down to $x \sim 10^{-7}$ for $Q^2 > 1$ GeV^2

→ Studies underway, common software group with pp and ee

Status and Plans

• CDR 2012 (630 pages, summarising 5 year workshop. 200 authors from 69 institutes)

• Renewed interest following

1) Possibility of 10^{34} cm^{-2} s^{-1} luminosity
2) Higgs discovery → closer look at what limits HL-LHC sensitivity and standalone ep possibilities
3) Associated technical developments (High gradient cavities, Energy recovery linacs)

• New International Advisory Committee and Coordination Group set up by CERN, with mandate to further develop LHeC, also in context of FCC.

• More, at LHeC web
http://lhec.web.cern.ch
and …

- LHeC Study Group (CDR), J Phys G39 (2012) 075001
- Klein & Schopper, CERN Courier, June 2014
- Newman & Stasto, Nature Phys 9 (2013) 448
- Bruening & Klein, Mod Phys Lett A28 (2013) 1130011

… with thanks to many experimentalist, theorist
& accelerator science colleagues, especially
Nestor Armesto, Max Klein, Uta Klein and Anna Stasto …

LHeC study group …

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