The Large Hadron electron Collider at CERN

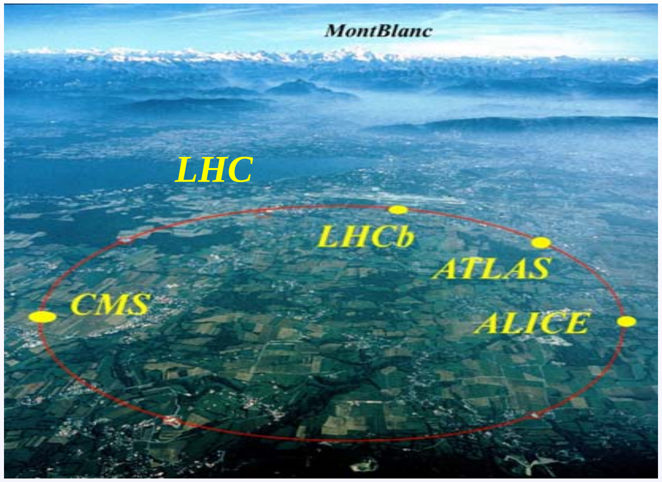
A. Polini

(for the LHeC Collaboration)

Outline:

- Introduction
- Accelerator, Interaction Region and Detector
- Physics Highlights
- Future and Outlook

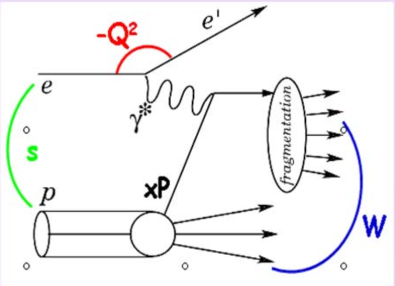
LHeC Challenge



Add an *electron* beam to the LHC

- Next generation $e^{\pm}p$ collider
- $e^{\pm}$ polarized beam
- *eA* collider

Rich physics program: *eq* physics at TeV energies



- precision QCD & electroweak physics
- boosting precision and range of LHC physics results
- beyond the Standard Model
- high density matter: low *x* and *eA*

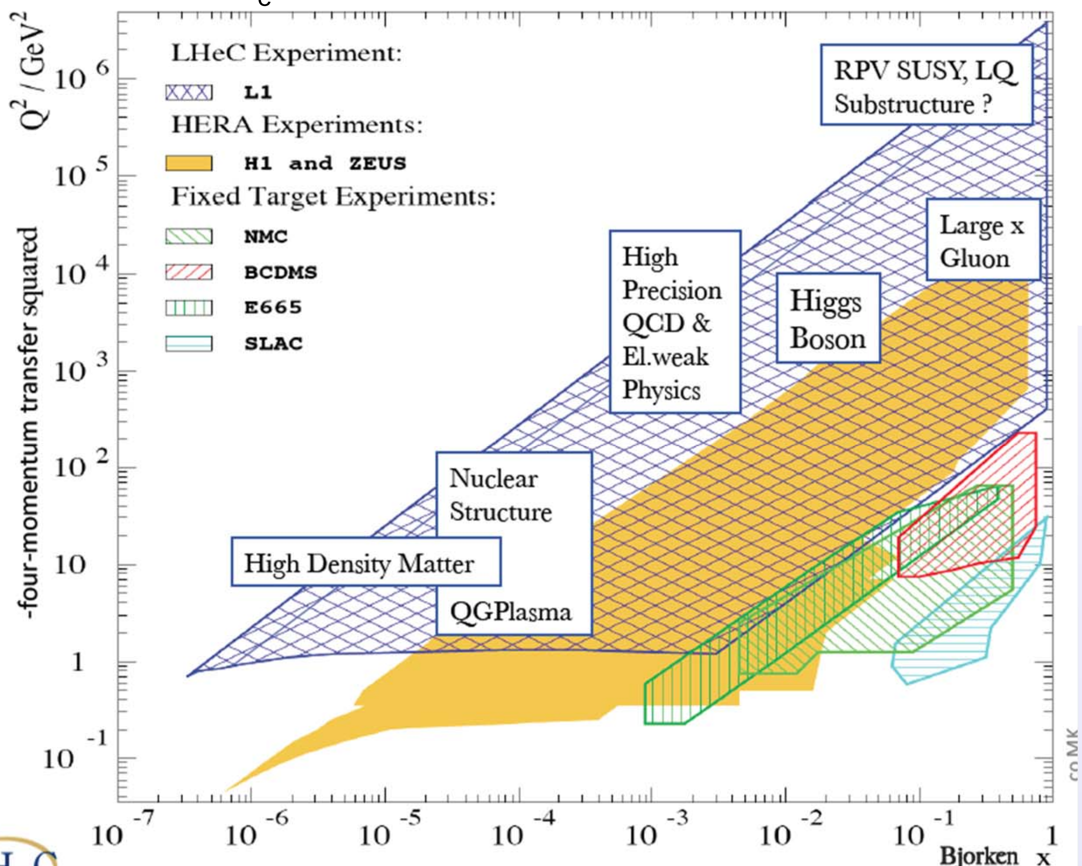
Tevatron/LEP/HERA (Fermiscale) → LHC/LC/LHeC (Terascale)

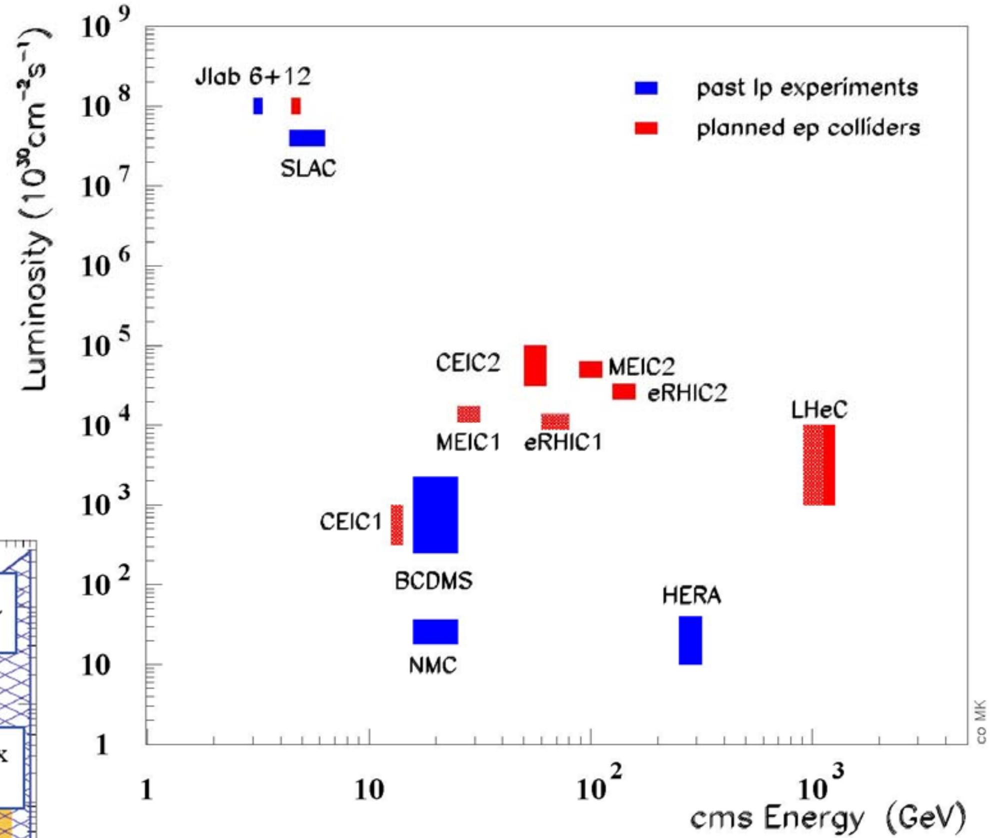
100 fold increase in luminosity, in Q^2 and $1/x$ w.r.t. HERA

LHeC Context

Latest & most promising idea to take lepton-hadron physics to the TeV centre-of-mass scale … at high luminosity

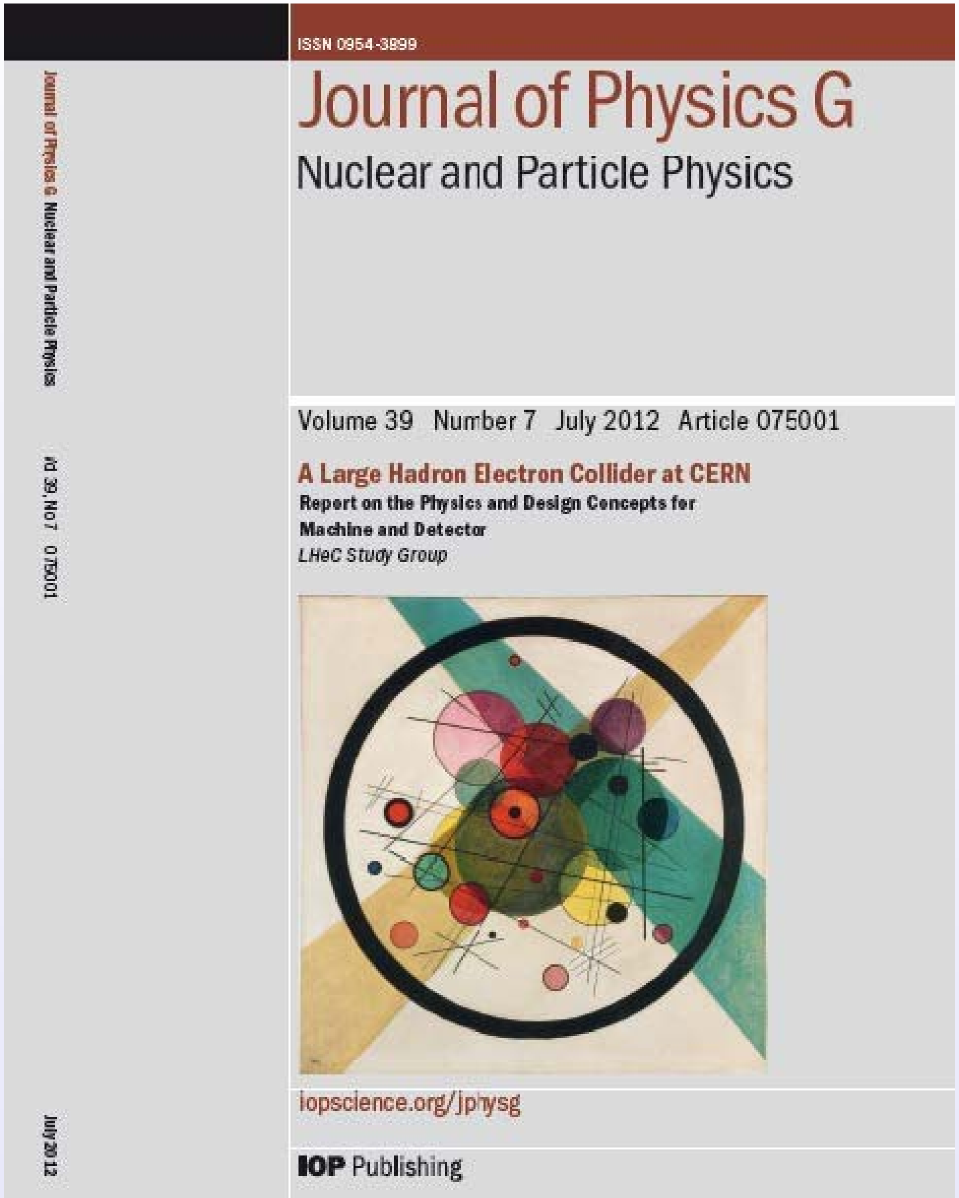
LHeC E_e=60 GeV : $\sqrt{s}$= 1.3 TeV





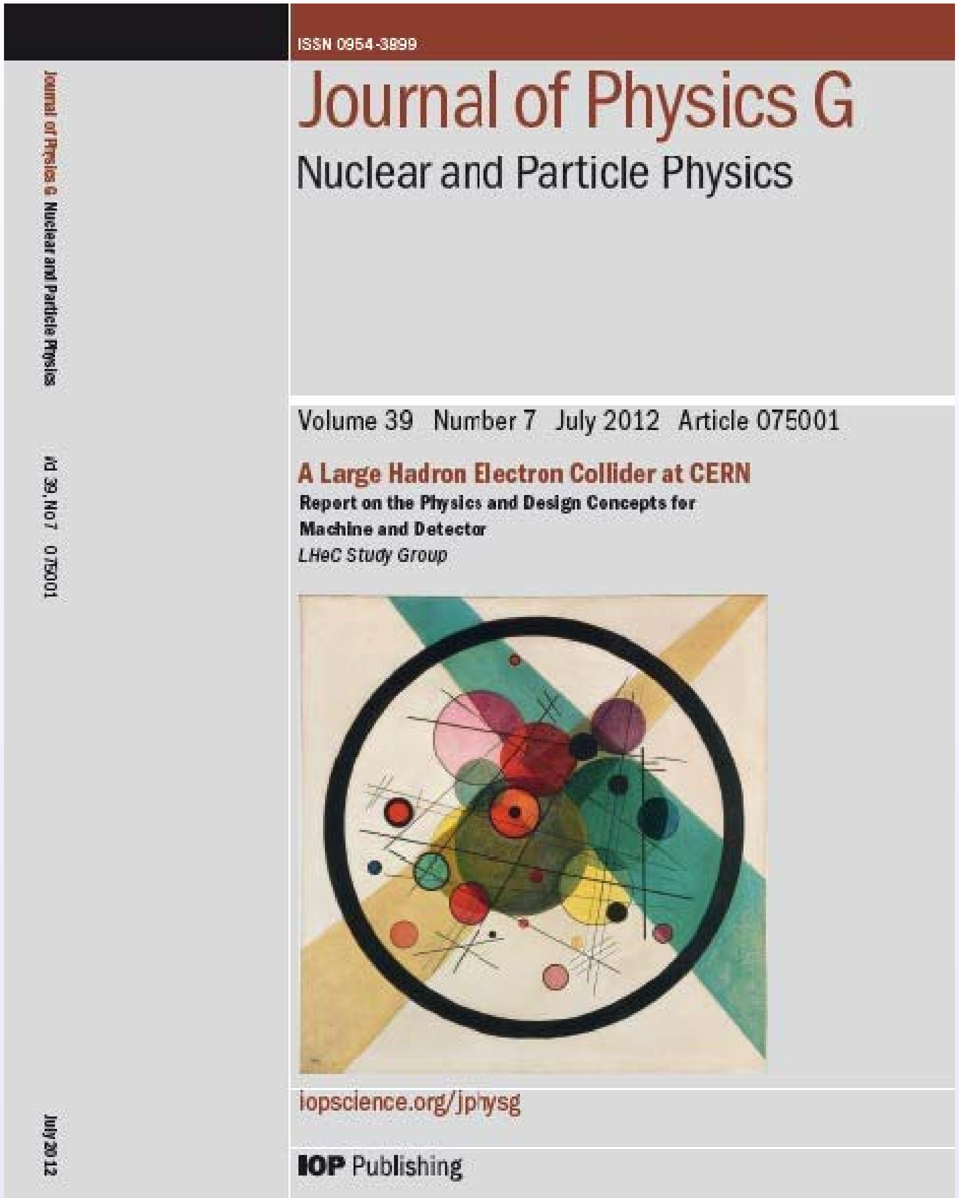
Designed to exploit intense hadron beams in high luminosity phase of LHC running from mid 2020s

Conceptual Design Report



- **I - Introduction**
  - Lepton-Hadron Scattering
  - Design Considerations
  - Executive Summary
- **II - Physics**
  - Precision QCD and Electroweak Physics
  - Physics at High Parton Densities
  - New Physics at High Energy
- **III - Accelerator**
  - Ring-Ring Collider
  - Linac-Ring Collider
  - System Design
  - Civil Engineering and Services
  - Project Planning
- **IV - Detector**
  - Detector Requirements
  - Central Detector
  - Forward and Backward Detectors
  - Detector Assembly and Integration
- **V - Summary**
  - Appendix

Conceptual Design Report



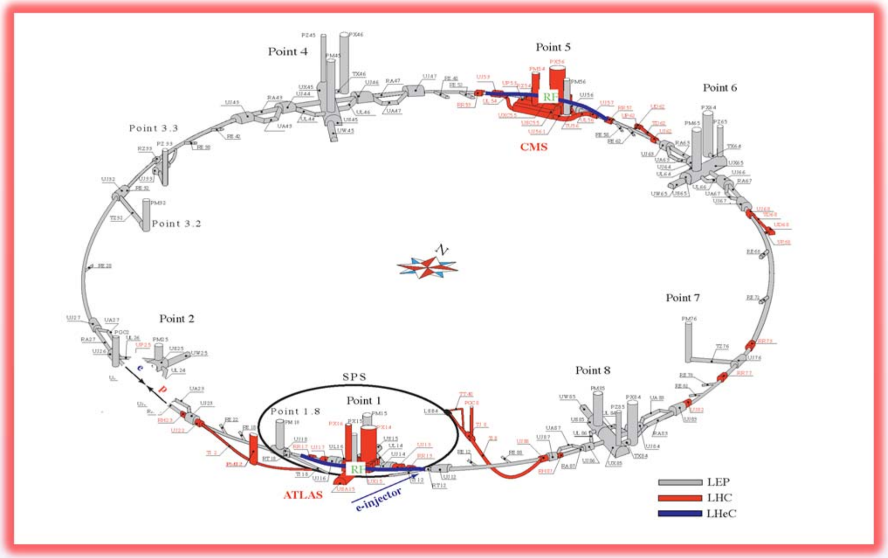
- J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]
- Published July 2012
- 630 pages, summarizing 5 year workshops commissioned by CERN, ECFA and NuPECC
- ~200 participants, 69 institutes

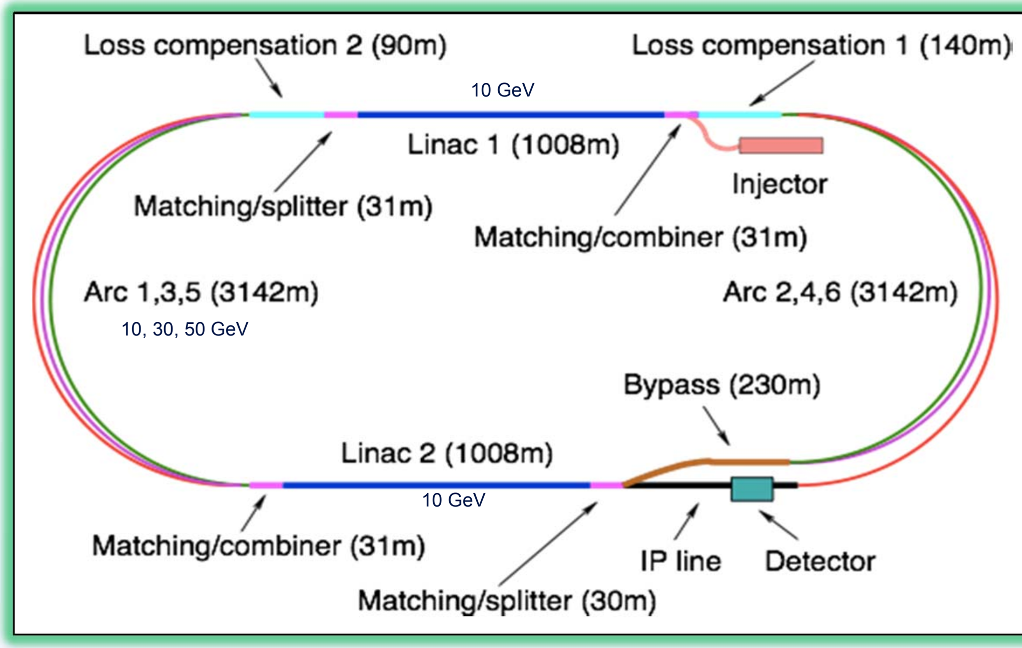
http://cern.ch/lhec

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]

$e^{\pm}$ beam options: RR and LR





■ Ring-Ring

- e-p and e-A (A=Pb, Au, …) collisions
- More “conventional” solution, like HERA, no difficulties of principle - at first sight - but constrained by existing LHC in tunnel
- polarization 40% with realistic misalignment assumptions

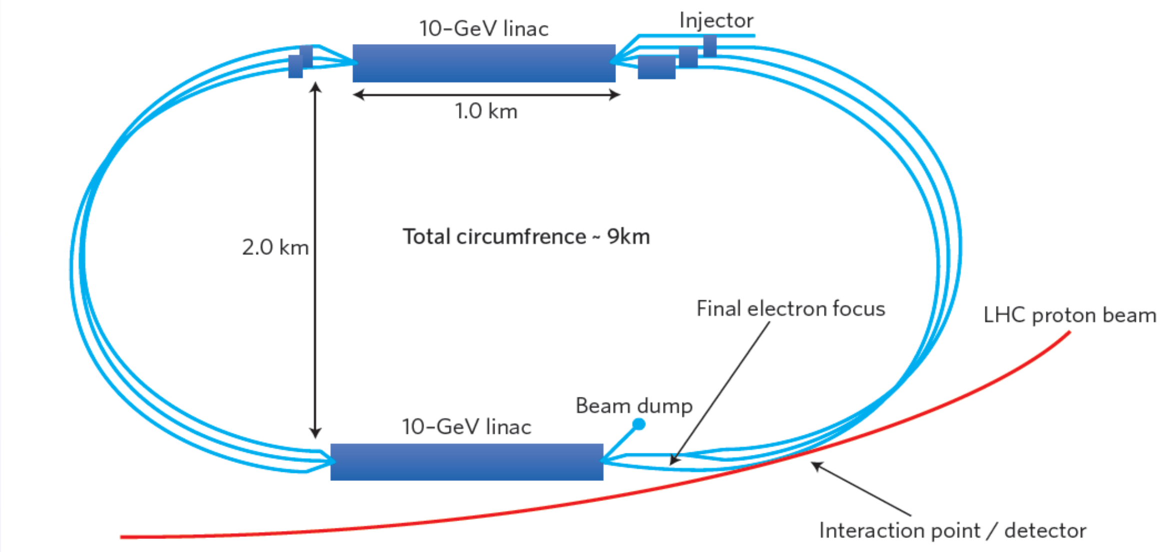
■ Linac-Ring ⬅

- e-p and e-A (A=Pb, Au, …) collisions, polarized e^- from source, somewhat less luminosity for e^+
- New collider type of this scale, Energy Recovery Linac

Baseline: Energy Recovery 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



Luminosity [$10^{33}cm^{-2}s^{-1}$]	**1-10****
Detector acceptance [deg]	**1**
Polarization [%]	**90**
IP beam sizes [µm]	**7**
Crossing angle [mrad]	**0**
e- L* [m]	**30**
Proton L* [m]	**15**
e- beta*$_{x,y}$ [m]	**0.12**
Proton beta*$_{x,y}$ [m]	**0.1**
Synchrotron power [kW]	**10**

- ep Lumi 10^{33} (10^{34} cm s^{-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 s^{-2} s^{-1} for eD (ePb)

** high luminosity achievable according to more recent estimates O. Bruening & M. Klein, *Mod. Phys. Lett. A* **28,** 1330011 (2013)

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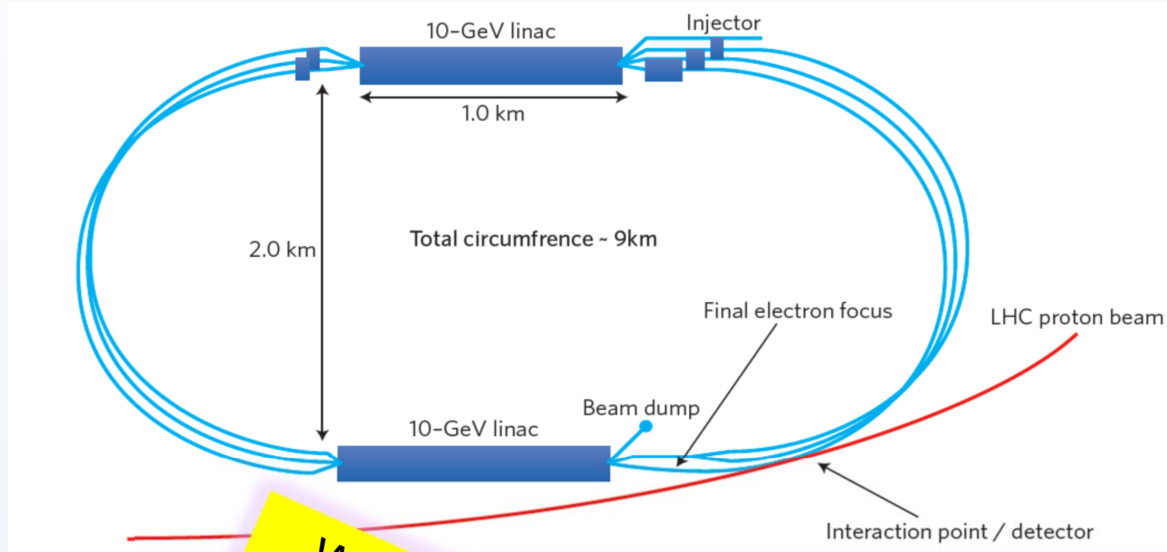

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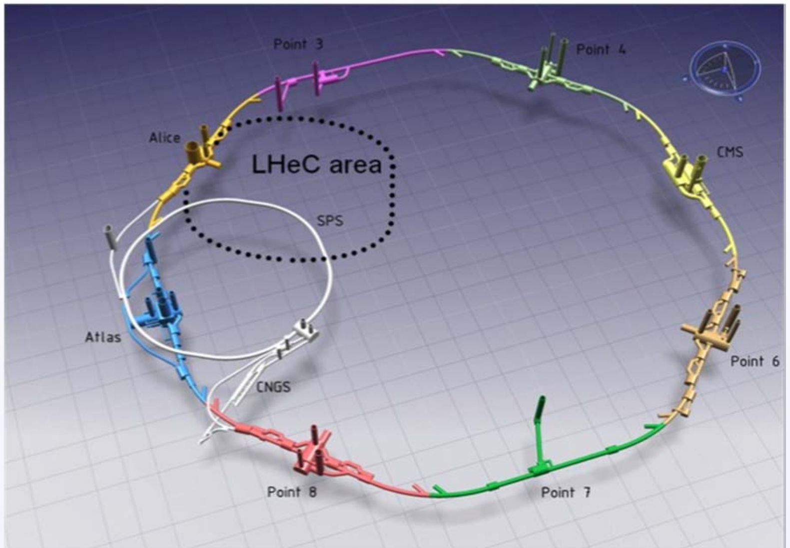
- ep Lumi … s^{-2} s^{-1})**
- 10 - 1…
- 100 fb^{-1} – …
- eD and eA collisi… …al to programme
- e-nucleon Lumi estimates ~ 1… for eD (ePb)

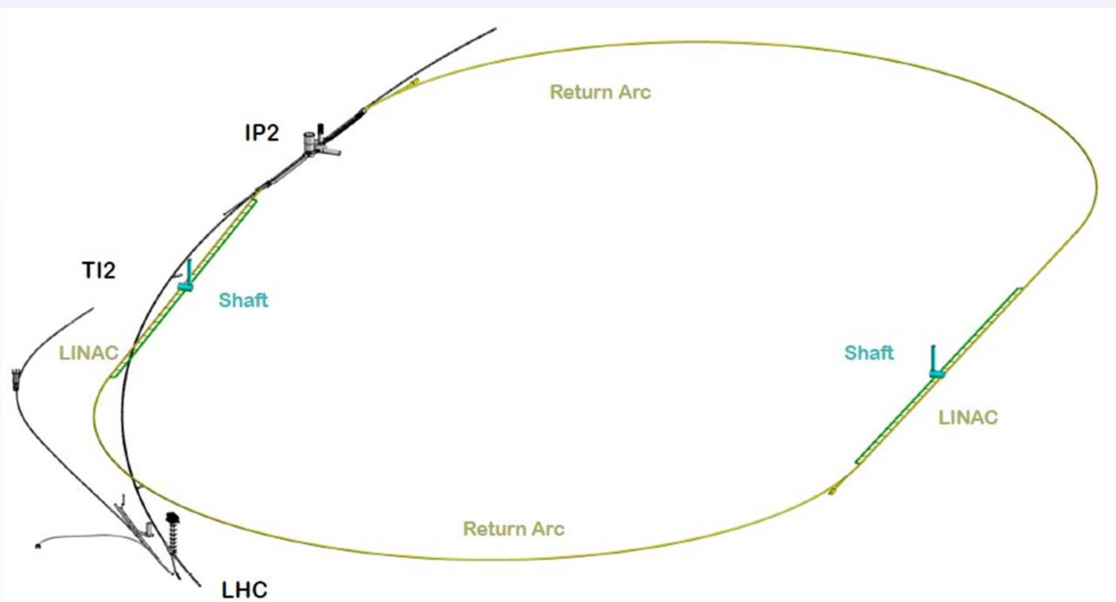
** high luminosity achievable according to mo… …ent estimates

With the Higgs discovery and measured cross section σ ~ 200fb there is a striking option to make the LHeC a clean Higgs factory with maximum luminosity

Civil Engineering Feasibility Studies

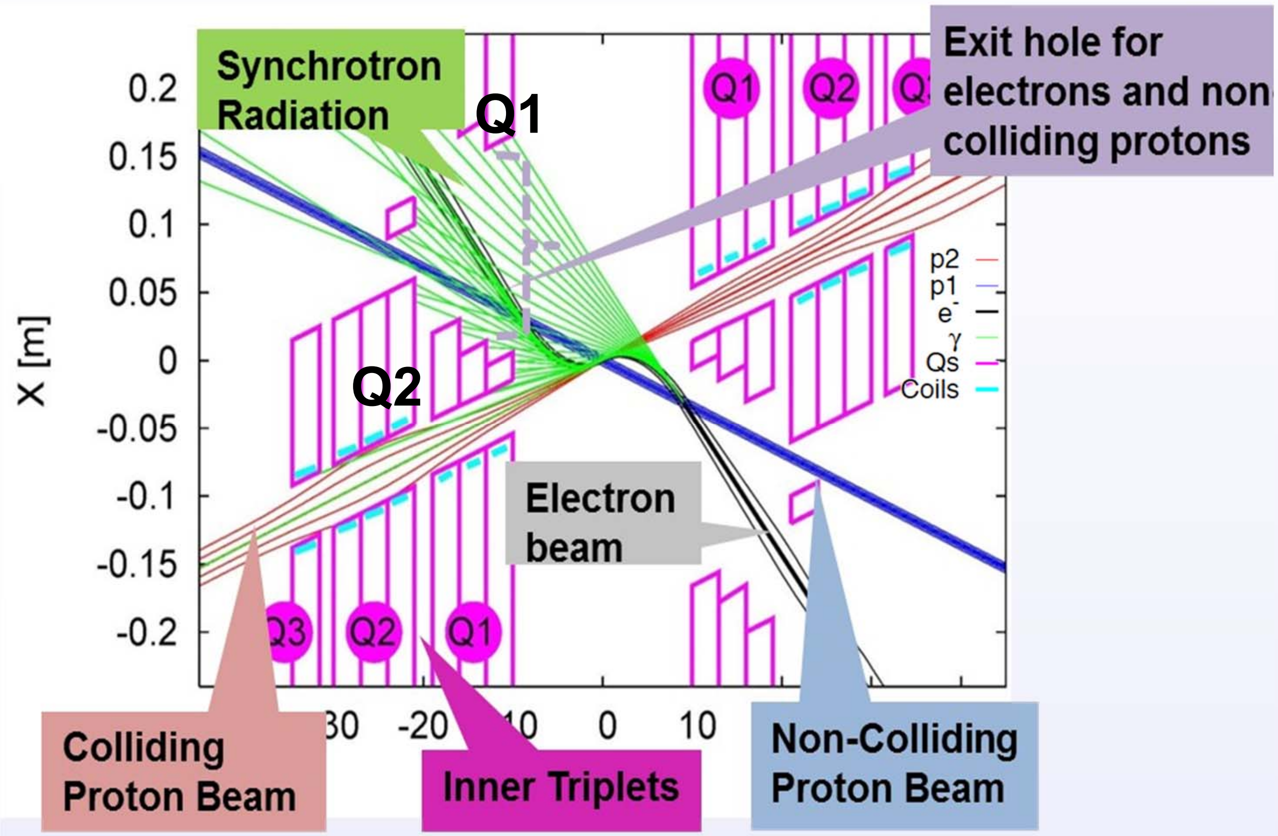


- ERL placed inside the LHC ring and tangential to IP2
- Two 1 km long LINACs; arcs have 1 km
- radius and are passed 3 times
- Whole racetrack ~9 km long (1/3 of the LHC length)



~ 960 cavities
~ 60 cryomodules per linac
~ 4500 magnets in the 2*3 arcs
~ 600 - 4 m long dipoles per arc
~ 240 - 1.2 m long quads per arc

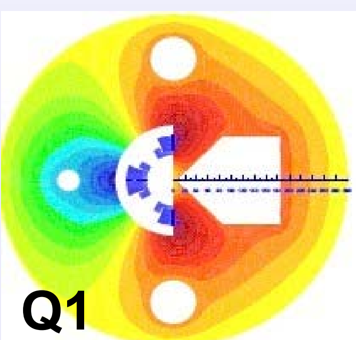
The Interaction Region

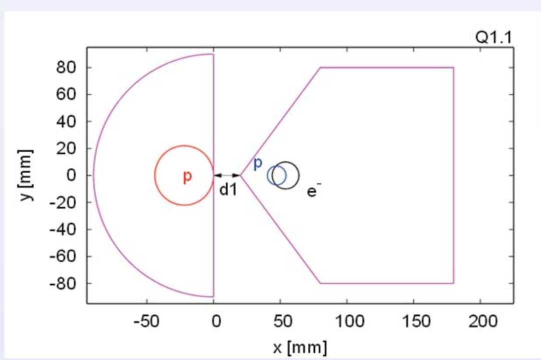


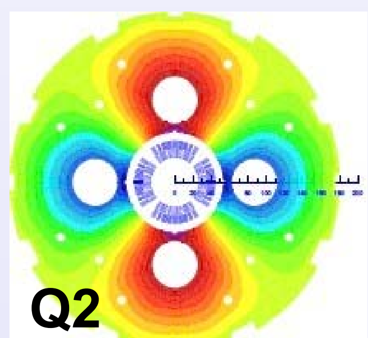
- 3 beam interaction region
- Optics compatible with LHC running and β*=0.1m
- Only the p beam colliding with the *e*- is focused
- Head-on collisions achieved via long dipole across interaction region

➔ High synchrotron radiation load

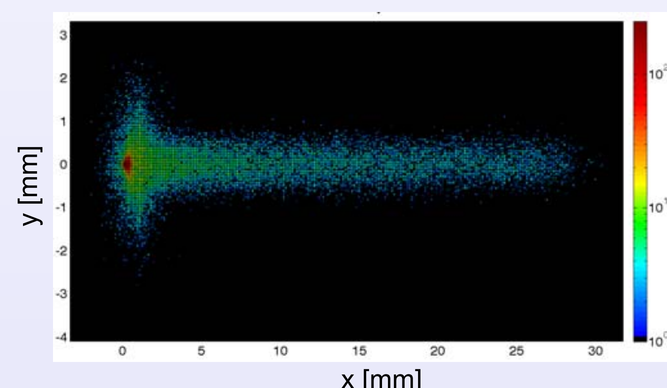
➔ Dipole in main detector



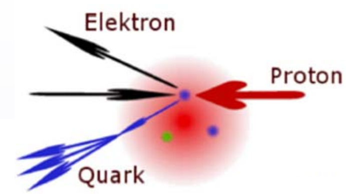


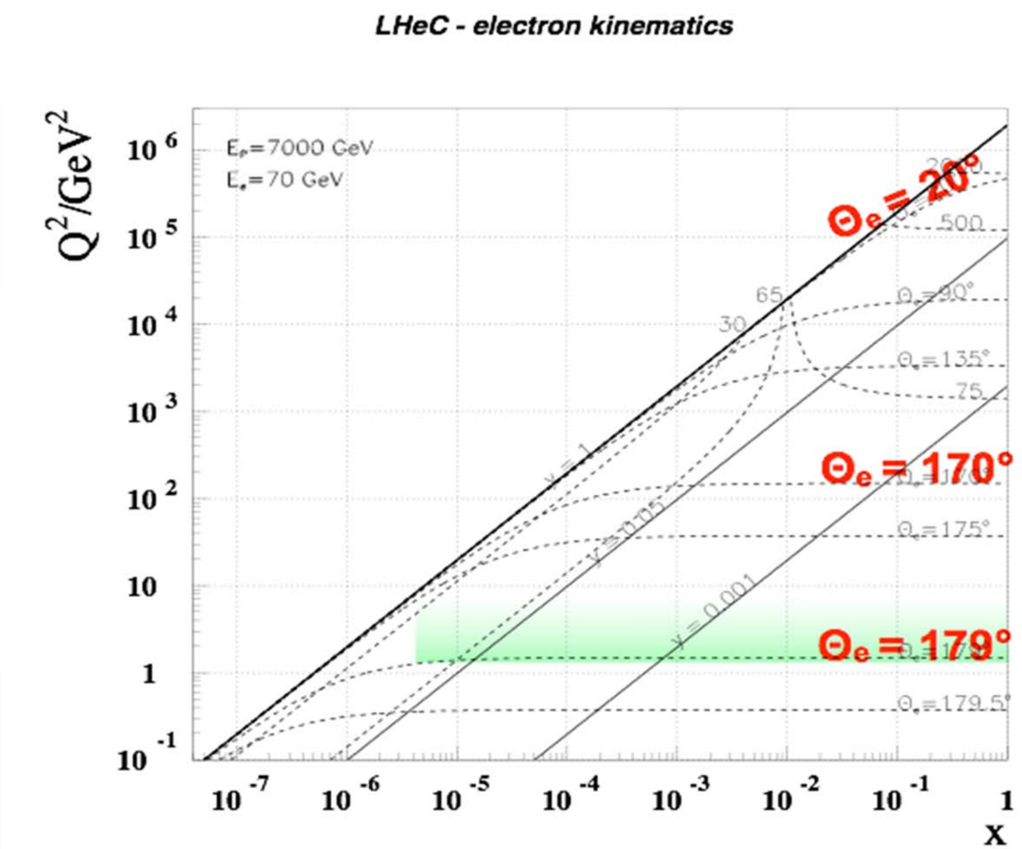


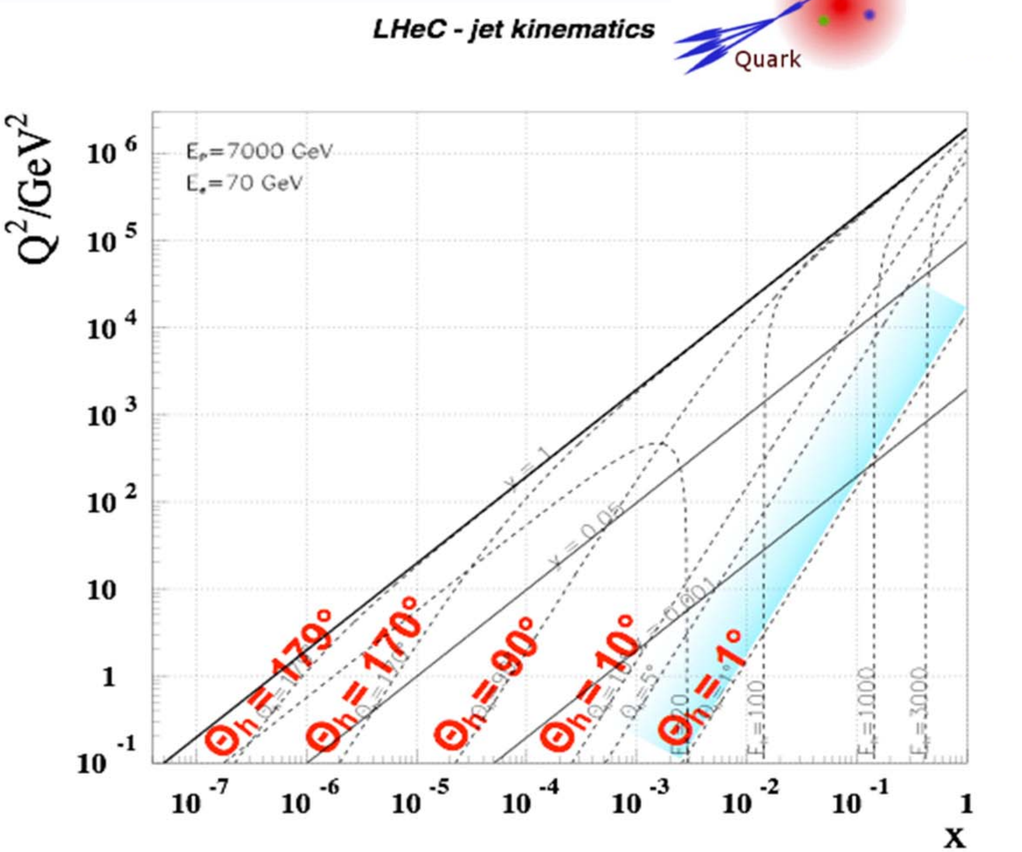
Photon Number Density at the IP



LHeC Kinematics







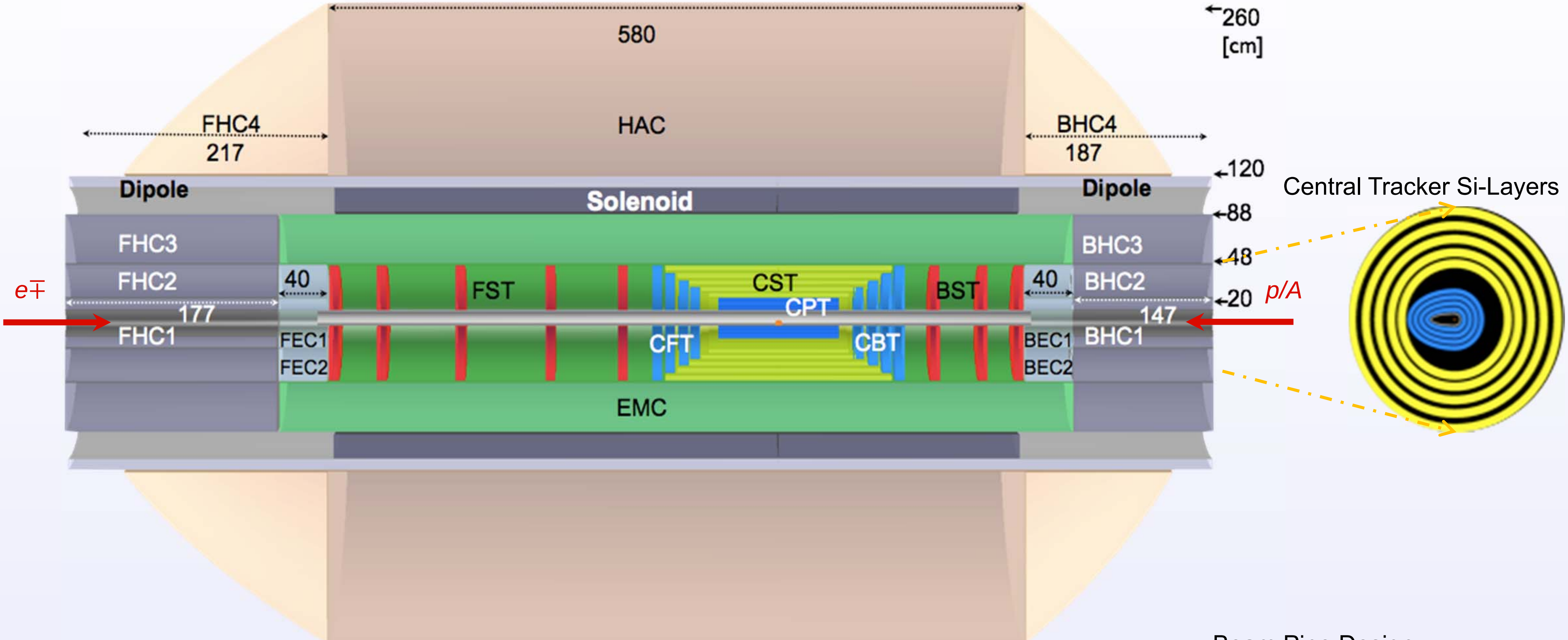
- High x and high Q^2: few TeV HFS scattered forward:

➔ Need forward calorimeter of few TeV energy range down to 10^o and below
Mandatory for charged currents where the outgoing electron is missing

- Scattered electron:

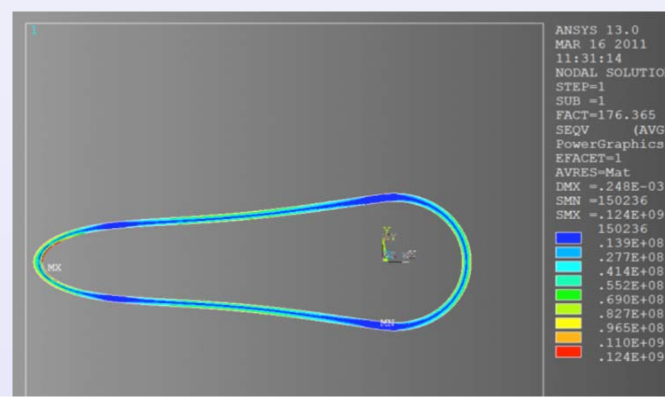
➔ Need very bwd angle acceptance for accessing the low Q^2 and high y region

Baseline Detector

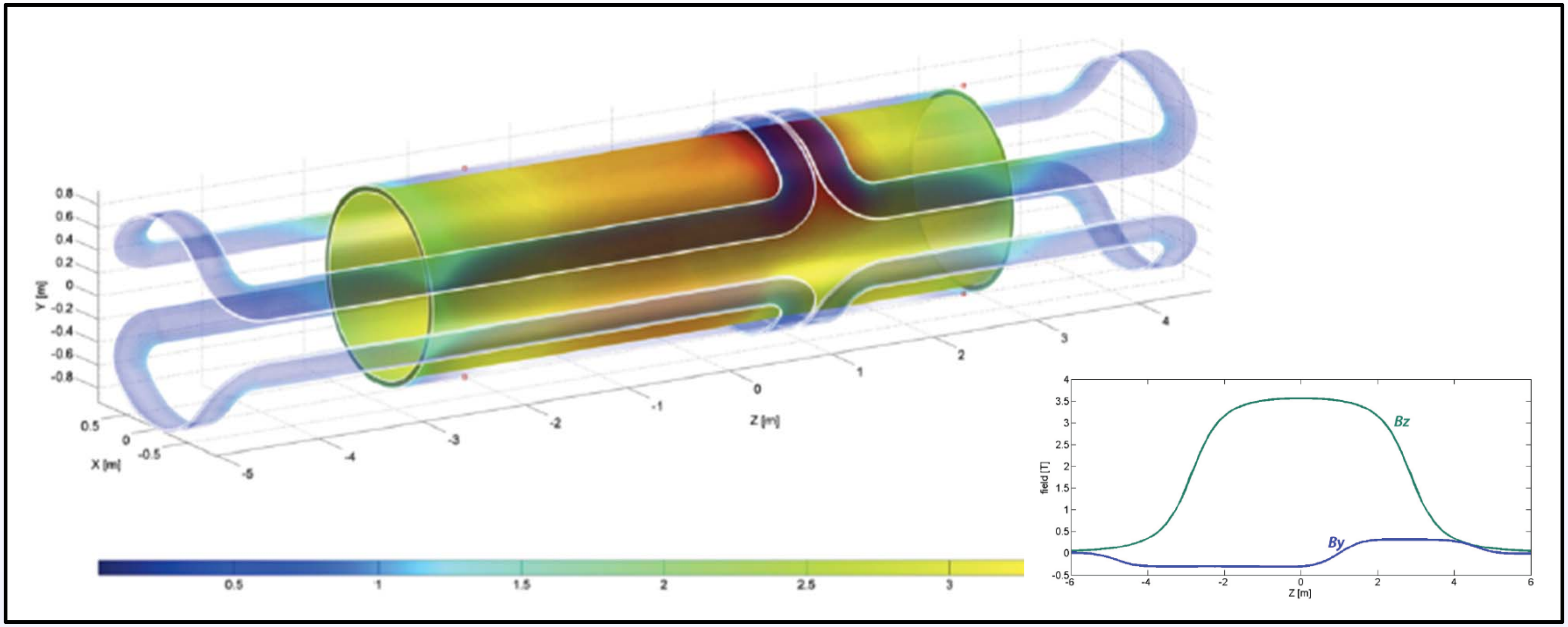


- High acceptance Silicon Tracking System ~1°
- Liquid Argon Electromagnetic Calorimeter
- Iron-Scintillator Hadronic Calorimeter
- Forward Backward Calorimeters: Si/W Si/Cu…

Beam Pipe Design



Magnets

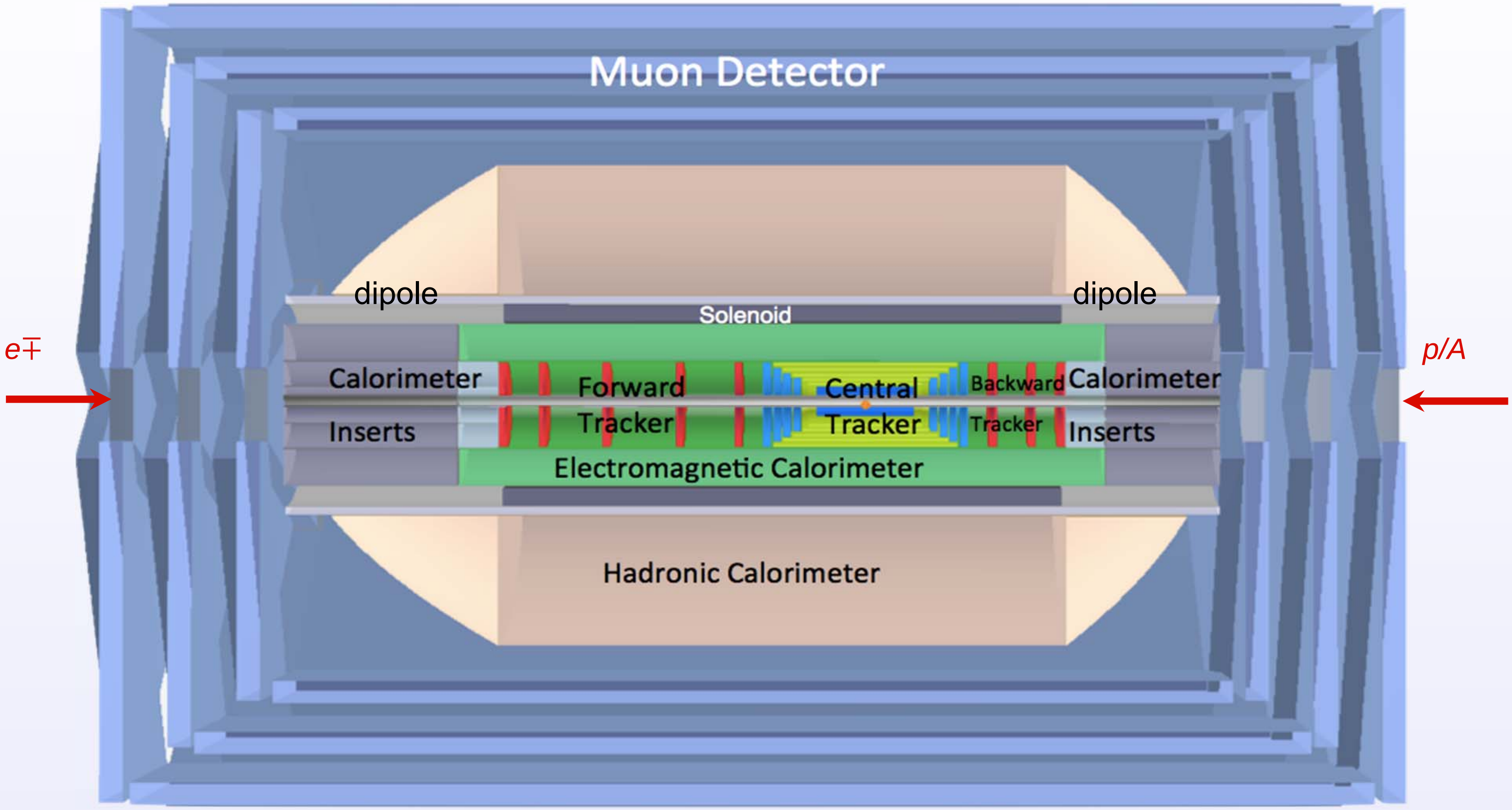


Baseline Solution:

- Solenoid (3.5 T) + dual dipole 0.3 T (Linac-Ring Option)
- Magnets (may be) embedded into EMC LAr Cryogenic System

➔ Need of study the Calorimeter Performance and impact of dead material between EMC and HAC sections; it might be possible placing the magnet system even in front of the EMC - at even lower radius at just outside of the tracking system

Baseline Detector

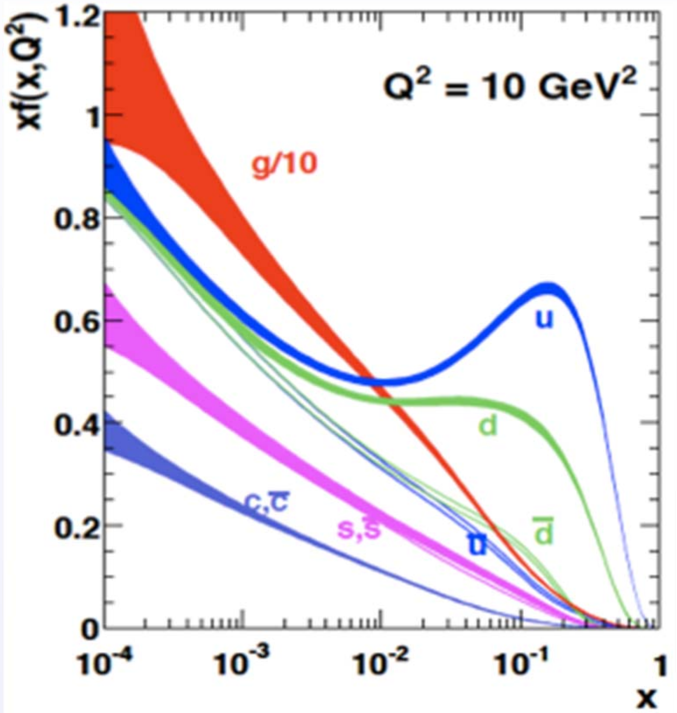


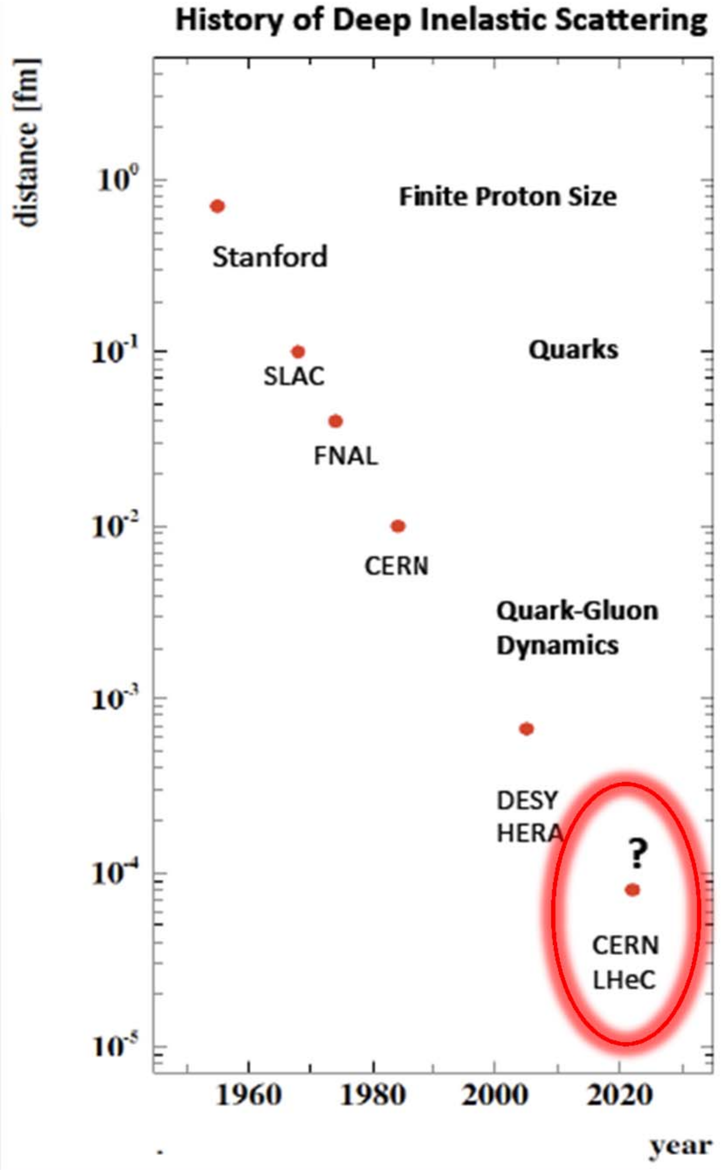
- Forward / backward asymmetry reflecting beam energies
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- e/γ taggers ZDC, proton spectrometer integral to design from outset system providing tagging, no independent momentum measurement

Physics Highlights

Deep Inelastic Scattering

- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...



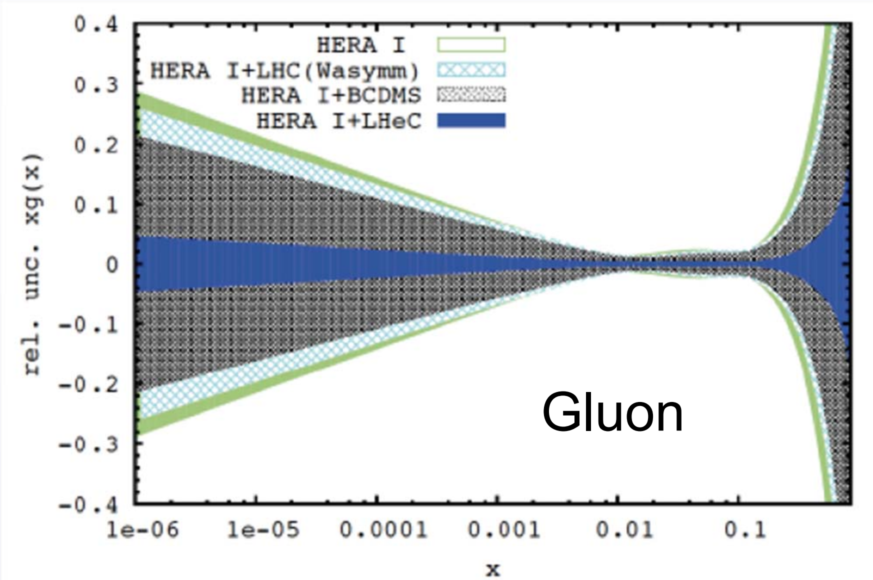


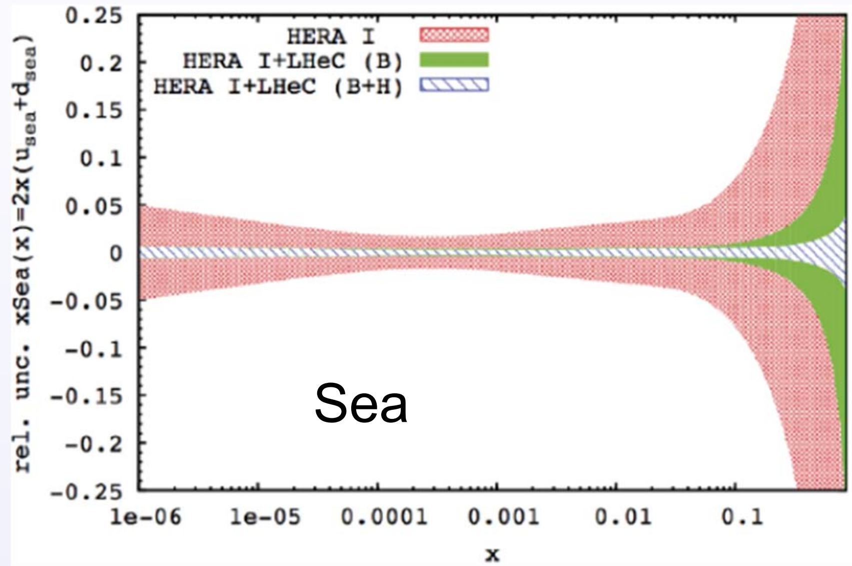
Still Many open questions:

- There was no electron ion program
- Move to even lower x
- Tests of saturations
- The gluon is poorly known at low and high x
- There is no precision measurement of α_s
- Thankfully half of that machine has already been built in Geneva

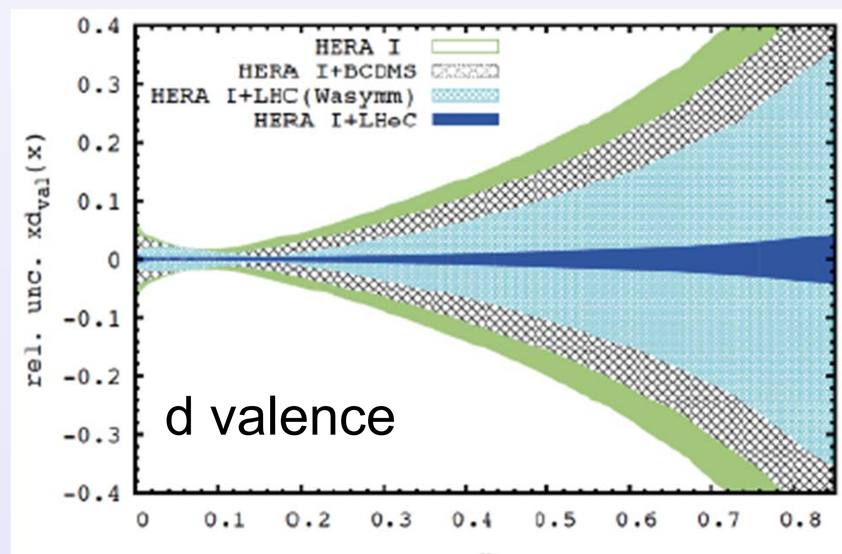
PDF Constraints at LHeC

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

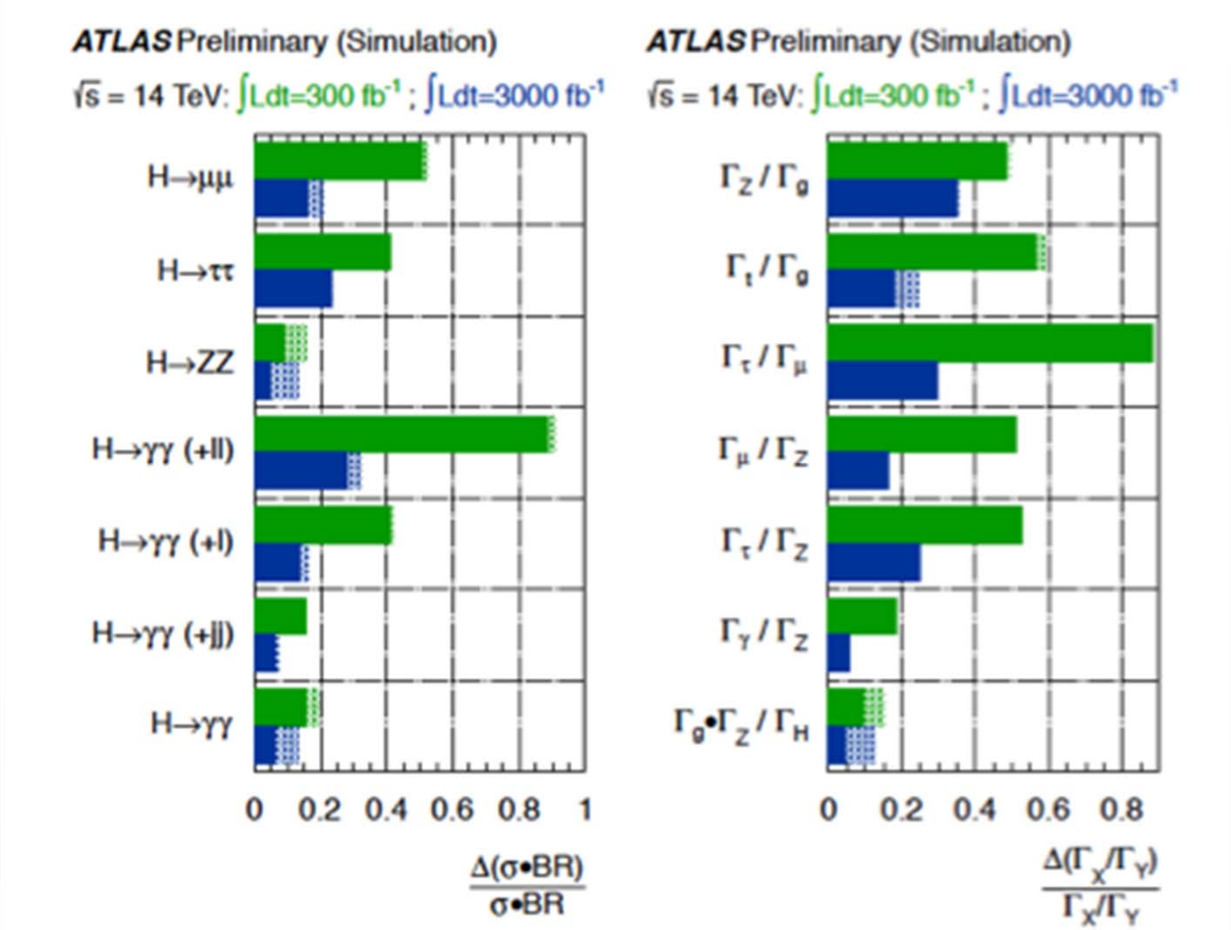


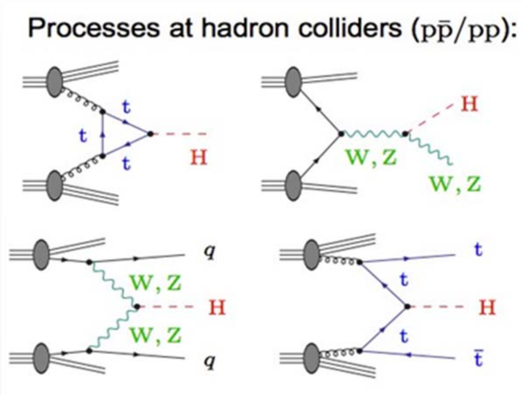


- impact at low x (kinematic range) and high x (luminosity)
- … precise light quark vector, axial couplings, weak mixing angle
- … full flavor decomposition



PDFs uncertainties and the Higgs @ LHC

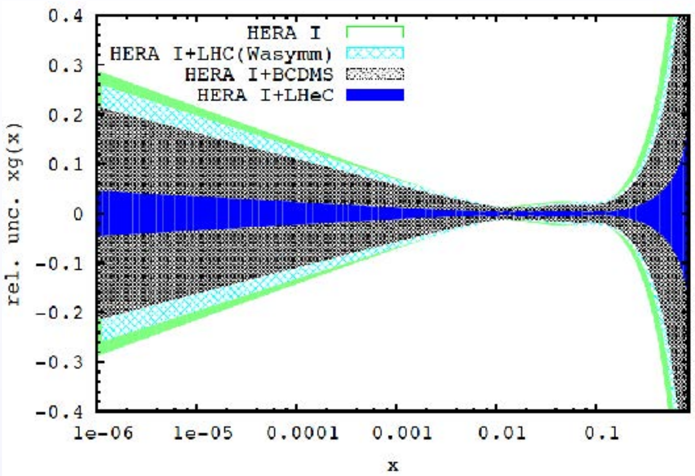


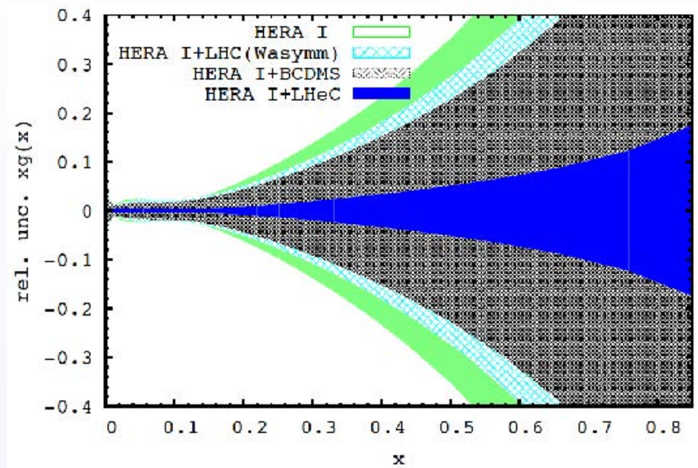


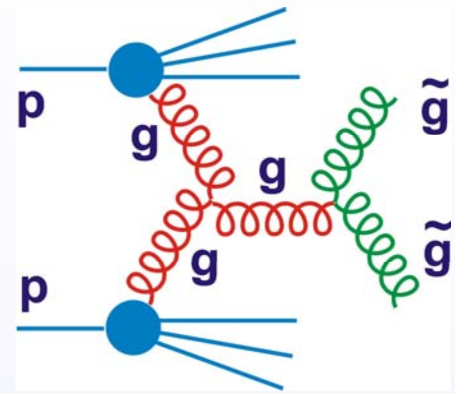
Dashed regions: scale & PDF contributions

- Many of the channels at LHC will be limited by PDF uncertainties
- With the LHeC, the huge improvements in knowledge of PDFs, precision of α_s will remove this, allowing the full exploitation of the LHC data for Higgs physics

Relevance of the high x region

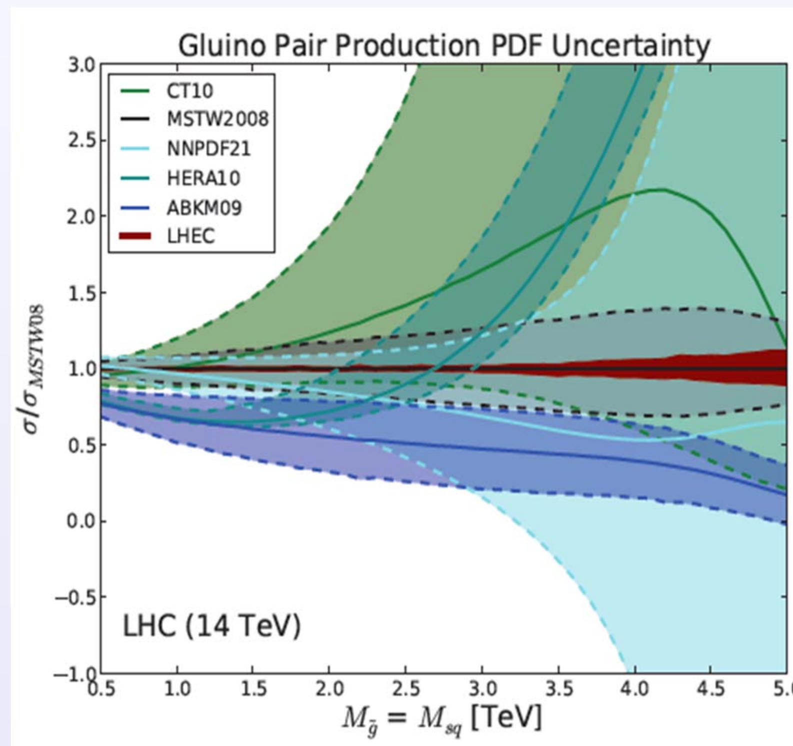




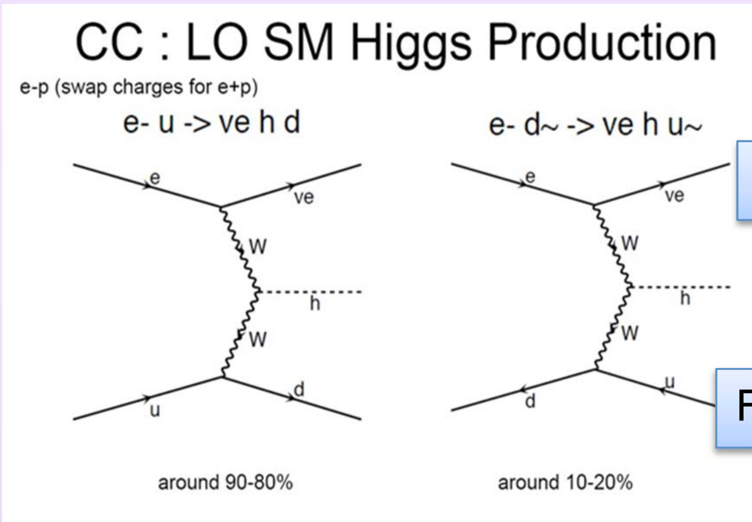


e.g. High Mass 2 Gluino Production at the LHC

- Signature is excess at 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 …
- The HL-LHC (search) programme requires a more precise understanding of QCD, (strong coupling, gluon, valence, factorisation, saturation, diffraction..) which the LHeC provides



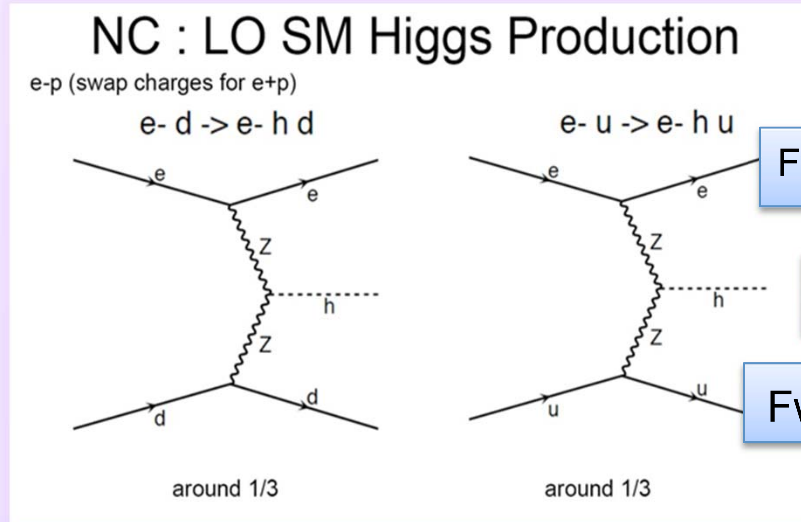
SM Higgs production in ep (i)



E_T^{miss}

WWH

Fwd jet



Fwd Electron

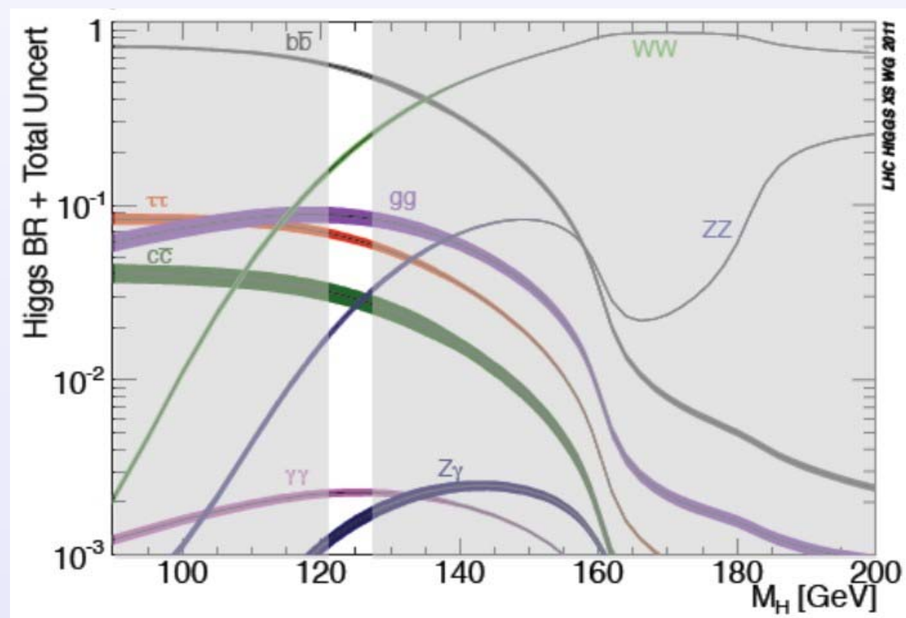
ZZH

Fwd jet

LHeC: E_e=60 GeV : √s= 1.3 TeV

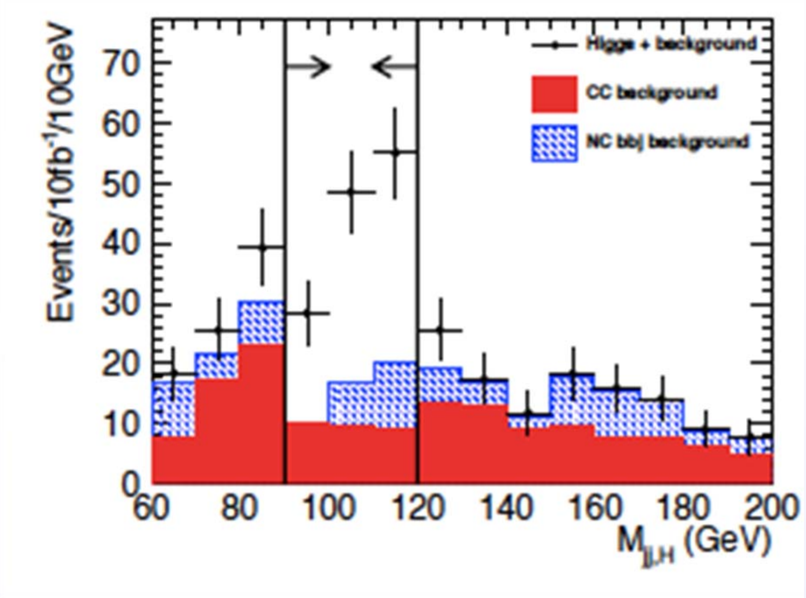
M_H=125 GeV

	CC e^-p	CC e^+p	NC e^-p
cross section [fb]	109	58	20
polarised cross section [fb] Pol. = 80%	**196**	N.A.	25



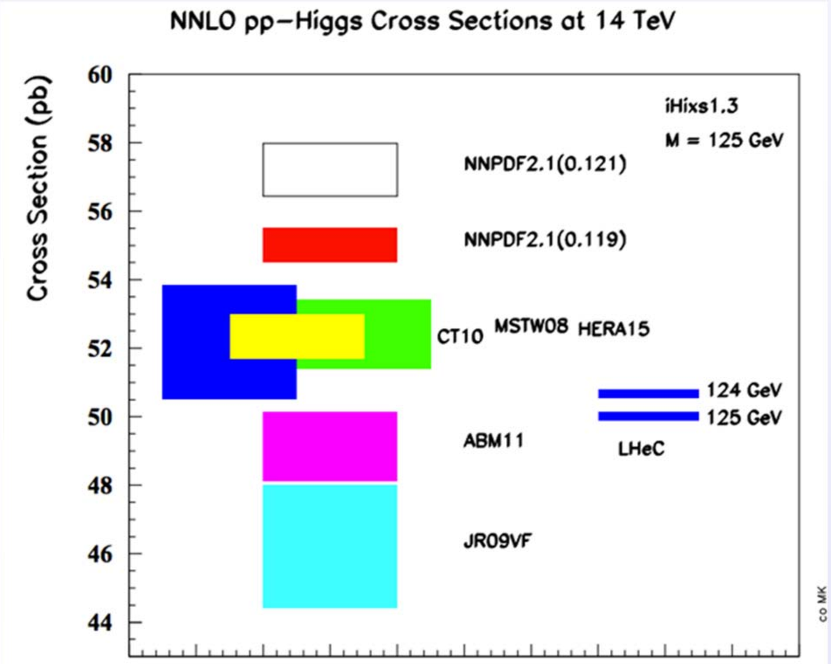
SM Higgs production in ep (ii)

- Study of $H \rightarrow b\bar{b}$ in generic simulated LHC detector (CDR:E_e=150 GeV; New E_e=60 GeV)
- Di-jet invariant mass after all selection →
- 90% lepton polarisation enhances signal by factor 1.9
- with a luminosity of 10^{34} luminosity, 10 times more data:
- ~5000 events @ Ee = 60 GeV $H \rightarrow b\bar{b}$ coupling to ~ 1%.



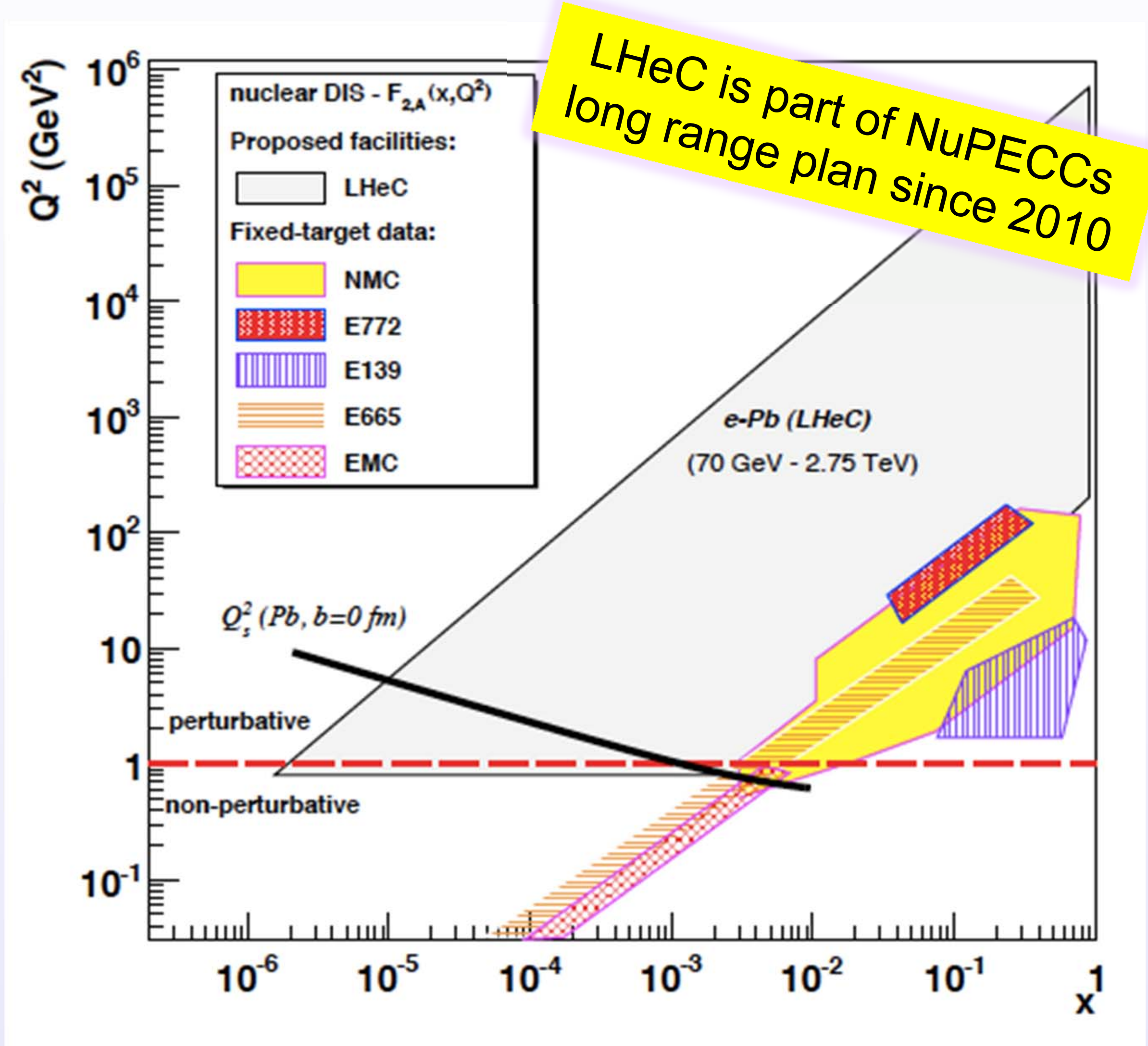
	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
H → bb signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1

- Precision from LHeC can add a very significant constraint on the mass of the Higgs →



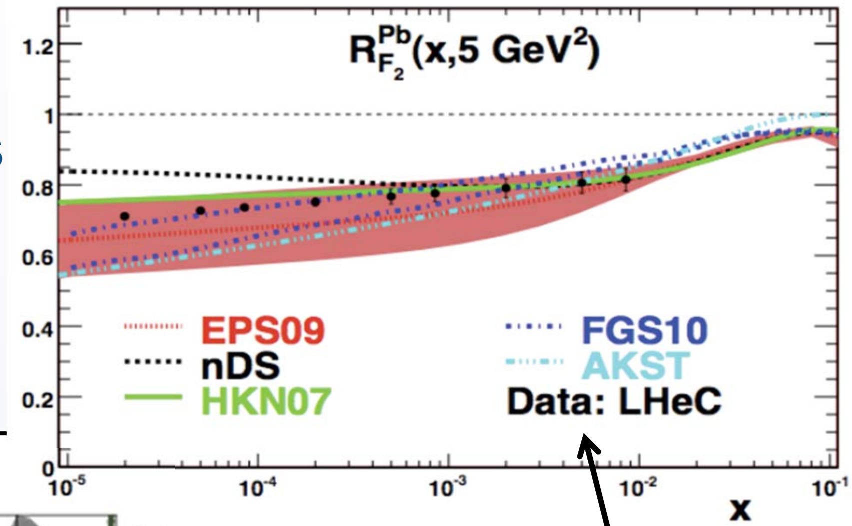
LHeC as an Electron-ion Collider

- Four orders of magnitude increase in kinematic range over previous DIS experiments.
- Revolutionise our view of the partonic structure of nuclear matter.
- Study interactions of densely packed, but weakly coupled, partons
- Ultra-clean probe of passage of `struck' partons through cold nuclear matter

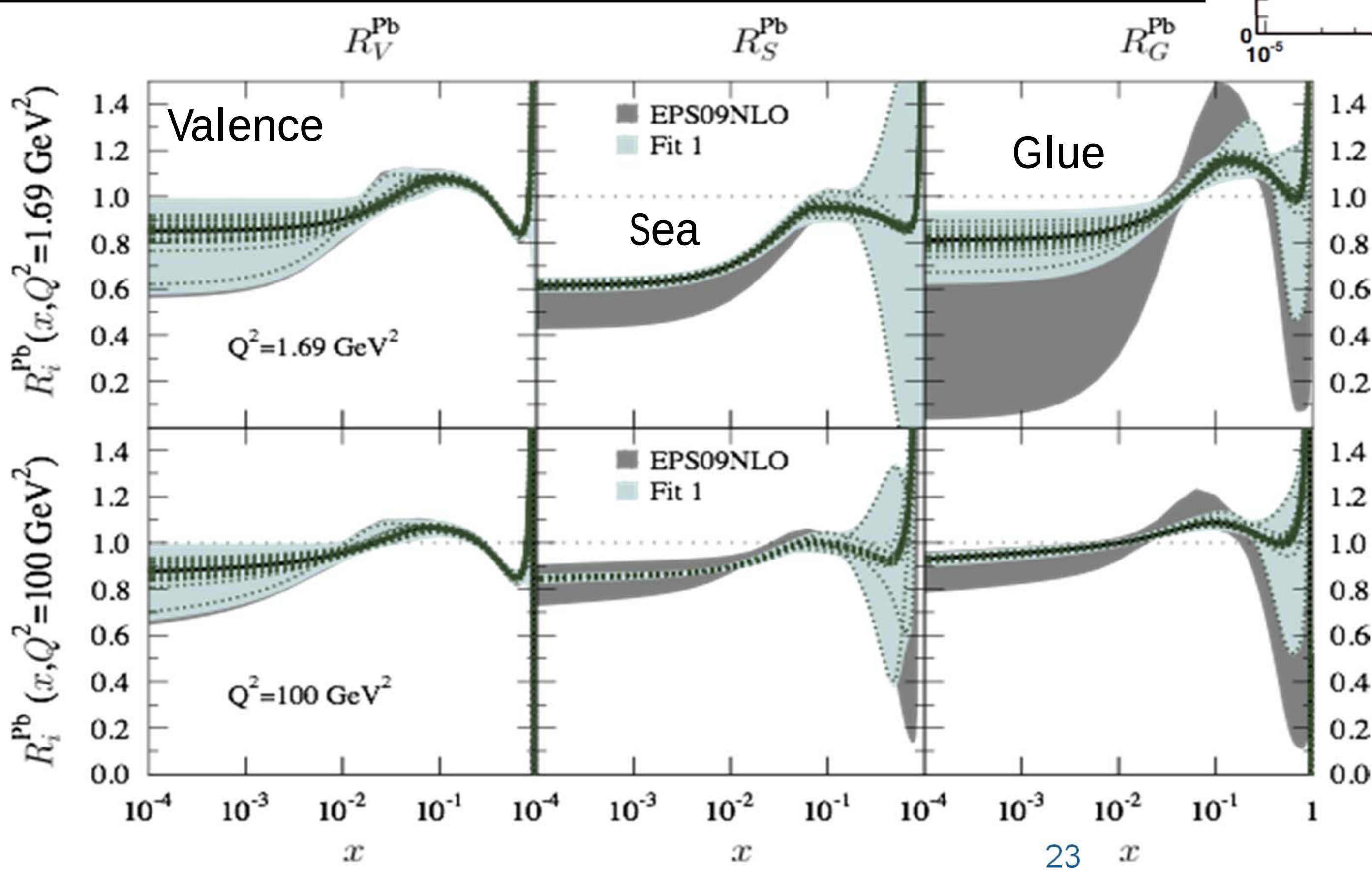


Impact of eA F_2 LHeC Data

- Simulated LHeC ePb F_2 measurement has huge impact on uncertainties and allows to establish a genuine nPDF basis in a region never measured before
- 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

CERN Mandate

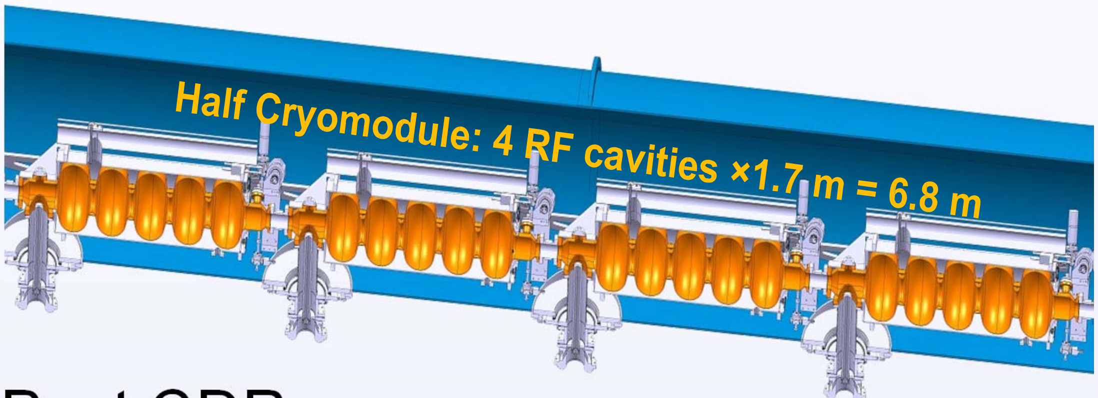
Studies and prototyping of key technical components:

- Superconducting RF system for CW operation in an ERL
- SC Magnet development of the insertion regions of the LHeC with 3 beams
- Studies related to the experimental beam pipes with large beam acceptance
- The design and specification of an ERL test facility for the LHeC
- The finalization of the ERL design for the LHeC (optics design, beam dynamics studies and identification of potential performance limitations)

(S.Bertolucci at Chavannes workshop 6/12 based on CERN directorate's decision to include LHeC in the Medium Term Plan)

Linac Design

- In the **CDR**: 8 cavities per 14 m long module
  Choice between O(720 MHz) and O(1.3 GHz)
  ~ 720 MHz had been baseline for CDR



Post CDR:

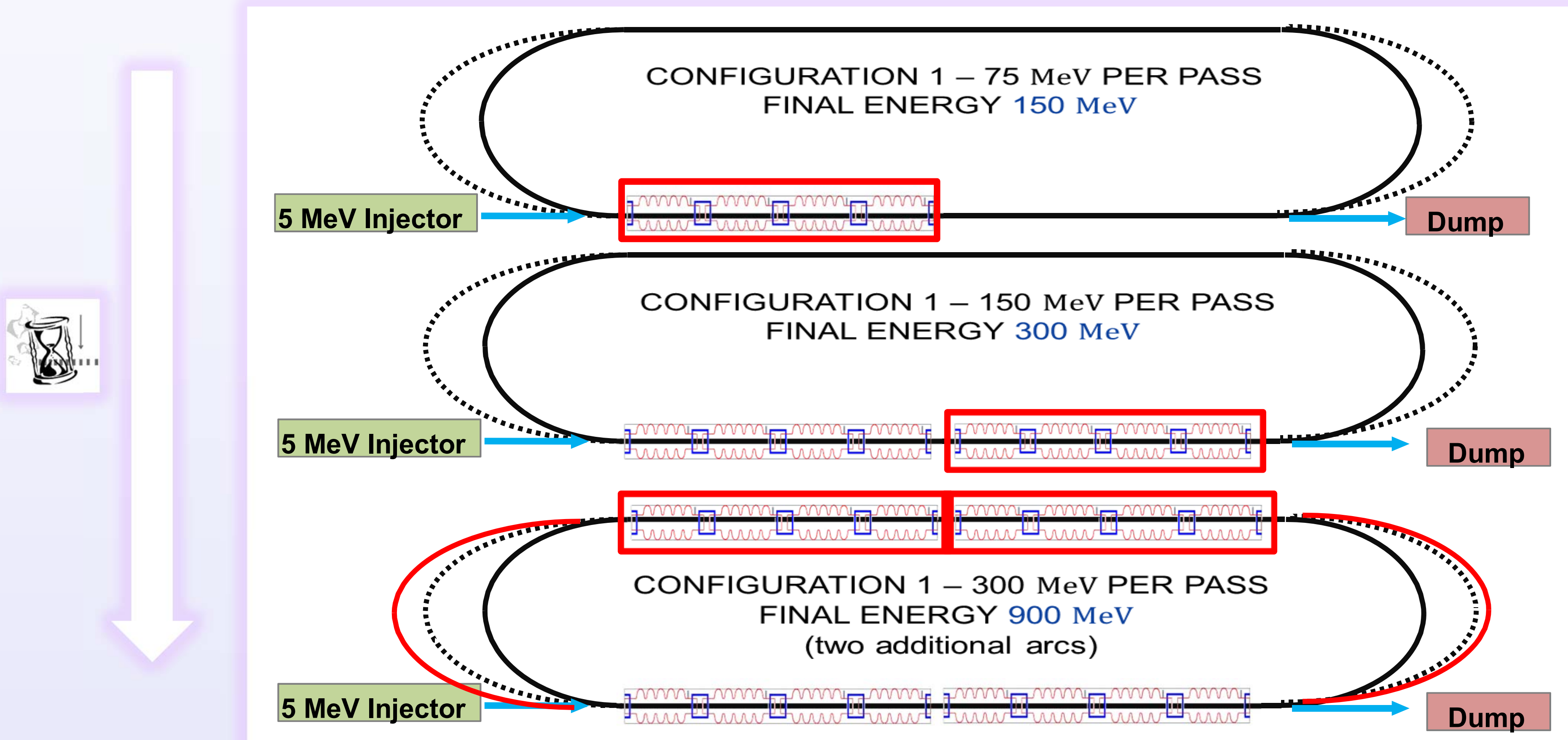
→ **FINAL CHOICE: 801.58 MHz**

- Frequency of a future LHC harmonic system
- It is (to less than a few kHz) equal to the existing SPS Landau system

LOWER FREQUENCY	
ADVANTAGES	**DISADVANTAGES**
Reduced losses	Somewhat higher RF cost Might be offset by reduced cryo cost or improved performance
Less required cooling power	
Reduced wakefield	

CERN ERL Test Facility

- **100-MeV** scale energy recovery demonstration of a recirculating superconducting linear accelerator
- Built-in flexibility
- **Roadmap up to 1-GeV** scale energy recovery demonstration of a recirculating superconducting linear accelerator



Summary and Outlook

Status

- The LHeC appears feasible and can be realized in parallel with HL-LHC
- The LHeC complements ideally the LHC pp and heavy ion program and provides fundamental input to reduce uncertainties
- A Conceptual Design Report and update documents available**
- Infrastructure investment with potential exploitation beyond LHeC
- Still significant room for optimization in design including a higher luminosity option

Plans

- Further develop and demonstrate Machine, Interaction Region, Detector and Detector Simulation
- Physics
- An ERL Test Facility at CERN

** http://cern.ch/lhec