A detector for future DIS at the energy frontier

ICHEP 2024, Prague

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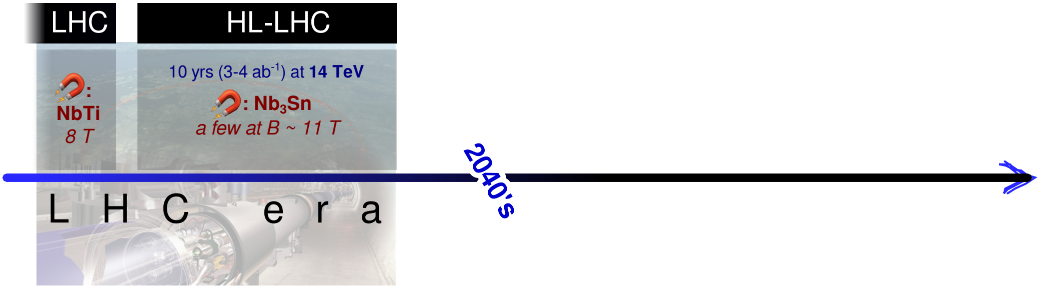
on behalf of the ep/eA@CERN Study Group

17-24 Jul 2024

Introduction – Future accelerators @ CERN



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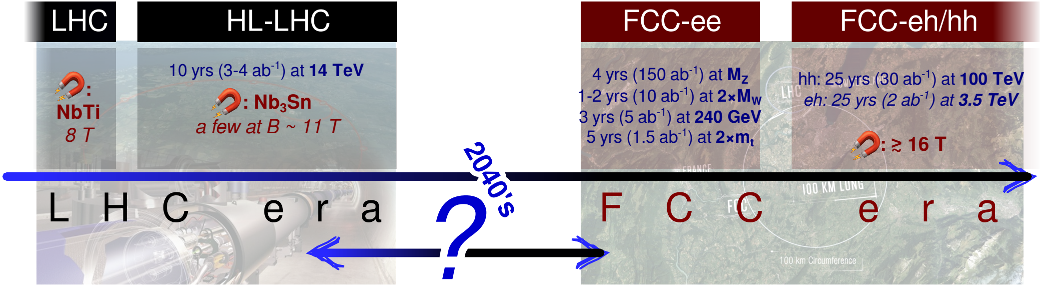
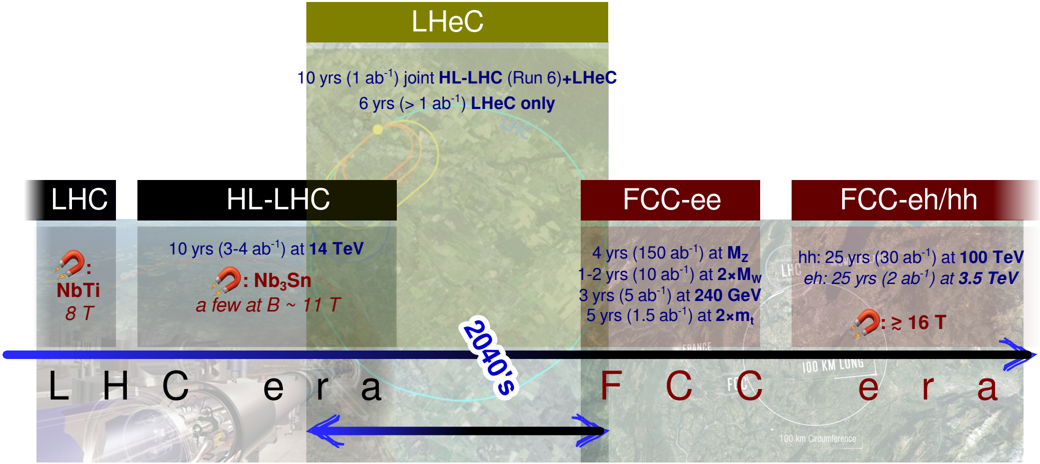
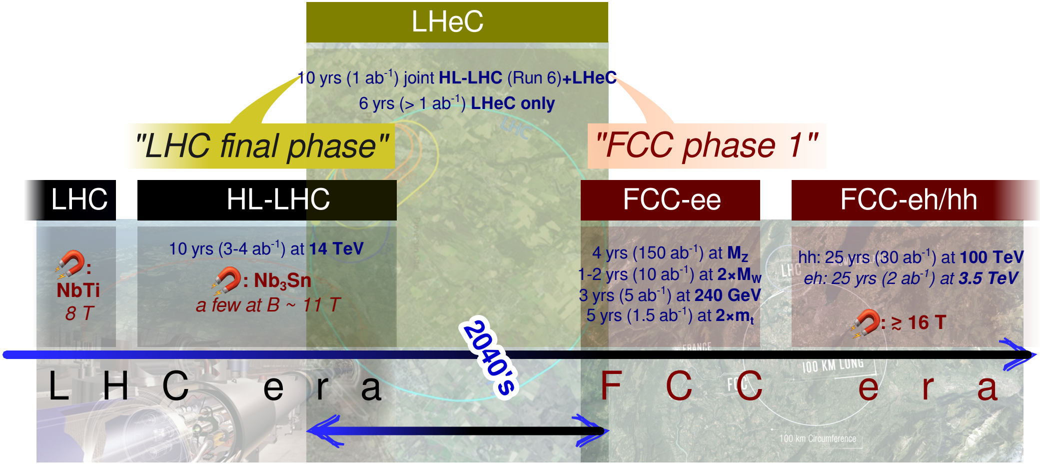


Introduction – Future accelerators @ CERN: LHeC?



Introduction – Future accelerators @ CERN: LHeC!



Introduction – Future accelerators @ CERN: LHeC: an impactful bridge between major colliders

ultimate upgrade of LHC physics reach

fast-track to new/impactful opportunities
at colliders for attractive SM/BSM physics

LHeC

10 yrs (1 ab^{-1}) joint **HL-LHC** (Run 6)**+LHeC**
6 yrs (> 1 ab^{-1}) **LHeC only**

"LHC final phase"

"FCC phase 1"

LHC

: **NbTi**
8 T

HL-LHC

10 yrs (3-4 ab^{-1}) at **14 TeV**
: **Nb_3Sn**
a few at B ~ 11 T

FCC-ee

4 yrs (150 ab^{-1}) at $\mathbf{M_Z}$
1-2 yrs (10 ab^{-1}) at $\mathbf{2\times M_W}$
3 yrs (5 ab^{-1}) at **240 GeV**
5 yrs (1.5 ab^{-1}) at $\mathbf{2\times m_t}$

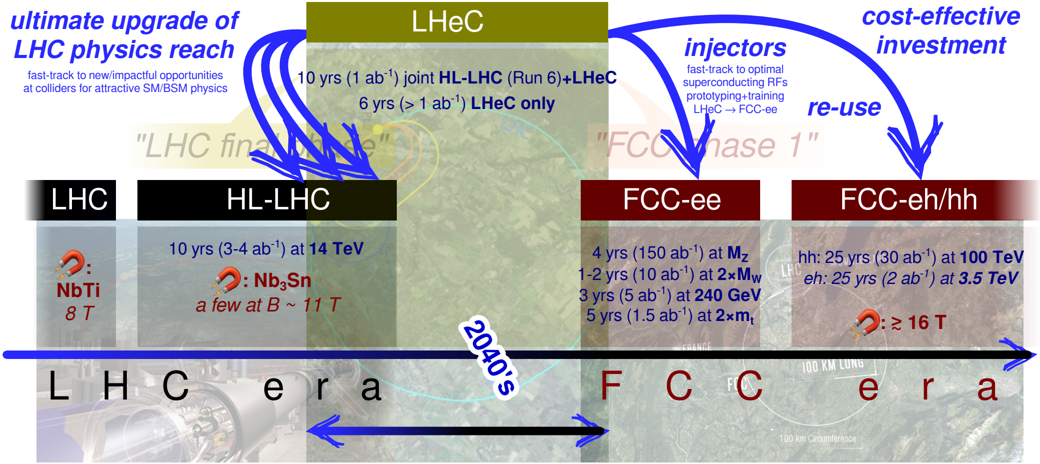
FCC-eh/hh

hh: 25 yrs (30 ab^{-1}) at **100 TeV**
*eh: 25 yrs (2 ab^{-1}) at **3.5 TeV***
: **≳ 16 T**

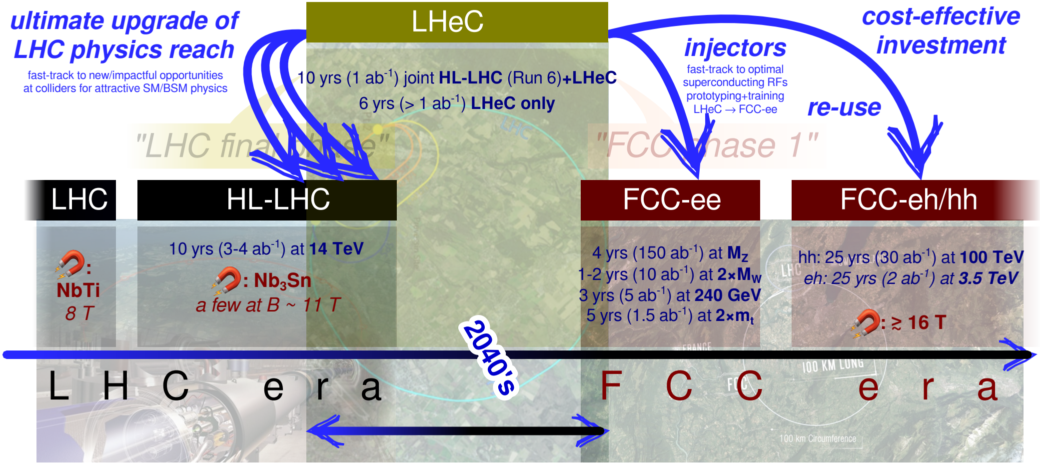
L H C era — **2040's** — F C C era

100 KM LONG
100 km Circumference

Introduction – Future accelerators @ CERN: LHeC: an impactful bridge between major colliders

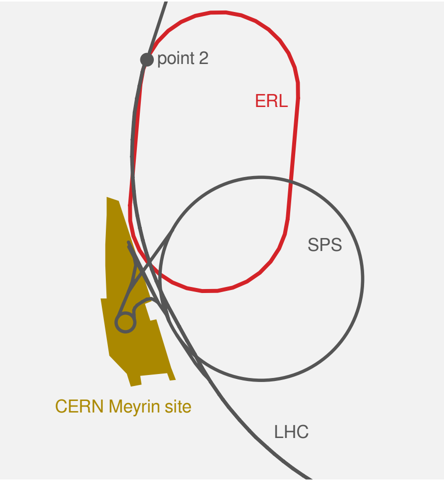


Introduction – Future accelerators @ CERN: LHeC: an impactful bridge between major colliders



LHeC as a potential link between last phase of the HL-LHC and first phase of the FCC eras (upon FCC approval)

LHeC – basic accelerator parameters



"Physicist information":
50 GeV *(electron beam)* $\times$ 7 TeV *(HL-LHC proton beam)*
$\longmapsto \sqrt{s} \simeq$ **1.2 TeV ep collider**
(HERA@DESY: 27.6 GeV $\times$ 920 GeV $\mapsto \sqrt{s} \simeq$ 320 GeV ep collider)
(FCC-eh: 60 GeV $\times$ 100 TeV $\mapsto \sqrt{s} \simeq$ 3.46 TeV ep collider)

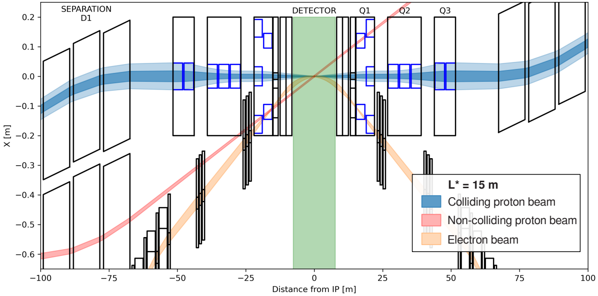
"Beam physicist information":
Electron injection through a 3-pass **energy recovery linac** (ERL) *à la* PERLE/bERLinPro ; operational parameters:

- 0.5nC bunches @ 24.95ns spacing, 20mA e^- current
- transm. normalised emittance $\epsilon \sim 30\mu$m
- 801.6MHz RF frequency, LINAC acceleration gradient @ 20MV/m
- $\lesssim$ 150MW constraint on power consumption

Technical documentation: LHeC CDR published **in 2012** [arXiv:1206.2913 [physics.acc-ph], J.Phys.G 39 (2012) 075001] , updated **in 2020** with HL-LHC technologies input [arXiv:2007.14491 [hep-ex], J.Phys.G 48 (2021) 11, 110501]

(talk@ICHEP: *The LHeC and FCC-eh experimental program* (J. d'Hondt) – 18.07, Club D)

LHeC beam parameters – concurrent ep/pp HL-LHC running



$x - s$ projection of the magnet layout for the LHeC interaction region for $L^* = 15$ m (Courtesy K. André)

"3-beam solution"

In electron-proton mode, in the **same phase space**,

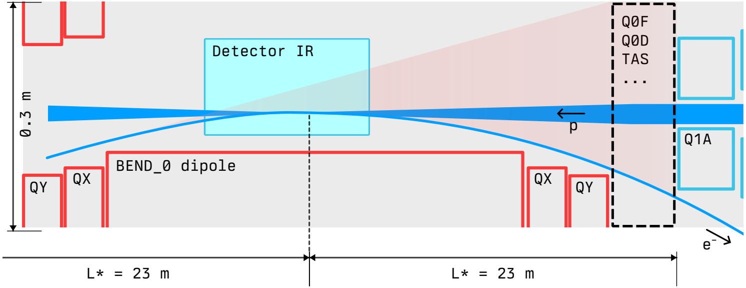
- 1 colliding **electron beam**
- 1 colliding **proton beam** (**B1**)
- 1 non-colliding proton beam (**B2**) with relaxed, high-β^* optics maximising separation in ep interaction region

Multi-parameters optimisation of interaction region

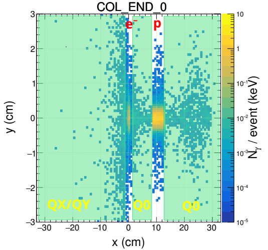
- **design luminosity** of 10^{34} cm^{-2}s^{-1} (HERA: $\mathcal{O}(10^{31}$ cm^{-2}s^{-1})) $\rightsquigarrow$ yearly $\sim$ 100fb^{-1}, **1ab^{-1} in total**
- 2 potential running conditions: (poster@ICHEP: *The LHeC: Basic Concepts and Layout of the Machine* (**K. André**, LF, B. Holzer, T. von Witzleben) – 19.07, Foyer Floor 2)
  - "standard HL-LHC" running mode: all 4 IPs in pp/pA/AA
  - concurrent running: **1 IP in ep, 3 IPs in pp**

Large fluxes of **synchrotron light** expected from steering of electron beam in the ep interaction region

- can potentially lead to premature aging of **subdetectors components**, as well as **all optical elements** downstream the e^- beam path



Schematic view of the electron and proton beamline elements in the vicinity of the ep interaction region.



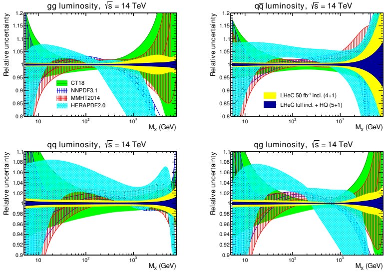
Study of effect of upstream shielding on synchrotron radiation flux at the end of the interaction region

- lately, major progresses on synchrotron radiation-gnostic lattice optimisation
  - optimisation driven by **critical energy** $E_c \sim \gamma^3/\rho$ and **radiated synchrotron power** $P_{\text{synch}} \sim \gamma^2/\rho^2$
  - beamline elements optimisation through BDSIM (Geant4+beamline simulation)
  - study of potential IR shielding to minimise radiation at optical elements downstream to the electron beam (TAS/proton quadrupoles/...)
  - direct handle to (horizontal) beam size, free drift length L^*, ...

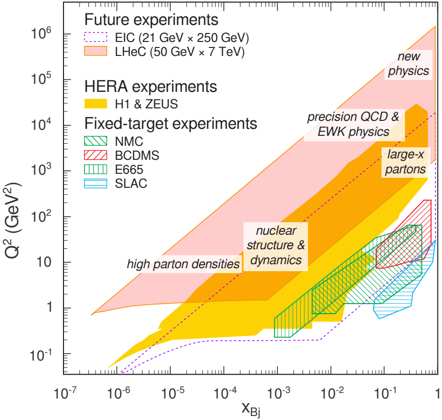
LHeC – kinematics range & detector constraints

Large coverage of the x_{Bj}/Q^2 phase space, enables precision QCD/QED physics measurements

- orders of magnitude improvement for PDFs @ LHeC
  - feedback loop for HL-LHC physics reach extension



Two-parton mass dependent parton luminosity uncertainty (J.Phys.G 48 (2021) 11, 110501)



(talk@ICHEP: *Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh* (C. Gwenlan) – 18.07, N. Hall)

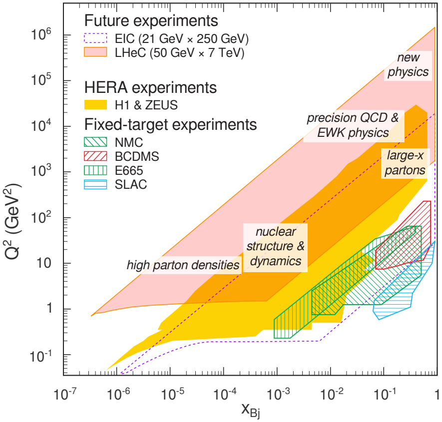
- main challenge: good detector **hermiticity** (sensitivity to small-Q^2 $\leftrightarrow$ high-θ_e reach)

LHeC – kinematics range & detector constraints

Large coverage of the x_{Bj}/Q^2 phase space, enables precision QCD/QED physics measurements

Flagship measurements provide **constraints to detector design**:

- inclusive DIS measurements
  - NC: exploiting e/h final states asymmetry (requires fine ECAL segmentation: e.g. LAr + rad-hard hadron calorimeter close to beam pipe)
  - CC: requires calorimeter hermiticity + good hadron resolution (e.g. plastic HCAL with good neutron absorption)
- possible *"Higgs factory"* with forward jets configuration
  - excellent flavour tagging in forward direction with low-material budget detectors (e.g. HV-CMOS)
  - paving stone to EWK physics at FCC-ee



LHeC – kinematics range & detector constraints

Large coverage of the x_{Bj}/Q^2 phase space, enables precision QCD/QED physics measurements

But also:

- QCD/strong sectors
  - reduction on $\delta(\alpha_S) \hookrightarrow 0.1\%$
  - discovery frontier for low-x processes
- expected improvements on all electroweak sectors
  - $\delta(M_\mathrm{W}) \hookrightarrow 10$ MeV
  - LEP-magnitude $\delta(\sin^2\theta_\mathrm{W}^\mathrm{eff}) \hookrightarrow 1.5 \times 10^{-4}$
  - top sector: CKM $|V_{tb}|$ precision: 5% (LHC) $\mapsto$ 1%, sensitivity to FCNC & $t\gamma/tW/tZ$ couplings
- gateway to **many other searches**
  - e.g. central exclusive $\gamma\gamma$ interactions (talk@ICHEP: *High energy $\gamma\gamma$ interactions at the LHeC* (LF, H. Khanpour, **K. Piotrzkowski**, Y. Yamazaki) – July 20, Club E)

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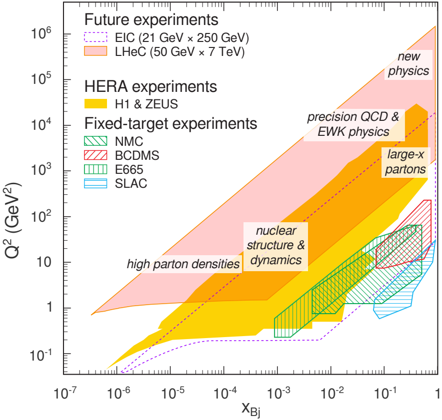
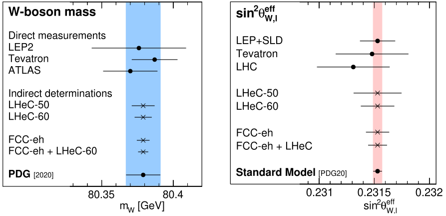


LHeC/FCC-eh – kinematics range & detector constraints

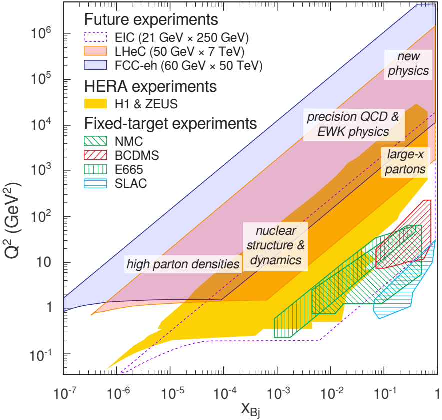
Large coverage of the x_{Bj}/Q^2 phase space, enables precision QCD/QED physics measurements

- as for HL-LHC/LHeC, FCC-eh reaches high sensitivity to precision physics
  - e.g. EWK parameters:

(talk@ICHEP: *General-purpose LHeC/FCC-eh high-en.(...)*, (D. Britzger) – 20.07, Club E)



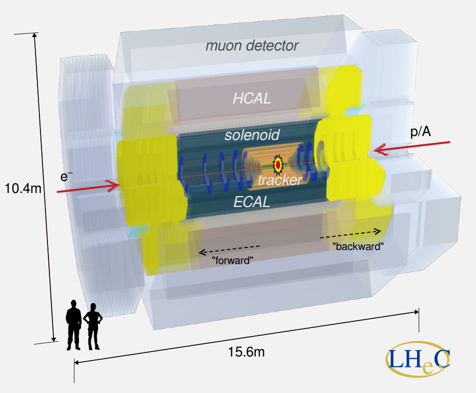
M_W and $\sin^2\theta_W^{\mathrm{eff}}$ uncertainty reduction with LHeC/FCC-eh (arXiv:2203.06237 [hep-ph])



- broad kinematic range for new physics/BSM searches:
  - requires good tagging performance for high-p_T/heavy flavour objects

(talk@ICHEP: *High precis. Higgs physics in ep scattering at CERN* (U. Klein) – 18.07, S.-Hall 2A)

LHeC detector design



Asymmetric detector concept, forward (proton) and backward (electron) subsections

From SR-optimised circular-elliptic beamline outwards:

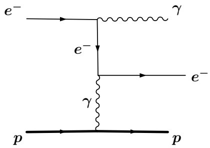
- central silicon tracker (HV-CMOS MAPS, $0.2X_0$ up to $\eta \sim 4.5$)
  - barrel: 6 layers of vertex locator (pixel), 4 layers of strips
  - endcaps: 7 layers (forward) + 5 layers (backward) of strips+(macro-)pixels, 1° tracking acceptance
- “accordion”, ATLAS-like LAr ECAL barrel
- central 3.5T solenoid + extended dipole ensuring head-on ep collisions
- plastic/scintillator HCAL
- muon RPC chambers

Additional ep/eA modes compatible with all “extended” pp/pA/AA plans @ HL-LHC

- joint ep/pp detector as opportunity for systematics reduction & cross-calibrations
- common detector technologies already available $\rightarrow$ **technically possible design**, with potential for extensions to FCC-eh (PID detectors, imaging ECAL, new tracking technologies, ...)

LHeC detector design (cont.)

Possible extension to forward/backward **scattered p/e beamlines instrumentation**



electron side

- tagger for photoproduction processes
- γ detection **for luminosity** estimation (*e.g.* with Bethe-Heitler ep $\to$ epγ)

proton side

- radiation-hard, Si/W zero-degree calorimeter *à la* ALICE FoCAL/CMS HGCAL (high segmentation in a very challenging environment)
- *Roman pots* **proton taggers**/trackers *à la CMS-PPS* (talk@ICHEP: *Physics results with the CMS PPS...* (G. Silveira *et al.*) – 20.07, Club E)

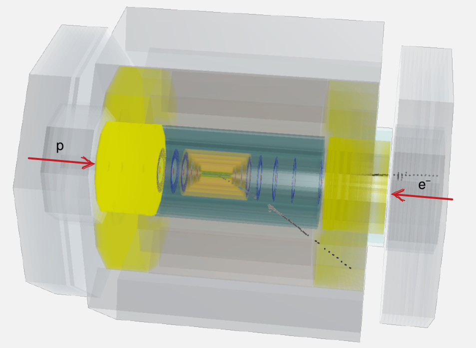
  $\rightsquigarrow$ depending on location, with reaches from $\sim 0.01 < (\xi \equiv \Delta p/p) \leq 0.1 - 0.2$
- possible extensions to even lower-ξ, *"Hamburg beam pipe"* (aka moveable beam pipe) insertion in "cold" region of the beampipe *à la FP420* [arXiv:0806.0302 [hep-ex], JINST 4 (2009) T10001]

Recent work on LHeC detector/beamline design optimisation

Optimisation of machine operational parameters **with simulation of detector response**

- common DD4hep/Geant4 offline simulation & reconstruction framework for a realistic LHeC detector geometry design
- "machine" input: input from BDSIM beamline dynamics simulation toolbox
- physics input: interfacing plugins to ep MC generators: Pythia 6/8, CepGen, . . .

Detector-fiducial IP parameters/synchrotron radiation optimisation with subdetectors geometry & placement



Event display of a DDG4/Geant4 simulation of a central exclusive $ep \to e(\gamma\gamma \to \mu^+\mu^-)p$ event as generated by CepGen inside the LHeC detector.

Summary and outlook

- LHeC/FCC-eh presents fresh challenges for 21st Century accelerators particle physics
  - large $x_{\rm Bj}$ — Q^2 spectrum for "HL-LHC scale DIS" studies
  - room for complementarity to HL-LHC in e.g. precision PDF in high Q^2, and precision EWK/Higgs physics physics cases, all in all **parallel to HL-LHC operation mode**

- "Technically possible" LHeC design exists from CDR-update, extension to FCC-eh yet to be studied in detail
  - first studies of synchrotron photon energy spectra and **critical energy**, with inputs from beamline optimisation/shielding already performed & providing some **promising insights** on beamline constraints
  - upgraded simulation toolbox ready for physics-oriented optimisation, first steps towards a TDR

A look forward

- Many opportunities for new innovation and connections:
  - synergies with (EIC, HL-LHC, ...) detectors that approach reality
  - new technologies in European DRD programme & developments towards future energy frontier colliders

- Timescales for realisation may be long...

  ... but the next European Strategy starts NOW

Dedicated study group for **ep/eA@CERN** established in 2023, **(many) more exciting prospective results to come!**

Interaction region optimisation – a bit of advertisement

1st workshop on the optimisation of beam dynamics & machine-detector interface for LHeC + FCC-eh

September 19-21, Kraków, Poland

https://indico.cern.ch/e/lhec-bdmdi-workshop/

Spares

Abstract

The proposed Large Hadron-electron Collider and the Future Circular Collider in electron-hadron mode will make possible the study of DIS in the TeV regime.

These facilities will provide electron-proton (nucleus) collisions with per nucleon instantaneous luminosities around $10^{34}(10^{33})$ cm^{-2}s^{-1} by colliding a 50-60 GeV electron beam from a highly innovative energy-recovery linac system with the LHC/FCC hadron beams, concurrently with other experiments for hadron-hadron collisions.

The detector design was updated in the 2020 Conceptual Design Report. Ongoing developments since then include an improved interaction region design, reflecting state-of-the-art synchrotron radiation simulations, together with a more detailed study of an all-silicon central tracking detector.

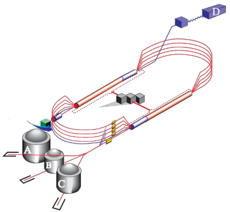
Additional capabilities for particle identification, enabling improved semi-inclusive DIS and eA studies, are also under study.

In this talk, we describe the current detector design and ongoing discussion in the framework of a new ep/eA study being carried out on behalf of CERN, highlighting areas of common interest with other future collider experiments and the new Detector R&D Collaborations in Europe.

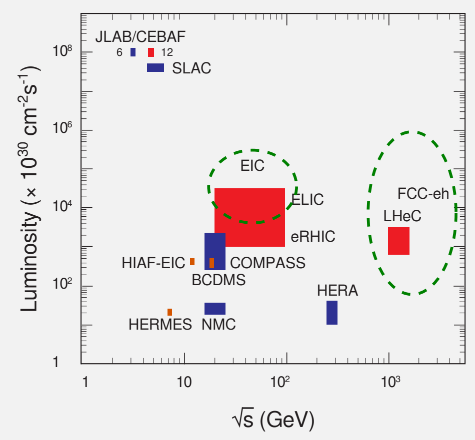
Current/future electron beamlines/ep colliders

Several planned/envisioned projects for fixed target, or ep/eA experiments ; e.g.

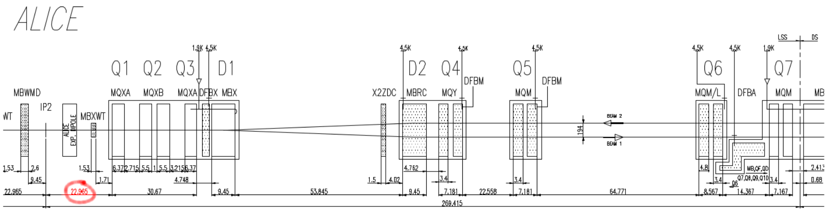
- JLAB ongoing fixed targets (CEBAF: 6/12 GeV electrons, energy recovery linac)



- LHeC/FCC-eh @ CERN
- On-target EIC @ BNL (early 2030s)



LHeC beamline: from $L^* = 15$ m to 23 m



Source: LHC Design Report, matching section in IR2 – 10.5170/CERN-2004-003-V-1

Larger free drift (half-)length $L^* \rightarrow$ increased space for experimental apparatuses + TAS/TCL/Qx

Requires a re-optimisation of the full beamline optics & Twiss parameters (K. André):

- **proton side**: no need for extra half-quadrupole
  - addition of two off-centered quadrupoles: Q0F and Q0D
  - increased space for dipole, same “crossing” angle at interaction point
- **electron side**: extra drift between detector dipole & Q1A, amended bending angle to maintain separation parameters