LHeC detector concept

e/μ-LHC initial discussion

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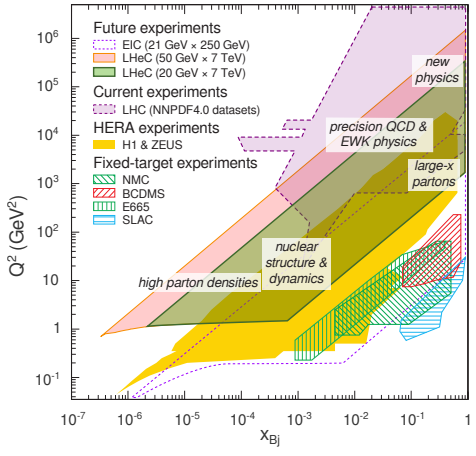
Introduction – LHeC kinematics range & detector constraints

Disclaimer: Multidecade-long history for the LHeC detector design optimisation reported in 2 CDRs [J.Phys.G 39 (2012) 075001], [J.Phys.G 48 (2021) 11, 110501] and reported in various occasions.
In this talk, will put an emphasis on the latest developments (2020–).

Large coverage of the x_{Bj}/Q^2 phase space

at the LHeC
- @1.2 TeV (E_e = 50 GeV)
- @0.75 TeV (E_e = 20 GeV)

- enables precision QCD/QED physics measurements
- thin (high-Q^2) overlap with EIC kinematics range → specific design choices to be made, driven by physics case

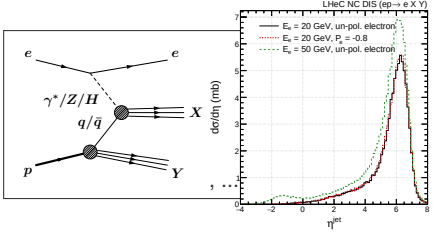


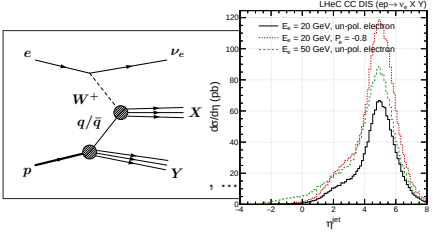
LHeC flagship measurements

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

Inclusive DIS measurements:

- main challenge: good detector **hermiticity** (sensitivity to small-Q^2 $\leftrightarrow$ high-θ_e reach)
- **NC**: large e/h final states asymmetry: requires fine ECAL segmentation, esp. in forward region
  - e.g. LAr + rad-hard hadron calorimeter close to beam pipe
- **CC**: requires calorimeter hermiticity + good hadron resolution
  - e.g. plastic HCAL (barrel + endcaps) with good neutron absorption



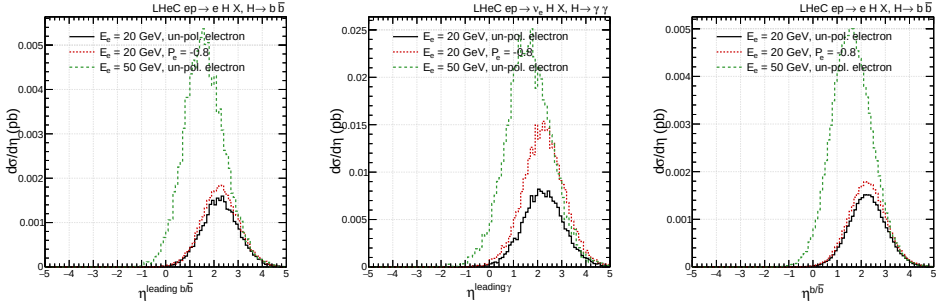


- **LHeC CDR** [J.Phys.G 48 (2021) 11, 110501] **proposal**: "accordion", ATLAS-like LAr ECAL barrel, plastic/scintillator HCAL

LHeC flagship measurements (cont.)

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

Possible *"Higgs factory"* with forward jets configuration



- need for good forward calorimetry coverage
- requires excellent flavour tagging in forward direction with low-material budget detectors
- **LHeC CDR** [J.Phys.G 48 (2021) 11, 110501] **proposal**: HV-CMOS MAPS central silicon tracker
  - $0.2X_0$ 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

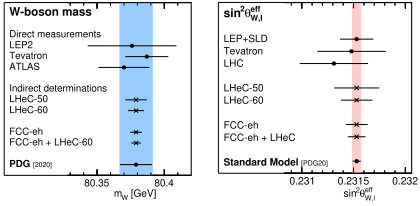
LHeC flagship measurements (cont.)

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
  - $\delta(M_W) \hookrightarrow 10$ MeV
  - LEP-magnitude $\delta(\sin^2\theta_W^{\text{eff}}) \hookrightarrow 1.5 \times 10^{-4}$
  - top sector: CKM $|V_{tb}|$ precision: 5% (LHC) $\mapsto$ 1%, sensitivity to FCNC & $t\gamma/tW/tZ$ couplings

[arXiv:2203.06237 [hep-ph]]

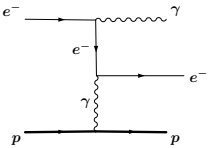


- gateway to **many other searches**, e.g. central exclusive $\gamma\gamma$ interactions → **see Hamzeh's talk**

- **requires good tagging performance for high-p_T /heavy flavour objects**

LHeC forward instrumentation

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 $\rightarrow$ epγ)

proton side

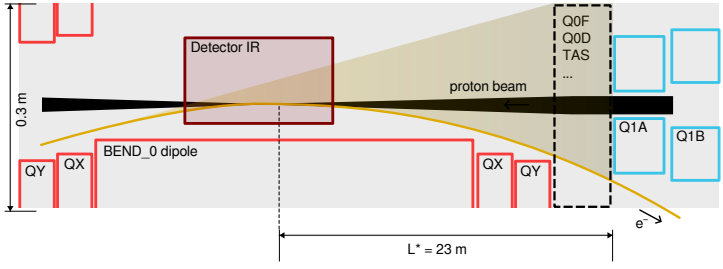
- radiation-hard, Si/W zero-degree calorimeter *à la* ALICE FoCAL/CMS HGCAL
  - high segmentation in a very challenging environment
- *Roman pots* **proton taggers**/trackers *à la CMS-PPS/ATLAS-AFP*
  $\rightsquigarrow$ depending on location, with reaches from $\sim 0.01 < (\xi \equiv \Delta p/p) \leq 0.1 - 0.2$
- possible extensions to even lower-ξ
  - e.g. *"Hamburg beam pipe"* (aka moveable beam pipe) *à la FP420* [arXiv:0806.0302 [hep-ex]], [JINST 4 (2009) T10001] insertion in "cold" region of the beampipe

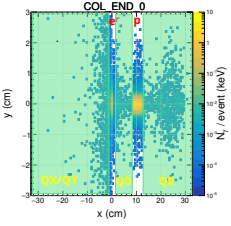
MDI/beamline design optimisation

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

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



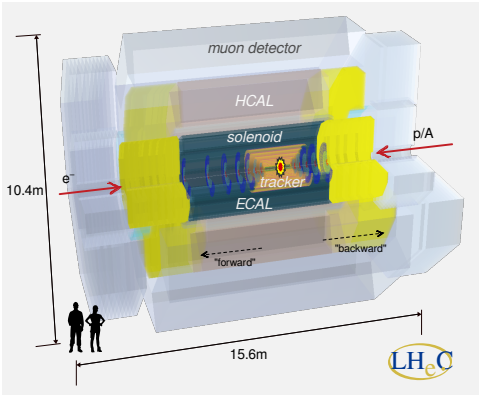


effect of upstream shielding on SR flux at IR exit

- lattice optimisation, incl. synchrotron radiation effects
  (**critical energy** & **radiated synchrotron power**: $E_c \sim \gamma^3/\rho$, $P_{\text{synch}} \sim \gamma^2/\rho^2$)
  - 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^*, …

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

LHeC CDR-level detector design – summary



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

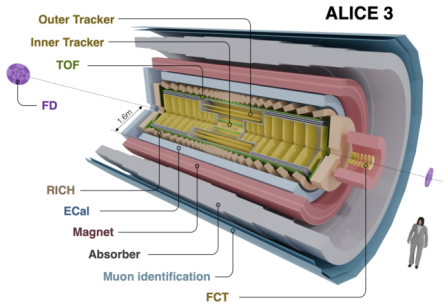
Additional ep/eA modes compatible with all "extended" pp/pA/AA plans @ HL-LHC

- joint ep/pp detector as opportunity for systematics reduction & cross-calibrations

“Soft digression” – ALICE 3 conceptual design(s)

Feb 2025 [CERN-LHCC-2025-002 ; LHCC-G-185]: 3 versions introduced @ LHCC to scope physics programme & allow design-based cost reduction

- version 1 (adapted from ALICE 3 LoI [arXiv:1902.01211 [physics.ins-det]])
  - 2T SC solenoid
  - Si MAPS (inner+outer tracker, barrel+endcaps), **large acceptance** $|\eta| < 4$, excellent resolution for Ξ_{cc} & Ω_{cc} studies
  - LGADs TOF layer ($\delta p_{\mathrm{T}}^{e} \sim 15$ MeV$/c$)
  - RICH (aerogel + SiPMs)
  - **$Pb+PbWO_4$ ECAL**, $|\eta| < 1.6$ (barrel) + **1-sided** $1.6 < \eta < 4$ endcap
  - **no HCAL**
  - MID+FD
- version 2: **no ECAL**, magnet (2T → 1T), absorber, and MTD reduction



- version 3-a: **50% reduction of Outer Tracker surface (3 disks), no vertex detector**, fTOF, fRICH endcaps: $|\eta| < 2$
- version 3-b: reduced RICH barrel acceptance $|\eta| < 0.8$

Technicalities – LHeC detector concept simulation

Fast simulation – Delphes model

Developed by U. Klein, P. Kostka (2016–), in Delphes repository since Oct 2020

Basic assumptions on detector capabilities:

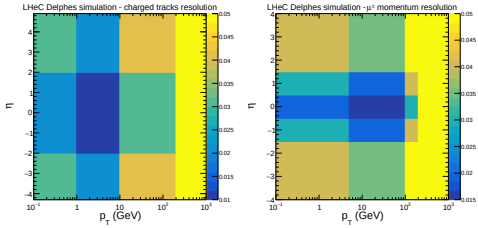
- magnet: 1.14m radius, 5.8m length, B_z = 3.8T
- ECAL resolution:

$$\sigma_E/E = \begin{cases} \frac{0.1}{\sqrt{E}} + 0.01 & (-4.4 < \eta < -2.1) \\ \frac{0.09}{\sqrt{E}} + 0.02 & (-2.1 < \eta < 2.7) \\ \frac{0.1}{\sqrt{E}} + 0.01 & (2.7 < \eta < 5) \end{cases}$$

- HCAL resolution:

$$\sigma_E/E = \begin{cases} \frac{0.4}{\sqrt{E}} + 0.04 & (-4.7 < \eta < -1.7) \\ \frac{0.4}{\sqrt{E}} + 0.02 & (-1.7 < \eta < 5.1) \end{cases}$$

- electron/photon tagging: fully efficient for $p_T^e(E_T^\gamma) > 500$ MeV$/c$, $-4.3 < \eta < 4.9$
- μ reconstruction: fully efficient for $|\eta| < 4$
- charged tracks/muon momentum resolution:

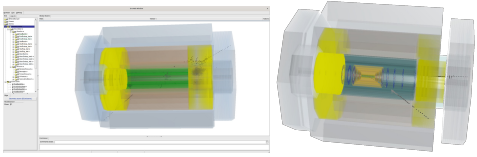


Status of the full simulation stack

State of the art (2023) – LHeD

LHeC detector integrated in DD4hep detector description toolkit since 2017

- 2 geometries assumptions for the central tracker: symmetric along z & asymetric



Major pros:

- standardised & modular geometry definition, can be easily adapted to user's needs (include chain possible, easy switch between conditions/assumptions)
- large community of DD4hep users, ensuring long term support

Major cons:

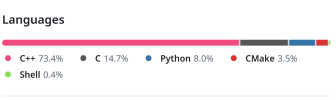
- DD4hep is not *per-se* a simulation toolset, more of a geometry conditions handler
  - available, but limited interfacing (through DDG4) to Geant4
  - barely interfaced to "standard" MC event generators (Pythia6/8, Herwig, ...)
- no definition of an event data model (EDM) for user-specific collections
- embryotic reconstruction algorithms support, very few available in standard codebase
- not very multithreading-safe

Status of the full simulation stack (cont.)

2024-2025 developments

Integration of LHeD into a standalone simulation toolbox

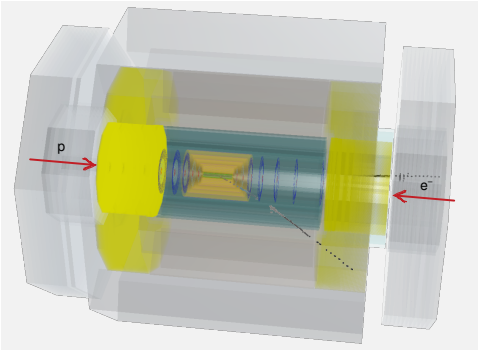
- based on Key4hep, broadly used nowadays (FCCSW for FCC-ee & FCC-hh, CEPCSW, HERD, μCollider, ...) stacks
  - eventually, based on Gaudi (LHCb/ATLAS/...), fully modular in algorithms, user data formats, and analysis sequences definition
  - Python-based configuration, C++ implementation of data formats, algorithms and producers/consumers
- base repository (for now): github:forthommel/lhecsw
  - mostly C++/Python, some validation ROOT codes (.C) & building directives (CMake/Shell)



- fully modular, one package for each subdetector simulation/reconstruction
  - equivalent structure to base CMSSW/Gaudi good practices
- geometry inherited from DD4hep implementation: Geometry/DD4hep
- EDM collections & user data bookkeeping: EDM4hep
  - "standard" data formats inherited from `podio`, LHeC-oriented derivatives available
- compatible with LCG standard software stacks available through `/cvmfs`

Event generators

- native (Key4hep) & ep-specific support of “major” generators
  - e.g. Pythia8, Pythia6
  - generic interface through HepMC2/HepMC3 event content
  - also interfaces smaller scale generators: CepGen for $\gamma\gamma$ physics
- MG5_aMC@NLO + Pythia8 direct interface under development
- interface to BDSIM beam dynamics simulation toolbox → feedback loop to beamline/shielding assumptions



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.

Examples – $\gamma\gamma \to l^+l^-$ in LHeD

- combination of standard Gaudi `Configurables` options and LHeC framework-specific includes
  - can be used to define a common/shared set of algorithms + parameterisation for future studies
  - automation of **internal conversion** between transient data formats (e.g. Pythia 8 → HepMC3 → Gaudi)
- base **EDM** objects definition from `podio`
  - ROOT (TTree/RNtuple) and SIO (SLAC) formats I/O
- Geant4 SimHits → (Rec)Hits **conversion algorithms**
  - currently handling a few algos w/ Geometry-sentient spatial/temporal resolution smearing for vertex/pixel trackers (`SimAlgos/Tracker`), and energy-smearing for calorimeters (`SimAlgos/Calorimetry`) ; more to follow
  - all collections of interest can be saved and reused for later stages of processing ; standard "producer/consumer" I/O structure
- Tracking (ACTS) under development, last paving stone before FullSim/Delphes comparisons & update of CDR assumptions

```
from Gaudi.Configuration import *
from Configurables import GenAlg
from Configurables import PodioOutput, FCCDataSvc
from Configurables import ApplicationMgr
from Generator.pythia8Interface_cff import *
from Geometry.geoservice_cfi import geoservice
from SimG4.sim_cff import geantservice, geantsim
from SimAlgos.digi_cff import digis

pythia8.preInitCommands = [
    'Beams:idA = 2212',     # beam 1 = proton
    'Beams:idB = 11',       # beam 2 = electron
    'Beams:frameType = 2', # beams are back-to-back, but with different energies
    'Beams:eA = 7000.',     # proton energy (GeV)
    'Beams:eB = 50.',       # electron energy (GeV)
    'PDF:lepton2gamma = on',
    'PhotonCollision:gmgm2mumu = on',
]
genalg = GenAlg("Pythia8", SignalProvider = pythia8)
genalg.hepmc.Path = "hepmc"

geantsim.eventProvider = pythia8Particles

out = PodioOutput("out", # PODIO output algorithm
    outputCommands = ["keep *"],
    filename = "output.root",
    OutputLevel = DEBUG,
)
podioevent = FCCDataSvc("EventDataSvc")

ApplicationMgr( # wrap everything together
    TopAlg = [
        genalg,
        pythia8HepMCConverter,
        Geantsim,
        *digis,
        out
    ],
    EvtSel = 'NONE',
    EvtMax = 100,
    ExtSvc = [podioevent, geoservice, geantservice]
)
```

Summary

Very mature design proposed

- relying on pre-existing technologies, or in well advanced R&D
- multiple design choices encompassed, with room for optimisation (technological bump-ready)

Modern **simulation toolset** under continuous development

- interfacing to modern event generators (Pythia, Herwig/mg5_aMC in development), incl. *ep*-specific MCs (inherited from HERA) through CepGen [Comput.Phys.Commun. 271 (2022) 108225]
- allows to study beamline constraints (synchrotron radiation, shielding, ...)

Thanks for your attention.

Spares

Physics case

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