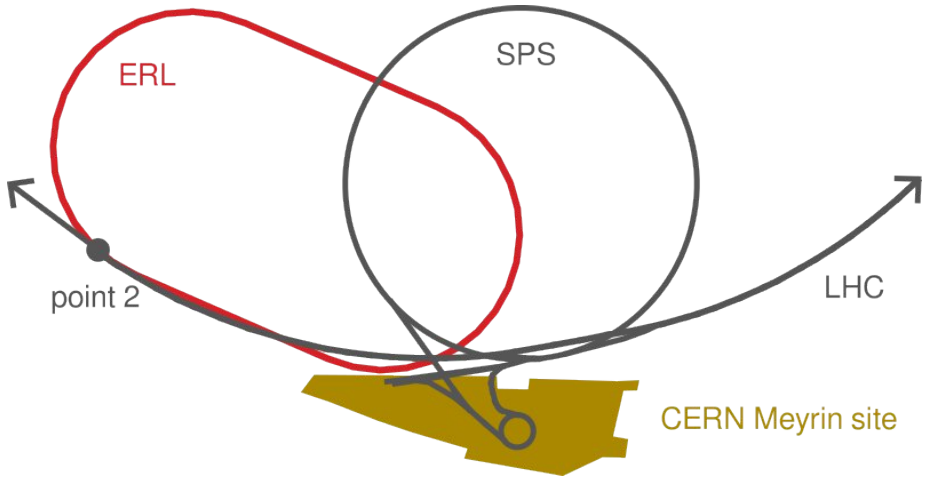
A detector for top-energy DIS

DIS2026 — 33rd International Workshop on Deep Inelastic Scattering and Related Subjects, Bologna (IT)

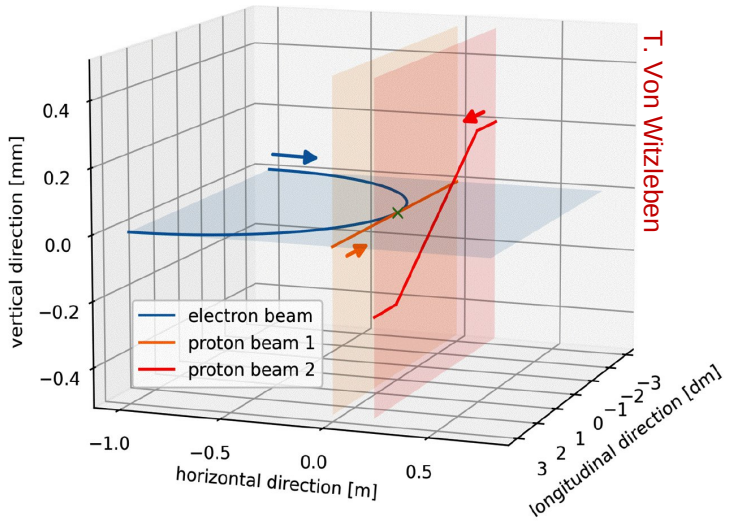
Laurent Forthomme (AGH University of Kraków),
on behalf of the LHeC Study Group

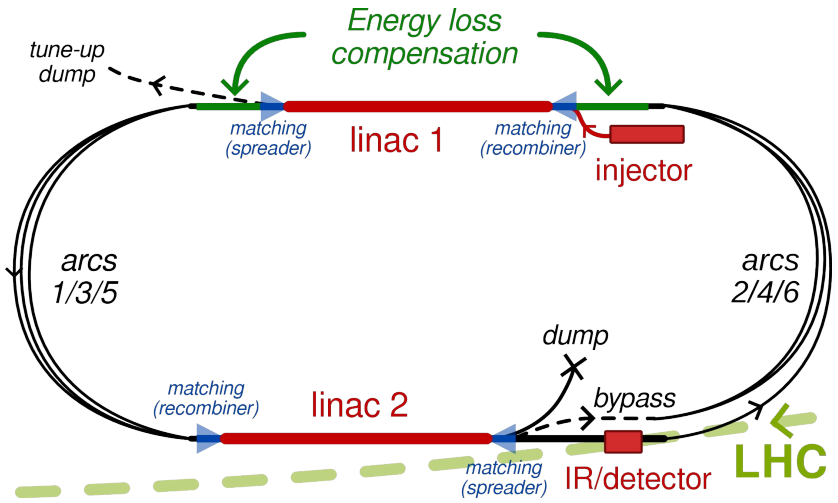


V. Kandinsky — Circles in a Circle (1923)

LHeC as a powerful tool for 21st Century DIS

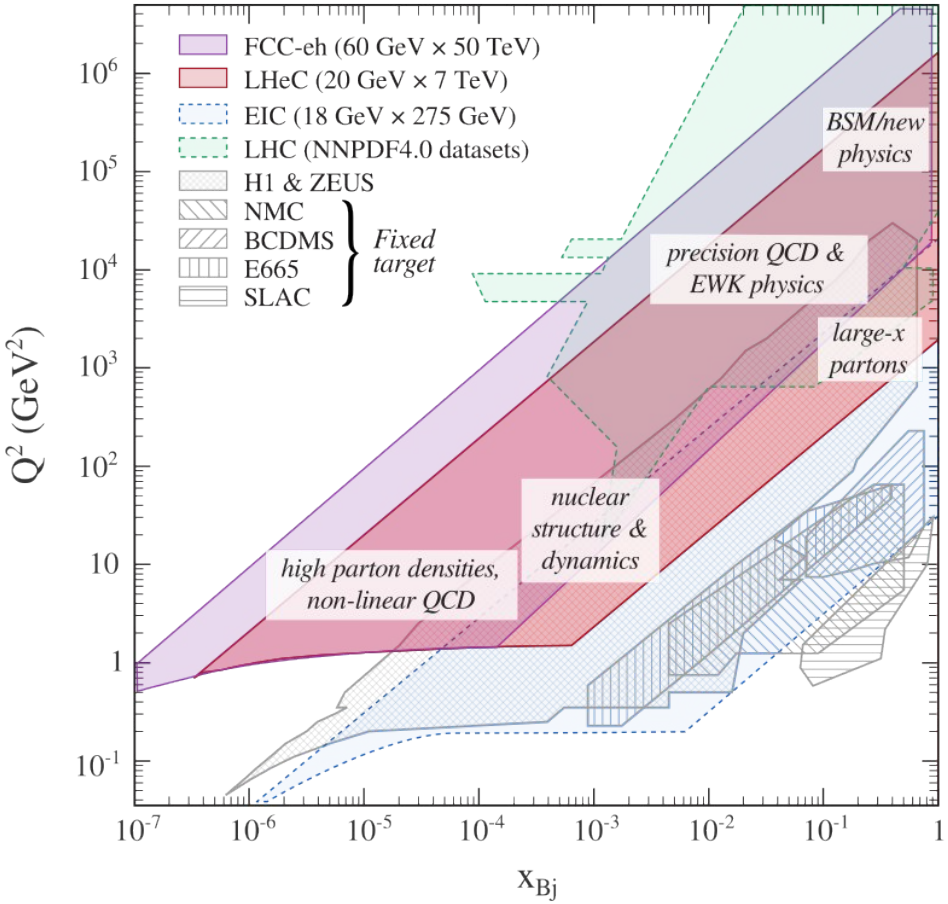
- Baseline: HL-LHC @ 7 TeV, with the addition of an electron beam **at one interaction point** (IP2)
  - Three-beam solution in the interaction region: e-p collision + additional proton as spectator
- Major constraints: able to operate with the (HL-)**LHC proton beam**, with strong energetic requirements ensuring the overall sustainability of the project: **power consumption < 150 MW** in highest luminosity operation mode
  - instantaneous **$L \sim 10^{34}\ cm^{-2}s^{-1}$** → 100 fb^{-1}/year → **1 ab^{-1} over full exploitation**
  - Very low pileup: $\langle\mu\rangle \sim 0.1$, and moderate radiation levels **($\ll 10^{14}$ 1-MeV n_{eq})**
- Energy-recovery linac (ERL) technology used as baseline for electron acceleration
  - two linacs with 20 MV/m acceleration, 3 tracks/interconnecting arcs
  - several lengths options studied, 1/4 of LHC circumference preferred
  - more details on ERLs: see talk by A. Stocchi (Wednesday@11:40)





LHeC + FCC-eh as powerful tools for 21st Century DIS

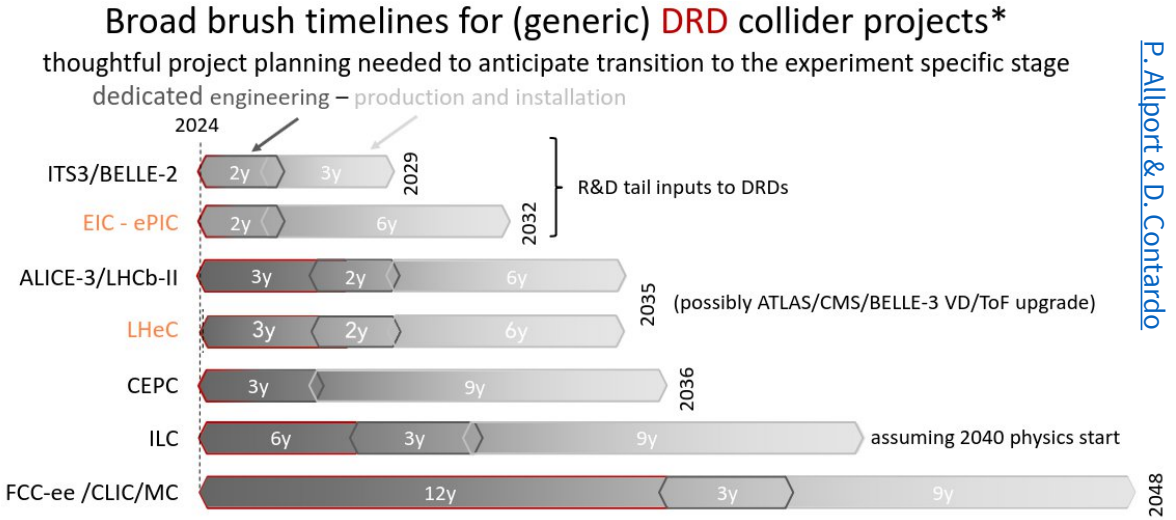
- Large physics potential for a “reasonable” cost (both in construction & operations)
  - for FCC-eh, minimal set of constraints for the construction & operation (incl. beamline dynamics & MDI) to make it a viable extension programme for FCC-hh
- **Will not cover the various physics cases** for e-h collisions in this presentation
- Well represented this year at DIS!
  - Plenary talk: EPPS/LHeC (J. D’Hondt, Friday@09:00)
  - Numerous parallel talks at this workshop, covering the multiple physics cases envisioned, both at LHeC & FCC-eh:
    - QCD@LHeC (F. Giuli, Tuesday@9:20)
    - top/EW@LHeC (P. Newman, Tuesday@12:00)
    - $\gamma\gamma$@LHeC (LF, Wednesday@10:20)
    - DIS@LHeC (K. Wichmann, Wednesday@14:50)
    - Higgs/BSM@LHeC (N. Armesto, Wednesday@15:10)



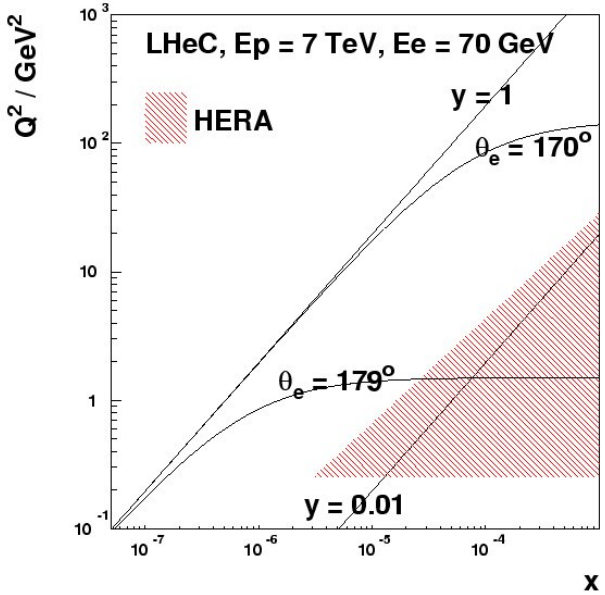
LHeD — a detector concept for e-p collisions at 1.2 TeV

A few, incompressible detector requirements & challenges:

- Technology already available, or in advanced R&D stage
  - important synergy with DRDn's progresses
- Good **quark flavour** measurement (esp. heavy flavours: b & c)
  - in general, good performance required for all high-p_T particles to pursue H, top, EW, BSM programme, like a modern, general purpose particle physics detector
- Instrumentation as close as feasible to the beam pipe
  - e.g. high-coverage of the polar angle: ~1° < θ < 179° for DIS & precision proton PDFs at very-low x_{Bj}
- Modular, both for installation & long-term access
  - assembly in surface prior to installation to fit with LHC operational schedule?



P. Allport & D. Contardo



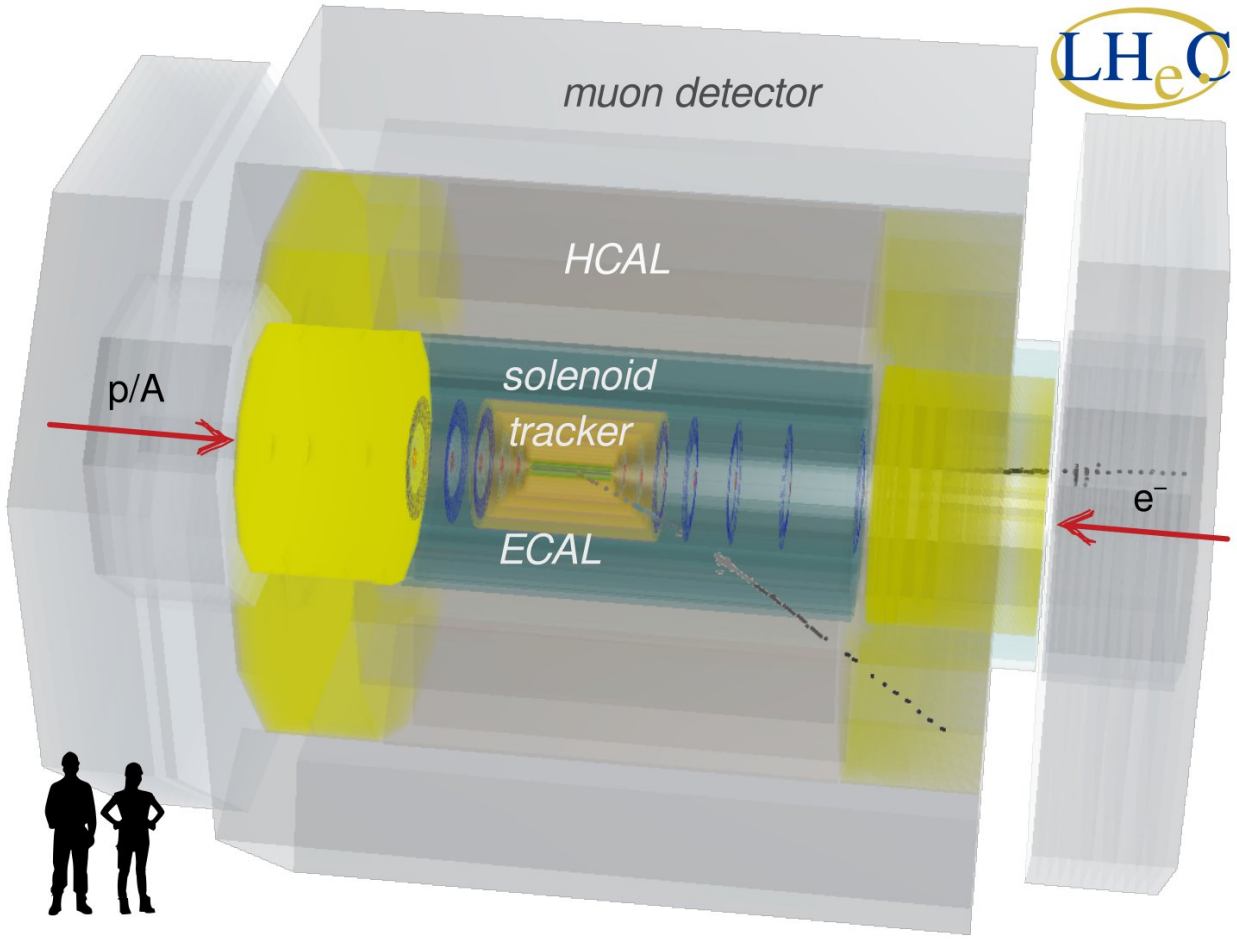
LHeD concept (2020 CDR)

- Compact form factor:
  - 13m (length) × 9m (diameter)
  - reminder: CMS → 21m × 15m, ATLAS → 45m × 25m
- Modular design: *"could be built tomorrow"*
  - likewise, could be set to operate both in ep and pp mode (large opportunities for systematic uncertainty reduction through cross-calibration)

… with its limitations

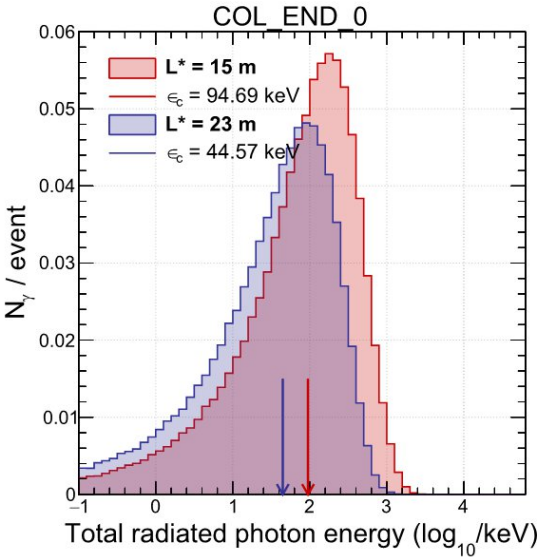
  - snapshot in time, with (ATLAS-like) technology from half-a-decade ago, with HL-LHC radiation tolerance requirements, …
  - room for large-scale improvements for e-p/e-A specific case (e.g. RICH particle identification, MPGD/LGAD tracking, …)

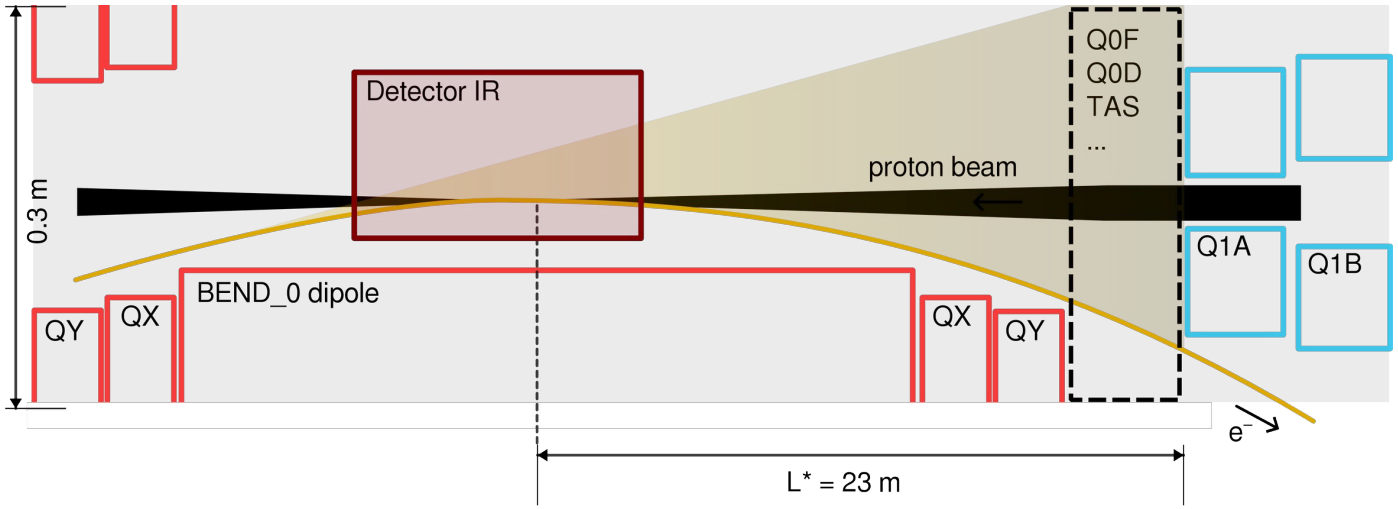
- As hermetic as can be, with backward/forward beamline instrumentation

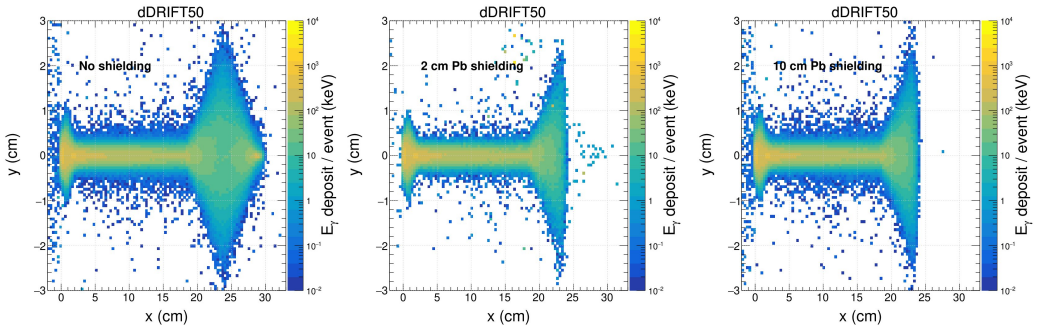


Interaction region & machine-detector interface

- Optimal IR design involves electron bending prior to its head-on collision to proton
  - requires shielding of critical beamline elements & detector from synchrotron radiation fanning
  - optimisation using full Geant4 (BDSIM) simulation of the interaction region, using a realistic geometry definition of local lattice, parametrisation of shielding parameters & material
  - longer IR section helps a lot there… (e.g. factor 2 in critical energy levels from L*=15m to 23m)

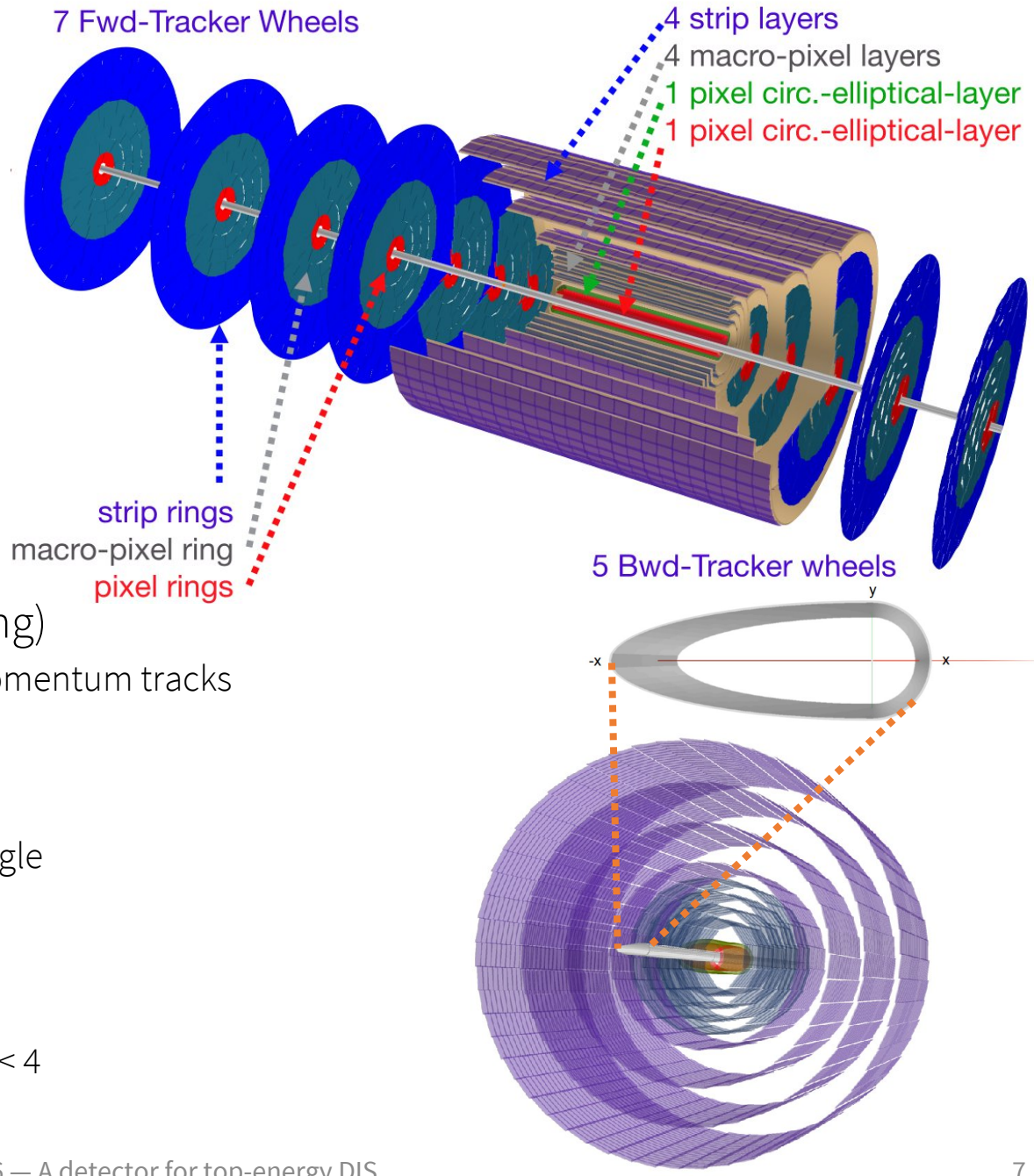






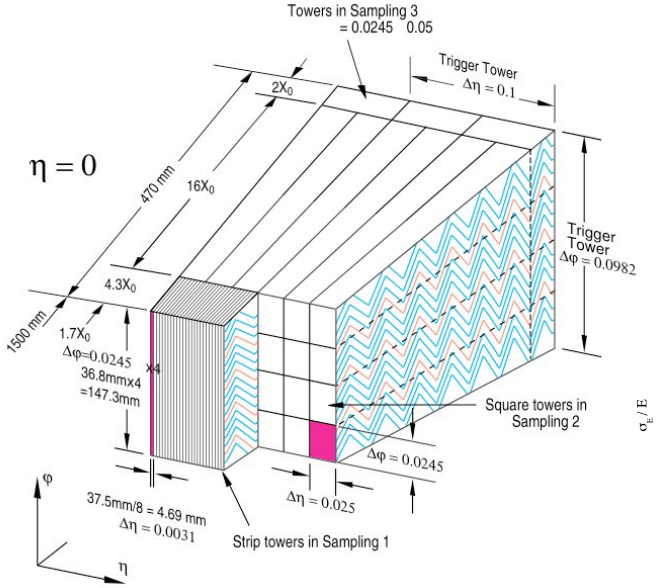
All-silicon tracker

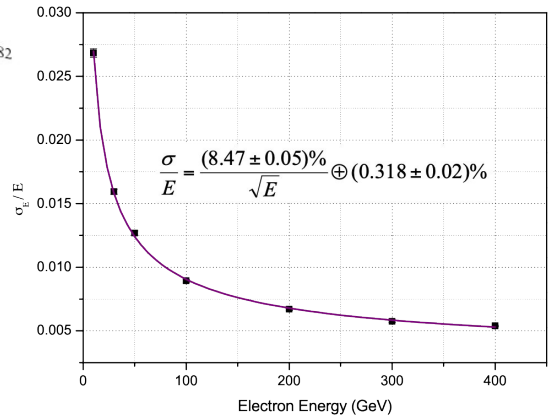
- As low material budget as possible
  - ultra-thin sensors (0.1mm thickness) to ensure small budget, both in barrel & forward/backward layers
  - radiation tolerance: up to 2×10^{15} 1-MeV-equiv. neutrons/cm^2 < HL-LHC fluence (10^{16} n_{eq}/cm^2)
  - between 2012 and 2020 CDR versions, change of technology: HV-CMOS, with integrated readout electronics (~0.2X_0 up to high-η)
- As close as possible to the beam (heavy flavour tagging)
  - transverse position resolution: around 30μm at η for high-momentum tracks
- Circular-elliptic beam pipe (fanning from SR)
  - bent innermost layers following the geometry (*à la* ALICE 3)
  - use of a secondary vacuum layer around IP to minimise ϕ-angle acceptance loss
- Endcap wheels: pixel + macro-pixel + strips
  - asymmetric in forward (proton) & backward (electron) directions: 5 layers for -3.5 < η < 0, 8 layers for 0 < η < 4

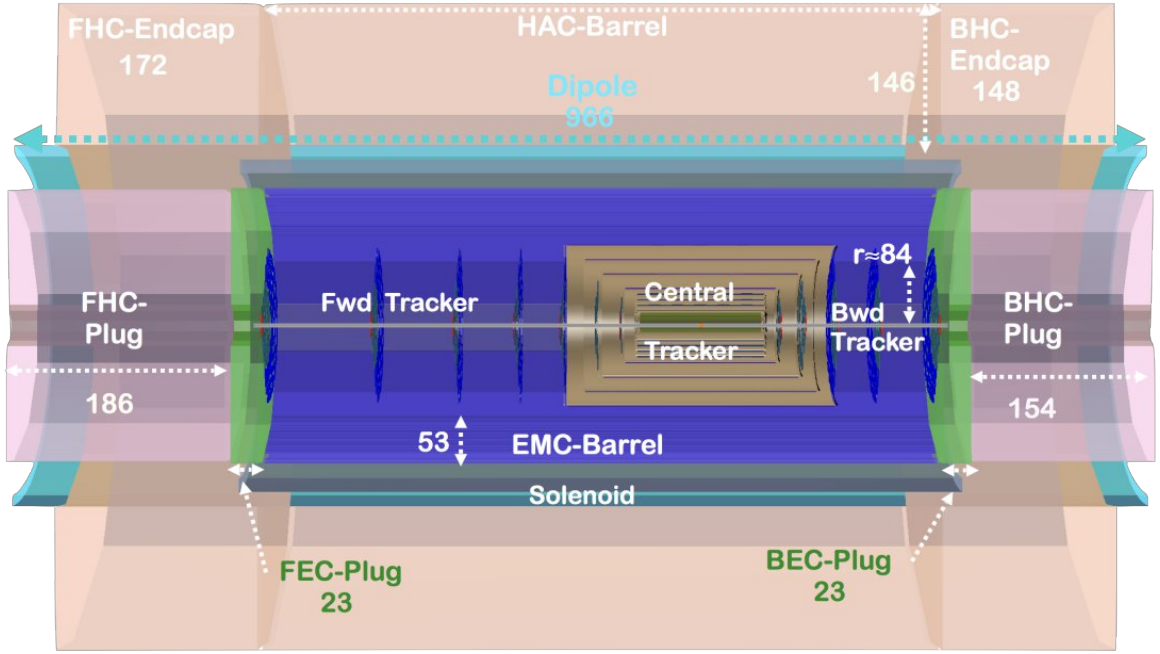


Calorimetry

- Barrel (-2.3 < η < 2.8) electromagnetic calorimeter (EMC):
  - optimal solution: LAr with ATLAS-like, “accordion”-like geometry (high-resolution/segmentation/stability under radiation) ; alternative: Si-Pb/Si-W easier to install inside L3 magnet
  - electromagnetic component located **inside the main solenoid, sharing the same cryostat** for material minimisation
- Barrel (HAC) + endcap (FHC/BHC) hadronic calorimeter
  - located right outside the solenoid
  - plastic scintillator + iron absorbers, required for good e-m/hadronic separation and energy resolution
- Forward/backward electromagnetic (FEC/BEC) & hadronic (FHC/BHC) plugs
  - finely segmented to ensure showering as compact as possible
  - silicon-based sensors, *à la* CMS HGCal & ALICE FoCAL
- Full acceptance: 25-50 X_0 & O(10λ)

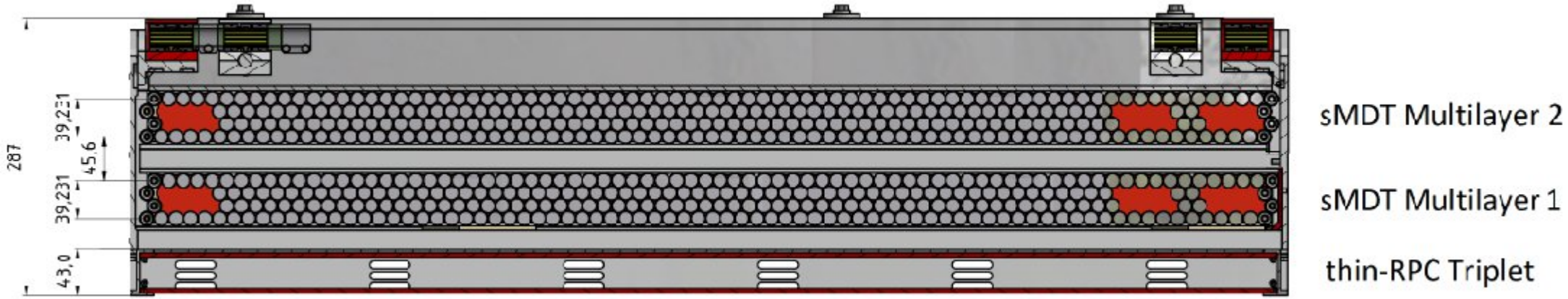




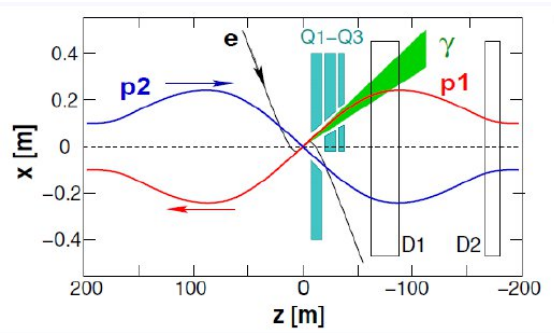


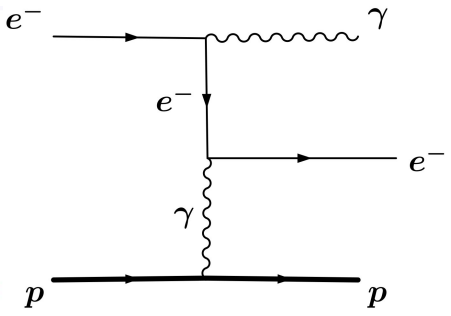
Muon detectors

- Muon system embedded in the return yoke
  - complementing momentum measurement from central tracker
  - direct detection of muons for very fast event tagging
- Technological choices based on recent developments for HL-LHC (e.g. ATLAS)
  - ultra-thin RPCs sustaining high rate & precise timing (< 1ns), 1mm gas gap
  - precise position measurement through drift tubes (sMTD) with ϕ~1.5cm

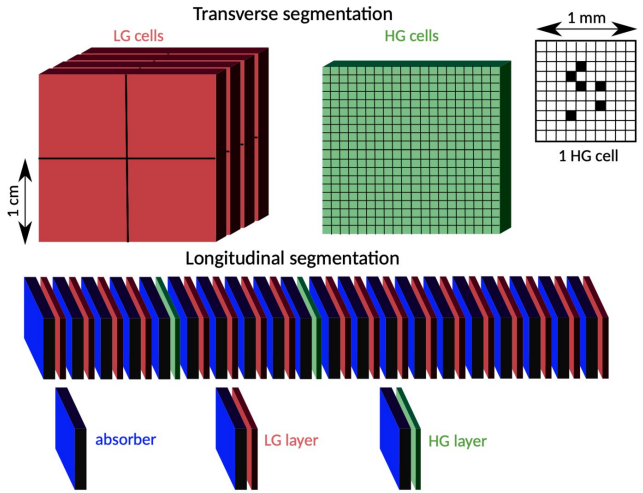


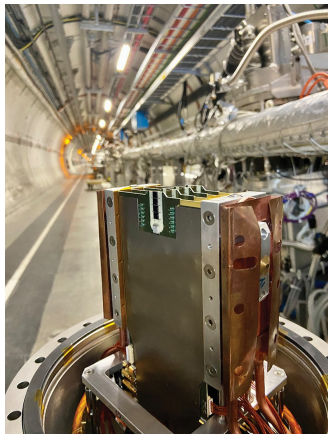
Forward/backward beamline instrumentation





- Electron direction (backward)
  - tagging photoproduction processes through measurement of scattered electrons (14-62m distance from interaction point)
  - likewise, luminosity measurement through photon detection & tagging of Bethe-Heitler (120m distance from IP) → O(1 GHz) at high-luminosity



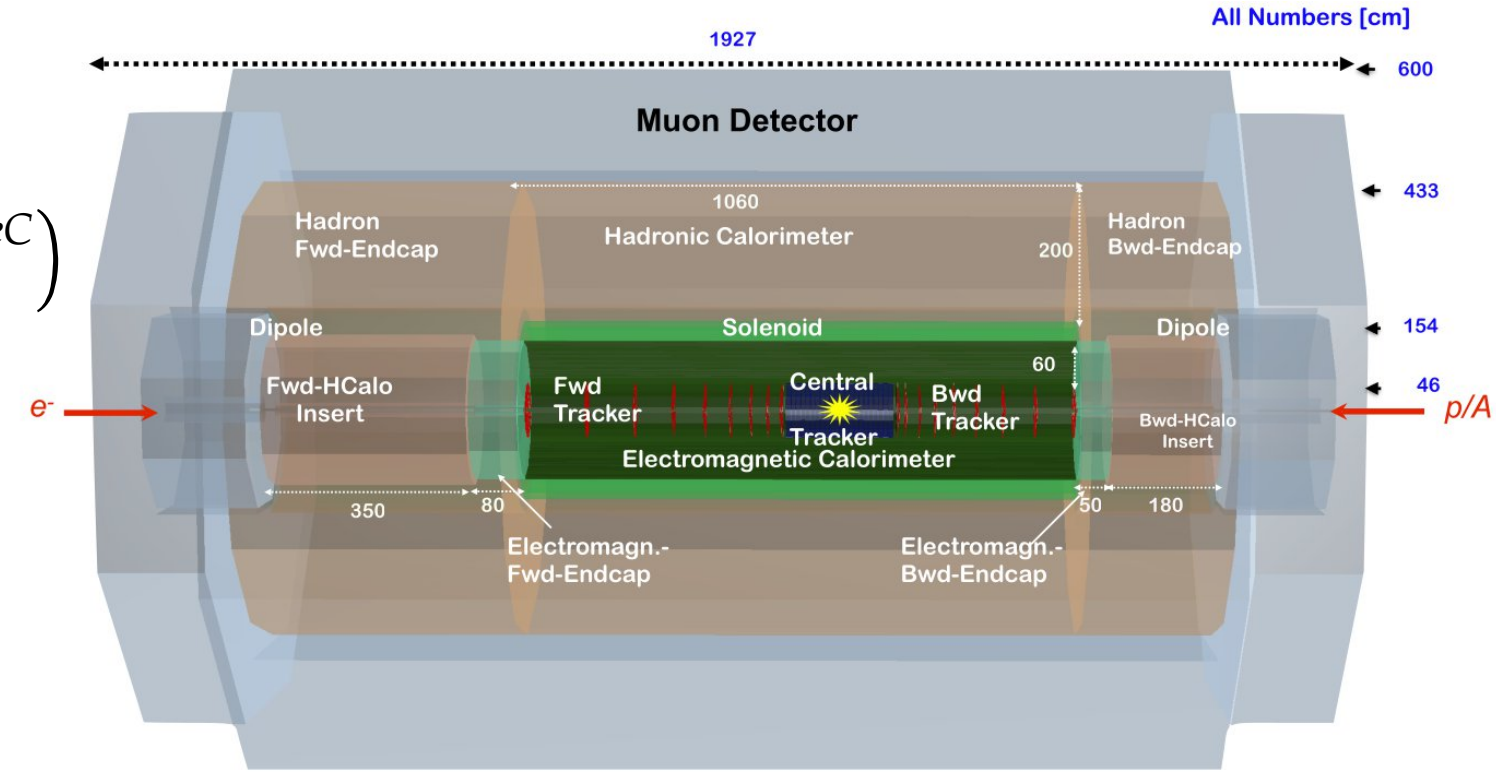


- Proton direction (forward)
  - calorimetry: zero-degree calorimeter (ZDC) with high segmentation *à la* ALICE FoCAL
    - radiation levels: 10^{15}-10^{16} n_{eq}/cm^2 → continuous operation possible all along running periods
    - Silicon-tungsten, 30cm-radius (around 100m distance from IP)
  - near-beam detectors for central exclusive processes tagging: Roman pots *à la* CMS-PPS & ATLAS-AFP, already demonstrated to operate fully in a harsh, radiation-hard LHC environment
    - could envision two locations for RP stations, as in CMS-PPS2 EoI: 200m from IP (ξ ~0.1), down to 120m from IP (ξ~0.2)
    - additionally, revive the insertion suggested by FP420 for very-low x/mass, ξ~0.002-0.01

FCC-eh detector layout

Largely based on LHeC detector layout

- Same calorimetry (12-15 λ) → extra extra scaling of the longitudinal dimensions, $\propto log\left(E_{p/e}^{FCC-eh}/E_{p/e}^{LHeC}\right)$
  - proton side: ~ ×2
  - electron side: ~ ×1.3
- imposing $1° < \theta < 179°$ tracker acceptance implies longer barrel + wheels
  - barrel: 6m (LHeC) → 9m (FCC-eh)
- Overall, still **not larger than CMS**...



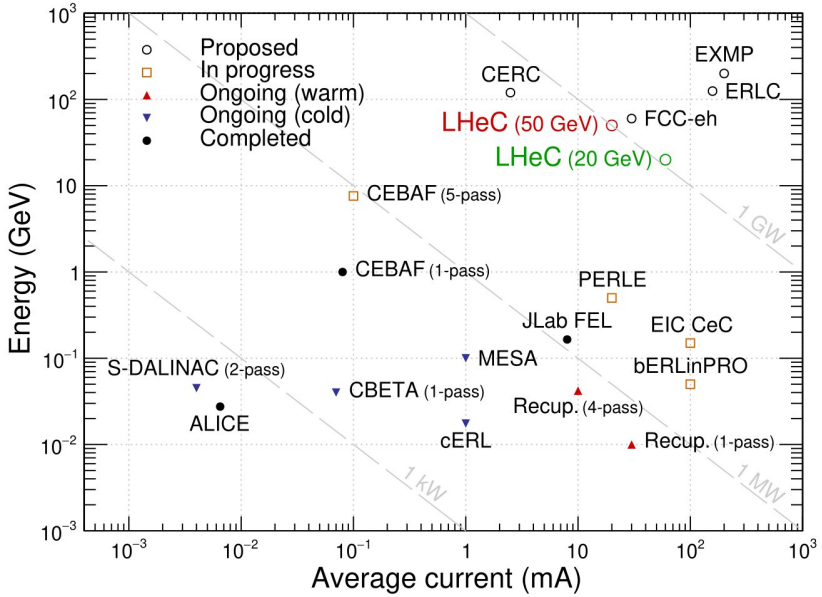
- Room for more advanced design choices than an overall dimensional rescaling
  - "same again only bigger", or "smarter"?

Simulation/reconstruction tools

- Fast simulation — Delphes 3 model developed since 2016 by U. Klein, P. Kostka et al.,
  - with basic assumptions on operational parameters
  - magnet: $\mathbf{B_z}$ = 3.8 T
  - tracking/muon detection efficiencies extracted from full simulation (LHeD in DD4hep)
  - calorimetry: ECAL $\frac{\sigma_E}{E} = \begin{cases} \frac{0.1}{\sqrt{E}} + 0.01 & -4.4 < \eta < -2.1 \\ \frac{0.09}{\sqrt{E}} + 0.02 & -2.1 < \eta < 2.7 \\ \frac{0.1}{\sqrt{E}} + 0.01 & 2.7 < \eta < 5 \end{cases}$, HCAL $\frac{\sigma_E}{E} = \begin{cases} \frac{0.4}{\sqrt{E}} + 0.04 & -4.7 < \eta < -1.7 \\ \frac{0.4}{\sqrt{E}} + 0.02 & -1.7 < \eta < 5.1 \end{cases}$
- LHeC offline simulation/reconstruction software being developed for future studies: LHeCSW
  - built on top of Key4hep stack (based on Gaudi, with DD4hep geometry, EDM4hep collections, podio I/O components, ...)
  - input formats for simulation: generic interface with HepMC2/3 event definition, Pythia 8, ...
  - support of ep-specific toolsets: CepGen for $\gamma\gamma$ interactions, Pythia 6, etc
  - interfacing to beam dynamics simulation toolboxes, e.g. BDSIM to act as feedback loop to beamline/shielding assumptions
  - **designed for modularity**, encompassing the most advanced design choices, detector technologies (e.g. forward/backward beamlines instrumentation), simulation & reconstruction algorithms

Staged LHeC

- Room for operating LHeC in steps, see e.g. low-energy "stage 1 LHeC" @ $\sqrt{s}$ = 0.75 TeV [arXiv:2503.20475 [hep-ex]/New J. Phys. 28 (2026) 013001]
  - single-pass ERL, dropping the need for splitting/recombination optics
  - increase of beam current (20 mA → 60 mA), still following the operational power constraints at highest-luminosity running mode (6×10^{33} cm^{-2}s^{-1})
- More than an experimental phase for e-h collisions at the LHC
  - can rely on ALICE 3 detector baseline with small modifications (HCAL & extension of ECAL for DIS, near-beam detectors instrumentation…)
  - physics case remains very competitive, altogether with HL-LHC projections: EW & top physics, BSM
  - ready for comparative eA/AA measurements at unprecedented scales

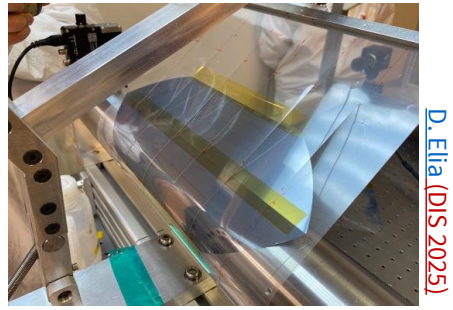


- After conventional LHeC operations, room for later extensions to **higher energy** lepton-hadron collisions, e.g. **LHμC**
  - See HELP4CERN talks: LHμC (K. Piotrzkowski, Tuesday@11:20), QCD@LHμC (P. Kotko, Wednesday@12:00), Higgs/EW/top@LHμC (H. Khanpour, Thursday@11:00)

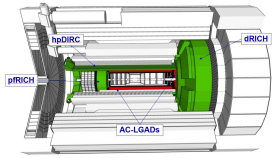
Synergies with other future projects

- EIC/ePIC to R&D effort for **tracking & PID technologies**
  - could consider switching to e.g. MGPDs as used in ePIC Si-vertex tracker (SVT)
    - e.g. large expertise in sensor bending procedure, inherited from ITS3
  - likewise, could profit from good performances expected from the "cocktail" of PID detectors (hpDIRC + ToF LGADs in barrel, RICH'es + ToF in endcaps)
- Input from spatial technologies developments
  - e.g. imaging ECAL using AstroPix, as in NASA Amego-X gamma-ray observatory

Room is left for lots of compromises with planned detector components!



D. Elia (DIS 2025)



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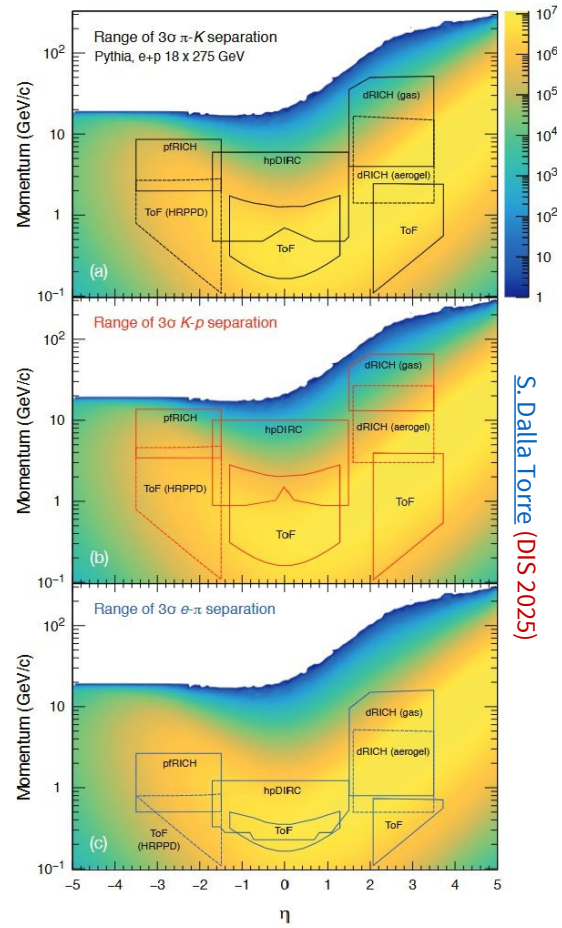
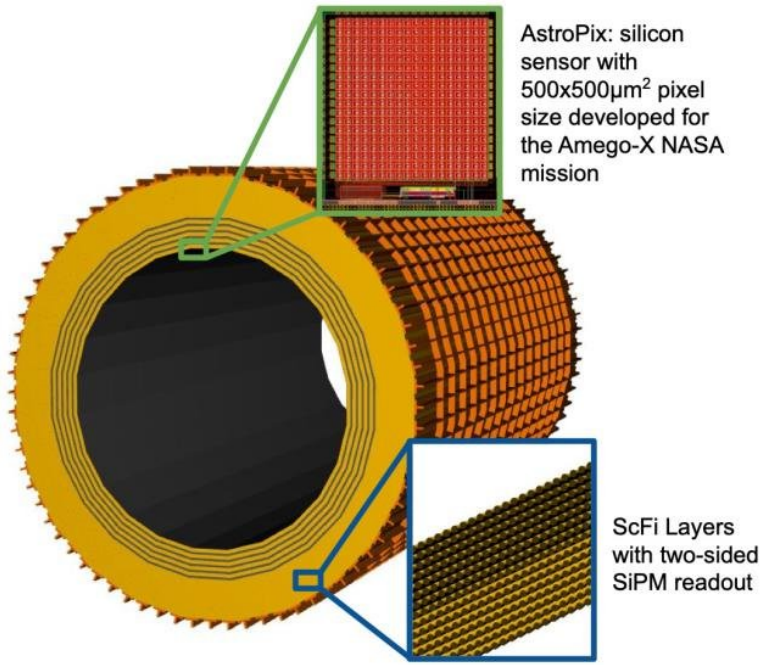
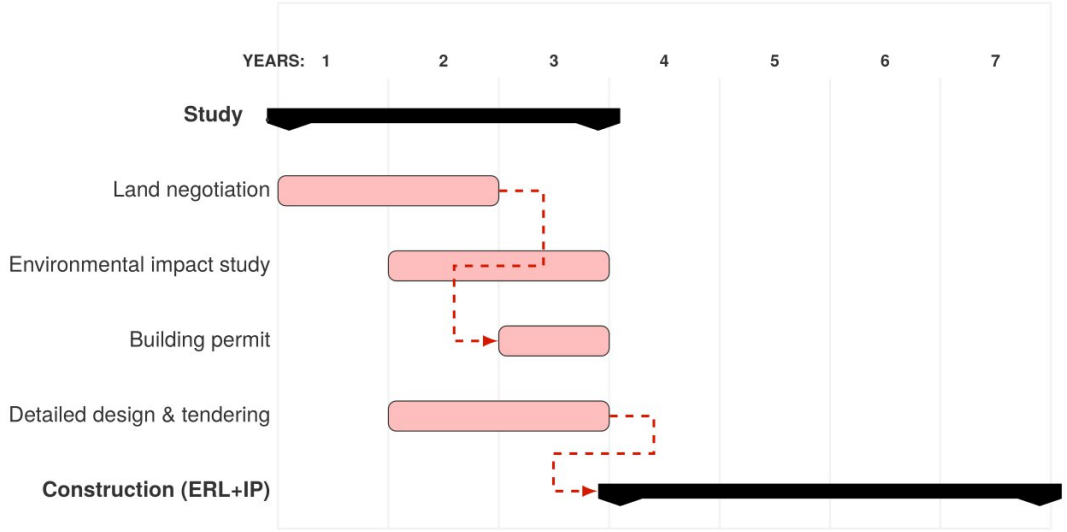


S. Dalla Torre (DIS 2025)



Feasibility & cost of LHeD

- LHeC: decade-long phasing, from the first land negociation to the end of construction
- First estimate of total LHeD cost: 360 MCHF
  - accounting for recent re-estimation of LHC/HL-LHC upgrades costs, not including magnet, beampipe, DAQ/trigger, mechanical structure, & infrastructure
  - largest fraction of cost (270 MCHF, 71%) from silicon sensors in forward calorimeters → compromise possible through e.g. choice of different sampling fractions, coarser granularity, re-use of other experiments' detectors, ...
  - major components of the detector concept inherited from ATLAS (+ CMS/ALICE/...) → assessing the various design choices (e.g. calorimetry, muon stations) might reduce the overall cost



- Computing resources: estimated at O(10%) of ongoing LHC experiments
  - development of a data acquisition scheme (either triggered, or streaming) is crucial
  - expected O(10kHz) rate for storage on tape, more study of the physics & background rates required
- Same level of staffing required as other LHC experiments → large opportunity for early-career researchers

Summary & outlook

- LHeC baseline detector based on **most recent**, but **already available** technology
  - aiming at minimising R&D programmes to be carried out
  - major challenges still in MDI (detector protection + increase of detector coverage)
  - further SR optimisation & developments foreseen for the shielding part

- Many developments ahead for the computing environment
  - major challenge in data collection: streamed DAQ, with no online triggering
  - offline software: fast simulation already available (Delphes) ; full simulation + software being prepared using widely used tools (DD4Hep, Key4Hep etc.)

- Detectors technologies: synergies possible with other future projects: EIC, but also ALICE 3!
  - room for compromises between design choices, large benefits & systematic uncertainties reduction from operating a single detector in several modes (AA/pA/pp + eA/ep)

Thanks for your attention!

Backup

Abstract

The Large Hadron electron Collider (LHeC) is the proposal to deliver electron-proton/nucleus collisions at CERN using the LHC beams and a 50 GeV electron beam from an Energy Recovery Linac. While initially foreseen [1] for concurrent electron-hadron and hadron-hadron operation, a standalone electron-hadron operation phase has been proposed [2] in view of the current LHC schedule. Thus, the LHeC becomes a bridge from the HL-LHC to the next flagship at CERN, and one of the possible projects in the 2026 Update of the European Strategy for Particle Physics [3], were the FCC-ee as plan A not feasible.

In this talk we review the status of the design of a detector for the LHeC, and its extension to the FCC-eh. We present the present technology choices with their expected performance. We also analyse the possible synergies with future projects like ePIC, ALICE3 and detectors for colliders. Finally, we review the feasibility and cost of such a detector.

[1] P. Agostini et al. (LHeC/FCC-he Study Group), J. Phys. G 48, 110501 (2021), arXiv:2007.14491 [hep-ex].
[2] F. Ahmadova et al., e-Print: 2503.17727 [hep-ex].
[3] The European Strategy for Particle Physics: 2026 Update - Recommendations by the European Strategy Group