An Experiment for Electron-Hadron Scattering at the LHC

D. Britzger and Y. Yamazaki for

K. D. J. André[1,2], L. Aperio Bella[3], N. Armesto[a,4], S. A. Bogacz[5], D. Britzger[6], O. S. Brüning[1], M. D'Onofrio[2], E. G. Ferreiro[4], O. Fischer[2], C. Gwenlan[7], B. J. Holzer[1], M. Klein[2], U. Klein[2], F. Kocak[8], P. Kostka[2], M. Kumar[9], B. Mellado[9,10], J. G. Milhano[11,12], P. R. Newman[13], K. Piotrzkowski[14], A. Polini[15], X. Ruan[9], S. Russenschuk[1], C. Schwanenberger[3], Y. Yamazaki[16]

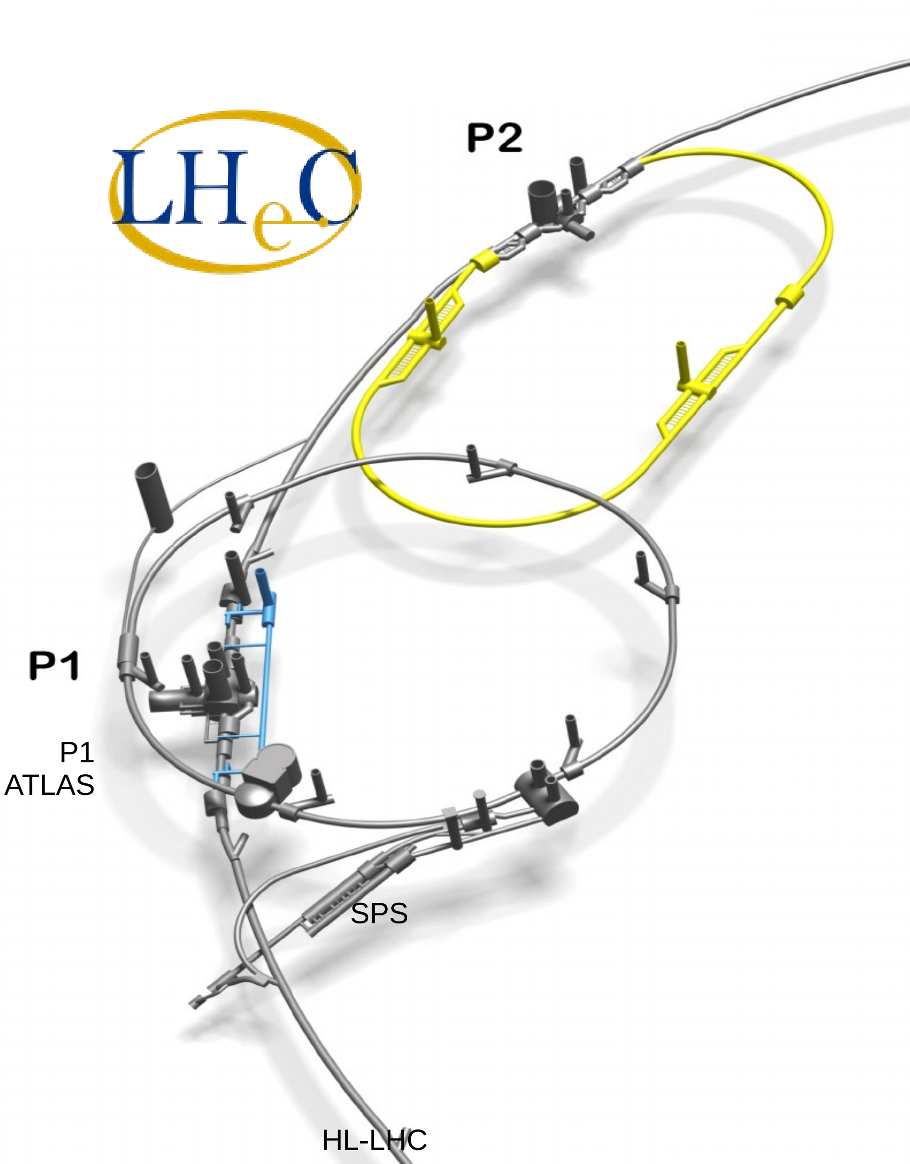
Off-shell conference, 07.07.2021

MAX-PLANCK-INSTITUT FÜR PHYSIK

LHeC

KOBE UNIVERSITY

Proposal for the 2030s – LHeC



LHeC – ep data in 2030s

- ERL electron ring attached to HL-LHC
- Similar concept than FCC-eh
  but realisable much earlier
- E_e = 50 GeV, L~10^{34}cm^{-2}s^{-1}

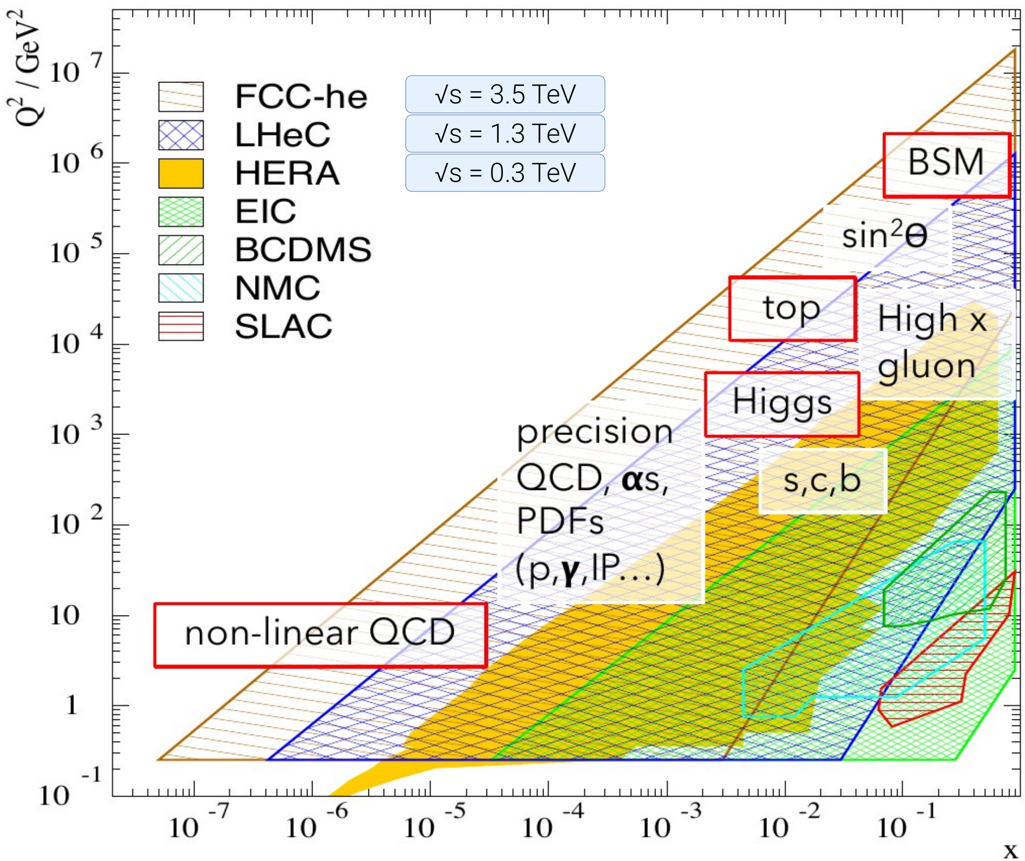
LHeC

- √s ~ 1.3 TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- Detector may possibly be shared with ALICE3/HI
  ((talk by F. Carnesecchi))

Relocatable

- electron-accelerator components can be relocated from HL-LHC to FCC-hh

Kinematic plane



LHeC

- Rich physics program at all scales
  - Higgs physics in NC and CC DIS
  - Top quark production
  - BSM physics and searches
  - Precision QCD
    Proton structure, substructure, strong coupling constant, jet physics, heavy quarks, ...
  - Electroweak physics
  - Heavy ion programme
  -

Low and high luminosity,

low and high-scale physics

→ Intense electron beam from ERL

Accelerator concept

Energy-recovery linac – a green technology?

Energy-recovery linacs (ERL)

- Well-proven accelerator concept
- Many facilites exist world-wide

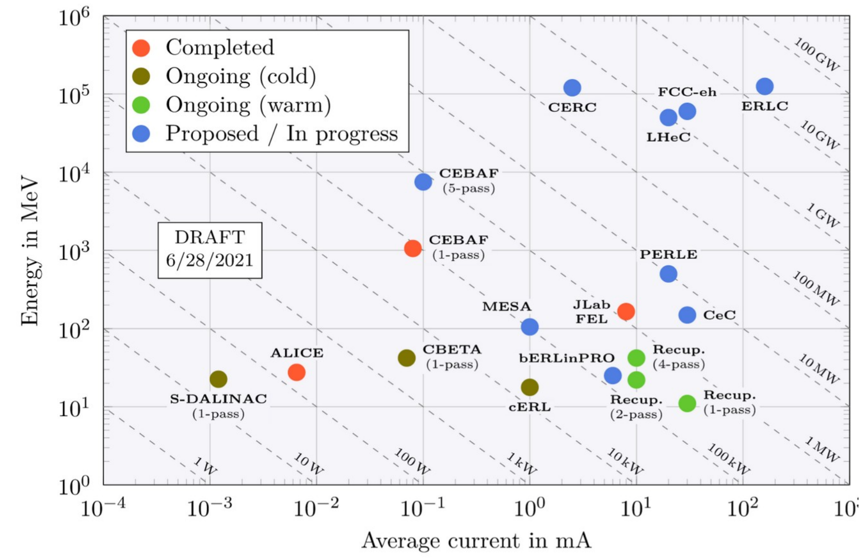
A new facility comprising all essential features ?

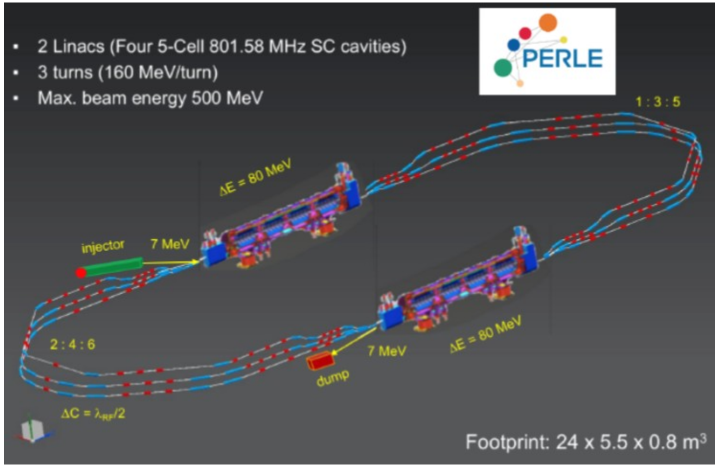
- high-current & high-energy & multi-pass
- optimised cavities & cryo-modules
- and a beam for collider experiments

PERLE at Orsay

- ERL demonstrator facility for LHeC needs
- 20mA, 802 MHz SRF, 3 turns → operation 2025+

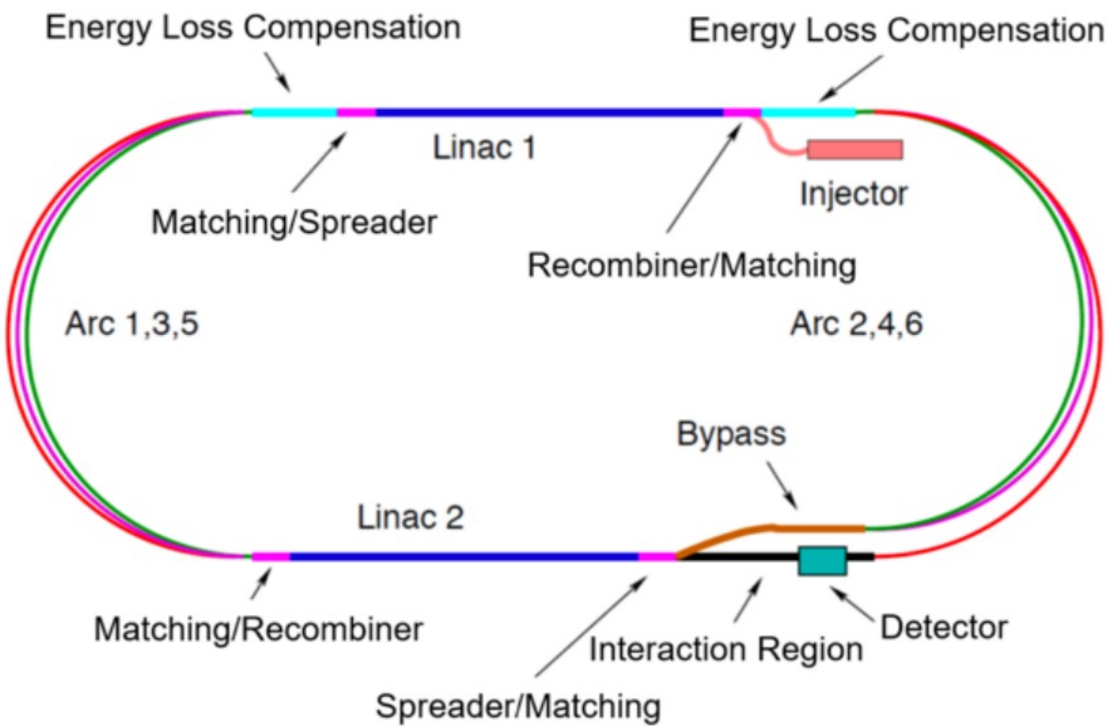
EPPSU 2020 strategy
Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. [...] The technologies under consideration include [...] energy recovery linacs





Accelerator Considerations

ERL geometry

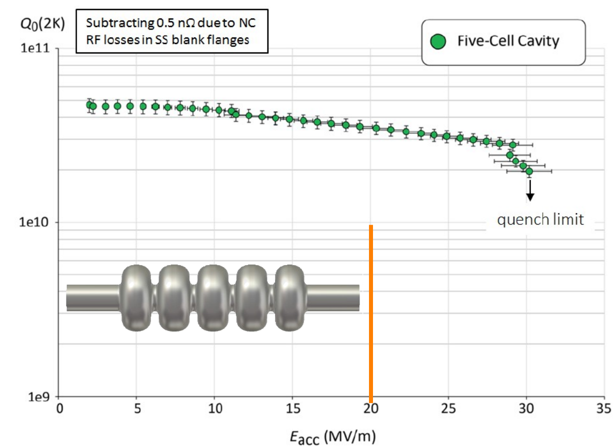


- Two SC linac accelerators
- three-pass return arcs

- ERL main parameters

Parameter	Unit	Value
Beam energy	GeV	50
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
trans. norm. emittance	μm	30
RF frequency	MHz	801.58
Acceleration gradient	MV/m	20.06
Total length	m	6665

- Q-parameter of 5-cell prototype



Beam optics & Front-to-End Tracking studies

Electron beam optics

- multi-turn acceleration to 50 GeV
- Sequence of linacs and arcs yield strong focussing and large vertical β-function in the mini beta quadrupoles
- Other peaks between linacs and arcs

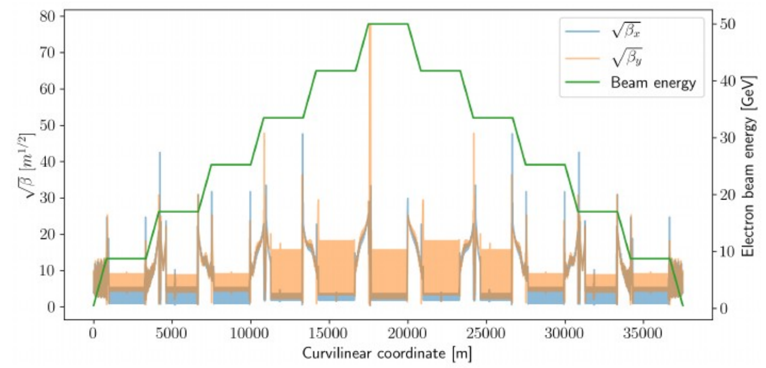


Fig. 22 Representation of the beta functions and the beam energy along the multi-turn ERL operation.

Front-to-end Tracking

- Emittance growth during the three turn acceleration
- Good agreement between anlytic result and simulation
- Excellent beam transmission and energy recovery efficiency is achieved, including synchrotron radiation and beam-beam disruption.

ERL size	$1/3\ C_{LHC}$	$1/4\ C_{LHC}$	$1/5\ C_{LHC}$
$\gamma\varepsilon_x^{\mathrm{inj}}$ [µm rad]	25.4	22.7	15.1
$\Delta p/p$ at IP	0.021 %	0.029 %	0.041 %
transmission	99.93 %	98.89 %	98.40 %
energy recovery	97.9 %	96.7 %	95.4 %

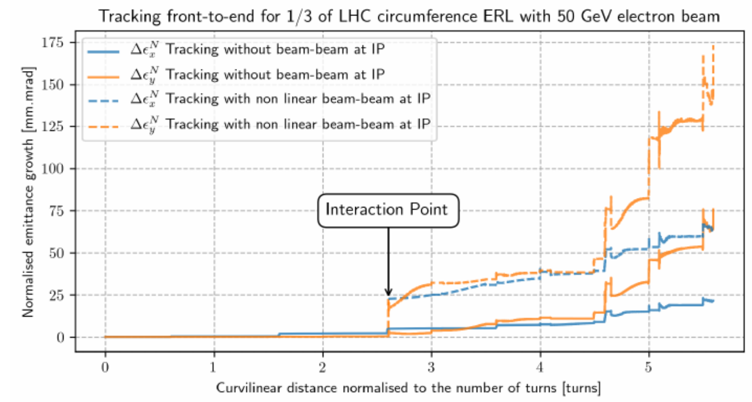
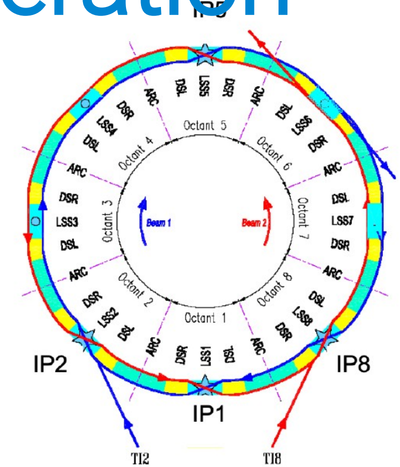


Fig. 23 Emittance growth along the curvilinear coordinate for the largest ERL design, corresponding to 1/3 of the LHC circumference.

Concurrent *eh* & *hh* Operation

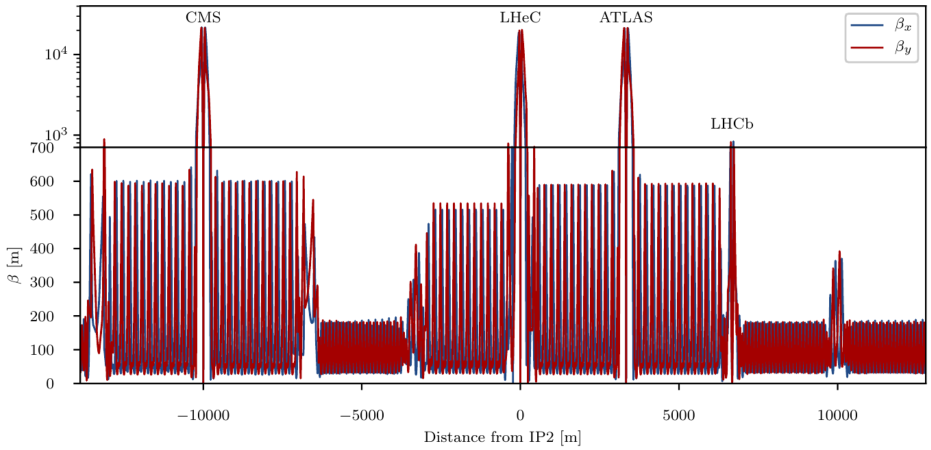
Two HL-LHC operation modes

- *hh* collisions at IP1,2,5,8 – no *e* beam
- *eh* collisions at IP2 <u>and</u> *hh* at IP1,5,8
  → non-colliding *p*-beam: symmetric orbit bump & vert. crossing

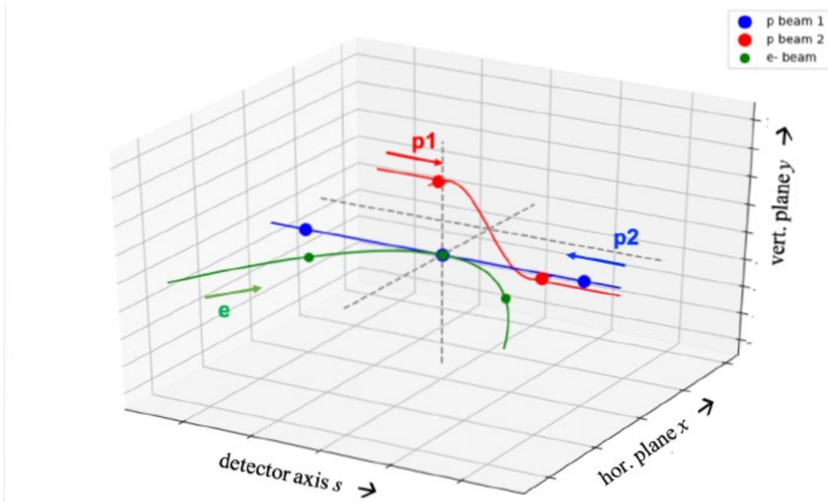


Three beam interaction region

- LHC proton beam optics



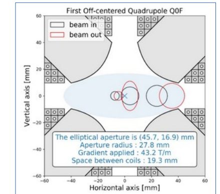
Schematic view of the three beams at IP2



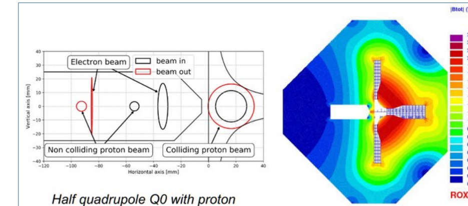
At IP2: same vertex for all interaction types (ep, eA, pp, AA) → optional hh running with LHeC-detector.

Interaction region design

Schematic view of focusing & beam separation scheme



Off-center quadrupole QOF/D with proton and electron beam envelopes

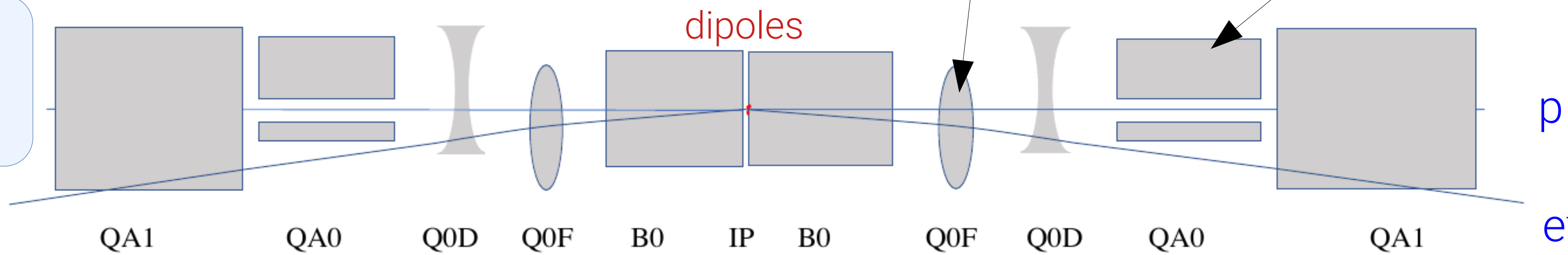


Half quadrupole Q0 with proton and electron beam envelopes

Half quadrupole Q0 magnet design

Different beam rigidities

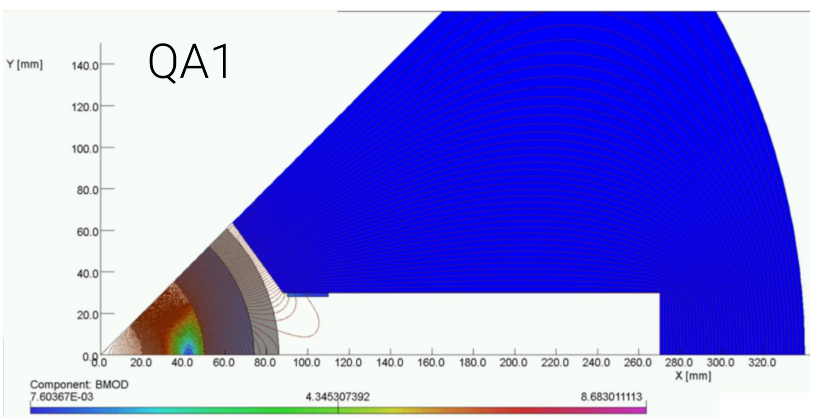
$$(B * \rho)_p = 23\,333\,\mathrm{T\,m}$$
$$(B * \rho)_e = 167\,\mathrm{T\,m}$$



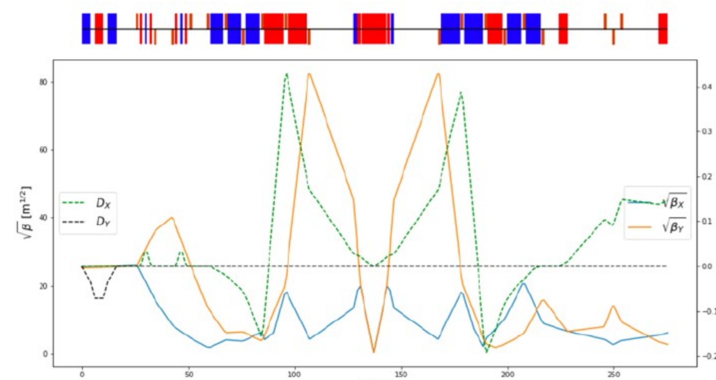
Same beam sizes at IP

$\beta_x(p) = \beta_x(e) \qquad \beta_y(p) = \beta_y(e)$

- First SC proton quadrupole (QA1)
  → needs to re-match the proton optics
  → field-free region for electron beam

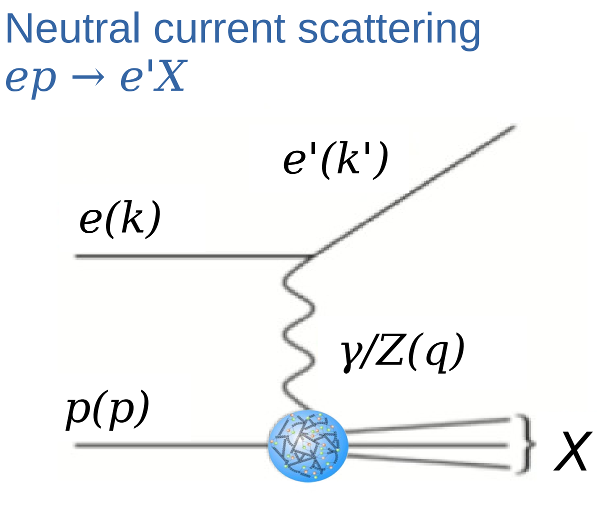


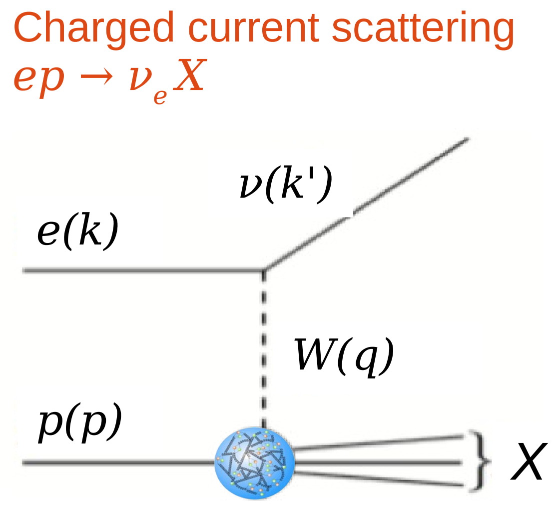
optical functions of the electron beam

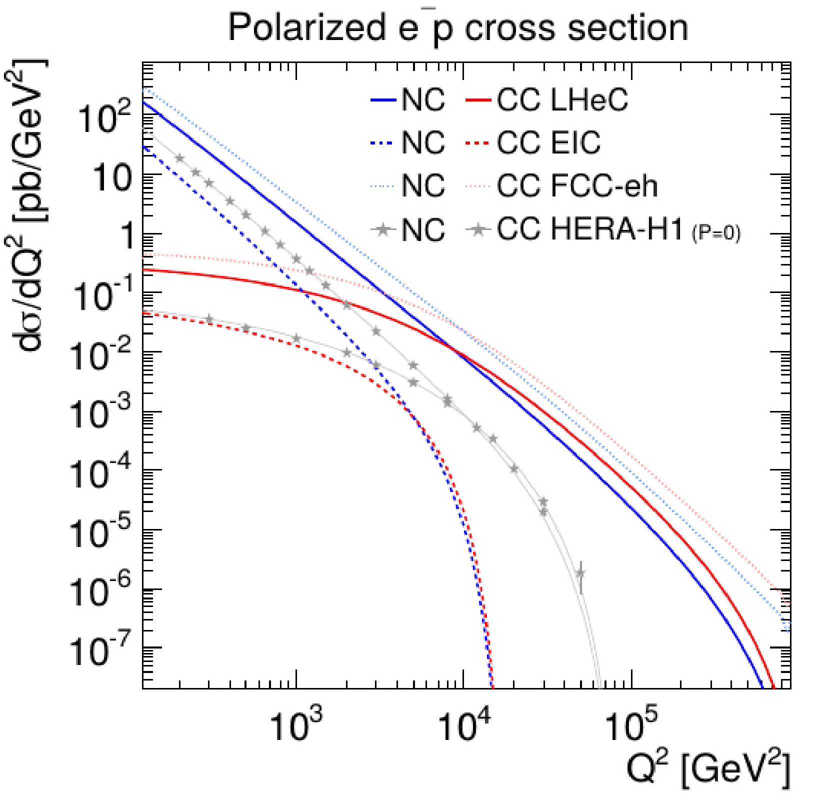


Physics

Deep-inelastic electron-proton scattering



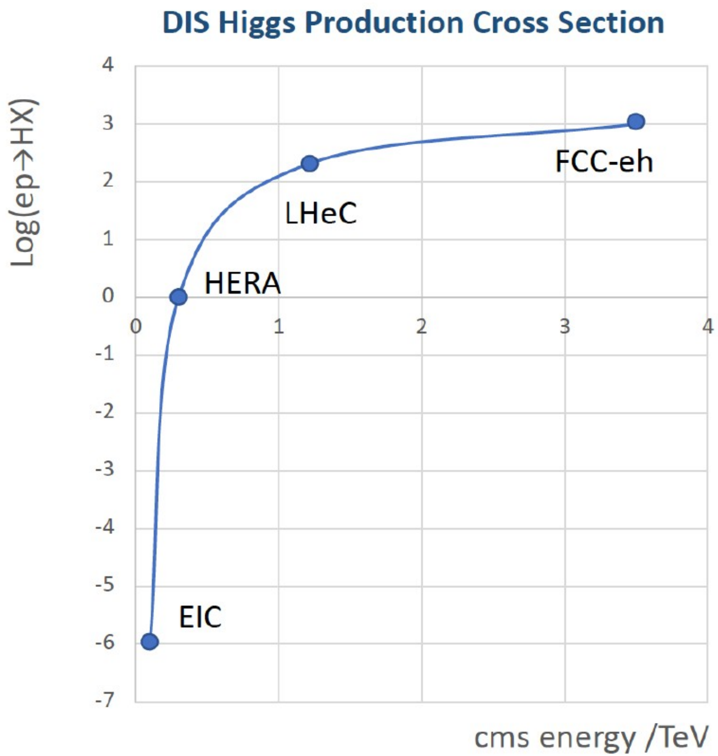




Deep-inelastic electron-proton scattering mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

Direct probe the structure of the proton → bound together by QCD dynamics
→ Very rich physics in 'hadronic final state' *X* ...

Higgs physics

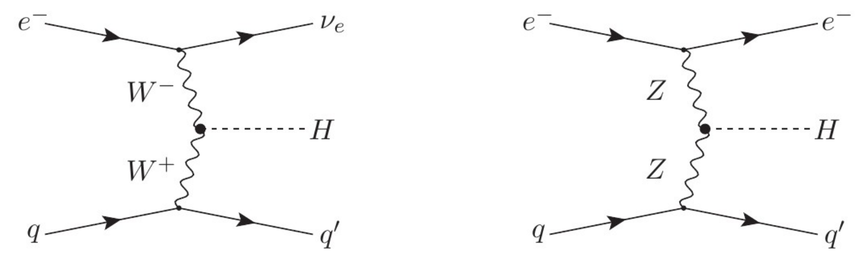


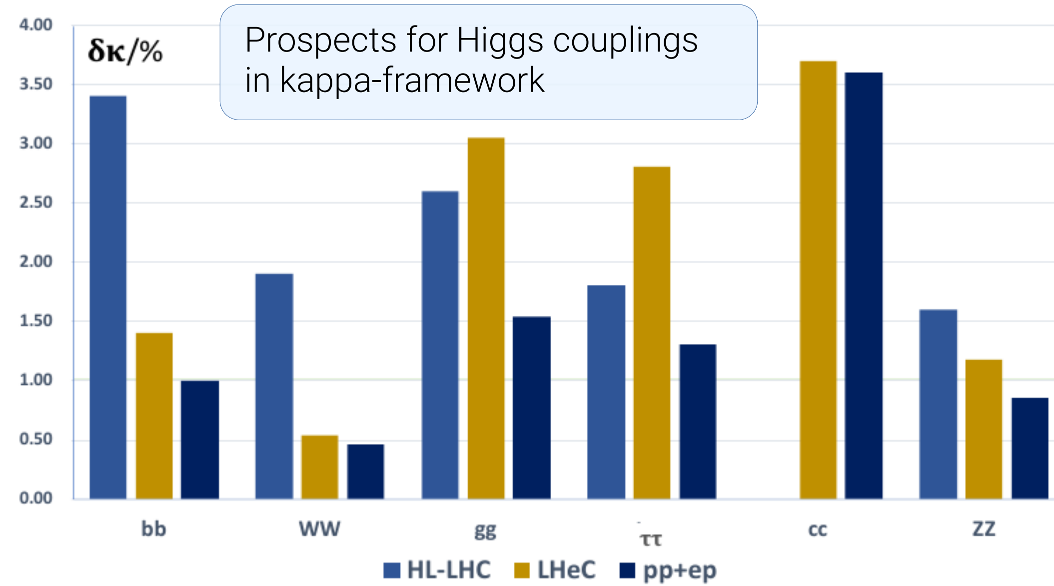
- Higgs-production cross section ~ 200pb
- Sensitivity to six decay channels

  bb, WW, gg, ττ, cc, ZZ

  (see also talk by M. Schott)

Higgs in CC and NC DIS

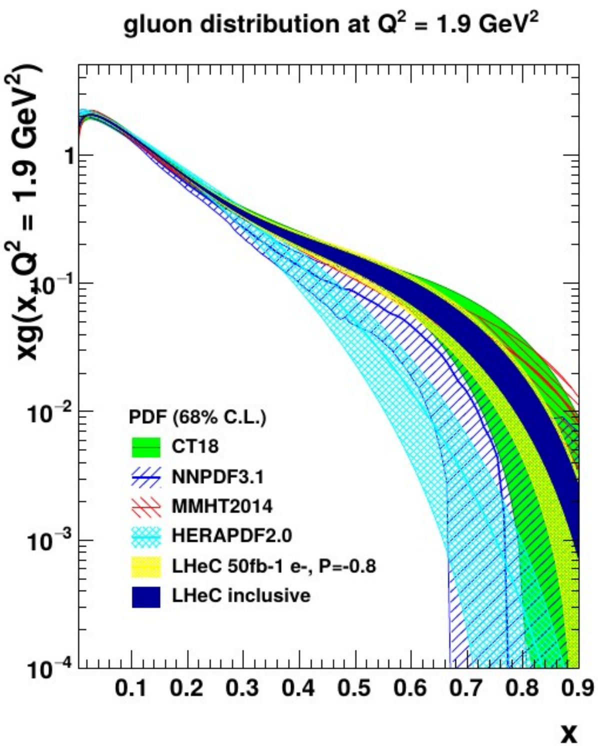


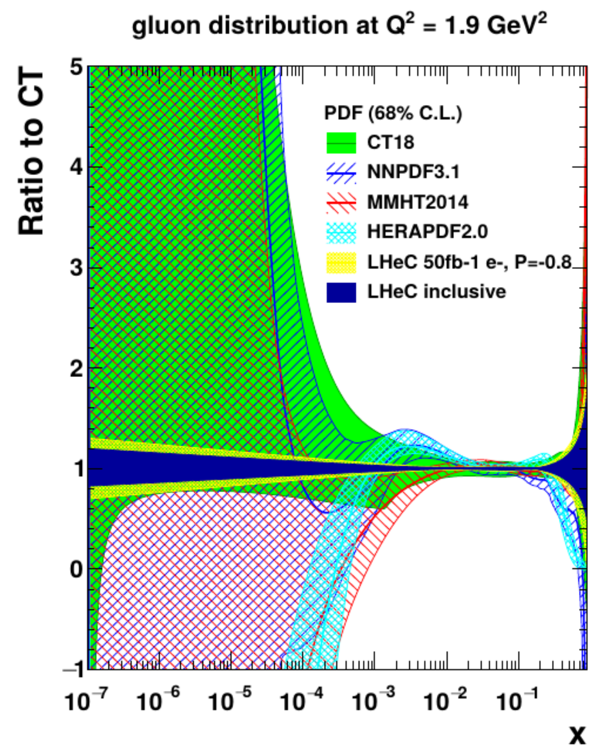


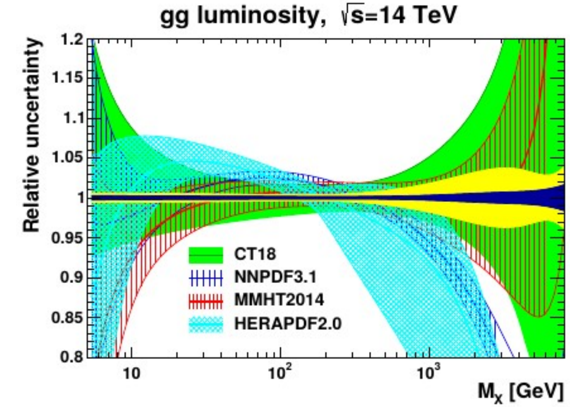
Proton structure measurements

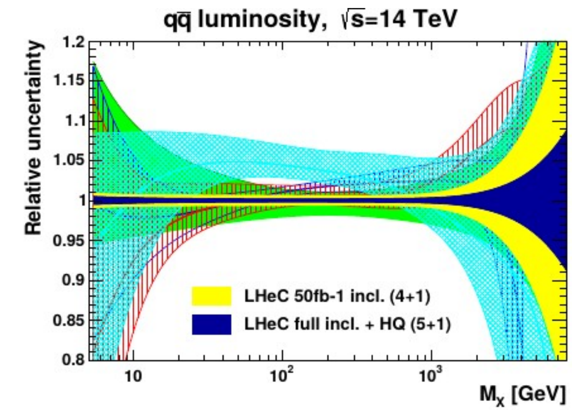
Color-neutral particle probes the interior of the proton

- Parton distribution functions (PDFs) of the proton with unprecedented precision
- Full determination of all flavors









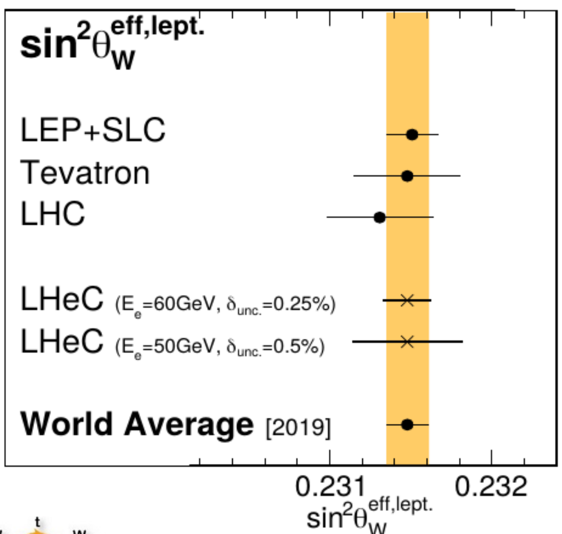
Precision Standard Model physics

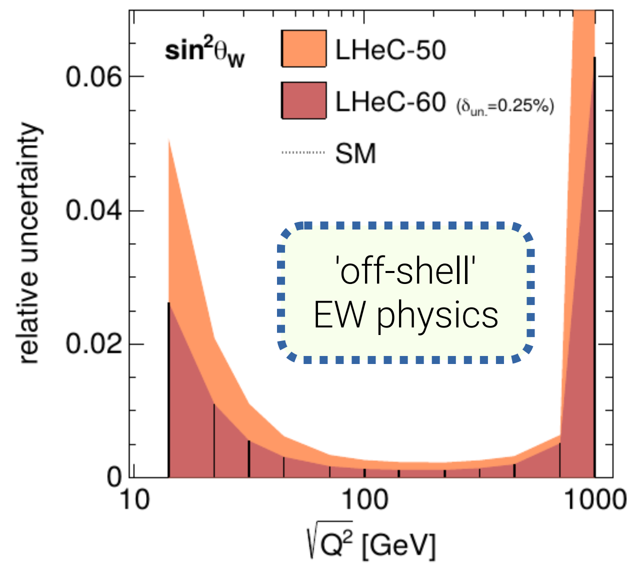
Electroweak sector

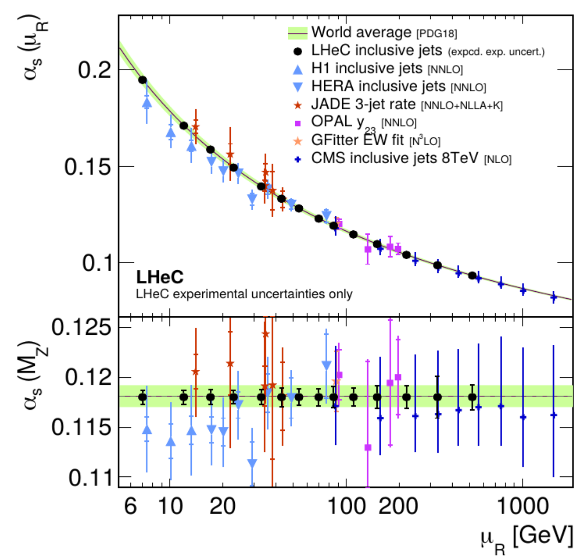
- Precision EW physics through inclusive DIS measurements (high-Q^2)
- EW physics in t-channel
  → Unique probe of scale-dependence
  → EW physics with charged currents

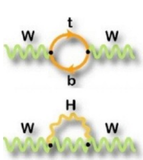
Strong sector

- All aspects of QCD with highest precision:
  Jet physics, heavy flavors (charm, beauty), fragmentation, hadronisation, etc…
- Strong coupling: ±0.00016 (0.15%)



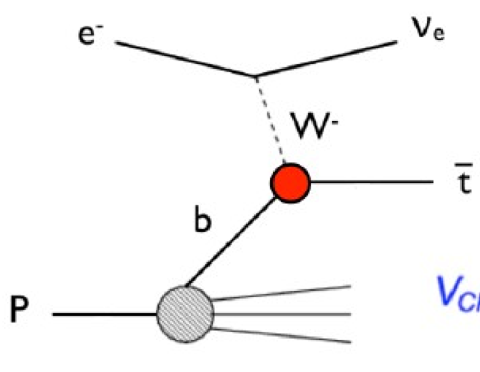






'Running' of fundamental SM couplings → Test of SM-gauge structure and sensitivity to BSM

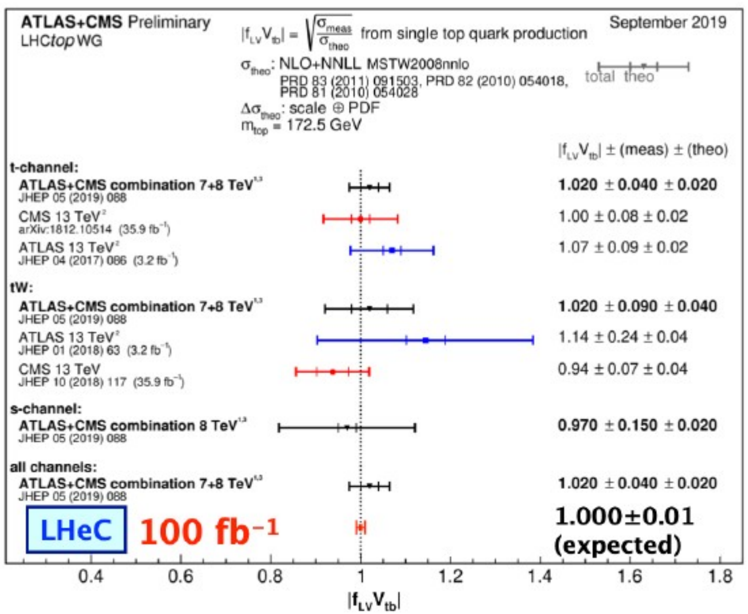
Top Quark physics



Top quark physics

FCNC, V_{tb}, V_{ts}, top-PDFs, ...

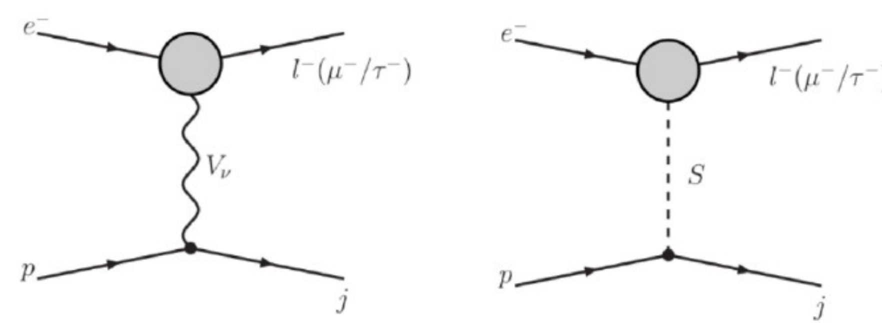
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



BSM

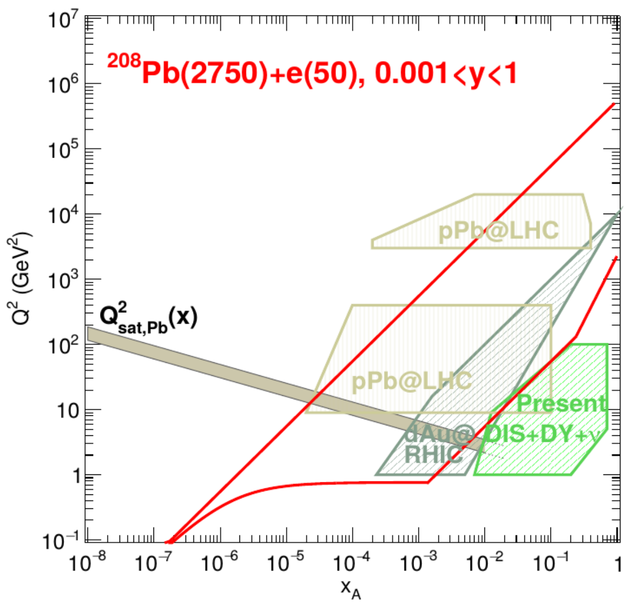
BSM & searches

- Leptoquarks
- SUSY: R-parity violating & R-parity conserving (prompt Higgsinos)
- BSM Higgs: charged higgs....
- Long-lived particles
- anomalous couplings (VVV,VVVV)
- Contact-interactions,
- Compositness,
- high-precision EW,
- sterile neutrinos, ... , ... , ... , ...



Heavy ion physics – eA and *AA* physics

eA unexplored kinematic region



•

Nuclear structure

- Complementary with HL-LHC
  (if factorization holds to such low-x?)
- LHeC much cleaner measurements, full flavor sensitivity, TMDs, GPDs, ...

pp and AA collisions

The updated accelerator-optics define the IP's of eA, AA and pp running-mode at the same vertex point

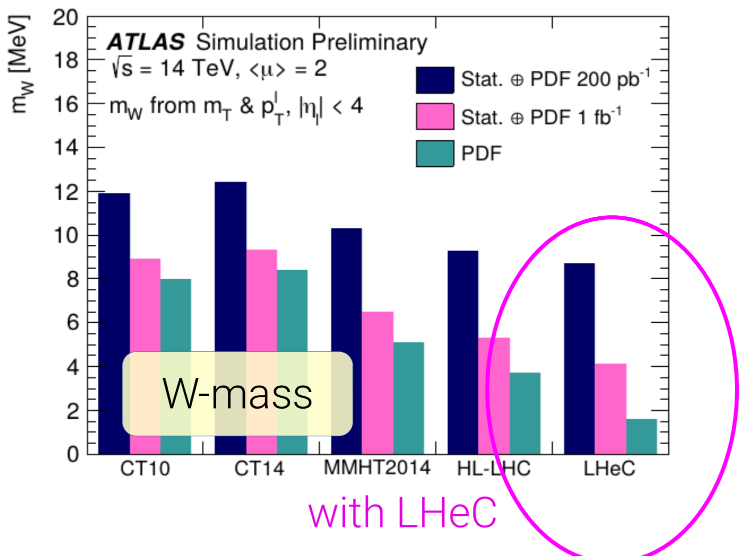
Full physics programme of *pp* and AA collision thinkable
→ 'only' subject to beam-time discussion

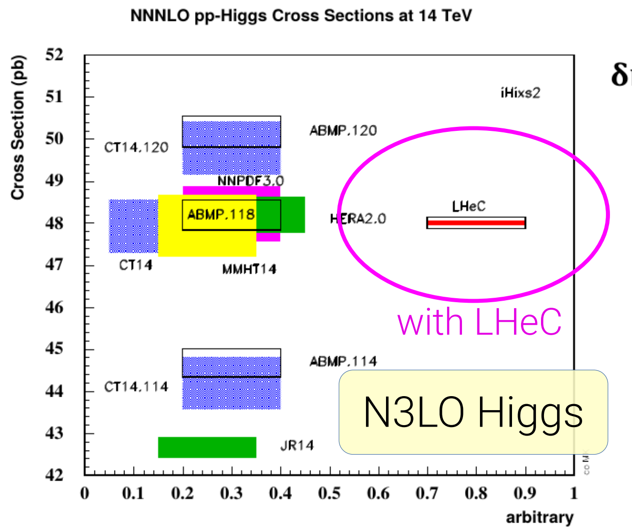
Cross-calibration of measurements in ep, pp, AA (syst. uncertianties, normalised measurements)

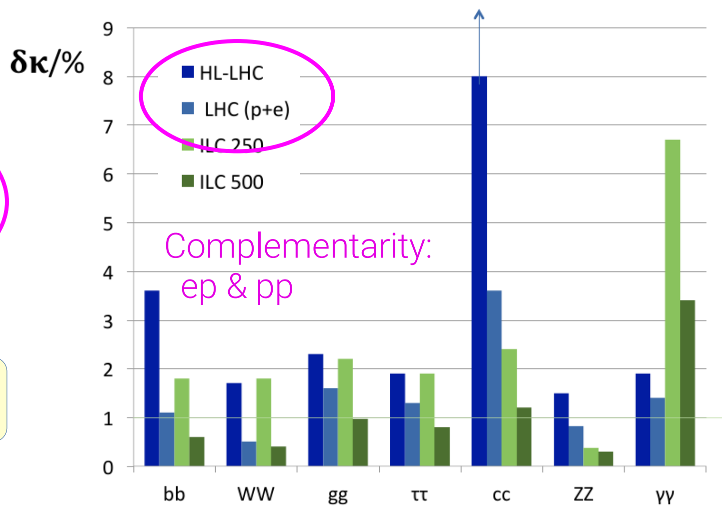
Benefit from excellently calibrated DIS-detector

Complementarity with *pp* physics at HL-LHC

- **At LHC…** many measurements are (already) nowadays limited by 'modelling' uncertainties, like PDF uncertainties, parton shower uncertainties, $\alpha_s(M_Z)$, etc…
  Several phenomenological interpretations are limited (N3LO Higgs,…), Searches …
- Low-x: gluon is poorly known nowadays (saturation, BFKL, etc…)
- High-x:







Precision measurements at LHeC, and the complementarity of the measurements will greatly turn the HL-LHC into a precision Higgs facility

Detector requirements

Detector Demands at LHeC

Neutral current (NC) $ep \to eX$

- Scattered electron e towards small angle (< 179°) to access low-Q^2events
- Hadron (X) forward-going (high-x)
- Flavour tagging for decomposing PDFs

Charged current (CC) $ep \to \nu X$

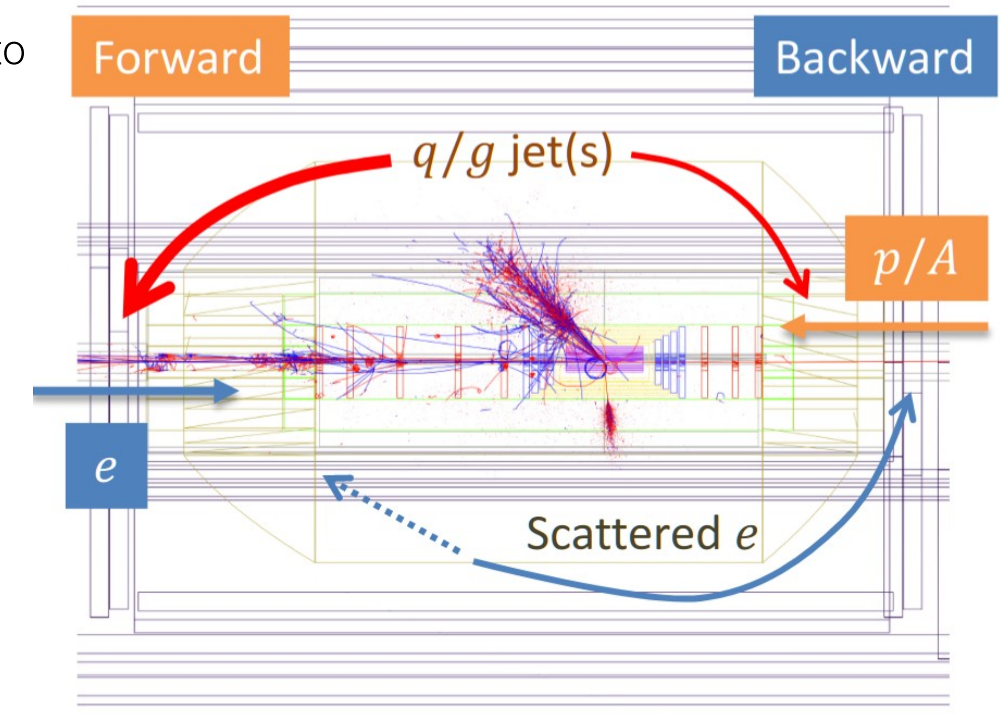
- missing pT: need hermetic detector*small beam holes (<1°) + good calorimeter energy resolution

Higgs couplings

- Flavor tagging in forward direction
- Jet resolution for jet mass (m_H) reoncstruction

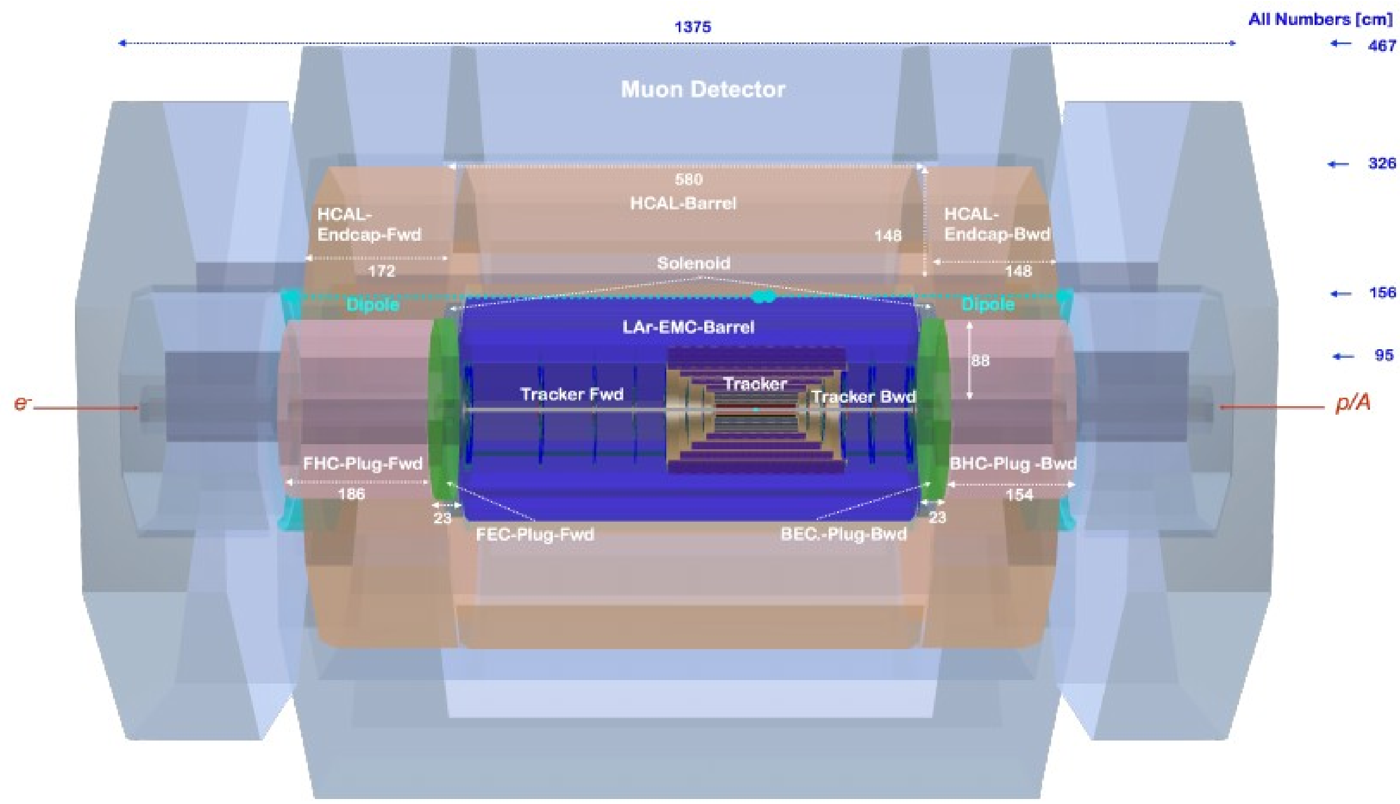
Diffraction, top-physics, photoproduction, BSM, …

No pile-up, much less radiation, etc…



Additional demands for AA (and pp) physics programme

Updated baseline detector design



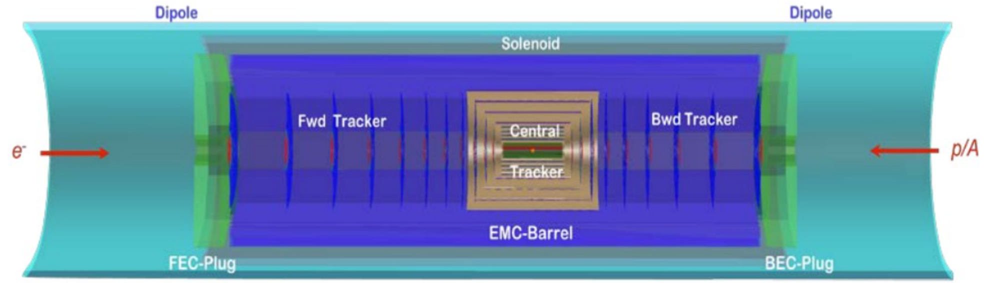
- Based on LHC & HERA experience & HL-LHC plans
- Aim: compact, modular and very hermetic detector
- Coverage: 1 to 179 degrees

Main components

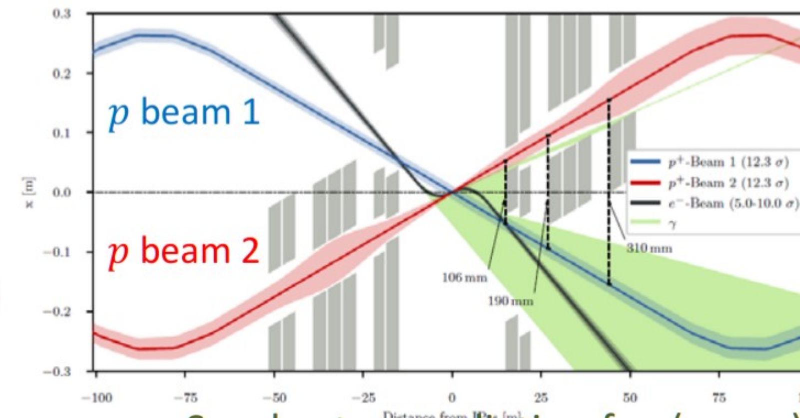
- High acceptance silicon tracking system
- LAr electromagnetic calorimeter
- Detector & steering magnets
- Iron-Scintillator hadronic calorimeter
- Forward backward calo (Si/W, Si/Cu, …)
- Forward (p/n) & Backward (e/γ) taggers
- Muon system

Magnetic field

- Dipole magnet integrated in the detector to bend electron beam
  - Beam-2 p and e brought in head-on collisions
  - Beam-1 traversing unaffected

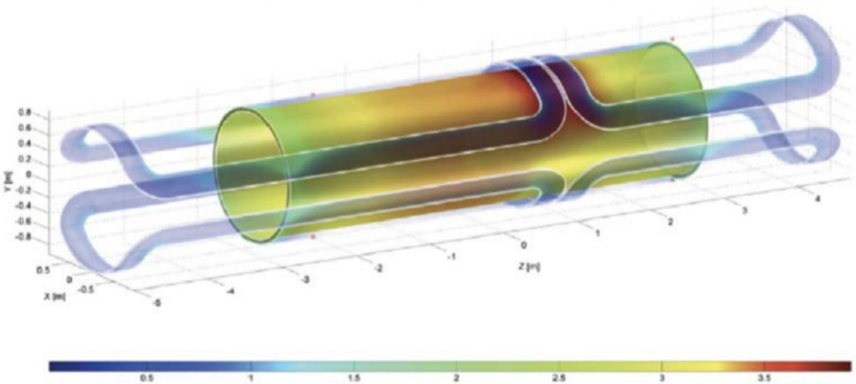


Re-desigend & optimised IR in CDR2020
Further improvements for this conference



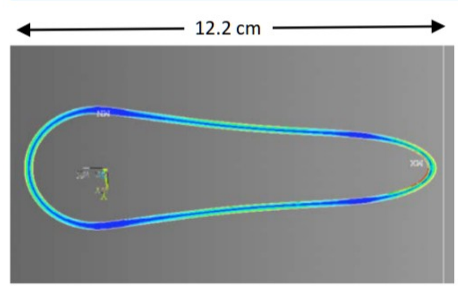
Synchrotron radiation fan (green)

- Updated Field values:
  - 3 Tesla (solenoid); 0.15 Tesla (dipole)

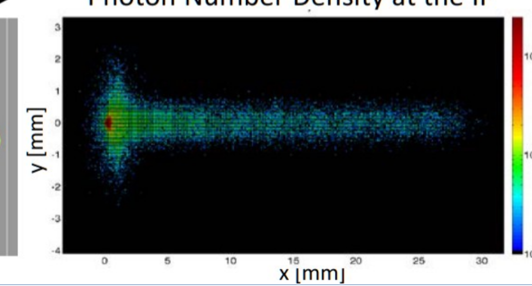


Circular/elliptical thin beam pipe to accommodate the outgoing synchrotron radiation fan:

- Specs & Studies from LHeC CDR: Beryllium 2.5-3 mm thickness
- Circular(x)=2.2cm; Elliptical(-x)=-10., y=2.2cm



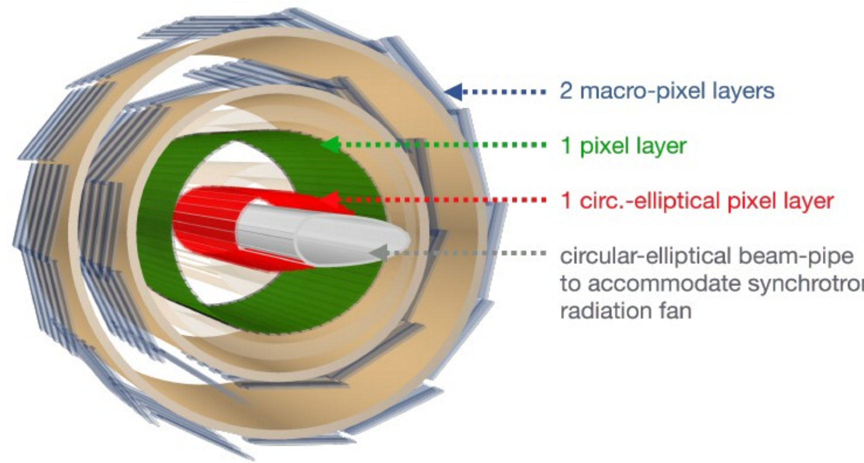
Photon Number Density at the IP

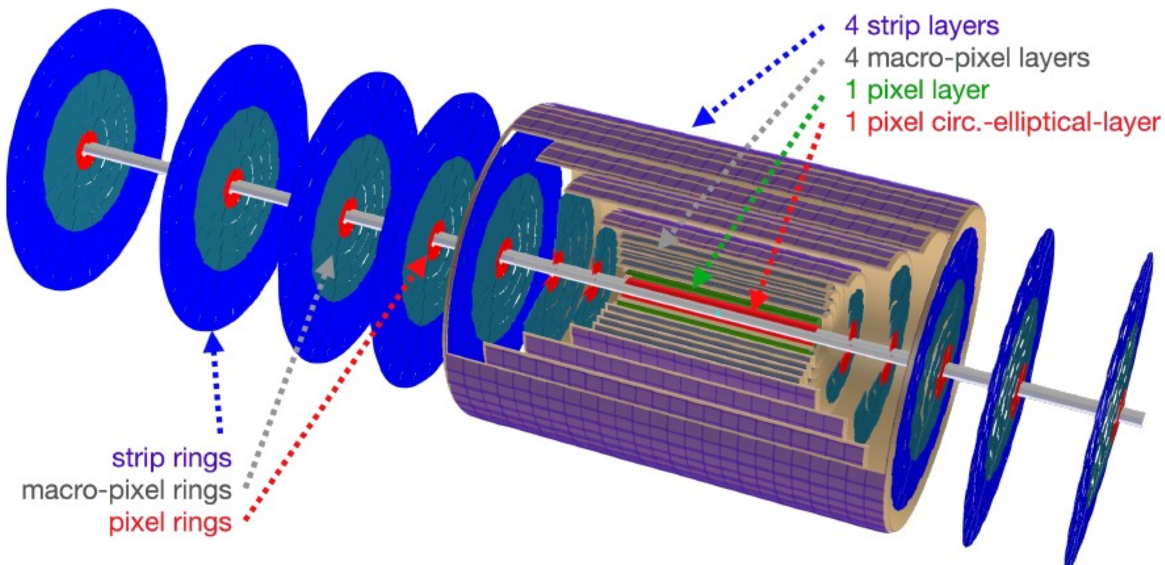


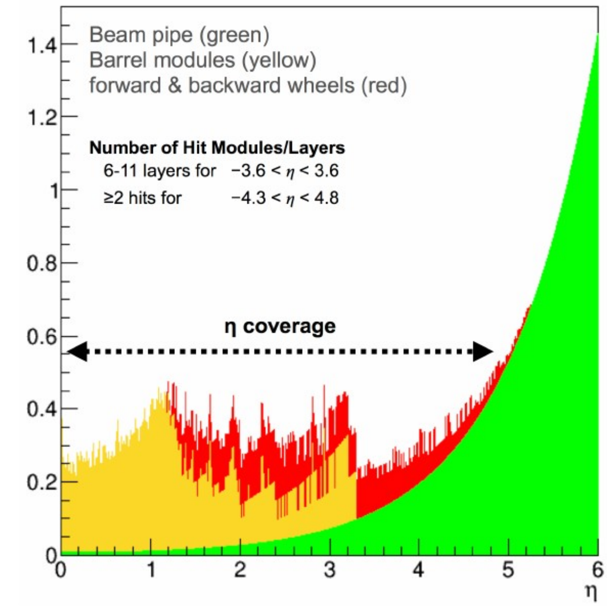
Central tracker

Option: Low-material tracker by DMAPS

- CMOS sensors (HV-CMOS) with integrated readout electronics
- Thin sensors: small material budget
- 5−8 layers for -3.5<η<4
- ≥2 hits for -4.2<η<5







Calorimetry

High-performance barrel calorimeter (EMC)

- New baseline design: Liquid Argon EMC with accordion structure (ATLAS like)
- EMC inside solenoid with shared cryostat

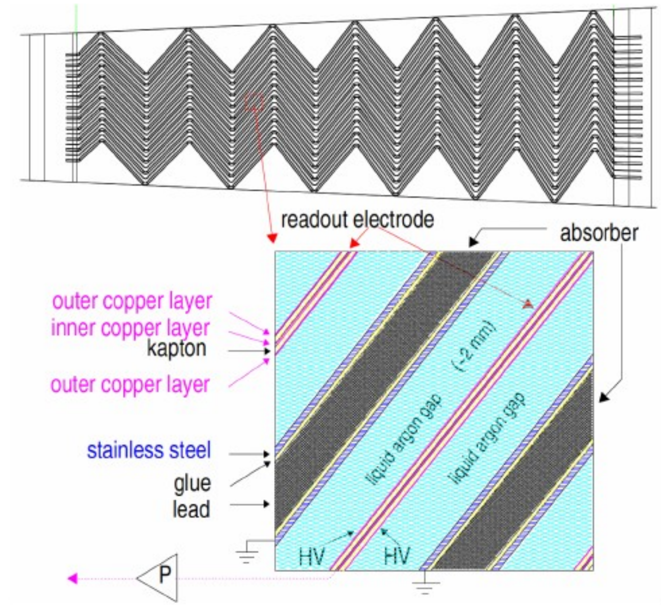
Hadronic calorimeter in barrel

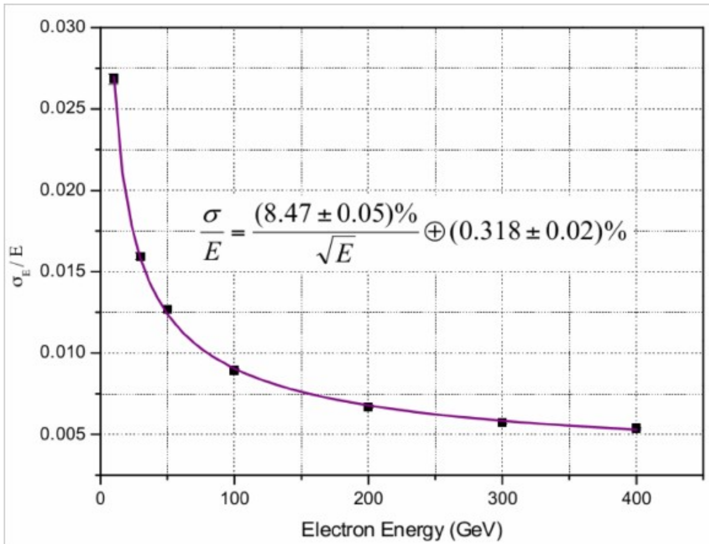
- sampling calorimeter (steel & scintillating tiles)

Fwd/Bwd Calorimeter

- Fine-segmented plugs with compact shower
- Radiation hard design (Fwd), e/π-separation (Bwd)

Baseline configuration		η coverage	angular coverage
EM barrel	LAr	$-2.3 < \eta < 2.8$	$6.6° - 168.9°$
Had barrel+Ecap	Sci-Fe	(~ behind EM barrel)	
EM+Had forward	Si-W	$2.8 < \eta < 5.5$	$0.48° -$
EM+Had backward	Si-Pb	$-2.3 < \eta < -4.8$	$-179.1°$





Muon System

Muons

- Higgs, direct W, LFV, semi-leptonic deca
- tagging, trigger, tracking,...

Baseline layout of muon system

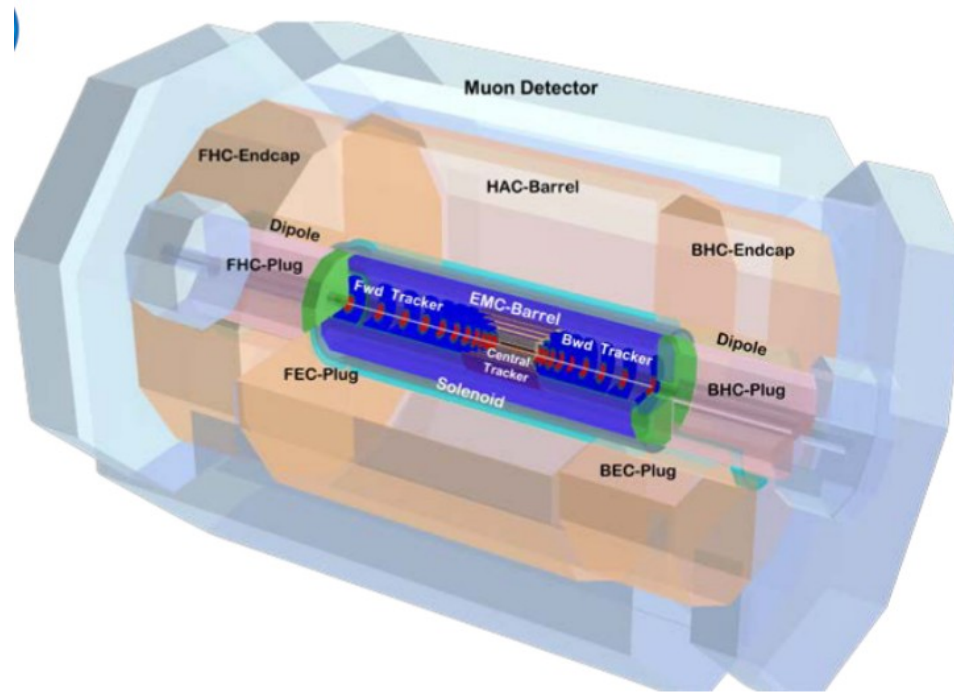
- Use solenoid return as B-field
- Good tagging & trigger capabilities
- 2 stations, each with 3 layers

Muon system

- Thin RPC (1mm gas gap) → high rate & timing (<1ns)
- sMDT φ = 1.5cm drift tubes for precise position measurement

Possible extensions & studies

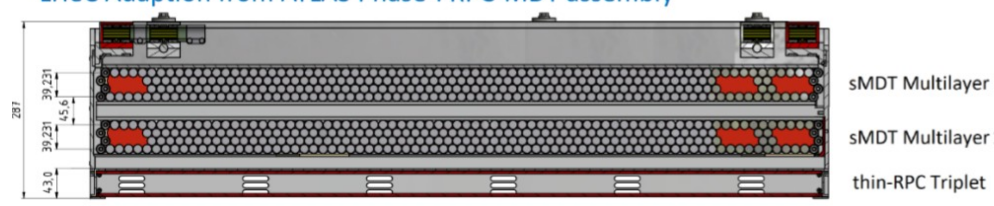
- Fwd toroid or outer solenoid
- Explore twin solenoid option



Some Specifications:

- Total area ~ 400 m²
- Single unit detect: 2-5 m²
- Max.rate: 3 kHz/cm²
- Rad. Hard.: 0.3 C/cm²
- Time res.: ~0.4 ns
- Spatial res.: 1mm (RPC); 80 µm (MDT single tube)

LHeC Adaption from ATLAS Phase-I RPC-MDT assembly



Summary

The proposed LHeC project

- 50 GeV electron from ERL on 7TeV proton (√s=1.3TeV), synchronous with LHC & high-luminosity *ep* collisions

Very rich physics programme

- Higgs, Proton structure, QCD, heavy flavors, Electroweak, HI, top-quark, searches, BSM, etc...
- Complementary and supportive to *pp* physics at HL-LHC

Recent updates

- Accelerator-optics define the IP's of *e*A, AA and pp running-mode at the same vertex point
- B-field 3.0T, HV-CMOS tracker with 10 layers, accordion-LAr, ...
- Larger silicon tracker (now 80cm in diameter)

- Apparent overlap with HI (A3) proposal (tracker, physics, LHC-P2, ...)
  → Why not combine the two and make the best out of IP2@HL-LHC?