Topical Review

Exploring the energy frontier with deep inelastic scattering at the LHC

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Abstract

A proposal is described for complementing the intense, high energy proton and ion beams of the Large Hadron Collider (LHC) with a novel electron energy recovery linac (ERL) to provide a next generation electron-hadron collider facility of more than 1 TeV center-of-mass energy. This Large Hadron Electron Collider (LHeC) will substantially extend the kinematic range covered by the first ep collider, HERA, and surpass its luminosity by a factor of several hundreds. This configuration will be a microscope for the substructure of matter with unprecedentedly clean resolution and a facility for new physics in the Higgs, strong interaction and electroweak sector with a strong discovery potential. The paper also describes the accelerator design and its main characteristics. As such it had been submitted to the deliberations on the future of European particle physics.

Keywords: deep inelastic scattering, large hadron electron collider (LHeC), energy recovery linear electron accelerator

(Some figures may appear in colour only in the online journal)

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Executive summary

The Large Hadron Collider determines the energy frontier of experimental collider physics for the next two decades. Following the current luminosity upgrade, the LHC can be further upgraded with a high energy, intense electron beam such that it becomes a twin-collider facility, in which *ep* operates concurrently with *pp*. A joint ECFA, CERN and NuPECC initiative led to a detailed conceptual design report (CDR) [1] for the Large Hadron Electron Collider (LHeC) published in 2012. The LHeC uses a novel, energy recovery linear (ERL) electron accelerator which enables TeV energy electron–proton collisions at high luminosity, exceeding that of HERA by nearly three orders of magnitude. The discovery of the Higgs boson and the surprising absence of BSM physics at LHC demand to extend the experimental base of particle physics suitable to explore the energy frontier, beyond *pp* collisions at the LHC. Following a mandate of the CERN Directorates and guided by an International Advisory Committee, this motivated representatives of more than 100 institutes to proceed, as sketched here, with the development of the accelerator, physics and detector prospects for the LHeC with the intention to publish an update of the CDR in early 2019 [2].

The very high luminosity and the substantial extension of the kinematic range in deep inelastic scattering (DIS) compared to HERA, make the LHeC a uniquely powerful TeV energy collider, which rests on a maximal exploitation of the LHC infrastructure. Realising an 'Electrons for LHC' [3] programme would create the cleanest, high resolution microscope accessible to the world, one may term a 'CERN Hubble Telescope for the Micro-Universe'. It is directed to unravel the substructure of matter encoded in the complex dynamics of the strong interaction, a necessary input for future hadron colliders, including HL-LHC. Being complementary to the LHC and a possible future e^+e^- machine, the LHeC would scrutinise the Standard Model (SM) deeper than ever before, and possibly discover new physics in the electroweak and chromodynamic sectors. Adding *ep* transforms the LHC into an outstanding, high precision Higgs facility. Through the extension of the kinematic range by about three orders of magnitude in lepton-nucleus (*eA*) scattering, the LHeC is the most powerful electron–ion research facility one can build in the next decades, for elucidating the chromodynamic origin of the Quark–Gluon-plasma and clarifying the partonic substructure and dynamics inside nuclei for the first time.

The LHeC physics programme reaches far beyond any specialised goal, it complements and sustains the physics at HL-LHC by providing new discovery potential in its final phase of operation. The LHeC represents a unique opportunity for CERN and its associated laboratories to build a full, new accelerator using modern technology. The ERL has major future applications, with *ep* at HE–LHC and FCC-*eh*, as an injector for FCC-*ee*, as a $\gamma\gamma$ Higgs facility [4, 5] or, beyond particle physics, as the highest energy XFEL of hugely increased brightness [6]. The main LHeC innovation is the first ever high energy application of energy recovery technology, based on high quality superconducting RF developments, a major contribution to the development of *green* collider technology. A novel *ep* experiment enables modern detection technology, such as HV CMOS Silicon tracking, to be further developed and exploited in a new generation, 4π acceptance, no pile-up, high precision collider detector in the decade(s) hence.

This paper focuses on physics providing also an overview on the machine. It is complemented by an Addendum describing further aspects of the LHeC project such as the operation and timelines for the accelerator and the detector. The development of multi-turn, high current, 802 MHz ERL technology, required for the LHeC, is described in an accompanying, separate strategy contribution of the PERLE Collaboration [7] on a 500 MeV ERL facility at Orsay, based on its CDR [8] published in 2017.

1. Physics

1.1. LHeC—the world's cleanest high resolution microscope

QCD is a gauge theory of asymptotically free partons, the dynamics of which has to be established experimentally for which DIS is the most appropriate means. DIS determines the momentum densities of partons, quarks and gluons, as functions of the negative four-momentum transfer squared, Q^2, between the scattering electron and proton and of the fraction, x, of the momentum of the parent proton carried by the parton. The DIS resolution of substructure is $\propto 1/\sqrt{Q^2}$, where 1 GeV corresponds to resolving distances of 0.2 fm. The LHeC covers an unprecedented range in Q^2 from below 1 GeV^2 to above a TeV^2. A salient feature of ep scattering is that one can freely, within the detector acceptances, prescribe Q^2. Thus the LHeC represents the cleanest deep microscope of matter the world can build.

In the future, major alterations of QCD may become manifest [9], such as the embedding of QCD in a higher gauge theory possibly unifying electroweak and strong interactions or colour may be freely observed. Crucial questions of QCD await to be resolved such as the confinement question, called one of the millenium puzzles to be explained [10], the possible relation of QCD to string theory and the use of to gravitation techniques (AdS-CFT), or the CP violation related to axions which may explain dark matter. Principal questions in QCD such as the existence of instantons, the reason for the occurence of diffraction in high energy collisions, new dynamics at high parton densities or the precision test for factorisation [11] all ought to be answered or/and studied much deeper. Proton structure extends to transverse dimensions, and a new field of research, related to generalised and unintegrated parton distributions, is to be explored. Similarly, huge deficits exist in the understanding of the parton structure of the neutron, the deuteron, nuclei, the photon and the Pomeron. QCD is complex and fundamental and the value of DIS extremely rich, reaching far beyond the sheer question of how well we know the parton distribution functions (PDF) in the proton.

The PDF capability of the LHeC has been studied in detail in the CDR [1]. The status of updating this, which will be completed early 2019, has been presented at length recently in [12] including a discussion on the importance and the prospect to measure α_s to per mille accuracy in DIS. The PDF programme of the LHeC is of unprecedented depth for the following reasons:

- For the first time it will resolve the partonic structure of the proton and nuclei completely, i.e. determine the u_v, d_v, u, d, s, c, b, the top and gluon momentum distributions through neutral (NC) and charged current (CC) cross section and direct heavy quark (s, c, b, t) PDF measurements in a hugely extended kinematic range, from $x = 10^{-6}$–0.9 and from Q^2 about 1–10^6 GeV^2.
- Very high luminosity, an unprecedented precision from new detector technology and the redundant evaluation of the event kinematics from the lepton and hadron final states will lead to extremely high PDF precision and to the determination of the various PDF analysis parameters, such as m_c (to 3 MeV), m_b (to 10 MeV) and V_{cs} (to below 1%), from the data themselves.
- Because of the high LHeC energy, the weak probes (W, Z) dominate the interaction at larger Q^2 and resolve the flavours, including the direct CC and NC measurements of heavy quarks. Thus no other data will be required: that is, there is no influence from higher twists or nuclear uncertainties or data inconsistencies, i.e. LHeC will be a unique base for PDFs, independently of the LHC, for predictions, discovery and novel tests of

theory. This includes a full understanding of the gluon which dominates the parton dynamics below the valence-quark region and generates the mass of the visible matter.

Given the impressive theoretical progress on pQCD, see e.g. [13, 14], one will have these PDFs consistently available at N^{3}LO as is required, for example, for the N^{3}LO $pp \rightarrow gg\,H$ cross-section calculations and enabling high precision SM LHC measurements such as of the Higgs couplings in pp or of $\sin^2(\theta_W)$. For QCD, this will resolve open issues (and probably creating new ones) on α_s, answer the question on the persistence (or not) of the linear parton evolution equations at small x, see section 2.2, and also decisively test whether factorisation holds or not between DIS and Drell–Yan scattering.

1.2. Novel dynamics and approaches in quantum chromodynamics

The LHeC offers clean and unique access to very low values of Bjorken-x, where novel QCD phenomena are predicted to occur. It has been known since the seminal work of Balitskii, Fadin, Kuraev and Lipatov that there are large logarithms of $\alpha_s \ln 1/x$ which need to be taken into account in the perturbative expansion in QCD, though next-to-leading order terms are large and unstable. Appropriate resummation schemes [15], combining BFKL and DGLAP dynamics, have been constructed which stabilise the solution. Recent fits that include the resummation of low-x terms within the DGLAP framework [16] show a marked improvement in the description of HERA data at low x and low Q^2. Such effects will be strongly amplified in the LHeC kinematic range and clarified.

Another phenomenon that has been predicted to occur at very low x and low scales is parton saturation, where the densely packed gluons start to recombine, slowing down the growth in their density with decreasing x. Simulations demonstrate that when saturation effects are present, standard DGLAP fits fail to describe the simulated LHeC data when F_2 and F_L (or $F_2^{\rm cc}$), are simultaneously included [1]. Knowledge of QCD dynamics at small x will have severe consequences for future high energy hadron colliders, influencing the predicted production rates of heavy particles such as electroweak and Higgs bosons. This can only be resolved with the LHeC in an unambiguous way as it requires high precision DIS data in a kinematic range extended compared to HERA and for Q^2 large enough for ensuring α_s to be small.

The LHeC will offer unprecedented capabilities for studying diffractive processes, based on either proton tagging or large rapidity gap signatures. As well as the semi-inclusive diffraction DIS process, $ep \rightarrow eYp$ and its eA analogue, exclusive J/Ψ, Υ production and deeply virtual Compton scattering can be measured precisely. With the large lever arm in x and Q^2, diffractive parton densities can be extracted over a wide kinematic domain and used to evaluate diffractive factorisation through their comparisons with diffractive jet and charm rates which was found at HERA to be broken. The deep theoretical relation between diffraction in ep scattering and nuclear shadowing will be explored. Measurements at low Q^2 and of F_L in diffraction will pin down higher twist effects and potentially reveal their relation to saturation. Inclusive eA measurements will permit extractions of diffractive nuclear parton densities for the first time.

The large statistics and high t resolution in exclusive channels will allow generalised parton densities to be extracted the Fourier transform of which yields the transverse spatial distribution of partons inside the hadron. Through the exclusive diffractive production of di-jets and charmed mesons, the Wigner functions can be extracted, simultaneously characterising the partonic momentum and transverse spatial structure, and thus revealing the size of the configurations in the nucleon wave function and offering sensitivity to Gribov
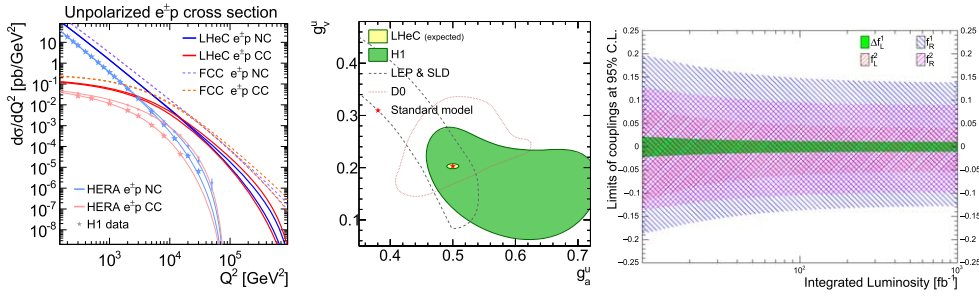
Figure 1. Left: unpolarised inclusive NC and CC DIS cross sections as a function of Q^2 at the LHeC, in comparison to HERA (H1 [21]) and FCC-*eh* expectations; middle: determination of the up-quark weak neutral current vector and axial-vector couplings with LHeC (yellow) compared with current determinations [22]; right: expected sensitivities as a function of the integrated luminosity on the SM and anomalous W_{tb} couplings [23, 24].

diffusion and chiral dynamics. The transverse nucleon gluonic size is an essential ingredient in saturation models and determines the initial conditions of the nonlinear QCD evolution equations. The nucleon transverse quark and gluon distributions also drive predictions of the underlying event structure in inclusive *pp* scattering and the rapidity gap survival probability in hard single and central exclusive diffraction.

Finally, low-*x* physics at the LHeC will have a deep impact on neutrino astronomy. The ultra-high energy neutrinos that are observed at the IceCube observatory typically interact at very low values of *x*, thus requiring large extrapolations relatively to current collider data. Similarly, the production of prompt neutrinos in the heavy meson decays, that dominate high energy atmospheric neutrino fluxes and may also contribute to astrophysical neutrino sources, is mostly determined by low *x* and low momentum scales, and is thus extremely sensitive to novel QCD dynamics as described above which only the LHeC will unravel.

1.3. Discovery through high precision: electroweak and top physics

At the LHeC, precision electroweak physics is performed through measurements of the inclusive neutral-current and charged-current DIS cross sections [17, 18], as well as measurements of more exclusive final states, such as charm or top production in CC DIS or direct production of EW gauge bosons. The measurements of inclusive NC and CC DIS cross sections at LHeC and FCC-*eh*, as displayed in figure 1, will extend to significantly higher scales with much larger cross sections than HERA. At the highest scales Q^2, accessible to the LHeC, up to about 70% of the NC cross section is mediated by *Z*-boson exchange or γZ-interference terms. These measurements provide very high precision determinations of the weak neutral current couplings of the light quarks, improving the presently best achieved uncertainties by very large factors [19], see figure 1. The quantum nature of the electroweak theory is further tested through unique measurements in the space-like region of the scale dependence of the effective weak mixing angle, from below the *Z* pole to about a TeV, with an uncertainty of $\sin^2\theta^\ell_{\text{eff}} \simeq 0.01\%$ [19]. Furthermore, the ρ-parameter and $\sin^2\theta_{\text{eff}}$ can be measured with high precision for different quark flavours, and, again, their scale-dependence is going to be determined for the first time. Noteworthy, these measurements are fully complementary to *ee* and *pp* colliders, which are performed in

the time like region. The high precision PDFs from LHeC permit the total uncertainty on $\sin^2\theta_W$ at the LHC to be twice better than that at LEP/SLD as was shown by ATLAS [20].

The huge electroweak effects and large e^- polarisation permit to precisely measure novel structure functions, such as $F_2^{\gamma Z}$, and to access hitherto unknown ones, such as $F_{bb}^{\gamma Z}$, while testing the universality of the interaction of partons in DIS with photons and Z bosons accurately for the first time. The CC electroweak sector can be uniquely accessed at high scales over many orders of magnitude in Q^2 at the LHeC. This provides a very precise determination of the W boson mass with an uncertainty of order 10 MeV in ep. Of high importance is the reduction of the PDF related uncertainty on M_W at HL-LHC to below 2 MeV which promises a 4×10^{-5} accuracy test of a most crucial electroweak parameter, as estimated by ATLAS [25]. Contrary to former beliefs, the LHC has become a precision measurement facility. With ep added it may see the SM fail.

The LHeC represents a novel top quark factory, with a total single t cross section of 1.9 (4.5) pb in ep at HL (HE) LHC [23]. The other important top-quark production mode is $t\bar{t}$ photo-production [26]. The high luminosity and the cleanliness of the final state make top quark physics in DIS an attractive and competitive research area for the first time. This includes high precision electroweak top quark measurements and sensitive searches for new physics.

One flagship measurement is the direct measurement of the CKM matrix element V_{tb} to 1% at just 100 fb^{-1}, which is a determination free of any model assumptions such as on the unitarity of the CKM matrix or the number of quark generations. LHeC has an outstanding search potential for anomalous top quark couplings: left-handed (L), and right-handed (R) W_{tb} vector (1) and tensor (2) couplings $f_{L,R}^{1,2}$ [23]. In the SM $f_L^1 = 1$ (with $f_L^1 \equiv 1 + \Delta f_L^1$), and $f_R^1 = f_L^2 = f_R^2 = 0$. Based on hadronic top quark decays only, the expected accuracies for these couplings as a function of the integrated luminosity are presented in figure 1 (right). Anomalous admixtures to the SM coupling f_L^1 can be measured at the 1% level already at 100 fb^{-1}, while anomalous contributions to the other couplings can be traced down to order 5%. Similarly, the CKM matrix elements $|V_{tx}|$ ($x = d, s$) can be extracted through the analysis of W boson and bottom (light) quark associated production channels, where the W boson and b-jet (light jet) final states can be produced via s-channel single top quark decay or t-channel top quark exchange [27]. Upper limits at the 2σ level down to $|V_{td}| < 0.06$ and $|V_{ts}| < 0.06$ can be achieved.

Flavour changing neutral current (FCNC) interactions constitute an excellent test of new physics because these are extremely suppressed in the SM [28]. FCNC $tu\gamma$, $tc\gamma$, tuZ, and tcZ couplings can be described in an effective theory, and 2σ limits obtained translate, as an example, into limits on the branching ratios Br($t \rightarrow q\gamma$) and Br($t \rightarrow qZ$) as small as 1×10^{-5} and 4×10^{-5}, respectively. In addition a sensitive search for anomalous FCNC tHq couplings is possible with an expected 2σ limit of Br($t \rightarrow qH$) $< 1.5 \times 10^{-3}$ [29]. Searches for anomalous $tt\gamma$ and ttZ chromoelectric and chromomagnetic dipole moments in $t\bar{t}$ production can be performed leading to expected accuracies down to the 5% level [26]. Other exciting results on top quark properties and promising searches for BSM physics in the top quark sector involve, for example, the first time measurement of the top-quark structure function inside the proton, the study of top-quark spin and polarisation, and the analysis of the CP-nature in ttH production.

1.4. Higgs: precision measurements and exotics

The deep exploration of the Higgs mechanism and its possible relation to physics beyond the SM will be the central theme of the HL-LHC and of all new energy frontier colliders under
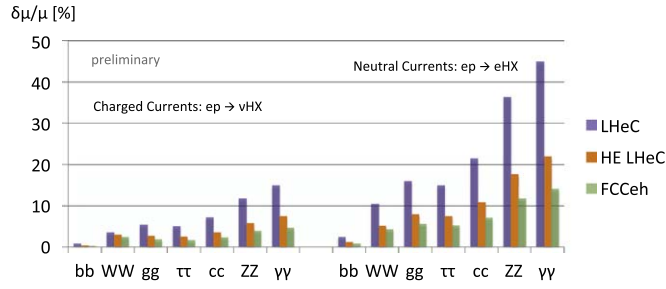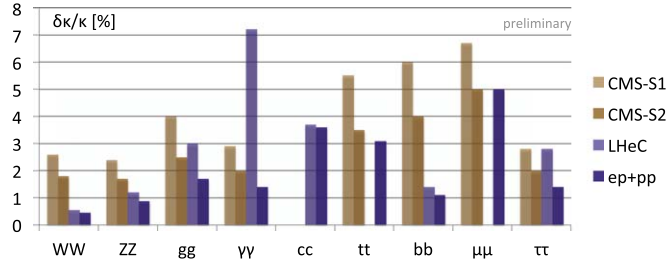
Figure 2. Uncertainties of signal strength determinations in the seven most abundant SM Higgs decay channels for the FCC-*eh* (green, 2 ab^{-1}), the HE LHeC (brown, 2 ab^{-1}) and LHeC (blue, 1 ab^{-1}), in charged and neutral current DIS production [30, 32].

discussion. The LHeC has a special role in this endeavour, mainly because *ep* transforms the LHC into a precision Higgs facility at moderate cost. The main Higgs production mechanism at LHeC is CC DIS, $ep \rightarrow H\nu X$. The Higgs production CC (NC) DIS cross section in LO QCD is $\sigma \simeq 190\ (26)$ fb. The Higgs boson in *ep* is thus dominantly produced via *WW* fusion, with a total event sample of 2×10^5 Higgs bosons, nearly 60% of which in the SM are decaying into $b\bar{b}$. Each decay, of significant branching, is simultaneously measured in $ZZ \rightarrow H$ production. CC and NC production are uniquely distinguished. With a pile-up of 0.1, the final state permits a clean reconstruction of a Higgs boson, which is rather centrally produced, and its decay.

The analysis of SM Higgs decays in *ep*, summarised in [30], has been performed in two major steps: First, very detailed simulations and signal extraction studies, BDT and independently cut based, were made for the dominant $H \rightarrow b\bar{b}$ and the challenging $H \rightarrow c\bar{c}$ channels. Second, prospects were evaluated for the seven most frequent decay channels both in NC and CC, in which acceptances and backgrounds were estimated with Madgraph, and efficiencies, distinguishing leptonic and hadronic decay channels for *W*, *Z*, and τ, were taken from prospective studies on Higgs coupling measurements at the LHC [31]. This provided an uncertainty estimate, comprising the signal-to-background ratio, acceptance and reconstruction efficiency effects, on the signal strength μ_i for each of the Higgs decay channels *i*. This method was benchmarked with the detailed simulations for charm and beauty decays mentioned above.

Figure 2 shows the estimated signal strength uncertainties for the 7 most frequent Higgs decay channels, measured in CC and NC, as expected for the LHeC, *ep* with HE–LHC and the FCC-*eh*. With the joint CC and NC measurements one constrains seven scaling parameters in the so-called κ formalism in a redundant way. The joint measurement of NC and CC Higgs decays provides eight constraints on κ_W and eight on κ_Z together with two each for the five other decay channels considered. With the dominating channel of $H \rightarrow b\bar{b}$ precisely determined, there follows a precise determination of the κ values, especially for the vector boson and *b* couplings, as is shown in figure 3. A feature worth noting is the 'transfer' of precision in signal strength from the μ_b in the CC (NC) channel to $\kappa_{W(Z)}$. Sub-percent precision is obtained at the FCC-*eh* as is described in the FCC submission owing to a five-fold enlarged H cross section as compared to the LHeC, twice the operation time and larger peak luminosity. Roughly, the *ep* Higgs measurements at HE–LHC are twice more precise than at HL-LHC.

Figure 3. Determination of the κ scaling parameter uncertainties with SM width: brown (light/dark): CMS with systematic error assumption S1/S2 [33]; light blue: LHeC; dark blue: joint κ fit to CMS (S2) and LHeC H decay signal strengths. Note that LHC has no significant charm result, while LHeC has no precise results for very rare processes, as $H \rightarrow \mu\mu$ [32].

Currently the HL-LHC prospects for the signal strength measurements are coming out. Initially we have jointly analysed the CMS [33] and LHeC measurement expectations. A remarkable synergy of the *pp* and *ep* Higgs measurement potentials is observed when comparing the CMS, the LHeC and the joint *pp* and *ep* fit results displayed in figure 3. Comparing for each channel the *pp* expectation with the joint result, one observes large improvements in many channels. LHeC provides precision for *bb*, *WW* and *ZZ* and a second generation result for charm, while HL-LHC determines the rarer channels particularly well, such as the $\mu\mu$ decay. A significant part of the systematics in the *pp* measurements is the theoretical uncertainty, see [33]. LHeC will remove a substantial part of it, by providing external, precise N^{3}LO determinations of PDFs and α_s, and thus also indirectly improve the prospects for the LHC Higgs measurements. In short, the LHeC has the potential to transform the LHC into a laboratory for high precision Higgs physics.

The Higgs mechanism is regarded as a window to new physics and its exploration reaches much beyond establishing its SM decays though these may reveal new physics too if they depart from expectation. For the LHeC, summarised in [30], a wide range of BSM Higgs physics topics has been studied. These regard the *ttH* SM (to 15(9)% with *ep* at HL (HE) LHC) and anomalous couplings, or the Higgs → invisible decay, a possible signature of Dark Matter (to 5(3)%). A large number of exotic Higgs LHeC prospect papers was published in recent years, as listed in [34]. For example, extended gauge theories predict the existence of further Higgs bosons, such as a five-plet, singly charged Higgs $H_5^{\pm}$ boson [35], which can be searched for at LHeC. Another example, difficult to study at the LHC, is an exotic Higgs decay mode into two new light scalars in a 4b final state which is well motivated in the next to minimal supersymmetric SM and extended Higgs sector models. The LHeC has energy larger than the e$^+$e$^-$ 250 GeV Higgs facilities and cleanliness better than pp which explains its discovery potential and complementarity to other facilities.

1.5. Beyond the SM with ep and empowering LHC searches for new physics

Because of the absence of colour exchange between the electron and proton beams, *ep* colliders are ideally suited for a detailed study of electroweak interactions. The fact that leptons and quarks have the same electric charge quantisation and the same number of flavours suggests compositeness from common fundamental constituents. Through contact interactions, it is estimated that compositeness scales O(40) TeV can be probed at the LHeC. Leptoquarks (LQ), predicted in technicolour theories, can be a direct
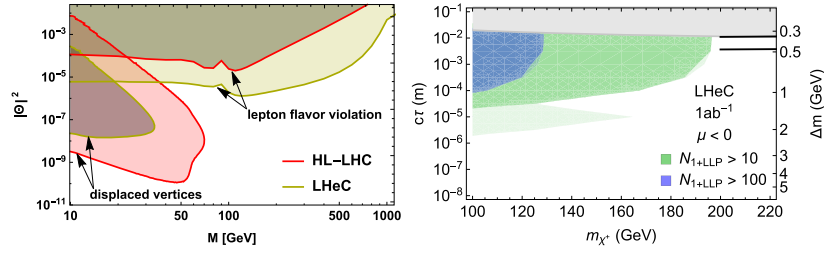
Figure 4. Left: prospects for direct right-handed neutrino searches at the LHeC, first estimates for HL-LHC prospects for comparison, based on [38]. Right: reach for long-lived Higgsinos in the mass (m_χ)—lifetime ($c\tau$) plane, compared to disappearing tracks at the HL-LHC [40], shown by the black lines. Light shading indicates the uncertainty in the predicted number of events due to different hadronization and LLP reconstruction assumptions. For details, see [41].

manifestation of such compositeness. In *ep* collisions, LQ's can be produced in an s-channel resonance, the signature being a peak in the invariant mass of the outgoing ℓq system. The signal strength allows to infer the coupling constant λ between the electron and the quark. This is barely possible at the LHC, where the dominant pair production process via the strong interaction is insensitive to λ. If LQ's exist with mass below the centre-of-mass energy of the collider, extreme sensitivity to λ can be achieved. Contrary to the LHC environment, at the LHeC many properties of the LQ's can be measured with good precision [1]. In addition, LQ-like signatures arise also in R-parity violating SUSY scenarios. If R-parity is violated, vertices are allowed that contain one SUSY particle only, with lepton or baryon number violation. The RPV couplings can be probed by e.g. multi-lepton and multijet signatures at the LHC. At the LHeC one can test anomalous *e–d–t* interactions $\lambda'_{131} < 0.03$ and also the product $\lambda'_{131}\lambda'_{i33}$ [36].

Anomalous couplings could be the first manifestations of electroweak interactions beyond the SM. Present constraints on anomalous triple vector boson couplings are dominated by LEP, but they are not free of assumptions. The WWZ and $WW\gamma$ vertices can be studied at LHeC in great detail. The process $e^-p \rightarrow e^-\mu^+\nu j$ allows a sensitivity of about 10^{-3} via a shape analysis [37]. Searches for anomalous W_{tb} couplings and top-quark FCNC interactions are discussed in section 2.3.

Models with right-handed sterile neutrinos can explain the generation of neutrino masses via a low-scale seesaw mechanism. Mixing between the active and sterile neutrinos is strongly constrained by LEP, ruling out a discovery at HL-LHC. The search prospects for the low-scale seesaw neutrinos at *ep* are dominated by lepton-flavour violating processes, e.g. $e^-p \rightarrow \mu^-W + j$, and by displaced vertices for masses below m_W [38]. Jet substructure may help to distinguish the signal from the few SM backgrounds [39]. The search prospects for direct right-handed neutrinos with the LHC and HL-LHC are shown in figure 4. It is evident that this topic is one of the very promising BSM areas to be exploited at the LHeC which is the only means to directly discover low-scale seesaw neutrinos with masses above the energy threshold at the *ee* Higgs facilities.

Electron–proton colliders at high energy can explore significant regions of supersymmetric parameter space for which hadron colliders have low sensitivity. Higgsinos (χ) with masses $\mathcal{O}(100)$ GeV are motivated by natural SUSY theories which avoid large fine-tuning. In this regime, the low energy charginos (χ^+)/neutralinos(χ^0) are all Higgsino-like and their masses are nearly degenerate. The light χ^+ (and χ^0) is produced in pairs via the charged and neutral currents and their decays yield final states without hard leptons. In case of
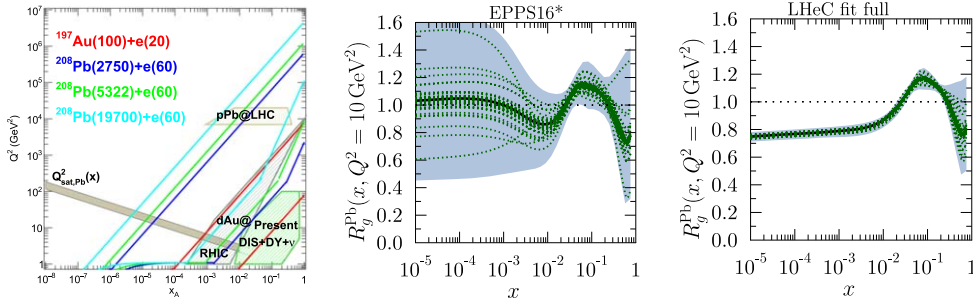
Figure 5. Left: x–Q^2 plane for future eA colliders also indicating the region covered by data used in present global fits and the estimated line of the saturation scale for Pb. Middle and right plots: Pb/p ratio of the gluon PDF in the modified EPPS16 analysis in [46], both for the present situation (middle) and including NC, CC and charm LHeC pseudo-data (right).

prompt production of Higgsinos, constraints can be placed only if slepton masses are light but still higher than the chargino and neutralino masses. An analysis based on boost-decision tree and optimised for $\Delta m(\tilde{l}, \chi^0) \simeq 10$ GeV scenarios shows discovery prospects with sensitivity for χ^+ and χ^0 masses up to 200 GeV On the other hand, if the chargino decays to final state particles that are either neutral or too soft to be reconstructed, while still in the tracker, it can be identified via a disappearing track. This kind of process can be targeted at the LHeC. The soft decay products of long-lived Higgsinos can be explicitly reconstructed ('displaced single pion'), and very short lifetimes can be probed assuming the visibility of tracks with $p_t \sim 0.1$ GeV. In the clean environment (i.e. low pile up) of the ep collider, such single low-energy charged tracks can be reliably reconstructed and tests of χ^+ with masses up to 200 GeV [41], see figure 4 (right) can be achieved. Overall, long-lived-particles (LLPs) can result from many other BSM theories, yielding spectacular signals in collider experiments. For exotic Higgs decays into pairs of light LLP, the LHeC can test proper lifetimes that are smaller than $\sim\mu$m, which is significantly better than the reach of the LHC [41], where the sensitivity is rather to a mm.

1.6. The case for energy frontier electron–ion scattering

HERA missed to study electron–ion collisions. The US based EIC proposals enlarge the range covered by fixed target experiments, see the Au + e red area in figure 5, and, through the advantages of the collider configuration, complemented by the ability to use polarised hadron beams and thus possibly solving the proton spin puzzle, have an interesting DIS programme [42] with the hope to have luminous collisions at BNL [43, 44] or Jlab [45] in the early thirties. The LHeC will give access to a completely unexplored region of the kinematic x–Q^2 plane for nuclei, extended by 3 orders of magnitude when compared to fixed target DIS data, see figure 5 left. It therefore is expected to thoroughly transform our present knowledge on parton structure in nuclei, settling the origin of the ridge correlation phenomenon and providing a new qualitative and quantitative understanding of the Quark–Gluon plasma within QCD.

In the standard collinear framework used to compute particle production in hadronic collisions, parton distributions inside nuclei (nPDFs) are basically unknown for x below 10^{-2} where the DIS data base ends, as is illustrated in figure 5. The scarcity of data for any single nucleus makes it moreover mandatory to combine information on different ones. The LHeC

eA data, with an expected luminosity of $10\,\mathrm{fb}^{-1}$ and their huge kinematic range provide a unique base, from NC, CC and heavy quark data, to resolve the nuclear parton structure completely [47] with very high precision as is illustrated in figure 5. This provides nuclear PDFs independently of proton PDFs and thus unprecedented information on nuclear binding as for example flavour dependent shadowing effects.

Diffractive nuclear parton densities have never been measured and can be extracted at the LHeC with similar precision to those inside the proton, against predictions of a much enhanced fraction of diffraction in *eA* as compared to *ep*. Exclusive LHeC vector meson production measurements are sensitive to the generalised parton densities inside nuclei and thus to the transverse partonic structure. Separating coherent diffraction, where the nucleus remains intact, from the incoherent case where it dissociates, will characterise the fluctuations in the spatial parton distributions in protons and nuclei, a vital ingredient in understanding hadronic collisions in both the soft and hard domains.

Being density effects, nonlinear QCD phenomena are enhanced by both a decrease in *x* and by an increase in the number of nucleons involved in the collision. At the LHeC, with is huge range in *x* for both *ep* and *eA*, one expects to discover or discard gluon saturation in the *ep* case and cleanly disentangle it from nuclear and also resummation effects. Fundamental studies on nuclear effects on hadronisation and QCD radiation will be constrained by particle and jet production measurements studied in the LHeC CDR [1].

The possibility is nowadays considered that the strong mean scalar field in a nuclear medium, which may be as large as half the mass of the nucleon at saturation density, will modify the internal structure of the bound hadrons [48]. Indeed, the self-consistent adjustment of the internal structure of the nucleon to such fields provides a natural saturation mechanism for nuclear matter. It is crucial to find ways to probe this novel picture of nuclear structure in which the objects occupying shell model orbitals have nucleon quantum numbers but internal structure that is altered by the medium. For example, does it explain the famous EMC effect, are bound nucleon form factors modified, etc? The LHeC, with its large energy reach, readily available nuclear beams and a detector designed to forensically analyse the detailed final states resulting from *e*-nucleus collisions, is ideally suited to provide definitive answers to these fundamental questions.

The LHeC as an electron ion collider, with its huge kinematic range and high precision, will all have profound implications to our understanding of all stages of heavy ion collisions at high energies; the wave function of the colliding nuclei; the particle production mechanism; the initial spatial and momentum distributions of produced partons prior to the emergence of a collective behaviour. This includes correlations such as those revealed by the ridge phenomenon, which may be explained both in perturbative frameworks, like the colour glass condensate, or in non-perturbative ones, like the inelastic collision of gluonic flux tubes associated with the QCD interactions responsible for quark confinement in hadrons and be ideally studied in electron-hadron scattering [49]. Furthermore, *eA* collisions will establish a baseline representing the normal (cold) nuclear medium, relative to which the effects of the hot dense medium can be contrasted for hard probes such as jets and quarkonia. The LHeC obviously is the ideal machine for revolutionising our understanding of nuclear structure - and Chromodynamics and the natural complement and eventual successor of the HI programme at the LHC once that ends.
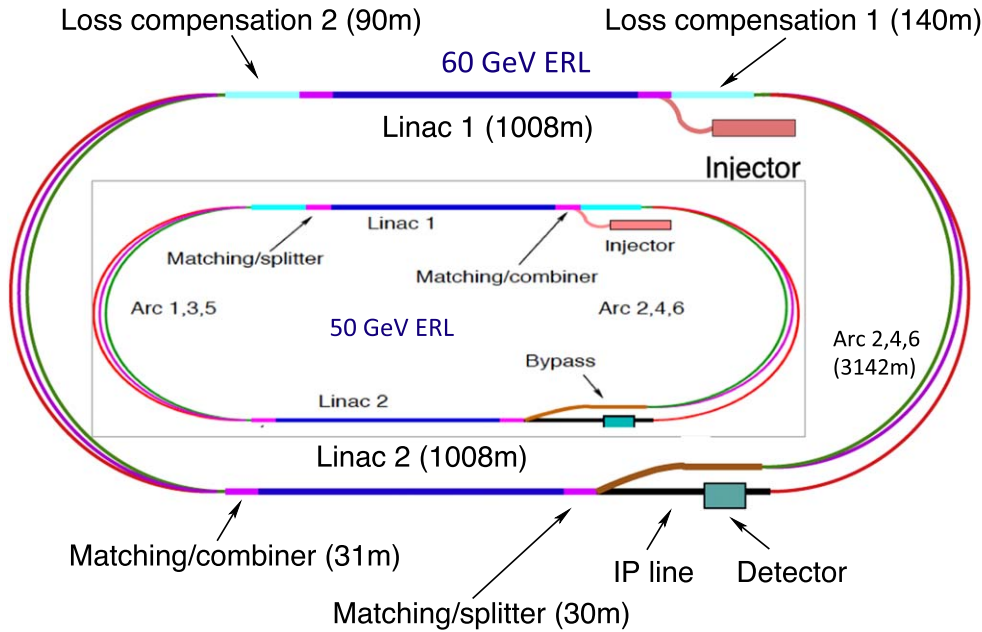
Figure 6. Schematic view of the three-turn LHeC configuration with two oppositely positioned electron linacs and three arcs housed in the same tunnel. Two configurations are shown: outer: default $E_e = 60$ GeV with linacs of about 1 km length and 1 km arc radius leading to an ERL circumference of about 9 km, or 1/3 of the LHC length. Inner: sketch for $E_e = 50$ GeV with linacs of about 0.8 km length and 0.7 km arc radius leading to an ERL circumference of the SPS size, i.e. 6.7 km or 1/4 of the LHC length. An energy larger than 50 GeV is crucial for searches, precision Higgs and low x physics. The 1/4 circumference configuration permits upgrading to about 55 GeV.

2. Overview on the LHeC accelerator design

The LHeC was basically designed in 2012, following extensive work and a final year of review prior to the publication of the CDR [1]. The Higgs discovery set a higher luminosity goal than foreseen in 2012 and the ERL frequency was finally set to 802 MHz, see [8]. The LHC performed extremely well and technology, especially on SRF, made significant progress, as may be also seen from the very successful first 802 MHz cavity fabrication and test, see the PERLE strategy paper [7]. The LHeC work in recent years was mainly characterised, apart from adapting the physics to the findings of the LHC, by studies in support of the 10^{34} luminosity goal, such as on beam-beam interactions or the IR design, many still ongoing, by renewed investigations on the civil engineering (CE) and by the foundation of an ERL development facility, PERLE at Orsay. The detector design and software developed considerably related to physics requirements, as from Higgs final state reconstruction, and connected to the rapid development of detector technology, especially by the HL-LHC detector upgrades. The current detector design and its possible implementation, like some of the here mentioned topics, are described in the Addendum.

The core of the LHeC electron accelerator complex consists of two superconducting 10 GeV linacs with an RF frequency of 802 MHz that are connected by arcs in an energy recovery racetrack configuration see figure 6. The beam is injected at the beginning of the first linac and passes three times through either linac, each time accelerated by about 10 GeV.

Then it collides with the proton beam in the detector before it passes another three times through the two linacs and is dumped. The timing for these passages is adjusted such that the beam is decelerated and transfers its energy back into the cavities. Before the arcs, a beam splitter is installed that distributes the beam into one of three beamlines in each arc, depending on its energy. At the end of the arcs the beams are recombined. Special acceleration stations at the end of the arcs compensate the energy loss due to synchrotron radiation. This configuration provides a colliding electron beam with a very high power but because of the energy recovery the RF power for the linacs remains very limited—it is only required to stabilise the RF amplitude and phase and compensate losses in the walls of the cavities. This feature, combined with the dump at only injection energy, makes the ERL of the LHeC a genuinely *green* novel accelerator technique.

The key collective effects have been studied. The optics design of the linacs optimises the beam stability over all six passages and in combination with the damping of transverse modes in the cavities ensures beam stability up to an electron beam bunch population of 4×10^9. Higher currents can be stabilised by further improving the damping. The electromagnetic fields of the proton bunches strongly disrupt the colliding electron bunches. Careful choice of electron collision optics minimises the impact on the electron beam emittance and maximises luminosity. The electron beam bunch pattern is matched to the circulating proton beam such that each electron bunch collides with a proton bunch. This maximises luminosity and also avoids non-colliding electron bunches that due to the lack of disruption will have a much larger emittance after the collision. The impact of the electron beam on the proton beam emittance, especially in case of beam jitter, is acceptable as detailed studies showed. Therefore the LHC can be used as a twin collider with concurrent *pp* and *ep* collisions. A potential instability that could be caused by trapping of ions in the beam can be mitigated by introducing gaps in the beam, which allow the ions to be removed; the charge of the remaining bunches is increased accordingly to maintain the luminosity.

This configuration, as detailed in [50], leads to peak luminosity values of about $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$. This appears possible owing to the expectations of a high proton beam brightness and small emittance of the HL-LHC proton beam. It furthermore requires electron currents of about 20 mA and eventually larger. For the interaction region (IR) design it calls for a β^* below 10 cm, which according to the ongoing IR design, sketched in the Addendum to this contribution, is indeed in reach. In a CERN official, joint paper on machine parameters of proposed future colliders at CERN, an operation scenario [51] was described for the LHeC with three phases of operation, following LS4, i.e. starting in the early thirties, which would permit to collect a luminosity of the order of 1 ab^{-1} with the LHeC, and of 2 ab^{-1} if the ERL was combined with HE–LHC or the FCC, owing to modified parameters [50] and longer operation than will be possible with the LHC. In electron-lead scattering with the LHeC, an integrated luminosity of O(10)fb^{-1} may be collected. This may be compared with the total luminosity of 1 fb^{-1} delivered in ep over HERA's lifetime. Since, moreover, the CMS energy of the LHeC in *eA* mode is much larger than in *ep* at HERA, one recognises the extreme reach of the CERN EIC programme using the ERL with the LHC.

The CE of the LHeC was studied for the CDR [1]. It was re-visited in connection with the FCC conceptual design. The studies have assumed that the IR for LHeC will be at LHC Point 2, which currently houses the ALICE detector. The location and size of the ERL, for both the LHeC and the FCC-*eh*, are sketched in figure 7. For LHeC as far as possible, any surface facilities have been situated on existing CERN land. The physical positioning for the project has been developed based on the assumption that the maximum underground volume possible should be housed within the Molasse Rock and should avoid as much as possible any known

Figure 7. Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of $1/3$ (outer, default with $E_e = 60$ GeV), $1/4$ (the size of the SPS, $E_e \simeq 55$ GeV) and $1/5$ (most inner track, $E_e \simeq 50$ GeV). Civil engineering chose point L as the position of the ERL at FCC, with two GPDs located at A and G.

geological faults or environmentally sensitive areas. The shafts, one per linac, leading to any on-surface facilities have been positioned in the least populated areas.

The LHeC as a recirculator has the attractive option to be used as an injector - into FCCee of high energy. In the initial Z pole phase, it could replace the currently considered 6 GeV S-band linac and prebooster and allowed a direct, flexible top-up injection at 46 GeV, leading to increased e^+e^- luminosity. For the higher energy stages, up to $t\bar{t}$, one would inject into the booster with 50 or 60 GeV electron energy which would considerably relax the field quality constraints known to arise in low energy injectors, and still make the S-band linac redundant.

3. A final remark

The LHeC CDR and its upgrade, the success of the DESY XFEL, the rapid international developments of SRF and ERL technology, all have revealed that complementing the LHC with a high energy ERL is a realistic, certainly challenging albeit unique opportunity. The time is 50 years after the discovery of quarks in *ep* scattering at Stanford. The LHeC linacs together are shorter than the 2 mile linac of SLAC Their energy and the size of the ERL configuration will eventually be determined in a cost-physics-effort optimisation where, as discussed in the Addendum, E_e shall not be lower than 50 GeV.

The LHeC is to complement the exploration of the TeV scale with the LHC and a possible future e^+e^- Higgs facility, as much as fixed target CERN muon and neutrino experiments accompanied the Sp$\bar{p}$S and PETRA/PEP in the exploration of the O(10)GeV scale, and HERA added crucial, independent information to Tevatron and LEP/SLC for the exploration of the Fermi scale. The SM was established over five decades through the interplay of energy frontier hadron–hadron, electron–positron and lepton–hadron experiments. Besides the discovery of quarks, DIS was instrumental in the discovery of asymptotic freedom, the clarification of the weak coupling of the electron, in the resolution of parton

dynamics and with the discovery of gluon dominance at $x \leqslant 0.1$. The current key question is about physics beyond the standard gauge theory of electroweak and strong interactions. A space-like *ep* experiment adds a possibly crucial, extra dimension to the 'bump hunting' time-like experiments. Using the singular hadron beams of the LHC for clarifying most pressing questions on the nature of the micro-universe, on the peculiarity of the Higgs mechanism and for expanding the search for new physics, by realising an 'Electrons for LHC' programme, is a most exciting option for the future of particle physics in the not too distant time.

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