Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC

A Contribution to the Update of the European Strategy on Particle Physics

LHeC and PERLE Collaboration

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Executive Summary

The time is 50 years after the birth of deep inelastic scattering with the discovery of partons in ep scattering at Stanford. Following the discovery of the Higgs boson at CERN, Guido Altarelli, who advised the LHeC for a decade, stated: "the possibility that the Standard Model holds well beyond the electroweak scale must now be seriously considered.. We are experiencing a very puzzling situation but, to some extent, this is good because big steps forward in fundamental physics have often originated from paradoxes. We highly hope that the continuation of the LHC experiments will bring new light on these problems." [1]. The LHeC is a TeV scale, luminous electron-proton and electron-ion collider, the best the world can build for decades ahead, which, exploiting the LHC infrastructure, offers an outstanding potential in support of this major task. It represents the cleanest, high resolution microscope to unravel the dynamics of partons, in collinear and 3D phase space, the most reliable environment to test and develop QCD, the only way to transform the LHC facility into a high precision Higgs physics laboratory, the necessary base for extending the LHC BSM physics search range, a unique facility for high precision electroweak and top physics, stand alone and in conjunction with pp, a prime facility for new sensitive searches for new physics, such as right-handed neutrinos, and the only way to resolve the parton dynamics in nuclei and establish the chromodynamic interpretation of the Quark-Gluon-Plasma and ridge phenomena. Based on energy recovery linac technology, a luminosity as high as $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is in reach for a novel generation electron accelerator, which may be added in a decade hence to the LHC at affordable cost and essentially in parallel to the LHC operation post LS3. The ERL technology has matured enormously through SRF developments making the LHeC a now realistic, still innovative prospect being supported with a $500\,\mathrm{MeV}$ electron energy, $20\,\mathrm{mA}$ current multi-turn facility PERLE at Orsay, submitted in parallel to the strategy. Beyond the detailed CDR [5] the LHeC design has been adapted to an order of magnitude enlarged luminosity, a next full civil engineering study has been performed, and the PERLE development, synergetic to FCC, has led to a first $802\,\mathrm{MHz}$ SC Niobium cavity exceeding the design constraints. The LHeC permits a novel 4π acceptance detector to be developed, based on the current design, and built in the twenties as an important opportunity for detector builders post the HL LHC upgrade design. The detector is designed in a modular way which permits its insertion within two years, as detailed in the addendum to this contribution. There are important technology and physics applications of PERLE and the LHeC, such as building a highest energy laser at CERN two orders of magnitude more intense than the XFEL at DESY. For particle physics, the LHeC is the only way to keep deep inelastic scattering as part of energy frontier physics. The LHeC complements the exploration of the TeV scale with the LHC and a possible future $\mathrm{e^+e^-}$ Higgs facility, as much as fixed target CERN muon and neutrino experiments accompanied the SppS and PETRA/PEP, or HERA added crucial, independent information to Tevatron and LEP/SLC. Once built, the electron ERL serves an even more powerful DIS configuration if the HL LHC is followed by the HE LHC, being as well the base for the FCC-eh. It is the joint availability of pp, ee and ep which gives maximum hope for resolving the paradoxes of modern particle physics.

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 deep inelastic scattering (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 $1\,\mathrm{GeV}$ corresponds to resolving distances of $0.2\,\mathrm{fm}$. The LHeC covers an unprecedented range in Q^2 from below $1\,\mathrm{GeV}^2$ to above $10^6\,\mathrm{GeV}^2$. 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** [2], 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 [3], its possible relation to gravitation (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** [4] 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, and they shall not be reduced to the sheer question of how well we know the PDFs in the proton.

The PDF capability of the LHeC has been studied in detail in the CDR [5] and the status of updating this, which will be completed early 2019, has been presented at length recently in [6] including 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 $\mathbf{u_v}$, $\mathbf{d_v}$, $\mathbf{u}$, $\mathbf{d}$, $\mathbf{s}$, $\mathbf{c}$, $\mathbf{b}$, **the top and gluon momentum distributions** through NC and CC cross section and direct heavy quark (s,c,b,t) PDF measurements in a hugely extended kinematic range, from below $x = 10^{-6}$ to $x = 0.9$ and in Q^2 from below the DIS region to $10^6\,\mathrm{GeV}^2$.

- Very high luminosity, an unprecedented precision from new detector technology and through the redundant evaluation of the event kinematics from the lepton and hadron final states will lead to **extremely high PDF precision** and to the fixation of the various PDF analysis parameters, such as m_c (to $3\,\mathrm{MeV}$), m_b (to $10\,\mathrm{MeV}$) and V_{cs} (to below $1\,\%$), from the data themselves.

- Because of the high LHeC energy, the weak probes (W, Z), unlike at HERA or the low energy EIC, dominate the interaction at larger Q^2 and resolve all flavours. 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 the unique base for PDFs, independently of the LHC, for predictions, discovery and novel tests of theory [1]. 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 [7], one will have these PDFs available at N³LO corresponding to the N³LO $pp \to gg\,H$ cross-section calculations demand and **enabling high precision SM LHC measurements such as on $\mathbf{M_W}$**. 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 Sect. 1.2, and also decisively test whether factorisation holds or not between DIS and Drell-Yan scattering.

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[1]This may then be confronted with so-called global PDF analyses based on an inclusive assembly of all possible sources for sensitivity to parton distributions, suffering from sizeable theoretical uncertainties and known and forthcoming difficulties of data compatibility which are hidden through so-called χ^2 tolerance criteria.

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 − 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, 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 [8] 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 with the LHeC.

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^{cc}), are simultaneously included [5]. Knowledge of QCD dynamics at small x will have severe consequences for future high energy hadronic colliders, influencing 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 $J/\Psi, \Upsilon$ 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 diffraction measurements will permit first precision extractions of diffractive parton densities.

The high statistics and 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 diffusion and chiral dynamics. The transverse nucleon gluonic size is an essential ingredient in saturation models and determines the initial conditions of the non-linear QCD evolution equations. The nucleon transverse quark and gluon distributions also drive predictions of the underlying event structure in inclusive 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 [11, 12], as well as measurements of more exclusive final states, such as charm or top production in CC 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 Fig. 1, will extend to significantly higher scales with much larger cross sections than HERA. At 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 [13], see
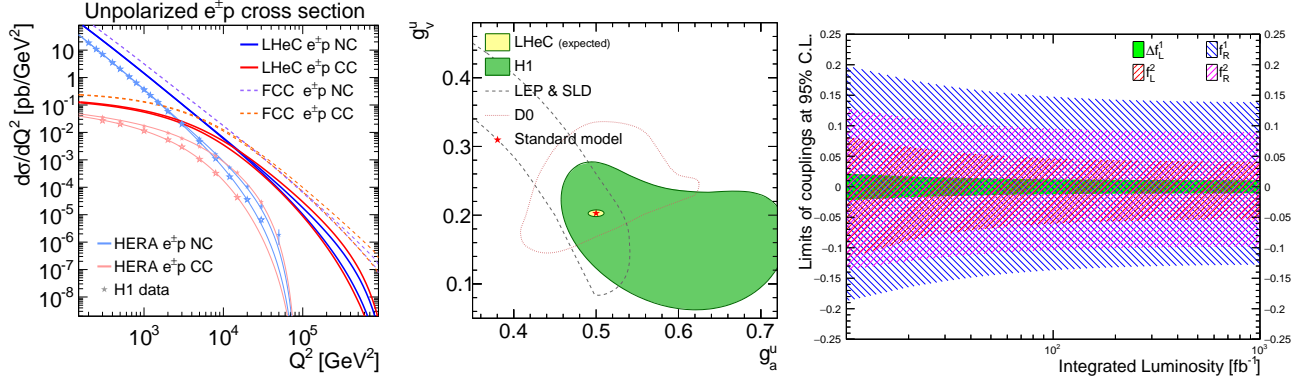
Figure 1: Left: Unpolarised inclusive NC and CC DIS cross sections as a function of Q^2 at the LHeC, in comparison to HERA (H1 [9]) and FCC-eh expectations; Middle: Determination of the up-quark weak neutral current couplings from LEP/SLD, D0, H1 and the LHeC; Right: Expected sensitivities as a function of the integrated luminosity on the SM and anomalous Wtb couplings [10]

Fig. 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 $\sin^2\theta_{\mathrm{eff}}^{\ell} \simeq 0.3\,\%$ [11]. Furthermore, the ρ-parameter and $\sin^2\theta_{\mathrm{eff}}$ 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 3 times better than that at LEP as was shown by ATLAS [?].

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 PDFs**, 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 similar crucial importance is the reduction of the PDF related uncertainty on M_W at HL LHC to below 3 MeV.

Due to the much increased cms energy compared to HERA, the LHeC represents a **novel top quark factory**, with a total single t cross section of $1.9\,(3.7)$ pb at HL (HE) LHC [10]. The other important top-quark production mode is $t\bar{t}$ photo-production with a total cross section of 23 fb at the LHeC [14]. The high luminosity and the cleanliness of the final state make top physics in DIS an attractive and competitive research area for the first time. This includes high precision electroweak top measurements and sensitive searches for new physics.

One **flagship measurement is the direct measurement of the CKM matrix element $\mathbf{V_{tb}}$** to $1\,\%$ at just $100\,\mathrm{fb}^{-1}$, 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 $f_{L,R}^{1,2}$ [10]. 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 Fig. 1 (right). The SM coupling f_L^1 can be measured at per cent level already at $100\,\mathrm{fb}^{-1}$, while anomalous admixtures can be traced 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 [15].

Single t quark CC production can also be used to search for **Flavour Changing Neutral Currents** (FCNC) $tu\gamma$, $tc\gamma$, tuZ, and tcZ couplings with high sensitivity [16]. Limits on the respective FCNC top-quark branching ratios will improve on existing limits from the LHC by about $1-2$ orders of magnitude. In
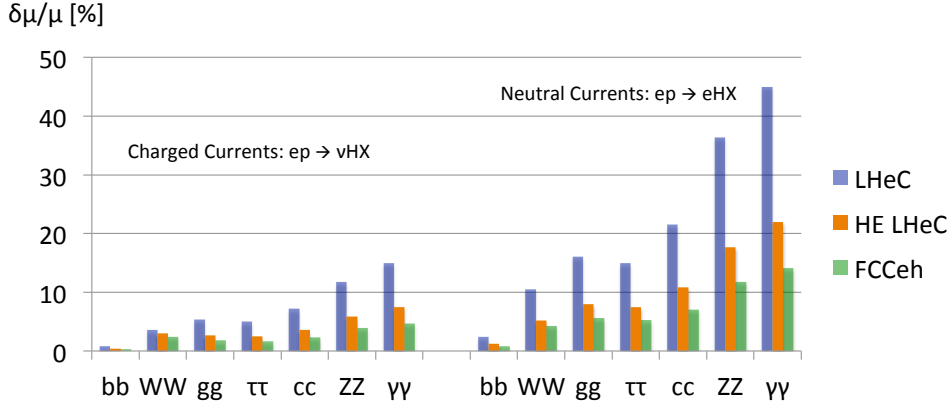
Figure 2: Uncertainties of signal strength determinations in the seven most abundant SM Higgs decay channels for the FCC-eh (green, $2\,\mathrm{ab}^{-1}$), the HE LHeC (brown, $2\,\mathrm{ab}^{-1}$) and LHeC (blue, $1\,\mathrm{ab}^{-1}$), in charged and neutral current DIS production.

top-quark pair production sensitive searches for anomalous $t\bar{t}\gamma$ and $t\bar{t}Z$ chromoelectric and chromomagnetic dipole moments in $t\bar{t}$ production can be performed leading to expected accuracies down to the 5% level [14].

Other exciting results of top quark properties and promising **searches for BSM physics in the top quark sector** involve, for example, the first time investigation of the top quark structure function inside the proton, the study of top quark spin and polarization in DIS, the analysis of the CP-nature in $t\bar{t}H$ production, and a sensitive search for anomalous FCNC tHq couplings.

1.4 Higgs: Precision Measurements and Exotics

The deep exploration of the Higgs mechanism and its possible relation to physics beyond the SM, for decades ahead, will be the central theme of the HL LHC and of all new energy frontier colliders under discussion. Owing to the intense LHC proton beams, 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 charged current deep inelastic scattering, $ep \to H\nu X$. The Higgs production CC (NC) DIS cross section in LO QCD is $\sigma \simeq 190\,(26)\,\mathrm{fb}$. The Higgs boson in ep is thus dominantly produced via WW fusion, with a total event sample of $2 \cdot 10^5$ Higgs bosons, nearly $60\,\%$ of which in the SM are decaying into $b\bar{b}$. Each decay, of significant branching, is simultaneously also measured in $ZZ \to H$ production. Uniquely, CC and NC production are distinguished and the final state, with a pile-up of 0.1, permits for 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 [17], has been performed in two major steps: First, very detailed simulations and Higgs extraction studies were made for the dominant $H \to b\bar{b}$ and the challenging $H \to c\bar{c}$ channels. These use samples generated by Madgraph5/Madevents, of both signal and background events, with fragmentation and hadronization in PYTHIA followed by a fast detector simulation with DELPHES as testbed for the ep detector. Both cut based and boosted decision tree (BDT) analyses were performed in independent evaluations.

Second, an analysis was established 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 [18]. This provided a systematic scale factor, which comprised the signal-to-background ratio and the product of acceptance and reconstruction efficiency, and a corresponding uncertainty estimate on the signal strength μ_i for each of the Higgs decay channels i. The result, shown in Fig. 2 could be successfully benchmarked with the detailed simulations for charm and beauty decays described above.

With the joint CC and NC measurements of the various decays, considering the seven most abundant ones illustrated in Fig. 2, one constrains seven scaling parameters in the so-called κ formalism. The joint
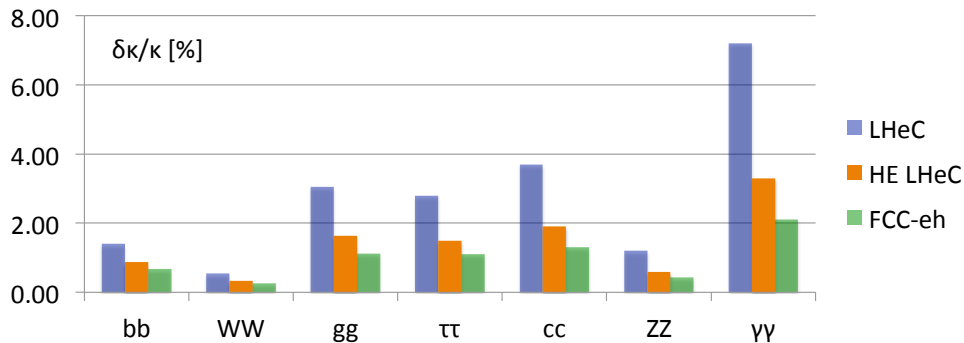
Figure 3: Determination of the κ scaling parameter uncertainties, from a joint SM fit of CC and NC signal strength results for the FCC-eh (green, $2\,\mathrm{ab}^{-1}$), the HE LHeC (brown, $2\,\mathrm{ab}^{-1}$) and LHeC (blue, $1\,\mathrm{ab}^{-1}$).

measurement of NC and CC Higgs decays provides nine constraints on κ_W and nine on κ_Z together with two each for the five other decay channels considered. Since the dominating channel of $H \to b\bar{b}$ is precisely determined, there follows **a astonishingly precise determination of the κ values**, to about a per cent for LHeC, as is shown in Fig. 3. A feature worth noting is the "transfer" of precision in signal strength from the μ_b in the CC channel to κ_W. The result is displayed in Fig. 3 for the standalone analyses of LHeC and HE LHeC. Sup-percent precision is obtained at the FCC-eh described in the FCC submission.

Currently the HL LHC prospects for the signal strength measurements are coming out. Initially we have jointly analysed the CMS [19] and LHeC μ measurement expectations[2]. The result, presented in Fig. 3, shows a **striking synergy for pp and ep**. The HL LHC results, for the non-rare channels, are systematics dominated. One presents pp prospects for a systematic level S_1 and, somehow *ad hoc*, also uses a level S_2 which halves the $S1$ systematics. The *ep & pp* analysis is carried out for both S_1 and S_2. A significant part of the systematics is the theoretical uncertainty, see [19]. LHeC will remove a substantial part of it, by providing external precision determinations of PDFs and α_s. One therefore may consider the *ep & pp*(S_2) result as the best possible estimate for the LHC Higgs facility at large, which indeed has the potential for **the LHC to become a laboratory for high precision Higgs physics**: The striking result is that the LHC, with prospects of measuring the width in *pp* to $5\,\%$ [19], can provide SM Higgs measurements for the dominant channels as accurate as for example the ILC, and much more accurate for the rare channels than any e^+e^- collider, owing to the very large Higgs production cross section at the LHC. This high level of precision may as well be used to constrain EFT parameters which was beyond the κ framework analysis presented here.

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 when they depart from expectation. For the LHeC, summarised in [17], a wide range of **BSM Higgs physics topics** has been studied in quite some detail. These regard the *tth* SM (to $15\,(9)\,\%$ with *ep* at HL (HE) LHC) and anomalous couplings, or the Higgs-to-invisible decay, a possible signature of Dark Matter (to $5\,(3)\,\%$). Furthermore, a large number of exotic Higgs LHeC prospect papers was published in recent years, as listed in [20]. For example, extended gauge theories predict the existence of further Higgs bosons, such as a five-plet, singly charged Higgs $H_5^{\pm}$ boson [21], 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 Standard Model and extended Higgs sector models. The LHeC has energy larger than e^+e^- and cleanliness better than *pp* which explains its discovery potential and complementarity to other facilities.

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[2]At the time of this draft the ATLAS results were not yet available but shall be considered as time permits.

1.5 Beyond the Standard Model with ep and LHC Searches Empowered

Because of the absence of color exchange between the electron and proton beams, *ep* colliders are ideally suited for a detailed study of electroweak interactions. They provide a clean environment, with negligible pileup. In the following, unless stated otherwise, prospects for BSM searches at *ep* are presented considering 60 GeV electron beam energy and total luminosity of 1 ab^{-1}.

The fact that leptons and quarks have the same electric charge quantization and the same number of flavours suggests compositeness from common fundamental constituents. Through contact interactions, it is estimated that compositeness scales $\mathcal{O}(40)$ TeV can be probed at the LHeC. Leptoquarks (LQ), predicted in technicolor theories, can also be a direct 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. As can be seen in Fig. 4 (left), if LQ's exist with mass below the center-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 Ref. [5]. 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 $\lambda'_{131}\lambda'_{i33}$ [22].
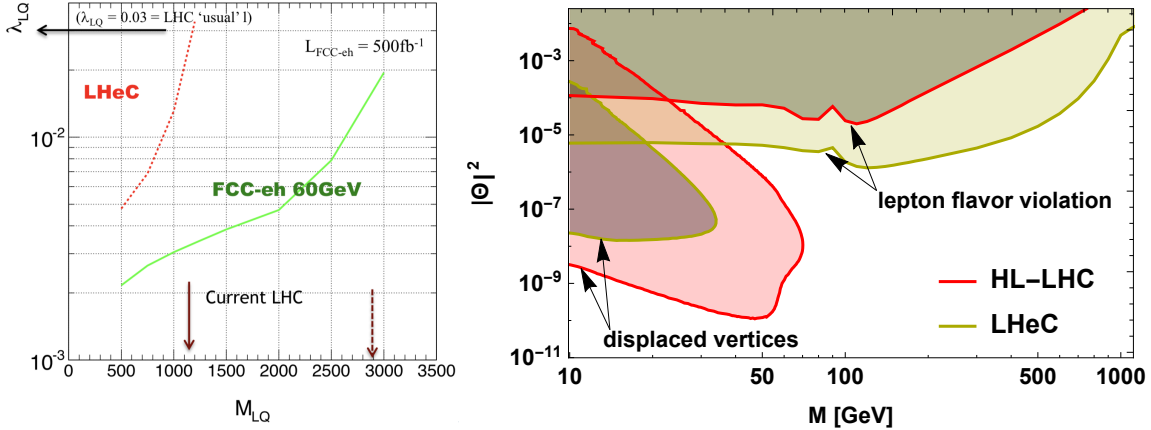

Figure 4: *Left:* Updated prospects for leptoquark searches at LHeC and FCC-he, including the LHC results from 2018 for comparison. *Right:* Prospects for direct right-handed neutrino searches at the LHeC, first estimates for HL-LHC prospects for comparison. This figure is based on results from ref. [23].

Anomalous couplings could be the first manifestations of electoweak interactions beyond the Standard Model. Present constraints on anomalous triple vector boson couplings are dominated by LEP, but they are not free of assumptions. The WWZ and WWγ vertices can be studied at LHeC in great detail. The process $e^-p \to e^-\mu^+\nu j$ allows a sensitivity of about 10^{-3} with 2-3 ab^{-1} via a shape analysis [24]. The top quark FCNC interactions, a good test of new physics because extremely suppressed in the SM, can be described in an effective theory, and the 2σ limits obtained translated into limits on the branching ratios $\mathrm{Br}(t \to u\gamma)$ and $\mathrm{Br}(t \to c\gamma)$ as small as 4×10^{-6} and 4×10^{-5} at respectively [25].

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-flavor violating processes, e.g. $e^-p \to \mu^-W + j$, and by displaced vertices for masses below m_W. For further details, also for a comparison with *ee* and *pp* colliders, see ref. [23]. Also important can be the study of jet substructure, which helps to distinguish the signal from the few SM backgrounds [26]. In general the *ep* colliders can provide complementary information to the *ee* and *pp*, and are the only known means to directly discover low-scale seesaw neutrinos with masses above the energy threshold of the *ee* collider. The

search prospects for direct right-handed neutrinos are shown in Fig. 4 (right).
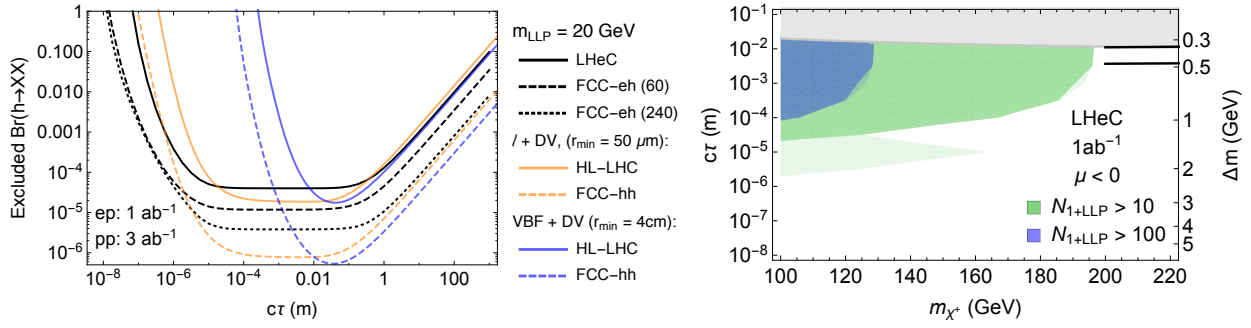

Figure 5: *Left:* Exotic Higgs branching fraction that can be excluded by the LHeC [27]. The LHC exclusion limits and the FCC-hh search prospects are shown by the gray area and the black lines, respectively. *Right:* Reach for long-lived Higgsinos in the mass (m_χ) - lifetime ($c\tau$) plane, compared to disappearing tracks at the HL-LHC [28], 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 ref. [27].

Electron-proton colliders 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 decays of the heavier χ^+ to $W^\pm \chi^0$ yields final states without hard leptons, which makes these processes difficult to investigate at the LHC, where only the missing transverse momentum is observable. At the LHeC light χ^+ (and χ^0) can be produced in pairs via the charged and neutral currents. A cut-based analysis of these processes at the LHeC, assuming prompt χ^+ decays, yields 2σ discovery prospects for masses up to 120 GeV [29]. More stringent constraints can be placed if slepton masses are light but still higher than the chargino and neutralino masses. An analysis based on boost-decision tree and optimized for $\Delta m(\tilde{l}, \chi^0)$ 10 GeV scenarios show an increase in discovery prospects with sensitivity for χ^+ and χ^0 masses up to 400 GeV.

Taking into account the displacement of the χ^+ decay, and the visibility of tracks with $P_t \sim 0.1$ GeV allows LHeC tests of χ with masses up to 200 GeV [27], cf. Fig. 5 (right). Considering non-prompt decays of Higgsinos thus significantly improves the discovery prospects compared to the prompt analysis.

Long-lived-particles (LLPs) can result from the near degeneracy of electoweakinos or 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 [27], where the sensitivity is $\sim$mm, cf. fig. 5 (left).

1.6   The Case for Energy Frontier Electron-Ion Scattering

he LHeC will give access to a completely unexplored region of the kinematic x–Q^2 plane for nuclei, see Fig. 6 left, thus transforming our present knowledge about their partonic structure.

In the standard collinear framework used to compute particle production in hadronic collisions, parton distributions inside nuclei (nPDFs) are basically unknown for x smaller than a few times 10^{-3} and are subject to large uncertainties elsewhere, see Fig. 6 middle. The scarcity of data for any single nucleus makes it mandatory to combine information on different ones. With scattering from a single nucleus at the LHeC, tests of factorisation with similar precision to the proton (Section **??**) will be possible. The impact of LHeC pseudodata on a global fit is illustrated in Fig. 6 right. Nuclear parton densities have never been measured in the diffractive case (Section 1.2). They can be extracted at the LHeC with similar precision to those inside the proton. 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.
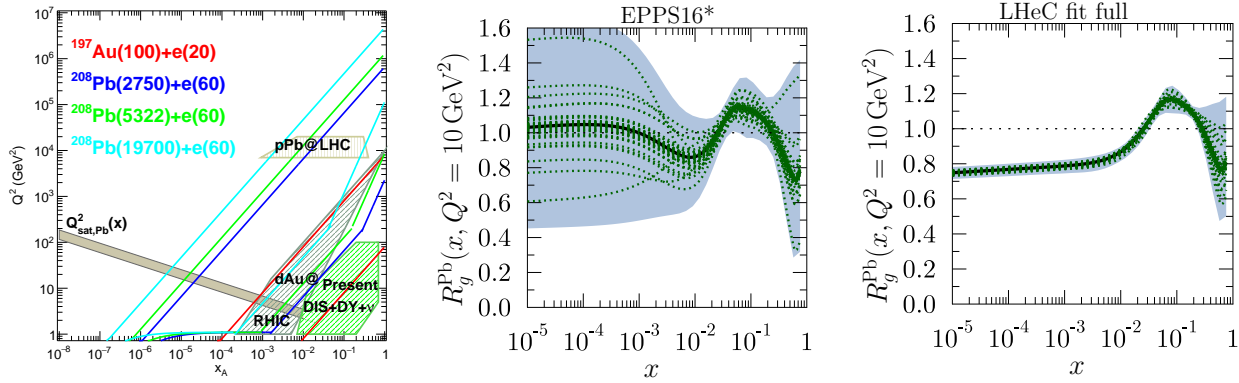
Figure 6: Left: x–Q^2 plane for an EIC (red), the LHeC (blue), the HE-LHeC (green) and the FCC-eh (turquoise), also indicating the region covered by data used in present global fits and the estimated line of the saturation scale for lead. Middle and right plots: Pb/p ratio of the gluon PDF in the modified EPPS16 analysis in [30], both for the present situation (middle) and including NC, CC and charm reduced cross section LHeC pseudodata (right).

Being density effects, non-linear QCD phenomena are enhanced by both a decrease in x and by an increase in the number of nucleons involved in the collision. Therefore, new linear phenomena like resummation can be disentangled from saturation effects through the simultaneous study of low x phenomena in ep and eA scattering. Nuclear effects on hadronisation and QCD radiation will also be constrained by particle and jet production measurements [5].

These studies 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, including correlations such as those revealed by the ridge phenomenon. 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.

2 The LHeC Facility

2.1 Configuration and Beam Stability   Daniel 0.5

The core of the LHeC electron complex consists of two superconducting 10 GeV linacs with an RF frequency of 800 MHz that are connected by arcs in a racetrack configuration, see Fig. **??**. 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 time through the two linacs and is dumped. The timing for these passages is ajusted 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.

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 a bunch charge of 4×10^9. Higher currents can be stabilised by further improving the damping. The electro-magnetic 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 will be 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. A potential instability that could be caused by trapping of ions in the beam is 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.

2.2   Lattice and Components   Alex 0.5

2.3   Civil Engineering   John 0.4

2.4   Parameters, Commissioning and Luminosity Profile   Oliver B 0.6

2.5   Interaction Region   Rogelio, Roman 0.4

2.6   Detector: Challenges and Baseline   Peter 1.0

2.7   Choice of Electron Beam Energy and Staging Options   Max+Oliver B 0.4

2.8   ERL Developments and the PERLE Facility   Erk 0.8

3   Physics Opportunities with the ERL beyond ep   Frank 0.5

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