Physics of Future Electron-Hadron Colliders

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QUICK LINKS

1. Introduction

The first ep collider ever built was HERA at DESY. Proposed in 1984 it started operating in 1992 mostly providing electron and proton beams of energy $E_e = 26.7\,\text{GeV}$ and $E_p = 920\,\text{GeV}$, resp. With its two collider experiments, H1 and ZEUS, HERA continued the programme of the fixed target deep inelastic scattering (DIS) experiments at much higher energies. Its legacy, summarised in [1], is the discovery of the rise of the sea quark and gluon distributions towards low Bjorken x, the proof of the resemblance of weak and electromagnetic interactions at scales given by the masses of the W and Z bosons, the discovery of diffractive DIS, a salient, consistent set of parton distributions (PDF) in the proton, further a variety of new concepts in the physics of DIS and the support of the development of perturbative QCD theory to NNLO. Recently, the combined neutral current (NC) $ep \to eX$ and charged current (CC) $ep \to \nu X$ inclusive cross section measurements have been published [2]. HERA also served a fixed target experiment, HERMES, which primarily was dedicated to explore the composition of the proton spin using the polarised electron beam of HERA scattered of a polarised nucleon target. All ep HERA experiments began a programme to study generalised parton distributions. The future DIS experiments discussed here will be based on ep and eA collider configurations, at medium energy with the EIC and emphasis on spin and nuclear structure, presented in Section 2, and at the energy frontier with the LHeC and emphasis on Higgs, QCD and LHC related physics, presented in Section 3.

There are three principal advantages of an ep collider experiment over a fixed target DIS experiment: i) the cms energy squared is $s = 4E_eE_p$ is much larger than $2E_lM_p$ in lepton scattering off protons (mass M_p) at rest; ii) the acceptance of a DIS collider experiment is near to 4π as is important for both inclusive and semi-inclusive physics and iii) the reconstruction of the kinematics, expressed by the negative four-momentum squared Q^2 and the parton momentum fraction of the proton, Bjorken x, is redundant and measurements are correspondingly very precise. The clean theoretical and experimental conditions make the electron-hadron configuration especially attractive when compared with the hadron-hadron configuration that is primarily directed to searching for new states (in pp) or producing dense matter (in AA).

In the US, an EIC of energy $\sqrt{s} = 20 - 100\,\text{GeV}$ is under design, with two options studied at BNL and Jefferson Laboratory, while at CERN one considers building a LHeC of energy $\sqrt{s} = 300 - 1300\,\text{GeV}$. Recently, similar configurations have also been considered in China. Both the EIC and the LHeC consider operating with protons and ions, such as deuterium, lead and others. They are complementary in their kinematic coverage

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and resulting physics programme. The EIC, for example, is unique in colliding polarised electrons off polarised protons and light ions for solving the question of the origin of the nucleon spin. The LHeC, as the electron beam upgrade of the LHC, is unique in enabling the CERN Higgs programme to become precise and the LHC luminosity upgrade to be of undoubtful use. The new *eh* colliders promise to move the physics of deep inelastic scattering much forward and to answer many open, fundamental questions in particle and as well nuclear physics. Given their huge luminosity prospects, one can safely expect surprising discoveries to appear which are naturally elusive to the subsequent, exemplary forward look. The authors have shared writing this paper according to their involvement in the EIC (RE) and LHeC (MK) developments.

2. EIC

Our view of the structure of the atomic nuclei and the nucleons they contain has made quite a transformation in the last decades. A common picture found in textbooks shows a 3-valence quark structure of the nucleon, yet we now know that the inside of the nucleon is rather a complex many-body system with a large number of gluons and sea quarks. There is unambiguous evidence that these both play unexpected roles for defining the structure of nuclear matter around us. In order to understand how the properties and structure of all forms of nuclear matter emerge from the dynamics encoded in QCD, it is essential to precisely image gluons and sea quarks, and to understand the role they and their interactions play in protons, neutrons, and nuclei [3, 4].

For this, a new accelerator facility is required - the Electron-Ion Collider (EIC). EIC must make a qualitative leap in technical capabilities beyond previous electron scattering programs. It must reach collision energies far higher than are available even at the upgraded CEBAF. It will exceed the earlier *ep* collider HERA by providing:

- Luminosity a factor of 100-1000 times higher, allowing unprecedented three-dimensional imaging of the gluon and sea quark distributions and to explore correlations among them
- Extensive energy variability to explore the transition in nuclear properties from the region of sea quarks to that of abundant gluons at low x, down to 0.001 or 0.0001 or so
- Spin-polarised proton and light ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin, and the contribution of gluons and sea quarks to the nucleon-nucleon interaction

- Heavy-ion beams to reach much higher gluon densities than with proton beams, to study the role and behaviour of gluons in nuclei, and to enhance the discovery of collective effects of gluons

The new experimental capabilities provided by the EIC will and must be complemented by theoretical advances in lattice QCD calculations, and also in effective field theory approaches that are being developed precisely for the gluon-dominated regime in nucleons and nuclei.

2.1. Machine Configuration

The suite of worldwide facilities, current or anticipated to be in operation, does not provide the capabilities required to complete our understanding of the QCD structure of nuclear matter in all its forms. Much evidence points to the missing link being a polarised, high luminosity EIC, where physicists can probe both nucleons and nuclei in a regime where their properties are dominated by sea quarks and abundant gluons.

Two designs for a future EIC have evolved in the United States. At BNL the eRHIC design (Fig. 1, left) utilizes a new electron beam facility based on an Energy Recovery LINAC (ERL) to be built inside the RHIC tunnel to collide with existing high-energy polarised proton and nuclear beams [5]. At JLab the Medium energy Electron Ion Collider (MEIC) design (Fig. 1, right) employs a new electron and ion collider ring complex together with the 12 GeV upgraded CEBAF to achieve similar collision parameters [6, 7]. The EIC machine designs are aimed at achieving

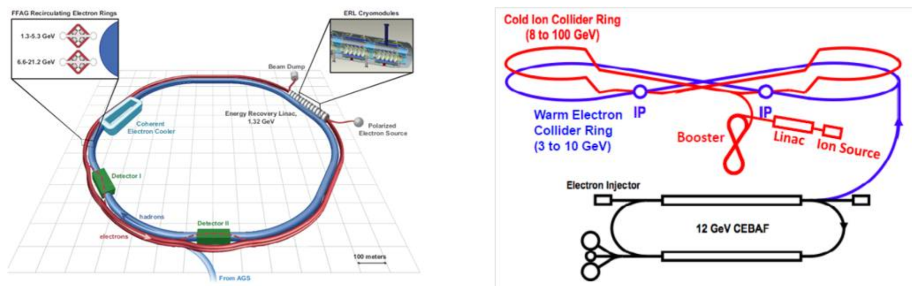

Fig 1: Left: The schematic of eRHIC at BNL, which would require construction of an electron beam facility to collide with one of the RHIC beams at up to three interaction points. Right: The schematic layout of MEIC at JLab, which would require construction of an ion linac and ion collider ring, and an electron collider ring with at least two interaction points, around the 12 GeV CEBAF.

- Highly polarized (70%) beams of electrons, protons and light nuclei
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable $\sqrt{s}$ from ~20 to ~100 GeV, upgradable to ~140 GeV

- High collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibility to have more than one interaction region

The EIC requirements will push accelerator designs to the limits of current technology to be validated by, partly ongoing, research and design. Cooling of the hadron beam is essential to attain the luminosities demanded by the science. The development of coherent electron cooling is underway at BNL, while the JLab design is based on conventional electron cooling techniques, but proposes to extend them to higher energy and to use bunched electron beams for the first time. An ERL at the highest possible energy and intensity is key to the realisation of eRHIC at BNL, and this technology is also important for electron cooling in MEIC at JLab. The eRHIC design at BNL requires a high intensity polarised electron source that would be an order of magnitude higher in intensity than the current state of the art, while the MEIC design at JLab will utilize a novel figure-8 storage ring design for both electrons and ions.

The physics-driven requirements on the EIC accelerator parameters combined with the demands of full kinematic coverage for measurements make the integration of the detector into the accelerator a particularly challenging feature of the design. Lessons learned from past experience at HERA strongly influenced the design of the EIC interaction region. Driven by needs for high precision on particle detection and identification of final state particles in both *ep* and *eA* programs, modern particle detectors will be at the heart of the EIC.

2.2. The 3D Structure of Matter

Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams off nucleons have taught us about how quarks and gluons (collectively called partons) share the momentum of a fast-moving nucleon. They have not, however, resolved the question of how partons share the nucleon's spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment. The earlier studies were limited to providing the longitudinal momentum distribution of quarks and gluons, a one-dimensional view of nucleon structure. The EIC is designed to yield much greater insight into the nucleon structure by facilitating multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavor. In such studies one must go beyond DIS in that either one or more hadrons produced in the electron-quark scattering process are detected, so-called semi-inclusive deep inelastic scattering experiments, or the complete final state is detected in so-called deep exclusive scattering experiments. Measurements of both of these processes enable the multi-dimensional mapping of the partons, requiring high luminosity for sufficient statistical precision to be achieved in the multi-dimensional kinematics governing these studies.

The 12 GeV upgrade of CEBAF at JLab [8] and COMPASS at CERN will initiate such studies, predominantly in the valence quark region and somewhat extending into the sea quark region. However, these programs will be dramatically extended at the EIC to explore the role of the gluons and sea quarks in determining the hadron structure and properties.

2.2.1. The Confined Motion of Partons Inside the Nucleon

Semi-inclusive DIS (SIDIS) measurements have two natural momentum scales: the large momentum transfer from the electron needed to achieve the desired spatial resolution, and the momentum of the produced hadrons perpendicular to the direction of the momentum transfer, which prefers a small value sensitive to the motion of confined partons. Remarkable theoretical advances over the past decade have led to a rigorous framework where information on the confined motion of the partons inside a fast moving nucleon is matched to transverse momentum dependent parton distributions (TMDs). In particular, TMDs are sensitive to correlations between the motion of partons and their spin, as well as the spin of the parent nucleon. These correlations can arise from spin-orbit coupling among the partons, about which very little is known to date. TMDs thus allow us to investigate the full three-dimensional dynamics of the proton, going well beyond the information about longitudinal momentum contained in conventional parton distributions. With both electron and nucleon beams polarised at collider energies, the EIC will dramatically advance our knowledge of the motion of confined gluons and sea quarks in ways not achievable at any existing or proposed facility.

2.2.2. Nucleon Tomography - Spatial Imaging of Gluons and Sea Quarks

By choosing particular final states in ep scattering, the EIC will probe the transverse spatial distribution of sea quarks and gluons in the fast-moving proton as a function of the parton's longitudinal momentum fraction, x. This spatial distribution yields a picture of the proton that is complementary to the one obtained from the transverse-momentum distribution of quarks and gluons, revealing aspects of proton structure that are intimately connected with the dynamics of QCD at large distances - where the coupling of QCD is strong. With its broad range of collision energies, its high luminosity and nearly hermetic detectors, the EIC could image the proton with unprecedented detail and precision from small to large transverse distances. The accessible parton momentum fractions x extend from a region dominated by sea quarks and gluons to one where valence quarks become important, allowing a connection to the precise images expected from the 12 GeV upgrade at JLab and COMPASS at CERN. The kinematic access the EIC provides for a range in x transitioning from the region of valence quarks, roughly above $x \sim 0.1$, through to region where the sea quarks may contribute to non-perturbative nucleon structure, roughly $0.01 < x <\sim 0.3$, into the region where gluons are abundant, roughly down to $x = 0.0001$ or 0.001, with sufficient resolution, hermeticity and luminosity to measure deep exclusive reactions, has been one of the fundamental assumptions of the EIC design.

The tomographic images obtained from cross-sections and polarization asymmetries for deep exclusive processes are encoded in generalised parton distributions (GPDs) that unify the concepts of parton densities and of elastic form factors. They contain detailed information about spin-orbit correlations and the angular momentum carried by partons, including their spin and their orbital motion.

2.3. A Spin Facility

An intense, worldwide experimental program over the past decades has shown that the spin of quarks and antiquarks is only responsible for ~30% of the proton spin. Recent RHIC results indicate that the gluons' spin contribution in the currently explored kinematic region is non-zero, but not yet sufficient to account for the missing 70% of the proton's spin. The EIC due to its emphasis on polarised electrons colliding with polarised protons and light ions, will settle this conundrum.

First, the energy range of the EIC gives access to the region of small-x of relevance to the DIS experiments. The partons' total helicity contribution to the proton spin is known to be sensitive to the minimum x accessible by the existing experiments. With the unique capability to reach two orders of magnitude lower in x and to span a wider range of momentum transfer Q than previously achieved, the EIC would offer the most powerful tool to precisely quantify how the spin of gluons (see Fig. 2, left) and that of quarks of various flavors contribute to the proton's spin. The EIC would realize this by colliding longitudinally polarised electrons and nucleons, with both inclusive and semi-inclusive DIS measurements.

EIC will make a huge impact on our knowledge of the gluon's helicity contribution $\Delta(G)$, reducing the present uncertainties by roughly a factor of 10, combined with a ~2-3 impact on the quark helicity contribution $\Delta(\Sigma)$. Such gains in knowledge will be unmatched by any other existing or anticipated facility. This would definitively resolve any question of whether parton spin preferences alone can account for the overall proton spin, or whether additional contributions are needed from the orbital angular momentum of partons in the nucleon.

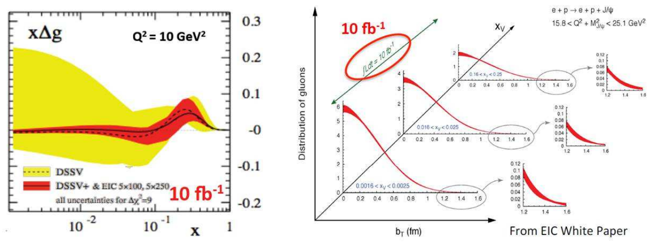

Fig 2: Left: The uncertainty bands on the gluon helicity parton distribution, in an analysis by DSSV [9] without (light band) and with projected EIC data (darker band). Right: The projected precision of the transverse spatial distribution of gluons as obtained from the cross-sections of exclusive J/Ψ production at an EIC. The distance of the gluon from the center of the proton is b_T in femtometers, and the kinematic quantity $x_V = x_B(1 + M^2_{J/\Psi}/Q^2)$ determines the gluon's momentum fraction.

The detection of exclusive J/Ψ meson production would provide unprecedented maps showing how the gluons are distributed in space within a plane perpendicular to the parent proton motion (see Fig. 2, right), as defined within the GPD formalism above. Such particular maps encode vital information, inaccessible without EIC, on the amount of proton spin associated with the gluons' orbital motion.

2.4. The Nucleus, a QCD Laboratory

The nucleus is a QCD "molecule", with a complex structure corresponding to bound states of nucleons. Understanding the formation of nuclei in QCD is an ultimate long-term goal of nuclear science. The long-range, attractive character of nuclear binding has been long known to be of Yukawa type, with pions as the effective carrier of the strong force. The QCD origin of the shorter-range, repulsive character required to maintain stable nuclei is however not known, and the role of gluons in nuclei remains elusive. With its wide kinematic reach, combined with the capability to probe a variety of nuclei in DIS, semi-inclusive DIS, diffractive and deep exclusive scattering measurements, the EIC can indeed explore the internal 3-dimensional sea quark and gluon structure of a fast-moving nucleus. For example, we do not know how gluons are distributed in space - do they follow the confinement radius predetermined by quarks, or whether they contribute to nuclear structure.

The nucleus itself is an unprecedented QCD laboratory for discovering the collective behavior of gluonic matter. The HERA discovery of the large rise of the gluons at small x is a corollary of gluon splitting. But, the gluons can also recombine. It is predicted that, at very high gluon densities, the probability for gluons to recombine must counterbalance the probability for gluons to split, leading to saturation of the gluon density. This state of gluon saturation is predicted to have universal properties inside nucleons and other hadrons, as well as inside all nuclei.

2.4.1. Gluons and the Binding of Nuclei

The ability of the EIC to collide electrons with nuclei, from light to heavy and at varying energies, presents us with new and exciting ways to study and understand nuclear matter. The use of light nuclei with 2 to 12 nucleons, whose nuclear structure is experimentally well studied and well described by existing models, will allow us to study the nucleon-nucleon force at short distances, but from the point of view of quarks and gluons. The recently discovered intriguing correlation between the quark motion inside the nucleus and the nucleon-nucleon force at short distance would further enhance such studies at the EIC. Detection of spectators (those nuclear fragments which do not participate in the DIS process) from a nucleus can identify the active nucleon and studies the nuclear binding effects and what role the partons play in them.

Because the role of gluons in nuclear binding is unclear, and the near-complete lack of experimental constraints, there is not much knowledge about the possible modification of gluon distributions in nuclei. The gluons could follow the nuclear modifications noted for the quark momentum distributions, known as the nuclear EMC effect, or not. Similar, in the region of smaller x it remains unclear to what extent the gluons are prone to the shadowing effects noted in ratios of nuclear structure functions. The EIC would not only constrain the possible modification of gluon (momentum) distributions, albeit not as precise as possible with the LHeC, but also allow in great detail determination of the completely unknown gluon spatial distributions in nuclei, for example from coherent ϕ vector medon production in eA scattering, due to the excellent and hermetic forward detector capabilities of recoil nuclei.

2.4.2. The Collective Behaviour of Gluons

By colliding electrons with heavy nuclei, the EIC will provide access to an uncharted regime of all nuclear matter, where gluons are abundant and dominate its behaviour. With higher gluon densities, the gluons are anticipated to act collectively, rather than independently, and ultimately reach a state of saturation, as predicted to be universal in all nucleons and nuclei. Heavy ion beams at the EIC could provide precocious access to the collective behaviour of gluons underlying this phenomenon. The virtual photon exchanged in the electron scattering process probes matter coherently over a characteristic length proportional to $1/x$, which can exceed the diameter of a Lorentz-contracted nucleus. This implies that the gluons within any nucleon in the nucleus could notice the gluons in another nucleon. This acts as an amplification effect on the gluon density, and is expected to enhance the probability for gluon recombination. Might the effects of gluon recombinations be observed in *eA* collisions, it would directly point to the collective behaviour of gluons.

If the observation of collective behaviour of gluons would be observed in various nuclei, it would point to the universal property of this effect. Note that the observation of the onset of such gluon recombination effects could very well occur at energies much below those where the gluon splitting and gluon recombination mechanisms are comparable, the latter defining the saturation scale. The onset of saturation itself can lead to dramatic predicted effects in comparisons of *ep* and *eA* collisions at an EIC. For example, in some cases the probability for a nucleus to remain intact in a high-energy diffractive process more than doubles in the *eA* case as compared to the typical 10-15% probability for diffractive scattering found in *ep* at HERA. Measurements of the spatial distribuitions of gluons in nuclei, as described above, could also be performed in a variety of nuclei transcending the regions where the onset of collective behaviour of gluons, and/or the onset of saturation, is found. This would open a new QCD frontier where the onset towards a universal form of gluon matter with characteristic collective behaviour is witnessed.

2.5. The Formation of Hadrons from Quarks and Gluons

The process of how colored quarks and gluons propagate through matter and bind themselves through interactions in patterns of massive hadrons, with different properties remains largely unknown in nuclear science. As a consequence of confinement, any individual quark or gluon vigorously struck in a scattering process must hadronize in a process commonly described by fragmentation functions. Our understanding of these suffers from the same shortcomings as the one-dimensional (1D) parton (spin and momentum) distributions in the description of nucleon structure. The partons exhibit three-dimensional (3D) confined motion inside nucleons, reflecting the 3D structure of the nucleon. Hadrons can emerge from a vehement electron-quark scattering process only by the struck quark binding with another. At minimum, one additional antiquark is required, to be picked up either from the QCD vacuum or the remnant beam (target) fragments. The final hadron can accumulate a momentum transverse to the beam direction by a convolution of the transverse momentum of the struck quark and the transverse momentum of the additional antiquark. This then turns the understanding of the emergence of hadrons from color charge into a correlated 3D problem.

The EIC presents us with the tools to dial with precision, the formation of light and heavy hadrons inside or outside the nuclear medium.

This will offer a fresh window into how fast quarks and gluons propagate through the QCD vacuum, with *ep*, or through nuclear matter, with *eA*, and are ultimately confined. The EIC will due to its high luminosity and hermetic detector capaibilties, even for nuclear fragments, be able to probe correlations between hadrons produced in the electron-quark scattering process, or correlations with hadrons in the target remnants. It also can probe, for example, the dramatic difference between the production of a π and a D^0 meson as anticipated by a mass dependence of the quark energy loss.

3. LHeC

The LHeC constitutes the project to eventually realise an electron-proton and electron-ion collider in the LHC tunnel at CERN, following the e^+e^- collider LEP and accompanying the $pp/AA/pA$ collider LHC in its final phase which has recently been projected to take until 2037. The machine design had a ring-ring and a linac-ring *ep* option [10], and for reasons of installation difficulties and technology innovation, tentative preference has been given to building a linac in energy recovery technology tangent to and inside the LHC ring. This configuration is also the baseline for the FCC-he study, see below. The LHeC design greatly exceeds HERA's parameters and has four major physics goals:

- it is the finest possible microscope the world could build, of resolution $d \propto 1/\sqrt{Q^2}$ varying by 4 orders of magnitude, which will resolve the partonic substructure of protons and neutrons with hitherto unaccessible clarity;

- with a production cross section as large as at the ILC, the LHeC promises to be the next machine which can study the Higgs boson, with per cent level precision as is required for possibly seeing new physics associated with it;

- a new level of information on QCD (PDFs foremost) and electroweak phenomena (as related to the top quark and $\sin^2\theta_W(\mu)$) transforms the LHC in a precision facility as that lacks external information it cannot provide by its nature [11]. This is especially relevant for the gluon density which hinders searching for new physics when the HL-LHC will require to pin down new physics at high masses corresponding to large Bjorken x;

- by extending the kinematic range in Q^2 and $1/x$ by $3-4$ orders of magnitude it will almost certainly revolutionise the view on nuclear substructure and eventually enable a QCD interpretation of phenomena related to the quark-gluon plasma (QGP).

The following is a brief summary of the machine and physics investigations. It leaves out the major achievement of designing an LHeC detector. It neither describes the ongoing studies directed to various technology items, such as the development of high quality ERL SCRF, and updates of the physics programme, such as the $H \to c\bar{c}$ study. Much information is collected at the LHeC web page and updates are presented at regular workshops.

3.1. Machine Configuration

The LHeC is an electron-proton (ep) and electron-ion (eA) complement of the Large Hadron (pp and AA/p) Collider. In 2012 a detailed conceptual design report (CDR) was published [10] covering the physics, accelerator and detector aspects of the project. In the LHeC default configuration two super-conducting linacs are used to obtain a polarised electron beam of 60 GeV energy in a 3-pass racetrack configuration illustrated in Fig. 3. LHeC operation is fully transparent to the LHC collider experiments

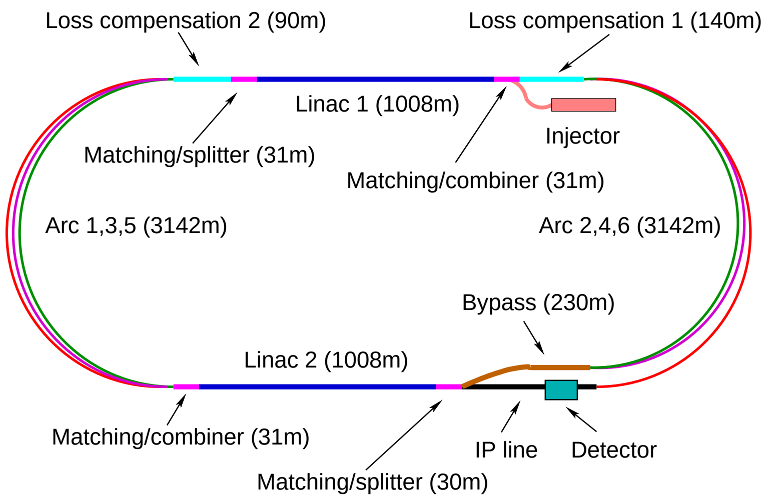

Fig 3: Schematic view of the default LHeC configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite linear structures made of 60 cavity-cryo modules each. The arc radius is about 1 km and the circumference chosen to be 1/3 of that of the LHC. The beam is decelerated for recovering the beam power after having passed the IP.

thanks to the low lepton bunch charge and resulting small beam-beam tune shift experienced by the protons. The LHeC is thus designed to run simultaneously with pp (or AA) collisions in order to reduce the cost and optimise the physics return since a concurrent operation with the

LHC can have a direct impact on the HL LHC physics programme as is sketched below.

With an anticipated value of $L = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the LHeC has the potential to surpass the luminosity of HERA by 2-3 orders of magnitude, for a summary of its characteristic high luminosity parameters see [12]. Its centre of mass energy is 1.3 TeV, roughly twice as large as that of the linear e^+e^- collider ILC under consideration. The LHeC could take a luminosity of $1\,\mathrm{fb}^{-1}$ in a few days which corresponds to the total data sample collected by H1 and ZEUS in a long period of 15 years of operation, while also extending their kinematic reach, of maximum Q^2 and $1/x$, by factors of about 20. The LHeC constitutes a machine moving the energy frontier of particle physics much forward at modest additional expense.

The energy recovery linac under design for the LHeC has been adopted as the default electron beam option for the electron-hadron collider of the FCC complex currently under study for CERN. Combined with a potential proton beam of $Ep = 50$ TeV energy, the FCC-he collider would reach a centre of mass energy of $\sqrt{s} = 2\sqrt{E_e E_p}$ of 3.5 TeV at a similar luminosity as the LHeC. The physics potential of that machine is correspondingly impressive. Exceeding the reach of the LHC it probes, for example, for the existence of lepto-quarks with masses near to $\sqrt{s}$ or for contact interaction to hundreds of TeV energy scale. The production cross section of the Higgs boson at the FCC-he is five times larger than that of the FCC-ee, and the self-coupling of the Higgs boson possibly accessible in a configuration much cleaner than that of FCC-pp. As part of the FCC design study, the electron-hadron physics potential and experimental configuration is currently evaluated but not further presented in this paper. It may be noted that again one considers a synchronous operation of *ep* and *pp*, now from the start of the *pp* collider, which made the FCC-he collider a natural successor of the LHeC, should the FCC eventually become reality.

3.2. Deeper into Matter

The momentum distribution functions of partons (PDFs) are measured in DIS. They can also be constrained in *pp* scattering at the LHC, however, in a much inferior environment: the theory is subject to non-perturbative corrections, even in Drell-Yan W or Z production through unavoidable kinematic cuts, the experimental environment is less clean, due to pile-up and for the lack of the redundancy provided by the electron and hadron kinematic reconstruction in DIS, and finally because there is no real equivalent to the large variation of Q^2 as characterises an *ep* collider. HERA has deepened the understanding of quark-gluon dynamics substantially, with i) the first quantitative determination of the gluon density without

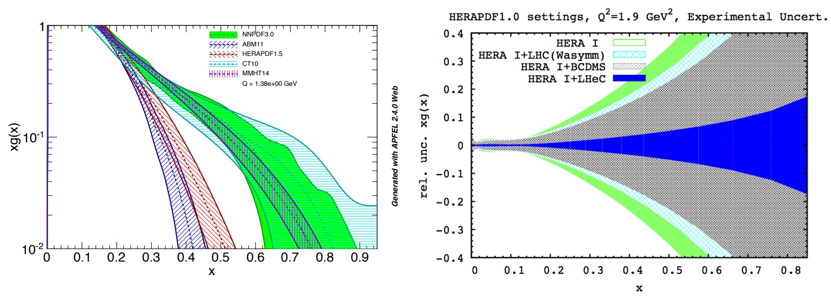

Fig 4: Status of determinations of the gluon distribution in recent PDF fits (left) and the prospect from the LHeC (right). It can be seen that the LHeC will eventually reduce the uncertainties of xg which presently are extremely large at high x to below 10 % at $x \simeq 0.6$.

which one would not have known the Higgs production cross section at the LHC, for example, and ii) the extension of the kinematic range of Bjorken x down to values of 10^{-4} in the perturbative region, where α_s is below 1. However, owing to restrictions of beam energy and luminosity, major parts of the DIS programme have not been completed: the low x region has been explored but no sign for parton dynamics beyond the linear evolution equations could be established; the full set of PDFs could not be resolved, with large uncertainties left at high x, the beauty density known to only about $10 - 20$ %, the strange density unknown, intrinsic quark states undetected, etc; the gluon (xg) and quark densities at high x are so uncertain that this will represent a decisive problem for high mass searches at the LHC when the HL LHC operates, see Sect. 3.5. These serious drawbacks can all be resurrected with the LHeC: the luminosity is orders of magnitude larger than that at HERA such that the high x behaviour (d/u, xg) of PDFs will be clarified, 60 years hence after the discovery of quarks; the Q^2 range extends so far beyond the masses squared of the Z and W that both NC (through photon and Z exchange) and CC cross sections will permit a complete unfolding of the partonic content of the proton, in a hugely extended kinematic range; all four heavier quark distributions will be directly measurable in an unaccessed range of Q^2 and x, strange (accurately for the first time) charm and beauty (extermely precisely below and much beyond threshold) and even the top distribution (never accessed before); any non-linear gg interaction effect would be observed in an x range down to 10^{-5} for Q^2 exceeding M_p^2.

Beyond the programme of completely unfolding the PDFs of the proton there is a huge, first class DIS programme ahead: measurements of the neutron, nuclear, Pomeron and photon structure; searches for substructure or partons and new interactions; measurements of generalised and unintegrated parton distributions which are left at inferior state with HERA finished, and also, to give a further example, the exploration of QCD Higgs phenomena, leading much beyond the precision determination of the Higgs couplings. The LHeC is a precision facility for electroweak physics, through huge sensitivity to the weak NC and $\sin^2\theta_W$, the running of which with $\sqrt{Q^2}$ is measurable from a few 10 GeV up to nearly 1 TeV. It is also a top quark factory and unprecedented constraints can be obtained on its anomalous couplings. The LHeC is a laboratory for new physics.

3.3. Grand Unification and the Strong Coupling Constant

The SM combines the electromagnetic, weak and strong interactions based on similar gauge field theory principles. Their coupling constants, through loop corrections, depend on the scales of the processes considered. Despite the phenomenological success of the $SU(2)_L xU(1)$ theory which mixes the weak and electromagnetic interactions, there has no genuine unification of these interactions been achieved within a higher gauge group, for which SU(5) had been a historic but not successful example. In Grand Unified Theories (GUTs) the three coupling "constants" approach a common value at the scale of the Planck mass. Any calculation of this limit is hindered by the dominating uncertainty of the strong interaction constant α_s, see [10]. The determination of α_s is a most complex task and the current situation, despite massive efforts [13], not satisfactory. At the LHeC, α_s can be measured to per mille precision due to the very large Q^2 for exploiting the α_s-dependent scaling violations of the inclusive cross sections, and the provision of the extra information required. This will provide a measurement which is more precise than the current world average of the coupling constant, and unlike today it will be based on one coherent determination. The total experimental uncertainty on α_s is estimated to be 0.2 % from the LHeC alone and 0.1 % when combined with HERA. Relying solely on inclusive DIS *ep* data at large Q^2, this determination is free of higher twist, hadronic and nuclear corrections, unlike any of the recent global QCD fit analyses. A similar precision can be obtained at the LHeC in jet based analyses which hitherto tend to provide larger values of α_s than the inclusive NC and CC cross sections. The unprecedented LHeC measurements of PDFs will reduce the resulting uncertainties as from the behaviour at low x or the treatment of charm and beauty contributions to the adequate level, with, for example, an expected precision on the charm mass improved by a factor of 20 to 3 MeV as compared to HERA. The measurement of α_s at the LHeC requires pQCD for DIS to be formulated at N^{3}LO. It so represents a genuine long term physics programme of highest reward: it may discriminate GUT theories, similar to when a measurement of $\sin^2\theta_W$ excluded SU(5), provide the required precision for Higgs physics at the LHC and lead to unexpected observations in QCD. It will eventually challenge the use of lattice QCD calculations which currently dominate the precision of determination of the strong coupling but stand on a different base than comparisons of data with pQCD.

3.4. A Next Higgs Facility

The Higgs mechanism is responsible for generating masses of the weak gauge bosons as well as the elementary fermions. Its simplest representation generates an extra scalar field, $J^{CP} = 0^{++}$, that is referred to as the SM Higgs boson (H). Recent ATLAS and CMS measurements, following the discovery in 2012, are consistent with the expected H decay rates into various channels, such as $H \to \gamma\gamma$ and $H \to 4l$. Particle physics is far from being 'after the Higgs', the exploration of the properties of the SM Higgs boson has begun to become a focus of modern particle physics. High precision is required to verify the theoretical predictions and to find possible departures from new physics. The cross section in pp collisions at the LHC is large, dominantly due to gluon-gluon fusion via a top-quark loop. However large background, theoretical uncertainties and complex experimental conditions, related to a high pile-up at rising luminosities, limit the ultimate precision of Higgs coupling measurements to typically O(10) % at the LHC. An important prospect for the LHeC, with its unique ep configuration, is the transformation of the LHC facility into a precision Higgs physics laboratory when pp and ep take synchronously data of high luminosity. This is for two reasons: i) being free of the pp complications, with lower background, small theoretical uncertainties and cleaner final state with no-pileup, the LHeC has the potential to measure Higgs decays with high precision, especially those as $H \to b\bar{b}$ which are very difficult (bb) or impossible (cc) to access at the LHC, see Fig. 5; ii) with its unprecedented potential (see 3.2) of resolving the partonic structure of the proton, i.e. of precisely determining the then complete set of PDFs at N^3LO and of measuring the strong coupling constant α_s to per mille accuracy, the LHeC greatly reduces the theoretical, i.e. external uncertainties of the LHC (pp) Higgs measurements. The resulting Higgs coupling measurements from the LHC and LHeC then will reach the few % level and challenge the potential of future e^+e^- colliders as they would come much earlier and at a small fraction of an ILC or CLIC cost.

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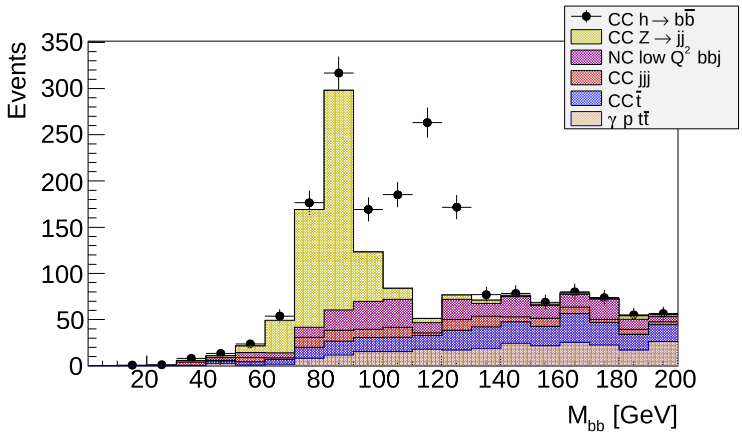

Fig 5: Simulation of the reconstruction of the Higgs decay into two b-quarks with the LHeC, for 100 fb^{-1} luminosity, which corresponds to a year of operation at the maximum design luminosity, from [14]. The $b\bar{b}$ decay is expected to be cleanly observable and the $H \to b\bar{b}$ coupling should be measurable eventually with 1 % precision. The leading graph for Higgs production in e^-p scattering is its emission from a W in CC, or, at smaller rate also from Z exchange in NC scattering. Therefore, besides the very high precision, it is advantageous that the WWH and ZZH couplings can uniquely be distinguished and measured. Unlike at the LHC, with the LHeC the second generation fermion decay $H \to c\bar{c}$ will be accessible also. Since, furthermore, the PDF and α_s related uncertainties of the pp Higgs measurements can be essentially removed through the LHeC programme, there is a striking prospect for the LHC facility to become a precision Higgs laboratory.

3.5. New Physics and the HL-LHC

The HL-LHC is the highest priority of global particle physics. It describes the programme to enlarge the integrated luminosity in the second part of LHC operation, currently projected to end in 2037, by a factor of ten for collecting 3 ab^{-1}. This will allow to exploit the potential for Higgs physics maximally and to search for rare processes. New physics may be hidden at high masses. In the pair production of a hypothetical new particle of mass M, at the LHC maximally a range of $M \leq E_p \sqrt{x_1 x_2}$ may be probed, where E_p is the proton beam energy, finally expected to be 7 TeV at the LHC, and $x_{1,2}$ are the Bjorken-x values of the two partons which in a Drell-Yan interaction lead to the generation of that new particle. The probability for the occurence of a high value of x decreases like $(1 - x)^3$ when approaching 1 which underlines why maximum luminosity at the LHC is an ultimate goal. This, however, is not enough because of the poor knowledge of the PDFs at large x. This problem has been illustrated for gluino pair production in MSSM SUSY at the LHC [11]. The LHC measurements at HL-LHC are expected to reach a range of 4 TeV gluino mass, corresponding to an average $\sqrt{x_1 x_2} = x$ of about 0.6.

There, however, the current uncertainty of xg is so large that it may become impossible to correctly interprete new signals for physics, see Fig. 6. Limits can be improved with luminosity increase: with the HL-

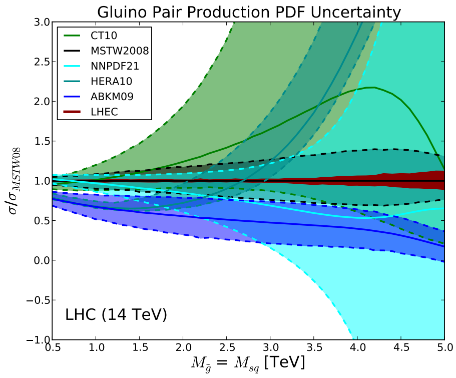

Fig 6: Calculation of gluino pair production in NLO SUSY-QCD. The error bands are around central values (solid lines) and correspond to the uncertainty quotations of the various PDF groups. The red band of uncertainty for the LHeC corresponds to the projected full PDF errors including their correlations.

LHC, typically a $0.5 - 1$ TeV gain in high mass reach is obtained. Like for the MSSM example shown, similarly, the projections for heavy boson searches, for extra dimensions or contact interactions exhibit the problem that the PDF information will severely limit or prevent conclusions to be reliably drawn. External, reliable precision information on the PDFs at large x is necessary for indeed exploiting the potential that HL-LHC project offers. The electron beam upgrade of the LHC combined with (and following) the luminosity upgrade will transform the LHC into a facility of much further reach than current projections often envisage. It may finally be noted that one is not just talking about "better PDFs", one thereby is returning to fundamental questions of QCD, such as questions of factorisation, resummation and non-linear evolution. When it comes to new, possibly subtil physics observations these will have to be re-examined for which the LHeC and LHC together provide the necessary experimental base.

3.6. Importance and Solutions to Low x Physics

HERA discovered the rise of the gluon (and sea quark) density at fixed Q^2 when Bjorken x decreases. The known linear (DGLAP) evolution equations are known to neglect terms $\propto \ln(1/x)$ which become large when x approaches zero. They may eventually need to be replaced by a BFKL type formalism. Low x physics is the area of the CFT-AdS correspondence which relates SUSY in higher dimensions to QCD. The LHC involves processes with x as low as 10^{-5} and the currenty discussed FCC pp collider would reach even lower in x. A further crucial ingredient to low x physics comes from ultra-high energy neutrino physics. With the observation by ICECUBE of a few neutrino events of astrophysical origin UHEν physics has made a step forward which is related to charm and very low x PDFs. Thus major developments and expectations in theory as well as reliable predictions for the FCC and UHE neutrinos require to understand low x physics. This cannot be achieved without the LHeC. In the LHeC design report [10] it has been studied in considerable detail how new low x physics at the LHeC may be approached. This includes DIS diffraction and investigations of vector meson production (J/ψ and Υ). A decisive role, because of their stringent theoretical base, play the precision measurements of the two structure functions F_2 and F_L at low x and of their Q^2 dependence. Approximately, F_2 determines the quark distributions while F_L and $\partial F_2/\partial Q^2$ fix the gluon distribution at low x. The two functions are not independent but sensitive to departures from conventional DGLAP evolution in a different way. While one may parameterise such departures "away" when one fits F_2, this was proven to run into conflict with precision data on F_L. The LHeC provides the necessary input, precision F_2 *and* precision F_L data at an unprecedented reach towards low x, for resolving the principal questions open in low x physics. Low x at the LHeC is an area for discovery and new questions will arise leading this field, which was opened with HERA, much further. An example is the generalised gluon distribution and the 3D view on the parton dynamics, as sketched in the EIC section above, which will be studied down to lower x values with the LHeC owing to the larger ep beam energies.

3.7. Substructure of Nuclei

The quark-gluon dynamics inside nuclei is far from clear. HERA had accelerated neither heavier nuclei nor deuterons. Thus, nuclear PDFs rely on fixed target data and some heavy ion data such as π° production - the status is as unsatisfying as was the proton structure resolution prior to HERA. The current procedure to determine nuclear PDFs is approximate and questionable in both theoretical and experimental regard. The procedure uses a given set of proton PDFs and determines the phenomeonological parameters of a nuclear correction factor, yet the choice of pPDFs is arbitrary and the factorisation ansatz questionable. That determination is for only one valence, a common sea and the gluon distribution. The LHeC promises the equivalent of 1 fb^{-1} of luminosity for ePb collisions at LH(e)C energies. With its large Q^2 and $1/x$ range, NC, CC and heavy quark structure functions can be measured very precisely, with radiative corrections $\propto Z^2$ as a special challenge. Thus a flavour resolved determination of genuine, nuclear PDFs can be performed for the first time and the nuclear corrections be determined for each parton separately. This will put the physics of nuclear substructure on completely different and solid grounds. A series of long predicted effects will eventually become accessible such as the black body limit of F_2, the possible amplification of the gluon density by $A^{1/3}$, Gribov's relation of shadowing to diffraction and many more. The eA physics programme will allow to formulate the theory of dense hadronic matter formation as it determines the QGP initial state. The secrets of confinement will be studied with nuclear diffraction or hadronisation inside or outside the nuclear meadium, via a variation of the energy transfer between electron and nucleus. Finally, one considers to take high energy electron-deuteron data, with a new injector for deuterons into the LHC, which would permit a deep study of neutron structure and of parton symmetry relations for the first time. It would also allow to separate the non-singlet from the singlet evolution and therefore base QCD predictions and the derivation of xg and of α_s on new grounds. Tagging spectator protons in eD scattering allowed accessing the neutron substructure basically free of Fermi motion corrections which presently hinder any clear resolution of the valence-quark behaviour at large x. Constraints on nuclear PDFs are currently obtained from Drell-Yan vector boson production in pPb scattering at the LHC. For principal reasons (the limited Q^2 range since $Q^2 \simeq M^2_{Z,W}$) and practical limitations for highest precision, these are consistency checks rather than measurements. The dynamics of parton interactions and the partonic structure of nuclei are prime subjects of research and cannot be resolved without the LHeC in the nearer future. The extension of the kinematic coverage by 4 orders of magnitude and the application of ep collider techniques to eA lead to the expectation of a revolution of our knowledge of the inner structure of nuclei. This is an area where the EIC and LHeC measurements both would be important to co-exist for their complementary coverage and since this field is theoretically and experimentally demanding enough to justify two maximally independent approaches. QCD is the richest part of the SM and it deserves a much bigger effort.

4. Summary

The LHeC and EIC electron-hadron colliders build upon the legacy of the first and only ep collider ever built, yet promise to provide transformational science insights. Both EIC and LHeC consider polarised electrons colliding with protons and ions, such as deuterium, lead and others, while their envisioned physics programme is both complementary and unique.

The EIC is unique in colliding polarised electrons off polarised protons and light nuclei, providing the spin degrees of freedom essential to pursue its physics programme driven by spin structure, multi-dimensional tomographic images of protons and nuclei, and discovery of the role of collective effects of gluons in nuclei. Its hermetic detection capability of correlated fragments promises to finally shed further light on the microscopic origin of the formation of hadrons from quarks and gluons.

The LHeC is unique in its energy reach, coupled with high luminosity, which make it the finest microscope to the substructure of matter the world may build. This will allow a physics programme to completely unfold the parton distributions of the proton, search for grand unification and new physics, and it will transform the LHC facility into a precision Higgs laboratory. The LHeC will determine the gluon distribution at low x for finding saturation and high x for enabling searches at the HL LHC. Its eA programme is of largest scope.

These future electron-hadron colliders promise to move the physics of deep inelastic scattering much forward and to answer fundamental questions in particle as well as nuclear physics. Deep inelastic scattering has discovered quarks, and has provided strong foundations of QCD. The HERA ep collider has opened a new chapter of QCD physics discovering a wall of gluons residing deep inside matter. The proposed EIC and LHeC colliders promise to continue this story of success: one can safely expect surprising discoveries coupled with tremendous progress in sight. The complexity of hadronic matter, the exploitation of the LHC and search for and possible interpretation of new physics, the route beyond the Higgs discovery, the development of neutrino astrophysics, the development of perturbative QCD and the physics of confinement - particle physics needs DIS physics to continue. Designs of accelerators and detectors, all based on novel technology, have been made. Unlike in other areas, this is a challenging and realistic horizon.

References

[1] M. Klein and R. Yoshida. Collider Physics at HERA. *Prog.Part.Nucl.Phys.*, 61:343–393, 2008.

[2] H. Abramowicz et al. Combination of Measurements of Inclusive Deep Inelastic $e^{\pm}p$ Scattering Cross Sections and QCD Analysis of HERA Data. 2015.

[3] Daniel Boer, Markus Diehl, Richard Milner, Raju Venugopalan, Werner Vogelsang, et al. Gluons and the quark sea at high energies: Distributions, polarization, tomography. 2011.

[4] A. Accardi, J.L. Albacete, M. Anselmino, N. Armesto, E.C. Aschenauer, et al. Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all. 2012.

[5] E.C. Aschenauer, M.D. Baker, A. Bazilevsky, K. Boyle, S. Belomestnykh, et al. eRHIC Design Study: An Electron-Ion Collider at BNL. 2014.

[6] S. Abeyratne, D. Barber, A. Bogacz, P. Brindza, Y. Cai, et al. MEIC Design Summary. 2015.

[7] S. Abeyratne, A. Accardi, S. Ahmed, D. Barber, J. Bisognano, et al. Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab. 2012.

[8] Jozef Dudek, Rolf Ent, Rouven Essig, K.S. Kumar, Curtis Meyer, et al. Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab. *Eur.Phys.J.*, A48:187, 2012.

[9] Daniel de Florian, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang. Extraction of Spin-Dependent Parton Densities and Their Uncertainties. *Phys.Rev.*, D80:034030, 2009.

[10] J L Abelleira Fernandez and the LHeC Study Group. A large hadron electron collider at cern. *Journal of Physics G: Nuclear and Particle Physics*, 39(7):075001, 2012.

[11] J.L. Abelleira Fernandez et al. On the Relation of the LHeC and the LHC. 2012.

[12] Oliver Bruening and Max Klein. The Large Hadron Electron Collider. *Mod.Phys.Lett.*, A28(16):1330011, 2013.

[13] S. Moch, S. Weinzierl, S. Alekhin, J. Blumlein, L. de la Cruz, et al. High precision fundamental constants at the TeV scale. 2014.

[14] Uta Klein. Higgs Physics at the LHeC. *Contribution to ICHEP, Valencia*, 2014.