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The LHeC Conceptual Design

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A brief overview is given on the physics, accelerator and detector design of the Large Hadron Electron Collider, the LHeC, which is the first deep inelastic scattering collider to possibly operate at the TeV energy scale. The design is directed to achieve integrated luminosities of O(100) fb^{-1}, in synchronous *pp* and *ep* operation. A dedicated state of the art detector is envisaged to be built of very high precision and with acceptance down to small angles to access extreme values of negative four-momentum transfers squared $Q^2 > 10^6\,\text{GeV}^2$ and of Bjorken x, $10^{-6} < x < 0.9$. A new laboratory may thus be opened at CERN to accompany the LHC efforts for exploring the TeV energy scale with deep inelastic scattering measurements of unprecedented precision, scope and range, including a far reaching electron-ion scattering programme.

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1. Deep Inelastic Scattering and Particle Physics

Since the discovery of proton substructure in electron-proton (ep) scattering at SLAC in 1969, deep inelastic lepton-nucleon scattering (DIS) has been an important part of the evolution of particle physics into the smallest dimensions, related to the largest energies. The physics at HERA [1] has led to a new understanding of quark-gluon interaction dynamics and provides a basis for the TeV scale pp experiments at the LHC. At each step of increase in energy, DIS experiments, e^+e^- and pp or $\overline{p}p$ experiments, have explored the physics phenomena, which appeared to be accessible then, in an often complementary way. At the O(10) GeV energy scale, DIS experiments discovered quarks, weak neutral currents and their isospin structure, and supported the hypothesis of asymptotic freedom, while in e^+e^- the J/ψ, colour and gluon jets were observed. Meanwhile, in hadron scattering the Drell Yan parton-parton scattering, jets, charm and the W and Z were discovered. A new series of colliders, HERA, LEP and the Tevatron, then pursued the investigation of the Fermi energy scale at O(100) GeV. HERA, which was the first ep collider ever built, measured the gluon density and discovered the role of heavy quarks in the proton, diffractive DIS and the rise of the parton (gluon and sea quark) densities towards low Bjorken x. LEP, much like HERA for the strong interaction, brought the understanding of the electroweak interaction to a new level of accuracy and art, specifically with the prediction of the top quark mass, the high precision measurement of the Z mass and the determination of the number of (light) neutrinos to be 3. At the Tevatron the bottom and the top quarks were found and the W mass is measured to high precision while the search for the Standard Model (SM) Higgs particle at Fermilab is not yet concluded. All three colliders have set limits to new physics, e.g. supersymmetric particles must have masses in excess of a few hundred GeV. At the Fermi scale, physics beyond the SM has been elusive. The first year of the LHC has opened the window of accelerator particle physics to the O(1000) GeV energy range [2]. From the physics results obtained with the first 40 pb^{-1} of luminosity at cms energy of 7 TeV in pp scattering, new limits have been set, often already exceeding those obtained previously. It is expected that the question of the existence of the SM Higgs particle will be solved in the year 2012 from about 5 fb^{-1} of data analysed by the ATLAS and CMS Collaborations. It is for this time that the question will arise how to develop the unique field of accelerator particle physics at the energy frontier further [3]. For years there have been developments pursued for the development of new e^+e^- colliders [4], and possibly a muon collider, to study the TeV energy scale. A future for DIS at the TeV scale is offered by the intense, high energy beams of the LHC [5]. A strong collaborative effort of accelerator, experimental and theoretical physicists is underway [6] for designing the LHeC, i.e. a fifth large experiment for the LHC, based on attaching a 60 GeV electron beam to the proton and ion beams of the LHC. This would extend the kinematic range in negative four-momentum transfer Q^2 and $1/x$, and increase the luminosity with respect to HERA, by about two orders of magnitude, reaching Q^2 values as large as 10^5 times the Q^2 value of about 10 GeV^2 of the famous ep experiment at SLAC.

2. Physics with the LHeC

The physics of the LHeC is concerned with new phenomena possibly ocurring in the fusion of electrons and partons at TeV energies. The cross sections of singly produced new states coupling

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to electrons and quarks are about a hundred times higher than in pp scattering. The control over the initial state, the electron charge and polarisation, and the distinction between neutral and charged currents make the LHeC particularly suitable for the investigation of resonant lepto-parton states should these exist in the mass range accessible to the LHeC. The collider has a specific potential to study the $eeqq$ interaction, the Higgs to $b\overline{b}$ decay and excited leptons. Contact interactions may be probed at scales of up to 70 TeV. The detector and its kinematic range will allow to measure α_s to per mille precision, about ten times more accurate than hitherto. Such a measurement is of fundamental importance for the question of grand unification, i.e. whether the running coupling constants indeed approach a common value at the Planck scale. It is not clear today whether inclusive DIS and jet based analyses indeed lead to a common value of α_s. Obviously the attempt to achieve such an accuracy would be an enormous stimulus to the development of experimental techniques and of perturbative QCD. With the very high energy and luminosity, completely new phenomena in DIS become accessible. The LHeC, for example, is a single top (anti-top) quark factory with a cross section of O(10) pb in W^+b ($W^-\overline{b}$) fusion. This not only allows unique checks of the particle-antiparticle nature of the top quark but also to study the appearance of top versus Q^2, i.e. the development and precise investigation of the treatment of heavy quarks in QCD, then including t. Accurate measurements of the strange and anti-strange quark distributions in the proton appear to be possible for the first time. Based on its tremendous energy range and luminosity, the LHeC is the first collider, which will resolve the proton quark structure completely, by directly measuring all sea and valence quark distributions. This leads to the most accurate and complete set of constraints to pQCD parton distribution function (PDF) analyses, which nowadays cannot be performed without a number of assumptions on the behaviour of the partons and therefore grossly tend to overestimate the intrinsic accuracy on our knowledge on the PDFs. The proton at low x seems largely to be determined by the gluon density xg. It is the gluon-gluon interaction which determines the baryonic mass of the universe. A hugely improved determination of xg becomes possible, extending over six orders of magnitude in x. The present low x determinations of xg are unstable below $x \lesssim 0.001$ because the Q^2 range of the available data on $\partial F_2/\partial \ln Q^2$ is not sufficient. Therefore, attempts to find the predicted saturation of the gluon density at low x at HERA are bound to be inconclusive. The LHeC is to discover and investigate a new phase of hadronic matter, in which the coupling constant is small but the parton densities at low x are high. In this regime, the linear DGLAP parton evolution equations are expected to fail and BFKL or BK type evolution equations, which incorporate the sizeable $\ln 1/x$ and non-linear effects, must hold. This region is thus of particular relevance for crucial theoretical developments [8] which are of importance also for heavy ion physics and super-high energy neutrino physics. QCD is often limited to the prediction of PDFs and jets as essentials for finding physics beyond the SM. However, with the development of new concepts as diffractive DIS or unintegrated partons, with the prediction of as yet unobserved phenomena like instantons or odderons, for example, the development of QCD and the understanding of parton interactions are far from being complete and will profit enormously from the LHeC. A further major subject is electron-ion scattering, which will determine the nuclear parton distributions in the LHC kinematic range and is expected to discover striking new phenomena as the black body limit of F_2, colour transparency or a large increase of the fraction of diffractive scattering, possibly up to 50 %. It is the unique high energy of the LHeC which will allow to disentangle gluon saturation from nuclear effects because it will be observed both in eA, with some enhancement factor $A^{1/3}$, and in ep. With deuterons the neutron structure becomes directly accessible: by tagging the spectator proton in eD interactions one gets rid of the Fermi motion correction plaguing the interpretation of nuclear DIS data for decades while with Gribovs relation of diffraction to shadowing the low x measurements on deuterons should become controllable. For eA and eD, the LHeC extends the kinematic range covered by DIS experiments by $3-4$ orders of magnitude as proposals to run HERA in eN mode had not been pursued for DESY had different hopes. The list of new directions and superb subjects is much longer than indicated above, incorporating forward jet physics to determine the mechanism of parton emission, the investigation of the gluon structure of the photon, the determination of electroweak light quark couplings ten times better than before or the study of heavy quarkonium production in the saturation regime. There will be new features in DIS which escaped present attention.

3. Accelerator Concepts and Detector

The accelerator design is to achieve a peak luminosity of about $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and integrated luminosities of O(100) fb^{-1}. These may be realised if the LHeC running time extends over a period of about 10 years and when ep and pp operation proceeds synchronously as is made possible with the small tune shift in ep. A wall-plug power limit has been set at 100 MW. The default electron beam design energy, E_e, has been chosen to be 60 GeV, in order to limit the synchrotron radiation losses and the dimensions of the project. An option for a much higher E_e is also considered, since new physics phenomena possibly occuring at the LHC may demand to raise E_e to beyond the 60 GeV, and for E_p too [7]. The luminosity goals appear to be achievable in two configurations, i) a so-called ring-ring (RR) collider, using a set of 3080, 5.35 m long normal conducting dipoles combined with 96 super conducting (sc) cavities of 721 MHz frequency and ii) a so-called linac-ring (LR) collider using a total of 1056, 721 MHz sc cavities, operated at 18 MV/m gradient in CW mode for energy recovery, combined with 3600, 4 m long normal conducting dipole magnets stacked in 2×3 return arcs. The RR civil engineering is determined by the bypasses around the operating LHC experiments, for which case studies have been performed for ATLAS and CMS, requiring approximately 3 km of new tunnels in which the rf system may also be housed. The 60 GeV race-track LR configuration can be realised with a new 9 km tunnel. The design study report on the LHeC [6] will contain detailed descriptions of the accelerator work packages, including injectors and sources. For the RR, special care was given to i) the possibility to install a new accelerator on top of the LHC, with first engineering considerations and with the design of an asymmetric FODO cell to account for the so-called cryo-jumpers of the LHC, ii) to prototyping the ring dipole magnets, at Novosibirsk and at CERN, in order to check the field reproducibility of 10^{-4} as is required for a low energy injector of 10 GeV, iii) the civil engineering of the bypasses etc. For the LR, special attention was given to i) the possibility of head-on collisions, ii) to multi-bunch wakefield and emittance growth problems and, still in progress, iii) the possibility to achieve high luminosity with positrons too. The accelerator design study has been a fruitful collaboration of experts from many institutes with CERN, among them Ankara, BNL, BINP, Cockcroft, Cornell, DESY, EPFL, Jlab, INFN, KEK, LAL, Liverpool University and SLAC. There have been many useful contacts established to the developments of CLIC, the ILC, eRHIC/EIC, the SPL, XFEL and other projects.

The new ep/A detector at the LHeC has to basically be a precision instrument of maximum acceptance and fine resolution for the reconstruction of complex final states. The acceptance has to extend as close as possible to the beam axis because of the interest in the physics at extreme x and Q^2. The dimensions of the detector are constrained by the radial extension of the beam pipe in combination with maximum polar angle coverage. Much care has been taken to design an interaction region accounting for three beams, by using combined function superconducting magnets, to estimate and screen the direct and backscattered synchrotron radiation and to free the detector from machine elements in a ± 6 m long region, apart from a special maximum luminosity configuration. A further general demand is a high modularity enabling much of the detector construction to be performed above ground for keeping the installation time to a minimum, and to be able to access inner detector parts within reasonable shut down times. The time schedule of the project requires to have a detector ready within about ten years. This prevents any significant $R+D$ programme to be performed. The choice of components fortunately can rely on the vast experience obtained at HERA, the LHC, including its detector upgrades to come, and on ILC detector development studies. The current design status can be found here [6]. The detector is a challenging but a state-of-the-art detector, asymmetric in its technology choice and dimensions, with e, γ, p, n and d taggers. The dimensions of the present main detector design, in terms of its approximate length and diameter, are $12 \times 10\,\mathrm{m}^2$ to be compared with $21 \times 15\,\mathrm{m}^2$ of CMS and $45 \times 25\,\mathrm{m}^2$ of ATLAS.

The next steps of the project are: the completion of the design report, the discussion of the LHeC in the European strategy process and further by ECFA and NuPECC, which has put the LHeC on its long range plan 2010, preparations of international collaborations on the more detailed designs of the technical components, for one of the RR and LR options, and of the detector, an update of the physics programme in the light of the 2011/12 LHC results, and possibly beyond, should CERN and the international development of particle physics support this so promising project further.

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