LHEC: THE LARGE HADRON ELECTRON COLLIDER[1]

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The possibility of an upgrade, LH*e*C, to the LHC at CERN is presented in which electron(positron)-proton (*ep*) physics at the TeV energy scale is realized by adding a 70 GeV electron(positron) storage ring to the LHC tunnel. An *ep* luminosity of 10^{33} cm^{-2} s^{-1} which is possible when the stored beam is in collision with the 7 TeV LHC proton beam, is demonstrated. The physics horizon is outlined. Introduction

1. 2007: a vintage year for Physics

Next year, 2007, looks to have every chance of being a vintage year for physics. In July, the world's only high energy particle collider, HERA will complete data-taking. HERA is a unique and remarkable scientific tool. Electron(positron)-proton (*ep*) physics combines the features characteristic of discovery with the features characteristic of precision. This is because we understand lepton and vector boson physics, and because we have an established and quantitative phenomenology of the deep structure of the proton. As HERA reaches its limax, towards the end of vintage year 2007, the first TeV CM energy, proton-proton, collisions will be achieved.

2. The Lepton-Hadron TeV Dimension

The LHC will be a unique source of hadronic matter at immense energy (7 TeV). All possibilities for discovery and understanding with such beams must be explored. With this in mind, the scope and the importance of physics at HERA, which probes so much at its energy scale of 0.3 TeV, therefore points to a new round of lepton-hadron physics at the new energy scale of the LHC. It obviously requires an electron (positron) beam of the highest possible energy

optimized for collisions of the highest possible luminosity with the LHC *p* and ion beams.

The push to establish electron-positron annihilation at a CM energy commensurate with the discovery reach at LHC is the driver for the International Linear Collider (ILC). Whenever the collision of such an ILC beam with a co-located TeV hadron beam, for example at the Tevatron or at HERA, is considered, lack of luminosity is always a major issue (figure 1) [1]. This is also the case when the collision of a future, CLIC-technology based, electron beam with a "super-bunched" LHC proton beam is considered – QCD Explorer [2].
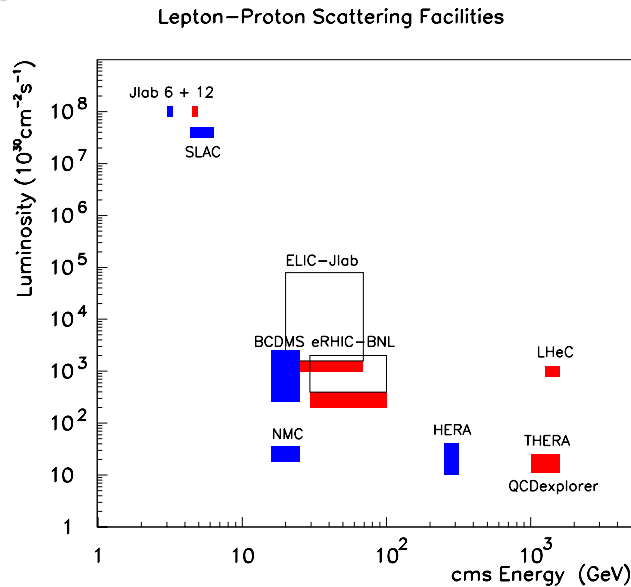
Lepton–Proton Scattering Facilities

Figure 1: Luminosity achieved or foreseen at high energy, lepton-hadron, experiments aimed at probing matter through inelastic scattering since the pioneering experiment at SLAC in the late 1960s; THERA and QCD-explorer are possibilities involving presently available hadron beams at HERA and the LHC which use "single-pass" linear collider electron beams; LH*e*C involves the construction of a 70GeV/c electron storage ring in the LHC tunnel at CERN; the estimated luminosity at LH*e*C is notable and is the reason why such an option is reported in more detail here.

Here the possibility of an electron ring of energy 70 GeV in collision with LHC hadron beams (that is *ep* CM energy of 1.4 TeV) - a Large Hadron Electron Collider or LH*e*C - is considered [3]. The physics scope and impact of an LH*e*C follows developments which improve hadron beam intensity and

delivery with the purpose of sustaining the LHC *pp* and ion physics programs at the cutting edge. The LH*e*C is therefore an upgrade of the LHC facility at CERN, and not a new, €multi-billion, global project.

3. Kinematic Reach at an LHeC

The kinematic reach of a lepton-hadron collider is best expressed in terms of the Bjørken-*x* and Q^2 variables. Figure 2 shows the resulting kinematic reach of the LH*e*C in comparison with previous experiments. The LH*e*C probes the lepton-quark interaction well into the TeV energy domain.
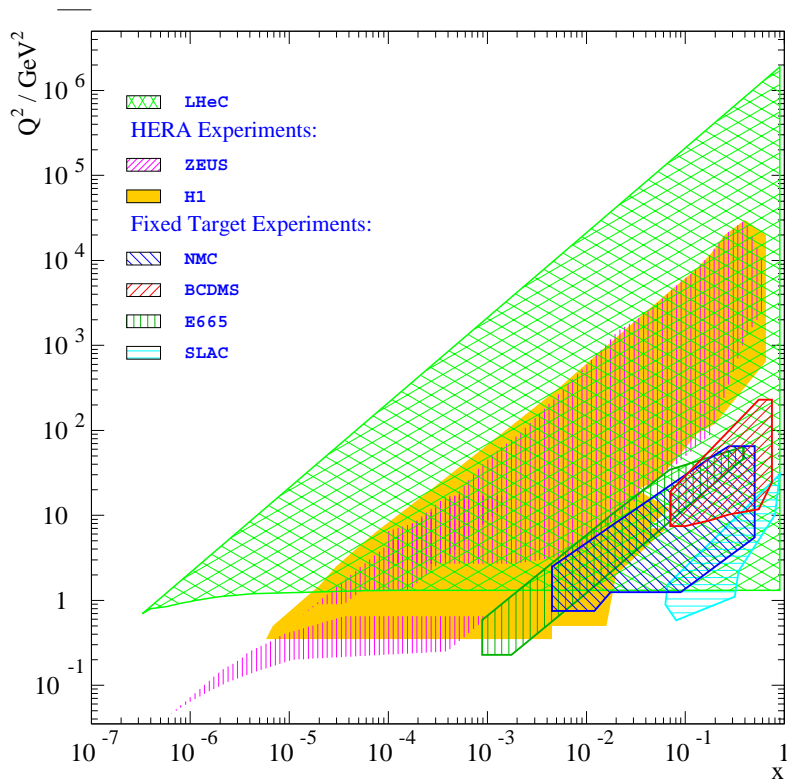

Figure 2: Kinematic reach in terms of Bjørken-*x* and Q^2 at lepton-proton experiments.

The LHC, at 14 TeV *pp* CM energy, will extend the energy scale of parton-parton interactions into the multi-TeV domain, but with no a priori clarity on the nature of the initial state. The electroweak lepton probe at the LH*e*C resolves the

 flavour composition of the quarks sea. The LH*e*C alone thus meets the challenge of probing with precision the TeV energy scale of lepton-quark interactions.

4. LH*e*C: a machine for *ep* collisions with *both* energy *and* luminosity

4.1. *Luminosity*

Before bothering the machine physicist, the experimental particle physicist often resorts to the "backs of envelopes". Given

- the LHC proton beam, namely bunches with 7 TeV energy, each with 1.67×10^{11} protons, of length 7.55 cm,
- with inter-bunch spacing of 25 ns,
- with a normalized transverse emittance[2] ε_{pN} of 3.75 μm, and
- with a lesson in what really limits the current in an electron storage ring in the (once LEP) LHC tunnel, namely synchrotron radiation power loss defining the RF power consumption to be 50 MW, i.e. 28% of the CERN site load,

(s)he can plug numbers into a formula for luminosity

$$ L = \frac{I_e \cdot N_p \cdot \gamma_p}{4 \cdot \pi \cdot e \cdot \epsilon_{pN}\sqrt{\beta_{xp}\beta_{yp}}} $$

to get $L = 1.15 \times 10^{33} (\beta_{xp}\,\beta_{yp})^{-1/2}$ cm^{-2} s^{-1}. Thus, for a plausible set of transverse β-functions, β_{xp} and β_{yp}, of the proton beam, L is more than a factor 10 larger than that of any lepton-proton experiment, since that at SLAC in the late 1960s. With a lepton storage ring and the presently envisaged LHC proton beam, an astounding luminosity looks possible (at of course an astounding CM energy!).

   This result relies on the feasibility of colliding an appropriately focused, stored, electron beam with an appropriately focused, stored, LHC proton (and ion) beam. Cutting short (undeservedly) work of substantial technical detail (see [3]) to its barest conclusions, it turns out to be possible to establish LHC bunches in collision with bunches in a plausible electron ring in the LHC interaction region (IP) IP8. Table 1 summarises the main parameters which are achieved, resulting in a luminosity of 1.04×10^{33} cm^{-2} s^{-1}.

   The above assumes the experiment at LH*e*C to be situated in IP8. What seems *not* to be the case is a clash of interests between the LHC *pp* programme and LH*e*C physics. The design work reported here for the IP8 interaction region

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[2] An emittance ε of a beam in a transverse dimension with Lorentz factor γ is specified as $\gamma\varepsilon_N$ where ε_N is the normalized emittance in that dimension.

so far takes into account the fact that the electron-proton,beam-beam, interaction should not in any way affect the *pp* luminosity at IP1 (ATLAS), IP2 (ALICE), and IP5 (CMS) in LHC. Furthermore, given the existence of the survey shafts and tunnels at these three IPs (figure 3), it is feasible to contemplate minimal civil engineering work to create a bypass tunnel (2 m diameter with each section about 250 m long) for the electron beam connecting the survey tunnel at each of these IPs directly to the LHC tunnel. The resulting IP has the beams crossing at 0.5 mrad with the "unused" proton beam passing through the experiment displaced vertically above the IP. In this way it seems plausible to contemplate LHC data-taking in which both *ep* and *pp* interactions are recorded simultaneously (of course in different experiments!).

Table 1. Basic LH*e*C machine parameters

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	25.9	0.501
Vertical Beam Emittance	nm	5	0.501
Horizontal β-functions at IP	cm	3.77	180
Vertical β-function at the IP	cm	4.44	50
Energy loss per turn	GeV	0.676	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.04	

4.2. *ep Interaction Region*

The first look at realistic LH*e*C optics at IP8 leaves many metres along the beam axes for experimentation, with access for detectors down to about 9.4°. For the low-*x* physics programme, where luminosity is not a limitation, these low-*β* quadrupoles could be removed to facilitate "forward" and "backward" detectors at smaller angles, down to about 1°. The details of the optics for an interaction region for such low-*x* data-taking remain to be resolved.

4.3. *Summary*

The first evaluation of the feasibility of *ep* collisions with good luminosity at an LHeC which is presented above looks extremely promising. Substantial further work is necessary before technical designs can be established for the LH*e*C electron ring and injection, and for beam delivery to IP8 with full luminosity.

  This design work will take a number of years with a suitably composed design team. This state of affairs suggests a timeline for the realisation of an LH*e*C of most likely a decade, in which the next "milestone" should be the completion of a Letter of Intent in the next two years, and then a Technical Design Report to the LHC Committee at CERN as soon as possible after that[3].

  By the time LH*e*C data-taking is commonplace, the challenge at the LHC of further increases in hadron intensity will be underway. The LH*e*C thus has a unique long term potential both of luminosity growing beyond 10^{33} cm^{-2} s^{-1} and of an *ep* CM energy which will remain unsurpassed for surely a substantial fraction of this century.
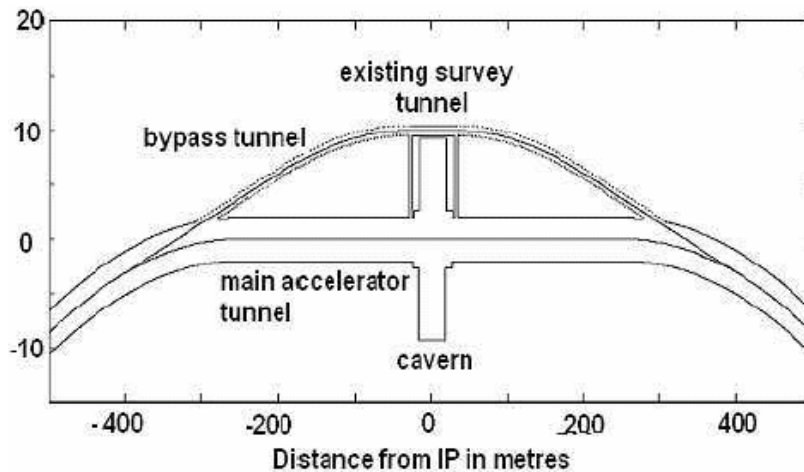

Figure 3: Schematic showing the layout of the additional tunnels for the electron bypass connecting the survey tunnel to the main LHC tunnel.

5. The Physics Horizon

5.1. *Why both Leptons and Quarks?*

The triumph of the SM has posed a number of new questions. Notable amongst them is the fact that the SM offers no understanding of the relationship between fermions which are hadrons, and fermions which are leptons, beyond their mutual interaction through the electroweak interaction. Exactly two decades ago, Salam neatly summarized the situation (figure 4) [5]. High energy, that is

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[3] This time-base bears an uncanny similarity to the TeVatron-HERA era, when the first HERA physics appeared in 1992 about a decade after the turn-on of the TeVatron!

short distance, interactions of leptons and hadrons must eventually reveal this unification in the form of "leptoquark" excitations which are manifest as "new physics".

The LH*e*C as proposed here (70 GeV ⊗ 7 TeV) makes possible precision measurements of electron(positron)-quark physics up to 1.4 TeV CM, "formation", energy. As a function of lepton-quark CM energy, it will be possible at LH*e*C to probe the lepton-jet final states associated with initial *ep* formation (*e*-quark and *e*-gluon) with precision, taking advantage a) of all the features of a known production mechanism, b) of a detailed set of distinct final states based on hadron topology – lepton and jet(s), and c) of even the spin-parity mix in these final states. One can anticipate the quantification of a new lepton-quark spectroscopy, which, through crossed *u*-channel interference (figure 4), could also extend to lepton-quark masses well above the kinematic limit.
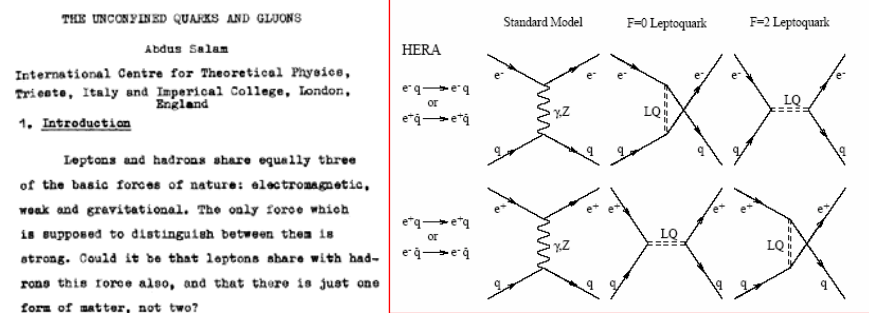

Figure 4: Text and figure taken from the presentation of Salam at ICHEP86; the diagrams contributing to new electron(positron)-quark physics through the "strong interaction" of leptons with quarks through leptoquark phenomena are shown.

An LH*e*C thus addresses one of the great questions of contemporary physics, and it will do so with the unique combination of TeV-energy reach and precision, characteristic of all lepton-hadron experiments hitherto, and of HERA in particular. If we believe (as we continually say we do) that the LHC will reveal the new physics for which we yearn, then the lepton-quark vision with LH*e*C is even more irresistible.

5.2. *The Standard Model at TeV energies*

The LH*e*C brings to the TeV energy scale both precision and kinematic reach par excellence. AS an example, it will be possible at the LH*e*C to evaluate

the strong coupling constant α_S in a multitude of ways involving the kinematics both of the scattered lepton and of the final state. Presently α_S is the least well known fundamental constant of the Universe: at HERA a final measurement will probably achieve an accuracy of 1 to 2%. At LH*e*C one can anticipate a "few parts per mil". At this level, which will be unique at the TeV energy scale, the significance of the extrapolation of the strong coupling constant to a putative grand-unification scale could well provide new insight into the underlying nature of QCD.

5.3. *Discovery at the LHC: Extrapolation and Interpolation?*

HERA provides the most precise and comprehensive set of measurements of the partonic composition (parton distribution functions - pdf's) of the proton hitherto. All the interactions of primary concern for the discovery and understanding of new physics at the LHC rely totally on a priori knowledge of the partonic composition of the proton. Without measurements of the proton pdf's at the LHC momentum transfer scale, one is therefore faced with substantial extrapolation, and that means additional assumptions with additional (systematic) uncertainties must be included in any SM prediction when gauged against a putative discovery.
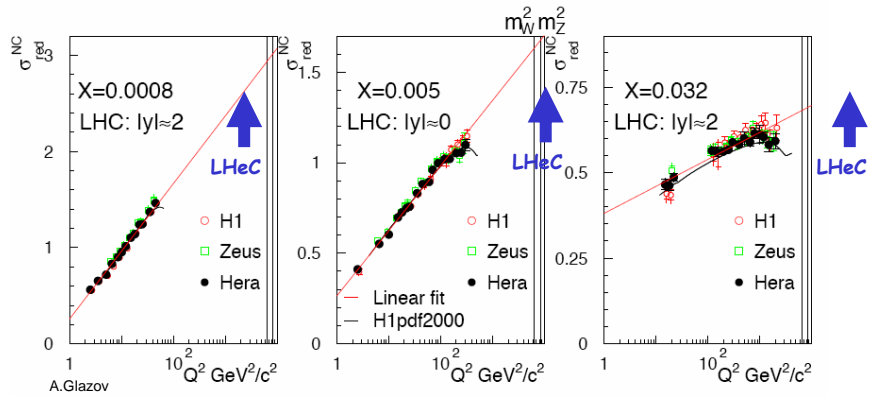

Figure 5: Measurements of the neutral current reduced cross sectionfor three different values of rapidity at LHC, which broadly correspond to three different values of x_{Bj}; the arrows indicate the required extrapolation if the measurements are to be used to establish consistency, or otherwise, with the SM; the curves assume present HERA parton distribution functions and standard (DGLAP) evolution; a linear dependence in $\ln Q^2$ is also shown for comparison.

Extrapolation is a hazardous business, especially when it may depend on physics which has yet to be discovered! Figure 5 shows the reduced neutral current (NC) cross section for different Bjørken-x, corresponding to different final state rapidities for the parton-parton interaction at the LHC, with the maximum Q^2 value marked at which similar measurements can be made at the LHeC. Do we believe that we understand parton evolution extrapolating over two whole orders of magnitude., even with logarithmic dependence?

The LHeC is thus the only way to reduce the systematic uncertainties which arise in the huge extrapolations inherent in the SM template applied at LHC energies.

5.4. *Summary*

The physics horizon at the LHC is unique – the combination of *pp* CM energy and luminosity will probe matter at the multi-TeV scale for the first time. The challenge of the LHC era will be *both* to discover the new physics, *and* to understand it. The LHeC will open a new window at the TeV energy scale based on *both* discovery *and* precision measurement.

6. Experimentation at the LHeC

The major feature of the LHeC (70 GeV $\otimes$ 7 TeV) kinematics is the electron-hadron beam momentum asymmetry, giving rise to the *ep* system moving in the proton beam direction with a Lorentz γ of about 5, compared with about 3 at HERA. This has the desirable feature that low-x scattered electrons are boosted to larger angles, and the undesirable feature that high Q^2 physics is boosted to more forward angles.

The challenge at LHeC is thus to instrument in the "forward" (hadron beam) direction to an extent that one can resolve complex jet structures at the TeV level. For the option described in section 3 aimed at the highest luminosity, "forward" means down to about 10°, and the challenge is to improve on instrumentation at HERA using the developments of the last 15 years in segmented track and calorimeter detectors. For low-x physics, the challenge is to get as close to the beam pipe as possible for multiparticle reconstruction.

7. Conclusion and Summary

An LHeC consisting of a 70 GeV electron or positron beam in collision with the 7 TeV proton and ion beams at the LHC can be built. Because of the huge intensity of the LHC hadron beams, an astounding, *ep* luminosity of 10^{33} cm^{-2} s^{-1}

appears feasible, which will in principle increase further with improvements in the LHC hadron beam intensity.

With such *ep* luminosity, the physics programme at the LH*e*C could well be pivotal in the era of TeV physics at the LHC, much as lepton-proton physics has been pivotal throughout the development of the Standard Model in the late 20th century. LH*e*C physics, like all *ep* experiments hitherto, will bring the features of discovery *and* understanding. It seems that it will be possible to run the LH*e*C (*ep* and *e*-ion) simultaneously with the LHC (*pp* and ion-ion).

The LH*e*C horizon is already realisable technically. Many of the advances in accelerator science and technology which have occurred in the last two decades can be used to improve the second (after LEP) generation, electron/positron, ring in the LHC tunnel. The impressive developments which continue to make the LHC possible will automatically facilitate further improvements of the LH*e*C. The LH*e*C is thus more naturally considered as an upgrade to the LHC project which adds substantially to the physics scope of the latter. Unquestionably, there is clearly very good reason to pursue further the possibility of an LH*e*C at CERN, and to do so as rapidly as possible.

Acknowledgements

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