THERA - ELECTRON PROTON SCATTERING AT $\sqrt{s} \simeq 1$ TEV

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First results, as obtained for the DIS2000 workshop, are briefly summarized of a study of the physics and experimental aspects of a future superconducting electron-proton collider, THERA, using the envisaged e^+e^- linear collider TESLA and the HERA proton ring at DESY. THERA enables the energy frontier in deep inelastic physics to be raised up to about $\sqrt{s} \simeq 1$ TeV, i.e. studies at momentum transfers squared Q^2 of nearly 1,000,000 GeV^2 and Bjorken x as low as 10^{-6} in the perturbative region.

1 Introduction

THERA[a] is the name for a new electron-proton collider which may be realized at DESY as the natural successor to HERA. Using polarized electrons or positrons, accelerated up to $E_e \simeq 250...500$ GeV in the linear collider TESLA, and protons of $E_p \simeq 400...900$ GeV from HERA, THERA would allow electron-proton scattering physics to be pursued at very high energies, $\sqrt{s} \simeq 1$ TeV where $s = 4E_eE_p$.

Electron-proton machines [1] are difficult to realize since two types of particles in different types of accelerator systems have to collide with high luminosity. Deep inelastic physics takes time and patience. HERA has been successfully realizing its first phase with a huge technical and physics programme based on an integrated luminosity of nearly 200 pb^{-1} which was delivered with increasing rate during the last eight years. The large *cms* energy of HERA lead to unexpected observations which developed into fundamental branches of high energy physics: the fields of low x physics, governed by the observation of high gluon and sea quark densities, of hard diffractive processes and of charm physics. In the high luminosity phase of HERA, starting in 2001, intense research efforts will be directed towards the region of largest Q^2 and large x. Moreover, forthcoming precision measurements at low x, e.g. of the longitudinal and the charm structure functions, will allow QCD to be studied at a much deeper level than previously. Possible observation of then less rare events may lead to new discoveries. So far quarks exhibit no substructure and leptoquarks have proved elusive. Advancing the energy frontier in ep physics

[a]THERA, a village known to the ancients as Kalliste, which means *most beautiful*, was founded about 3000 years ago by *Thera* who invented an ingenious water pipe system permitting life on the 369 m high mountain Messavouno.

will be mandatory when HERA physics comes to an end.

This paper summarizes some of the preliminary results of a study [2] which has the goal of complementing the TESLA proposal by its major option, regarded to be electron and positron collisions with HERA protons. While most of the physics arguments given here and elsewhere [3,4] are valid for any *ep* machine in this energy range, if e.g. the LHC would be complemented by a new electron accelerator, the study group has focussed on TESLA and HERA for the following reasons: i) high electron energies of a few hundreds of GeV are achievable only in linear colliders, and the standing wave type of superconducting cavities at TESLA allows both arms of the linear collider to be used for accelerating and transporting the electron beam, the time structure of which fits that of HERA; ii) in TESLA the electrons have high polarization, and the symmetric electron and proton beam energy configuration of THERA ensures full acceptance at high x for Q^2 bigger than a few 1000 GeV^2; iii) the HERA superconducting proton ring has been a huge investment and major success, and may support high energy physics for longer than HERA's anticipated lifetime. The experimental challenges of THERA are an unfavourable kinematic configuration at low x and the need to develop means of proton beam cooling in the TeV range which may be required for luminosities in excess of $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

2 Experimentation and Kinematics

The *ep* scattering kinematics determine the design of the detector. At very high $Q^2 > 4 \cdot 10^5$ GeV^2, electrons are scattered in the forward direction with energies of several hundreds of GeV, limited by E_p. At high x, for all Q^2, jets of similarly high energy are scattered into the forward and central detector regions, where forward is unfortunately termed to be the direction of the proton beam. Thus the main parts of a THERA detector will resemble the HERA detectors H1 and ZEUS, although the very high electromagnetic and hadronic energies are scattered more centrally into the detectors than at HERA.

The backward region, essential for low x physics, has to be newly designed. Because of the relation $Q^2 = 4E_eE_e' \cos^2(\theta_e/2)$, the region of Q^2 of a few GeV^2 can be accessed only with very large electron scattering angles compensating for the then very large electron beam and scattered energies. In the low x region, with y between 0.1 and 1, one has $E_e' \simeq E_e \cdot (1-y)$ and $E_h \simeq E_e \cdot y$. Thus, compared to HERA, about 10-20 times higher electron and hadron energies are scattered into the backward detectors. A highly granular, multilayer tracking and calorimetric detector is required, as sketched in [3], extending over typically 10 m in z in the electron beam direction. Thus, low x physics at THERA requires a rather classic "forward spectrometer" placed in the backward region.

The layout of the interaction region at THERA is determined by superconducting, proton beam focusing magnets, about 10 m away on either side of the interaction point. Access down to very small angles of typically 5 mrad is possible. A synchrotron radiation fan will extend to roughly 10 cm by 1 cm at 10 m distance from the vertex. The time structure of HERA dictates a z vertex extension of about ± 10 cm. The tiny transverse TESLA beam dimensions result in an interaction spot of 20 μm diameter, which is of great advantage for heavy flavour tagging. Electron, photon and proton taggers will find places to be installed.

3 Strong Interaction Dynamics at Low x

Due to the very high *cms* energy s at ep colliders, the low $x = Q^2/sy$ domain can be studied in the perturbative region. HERA experiments have observed a large sea quark density, the gluon to dominate the interaction, hard diffraction to be sizeable and DGLAP possibly in trouble in less inclusive processes. However, no parton saturation has been observed, the black disc limit has not been reached, and a field theory accounting for the large $\ln(1/x)$ logarithms has not been established, despite substantial theoretical efforts and progress. Rates of pp interactions at the LHC, extending to $x \simeq 10^{-6}$, cannot be reliably predicted without having understood the gluon interaction dynamics at low x. Predictions of ultra high energy ($E_\nu \leq 10^{12}$ GeV) neutrino reactions from active galactic nuclei and gamma-ray bursts, as studied by the AMANDA, NESTOR and ANTARES experiments, presently rely on extrapolation of the HERA parton distributions towards much lower x than experimentally accessed. The pandora box of low x physics has been opened and cannot be closed.

Using an initially modest luminosity of roughly 10 pb^{-1} per year, THERA will explore the field of low x physics much further into a kinematic range in which striking changes of various, related observables are predicted to occur. From the many studies made in the working group [2] a few examples may be given here: i) A regime of high parton densities is entered[5], for $\kappa = 3\pi^2\alpha_s/2Q^2 \cdot xg/\pi R^2 >> 1$. Because of unitarity the rise of F_2 and of $dF_2/d\log Q^2 \propto xg$ towards low x has to be tamed, and gluon shadowing is expected [6] to set in where $xg(x, Q^2) \simeq 6 \cdot Q^2$, outside the reach of HERA but just within that of THERA, see Fig. 1; ii) the W dependence of the J/ψ cross section will likely be damped due to the blackening of the interaction, i.e. change from $\sigma \propto W^{0.8}$ to a slower rise [2] $\propto W^{0.3}$. Low x physics leads to a revival of dipole models of the photon-nucleon interaction [7] because the coherence length increases with $1/x$; iii) the kinematic range in diffraction will be extended by an order of magnitude in M_X and to lower $\beta = x/x_P = Q^2/(Q^2 + M_X^2)$. This provides the phase space for diffractive jet production necessary if perturbative two-gluon exchange is to be distinguished from the effects of a a resolved pomeron; the nature of diffraction [8] may finally be understood; iv) the diffractive parton densities are related to nuclear shadowing [9], which has not been studied yet at low x. Parton saturation will be enhanced in electron-nucleus interactions; v) particularly striking changes are anticipated for forward jet production at low x as is illustrated in Fig. 2. While presently the observed cross section can still be described with DGLAP dynamics and resolved photon contributions with suitably chosen scales $> p_t^2$, at THERA a huge, BFKL type "signal over DGLAP noise" is expected to be seen. This effect is much enhanced close to the proton beam direction.

4 Heavy Quarks and the Structure of the Photon

The large gluon distribution at low x is responsible for remarkably large heavy flavour production cross sections, photon-gluon fusion ($\gamma g \to cc$) representing about a quarter of the DIS low x cross section. A theoretical description of quark-gluon interactions at low x inevitably requires a consistent treatment of charm and beauty production near and away from the production thresholds $Q, p_t \simeq m_{c,b}$. The integrated heavy flavour cross sections at THERA are about a factor of five larger than at HERA, in photoproduction, DIS and charged current charm production. As is illustrated in Fig. 3, heavy quark production will be observed at THERA with much lower x, and also higher p_t. This will extend charm physics into a new region, and permit beauty to be studied in quite some detail, comparable to charm at HERA. High precision backward tracking is required, preferably with muon detection for beauty physics.

In photoproduction the extended phase space provides access to resolved gluon and heavy flavour processes, i.e. gluon-gluon production of charm pairs ($gg \to cc$) and charm excitation ($cg \to gc$). An interesting process is gluon-quark Compton scattering ($g_\gamma q \to \gamma q$) leading to prompt photon production at large photon $p_t \geq 10$ GeV. For $\eta_\gamma > 0$ this process represents a nearly ten times larger fraction of the cross section than at HERA [10]. The heavy flavour and gluon structure of the photon will be a field of major interest at THERA, complementary to photon structure measurements at TESLA.

5 Physics at Large x and Very High Q^2

THERA is a machine where electroweak interactions really probe proton structure, the γZ interference part of the DIS ep cross section exceeding the photon exchange part at large x and Q^2. Thus lepton polarization effects are huge and can be used to search for right-handed charged currents, and to extract with high precision the up and down quark distributions at large x and Q^2 up to roughly 100,000 GeV^2, for example. The strong coupling constant is currently measured in DIS to an experimental accuracy [11] of 1.5 %, comparable to the world measurements but worse than the coupling constants α_{elm} or G_F for which huge efforts have been made in reaching high precision. Preliminary estimates yield an expected precision of $\delta\alpha_s(M_Z^2) \simeq 0.5\%$ if THERA high x, and also low x, data are added to previous DIS measurements. This requires theory to be formulated in 3 loops which is being actively pursued [12].

The large THERA energies provide an extended phase space for searches for new particles [4] such as leptoquarks, excited fermions and supersymmetric particles. Very detailed studies have been performed in the THERA study group [2,13]. With a luminosity of 100 pb^{-1} THERA excludes a bigger range in the coupling-mass parameter space than TESLA with 10 fb^{-1}, but it may not compete with LHC limits apart from the region of possibly small branching fractions ($LQ \rightarrow eq$). If, however, leptoquarks were discovered at LHC at masses below about 700 GeV, charge and polarization tuning will make THERA the ideal place for LQ spectroscopy [14]. Limits for excited electrons and neutrinos can be extended to about 600 GeV.

6 Accelerator Aspects

The THERA setup [15] is sketched in Fig. 4. TESLA is to be built tangentially to HERA which permits ep collisions in the West hall on the DESY site. An about 100 m long, passive connection line is necessary to access the HERA tunnel. The direction of protons in HERA has to be reversed, and 7T magnets are required for injecting protons to HERA. An electron beam dump has to be built made of about 8m^3 of water surrounded by 4m thick concrete walls. The HERA bunch crossing time has to follow the law $96 \cdot 11/n$ ns. For n=3 this yields 352 ns which can be matched to TESLA, presently designed to have 337 ns time separation between the 2800 bunches which form trains with a repetition rate of 5 Hz. THERA will not be limited to modest luminosity of $\sim$10^{30}cm^{-2}s^{-1} if measures can be developed along several anticipated directions: flat beams reducing the growth of intra-beam scattering, dynamic focussing of the proton beam synchronously to the electron beam, proton beam cooling and power upgrades of TESLA. Most of these and other possible means require strong research and development efforts on the proton machine.

Operation of THERA can be envisaged parallel to TESLA operation if positrons are transfered to HERA after e^+e^- collisions. These have an estimated energy spread of about 5%. Also, bunches may perhaps be shared between ep and e^+e^- operation. Dedicated operation of TESLA for ep collisions may make use of both TESLA arms for electrons, providing highest E_e, or of one arm for positrons with the default energy of $E_e = 250$ GeV. The lepton beam energy is limited to about $E_e \simeq 500$ GeV by the requirement that the beams have to be separated after ep collisions, for running at $E_p \simeq 920$ GeV.

Several important options for THERA were considered by the working group in detail: eA collisions for dense parton and nuclear effects, polarized $\vec{e}\,\vec{p}$ collisions to study nucleon spin structure at very low x and very high Q^2, and real photon-proton collisions using Compton backscattered laser light which yields an intense, energetic, nearly monochromatic photon beam.

7 Summarizing Remarks

The discussion of ep colliders began after the SLAC ep experiment[16] in the early seventies[17], in the years when QCD was born and even before the CERN deep inelastic muon-scattering experiments were proposed. A sequence of proposals was then discussed, based on DORIS, PETRA, SPS or in Canada, on how to reach higher energies in deep inelastic scattering, a development which led to the HERA machine. Figure 5 illustrates the impressive progress made in resolving the smallest nucleon dimensions in the previous century. HERA, combined with the superconducting TESLA e^+e^- collider, provides all the necessary components and an experienced community to probe the proton down to nearly 10^{-19}m. The gain in spatial resolution, relative to HERA, is a factor of 3-4, about the difference which separated Hofstadters form factor measurements from the discovery of partonic substructure at SLAC. The pace of history tells that ten years are an appropriate, perhaps optimistic time scale to discover deep inelastic parton saturation at very low x and new phenomena at huge Q^2 scales. Last but not least, understanding pp and ee collisions at the TeV scale and forthcoming neutrino DIS experiments will be incomplete without ep physics studied in the new energy range.

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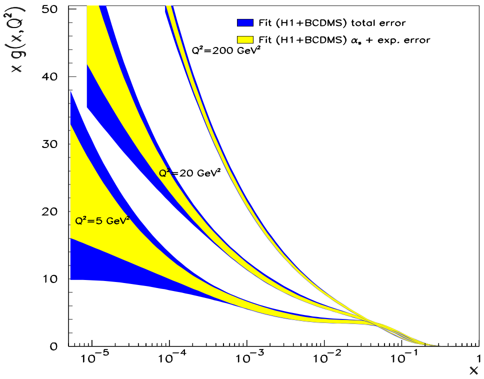

Figure 1: *The gluon distribution measured at HERA, if extrapolated into the THERA range of x below 10^{-4}, is expected to reach the unitarity limit, in the perturbative region.*

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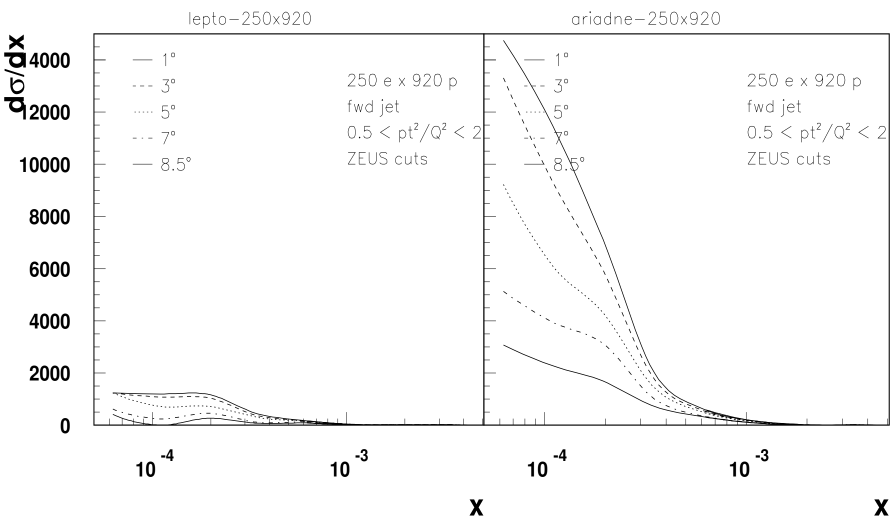

Figure 2: *Cross section of forward jet production in LEPTO (left) and Ariadne (right) demonstrating the effect of BFKL type deviations from the k_t ordered gluon emission in DGLAP. Note that the acceptance at HERA is limited to about $x \geq 4 \cdot 10^{-4}$ where these effects are still modest.*

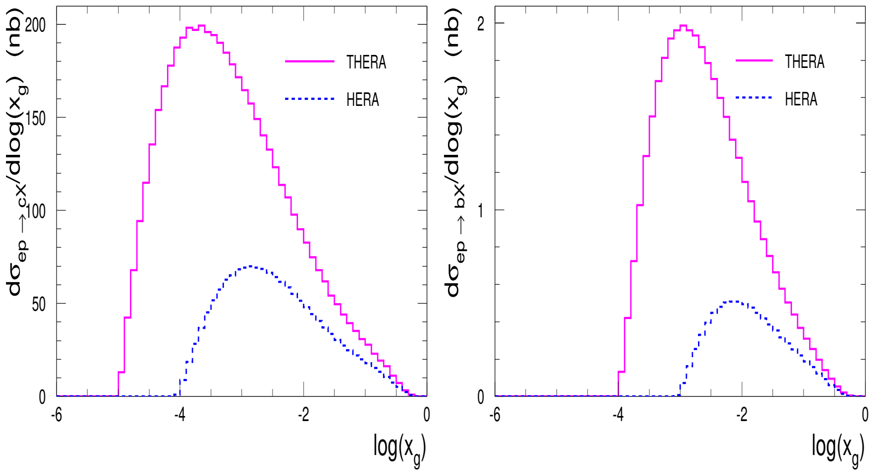

Figure 3: *Cross sections of charm (left) and beauty production (right) for $0 < Q^2 < 100$ GeV^2 in NLO QCD illustrating the extension towards much lower x and the cross section increase at THERA.*

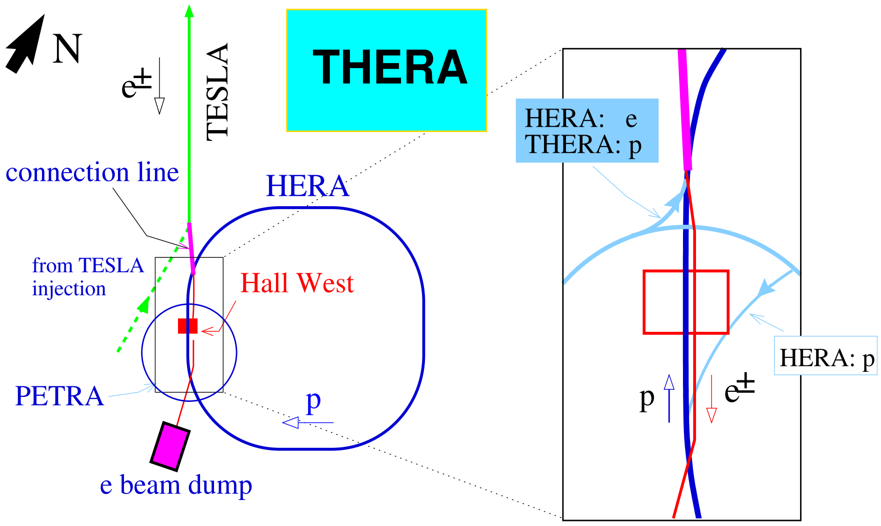

Figure 4: *Sketch of the THERA ep collision setup at DESY.*

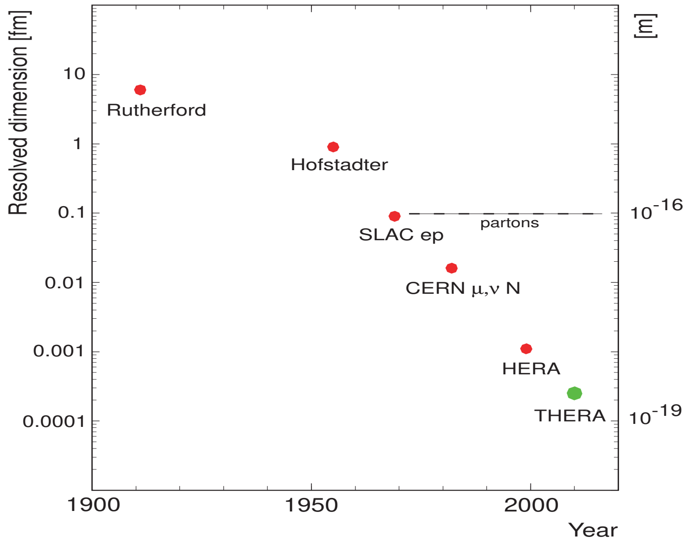

Figure 5: *History of deep inelastic scattering experiments illustrated by the increase of their resolution power over time.*