A REVIEW OF TEV SCALE LEPTON-HADRON AND PHOTON-HADRON COLLIDERS

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Abstract

The investigation of lepton-hadron and photon-hadron collisions at TeV scale is crucial both to clarify the strong interaction dynamics from nuclei to quark-parton level and for adequate interpretation of experimental data from future hadron colliders (LHC and VLHC). In this presentation different TeV scale lepton-hadron and photon-hadron collider proposals (such as THERA, "LEP"-LHC, QCD Explorer etc) are discussed. The advantages of linac-ring type colliders has been shown comparatively.

INTRODUCTION

It is known that lepton-hadron collisions have been playing a crucial role in exploration of deep inside of matter. For example, the quark-parton model was originated from investigation of electron-nucleon scattering. The HERA with $\sqrt{s} \approx 0.3$ TeV has opened a new era in this field extending the kinematics region by two orders both in high $Q^2$ and small $x$ with respect to fixed target experiments. However, the region of sufficiently small $x$ ($\leq 10^{-5}$) and simultaneously high $Q^2$ ($\geq 10$ GeV$^2$), where saturation of parton densities should manifest itself, is not currently achievable. The investigation of physics phenomena at extreme small $x$ but sufficiently high $Q^2$ is very important for understanding the nature of strong interactions at all levels from nucleus to partons.

At the same time, the results from lepton-hadron colliders are necessary for adequate interpretation of physics at future hadron colliders. Concerning LHC, which hopefully will start in 2007, a $\sqrt{s} \approx 1$ TeV ep collider will be very useful in earlier 2010's when precision era at LHC will begin.

Finally, multi-TeV center of mass energy ep colliders are competitive to future hadron and lepton colliders in search for the BSM physics.

TEV SCALE LEPTON-HADRON COLLIDERS

Today, linac-ring type machines seem to be the main way to TeV scale in lepton-hadron collisions (see [1, 2] and references therein). Construction of future linear collider or a special e-linac tangentially to existing (HERA, Tevatron, RHIC) or planned (LHC, VLHC) hadron rings will provide a number of new powerful tools in addition to ep and eA options:

- TeV scale $\gamma p$ [3] (see also [4]) and $\gamma A$ [5] colliders
- FEL-Nucleus colliders [6] (see also [7]).

Standard Type ep Colliders

There are several standard (ring-ring) type ep collider proposals with $\sqrt{s} \geq 1$ TeV. The first one is an ep option for LHC, which assumes a construction of 67.3 GeV electron ring in the LHC tunnel [8]. Concerning the VLHC based ep collider, a construction of 180 GeV e-ring in the VLHC tunnel is proposed in [9]. However, a construction of an additional e-ring in the LHC and VLHC tunnels might cause a lot of technical problems (an example is inevitable removing of the LEP from the tunnel in order to assemble the LHC). Recently, linac-ring analogues of these proposals are discussed in [10]. It is shown that linacs will give opportunity to obtain the same $\sqrt{s}$ and luminosities with much shorter lengths.

| Collider | eLHC | eVLHC |
|----------|------|-------|
| $E_e$ (GeV) | 67.3 | 180   |
| $E_p$ (TeV) | 7    | 50    |
| $\sqrt{s}$ (TeV) | 1.37 | 6     |
| Ring circumference (km) | 26.66 | 531   |
| Luminosity ($10^{32} \text{cm}^{-2} \text{s}^{-1}$) | 1.2  | 1.4   |
| Linac length | 2.9  | 7.7   |
| Luminosity ($10^{32} \text{cm}^{-2} \text{s}^{-1}$) | 1.6  | 2.3   |

Figure 1: The development of the resolution power of the experiments exploring the inner structure of matter over time from Rutherford experiment to CLIC@VLHC.

Table 1: LHC and VLHC based ep colliders: e-ring vs e-linac (for TESLA-like linac)
**THERA, ILC-Tevatron and QCD Explorer**

Three versions of TESLA-HERA based ep collisions are considered in the TESLA TDR [11]: $E_e = 250 \text{ GeV}$ and $E_p = 1 \text{ TeV}$ with $L = 0.4 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$; $E_e = E_p = 500 \text{ GeV}$ with $L = 2.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and $E_e = E_p = 800 \text{ GeV}$ with $L = 1.6 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$.

Main parameters of ILC-Tevatron based lepton-hadron colliders are discussed in [12]. With nominal Tevatron parameters, the luminosity for ep (e$p$) collisions is calculated to be $8 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ ($4.6 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$). The THERA [10] like upgrade of the proton beam parameters (namely, $\sigma_p=10 \text{ µm}$ with $\beta_p=10 \text{ cm}$) leads to $L_{ep} = 1.2 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$.

QCD Explorer assumes a collision of 75 GeV CLIC electron bunches with 7 TeV LHC proton beam [13, 14]. Super-bunch upgrade of the LHC will give opportunity to achieve $L_{ep} = 1.1 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$ [13]. Otherwise, a radical upgrade of CLIC beam is necessary to achieve sufficiently high luminosity [10].

In spite of approximately equal center of mass energies, QCD Explorer is more advantageous than THERA and ILC-Tevatron for exploration of small $x_t$ region [10].

**ILC”-LHC**

The center of mass energy which will be achieved at this machine ($0.5 \text{ TeV “ILC” electron beam on 7 TeV energy LHC proton beam}$) is an order higher than HERA. Certainly, $L_{ep} \approx 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ is quite realistic estimation for “TESLA”-LHC (the factor 7 comparing to THERA is straightforward due to larger value of $\gamma_p$ at LHC). For “CLIC”-LHC, $L_{ep} \approx 10^{31} \text{ cm}^{-2} \text{s}^{-1}$ can be achieved with super bunch structure of LHC and nominal parameters of 0.5 TeV CLIC. The ep option, which extend both the $Q^2$-range and $x$-range by more than two orders of magnitude compared to those explored by HERA, has a strong potential for both SM and BSM research. Concerning $\gamma p$ option, the advantage in spectrum of back-scattered photons will clearly manifest itself in a search for different phenomena. Rough estimations [2] show that the total capacity of ep and $\gamma p$ options for BSM physics (SUSY, compositness etc) research essentially exceeds that of a 0.5 TeV linear collider. Discovery limits for different phenomena obtained by “simple” rescale of corresponding results from [15] are presented in Figure 2. Detailed study for exited electrons [16] confirms “fingertip” estimations given in the Figure.

In the case of LHC nucleus beam IBS effects in main ring are not crucial because of large value of $\gamma_A$. The main principal limitation for heavy nuclei coming from beam-beam tune shift may be weakened using flat beams at collision point. Rough estimations show that $L_{nA} A \approx 10^{31} \text{ cm}^{-2} \text{s}^{-1}$ can be achieved at least for light and medium nuclei. For $\gamma A$ option, limitations on luminosity due to beam-beam tune shift is removed in the scheme with deflection of electron beam after conversion [3] and sufficiently high luminosity can be achieved for heavy nuclei, too. Certainly, nuclei options of “ILC”-LHC will bring out great opportunities for QCD and nuclear physics research. For example, $\gamma A$ option will five an opportunity to investigate quark-gluon plasma at very high temperatures but relatively low nuclear density (according to VMD, proposed machine will be at the same time $\rho$-nucleus collider).

**CLIC”-VLHC**

Concerning high energy frontiers, even 1 TeV e-linac will provide $\sqrt{s_{ep}} = 20 \text{ TeV}$, whereas 3 (5) TeV CLIC will give $\sqrt{s_{ep}} = 34 (45) \text{ TeV}$. Taking in mind THERA estimations one can expect $L_{ep} \approx 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ for “ILC”-VLHC, whereas $L_{ep} \approx 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ is rather conservative estimation for “CLIC”-VLHC. Let me remind that $\gamma p$ option will provide almost the same center of mass energy and luminosity as ep option. Obviously, Linac-VLHC will give opportunity to investigate a lot of particle physics phenomena in a best manner.

| Colliders   | Hadron | Lepton | Lepton-Hadron |
|-------------|--------|--------|---------------|
| 1990’s      | Tevatron | SLC/LEP | HERA          |
| $\sqrt{s}$, TeV | 2      | 0.1/0.1 → 0.2 | 0.3            |
| L, $10^3 \text{ cm}^{-2} \text{s}^{-1}$ | 1      | 0.1/1     | 1             |
| 2010’s      | LHC     | “NLC”(TESLA) | “NLC”-LHC     |
| $\sqrt{s}$, TeV | 14     | 0.5 → 1(0.08) | 3.7 → 5.3(4.7) |
| L, $10^3 \text{ cm}^{-2} \text{s}^{-1}$ | 10^3   | 10^3      | 1 10^3        |
| 2020’s      | VLHC    | CLIC    | “CLIC”-VLHC   |
| $\sqrt{s}$, TeV | 200    | 3        | 3             |
| L, $10^3 \text{ cm}^{-2} \text{s}^{-1}$ | 10^3   | 10^3      | 10^3 1 10^3   |

**CONCLUSION**

The importance of linac-ring type ep colliders was emphasized by Professor B. Wiik at Europhysics HEP Conference in 1993 [17]. Following previous article [18], he argued TESLA type accelerator to be used as linac. The argument is still valid for LHC-based ep, $\gamma p$, eA and $\gamma A$ colliders. Concerning VLHC-based ep and $\gamma p$ colliders, CLIC type linear accelerator seems to be advantageous, since the energy of TESLA of reasonable size is less than 1 TeV.

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Figure 2: “Fingertip” estimations of discovery limits at the LHC (blue), ILC*LHC (red) and ILC (blue). Upper-left picture contains: the neutral Higgs, a charged Higgs, the fourth SM family quarks and leptons. Down-right picture contains: strong sparticles (gluino and squarks), weak sparticles (neutralino, chargino and sleptons), leptoquark and Z’ from E6. Down-left picture contains: W’, compositness scale, excited quarks and leptons.