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Review

Collider physics at high energies and low luminosities

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Abstract. While very high acceleration gradients are expected in novel accelerating schemes such as those discussed by IZEST, generating high luminosities will be extremely challenging and will likely require a separate technology revolution. It is important to determine if a low-luminosity but high energy collider would have serious interest from a particle physics perspective. We consider a process involving physics beyond the Standard Model that would be detectable at high energies without requiring the types of luminosities normally quoted for future colliders, "classicalization". In this example, scattering cross sections grow with a power of the center-of-mass energy, thereby reducing the luminosity requirement at high energies. Another process discussed is deep-inelastic-scattering of electrons on protons, where a precision measurement of the energy dependence of the scattering cross section could yield information about physics processes at much higher scales.

1 Introduction

The main focus of the particle physics community, when considering future accelerators, has been on high luminosity colliders since annihilation cross sections scale as $1/s$, with s the square of the center-of-mass energy. This focus has led to International Linear Collider (ILC), Compact Linear Collider (CLIC) or Muon Collider parameter sets requiring luminosities in excess of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for center-of-mass energies beyond 1 TeV. This requirement on the luminosity then leads to very demanding requirements on parameters such as beam sizes at the interaction point, repetition rate, etc., and huge power requirements. The former will be difficult to achieve technologically, while the latter will be very hard to justify in an age of diminishing energy resources and increasing energy costs.

The size of the linear accelerators (ILC and CLIC) are primarily determined by the accelerating gradient, and it is not possible to build compact TeV-scale electron-positron colliders based on known RF technology. Novel acceleration schemes, such as plasma-wakefield acceleration, are currently under study and could provide the basis for a compact high energy linear collider. While very high acceleration gradients have been demonstrated, generating high luminosities with such accelerators will be extremely challenging and will likely require a technology revolution. For a muon

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collider, the requirement of high luminosity puts very demanding constraints on the power needed for the proton driver used to produce the muons and the phase space cooling scheme for the muon beam. These tough requirements lead to parameter sets which, while progress has certainly happened, still cannot be met today and remain a major challenge. It is therefore important to discuss the physics opportunities at a high energy but much reduced luminosity collider, since such colliders could become available in the future at acceptable cost.

Clearly, we are looking for processes that either have a threshold effect at high energy, such that reaching the high energy even with low luminosity would uncover a brand new physics, or we require processes where cross sections are growing with energy. One such process is well known – the scattering via the strong force. Proposals have been made that such a behaviour could be more universal. The list of topics we discuss is incomplete, and some of the ideas, while exciting, are quite speculative. The intent here is to point out that there are interesting physics topics for a high energy, low luminosity collider and to initiate a more thorough discussion of the scientific interest in such an option for the future of accelerator based particle physics.

2 Classicalization

The recently discovered [1,2] light Higgs particle [3–6] acts in the Standard Model to restore perturbative unitarity for weak interactions. However, the "hierarchy problem" remains; i.e., the vast difference in scales between the different forces. The usual theoretical approach to attacking this problem is to introduce new interactions which set in at the higher energy scales, such as supersymmetry [7]. However, there are alternative approaches to correcting the high energy behavior of scattering cross sections which do not require such weakly-coupled new physics, such as "classicalization" [8]. In this approach, a new scale becomes manifest at an intermediate energy – the classicalization scale – whereby scattering already becomes effectively classical (black disk scattering) at relatively low energies. This then leads to scattering cross sections that grow with energy. An example of this type of behavior is seen in the strong interactions, where the total cross section is saturated by the non-perturbative gluon cloud present in hadrons. A theory incorporating these basic concepts is the color-glass-condensate [9] model.

In a class of theories with low (TeV) scale Planck mass [10] that are motivated by the hierarchy problem, scattering cross-sections will grow at high-energies in a manner similar to the strong interaction cross sections. The cause for this growth is the production of N- particle states called classicalons, that are related to black holes. A class of spin-2 theories for which the growth of the classicalon production cross section can compete with strong interaction cross sections has been identified [11]. In these theories, at 100 TeV center-of-mass energy, black hole production with graviton occupation number $N = 10^4$ would have similar cross section to the total cross section for strong interactions. At $s = 10\,\mathrm{TeV}^2$, the scattering cross section for classicalon production could be as large as 0.3% that of QCD. This should be easily measurable with a collider with luminosity $\mathcal{L} = 10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ or even lower.

3 QCD and "Beyond the Standard Model" Physics

It is commonly assumed that there is a decoupling between the short-distance physics at high energies and the long-distance physics associated with lower energies. The discussion of classicalization above shows that this is not necessarily the case. Further evidence comes from an analysis of the HERA small-x data in the context of the

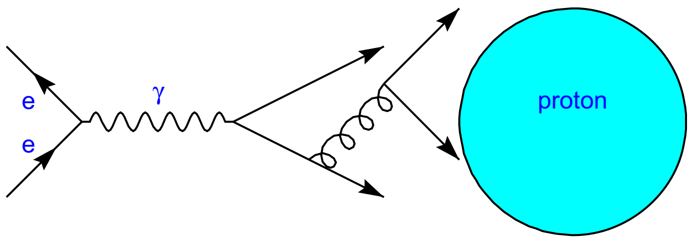

Fig. 1. Photon fluctuations scattering on the proton in the proton rest frame.

BFKL formalism [12,13]. It was shown that indeed, since QCD evolution produces a random walk in transverse momentum, there is a mixing of large and small virtualities and therefore of scales. This means that the behavior of the structure functions depend on the physics of high energy scales, and therefore on any physics beyond the Standard Model. The HERA data was interpreted in the framework of the BFKL approach to parton density evolution, and it was shown that indeed sensitivity to TeV and beyond scale physics can be extracted from structure functions data [14]. While the indications are to-date not specific as to the scale or the nature of any new physics, performing such an analysis with higher energy data would yield considerably more information. In particular, data from high energy $\gamma\gamma$ collisions would be very important in this regard, as they would be less sensitive to infrared boundary conditions such as the low-scale structure of the proton (in the HERA example). Further evaluation is clearly needed to determine the discovery power in this approach.

4 Total photon-proton cross section

The small-x behavior of the proton structure function F_2 measured in electron-proton scattering is striking and has inspired many models and parametrizations. The scattering process can be viewed in the following way: the electron radiates a photon, and this then interacts with the proton. The standard Hand convention [15] is used to define the photon flux, yielding the relation:

$$F_2^P = \frac{Q^4(1-x)}{4\pi^2\alpha(Q^2 + (2xM_P)^2)}\sigma^{\gamma P}$$

where α is the fine structure constant and M_P is the proton mass, while x is the Bjorken scaling variable and Q^2 the negative of the four-momentum squared carried by the photon (virtuality).

The behavior of $\sigma^{\gamma P}$ was studied [16] in the proton rest frame in terms of the coherence length [17] of the photon fluctuations, l, and the virtuality, Q^2. The physical picture is given in Fig. 1, where the electron acts as a source of photons, which in turn acts as a source of quarks, antiquarks and gluons. The partonic wavefunction of the photon state is dependent on l and Q^2. The proton is viewed as a set of interaction centers for the incoming partons.

The maximum value of the coherence length for the process is directly proportional to the square of the center-of-mass energy, and higher energies will therefore reveal more of the structure of the virtual fluctuations at the heart of matter. On the other hand, the relevant cross sections are large and a collider with a luminosity of $10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ would be sufficient to study this fundamental physics. Figure 2 shows the cross sections as a function of l for different values of Q^2. It is seen that the cross sections tend to merge at large values of the coherence length, indicating that the photon state has lost the memory of its creation after long enough coherence length.

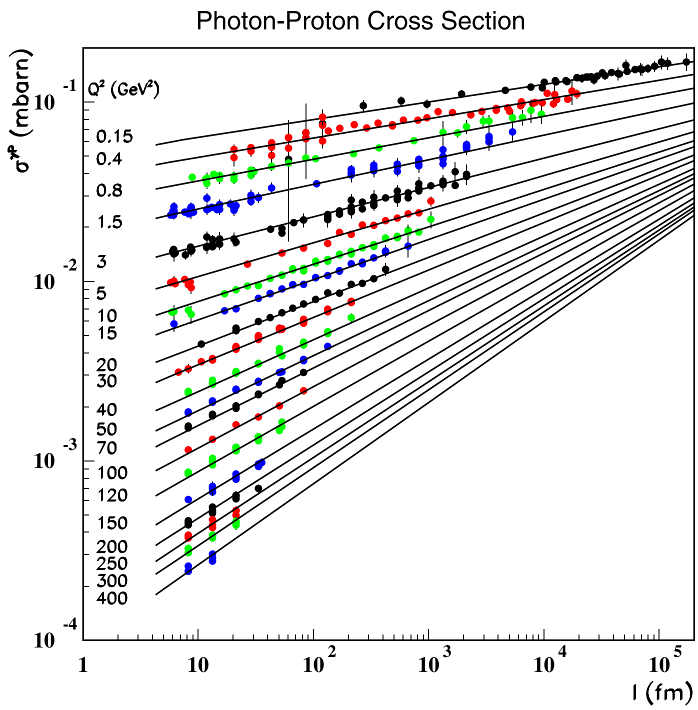

Fig. 2. The cross section $\sigma^{\gamma P}$ versus l. The lines are fitted curves of the form $\sigma = \sigma_0 l^{\lambda_{\rm eff}}$ for individual Q^2 values.

5 Summary

It is useful to decouple achieving very high energies in a particle collider based on electrons from the requirement for very high luminosities. While standard s-channel physics indicates that extremely high luminosities will be needed at TeV and beyond energy scales, there are physics questions which can be probed with lower luminosities. We have listed a number of physics topics in this contribution to indicate that such physics topics exist, and hope that this will lead to further investigations of physics topics that would rely primarily on energy and not on luminosity.

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