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Photon-Nucleon Collider based on LHC and CLIC

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We describe the scheme of a photon-nucleon collider where high energy photons generated by Compton backscattering off a CLIC electron beam, at either 75 GeV or 1.5 TeV are collided with protons or ions stored in LHC. Different design constraints for such a collider are discussed and achievable luminosity performance is estimated.

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PHOTON-NUCLEON COLLIDER BASED ON LHC AND CLIC*[#]

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Abstract

We describe the scheme of a photon-nucleon collider where high energy photons generated by Compton back-scattering off a CLIC electron beam, at either 75 GeV or 1.5 TeV are collided with protons or ions stored in LHC. Different design constraints for such a collider are discussed and achievable luminosity performance is estimated.

INTRODUCTION

Earlier the idea of using high energy photon beams obtained by Compton back-scattering of laser light off a beam of high energy electrons was advanced for γe and γγ colliders (see [1] and references therein). Later the same method was proposed for constructing γp colliders on the basis of some possible combinations of linac ring type ep machines. Rough estimates for the main parameters of γp collisions were given in [2,3]. In [3], the dependence of these parameters on the distance *z* between conversion region and collision point was analyzed using the approximation of a pencil electron beam with Gaussian profile. Actually, the construction of CLIC (or ILC) tangentially to LHC would provide a number of additional opportunities to investigate photon-nucleon interactions at the TeV scale.

We consider three different energies for the electron beam: 30 GeV, 75 GeV and 1.5 TeV. Colliding the 7 TeV LHC proton beam with 75-GeV CLIC electron bunches is called the QCD-Explorer scheme, since it can extend the low-x reach of HERA by two orders of magnitude, providing discoveries as fundamental for the QCD as the Higgs Boson is for the electro-weak interactions [4]. In 2004, a QCD-Explorer based on the super-bunched LHC option was considered. It was shown to reach a sufficiently high luminosity [5]. However at a recent workshop held at CERN [6], the super-bunch option was discarded for LHC proton-proton collisions. Though this does not strictly rule out the use of super-bunches for ep or pγ collisions, we include some alternative scenarios for reaching an acceptable luminosity in γp collisions. The alternatives are based either on the standard CLIC beam or on a 30 GeV ILC-like s.c. linac as was newly suggested [7]. The CLIC option without super-bunch assumes a reduced proton bunch spacing of 5 ns.

At the end of this paper we present a short survey of the physics potential for a high-energy γp collider.

LUMINOSITY

While computing luminosity, electron beam density was chosen as

$$\rho_e = \frac{1}{2\pi\sigma_e^{\,2}} e^{-\frac{x^2+y^2}{2\sigma_e^{\,2}}} . \qquad (1)$$

We assume that the optical functions of the electron beam to be the same in *x* and *y* (round beam). Choosing the electron density of Eq. (1) modifies the differential luminosity relation derived in [3] as

$$\frac{dL_{\gamma p}}{d\omega} = \frac{f(\omega) 0.65 n_e n_p f_\gamma}{2\pi\left(\sigma_e^{\,2}+\sigma_p^{\,2}\right)} \exp\left[\frac{-z^2\theta_\gamma(\omega)^2}{2\left(\sigma_e^{\,2}+\sigma_p^{\,2}\right)}\right] \qquad (2)$$

where ω is the energy of the high energy photon, z is the distance between the conversion region (CR) to the collision point, $\theta_\gamma(\omega)$ is the angle between high energy photons with energy ω and electron beam direction. This angle is given by (for small θ_γ)

$$\theta_\gamma(\omega) = \frac{m_e}{E_e}\sqrt{\frac{E_e x}{\omega} - (x+1)} \qquad (3)$$

where $x = 4E_e\omega_0 / m_e^{\,2}$ and ω_0 is the laser photon energy. In order to avoid e^+e^- pair creation in the conversion region *x* should be less 4.83. In Eq. (2), $f(\omega)$ is the normalized differential Compton cross section as defined in [8]. The factor of 0.65 stems from the maximum value of the electron-to-photon conversion coefficient [1].
The total γp collision luminosity is

$$L_{\gamma p} = \int_0^{\omega_{\max}} \frac{dL_{\gamma p}}{d\omega} d\omega \qquad (4)$$

Making a change of variable in Eq. (2) and introducing the γp invariant mass

$$W_{\gamma p} = 2\sqrt{\omega E_p} \qquad (5)$$

with E_p denoting the proton beam energy, the γp differantial luminosity can be rewritten as

$$\frac{dL_{\gamma p}}{dW_{\gamma p}} = \frac{W_{\gamma p}}{2E_p} \frac{f\left(\frac{W_{\gamma p}^2}{4E_p}\right) 0.65 n_e n_p f_\gamma}{2\pi\left(\sigma_e^{\,2}+\sigma_p^{\,2}\right)} \exp\left[\frac{-z^2\theta_\gamma\left(\frac{W_{\gamma p}^2}{4E_p}\right)^2}{2\left(\sigma_e^{\,2}+\sigma_p^{\,2}\right)}\right] \qquad (6)$$

QCD-Explorer Based Gamma-Nucleon Collider

Gamma-nucleon collision beam parameters for three scenarios are listed in Tables 1-3. Table 1 refers to the collision of a 75-GeV CLIC beam and ultimate LHC bunches spaced at 5 ns, Table 2 to a 30-GeV linac beam colliding with ultimate LHC proton bunches spaced at 300 ns, and Table 3 again to the 75-GeV CLIC beam, this time colliding with proton super-bunches. Figures 1, 2 and 3 show, for the same three scenarios, respectively, the differential luminosity spectrum and the dependence of the total luminosity on the distance *z*, according to (6).

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Table 1: beams parameter for 75 GeV CLIC-1 colliding with an 5 ns-spacing bunched LHC proton beam (each proton bunch interacts with 50 electron bunches over a total length of 2 m).

parameter	symbol	electrons	protons
beam energy	E_b	75 GeV	7 TeV
bunch population	N_b	2.56×10^9	$1.7\ 10^{11}$
rms bunch length	σ_z	31 µm (Gaussian)	37.8 mm (Gaussian)
bunch spacing	L_{sep}	0.267 ns	5 ns
# bunches	n_b	220	12
IP beta function	$\beta^*_{x,y}$	0.25 m	0.25 m
IP spot size	$\sigma_{x,y}$	11 µm	11µm
full interaction length	l	2 m	
rms emittances	$\gamma\varepsilon_{x,y}$	73 µm	3.75 µm
repetition rate	f_{coll}	150 Hz	
luminosity (z = 2m, $\lambda_e\lambda_0$=-1)		2.84×10^{29} cm^{-2}s^{-1}	

Table 2: Beam parameters for an `ILC-linac` colliding with the ultimate proton LHC beam

parameter	symbol	electrons	protons
beam energy	E_b	30 GeV	7 TeV
bunch population	N_b	2×10^{10}	$1.7\ 10^{11}$
rms bunch length	σ_z	150 µm (Gaussian)	75.5 mm (Gaussian)
bunch spacing	t_{sep}	300 ns	25 ns
# bunches	n_b	2820	2808
IP beta function	$\beta^*_{x,y}$	0.25 m	0.25 m
IP spot size	$\sigma_{x,y}$	11 µm	11µm
rms emittances	$\gamma\varepsilon_{x,y}$	28 µm	3.75 µm
repetition rate	f_{coll}	5 Hz	
luminosity (z = 1m, $\lambda_e\lambda_0$=-1)		8.33×10^{29} cm^{-2}s^{-1}	

Table 3: Beam parameters for 75-GeV CLIC-1 colliding with an LHC proton superbunch

parameter	symbol	electrons	protons
beam energy	E_b	75 GeV	7 TeV
bunch population	N_b	2.56×10^9	$3.7\ 10^{13}$
rms bunch length	σ_z	31 µm (Gaussian)	5.09 m (Uniform)
bunch spacing	L_{sep}	0.267 ns	N/A
# bunches	n_b	220	1
effective line density	λ	$3.2\ 10^{10}$ m^{-1}	$2.1\ 10^{12}$ m^{-1}
IP beta function	$\beta^*_{x,y}$	0.25 m	0.25 m
IP spot size	$\sigma_{x,y}$	11 µm	11µm
full interaction length	l	2 m	
rms emittances	$\gamma\varepsilon_{x,y}$	73 µm	3.75 µm
repetition rate	f_{coll}	150 Hz	
luminosity (z = 2m, $\lambda_e\lambda_0$=-1)		1.057×10^{31} cm^{-2}s^{-1}	

λ_e :Electron beam helisitie,λ_0 : Laser beam helisitie

The figures illustrate that the relative polarization of laser and electron beam has a significant influence on the total luminosity and, in particular, on the luminosity spectrum.

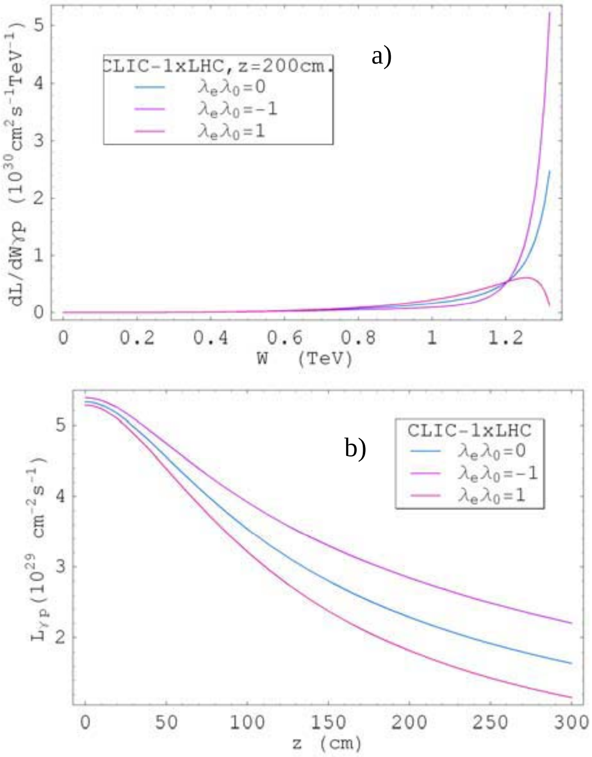

Figure 1: a) CLIC-1×LHC γp luminosity distribution for various polarization combinations b) CLIC×LHC total luminosity variation with z.

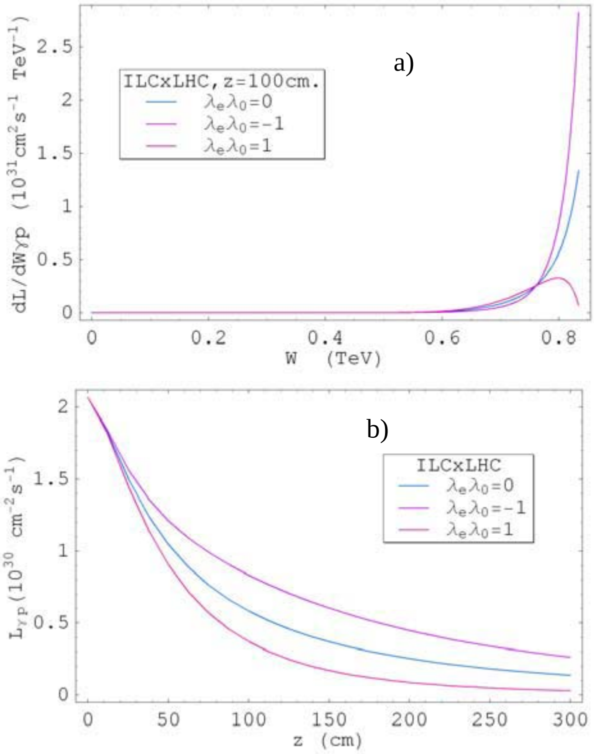

Figure 2: ILC×LHC γp luminosity distribution for various polarization combinations b) ILC×LHC total luminosity variation with z.

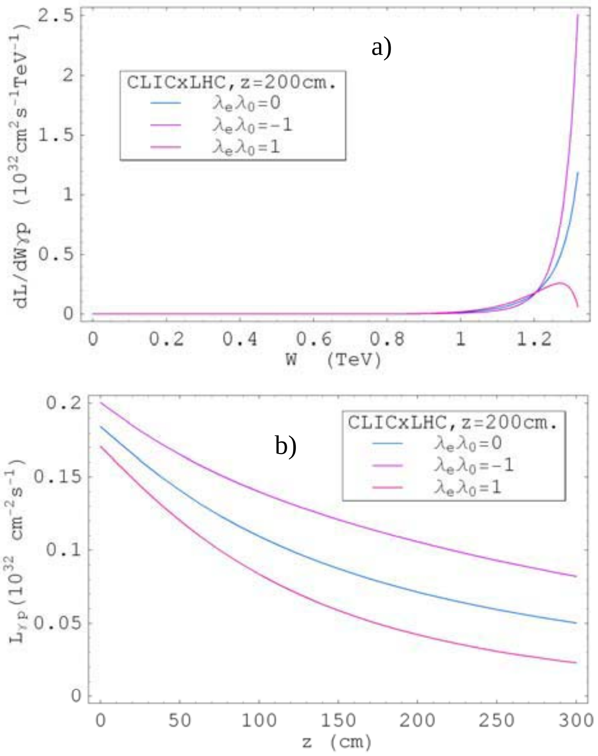

Figure 3. CLIC×LHC super bunched option p luminosity distribution for various polarization combinations b) CLIC×LHC total luminosity variation with z.

Energy Frontier Gamma-Nucleon Collider

At ultimate electron-beam energies of 1.5 TeV for CLIC and 0.5 TeV for ILC, the expected luminosities stay about the same, but the distance between interaction and conversion point could be increased.

PHYSICS POTENTIAL OF GAMMA-NUCLEON COLLIDERS

The physics search potentials for γp and γA colliders are discussed in [9-10]. For the energies of the QCD Explorer, the total production cross-section of hadron is about 100 μb. About 10^4 di-jet events with $p_t > 100$ GeV will be produced per year of operation. This collider will give information on hadronic structure of real photons. More than 10^7 (10^6) $c\bar{c}$ ($b\bar{b}$) quark pairs per operating year will provide an opportunity to explore the region of extremely small x_g ($\sim 10^{-5}$). Single W and Z boson productions with anomalous interactions ($\sim 10^3$ events/year) can be expected to be observed. The QCD Explorer will have discovery limit of 0.9 TeV for excited quarks and SUSY particles. Especially, the qq^* vertex will be investigated in detail. Single production of t-quark and fourth family quarks due to anomalous γ-c-Q or γ-u-Q (Q=t, u_4) and γ-s-d_4 or γ-d-d_4 interactions can be investigated.

The physics potential for γA collider with γ's produced from 75 GeV electrons comprises the following items:

- investigation of the total cross-section to understand the real mechanism of γ-nucleus interactions at high energies;
- the investigation of the hadronic structure of the photon in a nuclear medium;
- according to the VMD, the proposed machine will be also ρ-nucleus collider;
- the formation of quark-gluon plasma at very high temperatures, but relatively low nuclear density;
- measurement of the gluon distribution at extremely small x_g in a nuclear medium;

The physics research potentials of the energy frontier γp and γA colliders will be similar to those above, but extending the kinematical region (i.e., 1.8 TeV discovery limit for excited quarks and 10^{-6} for x_g). Still unforeseen physics events may be expected.

CONCLUSION

We presented three configurations for a gamma-nucleon collider based on the LHC and a moderate CLIC or ILC linac operating at 75 GeV or 30 GeV, respectively. The CLIC-based options promise luminosities between $3\text{x}10^{29}$ cm^{-2}s^{-1} and 10^{31} cm^{-2}s^{-1} and the ILC-based scheme about $8\text{x}10^{29}$ cm^{-2}s^{-1}, rather independent of linac energy. The physics case for such a collider was given.

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