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Discovery Limits for New Resonances at ep and γp Colliders

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Abstract

We study the resonance production of new particles at Linac-Ring type ep and γp colliders.

1. Introduction

As in the history of physics, proposal of a new level of substructure seems to be the right approach to a new physics. Beyond the Standard Model, where quarks and leptons are built out of constituents, one expects the existence of excited states [1,2]. These states would have masses which are of the order of compositeness scale $\Lambda \geq 1$ TeV. Such a large mass scale far exceeds those of present accelerators. Therefore, no experimental support has been obtained yet for any theory of new constituents and their interaction. As a preparation for the future experiments, searches for the signature of excited quarks and leptons have intensively been carrying on.

In this study, we consider the production of excited states at Linac-Ring type ep colliders [3-7] and γp colliders based on them [5,7-10]. The high center of mass energy of these machines enables us to search for leptoquarks and electron family particles (excited electrons, leptogluons, SUSY selectrons etc.). Furthermore, the signals are comperatively clean in making new processes conspicuous at ep colliders. TeV energy γp colliders seem more appealing than collisions with quasi-real photons, because of their hard spectrum and simplier kinematics.

Here, we consider scalar and vector leptoquarks, leptogluon(e_8) productions at ep and excited quark, colour octet boson(Z_8) productions at γp colliders. Corresponding Feynman diagrams are shown in figures 1(a)-1(d). In Table 1, we present the main parameters namely center of mass energy and luminosities, for Linac-Ring type [7,10] ep and γp collider proposals which seem more realistic for today.

Table 1. Main parameters of Linac-Ring type *ep* and γp colliders

Machines	$\sqrt{s_{ep}}$ (TeV)	L_{ep} ($10^{31} cm^{-2} s^{-1}$)	$\sqrt{s_{\gamma p}^{max}}$ (TeV)	$L_{\gamma p}$ ($10^{31} cm^{-2} s^{-1}$)
HERA+LC	1.28	1.2	1.16	2.5
LHC+Linac	3.04	27	2.77	50.0
LHC+TESLA	5.50	13	5.06	50.0

2. Total cross-section for the resonances

The resonance production cross-section formula for *ep* collision is given by

$$\sigma = \int_{x_{min}}^{1} dx f_{q(g)}(x)\hat{\sigma}(xs) \tag{1}$$

here $x_{min} = M^2/s$, $\hat{\sigma}$ is the subprocess cross section and $f_q(x)$ is the sum of valence and sea quark distribution functions with appropriate momentum fraction x inside the proton and $f_g(x)$ is gluon distribution function. In this work, for up and down quark and gluon distribution functions are taken from Eichten *et.al.* [11]. Namely,

$$f_u(x) = \frac{1.78}{x} x^{0.5}(1 - x^{1.51})^{3.5} + \frac{0.182}{x}(1 - x)^{8.54} \tag{2}$$

$$f_d(x) = \frac{0.67}{x} x^{0.4}(1 - x^{1.51})^{4.5} + \frac{0.182}{x}(1 - x)^{8.54} \tag{3}$$

and

$$f_g(x) = \frac{1}{x}(2.62 + 9.17x)(1 - x)^{5.90} \tag{4}$$

Cross section formula for γp collision is

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_\gamma(\frac{\tau}{x}) f_{q(g)}(x)\hat{\sigma}(\tau s) \tag{5}$$

where f_γ the energy spectrum of the real photon [11-12] is the following

$$f_\gamma(y) = \frac{1}{D}\left[1 - y + \frac{1}{(1-y)} - \frac{4y}{\xi(1-y)} + \frac{4y^2}{\xi^2(1-y)^2}\right] \tag{6}$$

with D=1.84 for ξ=4.8. The subprocess cross section $\hat{\sigma}$ is obtained from Breit-Wigner formula [15]

$$\hat{\sigma} = \frac{4\pi(2j+1)}{2 \times 2} \frac{\Gamma_i \Gamma_f}{[(\hat{s} - M^2)^2 + \frac{1}{4}\hat{s}\Gamma^2]} \tag{7}$$

where j is the spin of the resonance particle, Γ_i and Γ_f are the decay widths for initial and final states. In a resonance case, $\hat{s}\Gamma^2 >> (\hat{s} - M^2)^2$, therefore Eq.(7) can be expressed in the following form,

$$\hat{\sigma} = \frac{4\pi^2(2j+1)\Gamma_i\Gamma_f}{M\Gamma}\delta(\hat{s} - M^2) \tag{8}$$

where $\hat{s} = \tau$s, and $\tau = M^2/s$. Taking $\Gamma_f = \Gamma$ we obtain

$$\hat{\sigma} = \frac{4\pi^2(2j+1)\Gamma_i}{Ms}\delta(\tau - \frac{M^2}{s}). \tag{9}$$

2.1. Scalar leptoquarks

The most general $SU(3)_C \times SU(2)_W \times U(1)_Y$ invariant Lagrangian for scalar leptoquark interaction with usual fermions has the form [16-18]:

$$\begin{aligned} L = {} & g_{1L}\bar{q}^c_L i\tau_2 l_L S_1 + g_{1R}(\bar{u}^c_R e_R + \bar{d}^c_R \nu_R)S'_1 + \tilde{g}_{1R}\bar{d}^c_R e_R \tilde{S}_1 \\ & +\tilde{g}'_{1R}\bar{u}^c_R \nu_R \tilde{S}'_1 + g_{3L}\bar{q}^c_L i\tau_2 \vec{\tau} l_L \vec{S}_3 + h_{2L}\bar{u}_R l_L R_2 \\ & +h_{2L}\bar{q}_L i\tau_2 e_R R'_2 + \tilde{h}_{2L}\bar{d}_R l_L \tilde{R}_2 + \tilde{h}_{2R}\bar{q}_L i\tau_2 \nu_R \tilde{R}'_2 + h.c. \end{aligned} \tag{10}$$

where q_L and l_L are the $SU(2)_W$ left handed quark and lepton doublets and $\psi^c = C\bar{\psi}^T$ is the charge conjugated fermion field. Scalar leptoquarks S_1, S'_1, $\tilde{S}_1$ and $\tilde{S}'_1$ are $SU(2)_W$ singlets, R_2, R'_2, $\tilde{R}_2$ and $\tilde{R}'_2$ are $SU(2)_W$ doublets, and S_3 is an $SU(2)_W$ triplet. Note that the terms with right handed neutrino are absent in the Ref. [16,17]. We believe that these terms must be included into the Lagrangian because of the lepton-quark symmetry. The decay width of scalar leptoquark is obtained as

$$\Gamma(S \to lq) = \frac{g_i^2}{16\pi}M_S, \tag{11}$$

we use the conventional parametrization $g_i^2 = 4\pi k_i \alpha_{em}$, where g_i denotes $g_{1L,\ldots}$, h_{2R} in our calculations. With this width Eq.(9) yields the subprocess cross section, for k=1,

$$\hat{\sigma} = \frac{\pi^2\alpha_{em}}{s}\delta(x - \frac{M_S^2}{s}). \tag{12}$$

Carrying Eq.(12) together with Eq.(2) and Eq.(3) into the Eq.(1), we obtain total cross sections for up and down quarks, respectively.

2.2. Vector leptoquarks

For vector leptoquark interactions with fermions we take the following most general Lagrangian [16] which is invariant under $SU(3)_C \times SU(2)_W \times U(1)_Y$:

$$\begin{aligned} L = {} & (g_{2L}\bar{d}^c_R\gamma^\mu l_L + g_{2R}\bar{q}^c_L\gamma^\mu e_R)V_{2\mu} + \tilde{g}_{2L}\bar{u}^c_R\gamma^\mu l_L\tilde{V}_{2\mu} + g'_{2R}\bar{q}^c_L\gamma^\mu\nu_R V'_{2\mu} \\ & +(h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R + h_{1R}\bar{u}_R\gamma^\mu\nu_R)U_{1\mu} \\ & +\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + \tilde{h}'_{1R}\bar{d}_R\gamma^\mu\nu_R\tilde{U}'_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L\vec{U}_{3\mu} + h.c. \end{aligned} \tag{13}$$

here q_L and l_L are the $SU(2)_W$ left handed quark and lepton doublets, and $\psi^c = C\bar{\psi}^T$ is the charge conjugated fermion field. Vector leptoquarks U_1, $\tilde{U}_1$ and $\tilde{U}_1'$ are $SU(2)_W$ singlets, V_2, V_2', $\tilde{V}_2$ are $SU(2)_W$ doublets and U_3 is an $SU(2)_W$ triplet.The subscripts L and R for the coupling constants refer to lepton chirality. The Lagrangian Eq.(10) again differs from the one of Ref.[16] with the terms having right handed neutrino. Calculation of the decay width of vector leptoquark gives

$$\Gamma(V \to lq) = \frac{g_i^2}{24\pi} M_V \tag{14}$$

here $g_i^2 = 4\pi\alpha_{em}k_i$. Then, the resulting subprocess cross section, for k=1, is

$$\hat{\sigma} = \frac{2\pi^2\alpha_{em}}{s}\delta(x - \frac{M_V^2}{s}). \tag{15}$$

Following the above mentioned route, the total cross sections can be calculated for up and down quarks.

2.3. Leptogluons (e_8)

Leptogluons are colour-octet excitations of lepton states. At *ep* colliders leptogluons would be produced as narrow s-channel resonances through the direct fusion of a lepton and a gluon from proton. The Lagrangian between ordinary electron and gluon [20] is given by

$$L = \frac{1}{2\Lambda}\sum_l \left[\bar{l_8}^{\alpha} g_s \sigma_{\mu\nu} G_\alpha^{\mu\nu} (\eta_L l_L + \eta_R l_R) + h.c.\right] \tag{16}$$

where $G_\alpha^{\mu\nu}$ is the field stress tensor for the gluon, index α (1,2,...,8) denotes the colour, g_s is the QCD gauge coupling, η_L and η_R are the chirality factors, l_L and l_R denote left and right spinor components of the lepton and $\sigma_{\mu\nu}$ is the anti-symmetric tensor, Λ is the compositeness scale ($\sim TeV$). For η_L=1 and η_R=0, we obtain the decay width of leptogluon

$$\Gamma(e_8 \to eg) = \frac{\alpha_s}{4\Lambda^2} M_{e_8}^3 \tag{17}$$

or equivalently,

$$\Gamma(e_8 \to eg) = \frac{\alpha_s \lambda^2}{4} M_{e_8} \tag{18}$$

where α_s is the strong coupling constant and $\lambda = M_{e_8}/\Lambda$. Carrying this result into Eq.(9) gives the subprocess cross section

$$\hat{\sigma} = \frac{2\pi^2\lambda^2\alpha_s}{s}\delta(x - \frac{M_{e_8}^2}{s}). \tag{19}$$

Using the gluon distribution function [11] in Eq.(1) we obtain the total cross section.

2.4. Excited quarks ($u^\star, d^\star$)

The coupling between the excited spin 1/2 quarks and massless gauge bosons is given by the effective Lagrangian of the magnetic moment type [21-24]

$$L = \frac{1}{2\Lambda}\bar{q}^\star \sigma_{\mu\nu}(g_s f_s \frac{\lambda^\alpha}{2} G^{\mu\nu}_\alpha + e e_q f_\gamma F^{\mu\nu}) q_L + h.c., \tag{20}$$

here $\Lambda \sim M^\star$, $G^{\mu\nu}$ and $F^{\mu\nu}$ are the field stress tensors for the gluon and photon, λ^α is 3×3 Gell-Mann matrices, f_s and f_γ are dimensionless constants, e_q is the charge of the excited up or down quark, $M^\star$ is the mass of the excited quark. The width of the excited quarks decay into ordinary quark and photon is

$$\Gamma(q^\star \to q\gamma) = \frac{\alpha_{em} e_q^2}{4} M^\star \tag{21}$$

By the use of Eq.(9) the subprocess cross section is obtained as

$$\hat{\sigma} = \frac{2\pi^2 e_q^2 \alpha_{em}}{s} \delta(\tau - \frac{M^{\star 2}}{s}). \tag{22}$$

Using the photon energy spectrum given in Eq.(6) and up and down quarks distribution functions given in Eq.(2) and Eq.(3) respectively, Eq.(5) leads to the total cross sections.

2.5. Colour octet Z boson (Z_8)

In some models, the intermediate vector bosons are treated as bound states of colour preons [25]. In this case one can predict the existence of colour excited intermediate vector boson, octet in colour, with masses of several hundreds of GeV. In γp collisions the Z_8 may be produced via γg fusion. The $Z_8 \to \gamma g$ decay proceeds due to preon annihilation into photon and gluon; hence if the $M_{Z_8} \sim \Lambda$ we might take [8]

$$\Gamma(Z_8 \to \gamma g) = \alpha_{em} \alpha_s M_{Z_8} \tag{23}$$

Then, subprocess cross section is given by

$$\hat{\sigma} = \frac{3\pi^2 \alpha_{em} \alpha_s}{s} \delta(\tau - \frac{M^2_{Z_8}}{s}). \tag{24}$$

The total cross section of the colour vector boson production can be calculated from Eq.(5) by using Eq.(6) for the photon distribution and Eq.(4) for gluon distribution.

3. Discussion and conclusion

In this work, we have considered the total cross sections of resonance particle productions in *ep* and γp collisions. Corresponding cross sections are presented in Table 2, assuming the masses of new particles to be equal to 1 TeV. These values multiplied by the integral luminosity per year, which can be obtained multiplying the luminosity values taken from Table 1 by the factor of 10^7, give the number of expected events. As can be seen from the Table 3, number of events, particularly for LHC+Linac1 and LHC+TESLA, are sufficiently large for investigation of the properties of new particles in detail. In Table 4, we present achievable mass values for new particles at various proposed machines by taking 100 events per year as discovery limits. From Table 4, it is quite clear that at these machines, we can reach masses of order of few TeV. Due to clear signatures, we may even take 25 events per year as discovery limits. In this case, achievable mass values become somewhat larger as presented in Table 5.

The recent experimental lower mass bounds [26] are much smaller in comparison with the values given in Table 4 and 5. Leptoquarks and leptogluons will be produced in resonance mode at LHC+LEP where masses reach up to 1.0-1.2 TeV. In this sense, LHC+LEP is comparable with HERA+LC and the Table 4 exhibits the advantage of LHC+Linac1 and LHC+TESLA proposals. Linear e^+e^- colliders will allow to reach the masses up to 1 TeV [27], however larger values cannot be achieved due to CM energy limitation.

Table 2. Total cross sections σ(pb) for the resonance particles with 1 TeV masses

	HERA+LC $\sqrt{s}$=1.28 TeV	LHC+Linac1 $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	4.2	16.9	13.1
S(ed)	0.9	8.7	8.8
V(eu)	8.4	33.8	26.2
V(ed)	1.8	17.5	17.5
$u^\star$	0.2	11.3	12.3
$d^\star$	0.01	1.2	1.7
e_8	24.95	1450.0	1982.8
Z_8	0.01	7.7	15.3

Table 3. Number of expected events per year for the resonance particles with 1 TeV masses

	HERA+LC $\sqrt{s}$=1.28 TeV	LHC+Linac1 $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	1.5×10^3	1.4×10^5	5.1×10^4
S(ed)	3.2×10^2	7.1×10^4	3.4×10^4
V(eu)	3.0×10^3	2.7×10^5	1.0×10^5
V(ed)	6.3×10^2	1.4×10^5	6.8×10^4
$u^\star$	1.4×10^2	1.8×10^5	1.9×10^5
$d^\star$	8	1.9×10^4	2.7×10^4
e_8	9.0×10^3	1.2×10^6	7.7×10^6
Z_8	8	1.2×10^5	2.4×10^5

Table 4. Upper limits for resonance particles masses (TeV) when 100 events per year are taken in *ep* and γp colliders.

	HERA+LC $\sqrt{s}$=1.28 TeV	LHC+Linac1 $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	1.16	2.80	4.65
S(ed)	1.07	2.60	4.10
V(eu)	1.18	2.85	4.83
V(ed)	1.10	2.67	4.35
$u^\star$	1.00	2.50	4.35
$d^\star$	0.85	2.15	3.65
e_8	1.16	2.77	4.78
Z_8	0.88	2.18	3.75

Table 5. Upper limits for resonance particles masses (TeV) when 25 events per year are taken in *ep* and γp colliders.

	HERA+LC $\sqrt{s}$=1.28 TeV	LHC+Linac1 $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	1.19	2.88	4.95
S(ed)	1.12	2.70	4.55
V(eu)	1.21	2.90	5.02
V(ed)	1.14	2.75	4.70
$u^\star$	1.05	2.58	4.53
$d^\star$	0.93	2.30	3.90
e_8	1.18	2.83	4.93
Z_8	0.93	2.30	3.95

Leptoquarks, leptogluons, excited quarks and colour octet bosons with masses of few TeV will be produced at LHC. The advantage of Linac-Ring type *ep* and γp colliders are the following:

i) At these machines, leptoquarks and leptogluons will be produced in resonance mode

ii) These machines have lower background than the case of hadronic colliders.

In conclusion, Linac-Ring type *ep* and γp colliders will be good machines to search for new particles.

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