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Resonance Production of New Resonances at ep and γp Colliders

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Abstract

We study the resonance production of new particles predicted by preonic models at Linac-Ring type ep and γp colliders. It is shown that these machines will allow to investigate the new particles with masses up to few TeV scale.

1. Introduction

Over the past few years, enormous amount of efforts has gone into solving the open problems of the standard model. The most promising approach in this direction is compositeness in which the leptons and quarks are assumed to be a bound states of fundamental particles called preons [1]. Composite models of quarks and leptons exhibit a rich spectrum which includes excitations of the known particles and some bound states which carry rather unusual quantum numbers (leptoquarks, leptogluons,etc..). Since the compositeness scale Λ is expected to be in the order of TeV, masses of these excited states should lie around this value. 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 interactions.

The production of leptoquarks have already been analyzed in the literature at ep [2], e^+e^- [3], $e\gamma$ [4] and pp, $p\bar{p}$ colliders [5]. The studies of excited quarks are investigated at pp, $p\bar{p}$ [6], ep and γp colliders [7].

In addition to the known machines, the plans have been developed to construct a Linac-Ring type ep collider and on them TeV energy γp colliders [8]. Standard type ep colliders like HERA and LHC+LEP are far from being able to reach TeV scale at the constituent level. Therefore, the new type ep and γp colliders seem very attractive for new physics at TeV scale. Single and pair productions of scalar and vector leptoquarks at γp colliders have been investigated in Ref. [9]. The search for SUSY particles at γp colliders was considered in Ref. [10]. For the HERA+LC collider physics program including the supersymmetric partners, leptoquark production and heavy quark investigations have been examined in detail in Ref. [11].

In this work, we continue to develop the physics program of Linac-Ring type ep and γp colliders by investigating resonance production of scalar and vector leptoquarks, leptogluon (e_8), excited quarks and colour octet boson (Z_8). Corresponding Feynman diagrams are shown in Figures 1(a)-1(d).

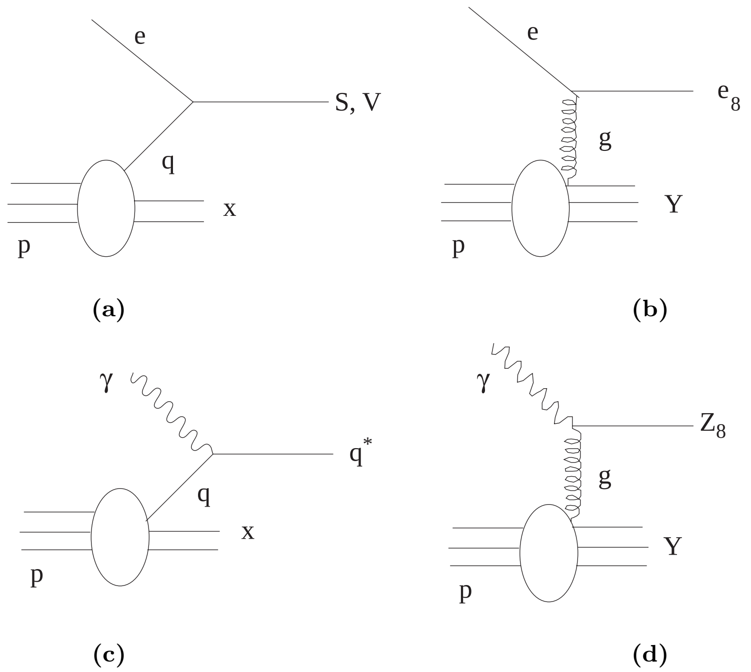

Figure 1. Feynman diagrams for the resonance productions at ep and γp colliders.

The paper is organized as follows: In section 2, we give resonance production cross section formulae for ep and γp collisions. In section 3, the Lagrangians, decay widths and corresponding subprocess cross sections are presented. Numerical results have been discussed in section 4.

2. Total cross-section for the resonances

The total cross section of resonance production in ep collisions is given by

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

Here $x_{min} = M^2/s$, M is the mass of the corresponding resonance, $\hat{\sigma}$ is the subprocess cross section, $f_q(x)$ is the sum of valence and sea quark distribution functions and $f_g(x)$ is gluon distribution function with appropriate momentum fraction x inside the proton. There have been recent analyses containing all the new experimental information on parton distributions. In this work, up and down quarks and gluon distribution functions are taken from paper by Martin *et al*. [12].

Cross section formula for γp collisions is

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_\gamma(\frac{\tau}{x}) f_{q(g)}(x) \hat{\sigma}(\tau s), \tag{2}$$

where $\tau = M^2/s$ and f_γ is the energy spectrum of the real photon [13];

$$f_\gamma(y) = \frac{1}{D}\left[1 - y + \frac{1}{(1-y)} - \frac{4y}{\xi(1-y)} + \frac{4y^2}{\xi^2(1-y)^2}\right], \tag{3}$$

with D=1.84 for ξ=4.8.

The subprocess cross section $\hat{\sigma}$ is obtained from the Breit-Wigner formula [14]

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

where $\hat{s} = \tau s$ and 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, $\hat{s}\Gamma^2 \gg (\hat{s} - M^2)^2$, and therefore Eq.(4) can be expressed in the following form:

$$\hat{\sigma} = \frac{4\pi^2(2j+1)\Gamma_i\Gamma_f}{M\Gamma} \delta(\hat{s} - M^2), \tag{5}$$

where $\hat{s} = \tau$s, and $\tau = M^2/s$. Summing over final states we obtain

$$\hat{\sigma} = \frac{4\pi^2(2j+1)\Gamma_i}{Ms} \delta(\tau - \frac{M^2}{s}). \tag{6}$$

3. Subprocess cross sections

i) Leptoquarks: Leptoquarks are colour triplet particles which couple to a lepton-quark pair and are naturally present in many theories beyond the standard model which relate leptons and quarks at a more fundamental level. Leptoquarks are a good example of new physics to study at ep machines. The scalar and vector leptoquark interaction Lagrangian consistent with the symmetries of $SU(3)_C \times SU(2)_W \times U(1)_Y$ is given by Buchmüller *et al*. [2],

$$\begin{aligned} L_S = g_{1L}\bar{q}_L^c i\tau_2 l_L S_1 + g_{1R}(\bar{u}_R^c e_R + \bar{d}_R^c \nu_R)S_1' + \tilde{g}_{1R}\bar{d}_R^c e_R \tilde{S}_1 \\ +\tilde{g}_{1R}'\bar{u}_R^c \nu_R \tilde{S}_1' + g_{3L}\bar{q}_L^c i\tau_2 \vec{\tau} l_L \vec{S}_3 + h_{2L}\bar{u}_R l_L R_2 \\ +h_{2L}\bar{q}_L i\tau_2 e_R R_2' + \tilde{h}_{2L}\bar{d}_R l_L \tilde{R}_2 + \tilde{h}_{2R}\bar{q}_L i\tau_2 \nu_R \tilde{R}_2' + h.c. \end{aligned} \tag{7}$$

and

$$L_V = (g_{2L}\bar{d}^c_R\gamma^\mu l_L + g_{2R}\bar{q}^c_L\gamma^\mu e_R)V_{2\mu} + \tilde{g}_{2L}\bar{u}^c_R\gamma^\mu l_L\tilde{V}_{2\mu} + g'_{2R}\bar{q}^c_L\gamma^\mu\nu_R V'_{2\mu}$$
$$+(h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R + h_{1R}\bar{u}_R\gamma^\mu\nu_R)U_{1\mu}$$
$$+\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + \tilde{h}'_{1R}\bar{d}_R\gamma^\mu\nu_R\tilde{U}'_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L\vec{U}_{3\mu} + h.c., \quad (8)$$

where q_L and l_L denote 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. 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. Note that the terms with right handed neutrino are absent in the Ref. [2]. We understend that these terms must be included in the Lagrangian because of the lepton-quark symmetry. From Eq.(7) and Eq.(8) one can easily calculate decay widths of the scalar (j=0) and vector (j=1) leptoquarks

$$\Gamma(S \to lq) = \frac{g_i^2}{16\pi}M_S, \quad (9)$$

and

$$\Gamma(V \to lq) = \frac{g_i^2}{24\pi}M_V, \quad (10)$$

here we use the conventional parametrization $g_i^2 = 4\pi k_i\alpha_{em}$, where g_i denotes $g_{1L,...}$, h_{2R}. With these widths Eq.(6) yield the following cross sections, for scalar leptoquarks,

$$\hat{\sigma} = \frac{\pi^2\alpha_{em}k_i}{s}\delta(x - \frac{M_S^2}{s}), \quad (11)$$

and for vector leptoquarks,

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

ii) 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 interaction Lagrangian is given by [15]

$$L = \frac{1}{2\Lambda}\sum_l \left[\bar{l}_8^{\,\alpha} g_s\sigma_{\mu\nu}G_\alpha^{\mu\nu}(\eta_L l_L + \eta_R l_R) + h.c.\right], \quad (13)$$

where $G_\alpha^{\mu\nu}$ is the field strength 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. For η_L=1 and η_R=0, we obtain the decay width of leptogluon

$$\Gamma(e_8 \to eg) = \frac{\alpha_s}{4\Lambda^2} M_{e_8}^3 \tag{14}$$

or equivalently,

$$\Gamma(e_8 \to eg) = \frac{\alpha_s \lambda^2}{4} M_{e_8} \tag{15}$$

where α_s is the strong coupling constant and $\lambda = M_{e_8}/\Lambda$. Carrying this result into Eq.(6) gives the subprocess cross section

$$\hat{\sigma} = \frac{2\pi^2 \lambda^2 \alpha_s}{s} \delta(x - \frac{M_{e_8}^2}{s}). \tag{16}$$

iii) Excited quarks ($q^\star$): The coupling between the excited spin 1/2 quarks and massless gauge bosons is given by the effective Lagrangian of the magnetic moment type [6]

$$L = \frac{1}{2\Lambda} \bar{q}^\star \sigma_{\mu\nu} (g_s f_s \frac{\lambda^\alpha}{2} G_\alpha^{\mu\nu} + e e_q f_\gamma F^{\mu\nu}) q_L + h.c., \tag{17}$$

where $\Lambda \sim M^\star$, $G^{\mu\nu}$ and $F^{\mu\nu}$ are the field strength tensors for the gluon and photon, respectively, 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, and $M^\star$ is the mass of the excited quark. The width of the excited quarks can be computed from Eq.(17) to be

$$\Gamma(q^\star \to q\gamma) = \frac{\alpha_{em} e_q^2 f_\gamma^2}{4} M^\star, \tag{18}$$

and the subprocess cross section is obtained as

$$\hat{\sigma} = \frac{2\pi^2 e_q^2 \alpha_{em} f_\gamma^2}{s} \delta(\tau - \frac{M^{\star 2}}{s}). \tag{19}$$

According to Eq.(17), quarks can be excited also by gluon-quark fusion. For the time being, we omit the subprocesses due to the photon structure because these contributions are essential for low mass values whereas here we are interested in maximal achievable masses.

iv) Colour octet Z boson (Z_8): In some models, the intermediate vector bosons are treated as bound states of colour preons [16]. 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 (see Alekhin *et al.* (1991) in [7])

$$\Gamma(Z_8 \to \gamma g) = \alpha_{em} \alpha_s M_{Z_8} \tag{20}$$

Then, subprocess cross section is given by

$$\hat{\sigma} = \frac{3\pi^2 \alpha_{em}\alpha_s}{s}\delta(\tau - \frac{M_{Z_8}^2}{s}). \tag{21}$$

4. Numerical results

In numerical calculations we use parameters of Linac-Ring type ep and γp colliders given in Table 1 (Çiftçi *et al.* in [8]). The total cross sections of scalar and vector leptoquarks and leptogluon productions at ep collider can be easily obtained from Eq.(1) by inserting Eq.(11), Eq.(12) and Eq.(16), respectively. As an example, we present total cross section for $V(e^-u)$ leptoquarks in Fig.(2) and leptogluon productions in Fig.(3).

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

Calculation of excited quark and colour octet boson production at γp colliders is little more complicated because it needs additional integration over the energy spectrum of the real photon, in addition to the integration over quark or gluon distributions after carrying Eq.(19) and Eq.(21) into Eq.(2). As an example, total cross section for $u^\star$ and Z_8 production at different γp colliders are plotted in Figure (4) and Figure (5), respectively.

In Table 2, we present achievable mass values for new particles at various proposed machines by taking 100 events per year as discovery limits. For comparison, we also present achievable masses at LHC+LEP with parameters $\sqrt{s_{ep}} = 1.36$ TeV and luminosity $2.8 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$.

In Table 3, number of expected events per year for resonance particles with 1 TeV masses are given for different ep and γp colliders. The values in Table 3 are obtained by multiplying corresponding cross sections with the collider's luminosities and 10^7 s.

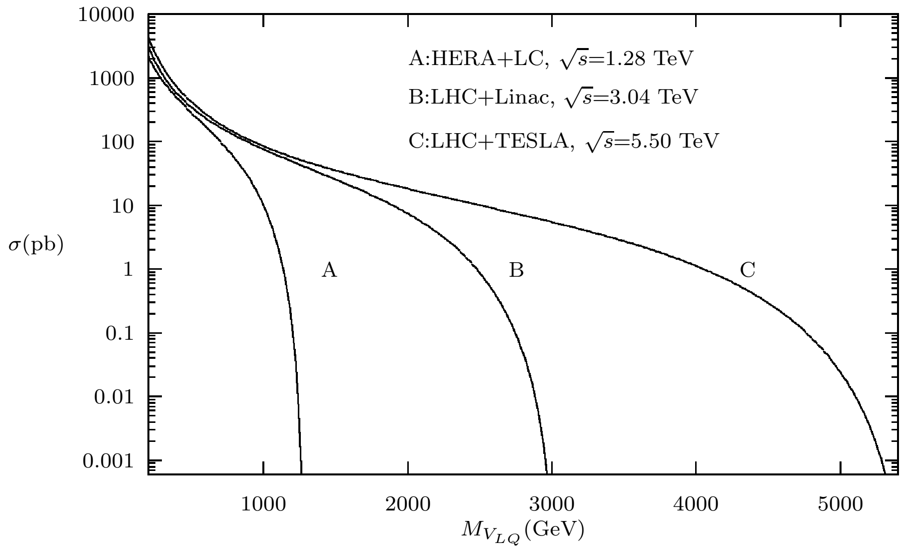

Figure 2. The total cross section for $V \rightarrow e^{-}u$ vector leptoquarks at ep colliders. Curve A, B and C correspond to HERA+LC, LHC+Linac and LHC+TESLA proposals, respectively.

Table 2. 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+LEP $\sqrt{s}$=1.36 TeV	LHC+Linac $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	1.11	1.28	2.76	4.66
S(ed)	0.97	1.19	2.48	3.98
V(eu)	1.14	1.29	2.81	4.80
V(ed)	1.02	1.21	2.58	4.20
e_8	1.13	1.27	2.76	4.78
$u^{\star}$	0.97	-	2.41	4.16
$d^{\star}$	0.74	-	1.96	3.20
Z_8	0.80	-	2.06	3.43

All particles considered above have quite clear signatures as shown in Table 4, where we also present main backgrounds. Detailed analysis of these items will be considered elsewhere. Here, we consider the signal of an electron accompained by a jet. In the case of vector leptoquarks, contributions to $eq \rightarrow eq$ subprocess come from vector leptoquark in the s-channel, γ and Z in the t-channel, leading to

$$(\frac{d\hat{\sigma}}{d\hat{t}})_{eq\rightarrow eq} = \frac{1}{16\pi\hat{s}^2}\Bigg[\frac{2g_e^4Q_q^2Q_l^2}{\hat{t}^2}(2\hat{s}^2 + 2\hat{s}\hat{t} + \hat{t}^2)$$

$$+ \frac{g_Z^4}{8(\hat{t}-M_Z^2)^2}\Big((|C_V^l|^2+|C_A^l|^2)(|C_V^q|^2+|C_A^q|^2)(2\hat{s}^2+2\hat{s}\hat{t}+\hat{t}^2)$$
$$+ 4C_V^l C_A^l C_V^q C_A^q(\hat{t}^2+2\hat{s}\hat{t})\Big) + \frac{g_{lq}^4}{8[(\hat{s}-M_V^2)^2+M_V^2\Gamma_V^2]}(3\hat{s}^2+7\hat{s}\hat{t}+8\hat{t}^2)$$
$$+ \frac{g_e^2 g_Z^2 Q_q Q_l}{2\hat{t}(\hat{t}-M_Z^2)}\Big(C_A^l C_A^q(\hat{t}^2+2\hat{s}\hat{t}) + C_V^l C_V^q(2\hat{s}^2+2\hat{s}\hat{t}+\hat{t}^2)\Big)$$
$$+ \frac{2g_e^2 g_{lq}^2 Q_q Q_l(\hat{s}-M_V^2)}{\hat{t}[(\hat{s}-M_V^2)^2+M_V^2\Gamma_V^2]}(\hat{s}^2+2\hat{s}\hat{t}+\hat{t}^2)$$
$$+ \frac{2g_{lq}^2 g_Z^2(\hat{s}-M_V^2)}{2(\hat{t}-M_Z^2)[(\hat{s}-M_V^2)^2+M_V^2\Gamma_V^2]}(C_A^l C_A^q + C_V^l C_A^q)(\hat{s}^2+2\hat{s}\hat{t}+\hat{t}^2)\Big] \quad (22)$$

where Q_q, Q_l are charges of u and d quarks and leptons, respectively. $C_{V,A}^l$ and $C_{V,A}^q$ are the vector and axial vector couplings in the GWS Model and $g_{lq}^2 = 4\pi\alpha_{em}k$, g_Z is the coupling constant of the weak interactions and M_Z becomes the mass of the Z boson. Γ_V stands for the decay width of vector leptoquark, M_V is the mass of vector leptoquark. Invariant mass distribution is presented in Figure (6) for $M_V = 1$ TeV and $k = 1$.

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

	HERA+LC $\sqrt{s}$=1.28 TeV	LHC+LEP $\sqrt{s}$=1.36 TeV	LHC+Linac $\sqrt{s}$=3.04 TeV	LHC+TESLA $\sqrt{s}$=5.50 TeV
S(eu)	600	2.3×10^4	3.0×10^5	1.6×10^5
S(ed)	64	2.9×10^3	1.9×10^5	1.4×10^5
V(eu)	1195	4.6×10^4	6.0×10^5	3.2×10^5
V(ed)	127	5.9×10^3	3.8×10^5	2.7×10^5
e_8	2339	1.2×10^5	8.0×10^6	6.3×10^6
$u^\star$	43	-	3.2×10^5	4.6×10^5
$d^\star$	28	-	3.6×10^4	8.1×10^4
Z_8	83	-	7.7×10^4	1.8×10^5

Requiring the significance level of the signal to be 5σ for a bin of 10 GeV around resonance, we plot in Fig.(7) discovery contour for vector leptoquark production in the plane $k \times M_V$.

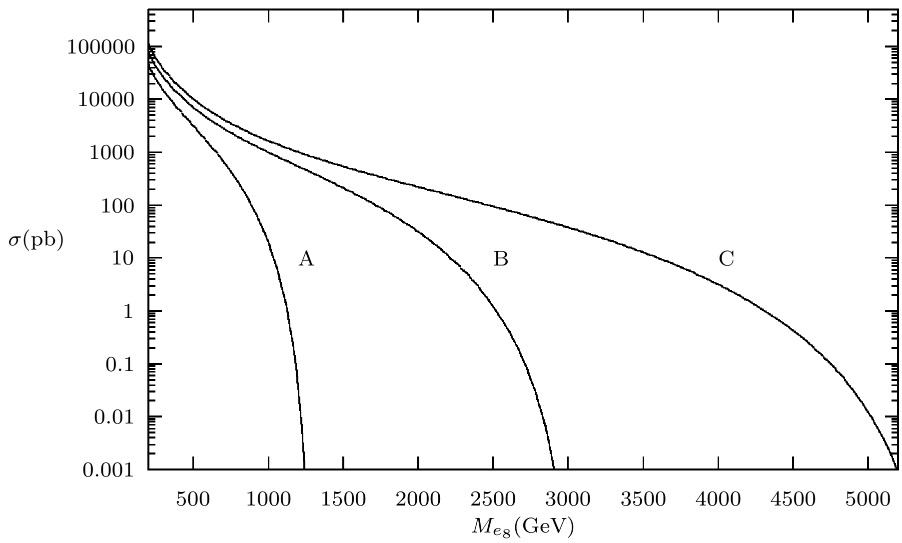

Figure 3. The total cross section for e_8 leptogluons at ep colliders. Curve symbols are the same as Fig.2

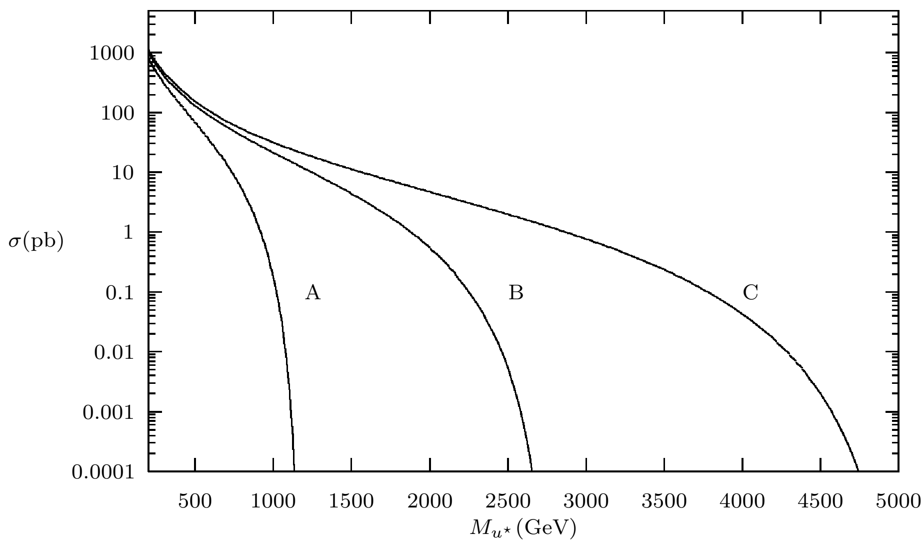

Figure 4. The total cross section for $u^\star$ excited quarks at γp colliders. Curve symbols are the same as Fig.2

As can be seen, vector leptoquarks will be observed with masses up to kinematical limit of the corresponding γp colliders: for HERA+LC when $k > 0.02$, for LHC+Linac when $k > 0.01$ and for LHC+TESLA when $k > 0.04$. It should be noted that discovery limits for LHC based γp colliders are in the same region with LHC pp collider.

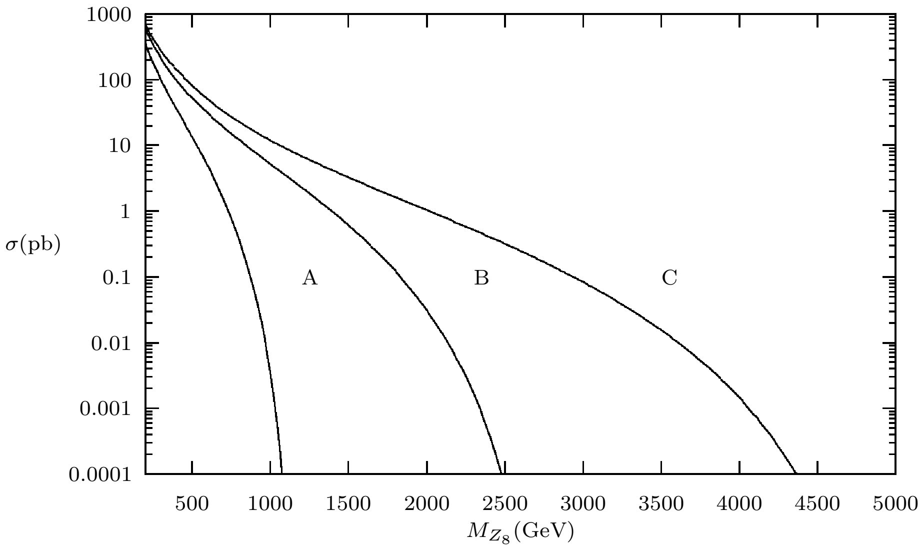

Figure 5. The total cross section for Z_8 colour octet Z bosons at γp colliders. Curve symbols are the same as Fig.2

Table 4. Signatures and standard model backgrounds

Resonances	Dominant decay modes	Signature	Main background (sub)processes
S_{lq},V_{lq}	$l+q$	e+jet	$lq \to lq$
	$\nu+q$	p_T^{miss}+jet	$lq \to \nu q'$
e_8	$e+g$	e+jet	$eq \to eq$
$q^\star$	$q+g$	jet+jet	$\gamma q \to gq$
			$\gamma g \to q\bar{q}$
Z_8	$Z+g$	l^+l^-+jet	$\gamma q \to Zq$
		jet+jet+jet	
		p_T^{miss}+jet	
	$q+\bar{q}$	jet+jet	$\gamma q \to gq$
			$\gamma g \to q\bar{q}$

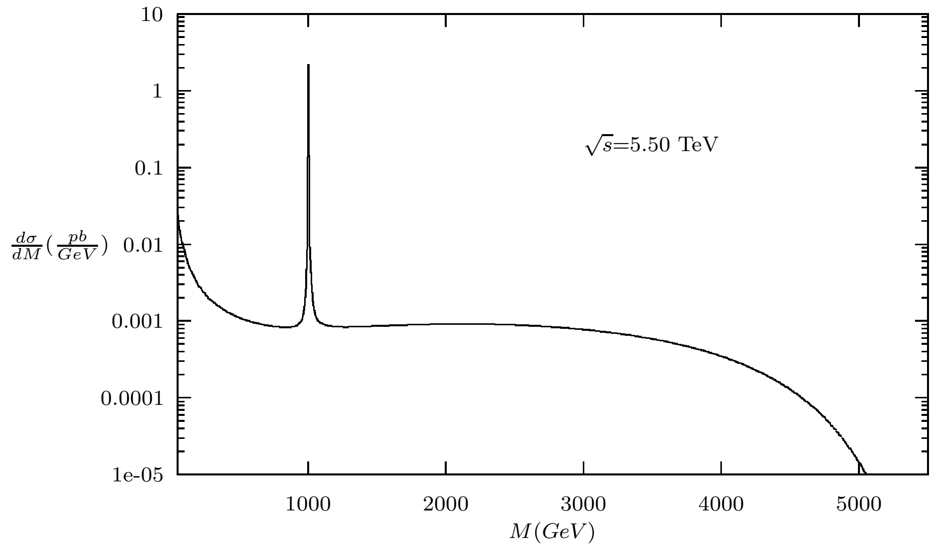

Figure 6. Invariant mass distribution for vector leptoquark production with 1 TeV masses at LHC+TESLA *ep* collider.

5. Conclusion

The recent experimental lower mass bounds for particles under consideration [17] are much smaller in comparison with the values given in Table 2. 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+Linac and LHC+TESLA proposals. Linear e^+e^- colliders will allow to reach the masses up to 1 TeV (Blumlein and Boos in [3]), however larger values cannot be achieved due to center of mass energy limitation.

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 may have lower background than hadron colliders.

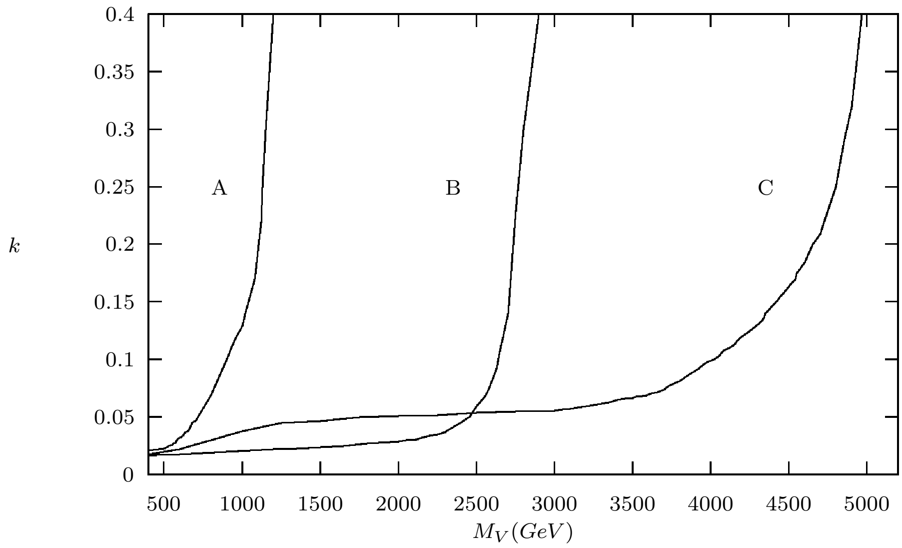

Figure 7. Discovery contour in the plane $(k \times M_V)$ for the resonance production $e + q \rightarrow V \rightarrow e + jet$. Curves A, B and C correspond to machines mentioned in Fig.(2),respectively.

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