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Indirect search for color octet electron at next-generation linear colliders

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Abstract – In this study we investigated indirect manifestations of color octet electron at the next-generation linear colliders: International Linear Collider (ILC) and Compact Linear Collider (CLIC). Namely, production of two gluons via color octet electron exchange is considered. Signal and background analysis have been performed taking into account initial state radiation and Beamstrahlung. We show that color octet electron (e_8) manifestation will be seen upto $M_{e_8} = 1.75\,\text{TeV}$ and $1.70\,\text{TeV}$ at ILC and CLIC with $\sqrt{s} = 0.5\,\text{TeV}$, respectively. CLIC with $\sqrt{s} = 3\,\text{TeV}$ will be sensitive upto $M_{e_8} = 6.88\,\text{TeV}$.

Introduction. – Predictions of Standard Model (SM) have so far been in agreement with results of numerous experiments. Therefore, SM has been in use to explain many puzzles related to fundamental particles and their interactions. However, there have been a number of fundamental problems (quark-lepton symmetry, family replication, hierarchy problems, charge quantization etc.) SM could not deal with. Furthermore, masses and mixings of leptons and quarks are fixed by hand. These problems forced physicists to go beyond SM. Extra dimensions, supersymmetry (SUSY), compositeness and so on have been created for solving these problems and to explain the physics underlying them.

Among these alternative models compositeness has explained the subjects of family replication and quark-lepton symmetry in the best manner. According to the theory of compositeness quarks, leptons, gauge bosons need to be composite particles made up of more basic constituents. These basic constituents, in other words substructural particles, are named preons. It is assumed that preons are what composes quarks, leptons and gauge bosons. It is also supposed that preons interactions lead to the development of many new types of particles such as leptoquarks, leptogluons, diquarks, dileptons and excited fermions.

We will be interested in color octet leptons that in the framework of composite models with colored preons [1–7] have the same status as the excited leptons. For instance, in the framework of fermion-scalar models, leptons would be a bound state of one fermionic preon and one scalar antipreon $l = (F\bar{S}) = 1 \oplus 8$ (both F and S are color triplets), then each SM lepton is thought to accompany with its own color octet partner [7]. There are many papers about manifestations of excited leptons at high-energy colliders whereas color octet leptons are discussed only in a few papers [7–10].

Resonant production of e_8 at future ep colliders have been analyzed in a recent paper [10], where also current limits on leptogluon masses are briefly discussed. It was shown that the e_8 discovery at the LHeC simultaneously will determine the compositeness scale.

In this paper we will consider indirect manifestation of color octet electrons at the next generation linear colliders: International Linear Collider (ILC) and Compact Linear Collider (CLIC). In the second section, we present the interaction Lagrangian of the leptogluons as well as signal cross-section for the process $e^-e^+ \to gg$ via t-channel e_8 exchange. The signal and background analysis performed at ILC and CLIC is given in the third section. In the last section we give an interpretation of obtained results and concluding remarks.

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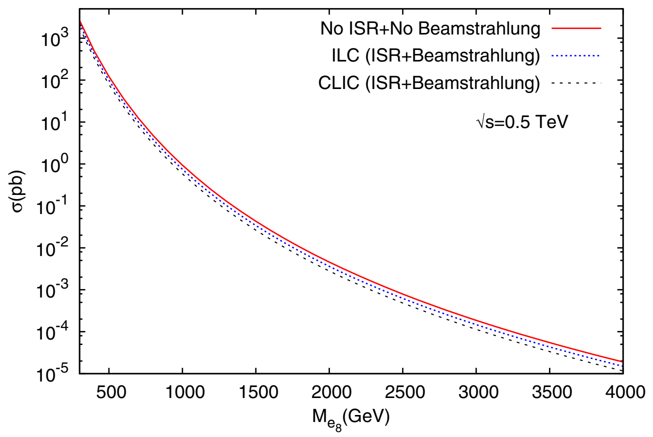

Fig. 1: (Colour on-line) Indirect production cross-sections for color octet electron at the ILC and CLIC1.

Table 1: Main parameters of ILC and CLIC. Here N is the number of particles in bunch. σ_x and σ_y are RMS beam sizes at Interaction Point (IP), σ_z is the RMS bunch length.

Collider Parameters	ILC	CLIC1	CLIC2
$E(\sqrt{s})$, TeV	0.5	0.5	3
$L(10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	2	2.3	5.9
$N\,(10^{10})$	2	0.68	0.372
σ_x (nm)	640	202	45
σ_y (nm)	5.7	2.3	1
σ_z (μm)	300	44	44

Interaction Lagrangian and indirect production cross-sections. – The interaction Lagrangian of leptogluons with the corresponding lepton and gluon is given by [9–11]

$$L = \frac{1}{2\Lambda}\sum_{l}\{\bar{l}_8 g_s G^{\alpha}_{\mu\nu}\sigma^{\mu\nu}(\eta_L l_L + \eta_R l_R) + \text{h.c.}\}, \qquad (1)$$

where $G^{\alpha}_{\mu\nu}$ is field strength tensor for gluon, index $\alpha = 1, 2, \ldots, 8$ denotes the color, g_s is gauge coupling, η_L and η_R are the chirality factors, l_L and l_R denote left and right spinor components of lepton, $\sigma^{\mu\nu}$ is the antisymmetric tensor and Λ is the compositeness scale, which is taken to be equal to M_{e_8}. The leptonic chiral invariance implies $\eta_L\eta_R = 0$. For numerical calculations we implement this Lagrangian into the CalcHEP program [12]. The analytic expression for the parton level differential cross-section for the process $e^-e^+ \to gg$ via t-channel e_8 exchange is given by

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(e^-e^+ \to gg) = -\frac{8}{\pi}\left(\frac{g_s}{\Lambda}\right)^4 \frac{\hat{t}^3(\hat{s}+\hat{t})}{\hat{s}^2(M_{e_8}^2-\hat{t})^2}, \qquad (2)$$

where $\hat{s}$ and $\hat{t}$ are Mandelsam variables and $\hat{\sigma}$ is partonic cross-section. The total cross-sections for the process at $\sqrt{s} = 0.5\,\text{TeV}$ are presented in fig. 1. Initial State Radiation (ISR) and Beamstrahlung effects at ILC and CLIC

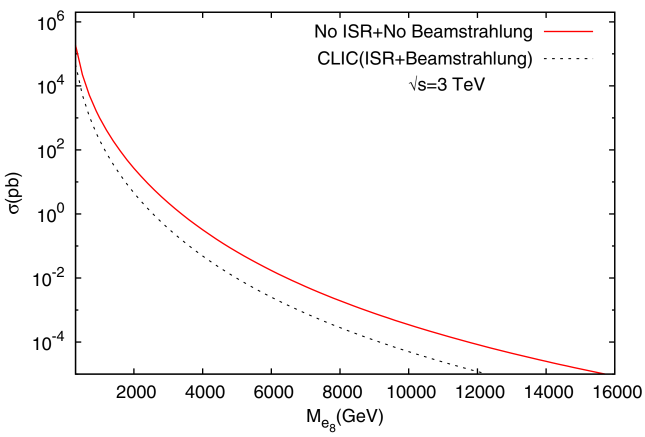

Fig. 2: (Colour on-line) Indirect production cross-sections for color octet electron at the CLIC2.

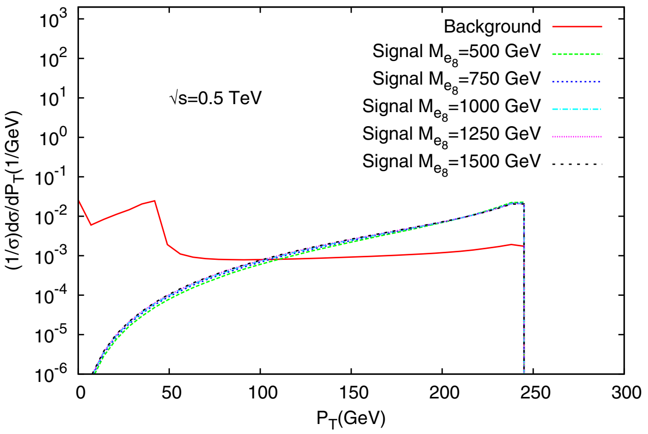

Fig. 3: (Colour on-line) Normalized transverse momentum distributions of final state jets for signal and background at the ILC.

are calculated with CalcHEP program using parameters given in table 1 [13–15].

In fig. 2 we present the results of similar calculations for the CLIC2 $\sqrt{s} = 3\,\text{TeV}$. It is seen that ISR and Beamstrahlung effects essentially reduce the cross-sections.

Figures 1 and 2 show that indirect manifestation of e_8 could be seen for e_8 mass values several times higher than those for direct pair production at corresponding center of mass energies, namely, 0.25 TeV at ILC/CLIC1 and 1.5 TeV at CLIC2.

Signal and background analysis. – Our signal process is $e^-e^+ \to gg$ and background processes are $e^-e^+ \to \gamma, Z \to jj$, where $j = u,\ \bar{u},\ d, \bar{d},\ c,\ \bar{c},\ s,\ \bar{s},\ b,\ \bar{b}$. In order to determine appropriate cuts we calculate transverse momentum (p_T), pseudorapidity (η) and invariant mass distributions for signal and background processes. Results for ILC are presented in figs. 3, 4 and 5, respectively (we plot normalized distributions which are more suitable for cut selections; σ stand for the total cross-sections of signal or background processes).

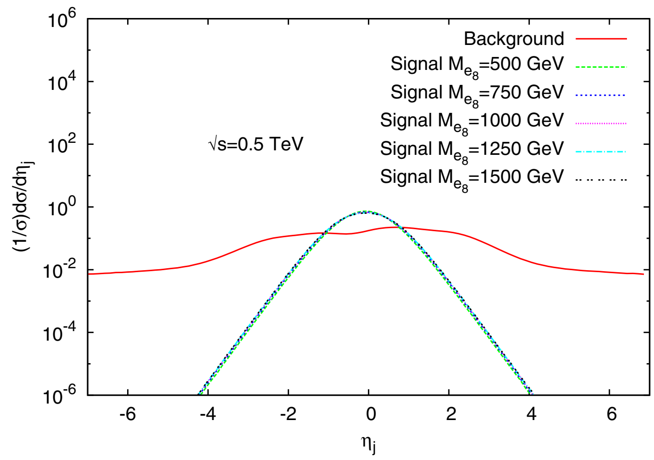

Fig. 4: (Colour on-line) Normalized pseudorapidity distributions of final state jets for signal and background at the ILC.

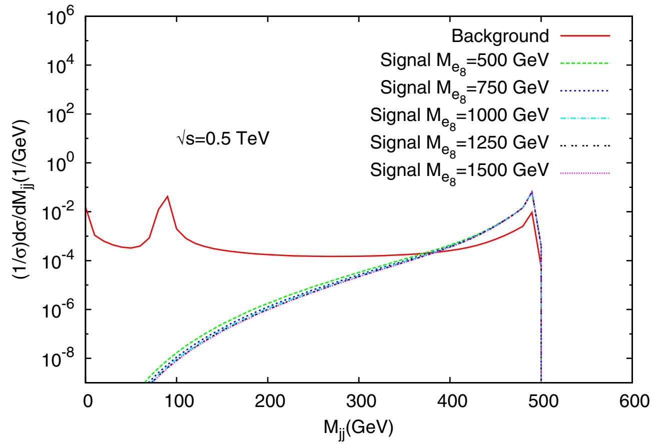

Fig. 5: (Colour on-line) Normalized invariant mass distributions of final state jets for signal and background at the ILC.

It is seen that selection cuts $p_T > 120\,\text{GeV}$, $|\eta| < 1$ and $375\,\text{GeV} < M_{inv}(jj) < 500\,\text{GeV}$ essentially suppress the background, whereas the signal remains almost unchanged. Let us mention that in fig. 5 one can see the so-called Z-radiative return; the scattering is especially favoured if one or more photons are emitted from the initial e^- or e^+, so that the energy is reduced to the mass of the Z boson.

As a result of similar analysis for CLIC1 and CLIC2 we will use the following sets of selection cuts: $p_T > 120\,\text{GeV}$, $|\eta| < 1$ and $350\,\text{GeV} < M_{inv}(jj) < 500\,\text{GeV}$ for CLIC1; $p_T > 350\,\text{GeV}$, $|\eta| < 1$ and $1000\,\text{GeV} < M_{inv}(jj) < 3000\,\text{GeV}$ for CLIC2.

In table 2, we present signal and background cross-sections for the ILC (CLIC1) after the above-mentioned cut sets. Corresponding values for CLIC2 are given in table 3.

For statistical significance, we use the following formula:

$$S = \frac{\sigma_s}{\sqrt{\sigma_s + \sigma_b}} \sqrt{L_{int}}, \qquad (3)$$

Table 2: Signal and background cross-sections after cuts for ILC and CLIC1. These cuts are $p_T > 120\,\text{GeV}$, $|\eta| < 1$ and $375\,\text{GeV} < M_{inv}(jj) < 500\,\text{GeV}$ for ILC and $p_T > 120\,\text{GeV}$, $|\eta| < 1$ and $350\,\text{GeV} < M_{inv}(jj) < 500\,\text{GeV}$ for CLIC1.

M_{e_8}, TeV	σ, pb	
	ILC	CLIC1
0.5	89.835	70.326
1	0.663	0.5091
1.5	0.030	0.0229
2	0.0032	0.0024
Background	1.757	1.763

Table 3: Signal and background cross-sections after cuts for CLIC2. These cuts are $p_T > 350\,\text{GeV}$, $|\eta| < 1$ and $1000\,\text{GeV} < M_{inv}(jj) > 3000\,\text{GeV}$.

M_{e_8}, TeV	σ, pb
2	4.0081
3	0.3078
4	0.0424
5	0.0084
6	0.00217
7	0.00067
8	0.00024
Background	0.0378

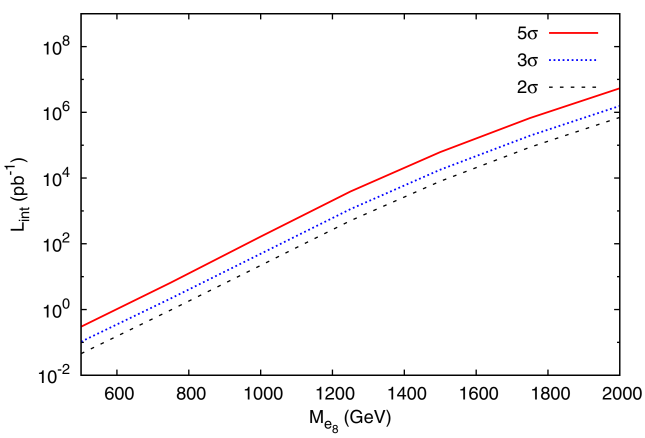

Fig. 6: (Colour on-line) The necessary integrated luminosity for the indirect observation of e_8 at the ILC.

where σ_s is signal cross-sections, σ_b is background cross-sections and L_{int} is integrated luminosity. In figs. 6, 7 and 8 the necessary integrated luminosities for 2σ exclusion, 3σ observation and 5σ (indirect) discovery of e_8 are plotted as a function of e_8 mass for ILC, CLIC1 and CLIC2, respectively. The reachable e_8 mass values for one and three year operation with nominal luminosities are given in table 4.

Up to now, we assumed the compositeness scale equal to the mass of color octet electron ($\Lambda = M_{e_8}$). In the general case this scale can be decoupled from the mass of new particles. For this reason below we consider limits for the compositeness scale as a function of the color octet

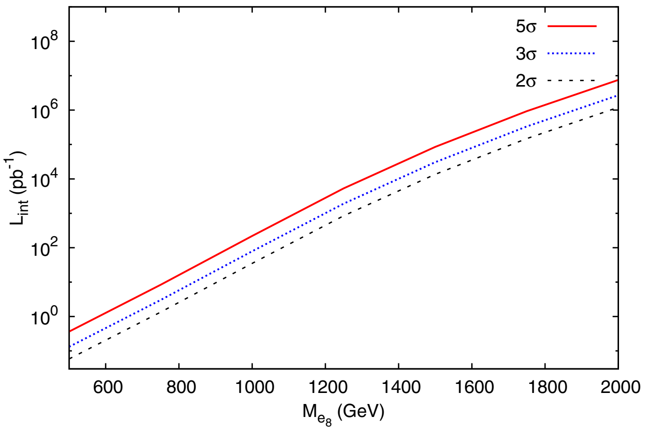

Fig. 7: (Colour on-line) The necessary integrated luminosity for the indirect observation of e_8 at the CLIC1.

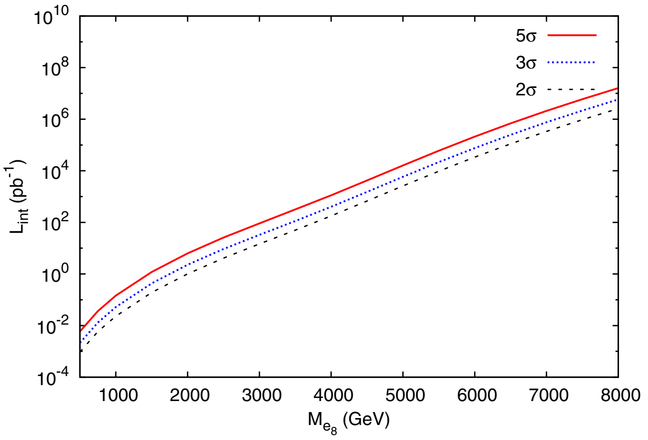

Fig. 8: (Colour on-line) The necessary integrated luminosity for the indirect observation of e_8 at the CLIC2.

Table 4: Reachable e_8 mass values for indirect discovery, observation and exclusion at the ILC, CLIC1 and CLIC2.

Colliders	years	5σ	3σ	2σ
ILC	1 year	1640 GeV	1750 GeV	1850 GeV
ILC	3 year	1760 GeV	1880 GeV	1980 GeV
CLIC1	1 year	1600 GeV	1710 GeV	1800 GeV
CLIC1	3 year	1720 GeV	1840 GeV	1920 GeV
CLIC2	1 year	6430 GeV	6880 GeV	7260 GeV
CLIC2	3 year	6930 GeV	7400 GeV	7810 GeV

electron mass. In this analysis we use $L_{int} = 200$, 230 and $590\,\text{fb}^{-1}$ for ILC, CLIC1 and CLIC2, respectively. These values correspond to one year operation with nominal luminosities. In figs. 9, 10 and 11 we plot reachable values of the compositeness scale as a function of M_{e_8} for ILC, CLIC1 and CLIC2, respectively.

Conclusion. – We show that, if $\Lambda = M_{e_8}$ (see table 4) ILC will give opportunity for indirect observation of

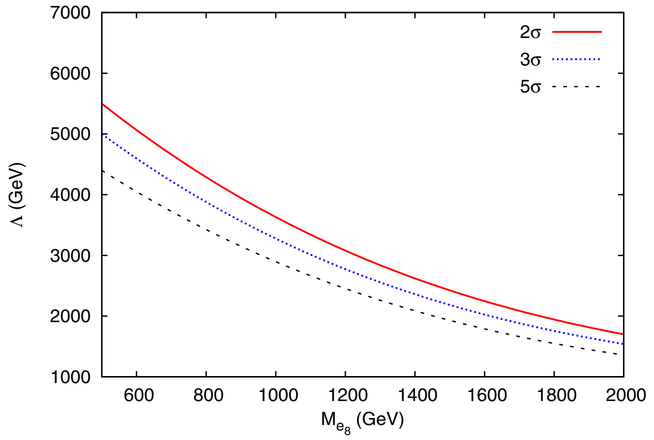

Fig. 9: (Colour on-line) Reachable values of the compositeness scale as a function of color octet electron mass for ILC with $\sqrt{s} = 0.5\,\text{TeV}$ and $L_{int} = 200\,\text{fb}^{-1}$.

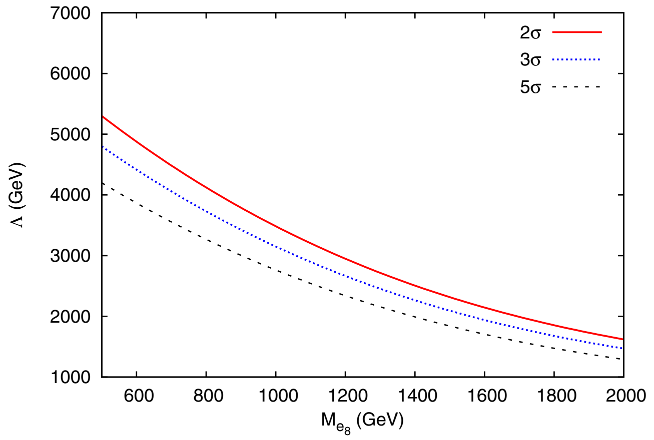

Fig. 10: (Colour on-line) Reachable values of the compositeness scale as a function of color octet electron mass for CLIC1 with $\sqrt{s} = 0.5\,\text{TeV}$ and $L_{int} = 230\,\text{fb}^{-1}$.

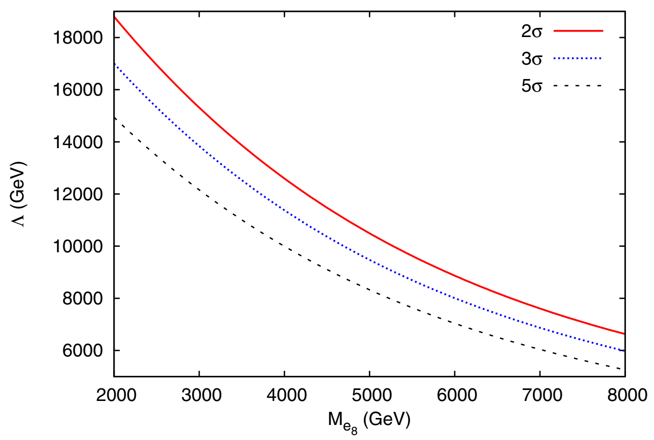

Fig. 11: (Colour on-line) Reachable values of the compositeness scale as a function of color octet electron mass for CLIC2 with $\sqrt{s} = 3\,\text{TeV}$ and $L_{int} = 590\,\text{fb}^{-1}$.

octet electron upto $M_{e_8} = 1750$ (1880) GeV during one (three) operation with nominal luminosity. Corresponding values for CLIC1 are about 40 GeV lower. Therefore, both ILC and CLIC1 will give opportunity to pass essentially the Tevatron capacity for color octet electron (e_8) search. CLIC2 will be sensitive to 4 times higher mass values, namely, e_8 masses upto 6880 (7400) GeV could be observed during one (three) year operation with nominal luminosity. These values essentially exceed the capacity of the LHC to observe color octet electron (e_8) via pair production. One can wonder about the indirect manifestation of e_8 at the LHC via crossed process $gg \to e^+e^-$. For $M_{e_8} = \Lambda = 6$ TeV this process has a cross-section 1.97×10^{-5} pb at the LHC with $\sqrt{s} = 14$ TeV, which should be compared with $\sigma = 2.52 \times 10^{-3}$ pb for $e^+e^- \to gg$ at the CLIC with $\sqrt{s} = 3$ TeV. The advantage of CLIC is obvious.

If the compositeness scale and color octet electron mass are decoupled (see figs. 9, 10 and 11), observable values of Λ at ILC and CLIC1 exceeds M_{e_8} for $M_{e_8} \lesssim 1700$ GeV (at $M_{e_8} = 500$ GeV observable Λ is 5000 GeV). At the CLIC2 Λ exceeds mass for $M_{e_8} \lesssim 7000$ GeV (at $M_{e_8} = 2000$ GeV observable Λ is 17000 GeV).

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