Production of Exotic Particles in Electron-Positron Collisions

Werner K. Sauter

Werner.sauter@ufpel.edu.br

Grupo de Altas e Médias Energias - Departamento de Física - Instituto de Física e Matemática, Universidade Federal de Pelotas, Campus Universitário, Rio Grande do Sul, Pelotas, Brasil

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Abstract

In this work, the results for cross sections of central exclusive exotic particles production in future linear electron-positron colliders are presented. These results show that the central production of charginos, dilatons, radions, axions and technipions can be measurable for the center-of-mass energies for these colliders. The results presented here, when compared with the production in hadronic colliders, have a smaller cross section, but with the advantage that the electron-positron collision does not have remnants coming from hadronic dissociation.

Keywords
Beyond SM particles · Peripheral collisions

1 Introduction

With the advent of the next generation linear colliders, the possibility of production of particles not predicted in the Standard Model (SM) in a new kinematic regime is open. One of the advantages of using electrons and positrons as projectiles is the absence of a known substructure, in contrast to complex structure of hadrons. Due to this simplification, it is possible to study the direct production of states beyond the Standard Model (BSM). The idea is to use the formalism of peripheral collisions to calculate total cross sections in electron-positron elastic collisions, $e^-e^+ \rightarrow e^-Xe^+$, where $X$ is a beyond Standard Model particle (see Fig. 1). In the present article, different possibilities for these exotic states are considered: charginos, radion, dilaton, technipion and axion. The BSM physics opportunities in future linear electron colliders are described in [1] for CLIC (Compact Linear Collider) and in [2] for ILC (International Linear Collider).

The central production of resonances is a realistic process to search and study the exotic particles states. In this class of process, the projectiles remain intact after the interaction and the angular distribution of produced particles (or their decay remnants) occupy a small region in the detector. In previous works, we already obtained results for magnetic monopoles [3], radion [4] and dilaton [5] production in hadron-hadron collisions. An advantage of this process is the measurement of the projectiles after the interaction, enabling the measurement of the energy deposited in the detector of the produced central state or by its decay products. Another advantage is its very clean experimental signature on the detector: two leptons separated by a rapidity interval (angle) of a central activity on the detector.

2 Theory

We use the simple model in equivalent photon approximation [6] to calculate the total cross sections, valid in different cases: electron-electron, proton-proton and ion-ion collisions. The expression for cross section of collision of two particles $A$ and $B$ reads

$$\sigma_{\text{tot}} = \int_{M_X^2/s}^1 dx_1 f_A^f(x_1) \times \int_{M_X^2/s}^1 dx_2 f_B^f(x_2) \sigma_{\gamma\gamma X}(\hat{s})$$

where $M_X$ is the mass of the central produced system, $s$ is the center-of-mass energy of the projectiles, $x_i$ is the fraction of the energy of the photon $i$, $\hat{s} = x_1 x_2 s$, $f_A^f(x)$ is the photon energy spectrum (or photon flux) produced by a charged particle $A$ or $B$ and $\sigma_{\gamma\gamma X}(\hat{s})$ is the cross section of production of a $X$ state by a fusion of a pair of photons.
For the electron collisions, we will use the photon energy spectrum [7]

\[
f_e^2(x) = \frac{\alpha_{\text{em}}}{2\pi} \left\{ \frac{1 - x}{x} \ln \left( \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} \right) + 2m_e^2 x \left[ \frac{1}{Q_{\text{max}}^2} - \frac{1}{Q_{\text{min}}^2} \right] \right\}
\]

where \(\alpha_{\text{em}}\) is the electromagnetic coupling constant and the photon virtualities are given by

\[
Q_{\text{max}}^2 = M_X^2, \quad Q_{\text{min}}^2 = \frac{m_e^2}{1 - x}
\]

and \(m_e\) is the electron mass.

A comparison with the luminosities of the electron, proton and nuclei is displayed in Fig. 2. In this figure, we plot the electron photon flux from the above expression, Eq. (2) with \(M_X = 1.0\) TeV; in the proton case, we plot the expressions from Drees et al. [8], from Nystrand [6] and the result of Wéiszacker and Williams for a point charge photon flux (see the expressions in [6]). Note the quite different behavior depending on the projectile: ions (lead, in the case) produce numerous photons at small \(x\) values, whereas, in large \(x\) values, the larger photon flux comes from electron projectiles, favoring the production of states with great masses.

The last term of the total cross section of production of central state is the cross section of the process \(\gamma\gamma \rightarrow X\), given by

\[
\sigma_{\gamma\gamma X} = 8\pi(2J + 1) \frac{1}{(W_{\gamma\gamma}^2 - M_X^2)^2 + M_X^2 \Gamma_{\gamma\gamma X}^2}
\]

\[
\sigma_{\gamma\gamma X} = 4\pi^2(2J + 1) \frac{\Gamma_{\gamma\gamma X}^2}{M_X^2} \delta(W_{\gamma\gamma} - M_X).
\]

where \(J\) is the spin of the produced state, \(\Gamma_{\gamma\gamma X}\) is the partial decay width of \(X\) in two photons, \(\Gamma_{\gamma\gamma X}^2\) is the total decay width, and \(W_{\gamma\gamma}^2\) is the two photons center-of-mass energy. In the case of a narrow resonance (\(\Gamma_{\gamma\gamma X}^2 \ll M_X^2\)) the above result, using a Dirac delta function, reads

\[
\sigma_{\gamma\gamma X} = 4\pi^2(2J + 1) \frac{\Gamma_{\gamma\gamma X}^2}{M_X^2} \delta(W_{\gamma\gamma} - M_X).
\]

After a straightforward calculation, the following expression (using properties of Dirac delta function) from Eq. (1) is obtained,

\[
\sigma_{\gamma\gamma X} = \frac{8\pi^2(2J + 1)}{M_X^4} \int_{M_X^2/f_x}^1 \frac{dx_1}{x_1^2} f_x(x_1) \Gamma_{\gamma\gamma X} \Gamma_{\gamma\gamma X} f_x \left( \frac{M_X^2}{x_1^2} \right)
\]

This is the final expression for the calculation of the cross section for \(e^- e^+ \rightarrow e^- X e^+\). In the following, we consider some particular cases of central produced particles to obtain the decay width in two photons, the remaining part of the cross section, Eq. (5).

### 3 Results

In this section, we will calculate the particle production considering photon-photon interactions for electron-positron collisions at CLIC/ILC energies. In particular, we will extend the
results for particle production in hadron collisions. All the cross sections are obtained using the planned energies for electron-positron colliders: $\sqrt{s} = 0.5 \text{TeV}$ for ILC; $\sqrt{s} = 380.0 \text{GeV}$, 1.5TeV and 3.0TeV for CLIC. The Future Circular Lepton Collider (FCC-ee) has a planned center of mass energy of $\sqrt{s} = 365 \text{GeV}$ and the results will be similar that ILC ones. The results are obtained using the two different photon luminosities. In the next subsections, we consider the particular cases of central produced systems.

### 3.1 Dilepton Production

Before considering more complex exotic states, let’s consider the production of dileptons. The dilepton production is one of the “standard candle” process of central production. This process ($\gamma\gamma \rightarrow l^+l^-$) has a well-known cross section, given by the Breit-Wheeler formula (see [9] and [10]),

$$\sigma_{\gamma\gamma \rightarrow l^+l^-}(W_{\gamma\gamma}) = \frac{4\pi\alpha_\text{em}^2}{W_{\gamma\gamma}^2} \left\{ 2 \ln \left[ 1 + \beta \right] - \beta \left[ 1 + \frac{1}{\sqrt{\gamma}} \right] \right\}.$$

where $m_l$ is the lepton mass, $\gamma = W_{\gamma\gamma}/2m_l$, $\beta^2 = 1 - 1/\gamma^2$.

The results for the energies planned in ILC/CLIC are shown in Fig. 3. In the result obtained, we consider a mass range with a high upper limit to consider, in addition to light particles, other particles such as charginos [11], supersymmetric leptonic partner of the SM of electroweak bosons. The present results are two orders of magnitude smaller in comparison with the results of [11], where it was considered hadron (proton and lead) collisions at LHC energies.

### 3.2 Radion

Several open problems in physics, such as the hierarchy problem (in few words, the huge discrepancy between the masses and couplings of the fundamental forces), have a possible solution in the existence of extra dimensions. There are several extra dimension scenarios in the literature. In recent years, the scenario proposed by Randall and Sundrum (RS) [12], in which there are two (3+1)-dimensional branes separated in a 5th dimension, has attracted a great deal of attention. This model predicts a Kaluza-Klein tower of gravitons and a graviscalar, called radion, which stabilize the size of the extra dimension without fine tuning of parameters and is the lowest gravitational excitation in this scenario. The mass of radion is expected to be $\approx 1 \text{TeV}$ which implies that the detection of the radion will be the first signature of the RS model.

In this paper we extend the previous studies for exclusive processes [4] (where only the radion is produced) for electron colliders. The signal would be a clear one with a radion tagged in the central region of the detector accompanied by two electrons. In contrast to the inclusive production (where several particles are produced), which is characterized by large QCD activity and backgrounds which complicate the identification of a new physics signal, the exclusive production will be characterized by a clean topology mediated by colorless exchanges. The $\gamma\gamma \rightarrow \Phi$ cross section can be expressed as follows

$$\sigma_{\gamma\gamma \rightarrow \Phi} = \frac{8\pi\alpha_\text{em}^2}{m_\Phi^3} \Gamma(\Phi \rightarrow \gamma\gamma).$$

The partial decay width of radion into two photons was calculated in [13, 14] and is given by:

$$\Gamma(\Phi \rightarrow \gamma\gamma) = \frac{\alpha_\text{em}^2 m_\Phi^3}{256 \pi^3 \Lambda_\Phi^2} \left\{ \frac{22}{6} - \left[ 2 + 3x_\gamma + 3x_m(2-x_m)T(x_\gamma) \right] \right. + \left. \frac{8}{3} x_\gamma \left[ 1 + (1-x_\gamma)T(x_\gamma) \right] \right\},$$

with $m_\Phi$ is the radion mass, $\Lambda_\Phi = \langle \Phi \rangle \approx \mathcal{O}(v)$, where $v$ the vacuum expectation value (VEV) of the Higgs field. $\Lambda_\Phi$ determines the strength of the coupling of the radion to the Standard Model particles. $x_i = 4m_i^2/m_\Phi^2$ (with $i = W, t$ denoting the $W$ boson and the top quark) and the auxiliary function $T(z)$ being given by

$$T(z) = \begin{cases} \sin^{-1}\left( \frac{1}{\sqrt{1-z}} \right)^2, & z \geq 1 \\ \frac{1}{4} \left[ \log \frac{1+\sqrt{1-z}}{1-\sqrt{1-z}} - i\pi \right]^2, & z < 1 \end{cases}$$

![Fig. 3](image-url) Cross section for the production of a pair of leptons: $e^+e^- \rightarrow e^+e^-$ for different energies ($\sqrt{s} = 0.5 \text{TeV}, \sqrt{s} = 1.5 \text{TeV}, \sqrt{s} = 3.0 \text{TeV}$) as a function of the lepton mass.
The result for cross section of production of radion as function of mass is displayed in Fig. 4.

### 3.3 Dilaton

The prediction of the existence of new scalar particles is a characteristic of several candidate theories beyond the SM (see, e.g., Ref. [15]). One of these particles is the dilaton, denoted as $\chi$, which is predicted to appear as a pseudo-Nambu-Goldstone boson in spontaneous breaking of scale symmetry [16]. In the particular scenario in which electroweak symmetry is broken via strongly coupled conformal dynamics, a neutral dilaton is expected with a mass below the conformal symmetry breaking scale $\Lambda_{cs}$ and couplings to standard model particles similar to those of the SM Higgs boson. The searching of the dilaton in inclusive proton-proton collisions at LHC energies motivated a lot of work, with particular emphasis in the discrimination of the dilaton from the SM Higgs signals [17–23]. In [5] we extend the previous study for exclusive processes.

The partial decay width of the dilaton into two photons, $\Gamma_{\chi \rightarrow \gamma\gamma}$, was calculated in [19] and is given by:

$$\Gamma_{\chi \rightarrow \gamma\gamma}(M_\chi) = C_\gamma \frac{\nu^2}{\Lambda_{cs}^2} \frac{G_F \alpha_{\text{em}} M_\chi^3}{128 \sqrt{2} \pi^3} |F_b(\tau_b) + \sum_f N_c Q_f^2 F_f(\tau_f)|^2$$

where $M_\chi$ is the dilaton mass, $\nu = 246 \text{ GeV}$ is the scale of electroweak symmetry breaking, $G_F$ is the Fermi constant, $N_c$ is the number of colors, $Q_f$ is the fermion charge and $\tau_i = 4m_i^2/M_\chi^2$. The boson and fermion loop functions are, respectively,

$$F_b(\tau) = 2 + 3\tau + 3\tau(2 - \tau)T(\tau)$$

$$F_f(\tau) = -2\tau[1 + (1 - \tau)T(\tau)]$$

Moreover, the coefficient $C_\gamma$ is given by [19]

$$C_\gamma = \frac{|-b_{EM} + \sum_{i=\text{fermions}} N_{c,i} Q_i^2 F_i(\tau_i)|^2}{|\sum_{i=\text{bosons}} N_{c,i} Q_i^2 F_i(\tau_i)|^2}$$

where $b_{EM} = -11/3$, the sum runs over fermions ($f$) and bosons ($b$), $N_{c,i}$ is the color multiplicity number ($N_{c,i} = 1$ for bosons and leptons and $N_{c,i} = 3$ for quarks) and $Q$ is the electric charge in units of $e$.

The result for cross section of production of dilaton as function of mass is displayed in Fig. 5.

### 3.4 Axion

The QCD axion was proposed to solve the strong-CP problem in QCD and is a candidate to constitute the cosmological dark matter. The axion has a rich phenomenology and for an introduction for it see [24–27]. In a few words, the strong-CP problem is the extremely small neutron electric dipole model, that indicates the fine-tuned cancellation of CP violation in QCD. Among other solutions, the Peccei-Quinn one dynamically cancels CP violation in QCD but introduces the axion, a pseudoscalar particle.
The central production of axions or ALPs (axion like particles) in hadronic collisions by photon or gluon fusion in central exclusive processes is analyzed in [28, 29]. Recently, [30] analyzed the virtual production of axions in CLIC. Here the results are obtained using the following expression for decay width \[24, 31, 32\],
\[ \frac{1}{\Lambda_{ay}^2} = 10^{-2} \text{GeV}^{-1}, 10^{-4} \text{GeV}^{-1} \]
are related with the axion coupling with photons. The result for cross section of production of axion as function of mass is displayed in Fig. 6.

### 3.5 Technipions

Light exotic states are predicted by high-scale strongly coupled dynamics, known as technicolor. In [33] the theory and results for the central exclusive production of technicolor particles, in particular, a neutral technipion, in hadron collisions in LHC are presented. One of the results of [33] is the dominance of the diphoton decay of technipion for light masses. We use this fact to obtain the cross section in electron-electron collisions. Using the previous formalism, the two-photon technipion decay width reads
\[ \Gamma(\tilde{\pi}_0 \rightarrow \gamma\gamma) = \frac{1}{4\pi} \frac{1}{\Lambda_{ay}^2} m_{\tilde{\pi}_0}^3 \]

where \(1 \text{GeV} < m_{\tilde{\pi}_0} < 100 \text{ GeV}\) and \(1/\Lambda_{ay}^2 = 10^{-2} \text{GeV}^{-1}, 10^{-4} \text{GeV}^{-1}\) are related with the axion coupling with photons. The result for cross section of production of axion as function of mass is displayed in Fig. 6.

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\[ \Gamma(\tilde{\pi}_0 \rightarrow \gamma\gamma) = \frac{m_{\tilde{\pi}_0}^3}{64\pi} \left| \frac{4\alpha_{em} g_{TC}}{\pi} \frac{M_{\tilde{Q}}}{m_{\tilde{\pi}_0}^2} \arcsin^2 \left( \frac{m_{\tilde{\pi}_0}}{2M_{\tilde{Q}}} \right) \right|^2 \]

where \(m_{\tilde{\pi}_0}\) is the technipion mass, \(g_{TC} = 10\) is a effective coupling and \(M_{\tilde{Q}}\) is the mass of techniquark.

The result for cross section of production of technipions as function of mass is displayed in Fig. 7.

### 4 Conclusions

In this work, estimates are presented for the cross section of BSM particles production in electron-positron linear colliders, expected to start into operation in the coming decade.
These colliders offer a unique opportunity to study these exotic states in a clear way.

This process is unfavorable in relation to the energy of center of mass and the photon luminosity of the hadron colliders, where it is possible to emit a large number of photons, available for interaction and later creation of states. But, as mentioned above, in large values of $x$, the electron luminosity surpass the hadron luminosity. In electron collisions, the final state is cleaner and also, due to the absence of (known) electron structure, we do not have the possibility of multiple final states in the detector, generated by the dissociation of hadronic projectiles.

The results for the cross section presented depend, in general, strongly on the mass of the produced particle, resulting, as expected, in small cross sections for large masses. It is also noted that the half-life of the produced states can be very short, and it is not possible to measure the state produced in the detector so only the products of decay can be measured. However, as we are considering different models, there are other free parameters that make the cross section measurable.

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Declarations

Conflict of Interest Not applicable.

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