Slepton pair production in $e^+e^-$ collision in supersymmetric left-right model

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Abstract

The pair production of sleptons in electron-positron collisions is investigated in a supersymmetric left-right model. The cross section is found considerably larger than in the minimal supersymmetric version of the Standard Model (MSSM) because of more contributing graphs. A novel process is a doubly charged higgsino exchange in u-channel, which makes the angular distribution of the final state particles and the final state asymmetries to differ from those of the MSSM. It also allows for the flavour non-diagonal final states $\tilde{e}\tilde{\mu}$, $\tilde{e}\tilde{\tau}$ and $\tilde{\mu}\tilde{\tau}$, forbidden in the MSSM. These processes also give indirect information about neutrino mixings since they depend on the same couplings as the Majorana mass terms of the right-handed neutrinos.
1. **Introduction.** By now the virtues of the supersymmetric (susy) models are well known, and in spite of the fact that no supersymmetric particles have been detected so far, there are hints that supersymmetry may be a part of the physical reality, see [1]. The rich phenomenology of supersymmetry has been widely studied in literature, most extensively in the framework of the minimal supersymmetric standard model (MSSM).

We have recently investigated the phenomenology of a supersymmetric model based on the left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge theory [2]. The left-right symmetric model (LR-model) is motivated in particular by the physics of neutrinos: the solar [3] and atmospheric [4] neutrino problems as well as the existence of a hot dark matter component [5] suggest that neutrinos should be massive. In the case of massive neutrinos, the LR-model is most natural. It can explain the small but finite neutrino masses by incorporating the see-saw mechanism [6]. However, exactly as is the case with the Standard Model, the LR-model is suffering from an unnatural Higgs sector, which can be made natural by supersymmetrizing the theory. Such a model was constructed in [2], [7].

In [2] the production of a doubly charged higgsino, $\tilde{\Delta}^{-+}$, was studied as a possible experimental signal of the susy LR-model in different operation modes ($e^+e^-$, $e^-e^-$, $e^-\gamma$ and $\gamma\gamma$) of the next linear collider. This particle occurs in the susy LR-model as a member of the Higgs triplet superfield. The neutral triplet scalar in this superfield is responsible for the breaking of the left-right symmetry, and it also plays a crucial role in the see-saw mechanism due to its lepton number violating Yukawa couplings with neutrinos. The higgsino production processes thus probe the most central ingredients of the LR-model.

In the present work we will study the production of a slepton pair in the susy LR-model with LEP200 and the next linear collider in mind, i.e. the process
\[ e^+ e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^-, \quad (1) \]

where \( \tilde{\ell}, \tilde{\ell}' = \tilde{e}, \tilde{\mu}, \tilde{\tau} \). The diagrams contributing are shown in Fig. 1. In s-channel (Fig. 1a), there is in addition to the MSSM diagrams also the diagram involving the heavy neutral gauge boson \( Z_2 \). From the Tevatron experiments, the lower limit of the new neutral gauge boson mass is \( m_{Z_2} \geq 310 \text{ GeV} \), and therefore we will assume in the following that the \( Z_2 \) exchange contribution can be neglected. Instead of the four neutralinos in the MSSM model, there are in the susy LR-model all together nine neutralinos that contribute to the \( t \)-channel diagram of Fig. 1b.

The reaction (1) partly tests the same parts of the theory as the higgsino production since it is mediated among others by the doubly charged higgsino (Fig. 1c). It is especially interesting that one has a chance to study the flavour changing couplings of the triplet higgsino, which may exist if neutrinos are supposed to mix and to oscillate. That is to say, in the susy LR-model the final state sleptons of (1) need not be of the same flavour, in contrast with the situation in the MSSM.

Experimentally, the slepton pair production is possibly one of the first susy processes to be seen. There are many reasons to that. Sleptons are supposed to be relatively light among the superpartners of the standard model particles. Also the decay pattern of sleptons is simple when compared with many other supersymmetric particles: in the case of a light slepton, one detects a lepton and a large amount of missing energy.

2. The supersymmetric left-right model. The particle content of the susy LR-model differs from the particle content of the MSSM in gauge sector, in Higgs sector, and in having also a weak isosinglet neutrino superfield which the right-handed neutrino belongs to. The Higgs sector of the model consists of two bidoublet superfields transforming under the \( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \) as \( (2, 2, 0) \),
\[ \hat{\phi}_{u,d} = \begin{pmatrix} \hat{\phi}_1^0 & \hat{\phi}_1^+ \\ \hat{\phi}_2^- & \hat{\phi}_2^0 \end{pmatrix}_{u,d}, \tag{2} \]

and two right-handed triplet superfields

\[ \hat{\Delta} = \begin{pmatrix} \frac{1}{\sqrt{2}} \hat{\Delta}^+ & \hat{\Delta}^{++} \\ \hat{\Delta}^0 & -\frac{1}{\sqrt{2}} \hat{\Delta}^+ \end{pmatrix}; \quad \hat{\delta} = \begin{pmatrix} \frac{1}{\sqrt{2}} \hat{\delta}^- & \hat{\delta}^0 \\ \hat{\delta}^{--} & -\frac{1}{\sqrt{2}} \hat{\delta}^- \end{pmatrix}, \tag{3} \]

which transform as \((1, 3, 2)\) and \((1, 3, -2)\), respectively. The hatted fields denote the chiral superfields of the corresponding field in the ordinary LR-model. Two bidoublets are needed to have a Kobayashi-Maskawa matrix not equal an identity, and the second triplet has to be added to avoid chiral anomalies, which would otherwise appear in the higgsino sector \([7]\). In the gauge sector one has an extra neutral \(\hat{Z}_R\) and charged \(\hat{W}_R^\pm\) gauge superfields corresponding to the \(SU(2)_R\) symmetry.

The superpotential of the supersymmetric left-right model is given by \([2, 7]\)

\[ W = h_{u,ij}^{Q} \hat{Q}_{L,i} \hat{\phi}_u \hat{Q}_{R,j} + h_{d,ij}^{Q} \hat{Q}_{L,i} \hat{\phi}_d \hat{Q}_{R,j} + h_{u,ij}^{L} \hat{L}_{L,i} \hat{\phi}_u \hat{L}_{R,j} + h_{d,ij}^{L} \hat{L}_{L,i} \hat{\phi}_d \hat{L}_{R,j} + h_{\Delta,ij} \hat{\Delta}_{R,i} \hat{\delta}_{L,j} \]

\[ + \mu_1 \text{Tr}(\tau_2 \hat{\phi}_d^{T} \tau_2 \hat{\phi}_d) + \mu_2 \text{Tr}(\hat{\Delta} \hat{\delta}), \tag{4} \]

where \(\hat{Q}_{L,i(R,i)}\) denote the left (right) handed quark superfields of generation \(i\) and correspondingly for leptons \(\hat{L}_{L,i(R,i)}\). Let us note that we have not included a left-handed triplet scalar superfield in our theory as it is unnecessary, unless one wants the superpotential to be manifestly left-right symmetric.

The Yukawa type interaction terms involving sleptons and higgsinos and derived from \([4]\) are given by
\[ \mathcal{L}_{\tilde{\nu}, \tilde{\chi}} = 2h_{\Delta,ij} \tilde{l}_{R,i} \tilde{\Delta}^{++} l_{R,j} + \sqrt{2} h_{\Delta,ij} \tilde{l}_{R,i} \tilde{\Delta}^{+} \nu_{R,j} \]

\[- \tilde{l}_{L,i} (h_{u,ij} \tilde{\phi}^0_{2u} + h_{d,ij} \tilde{\phi}^0_{2d}) l_{R,j} - \tilde{l}_{L,i} (h_{u,ij} \tilde{\phi}^0_{2u} + h_{d,ij} \tilde{\phi}^0_{2d}) \tilde{l}_{R,j} \]

\[- \tilde{l}_{R,i} (h_{u,ij} \tilde{\phi}^0_{1u} + h_{d,ij} \tilde{\phi}^0_{1d}) \tilde{\nu}_{L,j} - \tilde{l}_{R,i} (h_{u,ij} \tilde{\phi}^0_{1u} + h_{d,ij} \tilde{\phi}^0_{1d}) \nu_{R,j}. \] (5)

The interaction terms involving sleptons and gauginos are in turn given by

\[ \mathcal{L}_{\tilde{\nu}, \tilde{\chi}} = i g_L \left( - \frac{1}{\sqrt{2}} \tilde{l}_{L} \lambda^0_L \tilde{l}_{L}^* + \nu_L \lambda^+_L \tilde{\nu}_{L}^* + l_{L}^* \lambda^0_L \nu_{L}^* + \nu_L \lambda^+_L \tilde{\nu}_{L}^* \right) \]

\[ + i g_R \left( \frac{1}{\sqrt{2}} \tilde{l}_{R}^* \lambda^0_R \tilde{l}_{R}^* + \nu_R \lambda^+ R \tilde{\nu}_{R}^* + l_{R}^* \lambda^0_R \nu_{R}^* - \nu_R \lambda^+_R \tilde{\nu}_{R}^* \right) \]

\[ + \frac{i g_{B-L}}{2} \left( - \nu_L \lambda^0_{B-L} \tilde{\nu}_{L}^* - l_{B-L} \lambda^0_{B-L} \tilde{l}_{L}^* + l_{R}^* \lambda^0_{B-L} \tilde{l}_{R}^* + \nu_R \lambda^0_{B-L} \tilde{\nu}_{R}^* \right) + h.c. \] (6)

where \( \lambda^+_{L(R)} \) and \( \lambda^0_{L(R)} \) are the \( SU(2)_L \) gauginos and \( \lambda^0_{B-L} \) is the \( U(1)_{B-L} \) gaugino.

In the gaugino part of the Lagrangian there are no flavour changing interactions while in (5) the Yukawa coupling constants, the \( h \)'s, need not be diagonal.

The neutral gauginos and higgsinos mix with the mixing matrix \( N \),

\[ \tilde{\chi}^0_{\alpha} = \sum_{\beta=\text{gauginos, higgsinos}} N_{\alpha\beta} \psi^0_{\beta}. \] (7)

The \( \tilde{\chi}^0_{\alpha} \)'s form nine physical Majorana particles. Similarly the charged gauginos and higgsinos mix with the two mixing matrices \( C^\pm_{\alpha\beta} \),

\[ \tilde{\chi}^\pm_{\alpha} = \sum_{\beta=\text{gauginos, higgsinos}} C^\pm_{\alpha\beta} \psi^\pm_{\beta}. \] (8)

to form five physical Dirac particles. In the four component notation, the mixing can be written in the Lagrangian as follows.
\[ \mathcal{L}_{\tilde{\ell} \tilde{\chi}^0} = \frac{1}{2} g_L f^{L}_{\ell \alpha} \tilde{\ell} (1 + \gamma_5) \tilde{\chi}^0_\alpha (\cos \theta \tilde{\ell}_1 - \sin \theta \tilde{\ell}_2) - \frac{1}{2} g_R f^{R}_{\ell \alpha} \tilde{\ell} (1 - \gamma_5) \tilde{\chi}^0_\alpha (\sin \theta \tilde{\ell}_1 + \cos \theta \tilde{\ell}_2) + \text{h.c.,} \] (9)

where the \( \tilde{\ell}_{1,2} \) are the mass eigenstates of sleptons with the assumption that \( \theta \) is the mixing angle of the left- and right-s sleptons. In the following we will assume that \( \theta \ll 1 \) and identify \( \tilde{\ell}_1 \) with the left-slepton \( \tilde{l}_L \) and \( \tilde{\ell}_2 \) with the right-slepton \( \tilde{l}_R \).

Furthermore, we will assume that the two states are degenerate in mass, \( m_{\tilde{l}_L} = m_{\tilde{l}_R} \).

They differ in the opposite chiral structure of their interactions, and they can thus be distinguished in experiment for example by using polarized beams. The mixing factors \( f^{L,R}_{\ell \alpha} \) appearing in (9) are given by

\[ f^{L}_{\ell \alpha} = N_{\alpha 1} + \frac{g_{B-L}}{g_L} N_{\alpha 3}, \]
\[ f^{R}_{\ell \alpha} = N^{*}_{\alpha 2} + \frac{g_{B-L}}{g_R} N^{*}_{\alpha 3}. \] (10)

We have here neglected the contribution from the doublet higgsinos as their couplings are proportional to the respective Yukawa coupling constants and are therefore small.

The experimental signals of the process (1) depend on the decay products of the slepton. These have been studied in the case of the supersymmetric left-right model in [2]. Light sleptons decay to leptons and neutralinos: \( \tilde{l}_{L,R} \rightarrow l \tilde{\chi}^0_i \). If the left-sleptons \( \tilde{l}_L \) are heavier than one or more of the charginos, then also the decays \( \tilde{l}_L \rightarrow \nu \tilde{\chi}^- \) might have a large rate. The right-sleptons \( \tilde{l}_R \) will also decay, if they are heavy enough, to the doubly charged higgsino: \( \tilde{l}_R \rightarrow l^+ \tilde{\Delta}^{--} \). The other decay modes are kinematically suppressed. If the lightest supersymmetric particle is one of the neutralinos, the final state will consist of charged leptons and some missing energy.
Let us now go on to discuss how does the reaction (11) probe the various parameters of the superpotential (14). The Yukawa couplings $h_{L_{u,ij}}^L$ and $h_{L_{d,ij}}^L$ of the bidoublet Higgs fields are known to be small. Therefore this contribution is negligible, and consequently the dependence of the cross section on the bidoublet mass parameter $\mu_1$ is almost nonexistent. There is no amplitude involving the coupling $\tilde{\Delta}^0\tilde{\ell}e$, since that would violate the lepton number. Thus there is no dependence on the $\mu_2$-parameter either in neutralino changing graph. Only the gaugino part of the neutralinos contribute to the selectron pair production.

On the other hand, amplitudes with the $\tilde{\Delta}^{++}\tilde{\ell}e$ vertex do exist. This is important, since this makes it feasible to study by the slepton pair production the intergenerational coupling of the triplet Higgs to leptons. The only diagram, where the higgsino dependence is large, is the graph including the $\tilde{\Delta}^{\pm\pm}$ (Fig. 1c). Since this is a u-channel process, it is possible to separate its contribution to the reaction $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ from that of the t-channel neutralino diagrams by investigating angular distributions of the final state particles. The angular distribution will differ from that in the MSSM offering a definitive signal of the left-right symmetric susy theory. This will show up, for example, in the polarization asymmetry of the final state particles.

Even more definite signals of the susy LR-model would be the final states which break the separate lepton number conservation, i.e. $\tilde{e}\tilde{\mu}$, $\tilde{e}\tilde{\tau}$ and $\tilde{\mu}\tilde{\tau}$. Such final states are forbidden in the MSSM. In the susy LR-model they occur in reactions mediated by the triplet higgsino $\tilde{\Delta}^{++}$, and their strength is set by the coupling constants $h_{\Delta,ij}$ ($i \neq j$).

The constants $h_{\Delta,ij}$ appear also in the Majorana mass terms of the right-handed neutrinos, $h_{\Delta,ij}\langle\Delta^0\rangle\nu_{i,R}\nu_{j,R} \equiv M_{ij}\nu_{i,R}\nu_{j,R}$, and are therefore reflected in neutrino mixing and oscillation. The neutrino mixing is not, however, barely determined by
the triplet Higgs coupling. Indeed, the masses of light left components of neutrinos are given by the matrix

\[ m = -m_D M^{-1} m_D^T, \]

where also the Dirac mass matrix \( m_D \) is in general non-diagonal, and hence the dependence on \( h_{\Delta,ij} \) is generally highly non-trivial. Nevertheless, if one assumes quark-lepton symmetry or assumes that there exists a Grand Unified Theory where the LR-model is embedded, one is able to relate \( m_D \) with the quark mass matrix. In that case the information available from the non-diagonal slepton production would allow one to estimate neutrino mixing and thereby to test the various mixing schemes relevant e.g. for the solar and atmospheric neutrino problems.

On the other hand, the mixings and masses of the predominantly right-handed heavy neutrinos are in the first approximation given barely by the Majorana couplings \( h_{\Delta,ij} \).

For the MSSM, the formulas for the cross section of the slepton pair production have been given elsewhere, e.g. in [9]. These formulas can be adapted to the supersymmetric LR-model with obvious modifications taking into account the proper gauge couplings and the mixing of the neutralinos as given in eq. (10).

3. Results and discussion. The selectron pair production in supersymmetric LR-model has a large cross section when compared with the corresponding process in the MSSM. This is due to two factors, firstly the number of gauginos is larger and secondly the triplet higgsino contribution is large, though dependent on the unknown triplet higgsino coupling to the electron and selectron.

In Fig. 2 we present the total cross section of the selectron pair production as a function of the selectron mass \( m_{\tilde{e}} \) \( = m_{\tilde{e}_L} = m_{\tilde{e}_R} \) for a fixed triplet higgsino mass \( m_{\Delta} \) (the cross sections depend rather weakly on the value of \( m_{\Delta} \)). Here and in what
follows we have taken $h_{\Delta,ij} = 0.3$. Fig. 2a corresponds to the situation at LEP200 with $\sqrt{s} = 200$ GeV (here $m_\tilde{\Delta} = 110$ GeV) and Fig. 2b at a linear collider with $\sqrt{s} = 1$ TeV ($m_\tilde{\Delta} = 300$ GeV). We have assumed that the left-selectron and the right-selectron are not identified, the plotted cross section corresponding to the sum $\sigma(e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_L^-) + \sigma(e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-) + 2\sigma(e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_R^-)$. In the figures we have included two different supersymmetric LR-models, namely one with the soft gaugino masses $m_{\lambda_i} = 1$ TeV (LRM I) and another one with $m_{\lambda_i} = 200$ GeV (LRM II). In both cases we have taken $\mu_1 = \mu_2 = 200$ GeV. In the model LRM I the lightest neutralinos consist mainly of higgsinos, in LRM II mainly of gauginos. The cross sections in the two cases differ slightly, and the reason for that can be understood: in LRM I the $t$-channel processes are suppressed since the higgsino couplings are small, in LRM II there is no such suppression.

For comparison we have plotted in Fig. 2 also the corresponding cross section in the minimal supersymmetric standard model. The curve MSSM I(II) corresponds to the choice $m_{\lambda_i} = 1$ TeV (200 GeV), $\mu = 200$ GeV. As one can see, the cross sections in the susy LR-model are systematically appreciably larger than in the minimal supersymmetric standard model.

As mentioned, the most intriguing difference between the susy LR-model and the minimal susy standard model with respect to the slepton pair production is the existence of the $u$-channel process of Fig. 1c. This reaction, mediated by the $SU(2)_R$ triplet higgsino, occurs only for a right-handed electron and a left-handed positron, whereas in the $s$- and $t$-channel processes all chirality combinations may enter. Use of polarized beams could therefore give us more information of the triplet higgsino contribution. Assuming that the decay mode $\tilde{e} \rightarrow e\tilde{\chi}_0^0$ is dominant, in Fig. 3 we present the angular distribution of the final state electron $e^-$ for $\sqrt{s} = 1$ TeV, $m_{\tilde{e}} = M_\tilde{\Delta} = 300$ GeV in our two models LRM I and LRM II. In model LRM I
the $t$-channel contributions are suppressed since the light neutralinos are mainly consisting of the higgsinos. In Fig. 3a we present the angular distribution in the case the electron is right-handedly and the positron is left-handedly polarized ($P_{+-}$) and in the opposite case ($P_{-+}$). The distribution $P_{+-}$ is larger and it is slightly peaked in the backward direction because of the $u$-channel contribution. In the model LRM II (Fig. 3b) there is for the both polarization combinations a forward peak. In the case where the electron has right-handed polarization the forward peak is, however, less prominent, because there is a large backward enhancement due to the $u$-channel reaction.

The dependence of the angular distributions on the mass of the triplet higgsino $\tilde{\Delta}^-$ shows up clearly in the polarization asymmetry of the final state electrons in the cascade process $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$. As shown in Fig. 4, the longitudinal polarization asymmetry of the cross section,

$$A_{||} = \frac{\sigma(+-) - \sigma(+-)}{\sigma(+-) + \sigma(+-)}$$

(12)

(the first and second sign in parenthesis indicate the longitudinal polarization of the initial state electron and positron, respectively) is for those final state electrons originating in right-selectron decays quite sensitive on $M_{\tilde{\Delta}}$ (see the curves denoted by R). Particularly strong this effect is in the model LRM II (Fig. 4b) due to the interference of the $t$- and $u$-channel contributions, while in the model LRM I (Fig. 4a), where the $t$-channel is suppressed, the $M_{\tilde{\Delta}}$ dependence is less striking. In Fig. 4 we have also presented the asymmetry for electrons from the left-selectron decays (curve L), which does not depend on the triplet higgsino since $\tilde{e}_L$ does not couple with $\tilde{\Delta}$. Of course, if the origin of the final state electrons is not determined the curves L and R should be added up. We have assumed in Fig. 4 that the dominant decay channel of selectrons is $\tilde{e} \rightarrow e\tilde{\chi}_1^0$, where the neutralino $\tilde{\chi}_1^0$ is the lightest supersymmetric particle.
In the MSSM with the unification assumption the right-selectron is lighter than the left-selectron \( \bar{e}_R \). If only \( \bar{e}_R \)'s are produced, the difference between the MSSM and the supersymmetric left-right model would be especially large, more than an order of the magnitude, since in the MSSM there are no SU(2)\(_R\) gauginos and in the supersymmetric left-right model the right handed higgsino gives an extra contribution to the right slepton pair production.

Finally, the cross section of the pair production of smuons and staus are in general expected to be smaller than that of selectron pair production, since the neutralinos do not contribute. On the other hand the cross sections are in general larger than in the case of the MSSM because of the nondiagonal couplings of the triplet higgsinos.

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FIGURE CAPTION

**Figure 1.** Feynman diagrams for the slepton pair production in the supersymmetric left-right model.

**Figure 2.** The total cross section \( \sigma(e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_L^-) + \sigma(e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-) + 2\sigma(e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_R^-) \) as a function of the selectron mass \( m_{\tilde{e}} \) (a) for the collision energy \( \sqrt{s} = 200 \) GeV and triplet higgsino mass \( M_{\tilde{\Delta}} = 110 \) GeV, (b) for \( \sqrt{s} = 1 \) TeV, \( M_{\tilde{\Delta}} = 300 \) GeV. LRM I (II) refer to two supersymmetric left-right models and MSSM I (II) to two versions of the minimal supersymmetric Standard Model described in the text.

**Figure 3.** The angular distribution of the final state electron in the cascade process \( e^+e^- \rightarrow \tilde{e}^+\tilde{e}^- \rightarrow e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1 \) for \( \sqrt{s} = 1 \) TeV, \( M_{\tilde{\Delta}} = m_{\tilde{e}} = 300 \) GeV in the model (a) LRM I, (b) LRM II. \( P_{+-} \) corresponds to the case where the incoming electron has positive and the incoming positron has negative longitudinal polarization, and \( P_{-+} \) corresponds to the opposite case.

**Figure 4.** The longitudinal polarization asymmetry of the final state electrons from right-selectron decays (curves R) and from left-selectron decays (curve L) as a function of the collision energy a) in the model LRM I, b) in the model LRM II. It is assumed that \( \tilde{e} \rightarrow e\tilde{\chi}^0_1 \) is the dominant decay mode, where the neutralino \( \tilde{\chi}^0_1 \) is the lightest supersymmetric particle. The three curves denoted I, II and III correspond to the triplet higgsino masses \( M_{\tilde{\Delta}} = 300 \) GeV, 500 GeV and 800 GeV, respectively. It is assumed \( m_{\tilde{e}_L} = m_{\tilde{e}_R} = 60 \) GeV.
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