Constraints on neutrino parameters and doubly charged Higgs particles in the $e^-e^- \rightarrow W^-W^-$ process

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Abstract

Doubly charged Higgs s-channel resonances are analyzed in the $e^-e^- \rightarrow W^-W^-$ process. In our analysis recent stringent constraint on an effective neutrino mass $< m_\nu >$ coming from neutrinoless double-$\beta$ decay is implemented. It is shown that due to a very restrictive limit on $< m_\nu >$ the doubly charged Higgs resonance predicted by the Standard Model with additional Higgs triplets is below the detection limit. For the same reason also the $\Delta_{L}^-$ resonance can not be visible in the framework of the conventional Left-Right symmetric model. The situation is quite different for the $\Delta_{R}^-$ pole and large signal is possible here. Contributions of the s, t and u channels to the cross section around the $\Delta_{R}^-$ peak are also discussed.

The $e^-e^- \rightarrow W^-W^-$ process has most recently attracted some interest [1–6] as a possible option for the detection of new physics in a future $\sqrt{s} = 0.5–2$ TeV energy $e^-e^-$ facility. This reaction itself involves many phenomena outside the scope of the Standard Model (SM). Evidently if the lepton number conservation is violated then even a single occurrence of this process would establish a departure from the SM. The problem of neutrino mass and its nature is also very closely connected with this process. Furthermore, the detection of this reaction could give essential information about the existence of non-standard doubly charged Higgs particles.

Higgs fields are necessary for the spontaneous symmetry breaking (SSB) phenomenon. Although in the Standard Model based on the $SU_L(2) \times U_Y(1)$ gauge group there is only one physical scalar Higgs (not observed yet), there is no restriction for existence of higher representations of SU(2) for which other physical Higgs particles appear. Among them, a triplet representation ($\Delta^{--}, \Delta^-, \Delta^0$) that can generate a Majorana mass for neutrinos is of special interest [7]. This triplet multiplet includes a doubly charged Higgs field $\Delta^{--}$. Its detection would be the clearest evidence for existence of such a representation in Nature. Until now we know for sure that $\Delta^{--}$ with masses below $M_Z/2$ are excluded by the LEPI data [8]. However, heavier ones can exist and the possibility of their detection both in the lepton [9–12] and hadron [13–16] colliders has already been examined. In the $e^+e^-$
and $e^-\gamma$ colliders $\Delta^{--}$ masses may be probed almost up to the collision energies [12]. At HERA ($e^-p$ collision, $\sqrt{s} = 313$ GeV) masses up to $m_{\Delta^{--}} \approx 150$ GeV can be tested [13]. Both at the Tevatron [14] ($p\bar{p}$ collider, $\sqrt{s} = 2$ TeV) and LHC [14,16] ($pp$ collider, $\sqrt{s} = 14$ TeV) $\Delta^{--}$ can be found with masses up to 300 GeV and up to $\approx 1.2$ TeV, respectively. So we can see that doubly charged Higgs particles can be found in future $pp$, $p\bar{p}$ or $e^+e^-,e^-\gamma$ colliders in advance of an $e^-e^-$ option. The main feature of this option is that the $e^-e^-$ initial state is doubly charged and carries a finite lepton number. Thus SM activity is highly suppressed and clean signals from any non-standard physics can be looked for there. Especially direct $s$-channel $\Delta^{--}$ resonances are possible there. After discovering this particle in any other facility the $e^-e^-$ collider could be still used as a $\Delta^{--}$ factory that could precisely measure its mass, total decay width and couplings [14]. It is also possible that $\Delta^{--}$ will be not found in future facilities discussed above so even its approximate mass will be not known. Could still the $e^-e^-$ collision be useful in this case? We will also shortly discussed this situation later on.

$s$-channel resonances would be established via $\Delta^{--}$ decays. Possible decay modes are

$$\Delta^{--} \rightarrow W^-W^-, \quad \Delta^{--} \rightarrow \Delta^+\Delta^-,$$

$$\Delta^{--} \rightarrow l^-l^-.$$

We will focus here on the two gauge models where a non vanishing $\Delta^{--} \rightarrow W^-W^-$ coupling can exist:

(i) the Standard Model with a Higgs sector which contains a Higgs-triplet in addition to the standard doublet Higgs fields (DTM) [17,18];

(ii) the conventional left-right symmetric model (LR) [19].

For these models the $e^-e^- \rightarrow W^-W^-$ process with the $s$ channel exists.

The aim of this work is to investigate this process and to show how its $\Delta^{--}$ resonance is connected (and constrained) by neutrinos which are present in the $t$ and $u$ channels. To our best knowledge a discussion of the $e^-e^- \rightarrow W^-W^-$ process with doubly charged Higgs particles has not been performed yet from the point of view of neutrino characteristic (e.g. their possible mass spectrum, mixing angles with electron and CP parities).

In the LR model we have two doubly charged Higgs particles $\Delta_L^{--}$ and $\Delta_R^{--}$.

The cross section for $s$-channel poles ($\sqrt{s} = M_{\Delta_{L,R}^{--}}$) in the frame of this model can be written in the following way ($\beta = \sqrt{1 - 4\frac{M_W^2}{s}}$ and $\pm 1/2$ stands for helicities of incoming electrons)

$$\sigma^{res}(-1/2, -1/2) = \frac{4G_F^2M_W^4\beta}{\pi s}\cos^4\xi \left\{ \left( \frac{s}{2M_W^2} - 1 \right)^2 + 2 \right\} \left[ \sum_a \frac{(U_{L_{\alpha}}^2)^2 m_a}{\Gamma_{\Delta_{L}^{--}}} \right]^2,$$  \hspace{1cm} (1)

\footnote{All other possibilities (e.g. when a $\Delta^{--} \rightarrow W^-W^-$ coupling is vanishing) were discussed extensively in [14] recently.}
\[ \sigma^{res}(+1/2,+1/2) = \frac{4G_F^2 M_W^4 \beta}{\pi s} \sin^4 \xi \left\{ \left( \frac{s}{2M_W^2} - 1 \right)^2 + 2 \right\} \left[ \frac{\sum_a (U_R)_{ae}^2 m_a}{\Gamma_{\Delta R^-}} \right]^2. \] (2)

Matrices \( U_{L,R} \) are a part of the unitary matrix \( U = (U_L^*, U_R)^T \) which diagonalize 6 × 6 neutrino mass matrix \( M \) (see e.g. [3])

\[ M = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \] (3)

It is important that these s-channel cross sections are proportional to elements of neutrino mass matrix\(^2\)

\[
\sum_a (U_L^T)_{ea} m_a (U_L)_{ae} = (M_L^*)_{ee}, \\
\sum_a (U_R^T)_{ea} m_a (U_R)_{ae} = (M_R)_{ee}. \] (4)

The situation is akin to that in the \((\beta\beta)_0\nu\) process. It has been shown that for any realistic local gauge theory the existence of \((\beta\beta)_0\nu\) process implies that (an effective) electron neutrino must be of Majorana type with a nonzero mass [20]. For the \(e^-e^- \rightarrow W^-W^-\) process we can also recall another argument. A proper high energy behaviour of the cross section [2],[21] demands that all three s,t and u channels are needed simultaneously. That means that massive neutrinos must exist and they are exchanged in t and u channels\(^3\).

The \( \xi \) angle is connected with diagonalization of the charged gauge boson mass matrix and can be expressed in the following way [2]

\[ \xi \simeq \frac{M_W^2}{M_W^2}. \] (5)

The full cross section with t and u channels will not be given here as it can be found in e.g. [2],[3]. The only important information we need to know is that the helicity amplitudes for t and u channels with exchanged neutrinos are not directly proportional to \((M_{L,R})_{ee}\) (Eqs.(1-3)) because an additional neutrino mass relation comes from the neutrino propagator. However, for energies where the s-channel resonance appears these channels are negligible. Outside the s-channel resonance they can be important and then both mixing matrix elements \((U_{L,R})_{ee}\) and masses \(m_a\) must all be known separately.

\(^2\) Similarly considering the s channel resonance in the \(\mu^-\mu^- \rightarrow W^-W^-\) reaction, a future \(\mu^-\mu^-\) collider could give us information about another two elements of the neutrino mass matrix \(M\), e.g. \((M_L^*)_{\mu\mu}\) and \((M_R)_{\mu\mu}\).

\(^3\) Massless neutrinos give vanishing contributions of t and u channels to the total cross section even when right-handed interactions exist [2]
In the frame of the TDM model we are restricted to a $3 \times 3$ neutrino mass matrix $M = M_L$ [18] and the cross section for the $\Delta_{L}^{--}$ pole can be obtained from Eq.(1) by putting $\xi = 0$ (that means that only left-handed currents exist).

Let’s proceed to numerical results.

The DTM model predicts three massive neutrinos which can be identified with electron, muon and tau, respectively. They enter to the formula on $\sigma^{\text{res}}$ by the $\sum_a (U_L)_{ea}^2 m_a$ factor. However, this quantity is directly constrained by the absence of the $(\beta\beta)_{0e}$ decay. From experimental data an effective electron neutrino mass is extracted to be [22] (modified to our notation)

$$< m_{\nu} > = (M_{L}^*)_{ee} = \sum_a (U_L)_{ea}^2 m_a \leq 0.65 \text{ eV},$$

which implies that we don’t need to consider masses of all neutrinos and strength of their couplings with electron separately. To show how extremely strong this limit is let’s take the $\Delta_{L}^{--}$ resonance at CM energy equal to 200 GeV ($\sqrt{s} = 200 \text{ GeV} = M_{\Delta_{L}^{--}}$) and $\Gamma_{\Delta_{L}^{--}} \approx 10 \text{ GeV}$. Value of the width was adopted from [18] where $\Delta_{L}^{--}$ Higgs’ lifetime has been analyzed. This value varies with $s_H$ ($s_H = \sqrt{8v_T^2/(8v_T^2 + v_D^2)}$, $v_T,D$ are vacuum expectation values for Higgs triplet and doublet fields, respectively) about one order of magnitude for $0.1 < s_H < 0.995$.

The cross section is then

$$\sigma^{\text{res}(\Delta_{L}^{--})} (\sqrt{s} = 200 \text{ GeV}) \simeq 10^{-14} \text{ fb}.$$  (7)

Unavoidably it is below detection level.

For larger energies (and larger masses of doubly charged Higgs particles) the total width increases and the cross section at the $\Delta_{L}^{--}$ pole is smaller than given in Eq.(7). On the other hand the resonance would have to be extremely narrow ($\Gamma_{\Delta_{L}^{--}} \sim 0(1) \text{ keV}$) if the signal were to be detectable ($\sigma^{\text{res}(\Delta_{L}^{--})} \sim 0(1) \text{ fb}$).

We can conclude that the $\Delta_{L}^{--}$ resonance from the DTM model is under detection.

There are two doubly charged Higgses ($\Delta_{L,R}^{--}$) in the LR model. From Eqs.(2) and (6) we infer that situation for the $\Delta_{L}^{--}$ resonance is quantitatively the same as in the DTM case.

However, situation is different for the $\Delta_{R}^{--}$ resonance (Eq.(2)) because $\sigma^{\text{res}(\Delta_{R}^{--})}$ is proportional to $\sum_a (U_R)^2_{ea} m_a = (M_R)_{ee}$ (Eq.(4)). Taking into account that $(M_R)_{lk} >> (M_D)_{lk}$ and $M_R \leq \frac{2M_W^2}{g}$ [2] we have

$$O(1) \text{ GeV} << (M_R)_{ee} \leq \frac{2M_W^2}{g}.$$  (8)
We can see (Eq.(2)) that this factor can greatly enhance the resonance signal. Note, however, that this happens for +1/2 helicity polarization of incoming electrons where the reduction factor \( \sin^4 \xi \) is present so both factors must be examined simultaneously more carefully.

Let’s consider two versions of the left-right symmetric model, so-called Manifest or Quasi-Manifest L-R symmetric model (MLRS) and Non-Manifest L-R symmetric model (NMLRS). In the frame of NMLRS the present experimental bound on \( M_{W_2} \) is not so high and \( M_{W_2} \geq 600 \text{ GeV} \) is still possible [23]. However, for MLRS models the bound is larger, \( M_{W_2} \geq 1600 \text{ GeV} \) [24]. For these models in numerical discussion we use the lower limits.

Fig.1 portrays results for the \( \Delta_R^{--} \) resonance (\( \sqrt{s} = M_{\Delta_R^{--}} \)) for the NMLRS model. All lines are designed to maintain constant \( \sigma^{\text{res}}(\Delta_R^{--}) = 1 \text{ pb} \) while changing \((M_R)_{ee} \) and \( \Gamma_{\Delta_R^{--}} \). Values of \( (M_R)_{ee} \) satisfy inequality (8).

Above these lines (larger \( \Gamma_{\Delta_R^{--}} \)) \( \sigma^{\text{res}} < 1 \text{ pb} \).

We can see from this Figure that the reference level \( \sigma^{\text{res}}(\Delta_R^{--}) = 1 \text{ pb} \) (i.e. about \( 10^4 \) times larger than ‘the detection limit’ for this process [25]) can be easily achieved for \( \sqrt{s} \geq 500 \text{ GeV} \) for a wide range of \( (M_R)_{ee} \) and \( \Gamma_{\Delta_R^{--}} \) parameters. For \( M_{W_2}=1600 \text{ GeV} \) (the MLR model) \( \sin \xi \) (Eq.(5)) is smaller and to achieve the same values of \( \sigma^{\text{res}}(\Delta_R^{--}) \) much smaller values of \( \Gamma_{\Delta_R^{--}} \) are needed (e.g. \( \Gamma_{\Delta_R^{--}} \leq O(10) \text{ GeV} \) for \( \sqrt{s} = 1 \text{ TeV} \)).

Fig.1 shows only optimistic, on-peak results. A question may arise how this situation looks like at the off-peak s-channel energy region where s-channel contribution is less pronounced and t and u channel contributions start to play a role. This case is discussed in Fig.2 for \( M_{\Delta_R^{--}} = 500 \text{ GeV} \) with two parameters taken from the dotted line in Fig.1, i.e. \( \Gamma_{\Delta_R^{--}} \simeq 10 \text{ GeV} \) and \( (M_R)_{ee} = 500 \text{ GeV} \) (the asterisk). As it was already mentioned to make numerical calculations pertaining to off-peak energies we need to know not only the value of \( (M_R)_{ee} \) itself, as in the on-peak case (Eq.(2)), but also mixing matrix elements between heavy neutrinos and electron \((U_{L,R})_{eN_i} \) (i=1,2,3). It can be shown that the mixing matrix element \((U_R)_{eN} \) can be very large, \((U_R)_{eN} \simeq 1 \) (see [26] for theoretical and [27] for practical realization of this situation). Then, because of unitarity of the U mixing matrix other elements must fulfill the relation (i=2,3)

\[ |(U_R)_{eNi}| << |(U_R)_{eN}|. \] (9)

Taking into account relevant experimental constraints on heavy neutrino mixing angles with electron [22],[28] we can deduce (see [5],[29] for details) that the maximal mixing between heavy neutrino and electron predicted by present data and the LR model is \( (U_L)^2_{Ne} \approx 0.0027 \). In computations we take \( (U_L)^2_{Ne} = 0.001 \).

As we can see from Fig.2 for the discussed left-right model parameters, the contribution of the s channel to the total cross section is meaningful also outside the s channel resonance.
(i.e. for $\sqrt{s} = 500 \pm 10 \Gamma_{\Delta_R^{--}}$). That means that also without knowledge about the mass of $\Delta_R^{--}$ (which can originate from other facilities) we can try to look for it by fixing as many as possible energy settings to cover a wide range of possible $\Delta_R^{--}$ masses\footnote{This statement can be true only for large decay width of $\Delta_R^{--}$ (i.e. for $\Gamma_{\Delta_R^{--}} \geq 1$ GeV).}. Similar plots can be obtained also for both larger and smaller energies, as long as considered energies are at or nearby the $M_{\Delta_R^{--}}$ pole ($\sqrt{s} = M_{\Delta_R^{--}} \pm \text{(few) } \Gamma_{\Delta_R^{--}}$) and mixing angle $\xi$ is large enough (e.g. $M_{W^2}$ is not too massive (Eq.(5))).

Finally, let’s note that as long as the s channel dominates over t and u channels we can hardly say anything about CP parities of heavy neutrinos (the mixing angle of only one heavy neutrino with electron is important (Eq.(9)) and then interferences with the other ones disappear [2]).

In conclusion, we have shown, that due to a very precise bound on the effective neutrino mass $< m_\nu >$ taken from ($\beta\beta$)$_{0\nu}$ experiment, the s-channel resonance predicted by the DTM model is below detection in the $e^-e^- \rightarrow W^-W^-$ process. The LR model opens a possibility for its detection, especially when the NMLR version of this model (with a possible small value of the additional charged gauge boson $M_{W^2}$) is considered. Then the $\Delta_R^{--}$ Higgs particle resonance is attainable for a wide range of doubly charged Higgs masses and total widths. Detecting this resonance would give also information that massive Majorana neutrinos exist.

\footnote{The Gaussian shape of the $\sqrt{s}$ spectrum depends on beamstrahlung/bremsstrahlung effects. For $\sqrt{s} = 500$ GeV an average energy loss from these effects is estimated to be of the order of 3\% and a Gaussian peak can be controlled given pretty nice luminosity $L = 50 \text{ fb}^{-1}$ for a few years of running in its central 0.2\% peak region (i.e. for the Gaussian rms resolution $\sigma$ equals 1 GeV) [14]. For $\Gamma_{\Delta_R^{--}} \leq \sigma$ information about the mass of $\Delta_R^{--}$ particle would be desirable. Otherwise we could measure a signal not at the central peak but at a tail of the $\sqrt{s}$ spectrum where the luminosity would be not sufficient for getting an observable signal. For more details, among other things about predicted luminosities and beamstrahlung effects in the $\sqrt{s} = 0.5 \div 2$ TeV $e^-e^-$ collisions, see e.g. [30].}
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Fig. 1 This Figure shows lines with $\Gamma_{\Delta^- R}^\Delta$ and $(M_R)_{ee}$ parameters for which $\sigma^{res}(\sqrt{s} = M_{\Delta^- R}) = 1$ pb. Solid, dashed and dotted lines are for $\sqrt{s} = M_{\Delta^- R} = 2000, 1000, 500$ GeV, respectively. Above these lines $\sigma^{res}(\sqrt{s} = M_{\Delta^- R}) < 1$ pb. The asterisk denotes a point in $\Gamma_{\Delta^- R}^\Delta - (M_R)_{ee}$ coordinates which is used as a parameter in further calculations (Fig. 2).

Fig. 2 The cross section for the $e^- e^- \rightarrow W^- W^-$ process as a function of energy near the s-resonance ($M_{\Delta^- R} = 500$ GeV) for the left-right symmetric model with $\Gamma_{\Delta^- R}^\Delta = 10$ GeV and $(M_R)_{ee} = 500$ GeV (the asterisk in Fig. 1). Solid lines stand for the total cross sections, dashed lines stand for the cross sections after removing t and u channels (the s channel contribution only).