$W^- \rightarrow \tau \bar{\nu}_{\tau}$ 3-sigma anomaly in new physics beyond the standard model

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Among so-called three 3-sigma anomalies in high energy physics, the excess of the branching ratio $W^- \rightarrow \tau \bar{\nu}_{\tau}$ with respect to the electrons and muons is especially interesting because (1) in the standard model (SM), $W^- \ell \bar{\nu}_\ell$ is the pure left-handed charge-current which has been tested precisely already, at least for the first two generation fermions, and (2) the $W^\pm$ two-body leptonic decay is the cleanest one among three anomalies due to its simpler kinematics and less hadronic uncertainties.

In this paper, we explore the possibilities to account for the anomaly in type II two-Higgs-doublet model (2HDM) and minimal supersymmetric model (MSSM), as well as effective lagrangian approach by introducing anomalous left- and right-handed $W^- \tau \bar{\nu}_{\tau}$ couplings. Our results show that 2HDM and MSSM can hardly accommodate $W^- \rightarrow \tau \nu_{\tau}$ anomaly, and the anomaly is only marginally consistent to the measurements of $\tau \rightarrow \nu_{\tau} \ell \bar{\nu}_\ell$ at 95% confidence level with the presence of anomalous couplings. In the allowed regions, the right-handed coupling of $W^- \tau \nu_{\tau}$ shifts from 0 in SM to $\sim 0.12$ while the left-handed one from 1 to $\sim 1.005$. 
The standard model (SM) of high energy physics can successfully describe all experiments at LEP, SLD and Tevatron etc. at one-loop level, except three so-called 3-sigma anomalies: spread in $\sin^2 \theta_{eff}$ at the Z pole, NuTeV and W branching fractions. The last one is especially interesting because (1) in the SM, $W^- \ell \bar{\nu}_\ell$ is the pure left-handed charge-current which has been tested precisely already, at least for the first two generation fermions, and (2) the $W^\pm$ two-body leptonic decay is the cleanest one among three anomalies due to its simpler kinematics and less hadronic uncertainties. In the SM, the mass effects of leptons in $W^\pm$ leptonic two-body decays are negligible at LEP energy. Therefore, the branching fractions for electron, muon and tau decays should be the same. However the measurements from LEP show that an excess of the branching ratio $W^- \rightarrow \tau \bar{\nu}_\tau$ with respect to the other leptons is evident. The excess can be quantified with the two-by-two comparison of these branching fractions as

$$\frac{Br(W^- \rightarrow \mu \bar{\nu}_\mu)}{Br(W^- \rightarrow e \bar{\nu}_e)} = 0.994 \pm 0.020$$

(1)

$$\frac{Br(W^- \rightarrow \tau \bar{\nu}_\tau)}{Br(W^- \rightarrow e \bar{\nu}_e)} = 1.070 \pm 0.029$$

(2)

$$\frac{Br(W^- \rightarrow \tau \bar{\nu}_\tau)}{Br(W^- \rightarrow \mu \bar{\nu}_\mu)} = 1.076 \pm 0.028.$$  

(3)

While the branching fractions of W into electrons and muons perfectly agree, the branching fractions in taus with respect to electrons and muons differ by more than two standard deviations, where correlations have been taken into account. The ratio between the tau fractions and the average of electrons and muons can be computed:

$$\frac{2Br(W^- \rightarrow \tau \bar{\nu}_\tau)}{Br(W^- \rightarrow \mu \bar{\nu}_\mu) + Br(W^- \rightarrow e \bar{\nu}_e)} = 1.073 \pm 0.026.$$  

(4)

Before we proceed further, it is worthwhile to mention that the precise tests of neutral weak current at LEP experiments at Z-pole have reached to an accuracy of $O(0.1\%)$. Therefore it is challenging to find a solution to account for both $W \rightarrow \tau \bar{\nu}_\tau$ anomaly and $Z \rightarrow \tau \bar{\tau}$. Obviously new physics of oblique-type, i.e. new physics contributions enter only via vacuum polarization effects to gauge boson propagators of the SM, can hardly explain $W^- \rightarrow \tau \bar{\nu}_\tau$ anomaly because the corrections are the same for $\tau \bar{\nu}_\tau$ and $\mu \bar{\nu}_\mu$. The natural source for $W^- \rightarrow \tau \bar{\nu}_\tau$ anomaly is the flavor-dependent yukawa interactions among Higgs and fermions in multi-Higgs models such as type II two-Higgs-doublet model (2HDM) and minimal supersymmetric standard model (MSSM). In MSSM, the flavor-dependent
interactions also exist among chargino (neutrolino) slepton and lepton. Especially the well-known \( \tan \beta \) enhancement of yukawa couplings of the third family fermions may play a special role to accommodate W branching fractions anomaly. In this paper, we will firstly explore whether such kind of flavor-dependent interactions can account for the \( W^{-} \rightarrow \tau \bar{\nu}_{\tau} \) anomaly in the popular type II 2HDM and MSSM. Our numerical results show that these two models can hardly explain anomaly. Therefore we then study this issue under the framework of effective lagrangian approach. By introducing anomalous \( W \tau \bar{\nu}_{\tau} \) left- and right-handed couplings, the anomaly can be accommodated. However, the allowed parameters are only marginally consistent to the limits from measurements from \( \tau \rightarrow \nu_{\tau} \ell \bar{\nu}_{\ell} \).

In order to gauge the new physics contributions, we define

\[
\delta_{\text{new}} \equiv \frac{\Gamma^{NLO} - \Gamma^{NLO,SM}}{\Gamma^{0}}
\]

(5)

where \( \Gamma^{NLO}, \Gamma^{NLO,SM}, \Gamma^{0} \) are the decay widths at NLO in new models, at NLO in the SM, at tree-level in the SM respectively. Assuming the flavor-dependent interactions have negligible effects on \( W^{-} \rightarrow \mu \bar{\nu}_{\mu} \) and \( W^{-} \rightarrow e \bar{\nu}_{e} \), from eq. (4) we obtain

\[
\delta_{\text{new}} = 0.073 \pm 0.026.
\]

(6)

In the following we will study whether the new physics is compatible with such large effects.

In Ref.[3], the authors studied lepton universality violation in W decay in general 2HDM for large \( \tan \beta \). From their results, the two-Higgs doublet model usually predicts a decrease of \( \text{Br}(W^{-} \rightarrow \tau \bar{\nu}_{\tau}) \), except in the limit the Higgs mass splitting is small (\( \leq m_{W}/2 \)). Setting \( m_{A^{0}} = m_{H^{0}} = m_{H^{\pm}} \equiv m \) and neglecting \( m_{h^{0}} \) contributions, we can express

\[
\delta_{\text{new}} = \left( \frac{g_{m_{\tau}} \tan \beta}{6\pi m} \right)^{2}.
\]

(7)

For \( \tan \beta = 100 \) and \( m = 200 \text{ GeV} \)

\[
\delta_{\text{new}} \approx 0.001.
\]

(8)

Obviously the general 2HDM can hardly explain \( W^{-} \rightarrow \tau \bar{\nu}_{\tau} \) anomaly.

In MSSM, besides the enhanced Higgs-fermions couplings, the chargino and neutrolino interactions with lepton and slepton contain also \( m_{\tau} \tan \beta \) terms. In our analytical and numerical calculations, we use Feynarts, FormCalc and LoopTools [4] to evaluate the mass,
mixing angle etc. from input parameters, at the same time enforce the experimental constraints, for examples the chargino, neutralino and stau mass lower limits as well as $\rho$ parameter. Moreover we use these packages to calculate the decay width for both $W^- \to \tau \bar{\nu}_r$ and $Z \to \tau \bar{\tau}$ in the MSSM.

We have scanned the whole parameter space, and find that in the allowed parameter regions

$$\delta_{\text{new}} \leq 0.001. \quad (9)$$

It should be noted that for the large region of parameter space, $\delta_{\text{new}}$ is negative, which is the same with that in 2HDM. In the following we show the results of positive $\delta_{\text{new}}$ for certain typical parameters. In Fig. 1-3, we depict $\delta_{\text{new}}$ as functions of $\tan \beta$, $\mu$ for $W^- \to \tau \bar{\nu}_r$ and as a function of $\tan \beta$ for $Z \to \tau \bar{\tau}$. For these three figures, $m_{\tilde{\tau}_1} = 90$ GeV, $\mu = 100$ GeV, $m_{A_0} = M_2 = 1$ TeV, and other sfermion masses are taken as 1 TeV. From figures we can see clearly that in the allowed parameters in MSSM, it is impossible to account for $W^- \to \tau \bar{\nu}_r$ anomaly. Moreover the comparable $\delta_{\text{new}}$ in $W^- \to \tau \bar{\nu}_r$ and $Z \to \tau \bar{\tau}$ indicate that it is very hard to account for both charged- and neutral-currents data simultaneously.

Now we switch to the effective lagrangian approach. In this paper, we simply explore the anomalous couplings only for $W\tau \bar{\nu}_r$ sector which are written as

$$L = \frac{g}{\sqrt{2}} W^\mu \bar{\nu}_\mu \gamma^\mu ((1 + \delta_L) P_L + \delta_R P_R) \tau + h.c. \quad (10)$$

where $P_{L,R} = 1/2(1 \mp \gamma_5)$ and $\delta_L = \delta_R = 0$ for the SM case.

It is straightforward to write the constraint based on eq. 4 as

$$\left(1 + \delta_L\right)^2 + \delta_R^2 = 1.073 \pm 0.026. \quad (11)$$

Limits of anomalous couplings $\delta_L$ and $\delta_R$ can also be derived from precise measured Michel parameters which are extracted from the energy spectrum of the charged daughter lepton $\ell = e, \mu$ in the decays $\tau \to \nu_\tau \ell \bar{\nu}_\ell$ [7]. We can write the limits as

$$|1 + \delta_L| < 1.005 \text{ and } |\delta_R| < 0.12 \text{ at } 95\% \text{ CL.} \quad (12)$$

The allowed regions at 95% confidence level from eqs. 11 and 12 are shown in Fig.4. From the figure we can see that the allowed regions are severely constrained and measurements of $W^- \to \ell \bar{\nu}_\ell$ only marginally agree to those of $\tau \to \nu_\tau \ell \bar{\nu}_\ell$. In the allowed regions, the
right-handed coupling shifts from 0 in SM to \( \sim 0.12 \) while the left-handed one from 1 to \( \sim 1.005 \).

To summarize, in the popular type II 2HDM and MSSM, the \( \tan \beta \) enhanced flavor-dependent yukawa interactions have little impact on \( W^- \rightarrow \tau \nu_\tau \) anomaly. If the anomaly stands up to the scrutiny of the future high energy physics at LHC and ILC, there must be new physics other than general 2HDM and MSSM, for examples gauge models of generation non-universality \[5, 6\]. By introducing anomalous left- and right-handed couplings of \( W^- \tau \bar{\nu}_\tau \), we explore the anomaly under effective lagrangian approach. Our results show that \( W^- \rightarrow \tau \nu_\tau \) anomaly is only marginally consistent to the measurements of \( \tau \rightarrow \nu_\tau \ell \bar{\nu}_\ell \) at 95% confidence level. In the allowed regions, the right-handed coupling shifts from 0 in SM to \( \sim 0.12 \) while the left-handed one from 1 to \( \sim 1.005 \).

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FIG. 1: $\delta_{\text{new}}$ for $W^- \rightarrow \tau \bar{\nu}_\tau$ as a function of $\tan \beta$ where $m_{\tilde{\tau}_1} = 90 \text{ GeV}$, $\mu = 100 \text{ GeV}$, $m_{A^0} = M_2 = 1 \text{ TeV}$, and other sfermion masses are taken as 1 TeV.
FIG. 2: $\delta_{\text{new}}$ for $W^- \rightarrow \tau \bar{\nu}_\tau$ as a function of $\mu$ with $\tan \beta = 100$. Other parameters are the same with Fig. 1.
FIG. 3: $\delta_{\text{new}}$ for $Z \rightarrow \tau \bar{\tau}$ as a function of $\tan \beta$. Other parameters are the same with Fig.
FIG. 4: Allowed regions of $\delta_L$ and $\delta_R$ at 95% confidence level constrained by the measurements of $\tau \rightarrow \nu_\tau \ell \bar{\nu}_\ell$ (between two parallel lines and to the left of vertical line) as well as $W^- \rightarrow \ell \bar{\nu}_\ell$ (between two arcs).