Explaining The New CDF II W-Boson Mass Data In The Georgi-Machacek Extension Models

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ABSTRACT: Georgi-Machacek model can hardly account for the new CDF II data on W-boson mass in its original form. As anticipated, unless additional tree level $SU(2)_c$ custodial symmetry breaking effects are non-negligible, the new physics contributions to $\Delta m_W$ is always very small. Our numerical results show that ordinary GM model can contribute to $\Delta m_W$ a maximal amount 0.0012 GeV, which can not explain the new CDF II data on W boson mass. We propose to introduce small misalignment among the triplet VEVs to increase $\Delta m_W$, which can reach 0.06 GeV for $v_\xi - v_\chi \sim 6$ GeV, marginally explain the new data in 2$\sigma$ range. We also propose to extend the GM model with low scale RH neutrino sector, which can adopt the leptogenesis mechanism and act as a large $SU(2)_c$ breaking source because of its correlation with $h_{ij}$. With low scale RH neutrino mass scale of order $10^2 \sim 10^4$ TeV, the new physics contributions to $\Delta m_W$ can reach 0.03 GeV. Combining both small $SU(2)_c$ breaking effects, the small misalignment among the triplet VEVs and large $h_{ij}$ couplings, the 1$\sigma$ range of CDF II data on W boson mass can be obtained even for small splitting among the triplet VEVs with $v_\xi - v_\chi \approx 1$ GeV.
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1 Introduction

The standard model (SM) had already been corroborated by various contemporary collider experiments, including the 125 GeV Higgs boson by the Large Hadron Collider (LHC) [1, 2]. Despite its success, it still has many theoretical and aesthetical problems, such as the origin of tiny neutrino masses. Besides, new reported measurement of the W boson mass by the CDF II detector at the Fermilab Tevatron collider [3] gives

$$M_W = 80.433.5 \pm 6.4(stat) \pm 6.9(syst) = 80.433.5 \pm 9.4 MeV/c^2,$$  

(1.1)

using data corresponding to $8.8 fb^{-1}$ of integrated luminosity collected in proton-antiproton collisions at a 1.96 TeV center-of-mass energy. This measurement is in significant tension with the standard model expectation [4]

$$M_W = 80.357 \pm 4(inputs) \pm 4(theory) MeV/c^2.$$  

(1.2)

If such value of the new W boson mass persist and get confirmed by other experiments, they will indicate the existence of new physics beyond SM [5]. Many discussions and explanations had been given on this new CDFII W-boson data [6].

Electroweak symmetry breaking (EWSB) mechanism with extended Higgs sectors is still allowed, given the uncertainties in Higgs boson coupling measurements. So the problems of SM can possibly be explained in the Higgs extended models, such as the extended Georgi-Machacek (GM) model [7–37]. On the other hand, any extended Higgs sector must be carefully constructed to satisfy the stringent constraints from electroweak precision data, the most important one of which is the electroweak $\rho$ parameter. We know that tree level relation $\rho_{tree} = 1$ is automatically satisfied by Higgs sector of SM, which can respect the custodial $SU(2)_c$ global symmetry. GM model, which augments the SM Higgs sector with a complex $SU(2)_L$ triplet of hypercharge $Y = 1$ and a real $SU(2)_L$ triplet of $Y = 0$, can protect the relation $\rho_{tree} = 1$ with custodial symmetry preserving Higgs potential and vacuum alignment between the complex and real triplets. Therefore, a large triplet VEV $v_\Delta$ of order $\mathcal{O}(10)$ GeV is allowed for the vacuum aligned triplets in the GM model, unlike that in the minimal Higgs triplet model (HTM) whose $v_\Delta$ is constrained to be much smaller because of its violation of $SU(2)_c$ at tree level. GW model can provide tiny mass to neutrinos via the Type-II neutrino seesaw mechanism.

However, we anticipate that the new physics contributions to $\Delta m_W$ in GM model should be small because of the tree-level custodial $SU(2)_c$ symmetry, which protects the $\rho$ parameter from large deviations from unity. So, in order to increase $\Delta m_W$, additional explicitly $SU(2)_c$ symmetry breaking effects should be included. We propose to introduce slightly vacuum misalignment between the two triplet VEVs. We also propose an alternative GM extension model which augment the neutrino sector with low scale right-handed (RH) neutrino and adopt the type I+II seesaw mechanism similar to that in the Left-Right symmetric model. The presence of RH neutrino terms can not only be used to increase the value of $h_{ij}$ within the GM model, but also be used to understand the Baryon Asymmetry in the Universe (BAU). Satisfying Sakharov’s three conditions, leptogenesis mechanism can
readily explain the BAU. Net baryon number is generated by out-of-equilibrium L-violating decays of heavy Majorana neutrinos. Besides, low scale RH neutrino with large Yukawa couplings to leptons can have rich collider phenomenology.

This paper is organized as follows. In Sec 2, we review the GM model and discuss our low scale RH neutrino extension GM model. In Sec 3, we discuss the new physics contributions to CDFII W-boson mass in GM model and its various extensions. Sec 4 contains our conclusions.

2 GM model

In the GM model [7, 19], the Higgs sector contains the ordinary SM $SU(2)_L$ doublet Higgs field $\phi$ with hypercharge $Y = 1/2$ and two $SU(2)_L$ triplet Higgs fields: complex triplet Higgs $\chi$ with $Y = 1$ and real triplet $\xi$ with $Y = 0$. These fields can be written in the form of $SU(2)_L \times SU(2)_R$ symmetry

$$\Phi = \begin{pmatrix} \phi^0 & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^0 & \chi^+ & \chi^+ \\ \chi^- & \chi^0 & \chi^- \\ \chi^- & \chi^- & \chi^0 \end{pmatrix},$$

(2.1)

to track the symmetry preserved by the scalar potential, where the transformations of $\Phi$ and $\Delta$ under $SU(2)_L \times SU(2)_R$ as $\Phi \to U_L \Phi U_R^\dagger$ and $\Delta \to U_L \Delta U_R^\dagger$ with $U_{L,R} = \exp(i\theta_{L,R}^a T^a)$ and $T^a$ being the $SU(2)$ generators. The gauge invariant scalar potential are given as [19]

$$V(\Phi, \Delta) = \frac{1}{2} m_\phi^2 \text{tr} \left[ \Phi^\dagger \Phi \right] + \frac{1}{2} m_\chi^2 \text{tr} \left[ \Delta^\dagger \Delta \right] + \lambda_1 \left( \text{tr} \left[ \Phi^\dagger \Phi \right] \right)^2 + \lambda_2 \left( \text{tr} \left[ \Delta^\dagger \Delta \right] \right)^2 + \lambda_3 \text{tr} \left[ \left( \Delta^\dagger \Delta \right)^2 \right] + \lambda_4 \text{tr} \left[ \Phi^\dagger \Phi \right] \text{tr} \left[ \Delta^\dagger \Delta \right] + \lambda_5 \text{tr} \left[ \Phi^\dagger \sigma_a^2 \Phi \sigma_b^2 \right] \text{tr} \left[ \Delta^\dagger T^a \Delta T^b \right] + \mu_1 \text{tr} \left[ \Phi^\dagger \sigma_a^2 \Phi \sigma_b^2 \right] \left( P^\dagger \Delta P \right)_{ab} + \mu_2 \text{tr} \left[ \Delta^\dagger T^a \Delta T^b \right] \left( P^\dagger \Delta P \right)_{ab},$$

(2.2)

where $\sigma^a$ are the Pauli matrices, $T^a$ are the $3 \times 3$ matrix representation of the $SU(2)$ generators, and the similarity transformation relating the $SU(2)$ generators in the triplet and adjoint representations is given by

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}.$$

The scalar potential can trigger the EWSB by the VEVs

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} v_\phi, \quad \langle \chi \rangle = v_\chi, \quad \langle \xi \rangle = v_\xi.$$

(2.3)

When the two triplet VEVs align, $v_\chi = v_\xi = v_\Delta$, the global $SU(2)_L \times SU(2)_R$ symmetry of the potential ¹ is reduced to the custodial $SU(2)_c$ symmetry. The EWSB condition

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{2G_F} \approx (246 \text{GeV})^2,$$

(2.4)

¹Global $SU(2)_L \times SU(2)_R$ is explicitly broken by the Yukawa and the hypercharge gauge interactions.
can be recasted into \( s_H \) variable with \( s_H = \sin \theta_H \) for
\[
\tan \theta_H = 2\sqrt{2}v_\Delta/v_\phi .
\] (2.5)

Majorana neutrino masses can be obtained from the term
\[
\mathcal{L} \supseteq h_{ij} \overline{L}_i^c \tau_2 \chi L_j + \text{h.c.} ,
\] (2.6)
via the type II seesaw mechanism to give
\[
m_\nu \approx h_{ij}v_\Delta ,
\] (2.7)
with the triplet VEV \( v_\Delta \) triggered by the \( \mu_1 \) term once the doublet \( \phi \) gets a VEV to break the electroweak symmetry. For \( v_\Delta \sim \mathcal{O}(10) \) GeV, very tiny coupling \( h_{ij} \sim 10^{-13} \) is needed to give tiny neutrino mass, which is rather unnatural.

### 2.1 RH-neutrino Extended GM Model

Unlike MTH model, which extends the SM with one \( SU(2)_L \) triplet, ordinary GM model can hardly explain the recent \( \Delta m_W \) because of \( \rho_{tree} = 1 \) protected by the custodial symmetry. So, it is fairly interesting to seek for extensions of GM model to account for the new physics contribution \( \Delta m_W \) to W boson mass required by the new CDF II data. As Yukawa couplings always break the \( SU(2)_c \) preserved by the Higgs potential, we could introduce relatively large \( SU(2)_c \) breaking effects from Yukawa coupling terms. In ordinary GM model, the Yukawa couplings terms \( h_{ij} \overline{L}_i^c \tau_2 \chi L_j \) are responsible for neutrino masses generation, whose coupling strength should be rather tiny for \( v_\Delta \sim \mathcal{O}(10) \) GeV. So we need to find ways to consistently increase the coupling strength \( h_{ij} \). We propose that large \( h_{ij} \) can be naturally realized when an additional RH neutrino sector is introduced. The new RH neutrino sector in our extended GM model can be written as
\[
-\mathcal{L} \supseteq y_{N_{ij}}^N \overline{L}_{L,i} \phi N_{R,j} + \frac{1}{2}(M_R)_{ij}^N N_{R,i}^N C N_{R,j} + h_{ij} \overline{L}_i^c \tau_2 \chi L_j + \text{h.c.} ,
\] (2.8)
with \( N_{R,j} \) the RH neutrinos. After EWSB, it will lead to the neutrino mixing mass matrix of the form
\[
\mathcal{M}_\nu = \begin{pmatrix}
    h_{ij}v_\Delta y_{N_{ij}}^{N T} v_\phi \\
    y_{N_{ij}}^N v_\phi (M_R)_{ij}
\end{pmatrix} .
\] (2.9)

For simply, we choose \((M_R)_{ij} = M_{R,i} \delta_{ij}\) up to possible phases. So, the neutrino mass can be given as
\[
m_\nu \approx h_{ij}v_\Delta - v_\phi^2 (y_{N_{ij}}^N)^T M_{R,j}^{-1}(y_{N_{jk}}^N) ,
\] (2.10)
for \( M_R \gg v_\phi \gg v_\Delta \), which is in fact a mixed type I+II neutrino seesaw mechanism. Tiny neutrino mass of order \( 10^{-3} \) eV requires the cancelation among the two terms
\[
h_{ij}v_\Delta \approx \frac{(y_{N_{ij}}^N v_\phi)^2}{M_R} .
\] (2.11)
For $y^N \sim \mathcal{O}(1)$, $M_R \sim \mathcal{O}(1)$ TeV and $h_{ij} \sim \mathcal{O}(1)$, tiny neutrino mass requires $v_\Delta \sim \mathcal{O}(10)$ GeV, which is naturally allowed by GM model. The neutrino mass matrix can be diagonalized by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix $V_{PMNS}$ [38], so the form of $h_{ij}$ can take the form

$$h_{ij} = 2\sqrt{2}(V_{PMNS}^T)^{-1}\left(\frac{v(1-s^2_H)}{s_H M_{Ri}}\right)\delta_{ij}(V_{PMNS})^{-1}.$$  \hspace{1cm} (2.12)

The RH neutrino coupling form should take $y^N_{ij} = V_{PMNS}^{-1}$. However, large $|h_{ij}| \sim \mathcal{O}(1)$ is constrained stringently by the lepton flavor violation (LFV) processes. In fact, the main LFV signatures of the seesaw mechanism stem from muon decay, with the current bounds $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}, BR(\mu \to 3e) < 10^{-12}$. Other LFV process, such as $\mu - e$ conversion and LFV decays involving $\tau$ lepton, are subdominant. For scalar triplets of order 1 TeV, the typical magnitude of $|h_{ij}|$ is constrained to be less than $\mathcal{O}(10^{-2})$ by the $BR(\mu \to e\gamma)$ bound

$$BR(\mu \to e\gamma) \sim \frac{\alpha_{EM}}{192\pi}|h_{ij}|^4\left(\frac{m_W}{M_{H^{++}}}\right)^4.$$ \hspace{1cm} (2.13)

Due the correlation between $h_{ij}$ and $M_R$ in eq.(2.12), the scale of $M_R$ should typically be heavier than 50 TeV for $s_H < 0.2$.

We should note that, in ordinary GM model, the coupling $h_{ij}$ should be very tiny of order $10^{-13}$ for $v_\Delta \sim \mathcal{O}(10)$ GeV. With the augmentation of the RH neutrino sector, the allowed value of $h_{ij}$ can be greatly increased. On the other hand, large fine-tuning (FT) is still needed for the cancelation in eq.(2.10) to get the observed tiny neutrino masses. The larger the $M_R$ value, consequently a smaller $h_{ij}$ coupling term ( indicating a smaller $SU(2)$ breaking source), the smaller the FT is needed.

The introduction of RH neutrinos can be advantageous in cosmology. We would like the heavy Majorana neutrinos to be responsible for both the observed BAU and the neutrino oscillation data. In this context, it has been found [39, 40] that if the heavy singlet neutrinos have an hierarchical mass spectrum, a lower bound of about $10^8 \sim 10^9$ GeV on the leptogenesis scale can be derived. To obtain this lower bound, the size of the leptonic asymmetry between the heavy Majorana neutrino decay $N \to L\phi$ and its respective CP conjugate plays a key role. It has been shown in [39] that the leptonic CP asymmetry is not only analytically well-behaved but also can be of order unity if two of the heavy Majorana neutrinos have mass differences comparable to their decay widths. Due to this resonant effect, the bound on the RH neutrino mass scale from the requirement of generating sufficient lepton number asymmetry can be significantly lower in resonant leptogenesis scenario. Even TeV scale RH neutrino mass ($M_1, M_2 \sim \mathcal{O}(1)$ TeV) are still allowed to obtain sufficient baryon asymmetry. So, with $\mathcal{O}(100)$ TeV Majorana RH neutrino masses, this RH neutrino extended GM model can adopt the leptogenesis mechanism to generate the required baryon asymmetry in our universe.
3 New Contributions to $\Delta m_W$

The CDF II data on new W boson mass needs additional new contributions $\Delta m_W$ from new physics. Such new contributions to the W-boson masses can be calculated with the $S,T,U$ parameters [41–43]. Knowing the oblique parameters, one can obtain the shift of W-boson mass by new physics contributions in terms of the $S,T,U$ [41, 44] parameters

$$\Delta m_W = \frac{\alpha M_W}{2(c_W^2 - s_W^2)} \left( -\frac{1}{2} S + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2} U \right),$$

(3.1)

with

$$\alpha S = 4s_w^2 c_w^2 \left[ \Pi'_{ZZ}(0) - \frac{c_w^2 - s_w^2}{s_w c_w} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right],$$

$$\alpha T = \frac{\Pi_{WW}(0)}{m_w^2} - \frac{\Pi_{ZZ}}{m_Z^2},$$

$$\alpha U = 4s_w^2 \left[ \Pi'_{WW}(0) - c_w^2 \Pi'_{ZZ}(0) - 2s_w c_w \Pi'_{Z\gamma}(0) - s_w^2 \Pi'_{\gamma\gamma}(0) \right],$$

(3.2)

and $\alpha^{-1}(0) = 137.035999084, s_W^2 = 0.23126$.

We plot in fig.1 the possible values of $S,T$ with $U = 0$ that can give $\Delta m_W$ up to $1\sigma - 4\sigma$ range of new CDF II data. The green box is the $1\sigma$ constraints on $S$ and $T$ from various inputs combined with $M_Z$ [45]. It is obvious from the figure that new contribution to $\Delta m_W$ in the most favored range of $S,T$ (the red box with $S = 0.00 \pm 0.07$ and $T = 0.05 \pm 0.06$ [45]) can marginally reach the $1\sigma$ lower bound.

Ordinary GM model is constrained from measurements of SM quantities in collider experiments, such as the electroweak precision tests, the determination of the $Zb\bar{b}$ coupling, the measurement of the Higgs boson signal strengths and the unitary bounds. The value of $T$ parameter ($\propto \Delta \rho$) in ordinary GM model is not large because of the tree-level custodial $SU(2)_c$ symmetry. Its concrete value depends on the logarithm of the triplet-like Higgs boson masses and therefore not important at the one-loop level.

We scan the parameter space to see if the ordinary GM model can explain the CDF II data on W-boson mass. The code SARAH [47] is used to generate the input model file to link the Spheno [48] package, which has implemented various collider constraints. We require the predicted Higgs mass to lie between 124 GeV and 126 GeV. Bounds from stability of the electroweak vacuum, the unitarity of the perturbation theory [31] are imposed and the value $s_H$ is required to lie below 0.2. All the survived points need to pass the bounds in HiggsBounds [49], HiggsSignals [50] as well as GMCalc [51].

We show our numerical results in upper panels of fig.2. It can be seen that the survived points can not explain the CDF II data, which can contribute to $\Delta m_W$ a maximal amount 0.0012 GeV at one loop level. The corresponding heavy Higgs mass $m_{h_2}$ and the doubly charged Higgs $m_{H^{++}}$ mass are also shown in the upper right panel. Such a heavy $H^{++}$ can

$^2$Fixing $U = 0$ is motivated by the fact that $U$ is suppressed by an additional factor $M_{new}^2/M_Z^2$ compared to $S$ and $T$ [46]. Such a choice can greatly improves the precision on $S$ and particularly $T$.

$^3$The $T$ parameter can be increased in the GM model if we add terms that explicitly breaks the $SU(2)_c$ custodial symmetry.
Figure 1. Possible values of $S, T$ with $U = 0$ that can give $\Delta m_W$ up to $1\sigma - 4\sigma$ range of new CDF II data. The red box denotes the range $S = 0.00 \pm 0.07$ and $T = 0.05 \pm 0.06$ [45] while the green box denotes the range $S = -0.01 \pm 0.10$ and $T = 0.03 \pm 0.12$ [45].

give very small contributions to $\Delta a_\mu$ by the Barr-Zee diagrams, which can not account for the recently reported muon $g - 2$ anomaly [52].

As noted previously, the $T$ parameter can be increased in the GM model if additional $SU(2)_c$ custodial symmetry breaking effects are included. The most economical recipe without putting in by hand new $SU(2)_c$ breaking terms is to split the triplet VEVs at the tree level, that is, requiring misalignment between $v_\xi$ and $v_\chi$ by a small amount. With a small misalignment among the triplet VEVs, the $T$ parameter can be increased accordingly because of the slightly breaking of $SU(2)_c$ custodial symmetry at the tree level. From our numerical results, we can see in the lower panels of fig.2 that the new physics contribution $\Delta m_W$ is indeed correlated to the $SU(2)_c$ breaking parameter $v_\xi - v_\chi$. With the misalignment parameter $v_\xi - v_\chi$ taking approximately 5 GeV, new contribution $\Delta m_W$ can reach 0.049 GeV, explaining the CDF II data to $3\sigma$ range. Larger $v_\xi - v_\chi$ up to 14 GeV can increase further the value of $\Delta m_W$ up to 0.062 GeV, which can explain the CDF II data to $2\sigma$ range.

GM extension model with RH neutrinos and large Yukawa coupling strength can lead to large $|h_{ij}| \sim \mathcal{O}(10^{-2})$ couplings in eq.(2.12). As noted previously, FT in the cancelation of order $10^{-11}$ is needed to obtain tiny neutrino masses. Such cancelation is crucial to allow large $h_{ij}L_i^c\chi L_L$ couplings. Although the introduction of the RH neutrino sector will not enter the W-boson loops at one-loop level, larger values of $h_{ij}$ term will lead to larger tree level $SU(2)_c$ symmetry breaking effects, which are welcome to increase the new $\Delta m_W$.
Figure 2. We show the new physics contribution $\Delta m_\text{W}$ in ordinary GM model (the upper panels) and the GM model with a small misalignment among the triplet VEVs at the tree level (the lower panels). The dependences of $\Delta m_\text{W}$ on the mass of doubly charged scalar are also shown in both models. We also show explicitly the most stringent (model dependent) 846 GeV exclusion bound for doubly charged scalar.

We show the contributions to $\Delta m_\text{W}$ from such $h_{ij}$ terms in the left panel of fig.3. We can see in the left panels of fig.3 that our RH neutrino extended GM scenario without misalignment among the triplet VEVs cannot explain the new CDF II data on W-boson mass. The maximal contribution to $\Delta m_\text{W}$ is 0.03 GeV. Lower scale of $M_\text{R}$, which corresponds to larger value of $h_{ij}$, can possibly increase the new physics contributions to $\Delta m_\text{W}$. However, most of such points are ruled out by LFV constraints. Therefore, in comparison to ordinary GM model, large $h_{ij}$ terms (with the introduction of the RH neutrino sector) can increase the new physics contributions to $\Delta m_\text{W}$, but still not enough.

So, it is interesting to combine both small $SU(2)_c$ breaking effects to see the new physics contributions to $\Delta m_\text{W}$, that is, the presence of both large $h_{ij}$ coupling terms and the small misalignment among the triplet VEVs. It can be seen in the right panels of fig.3 that large $\Delta m_\text{W}$ can indeed be obtained easily. The 1σ range of CDF II data on W boson mass can be obtained even with tiny splitting among the triplet VEVs for $v_\xi - v_\chi \approx 1$ GeV. So it is advantageous to introduce the RH neutrino sector, which can not only explain easily the CDF II data on W boson mass, but also accommodate the leptogenesis mechanism and neutrino masses. It can also be seen that the total $SU(2)_c$ breaking effects are still not very large. The maximal contribution to $\Delta m_\text{W}$ is less than 0.08 GeV.
It is interesting to compare the GM model with the ordinary $SU(2)_L$ triplet extension model with $Y = 0$. In this case, the custodial $SU(2)_c$ symmetry is not kept. Consequently, we anticipate that this model can give large contribution to $\Delta m_W$. So, the new CDF II data on $m_W$ can at best be seen as a new constraint on such types of models. Numerical results show that the upper bound of doubly charged scalar is $1.1$ TeV if the new CDF II data on $\Delta m_W$ is explained in the $1\sigma$ range.

4 Conclusions

GM model can hardly account for the new CDF II data on W-boson mass in its original form. As anticipated, unless additional tree level $SU(2)_c$ custodial symmetry breaking effects are non-negligible, the new physics contributions to $\Delta m_W$ is always very small. Our numerical results show that ordinary GM model can contribute to $\Delta m_W$ a maximal amount $0.0012$ GeV, which can not explain the new CDF II data on W boson mass. We propose to introduce small misalignment among the triplet VEVs to increase $\Delta m_W$, which can reach $0.06$ GeV for $v_\xi - v_\chi \sim 6$ GeV, marginally explain the new data in $2\sigma$ range. We also propose to extend the GM model with low scale RH neutrino sector, which can adopt the leptogenesis mechanism and act as a large $SU(2)_c$ breaking source because of

Figure 3. We show the new physics contribution $\Delta m_W$ in the RH neutrino extended GM model without (left panels) and with (right panels) small misalignment among the triplet VEVs. The corresponding ranges of $M_R$ and the doubly charged scalar masses $m_{H^{++}}$ are also shown.
its correlation with $h_{ij}$. With low scale RH neutrino mass scale of order $10^2 \sim 10^4$ TeV, the new physics contribution $\Delta m_W$ can reach 0.03 GeV. Combining both small $SU(2)_c$ breaking effects, the small misalignment among the triplet VEVs and large $h_{ij}$ couplings, the 1$\sigma$ range of CDF II data on W boson mass can be obtained even for small splitting among the triplet VEVs with $v_\xi - v_\chi \approx 1$ GeV.

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