Atmospheric Neutrino Mixing and $b \to s$ Transitions: Testing Lopsided SO(10) Flavor Structure in $B$ physics

Xiangdong Ji, 1, 2 Yingchuan Li, 1 and Yue Zhang 2
1 Department of Physics, University of Maryland, College Park, Maryland 20742
2 Center for High-Energy Physics and Institute of Theoretical Physics, Peking University, Beijing 100080, P. R. China
(Dated: March 26, 2022)

We point out that the correlation between the large atmospheric neutrino mixing and the $b \to s$ transition, if exists, comes from the lopsided flavor structure in SO(10) grand unification theory. We suggest testing the correlation by studying the deviation of $S_{\phi K_S}$ and $S_{\eta'K_S}$ from the standard model predictions along with the constraints from $\Delta M_{B_d}$ and $b \to s \gamma$ in a realistic SO(10) model with lopsided flavor structure. We find a specific correlation between $S_{\phi K_S}$ and $S_{\eta'K_S}$ that is intrinsic to the lopsided structure and discuss how to confirm or rule out this flavor pattern by the more accurate measurements of these CP violation quantities in $B$ decay.

I. INTRODUCTION

The standard model (SM), although has passed many precision experimental tests, still has a number of outstanding problems which beg for a more fundamental theory. In terms of phenomenology, there is a number of places to test the more fundamental theory and, quite often, it is not one piece of phenomenology but a specific pattern of many pieces of phenomenology that fulfills this job.

Neutrino oscillation clearly indicates the beyond SM physics in that it violates the accidental symmetry $L_e, L_\mu, L_\tau$ of SM lepton flavor. Moreover, the tiny neutrino masses can be most naturally explained by the seesaw mechanism 1, indicating the Majorana nature of neutrinos that leads to violation of another accidental symmetry $B - L$ of SM at a very high scale close to the grand unification theory (GUT) scale. For this reason, studying neutrino oscillation in the GUT framework becomes particularly interesting.

In SO(10) GUT, quarks and leptons are unified into a single 16 multiplet, yet experimental data shows that the 2-3 (generation) mixing is dramatically different in the quark and lepton sectors. While the quark mixing angle $\theta_{23}^{CKM}$ is around 0.04, the lepton mixing angle $\theta_{23}^{PMNS}$ (atmospheric mixing angle) is quite large and could be a maximum of $\pi/4$. This difference can be rather naturally explained by the lopsidedness in the 2-3 sector of mass matrices of down-type quarks and charged leptons:

$$D_{23} \propto \begin{pmatrix} 0 & \sigma + \epsilon/3 \\ -\epsilon/3 & 1 \end{pmatrix}, \quad L_{23} \propto \begin{pmatrix} 0 & -\epsilon \\ \sigma + \epsilon & 1 \end{pmatrix}, \quad (1)$$

where $\sigma$ is of order one and generates large mixing for left-handed (LH) charged leptons and right-handed (RH) down-type quarks, while $\epsilon$ is much smaller than one and generates tiny mixing for RH charged leptons and LH down-type quarks. The group-theoretical origin of this lopsidedness can be most transparently seen in terms of the SU(5) multiplet— it is the charge conjugate of RH down-type quarks that sit together with LH lepton doublet in the 5 representation of SU(5). This lopsided structure can also be generated from SO(10) group structure.

Indeed, realistic SO(10) GUT models with lopsided mass matrices have been constructed in the literature. These different versions differ in many aspects but have the common structure as shown in Eq. (1). These models fit very well with all the fermion masses and mixings, including the neutrino sector through the first type of sea-saw mechanism, as well as producing the correct amount of baryon asymmetry through leptogenesis.

Given the successes of the SO(10) models with lopsided flavor structure, we are motivated to address the following question: what is the most characteristic feature of these models and where to test it?

From the lopsided structure itself as shown in Eq. (1), it is clear that the most characteristic feature of the models with lopsided structure is the large RH 2-3 mixing of down-type quarks associated with the large neutrino atmospheric mixing angle. The question is where and how to see its signature in other places for testing beyond SM physics. Clearly this RH mixing does not show up in the quark CKM (Cabbibo-Kobayashi-Maskawa) matrix, which is, in fact, the point of introducing lopsidedness to generate large lepton mixing and small quark mixing simultaneously. However, in the supersymmetry (SUSY) theory, this large RH mixing has the potential of generating sizable off-diagonal elements of soft mass matrices of squarks which, in turn, can be manifested in the flavor-changing neutral current interaction of down-type quarks, namely, the $b \to s$ transition.

The penguin dominated $b \to s$ transition has long been regarded as the golden channel for probing new physics. Moreover, if there are phases associated with the new physics contributing to this transition, there could be new CP violations in $B$ physics. Within the SM, the indirect CP asymmetry parameter $S_{\phi K_S}$ and $S_{\eta'K_S}$ are essentially the same as that of $B \to J/\psi K_S$: $S_{\phi K_S}^{SM} \approx S_{\phi K_S} \simeq S_{J/\psi K_S} = \sin 2\beta = 0.685 \pm 0.032$. However, the experimental values of $S_{\phi K_S}$ and $S_{\eta'K_S}$ from BaBar and
Belle \( E \) show large deviations from the SM prediction:

\[
S_{bK_S}^{\exp} = 0.50 \pm 0.25^{+0.07}_{-0.04} \quad \text{(BaBar),}
\]
\[
= 0.06 \pm 0.33 \pm 0.09 \quad \text{(Belle),}
\]
\[
S_{t'K_S}^{\exp} = 0.27 \pm 0.14 \pm 0.03 \quad \text{(BaBar),}
\]
\[
= 0.06 \pm 0.18 \pm 0.04 \quad \text{(Belle),}
\]

with the average of \( S_{bK_S}^{\exp} = 0.34 \pm 0.20 \) and \( S_{t'K_S}^{\exp} = 0.41 \pm 0.11 \), which display 1.7\( \sigma \) and 2.5\( \sigma \) deviations from the SM predictions, respectively. This significant discrepancy between SM prediction and experiment data has generated tremendous amount of effort in searching beyond SM physics.

Among these efforts, it has been pointed out in Ref. [6] that there could be correlation between the large atmospheric mixing and the large \( b \rightarrow s \) transition, based on the connection between LH charged leptons and RH down-type quarks in the framework of SO(10) GUT. However, it should be noted that, in fact, this correlation depends exclusively on the lopsided structure, which is the only way of realizing the possible connection between LH charged leptons and RH down-type quarks. Within other realistic SO(10) models [7] without lopsided structure, a set of parameters that are of the same order are combined constructively and destructively to give large atmospheric angle and small quark 2-3 mixing angle, respectively. Therefore, in these SO(10) models [7], there is typically no large RH down-type quark mixing associated with the large atmospheric mixing, and hence the correlation between atmospheric mixing and the \( b \rightarrow s \) transition is not realized.

Knowing the correlation between atmospheric neutrino mixing and the \( b \rightarrow s \) transition through the lopsided structure in SO(10), we test this possibility by investigating the predictions of CP conserving and CP violating observables associated with the \( b \rightarrow s \) transition in B physics from a particular lopsided SUSY SO(10) model constructed by us. [8]. Our study shows that the \( S_{bK_S} \) and \( S_{t'K_S} \) could indeed have large deviations from their SM values because of the large \( b \rightarrow s \) transition induced by the lopsided flavor structure in the SUSY context. Moreover, we find a particular pattern of correlation between \( S_{bK_S} \) and \( S_{t'K_S} \), which makes this class of models with lopsided structure distinguishable from other types of models. We expect, for example, the similar result from the model in [8], because these two models are nearly the same in the down-type quark sector.

This paper is organized as follows. Section II is devoted to the calculation of flavor violation parameters from the SO(10) model described in [8]. In Sec. III, we present the predictions of \( S_{bK_S} \) and \( S_{t'K_S} \), with the constraint from \( b \rightarrow s \gamma \) as well as the recent measurement of \( \Delta M_{B_S} \), in the model. Finally, we conclude in Sec. IV.

II. SUSY FLAVOR VIOLATION PARAMETERS FROM THE SO(10) GUT MODEL

The SUSY flavor violation and flavor-violating CP violation in the quark sector are induced by the off-diagonal elements of squark mass-squared matrices \( m_{AB}^2 \) with \( A,B = L,R \) indicating the chirality. In the mass insertion approximation (MIA) approach, the relevant parameters are \( \delta_{AB} \), which are the \( m_{AB}^2 \) divided by the average squark mass-squared. We restrict ourselves to studying the gluino contribution, which is believed to be the dominant one due to enhancement by the large gauge coupling \( \alpha_S \). In the gluino-induced contribution, the relevant parameters for the \( b \rightarrow s \) transition are the \( \delta_{LL,RR,LR,RL}^{d \phi K} \) of down-type quark. We are going to show how these parameters are calculated in the SO(10) GUT model in this section.

With the universality condition imposed at the SUSY breaking scale \( M_\ast \), we take as the Planck scale \( M_{Pl} = 10^{18}\text{GeV} \), and with the magnitude of \( \mu \)-parameter fixed from the radiative electroweak breaking, there are five SUSY parameters left: \( (m_0, m_{1/2}, A_0, \tan \beta, \phi_0) \). \( \tan \beta \) is fixed to be 10 when our SO(10) model is constructed to fit fermion masses [8]. The phase of \( \mu \)-parameter, \( \phi_\mu \), is constrained from the electric dipole moment (EDM) bounds, which, if assuming possible cancellation exists, restrict \( \phi_\mu \) to be within \( \pm \pi/10 \) from 0 or \( \pi \). [9]. We take the \( \phi_\mu \) to be in the range of \( (-\pi/10, \pi/10) \) for concreteness. Furthermore, we assume \( A_0 = 0 \) at \( M_\ast \) (see [10] for justification). A nonzero \( A_0 \) should not bring any significant change to the results since the alignment condition is assumed. Finally, we set two soft masses \( m_0 \) and \( m_{1/2} \), which are the universal soft scalar mass and gaugino mass at \( M_\ast \), respectively, to be within 1 TeV.

The off-diagonal elements of squark mass-squared matrices are generated from the renormalization group (RG) running between SUSY breaking scale \( M_\ast \) and the electroweak scale \( M_{EW} \). The GUT symmetry breaking scale, \( M_{GUT} = 2 \times 10^{16}\text{GeV} \), divides this running into two parts: above-\( M_{GUT} \) running and below-\( M_{GUT} \) running.

In the following discussion, we will stick to the super-KM basis for the squark fields, in which the neutral current quark-gaugino-squark vertices are diagonal.

Below the \( M_{GUT} \), there are two Yukawa couplings in the quark sector: \( \tilde{d}Y_d\chi H_d \) and \( \tilde{u}Y_u\chi H_u \). The running of \( (m_d^2)_{RR} \) is proportional to \( Y_dY_d^\dagger \) which is diagonal in the super-KM basis of RH down-type squarks. Therefore no off-diagonal element of \( (m_d^2)_{RR} \) should be generated from the below-\( M_{GUT} \) running. Nevertheless, the running of \( (m_d^2)_{LL} \) involve both \( Y_dY_d^\dagger \) and \( Y_uY_u^\dagger \). While the former is diagonal in the super-KM basis of LH down-type squarks, the latter is not and could generate the off-diagonal elements of \( (m_d^2)_{LL} \) \( \delta_{LL}^{d \phi K} \).

We have

\[
\delta_{LL}^{d \phi K} = \frac{3}{8\pi^2} (Y_d Y_u^\dagger)_{ij} \ln \left( \frac{M_{GUT}}{M_{EW}} \right) \tag{3}
\]

where the \( Y_a \) is in the basis of SU(2) doublet \( Q \) that \( Y_d \)
is diagonal.

Above the $M_{\text{GUT}}$, all the 16 fermions, including the RH neutrino, are in the 16 spinor representation of SO(10).

The soft mass-squared $m^2_{16}$ is renormalized by the single renormalizable operator $f_{33}161610_{\mu}$ in the model. As discussed in Ref. [12] the initial universal soft mass-squared $(m^2_{16})_{\text{M}} = \text{diag}(m^2_{3}, m^2_{0}, m^2_{0})$ is not kept at $M_{\text{GUT}}$: $(m^2_{16})_{\text{M,GUT}} = \text{diag}(m^2_{3}, m^2_{0}, m^2_{0} - \Delta m^2)$. The change of 3-3 element $\Delta m^2$ is due to the renormalization by the operator $f_{33}161610_\mu$:

$$
\Delta m^2 = \frac{60\eta^2_{0}}{16\pi^2} f_{33}^2 \ln(M_s/M_{\text{GUT}}).
$$

The parameter $f_{33}$ is not completely fixed in the model and we choose it to be 1/2, which is in the reasonable range. This non-universal, diagonal, soft mass-squared matrix is in the GUT basis. After being rotated to the super-KM basis, off-diagonal elements of $(m^2)^{d}_{RR,LL}$ are generated:

$$(m^2)^{d}_{RR,LL}|_{\text{super-KM}} = U^*_L R M_{16} L^* U_R$$

where $U_{L,R}$ are the unitary transformation matrices that diagonalize the down-type quark mass matrix $M^d_{R}$.

The $(\delta^d_{RR,LL})^\text{above-GUT}$ is obtained from $(m^2)^d_{RR,LL}|_{\text{super-KM}}$ divided by the average of its diagonal elements. Finally, the $(\delta^d_{RR,LL})^\text{above-GUT}$ is only from above-GUT running.

The point mentioned in Sec. I that the correlation between atmospheric neutrino mixing and $b \to s$ transition depends exclusively on the lopsided structure can be explicitly seen here: In the lopsided flavor structure, the 2-3 element of $M_d$ is large and induces a large 2-3 rotation $\theta^d_{23}$ in $U_R$. This large turn in production of large $(\delta^d_{23})^\text{above-GUT}$ as shown in Eq. (5). Finally, the large off-diagonal squark masses can generate a large $b \to s$ transition.

Although we set $A_0 = 0$ at $M_s$, it could be generated through radiative corrections. For $(m^2)^2_{RL,LR}$ the running below $M_{\text{GUT}}$, being proportional to $Y_d$, only induces diagonal elements in the super-KM basis. However, running from $M_s$ to $M_{\text{GUT}}$ does generate off-diagonal elements of $A_{LR,RL}$.

In the GUT basis

$$
A^d_{\text{RL,RL}}|_{\text{GUT}} = c \begin{pmatrix} 63 & 45\delta & 45\delta' \\ 45\delta & 0 & 45\sigma + 61\epsilon/3 \\ 45\delta' & -61\epsilon/3 & 63/2 \end{pmatrix} M_D,
$$

where $c = \frac{1}{3\sqrt{2}} g^2_{10} M_{1/2} \ln(M_{\text{GUT}}/M_s)$ and $\eta$, $\delta$, $\delta'$, $\epsilon$, and $M_D$ are parameters fixed in the model. The pre-coefficients 63/2, 45, and 61 are sums of Casimirs of SO(10) representation involved in the operator $16, 16, 10_H$, $16, 16, 10_{\mu}$, and $16, 16, 10_{\mu}$, respectively. Again, one simply applies $U_{L,R}$ on both sides of $A^d_{RL}$ to go to the super-KM basis

$$
A^d_{RL}|_{\text{super-KM}} = U^*_L A^d_{RL} U_R.
$$

III. FLAVOR-CHANGING NEUTRAL CURRENT EFFECTS IN B MESONS

The most general effective Hamiltonians $H_{e\mu}^{\Delta B=1}$ and $H_{\tau}^{\Delta B=2}$ for the non-leptonic $\Delta B = 1$ and $\Delta B = 2$ processes are

$$
H_{\text{eff}}^{\Delta B=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,3} \{ C_i(\mu) Q_i(\mu) + \tilde{C}_i(\mu) \tilde{Q}_i(\mu) \}
$$

$$
H_{\text{eff}}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu),
$$

where $C_i(\mu)$, $\tilde{C}_i(\mu)$ and $Q_i(\mu)$ are the Wilson coefficients and the local operators (not same in both hamiltonians), respectively. All the relevant contributions of high energy physics above W mass, including the SUSY particle contribution, enter the Wilson coefficients at $\mu = m_W$: $C(m_W)$ and $\tilde{C}(m_W)$. The matrix elements of local operators are, however, obtained at the energy scale of bottom quark mass $m_b$. Therefore, one needs to obtain the Wilson coefficients at low energy by solving the renormalization group equations of QCD and QED in the SM.

$$
C_i(m_b) = \sum_j U(m_b, m_W) C_j(m_W),
$$

where the evolution matrix $U(m_b, m_W)$ for $\Delta B = 1$ and $\Delta B = 2$ Wilson coefficients can be found in Ref. [13] and Ref. [14], respectively.

The SM and SUSY contributions to Wilson coefficients can be found in Refs. [13, 16]. It is worth noting that the SUSY contribution depends on the squark mass $m_{\tilde{q}}$ and gluino mass $m_{\tilde{g}}$, which are larger than the universal soft scalar mass $m_0$ and gaugino mass $m_{1/2}$ due to the
RG running. We use the matrix elements of local operators evaluated in QCD factorization (QCDF), developed in Ref. [17], which makes the strong phase calculable, yet introduces undetermined parameters $\rho_{H,A}$ and phases $\phi_{H,A}$.

To make prediction of $S_{0K_S}$, we first impose constraints on the parameter space by requiring the prediction of branching ratio and CP asymmetry of $b \to s\gamma$ and $\Delta M_{B_S}$ to be within the experimental bounds.

The gluino contribution to the branching ratio $b \to s\gamma$ is [15]

$$BR(b \to s\gamma)\tilde{g} = \frac{\alpha_s^2}{81\pi^2m_{\tilde{g}}} \{|m_{\tilde{g}}M_3(x)|(\delta_{LL}^d)_{23} \rangle + m_{\tilde{g}}M_1(x)\rangle^2 + L \leftrightarrow R\},$$

where the loop functions $M_1(x)$ and $M_3(x)$ with $x = m_{\tilde{g}}^2/m_t^2$ can be found in Ref. [15]. As discussed in Ref. [15], the experimental bound and the SM uncertainty together require that the gluino contribution $BR(b \to s\gamma)\tilde{g} < 4 \times 10^{-4}$. The bound on the CP asymmetry $A^{CP}_{b \to s\gamma}$ plays no significant role in constraining the parameter space. Therefore we neglect its discussion here, although we have included it in the calculation in the same way as in Ref. [16].

The D0 and CDF Collaborations [18] have reported new results for $\Delta M_{B_S}$:

$$17 \text{ ps}^{-1} < \Delta M_{B_S} < 21 \text{ ps}^{-1} \quad \text{(D0)},$$

$$\Delta M_{B_S} = 17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1} \quad \text{(CDF)},$$

while the best fit value in SM is $\Delta M_{B_S} = 17.5 \text{ ps}^{-1}$. This imposes the constraint $|R_{M}| = |M_{12}^{SU5Y}/M_{12}^{SM}| \leq 4/17$, where $M_{12} = \langle B_d^{0}|H^2_{\text{eff}}|B_s^{0}\rangle$. One should notice that this bound remains valid if one considers the uncertainty in the SM value and assumes $\Delta M_{B_S} = 21 \text{ ps}^{-1}$ [19].

The decay amplitudes of $B_d \to \phi K_s$ are given by [116]

$$A_{B_d \rightarrow \phi K_s} = -\frac{G_F}{\sqrt{2}} m_{B_d} E_{B_d} f_{\phi}$$

$$\times \sum_{i=1 \sim 10} H_i(\phi)(C_i + \tilde{C}_i),$$

where $f_{\phi} = 0.233\text{GeV}$ and $F_{B_d \rightarrow K_s} = 0.35$ is the transition form factor evaluated at transferred momentum of order of $m_{\phi}$. The $H_i$'s are dependent on QCDF parameters $\rho_{H,A}$ and $\phi_{H,A}$ in such a way as given in Ref. [16].

The SUSY contribution modifies the CP asymmetry as

$$S_{0K_s} = \sin 2\beta + 2\cos 2\beta \sin \theta_{\phi} \cos \delta_{\phi} R_{\phi} + O(R_{\phi}^2)$$

where $R_{\phi}$, $\theta_{\phi}$, and $\delta_{\phi}$ are defined in the ratio

$$A_{B_d \rightarrow \phi K_s}^{SU5Y}/A_{B_d \rightarrow \phi K_s}^{SM} \equiv R_{\phi} e^{i\theta_{\phi}} e^{i\delta_{\phi}}.$$

One thing worth noting is that due to the fact that, contrary to the $B \to \phi K$ transition, the initial and final states in $B \to \eta'K$ transition have opposite parity and therefore $\langle \eta'|K|B\rangle = -\langle \eta'|Q_i|B\rangle$, $C_i$ and $\tilde{C}_i$ appear in such combinations as $C_i - \tilde{C}_i$ in the amplitude.
exclusively due to the large $(\delta_S^{dL})$, which, together with Fig. 2, shows clearly that the large structure.

find the allowed $(\delta_{LR})$, which are discussed in Sec. II, the undetermined parameters $\rho_{H,A}$ are constrained by $BR(B_d \rightarrow \phi K_S)$ to be within $\rho_{H,A} \leq 2 \ [10]$, and the strong phase $\phi_{H,A}$ is not constrained.

By scanning over the allowed ranges of undetermined parameters $(m_0, m_{1/2}, \tan \beta, \phi_\mu)$ and imposing the bound of $\Delta M_{B_S}$, as well as $BR(b \rightarrow s \gamma)$ and $A_{CP}^{S}$, we find the allowed $(m_0, m_{1/2})$ shown in Fig. 1: There is a large parameter space of $m_0, m_{1/2}$ satisfying the bound.

The corresponding predictions of $S_{\theta K_S}$ and $S_{\eta' K_S}$ are shown in Fig. 2. From which we see that the large $(\delta_{RR}^{d})$ does push the $S_{\theta K_S}$ and $S_{\eta' K_S}$ off their SM value 0.685. For the purpose of comparison, we set by hand the $(\delta_{LR}^{d})$ to be of the size of $(\delta_{LL}^{d})$, which would be the case without lopsided structure, and present the corresponding prediction of $S_{\theta K_S}$ and $S_{\eta' K_S}$ in Fig. 3, which, together with Fig. 2, shows clearly that the large deviation of $S_{\theta K_S}$ and $S_{\eta' K_S}$ from their SM values are exclusively due to the large $(\delta_{LR}^{d})$ from the lopsided structure.

While Fig. 2 shows that the lopsided structure may explain the anomalies of both $S_{\theta K_S}$ and $S_{\eta' K_S}$, the correlation between the predictions of these two quantities, shown in Fig. 4, indicate an interesting pattern: the large $(\delta_{LR}^{d})$ push $S_{\theta K_S}$ and $S_{\eta' K_S}$ in opposite directions. For points that $S_{\theta K_S}$ goes small, the $S_{\eta' K_S}$ goes larger, and vice versa. As discussed above, this specific pattern is intrinsic to the large $(\delta_{RR}^{d})$, which induces large $(\delta_{RL}^{d})$ yet leaves $(\delta_{LR}^{d})$ small. Therefore, it is tightly associated with the lopsided flavor structure. This specific pattern of correlation between $S_{\theta K_S}$ and $S_{\eta' K_S}$ means that the lopsided flavor structure cannot be responsible for both anomalies simultaneously. If future experiments confirm that $S_{\theta K_S}$ and $S_{\eta' K_S}$ are indeed both significantly smaller than the SM values, the lopsided SO(10) model is ruled out unless one assumes that SUSY parameters are such that large $(\delta_{RL}^{d})$ from the lopsided structure makes no significant contribution to the $b \rightarrow s$ transition and the $S_{\theta K_S}$ and $S_{\eta' K_S}$ anomalies are from other beyond SM physics sources. On the other hand, if future experiments show the deviation of $S_{\theta K_S}$ and $S_{\eta' K_S}$ from their SM values in opposite directions, it would be a strong evidence for the lopsided flavor structure.

IV. CONCLUSION

In this paper, we pointed out that a possible correlation between large atmospheric neutrino mixing and the $b \rightarrow s$ transition, first discussed in Ref. [10], in fact, depends exclusively on the lopsided SO(10) structure. We studied the prediction of $S_{\theta K_S}$ and $S_{\eta' K_S}$ from a realistic SO(10) model with lopsided flavor structure with the constraints from $\Delta M_{B_S}$, $b \rightarrow s \gamma$ applied. We found that both quantities can show significant deviations from their SM values due to the lopsided flavor structure, but with a specific type of correlation. We discussed that the specific correlation of the two quantities can be used to test the flavor structure by future experiments.

X. Ji and Y. Li are partially supported by the U. S. Department of Energy via grant DE-FG02-93ER40762 and by National Natural Science Foundation of China (NSFC), and Y. Zhang is supported by the NSFC grants 10421503 and 10625521. Y. Li thanks R. N. Mohapatra, M. Ramsey-Musolf and P. Rastogi for helpful discussions and Z. Z. Xing for his hospitality at High Energy Institute of Physics, Beijing where part of this research was completed.

[1] P. Minkowski, Phys. Lett. B67, 421 (1977); M. Gell-Mann, P. Ramond, and R. Slansky, Supergravity (P. van Nieuwenhuizen et al. eds.), North Holland, Amsterdam, 1980, p. 315; T. Yanagida, in Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe (O. Sawada and A. Sugamoto, eds.), KEK, Tsukuba, Japan, 1979, p. 95; S. L. Glashow, The future of elementary particle physics, in Proceedings of the 1979 Cargèse Summer Institute on Quarks and Leptons (M. Lévy et al. eds.), Plenum Press, New York, 1980, pp. 687; R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 44, 912 (1980).
[2] C. H. Albright, K. S. Babu and S. M. Barr, Phys. Rev. Lett. 81, 1167 (1998); C. H. Albright and S. M. Barr, Phys. Rev. D 58, 013002 (1998); Phys. Rev. D 62, 093008 (2000); C. H. Albright, Phys. Rev. D 72, 013001 (2005);
[3] X. Ji, Y. Li and R. N. Mohapatra, Phys. Lett. B 633: 755, (2006).
[4] C. H. Albright and S. M. Barr, Phys. Rev. D 70, 033013 (2004); X. Ji, Y. Li and R. N. Mohapatra, S. Nasri, and Y. Zhang [arXiv:hep-ph/0605088];
[5] M. A. Giorgi, Babar Collaboration, Plenary Talk at XXXII Int. Conference on High Energy Physics, Beijing, China, 16-22 August 2004, [http://ichep04.ihep.ac.cn] Y. Sakai, Belle Collaboration, Plenary Talk at XXXII Int. Conference on High Energy Physics, Beijing, China, 16-22 August 2004, [http://ichep04.ihep.ac.cn]
[6] D. Chang, A. Masiero, and H. Murayama, Phys. Rev. D, 67, 075013 (2003); R. Harnik, D. T. Larson, H. Murayama, and A. Pierce, Phys. Rev. D, 69, 094024 (2004);
[7] See for an incomplete list of SO(10) model without lopsided structure: K. Babu, J. Pati, and F. Wilczek, Nucl. Phys. B566, 33 (2000); T. Blazek, S. Raby, and K. Tobe, Phys. Rev. D62, 055001 (2000); M.-C. Chen and K. T. Mahanthappa, Phys. Rev. D65, 053010 (2002); H. S. Goh, R. N. Mohapatra, and S. P. Ng, Phys. Rev. D68, 115008 (2003)
[8] S. Bertolini, F. Borzumati, A. Masiero, Nucl. Phys. B 294, 321 (1987); R. Barbieri, A. Strumia, Nucl. Phys. B 508, 3 (1997); M. Ciuchini, E. Franco, A. Masiero, L. Silvestrini, Phys. Rev. D 67, 075016 (2003)
[9] S. Abel, S. Khalil, and O. Lebedev, Nucl. Phys. B 606, 151 (2001)
[10] V. Barger, T. Falk, T. Han, J. Jiang, T. Li, and T. Plehn, Phys. Rev. D 64, 056007 (2001)
[11] Z. Chacko, M. A. Luty, A. E. Nelson and E. ponton, JHEP, 0001, 003 (2000); D. E. Kaplan, G. D. Kribs and M. Schmaltz, Phys. Rev. D62, 035010 (2000)
[12] R. Barbieri, L. Hall, and A. Strumia, Nucl. Phys. B 445, 219 (1995); Nucl. Phys. B 449, 437 (1995)
[13] G. Buchalla, A. J. Buras, M. E. Lautenbacher, Rev. Mod. Phys. 68, 1125 (1996)
[14] D. Becirevic, et. al. Nucl. Phys. B634, 105, (2002)
[15] F. Gabbiani, E. Gabrielli, A. Masiero, and L. Silvestrini, Nucl. Phys. B477, 321 (1996)
[16] E. Gabrielli, K. Huitu, and S. Khalil, Nucl. Phys. B710, 139 (2005)
[17] M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, Phys. Rev. Lett. 83, 1914 (1999); Nucl. Phys. B 591, 313 (2000); M. Beneke, M. Neubert, Nucl. Phys. B 651, 225 (2003); Nucl. Phys. B 675, 333 (2003)
[18] V. Abazov (D0 Collaboration), Phys. Rev. Lett. 97, 021802 (2006); G. Gomez-Ceballos (CDF Collaboration), [http://fpcp2006.triumf.ca/agenda.php]
[19] S. Khalil, Phys. Rev. D 74, 035005 (2006)