Bounds on R-parity violating supersymmetric couplings from leptonic and semi-leptonic meson decays

H. K. Dreiner

Physikalisches Institut der Universität Bonn, Nußallee 12, 53115 Bonn, Germany

M. Krämer

Institut für Theoretische Physik E, RWTH Aachen, 52056 Aachen, Germany

Ben O’Leary

School of Physics, University of Edinburgh, Edinburgh EH9 3JZ, Scotland

We present a comprehensive update of the bounds on R-Parity violating supersymmetric couplings from lepton-flavour- and lepton-number-violating decay processes. We consider $\tau$ and $\mu$ decays as well as leptonic and semi-leptonic decays of mesons. We present several new bounds resulting from $\tau$, $\eta$ and Kaon decays and correct some results in the literature concerning $B$-meson decays.

I. INTRODUCTION

When extending the symmetries of the Standard Model of particle physics (SM) \[1,2\] to include supersymmetry \[3\], the Yukawa couplings are fixed by the renormalisable superpotential \[4,5\]

\[
W = W_{P_6} + W^E_{P_6} + W^B_{P_6},
\]

\[
W_{P_6} = \epsilon_{ab} \left( h^E_{ij} L^a_i E^b_j + h^D_{ij} Q^a_i D^b_j + h^U_{ij} Q^a_i U^b_j + \mu H^a_u H^b_u \right),
\]

\[
W^E_{P_6} = \epsilon_{ab} \left( \frac{1}{2} \lambda_{ijk} L^a_i L^b_j \tilde{E}_k + \lambda'_{ijk} L^a_i Q^b_j D^b_k + \kappa L^a_i H^b_u \right),
\]

\[
W^B_{P_6} = \frac{1}{2} \epsilon_{rst} \lambda''_{ijk} \tilde{U}_r^i \tilde{D}_s^j \tilde{D}_t^k.
\]

Here, $i, j, k = 1, 2, 3$ are generation indices, $a, b = 1, 2$ are SU(2) and $r, s, t = 1, 2, 3$ are SU(3) indices. $L, \tilde{E}$ denote the lepton doublet and singlet left-chiral superfields; $Q, \tilde{U}, \tilde{D}$ denote the quark doublet and singlet superfields, respectively. $h^E, h^D, h^U, \lambda, \lambda', \lambda''$ are dimensionless coupling constants and $\mu, \kappa$ are mass mixing parameters.

Together the operators in $W^E_{P_6}$ and $W^B_{P_6}$ lead to rapid proton decay in disagreement with the experimental lower bounds on the proton lifetime \[6\]. A possible solution to this problem is to introduce the discrete $\mathbb{Z}_6$ symmetry, proton hexality, $P_6$ \[7\], which prohibits both $W^E_{P_6}$ and
as well the dangerous dimension-5 proton decay operators; this is the minimal supersymmetric Standard Model (MSSM) \cite{9}. (Note that the widely used discrete $\mathbb{Z}_2$ symmetry R-parity does not prohibit the dimension-five proton decay operators.) However, in order to stabilize the proton it is sufficient to prohibit either the superpotential $W^E_{P_b}$ via baryon-triality \cite{10, 11} or the superpotential $W^B_{P_b}$ via lepton-parity \cite{10}. Lepton-parity is not discrete gauge anomaly-free \cite{12} and we thus disregard it in the following. Baryon-parity has the further advantage of allowing for non-zero neutrino masses without the need for right-handed neutrinos. We thus consider here the total superpotential given by

$$W = W_{P_b} + W^E_{P_b}. \quad (I.5)$$

We shall focus exclusively on the tri-linear couplings. At any given scale the bi-linear terms $\kappa_i L_i H_2$ can be rotated away through a basis redefinition \cite{13}. This is not true, when embedding the theory in a more unified model, e.g. supergravity \cite{14, 15}. However, at $M_{Pl}$ the natural value is $\kappa_i = 0$ \cite{15}, which leads to $\kappa_i \ll M_W$ at low-energy. Thus the bi-linear terms are mainly relevant for neutrino masses, see for example \cite{11, 16}, and we shall neglect them in the following.

The tri-linear operators in $W^E_{P_b}$ lead to novel supersymmetric collider signatures beyond those of the MSSM \cite{17}. In particular, the operators in $W^E_{P_b}$ induce lepton flavour violation (LFV) as well as lepton number violation, neither of which has been observed \cite{18}.

There is an extensive literature on the resulting bounds on the operators $W^E_{P_b}$ from indirect processes, see e.g. Refs. \cite{13, 15, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30}, including also several overviews \cite{31, 32, 33, 34, 35, 36, 37, 38}. However, due to the improved data in particular on $B$-meson and $\tau$ decays, it is the purpose of this paper to present a systematic update of the bounds resulting from lepton decays as well as leptonic and semi-leptonic decays of mesons. In the process, we have found several new bounds resulting from $\tau$, $\eta$ and Kaon decays. We have also found a need to correct some results in the literature with respect to $B$-meson decays.

Our paper is organized as follows. In Sect. II A we start from an effective Lagrangian, where the supersymmetric scalar fermions have been integrated out and then present the treatment of the QCD bound state in Sect. II B. General analytic expressions for the decay rates of the various lepton and meson decays are shown in Sect. II C. In Sect. III we insert the present experimental results into the analytical expressions to obtain our new bounds. These are summarized in Tables II - XII. In Sect. IV we discuss the implications of our results. Formulæ for the meson decay constants and the general lepton and meson decay matrix elements are collected in the Appendices.
II. THEORETICAL ANALYSIS

A. Effective Lagrangian

Because the sfermions are constrained to be heavy, \( m_{\tilde{\nu}, \tilde{q}} \gtrsim 100 \text{ GeV} \gg M_B \) (this work does not consider the decays of particles heavier than B mesons), we approximate their propagators as static \( 1/m_{\tilde{f}}^2 \). This is equivalent to integrating out the sfermionic degrees of freedom to obtain an effective interaction Lagrangian \([39]\) and taking only the leading term in an expansion in inverse sfermion mass,

\[
L_{\text{eff}} = \sum_{g=1}^{3} \left\{ \frac{1}{m_{\tilde{\nu}}^2} \lambda_{gab} \lambda_{gcd}^* (\bar{l}^c P_R l^d)(\bar{t}^b P_L l^a) + \frac{1}{m_{\tilde{\nu}}^2} \lambda_{gik} \lambda_{gmn}^* (\bar{d}^m P_R d^m)(\bar{t}^k P_L l^i) + \text{h.c.} \right\}
\]

where (II.6) and (II.7) result from integrating out the sneutrino fields, and (II.8) and (II.9) result from integrating out the up-type and down-type squark fields respectively, using some Fierz identities. The index \( g \) denotes the generation. There are additional terms in the effective Lagrangian which arise when integrating out the charged sleptons, which we do not consider here: For the product of two \( LL\bar{E} \) or an \( LL\bar{E} \) and an \( LQ\bar{D} \) operator, these lead to neutrinos in the final state. Thus lepton flavour violation is not observable in the resulting lepton or meson decays; for the product of two \( LQ\bar{D} \) operators, the resulting meson decays are purely hadronic.

In the following, we shall assume that the decay is dominated by the exchange of a sfermion of a single generation, either because it is lighter than the others or because it has a larger product of couplings (the double coupling dominance convention). Subsequent expressions with an index \( g \) are thus implicitly for only one value of \( g \), though one may always deduce the general result by replacing expressions like \( |\lambda'_{gjk} \lambda'_{glm}/m_{\tilde{\nu}}^2| \) with \( |\sum_{g} \lambda'_{gjk} \lambda'_{glm}/m_{\tilde{\nu}}^2| \) etc.

It is also assumed in this paper that the sneutrino–higgsino and squark mixing can be neglected. Such mixings just add to the notational burden. If one insists on accounting for mixing, one can make the replacement \( |\lambda'_{gjk} \lambda'_{glm}/m_{\tilde{\nu}}^2| \rightarrow |\sum_{g,x,y} \lambda'_{xjk} U_{xg} U_{yg}^\dagger \lambda'_{glm}/m_{\tilde{\nu}}^2| \) etc. for squark mixing matrices \( U \), with a similar expression for mixing between the sneutrinos and Higgses.
B. Meson decay constants

The decay constant, \( f_V \), of a vector meson \( V \) with momentum \( p_V \) is defined as

\[
\langle 0 | \bar{q} \gamma^\mu q | V(p_V) \rangle = H_V^{\alpha \beta} f_V m_V \epsilon^\mu_V ,
\]

where \( \epsilon^\mu_V \) is the polarization vector of \( V \), \( m_V \) is the vector meson mass, and \( H_V^{\alpha \beta} \) is the coefficient of \( \bar{q}_\alpha q_\beta \) in the quark model wavefunction of the meson, e.g. \( H_{\rho}^{uu} = \frac{1}{\sqrt{2}} \), \( H_{\rho}^{dd} = -\frac{1}{\sqrt{2}} \).

For a pseudoscalar meson \( P \), we use the PCAC condition and define the decay constant \( f_P \) through the axial vector matrix element

\[
\langle 0 | \bar{q} \gamma^\mu \gamma^5 q | P(p_P) \rangle = i H_P^{\alpha \beta} f_P p^\mu_P ,
\]

where \( H_P^{\alpha \beta} \) is the analogue of \( H_V^{\alpha \beta} \). As described in Appendix A, the equation of motion for the quark fields can be used to derive the pseudoscalar matrix element from the axial vector matrix element (II.11). We find

\[
\langle 0 | \bar{q} \gamma^5 q | P(p_P) \rangle = \frac{i H_P^{\alpha \beta} f_P m_P^2}{\mu_P} .
\]

The factor \( \mu_P^{\alpha \beta} \) is proportional to the sum of current quark masses \( m_\alpha \) and \( m_\beta \), e.g. \( \mu_{\pi^0}^{uu} = -2m_u \) and \( \mu_{\pi^0}^{dd} = 2m_d \). For the proper definition of \( \mu_P^{\alpha \beta} \), a list of the coefficients \( H_P^{\alpha \beta} \) and more details see Appendix A.

C. Decay rates

The Feynman graphs and matrix elements for the various decays considered in this paper are given in Appendix B. Upon squaring the matrix elements, summing over the final spin states and averaging over the initial spin states, we arrive at the following expressions for the decay widths:

- For a heavy lepton \( a \) decaying into leptons \( b \) and \( c \) and an anti–lepton \( \bar{d} \),

\[
\Gamma_{a \to bcd} = \frac{m_a^5}{6144\pi^3 m_\rho^4} (\lambda_{gcd}^2 \lambda_{gba}^2 + \lambda_{gcd}^2 \lambda_{gab}^2 + \lambda_{gdb}^2 \lambda_{gca}^2 + \lambda_{gbd}^2 \lambda_{gac}^2) ,
\]

where we approximate the final state (anti–)leptons as massless.
• For a heavy lepton \( l \) decaying into a lepton \( k \) and a vector meson consisting of valence quark \( n \) and anti–quark \( m \), there are two cases: up–type squark–mediated:

\[
\Gamma_{l \rightarrow k + V} = \left| \sum_{d\text{-type}} (\lambda'^{l}_{ign} \lambda'^{k}_{gm}) H_{V}^{mn} \right|^{2} \frac{(m_{l}^{2} - m_{V}^{2})^{2}}{512 \pi m_{d}^{4}} \frac{|f_{V}|^{2}}{m_{l}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right),
\]

or down–type squark–mediated:

\[
\Gamma_{l \rightarrow k + V} = \left| \sum_{u\text{-type}} (\lambda'^{l}_{img} \lambda'^{k}_{kn}) H_{V}^{mn} \right|^{2} \frac{(m_{l}^{2} - m_{V}^{2})^{2}}{512 \pi m_{d}^{4}} \frac{|f_{V}|^{2}}{m_{l}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right),
\]

where we have introduced the notation \( \sum_{d\text{-type}} \) to mean only summing over the down–type quarks in the meson and \( \sum_{u\text{-type}} \) to mean summing over the up–type quarks.

• For a heavy lepton \( l \) decaying into a lepton \( k \) and a pseudoscalar meson consisting of valence quark \( n \) and anti–quark \( m \), there are three cases: up–type squark–mediated:

\[
\Gamma_{l \rightarrow k + P} = \left| \sum_{d\text{-type}} (\lambda'^{l}_{ign} \lambda'^{k}_{gm}) H_{P}^{mn} \right|^{2} \frac{(m_{l}^{2} - m_{P}^{2})^{2}}{512 \pi m_{d}^{4}} \frac{|f_{P}|^{2}}{m_{l}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right),
\]

down–type squark–mediated:

\[
\Gamma_{l \rightarrow k + P} = \left| \sum_{u\text{-type}} (\lambda'^{l}_{img} \lambda'^{k}_{kn}) H_{P}^{mn} \right|^{2} \frac{(m_{l}^{2} - m_{P}^{2})^{2}}{512 \pi m_{d}^{4}} \frac{|f_{P}|^{2}}{m_{l}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right),
\]

or sneutrino–mediated:

\[
\Gamma_{l \rightarrow k + P} = \left( \left| \sum_{d\text{-type}} \lambda'^{*}_{gki} \lambda'^{*}_{gm} \frac{H_{P}^{mn}}{\mu_{P}^{mn}} \right|^{2} + \left| \sum_{d\text{-type}} \lambda'^{*}_{gki} \lambda'^{*}_{gm} \frac{H_{P}^{mn}}{\mu_{P}^{mn}} \right|^{2} \right)
\times \frac{(m_{l}^{2} - m_{P}^{2})^{2}}{128 \pi m_{d}^{4}} \frac{|f_{P}|^{2}}{m_{l}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right).
\]

• For a vector meson \( V \) decaying into a lepton of generation \( k' \) and an anti–lepton of generation \( i' \), there are again two cases: up–type squark–mediated:

\[
\Gamma_{V \rightarrow k' + \bar{i}'} = \left| \sum_{d\text{-type}} (\lambda'^{k'gmn} \lambda'^{\bar{i}'gn'}) H_{V}^{m'n'} \right|^{2} \frac{(m_{V}^{2} - m_{P}^{2})^{2}}{768 \pi m_{d}^{4}} \frac{|f_{V}|^{2}}{m_{V}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right)
\]

or down–type squark–mediated:

\[
\Gamma_{V \rightarrow k' + \bar{i}'} = \left| \sum_{u\text{-type}} (\lambda'^{k'g'nm} \lambda'^{\bar{i}'g'm}) H_{V}^{m'n'} \right|^{2} \frac{(m_{V}^{2} - m_{P}^{2})^{2}}{768 \pi m_{d}^{4}} \frac{|f_{V}|^{2}}{m_{V}^{3}} \left( 1 + \mathcal{O} \left( \frac{m_{l}}{m_{V}} \right) \right).
\]
For a pseudoscalar meson $P$ decaying into a lepton of generation $k'$ and an anti-lepton of generation $i'$, there are again three cases: up–type squark–mediated:

$$
\Gamma_{P \rightarrow l k' \bar{l} i'} = \sum_{d-\text{type}} (\lambda'_{k'g'm'} \lambda'_{i'g'n'}) H_{P}^{m'n'} \left| \frac{2 (m_{P}^{2} - m_{l i'}^{2})^{2} |f_{P}|^{2} m_{i'}^{2}}{256 \pi m_{d g}^{4}} \right| \left( 1 + \mathcal{O} \left( \frac{m_{k'}}{m_{P}} \right) \right), \quad (\text{II.21})
$$

down–type squark–mediated:

$$
\Gamma_{P \rightarrow l k' \bar{l} i'} = \sum_{u-\text{type}} (\lambda'_{k'g'm'} \lambda'_{i'g'n'}) H_{P}^{m'n'} \left| \frac{2 (m_{P}^{2} - m_{l i'}^{2})^{2} |f_{P}|^{2} m_{i'}^{2}}{256 \pi m_{d g}^{4}} \right| \left( 1 + \mathcal{O} \left( \frac{m_{k'}}{m_{P}} \right) \right), \quad (\text{II.22})
$$
or sneutrino–mediated:

$$
\Gamma_{P \rightarrow l k' \bar{l} i'} = \left( \sum_{d-\text{type}} \lambda'_{g k' \bar{\nu} m'} \lambda'_{g n' \bar{\nu} m'} H_{P}^{m'n'} \right)^{2} + \left( \sum_{d-\text{type}} \lambda_{g k' \bar{\nu} m'} \lambda'_{g n' \bar{\nu} m'} H_{P}^{m'n'} \right)^{2} \times \left( \frac{64 \pi m_{d g}^{4}}{f_{P}^{2} m_{P}^{2}} \right) \left( 1 + \mathcal{O} \left( \frac{m_{k'}}{m_{P}} \right) \right), \quad (\text{II.23})
$$

### III. NUMERICAL RESULTS

We assume for simplicity the double coupling dominance hypothesis, that the bounds from any one experimental result are applied to only one product of couplings.

The input values for the various fermion and meson masses and decay constants are listed in Table II. All the $f_{P}$ values and masses were taken from the 2006 edition of Review of Particle Physics by the Particle Data Group (PDG) [18]. The $f_{V}$ values were calculated from $V \rightarrow e^{+}e^{-}$ according to

$$
\Gamma(V \rightarrow e^{+}e^{-}) = \frac{4 \pi \alpha^{2}}{3 m_{V}} f_{V}^{2} c_{V}, \quad (\text{III.24})
$$

where $c_{V}$ are factors determined by the electric charge of the quarks that built up the meson [41].

The experimental results on lifetimes, decay widths and branching fractions are also taken from the 2006 review of the PDG [18].

In Tables III, IV and V we present what may be considered the most interesting results of our analysis. The coupling combinations which had no bounds previously are collected in Table III. Those combinations which have improved by a factor of 30 or more are presented in Table IV, and the cases where the new combined bound is better than the previously published product of individual bounds are presented in Table V. Here and in the following, the symbol $[\tilde{f}]$ denotes $m_{\tilde{f}}/(100 \text{ GeV})$, i.e. the sfermion mass in units of 100 GeV. This also indicates the mediating
sfermion for the decay. The superscript †(-) in Table II indicates that this bound comes from a decay which involves a difference of couplings, so there could be a cancellation which would lead to the double coupling dominance hypothesis giving an excessively tight bound. While we also include very loose bounds in our listings, we note that couplings \( \lambda \gtrsim O(2\pi) \) would imply a breakdown of our perturbative analysis.

In Tables V to XV we collect all our bounds on the products of couplings \( \lambda_{ijk} \lambda_{lmn}' \). The results have been arranged so that the number made from reading off the indices of the couplings to make a six–digit number \( ijklmn \) ascends.

In the rightmost columns of Tables V to XV, “New” indicates a previously unpublished result (see also Table II), “Upd.” indicates that the bound has been updated and tightened in this paper, “Agr.” indicates that the bound has not changed and we agree with the previously published result [42], and “Unimp.” indicates that our bound from decay data is less strong than the previously published result, which in these cases is from a different experimental source (e.g. the non–observation of \( \mu \rightarrow e \) in \( ^{48}\text{Ti} \) gives a better bound on \( \lambda_{121} \lambda_{111} \tilde{\nu}_1^2 \) than that of \( \pi^0 \rightarrow e\bar{\mu} \)). “Corr.” indicates that we disagree with the previously published result [43], “Corr.(<)” indicating that our result is stronger than the incorrect previous bound and “Corr.(>)” indicating that our result is less strong. The reference in this column gives the previous published bound. Where two references are given, the comparison is between our bound on a product of two couplings and the product of the bounds on individual couplings.

Note that the \( B \rightarrow ll \bar{l} \) decays can proceed through Standard Model interactions [51]. However, the SM contribution is suppressed by a small CKM matrix element and by the decay only arising at one–loop level and has thus been neglected in our analysis.

IV. DISCUSSION

The bounds presented here generally update those presented in the literature, with the noted disagreement with some of the bounds coming from the \( B \) meson data. Many bounds have been improved, some through tighter experimental decay bounds like those from \( \tau \) decays, others through using \( \tau \rightarrow K_S l^- \) instead of \( \tau \rightarrow K^0 l^- \), which also leads to some previously unpublished bounds. The \( \eta \) decay data was also previously unpublished, but does not seem particularly useful, with bounds of order \( 10^2 \bar{f}_2^2 \). The decay \( \tau \rightarrow \eta l^- \) seems to give previously unpublished bounds too, which are more stringent. The decay \( \tau \rightarrow \phi l^- \) leads to bounds which are less strong
than those from $\tau \rightarrow \eta l^-$. Note, however, that $\tau \rightarrow \phi l^-$ is free from potential interference effects induced by the coupling of the mediating squark to both down and strange quarks.

Assuming that the sfermion masses are of order 100 GeV and taking the square root of the bound on a coupling product to be a rough guide to the bound on each coupling gives an estimate of the couplings $\lambda$ being of order 0.01, apart from the very tight bounds from the non-observation of $\mu \rightarrow e\nu\bar{e}$. The bounds on the couplings $\lambda'$ vary considerably, though those involving a third generation quark are consistently of order 0.01. Since these come from $B$ meson decays, they are likely to become even tighter with more data from $B$ factories.
### TABLE I: Input parameters.

| Pseudoscalar meson | Mass (in GeV) | $f_P$ (in GeV) | Fundamental fermion | Mass (in GeV) |
|---------------------|--------------|----------------|-------------------|--------------|
| $\pi^0$             | 0.135        | 0.130          | $e$               | $5.11 \times 10^{-4}$ |
| $K_S$               | 0.498        | 0.160          | $\mu$             | 0.106        |
| $K_L$               | 0.498        | 0.160          | $\tau$            | 1.777        |
| $\eta$              | 0.548        | 0.130          | $u$               | $3 \times 10^{-3}$ |
| $\eta'$             | 0.958        | 0.172          | $d$               | $6 \times 10^{-3}$ |
| $D_0$               | 1.86         | 0.25           | $s$               | 0.11         |
| $B_d$               | 5.28         | 0.2            | $c$               | 1.25         |
| $B_s$               | 5.37         | 0.2            | $b$               | 4.3          |

| Vector meson | Mass (in GeV) | $f_V$ (in GeV) |
|--------------|--------------|----------------|
| $\rho$       | 0.776        | 0.22           |
| $\rho^*$     | 0.896        | 0.23           |
| $\phi$       | 1.020        | 0.23           |
| $J/\psi$     | 3.10         | 0.41           |

### TABLE II: Coupling combinations which had no bounds previous to this work. The notation is explained in Sect. IV.

| Coupling combination | Bound | Decay |
|----------------------|-------|-------|
| $\lambda_{g21} \lambda'_{g22}$ | 2.1 | $[\bar{\nu}_{gL}]^2 \eta \rightarrow \mu\bar{e} + e\bar{\mu}$ |
| $\lambda_{g12} \lambda'_{g22}$ |       |       |
| $\lambda_{g13} \lambda'_{g12}$ | $9.7 \times 10^{-4}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow eK_S$ |
| $\lambda_{g31} \lambda'_{g21}$ |       |       |
| $\lambda_{g23} \lambda'_{g12}$ | $1.0 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow \mu K_S$ |
| $\lambda_{g32} \lambda'_{g21}$ |       |       |
| $\lambda'_{1g1} \lambda'_{3g2}$ | $2.3 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow e K_S$ |
| $\lambda'_{1g2} \lambda'_{2g2}$ | $1.5 \times 10^{-2}$ | $[\bar{\nu}_{gL}]^2 \eta \rightarrow \mu\bar{e} + e\bar{\mu}$ |
| $\lambda'_{1g2} \lambda'_{3g2}$ | $1.2 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow e \eta$ |
| $\lambda'_{1g2} \lambda'_{3g2}$ | $3.4 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow e \phi$ |
| $\lambda'_{2g1} \lambda'_{3g2}$ | $2.4 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow \mu K_S$ |
| $\lambda'_{2g2} \lambda'_{3g2}$ | $1.6 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow \mu \eta$ |
| $\lambda'_{2g2} \lambda'_{3g2}$ | $3.4 \times 10^{-3}$ | $[\bar{\nu}_{gL}]^2 \tau \rightarrow \mu \phi$ |
| Coupling combination | From this work | Previously published |
|----------------------|---------------|---------------------|
|                     | Bound         | Decay              | Bound         | Decay   | Key       |
| \( \lambda_{g13} \lambda'_{g22} \) | \( 4.6 \times 10^{-4} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow e\eta \) | \( 1.6 \times 10^{-2} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow e\eta \) | Upd. [45] |
| \( \lambda_{g31} \lambda'_{g22} \) | \( 1.7 \times 10^{-3} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \mu \eta \) | \( 1.7 \times 10^{-2} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \mu \eta \) | Upd. [45] |
| \( \lambda_{g23} \lambda'_{g21} \) | \( 6.7 \times 10^{-5} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \pi^- \nu \) | \( 1.7 \times 10^{-3} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \pi^- \nu \) | Upd. [38] |
| \( \lambda_{g32} \lambda'_{g22} \) | \( 3.7 \times 10^{-4} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \mu \eta \) | \( 1.7 \times 10^{-2} [\tilde{\nu}_gL]^2 \) | \( \tau \rightarrow \mu \eta \) | Upd. [38] |

**TABLE III:** Coupling combinations which have improved by a factor of 30 or more compared to those published before this work.

| Coupling combination | From this work | Previously published |
|----------------------|---------------|---------------------|
|                     | Bound         | Decay              | Bound         | Decay   | Key       |
| \( \lambda_{11g} \lambda'_{13g} \) | \( 1.2 \times 10^{-3} [\tilde{d}_{Rg}]^2 \) | \( \tau \rightarrow e\pi^0 \) | \( 0.05 \) | \( [\tilde{d}_{Rg}] \) | APV in Cs | Upd. [38] |
|                     | \times 0.12   | \( \tau \rightarrow \pi^- \nu \) | \( 3.5 \times 10^{-2} [\tilde{d}_{Rg}]^2 \) | \( \pi^- \rightarrow \mu \nu \) | Upd. [38] |
| \( \lambda_{12g} \lambda'_{21g} \) | \( 9.0 \times 10^{-3} [\tilde{d}_{Rg}]^2 \) | \( D^0 \rightarrow \mu \bar{\nu} \) | \( 0.21 \) | \( [\tilde{d}_{Rg}] \) | \( A_{FB}^\prime \) | Upd. [38] |
|                     | \times 5.9 \times 10^{-2} [\tilde{d}_{Rg}]^2 | \( \pi^- \rightarrow \mu \bar{\nu} \) | \( [\tilde{d}_{Rg}] \) | \( \pi^- \rightarrow \mu \bar{\nu} \) | Upd. [36] |

**TABLE IV:** Coupling combinations where the combined bound is now better than the product of the individual bounds.
| $(\lambda_{ijk}, \lambda_{lmn})$ | From this work | Previously published |
|----------------|----------------|---------------------|
| $ijk lmn$ | Bound | Decay | Bound | Key |
| 121 123 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu e \bar{\mu}$ | $2.1 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 121 131 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu e \bar{e}$ | $2.0 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 121 132 | $5.6 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu \bar{\mu} \bar{e}$ | $1.9 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 122 123 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu \mu \bar{\mu}$ | $2.2 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 122 131 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu e \bar{\mu}$ | $2.1 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 122 132 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L1}]^2$ | $\tau \rightarrow \mu \mu \bar{e}$ | $2.2 \times 10^{-3}$ | $[\tilde{\nu}_{L1}]^2$ | Upd. [47] |
| 211 212 | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L2}]^2$ | $\mu \rightarrow e e \bar{e}$ | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L2}]^2$ | Agr. [21] |
| 211 213 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.7 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 211 231 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.7 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 211 232 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.0 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 212 213 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.0 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 212 231 | $5.2 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $1.9 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 212 232 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L2}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.1 \times 10^{-3}$ | $[\tilde{\nu}_{L2}]^2$ | Upd. [47] |
| 311 312 | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L3}]^2$ | $\mu \rightarrow e e \bar{e}$ | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L2}]^2$ | Agr. [21] |
| 311 313 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.7 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 311 321 | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L3}]^2$ | $\mu \rightarrow e e \bar{e}$ | $6.6 \times 10^{-7}$ | $[\tilde{\nu}_{L2}]^2$ | Agr. [21] |
| 311 323 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.0 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 312 313 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.0 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 312 323 | $5.6 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $1.9 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 313 321 | $5.2 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $1.9 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 313 322 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.1 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 321 323 | $7.0 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.1 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |
| 322 323 | $6.8 \times 10^{-4}$ | $[\tilde{\nu}_{L3}]^2$ | $\tau \rightarrow e e \bar{e}$ | $2.2 \times 10^{-3}$ | $[\tilde{\nu}_{L3}]^2$ | Upd. [47] |

TABLE V: Bounds on $(\lambda_{ijk}, \lambda_{lmn})$: all but those from $\mu \rightarrow e e e$ are updated from reference [47]. The presented $\mu \rightarrow e e e$ bounds agree with those in reference [21].
| $(\lambda_{ijk}, \lambda_{lmm})$ | From this work | Previously published |
|-----------------|-----------------|---------------------|
| $ijk$ $lmn$ | Bound | Decay | Bound | Decay | Key |
| 121 111 | $1.2 \times 10^{-2}$ $|\tilde{\nu}_{L_1}|^2$ | $\pi^0 \rightarrow e\bar{\mu}$ | $2.1 \times 10^{-8}$ $|\tilde{\nu}_{L_1}|^2$ | $\mu \rightarrow e$ in $^{48}$Ti | Unimp. [48] |
| | $0.39$ | $|\tilde{\nu}_{L_1}|^2$ | $\eta \rightarrow \mu \bar{e} + e\bar{\mu}$ | | |
| | $0.41$ | $|\tilde{\nu}_{L_1}|^2$ | $\pi^0 \rightarrow \mu \bar{e}$ | | |
| | $16$ | $|\tilde{\nu}_{L_1}|^2$ | $\eta \rightarrow \mu \bar{e} + e\bar{\mu}$ | | |
| 121 112 | $6.7 \times 10^{-9}$ $|\tilde{\nu}_{L_1}|^2$ | $K^0_L \rightarrow \mu \bar{e} / e\bar{\mu}$ | $6 \times 10^{-9}$ $|\tilde{\nu}_{L_1}|^2$ | $K^0_L \rightarrow \mu \bar{e} / e\bar{\mu}$ | $^{1(-)}$ Agr. [26] |
| 121 113 | $1.3 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | $2.3 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | Corr.(<) [27] |
| 121 121 | $6.7 \times 10^{-9}$ $|\tilde{\nu}_{L_1}|^2$ | $K^0_L \rightarrow \mu \bar{e} / e\bar{\mu}$ | $6 \times 10^{-9}$ $|\tilde{\nu}_{L_1}|^2$ | $K^0_L \rightarrow \mu \bar{e} / e\bar{\mu}$ | $^{1(-)}$ Agr. [26] |
| 121 122 | $2.1$ | $|\tilde{\nu}_{L_1}|^2$ | $\eta \rightarrow \mu \bar{e} + e\bar{\mu}$ | none | n/a |
| | $3.6 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\eta \rightarrow \mu \bar{e} + e\bar{\mu}$ | | |
| 121 123 | $7.6 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | $4.7 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | Corr.(>) [27] |
| 121 131 | $1.3 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | $2.3 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | Corr.(<) [27] |
| 121 132 | $7.6 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | $4.7 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{e}$ | Corr.(<) [27] |
| 122 113 | $6.2 \times 10^{-6}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | $1.5 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | Corr.(<) [27] |
| 122 123 | $1.2 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | $1.7 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow K^0 \mu \bar{\mu}$ | Upd. [30] |
| 122 131 | $6.2 \times 10^{-6}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | $1.5 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | Corr.(<) [27] |
| 122 132 | $1.2 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\mu}$ | $1.8 \times 10^{-5}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow K^0 \mu \bar{\mu}$ | Upd. [30] |
| 123 111 | $6.7 \times 10^{-5}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu \eta$ | $1.7 \times 10^{-3}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu \eta$ | Upd. [45] |
| | $1.0 \times 10^{-3}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu \pi^0$ | none | n/a |
| 123 112 | $1.0 \times 10^{-3}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu K_S$ | none | n/a |
| 123 113 | $2.2 \times 10^{-4}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\tau}$ | $6.2 \times 10^{-4}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \mu \bar{\tau}$ | Corr.(<) [27] |
| 123 121 | $1.0 \times 10^{-3}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu K_S$ | $7.6 \times 10^{-2}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu K^0$ | Upd. [45] |
| 123 122 | $3.7 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu \eta$ | $1.7 \times 10^{-2}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow \mu \eta$ | Upd. [45] |
| 123 131 | $2.2 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \tau \bar{\mu}$ | $6.2 \times 10^{-4}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \tau \bar{\mu}$ | Corr.(<) [27] |
| 131 111 | $8.5 \times 10^{-5}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e \eta$ | $1.6 \times 10^{-3}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e \eta$ | Upd. [45] |
| | $7.1 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e \pi^0$ | none | n/a |
| 131 112 | $9.7 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e K_S$ | $8.5 \times 10^{-2}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e K^0$ | Upd. [45] |
| 131 113 | $3.7 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \tau \bar{e}$ | $4.9 \times 10^{-4}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow \tau \bar{e}$ | Corr.(<) [27] |
| 131 121 | $9.7 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e K_S$ | none | n/a |
| 131 122 | $4.6 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e \eta$ | $1.6 \times 10^{-2}$ $|\tilde{\nu}_{L_1}|^2$ | $\tau \rightarrow e \eta$ | Upd. [45] |
| 131 131 | $3.7 \times 10^{-4}$ | $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow e \bar{\tau}$ | $4.9 \times 10^{-4}$ $|\tilde{\nu}_{L_1}|^2$ | $B^0 \rightarrow e \bar{\tau}$ | Corr.(<) [27] |

**TABLE VI:** Bounds on $(\lambda_{ijk}, \lambda_{lmm})$. 
| \( (\lambda_{ijk}, \lambda'_{lmn}) \) | From this work | Previously published |
|----------------|----------------|---------------------|
| \( ijk \) | Bound | Decay | Bound | Decay | Key |
| 132 111 | 6.7 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu \eta \) | 1.7 \times 10^{-3} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu \eta \) | Upd. [45] |
| 132 112 | 1.0 \times 10^{-3} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu K \) | 7.6 \times 10^{-2} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu K^0 \) | Upd. [45] |
| 132 113 | 2.2 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \tau \bar{\mu} \) | 6.2 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \mu \bar{\tau} \) | Corr.(<) [27] |
| 132 121 | 1.0 \times 10^{-3} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu K S \) | none | n/a | New |
| 132 122 | 3.7 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu \eta \) | 1.7 \times 10^{-2} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow \mu \eta \) | Upd. [45] |
| 132 131 | 2.2 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \mu \bar{\tau} \) | 6.2 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \mu \bar{\tau} \) | Corr.(<) [27] |
| 211 213 | 4.1 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | 1.7 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | Corr.(>) [27] |
| 211 223 | 2.3 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow e \bar{e} \) | 1.4 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow K^0 e \bar{e} \) | Unimp. [30] |
| 211 231 | 4.1 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | 1.7 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | Corr.(>) [27] |
| 211 232 | 2.3 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | 2.3 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow K^0 e \bar{e} \) | Unimp. [30] |
| 212 211 | 1.2 \times 10^{-2} \[ \bar{\nu}_L \] \[2\] | \( \pi^0 \rightarrow e \bar{e} \) | 2.1 \times 10^{-8} \[ \bar{\nu}_L \] \[2\] | \( \mu \rightarrow e \) in 48Ti | Unimp. [48] |
| 0.38 \[ \bar{\nu}_L \] \[2\] | \( \eta \rightarrow \mu e + e \bar{\mu} \) | 0.41 \[ \bar{\nu}_L \] \[2\] | \( \pi^0 \rightarrow \mu \bar{e} \) |
| 16 \[ \bar{\nu}_L \] \[2\] | \( \eta' \rightarrow \mu e + e \bar{\mu} \) | |
| 212 212 | 6.7 \times 10^{-9} \[ \bar{\nu}_L \] \[2\] | \( K^0 \rightarrow e \bar{e} / \mu e / e \bar{\mu} \) | 6 \times 10^{-9} \[ \bar{\nu}_L \] \[2\] | \( K^0 \rightarrow e \bar{e} / \mu e / e \bar{\mu} \) \( ^{(+)} \) Agr. [26] |
| 212 213 | 1.3 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | 2.3 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{e} \) | Corr.(>) [27] |
| 212 221 | 6.7 \times 10^{-9} \[ \bar{\nu}_L \] \[2\] | \( K^0 \rightarrow e \bar{e} / \mu e / e \bar{\mu} \) | 6 \times 10^{-9} \[ \bar{\nu}_L \] \[2\] | \( K^0 \rightarrow e \bar{e} / \mu e / e \bar{\mu} \) \( ^{(+)} \) Agr. [26] |
| 212 222 | 2.1 \[ \bar{\nu}_L \] \[2\] | \( \eta \rightarrow \mu e + e \bar{\mu} \) | none | n/a | New |
| 3.6 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \eta' \rightarrow \mu e + e \bar{\mu} \) | |
| 212 223 | 7.6 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow e \bar{\mu} \) | 4.7 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow e \bar{\mu} \) | Corr.(>) [27] |
| 212 231 | 1.3 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{\mu} \) | 2.3 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{\mu} \) | Corr.(<) [27] |
| 212 232 | 7.6 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow e \bar{\mu} \) | 4.7 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( B^0_s \rightarrow e \bar{\mu} \) | Corr.(>) [27] |
| 213 211 | 8.5 \times 10^{-5} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \eta \) | 1.6 \times 10^{-3} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \eta \) | Upd. [45] |
| 7.1 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \pi^0 \) | |
| 213 212 | 9.7 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \bar{K}_S \) | none | n/a | New |
| 213 213 | 3.7 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{\tau} \) | 4.9 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow e \bar{\tau} \) | Corr.(<) [27] |
| 213 221 | 9.7 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \bar{K}_S \) | 8.5 \times 10^{-2} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \bar{K}_S \) | Upd. [45] |
| 213 222 | 4.6 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \eta \) | 1.6 \times 10^{-2} \[ \bar{\nu}_L \] \[2\] | \( \tau \rightarrow e \eta \) | Upd. [45] |
| 213 231 | 3.7 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \tau \bar{e} \) | 4.9 \times 10^{-4} \[ \bar{\nu}_L \] \[2\] | \( B^0_d \rightarrow \tau \bar{e} \) | Corr.(<) [27] |

**TABLE VII**: Bounds on \( (\lambda_{ijk}, \lambda'_{lmn}) \) continued.
| \((\lambda_{ijk} \chi'_{lmn})\) | From this work | Previously published |
|-----------------|----------------|---------------------|
| 231 211         | 8.5 \times 10^{-5} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow e\eta | 1.6 \times 10^{-3} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow e\eta |
|                 | 7.1 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow e\pi^0 |                     |
| 231 212         | 9.7 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow eK_S | 8.5 \times 10^{-2} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow eK^0 |
| 231 213         | 3.7 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \tau \bar{\nu} | 4.9 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \tau \bar{\nu} |
| 231 221         | 9.7 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow eK_S | none n/a New |
| 231 222         | 4.6 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow e\eta | 1.6 \times 10^{-2} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow e\eta |
| 231 231         | 3.7 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow e\bar{\tau} | 4.9 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow e\bar{\tau} |
| 232 211         | 6.7 \times 10^{-5} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu\eta | 1.7 \times 10^{-3} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu\eta |
|                 | 1.0 \times 10^{-3} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \pi\pi^0 |                     |
| 232 212         | 1.0 \times 10^{-3} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu K_S | 7.6 \times 10^{-2} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu K^0 |
| 232 213         | 2.2 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \tau \bar{\nu} | 6.2 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \mu \bar{\tau} |
| 232 221         | 1.0 \times 10^{-3} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu K_S | none n/a New |
| 232 222         | 3.7 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu\eta | 1.7 \times 10^{-2} \, \hat{\nu}_{L2}^2 \quad \tau \rightarrow \mu\eta |
| 232 231         | 2.2 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \mu \bar{\tau} | 6.2 \times 10^{-4} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow \mu \bar{\tau} |
| 311 313         | 4.1 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 1.7 \times 10^{-5} \, \hat{\nu}_{L2}^2 \quad B_d^0 \rightarrow e\bar{\nu} |
| 311 323         | 2.3 \times 10^{-4} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 2.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow K^0 e\bar{\nu} |
| 311 331         | 4.1 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 1.7 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} |
| 311 332         | 2.3 \times 10^{-4} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 2.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow K^0 e\bar{\nu} |
| 312 311         | 1.2 \times 10^{-2} \, \hat{\nu}_{L3}^2 \quad \tau^0 \rightarrow e\bar{\nu} | 2.1 \times 10^{-8} \, \hat{\nu}_{L3}^2 \quad \mu \rightarrow e in 48Ti |
|                 | 0.38 \, \hat{\nu}_{L3}^2 \quad \eta \rightarrow \mu\bar{\nu} + e\bar{\nu} |                     |
|                 | 0.41 \, \hat{\nu}_{L3}^2 \quad \tau^0 \rightarrow \mu\bar{\nu} |                     |
|                 | 16 \, \hat{\nu}_{L3}^2 \quad \eta' \rightarrow \mu\bar{\nu} + e\bar{\nu} |                     |
| 312 312         | 6.7 \times 10^{-9} \, \hat{\nu}_{L3}^2 \quad K_L^0 \rightarrow \mu\bar{\nu} | 6 \times 10^{-9} \, \hat{\nu}_{L1}^3 \quad K_L^0 \rightarrow \mu\bar{\nu} |
|                 | 6 \times 10^{-9} \, \hat{\nu}_{L1}^3 \quad K_L^0 \rightarrow \mu\bar{\nu} |                     |
| 312 313         | 1.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 2.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} |
| 312 321         | 6.7 \times 10^{-9} \, \hat{\nu}_{L3}^2 \quad K_L^0 \rightarrow \mu\bar{\nu} | 6 \times 10^{-9} \, \hat{\nu}_{L1}^3 \quad K_L^0 \rightarrow \mu\bar{\nu} |
|                 | 6 \times 10^{-9} \, \hat{\nu}_{L1}^3 \quad K_L^0 \rightarrow \mu\bar{\nu} |                     |
| 312 322         | 2.1 \, \hat{\nu}_{L3}^2 \quad \eta \rightarrow \mu\bar{\nu} + e\bar{\nu} | none n/a New |
|                 | 3.6 \times 10^{-4} \, \hat{\nu}_{L3}^2 \quad \eta' \rightarrow \mu\bar{\nu} + e\bar{\nu} |                     |
| 312 323         | 7.6 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} | 4.7 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow e\bar{\nu} |
| 312 331         | 1.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow \mu\bar{\nu} | 2.3 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow \mu\bar{\nu} |
| 312 332         | 7.6 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow \mu\bar{\nu} | 4.7 \times 10^{-5} \, \hat{\nu}_{L3}^2 \quad B_d^0 \rightarrow \mu\bar{\nu} |

TABLE VIII: Bounds on \((\lambda_{ijk} \chi'_{lmn})\) continued.
| \((\lambda_{ijk}; \chi'_{lmn})\) | \(ijk lmn\) | From this work | Previously published |
|---|---|---|---|
| Bound | Decay | Bound | Decay | Key |
| 313 311 | \(8.5 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | \(1.6 \times 10^{-3}\) | \([\tilde{\nu}_{L1}]^2\) | \(\tau \rightarrow e\eta\) | Upd. [45] |
| 313 312 | \(7.1 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\pi^0\) | none | n/a | New |
| 313 313 | \(9.7 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK_S\) | none | n/a | New |
| 313 321 | \(9.7 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK_S\) | \(8.5 \times 10^{-2}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK^0\) | Upd. [45] |
| 313 322 | \(4.6 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | \(1.6 \times 10^{-2}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | Upd. [45] |
| 313 331 | \(3.7 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\pi^0\) | \(4.9 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow e\bar{\nu}\) | Corr.(<) [27] |
| 321 311 | \(1.2 \times 10^{-2}\) | \([\tilde{\nu}_{L3}]^2\) | \(\pi^0 \rightarrow e\bar{\mu}\) | \(2.1 \times 10^{-8}\) | \([\tilde{\nu}_{L3}]^2\) | \(\mu \rightarrow e\) in \(^{48}\)Ti | Unimp. [48] |
| 321 311 | \(0.38\) | \([\tilde{\nu}_{L3}]^2\) | \(\eta \rightarrow \mu e + e\bar{\mu}\) | \(0.41\) | \([\tilde{\nu}_{L3}]^2\) | \(\pi^0 \rightarrow \mu e\) | New |
| 321 311 | \(16\) | \([\tilde{\nu}_{L3}]^2\) | \(\eta' \rightarrow \mu e / e\bar{\mu}\) | \(3.6 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\eta' \rightarrow \mu e / e\bar{\mu}\) | New |
| 321 312 | \(6.7 \times 10^{-9}\) | \([\tilde{\nu}_{L3}]^2\) | \(K^0_L \rightarrow \mu e / e\bar{\mu}\) | \(6 \times 10^{-9}\) | \([\tilde{\nu}_{L1}]^3\) | \(K^0_L \rightarrow \mu e / e\bar{\mu}\) | \(1\)(-) Agr. [26] |
| 321 313 | \(1.3 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu e\) | \(2.3 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu e\) | Corr.(<) [27] |
| 321 321 | \(6.7 \times 10^{-9}\) | \([\tilde{\nu}_{L3}]^2\) | \(K^0_L \rightarrow \mu e / e\bar{\mu}\) | \(6 \times 10^{-9}\) | \([\tilde{\nu}_{L1}]^3\) | \(K^0_L \rightarrow \mu e / e\bar{\mu}\) | \(1\)(-) Agr. [26] |
| 321 322 | \(2.1\) | \([\tilde{\nu}_{L3}]^2\) | \(\eta \rightarrow \mu e + e\bar{\mu}\) | none | n/a | New |
| 321 323 | \(7.6 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_s \rightarrow \mu e\) | \(4.7 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_s \rightarrow \mu e\) | Corr.(>) [27] |
| 321 331 | \(1.3 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow e\bar{\mu}\) | \(2.3 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow e\bar{\mu}\) | Corr.(>) [27] |
| 321 332 | \(7.6 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_s \rightarrow e\bar{\mu}\) | \(4.7 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_s \rightarrow e\bar{\mu}\) | Corr.(>) [27] |
| 322 313 | \(6.2 \times 10^{-6}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\mu}\) | \(1.5 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\mu}\) | Corr.(<) [27] |
| 322 323 | \(1.2 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\mu}\) | \(1.7 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow K^0\mu\bar{\mu}\) | Upd. [30] |
| 322 331 | \(6.2 \times 10^{-6}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\mu}\) | \(1.5 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\mu}\) | Corr.(<) [27] |
| 322 332 | \(1.2 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_s \rightarrow \mu\bar{\mu}\) | \(1.8 \times 10^{-5}\) | \([\tilde{\nu}_{L1}]^3\) | \(B^0_d \rightarrow K^0\mu\bar{\mu}\) | Upd. [30] |
| 323 311 | \(6.7 \times 10^{-5}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | \(1.7 \times 10^{-3}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | Upd. [45] |
| 323 312 | \(1.0 \times 10^{-3}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK_S\) | none | n/a | New |
| 323 313 | \(2.2 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\tau}\) | \(6.2 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\tau}\) | Corr.(<) [27] |
| 323 321 | \(1.0 \times 10^{-3}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK_S\) | \(7.6 \times 10^{-2}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow eK^0\) | Upd. [45] |
| 323 322 | \(3.7 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | \(1.7 \times 10^{-2}\) | \([\tilde{\nu}_{L3}]^2\) | \(\tau \rightarrow e\eta\) | Upd. [45] |
| 323 331 | \(2.2 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\tau}\) | \(6.2 \times 10^{-4}\) | \([\tilde{\nu}_{L3}]^2\) | \(B^0_d \rightarrow \mu\bar{\tau}\) | Corr.(<) [27] |

**TABLE IX:** Bounds on \((\lambda_{ijk}; \chi'_{lmn})\) continued.
| \((\lambda'_{ijk} \lambda'_{lmn})\) | From this work | | Previously published |
|---|---|---|---|
| | Bound | Decay | Bound | Decay | Key |
| 111 113 | 2.6 \(\times 10^{-2}\) \([\tilde{u}_{L1}]^2\) | \(B_d^0 \rightarrow \bar{e} \bar{e}\) | 0.03 \(\times 10^{-8}\) \([\tilde{u}_{L1}]^2\) | APV in Cs | Unimp. [38], \(|\bar{u}_{L1}|\) |
| 111 211 | 0.36 \([\tilde{d}_{R1}]^2\) | \(\pi^0 \rightarrow e \bar{\mu}\) | 4.5 \(\times 10^{-8}\) \([\tilde{d}_{R1}]^2\) | \(\mu \rightarrow e + \bar{e} \bar{\mu}\) in \(^{48}\)Ti | Unimp. [48] |
| | 11 | \([\tilde{d}_{R1}]^2\) | \(\pi^0 \rightarrow e \bar{\mu}\) | 1.5 \(\times 10^{+2}\) \([\tilde{d}_{R1}]^2\) | \(\eta \rightarrow \bar{e} \bar{\mu} + e \bar{\mu}\) |
| | 1.9 \(\times 10^{+4}\) \([\tilde{d}_{R1}]^2\) | \(\eta' \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) |
| 111 211 | 0.36 \([\tilde{u}_{L1}]^2\) | \(\pi^0 \rightarrow e \bar{\mu}\) | 4.3 \(\times 10^{-8}\) \([\tilde{u}_{L1}]^2\) | \(\mu \rightarrow e \bar{\mu} + e \bar{\mu}\) in \(^{48}\)Ti | Unimp. [48] |
| | 11 | \([\tilde{u}_{L1}]^2\) | \(\pi^0 \rightarrow e \bar{\mu}\) | 1.5 \(\times 10^{+2}\) \([\tilde{u}_{L1}]^2\) | \(\eta \rightarrow \bar{e} \bar{\mu} + e \bar{\mu}\) |
| | 1.9 \(\times 10^{+4}\) \([\tilde{u}_{L1}]^2\) | \(\eta' \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) |
| 111 212 | 2.7 \(\times 10^{-7}\) \([\tilde{u}_{L1}]^2\) | \(K_L^0 \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) | 3 \(\times 10^{-7}\) \([\tilde{u}_{L1}]^2\) | \(K_L^0 \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) | \(\omega(-)\) Agr. [26] |
| 111 213 | 1.6 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(B_d^0 \rightarrow \bar{e} \bar{\mu}\) | 4.7 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(B_d^0 \rightarrow \bar{e} \bar{\mu}\) | Upd. [27] |
| 111 221 | 2.8 \(\times 10^{-2}\) \([\tilde{d}_{R1}]^2\) | \(D^0 \rightarrow e \bar{\mu}\) | 0.02 \([\tilde{d}_{R1}]^2\) | APV in Cs | Unimp. [38], \(|\bar{u}_{L1}|\) |
| | \(\times 0.21\) \([\tilde{d}_{R1}]^2\) | | | \(\rightarrow e^+e^-\) | |
| 111 311 | 1.2 \(\times 10^{-3}\) \([\tilde{d}_{R1}]^2\) | \(\tau \rightarrow e \pi^0\) | 0.02 \([\tilde{d}_{R1}]^2\) | APV in Cs | Unimp. [38], \(|\bar{u}_{L1}|\) |
| | \(\times 0.12\) \([\tilde{d}_{R1}]^2\) | | | \(\tau \rightarrow e\pi^0\) | |
| | 2.0 \(\times 10^{-3}\) \([\tilde{d}_{R1}]^2\) | \(\tau \rightarrow e \eta\) | | | |
| | 2.4 \(\times 10^{-3}\) \([\tilde{d}_{R1}]^2\) | \(\tau \rightarrow e \rho^0\) | | | |
| 111 311 | 1.2 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e \pi^0\) | 2.4 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e \rho^0\) | Upd. [45] |
| | 2.0 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e \eta\) | | | |
| | 2.4 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e \rho^0\) | | | |
| 111 312 | 2.3 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e K_S^0\) | none | n/a | New |
| | 3.6 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(\tau \rightarrow e K_S^0\) | | | |
| 111 313 | 2.7 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(B_d^0 \rightarrow e \bar{\tau}\) | 5.9 \(\times 10^{-3}\) \([\tilde{u}_{L1}]^2\) | \(B_d^0 \rightarrow e \bar{\tau}\) | Upd. [27] |
| 112 113 | 9.3 \([\tilde{u}_{L1}]^2\) | \(B_s^0 \rightarrow e \bar{\tau}\) | 4.3 \(\times 10^{-4}\) \([\tilde{u}_{L1}]^2\) | \(b \rightarrow e \bar{\tau}\) | Unimp. [28] |
| 112 211 | 2.7 \(\times 10^{-7}\) \([\tilde{u}_{L1}]^2\) | \(K_L^0 \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) | 3 \(\times 10^{-7}\) \([\tilde{u}_{L1}]^2\) | \(K_L^0 \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) | \(\omega(-)\) Agr. [26] |
| 112 212 | 0.36 \([\tilde{d}_{R2}]^2\) | \(\pi^0 \rightarrow e \bar{\mu}\) | 4.5 \(\times 10^{-8}\) \([\tilde{d}_{R2}]^2\) | \(\mu \rightarrow e + \bar{e} \bar{\mu}\) in \(^{48}\)Ti | Unimp. [48] |
| | 1.1 \([d_{R2}]^2\) \(\pi^0 \rightarrow e \bar{\mu}\) | | | | |
| | 1.6 \(\times 10^{+2}\) \([d_{R2}]^2\) | \(\eta \rightarrow \bar{e} \bar{\mu} + e \bar{\mu}\) | | | |
| | 1.9 \(\times 10^{+4}\) \([d_{R2}]^2\) | \(\eta' \rightarrow \bar{e} \bar{\mu}/e \bar{\mu}\) | | | |

**TABLE X:** Bounds on \((\lambda'_{ijk} \lambda'_{lmn})\).
| $(\lambda'_{ijk}, \lambda'_{lmn})$ | From this work | Previously published |
|----------------------------------|----------------|---------------------|
| $ijk$  | Bound       | Decay | Bound | Decay | Key |
| 112 212 | $76[\hat{u}_{Li}]^2 \eta \to \mu\bar{e} + e\bar{\mu}$ | none | n/a | New |
| 112 213 | $9.4 \times 10^{-3}[\hat{u}_{Li}]^2 B_s^0 \to e\mu$ | $2.7 \times 10^{-4}[\hat{u}_{Li}]^2 b \to se\mu$ | Unimp. [28] |
| 112 222 | $2.8 \times 10^{-2}[\hat{d}_{R2}]^2 B^0 \to e\mu$ | $0.02 \times 0.21[\hat{d}_{R2}] \tau \to \pi^-\nu_{\mu}$ | APV in Cs | Unimp. [38] |
| 112 311 | $2.3 \times 10^{-3}[\hat{u}_{Li}]^2 \tau \to eK_S$ | $2.7 \times 10^{-3}[\hat{u}_{Li}]^2 \tau \to eK^{*0}$ | Upd. [45] |
| 112 312 | $1.2 \times 10^{-3}[\hat{d}_{R2}]^2 \tau \to e\pi^0$ | $0.02 \times 0.12[\hat{d}_{R2}] \tau \to \pi^-\nu_{\mu}$ | APV in Cs | Upd. [38] |
| 113 211 | $1.6 \times 10^{-3}[\hat{u}_{Li}]^2 B^0_d \to e\mu$ | $4.7 \times 10^{-3}[\hat{u}_{Li}]^2 B^0_d \to \mu\bar{e}$ | Upd. [27] |
| 113 212 | $9.4 \times 10^{-3}[\hat{u}_{Li}]^2 B_s \to e\mu$ | $2.7 \times 10^{-4}[\hat{u}_{Li}]^2 b \to se\mu$ | Unimp. [28] |
| 113 213 | $0.36[\hat{d}_{R3}]^2 \pi^0 \to e\mu$ | $4.5 \times 10^{-8}[\hat{d}_{R3}]^2 \mu \to e$ in $^{48}$Ti | Unimp. [48] |
| 113 223 | $2.8 \times 10^{-2}[\hat{d}_{R3}]^2 B^0 \to e\mu$ | $0.02 \times 0.21[\hat{d}_{R3}] \tau \to \pi^-\nu_{\mu}$ | APV in Cs | Unimp. [38] |
| 113 311 | $2.7 \times 10^{-3}[\hat{u}_{Li}]^2 B^0_d \to \tau\bar{\epsilon}$ | $5.9 \times 10^{-3}[\hat{u}_{Li}]^2 B^0_d \to \tau\bar{\epsilon}$ | Upd. [27] |
| 113 313 | $1.2 \times 10^{-3}[\hat{d}_{R3}]^2 \tau \to e\pi^0$ | $0.02 \times 0.12[\hat{d}_{R3}] \tau \to \pi^-\nu_{\mu}$ | APV in Cs | Upd. [38] |
| 113 313 | $2.0 \times 10^{-3}[\hat{d}_{R3}]^2 \tau \to e\pi^0$ | $2.4 \times 10^{-3}[\hat{d}_{R3}]^2 \tau \to e\rho^0$ | Upd. [38] |

TABLE XI: Bounds on $(\lambda'_{ijk}, \lambda'_{lmn})$ continued.
| \((\Lambda'_{ijk} \Lambda'_{lmn})\) | From this work | Previously published |
|-----------------|----------------|-------------------|
| \(i j k\) \(l m n\) | Bound | Decay | Bound | Decay | Key |
| 121 123 | \(2.6 \times 10^{-2} \left[ \tilde{u}_{L2} \right]^2\) | \(B^0 \rightarrow e\bar{e}\) | 0.03 | \(\left[ \tilde{u}_{L2} \right]\) A^b_{FB} | Unimp. [38], \(\times 0.18\) |
| 121 211 | \(9.0 \times 10^{-3} \left[ \tilde{d}_{R1} \right]^2\) | \(D^0 \rightarrow \mu\bar{e}\) | 0.21 | \(\left[ \tilde{d}_{R1} \right]\) A^b_{FB} | Upd. [38], \(\times 5.9 \times 10^{-2} \left[ \tilde{d}_{R1} \right]\) |
| 121 221 | \(1.6 \left[ \tilde{d}_{R1} \right]^2\) | \(J/\psi \rightarrow \mu\bar{e}/e\bar{\mu}\) | 0.21 | \(\left[ \tilde{d}_{R1} \right]\) A^b_{FB} | Unimp. [38], \(\times 0.21\) |
| 121 222 | \(0.36 \left[ \tilde{u}_{L2} \right]^2\) | \(\pi^0 \rightarrow e\mu\) | 4.3 \times 10^{-8} \left[ \tilde{u}_{L2} \right]^2 | \(\mu \rightarrow e\) in 48Ti | Unimp. [48] |
| 11 | \(\left[ \tilde{u}_{L2} \right]^2\) | \(\pi^0 \rightarrow \mu\bar{e}\) | |
| 1.5 \times 10^{+2} | \(\left[ \tilde{u}_{L2} \right]^2\) | \(\eta \rightarrow \mu\bar{e} + e\bar{\mu}\) | |
| 1.9 \times 10^{+4} | \(\left[ \tilde{u}_{L2} \right]^2\) | \(\eta' \rightarrow \mu\bar{e}\) | |
| 121 222 | \(2.7 \times 10^{-7} \left[ \tilde{u}_{L2} \right]^2\) | \(K^0_{L} \rightarrow \mu\bar{e}/e\bar{\mu}\) | 3 \times 10^{-7} \left[ \tilde{u}_{L2} \right]^2 | \(\mu^0 \rightarrow e\bar{\mu}\) | Upd. [26] |
| 121 223 | \(1.6 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2\) | \(B^0 \rightarrow e\bar{\mu}\) | 4.7 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2 | \(B^0_d \rightarrow e\bar{\mu}\) | Upd. [27] |
| 121 321 | \(5.9 \left[ \tilde{d}_{R1} \right]^2\) | \(J/\psi \rightarrow \tau\bar{e}/e\bar{\tau}\) | 0.21 | \(\left[ \tilde{d}_{R1} \right]\) A^b_{FB} | Unimp. [38], \(\times 0.52\) |
| 121 321 | | \(\tau \rightarrow e\pi^0\) | 2.4 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2 | \(\tau \rightarrow e\rho^0\) | Upd. [45] |
| 121 322 | \(1.2 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2\) | \(\tau \rightarrow eK_S\) | none | n/a | New |
| 121 323 | \(2.0 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2\) | \(\tau \rightarrow eK^{*0}\) | none | n/a | New |
| 121 222 | \(4.1 \left[ \tilde{u}_{L2} \right]^2\) | \(B^0 \rightarrow e\bar{\tau}\) | 5.9 \times 10^{-3} \left[ \tilde{u}_{L2} \right]^2 | \(B^0_d \rightarrow e\bar{\tau}\) | Upd. [27] |
| 122 123 | \(9.0 \times 10^{-3} \left[ \tilde{d}_{R2} \right]^2\) | \(D^0 \rightarrow \mu\bar{e}\) | 0.21 | \(\left[ \tilde{d}_{R2} \right]\) A^b_{FB} | Upd. [38], \(\times 5.9 \times 10^{-2} \left[ \tilde{d}_{R2} \right]\) |
| 122 212 | \(2.7 \times 10^{-7} \left[ \tilde{u}_{L2} \right]^2\) | \(K^0_{L} \rightarrow \mu\bar{e}/e\bar{\mu}\) | 3 \times 10^{-7} \left[ \tilde{u}_{L2} \right]^2 | \(K^0_{L} \rightarrow \mu\bar{e}/e\bar{\mu}\) | Upd. [26] |
| 122 222 | \(1.6 \left[ \tilde{d}_{R2} \right]^2\) | \(J/\psi \rightarrow \mu\bar{e}/e\bar{\mu}\) | 0.21 | \(\left[ \tilde{d}_{R2} \right]\) A^b_{FB} | Unimp. [38], \(\times 0.21\) |
| 122 222 | \(76 \left[ \tilde{u}_{L2} \right]^2\) | \(\eta \rightarrow \mu\bar{e} + e\bar{\mu}\) | none | n/a | New |
| 11 \times 10^{+5} | \(\left[ \tilde{u}_{L2} \right]^2\) | \(\eta' \rightarrow \mu\bar{e}\) | none | n/a | New |

TABLE XII: Bounds on \((\Lambda'_{ijk} \Lambda'_{lmn})\) continued.
| $(\lambda'_{ijk} \lambda'_{lmn})$ | From this work | Previously published |
|---|---|---|
| **ijk lmn** | Bound | Decay | Bound | Decay | Key |
| 122 233 | $9.4 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0 \to e\bar{\mu}$ | $2.7 \times 10^{-4}$ | $[\tilde{u}_{L2}]^2 b \to s e\bar{\mu}$ | Unimp. [28] |
| 122 321 | $2.3 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 \tau \to e K^0_S$ | $2.7 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 \tau \to e K^0_S$ | Upd. [45] |
| | $2.9 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 \tau \to e K^0_S$ | | | |
| 122 322 | $5.9$ | $[\tilde{d}_{R2}]^2 J/\psi \to \tau e/\tau \tau$ | | | |
| | | $0.21$ | $[\tilde{d}_{R2}]^2 A_{FB}^{\tau \tau}$ | Upd. [40] |
| | | $\times 0.52$ | $[\tilde{d}_{R2}]^2 D_{s}^{+} \to \tau \bar{\nu}$ | |
| 122 322 | $1.7 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 \tau \to e \eta$ | none | n/a | $^{(\leftarrow)}$ New |
| | $3.4 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 \tau \to e \phi$ | | | |
| 123 213 | $9.0 \times 10^{-3}$ | $[\tilde{d}_{R3}]^2 D^0 \to \mu \bar{e}$ | $0.21$ | $[\tilde{d}_{R3}]^2 A_{FB}^{D^0}$ | Upd. [38] |
| | | $\times 5.9 \times 10^{-2}$ | $[\tilde{d}_{R3}]^2 \pi^0 \to \mu \bar{\nu}$ | | |
| 123 221 | $1.6 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0_d \to \mu \bar{e}$ | $4.7 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0_d \to \mu \bar{e}$ | Upd. [27] |
| 123 222 | $9.4 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0_d \to \mu \bar{e}$ | $2.7 \times 10^{-4}$ | $[\tilde{u}_{L2}]^2 b \to s e \bar{\mu}$ | Unimp. [28] |
| 123 223 | $1.6$ | $[\tilde{d}_{R3}]^2 J/\psi \to \mu \bar{e} / e \bar{\mu}$ | $0.21$ | $[\tilde{d}_{R1}]^2 A_{FB}^{\tau \tau}$ | Unimp. [38], |
| | | $\times 0.21$ | $[\tilde{d}_{R1}]^2 D_{s}^{+} \to \tau \bar{\nu} K^+$ | | |
| 123 321 | $2.7 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0_d \to \tau \bar{e}$ | $5.9 \times 10^{-3}$ | $[\tilde{u}_{L2}]^2 B^0_d \to \tau \bar{e}$ | Upd. [27] |
| 123 323 | $5.9$ | $[\tilde{d}_{R3}]^2 J/\psi \to \tau e / e \tau$ | $0.21$ | $[\tilde{d}_{R3}]^2 A_{FB}^{\tau \tau}$ | Unimp. [38], |
| | | $\times 0.52$ | $[\tilde{d}_{R3}]^2 D_{s}^{+} \to \tau \bar{\nu}$ | | |
| 131 133 | $2.6 \times 10^{-2}$ | $[\tilde{u}_{L3}]^2 B^0_d \to e \bar{e}$ | $0.03$ | $[\tilde{u}_{L3}]^2$ | APV in Cs |
| | | $\times 0.18$ | $[\tilde{u}_{L3}]^2 A_{FB}^{\tau \tau}$ | | |
| 131 231 | $0.36$ | $[\tilde{u}_{L3}]^2 \pi^0 \to e \bar{\mu}$ | $4.3 \times 10^{-8}$ | $[\tilde{u}_{L3}]^2 \mu \to e$ in $^{48}Ti$ | Unimp. [48] |
| | $11$ | $[\tilde{u}_{L3}]^2 \pi^0 \to e \bar{\mu}$ | | | |
| | $1.5 \times 10^{+2}$ | $[\tilde{u}_{L3}]^2 \eta \to e \bar{\mu} + e \bar{\mu}$ | | | |
| | $1.9 \times 10^{+4}$ | $[\tilde{u}_{L3}]^2 \eta \to e \bar{\mu}$ | | | |
| 131 232 | $2.7 \times 10^{-7}$ | $[\tilde{u}_{L3}]^2 K^0_L \to \mu \bar{e} / e \bar{\mu}$ | $3 \times 10^{-7}$ | $[\tilde{u}_{L3}]^2 K^0_L \to \mu \bar{e} / e \bar{\mu}$ | $^{(\leftarrow)}$ Agr. [26] |
| 131 233 | $1.6 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 B^0_d \to e \bar{\mu}$ | $4.7 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 B^0_d \to e \bar{\mu}$ | Upd. [27] |
| 131 331 | $1.2 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e \pi^0$ | $2.4 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e \rho^0$ | Upd. [45] |
| | $2.0 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e \eta$ | | $^{(\leftarrow)}$ |
| | $2.4 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e \rho^0$ | | | |
| 131 332 | $2.3 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e K_S$ | none | n/a | New |
| | $3.6 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 \tau \to e K^0_S$ | | | |
| 131 333 | $2.7 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 B^0_d \to e \bar{\tau}$ | $5.9 \times 10^{-3}$ | $[\tilde{u}_{L3}]^2 B^0_d \to e \bar{\tau}$ | Upd. [27] |
| 132 133 | $4.1$ | $[\tilde{u}_{L3}]^2 B^0_s \to e \bar{e}$ | $4.3 \times 10^{-4}$ | $[\tilde{u}_{L3}]^2 b \to s e \bar{\mu}$ | Unimp. [28] |

TABLE XIII: Bounds on $(\lambda'_{ijk} \lambda'_{lmn})$ continued.
| $i j k$ | $l m n$ | From this work | Previously published |
|-------|-------|----------------|----------------------|
| 132 231 | $2.7 \times 10^{-7} \left[\tilde{u}_{L3}\right]^2$ | $K^0_L \rightarrow \mu e/\epsilon\mu$ | $3 \times 10^{-7} \left[\tilde{u}_{L3}\right]^2$ |
| 132 232 | $76 \left[\tilde{u}_{L3}\right]^2$ | $\eta \rightarrow \mu e + e\mu$ | none n/a |
| 132 233 | $9.4 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $B^0_s \rightarrow \epsilon\mu$ | $2.7 \times 10^{-4} \left[\tilde{u}_{L3}\right]^2$ |
| 132 331 | $2.3 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow e K_S$ | $2.7 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 132 332 | $1.2 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow e\eta$ | none n/a |
| 133 231 | $1.6 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $B^0_d \rightarrow \mu\epsilon$ | $4.7 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 133 232 | $9.4 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $B^0_s \rightarrow \mu\epsilon$ | $2.7 \times 10^{-4} \left[\tilde{u}_{L3}\right]^2$ |
| 133 331 | $2.7 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $B^0_d \rightarrow \tau\epsilon$ | $5.9 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 211 213 | $5.4 \times 10^{-4} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow e K^{*0}$ | $2.1 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ |
| 211 311 | $1.6 \times 10^{-3} \left[\tilde{u}_{R1}\right]^2$ | $\tau \rightarrow \mu\eta$ | $4.4 \times 10^{-3} \left[\tilde{d}_{R1}\right]^2$ |
| 133 233 | $9.4 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow e\phi$ | $3.4 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 133 332 | $1.2 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow \epsilon\phi$ | none n/a |
| 211 311 | $1.6 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu\eta$ | $4.4 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ |
| 133 333 | $2.7 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow \mu\pi^0$ | $4.3 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 211 312 | $2.4 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu K_S$ | none n/a |
| 133 232 | $9.4 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ | $\tau \rightarrow \mu K^{*0}$ | $3.6 \times 10^{-3} \left[\tilde{u}_{L3}\right]^2$ |
| 212 213 | $1.0 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu\pi^0$ | $4.3 \times 10^{-3} \left[\tilde{d}_{R2}\right]^2$ |
| 212 311 | $2.4 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu K_S$ | $3.6 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ |
| 212 312 | $9.2 \times 10^{-4} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu\eta$ | none n/a |
| 213 311 | $1.6 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ | $\tau \rightarrow \mu\phi$ | $3.4 \times 10^{-3} \left[\tilde{u}_{L1}\right]^2$ |
| 213 313 | $1.6 \times 10^{-3} \left[\tilde{d}_{R3}\right]^2$ | $\tau \rightarrow \mu\eta$ | $4.4 \times 10^{-3} \left[\tilde{d}_{R3}\right]^2$ |

TABLE XIV: Bounds on $(\lambda'_{ijk})$ continued.
| $i \kappa \lambda'_{mn}$ | From this work | Previously published |
|-----------------|----------------|-------------------|
| $\lambda'_{ijk}$ | Bound | Decay | Bound | Decay | Key |
| 221 223 | $5.4 \times 10^{-4}$ | $B_{s}^{0} \rightarrow \mu \bar{\mu}$ | $2.1 \times 10^{-3}$ | $B_{d}^{0} \rightarrow \mu \bar{\mu}$ | Upd. [27] |
| 221 321 | $2.9$ | $[d_{R1}]^{2}$ | $J/\psi \rightarrow \tau \bar{\mu} / \mu \bar{\tau}$ | $0.21$ | $[d_{R1}]^{2}$ | $B_{s}^{0} \rightarrow \tau \bar{\mu} K^{0}$ | Upd. [49] |
| 221 321 | $4.3 \times 10^{-3}$ | $\tau \rightarrow \mu \bar{\tau}$ | $[\tilde{d}_{R1}]^{2}$ | $\tau \rightarrow \mu \rho^{0}$ | Unimp. [50] |
| 221 321 | $1.6 \times 10^{-3}$ | $\tau \rightarrow \mu \eta$ | $4.4 \times 10^{-3}$ | $\tau \rightarrow \mu \rho^{0}$ | Upd. [45] |
| 221 322 | $2.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}$ | none | n/a | New |
| 221 322 | $3.6 \times 10^{-3}$ | $\tau \rightarrow \mu K^{*0}$ | none | n/a | New |
| 222 223 | $1.0 \times 10^{-3}$ | $B_{s}^{0} \rightarrow \mu \bar{\mu}$ | $4.6 \times 10^{-5}$ | $B_{d}^{0} \rightarrow K^{0} \mu \bar{\mu}$ | Unimp. [30] |
| 222 321 | $2.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}$ | $3.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}^{*0}$ | Upd. [45] |
| 222 322 | $2.9$ | $[d_{R2}]^{2}$ | $J/\psi \rightarrow \tau \bar{\mu} / \mu \bar{\tau}$ | $0.21$ | $[d_{R2}]^{2}$ | $B_{s}^{0} \rightarrow \tau \bar{\mu} K^{0}$ | Upd. [49] |
| 222 322 | $3.4 \times 10^{-3}$ | $\tau \rightarrow \mu \phi$ | none | n/a | Upd. [27] |
| 222 322 | $1.6 \times 10^{-3}$ | $\tau \rightarrow \mu \eta$ | $4.4 \times 10^{-3}$ | $\tau \rightarrow \mu \rho^{0}$ | Upd. [27] |
| 222 323 | $2.9$ | $[d_{R3}]^{2}$ | $J/\psi \rightarrow \tau \bar{\mu} / \mu \bar{\tau}$ | $0.21$ | $[d_{R3}]^{2}$ | $B_{s}^{0} \rightarrow \tau \bar{\mu} K^{0}$ | Upd. [49] |
| 231 331 | $1.6 \times 10^{-3}$ | $\tau \rightarrow \mu \eta$ | $4.4 \times 10^{-3}$ | $\tau \rightarrow \mu \rho^{0}$ | Upd. [27] |
| 231 332 | $2.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}$ | none | n/a | New |
| 231 333 | $1.6 \times 10^{-3}$ | $B_{d}^{0} \rightarrow \mu \bar{\mu}$ | $7.3 \times 10^{-3}$ | $B_{d}^{0} \rightarrow \mu \bar{\mu}$ | Upd. [27] |
| 232 223 | $1.0 \times 10^{-3}$ | $B_{s}^{0} \rightarrow \mu \bar{\mu}$ | $4.6 \times 10^{-5}$ | $B_{d}^{0} \rightarrow K^{0} \mu \bar{\mu}$ | Unimp. [30] |
| 232 331 | $2.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}$ | $3.4 \times 10^{-3}$ | $\tau \rightarrow \mu K_{S}^{*0}$ | Upd. [45] |
| 232 331 | $1.6 \times 10^{-3}$ | $B_{d}^{0} \rightarrow \tau \bar{\mu}$ | $7.3 \times 10^{-3}$ | $B_{d}^{0} \rightarrow \tau \bar{\mu}$ | Upd. [27] |

TABLE XV: Bounds on $(\lambda'_{ijk} \lambda'_{lmn})$ continued.
APPENDIX A: MESON DECAY CONSTANTS

We have defined the decay constants of vector and pseudoscalar mesons through

\[ \langle 0 | \bar{q}_\alpha \gamma^\mu q_\beta | V(p\nu) \rangle \equiv H^\alpha_\nu f_V m_V \epsilon^\mu_V \]  
(A.1)

and

\[ \langle 0 | \bar{q}_\alpha \gamma^\mu \gamma^5 q_\beta | P(pP) \rangle \equiv i H^\alpha_P f_P P^\mu_P , \]  
(A.2)

where \( H^\alpha_\nu \) is the coefficient of \( \bar{q}_\alpha q_\beta \) in the quark model wavefunction of the meson. As \( H^\alpha_\nu \) is not standard notation we shall describe it in some detail. Firstly, it is only of relevance to the light mesons composed of \( u, d, s \)-quarks, as it is assumed that the charmed and bottom meson wavefunctions consist entirely of one quark bilinear, e.g. \( D^0 \) is entirely \( dc \), so \( H^d_{D^0} = 1 \) and all other \( H^\alpha_{D^0} = 0 \). Hence for mesons which are not part of the light \( \text{SU}(3)_{uds} \) octet or singlet, \( H^\alpha_{V/P} = 1 \) for the relevant \( \alpha \) and \( \beta \). Similarly for the charged light mesons, e.g. \( K^+ \) is entirely \( \bar{s}u \), hence \( H^s_{K^+} = 1 \). For the neutral light mesons, we obtain \( H^\alpha_P \) from the standard PDG [18] definition of the pseudoscalar decay constant

\[ \sqrt{2} \langle 0 | \bar{q} \gamma^\mu \gamma^5 \frac{\lambda^a}{2} q | P^b(p) \rangle = i \delta^{ab} f_P P^\mu , \]  
(A.3)

where \( q \) is the vector \( q = (u, d, s)^T \), and \( a, b \) are \( \text{SU}(3) \)-flavour indices. \( P^b(p) = \bar{q}\lambda^b q \) denotes a basis vector of the eight-dimensional representation of flavour \( \text{SU}(3) \), and \( \lambda^a \) are the Gell-Mann matrices (normalized such that \( \text{tr} (\lambda^a \lambda^b) = 2 \delta^{ab} \); also here \( \lambda^0 \) is defined as \( \frac{1}{\sqrt{3}} \) times the three–by–three identity matrix). To relate (A.2) and (A.3) we note that the quark bilinears \( \bar{q}_\alpha q_\beta \) can be written as linear combinations of \( \bar{q}\lambda^a q \), so that

\[ \langle 0 | \bar{q}_\alpha \gamma^\mu \gamma^5 q_\beta | P^b(p) \rangle = \sum_a C^a_{\alpha\beta} \langle 0 | \bar{q} \gamma^\mu \gamma^5 \frac{\lambda^a}{2} q | P^b(p) \rangle = C^b_{\alpha\beta} \frac{i}{\sqrt{2}} f_P P^\mu . \]  
(A.4)

Expressing the physical meson states \( |P\rangle \) in terms of the basis states \( |P^b(p)\rangle \), we arrive at the generic equation (A.2), where the coefficients \( H^\alpha_P \) are given as \( \frac{1}{\sqrt{2}} C^a_{\alpha\beta} \).

Let us consider a specific example and determine \( \langle 0 | \bar{u} \gamma^\mu \gamma^5 u | \pi^0 \rangle \). We find

\[ \langle 0 | \bar{u} \gamma^\mu \gamma^5 u | \pi^0(p) \rangle = \langle 0 | \bar{q} \left( \sqrt{\frac{2}{3}} \frac{\lambda^0}{2} + \frac{\lambda^3}{2} + \frac{1}{\sqrt{3}} \frac{\lambda^8}{2} \right) \frac{\pi^3(p)}{2} \rangle = i \sqrt{\frac{2}{3}} f_{\pi} P^\mu , \]  
(A.5)

and hence \( H^u_{\pi^0} = \frac{1}{\sqrt{2}} \). Note that with our definition (A.3), \( f_{\pi} = 130 \text{ MeV} \).

In our numerical analysis we take into account \( \eta^0 - \eta^8 \) mixing, so \( \eta \) and \( \eta' \) are not exactly \( \frac{1}{\sqrt{6}} (\bar{u}u + \bar{d}d - 2\bar{s}s) \) and \( \frac{1}{\sqrt{3}} (\bar{u}u + \bar{d}d + \bar{s}s) \), but mixtures with a mixing angle \( \theta_\eta = -11.5^\circ = 0.052 \) radians [18], e.g. \( \langle 0 | \bar{s} \gamma^\mu \gamma^5 s | \eta(p) \rangle = i [\cos(\theta_\eta) H^{s\eta}_{s\eta} f_{s\eta} - \sin(\theta_\eta) H^{s\eta}_{s\eta} f_{s\eta}] P^\mu \). For \( \phi \) and \( \omega \) we assume
ideal mixing, so that $\phi = \bar{s}s$ and $\omega = (\bar{u}u + \bar{d}d)/\sqrt{2}$. The non-trivial coefficients $H_P^{\alpha\beta}$ can be read off the quark bilinear coefficients listed in Table XVI. The $H_V^{\alpha\beta}$ are defined to be the same as the $H_P^{\alpha\beta}$ for their pseudoscalar counterparts.

Let us now discuss the derivation of the pseudoscalar matrix element from the axial vector matrix element (A.2) in its general form

$$\sqrt{2}\langle 0 | A_\mu^a(x) | P^b(p) \rangle = i \delta^{ab} f_P p^\mu \exp(-i p \cdot x),$$

(A.6)

with $A_\mu^a = \bar{q} \gamma_\mu \gamma^5 \frac{1}{2} \lambda^a q$. Applying $\partial^\mu$ to both sides leads to

$$\sqrt{2}\langle 0 | \partial^\mu A_\mu^a | P^b(p) \rangle = \delta^{ab} f_P m_P^2 \exp(-i p \cdot x).$$

(A.7)

Now

$$\partial^\mu A_\mu^a = \partial^\mu \left( \bar{q} \gamma_\mu \gamma^5 \frac{1}{2} \lambda^a q \right) = \left( \partial^\mu \bar{q} \gamma^5 \frac{1}{2} \lambda^a q + \bar{q} \gamma_\mu \gamma^5 \frac{1}{2} \lambda^a q \right) = \bar{q} \gamma^5 \frac{i}{2} \{ \lambda^a, M \} q$$

(A.8)

assuming that the quark fields satisfy the Dirac equation, and $M$ here is defined as

$$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}. $$

(A.9)

Combining this result with equation (A.7) at $x = 0$ leads to

$$\langle 0 | \bar{q} \gamma^5 \frac{1}{2} \{ \lambda^a, M \} q | P^b(p) \rangle = \frac{-i}{\sqrt{2}} \delta^{ab} f_P m_P^2. $$

(A.10)

Since

$$\langle 0 | \bar{q}_\alpha \gamma^5 (m_{q_\alpha} + m_{q_\beta}) q_\beta | P^b(p) \rangle = \sum_a C_{\alpha\beta}^a \langle 0 | \bar{q} \gamma^5 \frac{1}{2} \{ \lambda^a, M \} q | P^b(p) \rangle = C_{\alpha\beta}^b \frac{-i}{\sqrt{2}} f_P m_P^2, $$

(A.11)
where \( C^a_{\alpha\beta} \) is defined such that \( \bar{q}_\alpha q_\beta = C^a_{\alpha\beta} \bar{q}^a_q q \), we arrive at

\[
\langle 0 | \bar{q}_\alpha \gamma^5 q_\beta | P^b(p) \rangle = \frac{C^b_{\alpha\beta}}{(m_{q_\alpha} + m_{q_\beta})} \frac{-i}{\sqrt{2}} f_P p^2 . \tag{A.12}
\]

By comparison with equation (II.12), \( \mu^\alpha_{P\beta} \) is identified as

\[
\mu^\alpha_{P\beta} = \frac{-H^\alpha_{P\beta} \sqrt{2}(m_{q_\alpha} + m_{q_\beta})}{C^b_{\alpha\beta}} . \tag{A.13}
\]

Take the neutral pion as an example:

\[
2m_u \langle 0 | \bar{u}_\gamma \gamma^5 u | \pi^0(p) \rangle = \langle 0 | q_5 \left\{ \left( \frac{\sqrt{2}}{3} \lambda^0 + \frac{\lambda^3}{2} + \frac{1}{\sqrt{3}} \frac{\lambda^8}{2} \right) , M \right\} q | \pi^3(p) \rangle = \frac{-i}{\sqrt{2}} f_\pi m_\pi^2 , \tag{A.14}
\]

so that \( \mu^{uu}_{\pi^0} = -2m_u \) and analogously \( \mu^{dd}_{\pi^0} = 2m_d \). We note that this result is in disagreement with [52].

**APPENDIX B: FEYNMAN GRAPHS AND MATRIX ELEMENTS**

In this Appendix we present the Feynman graphs and matrix elements of the various decays.

1. **Charged lepton decaying into two charged leptons and one charged anti-lepton**

   This process proceeds through the exchange of a sneutrino \( \tilde{\nu} \) in the \( t \) - and \( u \)-channel:

   ![Feynman Diagram](image)

   The matrix element for this decay is given by

   \[
iM_{a\rightarrow bc\bar{d}} = \langle l^b(p_{l^b}), l^c(p_{l^c}), \bar{l}^d(p_{\bar{l}^d}) | \bar{\tilde{\nu}}^k \lambda_{jik} P_L i \tilde{\nu} \bar{l}^j | \tilde{\nu}^*_{\alpha\beta} P_R l^\alpha \bar{l}^\beta | l^a(p_{l^a}) \rangle
   = \frac{i}{m_{\tilde{\nu}}^2} \left( \left[ \bar{u}(p_{\tilde{\nu}}) \lambda^*_{gda} P_R u(p_{l^a}) \right] \left[ \bar{u}(p_{l^c}) \lambda_{gcd} P_L v(p_{\bar{l}^d}) \right] - \left[ \bar{u}(p_{\tilde{\nu}}) \lambda_{gdb} P_R u(p_{l^a}) \right] \left[ \bar{u}(p_{l^c}) \lambda^*_{gca} P_L v(p_{\bar{l}^d}) \right]
   - \left[ \bar{u}(p_{\tilde{\nu}}) \lambda_{gac} P_R u(p_{l^a}) \right] \left[ \bar{u}(p_{l^c}) \lambda_{gbd} P_L v(p_{\bar{l}^d}) \right]
   + \left[ \bar{u}(p_{\tilde{\nu}}) \lambda_{gab} P_R u(p_{l^a}) \right] \left[ \bar{u}(p_{l^c}) \lambda_{gcd} P_L v(p_{\bar{l}^d}) \right] \right) . \tag{B.1}
   \]
2. Charged lepton decays into a charged lepton and a neutral vector meson

Charged leptons can decay into a vector meson and a charged lepton through the exchange of a left-handed up-type squark or a right-handed down-type squark:

\[
\begin{aligned}
\psi_i &
\rightarrow
\psi_k + \mathcal{V} \\
\psi_i &
\rightarrow
\tilde{u}^m_R + \mathcal{V}
\end{aligned}
\] 

The matrix element for this process is given by

\[
i\mathcal{M}_{\psi_i \rightarrow \psi_k + \mathcal{V}} = 
\langle \text{out states}|\left(\left[-i\lambda'_{ij n} \tilde{u}_R^j \tilde{d}_L^m \bar{d}_n \mathcal{V}\right] - i\lambda'_{kmn} \tilde{u}_R^m \tilde{d}_L^k \bar{d}_n \mathcal{V}\right)|\text{in states}\rangle
\]  

After some use of Fierz identities (and dropping the left/right subscripts on the squarks, as only “left–handed” up–type squarks or “right–handed” down–type squarks appear) we find

\[
i\mathcal{M}_{\psi_i \rightarrow \psi_k + \mathcal{V}} = 
\langle \text{out states}|\left(\frac{1}{4} \left[\sum_{d\text{-type}} \lambda'_{ij n} \lambda'_{kmn} \tilde{u}_R^j \bar{d}_n \bar{d}_m \mathcal{V} \tilde{d}_l + \left[i\lambda'_{kmn} \tilde{u}_R^m \bar{d}_L^k \bar{d}_n \mathcal{V}\right] \bar{d}_m \mathcal{V}\right]|\text{leptons in}\rangle
\]  

Contracting the meson state with the quark bilinear results in

\[
i\mathcal{M}_{\psi_i \rightarrow \psi_k + \mathcal{V}} = 
\langle \text{leptons out}|\left(\frac{1}{4} \left[\sum_{d\text{-type}} \lambda'_{ij n} \lambda'_{kmn} \tilde{u}_R^j \bar{d}_n \bar{d}_m \mathcal{V} \tilde{d}_l + \left[i\lambda'_{kmn} \tilde{u}_R^m \bar{d}_L^k \bar{d}_n \mathcal{V}\right] \bar{d}_m \mathcal{V}\right]|\text{leptons in}\rangle
\] 

where we have introduced the notation \(\sum_{d\text{-type}}\) to mean only summing over the down–type quarks in the meson and \(\sum_{u\text{-type}}\) to mean summing over the up–type quarks. The \(m\) and \(n\) in \(H_{\mathcal{V}}^{mn}\) are the generation indices of the appropriate quarks and can be used in standard
summation convention with the $m$ and $n$ appearing in the coupling indices. For example, for the decay \( \tau \to e\rho^0 \), we have

\[
i \mathcal{M}_{\tau \to e\rho^0} = \\
\frac{1}{4} \left[ \sum_{d\text{-type}} \lambda'_{3gm} \lambda'_{1gm} H_{\rho^0}^{mm*} \left( -\frac{i}{m_{d\nu}^2} \right) - \sum_{u\text{-type}} \lambda'_{3mg} \lambda'_{1ng} H_{\rho^0}^{nn*} \left( -\frac{i}{m_{u\nu}^2} \right) \right] \left[ \bar{u}(p_e) P_R \gamma^\mu u(p_\tau) \right] f_\rho^* m_\rho \epsilon_\rho^* \mu
\]

\[
= -\frac{1}{4} \left[ (\lambda'_{3g1} \lambda'_{1g1} H_{\rho^0}^{dd*} + \lambda'_{3g1} \lambda'_{1g2} H_{\rho^0}^{ds*} + \lambda'_{3g1} \lambda'_{1g3} H_{\rho^0}^{ds*} + \lambda'_{3g2} \lambda'_{1g1} H_{\rho^0}^{dd*} + \ldots) \frac{i}{m_{d\nu}^2} \right] \left[ \bar{u}(p_e) P_R \gamma^\mu u(p_\tau) \right] f_\rho^* m_\rho \epsilon_\rho^* \mu
\]

\[
= -\frac{1}{4} \left[ (\lambda'_{3g1} \lambda'_{1g1} \cdot \frac{1}{\sqrt{2}} + \lambda'_{3g1} \lambda'_{1g2} \cdot 0 + \lambda'_{3g1} \lambda'_{1g3} \cdot 0 + \lambda'_{3g2} \lambda'_{1g1} \cdot 0 + \ldots) \frac{i}{m_{d\nu}^2} \right] \left[ \bar{u}(p_e) P_R \gamma^\mu u(p_\tau) \right] f_\rho^* m_\rho \epsilon_\rho^* \mu
\]

\[\text{(B.5)}\]

3. \textbf{Charged lepton decays into a charged lepton and a neutral pseudoscalar meson}

In addition to the two diagrams above, which can lead to pseudoscalar mesons as well as vector mesons, there is a further diagram for the decay into pseudoscalar mesons that is mediated by a sneutrino:

\[\text{The contribution from the squark–mediated diagrams is given by}\]

\[
i \mathcal{M}_{\tilde{q} \to l^+ + P} = \langle \text{out states} \left| \frac{1}{4} [\lambda'_{ijm} \lambda'_{kim} \bar{u}^j \bar{u}^t \bar{d}^n (\gamma^\mu + \gamma^\mu \gamma_5) d^m \right] \right| \text{in states} \rangle \]

\[\text{(B.6)}\]
Contracting the meson state with the quark bilinear one finds

\[ i M_{l^{-} \rightarrow s^{+} + P} = \langle \text{lepton out states} | \frac{1}{4} \left[ \sum_{d-\text{type}} \lambda'_{ijm} \lambda'_{kmn} H^{mn*}_{P} \tilde{u}^{t} \tilde{u}^{*} \right. \]

\[ - \sum_{u-\text{type}} \lambda'_{imj} \lambda'_{kmn} H^{mn*}_{P} \tilde{d}^{t} \tilde{d}^{*} \right] \langle \tilde{P} R \gamma_{\mu} l^{i} | \text{lepton in states} \rangle f_{P}^{\mu}_{P} \]

\[ = \frac{1}{4} \left[ \sum_{d-\text{type}} \lambda'_{ijn} \lambda'_{knn} H^{mn*}_{P} \left( -\frac{i}{m_{\tilde{\nu}}^{2}} \right) - \sum_{u-\text{type}} \lambda'_{img} \lambda'_{knm} H^{mn*}_{P} \left( -\frac{i}{m_{\tilde{\nu}}^{2}} \right) \right] \]

\[ \times \left[ \bar{u}(p_{\tilde{\nu}}) P R \gamma_{\mu} u(p_{l}) \right] f_{P}^{\mu}_{P} \]  

(B.7)

The contribution from the sneutrino–mediated diagrams is given by

\[ i M_{l^{-} \rightarrow s^{+} + P} = \langle \text{out states} | \left[ i \lambda_{jkj} P L \tilde{\nu}^{l} + \lambda_{jkl} \tilde{\nu}^{l*} P R \right] l^{i} \rangle \]

\[ \times \left[ d^{m} \left( \lambda'_{tnm} P L \tilde{d}^{l} + \lambda'_{mnm} P R \tilde{d}^{l*} \right) d^{m} \right] \langle \text{in states} \rangle \]

\[ = \frac{-i}{2m_{\tilde{\nu}}^{2}} \sum_{d-\text{type}} \left[ \bar{u}(p_{\tilde{\nu}}) \lambda_{gik} P L u(p_{l}) \lambda'_{gmn} - \bar{u}(p_{\tilde{\nu}}) \lambda_{gki} P R u(p_{l}) \lambda'_{gmn} \right] \left[ \frac{H^{mn*}_{P} f_{P} m_{P}^{2}}{\mu_{P}^{mn}} \right]^{*} \]  

(B.8)

noting that the sneutrino does not couple to up–type quarks.

For the case of a meson decaying into a lepton and an anti–lepton, the matrix elements are identical up to making the appropriate index substitutions in the couplings.

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Our effective Lagrangian is to be compared with those in [21], [22], [23], [27] and [31] (noting that both [22] and [31] use the convention where there is no factor of $1/2$ before the $\lambda$ terms). We disagree with the form of the effective Lagrangians in [21] and [27], and agree with those in [22], [23] and [31]. We note, however, that through projection onto vector or pseudoscalar quark bilinears the difference with [27] reduces to a simple overall sign error of the matrix element, which is then eliminated by squaring. Accordingly, this has no ill effects in the quadratic coupling dominance convention. Also, in the case of [21] we note that it is merely that the wrong coupling in the second term of their equation (7) has the $*$ denoting complex conjugation.

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In all these cases, it turns out we are agreeing with [26], though [26] only gives the bounds to the first significant figure, and we assume that the differences ($6.7 \times 10^{-9}$ compared to $6 \times 10^{-9}$ and $2.7 \times 10^{-7}$ compared to $3 \times 10^{-7}$) arise from rounding errors.

We do not agree with the bounds presented in [38], which are just those taken from [27]. We believe that [27] presented incorrect bounds, and that this arises from their equation (13) for the decay width $\Gamma(B_q \rightarrow l^- l^+l^+)$. We find that the ratio of the decay width (13) in [21] over our decay width (II.23) is $4(m_b + m_q)^2/M_{B_q}^2$. While $m_b + m_q \approx M_{B_q}$ for heavy mesons, we believe that equation (13) in [27] misses a factor $1/4$ which results in too tight bounds. However, as the experimental bounds for many of the rare $B$ decay branching ratios have improved, we still obtain bounds for the couplings associated with these decays tighter than in [27]. Note that we agree with the corresponding equation (8) in [22] (taking into account that [22] defines the couplings $\lambda$ such that the superpotential does not have the factor of $1/2$ before the trilinear lepton term) and with the generic result in [44].

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