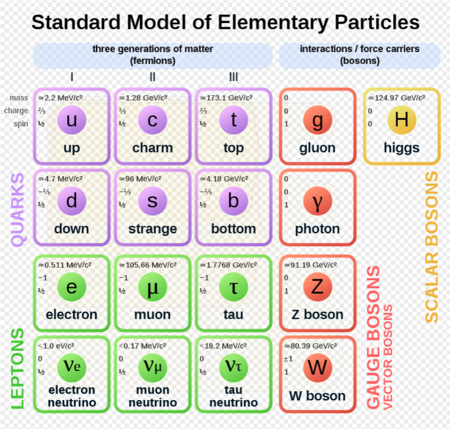
A Tale of Invisibility: Constraints on New Physics in $b \to s\nu\nu$

Tobias Felkl

In Collaboration with **Michael A. Schmidt**, **Sze Lok Li**; arXiv: 2111.04327
Sydney Consortium of Particle Physics & Cosmology
School of Physics, University of New South Wales, Sydney, Australia

Seminar Talk @ Brookhaven National Laboratory
9 December 2021

Motivation: Flavour Physics



MissMJ, Cush, PBS NOVA [1], Fermilab, Office of Science, United States Department of Energy, Particle Data Group, Public Domain

Flavour structure of nature more complicated than in SM

- Neutrino oscillations: Lepton flavour not exactly conserved
- Magnetic dipole moment of the muon, ... (?)

Motivation: Flavour-Changing Neutral Currents

New physics is expected to have small effects $\rightarrow$ Rare processes.

Flavour-Changing Neutral Currents:

- Loop Suppression: $\sim 1/(16\pi^2) \sim 1/100$.
- CKM Suppression: $|V_{ij}| \approx \lambda^n \approx 0.2^n$ with $n = 1, 2, 3$ for $i \neq j$
- GIM suppression: $\mathcal{A} = \underbrace{\sum_{i=u,c,t} V_{ib}^* V_{is}\, f(0)}_{=0} + \sum_{i=u,c,t} V_{ib}^* V_{is} \frac{m_i^2}{m_W^2} f'(0) + \ldots$

New physics: GIM suppression generically does not hold anymore.

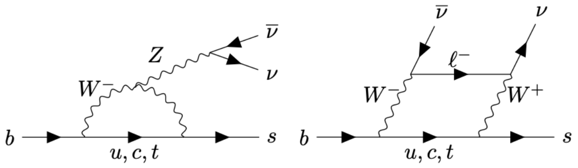


Figure 1 – Lowest-order SM Feynman diagrams for $b \rightarrow s\nu\bar{\nu}$ transitions.

Belle-II collaboration, 55th Rencontres de Moriond on Electroweak Interactions and Unified Theories, 5, 2021, 2105.05754

Motivation: Rare Processes with Missing Energy

Possible enhancement in two ways:

- new intermediate states
- exotic final states which escape undetected

Complete factorisation of amplitudes into hadronic and leptonic parts

Belle-II experiment projected to measure these decays (uncertainties $\approx 10\%$)

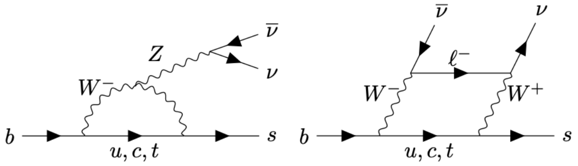
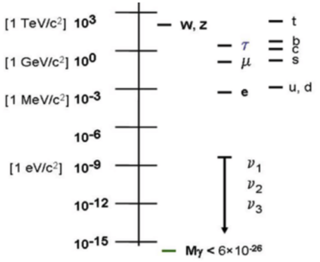


Figure 1 – Lowest-order SM Feynman diagrams for $b \to s\nu\bar{\nu}$ transitions.

Belle-II collaboration, 55th Rencontres de Moriond on Electroweak Interactions and Unified Theories, 5, 2021, 2105.05754

Contents



M. Kozlowski, J. Marciak-Kozlowska, Extrasensory Perception Phenomena, 978-3-659-82947-5, 2016

Particle content of the SM:

- Light particles: $g,\ \gamma,\ \nu,\ e,\ u,\ d,\ s,\ \mu,\ c,\ \tau,\ b$
- Heavy particles: $W,\ Z,\ h,\ t$

Separation of mass scales
→ "Remove" heavy particles from theory.

Low-Energy Effective Theory (LEFT) with additional sterile neutrinos

$$\mathcal{L} = \sum_{X=L,R} C_{\nu d}^{\mathrm{VLX}} \mathcal{O}_{\nu d}^{\mathrm{VLX}} + \left(\sum_{X=L,R} C_{\nu d}^{\mathrm{SLX}} \mathcal{O}_{\nu d}^{\mathrm{SLX}} + C_{\nu d}^{\mathrm{TLL}} \mathcal{O}_{\nu d}^{\mathrm{TLL}} + \mathrm{h.c.} \right) \tag{1}$$

J. Aebischer, M. Fael, C. Greub, J. Virto, JHEP 09 (2017) 158, 1704.06639

E.E. Jenkins, A.V. Manohar, P. Stoffer, JHEP 03 (2018) 016, 1709.04486

EFT framework

Effective Operators:

$$
\begin{aligned}
\mathcal{O}^{\mathrm{VLL}}_{\nu d,\alpha\beta sb} &= (\overline{\nu_{L\alpha}}\gamma_\mu \nu_{L\beta})(\overline{s_L}\gamma^\mu b_L) & \mathcal{O}^{\mathrm{VLR}}_{\nu d,\alpha\beta sb} &= (\overline{\nu_{L\alpha}}\gamma_\mu \nu_{L\beta})(\overline{s_R}\gamma^\mu b_R) \\
\mathcal{O}^{\mathrm{SLL}}_{\nu d,\alpha\beta sb} &= (\overline{\nu^c_{L\alpha}}\nu_{L\beta})(\overline{s_R} b_L) & \mathcal{O}^{\mathrm{SLR}}_{\nu d,\alpha\beta sb} &= (\overline{\nu^c_{L\alpha}}\nu_{L\beta})(\overline{s_L} b_R) \\
\mathcal{O}^{\mathrm{TLL}}_{\nu d,\alpha\beta sb} &= (\overline{\nu^c_{L\alpha}}\sigma_{\mu\nu}\nu_{L\beta})(\overline{s_R}\sigma^{\mu\nu} b_L)
\end{aligned}
\tag{2}
$$

Left- or right-handed projector in quark bilinears

Only one sizeable Wilson coefficient in the SM:

$$
C^{\mathrm{VLL,SM}}_{\nu d,\alpha\alpha sb} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}V^*_{ts}V_{tb}\left(\frac{X}{\sin^2\theta_W}\right) \approx 0.01\ \mathrm{TeV}^{-2} \tag{3}
$$

$\rightarrow$ Contributions to $\mathcal{O}^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb}$ and $\mathcal{O}^{\mathrm{VLR}}_{\nu d,\alpha\alpha sb}$ **interfere** with the SM.

Observables: Predictions, Bounds, Projections

Observable	SM prediction LQCD+LCSR	Current constraint	Belle II: Uncertainties 5 ab^{-1}	50 ab^{-1}
$Br(B^0 \to K^0 \nu\bar{\nu})$	$(4.1 \pm 0.5) \times 10^{-6}$	$< 2.6 \times 10^{-5}$		
$Br(B^+ \to K^+ \nu\bar{\nu})$	$(4.4 \pm 0.7) \times 10^{-6}$	$< 1.6 \times 10^{-5}$	30%	11%
$Br(B^0 \to K^{*0} \nu\bar{\nu})$	$(11.6 \pm 1.1) \times 10^{-6}$	$< 1.8 \times 10^{-5}$	26%	9.6%
$Br(B^+ \to K^{*+} \nu\bar{\nu})$	$(12.4 \pm 1.2) \times 10^{-6}$	$< 4.0 \times 10^{-5}$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	0.49 ± 0.04			0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	0.49 ± 0.04			0.077
$Br(B \to X_s \nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 6.4 \times 10^{-4}$		

Employed LQCD+LCSR form factors:

- $B \to K\nu\nu$: N. Gubernari, A. Kokulu, D. van Dyk, JHEP 01 (2019) 150, 1811.00983
- $B \to K^*\nu\nu$: A. Bharucha, D.M. Straub, R. Zwicky, JHEP 08 (2016) 098, 1503.05534
  S. Descotes-Genon, A. Khodjamirian, J. Virto, JHEP 12 (2019) 083, 1908.02267

W. Altmannshofer, A.J. Buras, D.M. Straub, M. Wick, JHEP 04 (2009) 022, 0902.0160

1702.03224, 1303.7465, 1303.3719, hep-ex/0010022

Belle II Physics Book, PTEP 2019 (2019) 123C01, 1808.10567

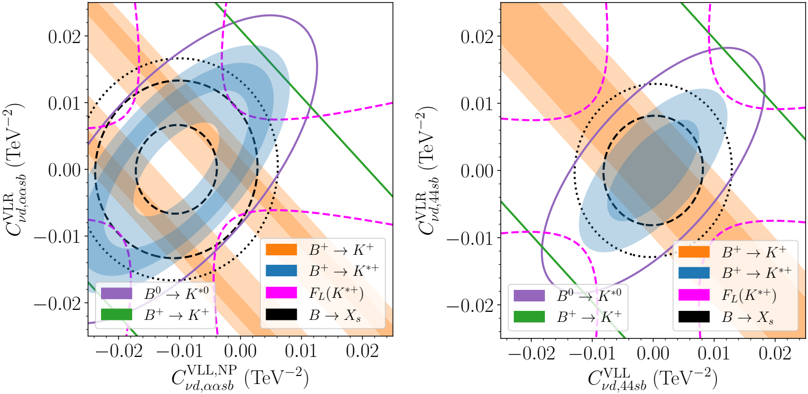
One Operator with Massless Neutrinos

Operator	Current Bound Value [TeV^{-2}]	Current Bound Λ_{NP} [TeV]	Current Bound Observable	Future Sensitivity (50 ab^{-1}) Value [TeV^{-2}]	Future Sensitivity (50 ab^{-1}) Λ_{NP} [TeV]	Future Sensitivity (50 ab^{-1}) Observable
$\mathcal{O}^{\text{VLL,NP}}_{\nu d,\alpha\alpha sb}$	0.028	6	$B \to K^* \nu\nu$	0.023	7	$B \to K^{(*)} \nu\nu$
$\mathcal{O}^{\text{VLR}}_{\nu d,\alpha\alpha sb}$	0.021	7	$B \to K \nu\nu$	0.002	25	$B \to K^{(*)} \nu\nu$
$\mathcal{O}^{\text{VLL}}_{\nu d,\gamma\delta sb}$	0.014	9	$B \to K^* \nu\nu$	0.006	13	$B \to K^{(*)} \nu\nu$
$\mathcal{O}^{\text{SLL}}_{\nu d,\gamma\gamma sb}$	0.012	10	$B \to K^{(*)} \nu\nu$	0.002	25	$B \to K \nu\nu$
$\mathcal{O}^{\text{SLL}}_{\nu d,\gamma\delta sb}$	0.009	10	$B \to K^{(*)} \nu\nu$	0.002	25	$B \to K \nu\nu$
$\mathcal{O}^{\text{TLL}}_{\nu d,\gamma\delta sb}$	0.002	25	$B \to K^* \nu\nu$	0.0009	35	$B \to K^* \nu\nu$

$\alpha \in (1,2,3)$ and γ and δ arbitrary, but $\gamma \neq \delta$

$$\Lambda_{\text{NP}} \approx \frac{1}{\sqrt{|C^{\text{XLY}}_{\nu d}|}} \tag{4}$$

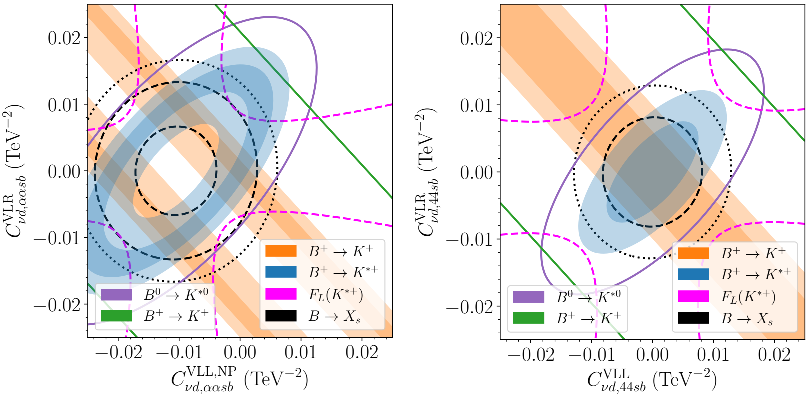
Two Operators with Massless Neutrinos



Current bounds: solid lines (violet, dark green)

Viable regions in parameter space if SM predictions get confirmed:
5 (50) ab^{-1}: Light (Dark) shaded regions, (pink dashed lines)

$B \to X_s \nu\nu$: Assumed sensitivity of 50% (20%); black dotted (dashed) lines

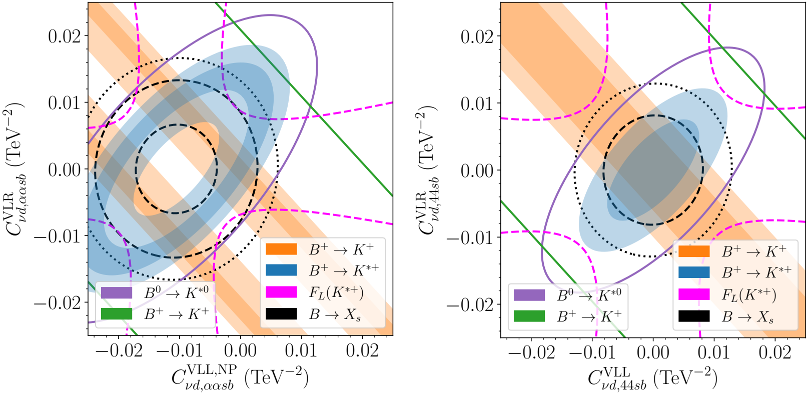


Straight bands: $\propto |C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} + C^{\mathrm{VLR}}_{\nu d,\alpha\alpha sb}|^2 \to$ exact cancellations

Ellipses:

- no interference between operators
- $\propto A(q^2)\, |C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} + C^{\mathrm{VLR}}_{\nu d,\alpha\alpha sb}|^2 + B(q^2)\, |C^{\mathrm{VLL}}_{\nu d,\alpha\alpha sb} - C^{\mathrm{VLR}}_{\nu d,\alpha\alpha sb}|^2$
  $\to$ partial cancellations

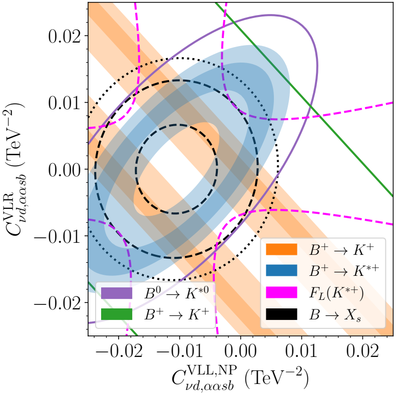
Two Operators with Massless Neutrinos

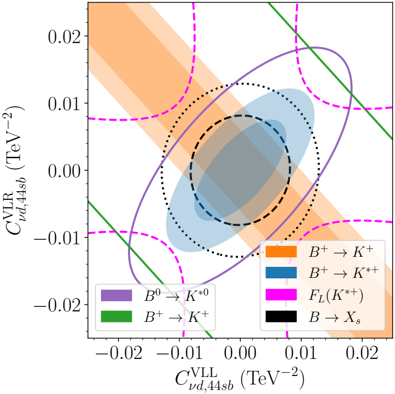


Viable region: $(0, 0)$; another one for interference with SM: $(-2|C^{\mathrm{VLL,SM}}_{\nu d,\alpha\alpha sb}|, 0)$

Interference with SM: Too efficient cancellations assumed absent
$\rightarrow$ centre region excluded

Two Operators with Massless Neutrinos

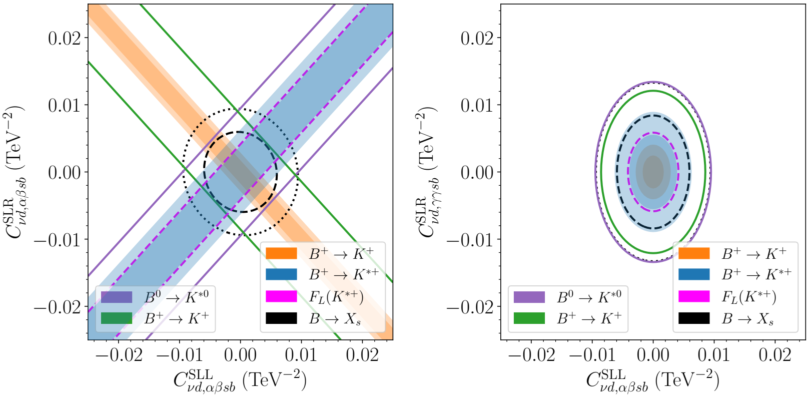




Left: Two more viable regions $(-1, \pm 1)\,|C^{\rm VLL,SM}_{\nu d,\alpha\alpha sb}|$ $\rightarrow$ $\Lambda_{\rm NP} \approx 10$ TeV

$B \to X_s \nu\nu$ probe almost exclusively so-far inaccessible parameter space, partly less prone to cancellations than $B \to K\nu\nu$ and $B \to K^*\nu\nu$

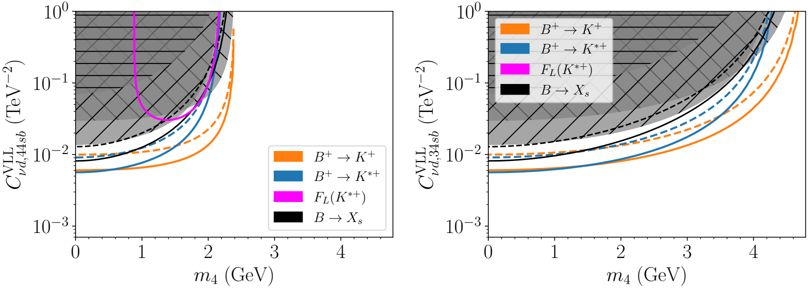
Two Operators with Massless Neutrinos



$B \to K^*\nu\nu \propto |C^{\mathsf{SLL}}_{\nu d,\alpha\beta sb} - C^{\mathsf{SLR}}_{\nu d,\alpha\beta sb}|^2 \to$ also just straight band

elliptic shape on the right: contributions to off-diagonal vs. diagonal elements

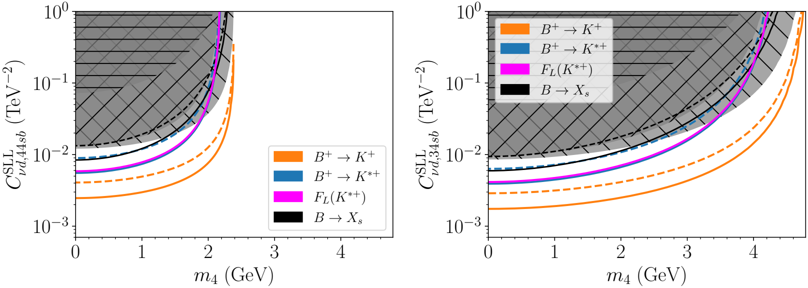
Massive Neutrinos



\\\\ (//) [–] **hatching**: **Current bounds** on $B \to K^+(K^{*0})[X_s]\nu\nu$
Dashed (solid) **lines**: **Future sensitivities** for 5 (50) ab^{-1}

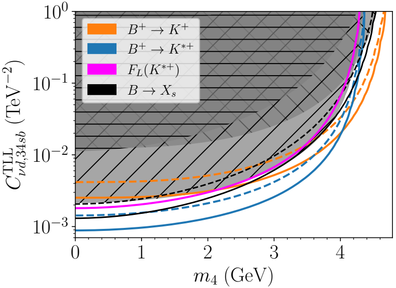
Generic effect: weakening bounds on WCs due to phase-space suppression

Vector operators: $B \to K\nu\nu$ more stringent for larger neutrino masses



\\ (//) [–] **hatching**: **Current bounds** on $B \to K^+(K^{*0})[X_s]\nu\nu$
Dashed (solid) **lines**: **Future sensitivities** for 5 (50) ab^{-1}

Scalar operators: $B \to K\nu\nu$ most competitive for entire mass range;
More stringent bounds than on vector operators irrespective of symmetries

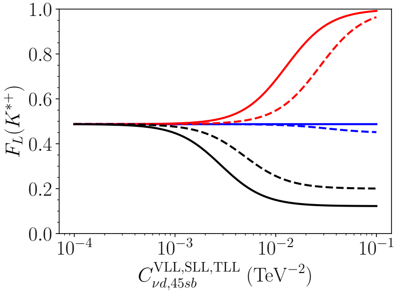


\\\\ (//) [–] **hatching**: **Current bounds** on $B \to K^+(K^{*0})[X_s]\nu\nu$
Dashed (solid) **lines**: **Future sensitivities** for 5 (50) ab^{-1}

$m_4 \gtrsim 4$ GeV:

- $B \to K\nu\nu$ more stringent than $B \to K^*\nu\nu$
- bound less strong than the one on scalar operator

$m_4 \lesssim 2.6$ GeV: inclusive mode superior to $B \to K\nu\nu$

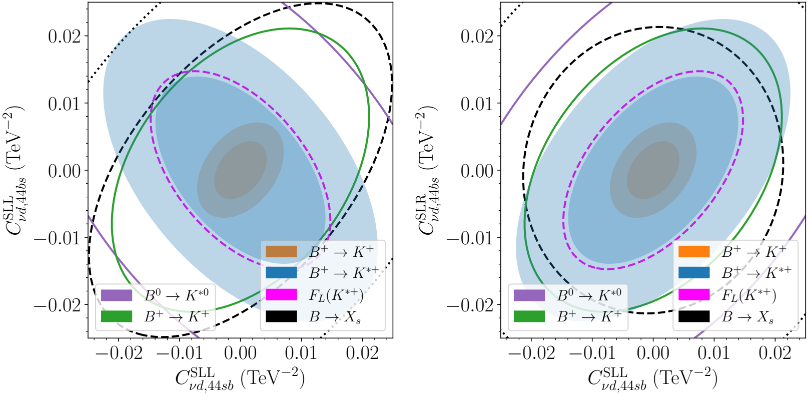


Solid [dashed] lines for $m_{4,5} = 0$ [1.5] GeV.

50-ab^{-1} data set: only $F_L(K^{*+}) \in (0.37, 0.61)$ compatible with SM at 1σ

Sharp distinction between scalar operators and vector/tensor operators

Massive Neutrinos



Amplitudes receive contributions from $\mathcal{O}^{\rm XLY}_{\nu d,\alpha\beta sb}$ and $\mathcal{O}^{\rm XLY\dagger}_{\nu d,\alpha\beta bs}$ for X = S or T

Interference if both neutrinos are massive. Here: $m_4 = 1.5$ GeV

$B \to K^*\nu\nu$: Distinction between operators of same/opposite chiralities

A Hint for New Physics?

Several analyses by Belle, Belle II, BaBar
$\to$ Simple weighted average:
$\mathrm{Br}(B^+ \to K^+\nu\nu) = (1.1 \pm 0.4) \times 10^{-5}$

Belle-II collaboration, 55th Rencontres de Moriond on Electroweak Interactions and Unified Theories, 5, 2021, 2105.05754

1303.3719, 1303.7465, 1702.03224

SM expectation $\mathrm{Br}(B^+ \to K^+\nu\nu) = (4.4 \pm 0.7) \times 10^{-6}$

Interpretation as hint for new physics: SM + massless sterile neutrino

	$\mathcal{O}^{\mathrm{VLL}}_{\nu d,44sb}$	$\mathcal{O}^{\mathrm{SLL}}_{\nu d,44sb}$	$\mathcal{O}^{\mathrm{SLL}}_{\nu d,34sb}$	$\mathcal{O}^{\mathrm{TLL}}_{\nu d,34sb}$	Bound	SM
WC	$22.3^{+5.97}_{-8.31}$	$9.12^{+2.44}_{-3.40}$	$6.45^{+1.72}_{-2.40}$	$9.33^{+2.50}_{-3.48}$		0
$B^0 \to K^{*0}\nu\nu$	$2.89^{+1.05}_{-1.05}$	$1.45^{+0.18}_{-0.18}$		$13.5^{+7.5}_{-7.5}$	1.8	$1.16^{+0.11}_{-0.11}$
$B^+ \to K^{*+}\nu\nu$	$3.11^{+1.13}_{-1.13}$	$1.57^{+0.20}_{-0.20}$		$14.6^{+8.1}_{-8.1}$	4.0	$1.24^{+0.12}_{-0.12}$
$B \to X_s\nu\nu$	$1.01^{+0.37}_{-0.37}$	$0.494^{+0.055}_{-0.055}$		$4.57^{+2.53}_{-2.53}$	6.4	$0.27^{+0.02}_{-0.02}$

Table: Wilson coefficients in 10^{-3} TeV^{-2},
$\mathrm{Br}(B \to K^*)$ in 10^{-5}, $\mathrm{Br}(B \to X_s)$ in 10^{-4}

$\mathrm{Br}(B \to K^0\nu\nu) = (1.02 \pm 0.37) \times 10^{-5}$, almost completely compatible @1σ

Conclusions

Combination $B \to K\nu\nu$, $B \to K^*\nu\nu$ very powerful

Most competitive single-operator bound for large neutrino masses: $B \to K\nu\nu$

Vector, tensor operators:

- $B \to K^*\nu\nu$ more competitive for smaller neutrino masses
- Suitable probe: $B \to X_s\nu\nu$

Scalar operators:

- Interference (massive neutrinos): $B \to K^*\nu\nu$, $F_L \to$ chiralities
- Compelling explanation for weighted average of $\mathrm{Br}(B^+ \to K^+\nu\nu)$

Felkl, T., Li, S.-L. & Schmidt, M.A.. arXiv: 2111.04327
A Tale of Invisibility: Constraints on New Physics in $b \to s\nu\nu$.

Thank you for your attention!

Back-Up

Renormalisation Group Running

Renormalisation group running:

$$C_{\nu d}^{\mathrm{SLL}}(4.8\ \mathrm{GeV}) = 1.370\, C_{\nu d}^{\mathrm{SLL}}(m_Z)\ , \qquad C_{\nu d}^{\mathrm{TLL}}(4.8\ \mathrm{GeV}) = 0.900\, C_{\nu d}^{\mathrm{TLL}}(m_Z)\ .$$

K.G. Chetyrkin, J.H. Kuhn, M. Steinhauser, Comput. Phys. Commun. 133 (2000) 43, 0004189

Decay Rate $B \to K\nu\nu$

One observable particle in final state: K

$$q^2 \equiv (p_\alpha + p_\beta)^2$$

Källén function $\lambda_{BK} \equiv \lambda(m_B^2, m_K^2, q^2)$ with
$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + xz + yz)$

Expression for massless neutrinos:

$$\frac{d\Gamma(B \to K\nu_\alpha\nu_\beta)}{dq^2} = \frac{\sqrt{\lambda_{BK}}\,q^2}{(4\pi)^3 m_B^3 (1+\delta_{\alpha\beta})} \left[\frac{\lambda_{BK}}{24q^2} |f_+|^2 \left| C^{\text{VLL}}_{\nu d,\alpha\beta sb} + C^{\text{VLR}}_{\nu d,\alpha\beta sb} \right|^2 \right.$$
$$+ \frac{(m_B^2 - m_K^2)^2}{8(m_b - m_s)^2} |f_0|^2 \left(\left| C^{\text{SLL}}_{\nu d,\alpha\beta sb} + C^{\text{SLR}}_{\nu d,\alpha\beta sb} \right|^2 + \left| C^{\text{SLL}}_{\nu d,\alpha\beta bs} + C^{\text{SLR}}_{\nu d,\alpha\beta bs} \right|^2 \right)$$
$$\left. + \frac{2\lambda_{BK}}{3(m_B + m_K)^2} |f_T|^2 \left(\left| C^{\text{TLL}}_{\nu d,\alpha\beta sb} \right|^2 + \left| C^{\text{TLL}}_{\nu d,\alpha\beta bs} \right|^2 \right) + (\alpha \leftrightarrow \beta) \right]$$

Decay Rate $B \to K^* \nu\nu$

Two observable particles in the final state: $K^* \to K, \pi$

Expression for massless neutrinos:

$$\frac{d\Gamma(B \to K^* \nu_\alpha \nu_\beta)}{dq^2} = \frac{\sqrt{\lambda_{BK^*}} q^2}{(4\pi)^3 m_B^3 (1 + \delta_{\alpha\beta})} \Bigg[\frac{\lambda_{BK^*} |V|^2}{12(m_B + m_{K^*})^2} \left| C^{\text{VLL}}_{\nu d,\alpha\beta sb} + C^{\text{VLR}}_{\nu d,\alpha\beta sb} \right|^2$$

$$+ \left(\frac{8 m_B^2 m_{K^*}^2}{3q^2} |A_{12}|^2 + \frac{(m_B + m_{K^*})^2 |A_1|^2}{12} \right) \left| C^{\text{VLL}}_{\nu d,\alpha\beta sb} - C^{\text{VLR}}_{\nu d,\alpha\beta sb} \right|^2$$

$$+ \frac{\lambda_{BK^*}}{8(m_b + m_s)^2} |A_0|^2 \left(\left| C^{\text{SLR}}_{\nu d,\alpha\beta sb} - C^{\text{SLL}}_{\nu d,\alpha\beta sb} \right|^2 + \left| C^{\text{SLR}}_{\nu d,\alpha\beta bs} - C^{\text{SLL}}_{\nu d,\alpha\beta bs} \right|^2 \right)$$

$$+ \left(\frac{32 m_B^2 m_{K^*}^2 |T_{23}|^2}{3(m_B + m_{K^*})^2} + \frac{4\lambda_{BK^*} |T_1|^2 + 4(m_B^2 - m_{K^*}^2)^2 |T_2|^2}{3q^2} \right)$$

$$\left(\left| C^{\text{TLL}}_{\nu d,\alpha\beta bs} \right|^2 + \left| C^{\text{TLL}}_{\nu d,\alpha\beta sb} \right|^2 \right) + (\alpha \leftrightarrow \beta) \Bigg]$$

Longitudinal Polarisation Fraction F_L

Two observable particles in the final state: $K^* \to K, \pi$
$\to$ Polarisation carries independent information

Expression for massless neutrinos:

$$F_L = 1 - \sum_{\alpha,\beta} \frac{1}{3(4\pi)^3 m_B^3 (1+\delta_{\alpha\beta})\Gamma(B \to K^*\nu\nu)} \int dq^2 \sqrt{\lambda_{BK^*}}$$
$$\times \left(\frac{\lambda_{BK^*}|V|^2 q^2}{4(m_B + m_{K^*})^2} \left| C^{\text{VLL}}_{\nu d,\alpha\beta sb} + C^{\text{VLR}}_{\nu d,\alpha\beta sb} \right|^2 \right.$$
$$+ \frac{(m_B + m_{K^*})^2 q^2 |A_1|^2}{4} \left| C^{\text{VLL}}_{\nu d,\alpha\beta sb} - C^{\text{VLR}}_{\nu d,\alpha\beta sb} \right|^2$$
$$+ \left(2\lambda_{BK^*}|T_1|^2 + 2(m_B^2 - m_{K^*}^2)^2 |T_2|^2 \right) \left(\left| C^{\text{TLL}}_{\nu d,\alpha\beta sb} \right|^2 + \left| C^{\text{TLL}}_{\nu d,\alpha\beta bs} \right|^2 \right)$$
$$\left. + (\alpha \leftrightarrow \beta) \right)$$

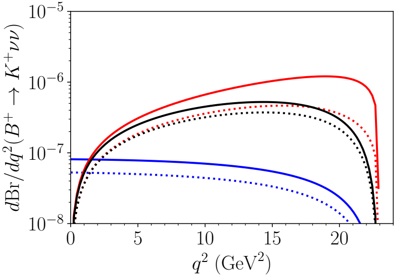
$B \to X_s \nu\nu$

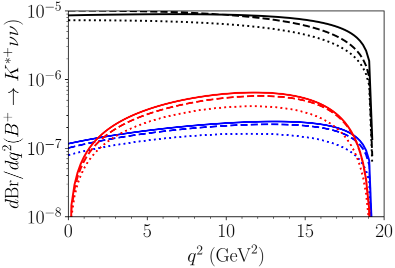
Inclusive mode: All final states with a constituent s quark

Leading order: Decay width of a free b quark ("quark-hadron duality")

Expression for massless neutrinos:

$$\frac{d\Gamma_{\text{incl}}^{\nu_\alpha\nu_\beta}}{dq^2} = \frac{\sqrt{\lambda(m_b^2, m_s^2, q^2)}}{768\pi^3 m_b(1+\delta_{\alpha\beta})}\Bigg(\left(3\frac{q^2}{m_b^2}(m_b^2+m_s^2-q^2)+\frac{1}{m_b^2}\lambda(m_b^2,m_s^2,q^2)\right)$$
$$\left[\left|C^{\text{VLL}}_{\nu d,\alpha\beta sb}\right|^2+\left|C^{\text{VLL}}_{\nu d,\beta\alpha sb}\right|^2+\left|C^{\text{VLR}}_{\nu d,\alpha\beta sb}\right|^2+\left|C^{\text{VLR}}_{\nu d,\beta\alpha sb}\right|^2\right]$$
$$-12q^2\frac{m_s}{m_b}\text{Re}\big(C^{\text{VLL}}_{\nu d,\alpha\beta sb}C^{\text{VLR}*}_{\nu d,\alpha\beta sb}+C^{\text{VLL}}_{\nu d,\beta\alpha sb}C^{\text{VLR}*}_{\nu d,\beta\alpha sb}\big)$$
$$+2\Big[3\frac{q^2}{m_b^2}(m_b^2+m_s^2-q^2)\Big[\left|C^{\text{SLL}}_{\nu d,\alpha\beta sb}\right|^2+\left|C^{\text{SLR}}_{\nu d,\alpha\beta sb}\right|^2+\left|C^{\text{SLL}}_{\nu d,\alpha\beta bs}\right|^2+\left|C^{\text{SLR}}_{\nu d,\alpha\beta bs}\right|^2\Big]$$
$$+12q^2\frac{m_s}{m_b}\text{Re}\big(C^{\text{SLL}}_{\nu d,\alpha\beta sb}C^{\text{SLR}*}_{\nu d,\alpha\beta sb}+C^{\text{SLL}}_{\nu d,\alpha\beta bs}C^{\text{SLR}*}_{\nu d,\alpha\beta bs}\big)\Big]$$
$$+32\left(3\frac{q^2}{m_b^2}(m_b^2+m_s^2-q^2)+\frac{2}{m_b^2}\lambda(m_b^2,m_s^2,q^2)\right)\left[\left|C^{\text{TLL}}_{\nu d,\alpha\beta sb}\right|^2+\left|C^{\text{TLL}}_{\nu d,\alpha\beta bs}\right|^2\right]\Bigg)$$



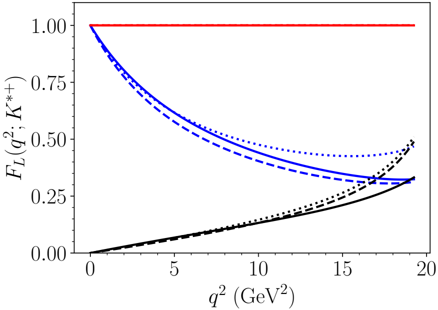


Vector, scalar, tensor operators: $C^{\mathrm{VLL}}_{\nu d,23sb} = C^{\mathrm{SLL}}_{\nu d,23sb} = C^{\mathrm{TLL}}_{\nu d,23sb} = 0.01\ \mathrm{TeV}^{-2}$
Solid lines: FFs used in this analysis

Dotted lines (LCSR) and dashed lines (LQCD+LCSR for $B \to K^*$) from
N. Gubernari, A. Kokulu, D. van Dyk, JHEP 01 (2019) 150, 1811.00983

$$F_L = \frac{4}{9} \frac{\left\langle Nq^2 \left(|\bar{H}^V_{0\alpha\beta}|^2 + |\bar{H}^A_{0\alpha\beta}|^2 + \frac{3}{2}|\bar{H}^S_{\alpha\beta}|^2 + \frac{3}{2}|\bar{H}^P_{\alpha\beta}|^2 + 2|\bar{H}^{T_t}_{0\alpha\beta}|^2 + |\bar{H}^T_{0\alpha\beta}|^2 \right) \right\rangle}{\left\langle \bar{G}_0^{0,0} \right\rangle},$$

$$F_T = 1 - F_L = \frac{4}{9} \frac{\left\langle \sum_{a=\pm} Nq^2 \left(|\bar{H}^V_{a\alpha\beta}|^2 + |\bar{H}^A_{a\alpha\beta}|^2 + 2|\bar{H}^{T_t}_{a\alpha\beta}|^2 + |\bar{H}^T_{a\alpha\beta}|^2 \right) \right\rangle}{\left\langle \bar{G}_0^{0,0} \right\rangle}$$



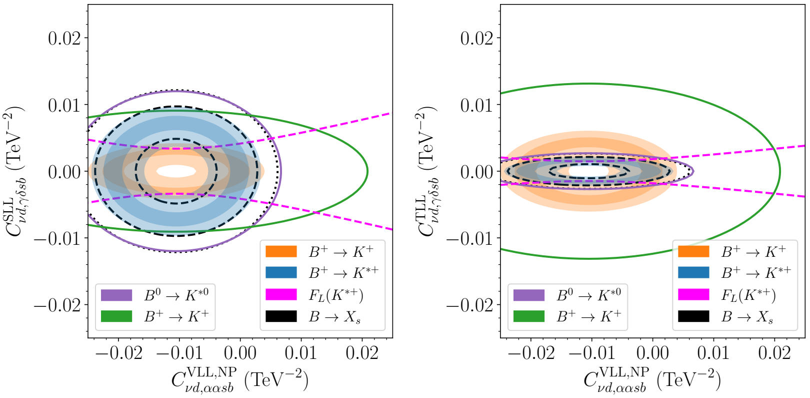
$q^2 \to 0$:

- $q^2|H^{V(A)}_{0\alpha\beta}|^2 \to$ const.
- $q^2|H^{V(A)}_{\pm\alpha\beta}|^2 \to 0$
- $q^2|H^{T(T_t)}_{0\alpha\beta}|^2 \to 0$
- $q^2|H^{T(T_t)}_{\pm\alpha\beta}|^2 \to$ const.

Vector, scalar, tensor operators

Note: No SM contribution

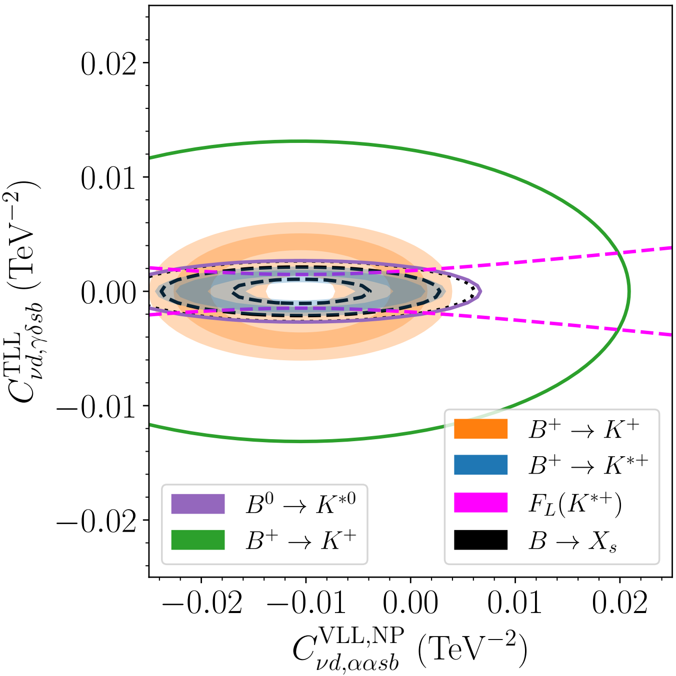
Two Operators with Massless Neutrinos

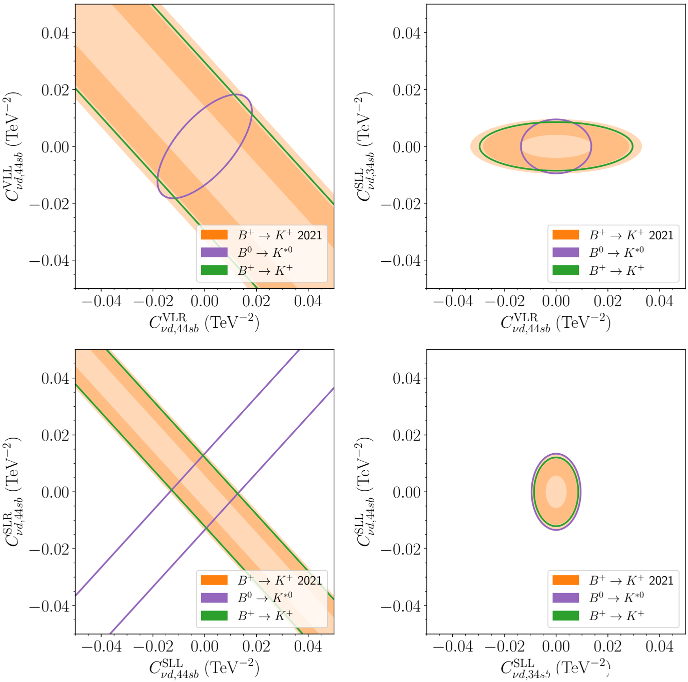


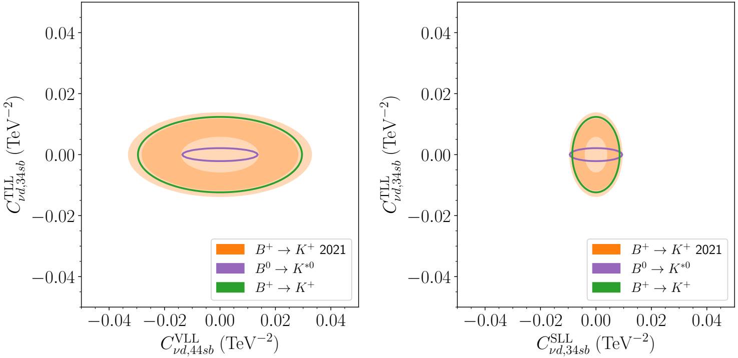
No interference: Cancellation of SM contribution ...

- ... do not noticeably relax single-operator bounds
- ... already efficiently probed with 5 ab^{-1}

$F_L(K^*)$ and $B \to K^*\nu\nu$ efficient; moderate improvement via $B \to K\nu\nu$


0.02
0.01
0.00
−0.01
−0.02
$C^{\mathrm{TLL}}_{\nu d,\gamma\delta sb}$ (TeV^{-2})
−0.02
−0.01
0.00
0.01
0.02
$C^{\mathrm{VLL,NP}}_{\nu d,\alpha\alpha sb}$ (TeV^{-2})
$B^0 \to K^{*0}$
$B^+ \to K^+$
$B^+ \to K^+$
$B^+ \to K^{*+}$
$F_L(K^{*+})$
$B \to X_s$


$C^{\mathrm{VLL}}_{\nu d,44sb}$ (TeV^{-2})
$C^{\mathrm{VLR}}_{\nu d,44sb}$ (TeV^{-2})
$C^{\mathrm{SLL}}_{\nu d,34sb}$ (TeV^{-2})
$C^{\mathrm{SLR}}_{\nu d,44sb}$ (TeV^{-2})
$C^{\mathrm{SLL}}_{\nu d,44sb}$ (TeV^{-2})
$B^+ \to K^+$ 2021
$B^0 \to K^{*0}$
$B^+ \to K^+$
0.04
0.02
0.00
−0.02
−0.04


0.04
0.02
0.00
−0.02
−0.04
$C^{\mathrm{TLL}}_{\nu d,34sb}$ (TeV^{-2})
$C^{\mathrm{VLL}}_{\nu d,44sb}$ (TeV^{-2})
$C^{\mathrm{SLL}}_{\nu d,34sb}$ (TeV^{-2})
$B^+ \to K^+$ 2021
$B^0 \to K^{*0}$
$B^+ \to K^+$

Form Factors

$B \to P$ transition, with $P = \pi,\ K,\ \bar{D}$

$$\langle P(k)|\overline{d}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_P^2}{q^2} q^\mu\right] f_+(q^2) + \frac{m_B^2 - m_P^2}{q^2} q^\mu f_0(q^2),$$

$$\langle P(k)|\overline{d}\sigma^{\mu\nu} q_\nu b|B(p)\rangle = \frac{i f_T(q^2)}{m_B + m_P}\left(q^2(p+k)^\mu - (m_B^2 - m_P^2) q^\mu\right), \tag{5}$$

For $B \to V$ decay, where $V = \rho,\ K^*,\ \bar{D}^*$

$$\langle V(k,\eta)|\overline{d}\gamma^\mu b|B(p)\rangle = \epsilon^{\mu\nu\rho\sigma}\eta_\nu^* p_\rho k_\sigma \frac{2V}{m_B + m_V},$$

$$\langle V(k,\eta)|\overline{d}\gamma^\mu\gamma_5 b|B(p)\rangle = i\eta_\nu^*\Big[g^{\mu\nu}(m_B + m_V)A_1 - \frac{(p+k)^\mu q^\nu}{m_B + m_V} A_2 - q^\mu q^\nu \frac{2m_V}{q^2}(A_3 - A_0)\Big],$$

$$\langle V(k,\eta)|\overline{d}i\sigma^{\mu\nu} q_\nu b|B(p)\rangle = \epsilon^{\mu\nu\rho\sigma}\eta_\nu^* p_\rho k_\sigma 2T_1, \tag{6}$$

$$\langle V(k,\eta)|\overline{d}i\sigma^{\mu\nu}\gamma_5 b|B(p)\rangle = i\eta_\nu^*\Bigg[(g^{\mu\nu}(m_B^2 - m_V^2) - (p+k)^\mu q^\nu) T_2 + q^\nu\left(q^\mu - \frac{q^2}{m_B^2 - m_V^2}(p+k)^\mu\right) T_3\Bigg],$$

where η is the polarisation vector of the vector meson.

Form Factors

A_3 is a redundant quantity:

$$A_3 \equiv \frac{m_B + m_V}{2m_V} A_1 - \frac{m_B - m_V}{2m_V} A_2. \tag{7}$$

Replace A_2 and T_3 by

$$\begin{aligned} A_{12} \equiv& \frac{(m_B + m_V)^2 (m_B^2 - m_V^2 - q^2) A_1 - \lambda(q^2, m_B^2, m_V^2) A_2}{16 m_B m_V^2 (m_B + m_V)}, \\ T_{23} \equiv& \frac{(m_B^2 - m_V^2)(m_B^2 + 3m_V^2 - q^2) T_2 - \lambda(q^2, m_B^2, m_V^2) T_3}{8 m_B m_V^2 (m_B - m_V)}. \end{aligned} \tag{8}$$

Three identities for the form factors at $q^2 = 0$:

$$\begin{aligned} f_+(q^2 = 0) =& f_0(q^2 = 0), \\ A_0(q^2 = 0) =& A_3(q^2 = 0), \\ T_1(q^2 = 0) =& T_2(q^2 = 0). \end{aligned} \tag{9}$$

Combining Eqs. (7), (8), and (9), one obtains

$$A_{12}(q^2 = 0) = \frac{m_B^2 - m_V^2}{8 m_B m_V} A_0(q^2 = 0). \tag{10}$$

LEFT operators can be related to basis used in

J. Gratrex, M. Hopfer, R. Zwicky, Phys. Rev. D 93 (2016) 054008, 1506.03970

$$\mathcal{L} = \frac{1}{2} c_H \sum_i \sum_{\alpha,\beta} (C_{i,\alpha\beta} O_{i,\alpha\beta} + C'_{i,\alpha\beta} O'_{i,\alpha\beta}) \tag{11}$$

The operators are given by

$$\begin{aligned} O_{S(P)\alpha\beta} &= (\overline{s_L} b)(\overline{\nu_\alpha} (\gamma_5) \nu_\beta) \, , \qquad O_{V(A)\alpha\beta} = (\overline{s_L} \gamma^\mu b)(\overline{\nu_\alpha} \gamma_\mu (\gamma_5) \nu_\beta) \, , \\ O_{\mathcal{T}\alpha\beta} &= (\overline{s_L} \sigma^{\mu\nu} b)(\overline{\nu_\alpha} \sigma_{\mu\nu} \nu_\beta) \, . \end{aligned} \tag{12}$$

Primed operators obtained by replacing $s_L \to s_R$, i.e. $O' = O|_{s_L \to s_R}$.

$$\begin{aligned} C_{V\alpha\beta} &= C^{\text{VLL}}_{\nu d,[\alpha\beta]sb} & C_{A\alpha\beta} &= -C^{\text{VLL}}_{\nu d,(\alpha\beta)sb} \\ C'_{V\alpha\beta} &= C^{VLR}_{\nu d,[\alpha\beta]sb} & C'_{A\alpha\beta} &= -C^{VLR}_{\nu d,(\alpha\beta)sb} \\ C_{S\alpha\beta} &= C^{\text{SLR}}_{\nu d,(\alpha\beta)sb} + C^{\text{SLL}*}_{\nu d,(\beta\alpha)bs} & C_{P\alpha\beta} &= -C^{\text{SLR}}_{\nu d,(\alpha\beta)sb} + C^{\text{SLL}*}_{\nu d,(\beta\alpha)bs} \\ C'_{S\alpha\beta} &= C^{\text{SLL}}_{\nu d,(\alpha\beta)sb} + C^{\text{SLR}*}_{\nu d,(\beta\alpha)bs} & C'_{P\alpha\beta} &= -C^{\text{SLL}}_{\nu d,(\alpha\beta)sb} + C^{\text{SLR}*}_{\nu d,(\beta\alpha)bs} \\ C_{\mathcal{T}\alpha\beta} &= 2C^{\text{TLL}*}_{\nu d,[\beta\alpha]bs} & C'_{\mathcal{T}\alpha\beta} &= 2C^{\text{TLL}}_{\nu d,[\alpha\beta]sb} \end{aligned} \tag{13}$$

with the neutrino flavours α, β.

$$M_{(ab)} \equiv \frac{1}{2}(M_{ab} + M_{ba}) \qquad M_{[ab]} \equiv \frac{1}{2}(M_{ab} - M_{ba}) \, . \tag{14}$$