CHALLENGING MAJORANA EFFECTS IN $B \to K^{(*)}\nu\nu$ DECAYS

Claire Chevallier[a]

based on arxiv.2604xxxx in collaboration with A. Abada[a], L. Leal[b], A. Llauradó Filella[a], O. Sumensari[a], R. Zukanovich Funchal[b]

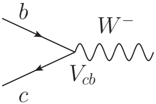
[a]Université Paris-Saclay & IJCLab, Orsay
[b]Universidade de São Paulo

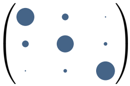
April 20, 2026

FCNCs in the Standard Model

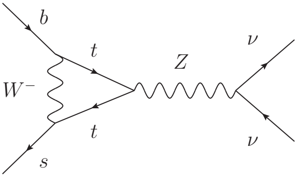
- $B \to K\nu\nu$ is a $b \to s\nu\nu$ transition $\Rightarrow$ **F**lavor **C**hanging **N**eutral **C**urrent (FCNC) : forbidden at tree-level in the SM

- In the SM, only **charged currents** allow flavor changing transitions through the CKM matrix

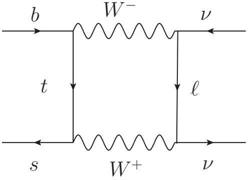


$V_{CKM} =$ 

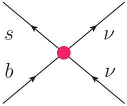
- In the SM, $b \to s\nu\nu$ is a **loop-level** process (GIM mechanism) :



$+$



$E \lessapprox m_W$

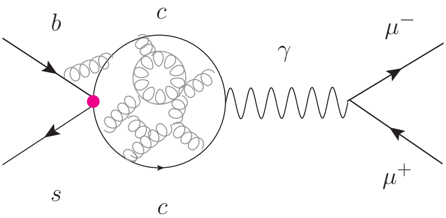


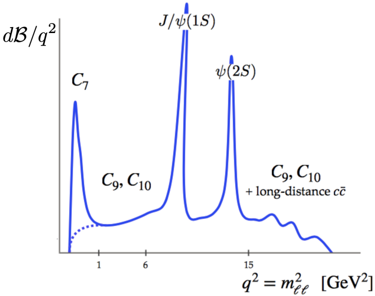
$(\bar{s}\gamma^\mu b_L)(\bar{\nu}\gamma_\mu \nu_L)$

Highly suppressed process $\Rightarrow$ sensitive to New Physics (NP) contributions !

Why focusing on $b \to s$ with neutrinos ?

- In principle, $b \to s\, l^+ l^-$ decays are also very sensitive to NP contributions
- LHCb, and CMS/Atlas have precisely measured several $b \to s\mu\mu$ observables, with results that seem to disagree with the SM
- However, these observables are plagued with **long-distance $c\bar{c}$ contributions**, which are theoretically **very challenging** to predict





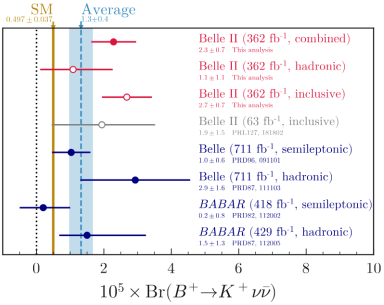
⇒ Decay modes with neutrinos are theoretically cleaner !

Why should we go beyond the Standard Model?

- Belle II efforts provided in 2023 the first measurement [1] :
  $\mathcal{B}(B \to K\text{'inv'}) = (2.3 \pm 0.5(stat)^{+0.5}_{-0.4}(syst)) \times 10^{-5}$ which is about **3σ** above the SM prediction
- Neutrinos are not detected (**missing energy**) so any $b \to s\text{'inv'}$ transition would contribute to the measurement

<u>BSM solutions</u> :

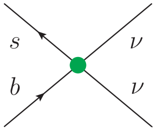
- SMEFT : $b \to s\nu\bar{\nu}$ [2, 3]
- Sterile neutrinos : $b \to sNN$, $b \to s\nu N$ [4, 5]
- Light invisible particles (DM, ALPs, ...) : $b \to sX$ [6, 7, 8, 9, 10]



In this talk, we focus on scenarios with **Majorana neutrinos** and the interplay with **neutrino physics** observables

LEFT (effective interactions to **SM neutrinos**)

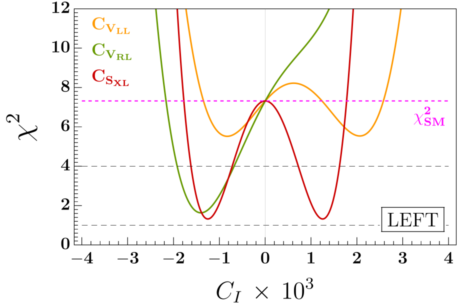
At low energies, we focus on the effective interactions



$$\sum_{X=L,R} \frac{C_{V_{XL}}}{v^2} O_{V_{XL}} + \frac{C_{S_{XL}}}{v^2} O_{S_{XL}} ,$$

$$O_{V_{XL}} = (\bar{s}\gamma^{\mu} b_X)(\bar{\nu}_L \gamma_{\mu} \nu_L),\ O_{S_{XL}} = (\bar{s} b_X)(\overline{\nu_L^C} \nu_L) .$$

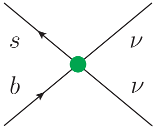
Lepton Number Violating !



- Both vector and scalar operators can accomodate the Belle-II data
- Differently from vector operators, the scalar ones change the kinematical distribution of $B \to K\nu\nu$ decay
  $\Rightarrow$ **testable prediction !**

LEFT (effective interactions to **SM neutrinos**)

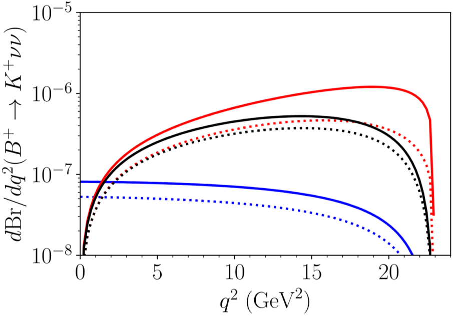
At low energies, we focus on the effective interactions



$$\sum_{X=L,R} \frac{C_{V_{XL}}}{v^2} O_{V_{XL}} + \frac{C_{S_{XL}}}{v^2} O_{S_{XL}} \,,$$

$$O_{V_{XL}} = (\bar{s}\gamma^{\mu} b_X)(\bar{\nu}_L \gamma_{\mu} \nu_L), \; O_{S_{XL}} = (\bar{s} b_X)(\overline{\nu_L^C} \nu_L) \,.$$

Lepton Number Violating !



- Both vector and scalar operators can accomodate the Belle-II data
- Differently from vector operators (●), the scalar ones (●) change the kinematical distribution of $B \to K\nu\nu$ decay
  $\Rightarrow$ **testable prediction !** [3]

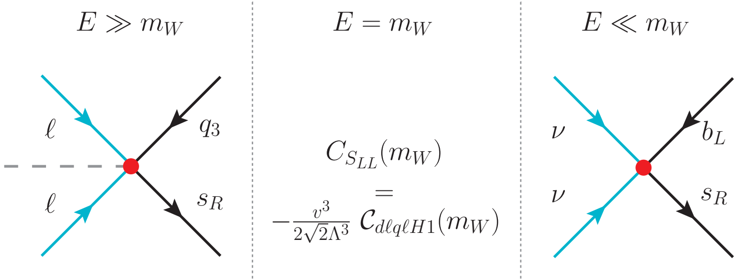
Are scalar contributions to $B \to K\nu\nu$ decay compatible with neutrino physics observables ?

$\Rightarrow$ relevant question as they are LNV

(i) in a scenario involving only **SM neutrinos** ?

SM neutrinos only (SMEFT)

- At **low energies**, we have $(\bar{s} b_L)(\overline{\nu_L^c} \nu_L)$
- Above the EW scale, **SU(2)** symmetry is restored: the allowed d.o.f are $\ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, $q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, H, $d_R, \ldots$

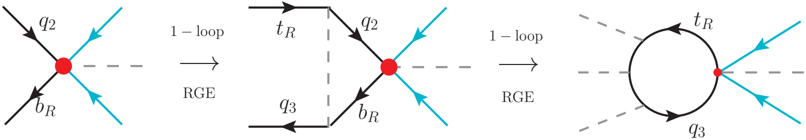


$\mathcal{O}_{d\ell q\ell H1} = \epsilon^{ab}\epsilon^{de}\,(\overline{s_R}\,\ell_a)\left(\overline{\ell_d^c}\,q_3^b\right) H^e$

$O_{S_{LL}} = (\bar{s} b_L)\,(\overline{\nu^c}\nu_L)$

Lepton Number Violating operator comes from **dim 7** SMEFT operator

Majorana effects of the dim 7 SMEFT operator



$\mathcal{O}_{d\ell q\ell H1} = \epsilon^{ab}\epsilon^{de}\left(\overline{b_R}\,\ell_a\right)\left(\overline{\ell^c_d}\,q^b_2\right)H^e$ $\quad\mathcal{O}_{qu\ell\ell H} = \epsilon_{ab}(\bar{q}_2 t_R)(\overline{\ell^c}\ell_a)H^b$ $\quad\mathcal{O}^{(7)}_{LH} = \left(\overline{\ell^c}\tilde{H}^*\right)\left(\tilde{H}^\dagger\ell\right)\left(H^\dagger H\right)$

Through running effects [11], the scalar operator generates contributions to $\mathcal{O}^{(7)}_{LH}$

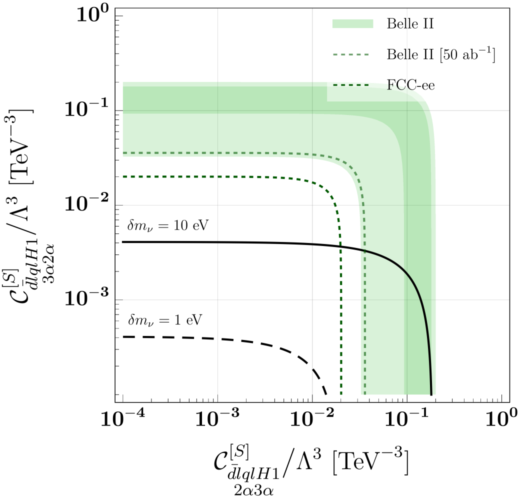
$\Rightarrow$ After EWSB, $\frac{\mathcal{C}^{(7)}_{LH}}{\Lambda^3}\mathcal{O}^{(7)}_{LH} \supset \delta m_\nu\,\overline{\nu^c_L}\nu_L$ $\Rightarrow$ gives rise to a **majorana mass term for neutrinos** !

$$\delta m_\nu = \frac{N_c}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}\log^2\left(\frac{\mu_{\rm ew}}{\Lambda}\right)\left[\left(y_u y_u^\dagger\right)^2 y_d - \frac{1}{4}\,y_u y_u^\dagger\,y_d y_d^\dagger y_d\right]_{ji}\mathcal{C}^{[S]}_{\underset{ij}{\bar{d}\ell q\ell H1}}(\Lambda) + \ldots$$

$$\simeq \mathcal{C}_{\underset{32}{\bar{d}\ell q\ell H1}}(\Lambda)\times\frac{2.4\,\mathrm{keV}}{(\Lambda/1\,\mathrm{TeV})^3} + \mathcal{C}_{\underset{23}{\bar{d}\ell q\ell H1}}(\Lambda)\times\frac{54\,\mathrm{eV}}{(\Lambda/1\,\mathrm{TeV})^3} + \ldots$$

y_u contains the CKM matrix and allows for flavor changing transitions!

Numerical analysis (SMEFT)



- → Fitting the experimental value of $\mathcal{B}(B \to K\nu\nu)$ implies a contribution to m_ν above 10 eV !
- → This scenario can only be viable, with at least **1% tuning** (ex : cancellation from dim 5 Weinberg operator)
- → A **scalar** operator in a scenario with only **SM neutrinos** seems highly disfavored

How to consistently have scalar operators without spoiling the tiny neutrino masses ?

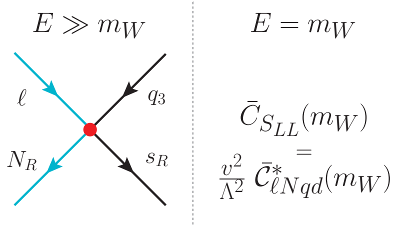
Are scalar contributions to $B \to K\nu\nu$ decay compatible with neutrino physics observables ?

(i) in a scenario involving only **SM neutrinos** ? *No*

(ii) in a scenario involving a **sterile neutrino** ?

Way out : adding a light sterile neutrino N_R

- At **low energies**, instead of $(\bar{s}b_L)(\overline{\nu_L^c}\nu_L)$ we have $(\bar{s}b_L)(\overline{N_R}\nu_L)$, mediating $b \to s\nu N$
- Above the EW scale, **SU(2)** symmetry is restored: the allowed d.o.f are ℓ, q, H, d_R, ... , and N_R ! (singlet of SM gauge group)

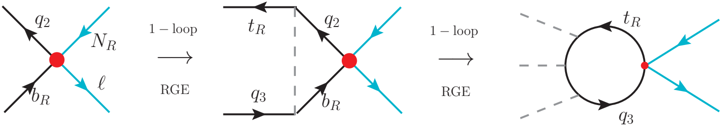


$\bar{\mathcal{O}}_{\ell Nqd} = (\bar{\ell}N_R)(\overline{q_3}s_R)$ $\bar{O}_{S_{LL}} = (\bar{s}b_L)\,(\overline{N_R}\nu_L)$

Dim 6 Lepton Number Conserving νSMEFT operator :

$\to$ Higher scale of NP compared to SMEFT scenario (dim 6 vs dim 7)

Running effects of dim 6 νSMEFT operator



$\bar{\mathcal{O}}_{\ell Nqd} = (\bar{\ell} N_R)(\overline{q_2} b_R)$ $\bar{\mathcal{O}}^{\dagger}_{Nlqu} = (\bar{\ell} N_R)(\overline{t_R} q_3)$ $\bar{\mathcal{O}}_{NH} = (\bar{\ell}\tilde{H} N)(H^{\dagger} H)$

Through running effects, the scalar operator generates contributions to $\bar{\mathcal{O}}_{NH}$

$\Rightarrow$ After EWSB, $\frac{\bar{\mathcal{C}}_{NH}}{\Lambda^2}\bar{\mathcal{O}}_{NH} \supset \delta m_D \overline{\nu_L} N_R$ $\Rightarrow$ gives rise to a **Dirac mass term for neutrinos !**

$$\delta m_D = -\frac{N_c\sqrt{2}}{(16\pi^2)^2}\frac{v^3}{\Lambda^2}\log^2\left(\frac{\mu_{ew}}{\Lambda}\right)\left[y_d^{\dagger}(y_u y_u^{\dagger})^2 - \frac{1}{4} y_d^{\dagger} y_d y_d^{\dagger} y_u y_u^{\dagger}\right]_{ji} \bar{\mathcal{C}}^{(1)}_{\substack{\ell Nqd \\ ij}} + \dots$$

$$\simeq -\bar{\mathcal{C}}_{\substack{\ell Nqd \\ 23}}(\Lambda) \times \frac{14\,\mathrm{keV}}{(\Lambda/1\,\mathrm{TeV})^2} - \bar{\mathcal{C}}_{\substack{\ell Nqd \\ 32}}(\Lambda) \times \frac{0.3\,\mathrm{keV}}{(\Lambda/1\,\mathrm{TeV})^2} + \dots,$$

y_u contains the CKM matrix and allows for flavor changing transitions!

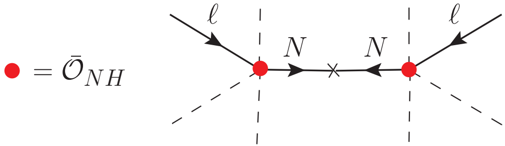
Seesaw like suppression of the mass

- N_R is a singlet of $SU(3)_c \times SU(2)_L \times U(1)_Y$ so it has a Majorana mass term $-\frac{m_N}{2}\overline{N_R^c}N_R$ and therefore, we have a non-diagonal mass matrix:

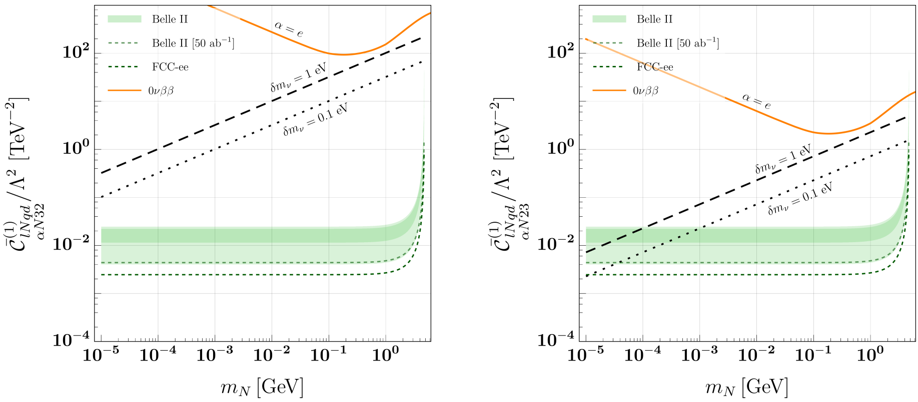
$$-\frac{1}{2}\left(\overline{\nu_L^c} \quad \overline{N_R}\right)\begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} \simeq -\frac{1}{2}\left(\overline{\nu_L'^c} \quad \overline{N_R'}\right)\begin{pmatrix} \frac{m_D^2}{m_N} & 0 \\ 0 & m_N \end{pmatrix}\begin{pmatrix} \nu_L' \\ N_R'^c \end{pmatrix}$$

with $\nu_L \simeq (1 - \frac{|U_{\ell N}|^2}{2})\nu_L' + U_{\ell N}\, N_R'^c$, $U_{\ell N} \simeq \frac{m_D}{m_N}$ and $m_\nu \simeq \frac{m_D^2}{m_N}$

- Through running, we generate $\bar{\mathcal{O}}_{NH}$ and diagrammatically, we see that we can then have a **Weinberg-like operator** at tree level



Numerical analysis (νSMEFT)



→ Through RGE evolution, $\bar{\mathcal{O}}_{\ell Nqd}$ with $\bar{s}b$ quarks contributes to $0\nu\beta\beta$ decays (orange line).

$\bar{\mathcal{O}}_{\ell Nqd}$ can accomodate the experimental value of $\mathcal{B}(B \to K\nu\nu)$ while remaining consistent with **bounds on neutrino observables**

Are scalar contributions to $B \to K\nu\nu$ decay compatible with neutrino physics observables ?

(i) in a scenario involving only **SM neutrinos** ? *No*

(ii) in a scenario involving a **sterile neutrino** ? *Yes*

Can we have a UV completion generating a dominant scalar contribution ?

Example of UV completion

We introduce a S_1 scalar leptoquark $(\bar{3}, 1, 1/3)$ at high energies

$$\mathcal{L}_{S_1} \supset y_i^L \, \overline{q_i^C} \, \epsilon \, \ell \, S_1 + \bar{y}_i^R \, \overline{d_i^C} N \, S_1 + \mathrm{h.c.}$$

We generate scalar and vector four-fermion operators at dimension 6.
Can the scalar operator dominate over the vector ones ?

We'll have

$$\bar{C}^{sb}_{S_{LL}} \propto \frac{v^2}{m^2_{S_1}} y_3^L \bar{y}_2^R , \quad \bar{C}^{sb}_{V_{LL}} \propto \frac{v^2}{m^2_{S_1}} y_2^L y_3^L , \quad \bar{C}^{sb}_{V_{RR}} \propto \frac{v^2}{m^2_{S_1}} \bar{y}_2^R \bar{y}_3^R .$$

For the scalar to dominate, in that case, we need,

$$\boxed{y_3^L > y_2^L , \quad \bar{y}_2^R > \bar{y}_3^R}$$

$\Rightarrow$ opposite hierarchy in ℓ and N couplings is required : can be made compatible with experimental data without fine tuning.

Summary / Outlook

- Low-energy scalar operators can explain the excess on $\mathcal{B}(B \to K\nu\nu)$, which would predict a distortion of the q^2-distribution $\to$ testable prediction !
- RGE running above the electroweak scale **connects** different sectors, **flavor physics and neutrino observables**.
- We have demonstrated that a scenario with a d=7 SMEFT operators suffer from a serious fine-tuning problem on neutrino mass
- We propose a solution with light RH neutrinos (keV $< m_N <$ 1 GeV) which can generate scalar operators while remaining consistent with neutrino physics constraints

RGE analyses provide essential constraints by connecting different energy scales

NB : The same analysis can be conducted for $K \to \pi\nu\nu$ decays. (cf back-up)

References

[1] I. Adachi et al. "Evidence for B+→K+$\nu\nu^{-}$ decays". In: *Phys. Rev. D* (2024). arXiv: 2311.14647 [hep-ex].

[2] Andrzej J. Buras et al. "$B \to K^{(*)}\nu\overline{\nu}$ decays in the Standard Model and beyond". In: *JHEP* (2015). arXiv: 1409.4557 [hep-ph].

[3] T. Felkl et al. "A tale of invisibility: constraints on new physics in b → s$\nu\nu$". In: *JHEP* (2021). arXiv: 2111.04327 [hep-ph].

[4] T. Felkl et al. "When energy goes missing: new physics in $b \to s\nu\nu$ with sterile neutrinos". In: *Eur. Phys. J. C* (2023). arXiv: 2309.02940 [hep-ph].

[5] S. Rosauro-Alcaraz et al. "Disentangling left and right-handed neutrino effects in $B \to K^{(*)}\nu\nu$". In: *Eur. Phys. J. C* (2024). arXiv: 2404.17440 [hep-ph].

[6] Murat Abdughani et al. "Constraining light dark matter and mediator with B+→K+$\nu\nu^{-}$ data". In: *Phys. Rev. D* (2024). arXiv: 2309.03706 [hep-ph].

[7] Lorenzo Calibbi et al. "Is dark matter the origin of the B→K$\nu\nu^{-}$ excess at Belle II?" In: *Phys. Rev. D* (2025). arXiv: 2502.04900 [hep-ph].

[8] W. Altmannshofer et al. "Light new physics in B→K(*)$\nu\nu^{-}$?" In: *Phys. Rev. D* (2024). arXiv: 2311.14629 [hep-ph].

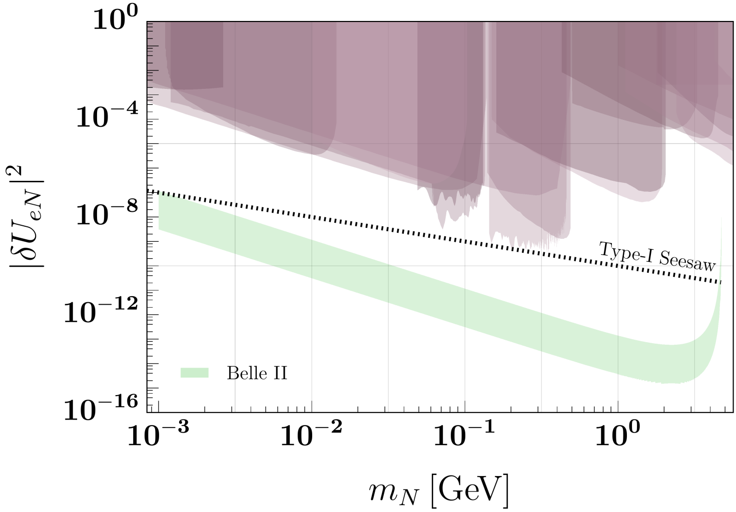
[9] Torben Ferber et al. "Displaced or invisible? ALPs from B decays at Belle II". In: *JHEP* (2023). arXiv: 2201.06580 [hep-ph].

[10] P. D. Bolton et al. "Signatures of light new particles in B→K(*)Emiss". In: *Phys. Rev. D* (2024). arXiv: 2403.13887 [hep-ph].

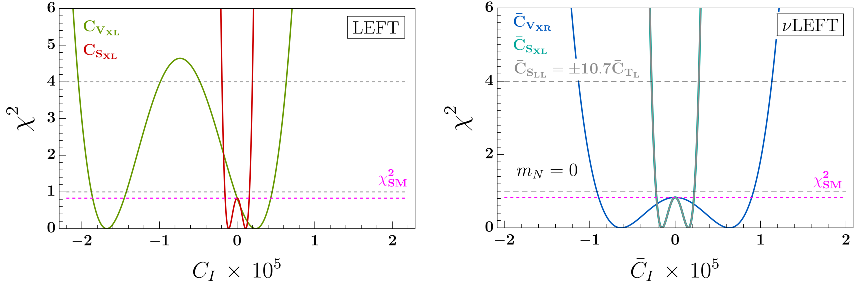
[11] D. Zhang. "Revisiting renormalization group equations of the SMEFT dimension-seven operators". In: *JHEP* (2024). arXiv: 2310.11055 [hep-ph].

BACK-UP

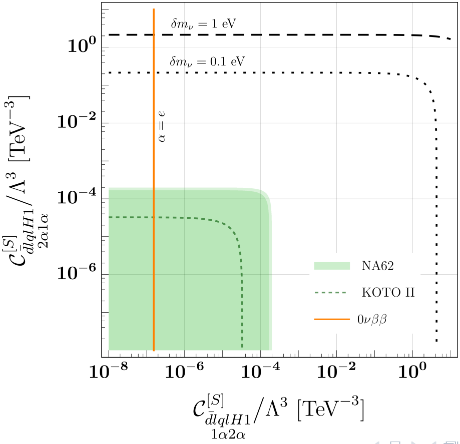
Induced mixing $B \to K\nu\nu$



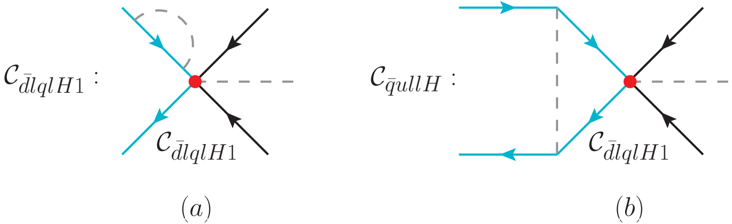
Low energy fit - $K \to \pi\nu\nu$

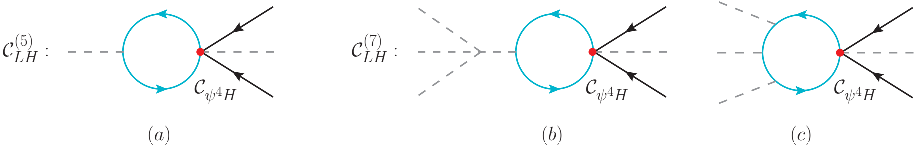


$$(\delta m_\nu)_{\alpha\beta} \simeq \mathcal{C}^{[S]}_{\substack{\bar{d}lqlH1\\2\alpha1\beta}}(\Lambda) \times \frac{0.46\,\mathrm{eV}}{(\Lambda/1\,\mathrm{TeV})^3} + \mathcal{C}^{[S]}_{\substack{\bar{d}lqlH1\\1\alpha2\beta}}(\Lambda) \times \frac{0.02\,\mathrm{eV}}{(\Lambda/1\,\mathrm{TeV})^3} + \ldots$$

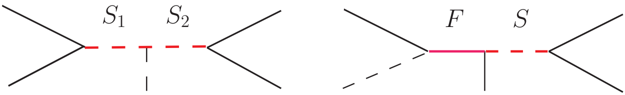


Full RGE - SMEFT





UV-completion issue



(a) (b)

νSMEFT-$K \to \pi\nu\nu$