Axions, Neutrinos, and Rare Decay Anomaly of Belle-II

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IFIC Valencia
Spain

Based on: Hati, Leite, **NN**, Valle, 2408.00060 [hep-ph]

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19th Patras Workshop on Axions, WIMPs and WISPs

17-09-2024

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Question: Can we explain neutrino mass, strong CP problem and Belle II anomaly from a single framework?

Based on: Hati, Leite, **NN**, Valle, 2408.00060 [hep-ph]

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Belle-II Anomaly

- The latest Belle II measurement: B ($B^+ \to K^+ + E_{\rm miss}$) = $(2.3 \pm 0.5) \times 10^{-5}$

Adachi et al. 2311.14647 [hep-ex]

- Interpreting "missing energy" as a pair of neutrinos leads to 2.7σ deviation from the SM

- The effective Lagrangian within the LEFT approach:

$$\mathcal{L}_{\rm LEFT}^{bs\nu\nu} \supset \frac{8G_F V_{tb}V_{ts}^*}{\sqrt{2}} \frac{\alpha}{4\pi} \sum_{\alpha\beta} \left[(C_L^{sb\alpha\beta} + C_L^{sb,\rm SM}\delta^{\alpha\beta})(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_L^\alpha\gamma^\mu\nu_L^\beta) + C_R^{sb\alpha\beta}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_L^\alpha\gamma^\mu\nu_L^\beta) \right]$$

NP **NP**

Define: $R^\nu_{K^{(*)}} = \frac{{\rm Br}(B \to K^{(*)}\nu\bar{\nu})}{{\rm Br}(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}}$

$R^\nu_K = 5.3 \pm 1.7$; Only Belle II **Adachi et al. 2311.14647 [hep-ex]**

$R^\nu_K = 2.93 \pm 0.90$; Belle II + previous results

Marzocca et. al. 2404.06533 [hep-ph]

$R^\nu_{K^*} = 1.0 \pm 1.1$; Belle II expt. with combination of all channels **Grygier et al. 1702.03224 [hep-ex]**

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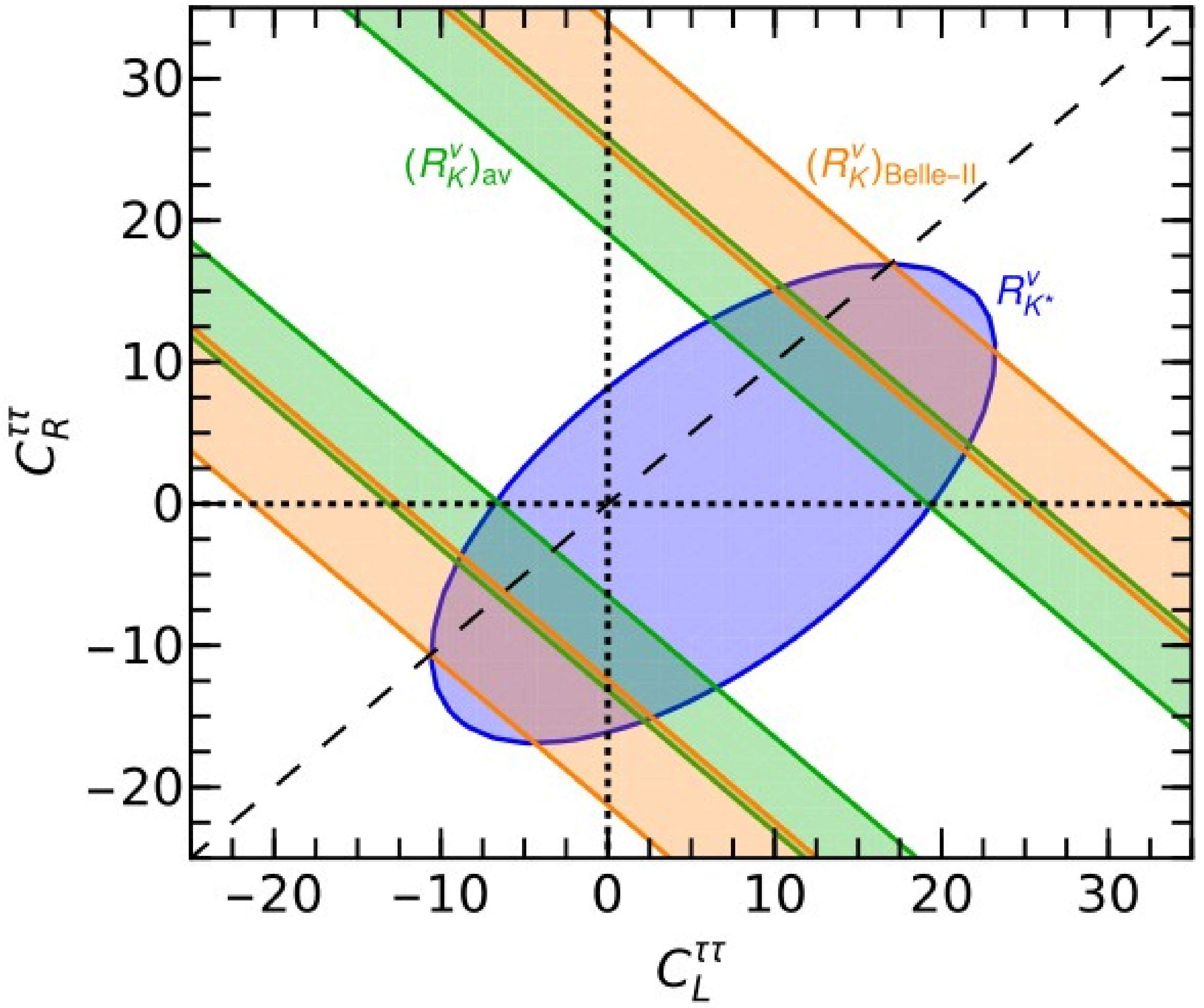


Note: $C_L^{\tau\tau} = 0, C_R^{\tau\tau} \neq 0$ **could explain the anomaly**

$C_R^{\tau\tau} \in [-6.49, -13.19]$ Green + blue regions

$[-12.41, -16.20]$ Orange + blue regions

Framework: KSVZ-type QCD axion model

Fields content:

Also see: Batra, Câmara, Joaquim, Srivastava, Valle, PRL 132 (2024) 5, 051801

SM Fields

Fields	$\mathcal{SM}$	$U(1)_{PQ}$	Families
L_L	$(1,2,-1/2)$	0	3
e_R	$(1,1,-1)$	0	3
Q_L	$(3,2,1/6)$	0	3
d_R	$(3,1,-1/3)$	0	3
u_R	$(3,1,2/3)$	0	3
Φ	$(1,2,1/2)$	0	1

BSM Fields

Fields	$\mathcal{SM}$	$U(1)_{PQ}$	Multiplicities	
Ψ_L	$(3,1,-1/3)$	0	2	Vector-like quarks
Ψ_R	$(3,1,-1/3)$	$-1/2$	2	
σ	$(1,1,0)$	$1/2$	1	
η	$(3,2,1/6)$	$-1/2$	1	Leptoquark-like
χ	$(3,1,-1/3)$	$-1/2$	1	Colored-scalars
Σ	$(\bar{6},1,2/3)$	1	1	

Interaction Lagrangian:

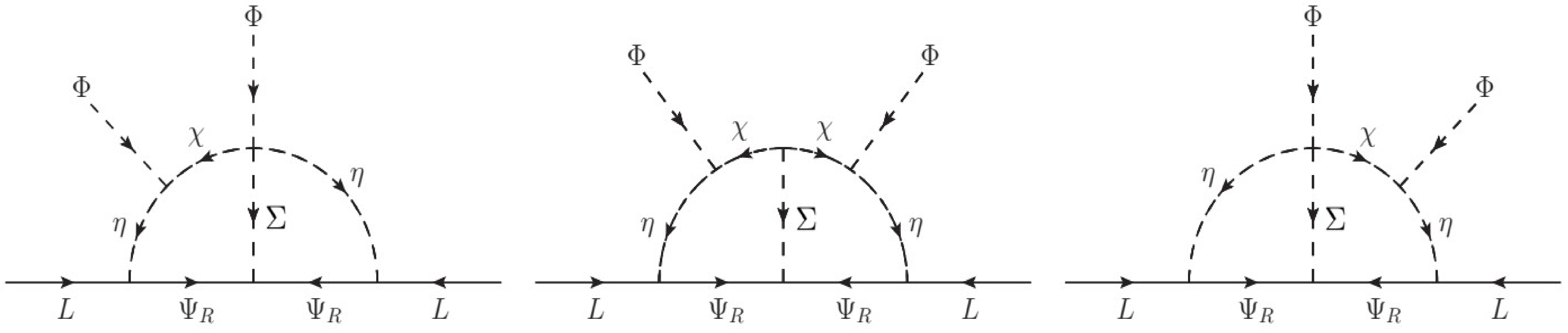
$$-\mathcal{L}_{\text{Yuk.}} \supset Y^{\Psi}_{ab}\overline{\Psi_{aL}}\Psi_{bR}\sigma + \frac{Y^{\Sigma}_{ab}}{2}\Psi^T_{aR}C\,\Sigma\,\Psi_{bR} + Y_{ia}\overline{L_{iL}}\,\tilde{\eta}\,\Psi_{aR} + M^{\Psi d}_{ai}\overline{\Psi_{aL}}d_{iR} + y^d_{ij}\,\overline{Q_{iL}}\,\Phi\,d_{jR} + \text{H.c.}$$

The relevant Lagrangian for η-mediated $b \to s\nu_\tau\overline{\nu_\tau}$ transition

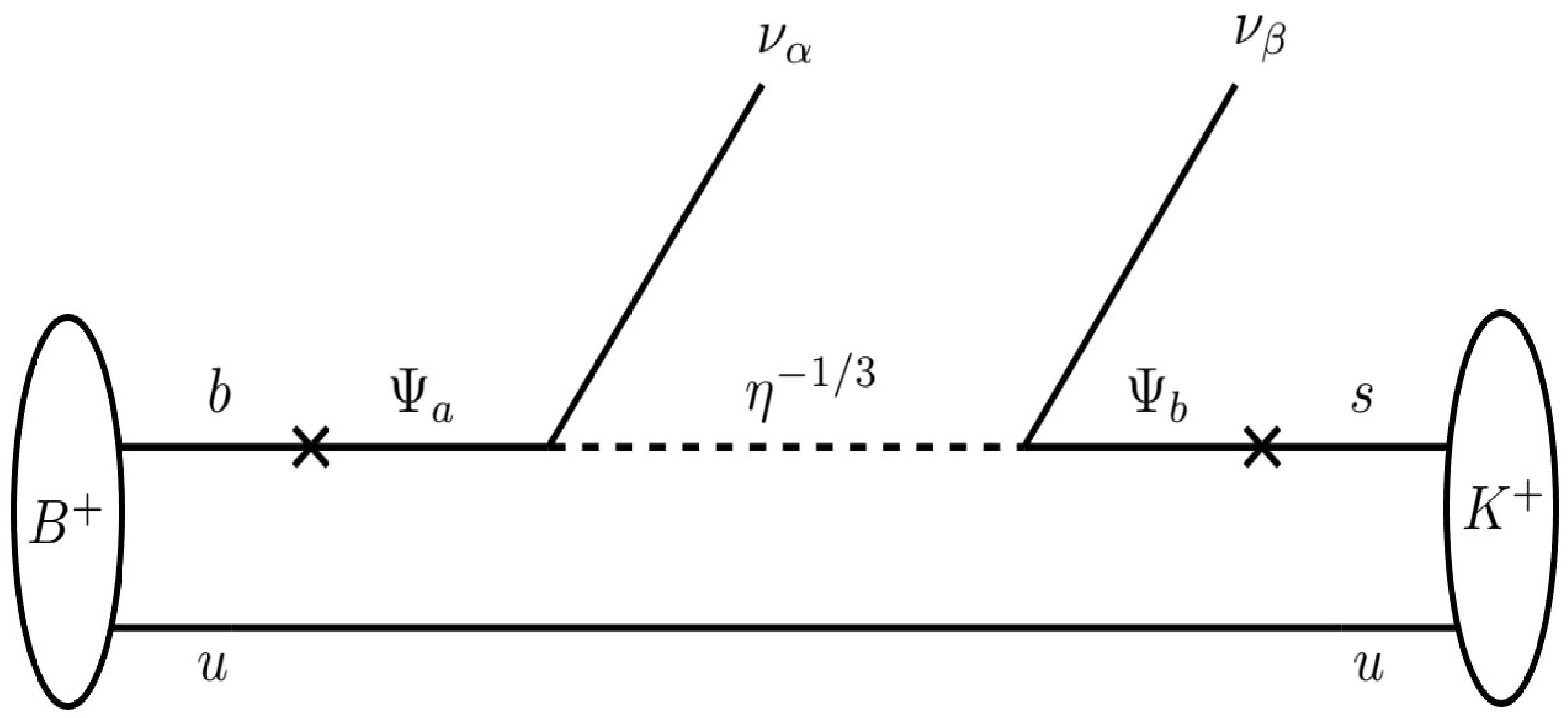
$$\mathcal{L}^{\text{mass}}_{\eta} = \overline{\nu_{\tau L}}\,\lambda_{33}\,b_R\,\eta^{1/3} + \overline{\nu_{\tau L}}\,\lambda_{32}\,s_R\,\eta^{1/3} + \overline{b_R}\,\lambda^*_{33}\,\nu_{\tau L}\,\eta^{-1/3} + \overline{s_R}\,\lambda^*_{32}\,\nu_{\tau L}\,\eta^{-1/3}$$

Cont...

Neutrino mass



The diagram for $b \to s\nu_\tau\overline{\nu_\tau}$ transition



The effective Lagrangian:

$$\mathcal{L}_{\text{eff}}^{bs\nu\nu} \supset -\frac{\lambda_{32}^*\lambda_{33}}{2m_\eta^2}\left(\bar{s}_R\gamma_\mu b_R\right)\left(\bar{\nu}_{\tau L}\gamma^\mu\nu_{\tau L}\right)$$

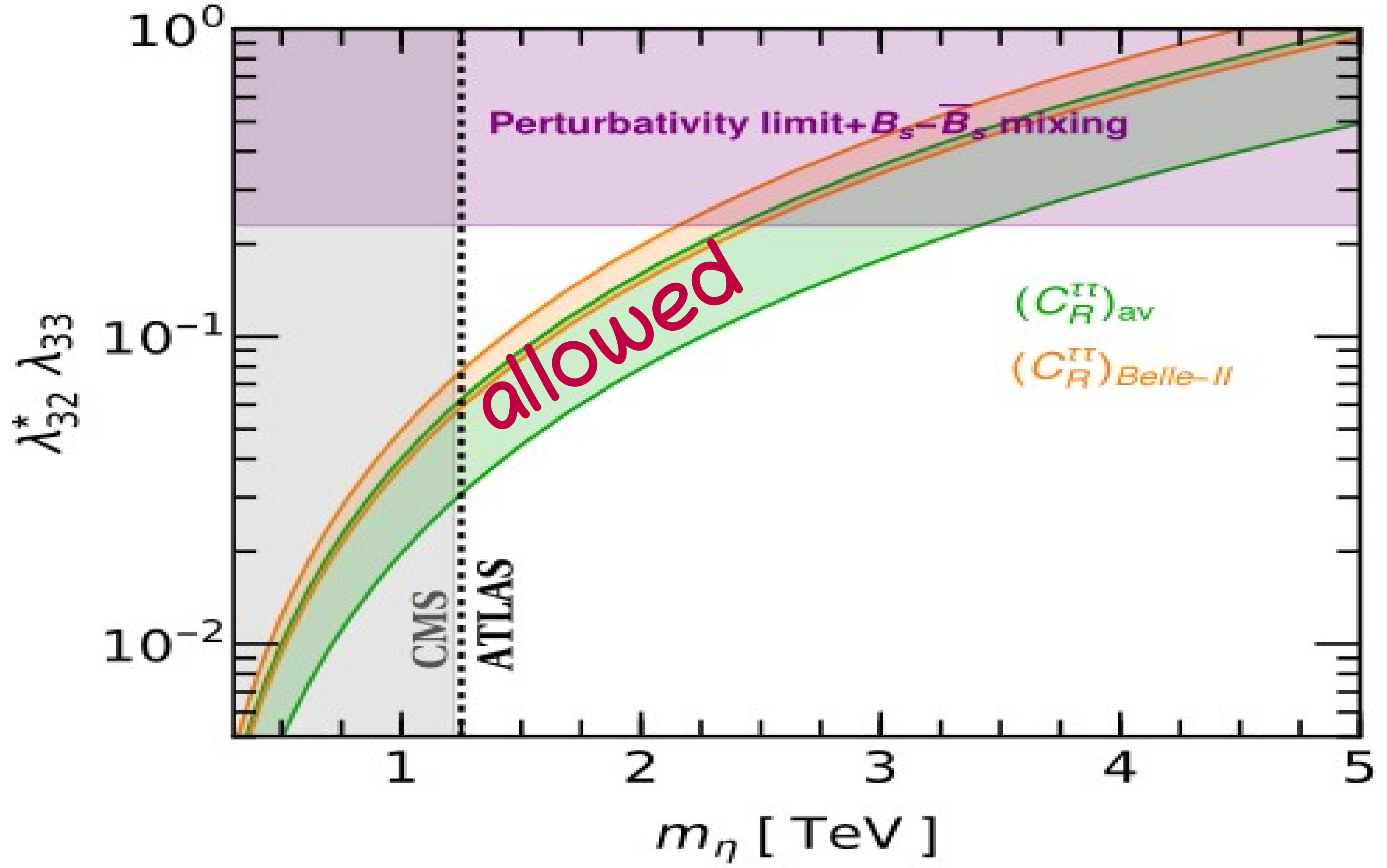
The relevant Wilson coefficient:

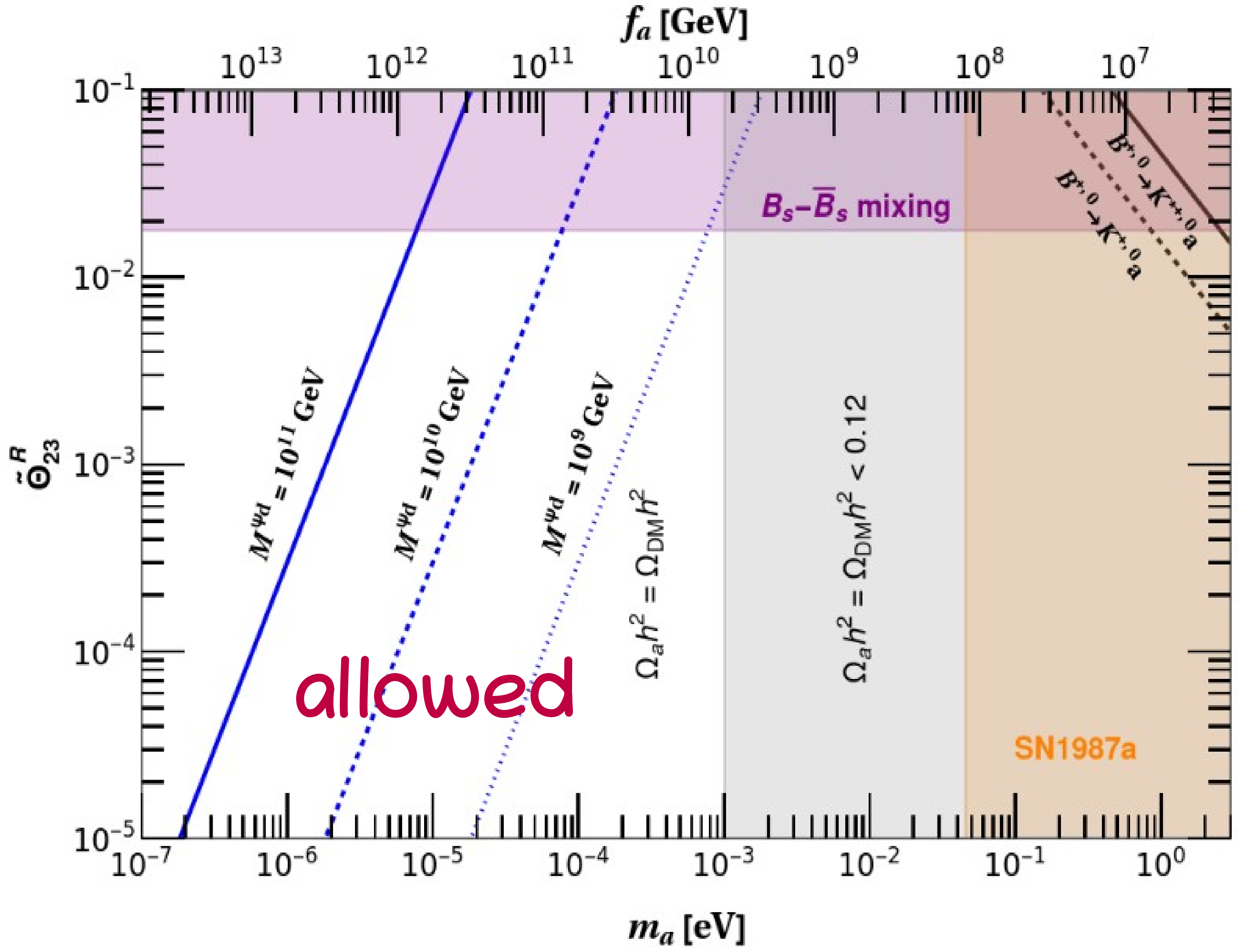
$$C_R^{sb\tau\tau} = -\left(\frac{8G_F V_{tb}V_{ts}^*}{\sqrt{2}}\frac{\alpha}{4\pi}\right)^{-1}\frac{\lambda_{32}^*\lambda_{33}}{2m_\eta^2}$$

Results

We have $C_R^{sb\tau\tau} = -\left(\frac{8G_F V_{tb}V_{ts}^*}{\sqrt{2}}\frac{\alpha}{4\pi}\right)^{-1}\frac{\lambda_{32}^*\lambda_{33}}{2m_\eta^2}$

Allowed parameter space that could explain $b \to s\nu_\tau\overline{\nu_\tau}$





Flavor-violating interaction terms between down-type quarks and the axion

$$\mathcal{L}_a^{\rm FV} = \frac{\partial_\mu a}{f_a}\overline{d_i'}\gamma^\mu\left(c_{ij}^V + c_{ij}^A\gamma_5\right)d_{jR}'$$

Where, $c_{bs}^V = c_{bs}^A = \frac{1}{2}\mathcal{Q}_R\,\tilde{\Theta}_{23}^R$

Mixing parameter

$$\tilde{\Theta}_{23}^R = \frac{M_{22}^{\Psi d}M_{23}^{\Psi d}}{M_2^{\Psi 2}} = \frac{M_{22}^{\Psi d}M_{23}^{\Psi d}}{(Y_{22}^\Psi f_a)^2} < 0.018$$ from $B_s - \bar{B}_s$ mixing

Final remarks

- The framework explains neutrino mass, strong CP problem and Belle II anomaly

- KSVZ-type QCD axion model has been adopted:

  The SM is extended with a new pair of vector-like isosinglet quarks, one scalar leptoquark, and two coloured scalar mediators with non-zero PQ charges.

- Crucial: Mass-mixing of vector-like quarks with the SM quarks explain the anomaly

- $B_s - \bar{B}_s$:Mixing is important to prove relevant parameter space

- The QCD axion in the model could explain the relic Dark matter abundance of the Universe