Possible scenarios for baryogenesis in the presence of a lepton number violating operator in the rare meson decays

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arXiv:2601.16422

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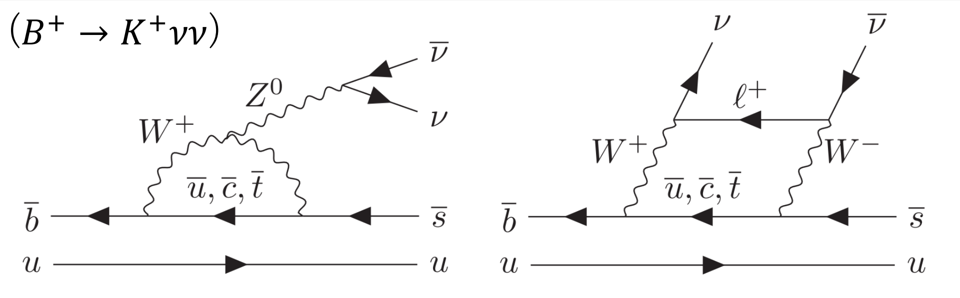
Introduction

- Rare meson decays: $B \to K\nu\nu, K \to \pi\nu\nu$

  Flavor changing processes -> suppressed by GIM mechanism

  Glashow, Iliopoulos, and Maiani, PRD (1970)



Belle II Collaboration, PRD (2024)

  Branching fractions

  Parrott et al. (HPQCD), PRD (2023)

  Buras, Eur. Phys. J. C (2023), etc.

$$\mathrm{Br}(B^+ \to K^+\nu\nu) = (5.58 \pm 0.37)\times 10^{-6}$$

$$\mathrm{Br}(K^+ \to \pi^+\nu\nu) = (8.60 \pm 0.42) \times 10^{-11} \qquad \mathrm{Br}(K_L \to \pi^0\nu\nu) = (2.94 \pm 0.15) \times 10^{-11}$$

- Those decay channels are sensitive to new physics (NP) effects.

- Measurements for the $B^+ \to K^+\nu\nu$ and $K^+ \to \pi^+\nu\nu$ decays Belle II Collaboration, PRD (2024); NA62 Collaboration, JHEP (2025)

  $\mathrm{Br}(B^+ \to K^+\nu\nu) = \left(2.3 \pm 0.5(\mathrm{stat.})^{+0.5}_{-0.4}(\mathrm{syst.})\right)\times 10^{-5}$ (Inclusive + hadronic tagging) -> 2.7σ excess from the SM

  $\mathrm{Br}(K^+ \to \pi^+\nu\nu) = 13.0^{+3.3}_{-3.0} \times 10^{-11}$

- Upper bound on the $K_L \to \pi^0\nu\nu$ decay at KOTO $\mathrm{Br} < 2.2 \times 10^{-9}$ (90% C.L.) KOTO Collaboration, PRL (2025)

Effective-field-theory approach

- Such (flavor-changing) NP effects are parametrized by effective operators.

Felkl, Li, and Schmidt, JHEP (2021); Buras, Harz, and Mojahed, JHEP (2024)
Fridell, Gráf, Harz, and Hati, JHEP (2024); Fridell, Ghosh, Okui and Tobioka, PRD (2024), and more

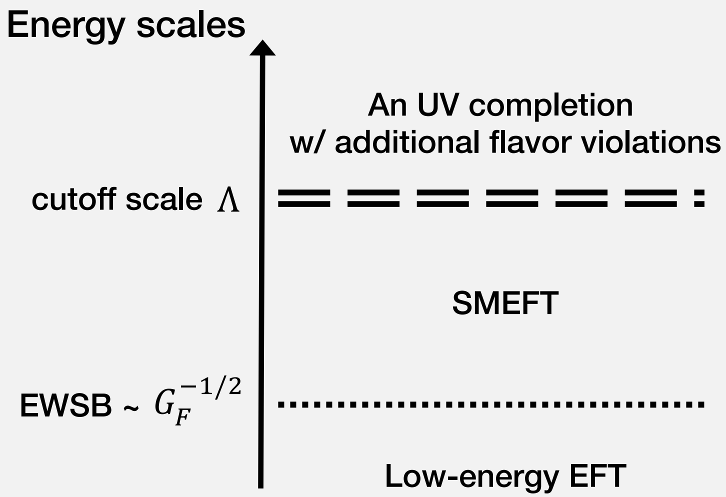
Several options: Dimensions? Symmetry? etc.

e.g.) the $b \to s\nu\nu$ transition

Dim.6 ($\Delta L = 0$) $\mathcal{L}_{\mathrm{LEFT}} \supset \frac{1}{\Lambda^2}(\bar{b}\gamma^{\mu}s)(\bar{\nu}\gamma_{\mu}\nu),$

Dim.7 ($\Delta L = 2$) $\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{1}{\Lambda^3}(\bar{L}d)(\bar{Q}L^C)H$ SU(2) contractions

-> $\mathcal{L}_{\mathrm{LEFT}} \supset \frac{\langle H \rangle}{\Lambda^3}(\bar{b}s)(\bar{\nu}\nu^C)$, $\frac{\langle H \rangle}{\Lambda^3}(\bar{b}\sigma^{\mu\nu}s)(\bar{\nu}\sigma^{\mu\nu}\nu^C)$



- Lepton number violation (LNV) is motivated by some BSM problems.

e.g.) Baryon-asymmetric Universe, Majorana nature of neutrinos, etc.

Scenarios for baryogenesis

- Baryon asymmetry of the Universe $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$ Planck (2018)

- Sakharov criteria for baryogenesis Sakharov (1967)

presence in the SM

B+L violation (sphaleron)
C violation (chiral EW theory)

absence in the SM

Sufficient CP violation
Out-of-thermal situations

Huet and Sather, PRD (1995)
Kajantie et al., PRL (1996)
D'Onofrio and Rummukainen, PRD (2016)

- Sphaleron process and baryogenesis $|0\rangle \leftrightarrow 9Q + 3L$

Dimopoulos and Susskind, PRD (1978),
Manton, PRD (1983), Klinkhamer and Manton, PRD (1984)

Sphaleron is in equilibrium from $T \sim 10^{12}\mathrm{GeV}$ to $T_{\mathrm{EWSB}} \sim 10^2\mathrm{GeV}$.

Assuming the other SM gauge and Yukawa interactions are in chemical equilibrium,

non-conserving charges are zero, i.e., B+ℓ=0.

baryon and lepton numbers are determined by B-ℓ.

$\Rightarrow$ $n_B, n_\ell \propto n_{B-\ell}$ (ℓ denotes left and right-handed leptons.)

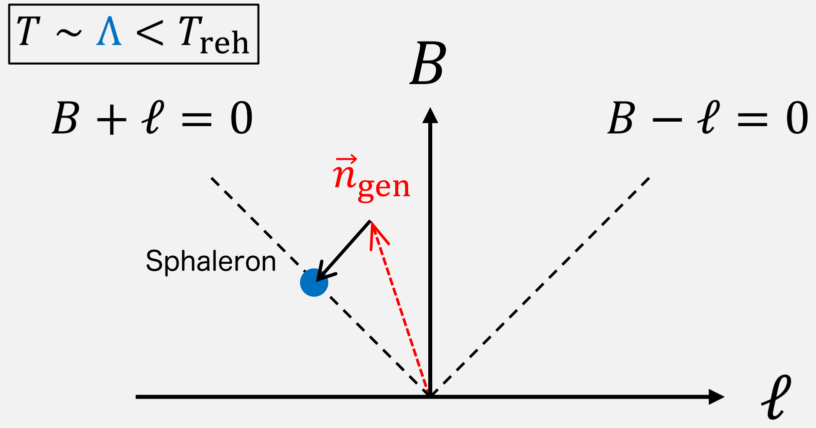
Harvey and Turner, PRD (1990)

Scenarios for baryogenesis

- Scenarios w/ B-ℓ violation decoupled at high temperatures

  Presence of $\vec{n}_{\rm gen}$ w/ $B-\ell$ direction at high temperatures
  Getting on the $B+\ell=0$ line via thermal sphalerons

  e.g.) Leptogenesis $\vec{n}_{\rm gen}=(\ell,0)$ Fukugita and Yanagida (1986),
  GUT baryogenesis $\vec{n}_{\rm gen}=(\ell,B)$ Yoshimura (1978), Weinberg (1979), and more

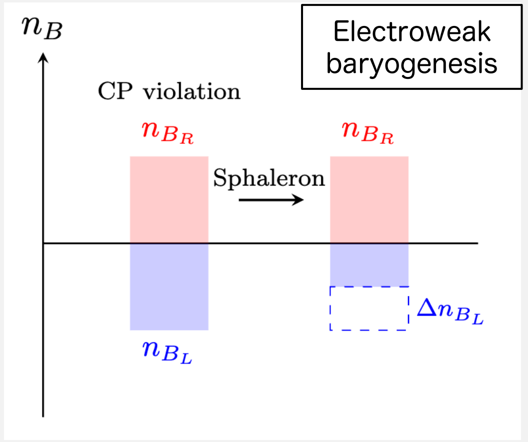


- Scenarios w/ non-thermal sphalerons or w/ B violation decoupled after sphaleron decoupling

  e.g.) Electroweak baryogenesis Kuzmin, Rubakov, and Shaposhnikov (1985)

  -> Left-handed asymmetry is generated by fast-moving bubble walls w/ CP violation, but total B and ℓ is conserved.

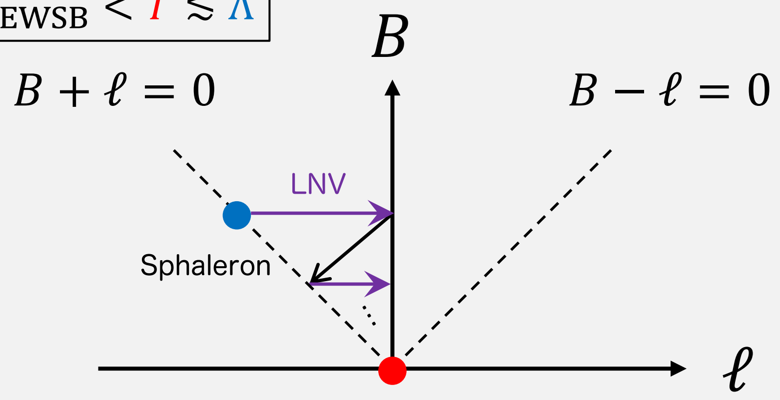
  -> (Out-of-equilibrium) sphalerons make total baryon asymmetry.



Lepton number washout

Deppisch, Harz, and Hirsch, PRL (2014); Deppisch, Harz, Hirsch, Huang, and Päs, PRD (2015);
Deppisch, Graf, Harz, and Huang, PRD (2018); Deppisch, Fridell, and Harz , JHEP (2020);

$T_{\rm EWSB} < T \lesssim \Lambda$



- What's happen if LNV operators are active?

  $\ell = 0$ and $B + \ell = 0$ (Le Chatelier's principle)
  -> $B = 0$ in the end

- LNV dim.7 operator in the rare meson decays ($d_p \to d_r \nu_\alpha \nu_\beta$)

$$\mathcal{L} = C^{pr}_{\alpha\beta}(\overline{d_p} L_\alpha)(Q_r L^C_\beta)H + C^{rp}_{\alpha\beta}(\overline{d_r} L_\alpha)(Q_p L^C_\beta)H + \mathrm{h.c.}$$

α, β: Indices for lepton flavor
p, r: Indices for quark flavor

cf.) Weinberg operator (dim.5) $\mathcal{L} = C^5_{\alpha\beta}\overline{L^C_\alpha} L_\beta HH + \mathrm{h.c.}$

2 <> 3 scatterings
violating lepton number by 2

Name: i	Process
(A1)	$\overline{d_p} L_\alpha \to \overline{Q_r}\,\overline{L_\beta}\,\overline{H}$
(A2)	$L_\alpha L_\beta H \to d_p \overline{Q_r}$
(A3)	$L_\alpha Q_r H \to d_p \overline{L_\beta}$
(A4)	$L_\alpha L_\beta Q_r \to d_p \overline{H}$
(A5)	$L_\alpha Q_r \to d_p \overline{L_\beta}\,\overline{H}$
(A6)	$L_\alpha L_\beta \to d_p \overline{Q_r}\,\overline{H}$
(A7)	$L_\alpha H \to d_p \overline{Q_r}\,\overline{L_\beta}$
(A8)	$\overline{d_p} L_\alpha H \to \overline{Q_r}\,\overline{L_\beta}$
(A9)	$\overline{d_p} L_\alpha L_\beta \to \overline{Q_r}\,\overline{H}$
(A10)	$\overline{d_p} L_\alpha Q_r \to \overline{L_\beta}\,\overline{H}$

- Boltzmann equation for $B/3 - \ell_\alpha$ (cutoff scale: Λ)

$$\frac{d\eta_{B/3-\ell_\alpha}}{dz} \sim -c_7 \frac{\Lambda_P}{\Lambda}\gamma^7_{\alpha\beta}\,\eta_{B/3-\ell_\beta} \times z^{-6} - c_5 \frac{\Lambda_P}{\Lambda}\gamma^5_{\alpha\beta}\,\eta_{B/3-\ell_\beta} \times z^{-2}$$ where $z = \Lambda/T$

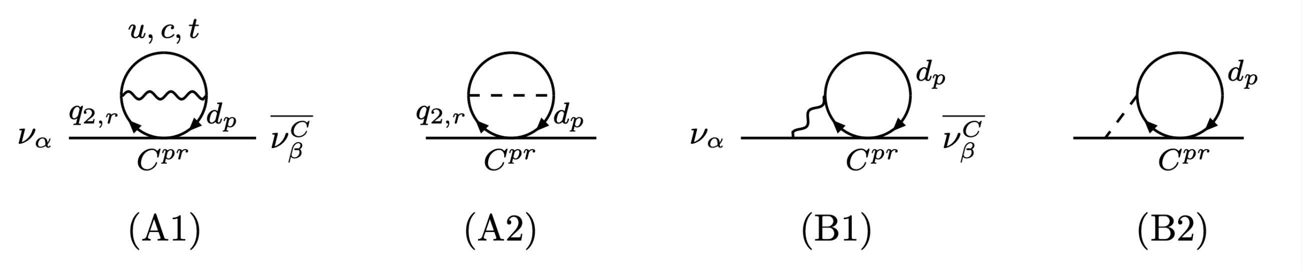
Strong washout at high temperatures ($T \sim \Lambda$)

Neutrino mass and $0\nu\beta\beta$ decay

- Dim.7 operators generate 2loop Majorana masses of the neutrinos.

  Associated w/ the Weinberg operator

  -> $m_{\nu,\alpha\beta} = m_{\nu,\alpha\beta}^{\text{dim.5}} + m_{\nu,\alpha\beta}^{\text{dim.7}}$

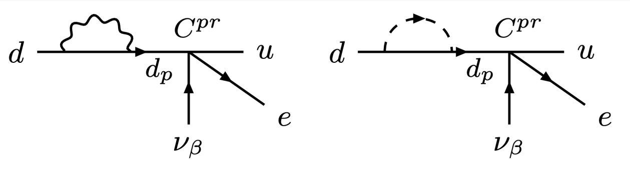


- $0\nu\beta\beta$ decay: relevant to the LNV operators for the first generation (electron)

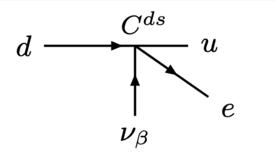
  Additional long-range contributions independent of the standard mass mechanism

  Vissani, JHEP (1999), and more

  Loop induced diagrams:

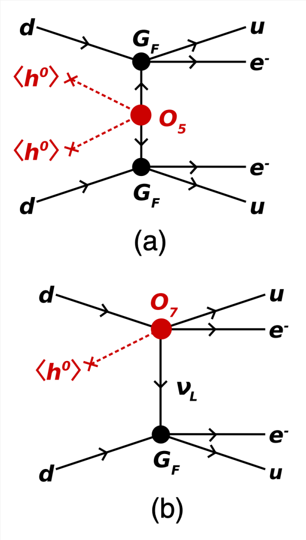


  But especially for C^{ds} $(s \to d\nu\nu)$, there is a tree level diagram:



  C^{ds} is tightly constrained by the current limit: $T_{\text{Xe}}^{1/2} > 3.8\times10^{26}\text{yr}$ (90% C.L.)

  KamLAND-Zen (2024)

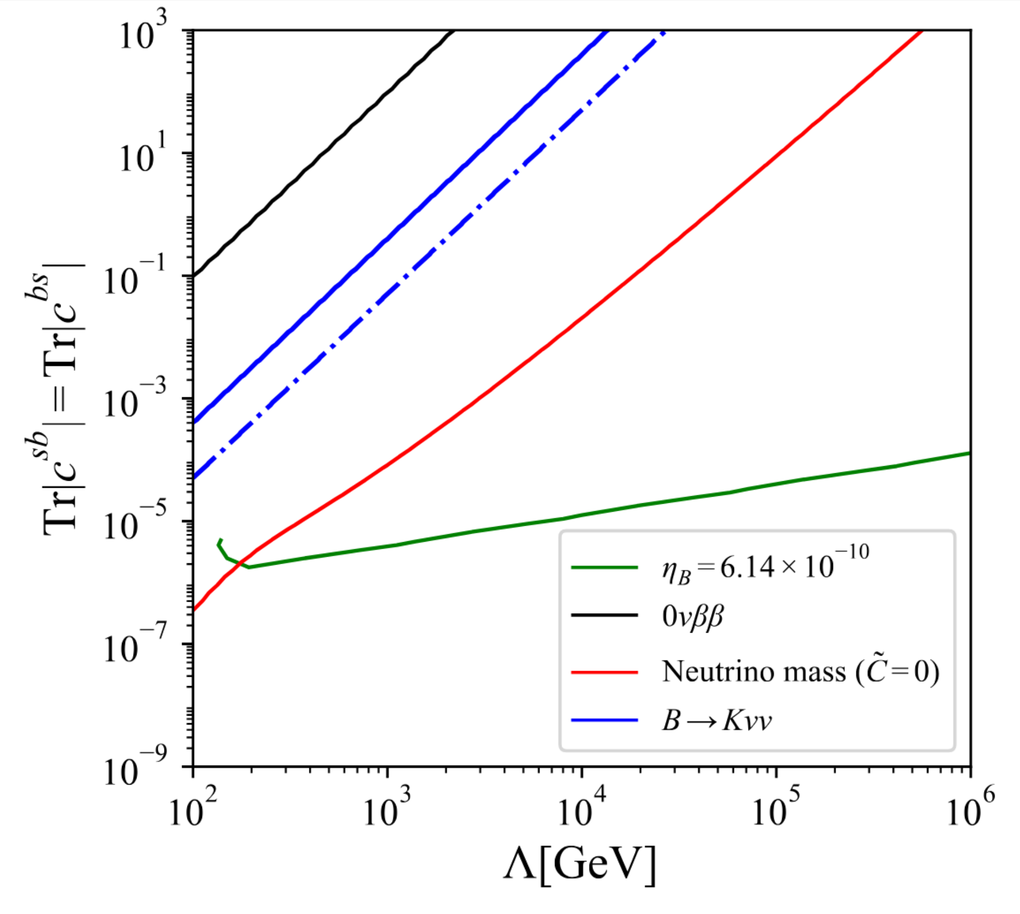


Deppisch et al., PRD (2018),

Deppisch et al., J. Phys. G (2012), etc.

Case1: Neutrino mass like

For the $B^+ \to K^+\nu\nu$ decay



- Lepton flavor structure of the dim.7 operators

$$C^{sb,bs}_{\alpha\beta} = \frac{c}{\Lambda^3}\times m^{\nu}_{\alpha\beta}$$

cf.) $m_{\nu,\alpha\beta} = m^{\mathrm{dim.5}}_{\nu,\alpha\beta} + m^{\mathrm{dim.7}}_{\nu,\alpha\beta}$

$\propto C^5_{\alpha\beta}$ $\propto C^{sb,bs}_{\alpha\beta}$

- Dimensionless coupling $c^{sb,bs}$ vs cutoff scale Λ
  - Constraints from $B^+ \to K^+\nu\nu$ measurement

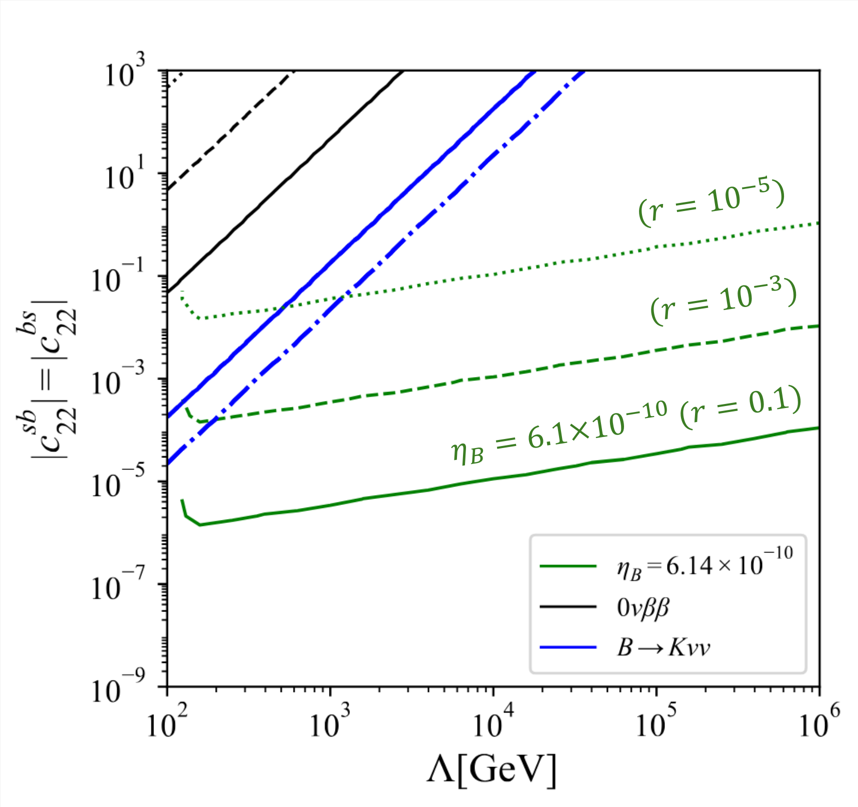
    arXiv:2507.12393;
    BelleII, PTEP (2019);

    Blue solid: bound from BelleII
    Blue dashdot: future prospect at BelleII w/ ∫Ldt=50at^{-1}

  - Green: $\eta_B = 6.14\times10^{-10}$, assuming initial $(\eta_{B/3-\ell_1}, \eta_{B/3-\ell_2}, \eta_{B/3-\ell_3}) = (1,1,1) \to \eta_B = O(1)$ at $T = \Lambda$
  - Red: Neutrino masses explained by purely dim.7
  - Black: Upper bound from the $0\nu\beta\beta$ decay

Case2: Specific flavor decoupling case

For the $B^+ \to K^+\nu\nu$ decay

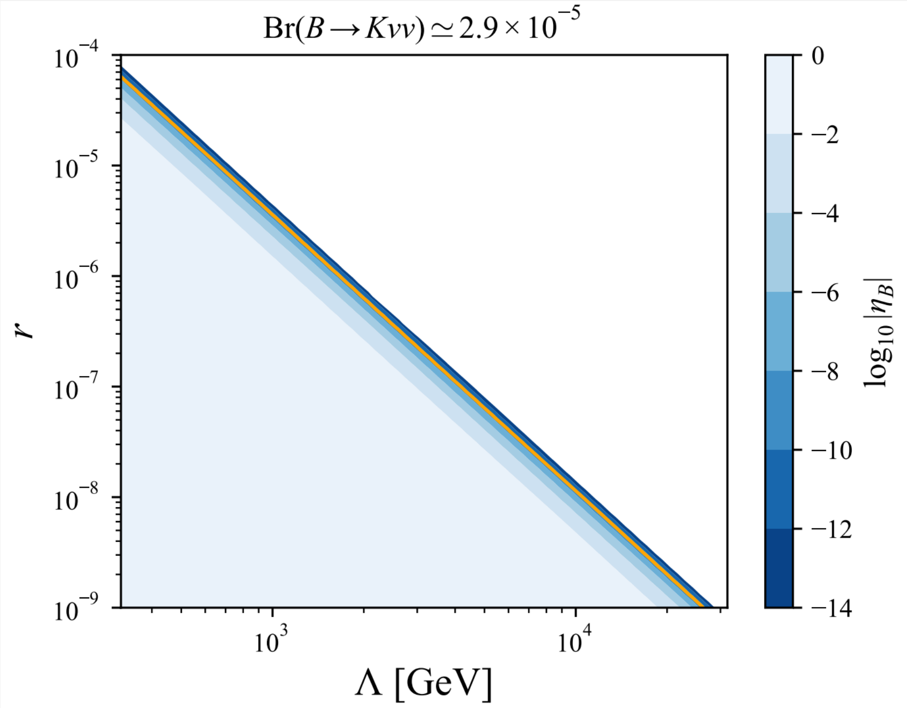


- Lepton flavor structure of the dim.7 operators

$$C_{\alpha\beta}^{sb,bs} = \frac{C}{\Lambda^3} \times \begin{pmatrix} r & r & r \\ r & 1 & 1 \\ r & 1 & 1 \end{pmatrix}_{\alpha\beta}$$

- Flavor mixing by dim.5 is negligibly small.

  -> Corresponding lepton number is conserved in $r \to 0$.



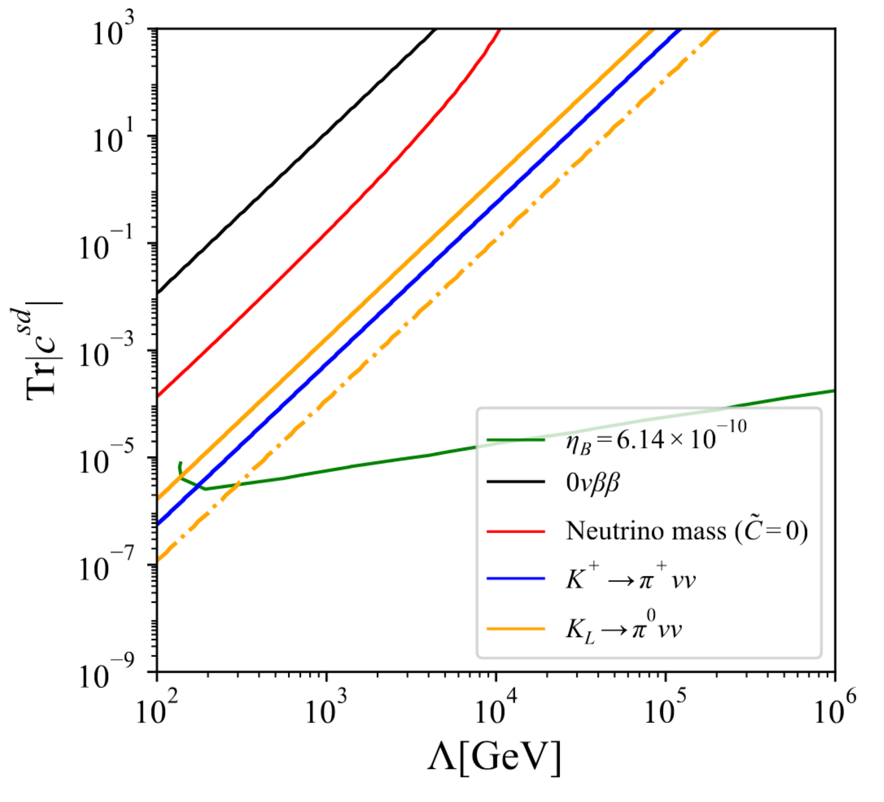
- In Case2, parameter spaces where sizable effects in $B^+ \to K^+\nu\nu$ are compatible with high scale B-ℓ genesis.

For Kaon rare decays (Case1)

- Similar analyses for C^{sd}, which is relevant to the $K \to \pi\nu\nu$ decays

Case 1 (Neutrino mass like)

cf.) $C^{sd}_{\alpha\beta} = \frac{c}{\Lambda^3} \times m^{\nu}_{\alpha\beta}$



Blue: NA62 bound
Orange: KOTO bound
Dashdot: future prospect at KOTOII

- For non-zero C^{ds}, please see backup.

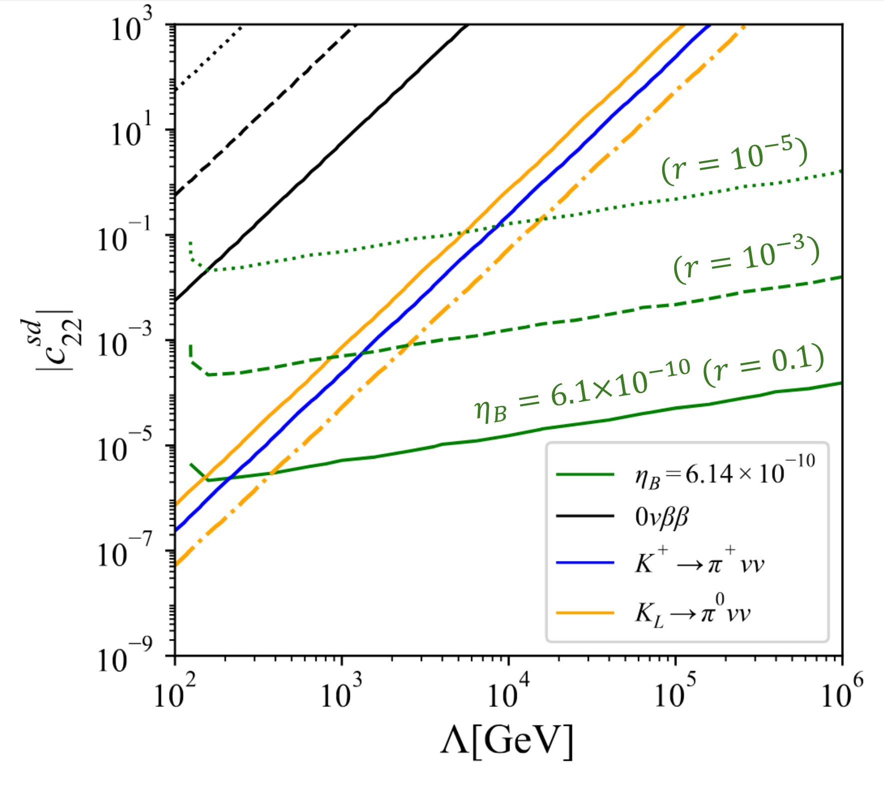
NA62 Collaboration, JHEP (2025);
KOTO Collaboration, PRL (2025);
arXiv:2505.02568;

For Kaon rare decays (Case2)

- Similar analyses for C^{sd}, which is relevant to the $K \to \pi \nu\nu$ decays

Case 2 (Specific flavor decoupling)

cf.) $C^{sd}_{\alpha\beta} = \frac{C}{\Lambda^3} \times \begin{pmatrix} r & r & r \\ r & 1 & 1 \\ r & 1 & 1 \end{pmatrix}_{\alpha\beta}$



Blue: NA62 bound
Orange: KOTO bound
Dashdot: future prospect at KOTOII

NA62 Collaboration, JHEP (2025);
KOTO Collaboration, PRL (2025);
arXiv:2505.02568;

- For non-zero C^{ds}, please see backup.

Summary

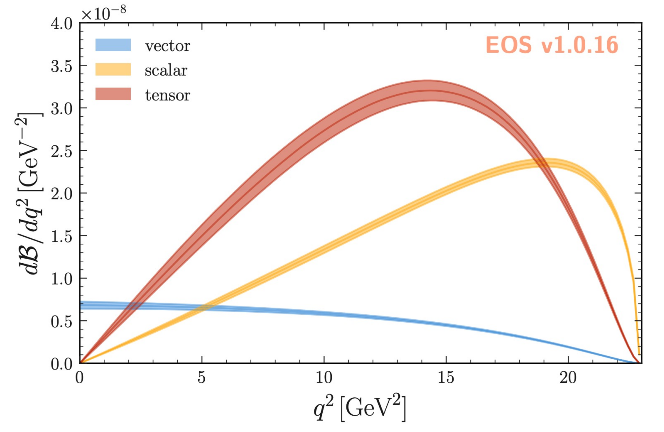
- The $B \to K\nu\nu$ and $K \to \pi\nu\nu$ decays
  - They are the rare processes in the SM and sensitive to new physics effects
- LNV dim.7 operators and baryogenesis
  - Contributing to the rare meson decays and the Majorana masses for the neutrinos
  - A scenario of baryogenesis: high scale B-ℓ genesis
  - In the presence of active LNV -> washout of initial baryon asymmetry
- Constraining the high scale B-ℓ genesis
  - In Case1 (neutrino mass), high scale B-ℓ genesis is not preferred in terms of sizable NP effects to the rare meson decays via dim.7.
  - They are compatible when a specific lepton flavor is conserved (Case2).

Back up

Scalar, vector, and tensor operators

- Dim.6 LEFT operators and q^2 ($=m_{\nu\nu}^2$) dependence BelleII Collaboration, arXiv:2507.12393

$$
\begin{aligned}
\mathcal{O}_{\rm VL} &= (\overline{\nu_L}\gamma_\mu \nu_L)\,(\overline{s_L}\gamma^\mu b_L)\\
\mathcal{O}_{\rm VR} &= (\overline{\nu_L}\gamma_\mu \nu_L)\,(\overline{s_R}\gamma^\mu b_R)\\
\mathcal{O}_{\rm SL} &= \left(\overline{\nu_L^c}\nu_L\right)(\overline{s_R} b_L)\\
\mathcal{O}_{\rm SR} &= \left(\overline{\nu_L^c}\nu_L\right)(\overline{s_L} b_R)\\
\mathcal{O}_{\rm TL} &= \left(\overline{\nu_L^c}\sigma_{\mu\nu}\nu_L\right)(\overline{s_R}\sigma^{\mu\nu} b_L)\ .
\end{aligned}
$$



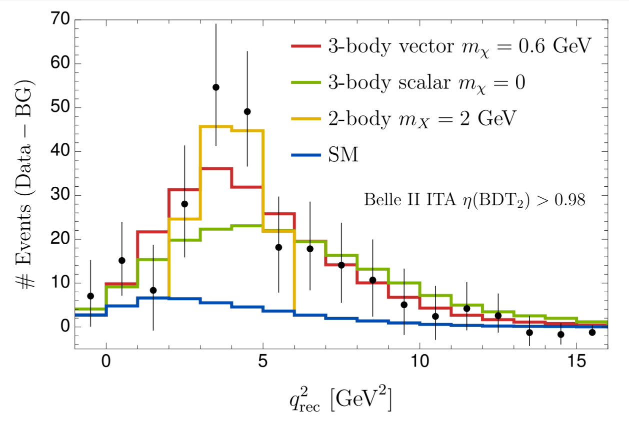
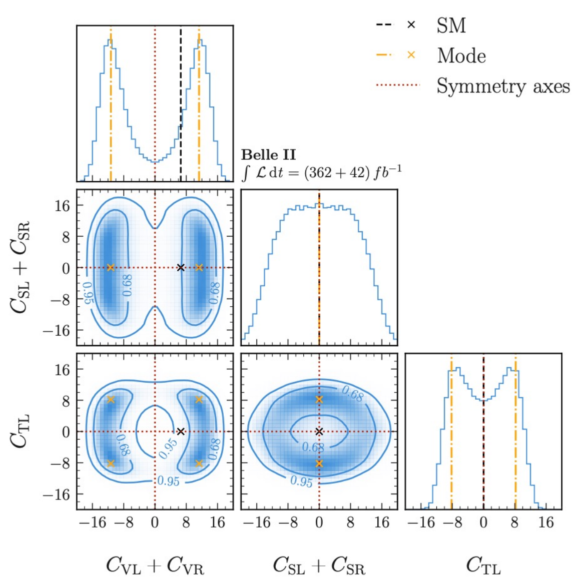


Fig. from Fridell, Ghosh, Okui and Tobioka, PRD (2024)

- Posterior for those coefficients with a uniformly flat prior

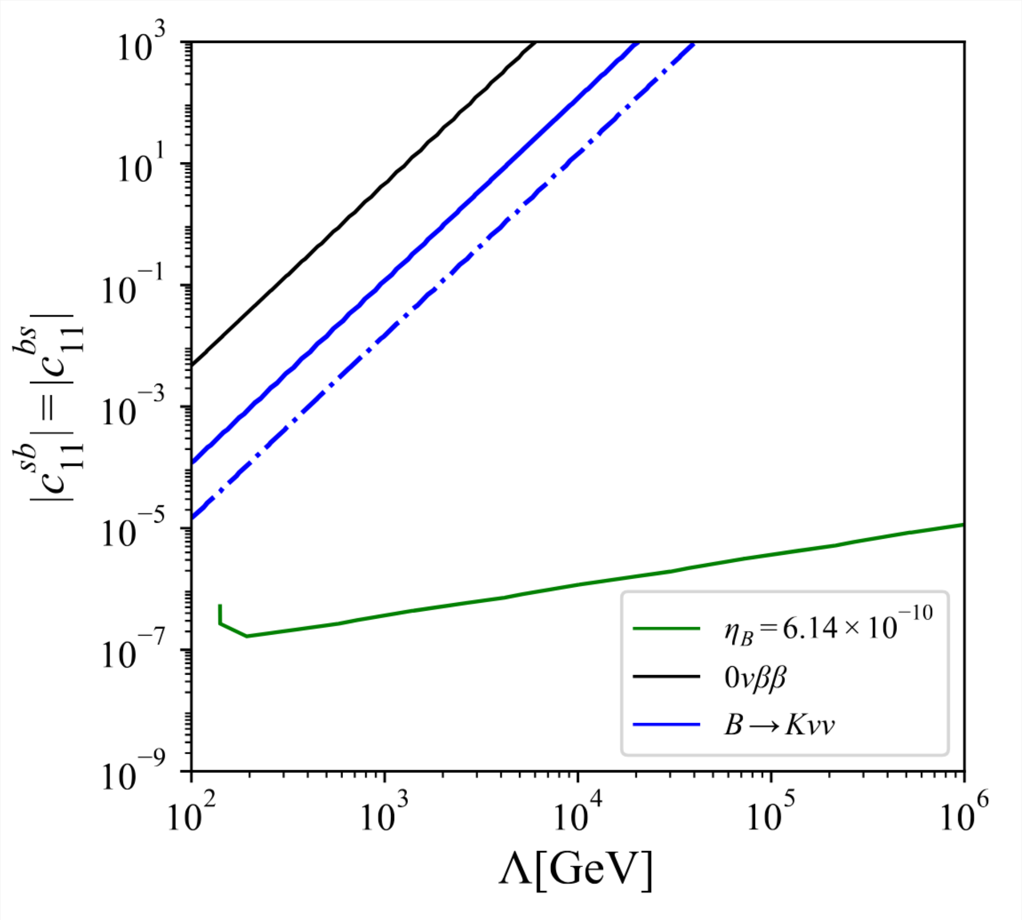
Table I. The mode of the posterior, and HDI at 68% and 95% for the (sums of the) WET Wilson coefficients in Eq. (9), derived from the posterior in Fig. 3.

Parameters	Mode	68% HDI	95% HDI
$\lvert C_{\rm VL}+C_{\rm VR}\rvert$	11.3	[7.8, 14.6]	[1.9, 16.2]
$\lvert C_{\rm SL}+C_{\rm SR}\rvert$	0.0	[0.0, 9.6]	[0.0, 15.4]
$\lvert C_{\rm TL}\rvert$	8.2	[2.3, 9.6]	[0.0, 11.2]



Case3: Lepton flavor universal

For the $B^+ \to K^+ \nu\nu$ decay



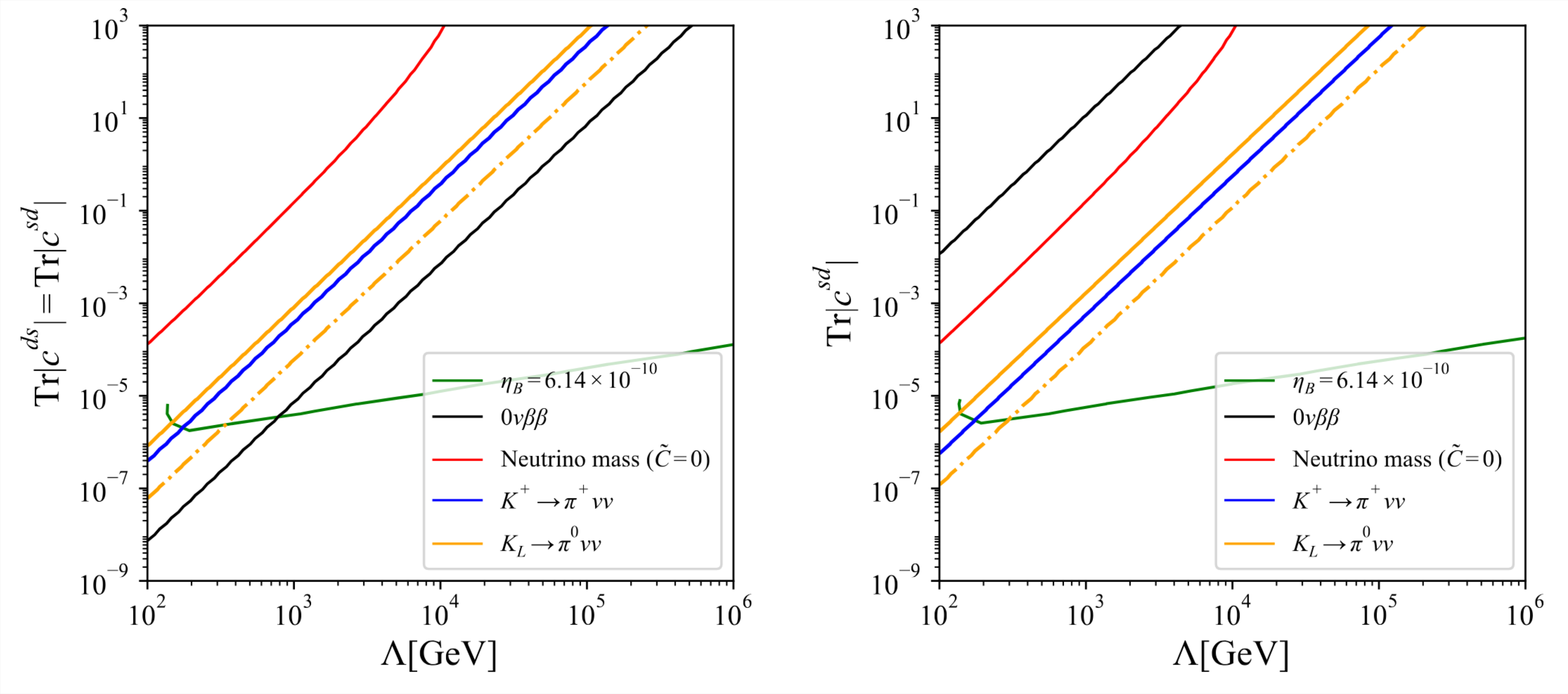
- Lepton flavor structure of the dim.7 operators

$$C_{\alpha\beta}^{sb,bs} = \frac{C}{\Lambda^3} \times \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{\alpha\beta}$$

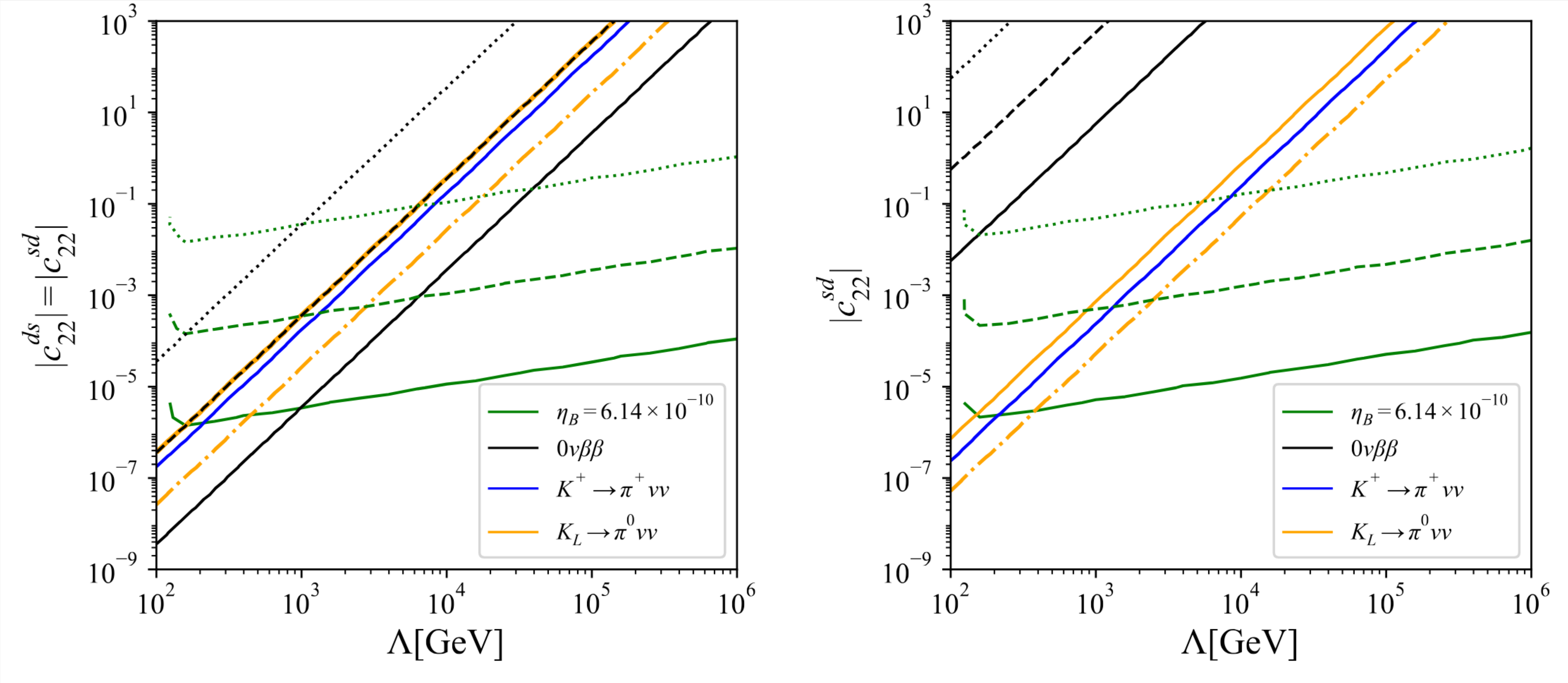
cf.) $m_{\nu,\alpha\beta} = m_{\nu,\alpha\beta}^{\text{dim.5}} + m_{\nu,\alpha\beta}^{\text{dim.7}}$

$\propto C_{\alpha\beta}^{5}$ $\propto C_{\alpha\beta}^{sb,bs}$

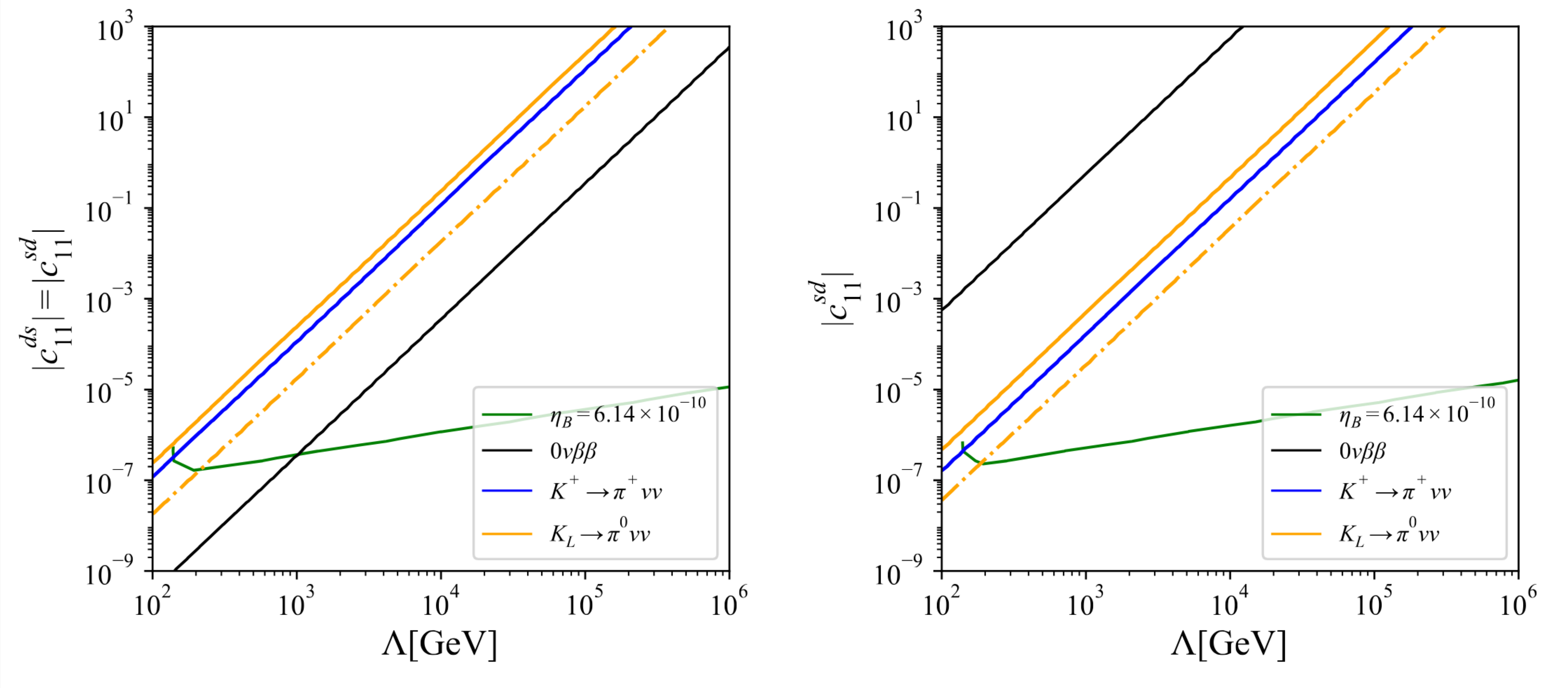
Case1 for Kaon decays



Case2 for Kaon decays



Case 3 for Kaon decays



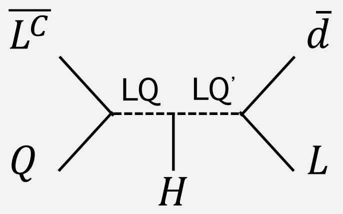
UV completions

Fridell, Gráf, Harz and Hati, JHEP 9 (2025) 050

	$\mathcal{O}_{LH}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{\bar{Q}uLLH}$
$\mathcal{S}$	Δ, N, Σ						
Ξ	Δ, Σ						
h			$\varphi, N, \Delta_3^\dagger$			$\varphi, U, Q_5^\dagger$	
Δ	$\mathcal{S}, \Xi, \Delta, \varphi, \Theta_1, \Theta_3, \Sigma$	$\Sigma, \Delta_1^\dagger$	$\varphi, \Sigma, \Delta_3^\dagger$		$\varphi, Q_5^\dagger, T_2$		$\varphi, Q_7, T_1^\dagger$
φ	Δ, N, Σ		h, Δ, N, Σ		Δ, N, Σ	h, Σ	Δ, N, Σ
Θ_1	Δ, Σ						
Θ_3	$\Delta, \Sigma_1^\dagger$						
S_1				$\tilde{R}_2, N, Q_5^\dagger$	$\tilde{R}_2, N, Q_5^\dagger$		
$\tilde{R}_2$				$S_1, \Delta_1^\dagger, Q_7$	S_1, S_3, N, Σ, T_2	S_3, Σ, U	
S_3					$\tilde{R}_2, \Sigma, Q_5^\dagger$	$\tilde{R}_2, \Sigma, Q_5^\dagger$	
N	$\mathcal{S}, \varphi, \Delta_1^\dagger$	$\Delta_1^\dagger$	h, φ	S_1, W_1', U_1	$\varphi, S_1, \tilde{R}_2$		$\varphi, U_1, \bar{V}_2^\dagger$
Σ	$\mathcal{S}, \Xi, \Delta, \varphi, \Theta_1, \Delta_1^\dagger, F_4$	$\Delta, \Delta_1^\dagger$	Δ, φ		$\varphi, \tilde{R}_2, S_3$	$\varphi, \tilde{R}_2, S_3$	$\varphi, \bar{V}_2^\dagger, U_3$

Field	Rep	Coupling to SM fields (+h.c.)
$\mathcal{S}$	$S(1,1,0)$	$\frac{1}{2}\kappa_{\mathcal{S}}\mathcal{S}H^\dagger H + \frac{1}{2}\lambda_{\mathcal{S}}\mathcal{S}\mathcal{S}H^\dagger H$
Ξ	$S(1,3,0)$	$\frac{1}{2}\kappa_\Xi H^\dagger \Xi^a \sigma^a H + \frac{1}{2}\lambda_\Xi (\Xi\Xi)\left(H^\dagger H\right)$
h	$S(1,1,1)$	$y_h h^\dagger \bar{L} i\sigma_2 L^c + \kappa_h h^\dagger \tilde{H}^\dagger H$
Δ	$S(1,3,1)$	$\frac{1}{4}\lambda_\Delta\left(\Delta^\dagger\Delta\right)\left(H^\dagger H\right) + \frac{1}{4}\lambda'_\Delta f_{abc}\left(\Delta^{a\dagger}\Delta^b\right)\left(H^\dagger\sigma^c H\right)$ $+y_\Delta \Delta^{a\dagger}\bar{L}\sigma^a i\sigma_2 L^c + \kappa_\Delta \Delta^{a\dagger}(\tilde{H}^\dagger\sigma^a H)$
φ	$S(1,2,1/2)$	$\lambda_\varphi\left(\varphi^\dagger H\right)\left(H^\dagger H\right) + y_\varphi^e \varphi^\dagger \bar{e} L + y_\varphi^d \varphi^\dagger \bar{d} Q + y_\varphi^u \varphi^\dagger i\sigma_2 \bar{Q}^T u$
Θ_1	$S(1,4,1/2)$	$\lambda_{\Theta_1}\left(H^\dagger\sigma^a H\right) C^I_{ab}\tilde{H}^b \epsilon_{IJ}\Theta_1^J$
Θ_3	$S(1,4,3/2)$	$\lambda_{\Theta_3}(H^\dagger\sigma^a\tilde{H})C^I_{ab}\tilde{H}^b\epsilon_{IJ}\Theta_3^J$
S_1	$S(\bar{3},1,1/3)$	$y^{ql}_{S_1} S_1 \bar{Q}^c i\sigma_2 L + y^{qq}_{S_1} S_1 \bar{Q} i\sigma_2 Q^c + y^{du}_{S_1} S_1 \bar{d} u^c + y^{eu}_{S_1} S_1 \bar{e}^c u$
$\tilde{R}_2$	$S(3,2,1/6)$	$y_{\tilde{R}_2}\tilde{R}_2^\dagger i\sigma_2 \bar{L}^T d$
S_3	$S(\bar{3},3,1/3)$	$y^{ql}_{S_3} S_3^a \bar{Q}^c i\sigma_2\sigma^a L + y^{qq}_{S_3} S_3^a \bar{Q}\sigma^a i\sigma_2 Q^c$
N	$F(1,1,0)$	$\lambda_N \bar{N}\tilde{H}^\dagger L$
Σ	$F(1,3,0)$	$\frac{1}{2}\lambda_\Sigma \bar{\Sigma}^a \tilde{H}^\dagger \sigma^a L$

e.g.)



UV completions

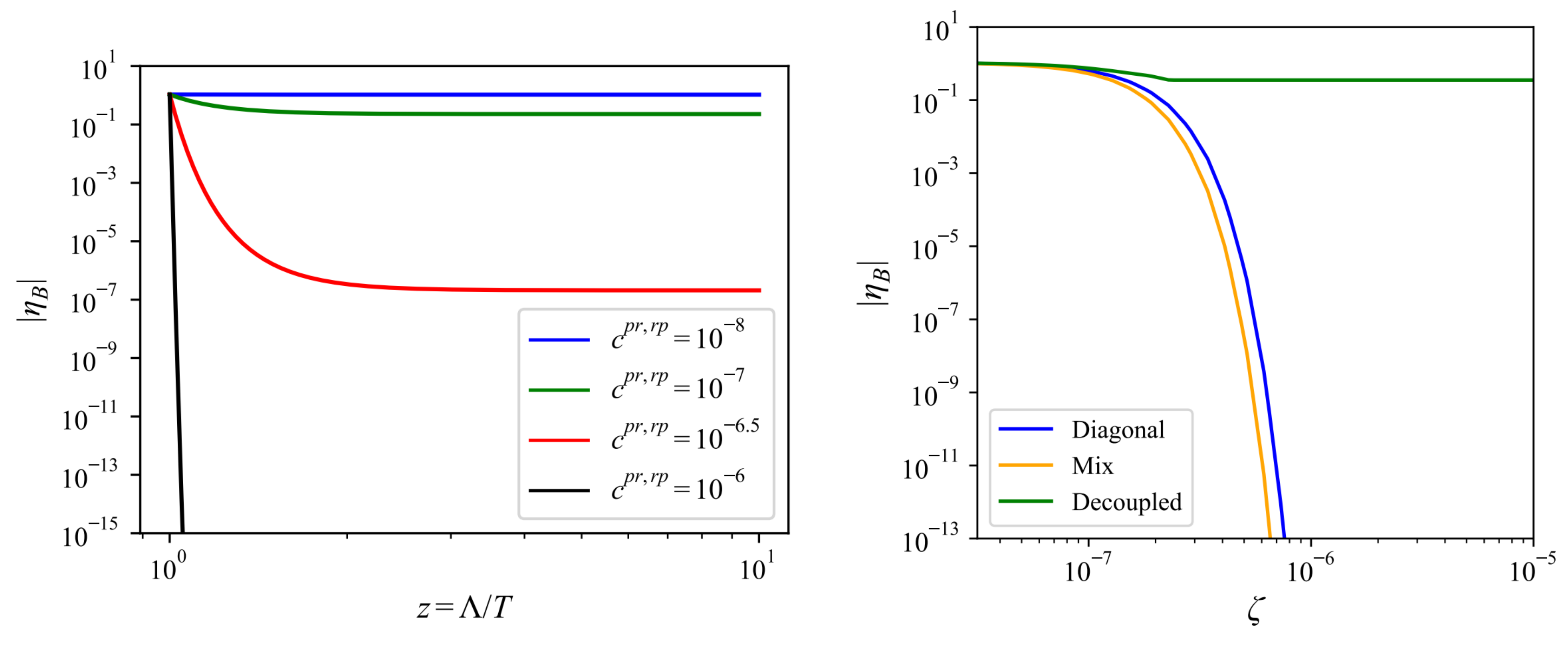
Fridell, Gráf, Harz and Hati, JHEP 9 (2025) 050

	$\mathcal{O}_{LH}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{\bar{Q}uLLH}$
$\Sigma_1^\dagger$	Θ_3						
$\Delta_1^\dagger$	N, Σ	Δ, N, Σ		$\tilde{R}_2, W_1', \bar{V}_2^\dagger$			
$\Delta_3^\dagger$			h, Δ				
F_4	Σ						
U						$h, \tilde{R}_2$	
$Q_5^\dagger$				$S_1, V_3, \bar{V}_2^\dagger$	Δ, S_1, S_3	h, S_3	
Q_7				$\tilde{R}_2, V_3, U_1$			Δ, U_1, U_3
$T_1^\dagger$							$\Delta, \bar{V}_2^\dagger$
T_2					$\Delta, \tilde{R}_2$		
W_1'				$N, \Delta_1^\dagger, V_3$			
V_3				$Q_5^\dagger, Q_7, W_1'$			
U_1				$N, Q_7, \bar{V}_2^\dagger$			$N, Q_7, \bar{V}_2^\dagger$
$\bar{V}_2^\dagger$				$\Delta_1^\dagger, Q_5^\dagger, U_1$			$N, \Sigma, T_1^\dagger,$ U_1, U_3
U_3							$\Sigma, Q_7, \bar{V}_2^\dagger$

Σ_1	$F(1,3,-1)$	$\frac{1}{2}\lambda_{\Sigma_1}\bar{\Sigma}_1^a H^\dagger \sigma^a L$
Δ_1	$F(1,2,-1/2)$	$\lambda_{\Delta_1}\bar{\Delta}_1 H e$
Δ_3	$F(1,2,-3/2)$	$\lambda_{\Delta_3}\bar{\Delta}_3 \tilde{H} e$
F_4	$F(1,4,1/2)$	$-$
U	$F(3,1,2/3)$	$\lambda_U \bar{U}\tilde{H}^\dagger Q$
Q_5	$F(3,2,-5/6)$	$\lambda_{Q_5}\bar{Q}_5 \tilde{H} d$
Q_7	$F(3,2,7/6)$	$\lambda_{Q_7}\bar{Q}_7 H u$
T_1	$F(3,3,-1/3)$	$\frac{1}{2}\lambda_{T_1}\bar{T}_1^a H^\dagger \sigma^a Q^b$
T_2	$F(3,3,2/3)$	$\frac{1}{2}\lambda_{T_2}\bar{T}_2^a \tilde{H}^\dagger \sigma^a Q^b$
W_1'	$V(1,1,1)$	$\frac{1}{2} g^{du}_{W_1'} W_1'^{\mu\dagger}\bar{d}\gamma_\mu u + g^{H}_{W_1'} W_1'^{\mu\dagger} i D_\mu H^T i\sigma_2 H$
V_3	$V(1,2,3/2)$	$V_3^\mu \bar{e}^c \gamma_\mu L$
U_1	$V(3,1,2/3)$	$g^{ed}_{U_1} U_1^{\mu\dagger}\bar{e}\gamma_\mu d + g^{lq}_{U_1} U_1^{\mu\dagger}\bar{L}\gamma_\mu Q$
$\bar{V}_2$	$V(\bar{3},2,-1/6)$	$g^{ul}_{\bar{V}_2}\bar{V}_2^\mu \bar{u}^c \gamma_\mu L + g^{dq}_{\bar{V}_2}\bar{V}_2^\mu \bar{d}\gamma_\mu i\sigma_2 Q^c$
U_3	$V(3,3,2/3)$	$g_{U_3} U_3^{a\mu\dagger}\bar{L}\gamma_\mu \sigma^a Q$

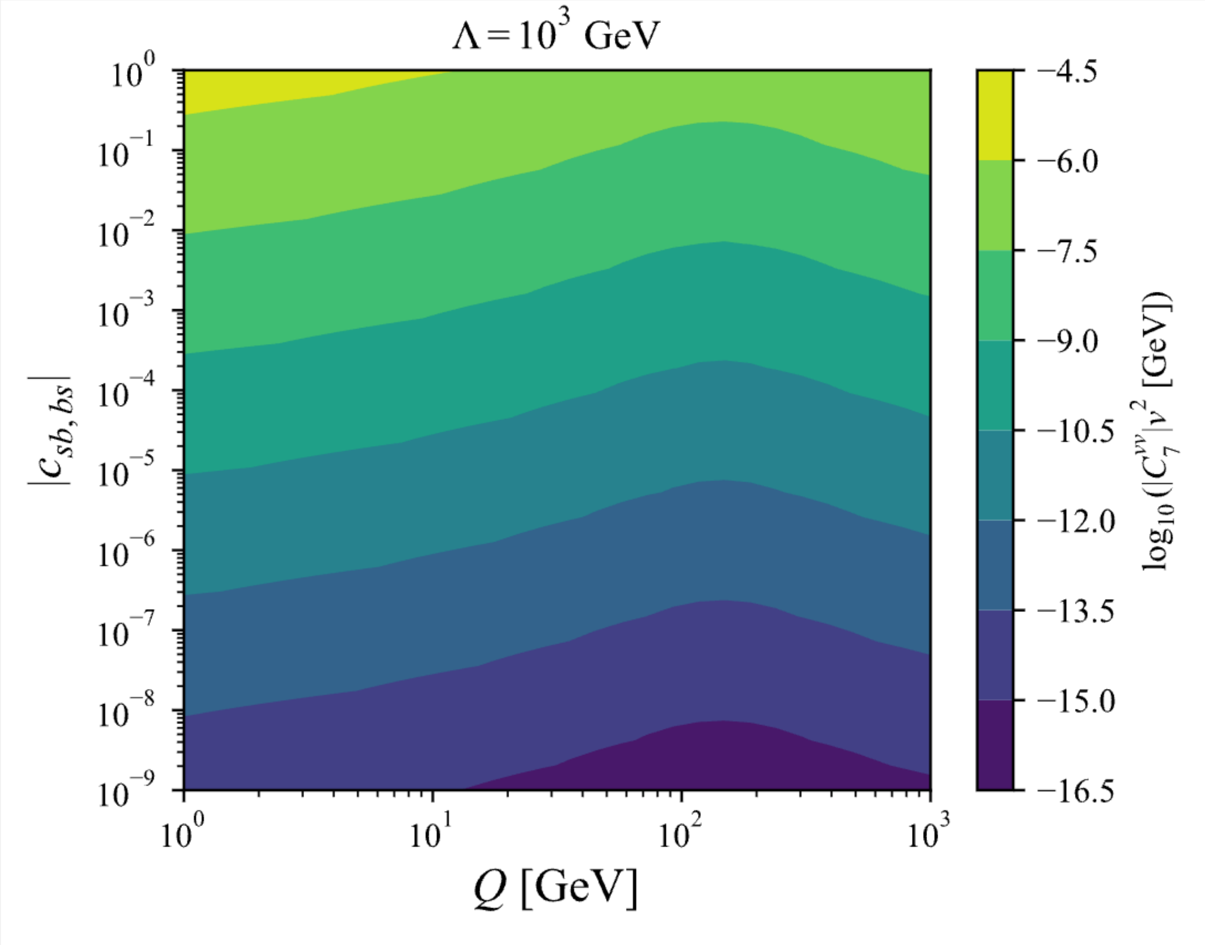
Baryon number washout

- Temperature & coupling dependences of baryon asymmetry



Neutrino mass

- Neutrino mass (renormalization scale dependence)



- C_7 is the contribution to the Weinberg operator from dim.7 operators.