FLAVOR CONSTRAINTS ON AXION-LIKE PARTICLE

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(IN PREPARATION)

OUTLINE

1. Axion-like particle couplings to the SM
2. SM induced FCNC with ALP (Model independent)
3. Analysis
4. Specific model (2HDM)
5. Summary

AXION-LIKE PARTICLE (ALP)

- Light and Weakly coupled to the SM
- Global U(1) PQ symmetry
- Good BSM candidate (e.g. DM, Strong CP, etc)
- Experimental bounds on ALP portal (e.g. Rare meson decay)

ALP COUPLINGS

- PQ-Symmetry

$$a \to a + c$$

- Derivative couplings

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \sum_{f=Q,u_R,d_R,L,e_R} c_f \bar{f} \gamma^\mu f + V(a)$$

ALP COUPLINGS

(DERIVATIVE VS. NON-DERIVATIVE)

$$\frac{\partial_\mu a}{f_{\mathrm{PQ}}} \bar{f}_L \gamma^\mu f_L$$

$$-\frac{m_f}{f_{\mathrm{PQ}}} i a \bar{f}_R f_L$$

- Gauge invariance
- Relevant at high energy scale

ALP COUPLINGS

(DERIVATIVE VS. NON-DERIVATIVE)

$$c_f \frac{\partial_\mu a}{f_{\rm PQ}} \bar{f} \gamma^\mu \gamma^5 f$$

$$-2 c_f \frac{i a}{f_{\rm PQ}} m_f \bar{f} \gamma^5 f$$

ALP COUPLINGS

(DERIVATIVE VS. NON-DERIVATIVE)

$$c_f \frac{\partial_\mu a}{f_{\rm PQ}} \bar{f} \gamma^\mu \gamma^5 f$$

$$-m_f \bar{f} \exp\left[2c_f \frac{ia}{f_{\rm PQ}} \gamma^5\right] f$$

- ex)

Axion scattering with electron (e+a→e+a)

Axion emission by nucleon via 1 pion exchange process (NN→NNa)

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RADIATIVE FCNC OF ALP

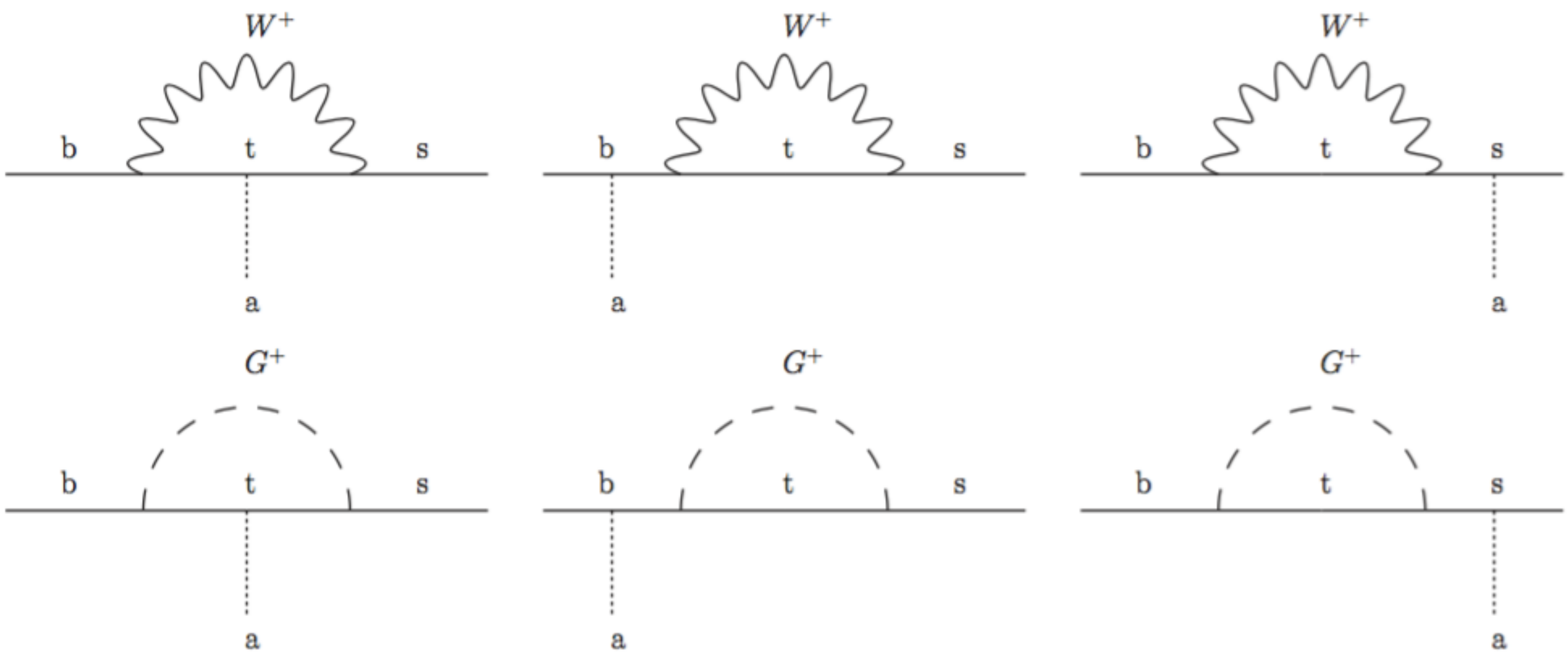

FIG. 1: Relevant diagrams for FCNC of ALP

RADIATIVE FCNC OF ALP

$$\frac{d}{d\ln\mu}c_Q = \frac{1}{(4\pi)^2}\left[(c_Q - c_u)\, y_u y_u^\dagger + (c_Q - c_d)\, y_d y_d^\dagger\right]$$

RADIATIVE FCNC OF ALP

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$$\frac{\left(y_t^{SM}\right)^2}{16\pi^2}\log\frac{\Lambda_{\rm UV}^2}{m_t^2}\left(-\frac{1}{2}c_Q + \frac{1}{2}c_u\right)V_{CKM}^{*t\alpha}V_{CKM}^{t\beta}\frac{a}{f_a}\bar{d}_\alpha\left[(im_d)_\alpha P_L - (im_d)_\beta P_R\right]d_\beta$$

LOW-SCALE EFFECTIVE COUPLINGS

- At high energy scale above the electroweak scale,

$$\frac{\partial_\mu a}{f_a}\left(c_Q\bar{Q}\gamma^\mu Q + c_u\bar{u}_R\gamma^\mu u_R + c_d\bar{d}_R\gamma^\mu d_R + c_L\bar{L}\gamma^\mu L + c_e\bar{e}_R\gamma^\mu e_R + c_H H^\dagger i\overleftrightarrow{D}^\mu H\right)$$
$$-\frac{a}{f_a}\left(c_{agg}\frac{g_s^2}{32\pi^2}G\tilde{G} + c_{aww}\frac{g^2}{32\pi^2}W\tilde{W} + c_{abb}\frac{g'^2}{32\pi^2}B\tilde{B}\right) + \mathcal{L}_a$$

- At QCD chiral symmetry breaking scale, the chiral perturbation theory should be considered to describe the physics of the strongly interacting particles

LOW-SCALE EFFECTIVE COUPLINGS

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_{\rm PQ}} A_l \bar{l} \gamma^\mu \gamma^5 l - \bar{c}_{a\gamma\gamma} \frac{a}{f_{\rm PQ}} \frac{e^2}{32\pi^2} F\tilde{F} + \mathcal{L}_{aN} + \mathcal{L}_{a\pi}$$

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$$A_l = (-c_L + c_e + c_H)/2$$

LOW-SCALE EFFECTIVE COUPLINGS

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$$q_A = \frac{C_{agg}}{2}\frac{M^{-1}}{tr\left[M^{-1}\right]}$$

$$\bar{c}_{a\gamma\gamma} = c_{a\gamma\gamma} - 12\, tr\left[q_A Q_E Q_E\right] - \sum_{f=\mu,e} 4A_f Q_f^2\left[1-2A\left(\tau_f\right)\right]$$
$$-2\kappa_0\frac{m_a^2}{m_\pi^2 - m_a^2} - 1.3\kappa_\eta\frac{m_a^2}{m_\eta^2 - m_a^2} - 2.9\kappa_{\eta'}\frac{m_a^2}{m_{\eta'}^2 - m_a^2}$$

$$\begin{aligned}\kappa_0 &= \frac{A_u - A_d}{2} - \frac{C_{agg}}{2}\frac{m_u^{-1} - m_d^{-1}}{m_u^{-1} + m_d^{-1} + m_s^{-1}}\\ \kappa_8 &= \frac{A_u - A_d}{2\sqrt{3}} - \frac{C_{agg}}{2\sqrt{3}}\frac{m_u^{-1} + m_d^{-1} - 2m_s^{-1}}{m_u^{-1} + m_d^{-1} + m_s^{-1}}\\ \kappa_9 &= \frac{A_u + 2A_d}{\sqrt{6}} - \frac{C_{agg}}{\sqrt{6}}\end{aligned}$$

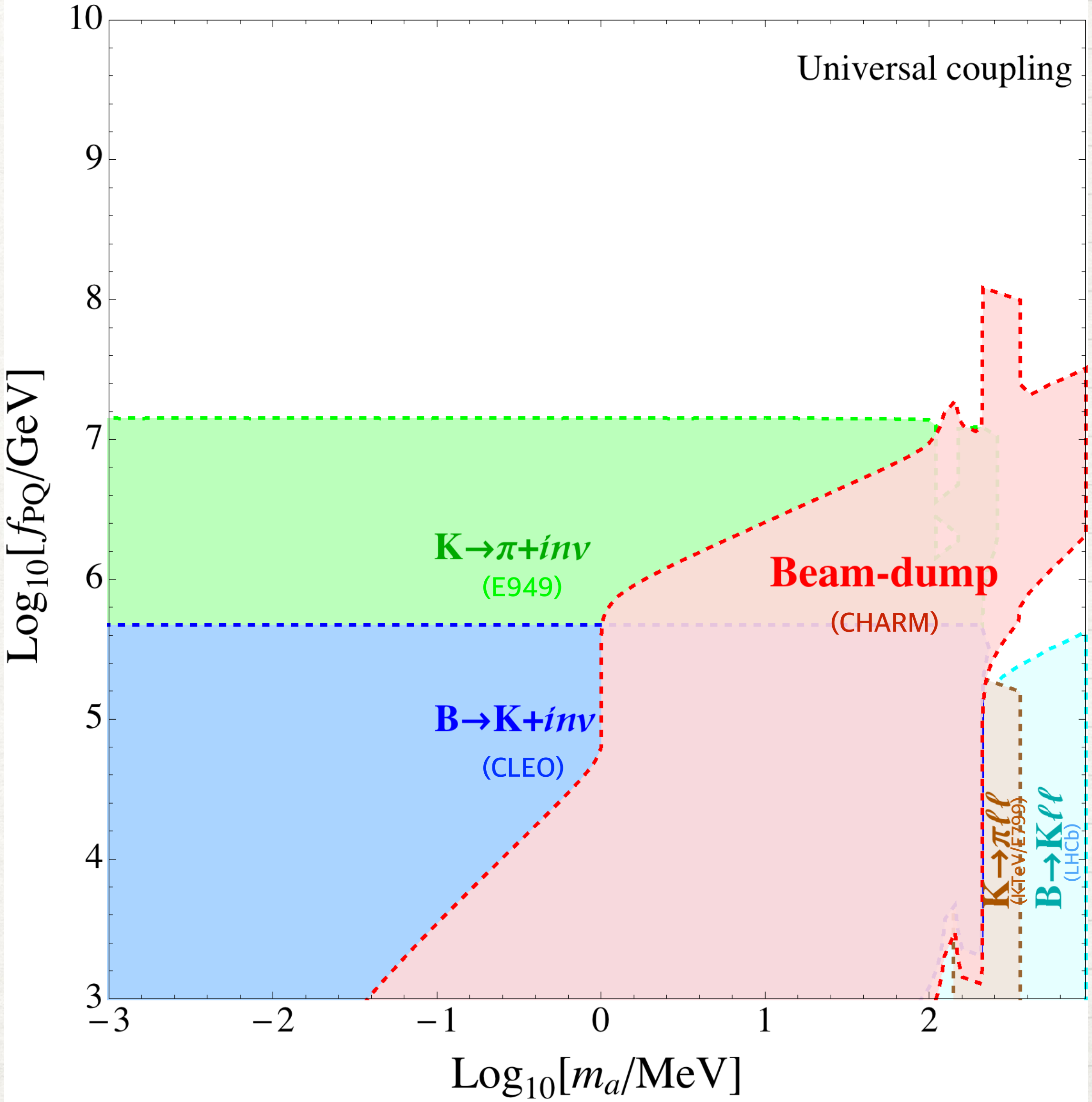
$$\begin{aligned}\kappa_\eta &= \kappa_8\cos\theta_{\eta\eta'} - \kappa_9\sin\theta_{\eta\eta'}\\ \kappa_{\eta'} &= \kappa_8\sin\theta_{\eta\eta'} + \kappa_9\cos\theta_{\eta\eta'}\end{aligned}$$

EXPERIMENTAL BOUNDS

- Universal couplings
- Flavor constraints

$$f_{PQ} \gtrsim 10^7 GeV$$

[Choi, Im, Park, Yun (in preparation)]



EXPERIMENTAL BOUNDS

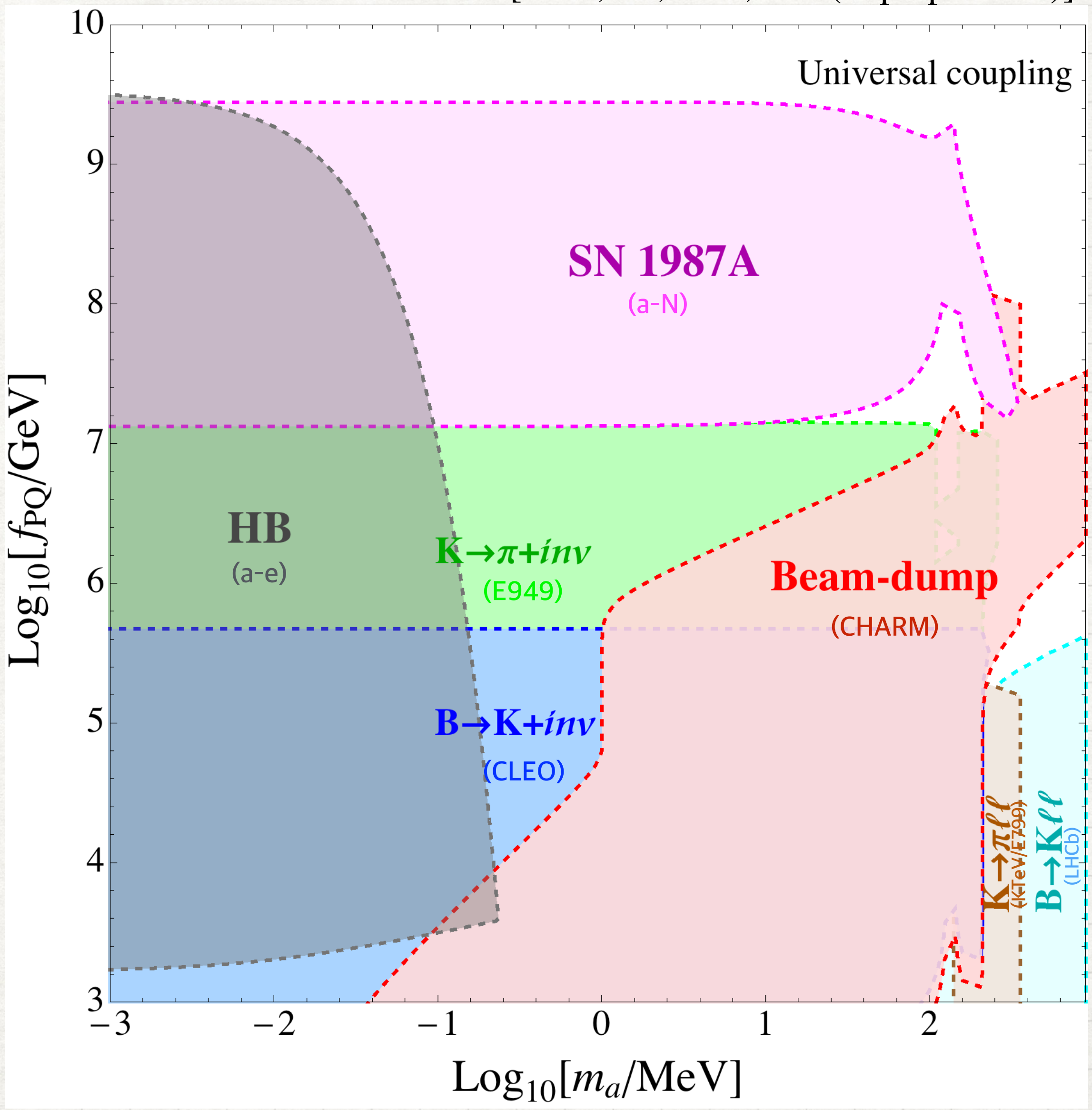
- Universal couplings
- Flavor constraints

$$f_{PQ} \gtrsim 10^7 GeV$$

- Axion mass < 100 MeV

$$f_{PQ} \gtrsim 10^9 GeV$$

[Choi, Im, Park, Yun (in preparation)]



SPECIFIC MODEL : ALP + 2HDM

- SM couplings

$$\frac{\partial_\mu a}{f_{\rm PQ}}\left(C_Q\bar{Q}\gamma^\mu Q + C_u\bar{u}_R\gamma^\mu u_R + C_d\bar{d}_R\gamma^\mu d_R + C_L\bar{L}\gamma^\mu L + C_e\bar{e}_R\gamma^\mu e_R + \sum_{i=1,2} C_i H_i^\dagger i\overleftrightarrow{D}^\mu H_i\right)$$

- Pseudoscalar mixing (Goldstone boson eaten by Z)

$$Z_\mu \;\rightarrow\; Z_\mu - \frac{2}{g_Z}\frac{\partial_\mu a}{f_{\rm PQ}}\left(\cos^2\beta C_1 + \sin^2\beta C_2\right)$$

$$A_\mu \;\rightarrow\; A_\mu + \cos^2\theta_W\frac{2}{e}\frac{\partial_\mu a}{f_{\rm PQ}}\left(\cos^2\beta C_1 + \sin^2\beta C_2\right)$$

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- Additional massive charged Higgs boson

$$-i\left(C_1 - C_2\right)\cos 2\beta \frac{\partial_\mu a}{f_{\rm PQ}}\left(\partial^\mu H^- \cdot H^+ - \partial^\mu H^+ \cdot H^-\right)$$
$$-m_W\left(C_1 - C_2\right)\sin 2\beta \frac{\partial^\mu a}{f_{\rm PQ}}\left(W_\mu^+ H^- + W_\mu^- H^+\right)$$

SPECIFIC MODEL : ALP + 2HDM

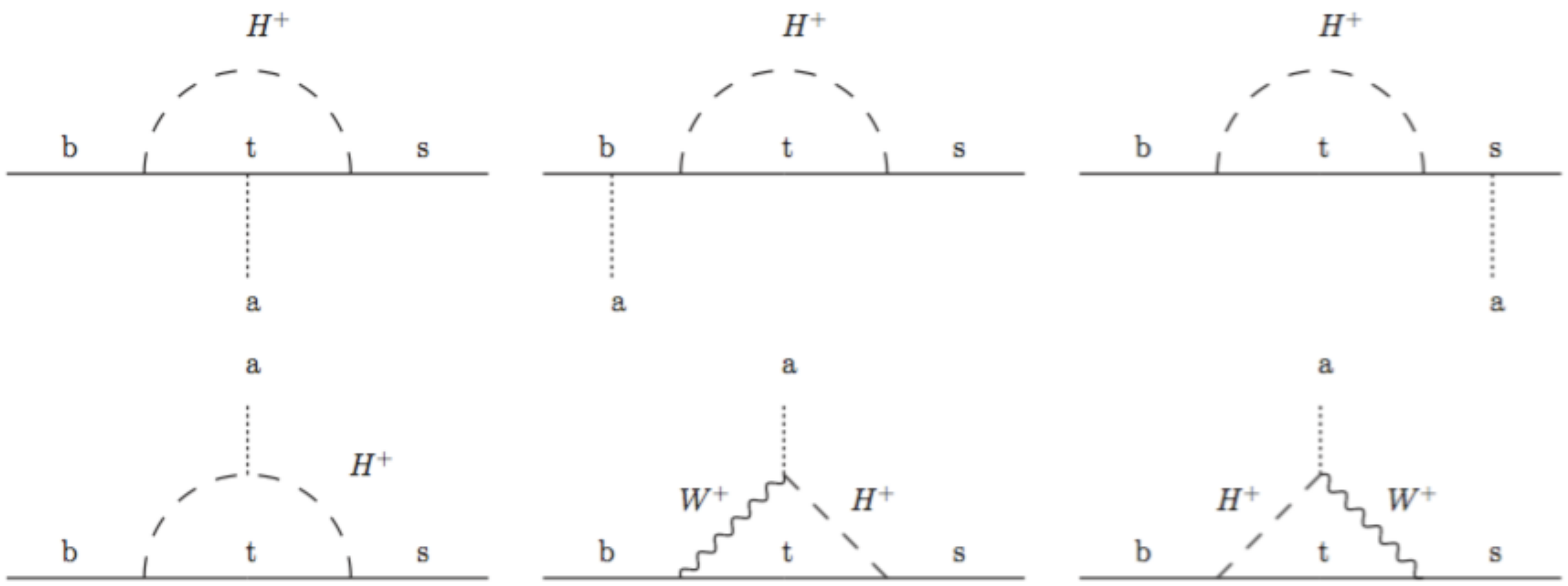

FIG. 2: Charged higgs loops to contribute FCNC of a

SPECIFIC MODEL : ALP + 2HDM

$$\frac{\left(y_t^{SM}\right)^2}{16\pi^2} V_{CKM}^{*t\alpha} V_{CKM}^{t\beta} \frac{a}{f_{\mathrm{PQ}}} \bar{d}_\alpha \left[(im_d)_\alpha P_L - (im_d)_\beta P_R\right] d_\beta$$

$$\times \left(\log \frac{\Lambda_{\mathrm{UV}}^2}{m_{H^\pm}^2} \left(\frac{1}{2} C_Q - \frac{1}{2} C_u + \frac{1}{2} C_2 \right) \frac{1}{\sin^2\beta} \right.$$

$$\left. + \log \frac{m_{H^\pm}^2}{m_t^2} \left[\left(\frac{1}{2} C_Q - \frac{1}{2} C_u + \frac{1}{2} C_2 \right) + \frac{C_1 - C_2}{2} \cos^2\beta \right] \right)$$

SPECIFIC MODEL : ALP + 2HDM

$SM + H^{\pm}$

$$\frac{\left(y_t^{SM}\right)^2}{16\pi^2} V_{CKM}^{*t\alpha} V_{CKM}^{t\beta} \frac{a}{f_{\rm PQ}} \bar{d}_\alpha \left[(im_d)_\alpha P_L - (im_d)_\beta P_R\right] d_\beta$$

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SM ~~$H^\pm$~~

ALP IN TYPE II 2HDM WITH SINGLET

$$\frac{\left(y_t^{SM}\right)^2}{16\pi^2} V_{CKM}^{*t\alpha} V_{CKM}^{t\beta} \frac{a}{f_{\rm PQ}} \bar{d}_\alpha \left[(im_d)_\alpha P_L - (im_d)_\beta P_R\right] d_\beta$$

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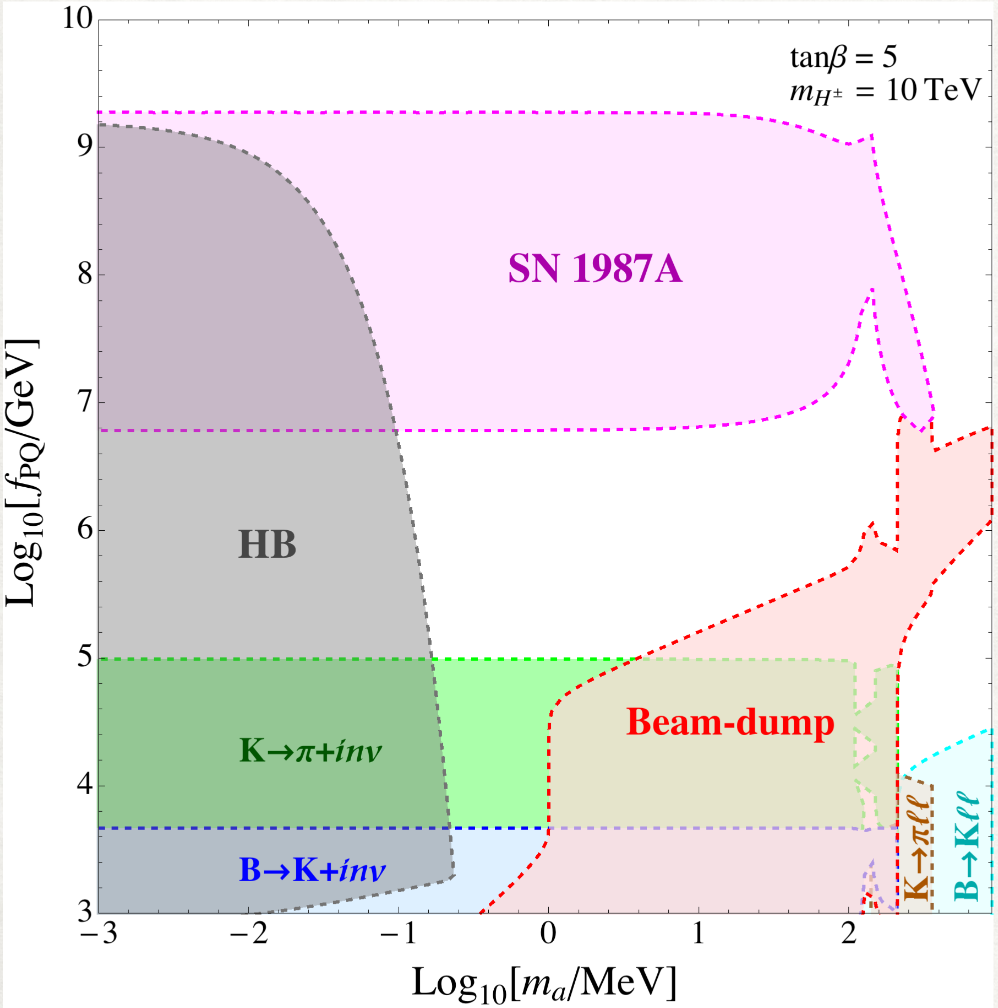

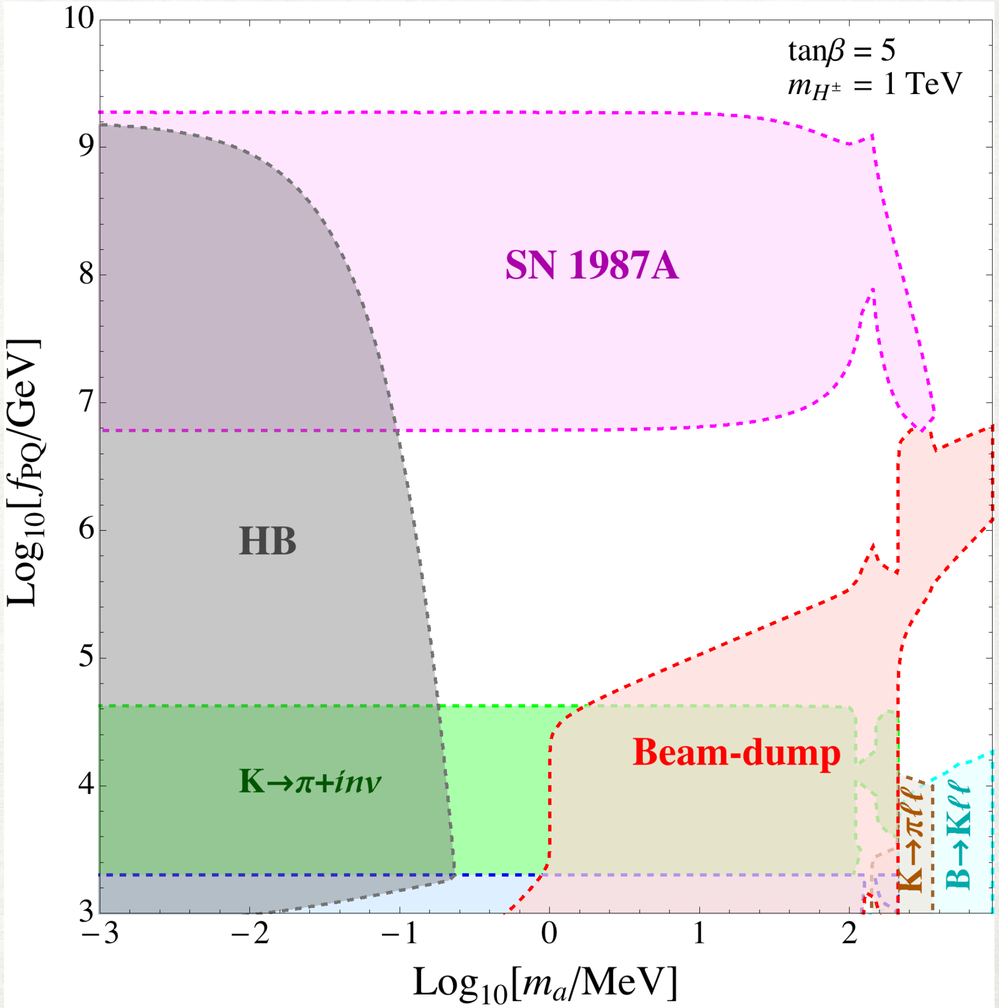

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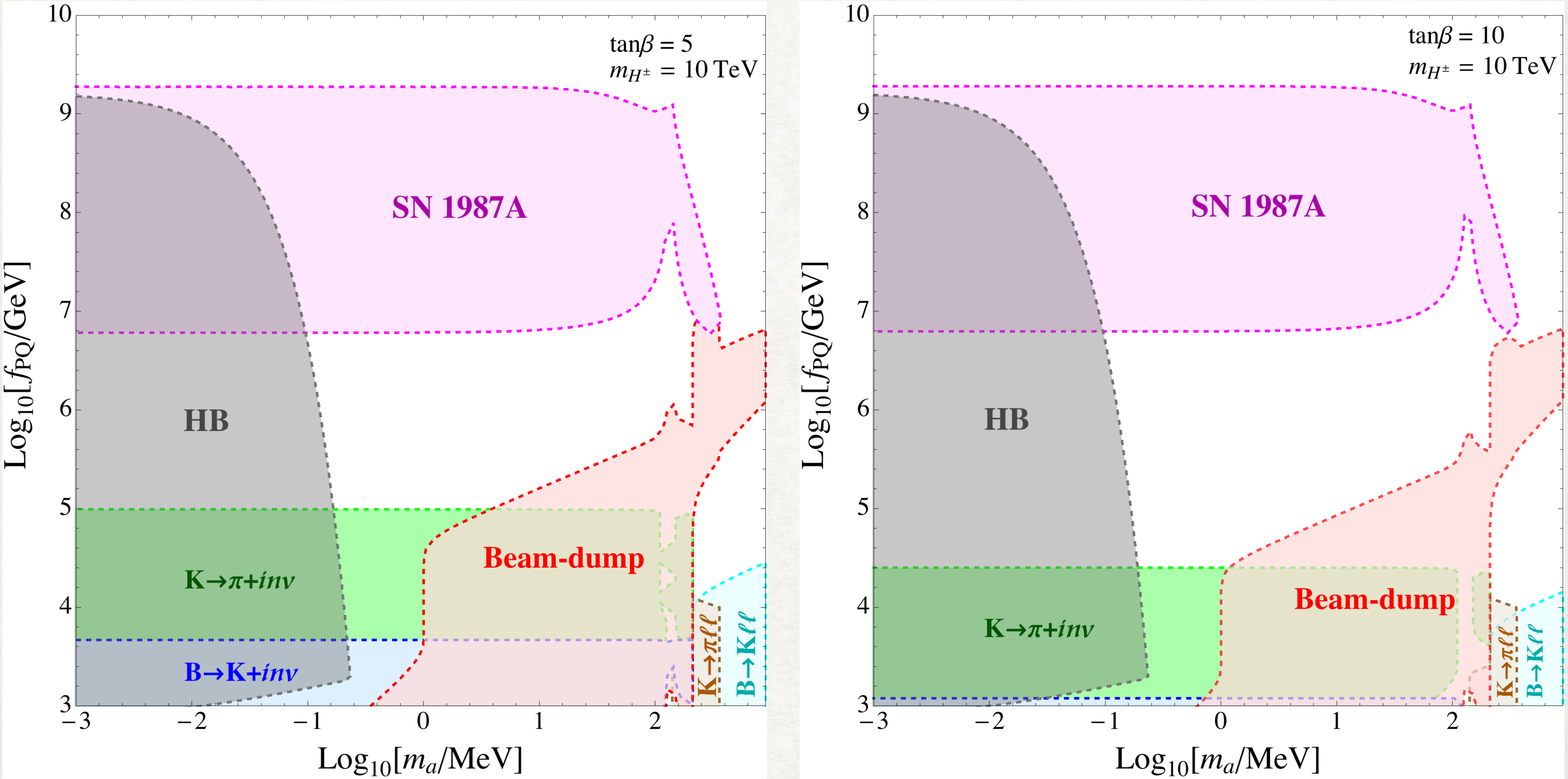

SUMMARY

- FCNC in an arbitrary coupling structure
- ALP + 2HDM (additional contribution from the charged Higgs boson)
- Update the low-scale effective Lagrangian (Chiral perturbation theory)
- Experimental bounds from FCNC