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$\mathrm{B} \to K + \mathit{invisible}$ in a model with axion-like particles

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Based on 2506.14876 with Ulrich Nierste

The Motivation

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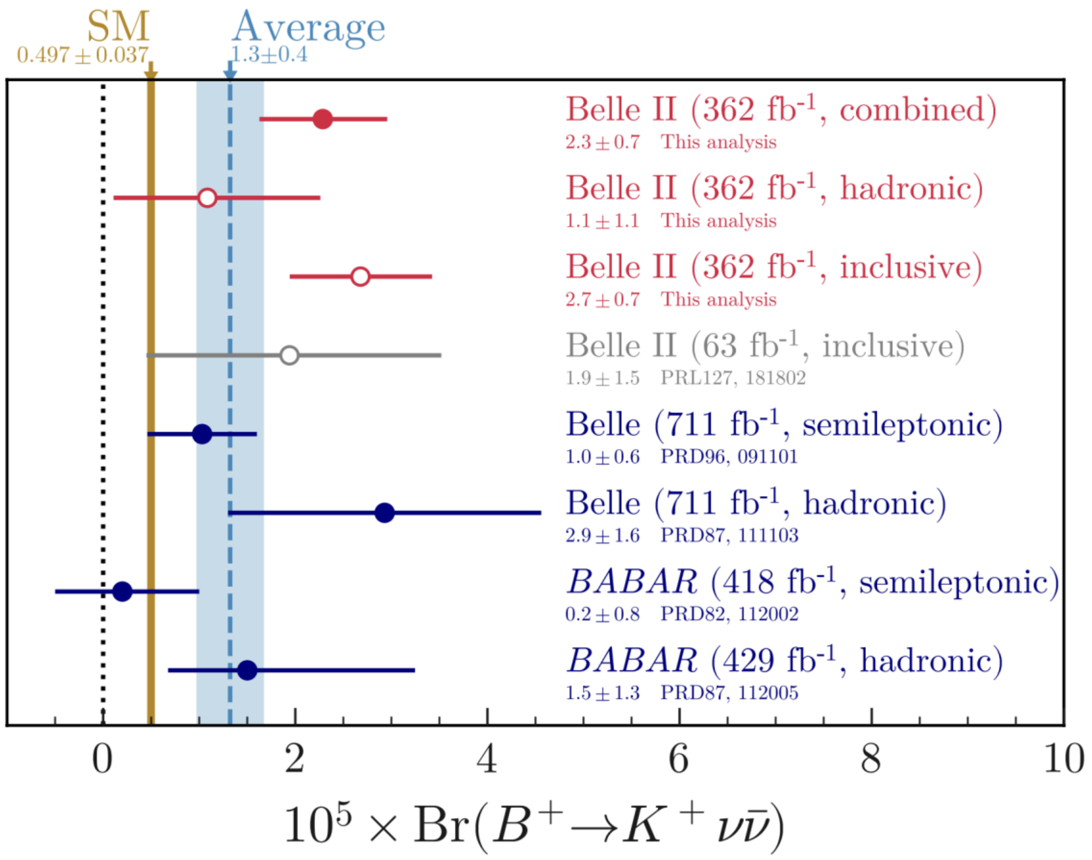
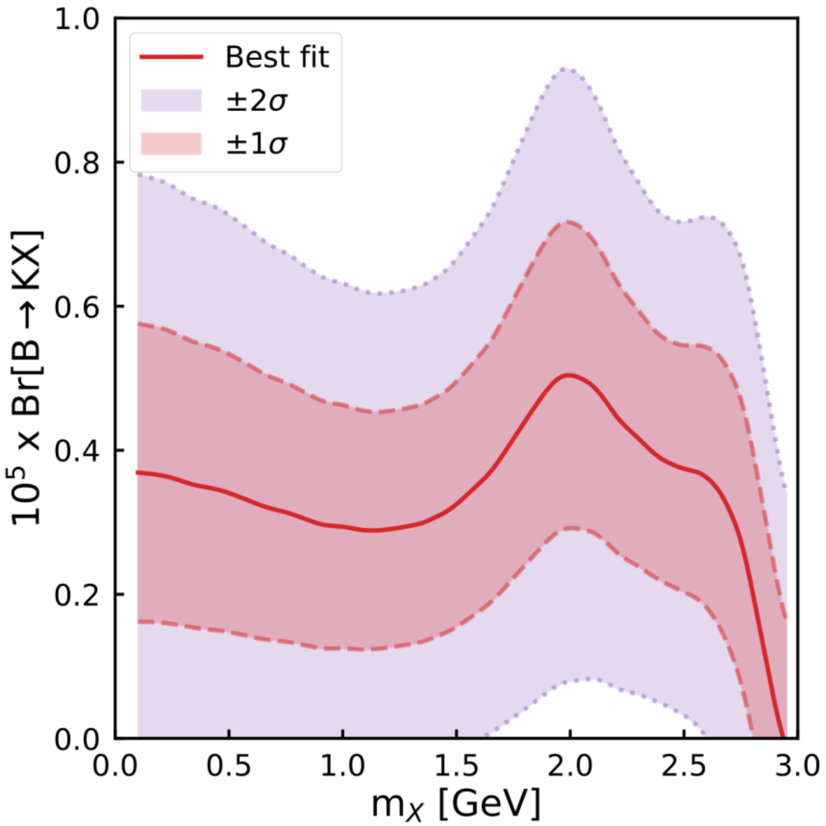
~~Recent~~ Belle-II $B \to K$ + inv. $\sim 3\sigma$ **localized** excess.



Belle-II 2311.14647



Altmannshofer et.al 23’

The Motivation

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Puzzle: lightness of a:

- Fine-tuning and implicit naturalness.
- A pseudo-Goldstone boson: Peccei, Quinn 77'
  - Massless a from spontaneous broken global symmetry.
  - $a \sim$ 2 GeV: global symmetry is never exact.

$$\mathcal{L}_a = \frac{\partial_\mu a}{2 f_a} C^V_{bs} \bar{s} \gamma^\mu b + \text{h.c.}$$

But, why? Testable?

$$F^V_{bs} \equiv 2 f_a / C^V_{bs} = 3.1^{+1.0}_{-0.5} \times 10^8 \, \text{GeV} \text{ is needed}$$

The Motivation

(Specific) Axion-EFT:

Batell, Pospelov, Ritz. 11'; Izaguirre, Lin, Shuve. 17'; Choi, Im, Park, Yun. 17'; Aloni, Soreq, Williams. 19'; Gavela, Houtz, Quilez, Del Rey, Sumensari, 19'; Chakraborty, Kraus, Loladze, Okui, Tobioka. 21'; Bauer, Neubert, Renner, Schnubel, Thamm, 21; Calibbi, Li, Mukherjee, Schmidt. 25'; Camalich, Ziegler. 25'; and more…

$$\mathcal{L} \supset \sum_{q=t,b} \frac{c_q}{f}\, \bar{q}\gamma^\mu\gamma_5 q\, \partial_\mu a, \quad \text{or} \quad \mathcal{L} \supset \frac{c_g}{f}\, a G^{\mu\nu}\widetilde{G}_{\mu\nu}.$$

- Elephant in the room:

$$\mathrm{Br}(B \to K a) \sim \left(\frac{1}{f} \ln \frac{\Lambda_{\mathrm{UV}}}{m_t}\right)^2$$

- UV completion needed.

  No bootstrap!

$B \to Ka$ with UV completion

DFSZ model: a minimal benchmark.

Dine, Fischler, Srednicki. 81'; Zhitnitsky. 80'

SM with 2HDM + complex singlet + Global $U(1)_{PQ}$

$$V_\Phi = \tilde{V}_{\text{moduli}}(|\Phi_u|, |\Phi_d|, |\Phi_u \Phi_d|, |\Phi_s|) + \lambda \Phi_s^2 \Phi_u \Phi_d^\dagger + \text{h.c.},$$

$$\mathcal{L}_Y = Y_u \overline{Q_L} u_R \Phi_u + Y_d \overline{Q_L} d_R \widetilde{\Phi}_d + Y_e \overline{L_L} e_R \widetilde{\Phi}_u + \text{h.c.}$$

$$\Phi_\alpha = \begin{pmatrix} \phi_\alpha^- \\ v_\alpha + (\rho_\alpha + i\eta_\alpha)/\sqrt{2} \end{pmatrix}, \quad \alpha = u, d, \quad \Phi_s = f + \frac{r_0 + i a_0}{\sqrt{2}}.$$

$$\mathcal{A}(b \to sa) = -\sin\theta \times \mathcal{A}(b \to sA).$$

Freytsis, Ligeti, Thaler. 10'

Mixing angle θ in $a - A$ mass term.

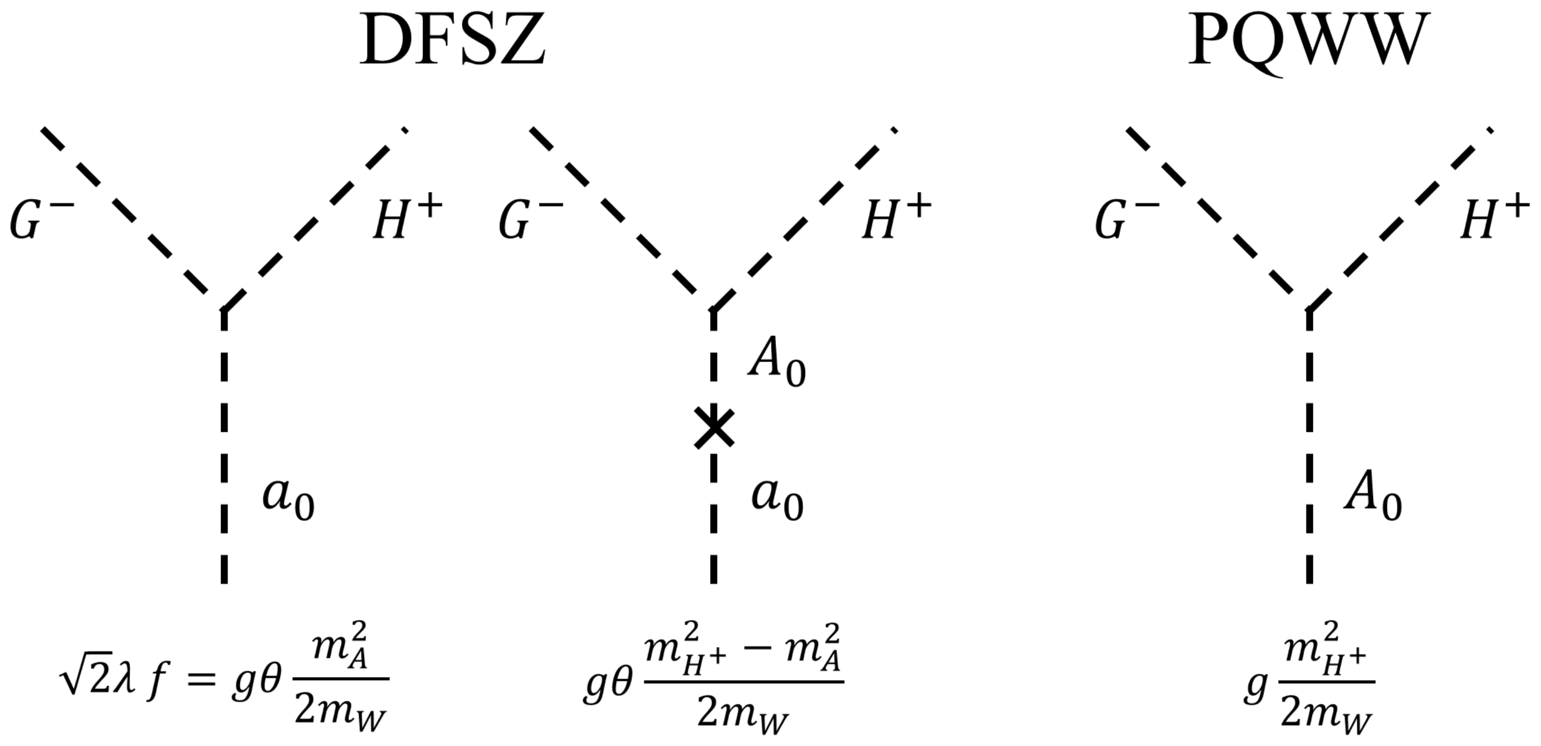
A, the CP-odd scalar of 2HDM.

Massless when $\lambda = 0$ (PQWW)

$B \to Ka$ with UV completion

When $\lambda \neq 0$:

- Massive A_0. Off-shell, unphysical $b \to sA$ amplitude.
- Mixing picture is wrong, however, mixing formula correct.
- Somehow similar to: Kachanovich, Nierste, Nisandzic. 20’. Higgs portal;



$$\mathcal{A}(b \to sa)_{\text{DFSZ}} \neq -\sin\theta \times \mathcal{A}(b \to sA_0)_{\text{DFSZ}},$$
$$\mathcal{A}(b \to sA_0)_{\text{DFSZ}} \neq \mathcal{A}(b \to sA_0)_{\text{PQWW}},$$

But two changes cancel each other:

$$\mathcal{A}(b \to sa)_{\text{DFSZ}} = -\sin\theta \times \mathcal{A}(b \to sA_0)_{\text{PQWW}}$$

$B \to Ka$ with UV completion

λ only disappears at 1-loop.
The complete result when $m_H \gg m_W$:

$$\mathcal{H}_{\rm eff} = \theta \frac{g^3 V_{ts}^* V_{tb}}{128\pi^2} \frac{m_t^2}{m_W^3} \left(X_1 \frac{1}{\tan\beta} + X_2 \frac{1}{\tan^3\beta} + X_3 \frac{\lambda}{16\pi^2} \right) \bar{s}\gamma^\mu P_L b\, \partial_\mu a.$$

decouple (→ θ) *GIM* (→ $\frac{m_t^2}{m_W^3}$) Z_2 (→ $\frac{1}{\tan^3\beta}$) *Lorentz* (→ $\bar{s}\gamma^\mu P_L b\, \partial_\mu a$)

$$X_1 = -\ln\frac{m_H^2}{m_t^2} + \frac{3m_W^4}{(m_t^2 - m_W^2)^2}\ln\frac{m_t^2}{m_W^2} + \frac{3(m_t^2 - 2m_W^2)}{m_t^2 - m_W^2},$$

$$X_2 = 0,$$

$$X_3 = \ln\frac{m_H^2}{m_t^2} + \frac{6m_W^2}{m_t^2 - m_W^2}\ln\frac{m_t^2}{m_W^2} + \frac{1}{2}.$$

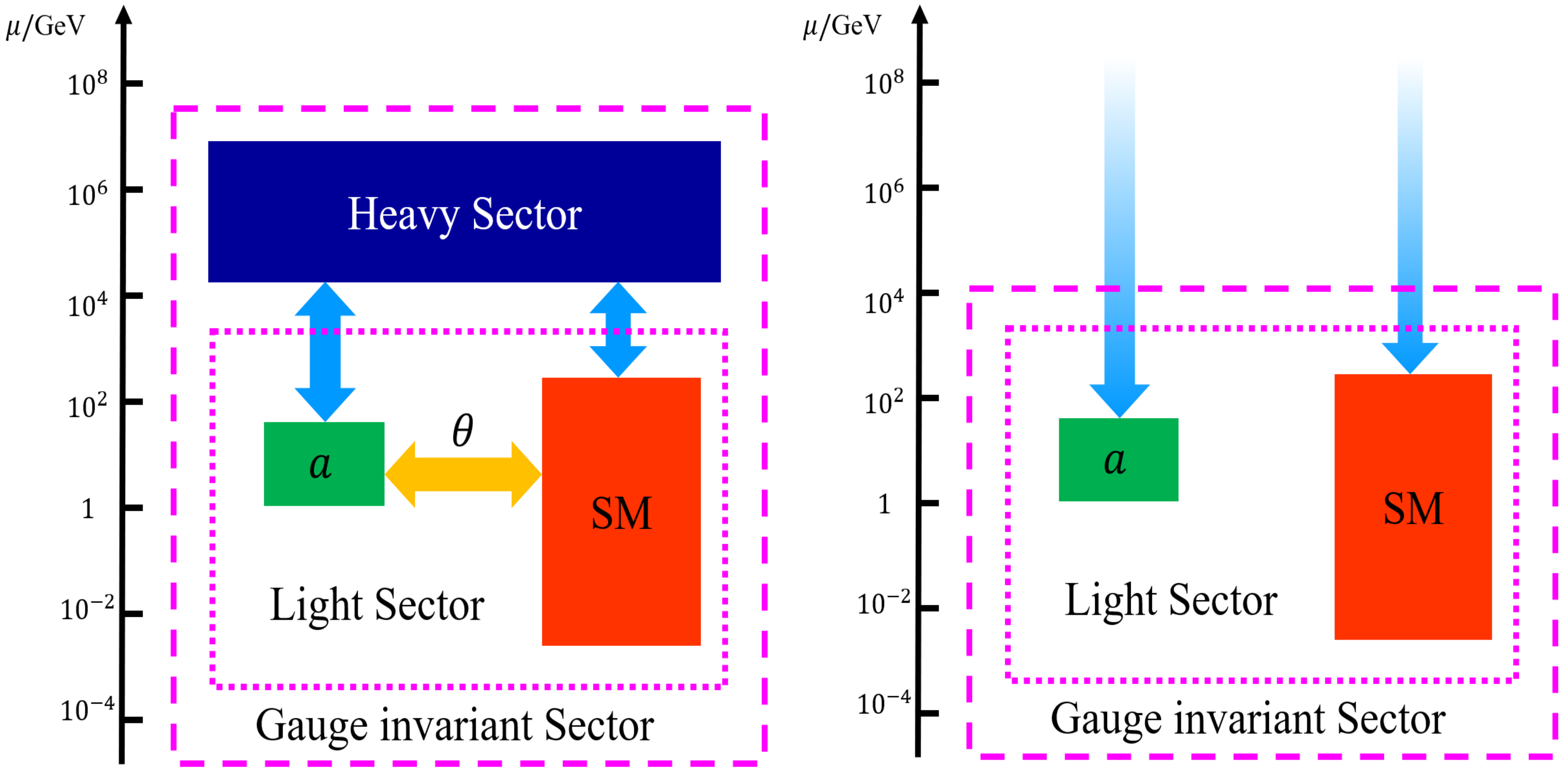
- X_1, X_2 are consistent with the mixing formula.
  Known for more than 40 years.
  Hall, Wise. 81'
- X_3 is **new**, arising at a **two-loop**.
  Enhanced when tanβ is large.
  See back-up for 2-loop diagrams.

Reflections: Apparent Non-decoupling

Among the three loop factors, only X_2 is suppressed by m_H^2.

$$\mathcal{H}_{eff} \sim \ln m_H \,,$$
but $\theta = 2\frac{\lambda f v}{m_H^2}$.

- Dimensionless θ, Wilson picture fails?
- The Light theory is not Gauge invariant when $\theta \neq 0$.



Reflections: Apparent Non-decoupling

necessary requirement for the decoupling of heavy particles: *at each stage of symmetry breaking the light subtheory has to be renormalizable*. In other words, whenever we isolate the heavy sector of the theory, the gauge invariance of the remaining light sector should not be broken. Senjanovic, Sokorac, 79'

Important lesson, if we:

- Change SM (data driven),
- Do Bottom-up analysis.

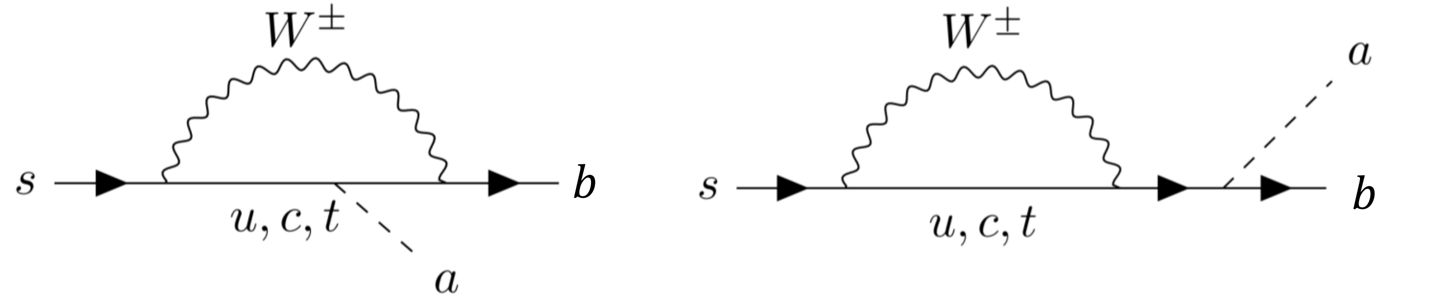
The result may be incomplete.
Must check Gauge invariance.

Example:
$\mu \to e\gamma$ in a 2HDM: $c_{\alpha\beta}$
Chang, Hou, Keung. 93';
Gunion, Haber. 03';
Davidson. 16'; Altmannshofer, et al. 20'.

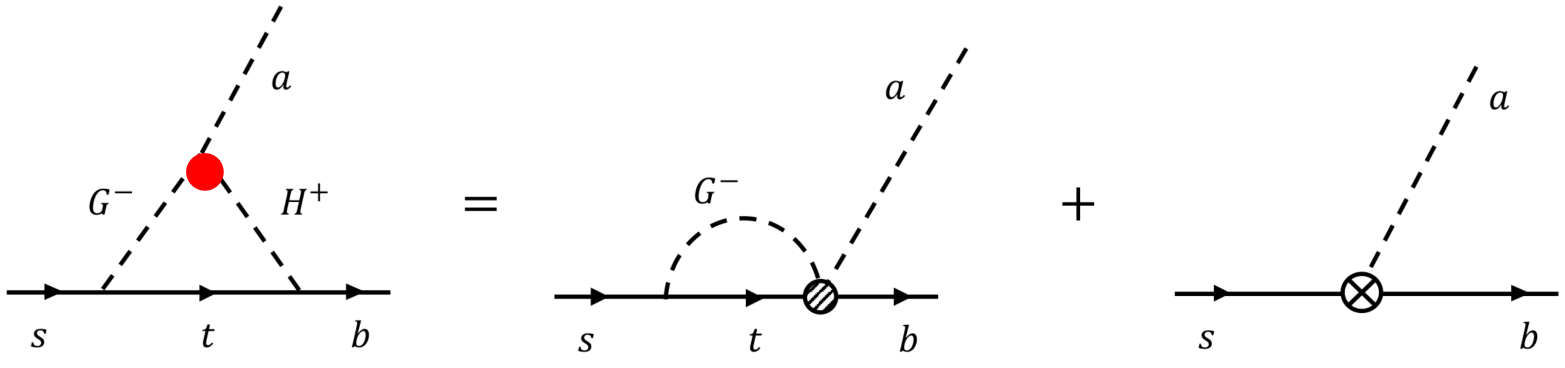
Reflections: Apparent Non-decoupling

The EFT must reveal apparent non-decoupling:

SM loop:
e.g. Alonso-Alvarez, et al. 21’



2HDM loop:



(a) (b) (c)

Unsupressed $\ln m_H$

Divergent: Captured by EFT?

Counter-term

G^-H^+a vertex:

● $g\theta \frac{m_H^2}{2m_W}$

Reflections: Apparent Non-decoupling

Some basis give the wrong result:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + ia \sum_{q=t,b} c_q \, \bar{q}\gamma_5 q.$$

Renormalizable, but **not SU(2)×U(1) invariant**

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\text{SM}} + i\frac{a}{v}\left(c_b \overline{Q}_L b_R \widetilde{H}_u + c_t \, \overline{Q}_L t_R H_u + \text{h.c.}\right) \\ &= \mathcal{L}_{\text{SM}} + ia \sum_{q=t,b} c_q \bar{q}\gamma_5 q + i\frac{a}{v}\left[c_b V_{tb} \bar{t}_L b_R G^+ \right. \\ &\quad \left. + c_t \left(V_{tb}^* \bar{b}_L t_R G^- + V_{ts}^* \bar{s}_L t_R G^-\right) + \text{h.c.}\right] + \ldots \\ &= \mathcal{L}_{\text{SM}} + \sum_{\psi_L = Q_L, t_R^c, b_R^c} \frac{c_\psi}{f} \, \overline{\psi}_L \gamma^\mu \psi_L \, \partial_\mu a + \ldots\end{aligned}$$

SU(2)×U(1) invariant, but **not renormalizable**

The **gauge invariant** EFT reproduces the correct **leading-log** term.

Beyond leading-log, the **counter term** is a **definition**.

Phenomenology: Explaining the Belle II excess

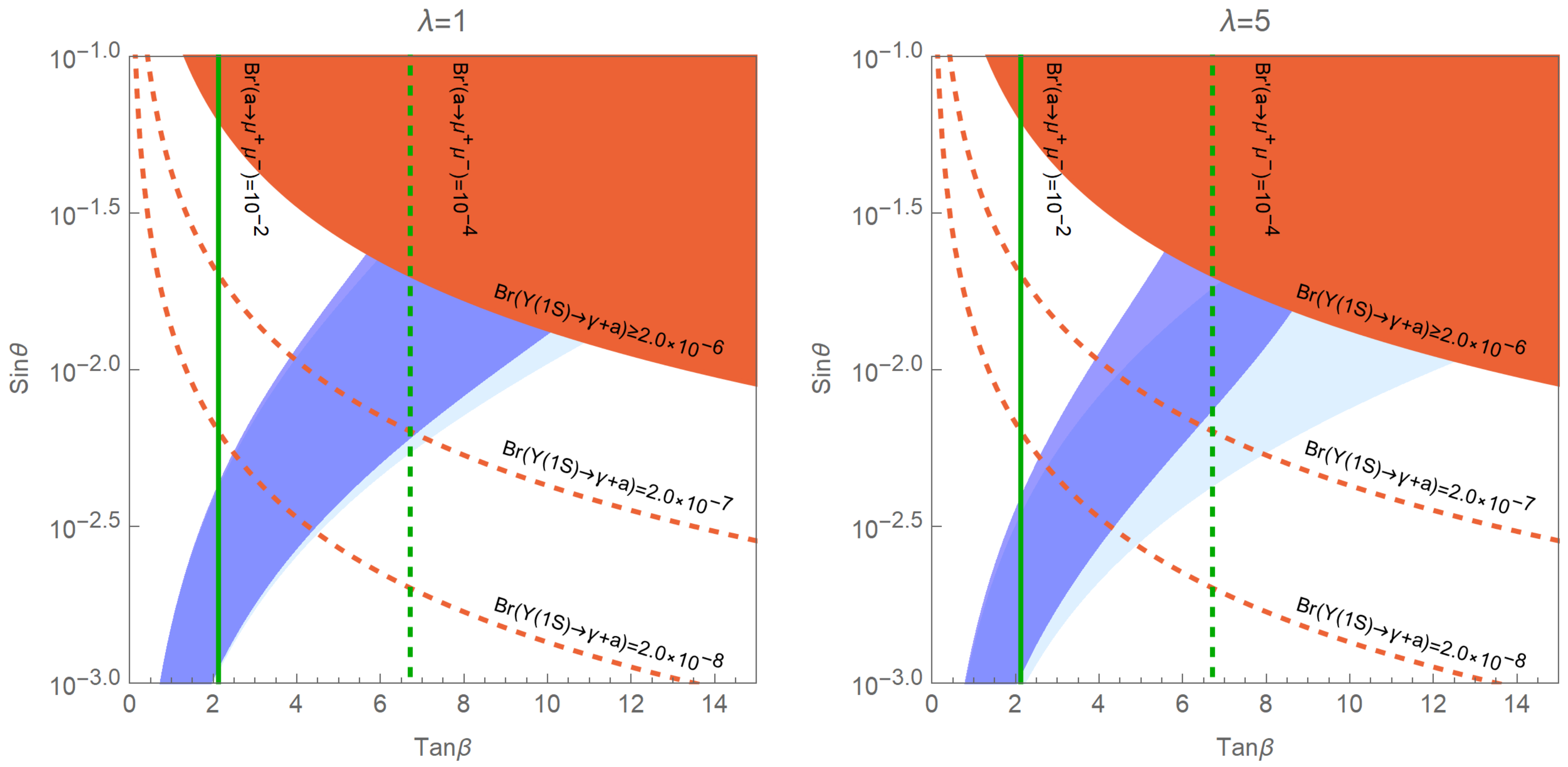
What we need?

$$\text{Br}(B \to Ka) \times \text{Br}(a \to \text{invisible}) \;=\; (1 \sim 9) \times 10^{-6},$$
$$\text{Br}(B \to Ka) \times \text{Br}(a \to \text{visible}) \;\lesssim\; \text{exclusive search limits.}$$

- $a \to \chi\chi$ gives invisible signals.
- $a \to \mu^+\mu^-$ constrains small tanβ.
- $\Upsilon \to \gamma a$ constrains large tanβ.

Need to extend DFSZ and couple a to a dark sector.

Phenomenology: Explaining the Belle II excess



Mixing only
Two-loop complete result

Conclusions: what we learnt?

- We find a two-loop enhanced correction to $b \to sa$.
- Decoupling heavy particles is conditional.
- Axion EFT can give the correct leading-log term.
- Related heavy NP at TeV scale, waiting for more signals in near future.

Thanks

$B \to Ka$ with UV completion

Some technical details on two-loop calculation:

- Thousands of diagrams at two loop, but only a few are relevant to X_3.
- Master integrals are well-known. Davydychev, Tausk. 92'; Nierste. 95'
- Cross checked within arbitrary gauge. Box+Penguin=Gauge inv