



B decays into light BSM particles

Ulrich Nierste

Institute for Theoretical Particle Physics (TTP)

Karlsruhe Institute of Technology



Collaborative Research Center TRR 257



Particle Physics Phenomenology after the Higgs Discovery



60th Recontres de Moriond - EW+U 2026

Outline

- B meson decays to **sterile neutrinos**
- B meson decays to axion-like particles (**ALPs**)

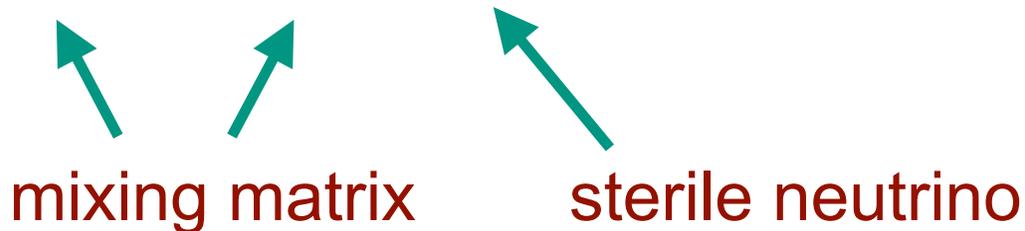
Sterile neutrinos

- heavy neutrino = Heavy Neutral Lepton

- sterile = gauge singlet

- usually studied: **mixing scenario**

$$\nu_\ell = U_{\ell j} \nu_j + U_{\ell j} N_j \quad \text{with } \ell = e, \mu, \tau, \text{ and } j=1,2,3$$

The diagram consists of two teal arrows pointing upwards. The first arrow points from the text 'mixing matrix' to the $U_{\ell j} \nu_j$ term in the equation above. The second arrow points from the text 'sterile neutrino' to the $U_{\ell j} N_j$ term in the equation above.

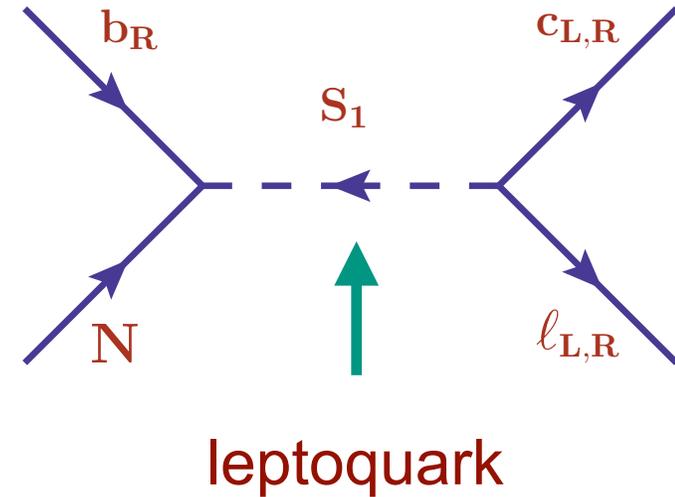
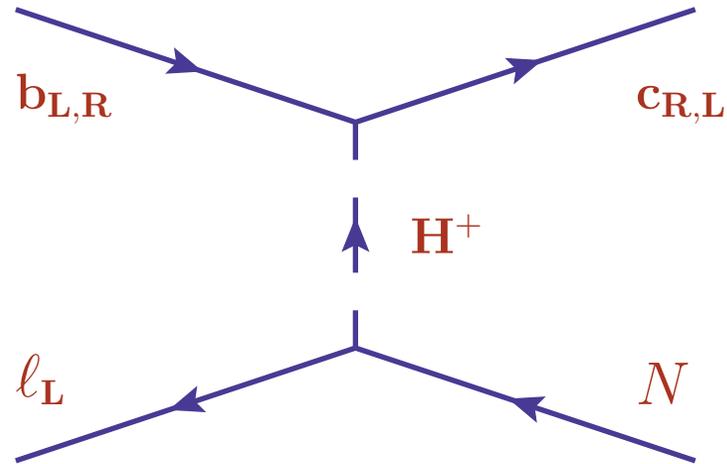
mixing matrix sterile neutrino

- ... but **B physics** is not competitive for mixing scenarios

- Yet **B decays** interesting, if some new **Yukawa** interaction couples **b** quark to N_j .

Sterile neutrinos

■ One could have



■ Here the sterile neutrino is exclusively produced in B meson decay.

■ We first assume that N is undetected.
(True, if N is light enough or decays to the dark sector.)

Effective hamiltonian

- Parametrise arbitrary new-physics interaction to dimension 6:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(\bar{c}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma^\mu \nu_{\ell,L}) + g_{V_R}^N (\bar{c}_R \gamma_\mu b_R) (\bar{\ell}_R \gamma^\mu N) + g_{S_L}^N (\bar{c}_R b_L) (\bar{\ell}_L N) \right. \\ \left. + g_{S_R}^N (\bar{c}_L b_R) (\bar{\ell}_L N) + g_T^N (\bar{c}_L \sigma_{\mu\nu} b_R) (\bar{\ell}_L \sigma^{\mu\nu} N) + \text{h.c.} \right]$$

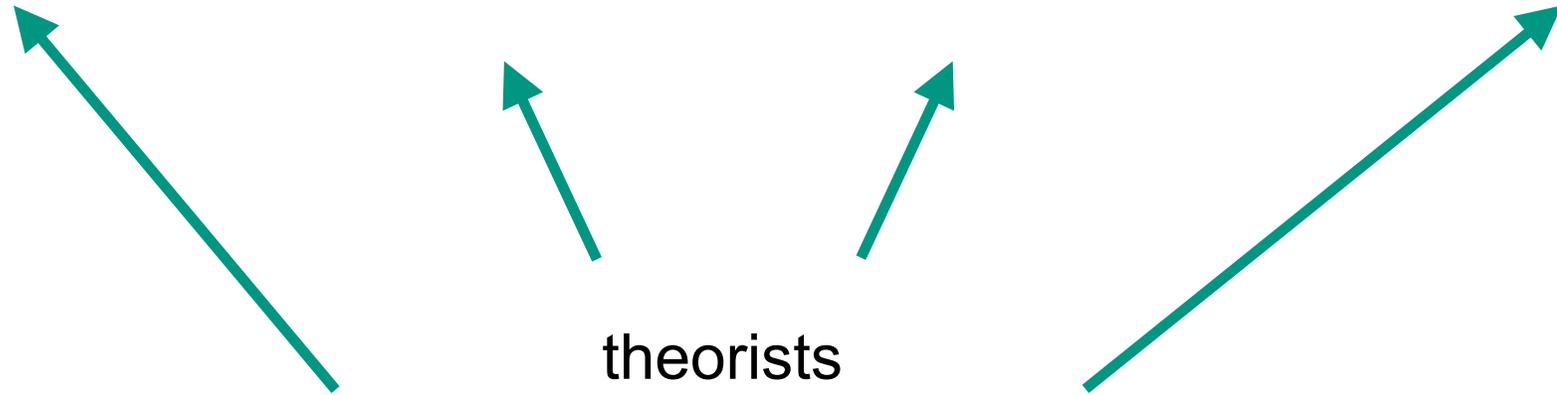
SM term 

Robinson, Shakya and Zupan, 1807.04753

- None of the N terms mimicks SM interaction \Rightarrow study angular distributions

Study of $B \rightarrow D^* \ell^+ N$ Belle data

Florian Bernlochner, Marco Fedele, Tim Kretz, and Markus T. Prim



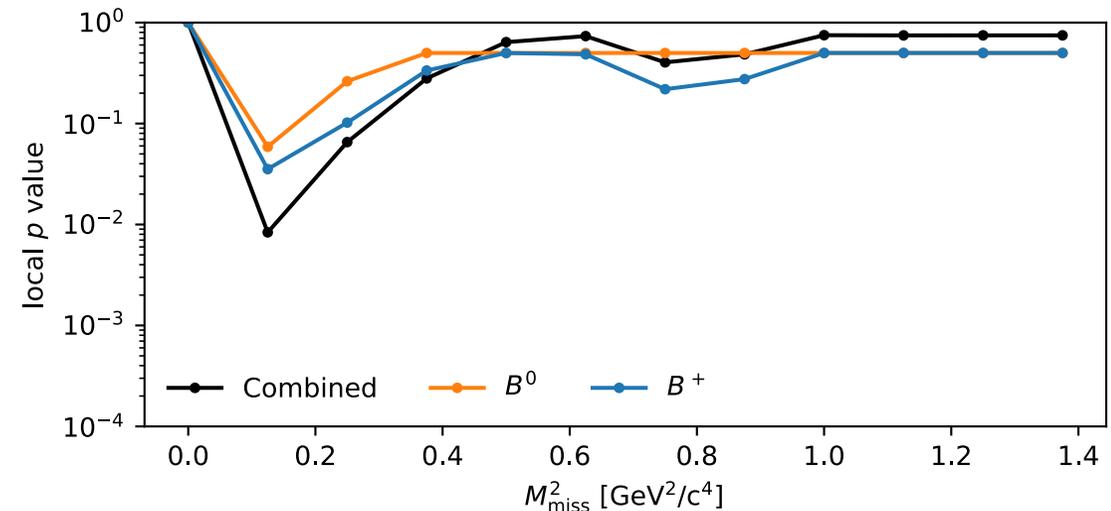
Belle (-II) group at University of Bonn

$\ell = e$ or μ

JHEP 01 (2025) 040

Study of $B \rightarrow D^* \ell^+ N$ Belle data

- Belle has vetoed $M_N > 50 \text{ MeV}$ in its angular distribution data.
 - Thus we were only sensitive to $M_N \leq 50 \text{ MeV}$. We find no hint of non-zero coefficients $g_{V_R}^N, g_{S_L}^N, g_{S_R}^N, g_T^N$ and place bounds of $\mathcal{O}(0.3)$
 - By $SU(2)$ symmetry $g_{S_R}^N, g_T^N$ are much better constrained by $b \rightarrow s \nu_L N$ decays, data on $B(B \rightarrow K^{(*)} + E_{\text{miss}})$ imply $|g_{S_R}^N|, |g_T^N| \leq 0.01$.
- Felkl, Giri, Mohanta, Schmidt, EPJ C 83,, no. 12 (2023) 1135.
- Nice (but statistically insignificant 😞) bump at $M_N = 354 \text{ MeV}$.



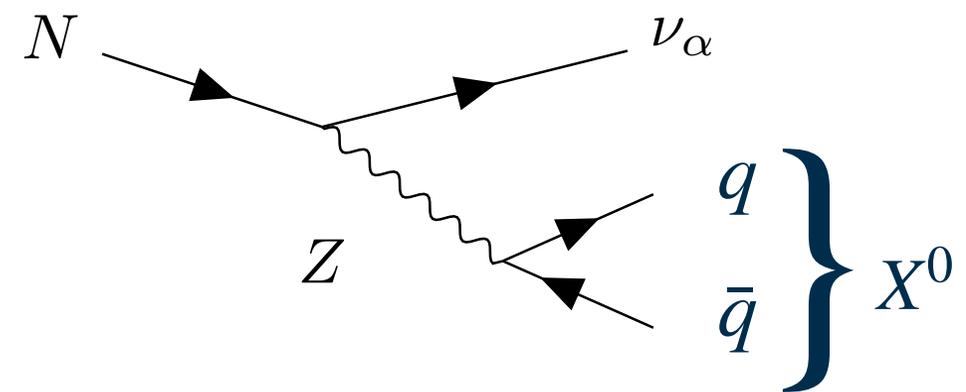
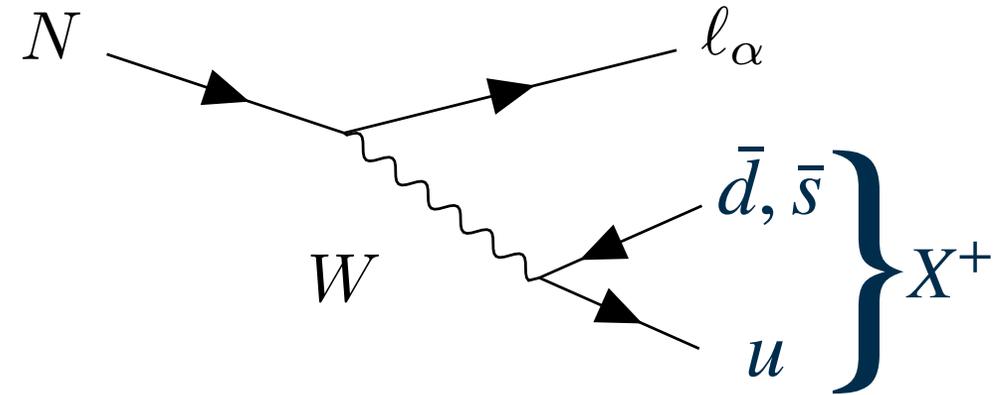
Sterile neutrino decay through mixing

- Best possible world: N is long-lived so that it decays with a displaced vertex.
- Assume that the decay is via mixing with only one active neutrino $\nu_{e,\mu,\tau}$:

$$N \rightarrow \ell^- X^+ \quad \text{or} \quad N \rightarrow \nu X^0$$

Dominant contribution to the decay rate for $X^{+,0}$ being a multi-hadron state.

- Need calculations of $\Gamma(N \rightarrow \ell + \text{hadrons})$ and $\Gamma(N \rightarrow \nu + \text{hadrons})$ to predict
 - the **lifetime** of N
 - and all **branching fractions**.



Sterile neutrino decay through mixing

Using five-loop results on current correlators from the literature we have calculated $\Gamma(N \rightarrow \ell + \text{hadrons})$ to order α_s^4 to determine the ranges for M_N for which perturbation theory works and reliable predictions are possible:

$$M_N > 1.5 \text{ GeV for } \ell = e, \mu$$

and

$$M_N > 3.0 \text{ GeV for } \ell = \tau.$$

T. Kretz, UN, arXiv:2512.00476

With $\Gamma(N \rightarrow \nu + \text{hadrons})$ (in progress) we will be able to delineate the region for **mass** and **mixing angle** for which N decays in the detector with a displaced vertex.

B decays to ALPs

- Phenomenological motivation: Belle II find $B(B^+ \rightarrow K^+ + \text{nothing})$ above the SM prediction for $B(B \rightarrow K\nu\bar{\nu})$ by 2.7σ .
- An **axion** is a pseudo-Goldstone boson of a **U(1)** symmetry (“Peccei-Quinn symmetry”)
 - **purpose**: solve the strong CP problem
 - fixed relation between mass and couplings
 - ⇒ no interesting collider phenomenology
- **ALP**: same, but with some extra explicit symmetry breaking
 - mass and couplings are independent
 - standard candidate for **Dark Matter** or mediator to the **Dark Sector**

DFSZ model

- Widely studied benchmark for an “invisible ALP” model, meaning that ALP couplings to SM particles are small.

Dine, Fischler, Srednicki, *Phys. Lett. B*104, 199 (1981)

Zhitnitsky, *Sov. J. Nucl. Phys.* 31, 260 (1980)

- The starting point is a **2HDM** with $U(1)_{PQ}$ symmetry rendering the pseudoscalar Higgs boson A_0 massless.

- Add a complex gauge singlet field with vev f ,

$$\Phi_s = f + \frac{r_0 + ia_0}{\sqrt{2}},$$

- Add a mixing term to the Higgs potential V which breaks all $U(1)$ symmetries,

$$V \supset \lambda \Phi_s^2 \Phi_u \Phi_d^\dagger .$$

ALP coupling to other Higgs bosons

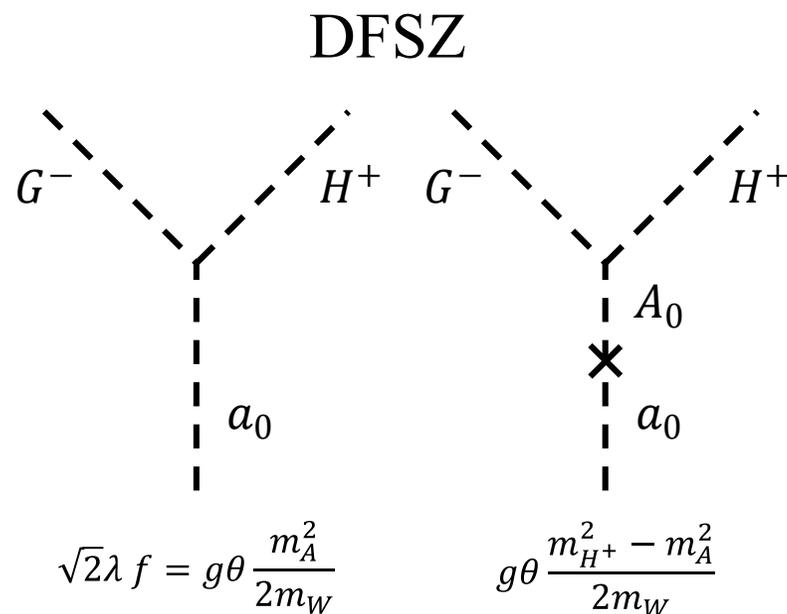
- Two effects of $V \supset \lambda \Phi_s^2 \Phi_u \Phi_d^\dagger$: \longrightarrow new couplings:

- Mass matrix with $a_0 - A_0$ mixing:

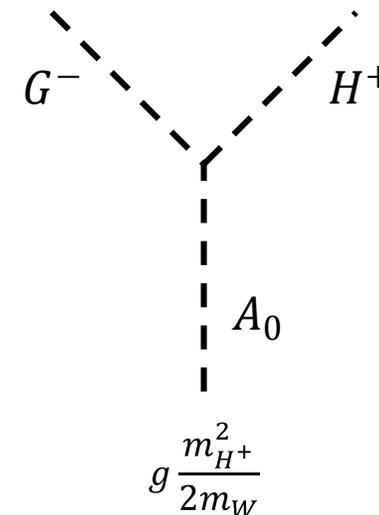
$$A_0 = A \cos \theta + a \sin \theta$$

- A is heavy, a is light, and

$$\sin \theta \sim \theta \ll 1$$



compare
with
2HDM



- m_A^2 term cancels and one gets the correct coupling from **2HDM** multiplied with θ

ALP coupling to other Higgs bosons

- We confirm the one-loop calculation of the $B \rightarrow K + a$ decay rate.

Freytsis, Ligeti, and Thaler, Phys. Rev. D 81, 034001

- At two-loop level the rule “ $\mathcal{A}(B \rightarrow Ka) = \theta \mathcal{A}(B \rightarrow KA^0)$ ” does not hold

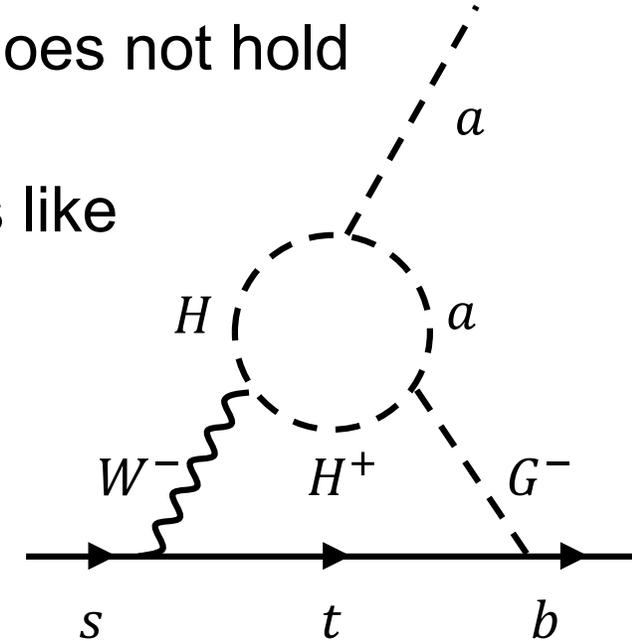
anymore. There are genuine contributions $\propto \lambda$ from diagrams like

- The two-loop calculation is enhanced by a factor of

$$\tan \beta = \frac{v_u}{v_d} \quad (\text{ratio of vevs of the two Higgs doublets})$$

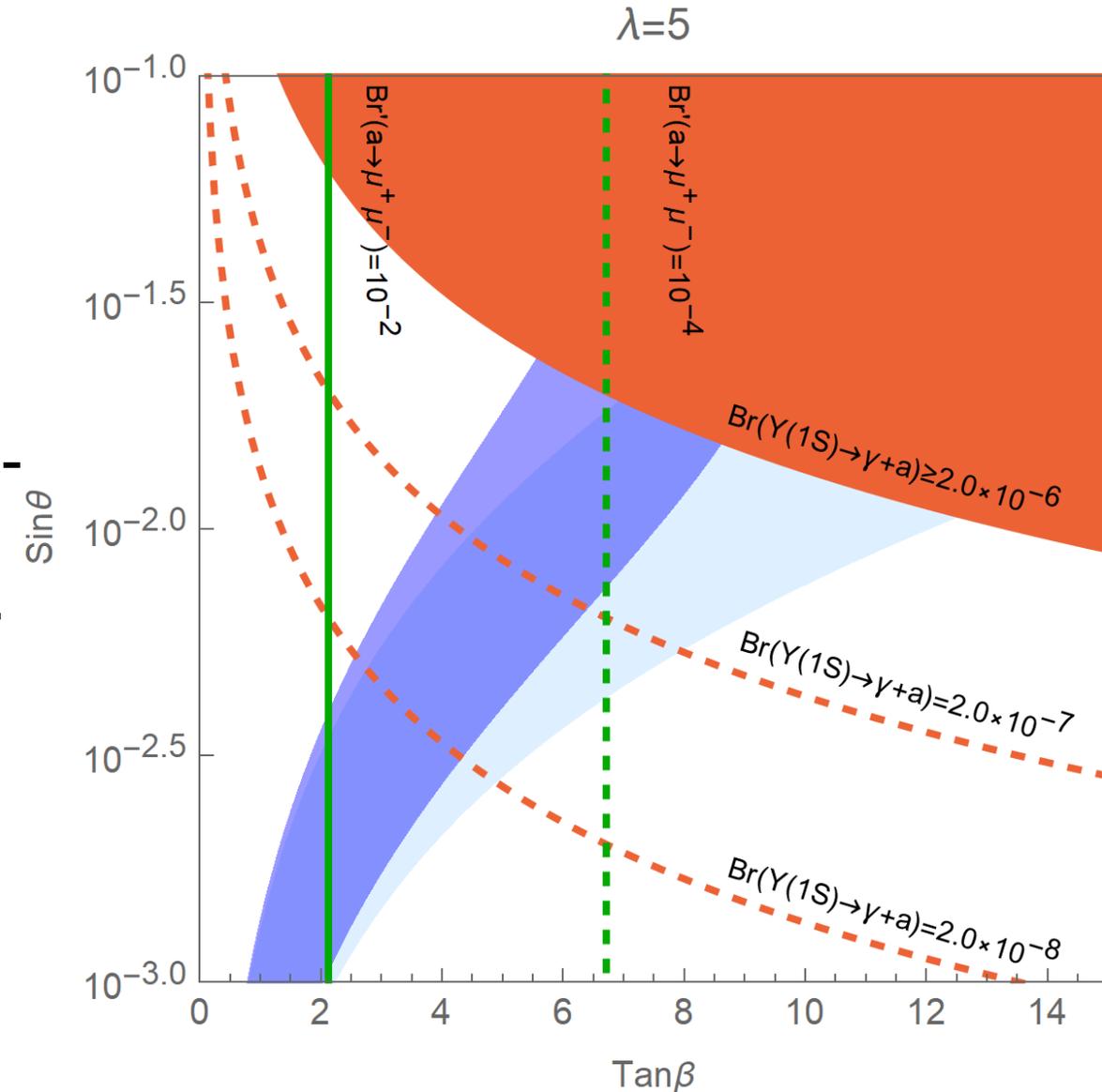
and non-negligible.

Gao, UN, Phys.Rev.D 112 (2025) 5, 055008



Phenomenology of $B \rightarrow Ka$

- Since **Belle II** sees missing energy, a must dominantly decay to the Dark Sector, beyond the **DFSZ** model.
- Belle II data hint at $m_a \sim 2 \text{ GeV}$.
- One-loop and two-loop contributions have opposite signs. Blue region explains Belle II data (**dark blue**: all, **light blue**: only one-loop).
- Look for **displaced vertex** decay $a \rightarrow \mu^+ \mu^-$. But branching fraction is unpredictable, since $B(a \rightarrow \text{dark sector})$ is free parameter.
- $Y(1S) \rightarrow \gamma a$ constrains the plot and could be “**smoking gun**” signal.



Summary

- Belle II can study B decays with missing energy.
- Detectable semileptonic B decays to final states with a sterile neutrino N can occur in e.g. 2HDMs, but not in the standard mixing scenarios.
- To study N decays we need predictions for the total decay rate, especially to find the parameter space with “sweet spot” lifetimes, leading to **displaced-vertex signals**.
The QCD calculations for $N \rightarrow \ell + \text{hadrons}$ is complete now.
- Belle II data for $B(B^+ \rightarrow K^+ + \text{nothing})$ can be explained with an ALP of mass around 2 GeV.
- ALPs of the popular DFSZ model can indeed explain the data, when amended by ALP decays to the dark sector.
- The parameter space of this model is efficiently constrained by other measurements.
!!!! Experimentalists: Look for $a \rightarrow \mu^+ \mu^-$ and $\Upsilon(1S) \rightarrow \gamma + \text{nothing}$!!!!
We communicate this through our established channels....



Psst!!! Hey, bud! C'mere.

Who? Me?

You can make a DISCOVERY
and become famous!
And it is JUST AROUND
the corner!

Wow, I can become
famous!!!

Just look for $a \rightarrow \mu^+ \mu^-$ and $\Upsilon(1S) \rightarrow \gamma a$!