The Search for Axion Like Particles (ALPs) in B Meson Decays at the LHCb

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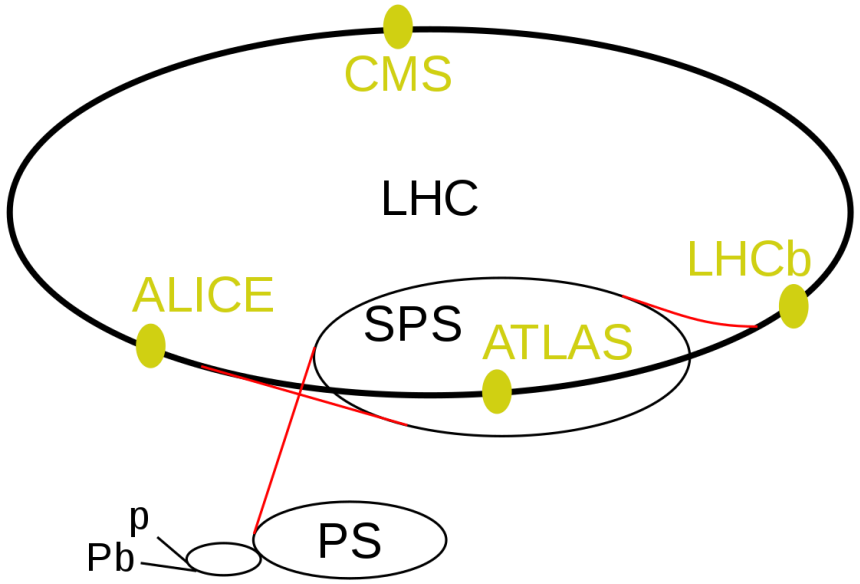

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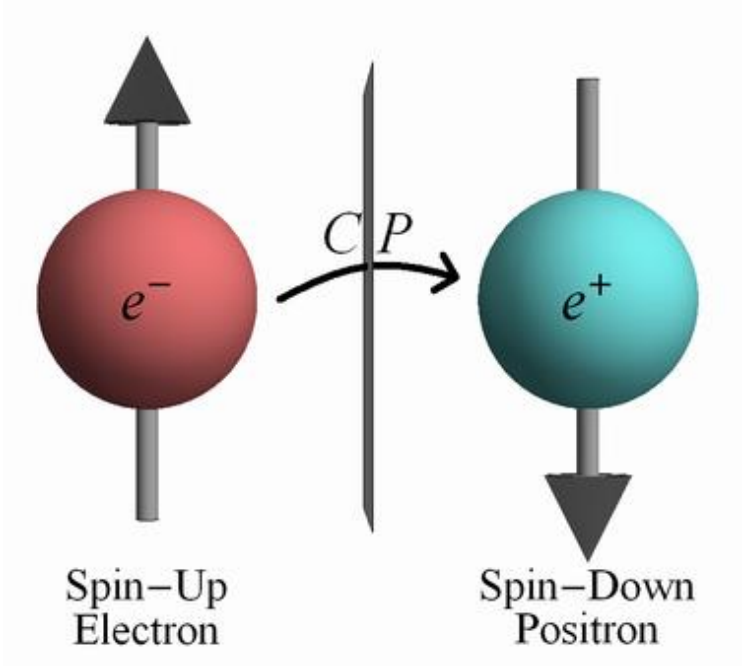
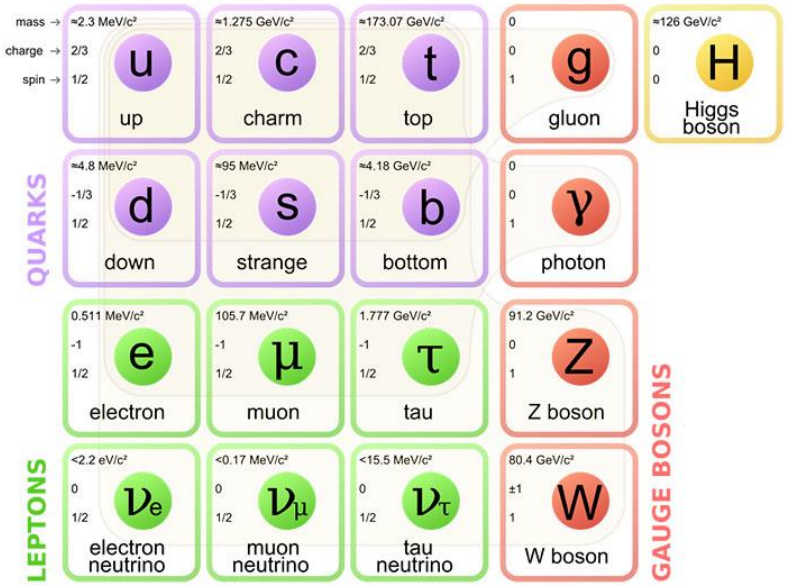
Background and Motivation

- CP symmetry is preserved in EM interactions but violated by weak interactions (Cronin & Fitch, 1964)
- CP violation is not observed experimentally in the strong force, despite being theoretically allowed **(Strong CP Problem).** Significant limitation of the Standard Model





The Strong CP Problem

- CP violation is **theoretically permitted** in the strong force (QCD) but there is **no experimental evidence of this**
- T QED Lagrangian (electromagnetism):

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}(i\gamma^{\mu}\mathcal{D}_{\mu} - m_e)\psi$$

- Consider the QCD (strong) Lagrangian written in the following form:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{g_s^2\theta}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{\psi}(i\gamma^{\mu}D_{\mu} - me^{i\theta'\gamma_5})\psi$$

  - The effects of the θ-dependent term are not observed experimentally. **Hence, θ must be very small**

D.Tong, *Lectures in Quantum Field Theory:* https://www.damtp.cam.ac.uk/user/tong/qft/one.pdf
C.T. Chan, *On the Symmetry Constraints of CP Violations in QCD*: https://arxiv.org/pdf/hep-ph/9704427.pdf

The Strong CP Problem and its Resolution

- Experimental measurements of neutron EDM => $|\theta| < 10^{-10}$

Solution: Promote θ to a **dynamic field** by adding a new symmetry that is spontaneously broken (Peccei & Quinn, 1977)*

- Spontaneous breaking of this **PQ symmetry** introduces a new **pseudoscalar (spin 0 and odd parity)** particle known as the **(QCD) axion**. (No experimental evidence of this)

*D.Tong, *Lectures in Quantum Field Theory:* https://www.damtp.cam.ac.uk/user/tong/qft/

Axion Like Particles (ALPs)

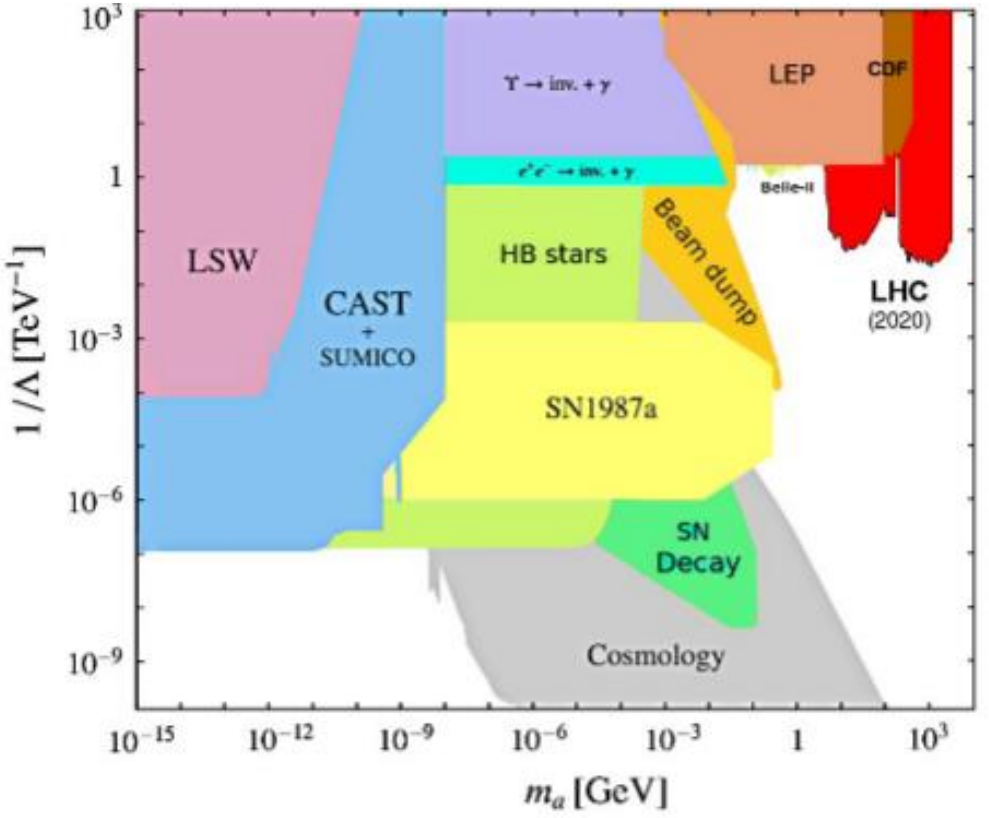
- Spontaneous breaking of an approximate symmetry **(not PQ)** can also generate other **axion-like particles (ALPs).**
- Masses and couplings to photons are independent for ALPs and are therefore far less constrained
- Couple predominantly to pairs of gauge bosons (e.g. $gg, \gamma\gamma, ZZ, \gamma Z, W^{\pm}$etc.) depending on the model being considered*

*Ringwald (2014) *Axions and Axion-Like Particles:* https://arxiv.org/pdf/1407.0546.pdf

** Isern et al. (2018) *Axions and the Cooling of White Dwarf Stars* https://arxiv.org/pdf/0806.2807.pdf

Experimental Searches for Axions and ALPs

- Spin-selection rules => light pseudoscalars naturally couple to photons
- Search strategies generally exploit the (inverse) Primakoff effect
- Notable search strategies (excluding collider searches):
  - **LSW (Light Shining Through Walls) Experiments**
    - **Any Light Particles Search (ALPS I)**
    - **ALPS II**
  - **Helioscope Searches**
    - **International Axion Observatory (IAXO)**
    - **CERN Axion Space Telescope (CAST)**
  - **Haloscope Searches**
    - **Axion Dark Matter Experiment (ADMX)**
    - **PIXIE**
    - **PRISM CMB**

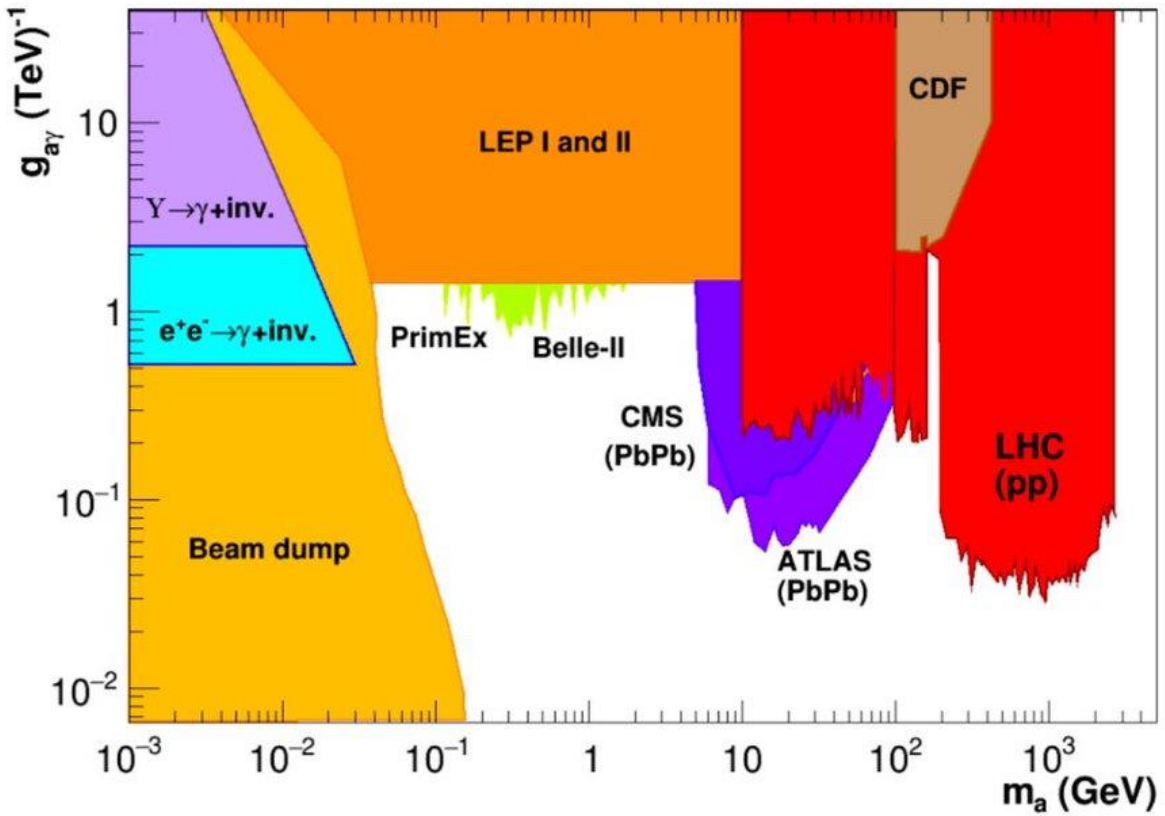


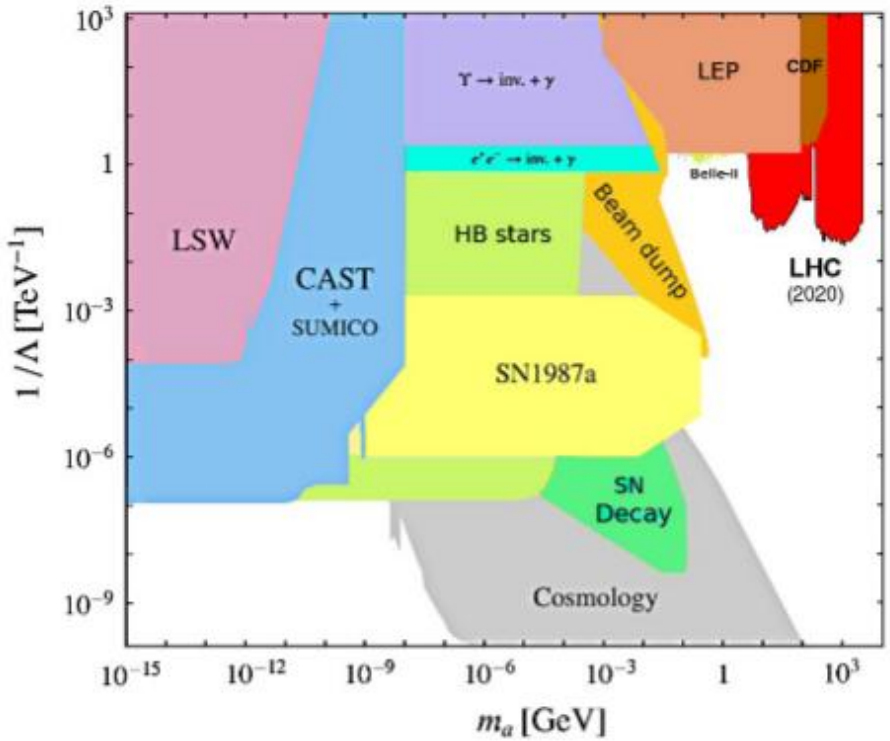
Source: A. Ringwald. *Axions and axion-like particles*, 2014.

Strategy: Search for ALPs at Colliders

0. Set limit on branching fraction of decay of interest using Monte Carlo (MC) simulated data to determine if analysis is viable/worth pursuing
1. Event selection (i.e. impose constraints on kinematic and shape variables to distinguish signal from background within MC simulated data)
2. Check optimised event selection against a real data sample to verify that MC simulation models the data
3. Perform a fit to extract the signal yield
4. Estimate systematic errors

Summary of Mass and Coupling Constraints

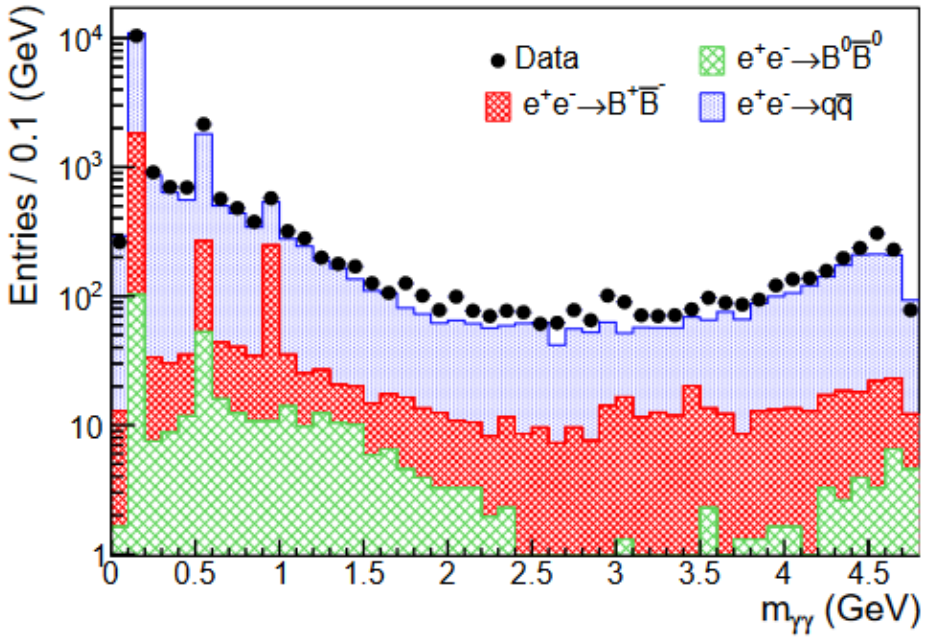




Strategy: Search for ALPs at LHCb

- Seek diphoton resonance structures
- Promising decay channel for search: $B^0 \to K^{*0} a_0, a_0 \to \gamma\gamma$
- ALPs produced in B-meson decays have a maximal mass of

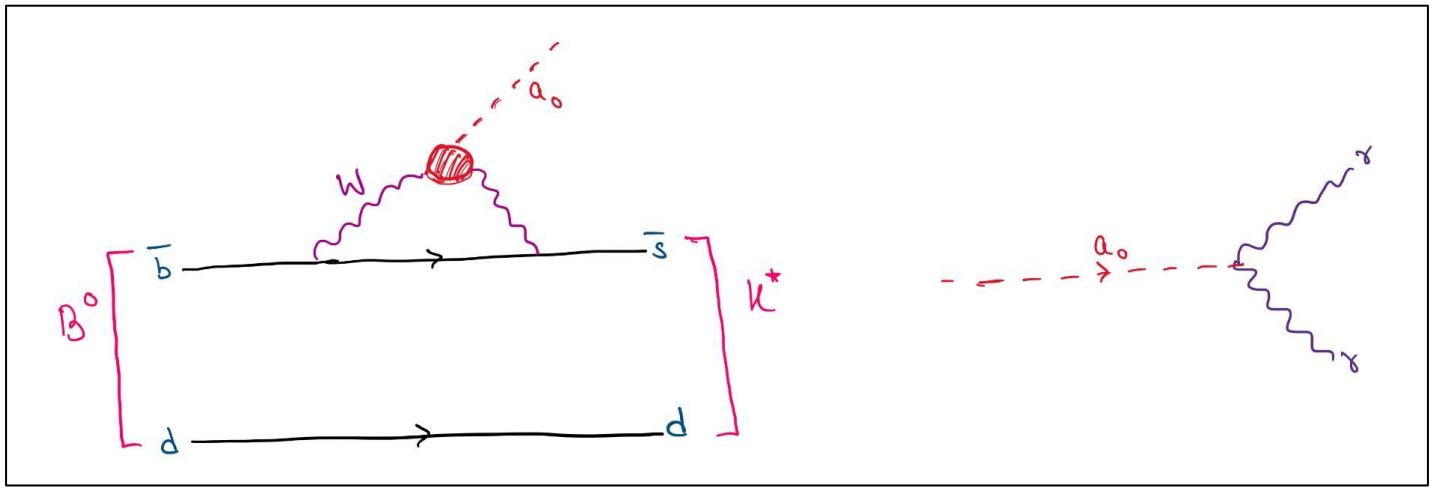
$$m_{a_0} = m_{B^0} - m_{K^*} = 5279.26 - 493.68\ MeV = 4785.58\ MeV$$

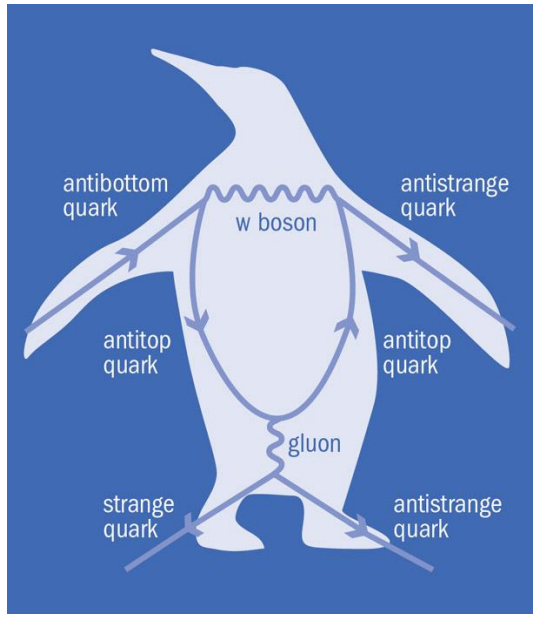


The BABAR Collaboration: *Search for Axion Like Particles in B Meson Decays:* https://arxiv.org/pdf/2111.01800.pdf

The $B^0 \to K^{*0} a_0, a_0 \to \gamma\gamma$ Decay

- Consider model where ALP couples to weak gauge bosons $W^{\pm}$, and gives rise to observable signatures (zero coupling with gluons)

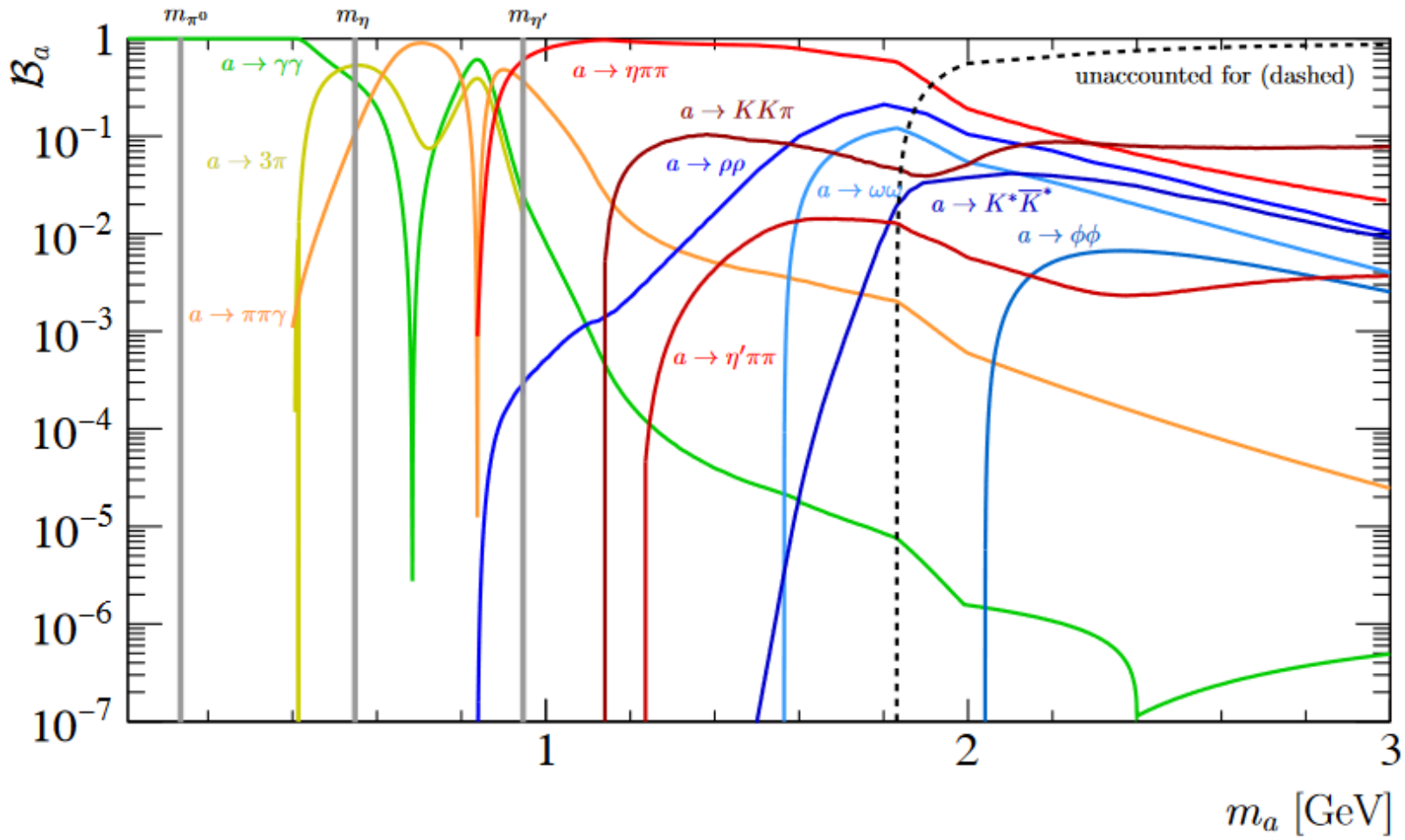




- Flavour Changing Neutral Current (FCNC) process ($\bar{b} \to \bar{s}$ quark transition)
- Electroweak penguin decay that proceeds at one-loop level

(R) Image Source: https://cerncourier.com/a/chasing-new-physics-with-electroweak-penguins/
Source: https://arxiv.org/abs/1611.09355

Plot of ALP Branching Fraction vs ALP Mass



https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.123.031803/supplemental.pdf