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

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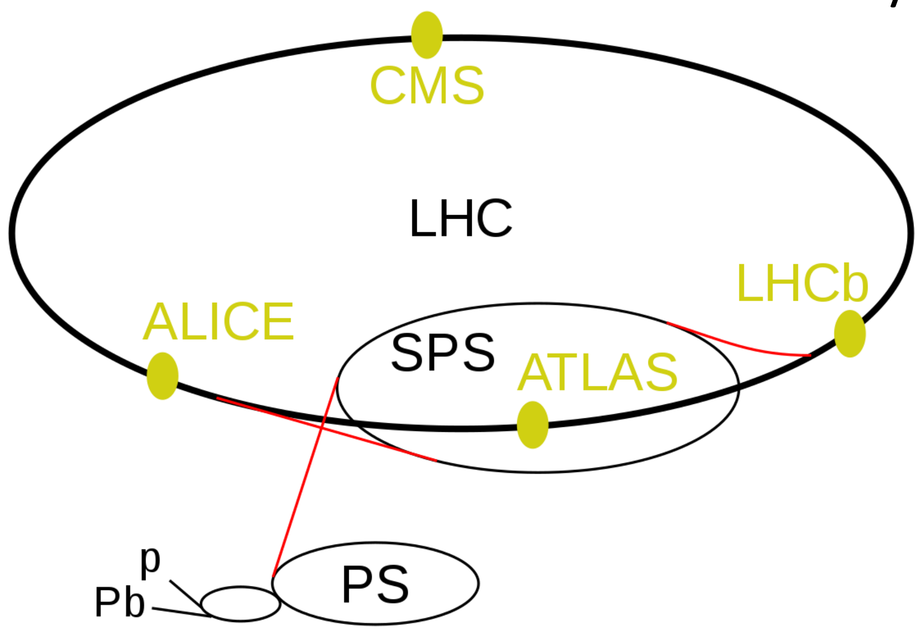
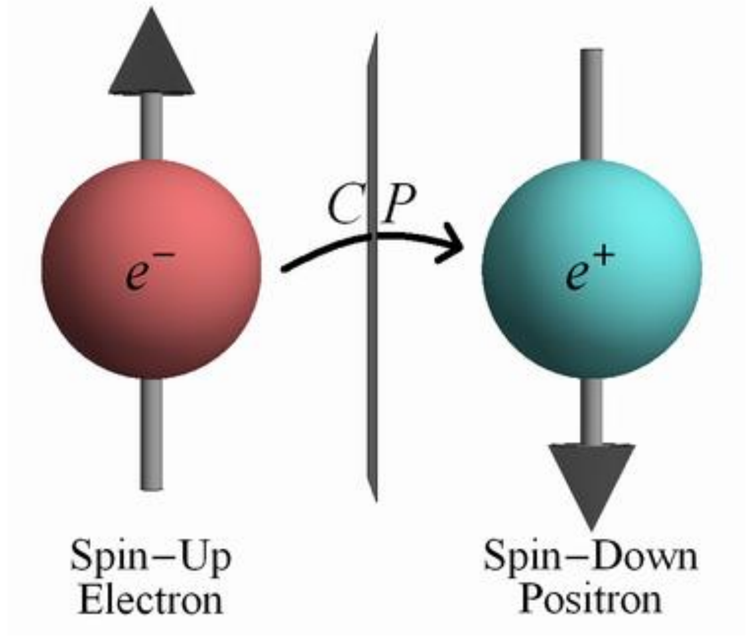
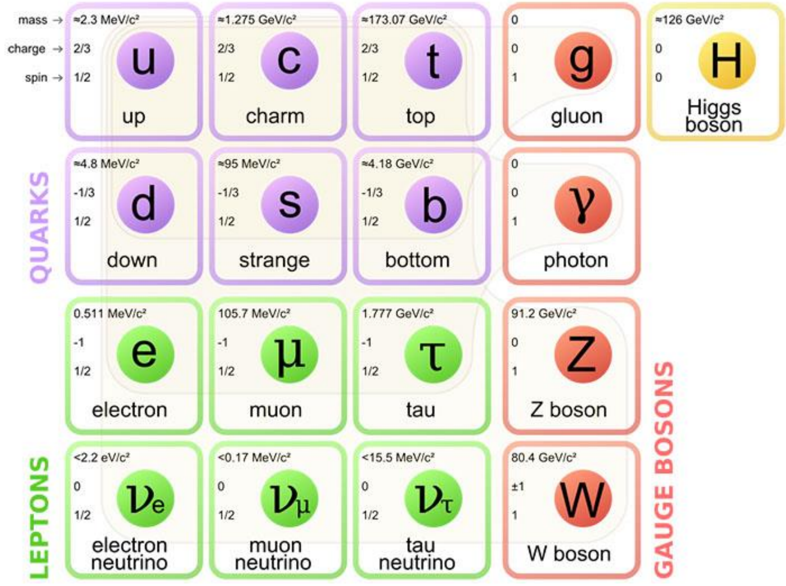


Background and Motivation

- 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:

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

  - The effects of the θ-dependent term are not observed experimentally. **Hence, $\boldsymbol{\theta}$ 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)

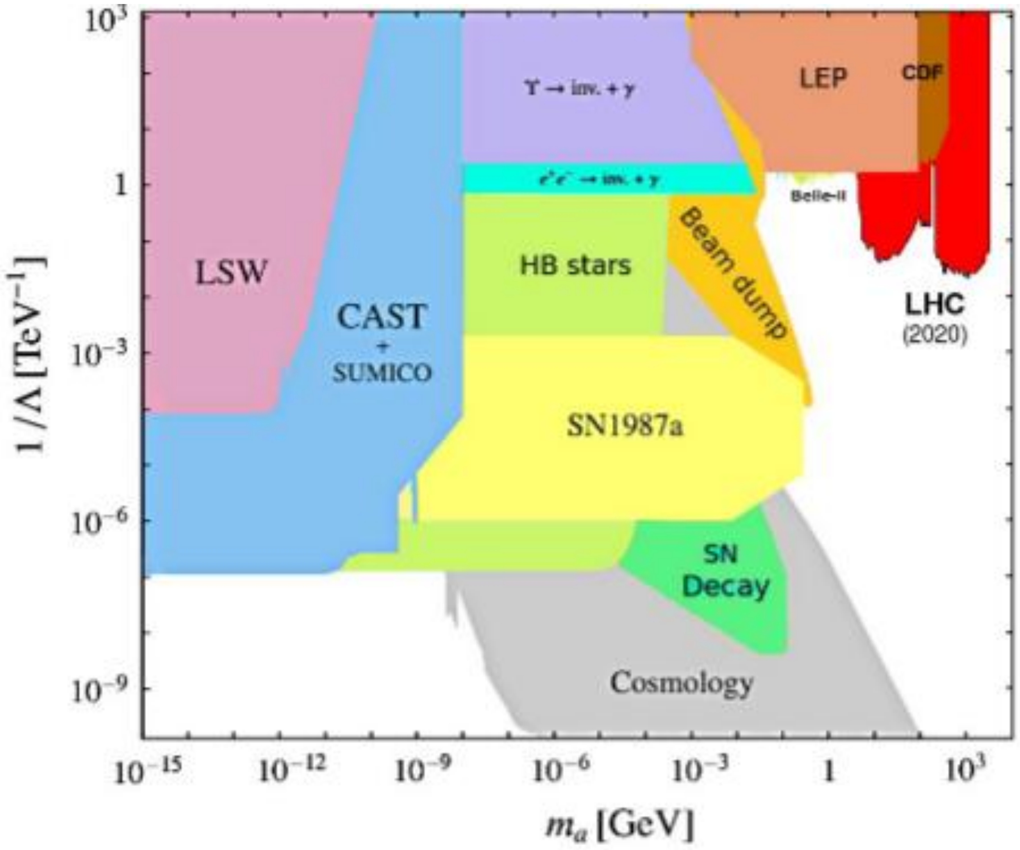
- Spontaneous breaking of an approximate symmetry **(not PQ)** can also generate other **axion-like particles (ALPs).**
- Masses and couplings to photons are independent for ALPs and are therefore far less constrained
- Couple predominantly to pairs of gauge bosons (e.g. $gg, \gamma\gamma, ZZ, \gamma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

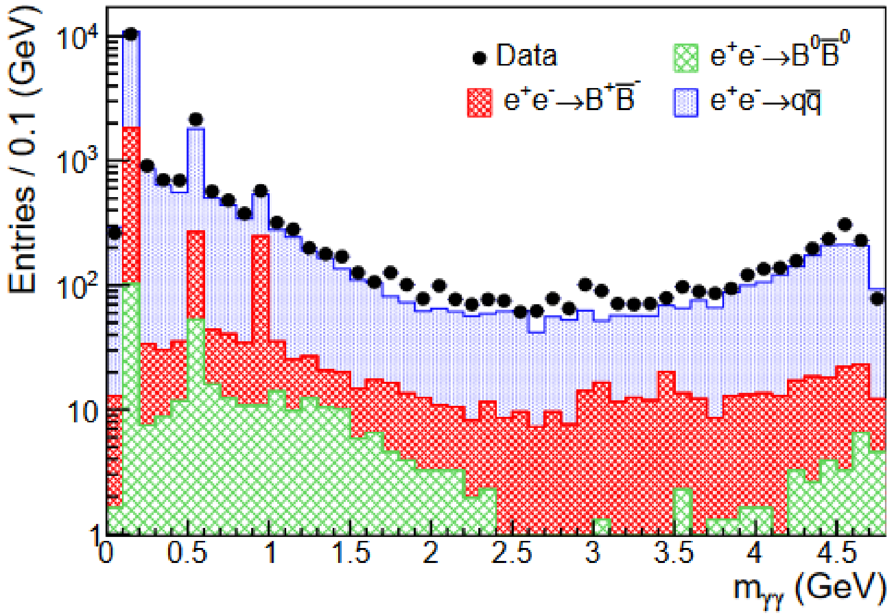
Strategy: Search for ALPs at Colliders

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

Strategy: Search for ALPs at LHCb

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

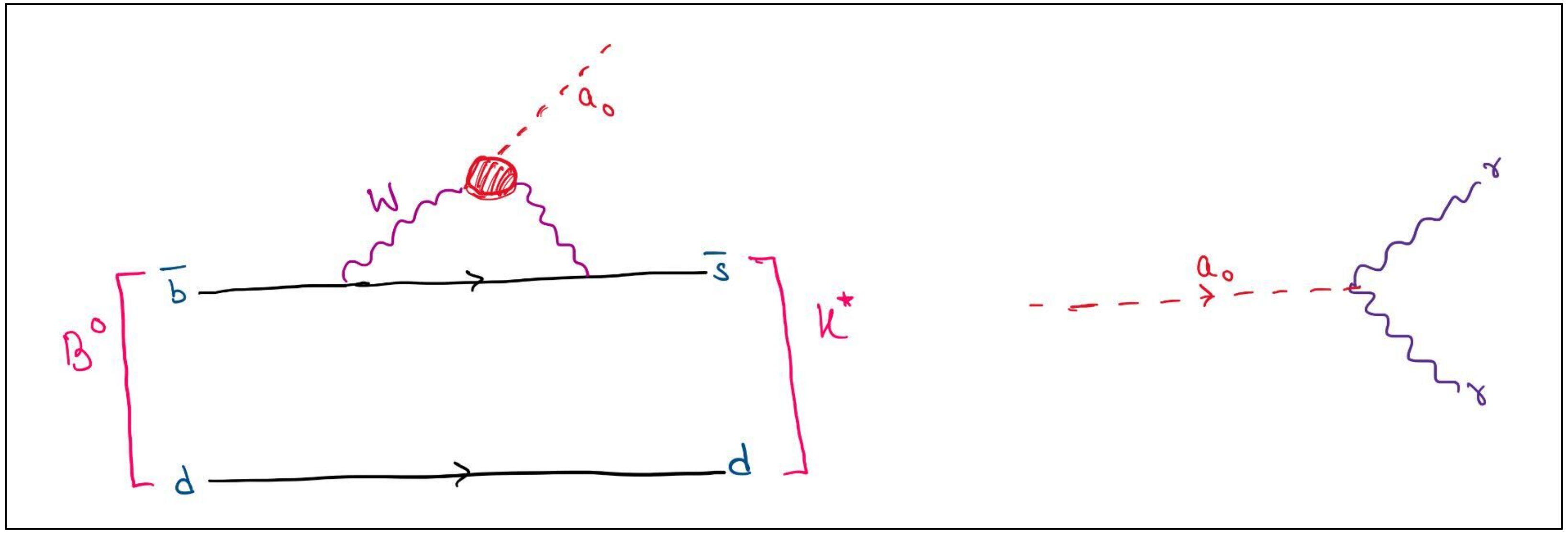
$$m_{a_0} = m_{B^0} - m_{K^*} = 5279.26 - 493.68\ MeV = 4785.58\ MeV$$



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

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

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

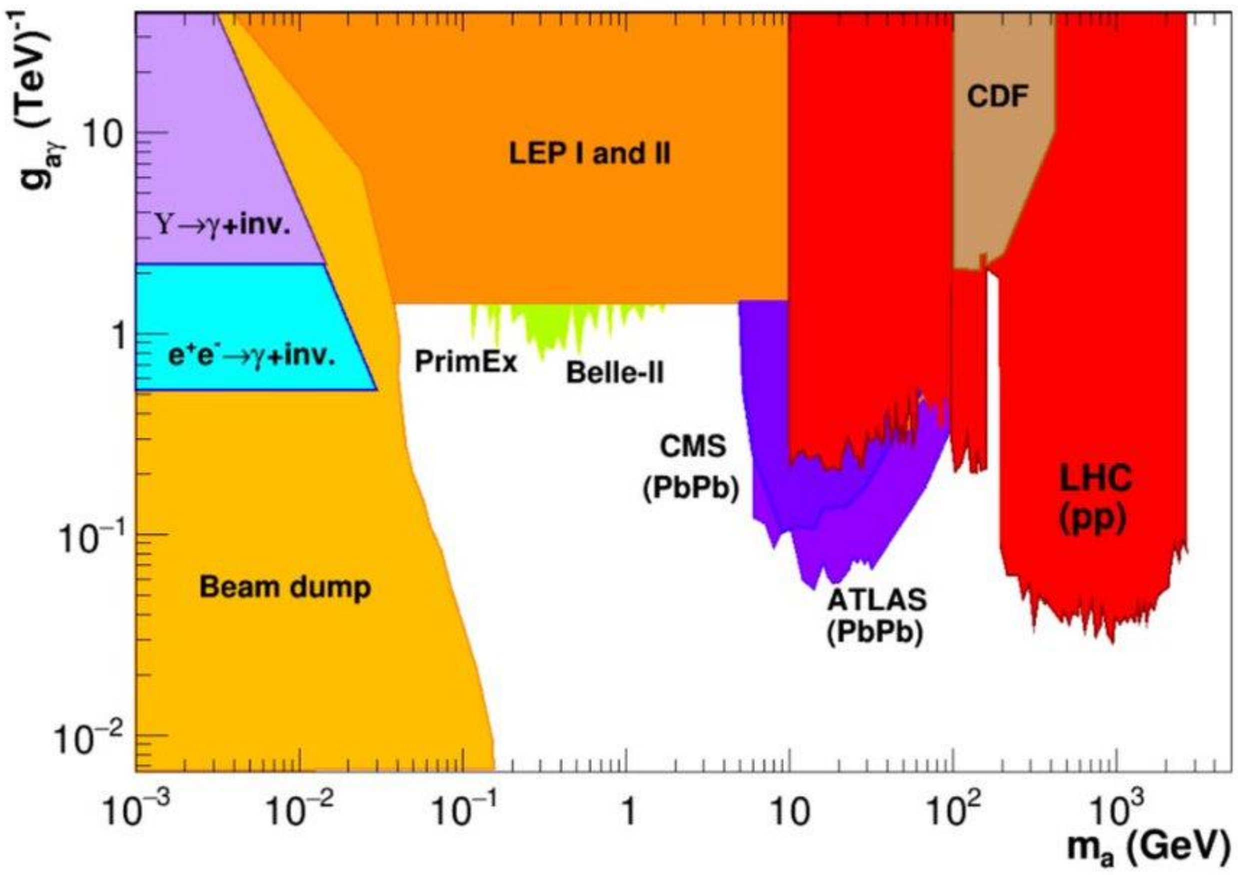


- Flavour Changing Neutral Current (FCNC) process ($\bar{b} \to \bar{s}$ quark transition)
- Electroweak penguin decay that proceeds at one-loop level

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

My Analysis (to date)

- **Setting limit on branching fraction of decay process to determine if analysis is viable/worth pursuing (i.e. Step 0 on Slide 6 => preliminary stages)**
- Relating the branching ratio to the mass and coupling strength of the ALP to photons
- Comparing the limits set on the mass and coupling strength to those in existing literature



http://arxiv.org/abs/2102.08971

Electromagnetic Trigger Efficiency Study

$$\frac{N_{K^*\gamma\gamma}}{N_{K^*\gamma}} = \frac{BR(B^0 \to K^{*0} a_0, a_0 \to \gamma\gamma)}{BR(B^0 \to K^{*0}\gamma)} \frac{\varepsilon_g^{\gamma\gamma}}{\varepsilon_g^{\gamma}} \frac{\varepsilon_t^{\gamma\gamma}}{\varepsilon_t^{\gamma}} \frac{\varepsilon_{rec}^{\gamma\gamma}}{\varepsilon_{rec}^{\gamma}} \frac{\varepsilon_{sel}^{\gamma\gamma}}{\varepsilon_{sel}^{\gamma}}$$

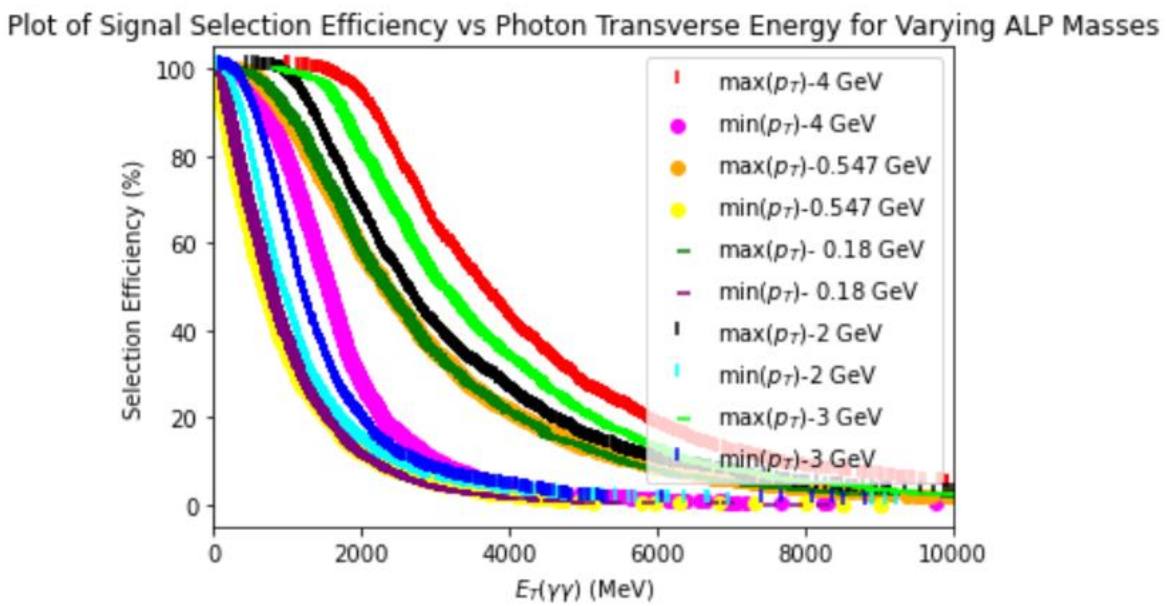
- Rearrange the expression for $BR(B^0 \to K^{*0} a_0, a_0 \to \gamma\gamma)$:

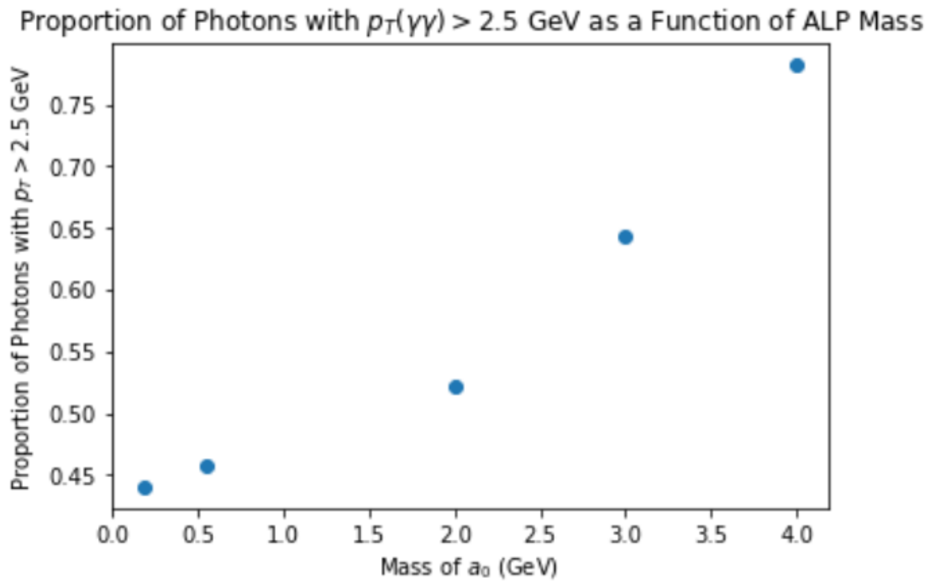
$$BR(B^0 \to K^{*0} a_0, a_0 \to \gamma\gamma) = \frac{N_{K^*\gamma\gamma}}{N_{K^*\gamma}} BR(B^0 \to K^{*0}\gamma) \frac{\varepsilon_g^{\gamma}}{\varepsilon_g^{\gamma\gamma}} \frac{\varepsilon_t^{\gamma}}{\varepsilon_t^{\gamma\gamma}} \frac{\varepsilon_{rec}^{\gamma}}{\varepsilon_{rec}^{\gamma\gamma}} \frac{\varepsilon_{sel}^{\gamma}}{\varepsilon_{sel}^{\gamma\gamma}}$$

- World average for $BR(B^0 \to K^{*0}\gamma) = (4.33 \pm 0.15) \times 10^{-5}$ (http://arxiv.org/abs/1209.0313)

Electromagnetic Trigger Study (contd.)

- Seek to determine how $\varepsilon^{\gamma\gamma}$ varies as a function of ALP mass





Link Between Branching Ratio, Coupling Strength and ALP Mass

$$BR(B^0 \to K^* a_0, a_0 \to \gamma\gamma) = \left(\frac{M_B^3}{16} |g_{abs}|^2 A_0^2(M_a^2) \lambda_{K^* a}^{\frac{3}{2}}\right) \tau_{B^0} \left(\frac{M_a^3 \alpha}{\Lambda^2} \left|C_{eff}^{\gamma\gamma}\right|^2\right) \tau_{a_0}$$

Here:

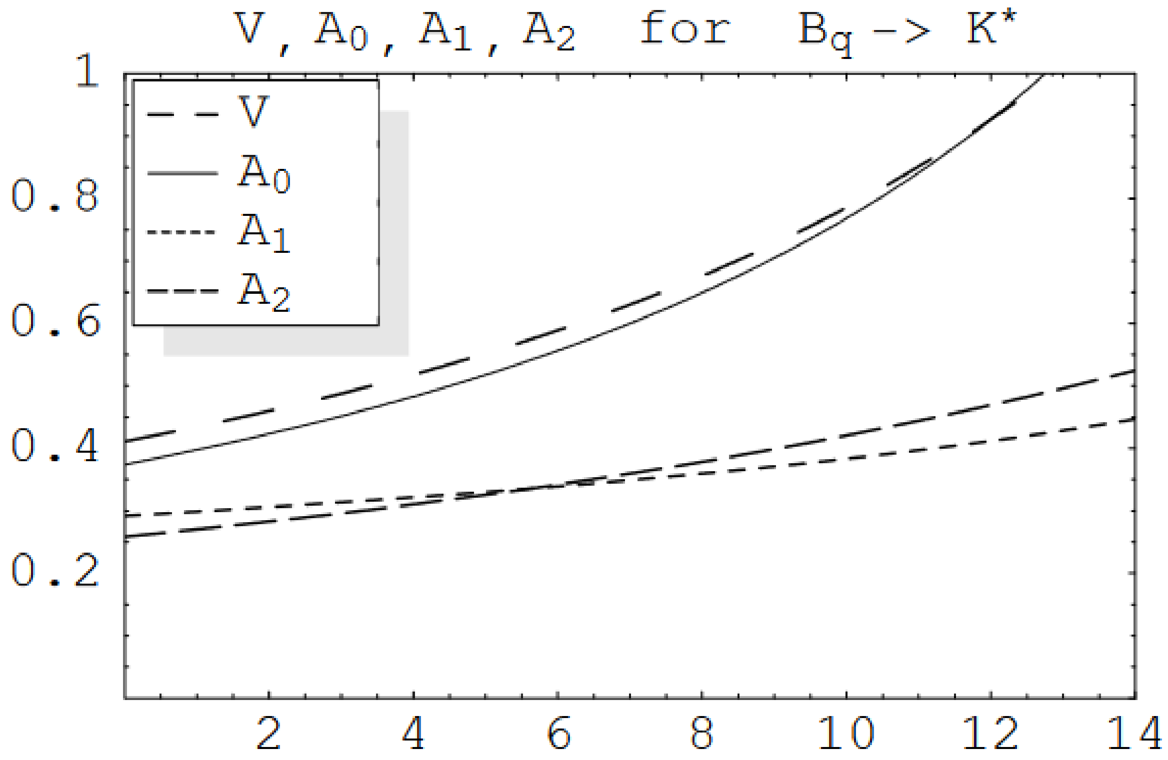
$$\lambda_{K^* a} = \left[1 - \frac{(M_a + M_{K^*})^2}{M_B^2}\right]\left[1 - \frac{(M_a - M_{K^*})^2}{M_B^2}\right]$$

And A_0 is the form factor of the pseudoscalar current (see next slide)

(Source: https://arxiv.org/abs/1611.09355)

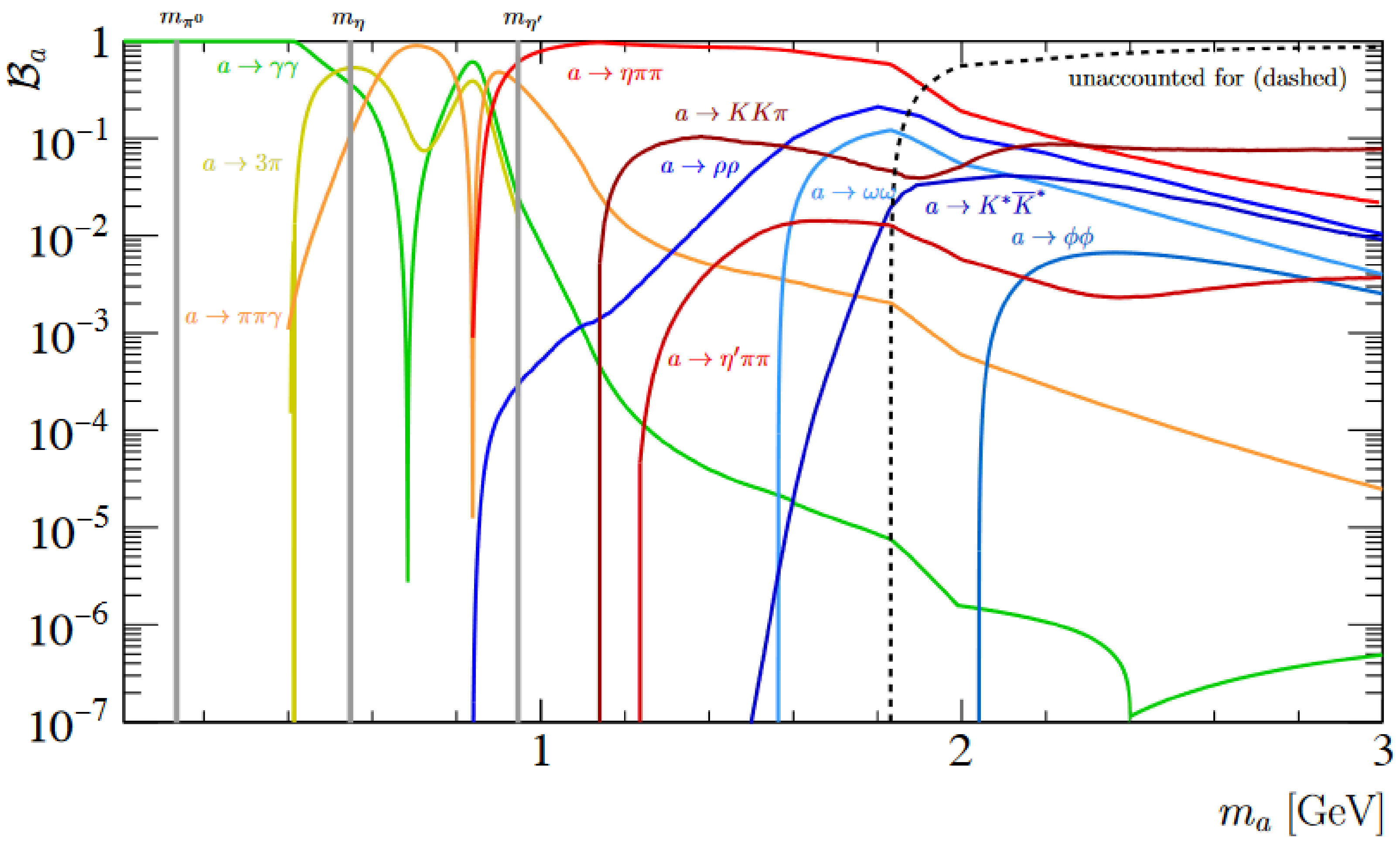
Plot of $\boldsymbol{A_0(q^2)}$ for $\boldsymbol{B_d \to K^*}$ Decays

$$BR(B^0 \to K^* a_0, a_0 \to \gamma\gamma) = \left(\frac{M_B^3}{16}|g_{abs}|^2 A_0^2(M_a^2)\lambda_{K^*a}^{\frac{3}{2}}\right)\tau_{B^0}\left(\frac{M_a^3\alpha}{\Lambda^2}\left|C_{eff}^{\gamma\gamma}\right|^2\right)\tau_{a_0}$$



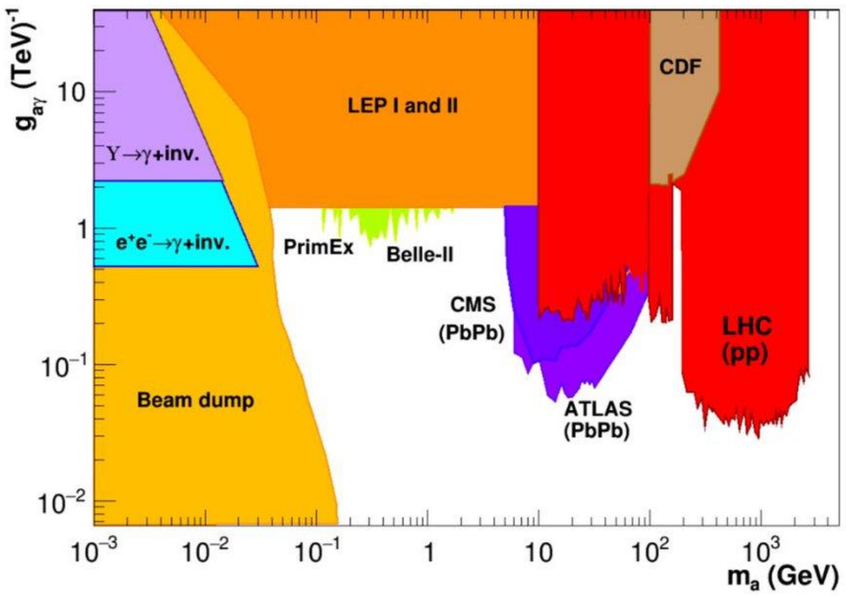
Source: https://arxiv.org/pdf/hep-ph/0412079.pdf

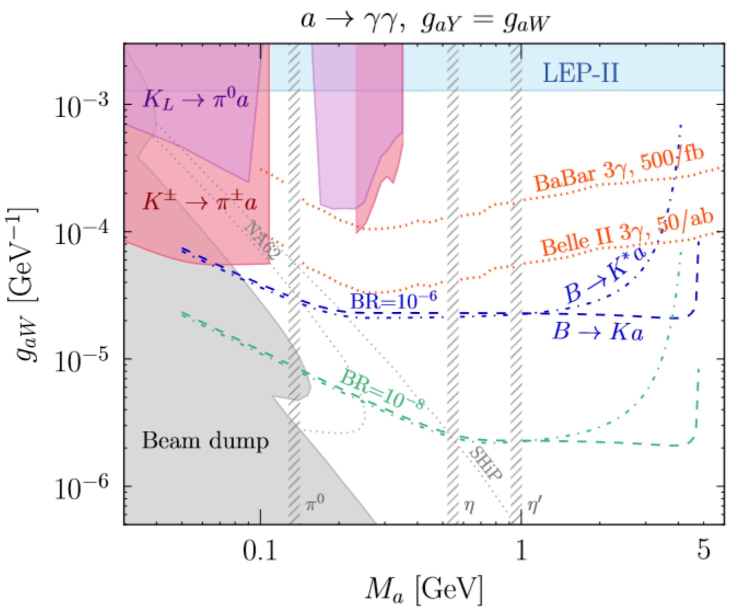
Plot of ALP Branching Fraction vs ALP Mass

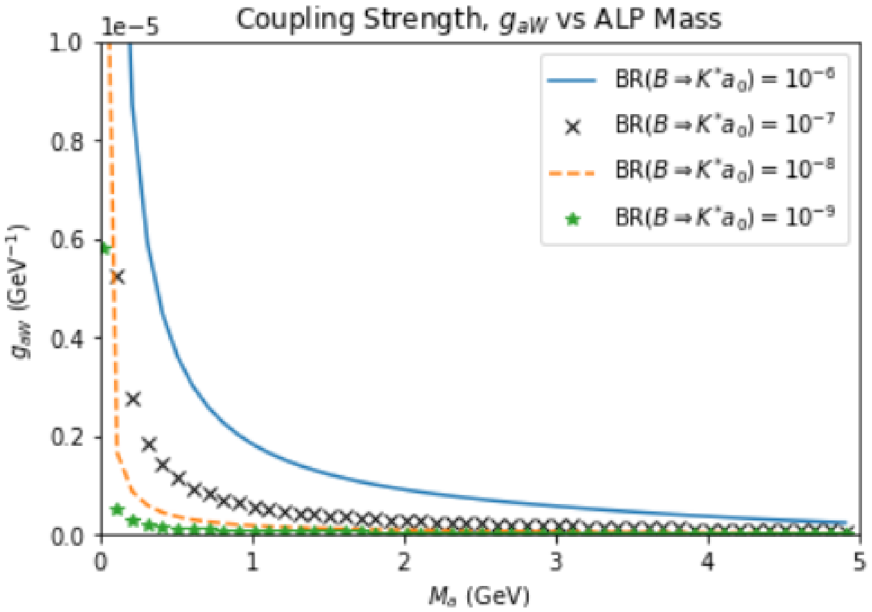


https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.123.031803/supplemental.pdf

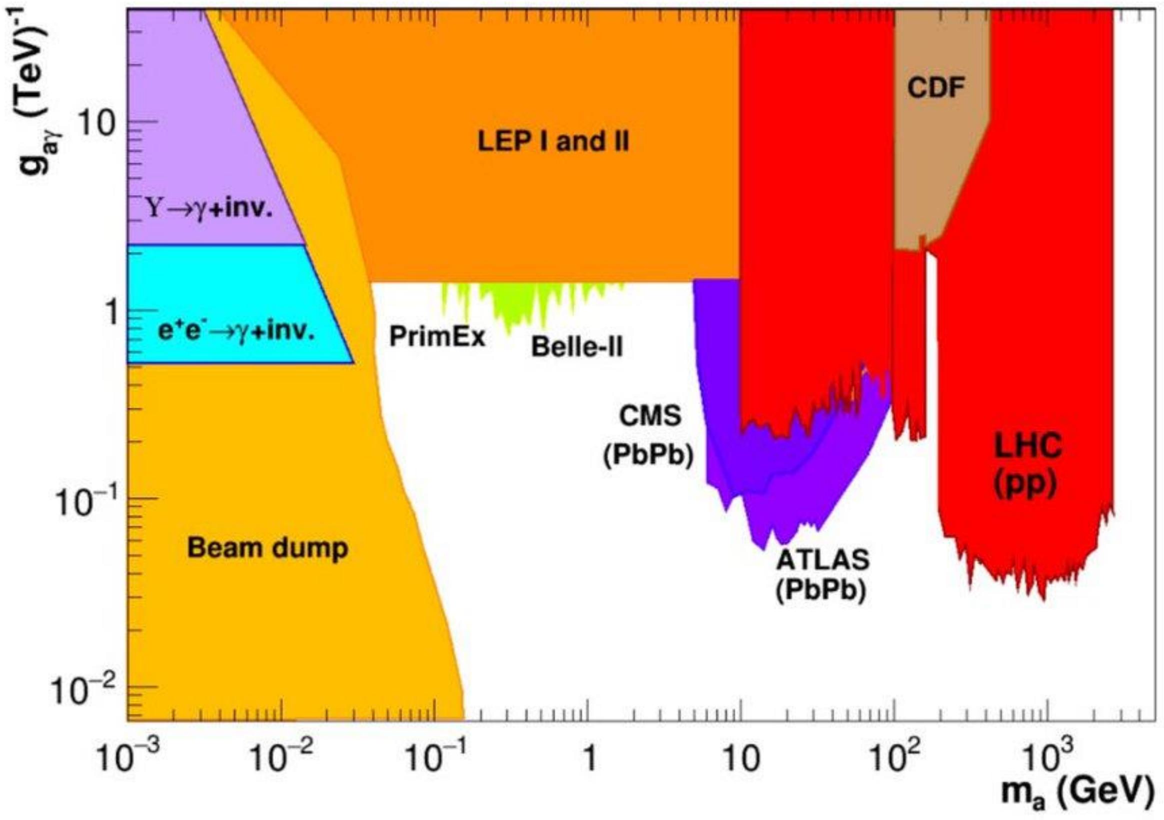
Coupling Strength vs ALP Mass (fixed Branching Ratio)

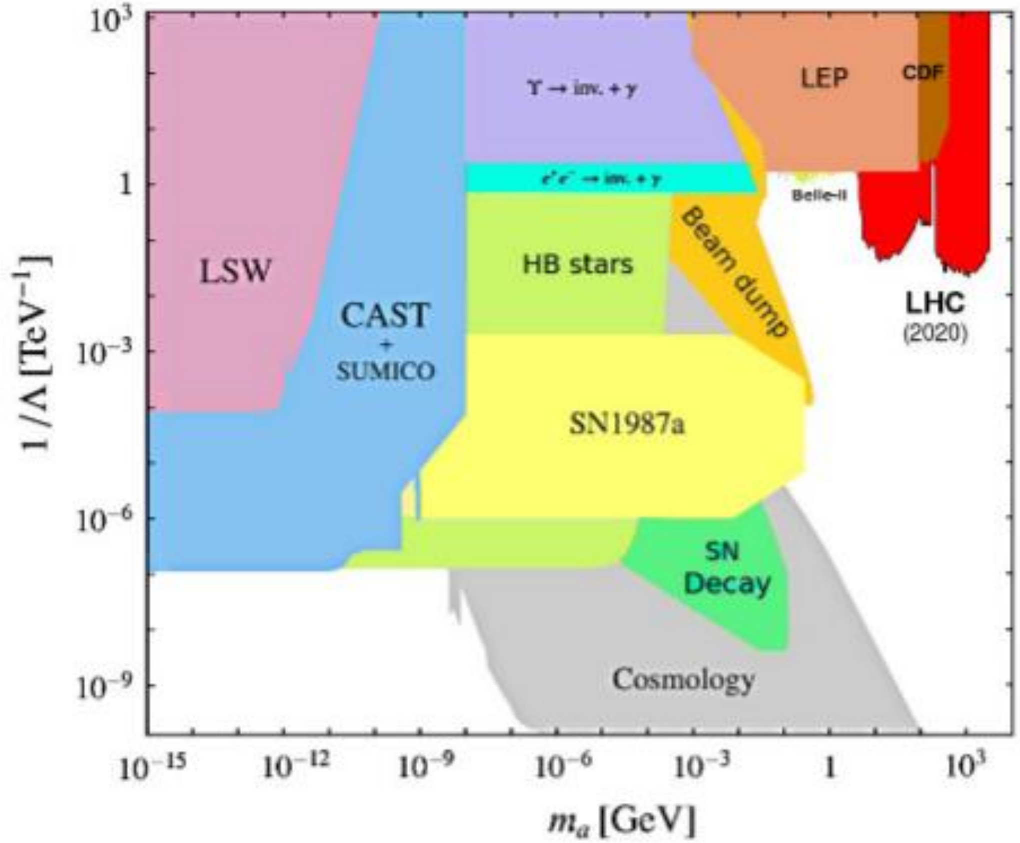






Summary of Mass and Coupling Constraints





Addendum: Upper Limit on Branching Ratio

- Compared the decay of interest to the following decay mode:
$$B^0 \rightarrow K^+\pi^-\pi^0$$
- Take $\int L\, dt = 9 \text{ fb}^{-1}$
- Take number of background events in decay of interest = 2475 (same as decay mode for comparison).
- Num of signal events in comparison decay mode = 547

$$\frac{S}{\sqrt{(S+B)}} = 1.64$$
$$\Rightarrow S \approx 85$$
$$\Rightarrow \#signal = \frac{9}{1} \times \frac{BR}{10^{-5}}(547) = 85$$
$$BR \approx 10^{-7}$$

Source: https://cds.cern.ch/record/1555739/files/CERN-THESIS-2013-051.pdf