Seeking axion-like particles through flavor observables

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Università degli Studi di Padova

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elusives
neutrinos, dark matter & dark energy physics

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Motivation

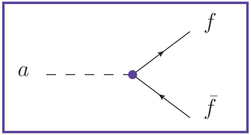
- The SM Higgs sector is the simplest possibility to accommodate experimental observations.
- Hierarchy, flavor and strong-CP problems remain unsolved.
- Maybe there exist more scalar states?
- What if these particles are lighter than $h(125)$?

  $\Rightarrow$ Renewed interest in light pseudoscalars (ALPs) in recent years.

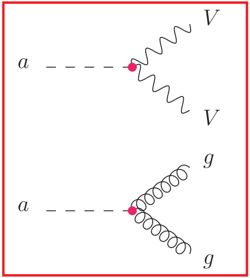
  $\Rightarrow$ Rich phenomenology at existing/planned experiments!

ALP $\equiv$ (light) pseudoscalar

...with derivative and/or anomalous couplings:



$$c_{aff}\,\frac{\partial_\mu a}{f_a}\,\bar{f}\gamma^\mu\gamma^5 f$$



$$c_V\,\frac{a}{f_a}\,V_{\mu\nu}\widetilde{V}^{\mu\nu}$$

$$c_G\,\frac{a}{f_a}\,G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$f_a \equiv$ scale of new physics

Light pseudoscalars

Why are they interesting?

They appear in many models beyond the SM:

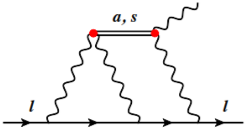
- Strong CP-problem, pNGB of a spontaneously broken symmetries, extensions of the Higgs sector (e.g. 2HDM, NMSSM), mediators to a hidden sector...

[See talks by Di Luzio, Soreq and Ziegler]

They can explain phenomenological puzzles:

- e.g. $(g-2)_\mu$ discrepancy.

[Marciano et al. '16]

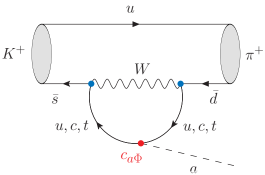


This talk: How can we **probe ALPs** in **flavor experiments**?

i) Flavor-changing probes of ALPs;

ii) ALP production via $e^+e^- \to \gamma a$ at B-factories.

FCNC constraints on ALP couplings



[Gavela, Houtz, Quilez, del Rey, **OS**. 1901.02031]

Our setup:

[Gavela, Houtz, Quilez, del Rey, **OS**. '19]

- Effective dim-5 Lagrangian: [Georgi et al. '86]

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{d=5} \supset & \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{m_a^2 a^2}{2} + c_{a\Phi}\, i \frac{\partial^\mu a}{f_a} \Phi^\dagger \overleftrightarrow{D}_\mu \Phi \\
& - c_G \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} - c_B \frac{a}{f_a} B_{\mu\nu} \widetilde{B}^{\mu\nu} - c_W \frac{a}{f_a} W^a_{\mu\nu} \widetilde{W}^{\mu\nu,a} + \dots\,,
\end{aligned}
$$

Our setup:

[Gavela, Houtz, Quilez, del Rey, **OS**. '19]

- Effective dim-5 Lagrangian: [Georgi et al. '86]

$$\mathcal{L}_{\text{eff}}^{d=5} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{m_a^2 a^2}{2} + c_{a\Phi}\, i \frac{\partial^\mu a}{f_a} \Phi^\dagger \overleftrightarrow{D}_\mu \Phi$$
$$- c_G \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} - c_B \frac{a}{f_a} B_{\mu\nu} \widetilde{B}^{\mu\nu} - c_W \frac{a}{f_a} W^a_{\mu\nu} \widetilde{W}^{\mu\nu,a} + \dots\,,$$

- $c_{a\Phi}$ is equivalent to Yukawa-like interactions:

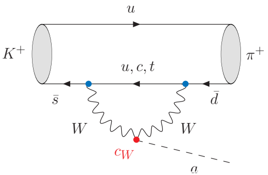
$$c_{a\Phi}\, i \frac{\partial^\mu a}{f_a} \Phi^\dagger \overleftrightarrow{D}_\mu \Phi \longrightarrow c_{a\Phi}\, i \frac{a}{f_a} \Big[\overline{Q}\, Y_u \widetilde{\Phi}\, u_R - \overline{Q}\, Y_d \Phi\, d_R - \overline{L}\, Y_\ell \Phi\, \ell_R \Big] + \text{h.c.}$$

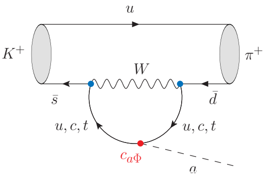
$\Rightarrow$ Flavor violation controlled by SM Yukawas!

- Working assumption: Derivative couplings to fermions neglected above – the loop effects from c_{att} are already described by $c_{a\Phi}$.

FCNC decays into ALPs: $K \to \pi a$, $B \to K a \ldots$

[Gavela et al. '19]





One-loop matching:

$$\mathcal{L}_{\text{eff}} \supset -g^a_{sd}\, (\partial_\mu a)\, \bar{s}\gamma^\mu P_L d$$

$$x_q = m_q^2 / m_W^2$$

FCNC decays into ALPs: $K \to \pi a$, $B \to K a \ldots$

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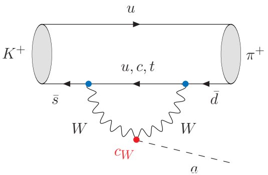
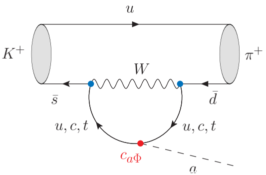




One-loop matching:

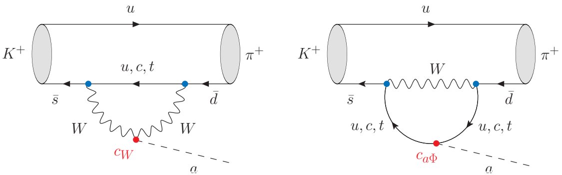
$$\mathcal{L}_{\text{eff}} \supset -g_{sd}^a \, (\partial_\mu a) \, \bar{s}\gamma^\mu P_L d$$

$$x_q = m_q^2/m_W^2$$

$$g_{sd}^a = g_w^2 \sum_{q=u,c,t} \frac{V_{qs} V_{qd}^*}{16\pi^2} \left[\frac{3\, c_W}{f_a} g(x_q) - \frac{c_{a\Phi}}{2\, f_a} x_q \log\left(\frac{f_a}{m_q}\right) \right]$$

FCNC decays into ALPs: $K \to \pi a$, $B \to K a \ldots$

[Gavela et al. '19]



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- c_W induces finite contributions – *GIM mechanism*. [Izaguirre et al. '16]

- $c_{a\Phi}$ contributions are logarithmically sensitive to f_a (in the $f_a \gg m_{\text{EW}}$ limit). For concrete models – e.g. 2HDM(+S):

  [Pich et al. '14], [Dror et al. '18], [Arnan, Becirevic, Mescia, **OS**. 1703.03426]...

ALP decays

$$\mathcal{L}_{\text{eff}}^{d=5} \supset -\, c_G \,\frac{a}{f_a}\, G_{\mu\nu}^{a} \widetilde{G}^{\mu\nu,a} - c_B \,\frac{a}{f_a}\, B_{\mu\nu} \widetilde{B}^{\mu\nu} - c_W \,\frac{a}{f_a}\, W_{\mu\nu}^{a} \widetilde{W}^{\mu\nu,a}$$
$$+\, c_{a\Phi}\, i\,\frac{a}{f_a}\left[\overline{Q}\, Y_u \widetilde{\Phi}\, u_R - \overline{Q}\, Y_d \Phi\, d_R - \overline{L}\, Y_\ell \Phi\, \ell_R\right] + \text{h.c.}$$

The relevant observables depend on ALP couplings, as well as possible interactions to a hidden sector.

We consider two benchmark scenarios: [Gavela et al. '19]

i) *Invisile* ALP: $\mathcal{B}(a \to \text{inv}) = 1.$

$\Rightarrow$ Observables: $K \to \pi + \text{inv},\ B \to K + \text{inv}.$

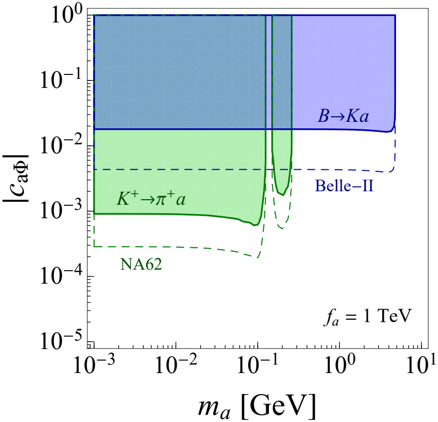
ii) *Visible* ALP: $a \to \gamma\gamma,\ \ell\ell$, and hadrons via c_{aW} and $c_{a\Phi}$.

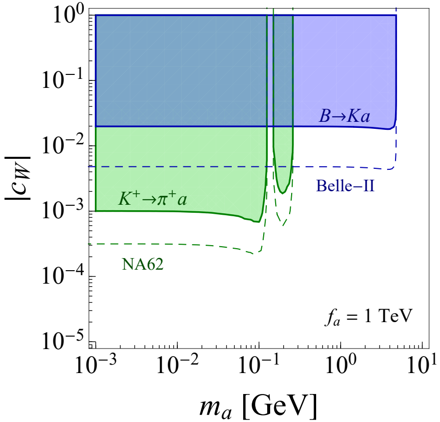
$\Rightarrow$ Observables: $K \to \pi\, a(\to ee, \mu\mu, \gamma\gamma),\ B \to K a(\to ee, \mu\mu, \gamma\gamma)$...

I. The invisible scenario

$\mathcal{B}(a \to \text{inv}) = 1$

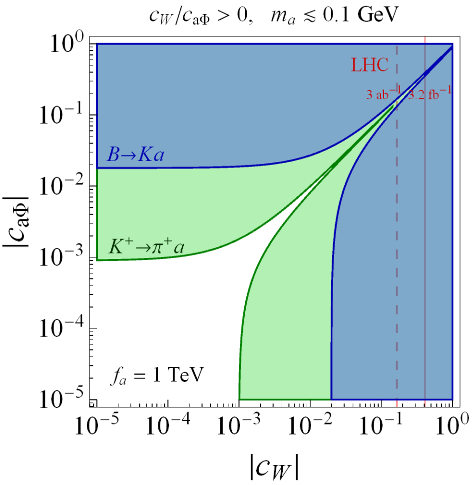
[Gavela, Houtz, Quilez, del Rey, **OS**. '19]





see also [Izaguirre.'16]

- Most stringent limits come from $K \to \pi\nu\bar{\nu}$ searches [E787, E949].
- What if $\{c_{a\Phi}, c_{aW}\}$ are simultaneously considered?



For fixed ALP mass:

- Unconstrained direction in $\{c_W, c_{a\Phi}\}$ for both $K \to \pi a$ and $B \to Ka$.

$\Rightarrow$ Other exp. constraints are needed!

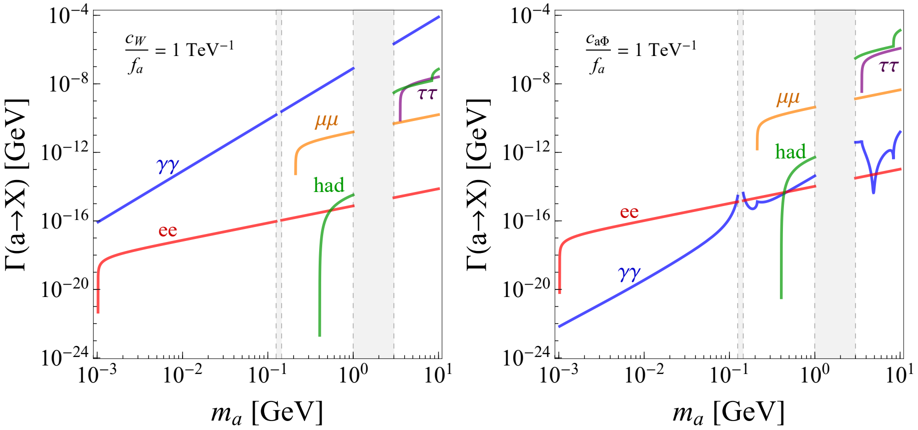
- Example: mono-W at the LHC

[Brivio et al. '17]

see also [Bauer et al. '17]

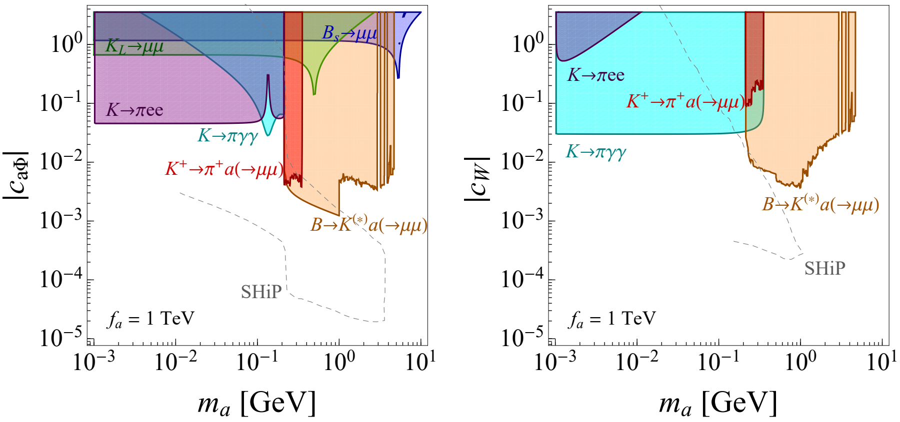
$\Rightarrow$ Other flavor observables can be helpful too! [2nd part of this talk!]

ALP decays induced by $c_{a\Phi}$ and c_W: see also [Bauer et al. '17]



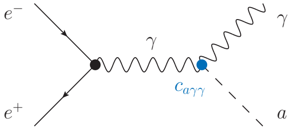
$\Rightarrow$ Many possible exp. signatures depending on m_a and $\{c_{a\Phi}, c_W\}$.

See talk by Soreq for $\Gamma(a \to \text{had})$ in $m_a \in (1,3)$ GeV.



- Most stringent limits come from LHCb searches for displaced vertices in $B \to K^{(*)} a(\to \mu\mu)$ [LHCb. '15, '16] see also [Dobrich et al. '18].
- Complementarity between K and B-meson decays. Opportunities for fixed-target facilities [e.g. SHiP]. [cf. back-up for two-coupling analysis]

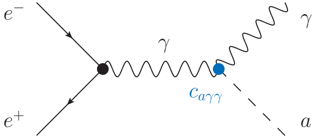
Revisiting ALP production at B-factories



[Merlo, Pobbe, Rigolin, **OS**. To appear]

What else can be done in flavor experiments?

ALPs can be produced in e^+e^- colliders via



$$c_{a\gamma\gamma} \equiv c_B \cos^2\theta_W + c_W \sin^2\theta_W$$

⇒ Direct probe of the ALP-photon coupling at low-energies.

⇒ Prospects for Belle-II explored in many works:

[Dolan et al. '18], [deNiverville et al. '18]...

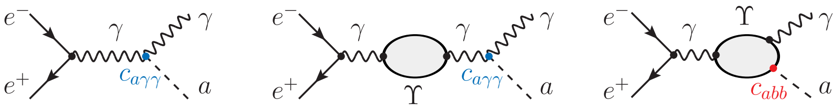
see also [Belle-II Physics Book]

Remainder of this talk:

⇒ Discuss the subtleties of these searches at B-factories.

What is different at B-factories?

B-factories operate at specific Υ resonances $\sqrt{s} = m_{\Upsilon(nS)}$:



i) How important are the resonant contributions?

ii) Working at $\sqrt{s} = m_{\Upsilon(nS)}$ allows us to probe another coupling:

$$\mathcal{L}_{\text{eff}}^{d=5} \supset c_{abb} \frac{\partial_\mu a}{2 f_a} \bar{b} \gamma^\mu \gamma_5 b \,.$$

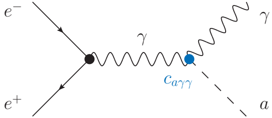
What is the interplay between $c_{a\gamma\gamma}$ and c_{abb}?

[NB. $c_{abb} = -c_{a\Phi}$ in the 1st part of this talk]

How large are the resonant contributions?

Non-resonant vs. resonant cross-section

- **Non-resonant**: [Marciano et al. '16, Dolan et al. '18]



$$\sigma(s)_{\text{non res.}} \propto \frac{c_{a\gamma\gamma}^2}{f_a^2}\left(1-\frac{m_a^2}{s}\right)^3 .$$

- **Resonant** (*naive Breit-Wigner*): [Merlo, Pobbe, Rigolin, **OS**. To appear]

$$\sigma(s)_{\text{res.}} = \sigma_{\text{peak}} \frac{m_\Upsilon^2\Gamma_\Upsilon^2}{(s-m_\Upsilon)^2+m_\Upsilon^2\Gamma_\Upsilon^2}\, \mathcal{B}(\Upsilon\to\gamma a)\,.$$

$\Rightarrow$ Effects overlooked so far in theory papers computing $\sigma(e^+e^-\to\gamma a)$.

To be careful: Non-negligible beam-energy uncertainty σ_W at B-factories

$\Rightarrow$ $\Gamma_{\Upsilon(nS)} \ll \sigma_W \approx 5~\mathrm{MeV}$ for $n = 1, 2, 3$.

$\Rightarrow$ Naive computation overestimates the resonant cross-section.

The **visible** resonant cross-section reads: [Eidelman et al. 1601.07987]

$$\langle \sigma_\mathrm{res} \rangle_\mathrm{vis} = \int \frac{\sigma_\mathrm{res}(s)}{\sqrt{2\pi}\sigma_W} \exp\left[-\frac{(\sqrt{s} - m_\Upsilon)^2}{2\,\sigma_W^2} \right] \mathrm{d}\sqrt{s}\,,$$

$$\overset{\Gamma_\Upsilon \ll \sigma_W}{=} \rho\,\sigma_\mathrm{peak}\,\mathcal{B}(\Upsilon(nS) \to \gamma a)\,,$$

where ρ is the cross-section suppression factor (for the narrow resonances):

$$\rho = \sqrt{\frac{\pi}{8}} \frac{\Gamma_\Upsilon}{\sigma_W} \approx 10^{-3}\,.$$

For scenarios with $|c_{a\gamma\gamma}| \gg |c_{abb}|$, the non-resonant contribution dominates, but the resonant one is non-negligible:

$\Upsilon(nS)$	Γ_Υ [keV]	σ_{peak} [nb]	ρ	$\langle\sigma_{\text{res}}\rangle_{\text{vis}}/\sigma_{\text{non res.}}$
$\Upsilon(1S)$	54.02	$3.9(18)\times 10^3$	6.1×10^{-3}	$\mathbf{0.53(5)}$
$\Upsilon(2S)$	31.98	$2.8(2)\times 10^3$	3.7×10^{-3}	$\mathbf{0.21(3)}$
$\Upsilon(3S)$	20.32	$3.0(3)\times 10^3$	2.3×10^{-3}	$\mathbf{0.16(3)}$
$\Upsilon(4S)$	20.5×10^3	2.10(10)	0.83	$3.0(3)\times 10^{-5}$

NB. $c_{abb}\equiv 0$.

⇒ Resonant contributions amount to $\mathcal{O}(10\%)$–$\mathcal{O}(50\%)$ corrections to σ_{tot}.

⇒ B-factories operating at $\Upsilon(4S)$ [i.e. above $B\overline{B}$ production threshold] can directly probe the non-resonant contribution.

Which searches can be performed at B-factories?

i) **Purely resonant**: $\Upsilon(1S)$ reconstructed from $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ or $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decays. cf. e.g. [BaBar, 1007.4646]

Direct probe of

$$\mathcal{B}(\Upsilon(1S) \to \gamma a) \times \mathcal{B}(a \to \dots) \propto \left[\frac{c_{a\gamma\gamma}}{f_a} \left(1 - \frac{m_a^2}{m_\Upsilon^2} \right) - 2 \frac{c_{abb}}{f_a} \right]^2 .$$

⇒ See [Wilczek. '77] for the computation of c_{abb} contribution, and [Masso. '95] for $c_{a\gamma\gamma}$.

⇒ We consider *both couplings*: possibility of *destructive interference*!

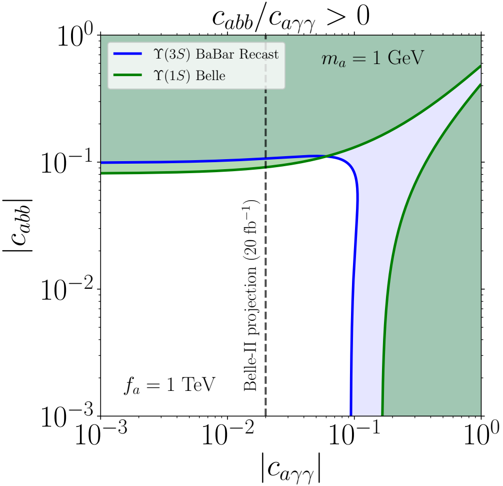
ii) **Purely non-resonant**: for $\sqrt{s} = m_{\Upsilon(4S)}$, the resonant contribution is negligible so one can directly probe $c_{a\gamma\gamma}$ ⇒ *No exp. searches thus far!*

iii) **Mixed (non-)resonant**: if $\Upsilon(nS)$ $(n = 1, 2, 3)$ is not reconstructed, then both resonant and non-resonant contributions become relevant. [cf. back-up]

Many searches at $\Upsilon(3S)$, cf. e.g. [BaBar, 0808.0017]

Illustration: Invisible scenario

- Complementarity: Unconstrained parameters from $\Upsilon(1S)$ decays [Belle, '18] are excluded by searches at $\Upsilon(3S)$ [BaBar, '08].



Caveat: background in $\Upsilon(3S)$ searches. [cf. back-up]

Summary and perspectives

Summary and perspectives

- FCNC observables provide the strongest constraints on ALPs in masses in the MeV-GeV range.

  NA62, LHCb and Belle-II.

- Effective operators can interfere destructively in $K \to \pi a$ and $B \to Ka$, leaving unconstrained regions in the parameter space.

  LHC and/or flavor observables might be helpful.

- Most general formulae for $e^+ e^- \to \gamma a$ at B-factories are provided, including resonant and non-resonant contributions, as well as general ALP interactions.

  Searches performed at different $\Upsilon(nS)$ resonances are complementary.

- Very rich data-set in existing/forthcoming flavor-physics experiments can be useful to test scenarios with light new physics states.

  High-precision era in flavor physics!

Thank you!

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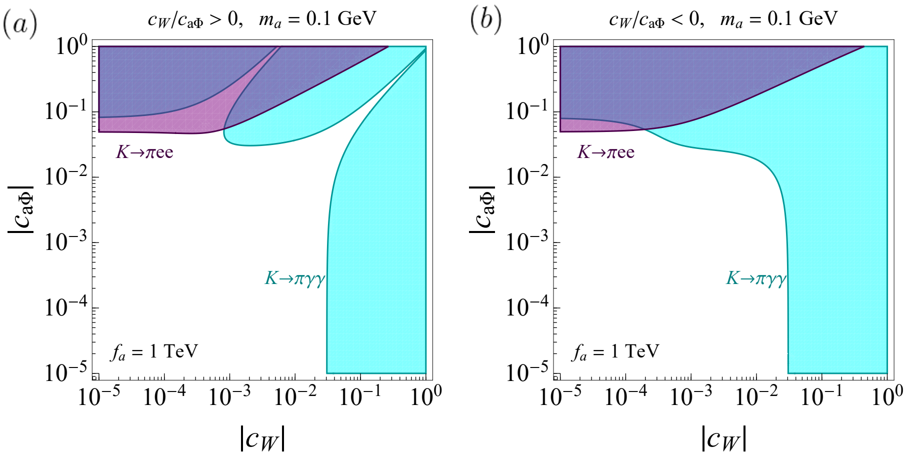
II. Visible scenario

[Gavela, Houtz, Quilez, del Rey, **OS**. '19]



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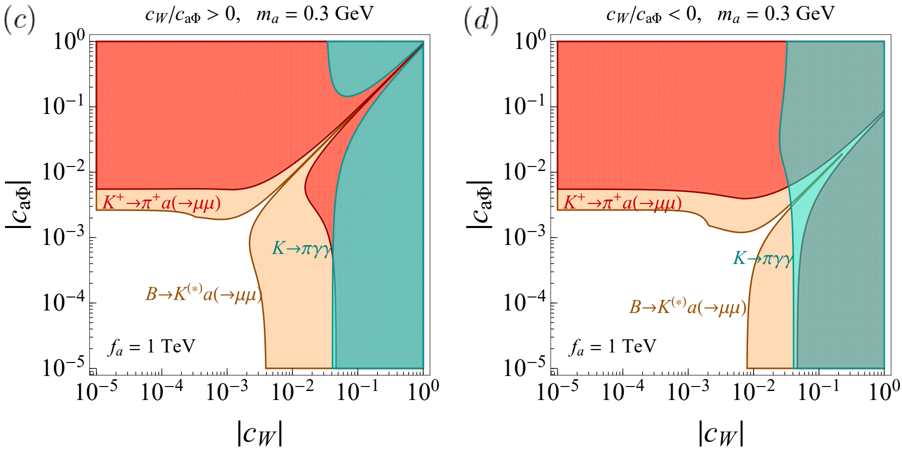
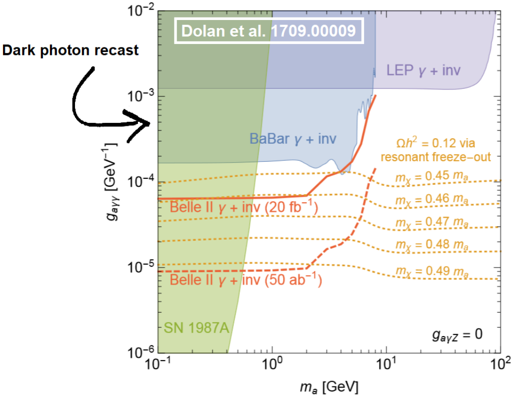
[Gavela, Houtz, Quilez, del Rey, **OS**. '19]



Comments on other analyses

BaBar dark-photon search in the mono-γ channel [BaBar. 1702.0332] has been recast by [Dolan et al. '18] $\Rightarrow \approx 2\times$ stronger constraints on $c_{a\gamma\gamma}$.



Interesting, but one should be careful:

- [BaBar. '17] combines data collected at different runs (resonant effects!?).
- Detection efficiencies are different for dark photons and ALPs [How much?].

On mixed (non-)resonant searches

- If the Υ decay is not reconstructed, both resonant and non-resonant contributions must be considered!

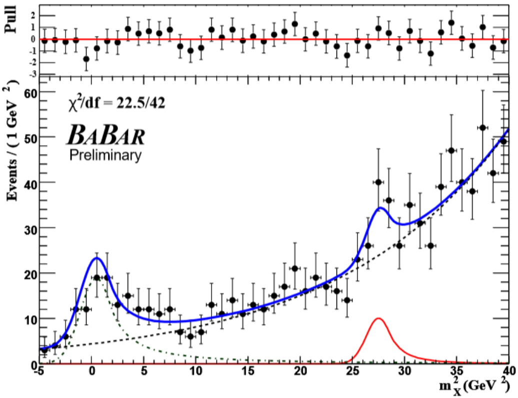
- e.g. for analyses at $\Upsilon(3S)$ [BaBar, 0808.0017], the limits on $\mathcal{B}(\Upsilon \to \gamma a)$ should be rescaled by a factor:

$$\frac{\langle \sigma_{\mathrm{res.}} + \sigma_{\text{non res.}} \rangle_{\mathrm{vis}}}{\langle \sigma_{\mathrm{res.}} \rangle_{\mathrm{vis}}} \approx 1 + \frac{\sigma_{\text{non res.}}}{\langle \sigma_{\text{res.}} \rangle_{\mathrm{vis}}} > 1$$

$\Rightarrow$ Limits on branching fraction are $\times$**7 more stringent** if $|c_{a\gamma\gamma}| \gg |c_{abb}|$!

$\Rightarrow$ Effects overlooked in theory papers, cf. e.g. [Cid Vidal et al. '18]

Small caveat: Background is often determined by using off-resonance samples, which contain the non-resonant contributions (peak in missing-mass distribution).



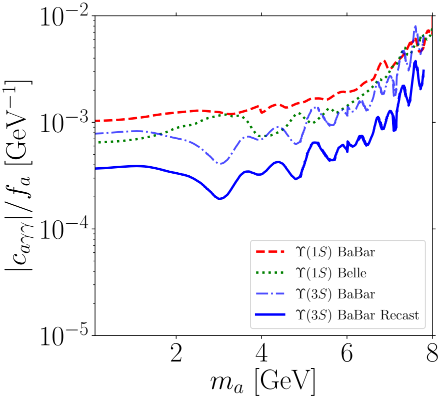
[BaBar. 0808.0017]

Figure 1: Sample fit to the high-energy dataset (122×10^6 $\Upsilon(3S)$ decays). The bottom plot shows the data (solid points) overlaid by the full PDF curve (solid blue line), signal contribution with $m_{A^0} = 5.2$ GeV (solid red line) $e^+e^- \to \gamma\gamma$ contribution (dot-dashed green line), and continuum background PDF (black dashed line). The top plot shows the pulls $p = (\text{data} - \text{fit})/\sigma(\text{data})$ with unit error bars.

[Merlo, Pobbe, Rigolin, **OS**. To appear]

Rescaled limits on $c_{a\gamma\gamma}$ from $\mathcal{B}(\Upsilon(3S) \to \gamma a) \times \mathcal{B}(a \to \mathrm{inv})$: **NB.** $c_{abb} \equiv 0$.

[BaBar, 0808.0017]



⇒ **More constraining** than limits from tagged $\Upsilon(1S)$ decays!

[BaBar, 1007.4646], [Belle, 1809.05222]

⇒ Similar conclusions apply to $\Upsilon(3S) \to \gamma a$, followed by $a \to \mu\mu$ [BaBar, 0905.4539], $a \to gg$ [BaBar, 1108.3549]...

$\Upsilon \to \gamma a$ in full generality

[Merlo, Pobbe, Rigolin, **OS**. To appear]

$$\mathcal{B}(\Upsilon \to \gamma a) = \frac{\alpha_{\rm em}}{216\,\Gamma_\Upsilon} m_\Upsilon f_\Upsilon^2 \left(1 - \frac{m_a^2}{m_\Upsilon^2}\right) \left[\frac{c_{a\gamma\gamma}}{f_a}\left(1 - \frac{m_a^2}{m_\Upsilon^2}\right) - 2\frac{c_{abb}}{f_a}\right]^2,$$

- $c_{a\gamma\gamma}$ contribution determined by decay constant (LQCD and/or exp).
- c_{abb} contribution far more intricate – QCD-structure dependent emission. [Wilczek. '77]