Meson Decays in Invisibles ALPs

Workshop on the SM and Beyond 31/08/22 — Corfu

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Mainly based on:
Merlo, Pobbe, Rigolin, Sumensari: JHEP, 06:091, 2019
Guerrera, Rigolin: Eur. Phys. J. C, 82(3):192, 2022
Gallo, Guerrera, Penaranda, Rigolin: Nucl. Phys. B, 979:115791, 2022
Guerrera, Rigolin: arXiv:22xx.xxxx (in preparation)

HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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- **Why Axion Like Particles (ALPs)?**
  - ALPs as (p)NGBs of a U(1) global symmetry breaking;
- **The ALP-Fermion Effective Lagrangian:**
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- **Meson Decays into Invisible ALPs:**
  - Hadronic Decays: $M \to M' \, a$ (i.e. $K \to \pi \, a$);
  - Leptonic Decays: $M \to \ell \, \nu_\ell \, a$ (i.e. $K, B \to \mu \, \nu_\mu \, a$);
  - Radiative Decays: $M \to \gamma \, a$ $\left(\text{i.e. } \Upsilon(ns) \to \gamma \, a\right)$;
- **Summary & Outlook**

Why Axion Like Particles ?

- Axion SOLUTION to the strong CP—problem:
  - Extend the SM with (at least) an extra scalar field endowed with a $U(1)_{PQ}$ global symmetry;
  - Spontaneous symmetry breaking (non linearly realised) at a scale $f_a \gg v_{EW}$ (invisible axions KSVZ, DFSZ). The only physical d.o.f. at low energy is the (p)NGB;
  - Through the axial anomaly an effective coupling with (at least) gluons are generated: $(a/f_a)\, Tr[G^{\mu\nu}\tilde{G}_{\mu\nu}]$
  - QCD non perturbative effects force the p(NGB) to take a vev (solution of strong CP problem) and a mass:

$$\boxed{\bar{\theta} = \theta + \frac{\langle a \rangle}{f_a} = 0}$$

$$\boxed{m_a f_a \approx m_\pi f_\pi}$$

Why Axion Like Particles ?

- Spontaneously broken global $U(1)$ symmetries are a common feature of many BSM frameworks;
- Many different HIERARCHY problems may be solved introducing an "AXION-LIKE PARTICLE":
  - Cosmology and Axion Inflation, Relaxion and EW Hierarchy, Flaxion and Flavour Symmetry;
- AXION vs ALPs: relation between m_a and f_a a;
  - AXION = fixed by QCD relations:

    $(10^{-7} \lesssim m_a \lesssim 1)$ eV and $(10^7 \lesssim f_a \lesssim 10^{12})$ TeV;
  - ALPs = free relation

    $m_a \sim$ GeV and $f_a \sim$ TeV can be considered;

The ALP—Fermion Effective Lagrangian

- The Dimension 5 Effective Lagrangian describing the interaction between ALP and SM particles (EW scale):

$$\delta\mathcal{L}_{\rm eff} = -\frac{c_G}{4}\frac{a}{f_a}G_a^{\mu\nu}\widetilde{G}^a_{\mu\nu} - \frac{c_B}{4}\frac{a}{f_a}B^{\mu\nu}\widetilde{B}_{\mu\nu} - \frac{c_W}{4}\frac{a}{f_a}W^{\mu\nu}\widetilde{W}_{\mu\nu}$$

$$\boxed{-\frac{\partial_\mu a}{2f_a}\left(\overline{Q}_L X_L\gamma^\mu Q_L + \overline{u}_R X_R^u\gamma^\mu u_R + \overline{d}_R X_R^d\gamma^\mu d_R\right) + c_{a\Phi}\frac{\partial_\mu a}{2f_a}\Phi^\dagger \overleftrightarrow{D}_\mu\Phi}$$

- Field dependent redefinition (y_i = hypercharge) induces shifts on DIM 5 operators (from kinetic terms):

$$\begin{cases} \Phi'(x) = e^{-i\,y_\Phi\,\alpha\frac{a(x)}{f_a}}\,\Phi(x) \\ \psi'_f(x) = e^{-i\,y_f\,\alpha\frac{a(x)}{f_a}}\,\psi_f(x) \end{cases} \qquad \begin{cases} \tilde{c}_{a\Phi} = c_{a\Phi} - 2\,y_\phi\,\alpha = 0 \\ \tilde{X}_{L,R} = X_{L,R} + 2\,y^f_{L,R}\,c_{a\Phi}\,\mathbb{I} \end{cases}$$

$c_{a\Phi}$ = universal ALP-fermion coupling

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$$\boxed{-\frac{\partial_\mu a}{2f_a}\left(\overline{Q}_L X_L\gamma^\mu Q_L + \overline{u}_R X^u_R\gamma^\mu u_R + \overline{d}_R X^d_R\gamma^\mu d_R\right) + c_{a\Phi}\cancel{\frac{\partial_\mu a}{2f_a}\Phi^\dagger \overleftrightarrow{D}_\mu\Phi}}$$

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$c_{a\Phi}$ = universal ALP-fermion coupling

The ALP—Fermion Effective Lagrangian

- In general, after EWSB, the effective ALP-fermions (quarks) couplings read: SMEFT-ALP running see Neubert talk

$$\boxed{-\frac{\partial_\mu a}{2f_a}\left\{\overline{U}(C_V^u + C_A^u\gamma_5)\gamma^\mu U + \overline{D}(C_V^d + C_A^u\gamma_5)\gamma^\mu D\right\}}$$

- It is customary to use the SM-fermion equations of motions and write the couplings in the "Yukawa basis":

$$\begin{aligned} i\frac{a}{2f_a}\Big\{&\overline{u}_i\big[(m_i - m_j)(C_V^u)_{ij} + (m_i + m_j)(C_A^u)_{ij}\gamma_5\big]\gamma^\mu u_j + \\ &+\overline{d}_i\big[(m_i - m_j)(C_V^d)_{ij} + (m_i + m_j)(C_A^d)_{ij}\gamma_5\big]\gamma^\mu d_j\Big\}\end{aligned}$$

leaving a total of $2 \times (6_V + 9_A) = 30$ independent couplings in the quark sector (+ 15 for charged leptons).

The ALP—Fermion Effective Lagrangian

In the spirit of MFV one can simplify the effective ALP-fermion Lagrangian to 6 (+3) independent couplings c_i :

$$i\,\frac{a}{f_a}\,c_i\,m_i\,\overline{\psi}_i\gamma_5\gamma^\mu\psi_i$$

- All Flavour Violating couplings will be loop-generated and controlled by CKM parameters;
- To obtain limits on flavour-violating tree-level couplings one can always rescale the results (loop + CKM factor);
- ☆ Flavour Factories are the main playground for studying ALP-fermions couplings for m_a in the KeV-GeV range;

Meson Decays into invisible ALP

- Mesonic decays into an invisible ALP are very clean channels for constraining ALP-fermion couplings:
  - Invisible ALP = long living ALP ($\tau_a \gtrsim 100$ ps) or decaying in an invisible sector (DM portal);
  - Very simple signature: missing energy/momentum;
- Three promising channels:

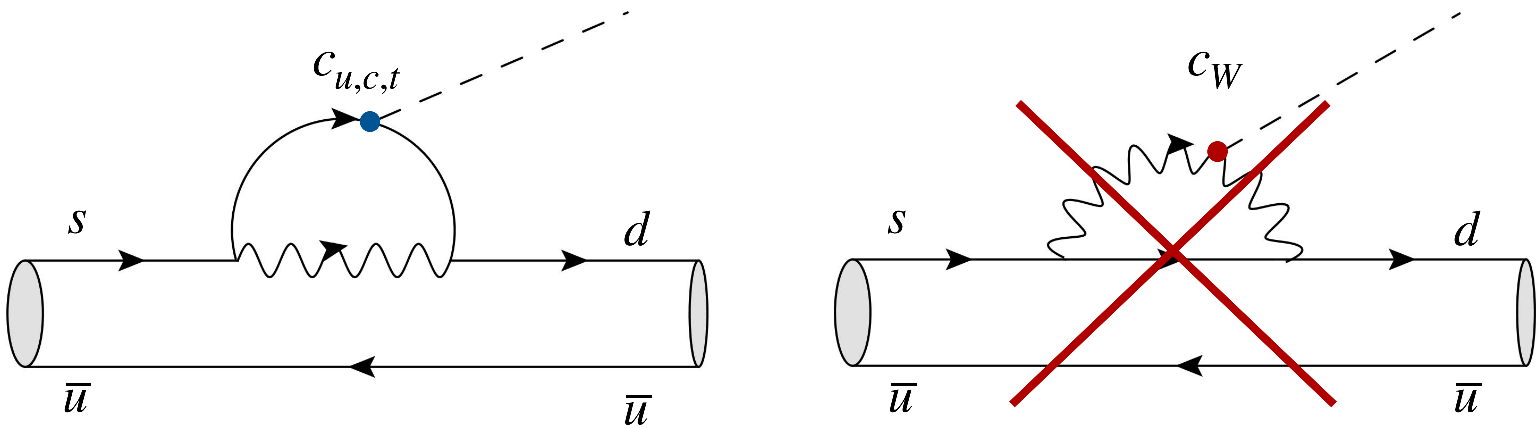
  i) Hadronic Decays: $M \to M' a$ (i.e. $K \to \pi a$, $B \to K a$);

  ii) Leptonic Decays: $M \to \ell \nu_\ell a$ (i.e. $K, B \to \mu \nu_\mu a$);

  iii) Radiative Decays: $M \to \gamma a$ $\left(\text{i.e. } \Upsilon(ns) \to \gamma a,\ B \to \gamma a\right)$;
- Visible ALP decays can be studied in a similar way (but in general suffer from a larger $1/f_a^2$ suppression);

i) Hadronic Meson Decays: $K \to \pi\, a$

- Penguins dominate the decay amplitude due to the top mass enhancement [Izaguirre et al 2017, Gavela et al. 2019]



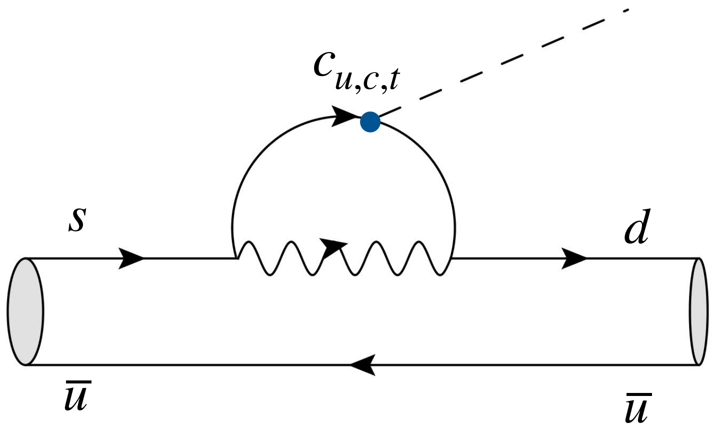
- Hadronization for penguin diagrams: LQCD [Carrasco et al 2016]

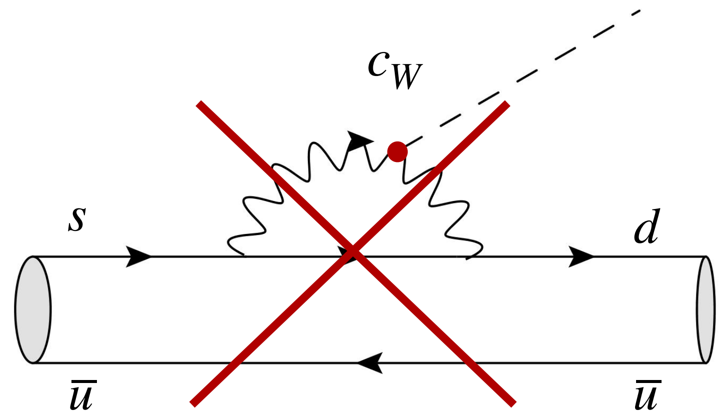
$$\langle \pi(p_\pi)|\bar{s}\gamma^\mu u|K(p_K)\rangle \equiv f_+(q^2)(p_K+p_\pi)^\mu + f_-(q^2)\,(p_K-p_\pi)^\mu$$

with $f_+(0) = f_0(0) = 0.9709\,(46)$ and a mild q^2 dependence

i) Hadronic Meson Decays: $K \to \pi\, a$

- Penguins dominate the decay amplitude due to the top mass enhancement [Izaguirre et al 2017, Gavela et al. 2019]



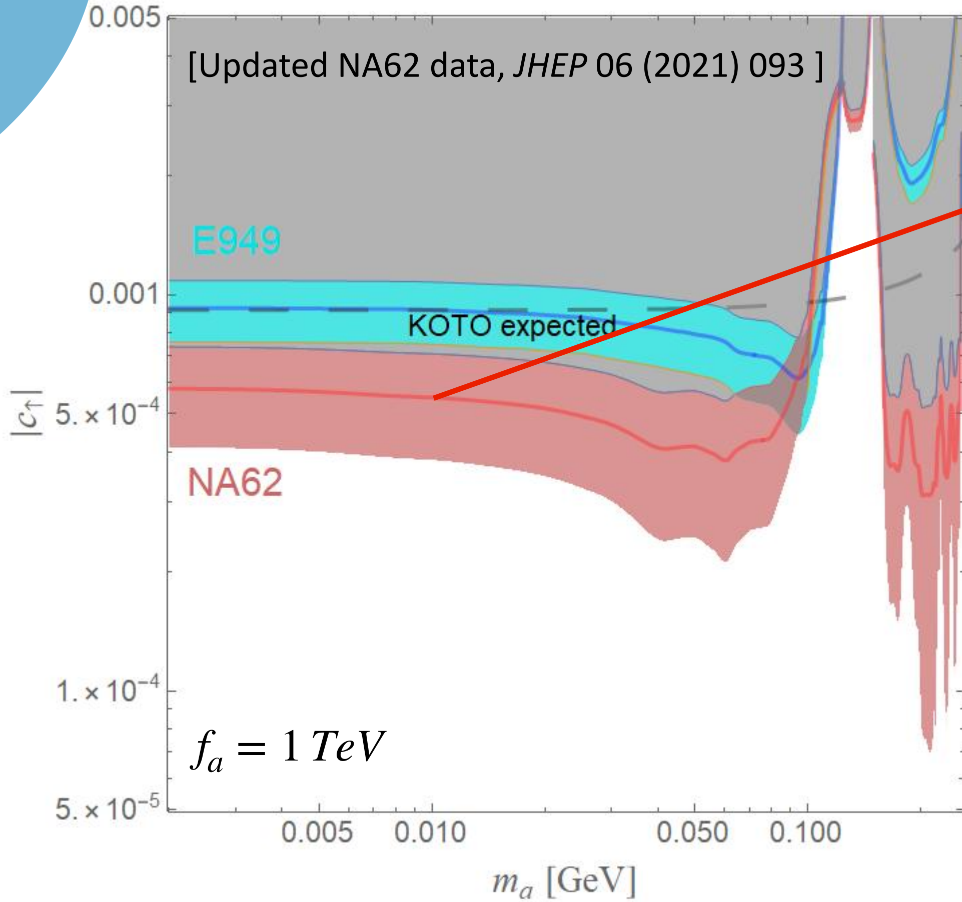


$$\mathcal{M}^L_{K^+} = \frac{G_F\, m_t^2}{4\sqrt{2}\pi^2}(V_{ts}V_{td}^*)\frac{M^2_{K^+}}{f_a}\left(1 - \frac{M^2_{\pi^+}}{M^2_{K^+}}\right)\left[f_+(m_a^2) + \frac{m_a^2}{M^2_{K^+} - M^2_{\pi^+}} f_-(m_a^2)\right]\sum_{q=u,c,t} c_{sd}^{(q)}$$

with $$c_{sd}^{(q)} = \frac{V_{qi}V_{qj}^*}{V_{ts}V_{td}^*}\left[\cancel{3\, c_W \frac{g(x_q)}{x_t}} - \frac{c_q\, x_q}{4\, x_t}\ln\left(\frac{f_a^2}{m_q^2}\right)\right] \qquad \left(x_q \equiv \frac{m_q^2}{M_W^2}\right)$$

i) Hadronic Meson Decays: $K \to \pi a$

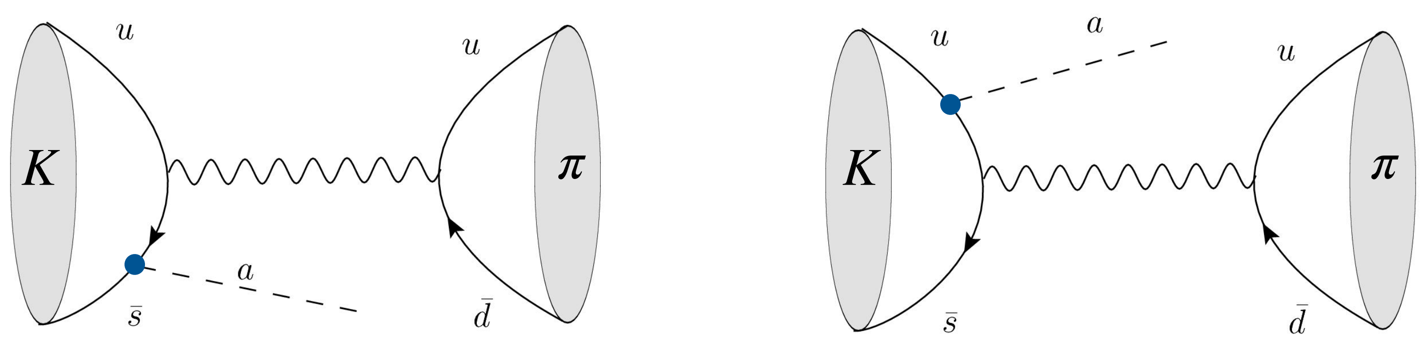
- Experiments provide strong limits on $c_{a\Phi} \approx c_t$ (charm contribution roughly 10%, $c_W = 0$) for all the m_a range:



$$c_{a\Phi} \lesssim 0.5 \times 10^{-4} \frac{f_a}{TeV}$$

i) Hadronic Meson Decays: $K \to \pi\, a$

- Tree–level diagrams can contribute to the decay. Are we sure they are (always) negligible?



- Similar diagrams with the ALP emitted from the π;
- The diagram with the ALP-W emission automatically vanishes due to the fully antisymmetric ALP-W vertex;
- One can estimate the hadronization form factors for tree-level diagrams applying the Brodsky-Lepage method;

i) Hadronic Meson Decays: $K \to \pi\, a$

- The hadronic part of the process (ALP emitted form the K meson) can be factorized as following:

$$\langle \pi | (\bar{u}\,\gamma^\mu P_L\, d) | 0 \rangle \, \langle 0 | (\bar{s}\,\Gamma_\mu\, u) | K \rangle$$

with the hard ALP-quark "hard" amplitude Γ_μ given by

$$\Gamma_\mu = \frac{4G_F}{\sqrt{2}} V_{us}^* V_{ud} \Big(\frac{c_s\, m_s}{f_a}\, \gamma_5\, \frac{\not{k}_a - \not{p}_{\bar{s}} + m_s}{m_a^2 - 2k_a \cdot p_{\bar{s}}} \gamma_\mu P_L \; - \; \frac{c_u\, m_u}{f_a}\, \gamma_\mu P_L\, \frac{\not{k}_a - \not{p}_u - m_u}{m_a^2 - 2k_a \cdot p_u}\, \gamma_5 \Big)$$

The hadronic matrix elements for π and K [Brodsky, Lepage 1980, Lepage, Brodsky 1981]

$$\langle 0 | \left(\bar{d}\,\gamma^\mu \gamma_5\, u | \pi \right) \rangle = i f_\pi\, p_\pi^\mu, \qquad \langle 0 | \left(\bar{d}\,\gamma^\mu\, u \right) | \pi \rangle = 0$$

$$\boxed{\langle 0 | \left(\bar{s}\,\Gamma^\mu\, u \right) | K \rangle = i f_K \int_0^1 dx\, \mathrm{Tr}\left[\Gamma^\mu \Psi_K(x) \right]} \qquad \begin{pmatrix} p_{\bar{s}} = x\, p_K \\ p_u = (1-x)\, p_K \end{pmatrix}$$

with x the fraction of momentum taken by the parton (s);

i) Hadronic Meson Decays: $K \to \pi a$

- The (pseudo-scalar) wave-function is defined in terms of two (phenomenological) functions $\phi_M(x)$, $g_M(x)$ [Brodsky, Lepage 1980, Lepage, Brodsky 1981]

$$\Psi_M(x) = \frac{1}{4}\phi_M(x)\gamma^5(\not{p}_M + g_M(x)M_M)$$

  - ☆ $\phi_M(x)$ describes the quark momentum distribution inside the meson;
  - ☆ $g_M(x)$ parameterizes the "bare" meson mass;

$$\phi_L(x) \propto x(1-x)$$

$$g_L(x) \approx 0$$

Light Meson ($m_u \sim m_d \approx 0$)
Symmetric Distribution

$$\phi_H(x) \propto \left[\frac{\xi^2}{1-x} + \frac{1}{x} - 1\right]^{-2}$$

$$g_H(x) \approx 1$$

Heavy Meson ($m_Q \gg m_q$)
Picked Distribution $\xi \approx m_q/m_Q$

i) Hadronic Meson Decays: $K \to \pi\, a$

- Following the BL approach one can estimate the tree-level contribution to the hadronic meson decay for an ALP emitted inside the K and π:

$$\mathcal{M}_{K^+} = \frac{G_F}{\sqrt{2}} (V_{us}^* V_{ud})\, f_K\, f_\pi\, (k_a \cdot P_\pi) \frac{M_K}{f_a} \times$$
$$\times \int_0^1 \left\{ \frac{c_s\, m_s\, \theta(x - \delta_a^K)}{m_a^2 - 2\, x\, k_a \cdot P_K} - \frac{c_u\, m_u\, \theta(1 - x - \delta_a^K)}{m_a^2 - 2\,(1-x)\, k_a \cdot P_K} \right\} \phi_K(x)\, g_K(x)\, dx$$

$$\mathcal{M}_{\pi^+} = \frac{G_F}{\sqrt{2}} (V_{us}^* V_{ud})\, f_K\, f_\pi\, (k_a \cdot P_K) \frac{M_\pi}{f_a} \times$$
$$\times \int_0^1 \left\{ \frac{c_d\, m_d\, \theta(x - \delta_a^\pi)}{m_a^2 - 2\, x\, k_a \cdot P_\pi} - \frac{c_u\, m_u\, \theta(1 - x - \delta_a^\pi)}{m_a^2 - 2\,(1-x)\, k_a \cdot P_\pi} \right\} \phi_\pi(x)\, g_\pi(x)\, dx$$

- Unphysical poles kinematically removed ($\delta_K = m_a/(2M_K)$)

i) Hadronic Meson Decays: $K \to \pi a$

- In the $m_a = 0$ limit, formulas looks quite simple.
  - K/π ratio: ALP mainly emitted from Kaon (after all ALPs couples through masses)

$$R_{\pi/K} = \left| \frac{\mathcal{M}_{\pi^+}}{\mathcal{M}_{K^+}} \right| \approx \left(\frac{g_\pi}{g_K} \right) \left(\frac{M_\pi}{M_K} \right)^2 \lesssim \left(\frac{M_\pi}{M_K} \right)^3 \simeq 0.01$$

  - Momentum distribution inside Kaon: Light or Heavy?

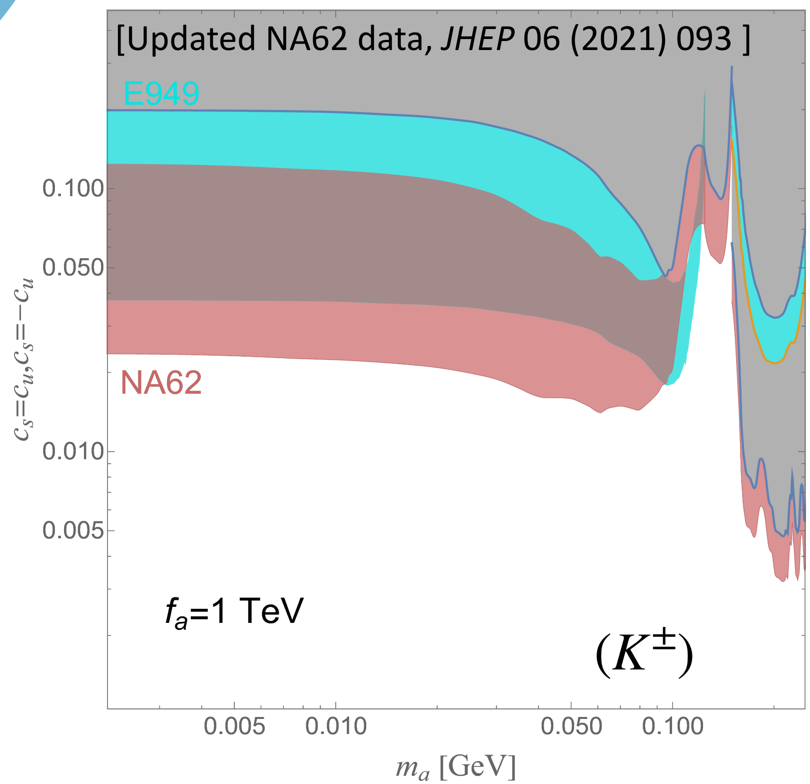
$$R^K_{L/H} = \left| \frac{\mathcal{M}^K_L}{\mathcal{M}^K_H} \right| \approx \frac{3}{2}$$

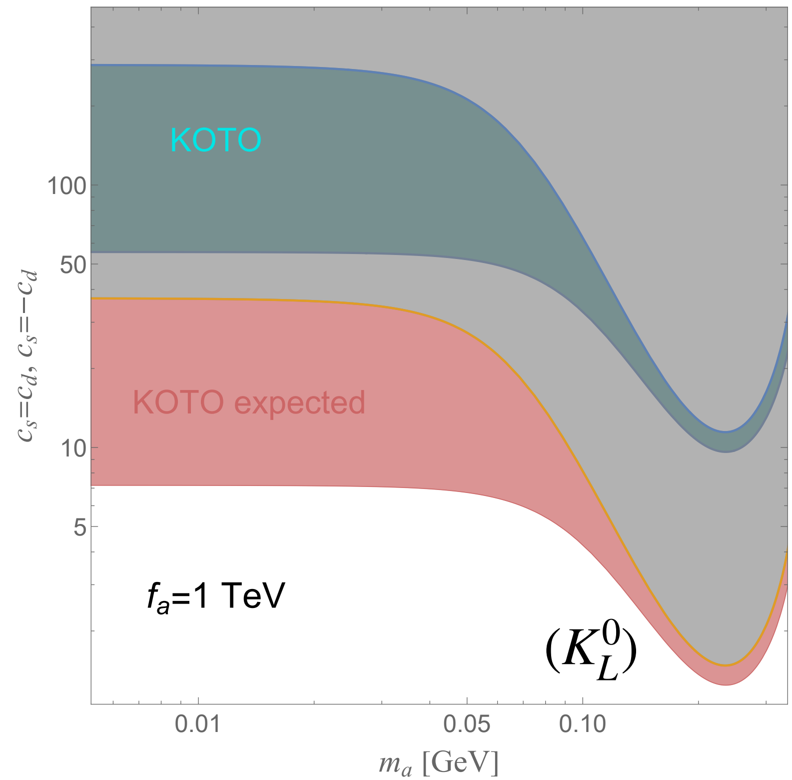
Most probably something in the middle:

$$\widehat{m}_u = m_u + \Lambda_K = \frac{M_K + m_u - m_s}{2}$$
$$\widehat{m}_s = m_s + \Lambda_K = \frac{M_K - m_u + m_s}{2}$$
$$\Longrightarrow \qquad \xi = \frac{\widehat{m}_u}{\widehat{m}_s} \approx \frac{M_K - m_s}{M_K + m_s}$$

i) Hadronic Meson Decays: $K \to \pi a$

- Tree-level diagrams provides sensitivity on ALP-light quark couplings: limits on c_s choosing $c_{u,d} = \pm c_s$ (with all the other ALP couplings set to 0)





i) Hadronic Meson Decays: $K \to \pi\, a$

- Tree-level vs one-loop comparison:
  - Tree-level vs penguin-loop ratio is small but yet not negligible:

$$R^K_{T/L} = \left| \frac{\mathcal{M}^T_{K^+}}{\mathcal{M}^L_{K^+}} \right| \approx 2\,\pi^2 \frac{f_K\, f_\pi}{m_t^2} \left| \frac{V^*_{us}\, V_{ud}}{V^*_{ts}\, V_{td}} \right| \simeq 0.01$$

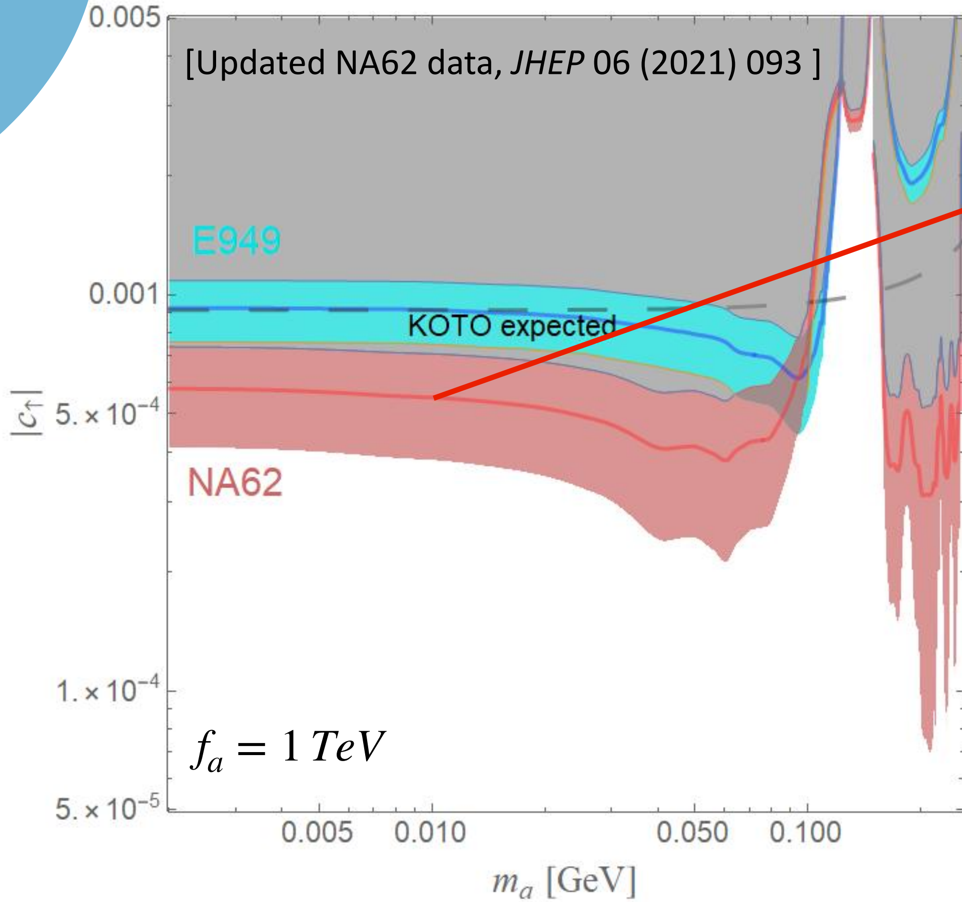
  - For the $K \to \pi\, a$ decay and in general for all down-type mesons the tree-level contribution is suppressed and can be neglected (in universal scenarios);
  - For up-type mesons one should care, for example:

$$R_{T/L}(B \to K\, a) \simeq R_{T/L}(B \to \pi\, a) \approx 10^{-6}$$

$$R_{T/L}(D \to K\, a) \simeq R_{T/L}(D \to \pi\, a) \approx 10$$

i) Hadronic Meson Decays: $K \to \pi a$

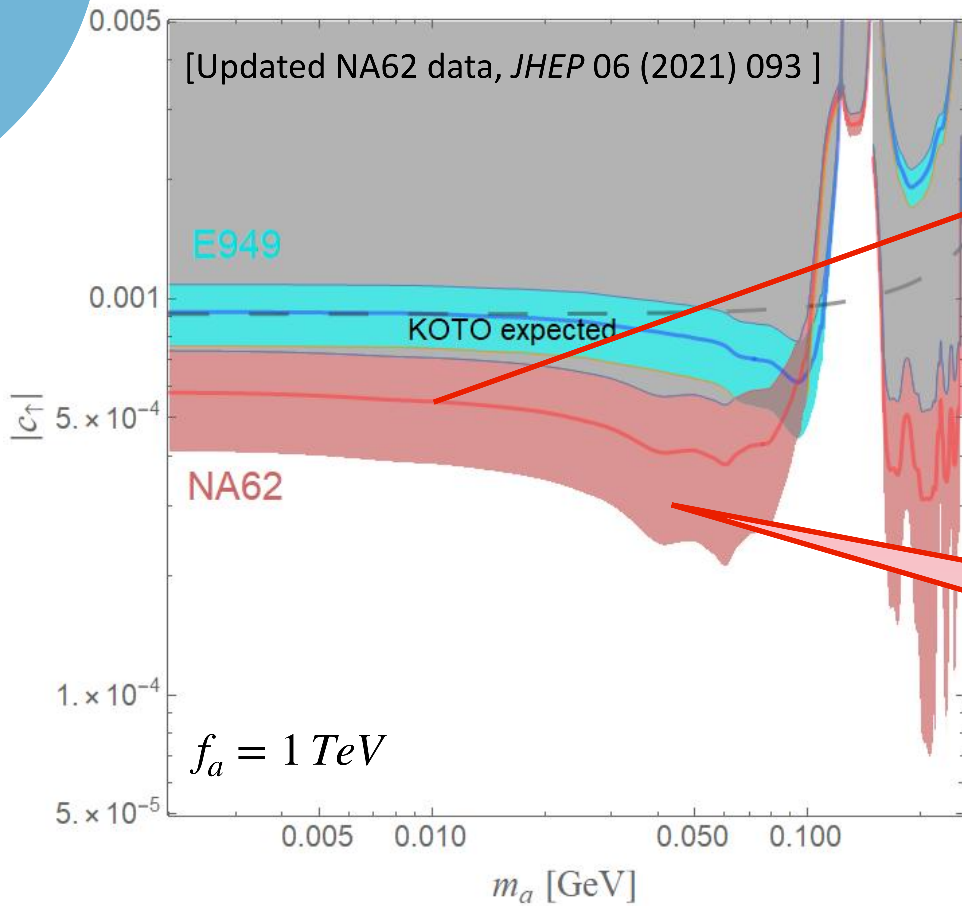
- In the non–universal scenario tree-level contributions can have a significant impact.



$$c_{a\Phi} \lesssim 5\times10^{-4}\frac{f_a}{TeV}$$

i) Hadronic Meson Decays: $K \to \pi\, a$

- In the non–universal scenario tree-level contributions can have a significant impact. A simple non-universal case:



$$c_{a\Phi} \lesssim 5 \times 10^{-4} \frac{f_a}{TeV}$$

$$c_t = c_c = c_u = c_\uparrow$$

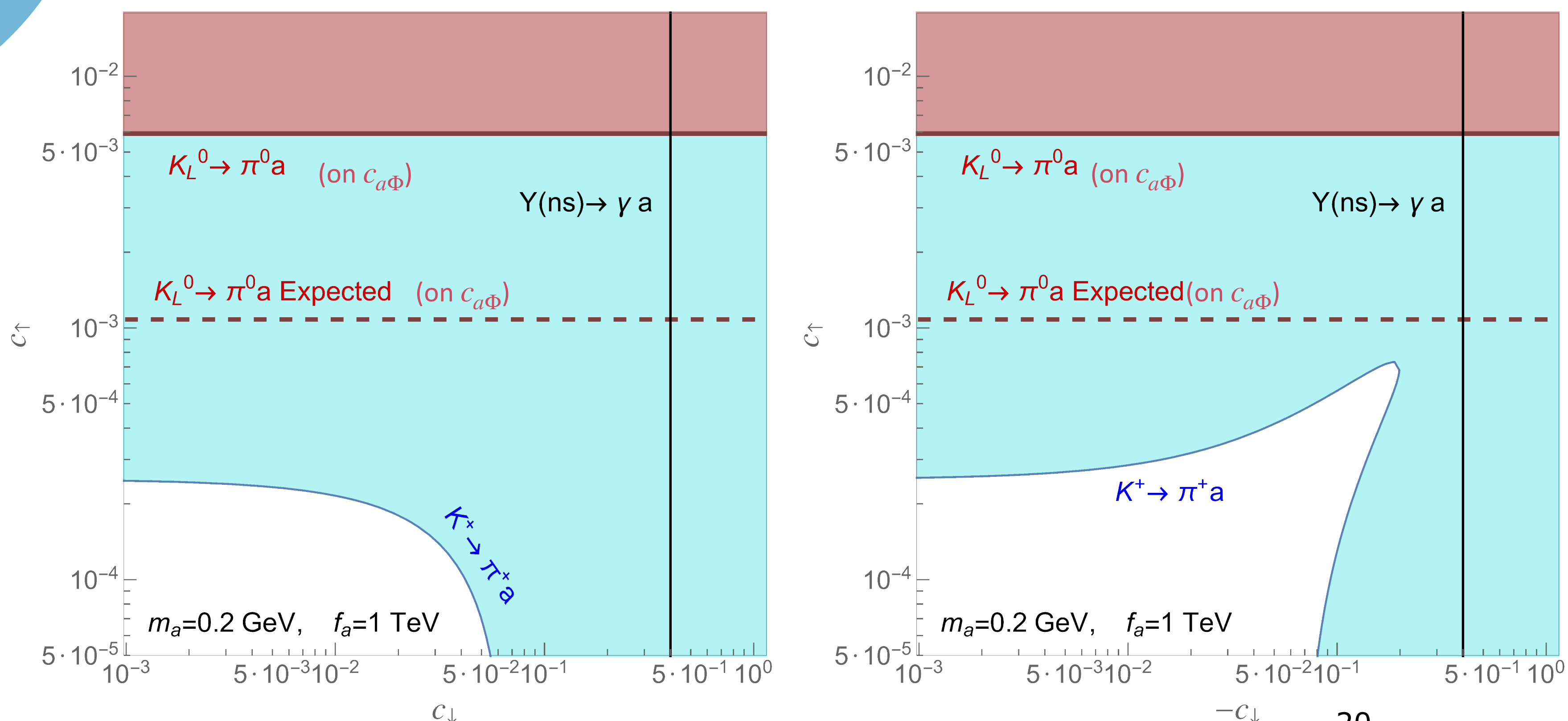
$$c_b = c_s = c_d = c_\downarrow$$

$$c_\downarrow \in (-0.05, +0.05)$$

$$c_\uparrow \lesssim [2, 8] \times 10^{-4} \frac{f_a}{TeV}$$

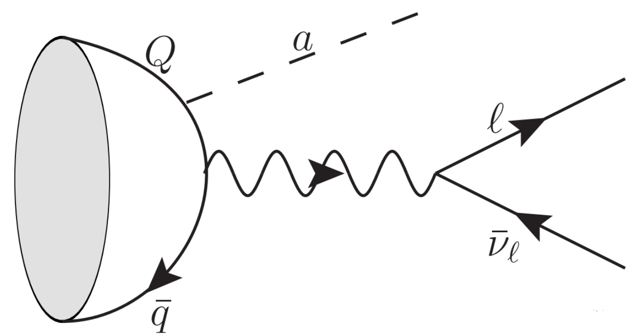
i) Hadronic Meson Decays: $K \to \pi\, a$

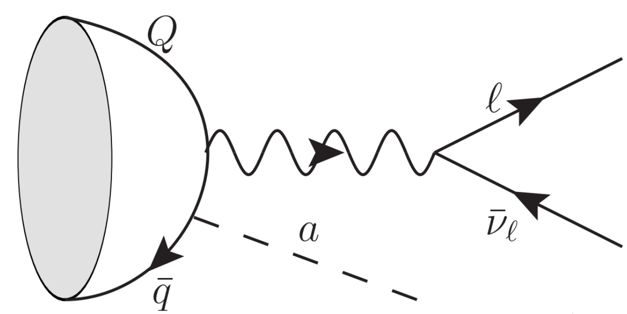
- Summary of two parameter $(c_\uparrow, c_\downarrow)$ fit for $m_a = 0.2$ GeV and $f_a = 1$ TeV. Bounds from $K_L^0 \to \pi^0 a$ (universal coupling) and $\Upsilon(ns) \to \gamma\, a$ decays are also shown.



ii) Leptonic Meson Decays in ALPs

- The analysis of leptonic meson decay in ALPs is very similar to the (tree-level) hadronic decays: [Aditya et al 2012 Guerrera et al 2021]





- The amplitude for a meson-emitted ALP reads:

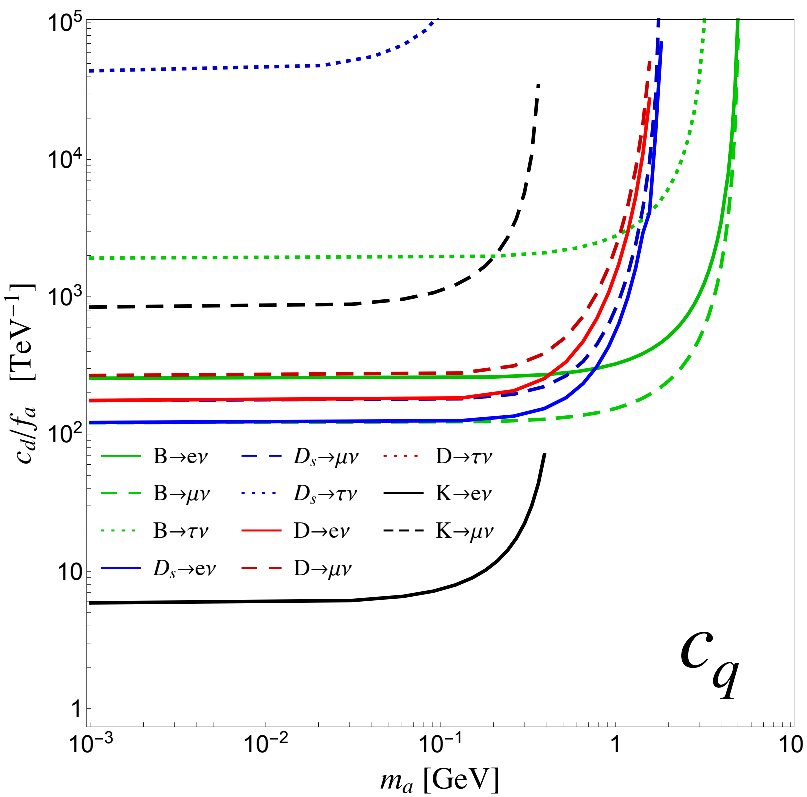
$$\mathcal{M}_h = \frac{4\,i\,G_F\,V_{qQ}}{\sqrt{2}}\,\frac{f_M}{f_a}\,\frac{M_M^2}{2\,p_a\cdot P_M}\left[c_Q\,\frac{m_Q}{M_M}\,\Phi_M^{(Q)}(m_a^2) - c_q\,\frac{m_q}{M_M}\,\Phi_M^{(q)}(m_a^2)\right]\left(\bar{\ell}\,\not{p}_a\,P_L\,\nu_\ell\right)$$

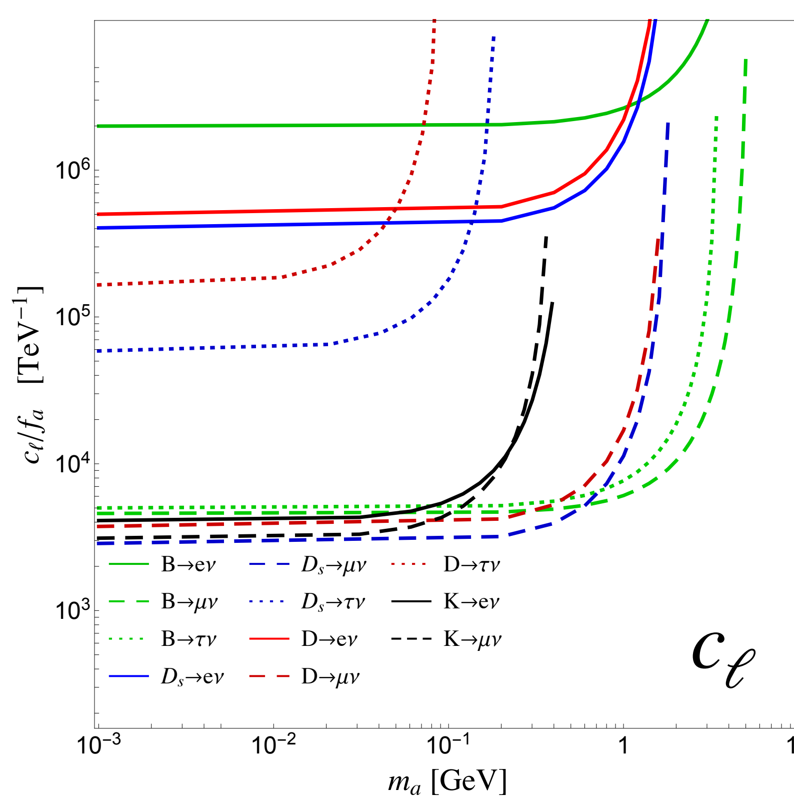
- The amplitude for a lepton-emitted ALP reads:

$$\mathcal{M}_\ell = -\frac{4\,i\,G_F\,V_{qQ}}{\sqrt{2}}\,\frac{f_M}{f_a}\left[c_\ell\,m_\ell\,\left(\bar{\ell}\,P_L\,\nu_\ell\right) - \frac{c_\ell\,m_\ell^2}{m_a^2 + 2\,p_a\cdot p_\ell}\left(\bar{\ell}\,\not{p}_a\,P_L\,\nu_\ell\right)\right].$$

ii) Leptonic Meson Decays in ALPs

- Lower sensitivity on ALP-quark couplings (vs. hadronic);
- Strongest available bounds on ALP-charged leptons couplings (for KeV $\leq m_a \leq$ few GeV);





iii) Radiative Meson Decays in ALPs

Meson radiative decays are also very clean signatures.

- Flavour Changing processes: $B^0 \to \gamma\, a$
  - The hadronization procedure is very similar to the one previously discussed for leptonic processes;
  - Preliminary results (shown in the summary table)
- Flavour Conserving processes: $\Upsilon(ns) \to \gamma\, a$ [Wilczek 1977]
  - Simplest case of BL procedure: the momentum distribution of a $b\,\overline{b}$ pair = 1/2;
  - Very interesting analysis (both theoretical and experimental implications);

iii) Radiative Meson Decays in ALPs

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Decays of Heavy Vector Mesons into Higgs Particles

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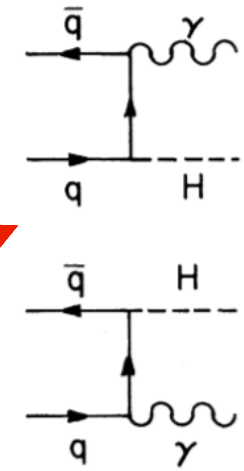
(Received 26 August 1977)

Estimates are presented for the decay of vector mesons composed of heavy quarks into states containing a Higgs boson. If the decays are kinematically allowed, they are probably experimentally accessible when the quark mass $m_q \gtrsim 4$ GeV.



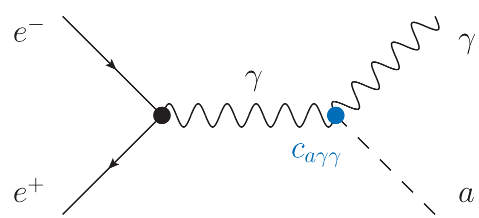
Resonant contribution = On-shell meson decay

- Resonant contributions provide a clear and direct access to ALP-quark couplings c_q ;
- Underlying assumption: negligible ALP-photon coupling c_γ (i.e. loop suppressed). Fine for independent limits on c_q .

iii) Radiative Meson Decays in ALPs

- At e^+e^- machines (BABAR and BELLE) both non-resonant and resonant contributions to ALP production can be in general present:
  - Several TH and EXP "interpretation" issues;

- Non-Resonant contribution to ALP production at e^+e^- collider is trivial and depend ONLY on c_γ:

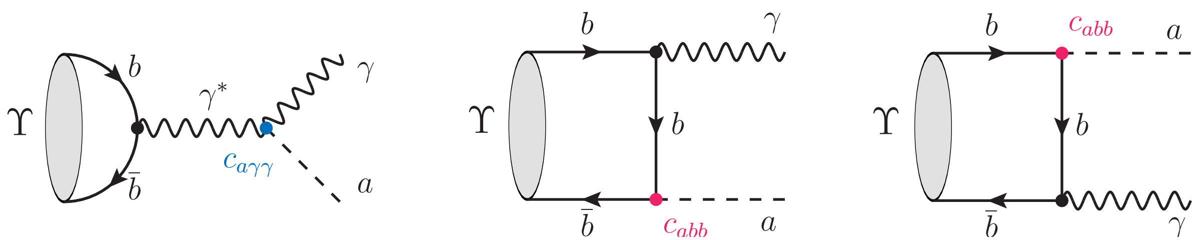


$$\sigma_{\rm NR}(s) = \frac{\alpha_{\rm em}}{24}\frac{c^2_{a\gamma\gamma}}{f_a^2}\left(1-\frac{m_a^2}{s}\right)^3$$

One may (naively) assume it's negligible w.r.t. resonant ones, if experiments are running at some $q\bar{q}$ resonance;

iii) Radiative Meson Decays in ALPs

- Resonant contributions to ALP production depend simultaneously on c_γ and c_q



In the Breit-Wigner approximation one has:

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

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

with the matrix element $\langle 0 | \bar{b}\gamma^\mu b | \Upsilon(p)\rangle = m_\Upsilon f_\Upsilon \varepsilon^\mu(p)$;

iii) Radiative Meson Decays in ALPs

Phenomenological analysis of $\Upsilon(ns) \to \gamma\, a$ is quite puzzling:

- $\Upsilon(1s,2s,3s)$ resonances are very narrow compared to BABAR/BELLE beam energy uncertainty ($\sigma_W \approx 5$ MeV);
- $\Upsilon(4s)$ very spread resonance (essentially no resonance). Analysis foreseen for BelleII;

$(c_b = 0)$

$\Upsilon(nS)$	Γ_Υ [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\langle\sigma_{\rm res}\rangle_{\rm vis}/\sigma_{\text{non res.}}$
$\Upsilon(1S)$	54.02			
$\Upsilon(2S)$	31.98			
$\Upsilon(3S)$	20.32			
$\Upsilon(4S)$	20.5×10^3			

iii) Radiative Meson Decays in ALPs

- The "visible" resonance contribution obtained by smearing and get reduced by a factor $\rho \approx 10^{-3}$ → subdominant;

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

[Eidelman et al. 1601.07987]

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

$$\boxed{\rho = \sqrt{\frac{\pi}{8}}\frac{\Gamma_\Upsilon}{\sigma_W} \sim 10^{-2} \div 10^{-3}}$$

$\Upsilon(nS)$	Γ_Υ [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\langle\sigma_{\rm res}\rangle_{\rm vis}/\sigma_{\text{non res.}}$
$\Upsilon(1S)$	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	$3.0(3)\times 10^{-5}$

iii) Radiative Meson Decays in ALPs

Which is cross-section to use? Resonant vs Non-Resonant?

- Experimental collaborations provide reconstructed vs non reconstructed (more often) $\Upsilon(ns)$ decays;
  - Reconstructed $\Upsilon(ns)$ decay: [Babar 1007.4646]

$$\Upsilon(2s) \to \Upsilon(1s)\,\pi^+\pi^-$$
$$\Upsilon(1s) \to \gamma\, a$$

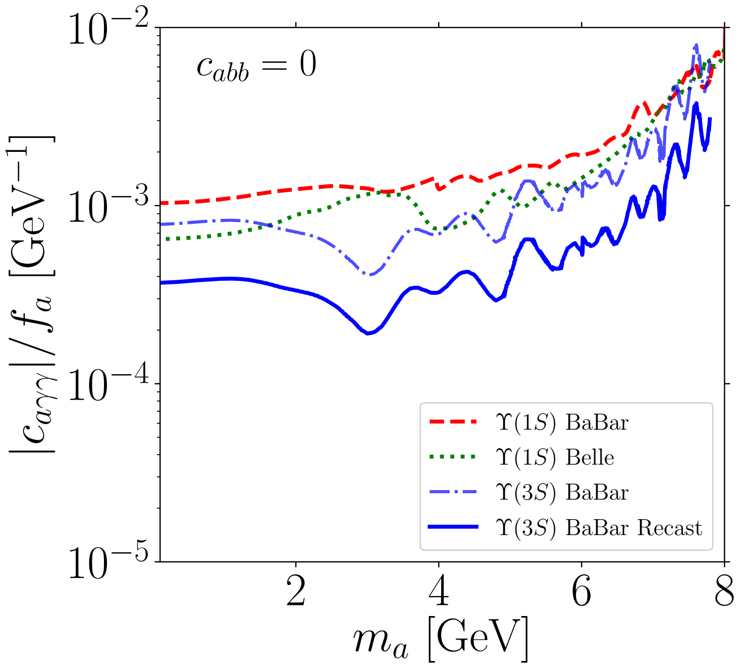
    Reconstructed = Resonant ONLY decay;
  - Non-Reconstructed $\Upsilon(ns)$ decays = Resonant + Non Resonant diagrams as one is integrating in the whole 5 MeV beam (not only in the 20-50 keV resonance);
- Some of the experimental provided $\mathscr{B}(\Upsilon \to \gamma\, a)$ need to be recasted as obtained by without the non-resonant term;

iii) Radiative Meson Decays in ALPs

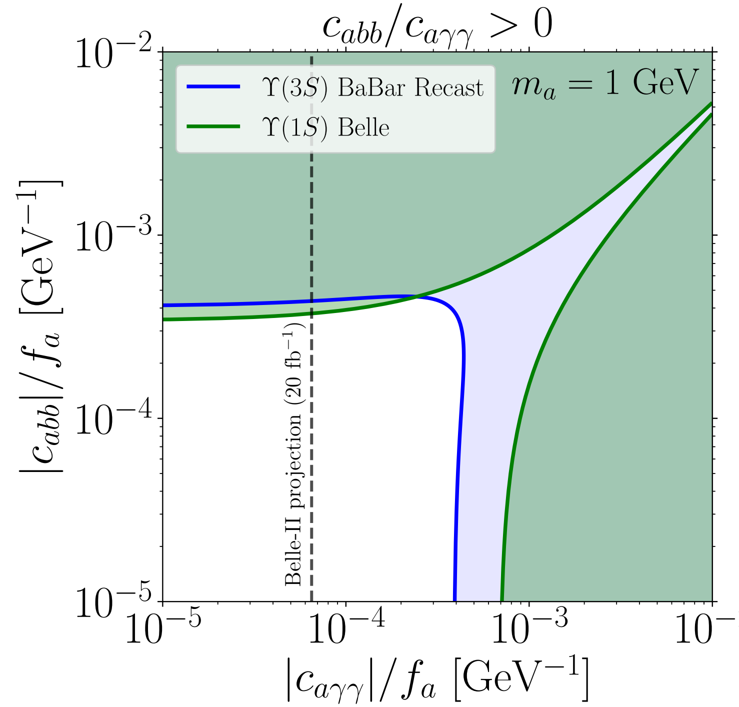
- Be careful in extracting (theoretical) information from $\Upsilon(ns)$. One cannot simply "average" different exp. data;

But there is a even more subtle (experimental) problem

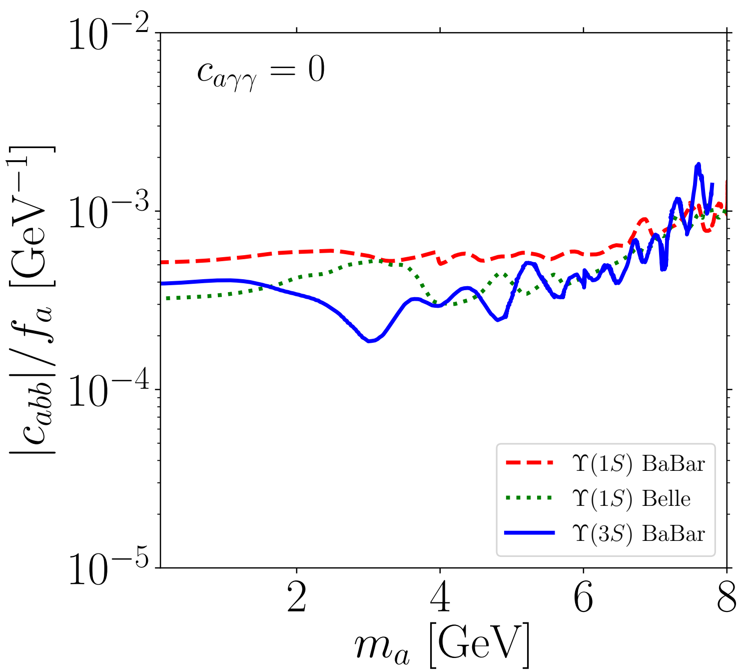
- Background: off-resonance data are subtracted from on-resonance one.
  - Assume implicitly that signal is ONLY resonant. But "Wilzcek-like" models are exceptions in Axion or ALPs frameworks;
  - As non-resonant contribution is typically larger than resonant one, this would cancel all the signal;
  - Alternative way to estimate background ?



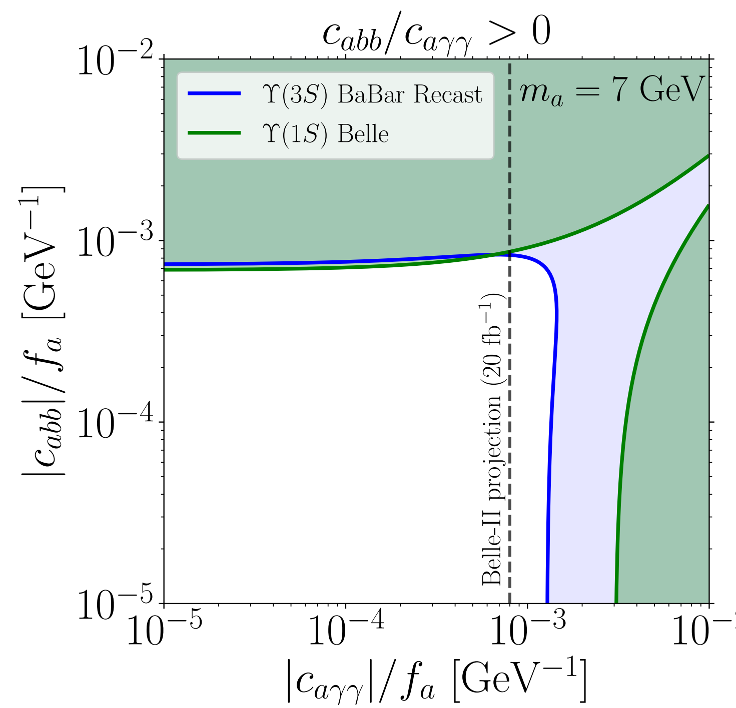
$c_{abb} = 0$
$|c_{a\gamma\gamma}|/f_a$ [GeV^{-1}]
m_a [GeV]
$\Upsilon(1S)$ BaBar
$\Upsilon(1S)$ Belle
$\Upsilon(3S)$ BaBar
$\Upsilon(3S)$ BaBar Recast



$c_{abb}/c_{a\gamma\gamma} > 0$
$m_a = 1$ GeV
$\Upsilon(3S)$ BaBar Recast
$\Upsilon(1S)$ Belle
Belle-II projection (20 fb^{-1})
$|c_{abb}|/f_a$ [GeV^{-1}]
$|c_{a\gamma\gamma}|/f_a$ [GeV^{-1}]



$c_{a\gamma\gamma} = 0$
$|c_{abb}|/f_a$ [GeV^{-1}]
m_a [GeV]
$\Upsilon(1S)$ BaBar
$\Upsilon(1S)$ Belle
$\Upsilon(3S)$ BaBar



$c_{abb}/c_{a\gamma\gamma} > 0$
$m_a = 7$ GeV
$\Upsilon(3S)$ BaBar Recast
$\Upsilon(1S)$ Belle
Belle-II projection (20 fb^{-1})
$|c_{abb}|/f_a$ [GeV^{-1}]
$|c_{a\gamma\gamma}|/f_a$ [GeV^{-1}]

Summary

- ALPs represent a wide class of models with common features (NP as new light degree of freedom);
- Flavour Factories optimal place for studying new light d.o.f in the (KeV-GeV) range;
- Three different type of Meson decays in INVISIBLE ALP:
  - Hadronic, Leptonic and Radiative Meson decays in Invisible ALPs;
- Bounds on ALP-fermion (FC) couplings;

Summary on ALP-fermion couplings