The Flavor of the ALP

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based on ongoing work with Martin Bauer, Sophie Renner, Marvin Schnubel & Andrea Thamm
Motivation

- **Axion-like particles** (ALPs) appear in many BSM scenarios and are well motivated: strong CP problem, mediator to hidden sector, pNGB of spontaneously broken global symmetry, possible explanation of $(g-2)_\mu$, …

- Assume the existence of a new pseudoscalar resonance $a$, which is a SM singlet and whose mass is protected by a (approximate) shift symmetry $a \rightarrow a + \text{const.}$

- Many studies of possible collider probes of ALPs exist
  

- Here we focus on effects of ALPs on **flavor observables**
  
  [see also: Izaguirre, Lin, Shuve 2016; Björkeroth, Chin, King 2018; Gavela, Houtz, Quilez, del Rey, Sumensari 2019]
The ALP couplings to the SM start at $D=5$ and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale):

$$\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} \left( \partial_\mu a \right) \left( \partial^\mu a \right) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\psi}_F \mathcal{C}_F \gamma_\mu \psi_F$$

$$+ \frac{g_s^2 C_{GG}}{\Lambda} G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + \frac{g^2 C_{WW}}{\Lambda} W_\mu^A \widetilde{W}^{\mu\nu,A} + \frac{g'2 C_{BB}}{\Lambda} B_\mu \tilde{B}^\mu$$

[Georgi, Kaplan, Randall 1986]
The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with a NP scale):

\[ \mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} \left( \partial_\mu a \right) \left( \partial^\mu a \right) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\psi}_F \, C_F \, \gamma_\mu \psi_F \]

\[ + g_s^2 \, C_{GG} \, \frac{a}{\Lambda} \, G_{\mu\nu}^A \, \tilde{G}^{\mu\nu,A} + g^2 \, C_{WW} \, \frac{a}{\Lambda} \, W_{\mu\nu}^A \, \tilde{W}^{\mu\nu,A} + g'2 \, C_{BB} \, \frac{a}{\Lambda} \, B_{\mu\nu} \, \tilde{B}^{\mu\nu} \]

[Georgi, Kaplan, Randall 1986]
Effective Lagrangian

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$$\mathcal{L}^{D \leq 5}_{\text{eff}} = \frac{1}{2} (\partial \mu a)(\partial \mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial \mu a}{\Lambda} \sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F + g_s^2 C_{GG} \frac{a}{\Lambda} G_\mu^A \tilde{G}^{\mu \nu, A} + g^2 C_{WW} \frac{a}{\Lambda} W_\mu^A \tilde{W}^{\mu \nu, A} + g^2 C_{BB} \frac{a}{\Lambda} B_\mu \tilde{B}^{\mu \nu}$$

EWSB

$$e^2 C_{\gamma \gamma} \frac{a}{\Lambda} F_{\mu \nu} \tilde{F}^{\mu \nu} + \frac{2 e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu \nu} \tilde{Z}^{\mu \nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu \nu} \tilde{Z}^{\mu \nu} + \ldots$$

$$C_{\gamma \gamma} = C_{WW} + C_{BB} \text{ etc.}$$

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$$+ e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \ldots$$

$$(C_{\gamma\gamma} = C_{WW} + C_{BB} \text{ etc.})$$

- $\mathcal{L}_{\text{eff}}^{D \leq 5}$ is the effective Lagrangian at D=5.
- $a$ is the ALP field.
- $F, W, B, Z$ are the field strength tensors of the SM gauge fields.
- $C_{GG}, C_{WW}, C_{BB}, C_{\gamma\gamma}, C_{\gamma Z}, C_{ZZ}$ are coefficients.
- $s_w, c_w$ are the sine and cosine of the weak mixing angle.
- $m_{a,0}$ is the mass of the ALP.
- $\Lambda$ is the NP scale.
- The sum runs over all fermion mass eigenstates (except the neutrinos).

[Georgi, Kaplan, Randall 1986]
Loop-induced ALP couplings

- Of particular relevance are the ALP couplings to photons and charged leptons; at 1-loop order we find:

\[
C_{\gamma\gamma}^{\text{eff}}(m_a \lesssim 1 \text{ GeV}) \approx C_{\gamma\gamma} - (1.92 \pm 0.04) C_{GG} - \frac{m_a^2}{m_\pi^2 - m_a^2} \left[ C_{GG} \frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32\pi^2} \right] \\
+ \sum_{q=c,b,t} \frac{N_c Q_q^2}{16\pi^2} c_{qq} B_1(\tau_q) + \sum_{\ell=e,\mu,\tau} \frac{c_{\ell\ell}}{16\pi^2} B_1(\tau_\ell) + \frac{2\alpha}{\pi} \frac{C_{WW}}{s_w^2} B_2(\tau_W)
\]
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only present for light ALPs
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\]

Heavy particles decouple \( \sim m_a^2/m_{W,f}^2 \)

\[
c_{\ell\ell}^{\text{eff}} = c_{\ell\ell}(\mu) \left[ 1 + \mathcal{O}(\alpha) \right] - 12Q_\ell^2 \alpha^2 C_{\gamma\gamma} \left[ \ln \frac{\mu^2}{m_\ell^2} + \delta_1 + g(\tau_\ell) \right] \\
- \frac{3\alpha^2}{s_w^4} C_{WW} \left( \ln \frac{\mu^2}{m_W^2} + \delta_1 + \frac{1}{2} \right) - \frac{12\alpha^2}{s_w^2 c_w^2} C_{\gamma Z} Q_\ell \left( T_3^\ell - 2Q_\ell s_w^2 \right) \left( \ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{3}{2} \right) \\
- \frac{12\alpha^2}{s_w^4 c_w^4} C_{ZZ} \left( Q_\ell^2 s_w^4 - T_3^\ell Q_\ell s_w^2 + \frac{1}{8} \right) \left( \ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{1}{2} \right)
\]
Fermion couplings after EWSB

After transformation to the mass basis, we obtain:

\[ \mathcal{L}_{\text{eff}} \geq \frac{\partial^{\mu} a}{\Lambda} \left( \bar{u}_L \, K_U \, \gamma_{\mu} \, u_L + \bar{u}_R \, K_u \, \gamma_{\mu} \, u_R + \bar{d}_L \, K_D \, \gamma_{\mu} \, d_L + \bar{d}_R \, K_d \, \gamma_{\mu} \, d_R + \bar{\nu}_L \, K_\nu \, \gamma_{\mu} \, \nu_L + \bar{\nu}_R \, K_\nu \, \gamma_{\mu} \, \nu_R + \bar{e}_L \, K_E \, \gamma_{\mu} \, e_L + \bar{e}_R \, K_E \, \gamma_{\mu} \, e_R \right) \]

with:

\[ K_U = U_u^\dagger \, C_Q \, U_u \,, \quad K_D = U_d^\dagger \, C_Q \, U_d \,, \quad K_E = U_e^\dagger \, C_L \, U_e \]

\[ K_f = W_f^\dagger \, C_f \, W_f \,; \quad f = u, d, e \]
Fermion couplings after EWSB

- After transformation to the mass basis, we obtain:

\[
\mathcal{L}_{\text{eff}} \supset \frac{\partial^\mu a}{\Lambda} \left( \bar{u}_L K_U \gamma_\mu u_L + \bar{u}_R K_u \gamma_\mu u_R + \bar{d}_L K_D \gamma_\mu d_L + \bar{d}_R K_d \gamma_\mu d_R \\
+ \bar{\nu}_L K_\nu \gamma_\mu \nu_L + \bar{e}_L K_E \gamma_\mu e_L + \bar{e}_R K_e \gamma_\mu e_R \right)
\]

with:

\[
K_U = U_u^\dagger C_Q U_u , \quad K_D = U_d^\dagger C_Q U_d , \quad K_E = U_e^\dagger C_L U_e \\
K_f = W_f^\dagger C_f W_f ; \quad f = u, d, e
\]

- Flavor-diagonal couplings from before:

\[
c_{u_iu_i} = (K_u)_{ii} - (K_U)_{ii} , \quad c_{d_id_i} = (K_d)_{ii} - (K_D)_{ii} , \quad c_{e_ie_i} = (K_e)_{ii} - (K_E)_{ii}
\]

M. Neubert: The flavor of the ALP
Minimal flavor violation (MFV)

- Strong phenomenological bounds on off-diagonal couplings motivate MFV ansatz:
  \[ C_Q = c_0^Q 1 + \epsilon \left( c_1^Q Y_u Y_u^\dagger + c_2^Q Y_d Y_d^\dagger \right) + \mathcal{O}(\epsilon^2) \]
  \[ C_u = c_0^u 1 + \epsilon c_1^u Y_u^\dagger Y_u + \mathcal{O}(\epsilon^2) \]
  \[ C_d = c_0^d 1 + \epsilon c_1^d Y_d^\dagger Y_d + \mathcal{O}(\epsilon^2) \]

- This implies:
  \[ K_U = c_0^Q 1 + \epsilon \left[ c_1^Q \left( Y_u^{\text{diag}} \right)^2 + c_1^Q V (Y_d^{\text{diag}})^2 V^\dagger \right] + \mathcal{O}(\epsilon^2) \]
  \[ K_D = c_0^Q 1 + \epsilon \left[ c_1^Q V^\dagger \left( Y_u^{\text{diag}} \right)^2 V + c_1^Q (Y_d^{\text{diag}})^2 \right] + \mathcal{O}(\epsilon^2) \]
  \[ K_u = c_0^u 1 + \epsilon c_1^u \left( Y_u^{\text{diag}} \right)^2 + \mathcal{O}(\epsilon^2) \]
  \[ K_d = c_0^d 1 + \epsilon c_1^d \left( Y_d^{\text{diag}} \right)^2 + \mathcal{O}(\epsilon^2) \]
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  \[ C_u = c_0^u \mathbf{1} + \epsilon c_1^u \mathbf{Y}_u \mathbf{Y}_u^\dagger + \mathcal{O}(\epsilon^2) \]
  \[ C_d = c_0^d \mathbf{1} + \epsilon c_1^d \mathbf{Y}_d \mathbf{Y}_d^\dagger + \mathcal{O}(\epsilon^2) \]

- Neglecting the down-type quark masses:

  \[ K_U \approx c_0^Q \mathbf{1} + \epsilon c_1^Q (\mathbf{Y}_t)^2 + \mathcal{O}(\epsilon^2) \]
  \[ K_D \approx c_0^Q \mathbf{1} + \epsilon c_1^Q \mathbf{V}^\dagger (\mathbf{Y}_t)^2 \mathbf{V} + \mathcal{O}(\epsilon^2) \]
  \[ K_u \approx c_0^u \mathbf{1} + \epsilon c_1^u (\mathbf{Y}_t)^2 + \mathcal{O}(\epsilon^2) \]
  \[ K_d \approx c_0^d \mathbf{1} \]
Low-energy effective Lagrangian

- Integrating out heavy SM fields, we find at 1-loop order ($i \neq j$):

\[
(K_D)_{ij}^{\text{eff}} = (K_D)_{ij} (\mu) + \frac{y_t^2}{16\pi^2} V_{ti}^* V_{tj} \left\{ c_{tt} \left[ \frac{1}{2} \ln \frac{\mu^2}{m_t^2} - \frac{7 - 8x_t + x_t^2 + 6 \ln x_t}{4 (1 - x_t)^2} \right] - 6g^2 C_{WW} \frac{1 - x_t + x_t \ln x_t}{(1 - x_t)^2} \right\}
\]

- For $\Lambda = \mu = 1$ TeV:

\[
(K_D)_{ij}^{\text{eff}} = (K_D)_{ij} (\Lambda) + V_{ti}^* V_{tj} [0.01 c_{tt} - 0.004 C_{WW}]
\]

- No corresponding contributions to up-type and lepton couplings
Low-energy effective Lagrangian

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\left. - 6g^2 C_{WW} \frac{1 - x_t + x_t \ln x_t}{(1-x_t)^2} \right\}
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- No corresponding contributions to up-type and lepton couplings
Rare decays of kaons and B mesons

- On-shell decays $K \rightarrow \pi a$ and $B \rightarrow K^{(*)} a$ provide very strong bounds if kinematically allowed.
- ALP can be long-lived or decay into photons or charged leptons.
- Due to ALP-$\pi^0$ mixing, the $K \rightarrow \pi a$ amplitude receives a contribution from the strong decay $K \rightarrow \pi\pi^0$, since:

\[
\pi^0 = \pi^0_{\text{phys}} - \frac{\epsilon m_a^2}{m_\pi^2 - m_a^2} a_{\text{phys}} + O(\epsilon^2); \quad \text{for } |m_\pi^2 - m_a^2| \gg 2\epsilon m_a m_\pi
\]

\[
\epsilon = \frac{f_\pi}{2\sqrt{2}\Lambda} \left[ (c_{uu} - c_{dd}) + 32\pi^2 C_{GG} \frac{m_d - m_u}{m_d + m_u} \right]
\]
Resulting bounds (95% CL)

- Model-independent upper limits:

| Observable                          | Mass Range [MeV] | ALP decay mode | Constrained coupling $c$ | Limit (95% CL) on $|c| \cdot (\frac{\text{Im}(\nu)}{\text{Im}(\nu)}) \cdot \sqrt{B}$ |
|-------------------------------------|-----------------|----------------|--------------------------|--------------------------------------------------|
| $B(K^+ \to \pi^+ \nu \nu)$          | $0 < m_a < 265$ (*) | Long-lived     | $(K_D + K_d)_{ds}$       | $4.9 \times 10^{-9}$                              |
| $B(B^+ \to K^+ \bar{\nu} \nu)$    | $0 < m_a < 4785$ | Long-lived     | $(K_D + K_d)_{sb}$       | $6.9 \times 10^{-6}$                              |
| $B(B \to K^* \bar{\nu} \nu)$      | $0 < m_a < 4387$ | Long-lived     | $(K_D - K_d)_{sb}$       | $5.1 \times 10^{-6}$                              |
| $B(\Upsilon \to \gamma (a_{\text{invisible}}))$ | $m_a < 9200$ | Long-lived     | $(K_D - K_d)_{bb}$       | $0.76$                                           |
| $B(K^+ \to \pi^+ \gamma \gamma)$  | $m_a < 108$     | $\gamma \gamma$ | $(K_D + K_d)_{ds}$       | $2.1 \times 10^{-8}$                              |
| $B(K^+ \to \pi^+ \gamma \gamma)$  | $220 < m_a < 354$ | $\gamma \gamma$ | $(K_D + K_d)_{ds}$       | $2.4 \times 10^{-7}$                              |
| $B(K^0_L \to \pi^0 \gamma \gamma)$ | $m_a < 110$     | $\gamma \gamma$ | Im$(K_D + K_d)_{ds}$     | $1.4 \times 10^{-8}$                              |
| $B(K^0_L \to \pi^0 \gamma \gamma)$ | $m_a < 363$     | $\gamma \gamma$ | Im$(K_D + K_d)_{ds}$     | $1.2 \times 10^{-7}$                              |
| $B(K_L \to \pi^0 e^+ e^-)$         | $140 < m_a < 362$ | $e^+ e^-$      | Im$(K_D + K_d)_{ds}$     | $2.9 \times 10^{-9}$                              |
| $dB/dq^2(B^0 \to K^{*0} e^+ e^-)_{[0.0,0.05]}$ | $0 < m_a < 224$ | $e^+ e^-$      | $(K_D - K_d)_{sb}$       | $8.3 \times 10^{-7}$                              |
| $dB/dq^2(B^0 \to K^{*0} e^+ e^-)_{[0.05,0.15]}$ | $224 < m_a < 387$ | $e^+ e^-$      | $(K_D - K_d)_{sb}$       | $6.5 \times 10^{-7}$                              |
| $B(K_L \to \pi^0 \mu^+ \mu^-)$    | $210 < m_a < 350$ | $\mu^+ \mu^-$ | Im$(K_D + K_d)_{ds}$     | $4.0 \times 10^{-9}$                              |
| $B(B^+ \to K^+ a_{\mu^+ \mu^-})$  | $250 < m_a < 4700$ (†) | $\mu^+ \mu^-$ | $(K_D + K_d)_{sb}$       | $4.4 \times 10^{-8}$                              |
| $B(B^0 \to K^{*0} a_{\mu^+ \mu^-})$ | $214 < m_a < 4350$ (†) | $\mu^+ \mu^-$ | $(K_D - K_d)_{sb}$       | $5.1 \times 10^{-8}$                              |
| $B(J/\psi \to \gamma a_{\mu^+ \mu^-})$ | $212 < m_a < 3000$ | $\mu^+ \mu^-$ | $(K_U - K_u)_{cc}$       | $0.16$                                           |
| $B(\Upsilon \to \gamma a_{\mu^+ \mu^-})$ | $212 < m_a < 9200$ | $\mu^+ \mu^-$ | $(K_D - K_d)_{bb}$       | $0.24$                                           |
| $B(B^+ \to K^+ \tau^+ \tau^-)$    | $3552 < m_a < 4785$ | $\tau^+ \tau^-$ | $(K_D + K_d)_{sb}$       | $8.2 \times 10^{-5}$                              |
| $B(\Upsilon \to \gamma a_{\tau^+ \tau^-})$ | $3500 < m_a < 9200$ | $\tau^+ \tau^-$ | $(K_D - K_d)_{bb}$       | $1.5$                                            |
| $B(\Upsilon \to \gamma a_{\text{hadrons}})$ | $300 < m_a < 7000$ | hadrons        | $(K_D - K_d)_{bb}$       | $0.56$                                           |
Interesting benchmark scenarios

- Consider some concrete scenarios in which only one ALP coupling is present at tree level (very conservative)
- All other ALP couplings are induced via loops in the EFT
- Calculate the relevant ALP branching ratios and the ALP decay length, which is relevant for determining which fraction of ALP decays can be reconstructed in the detector
Interesting benchmark scenarios

- **Scenario 1:** Bounds on $C_{WW}$, assuming all other couplings vanish at tree level.
Interesting benchmark scenarios

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![Diagram showing constraints on $C_{WW}$ vs. ALP mass. The diagram includes various decay modes such as $B_s \rightarrow \mu^- \mu^+$, $B \rightarrow K^+ \nu \bar{\nu}$, and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, with different lines and colors indicating different decay rates and constraints. The $Z$ boson width constraint is also shown.]
Interesting benchmark scenarios

- **Scenario 1:** Bounds on $C_{WW}$, assuming all other couplings vanish at tree level
Interesting benchmark scenarios

- **Scenario 2**: Bounds on \( c_{uu} = c_{cc} = c_{tt} \), assuming all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 2**: Bounds on $c_{uu} = c_{cc} = c_{tt}$, assuming all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 3**: Bounds on $c_{dd} = c_{ss} = c_{bb}$, assuming all other couplings vanish at tree level.

![Diagram showing constraints on ALP couplings](image)

For universal ALP couplings to down-type quarks $c_{dd} = c_{ss} = c_{bb}$, the constraints from flavour observables are shown in Figure 4. Since only couplings to down quarks are present, flavour-violating transitions between down quarks are not generated at one loop. Constraints from $\text{Br}(K^+ \rightarrow \pi^+ \nu \nu)$, $\text{Br}(K^+ \rightarrow \pi^+ \nu \nu)$, and $\text{Br}(K_L \rightarrow \pi^0 \gamma \gamma)$ show in purple, orange, and yellow in Figure 4, are therefore considerably weaker, because ALPs are only produced through ALP-pion mixing. In contrast to both ALPs coupled to $SU(2)_L$ gauge bosons and ALPs coupled to up-type quarks, radiative Upsilon decays lead to important constraints, because the coupling to b-quarks is induced at tree-level. Searches for resonances in $\Upsilon \rightarrow \gamma \gamma + \text{hadrons}$ provide the strongest limit for ALPs with masses $m_a < m_\pi$. The corresponding parameter space is shown in Figure 4 in light blue and dark green, respectively. All constraints are allow for ALP couplings of $|c_{dd}| / \Lambda < 10^{-1}$ and light ALPs with $m_a < 10^{-2}$ GeV are almost unconstrained by flavour observables.

Couplings of the ALP to leptons are not induced at the 1-loop level, and a new physics contribution to the anomalous magnetic moments of leptons is therefore negligible. The contribution of $Z \rightarrow a$ to the total $Z$ width results in the constraint $|c_{dd}| / \Lambda < 4.42 \text{ TeV}^{-1}$. The excluded parameter space is shown gray in Figure 4. Higgs decays are strongly suppressed for ALP.
Lepton flavor violation

- Interesting (and complementary) bounds on lepton flavor-violating couplings can be derived from decays such as $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ and $\mu \rightarrow e + \text{invisible}$

- Relevant diagrams:

- For simplicity, we will assume that one combination of couplings dominates
Model-independent upper bounds (assuming on-shell ALP):

| Observable | Mass Range [MeV] | ALP decay mode | Constrained coupling $c$ | Limit (95% CL) on $|c| \cdot (\text{TeV}) \cdot \sqrt{B}$ |
|------------|------------------|----------------|-------------------------|-----------------------------------------------|
| $B(\mu \rightarrow ea(\text{invisible}))$ | $13 < m_a < 80$ | Long-lived | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $3.8 \times 10^{-7}$ |
| $B(\mu \rightarrow ea(\text{invisible}))$ | $0 < m_a < 13$ | Long-lived | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $1.5 \times 10^{-6}$ |
| $B(\tau \rightarrow ea(\text{invisible}))$ | $0 < m_a < 1600$ | Long-lived | $\sqrt{|K^{\tau\mu}|^2 + |K^{\tau\mu}|^2}$ | $2.3 \times 10^{-4}$ |
| $B(\tau \rightarrow \mu a(\text{invisible}))$ | $0 < m_a < 1600$ | Long-lived | $\sqrt{|K^{\tau\mu}|^2 + |K^{\tau\mu}|^2}$ | $3.2 \times 10^{-4}$ |
| $B(\mu \rightarrow e\gamma\gamma)$ | $0 < m_a < 105$ | $\gamma\gamma$ | $\sqrt{|K^{e\gamma}|^2 + |K^{e\gamma}|^2}$ | $2.6 \times 10^{-6}$ |
| $B(\mu \rightarrow 3e)$ | $0 < m_a < 105$ | $e^+e^-$ | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $3.1 \times 10^{-7}$ |
| $B(\tau^- \rightarrow \mu^-e^+e^-)$ | $200 < m_a < 1671$ | $e^+e^-$ | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $6.1 \times 10^{-7}$ |
| $B(\tau \rightarrow 3e)$ | $200 < m_a < 1776$ | $e^+e^-$ | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $7.5 \times 10^{-7}$ |
| $B(\tau \rightarrow 3\mu)$ | $211 < m_a < 1671$ | $\mu^+\mu^-$ | $\sqrt{|K^{\tau\mu}|^2 + |K^{\tau\mu}|^2}$ | $6.6 \times 10^{-7}$ |
| $B(\tau^- \rightarrow \mu^-\pi^-K^+)$ | $633 < m_a < 1671$ | $\pi^-K^+$ | $\sqrt{|K^{e\mu}|^2 + |K^{e\mu}|^2}$ | $1.1 \times 10^{-6}$ |

Weaker bounds apply, if the ALP is too heavy to be on shell
Interesting benchmark scenarios

- **Scenario 1:** Bounds on $c_{\mu e} \equiv \sqrt{2|K_E|_{\mu e}^2 + 2|K_e|_{\mu e}^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1 \text{ TeV}^{-1}$ and all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 1**: Bounds on $c_{\mu e} \equiv \sqrt{2|K_{E}\mu e|^2 + 2|K_{e}\mu e|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\,\text{TeV}^{-1}$ and all other couplings vanish at tree level.

Note the important fact that $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ give rise to complementary constraints, and in many cases Mu3e will provide stronger bounds than MEG II!
Interesting benchmark scenarios

- **Scenario 1**: Bounds on $c_{\mu e} \equiv \sqrt{2|K_{E}\mu e|^2 + 2|K_{e}\mu e|^2}$ for different values of $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda$ (all other couplings vanish)
Interesting benchmark scenarios

- **Scenario 2:** Bounds on $c_{\tau\mu} \equiv \sqrt{2|K_E\tau\mu|^2 + 2|K_e\tau\mu|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\text{ TeV}^{-1}$ and all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 2**: Bounds on $c_{\tau\mu} \equiv \sqrt{2|\langle K_E \rangle_{\tau\mu}|^2 + 2|\langle K_e \rangle_{\tau\mu}|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1 \text{ TeV}^{-1}$ and all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 2**: Bounds on \( c_{\tau e} \equiv \sqrt{2|K_{E\tau}|^2 + 2|K_{e\tau}|^2} \), assuming \( c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\,\text{TeV}^{-1} \) and all other couplings vanish at tree level.
Interesting benchmark scenarios

- **Scenario 2:** Bounds on $c_{\tau e} \equiv \sqrt{2|\langle K_E \rangle_{\tau e}|^2 + 2|\langle K_e \rangle_{\tau e}|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1 \text{ TeV}^{-1}$ and all other couplings vanish at tree level.
Conclusions

❖ ALPs with masses below 10 GeV (and higher) would potentially lead to interesting new-physics effects in a variety of flavor observables

❖ Allows one to probe flavor-changing ALP couplings to quarks and leptons down to few $10^{-9} \Lambda/\text{TeV}$ (quarks) and few $10^{-7} \Lambda/\text{TeV}$ (leptons)

❖ In lepton case, ALP represent a class of models where future bounds from Mu3e experiment will outperform those of MEG II