Humboldt-Kolleg: Discoveries and Open Puzzles in Particle Physics and Gravitation
Kitzbühel, 24 June 2019

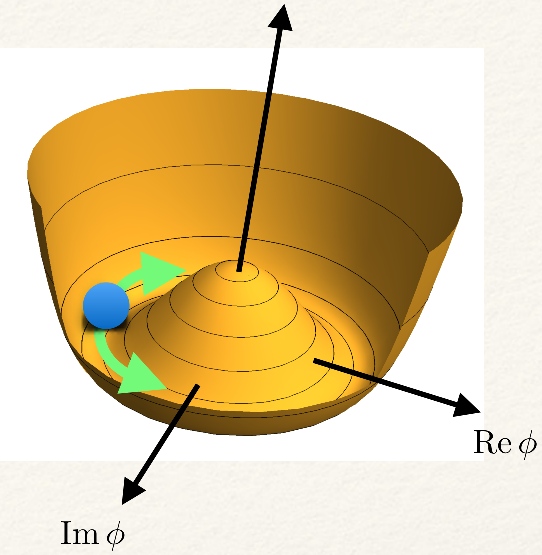
The Flavor of the ALPs

Matthias Neubert

PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

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 $(g\text{-}2)_\mu$, …

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

- Many studies of possible collider probes of ALPs exist
[Kim, Lee 1989; Djouadi, Zerwas, Zunft 1991; Rupak, Simmons 1995; Kleban, Ramadan 2005; Mimasu, Sanz 2014; Jäckel, Spannowsky 2015; Knapen, Lin, Lou, Melia 2016; Brivio et al. 2017; Bauer, MN, Thamm 2017; …]

- Here we focus on effects of ALPs on **flavor observables**
[also: Izaguirre, Lin, Shuve 2016; Björkeroth, Chin, King 2018; Gavela, Houtz, Quilez, del Rey, Sumensari 2019; …]

Effective Lagrangian

- 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):

[Georgi, Kaplan, Randall 1986]

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

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

EWSB

EWSB

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

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

$$\sum_f \frac{c_{ff}}{2}\, \frac{\partial^\mu a}{\Lambda}\, \bar f\, \gamma_\mu \gamma_5\, f$$ + flavor off-diagonal terms

Loop-induced ALP couplings

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

only present for light ALPs

$$C_{\gamma\gamma}^{\rm eff}(m_a \lesssim 1\,\text{GeV}) \approx C_{\gamma\gamma} - (1.92 \pm 0.04)\, C_{GG} - \frac{m_a^2}{m_\pi^2 - m_a^2} \left[C_{GG}\, \frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32\pi^2} \right]$$

$$+ \sum_{q=c,b,t} \frac{N_c Q_q^2}{16\pi^2}\, c_{qq}\, B_1(\tau_q) + \sum_{\ell=e,\mu,\tau} \frac{c_{\ell\ell}}{16\pi^2}\, B_1(\tau_\ell) + \frac{2\alpha}{\pi}\, \frac{C_{WW}}{s_w^2}\, B_2(\tau_W)$$

heavy particles decouple ~$m_a^2/m_{W,f}^2$

$$c_{\ell\ell}^{\rm eff} = c_{\ell\ell}(\mu) \left[1 + \mathcal{O}(\alpha)\right] - 12 Q_\ell^2\, \alpha^2 C_{\gamma\gamma} \left[\ln \frac{\mu^2}{m_\ell^2} + \delta_1 + g(\tau_\ell) \right]$$

$$- \frac{3\alpha^2}{s_w^4}\, C_{WW} \left(\ln \frac{\mu^2}{m_W^2} + \delta_1 + \frac{1}{2} \right) - \frac{12\alpha^2}{s_w^2 c_w^2}\, C_{\gamma Z}\, Q_\ell \left(T_3^\ell - 2 Q_\ell s_w^2\right) \left(\ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{3}{2} \right)$$

$$- \frac{12\alpha^2}{s_w^4 c_w^4}\, C_{ZZ} \left(Q_\ell^2 s_w^4 - T_3^\ell Q_\ell s_w^2 + \frac{1}{8} \right) \left(\ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{1}{2} \right)$$

Fermion couplings after EWSB

- After transformation to the mass basis, we obtain:

$$\mathcal{L}_{\text{eff}} \ni \frac{\partial^\mu a}{\Lambda} \Big(\bar{u}_L \, \boldsymbol{K}_U \, \gamma_\mu \, u_L + \bar{u}_R \, \boldsymbol{K}_u \, \gamma_\mu \, u_R + \bar{d}_L \, \boldsymbol{K}_D \, \gamma_\mu \, d_L + \bar{d}_R \, \boldsymbol{K}_d \, \gamma_\mu \, d_R$$

$$+ \bar{\nu}_L \, \boldsymbol{K}_\nu \, \gamma_\mu \, \nu_L + \bar{e}_L \, \boldsymbol{K}_E \, \gamma_\mu \, e_L + \bar{e}_R \, \boldsymbol{K}_e \, \gamma_\mu \, e_R \Big)$$

neutrino couplings can be removed by field redefinitions

with:

$$\boldsymbol{K}_U = \boldsymbol{U}_u^\dagger \, \boldsymbol{C}_Q \, \boldsymbol{U}_u \,, \qquad \boldsymbol{K}_D = \boldsymbol{U}_d^\dagger \, \boldsymbol{C}_Q \, \boldsymbol{U}_d \,, \qquad \boldsymbol{K}_E = \boldsymbol{U}_e^\dagger \, \boldsymbol{C}_L \, \boldsymbol{U}_e$$

$$\boldsymbol{K}_f = \boldsymbol{W}_f^\dagger \, \boldsymbol{C}_f \, \boldsymbol{W}_f \,; \quad f = u, d, e$$

- Flavor-diagonal couplings from before:

$$c_{u_i u_i} = (K_u)_{ii} - (K_U)_{ii} \,, \qquad c_{d_i d_i} = (K_d)_{ii} - (K_D)_{ii} \,, \qquad c_{e_i e_i} = (K_e)_{ii} - (K_E)_{ii}$$

Minimal flavor violation (MFV)

- Strong phenomenological bounds on off-diagonal couplings motivate MFV ansatz:

$$\boldsymbol{C}_Q = c_0^Q\,\mathbf{1} + \epsilon\left(c_1^Q\,\boldsymbol{Y}_u\,\boldsymbol{Y}_u^\dagger + c_2^Q\,\boldsymbol{Y}_d\,\boldsymbol{Y}_d^\dagger\right) + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{C}_u = c_0^u\,\mathbf{1} + \epsilon\,c_1^u\,\boldsymbol{Y}_u^\dagger\,\boldsymbol{Y}_u + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{C}_d = c_0^d\,\mathbf{1} + \epsilon\,c_1^d\,\boldsymbol{Y}_d^\dagger\,\boldsymbol{Y}_d + \mathcal{O}(\epsilon^2)$$

- This implies:

$$\boldsymbol{K}_U = c_0^Q\,\mathbf{1} + \epsilon\left[c_1^Q\,(\boldsymbol{Y}_u^{\rm diag})^2 + c_2^Q\,\boldsymbol{V}\,(\boldsymbol{Y}_d^{\rm diag})^2\,\boldsymbol{V}^\dagger\right] + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{K}_D = c_0^Q\,\mathbf{1} + \epsilon\left[c_1^Q\,\boldsymbol{V}^\dagger\,(\boldsymbol{Y}_u^{\rm diag})^2\,\boldsymbol{V} + c_2^Q\,(\boldsymbol{Y}_d^{\rm diag})^2\right] + \mathcal{O}(\epsilon^2)$$

related by CKM matrix $\boldsymbol{V}$

$$\boldsymbol{K}_u = c_0^u\,\mathbf{1} + \epsilon\,c_1^u\,(\boldsymbol{Y}_u^{\rm diag})^2 + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{K}_d = c_0^d\,\mathbf{1} + \epsilon\,c_1^d\,(\boldsymbol{Y}_d^{\rm diag})^2 + \mathcal{O}(\epsilon^2)$$

Minimal flavor violation (MFV)

- Strong phenomenological bounds on off-diagonal couplings motivate MFV ansatz:

$$\boldsymbol{C}_Q = c_0^Q\,\mathbf{1} + \epsilon\left(c_1^Q\,\boldsymbol{Y}_u\,\boldsymbol{Y}_u^\dagger + c_2^Q\,\boldsymbol{Y}_d\,\boldsymbol{Y}_d^\dagger\right) + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{C}_u = c_0^u\,\mathbf{1} + \epsilon\,c_1^u\,\boldsymbol{Y}_u^\dagger\,\boldsymbol{Y}_u + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{C}_d = c_0^d\,\mathbf{1} + \epsilon\,c_1^d\,\boldsymbol{Y}_d^\dagger\,\boldsymbol{Y}_d + \mathcal{O}(\epsilon^2)$$

- Neglecting the down-type quark masses:

$$\boldsymbol{K}_U \approx c_0^Q\,\mathbf{1} + \epsilon\,c_1^Q\,\left(\boldsymbol{Y}_t\right)^2 + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{K}_D \approx c_0^Q\,\mathbf{1} + \epsilon\,c_1^Q\,\boldsymbol{V}^\dagger\left(\boldsymbol{Y}_t\right)^2\boldsymbol{V} + \mathcal{O}(\epsilon^2)$$

only source of flavor violation

$$\boldsymbol{K}_u \approx c_0^u\,\mathbf{1} + \epsilon\,c_1^u\left(\boldsymbol{Y}_t\right)^2 + \mathcal{O}(\epsilon^2)$$

$$\boldsymbol{K}_d \approx c_0^d\,\mathbf{1}$$

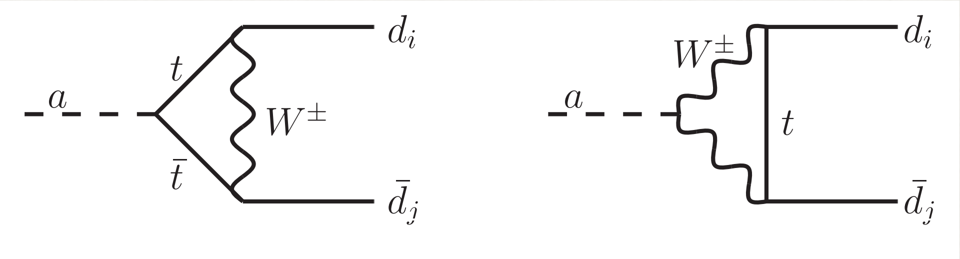
Low-energy effective Lagrangian

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

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

$$(K_d)_{ij}^{\text{eff}} = (K_d)_{ij}$$

[Izaguirre, Lin, Shuve 2016]



$x_t = m_t^2/m_W^2$

- For Λ=μ=1 TeV:

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

- No corresponding contributions to up-type quark and lepton couplings

Rare decays of kaons and B mesons

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

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

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

Resulting bounds (95% CL)

- Model-independent upper limits:

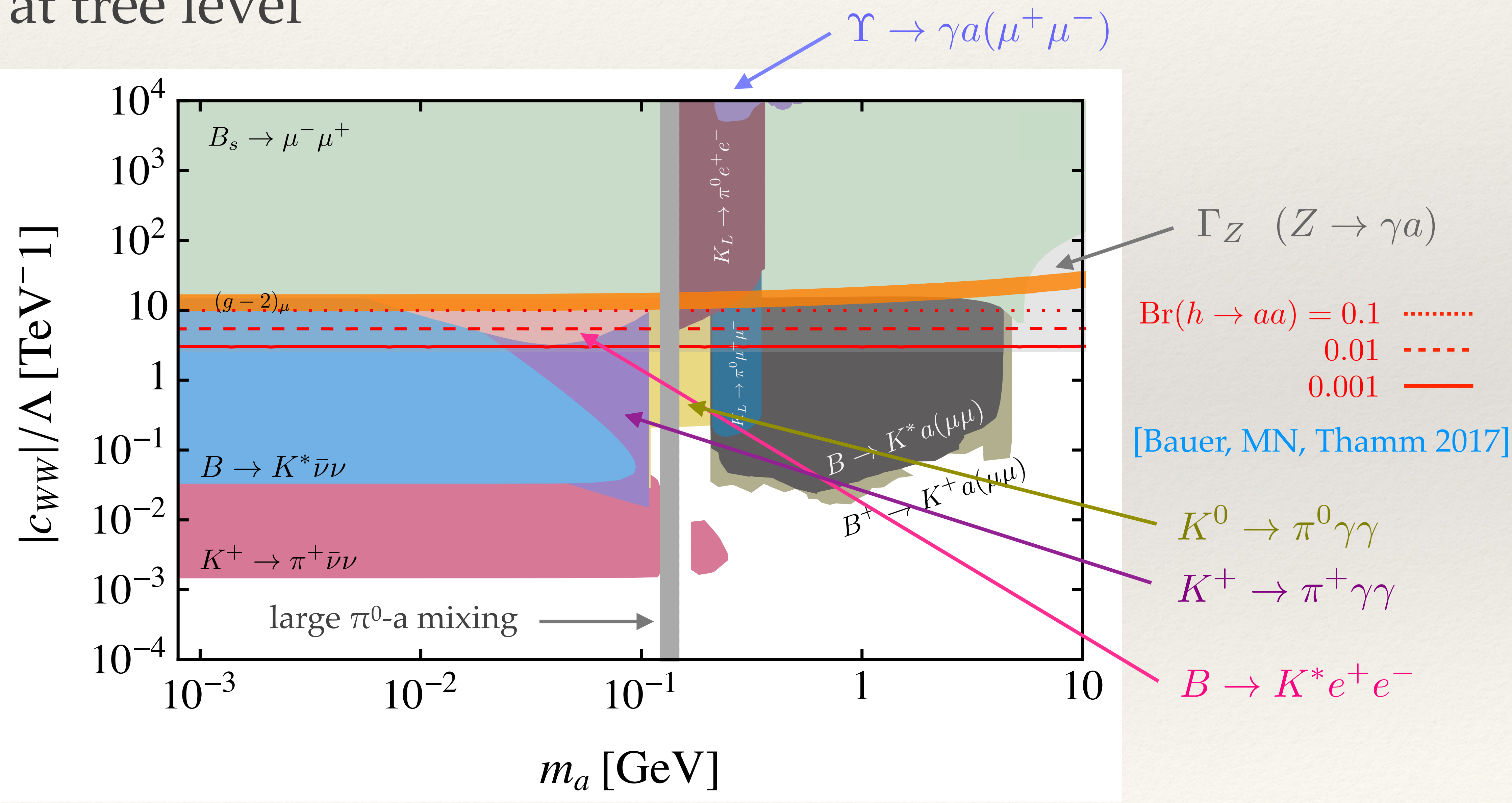
Observable	Mass Range [MeV]	ALP decay mode	Constrained coupling c	Limit (95% CL) on $\lvert c\rvert \cdot \left(\frac{\text{TeV}}{\Lambda}\right) \cdot \sqrt{\mathcal{B}}$
$\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)$	$0 < m_a < 265$ $(*)$	Long-lived	$(K_D + K_d)_{ds}$	4.9×10^{-9}
$\mathcal{B}(B^+ \to K^+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

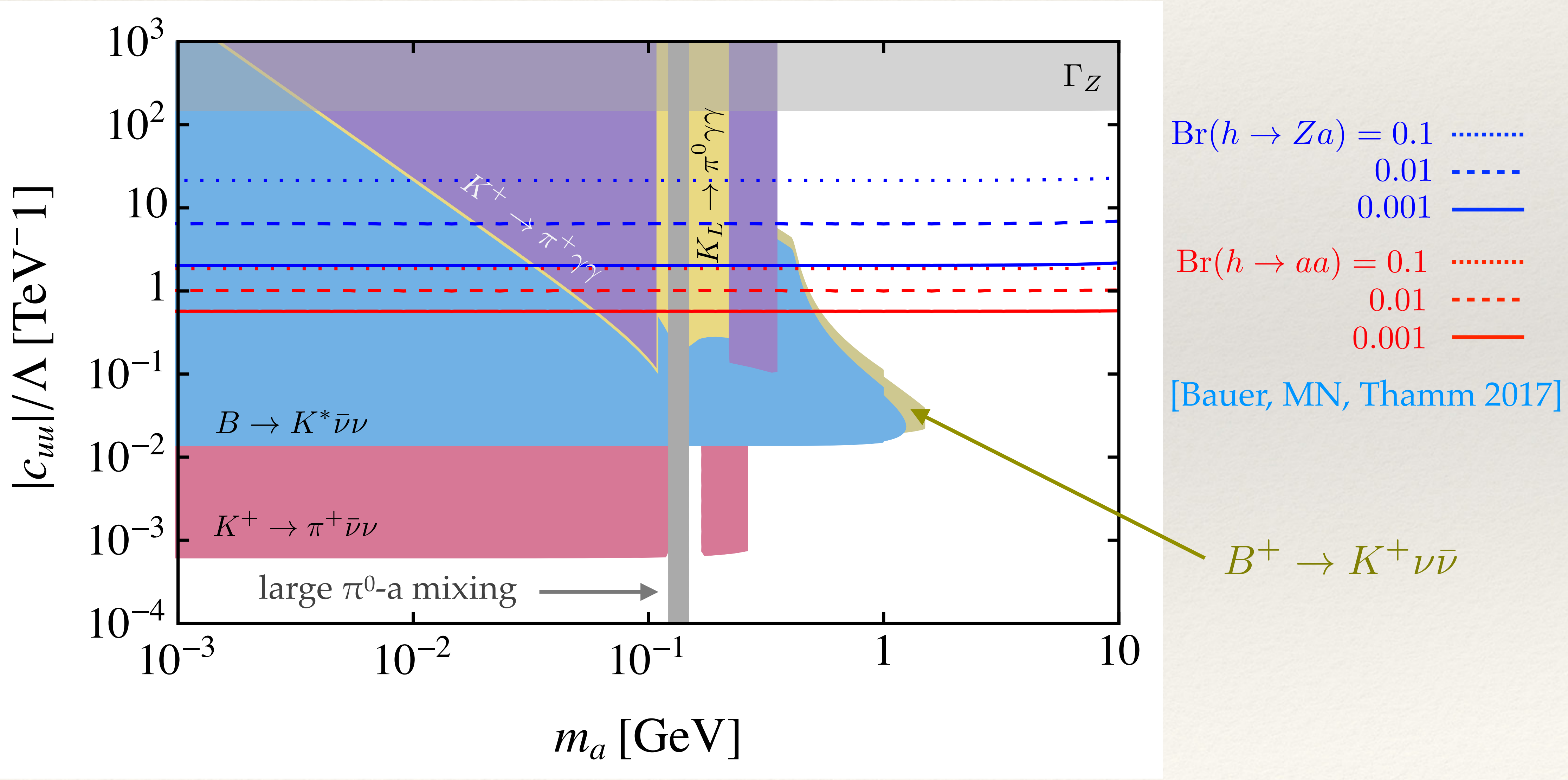
Interesting benchmark scenarios

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



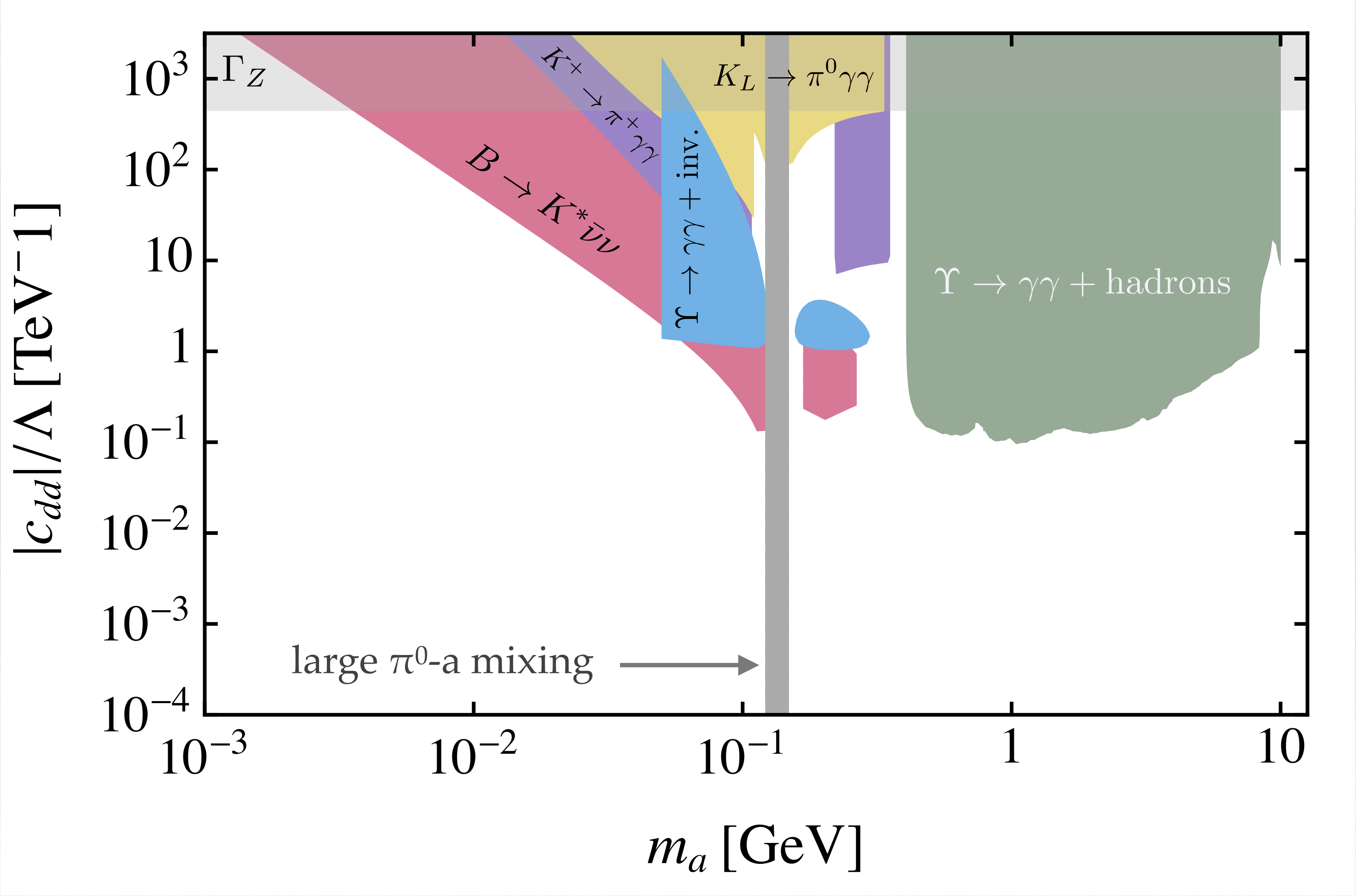
Interesting benchmark scenarios

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



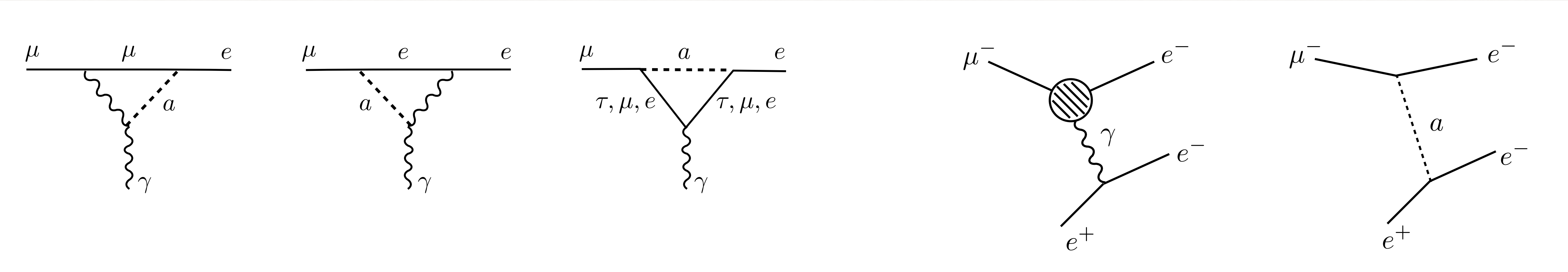
Interesting benchmark scenarios

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



Lepton flavor violation

- Interesting (and complementary) bounds on lepton flavor-violating couplings can be derived from decays such as $\mu \to e\gamma$, $\mu \to 3e$ and $\mu \to e +$ invisible (and corresp. τ decays)
- Relevant diagrams:



- For simplicity, we will assume that one combination of couplings dominates

Resulting bounds (95% CL)

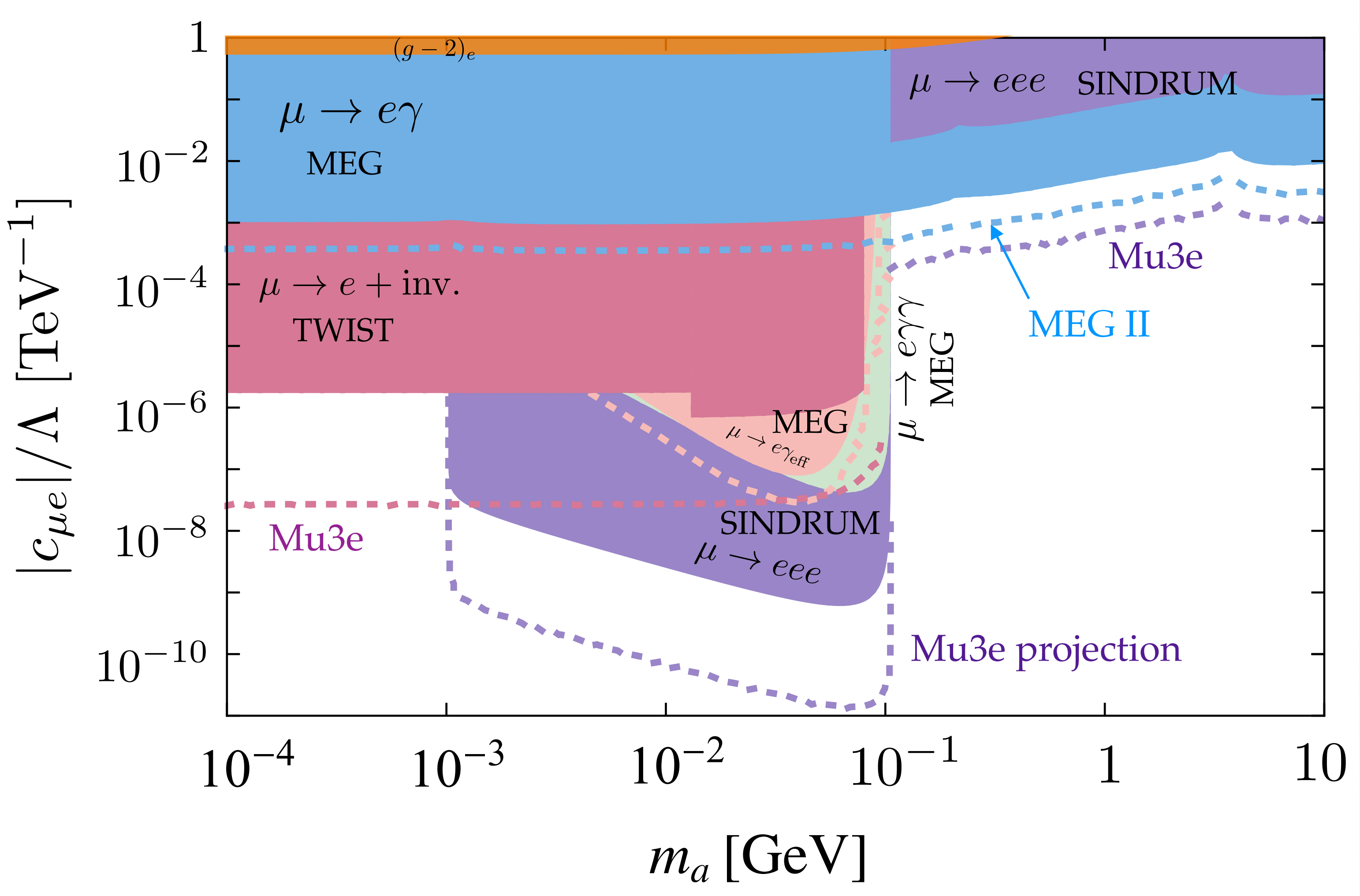
- Model-independent upper bounds (assuming on-shell ALP):

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

- Weaker bounds apply, if the ALP is too heavy to be on shell

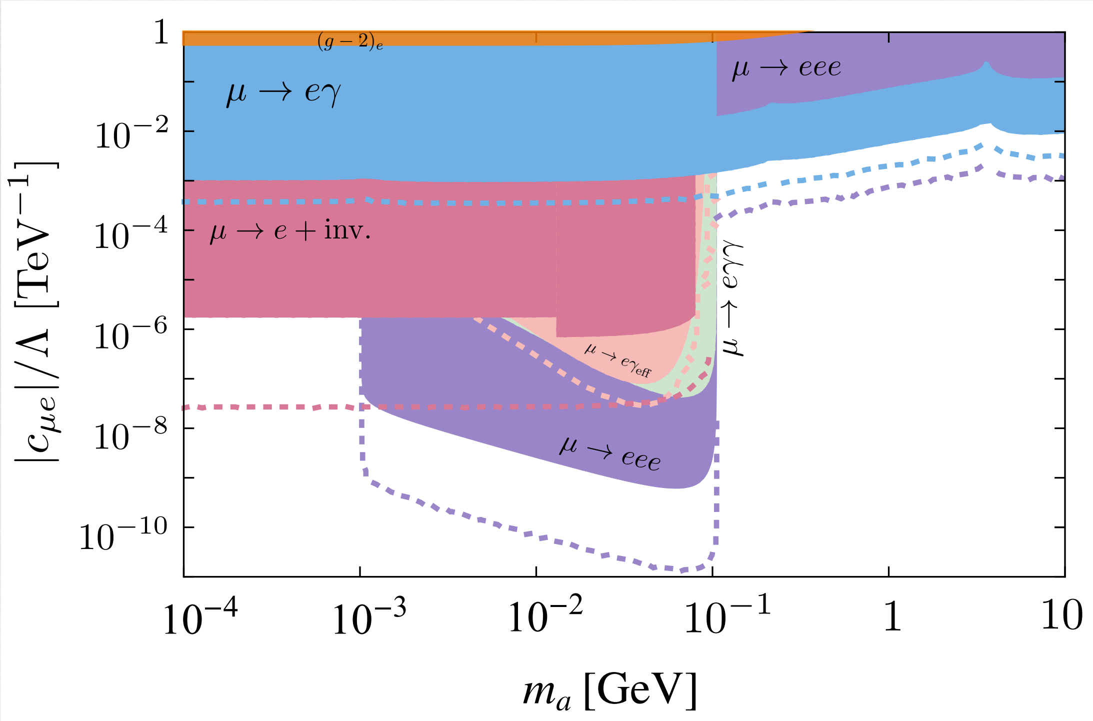
Interesting benchmark scenarios

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



Interesting benchmark scenarios

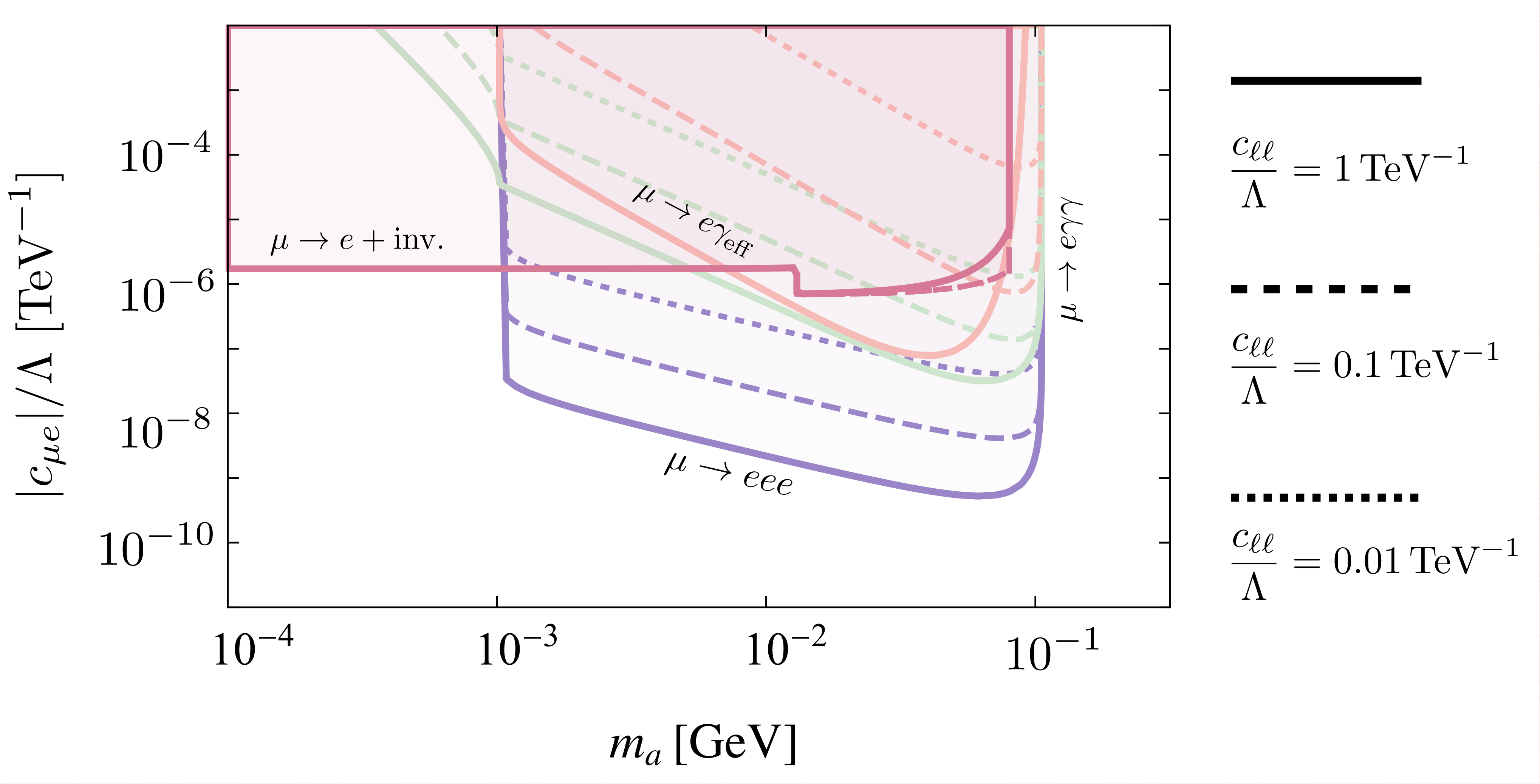
- **Scenario 1**: Bounds on $c_{\mu e} \equiv \sqrt{2|(K_E)_{\mu e}|^2 + 2|(K_e)_{\mu e}|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\,\text{TeV}^{-1}$and all other couplings vanish at tree level



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

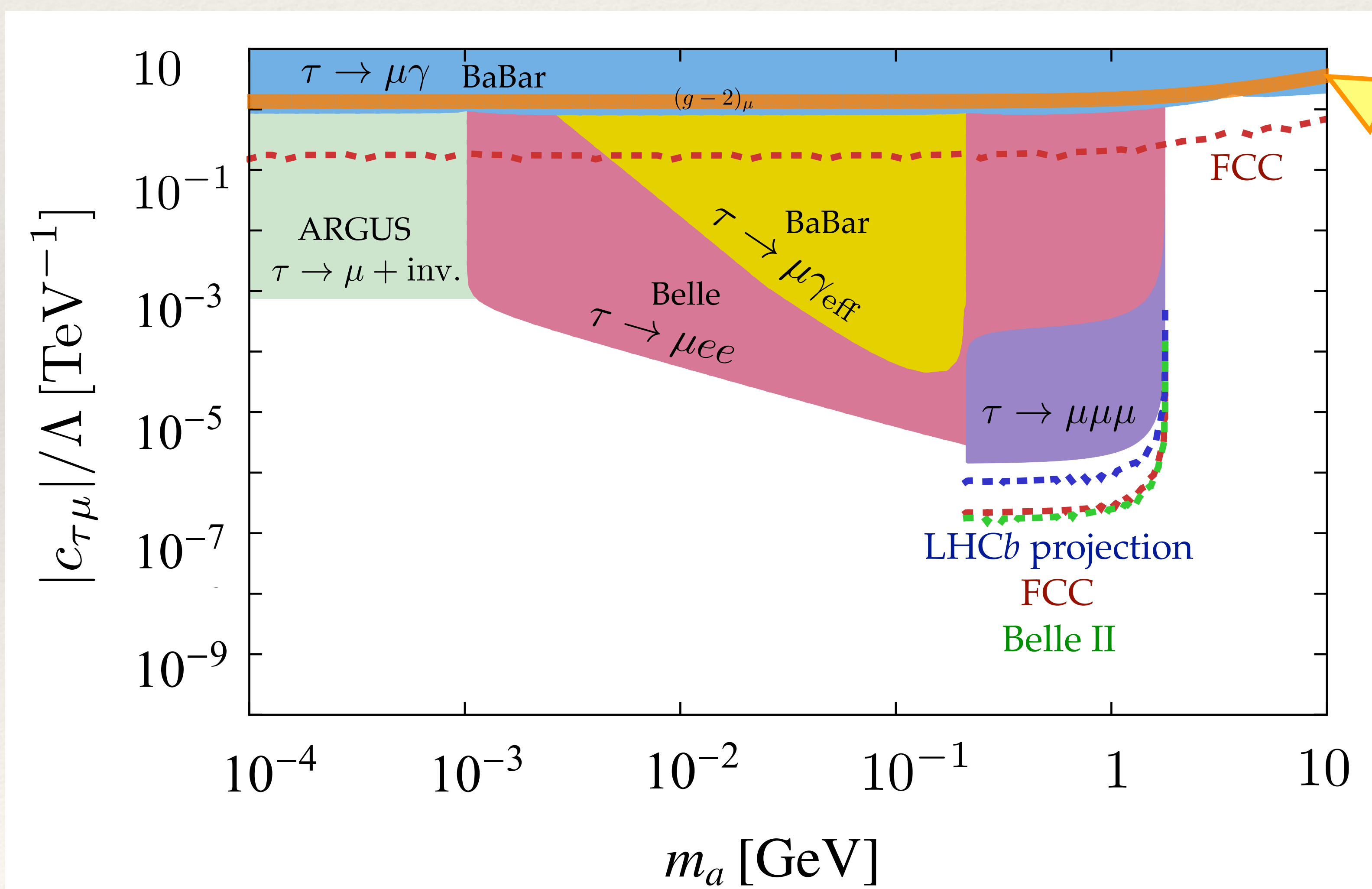
Interesting benchmark scenarios

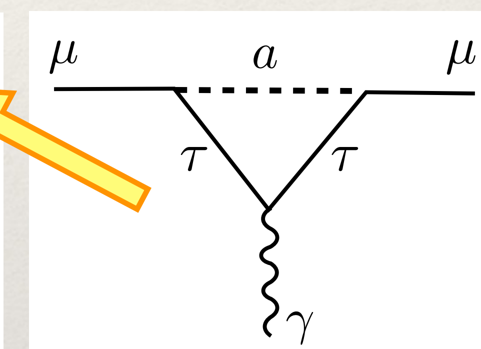
- **Scenario 1′**: Bounds on $c_{\mu e} \equiv \sqrt{2|(K_E)_{\mu e}|^2 + 2|(K_e)_{\mu e}|^2}$ for different values of $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda$ (all other couplings vanish)



Interesting benchmark scenarios

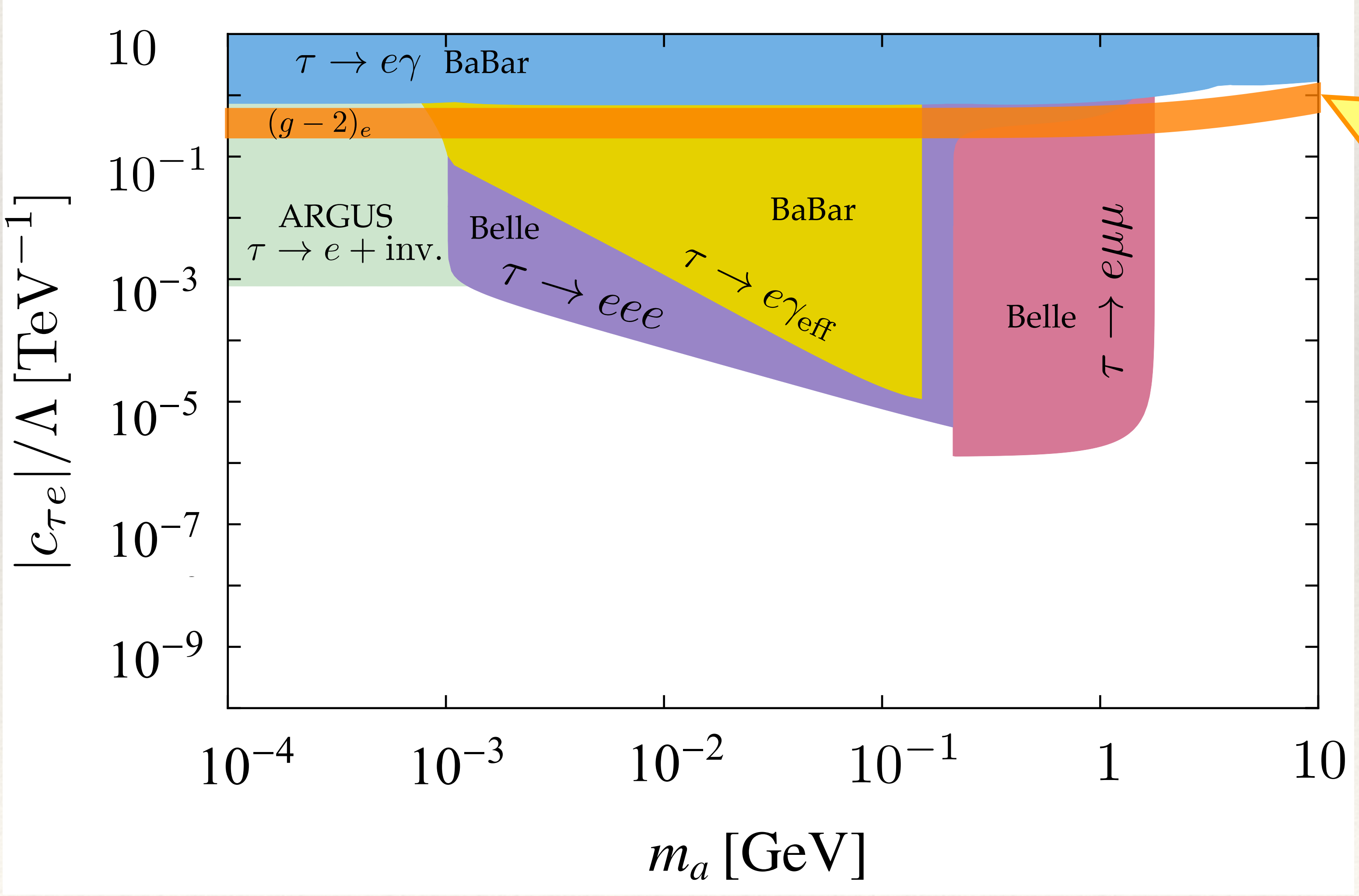
- **Scenario 2**: Bounds on $c_{\tau\mu} \equiv \sqrt{2|(K_E)_{\tau\mu}|^2 + 2|(K_e)_{\tau\mu}|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\,\text{TeV}^{-1}$and all other couplings vanish at tree level

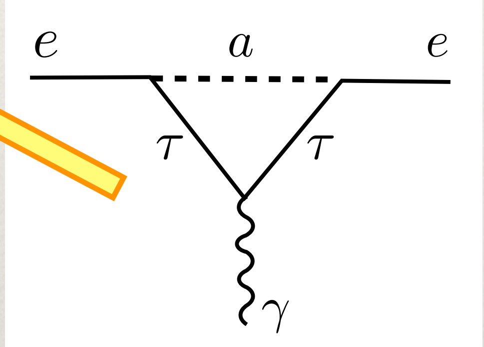




Interesting benchmark scenarios

- **Scenario 2**: Bounds on $c_{\tau e} \equiv \sqrt{2|(K_E)_{\tau e}|^2 + 2|(K_e)_{\tau e}|^2}$, assuming $c_{ee}/\Lambda = c_{\mu\mu}/\Lambda = c_{\tau\tau}/\Lambda = 1\,\mathrm{TeV}^{-1}$ 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} Λ/TeV (quarks) and few 10^{-7} Λ/TeV (leptons)
- In lepton case, ALP represent a class of models where future bounds from Mu3e experiment will outperform those of MEG II