Lepton flavour violation and axion-like particles

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Based on work with M. Bauer, M. Neubert, M. Schnubel and A. Thamm
1908.00008, 2110.10698

Muon4Future, Venice 2023

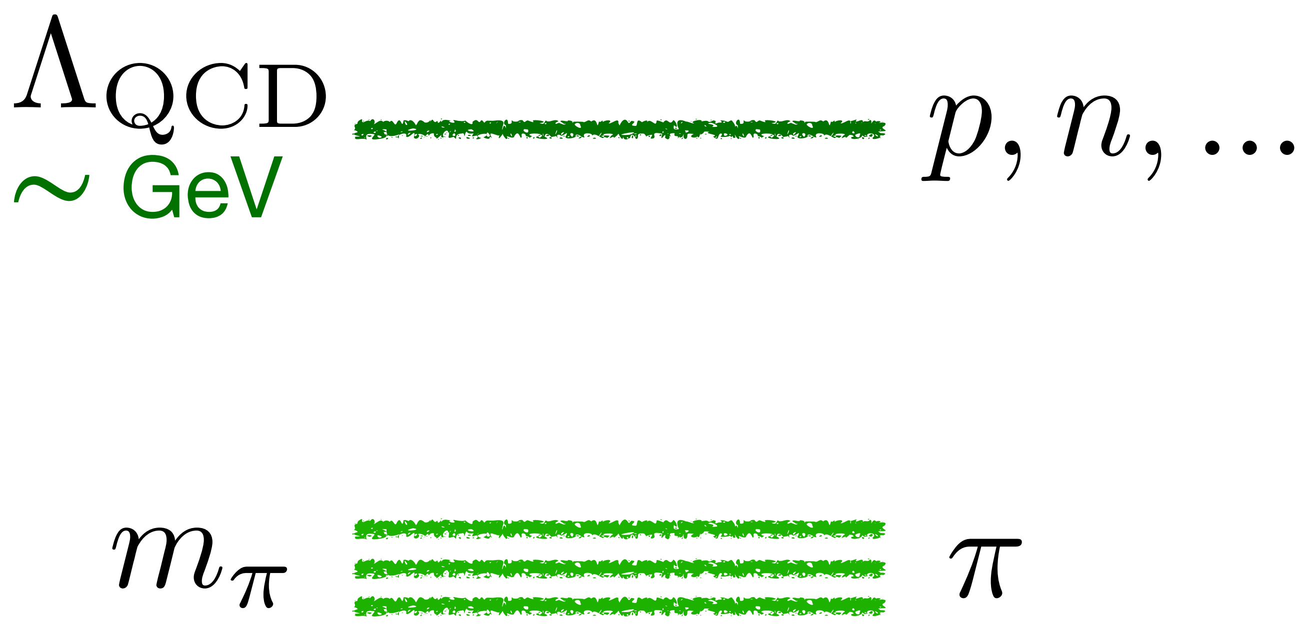
University of Glasgow

UK Research and Innovation

Why axion like particles (ALPs)?

MODEL-BUILDING MOTIVATIONS: Any dynamics with a spontaneously broken approximate global symmetry will produce light spinless particles

Analogy: QCD pions



Pions are pseudo goldstone bosons of an approximate spontaneously broken symmetry

BSM physics

ALP is a pseudo-goldstone boson (PNGB)

Pseudoscalar gauge singlet

Mass much below scale of BSM physics

Many motivated explicit models: e.g. QCD axion, dark sector models, flavon models, composite Higgs models, ...

Why ALPs? Motivations II

MODEL-INDEPENDENT MOTIVATIONS:

All new particles are heavy ($m \gg v$)? → SM EFT (or similar)

One or more light ($m \lesssim v$) BSM particles?

+ possibly higher spin...

spin 0

ALP
(Goldstone boson explains lightness)

spin 1/2

RH neutrino/heavy neutral lepton

spin 1

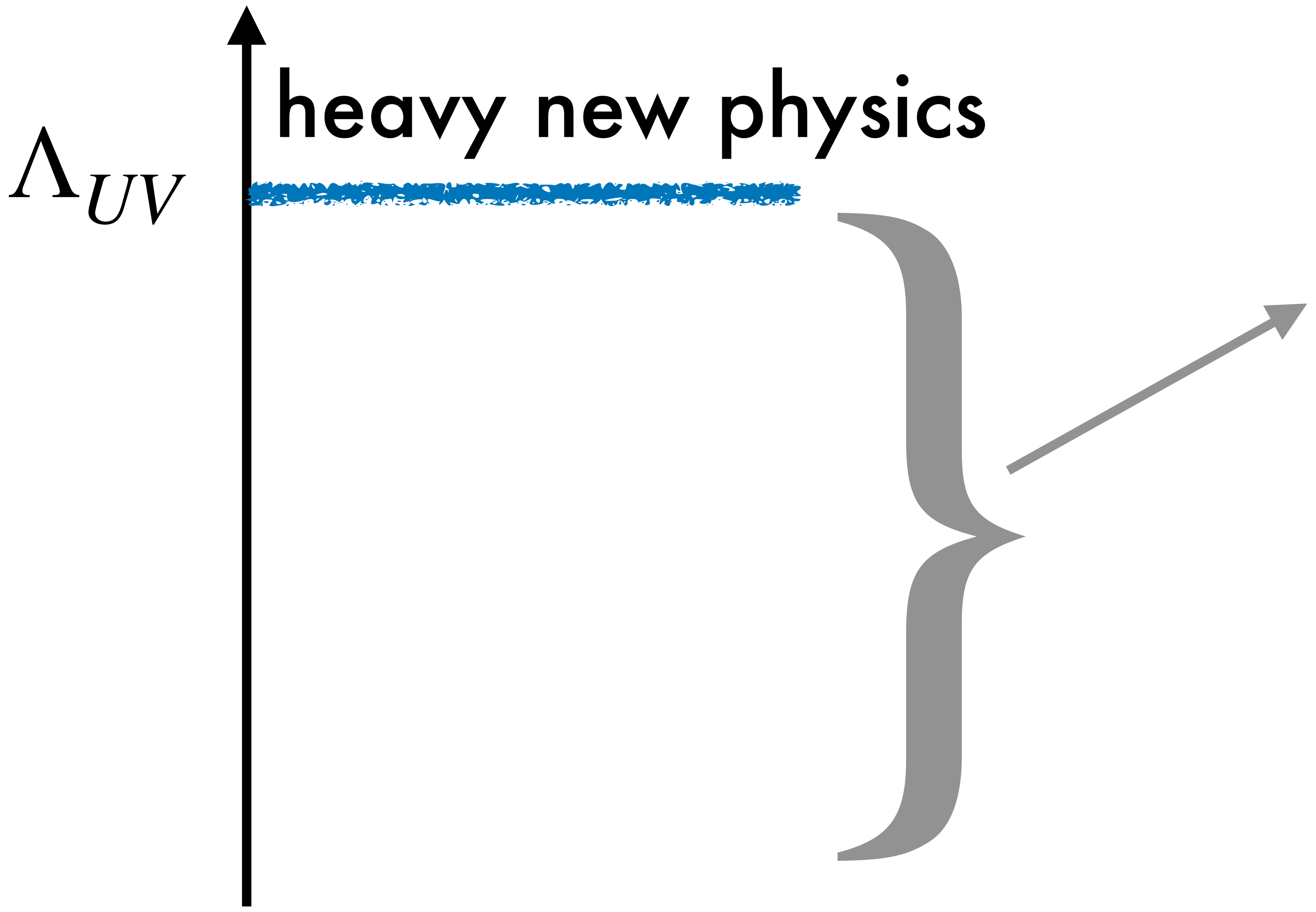
Dark photon/Z'

spin 3/2

e.g. gravitino/ composite dark sector resonance

ALP effective Lagrangian

Don't need to know the details of the UV physics to study ALP phenomenology



Here particle content is SM+ALP

Theory is an EFT, with ALP-SM couplings beginning at dimension 5

$$F = Q, u, d, L, e$$

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \mathbf{c}_F \gamma_\mu \psi_F + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\Lambda_{UV} = 4\pi f$$

Then the parameter space of the model depends on $m_a, f, \mathbf{c}_F, c_{XX}$

hermitian matrices in flavour space

Lepton flavour violating ALPs

$F = Q, u, d, L, e$

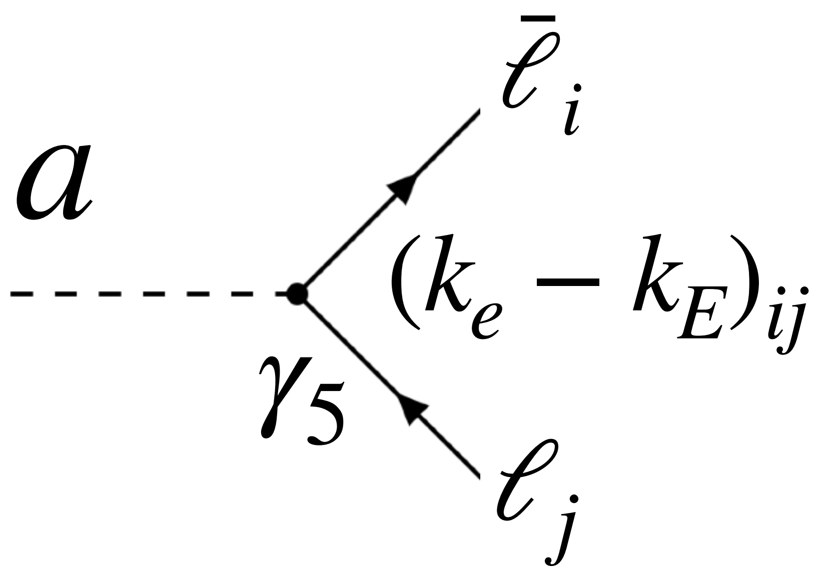
Bjorkeroth, Chun, King, 1806.00660
Bauer, Neubert, SR, Schnubel, Thamm, 1908.00008
Cornella, Paradisi, Sumensari, 1911.06279

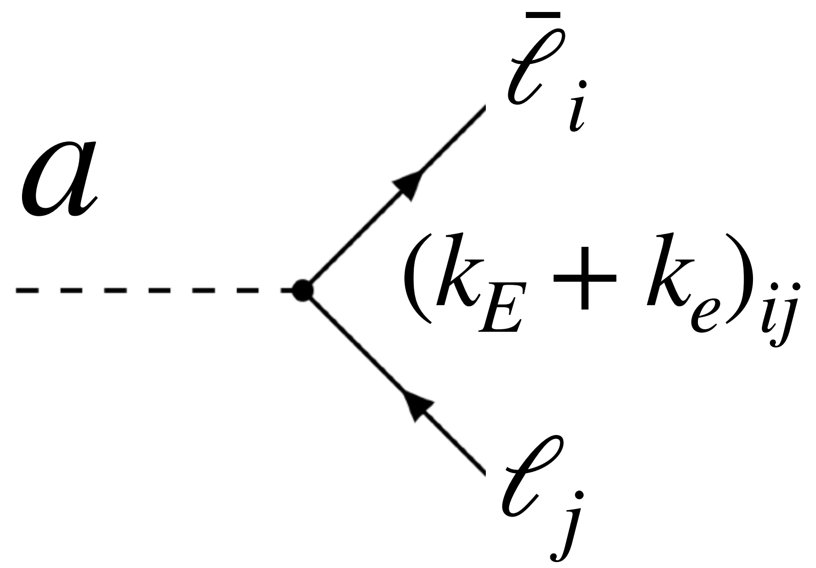
$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\psi_F$$
$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}$$

$$\Lambda_{UV} = 4\pi f$$

Zooming in on the fermionic couplings...

$$\mathcal{L}_{\rm eff}^{\rm LFV} = \frac{\partial^\mu a}{f}\,\left(\bar\ell_i(k_E)_{ij}\gamma_\mu P_L\ell_j + \bar\ell_i(k_e)_{ij}\gamma_\mu P_R\ell_j\right)$$





LFV ALPs can naturally arise as PNGBs of symmetries addressing

- the strong CP problem (DFSZ axion) Calibbi, Redigolo, Ziegler, Zupan, 2006.04795
- the flavour problem (familon) Linster, Ziegler 1805.07341, Calibbi, Redigolo, Ziegler, Zupan 2006.04795
- neutrino masses (majoron) Chikashige, Mohapatra, Peccei 1981, Schechter & Valle 1982, Garcia-Cely & Heeck 1701.07209, Heeck & Patel 1909.02029

if $i = j$, only pseudoscalar coupling

Light vs heavy BSM particles and LFV

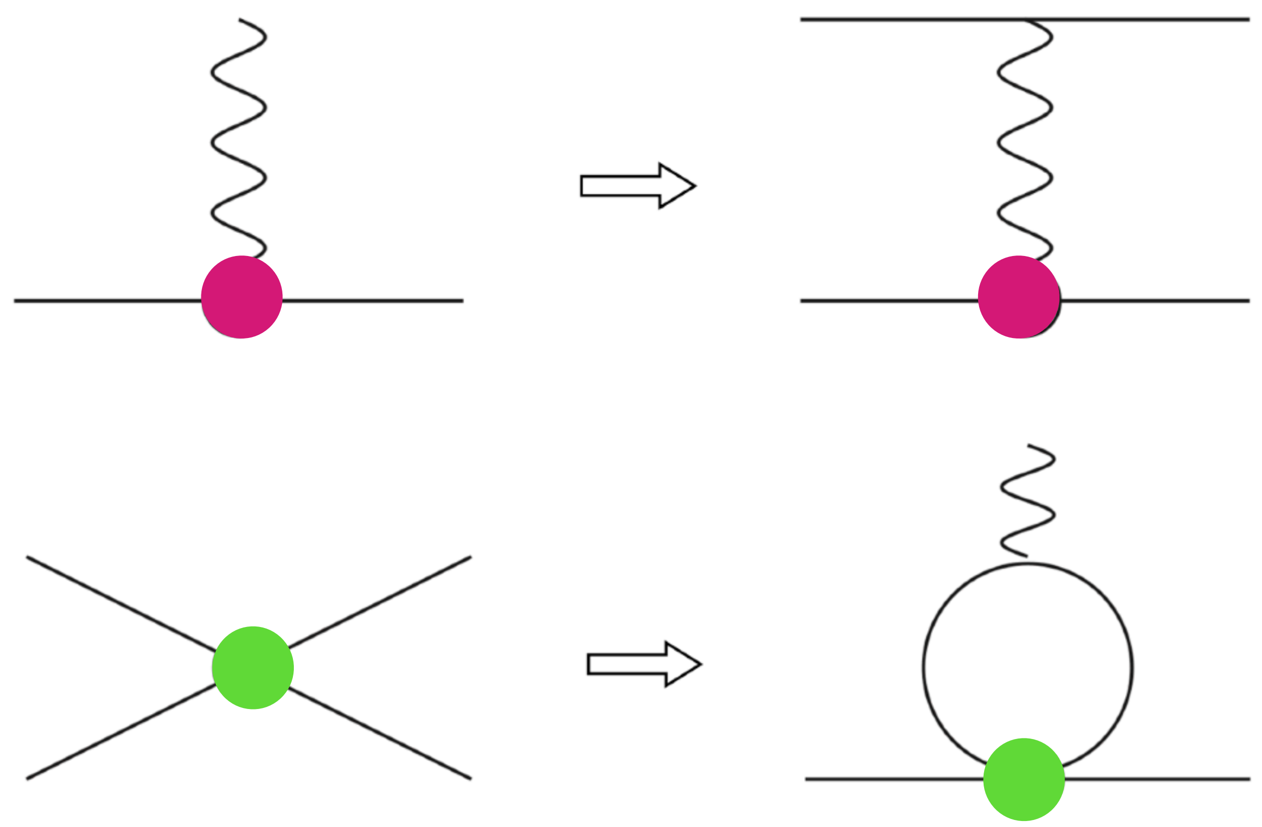
For LFV generated by heavy particles, expect certain patterns of effects

See A. Teixeira's talk

$$\mathcal{L} = \frac{C_1}{\Lambda^2} m_\mu \bar{\mu} \sigma_{\mu\nu} F^{\mu\nu} e + \frac{C_2}{\Lambda^2} (\bar{\mu}\Gamma_1 e)(\bar{e}\Gamma_2 e)$$

Dipole operator
$\mu \to e\gamma$

4-lepton operator
$\mu \to 3e$



Each operator generates the other

Calibbi & Signorelli, 1709.00294
Davidson, 2010.00317

Light vs heavy BSM particles and LFV

For LFV generated by heavy particles, expect certain patterns of effects

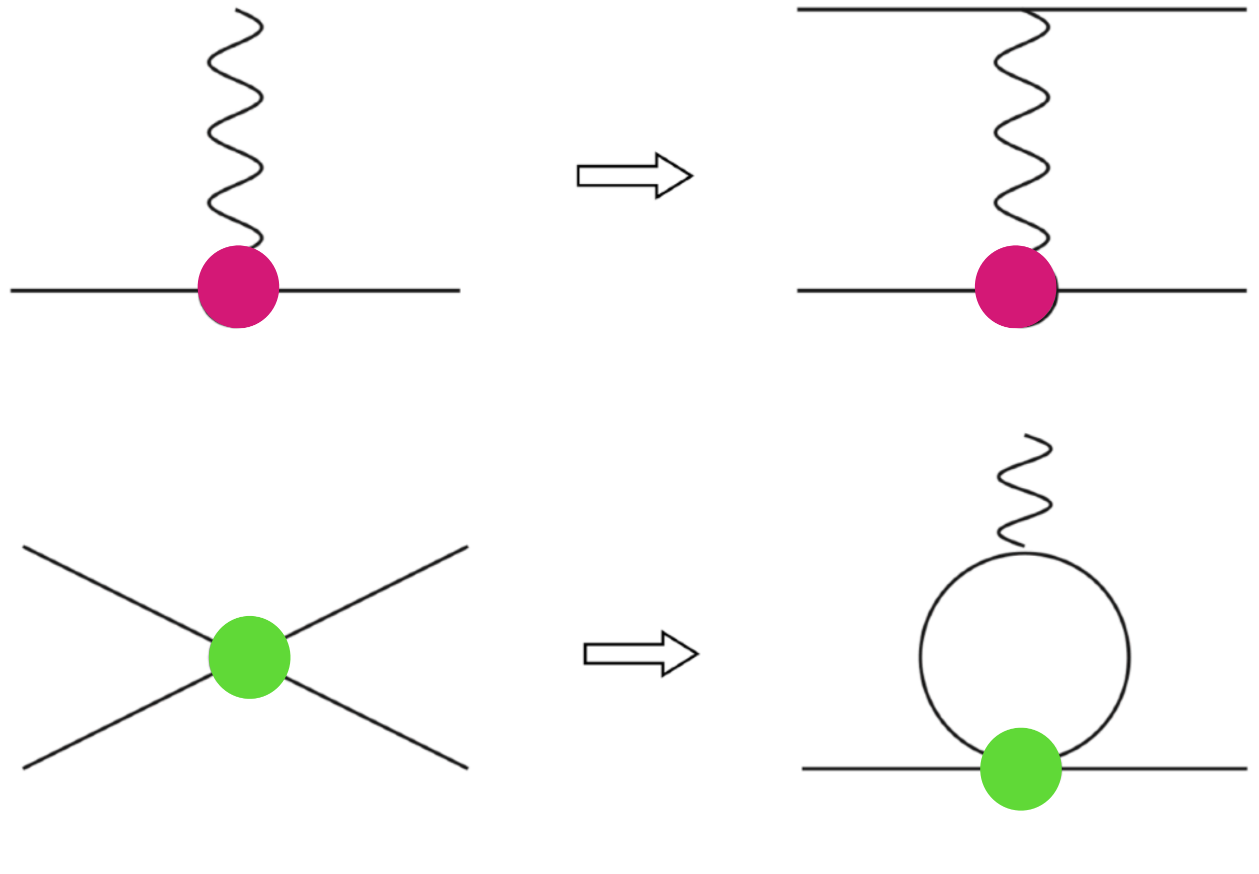
See A. Teixeira's talk

Contact interactions:

$$\mathcal{L} = \frac{C_1}{\Lambda^2} m_\mu \bar{\mu} \sigma_{\mu\nu} F^{\mu\nu} e + \frac{C_2}{\Lambda^2} (\bar{\mu}\Gamma_1 e)(\bar{e}\Gamma_2 e)$$

Dipole operator $\mu \to e\gamma$

4-lepton operator $\mu \to 3e$



Each operator generates the other

Calibbi & Signorelli, 1709.00294
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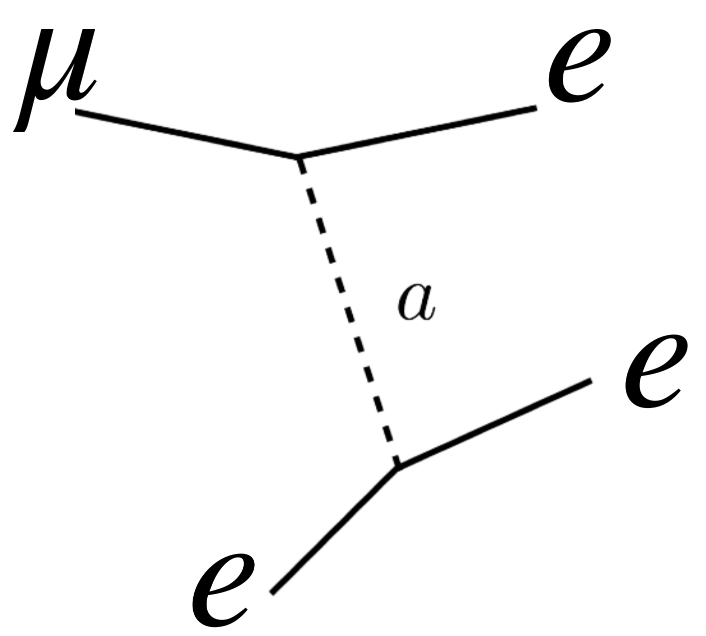
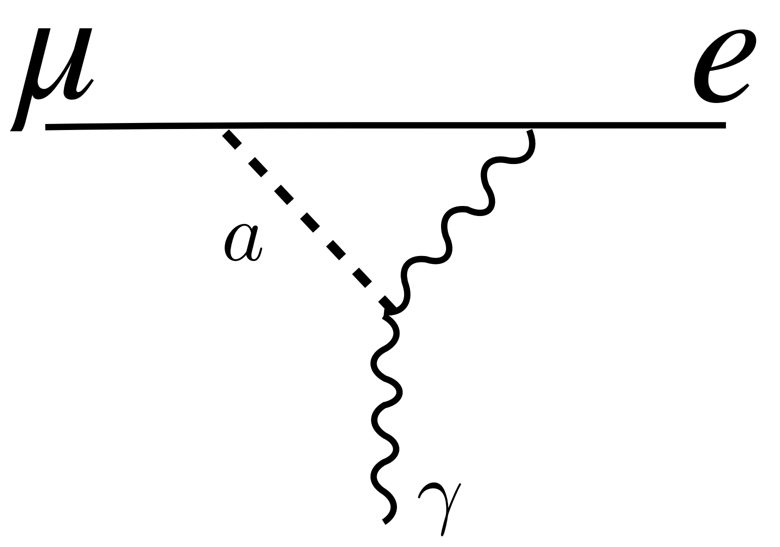
But with light particles, things can be different

If $m_a < m_\mu - m_e$, then can get a resonant contribution to $\mu \to 3e$

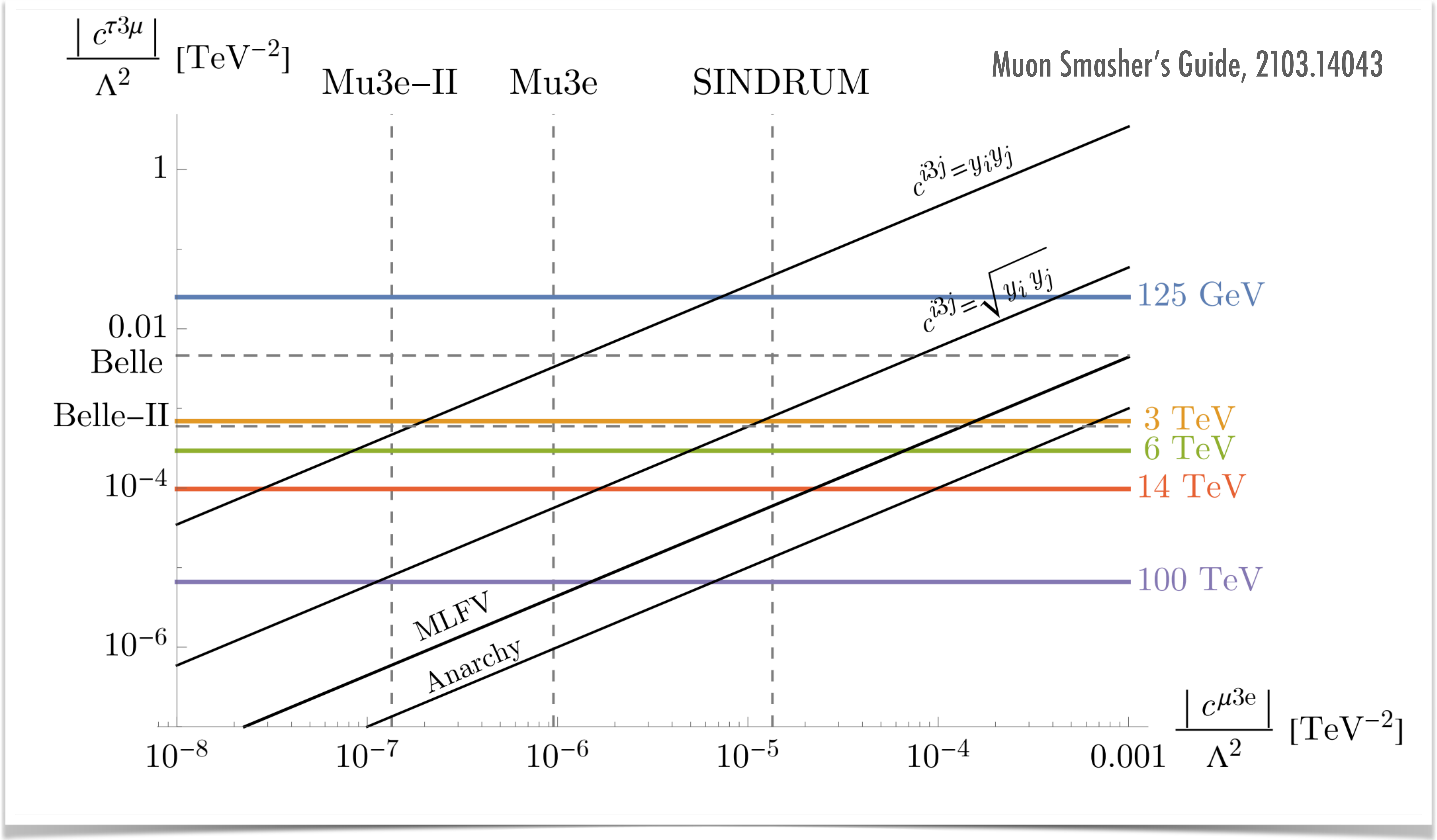
$\mu \to ea \ (a \to e^+e^-)$

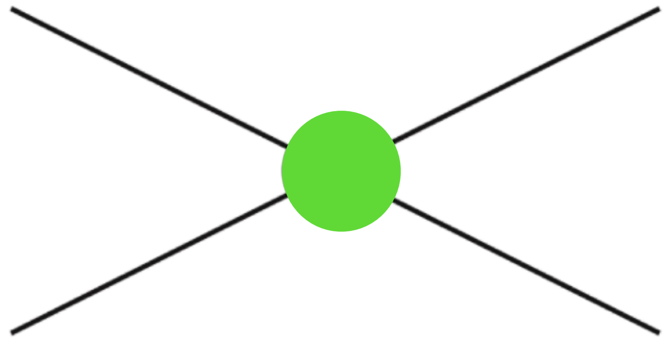


Can be orders of magnitude more sensitive than $\mu \to e\gamma$, which is loop generated



(Same argument for $\tau \to 3\mu$ and $\tau \to \mu\gamma$, etc)





rate $\propto s$

For light new physics ($m < \sqrt{s}$), the picture changes, need to think about direct production

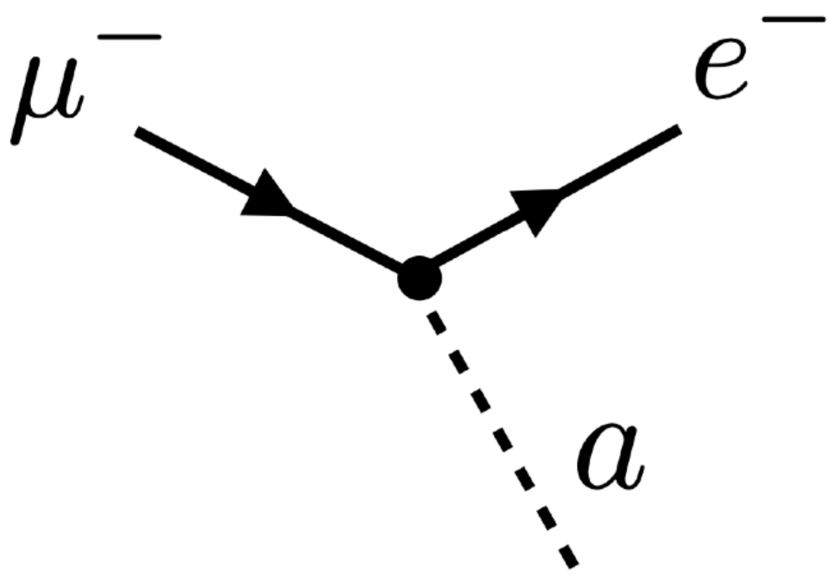
Electroweak production of ALPs at muon collider: Han, Li, Wang 2203.05484, Bao, Fan, Li 2203.04328

Production of ALPs at muon collider via $\tau \to \mu a$ decay: Haghighat, Najafabadi 2106.00505

Muon decays to ALPs

If LFV ALPs are light enough, can be produced on-shell in muon decays

Signatures depend strongly on ALP decay length and branching ratios



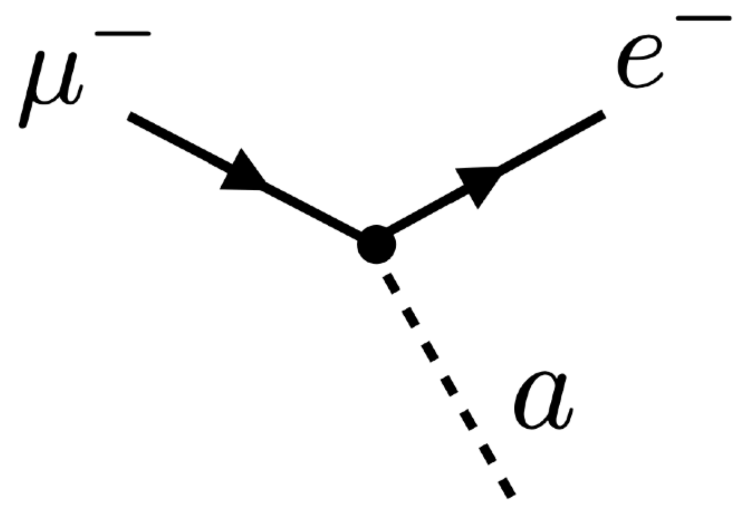
Decay mode:	**Signature:**
Long-lived	$\mu \to e + \text{invisible}$
$a \to \gamma\gamma$	$\mu \to e\gamma\gamma$ $(\mu \to e\gamma)$
$a \to e^+e^-$	$\mu \to 3e$

In many models, the ALP will contribute to all of these

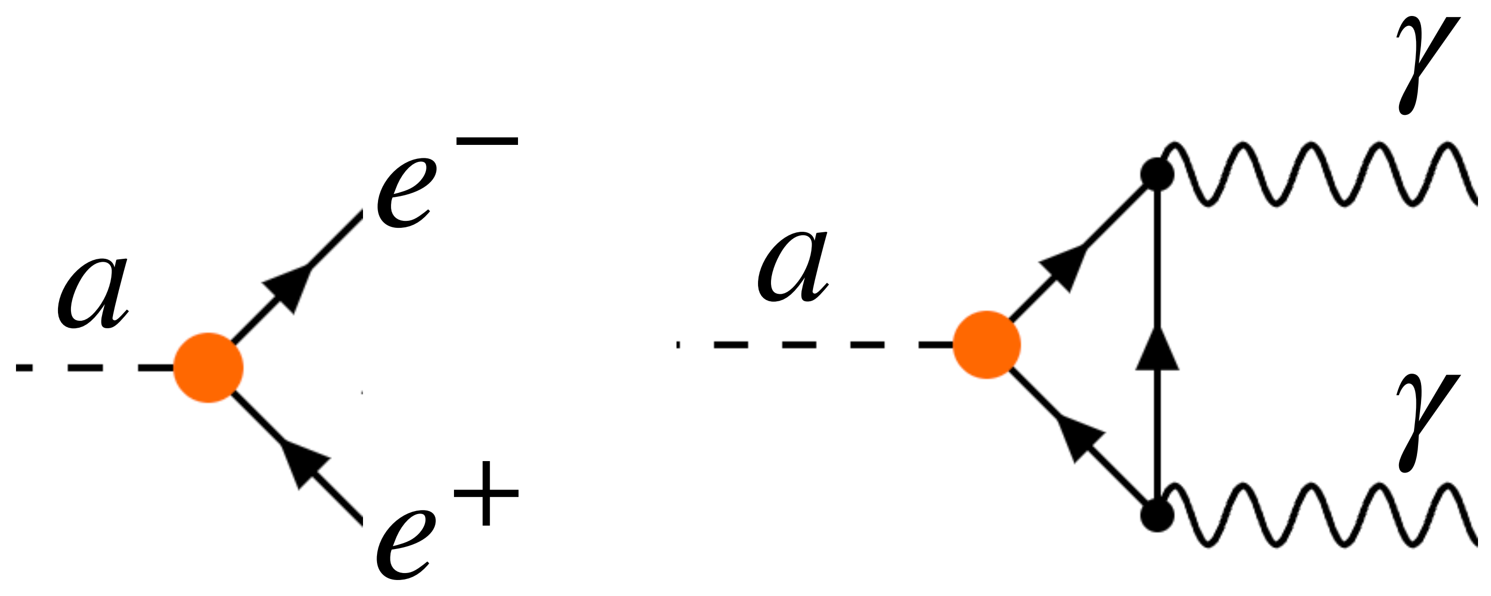
Effect of flavour conserving couplings

Simple scenario with only leptonic couplings at tree level

ALP production:



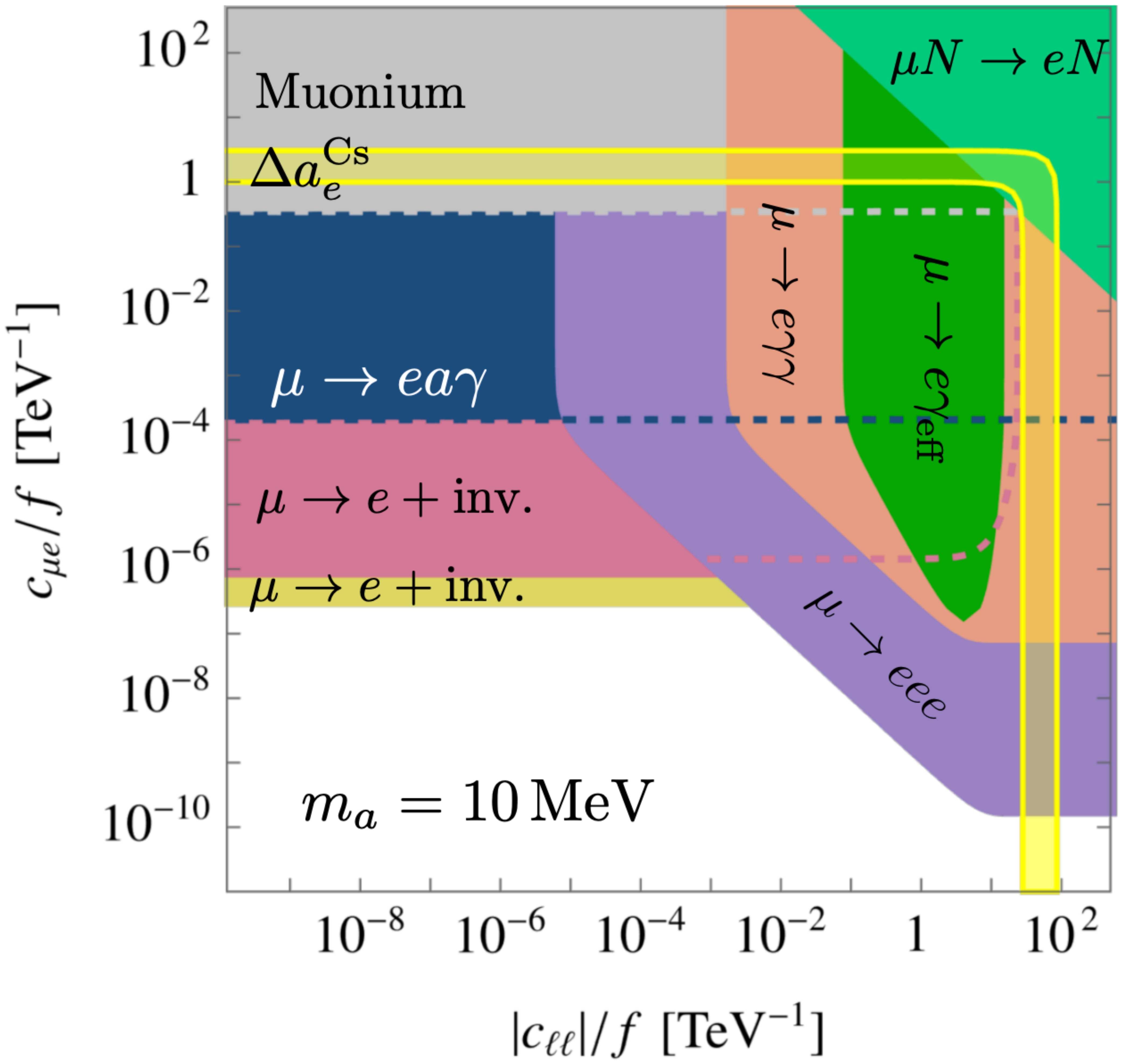
ALP decay:



$$\mathcal{L}_{\rm eff}^{\rm LFV} = \frac{\partial^\mu a}{f}\left(\bar{\ell}_i (k_E)_{ij}\gamma_\mu P_L \ell_j + \bar{\ell}_i (k_e)_{ij}\gamma_\mu P_R \ell_j\right)$$

$$c_{ij} \equiv \sqrt{|(k_e)_{ij}|^2 + |(k_E)_{ij}|^2} \quad i \neq j$$

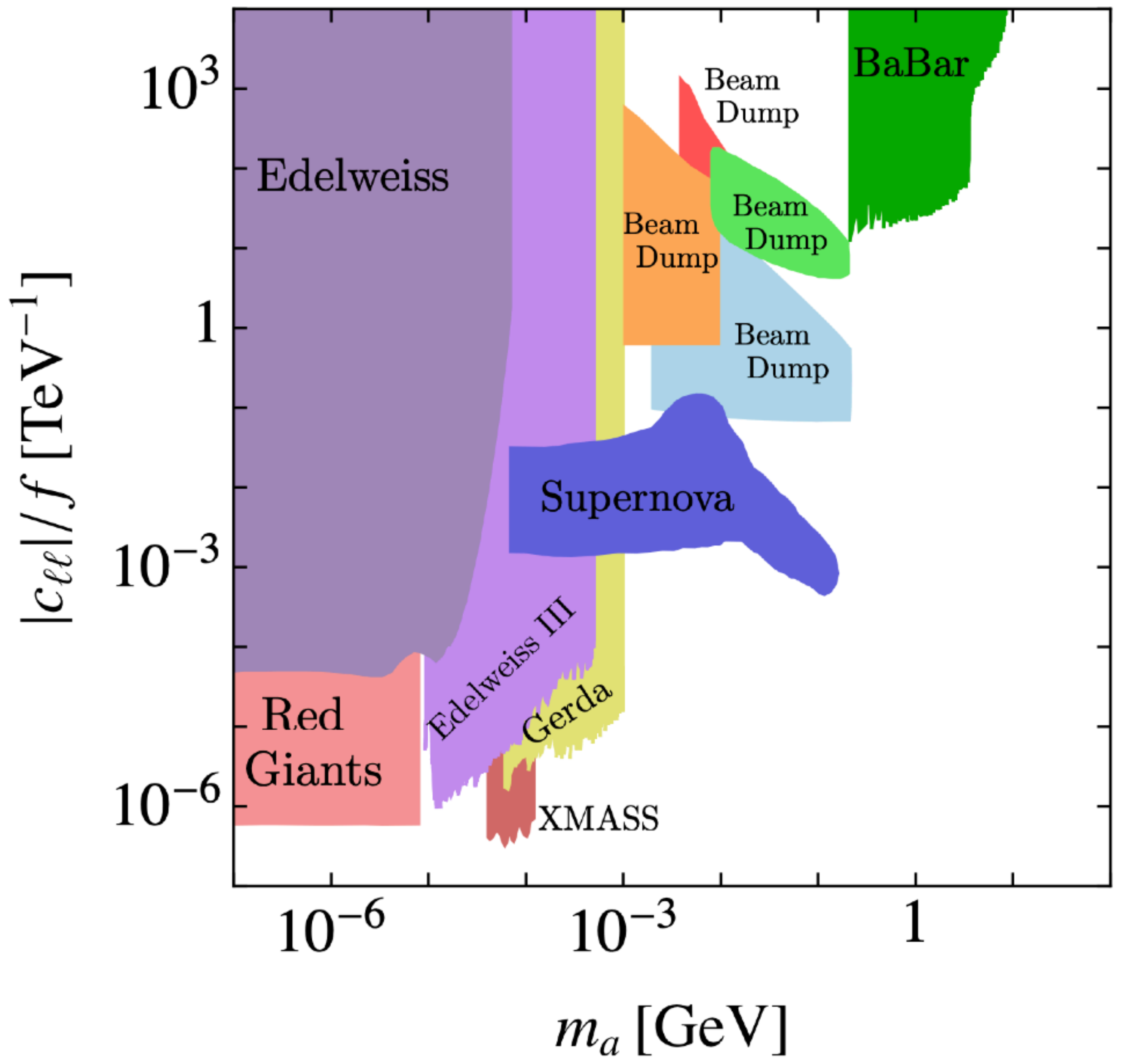
Bauer, Neubert, SR, Schnubel, Thamm, 2110.10698



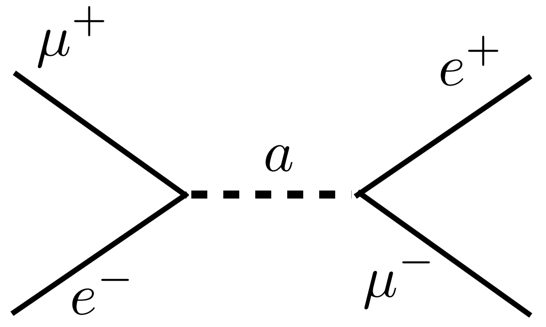
Mass dependence

For ALP masses too heavy to be produced in muon decays, $\mu \to e\gamma$ and $\mu \to 3e$ can still be constraining

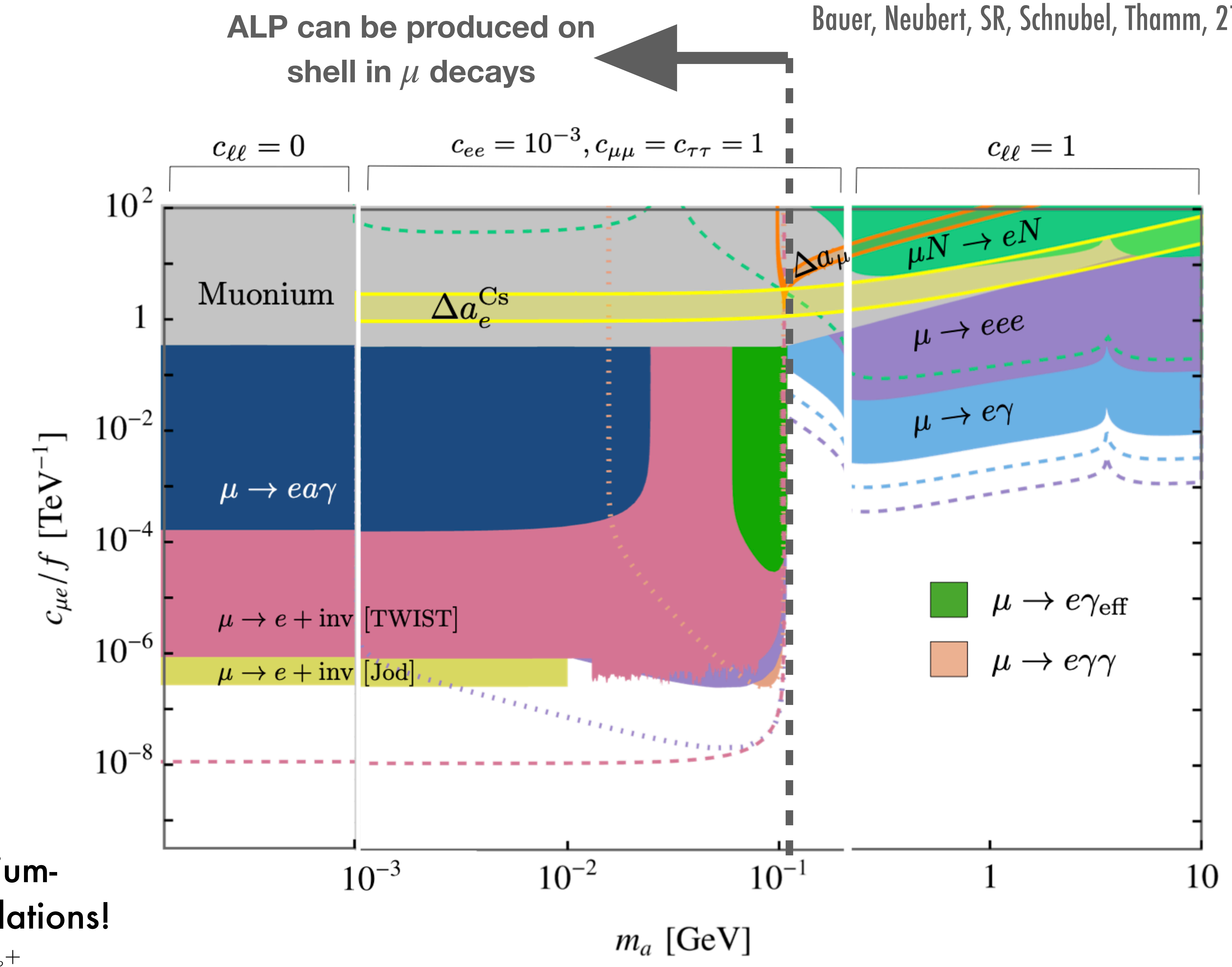
All* LFV bounds depend on choice for flavour-conserving couplings, chosen to be consistent with other bounds:



*except muonium-antimuonium oscillations!



Bauer, Neubert, SR, Schnubel, Thamm, 2110.10698



Projected limits: MEGII $\mu \to e + \mathrm{inv}$ * MEGII $\mu \to e\gamma$

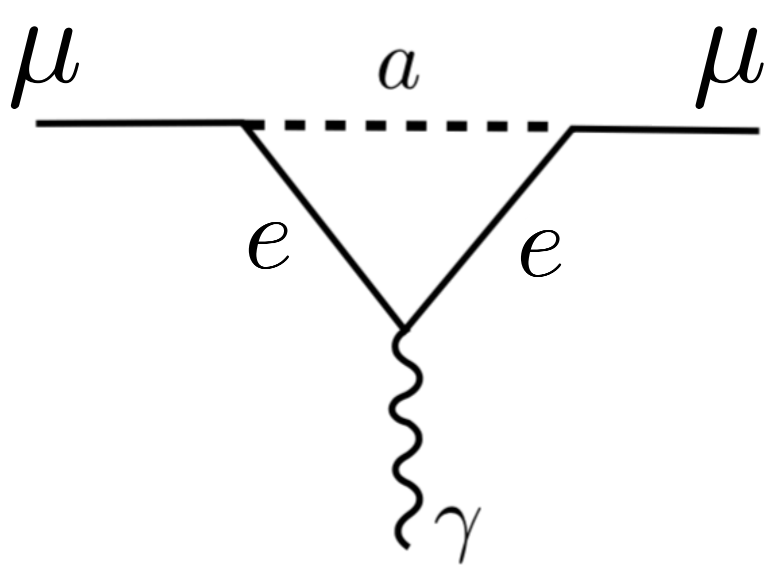
Mu3E $\mu \to 3e$

Could be improved with a forward calorimeter, see 2006.04795

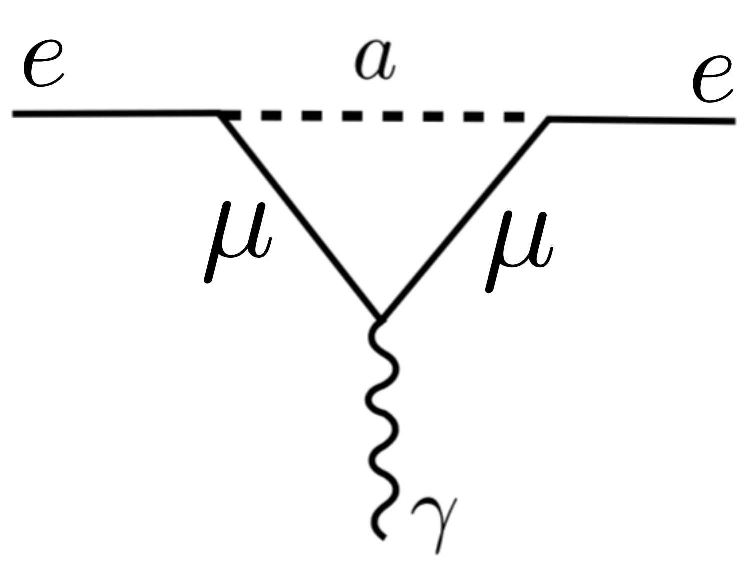
$(g-2)_\ell$ from $\mu - e$ lepton flavour violation

See P. Paradisi's talk

An ALP with $\mu - e$ couplings will give contributions to $(g-2)$ of electron and muon:

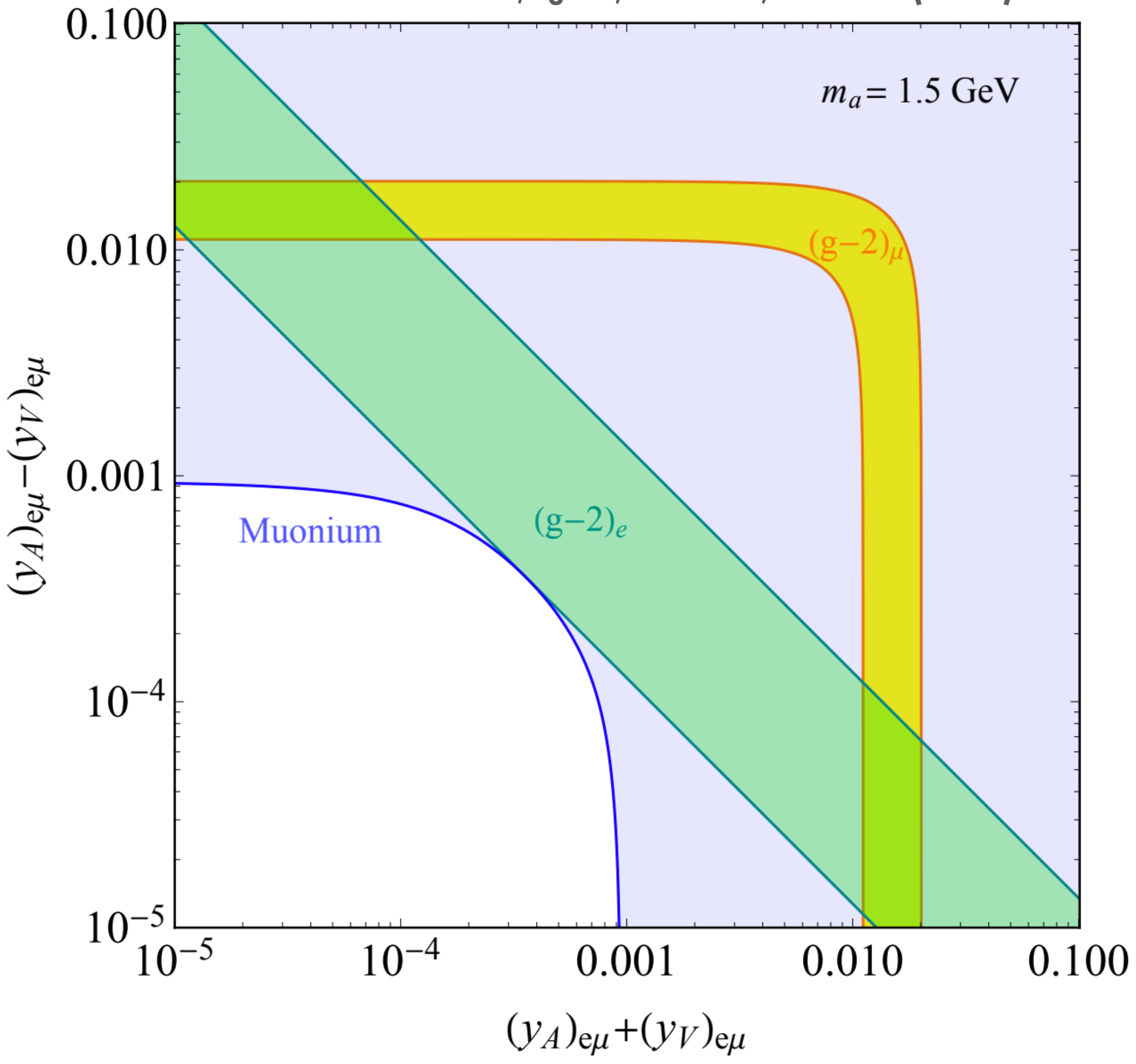


$(g-2)_\mu$

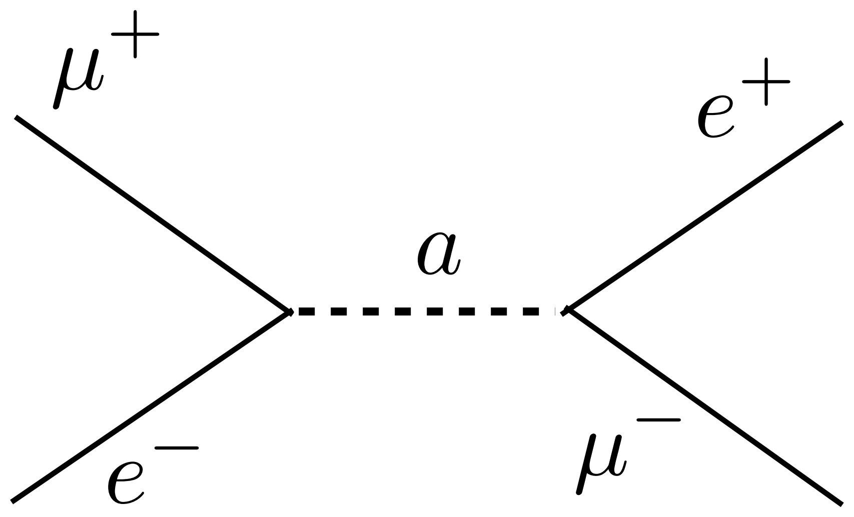


$(g-2)_e$

Endo, Iguro, Kitahara, JHEP 06 (2020) 040



But it will also contribute to muonium-antimuonium oscillations:

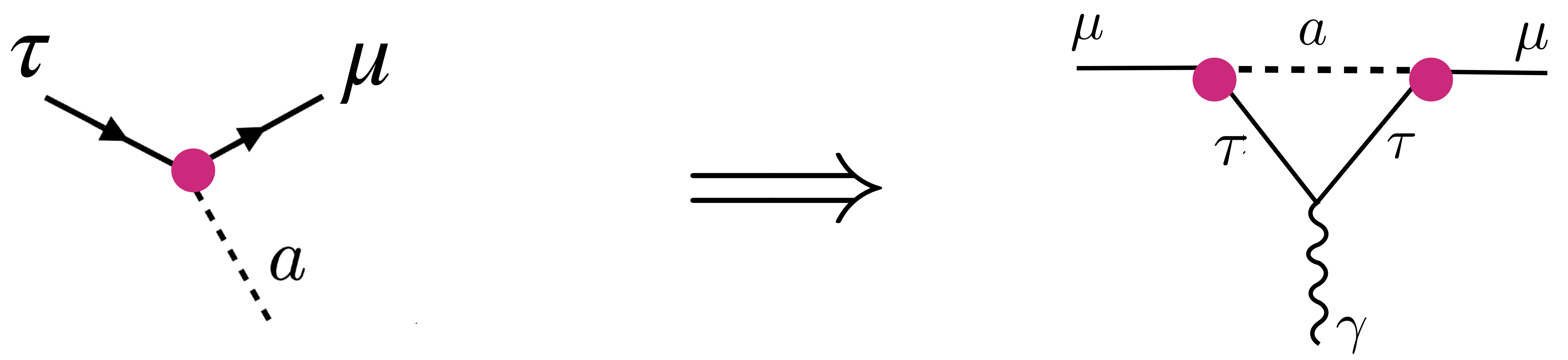


MACS collaboration, PRL 82 (1999) 49-52

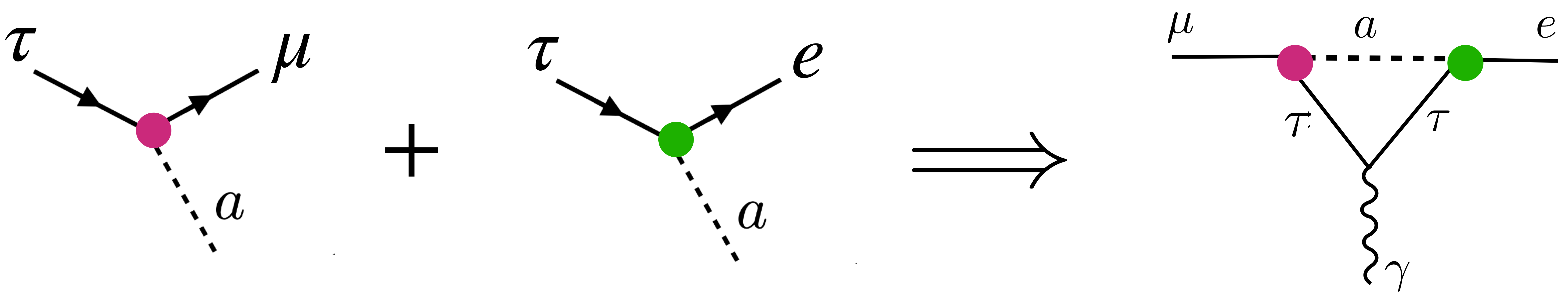
Lepton flavour violation with τs

An ALP with (only) couplings involving τs can nevertheless impact μ observables at loop level

The heavy τ in the loop enhances the effect



$(g-2)_\mu$



$\mu \to e\gamma$

Summary

- ALPs are a generic and motivated option for BSM physics
- Lepton flavour violating ALPs could be discovered in muon decays
- Interplays and complementarity with flavour conserving observables and LFV in τs

Backup

Lepton flavour violating ALPs

Bjorkeroth, Chun, King, 1806.00660
Bauer, Neubert, SR, Schnubel, Thamm, 1908.00008
Cornella, Paradisi, Sumensari, 1911.06279

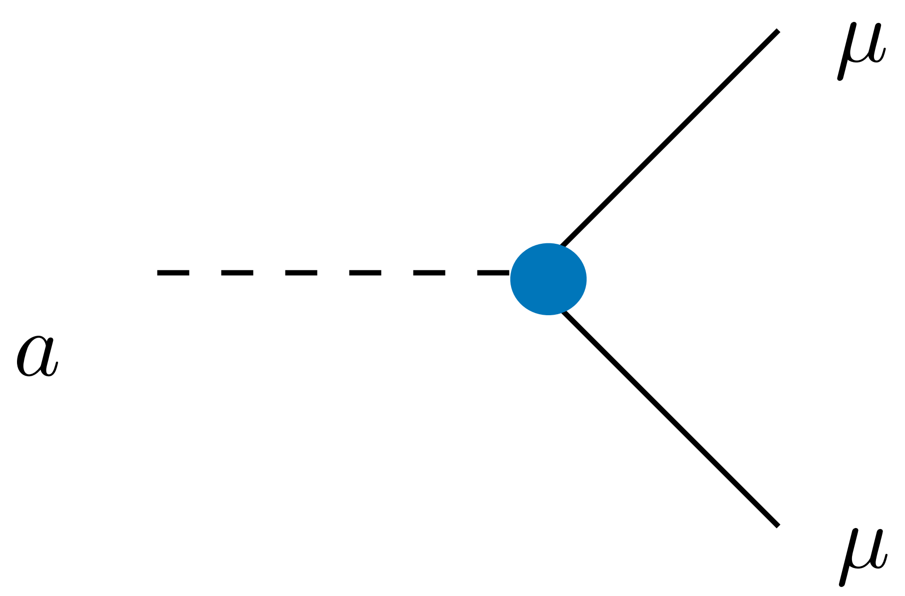
pseudoscalar coupling

$$\frac{\partial a}{f}\sum_i \bar{\ell}_i (k_E)_{ij}\gamma_\mu P_L \ell_j + \bar{\ell}_i (k_e)_{ij}\gamma_\mu P_R \ell_j = \frac{a}{f}\sum_i \bar{\ell}_i \left[(k_e)_{ij} - (k_E)_{ij}\right](m_i + m_j)\gamma_5 \ell_j + \bar{\ell}_i \left[(k_e)_{ij} + (k_E)_{ij}\right](m_i - m_j)\ell_j$$

scalar coupling

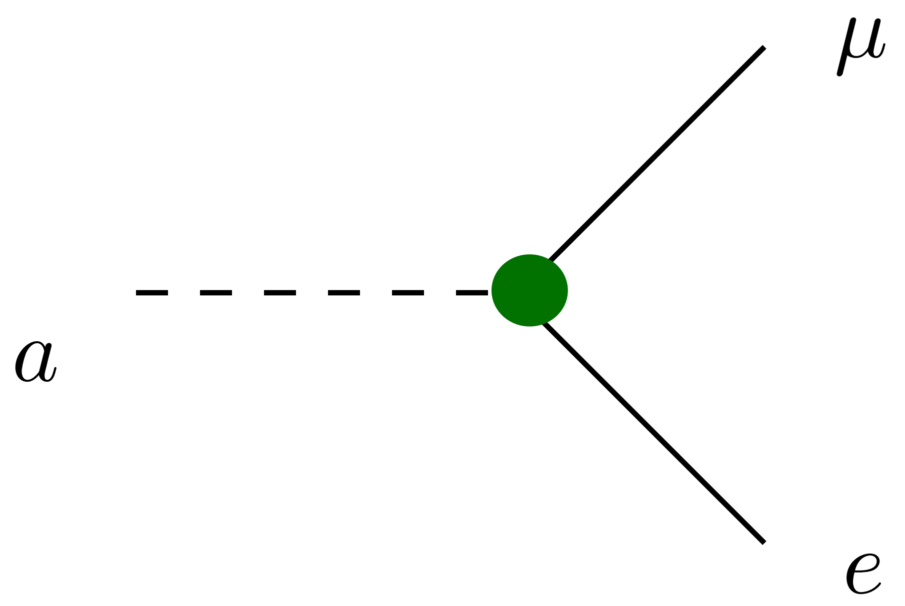
Flavour conserving

$$c_{\mu\mu} = (k_e)_{\mu\mu} - (k_E)_{\mu\mu}$$



Flavour violating

$$c_{\mu e} = \sqrt{|(k_e)_{\mu e}|^2 + |(k_E)_{\mu e}|^2}$$



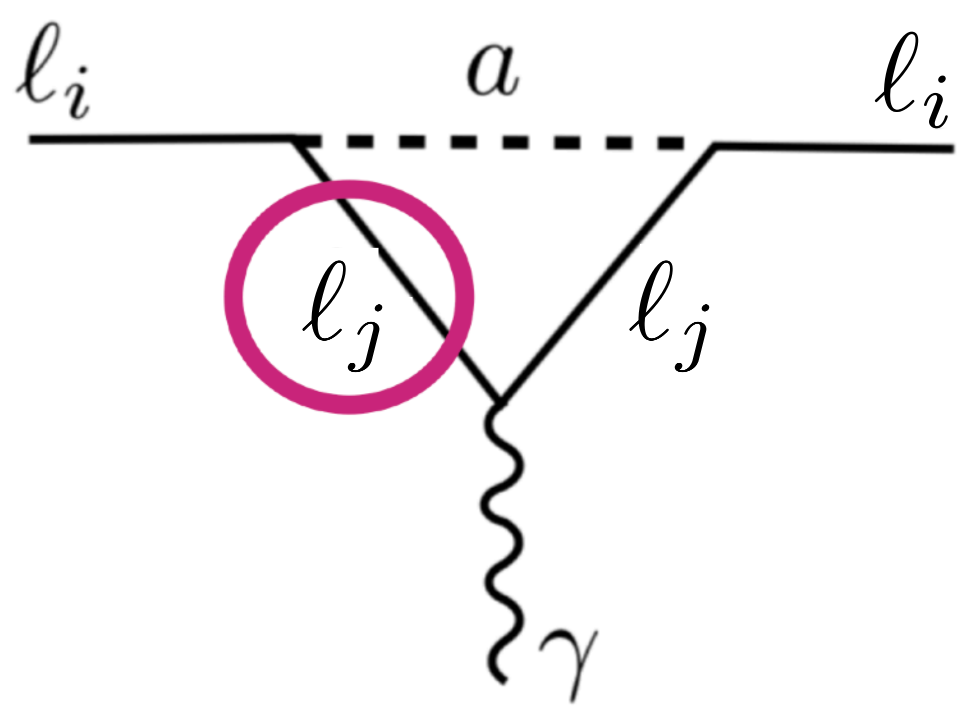
$(g-2)_\ell$ from lepton flavour violation

Lagrangian

Bauer, Neubert, SR, Schnubel, Thamm, PRL 124 (2020) 21

$$\mathcal{L}_{\rm eff}^{\rm LFV} = \frac{\partial^\mu a}{f}\left(\bar\ell_i (k_E)_{ij}\gamma_\mu P_L \ell_j + \bar\ell_i (k_e)_{ij}\gamma_\mu P_R \ell_j\right)$$

New contribution to (g-2), dependent on mass of lepton in loop



lighter lepton in loop $m_{\ell_j} < m_{\ell_i}$

$$\Delta a_{\ell_i} = \frac{m_{\ell_i}^2}{16\pi^2 f^2}\left(|(k_e)_{ij}|^2 + |(k_E)_{ij}|^2\right)\left(x_i^2 \ln\frac{x_i}{x_i-1} - x_i - \frac{1}{2}\right)$$

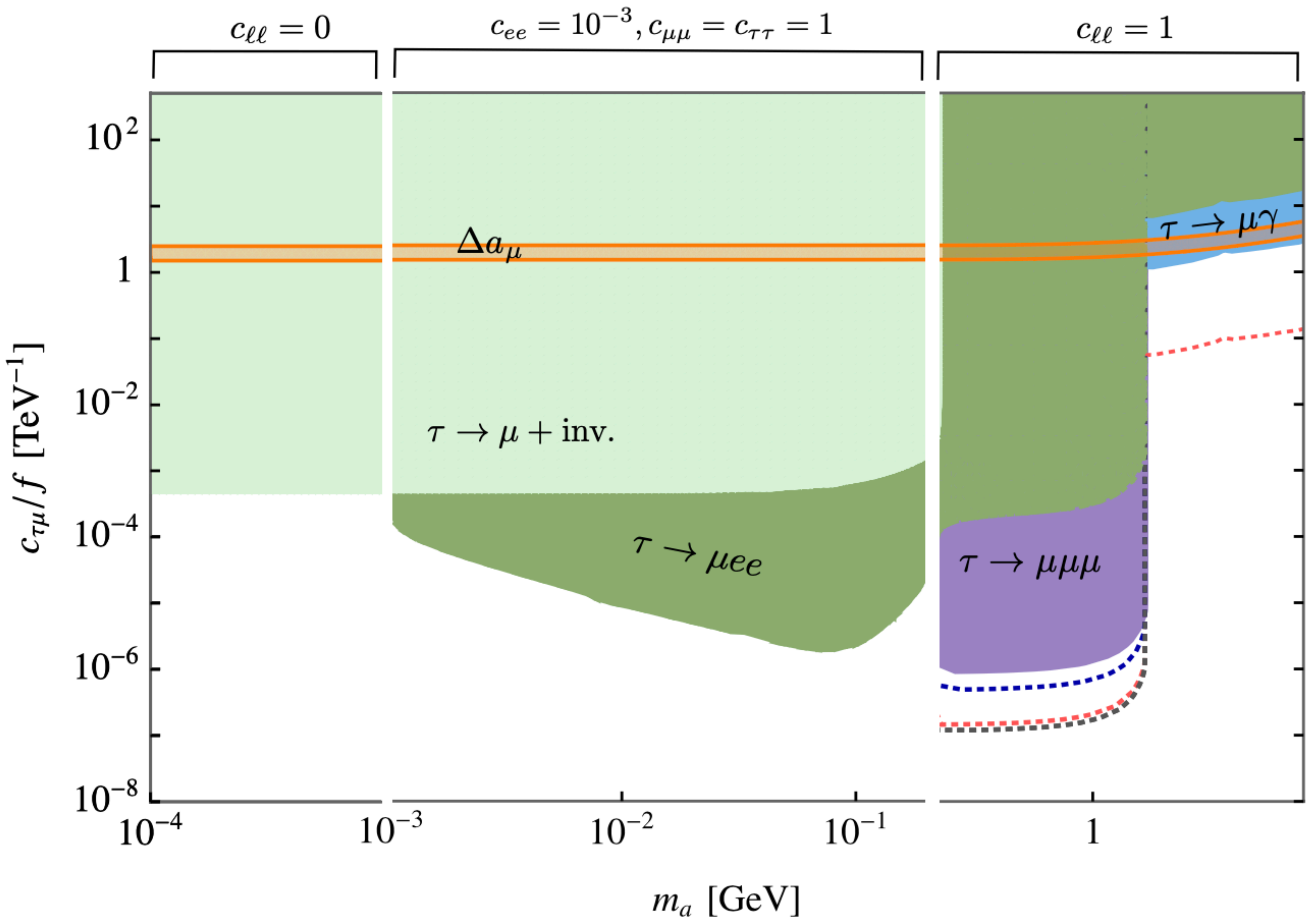
Always *positive* if $m_a > m_i$

heavier lepton in loop $m_{\ell_j} > m_{\ell_i}$

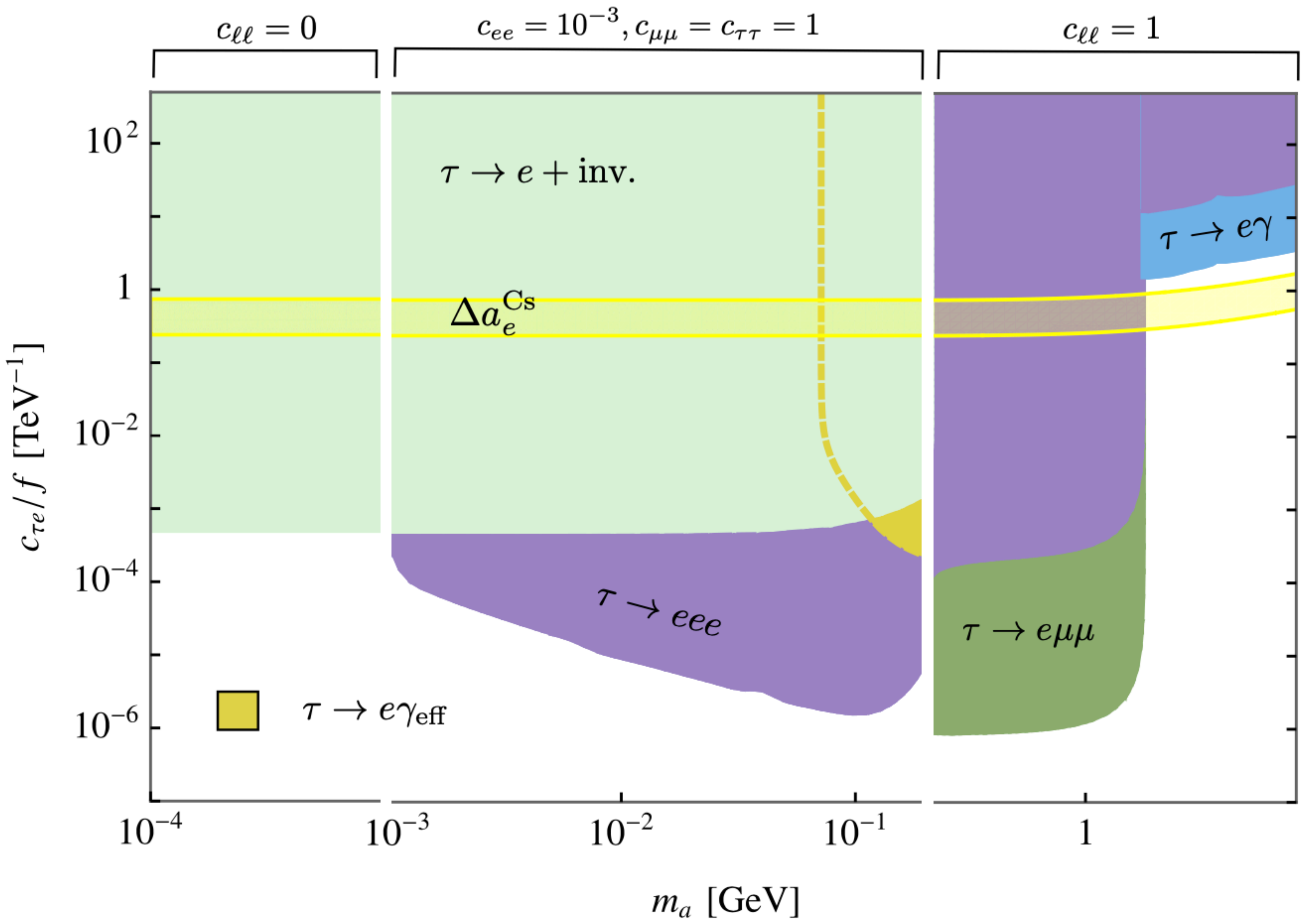
$$x_i = \frac{m_a^2}{m_{\ell_i}^2}$$

$$\Delta a_{\ell_i} = \frac{m_{\ell_i} m_{\ell_j}}{8\pi^2 f^2}{\rm Re}\left[(k_e)_{ij}^*(k_E)_{ij}\right]\left(x_j^2 \ln\frac{x_j}{(x_j-1)^3} - \frac{3x_j-1}{2(x_j-1)^2}\right)$$

Can be *positive or negative* depending on sign of couplings



$c_{\ell\ell} = 0$
$c_{ee} = 10^{-3}, c_{\mu\mu} = c_{\tau\tau} = 1$
$c_{\ell\ell} = 1$
Δa_μ
$\tau \to \mu\gamma$
$\tau \to \mu + \text{inv.}$
$\tau \to \mu ee$
$\tau \to \mu\mu\mu$
$c_{\tau\mu}/f$ [TeV^{-1}]
m_a [GeV]

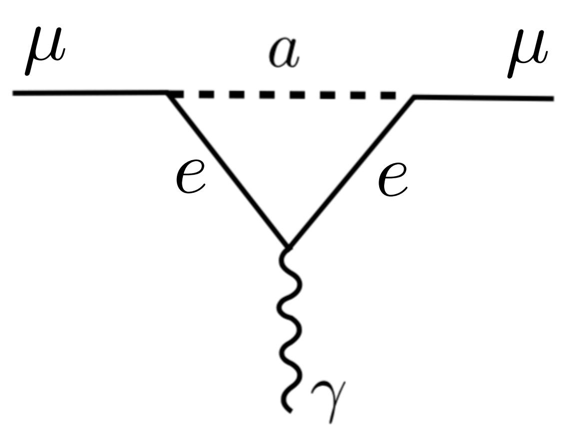


$c_{\ell\ell} = 0$
$c_{ee} = 10^{-3}, c_{\mu\mu} = c_{\tau\tau} = 1$
$c_{\ell\ell} = 1$
$\tau \to e + \text{inv.}$
$\tau \to e\gamma$
Δa_e^{Cs}
$\tau \to eee$
$\tau \to e\mu\mu$
$\tau \to e\gamma_{\text{eff}}$
$c_{\tau e}/f$ [TeV^{-1}]
m_a [GeV]

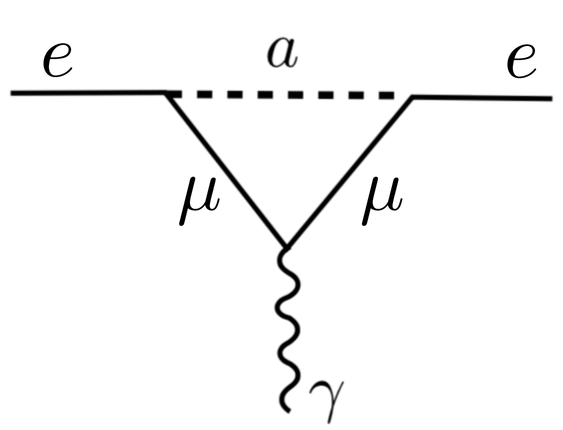
Combined explanations with LFV?

Bauer, Neubert, SR, Schnubel, Thamm, PRL 124 (2020) 21

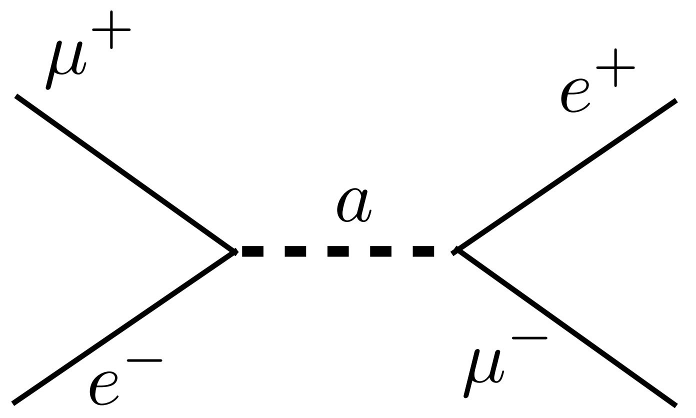
<u>μ-e couplings</u>



$(g-2)_\mu$



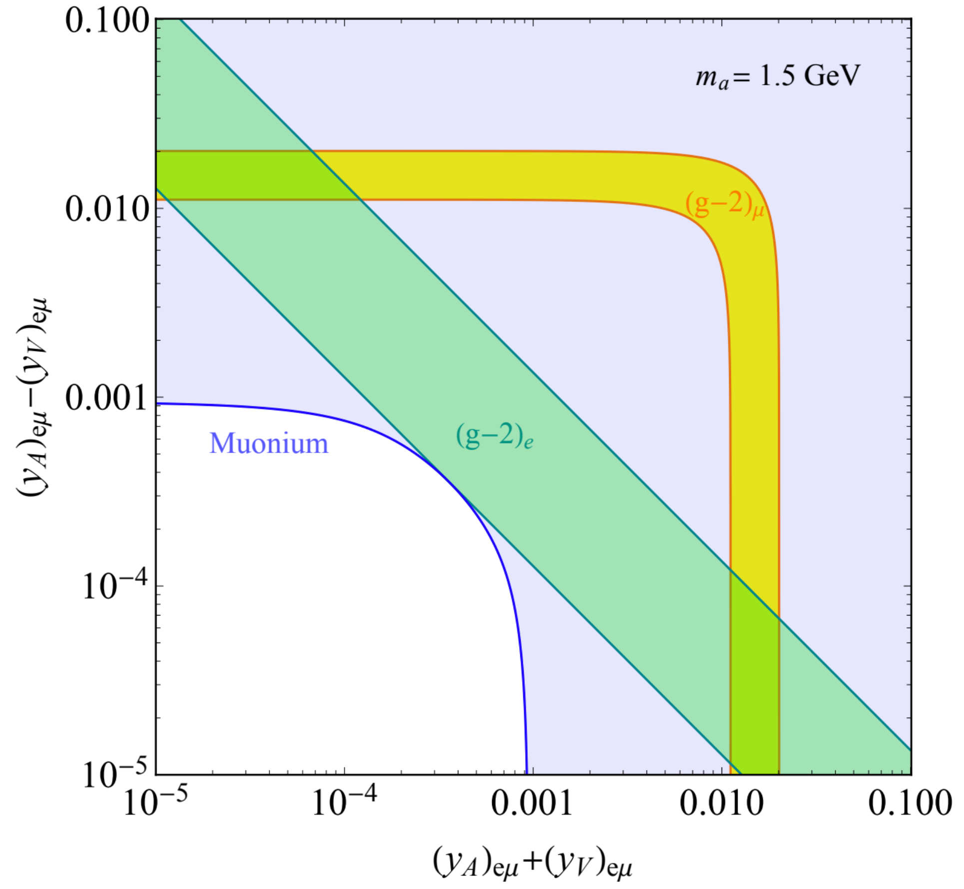
$(g-2)_e$



Muonium-antimuonium oscillations

MACS collaboration, PRL 82 (1999) 49-52

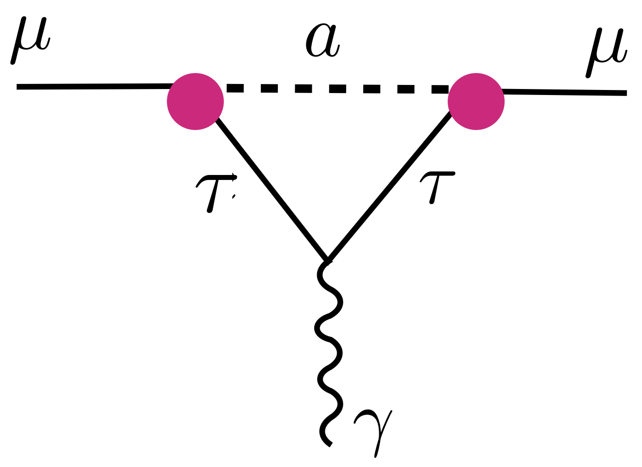
Endo, Iguro, Kitahara, JHEP 06 (2020) 040



$(g-2)_e$ viable for $m_a > 1.5$ GeV

<u>τ-μ or τ-e couplings</u>

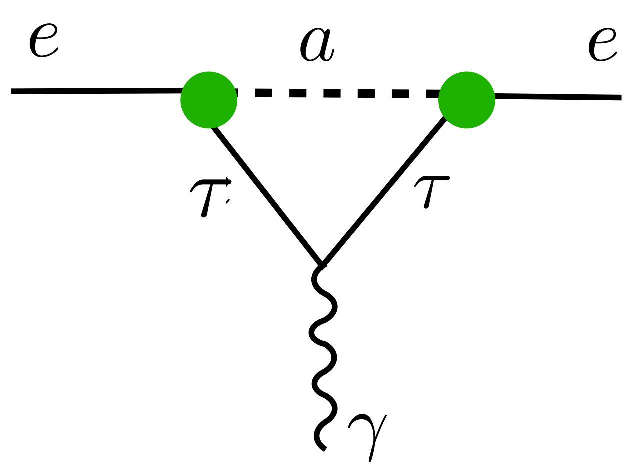
Can explain **either** (g-2)μ or (g-2)e with LFV couplings involving a τ



$(g-2)_\mu$

-Re$[(k_E)^*_{32}(k_e)_{32}] \approx 4$ for $f = 1$ TeV

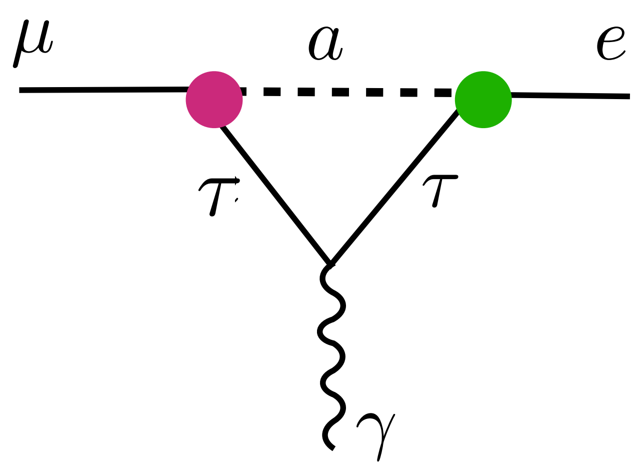
$+$



$(g-2)_e$

Re$[(k_E)^*_{31}(k_e)_{31}] \approx 0.32$ for $f = 1$ TeV

$\Longrightarrow$



$\mu \to e\gamma$

MEG collaboration, Eur. Phys. J. C 76 no. 8 434 (2016)