Axion-like Particles and Lepton Flavour Violation

Marvin Schnubel

MITP, Johannes Gutenberg University Mainz

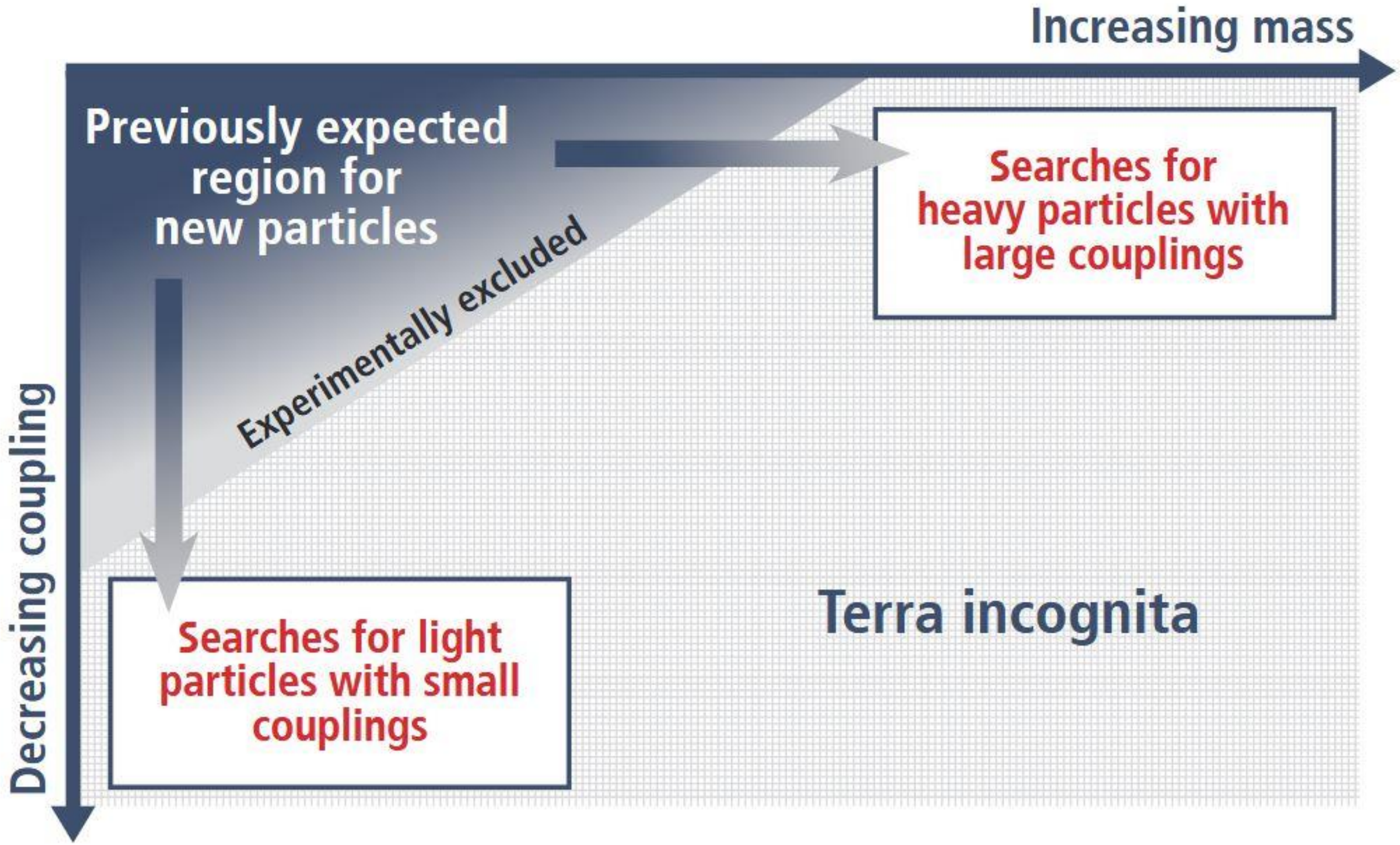
LF(U)V Workshop, Zurich, 04.-06.07.22

Based on work with M. Bauer, M. Neubert, S. Renner & A. Thamm

arXiv: 1908.00008, 2012.12272, 2102.13112, 2110.20698

Motivation

- Plenty of (in)direct hints for new physics, e.g. ν-oscillation, $R_{D(*),K(*)}$, $(g-2)_\mu$…



Motivation & the ALP Lagrangian

JG|U

Why axions/ALPs?	Why couple to leptons?
Strong CP Problem [Peccei, Quinn (1977), Wilczek (1978), Weinberg (1978)]	LF is accidental symmetry
Dark matter candidate [Ringwald (2016)]	No SM background
pNGBs of spont. broken U(1) symmetry [Chang, Chang, Chou, Keung (2000); Marciano, Masiero, Paradisi, Passera (2016)]	Tree-level LFV couplings possible!

Motivation & the ALP Lagrangian

JG|U

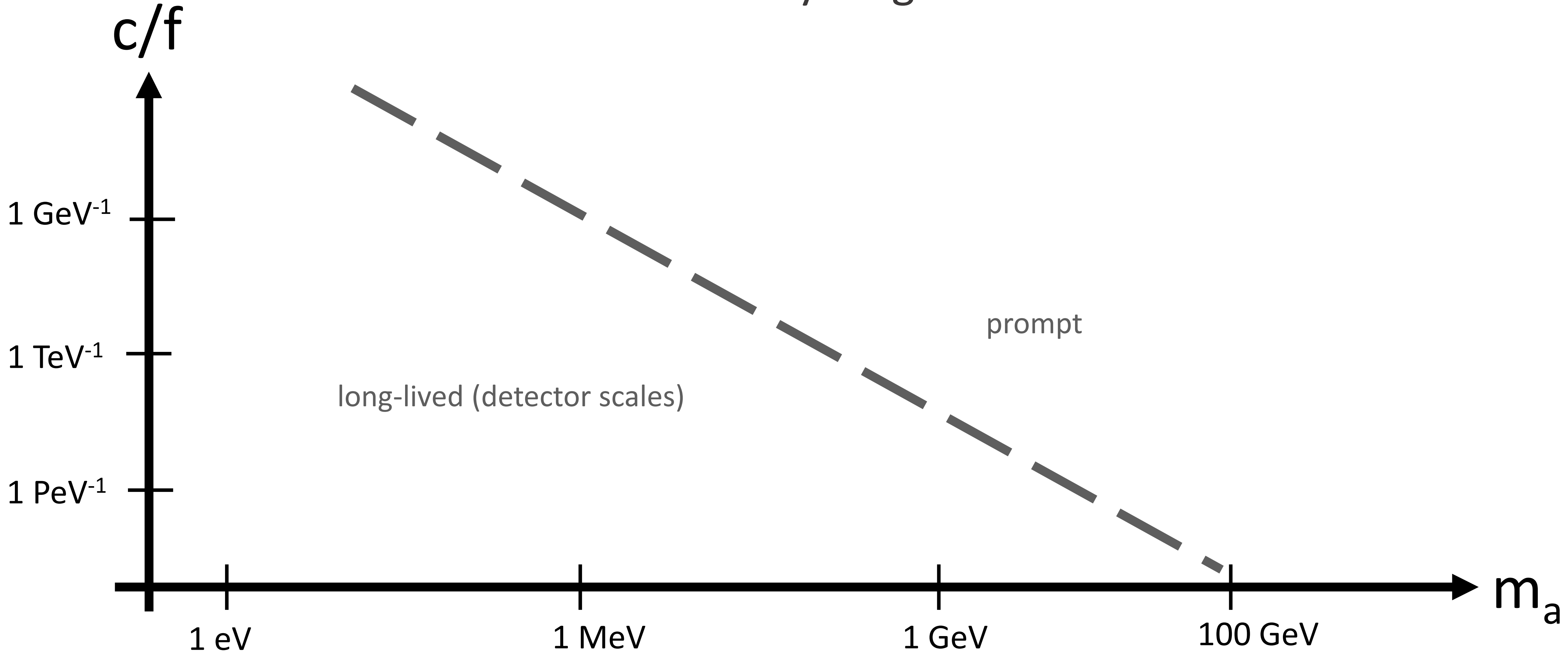
Why axions/ALPs?	Why couple to leptons?
Strong CP Problem [Peccei, Quinn (1977), Wilczek (1978), Weinberg (1978)]	LF is accidental symmetry
Dark matter candidate [Ringwald (2016)]	No SM background
pNGBs of spont. broken U(1) symmetry [Chang, Chang, Chou, Keung (2000); Marciano, Masiero, Paradisi, Passera (2016)]	Tree-level LFV couplings possible!

- general ALP Lagrangian: [Georgi, Kaplan, Randall (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{f} \sum_\ell \bar{\ell}\left(k_E P_L + k_e P_R\right)\gamma^\mu \ell + c_{\gamma\gamma}\frac{\alpha_{\text{QED}}}{4\pi}\frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

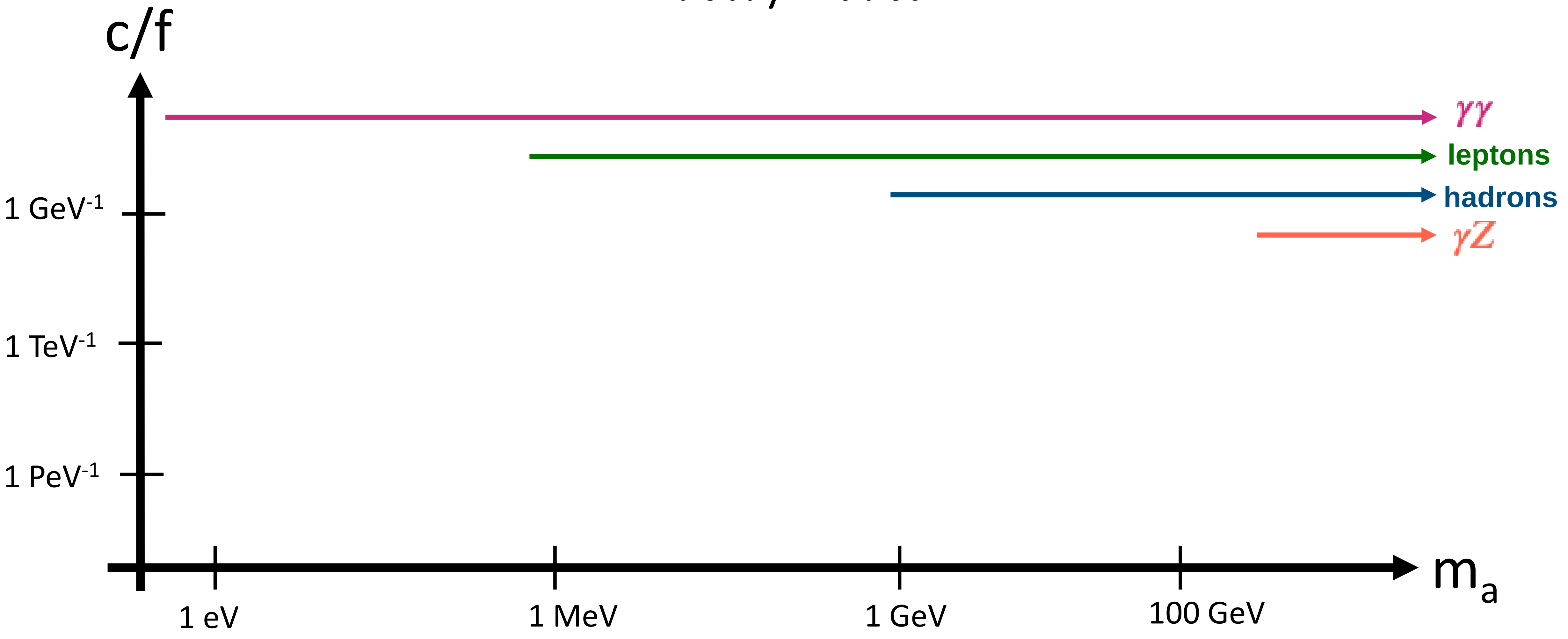
ALP pheno in a nutshell

ALP decay length



ALP pheno in a nutshell

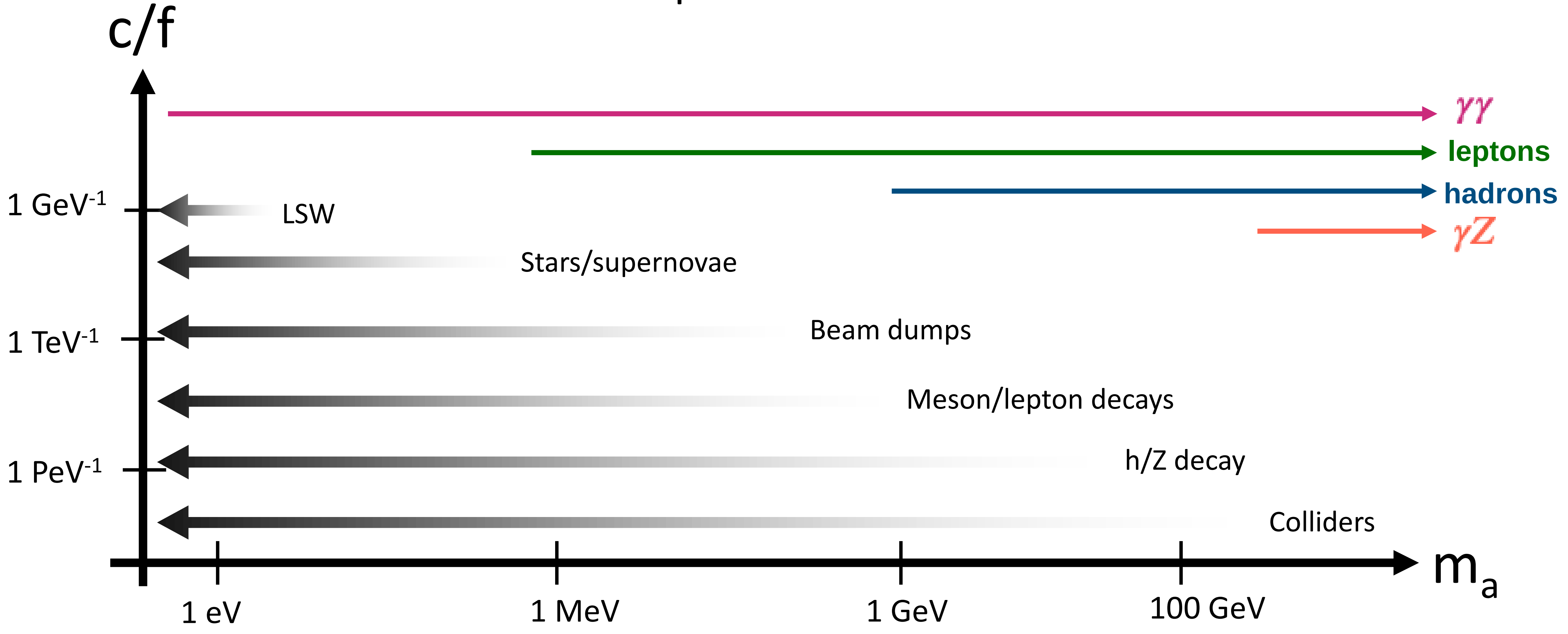
ALP decay modes



ALP pheno in a nutshell

JG|U

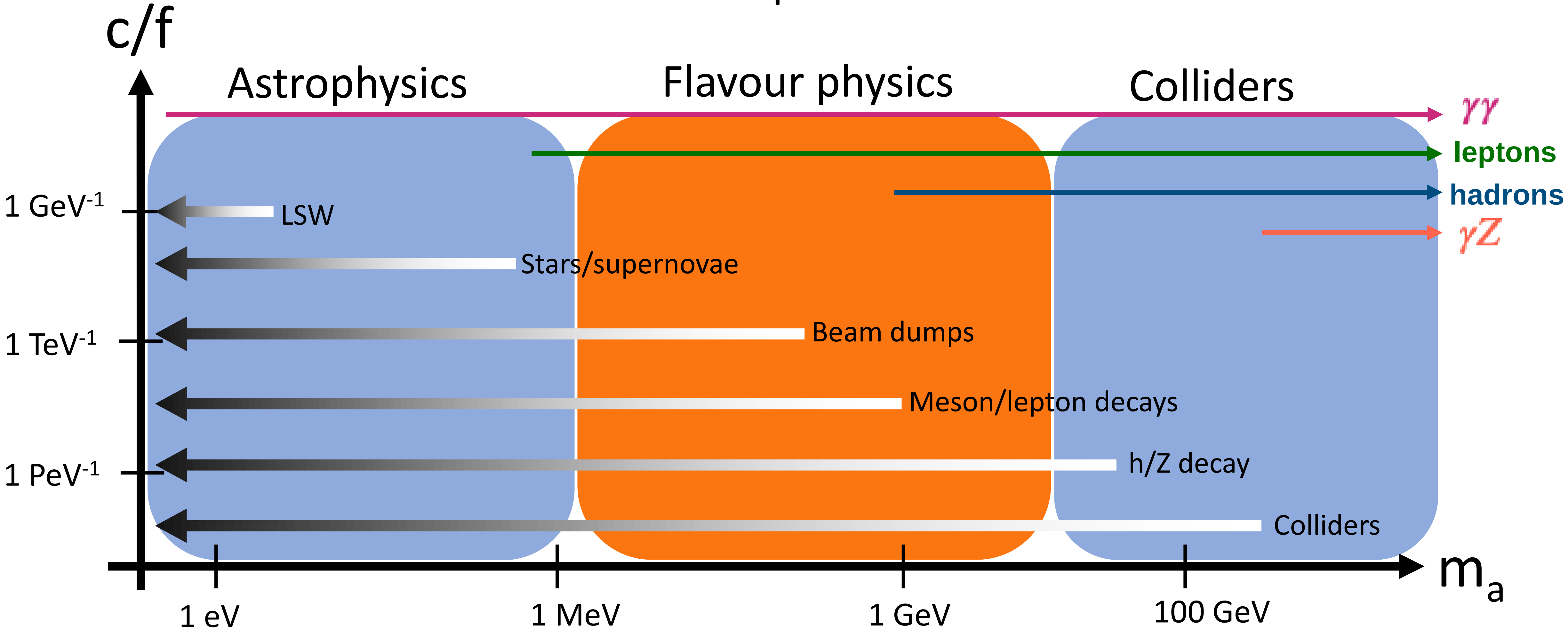
ALP production modes



ALP pheno in a nutshell

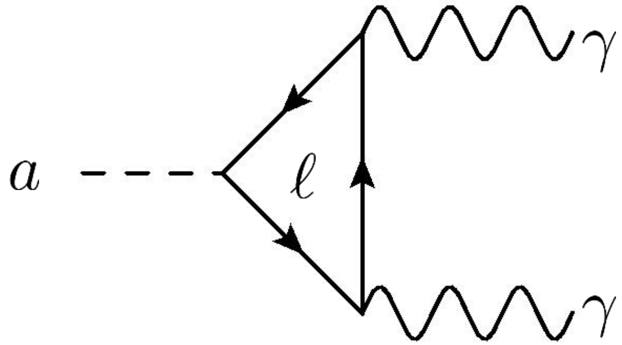
JG|U

How to probe ALPs?



Constraints on ALP-Lepton Couplings

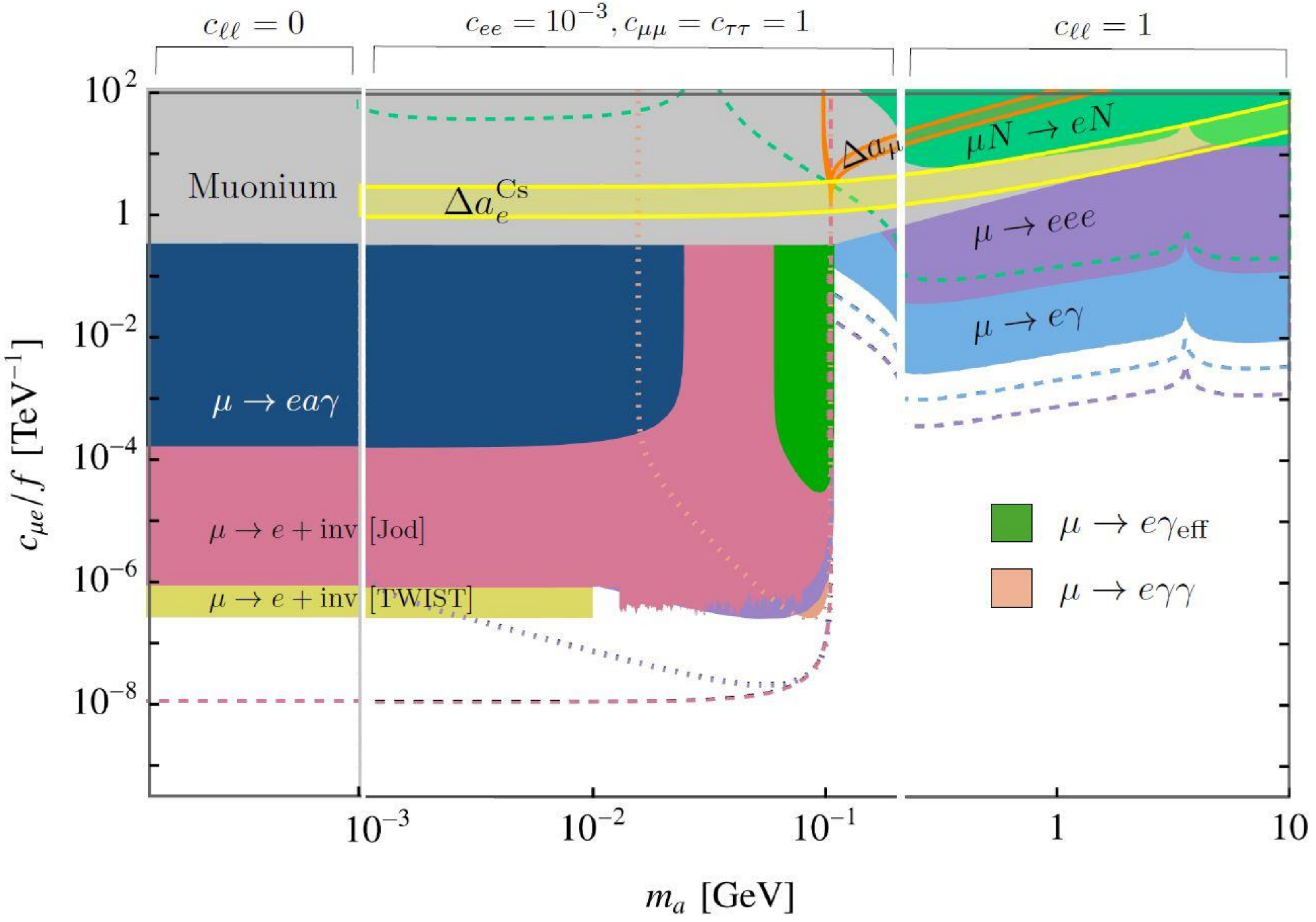
- Assume no tree-level photon coupling, effective coupling loop-induced:



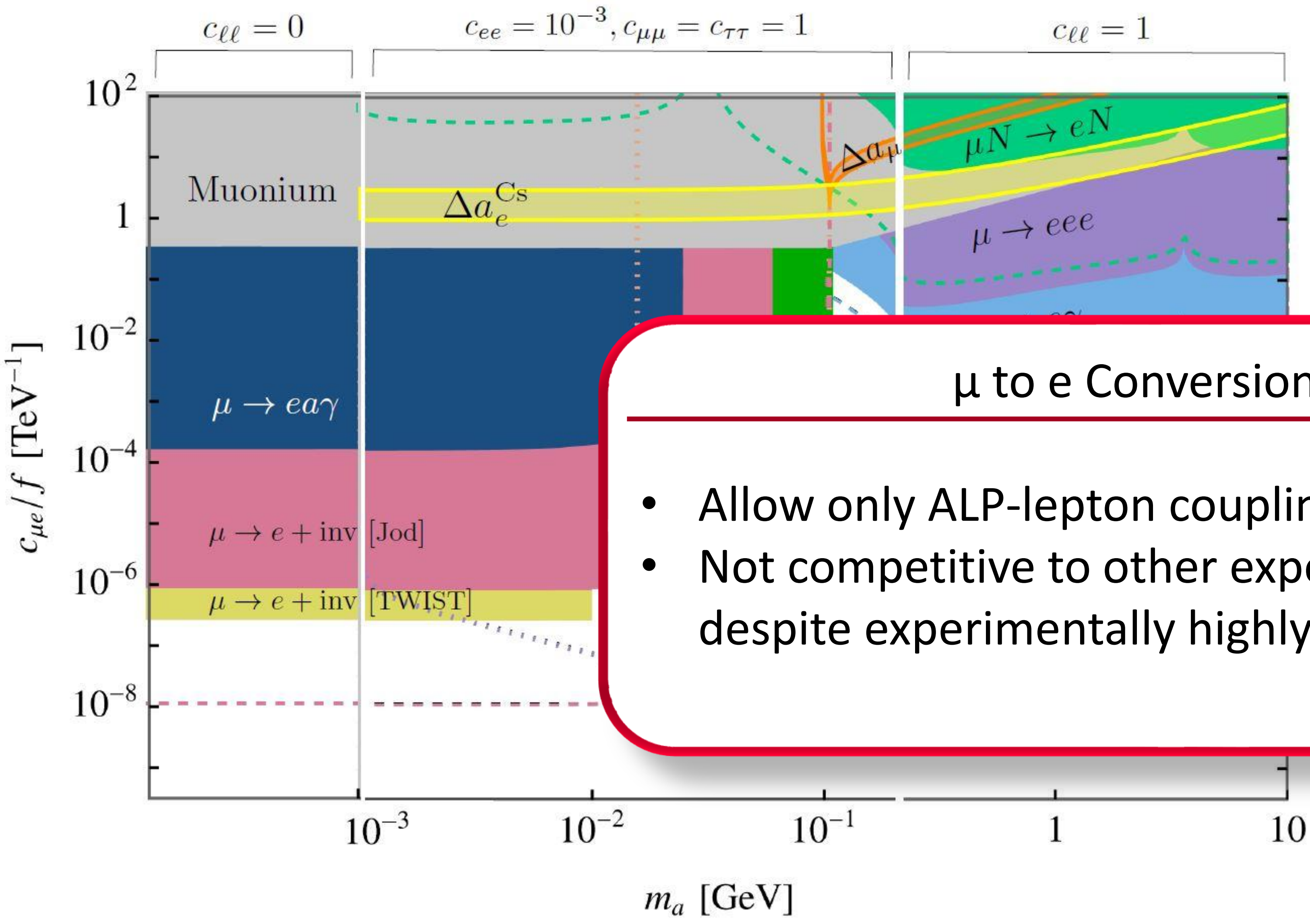
[Bauer, Neubert, Thamm (2017)]

- Effective branching ratios often depend on experimental cuts (e.g. time of flight, energy…) or the ALP decay length (in subsequent decays)
- Assume one LFV coupling to be dominant
- Focus on μ-sector, similar analysis can be done for tau-sector

Constraints on ALP-Lepton Couplings



Constraints on ALP-Lepton Couplings



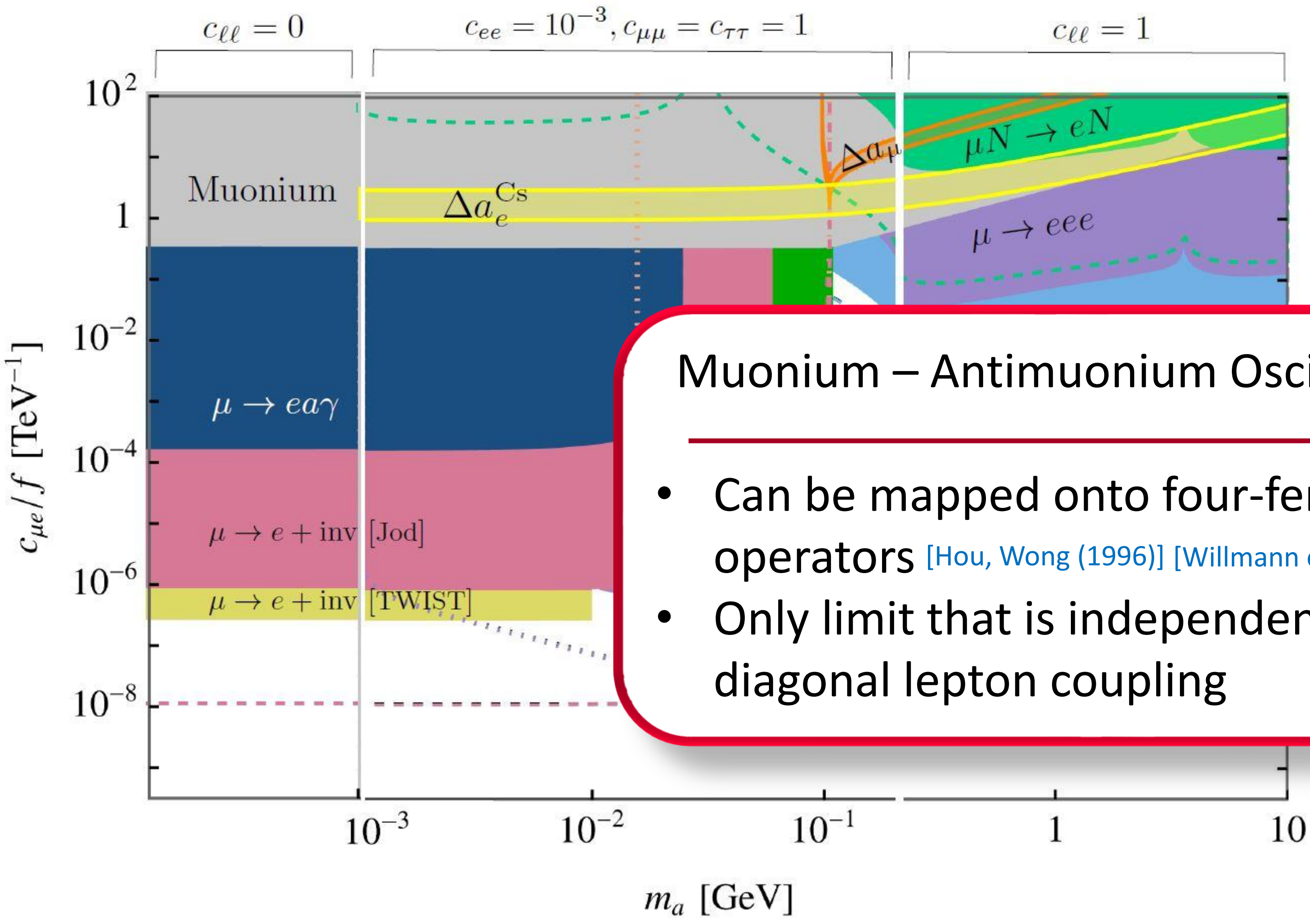
μ to e Conversion

- Allow only ALP-lepton couplings
- Not competitive to other experiments despite experimentally highly constraining

[SINDRUM-II (2006)]

Constraints on ALP-Lepton Couplings

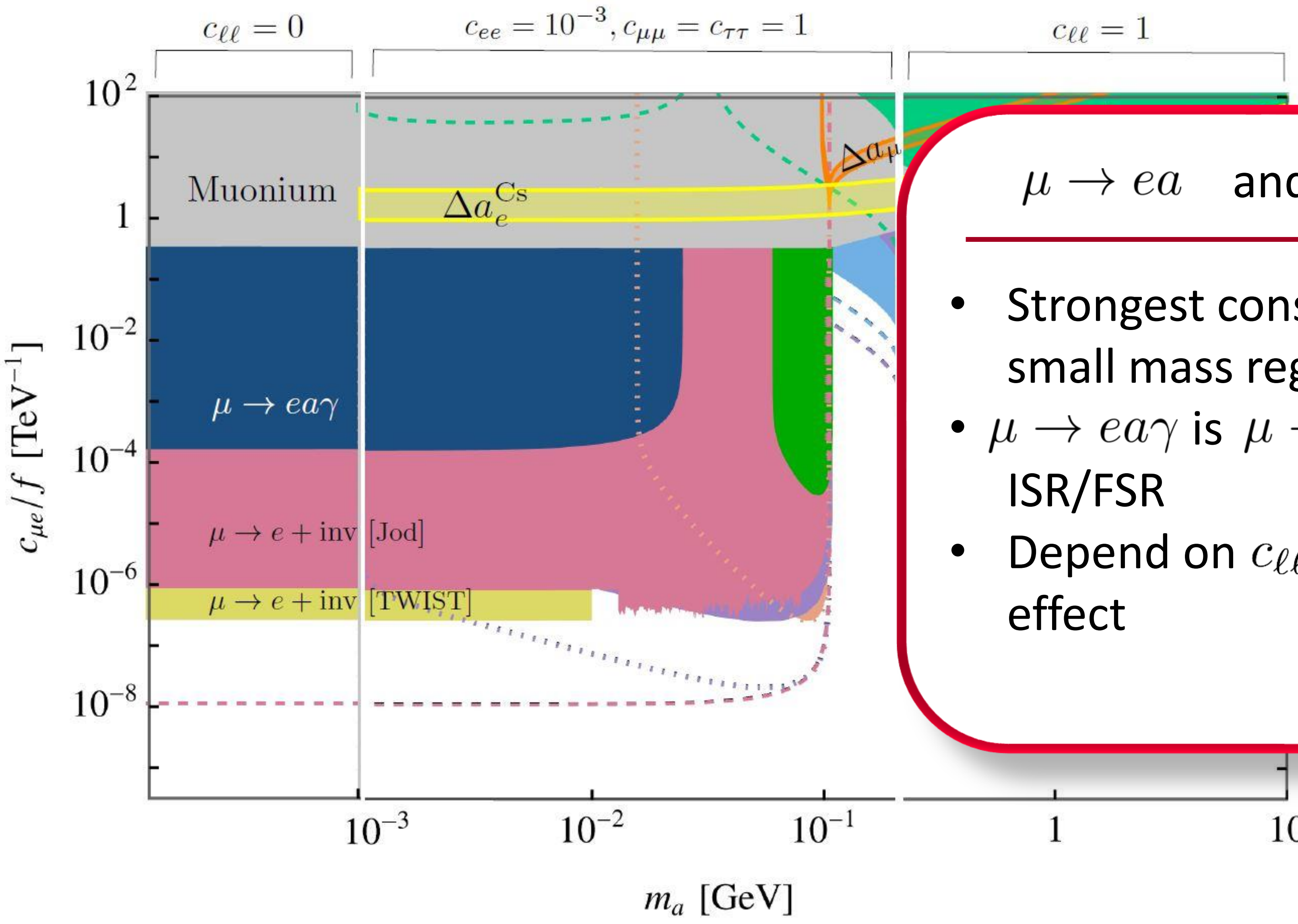
JG|U



Muonium – Antimuonium Oscillation

- Can be mapped onto four-fermion operators [Hou, Wong (1996)] [Willmann et al. (1999)]
- Only limit that is independent of $c_{\ell\ell}$ diagonal lepton coupling

Constraints on ALP-Lepton Couplings



$\mu \to ea$ and $\mu \to ea\gamma$

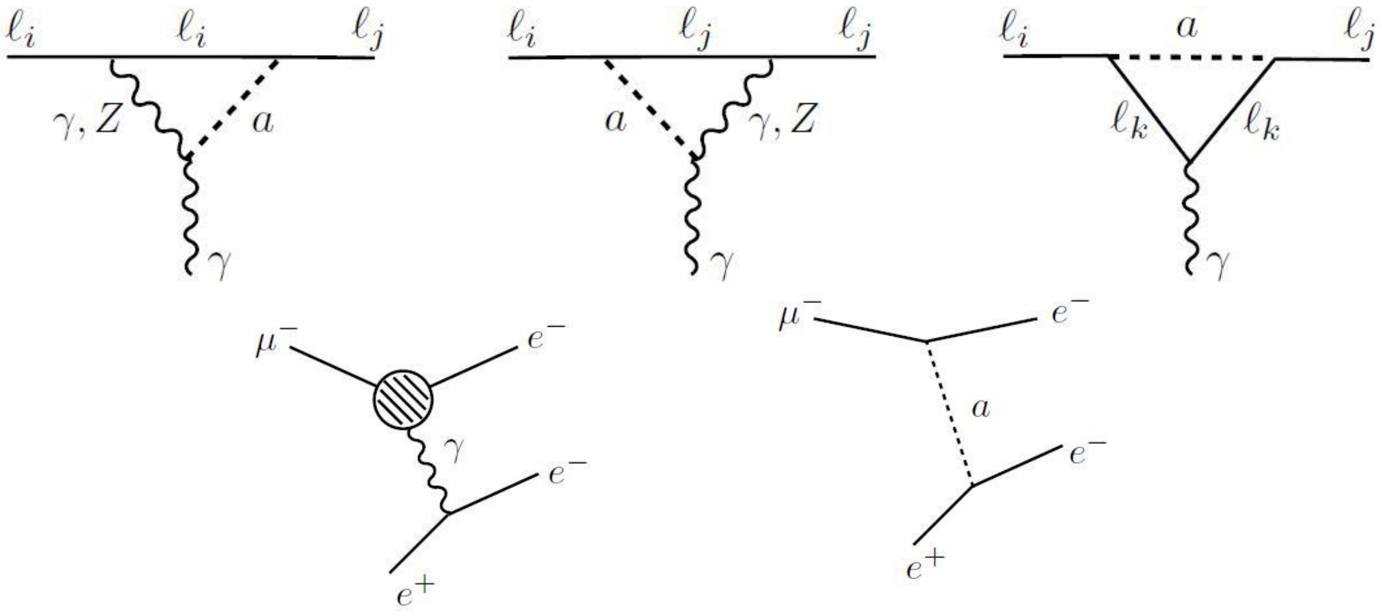
- Strongest constraints in small mass region
- $\mu \to ea\gamma$ is $\mu \to ea$ with ISR/FSR
- Depend on $c_{\ell\ell}$ via lifetime effect

Constraints on ALP-Lepton Couplings

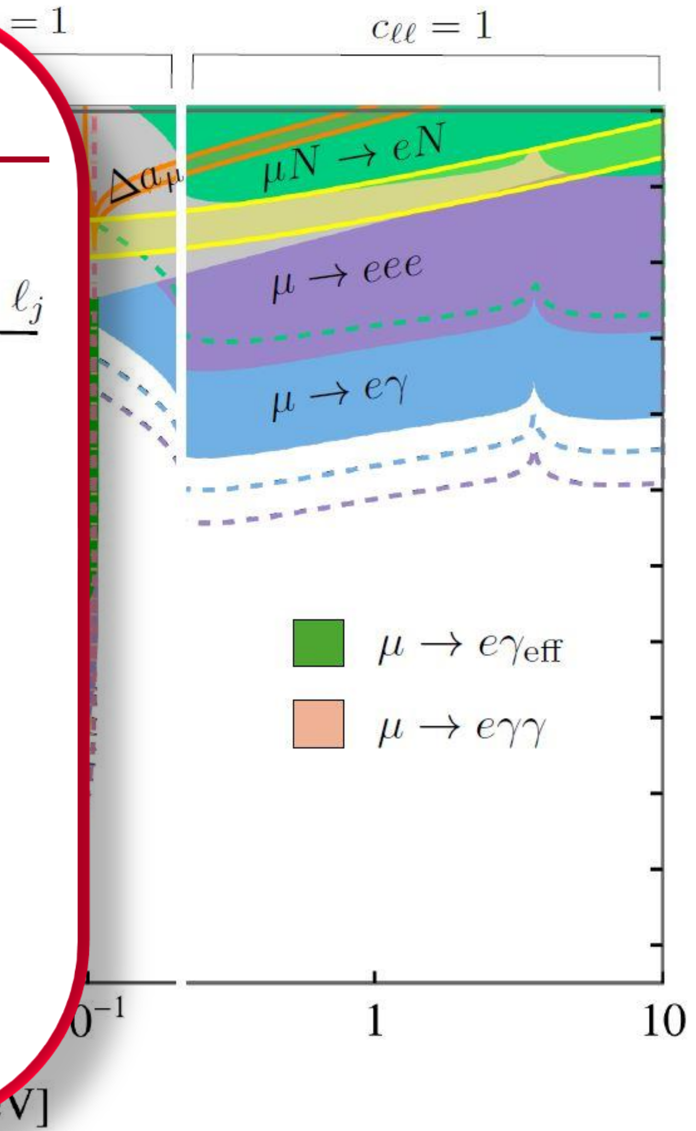
JG|U

Muon decays

- Strongest bounds for heavy ALPs

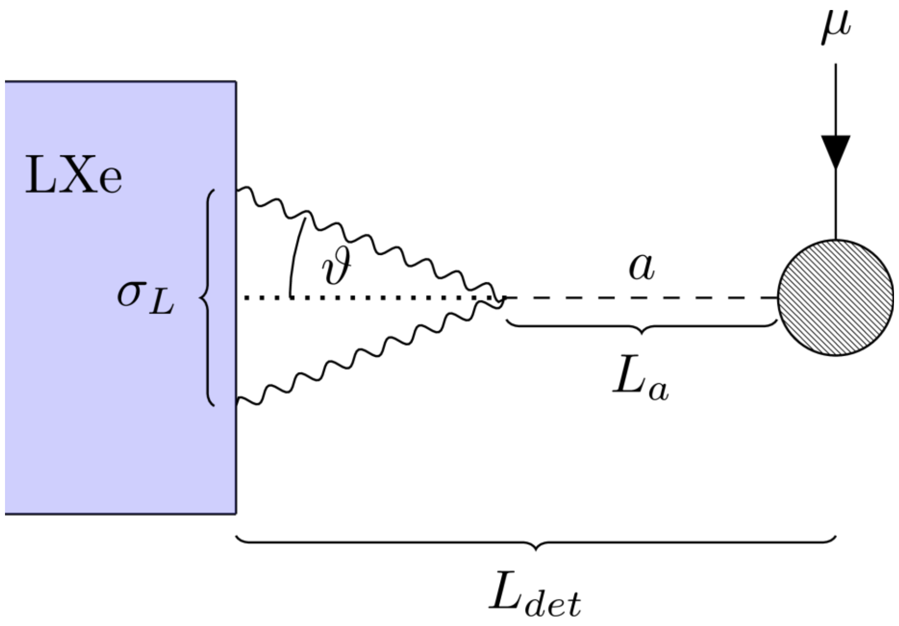


- Strongest limit achieved with on-shell ALP

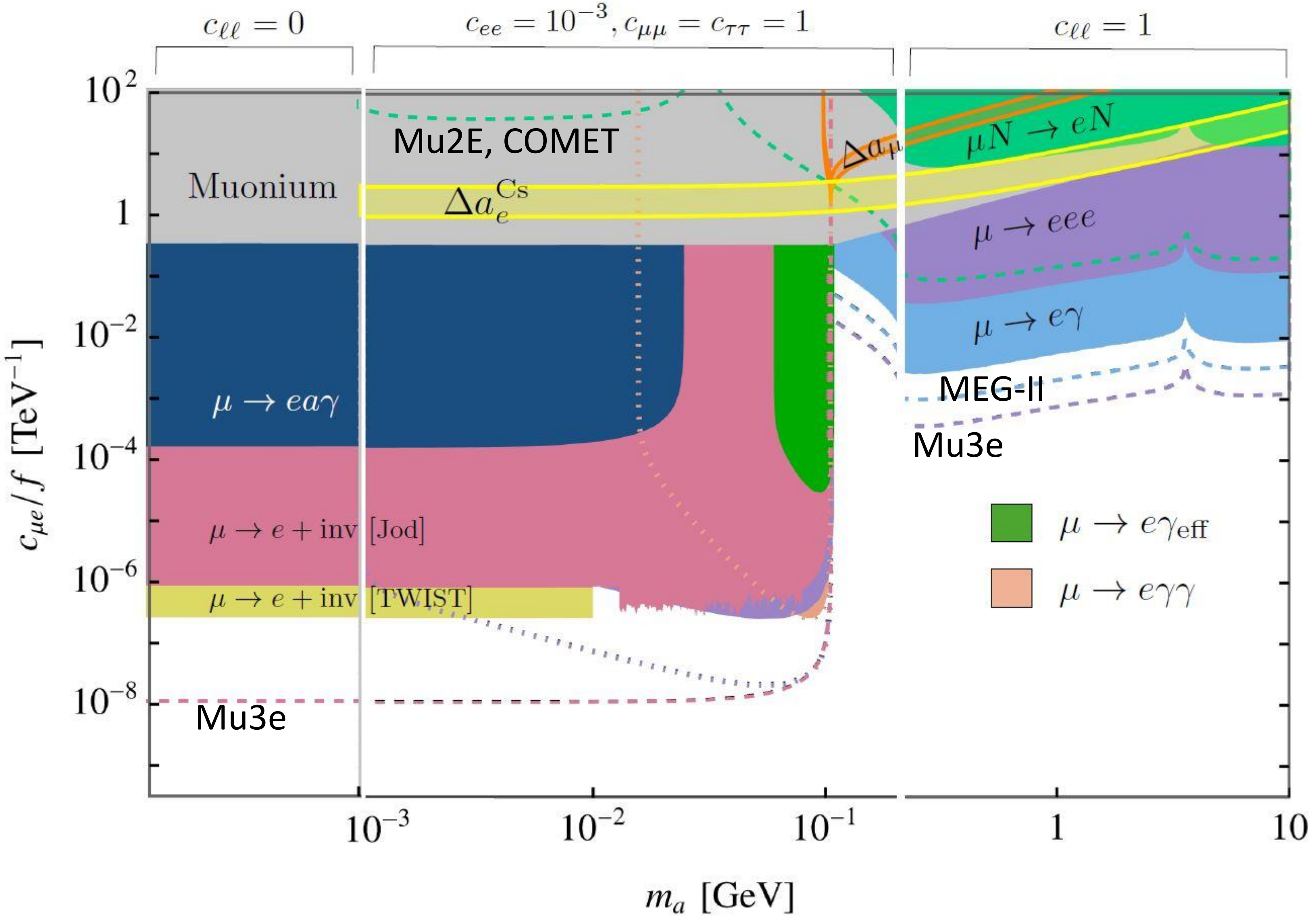


Details on Muon Decays

- For $2m_e<m_a<m_\mu$ can have subsequent $\mu \to ea,\; a \to ee$ decay
- $\mathrm{Br}(\mu \to 3e) \approx \mathrm{Br}(\mu \to ea) \times \mathrm{Br}(a \to ee)$
- Many orders of magnitude more sensitive to LFV couplings than e.g. $\mu \to e\gamma$
- Overcomes phase-space suppression of 3-body decay
- If ALP is boosted or decays close to detector, $\mu \to e\gamma\gamma$ can mimic $\mu \to e\gamma$



Constraints on ALP-Lepton Couplings



Anomalous magnetic Moments

- Currently, there is a tension between experiment and theoretical prediction for the anomalous magnetic moment of the muon $(g\text{-}2)_\mu$ of $4.2\sigma^{WP}/1.5\sigma^{BMW}$, and the electron $(g\text{-}2)_e$ of $2.4\sigma^{Cs}$ / $1.6\sigma^{Rb}$ [Bennet *et al* (2006), Kesharvarzi *et al* (2018), Davier *et al* (2020), BMW (2020)] [Hanneke, Fogwell, Gabrielse (2008) and (2011)]
- a_μ and a_e receive contribution from both flavor-conserving and -violating couplings [Bauer, Neubert, Thamm (2017), Chang *et al* (2001), Marciano *et al* (2016)]
- Explanation of both anomalies with $c_{e\mu}$ coupling or $c_{e(\mu)\tau}$ couplings is ruled out by Muonium oscillations or constraints from $\mu \to e\gamma$ [Endo, Iguro, Kitahara (2020)]
- Can explain both with
  - Non-universal ALP-lepton coupling $c_{ee} \sim -(10-30) \times c_{\mu\mu}$
  - Quite small $c_{\ell\ell}$, explain a_μ with $c_{\mu\tau}$ and a_e with $c_{e\mu}$

Conclusion & Outlook

- Studied lepton flavor-violationg ALP couplings and their constraints from decay and non-decay experiments
- When the ALP can decay resonantly, sensitivity is greatly increased
- Results from muon sector can be easily transferred to tau sector
- We have shown that searches for LFV transitions provide highly complementary constraints on ALP couplings to photons and leptons, strengthening the case for a broad program of experiments hunting LFV decays.

Conclusion & Outlook

- St lepton flavor-violating ALP couplings and their constraints from d decay experiments
- When the resonantly, sensitivity is greatly increased
- Results from muon easily transferred to tau sector
- We have shown that search sitions provide highly complementary constraints on AL hotons and leptons, strengthening the case for a broad progra nts hunting LFV decays.

Thank you for your attention!

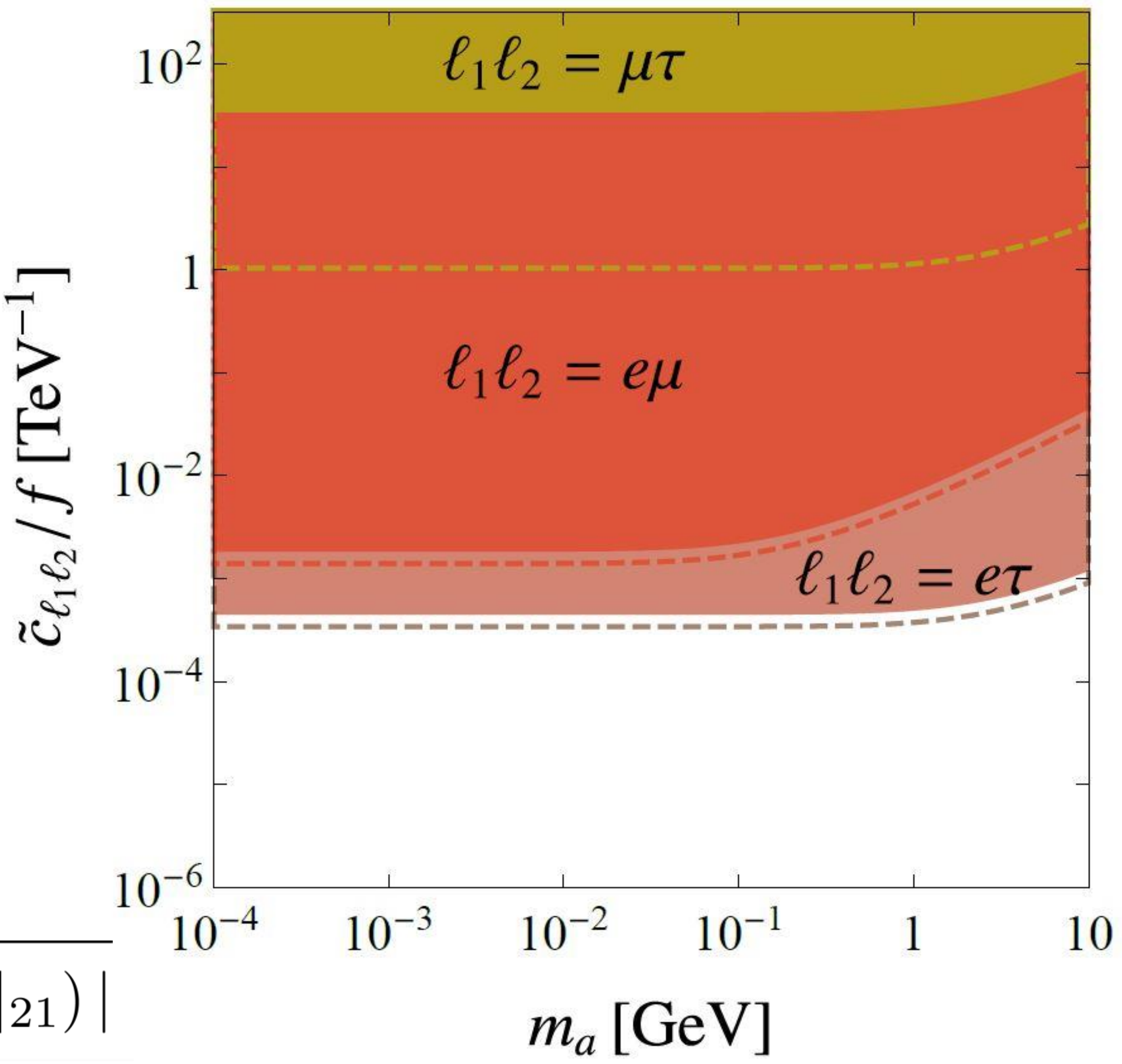
Backup Slides

Anomalous electric Moments

- Current measurements limit EDMs to
$$|d_e| < 1.1 \times 10^{-29} \mathrm{ecm}$$
$$|d_\mu| < 1.9 \times 10^{-20} \mathrm{ecm}$$

[Bernreuther, Suzuki (1991), Booth (1993), ACME Collaboration (2018)]

- SM predictions are ~10 orders of magnitude weaker than these limits.
  - ➢ parameter space for ALP-interactions, occur already at 1-loop

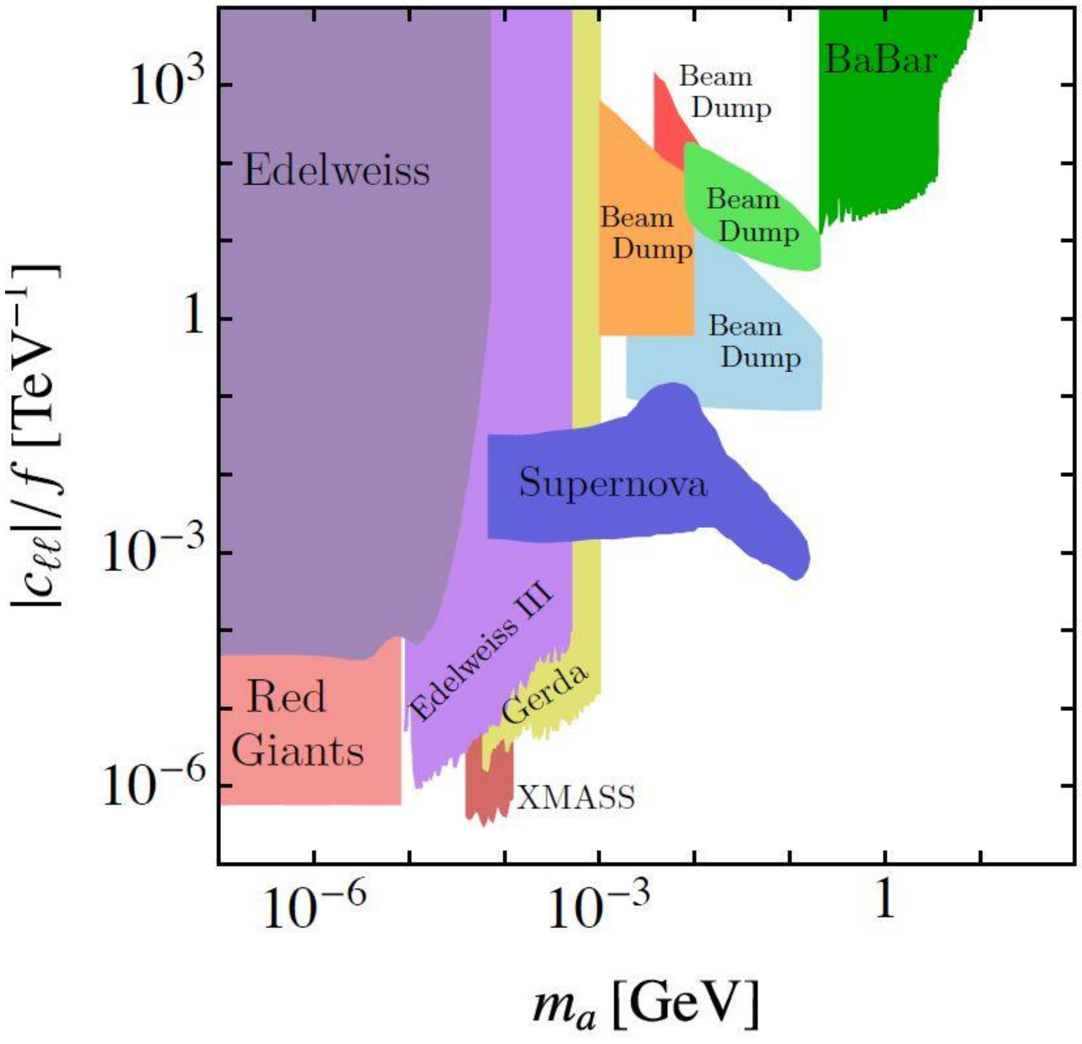


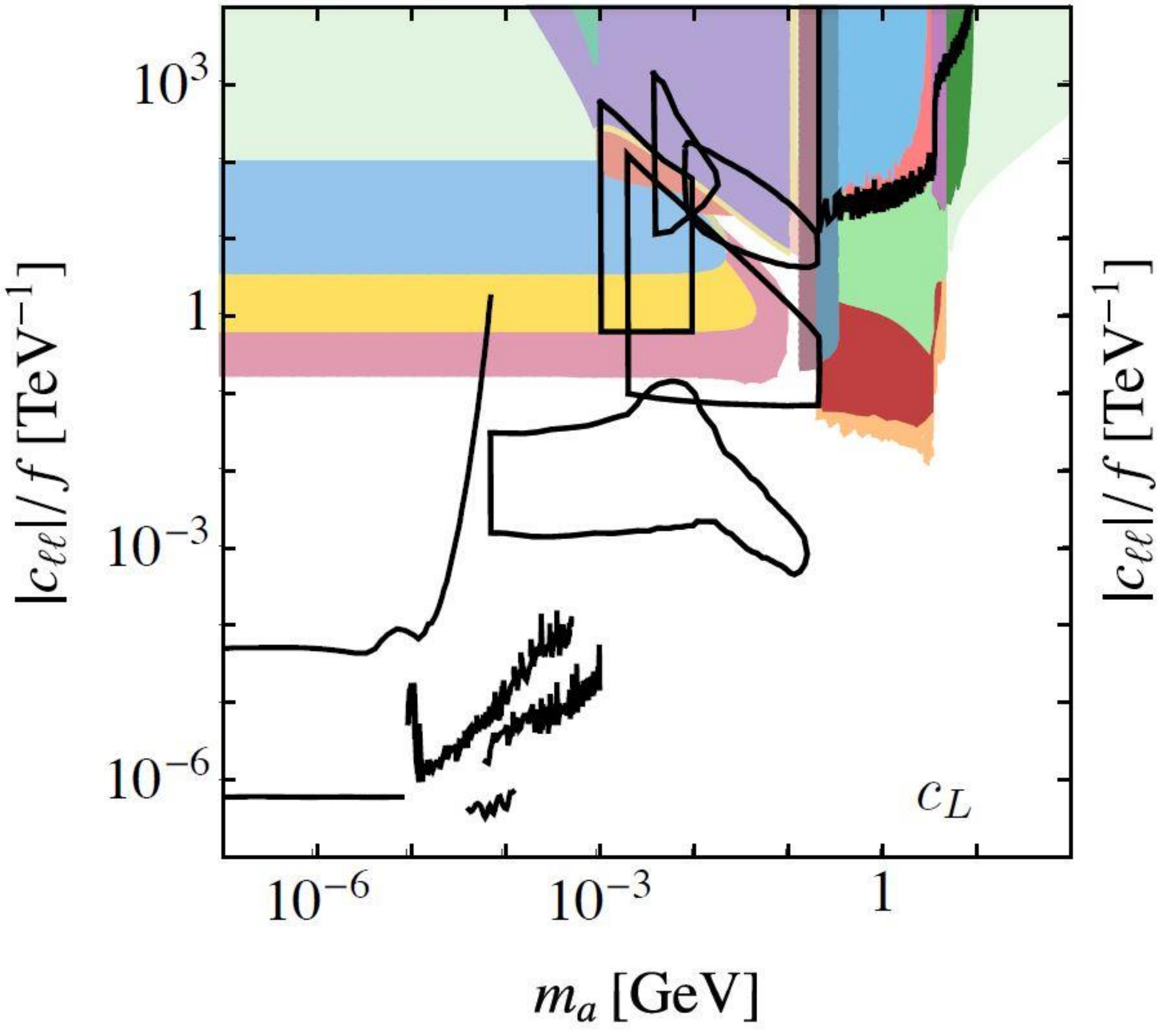
$$\tilde{c}_{\ell_1\ell_2} = \sqrt{|\mathrm{Im}\left([k_E]^*_{21}[k_e]_{21}\right)|}$$

Overview over Branching Ratios and Projections

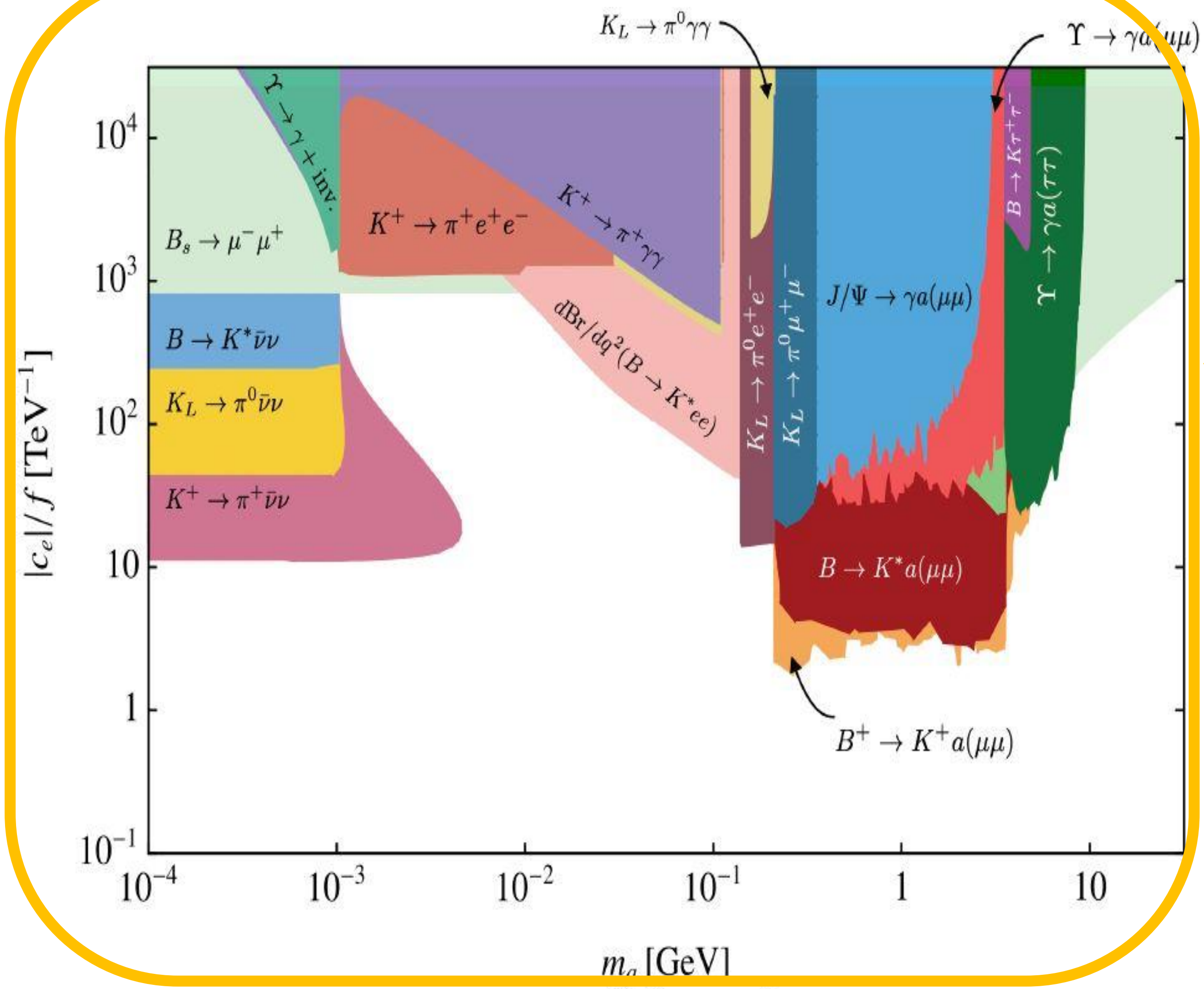
LFV Channel	Current limit	Projection
$\mu \to e\gamma$	4.2×10^{-13} [MEG Coll. (2016)]	6×10^{-14} [MEGII Coll. (2018)]
$\mu \to 3e$	1.0×10^{-12} [SINDRUM Coll. (1988)]	1×10^{-16} [Perrevoort, Mu3e (2018)]
$\mu \to ea, m_a < 13\,\mathrm{MeV}$	5.8×10^{-5} [Bayes *et al* (2014)]	1×10^{-8} [Perrevoort, Mu3e (2018)]
$\mu \to ea, m_a > 13\,\mathrm{MeV}$	9.0×10^{-6}	
$\mu \to ea\gamma$	1.1×10^{-9} [Bolton *et al* (1988)]	
$\mu \to e\gamma\gamma$	7.2×10^{-11} [LAMPF Coll (1986)]	
$\mu N \to eN$	7.0×10^{-13} [SINDRUM-II (2006)]	1×10^{-17} [Mu2e (2014)] [COMET (2020)]

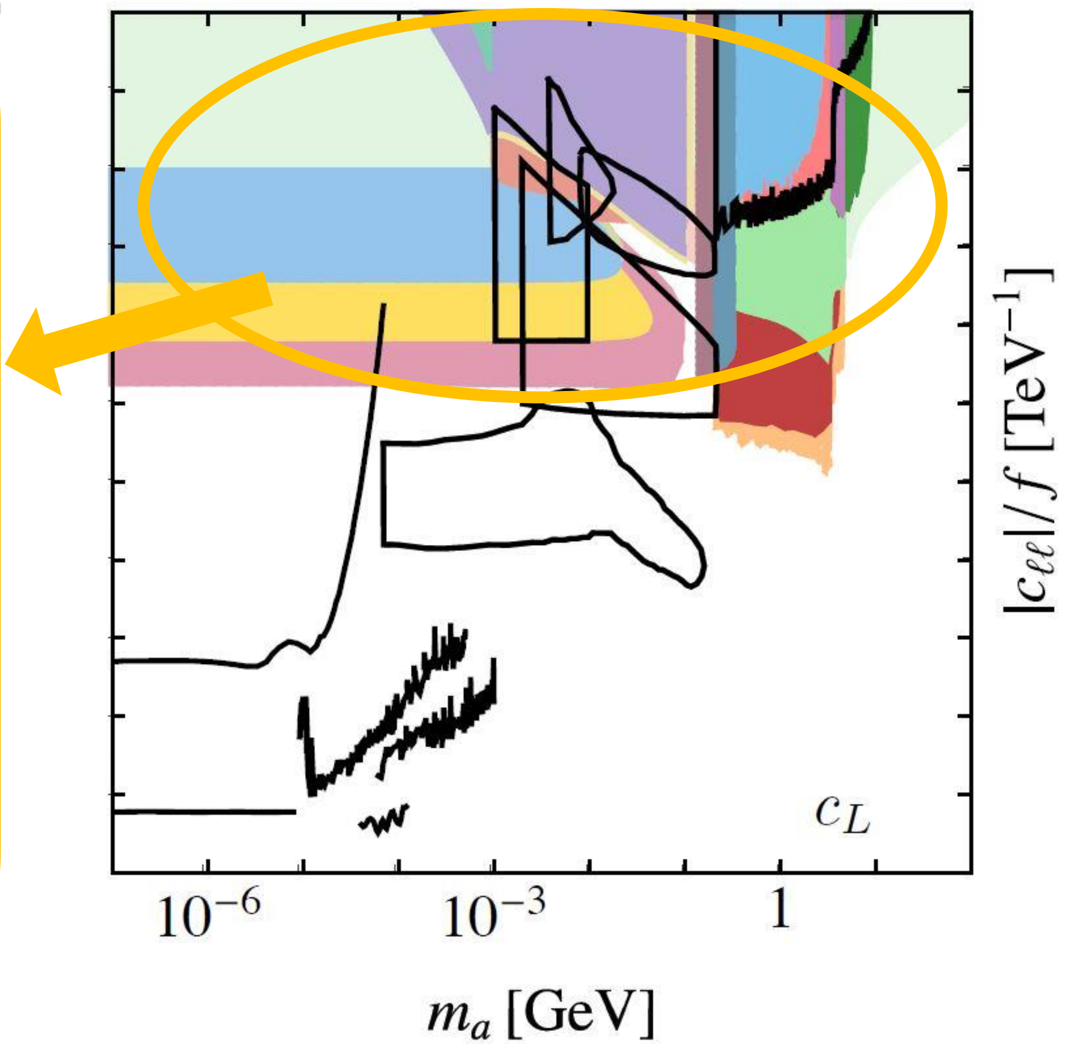
Constraints on ALP-Lepton Couplings



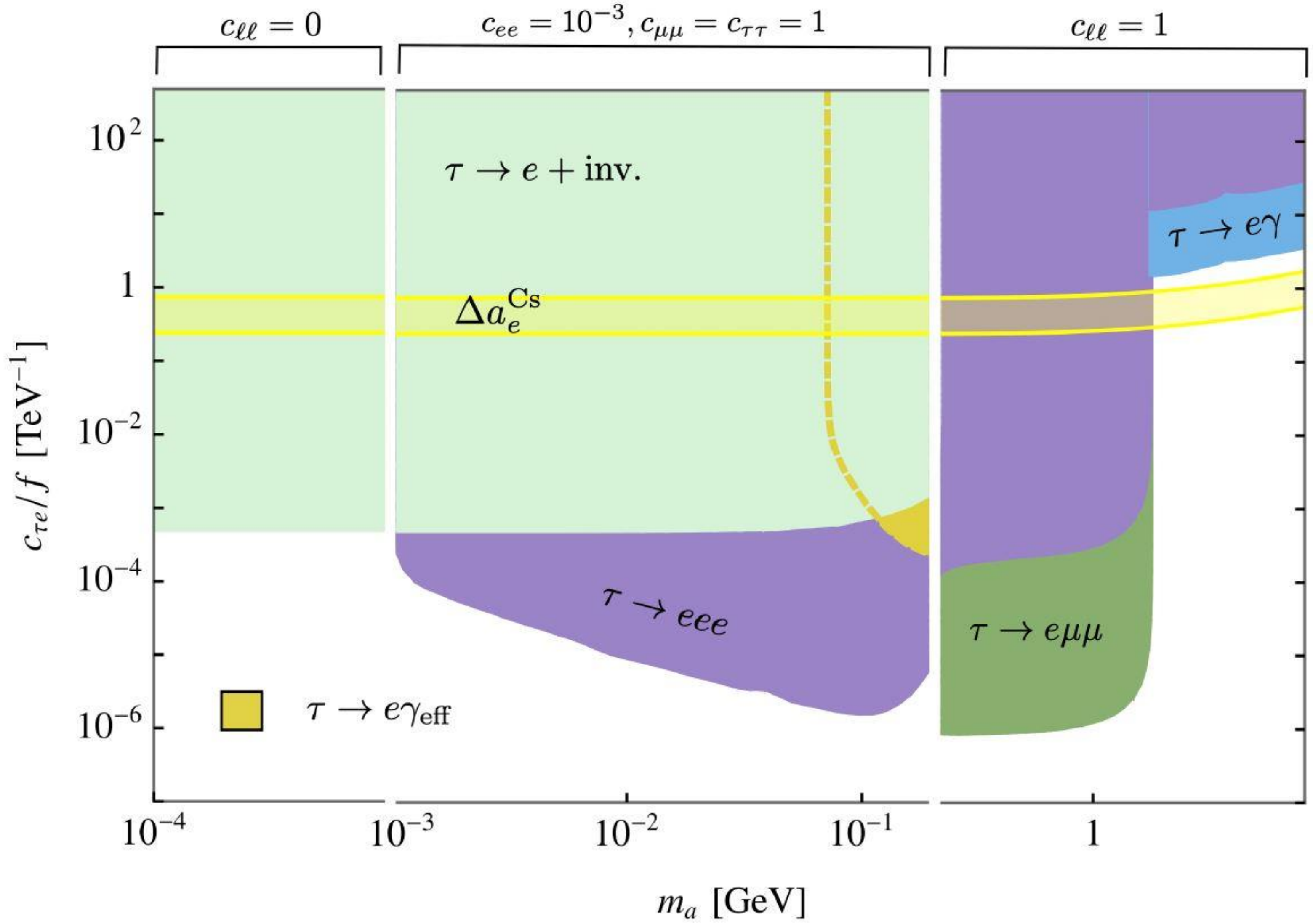


Constraints on ALP-Lepton Couplings

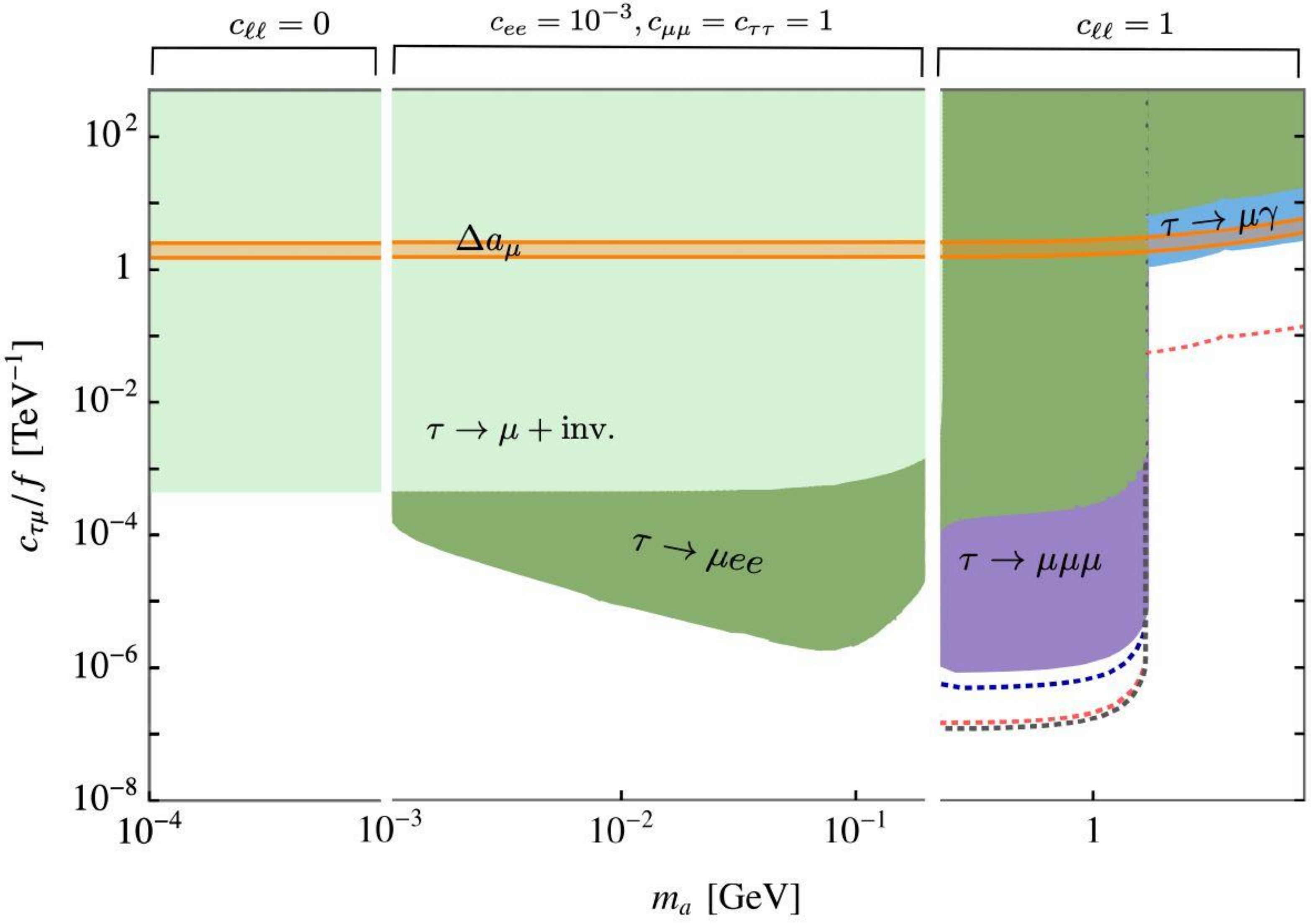




Constraints on ALP-Lepton Couplings



Constraints on ALP-Lepton Couplings



Anomalous magnetic Moments