International Workshop on Muon Physics at
the Intensity and Precision Frontiers (MIP 2025)

Probing Axion-Like Particles with Muons Across High and Low Energies

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Dark Matter exists! (About 27% of the energy of the universe)

DM direct detection searches and LHC searches for heavy new physics are giving increasingly tight constraints on WIMP models

This is why people increasingly focus *also* on other paradigms, *e.g.* axions, dark photons, light DM/light dark sectors etc.

Example: axion-like-particles (ALPs) (*often flavour-violating*) from a broad class of models with spontaneously broken global U(1)

Axion-like particles

Pseudo Nambu-Goldstone bosons: naturally *light* & *weakly* interacting

Many scenarios motivated by outstanding problems of the SM:

Puzzle	Broken global U(1) symmetry	PNGB
• Neutrino masses →	Lepton Number	Majoron
• Strong CP problem →	Peccei-Quinn	Axion
• Flavour problem →	Flavour symmetry (Froggatt-Nielsen)	Familon

Interesting interplay with cosmology/astrophysics:

- ALPs can be DM candidates or serve as portals to a light dark sector:

$$\mathcal{L}_{a\chi\chi} = \frac{\partial_\mu a}{2 f_a} C^A_{\chi\chi}\, \bar{\chi}\gamma^\mu\gamma_5\chi$$

← dark fermion

- Bounds from star cooling/supernovae (if light and feeble enough)

General interactions to leptons (dimension 5 operators):

Shift symmetry (PNGB!) → mass arises m_a from (small) explicit U(1) breaking

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij}\ \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij}\ \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

U(1)-breaking scale → coupling suppression

In general, these coupling are *lepton flavour violating* (LFV)

- That's natural if lepton U(1) charges are flavour non-universal
- Alternatively, flavour-violating couplings can be loop-induced

(for several explicit models see LC Redigolo Ziegler Zupan '20)

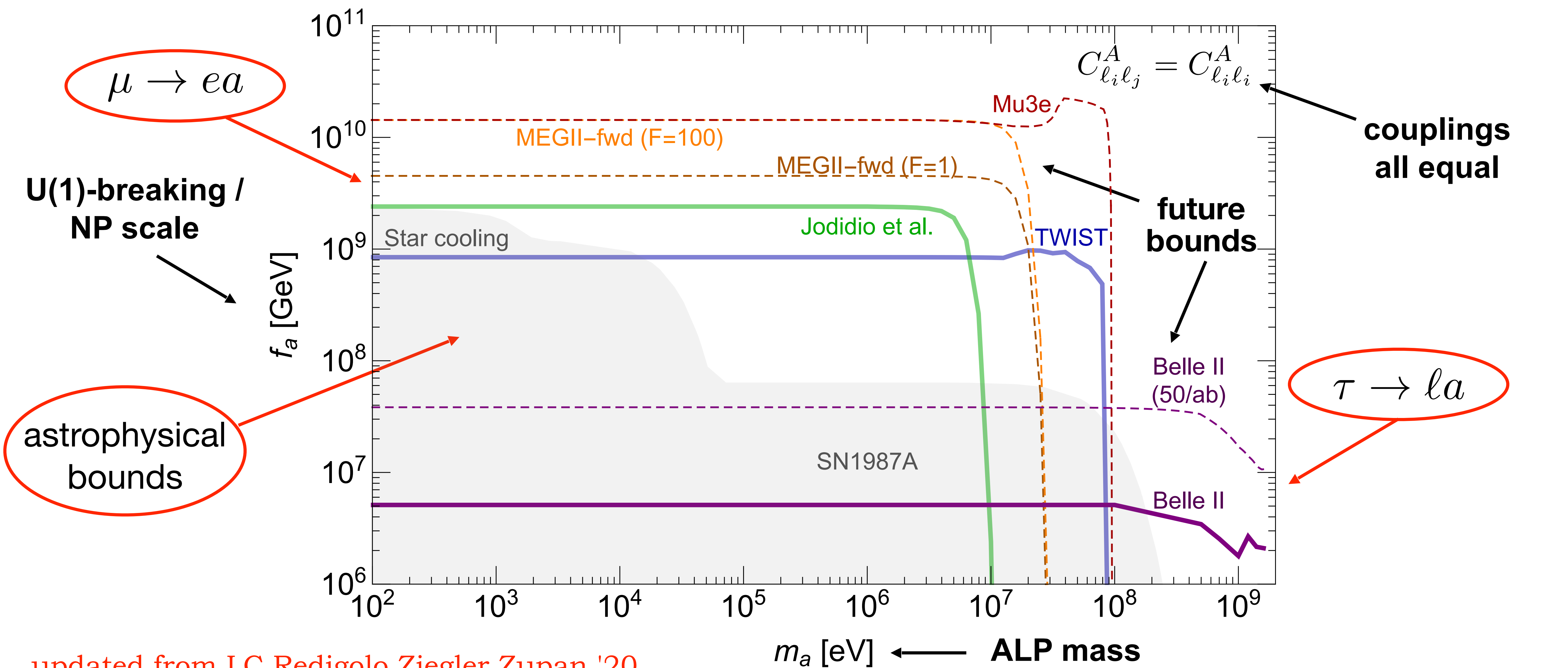
This generic Lagrangian induces 2-body LFV decays such as:

Feng et al. '97

$$\Gamma(\ell_i \to \ell_j\, a) = \frac{1}{16\pi} \frac{m^3_{\ell_i}}{F^2_{ij}} \left(1 - \frac{m^2_a}{m^2_{\ell_i}} \right)^2 \qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

Summary of searches for light *invisible* LFV ALPs

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a}\left(C^V_{ij}\,\bar{\ell}_i\gamma_\mu\ell_j + C^A_{ij}\,\bar{\ell}_i\gamma_\mu\gamma_5\ell_j\right) \Rightarrow \Gamma(\ell_i \to \ell_j\, a) = \frac{1}{64\pi}\frac{m^3_{\ell_i}}{f_a^2}\left(|C^V_{\ell_i\ell_j}|^2 + |C^A_{\ell_i\ell_j}|^2\right)\left(1 - \frac{m_a^2}{m^2_{\ell_i}}\right)^2$$



updated from LC Redigolo Ziegler Zupan '20

- Decays mediated by dimension-5 operators: much larger NP scales can be reached than with $\mu \to e\,\gamma$, $\mu \to eee$ etc. (from dim-6 operators)
- Mu/tau/astro interplay: if $m_a > m_\mu$ constraints mainly come from τ decays

What about heavier ALPs?

If $m_a > m_\mu$, constraints on LFV ALPs are much weaker

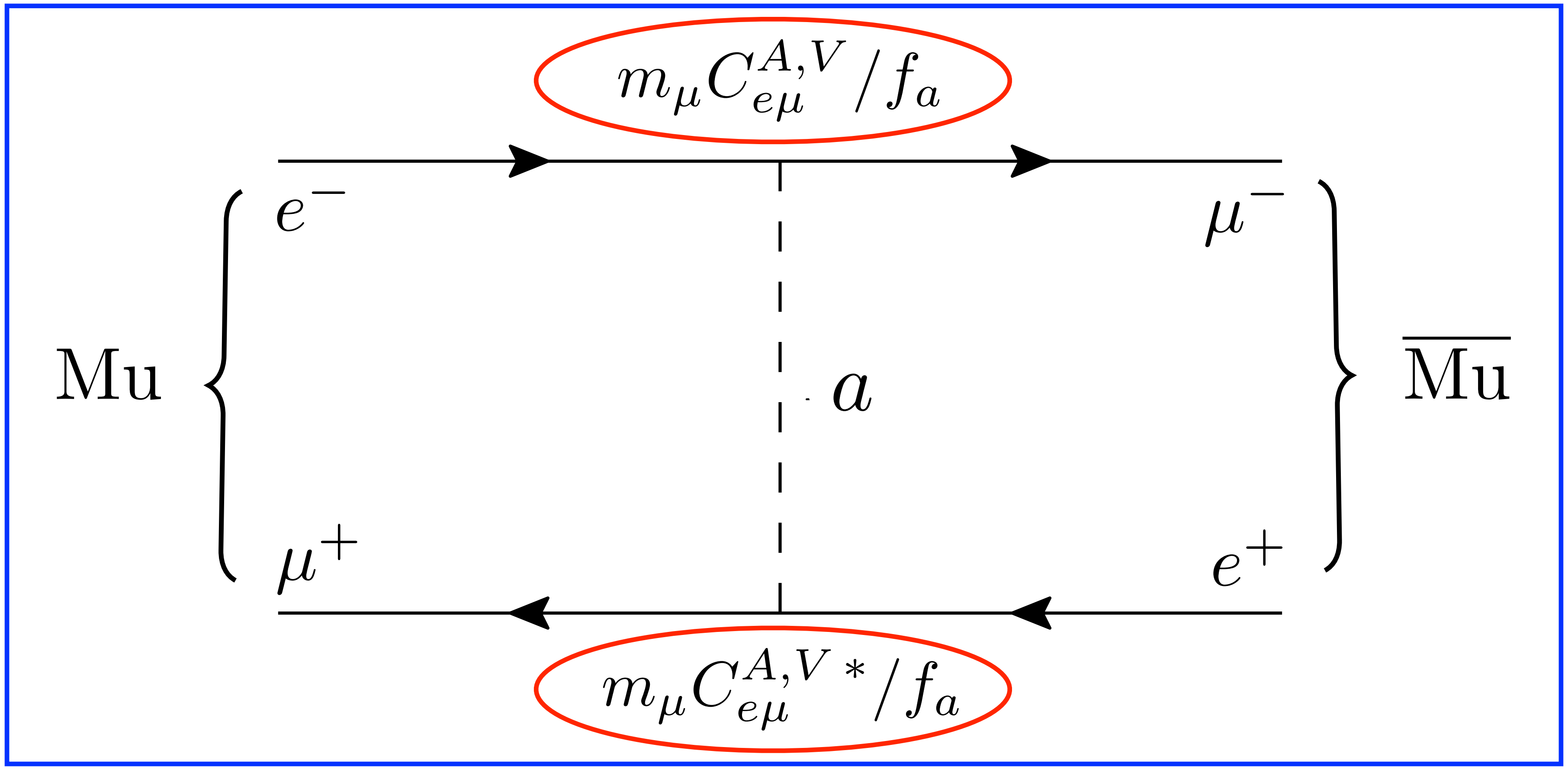
We have two possible strategies to test the μ-e interaction:

Indirect tests through processes they induce:
e.g. *muonium-antimuonium oscillations*

Direct production in muon beam collisions

→ also see talks by Li Qiang and Gao Le-Yuan

Low-energy test: muonium-antimuonium oscillations



$$P_{\text{Mu}\,\overline{\text{Mu}}} = \frac{m_\mu^4}{2\pi^2 a_B^6 \Gamma_\mu^2 [(m_\mu^2 - m_a^2)^2 + \Gamma_a^2 m_a^2] f_a^4} \left[|c_{0,0}|^2 \left| (C_{e\mu}^V)^2 - \left(1 + \frac{1}{\sqrt{1+X^2}}\right)(C_{e\mu}^A)^2 \right|^2 + |c_{1,0}|^2 \left| (C_{e\mu}^V)^2 - \left(1 - \frac{1}{\sqrt{1+X^2}}\right)(C_{e\mu}^A)^2 \right|^2 \right],$$

Limits on the oscillation probability: → Zhao Shihan's talk

Present: $P_{\text{Mu}\,\overline{\text{Mu}}} < 8.3 \times 10^{-11}$ MACS '98

x1000 improvement

Future: $P_{\text{Mu}\,\overline{\text{Mu}}} < 7 \times 10^{-14}$ MACE '24

High-energy option: the μTRISTAN proposal

μTRISTAN proposal : $\mu^+\mu^+$ and $\mu^+ e^-$ colliders

PTEP

Prog. Theor. Exp. Phys. **2022** 053B02(16 pages)
DOI: 10.1093/ptep/ptac059

μTRISTAN

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Hamada et al. '22

- The idea is to cool and focus μ^+ beams, a technology developed at JPARC [Abe et al., 1901.03047] → talks by S. Kamioka and Y. Sato
- The μ^+ beams could be accelerated up to 1 TeV and made to collide with :

30 GeV e^- beam

→ "Higgs factory" with $\sqrt{s} \simeq 346$ GeV

→ Expected integrated luminosity $\mathcal{L} = 1$ ab^{-1}

OR

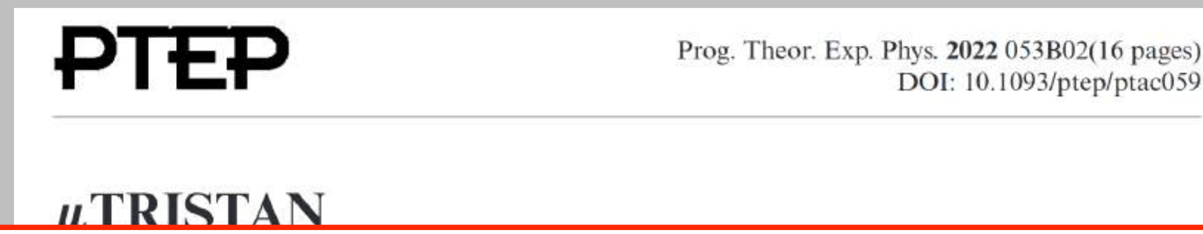
1 TeV μ^+ beam

→ "Discovery machine" with $\sqrt{s} = 2$ TeV

→ Expected integrated luminosity $\mathcal{L} = 100$ fb^{-1}

slide borrowed from L. Mukherjee

μTRISTAN proposal : $\mu^+\mu^+$ and μ^+e^- colliders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μTRISTAN

al. '22

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μ^+e^- collisions would make μTRISTAN an ideal environment to study cLFV!

For possible applications see Fridell et al. '23, Lichtenstein et al. '23

→ "Higgs factory" with $\sqrt{s} \simeq 346$ GeV

→ Expected integrated luminosity $\mathcal{L} = 1$ ab^{-1}

OR

→ "Discovery machine" with $\sqrt{s} = 2$ TeV

→ Expected integrated luminosity $\mathcal{L} = 100$ fb^{-1}

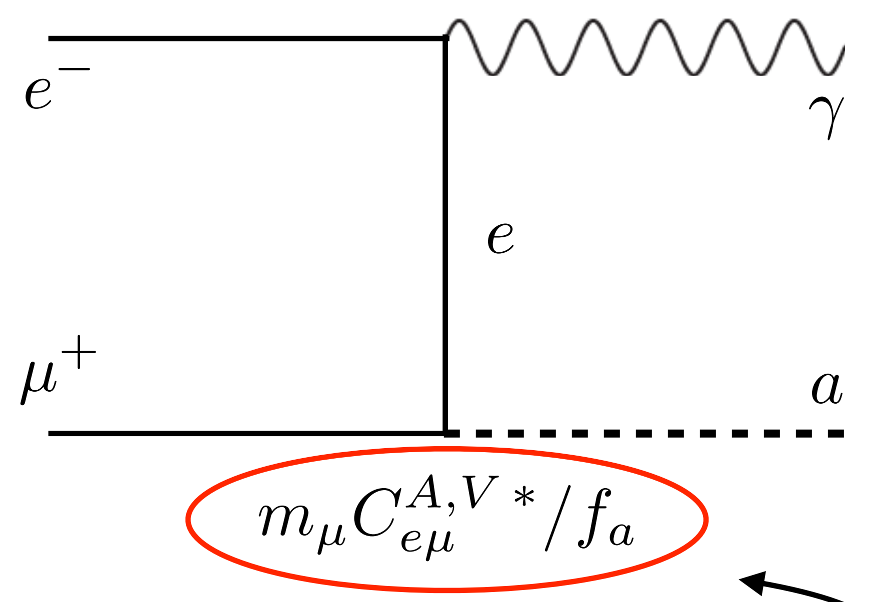
slide borrowed from L. Mukherjee

Most promising production mode (*see backup for other processes*):

$$\sigma(e^-\mu^+ \to a\gamma) \simeq \alpha \frac{m_\mu^2}{f_a^2} \frac{|C^A_{e\mu}|^2 + |C^V_{e\mu}|^2}{4s} |\eta|_{\rm max}$$

$$= \; 0.03 \text{ fb} \left(\frac{200\,\text{GeV}}{F_{e\mu}}\right)^2 \left(\frac{346\,\text{GeV}}{\sqrt{s}}\right)^2 \left(\frac{|\eta|_{\rm max}}{2.5}\right)$$

LC Li Mukherjee Yang '24



Heavier ALPs can decay promptly through the same LFV interactions

Charge combination $a \to \mu^- e^+$ virtually background-free:

Signal: $e^-\mu^+ \to \gamma a \to \gamma\mu^- e^+$

SM bg: $e^-\mu^+ \to \gamma\nu_e\bar{\nu}_\mu W^-(\to \mu^-\bar{\nu}_\mu)W^+(\to e^+\nu_e)$ $\quad [\sigma_{\rm B} \simeq 2\times 10^{-5}\text{ fb}]$

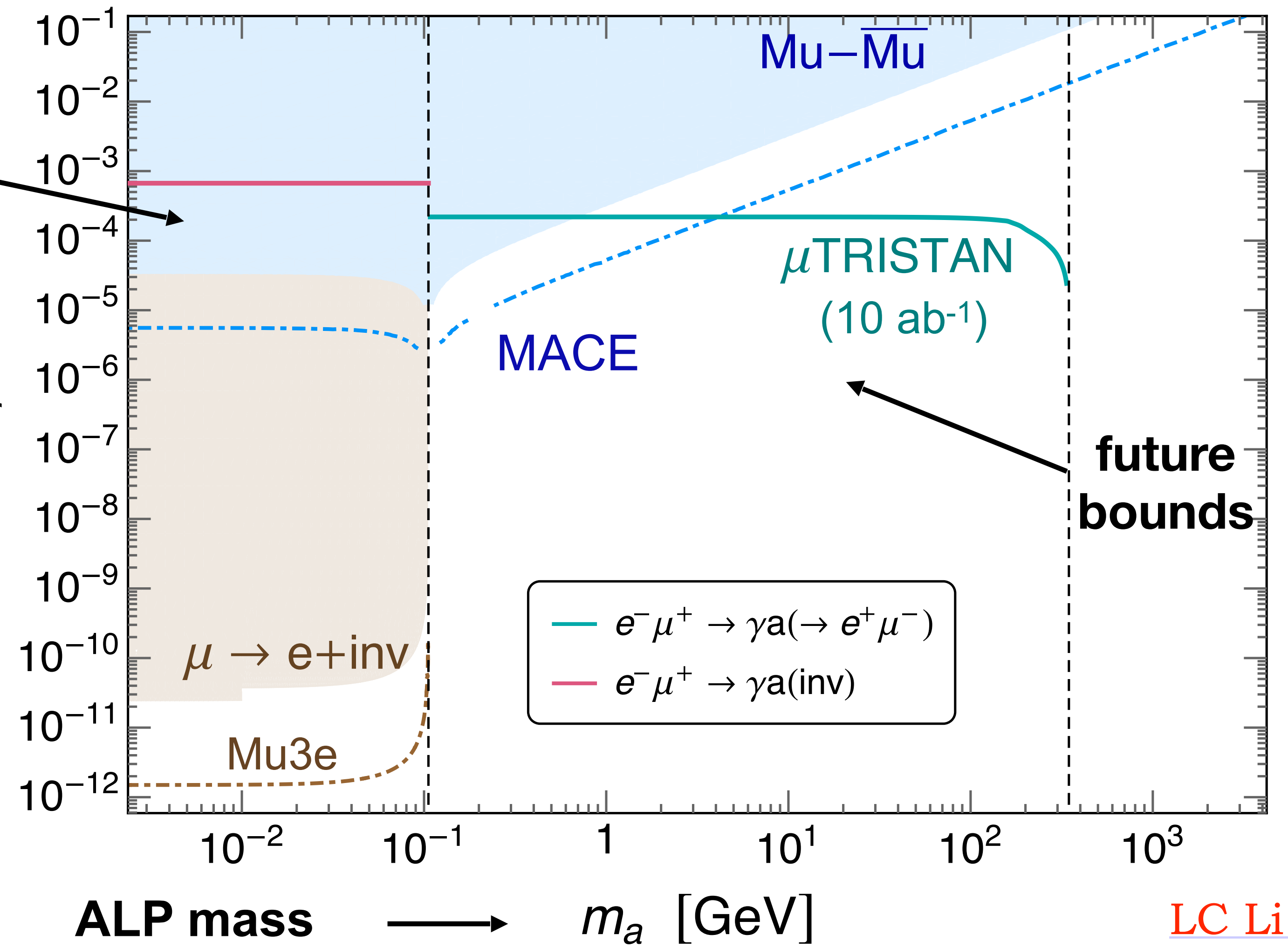
However, asymmetric beams reduce signal efficiency:

About 70% (50%) of ALP decay products fly outside the geometric acceptance for a detector with $|\eta|$<2.5 (3.5)

Future sensitivity to ALP μ-e interactions

Only LFV couplings $C_{e\mu}^{V,A}$

already excluded



future bounds

ALP coupling

$$g_{e\mu}^{A,V} \simeq \frac{m_\mu C_{e\mu}^{A,V}}{2 f_a}$$

ALP mass ⟶

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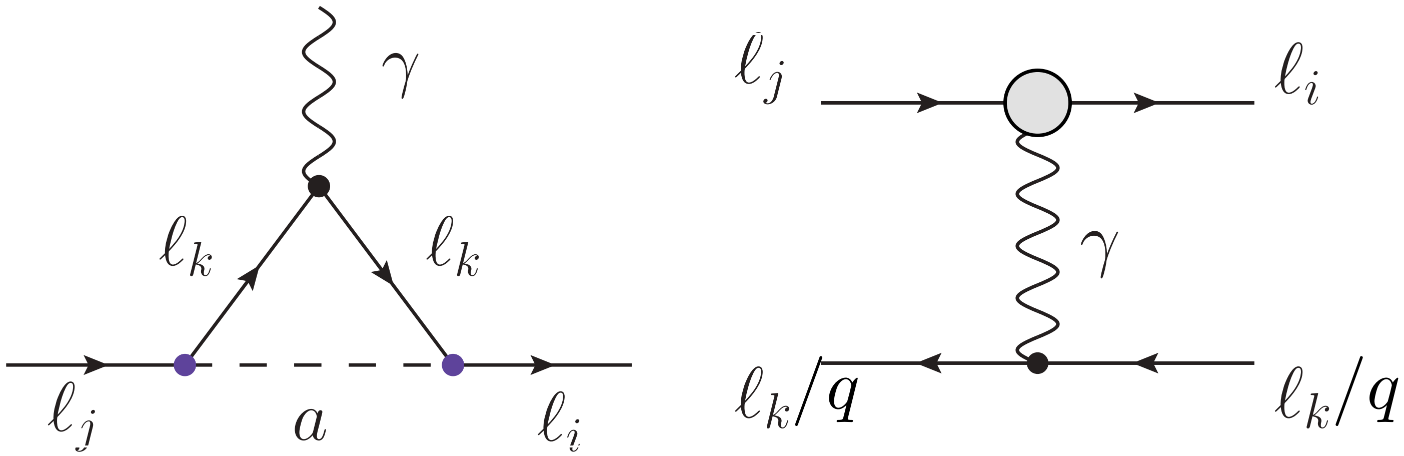
Interesting **interplay** between MACE and μTRISTAN

What if there are also substantial *flavour-conserving* (LFC) couplings?

One can also search for $a \to \mu^+\mu^-$ *but* low-energy LFV becomes stronger

Other interactions (LFC ones, in particular) lead to muon LFV decays:



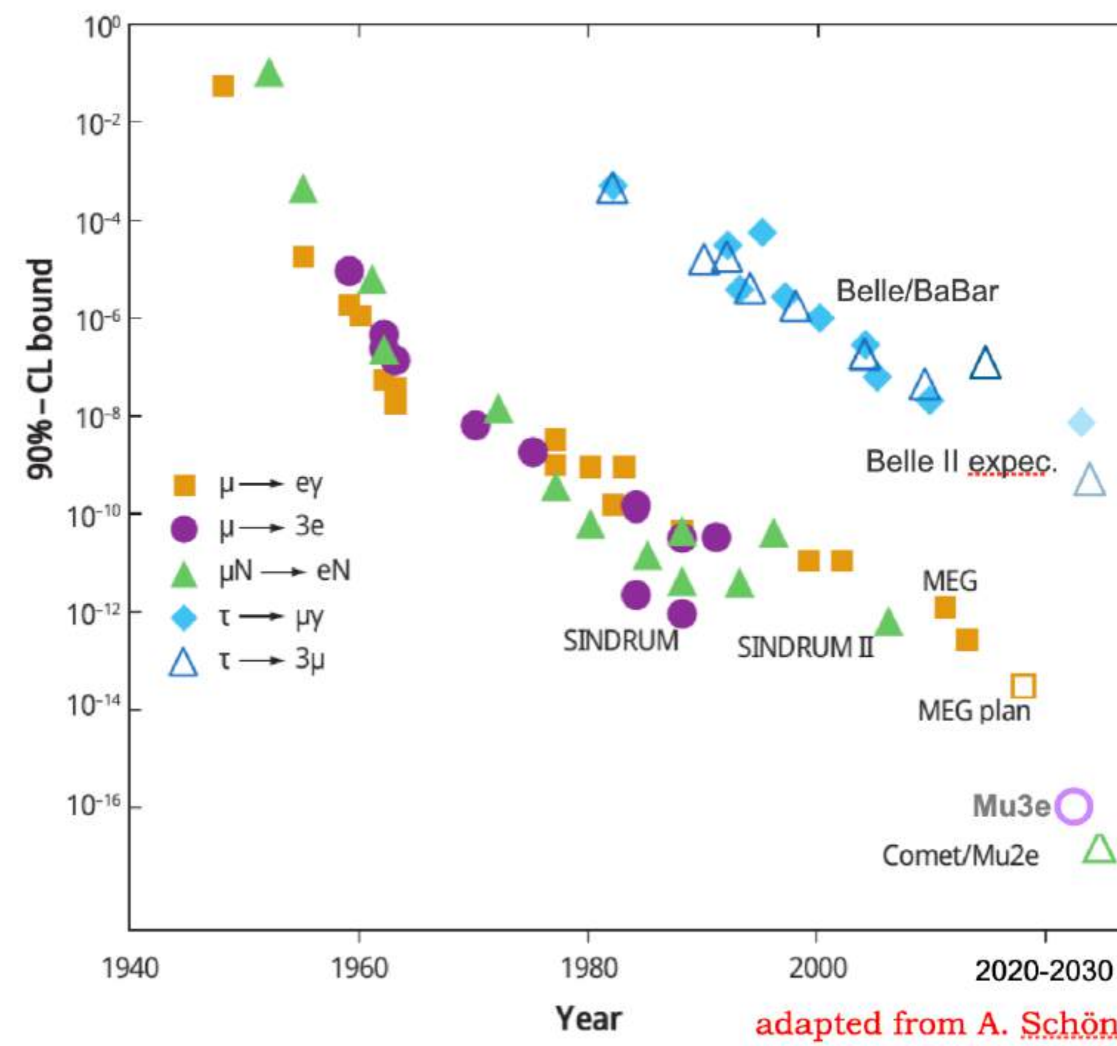
see e.g. Cornella Paradisi Sumensari '19

Stringent limits from:

$$\mu \to e\gamma$$

$$\mu \to eee$$

$$\mu\, \mathrm{N} \to e\, \mathrm{N}$$



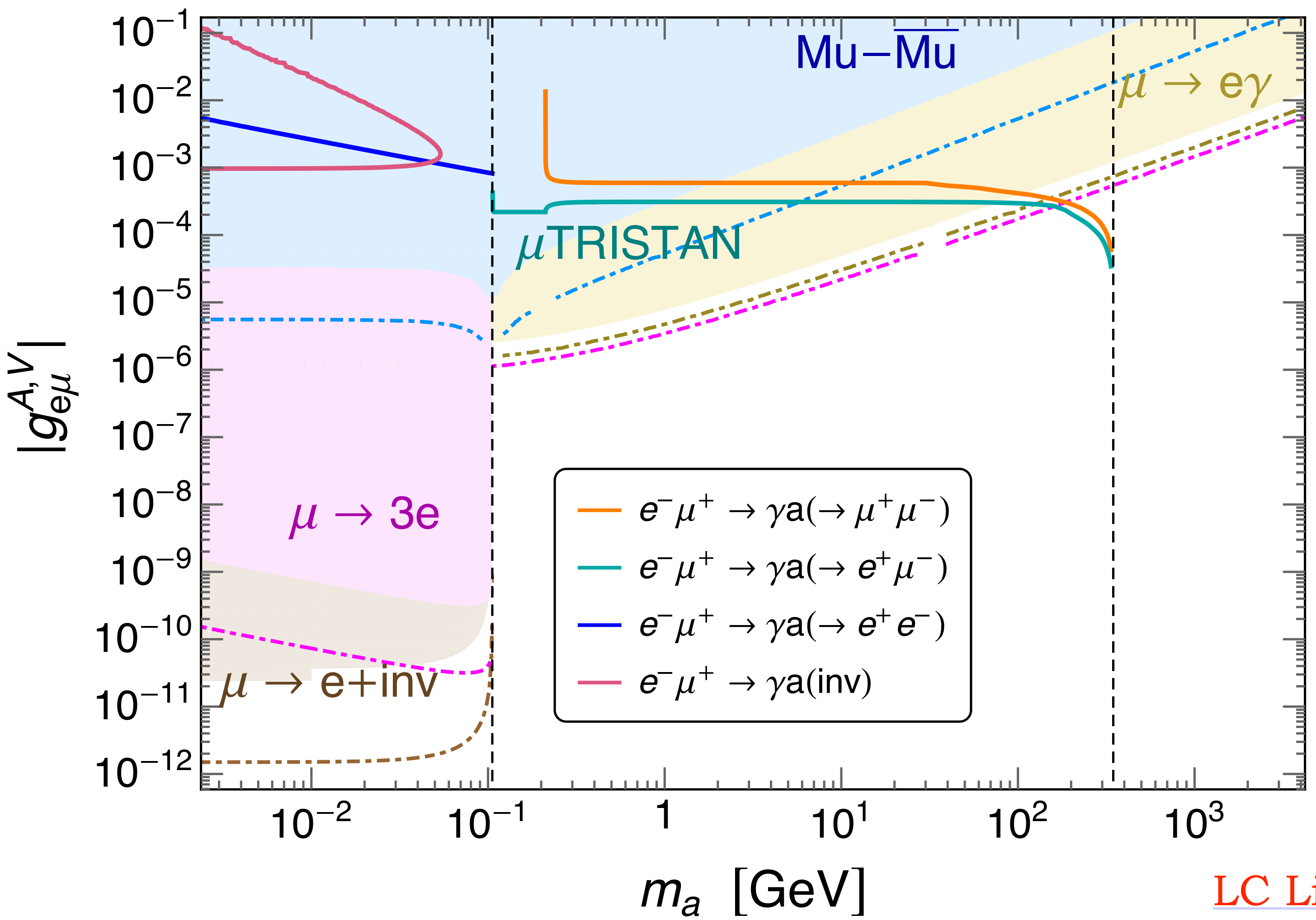
adapted from A. Schöning

For a pedagogical introduction (exp + th)

cf. LC and Signorelli '17

Future sensitivity to ALP μ-e interactions

LFV+LFC: $C^{V,A}_{e\mu} = C^{A}_{ee} = C^{A}_{\mu\mu}$



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μTRISTAN sensitivity could go beyond low-energy LFV constraints, only for very heavy ALPs, $m_a \gtrsim O(100)$ GeV

Summary

A wide class of new physics models entails axions/ALPs with flavour-violating couplings to SM leptons

Past (upcoming) searches for muon decays into invisible ALPs can test new physics scales up to 10^9 (10^{10}) GeV

Currently, ALPs heavier than muons are subject to much weaker constraints

Complementary tests on ALP μ-e interactions can be performed by MACE ($m_a \lesssim 5$ GeV) and μTRISTAN ($m_a \gtrsim 5$ GeV)

If flavour-conserving interactions are also sizeable, LFV muon decay set important constraints unless, $m_a \gtrsim 100$ GeV

Thanks!

Questions?

Additional slides

$\mu \to e\, a$: signal and background

Signal: monochromatic positron with $p_e = \sqrt{\left(\frac{m_\mu^2 - m_a^2 + m_e^2}{2m_\mu}\right)^2 - m_e^2}$

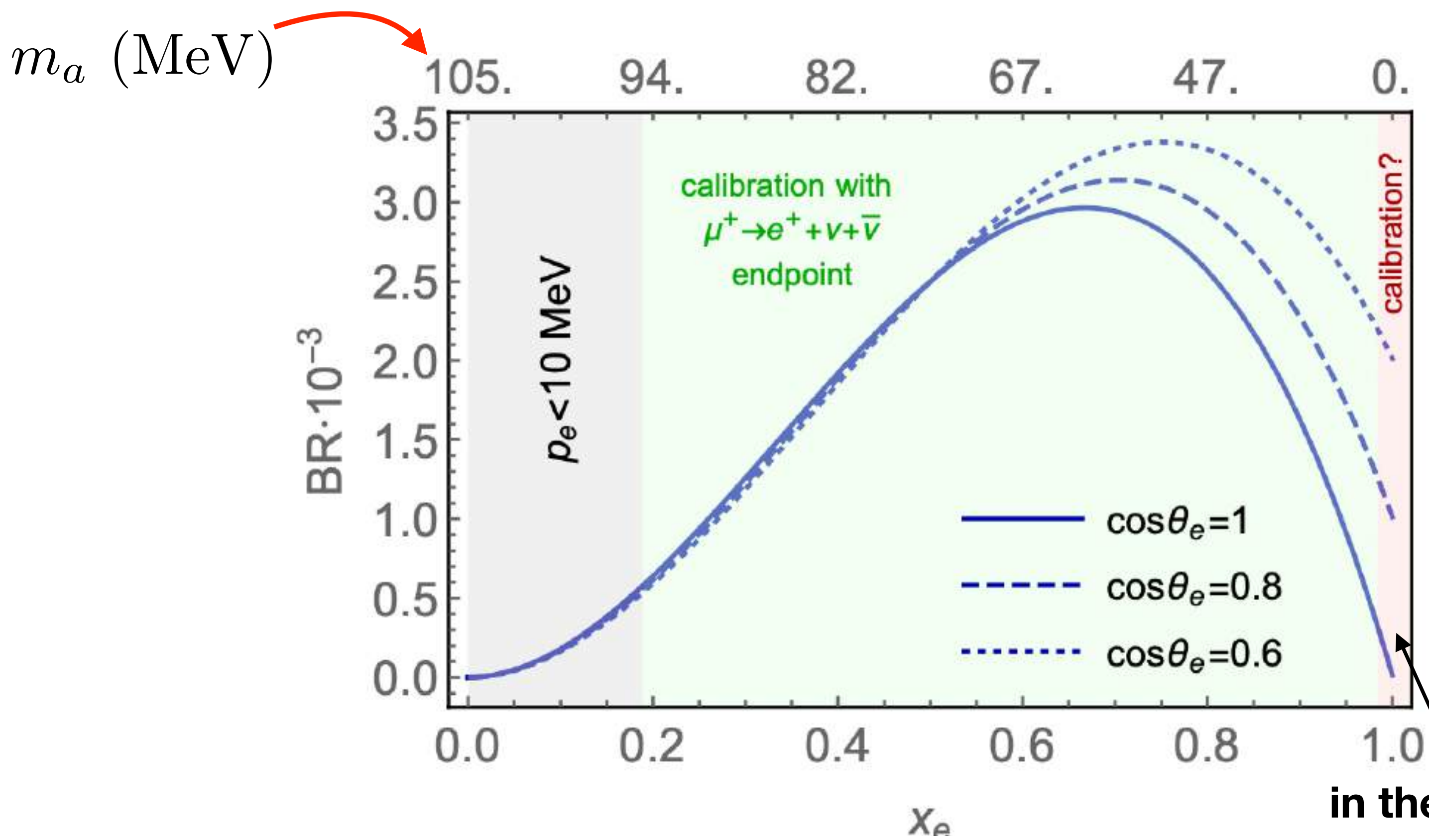
Differential decay rate: $\frac{\mathrm{d}\Gamma(\ell_i \to \ell_j\, a)}{\mathrm{d}\cos\theta} = \frac{m_{\ell_i}^3}{32\pi F_{\ell_i\ell_j}^2}\left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2 \left[1 + 2P_{\ell_i}\cos\theta \frac{C^V_{\ell_i\ell_j} C^A_{\ell_i\ell_j}}{(C^V_{\ell_i\ell_j})^2 + (C^A_{\ell_i\ell_j})^2}\right]$

signal depends on the chirality of the couplings

Michel spectrum: $\frac{\mathrm{d}^2\Gamma(\mu^+ \to e^+\, \nu_e\, \bar\nu_\mu)}{\mathrm{d}x_e\, \mathrm{d}\cos\theta} \simeq \Gamma_\mu \left((3 - 2x_e) - P_\mu (2x_e - 1)\cos\theta\right) x_e^2$ $\qquad x_e = \frac{2p_e}{m_\mu}$

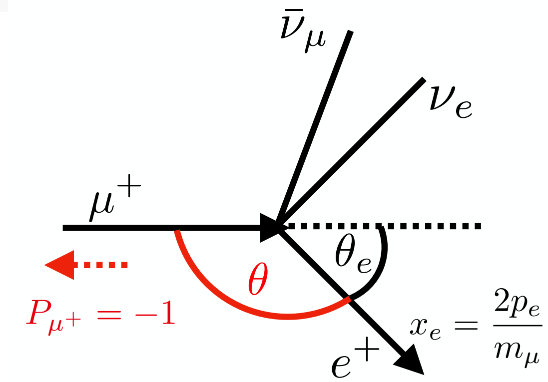
μ polarization

And "surface" muons are highly polarized (produced by pion decays at rest on the surface of the production target) → the SM background can be suppressed



in the massless case

the bkd goes to zero in the "forward"direction (the direction opposite to the muon polarization)



Currently strongest limit on $\mu \to e\, a$

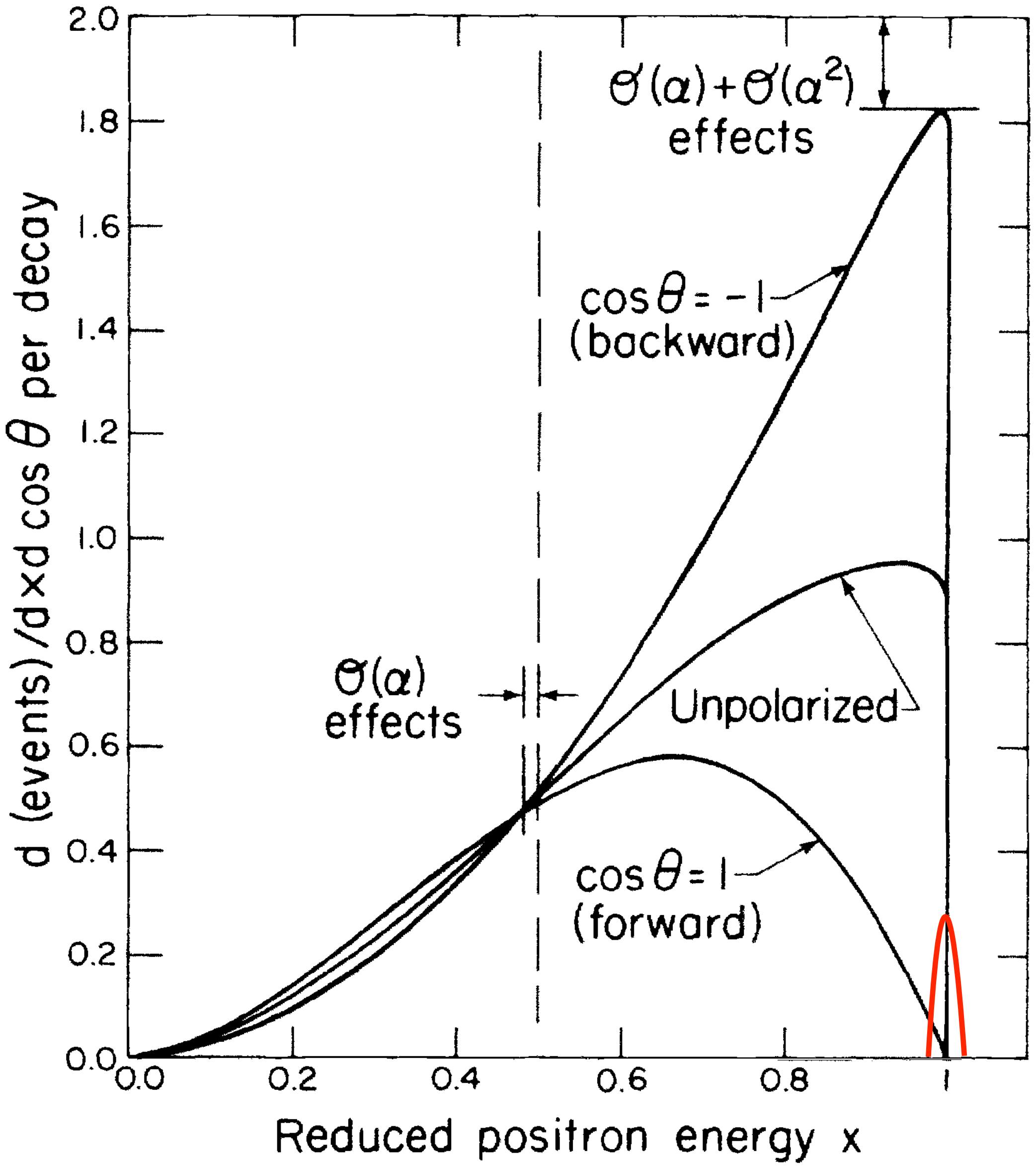
- Jodidio et al. (TRIUMF) 1986

Search for RH currents with 1.8×10^7 polarised μ^+ interpreted in terms of $\mu \to ea$ too

Ordinary $\mu \to e\bar{\nu}\nu$

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \Gamma_\mu \left((3-2x) - P(2x-1)\cos\theta\right) x^2$$

$$x = 2E_e/m_\mu$$



$\mu \to e\, a$ signal for $m_a \approx 0$: monochromatic e^+ at $m_\mu/2$

Unless it couples (V-A) like in the SM:

$$\frac{d\Gamma(\mu^+ \to e^+ a)}{d\cos\theta} = \frac{\Gamma_{\mu\to e\, a}}{2}\left[1 + 2P\cos\theta \frac{C^V_{e\mu} C^A_{e\mu}}{(C^V_{e\mu})^2 + (C^A_{e\mu})^2}\right]$$

for the *isotropic* case, they set the limit

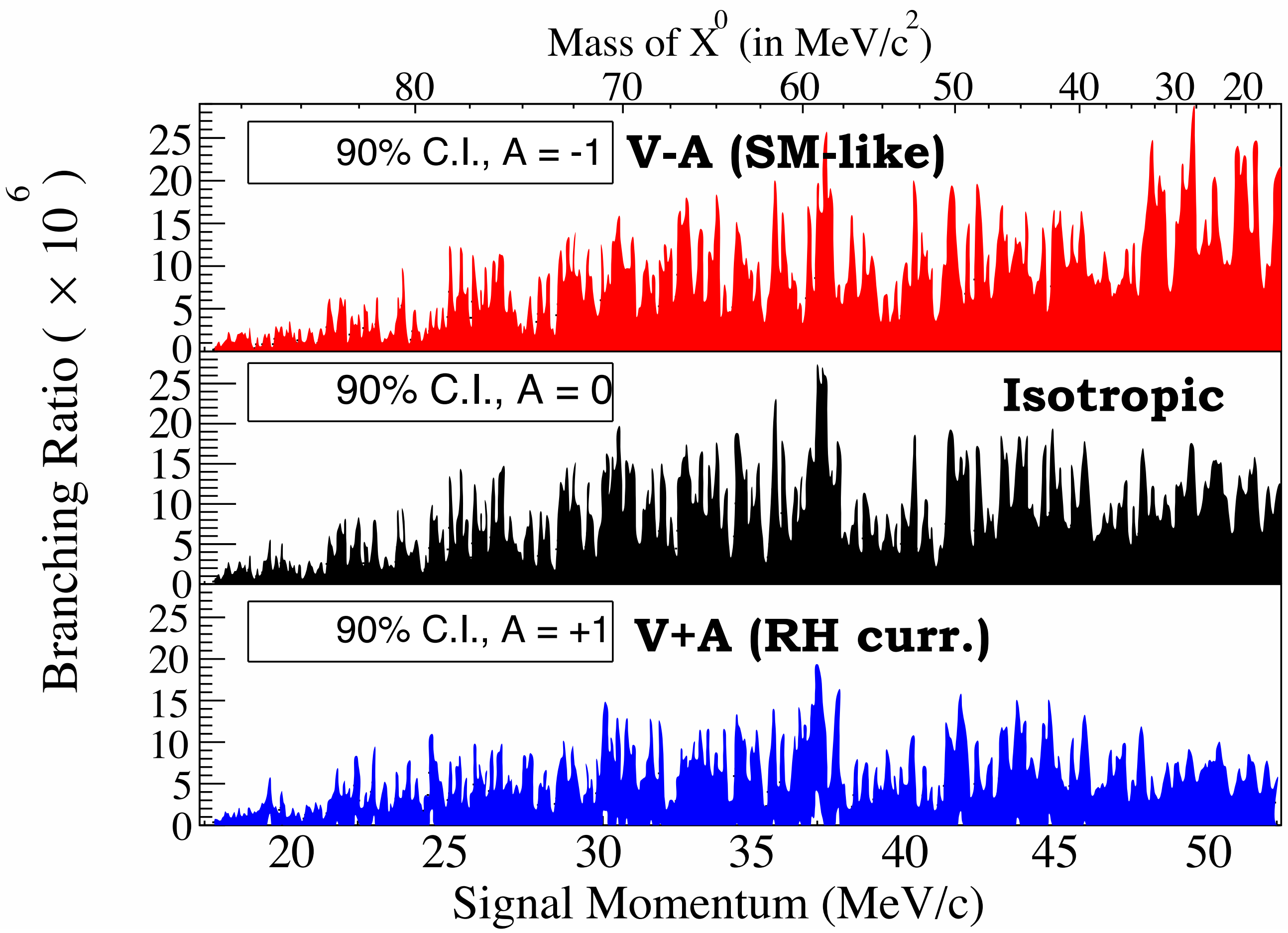
$$\Rightarrow \quad \mathrm{BR}(\mu^+ \to e^+ a) < 2.6 \times 10^{-6}$$

thus one gets

$$\Rightarrow \quad f_a/C^{V,A}_{e\mu} > 2.4 \times 10^9 \text{ GeV}$$

- TWIST 2014 Precise measurement of Michel parameters plus dedicated search for $\mu \to ea$ in the whole m_a range considering anisotropy of the signal

Limits (with $5.8{\times}10^8$ μ^+):



Decay Signal		90% C.L. (in ppm)	p-value
$A = 0$	Average	9	
	$p = 37.03$ MeV/c	26	0.66
	Endpoint	21	0.81
$A = -1$ SM-like	Average	10	
	$p = 37.28$ MeV/c	26	0.60
	Endpoint	58	0.80
$A = +1$	Average	6	
	$p = 19.13$ MeV/c	6	0.59
	Endpoint	10	0.90

For V-A coupl. and $m_a \approx 0$: $\text{BR}(\mu \to ea) < 5.8 \times 10^{-5}$

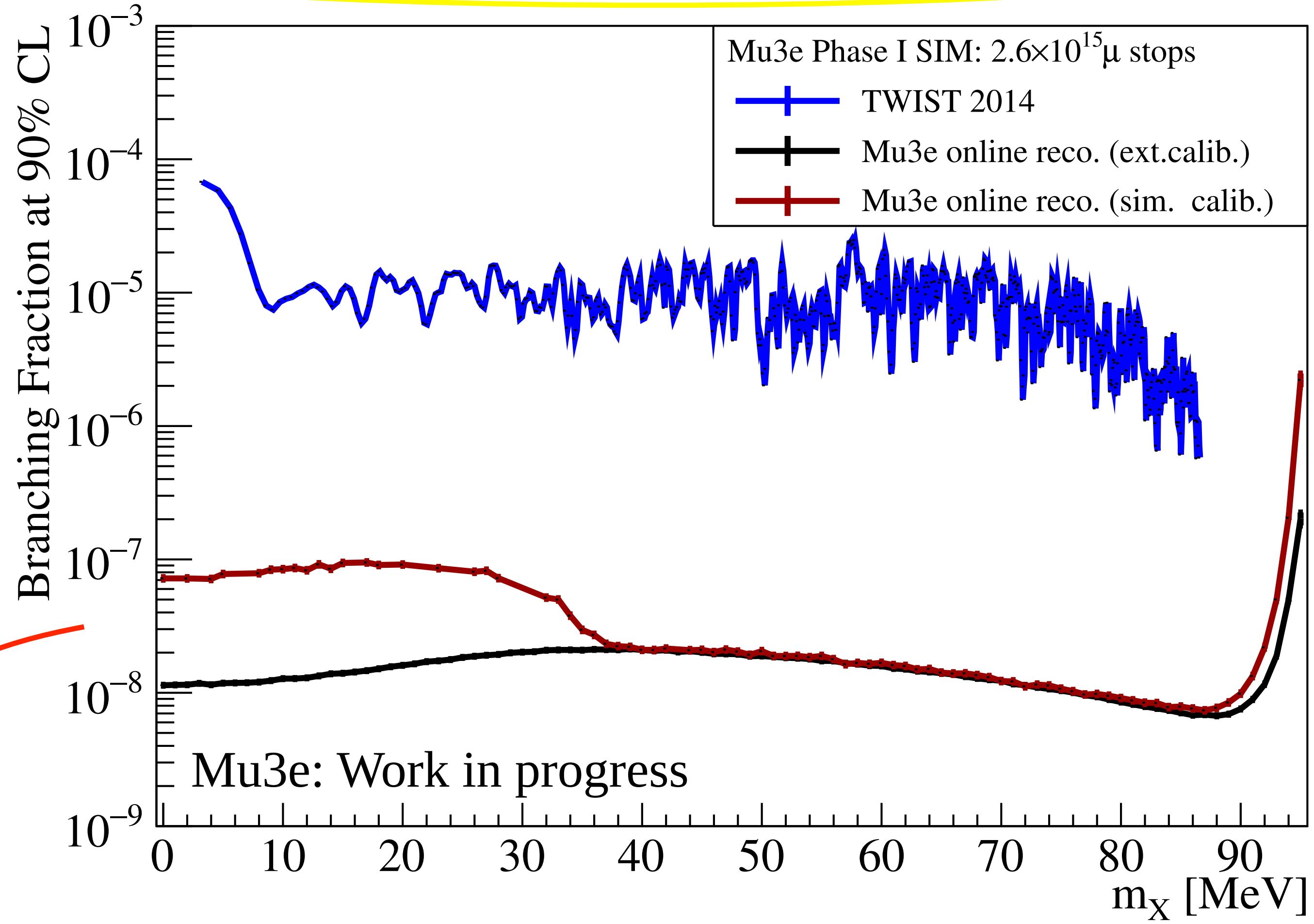
$$\Rightarrow \quad F_{\mu e} > 1.0 \times 10^9 \text{ GeV}$$

- Mu3e prospect for $\mu \to e\, a$

Perrevoort (Mu3e) ‘18

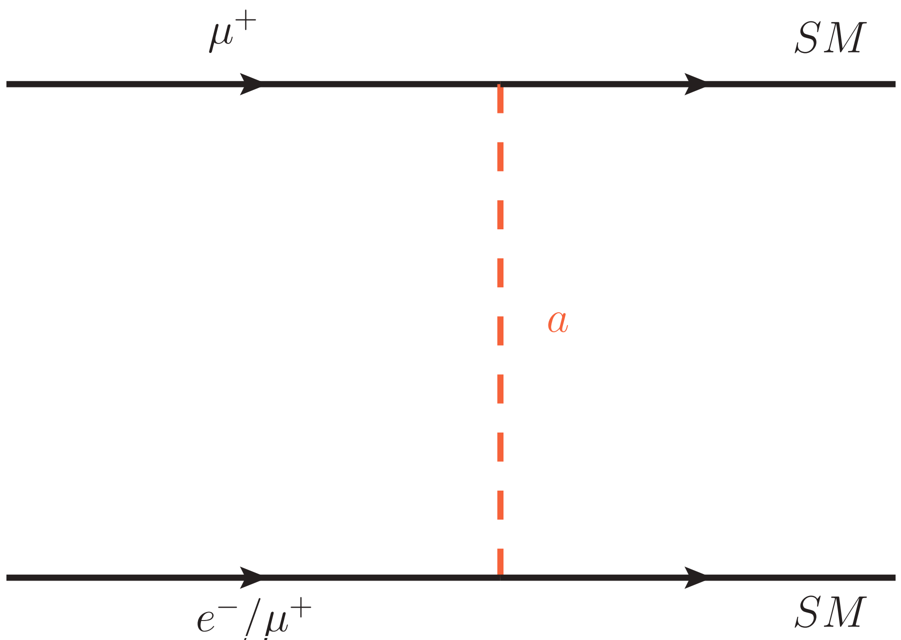
Potential search for performed on positron momentum histograms filled with *online* reconstructed short tracks

Expected limit for phase I ($2.6\times10^{15}\ \mu^+$):



$$m_a \approx 0\ :\quad \mathrm{BR}(\mu \to ea) < 7\times10^{-8} \quad \Rightarrow \quad F_{\mu e} \gtrsim 3\times10^{10}\ \mathrm{GeV}$$

ALP mediation



e.g, $\mu^+\mu^+ \to \ell^+\ell^+, \gamma\gamma,$
$e^-\mu^+ \to \ell^+\ell'^-$
$\sigma \propto 1/f_a^4$

Process	ALP couplings	Cross section (fb)
$e^-\mu^+ \to e^+\mu^-$	$C^A_{e\mu}$ or $C^V_{e\mu}$	9.7×10^{-9}
	$C^A_{e\mu} = C^V_{e\mu}$	5.1×10^{-8}
$e^-\mu^+ \to \gamma\gamma$	$C^A_{e\mu}$ or $C^V_{e\mu}$, C_γ	4.3×10^{-7}
	$C^A_{e\mu} = C^V_{e\mu}$, C_γ	8.5×10^{-7}
$e^-\mu^+ \to \mu^-\tau^+$	$C^A_{\mu\tau} = C^A_{e\mu}$ or $C^V_{\mu\tau} = C^V_{e\mu}$	3.1×10^{-6}
	$C^A_{\mu\tau} = C^V_{\mu\tau} = C^A_{e\mu} = C^V_{e\mu}$	7.3×10^{-6}
$e^-\mu^+ \to \tau^-\tau^+$	$C^A_{\mu\tau} = C^A_{e\tau}$ or $C^V_{\mu\tau} = C^V_{e\tau}$	2.9×10^{-4}
	$C^A_{\mu\tau} = C^V_{\mu\tau} = C^A_{e\tau} = C^V_{e\tau}$	1.0×10^{-3}
$\mu^+\mu^+ \to e^+e^+$	$C^A_{e\mu}$ or $C^V_{e\mu}$	2.3×10^{-10}
	$C^A_{e\mu} = C^V_{e\mu}$	1.2×10^{-9}
$\mu^+\mu^+ \to \tau^+\tau^+$	$C^A_{\tau\mu}$ or $C^V_{\tau\mu}$	2.3×10^{-5}
	$C^A_{\tau\mu} = C^V_{\tau\mu}$	9.4×10^{-5}

Cross sections too suppressed!

ALP production processes at μTRISTAN

Process	ALP couplings	m_a (GeV)	Cross section (fb)
$e^-\mu^+ \to a\gamma$	$C^A_{e\mu} = C^V_{e\mu}$	1	3.0×10^{-2}
		10	3.0×10^{-2}
		100	3.3×10^{-2}
$e^-\mu^+ \to aZ$	$C^A_{e\mu} = C^V_{e\mu}$	1	5.9×10^{-2}
		10	4.8×10^{-2}
		100	3.1×10^{-2}
$e^-\mu^+ \to \mu^-\mu^+ a$	$C^A_{e\mu} = C^V_{e\mu}$	1	1.4×10^{-3}
		10	1.1×10^{-3}
		100	7.2×10^{-4}
$e^-\mu^+ \to e^-e^+ a$	$C^A_{e\mu} = C^V_{e\mu}$	1	8.0×10^{-3}
		10	4.2×10^{-3}
		100	9.8×10^{-4}
$e^-\mu^+ \to e^-\tau^+ a$	$C^A_{\mu\tau} = C^V_{\mu\tau}$	1	1.4
		10	0.93
		100	8.6×10^{-2}
$e^-\mu^+ \to \tau^-\mu^+ a$	$C^A_{e\tau} = C^V_{e\tau}$	1	3.3×10^{-2}
		10	1.7×10^{-2}
		100	2.3×10^{-3}
$\mu^+\mu^+ \to \mu^+e^+ a$	$C^A_{e\mu} = C^V_{e\mu}$	1	8.7×10^{-4}
		10	5.1×10^{-4}
		100	1.8×10^{-4}
$\mu^+\mu^+ \to \mu^+\tau^+ a$	$C^A_{\mu\tau} = C^V_{\mu\tau}$	1	0.23
		10	0.14
		100	0.05

Event analysis

- Signal and background events are generated using MADGRAPH, PYTHIA, and MADSPIN.
- Detector response is simulated using DELPHES.
- Resulting events are analysed using ROOT.
- We apply the default basic generator-level cuts on the final-state photons or charged leptons in MADGRAPH.
- Statistical significance is defined as

$$\mathcal{S} = \frac{N_{\rm S}}{\sqrt{N_{\rm S} + N_{\rm B}}}\,, \quad N_{\rm S(B)} = \sigma_{\rm S(B)} \times \varepsilon_{\rm S(B)} \times \mathcal{L}\,,$$

- Signal efficiency : $\varepsilon_S \equiv \varepsilon_{\rm sel} \times \varepsilon_{\rm cut}$

$\varepsilon_{\rm sel}$ ↙ selection efficiency ↓ Includes geometric acceptance of detector and particle id probabilities

$\varepsilon_{\rm cut}$ ↘ signal acceptance after cuts.

- Finally, we show the expected 95% CL exclusion potential of μTRISTAN.

Geometric efficiency of ALP decay products

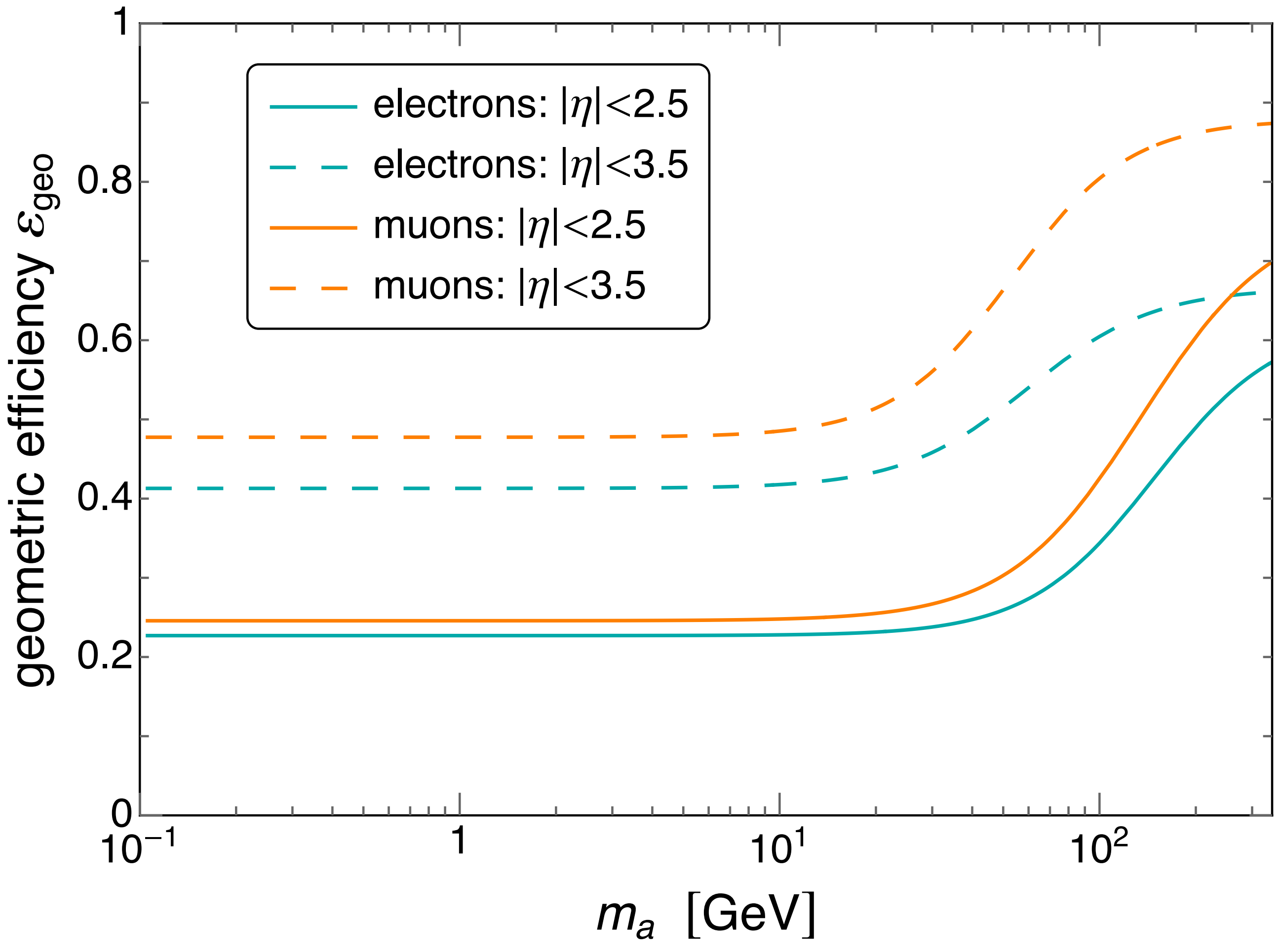
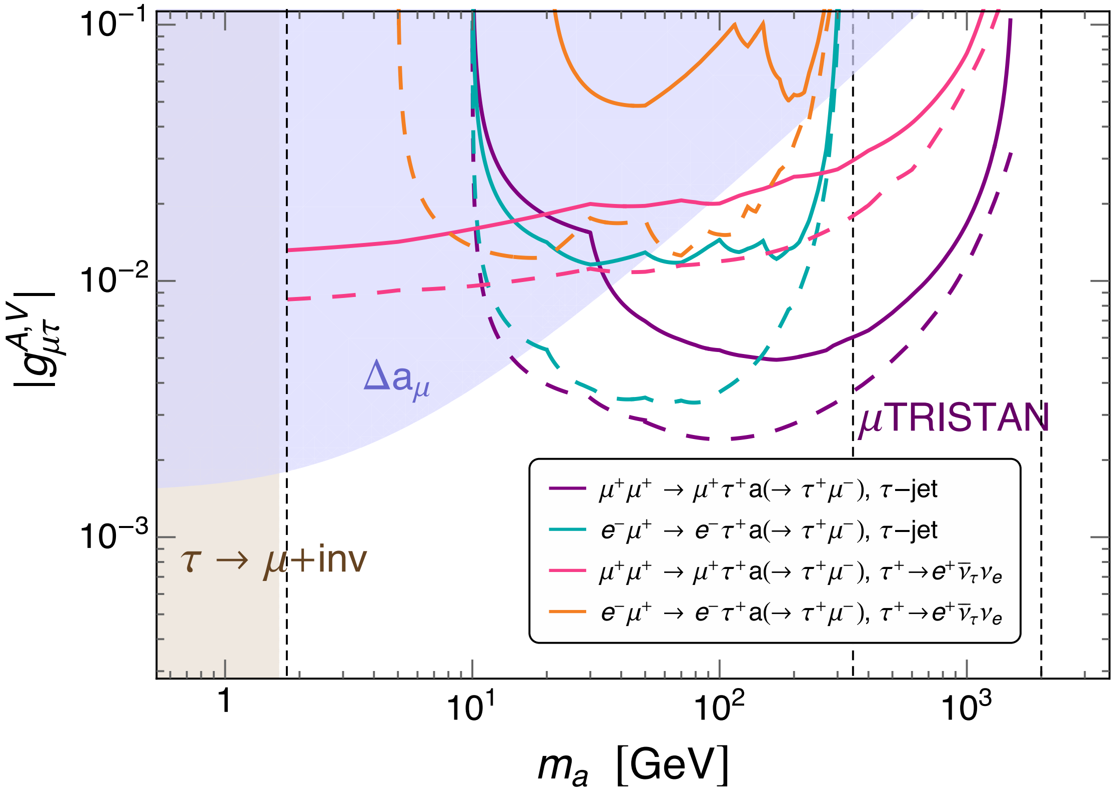
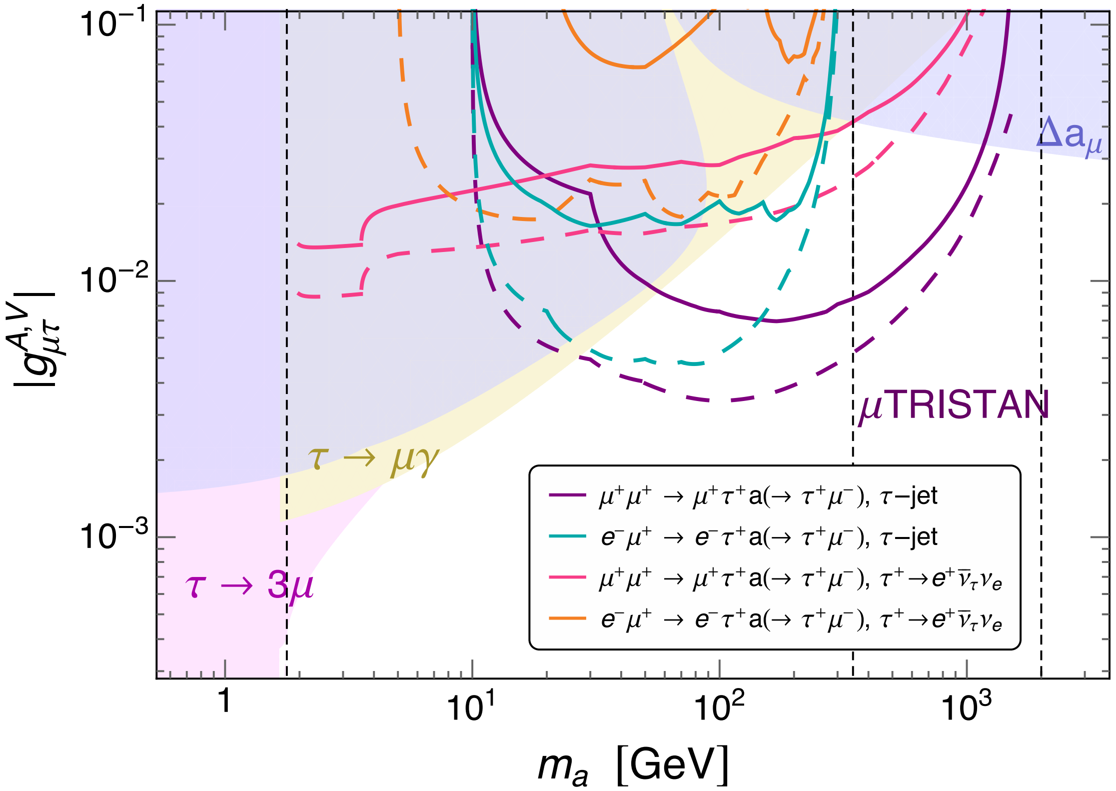


Figure 3: Geometric efficiency of electrons and muons from ALP decays as a function of the ALP mass, for two different designs of the detector: $|\eta|_{\rm max} = 2.5$ (solid lines) and $|\eta|_{\rm max} = 3.5$ (dashed lines).

μTRISTAN prospects for tau LFV

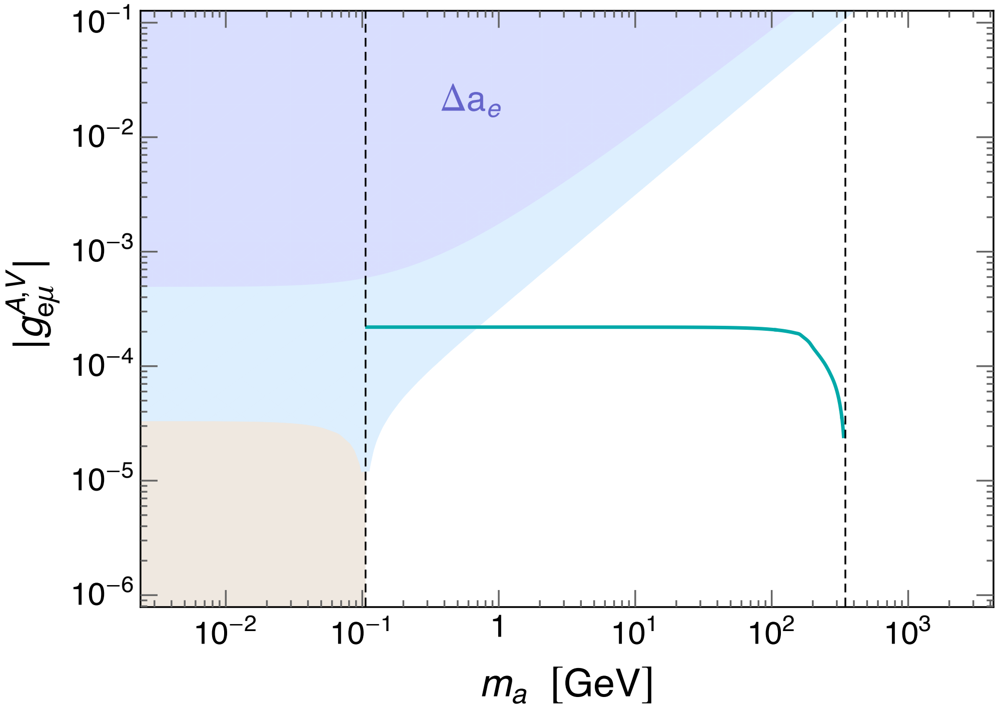


(a) LFV (μ-τ) couplings only

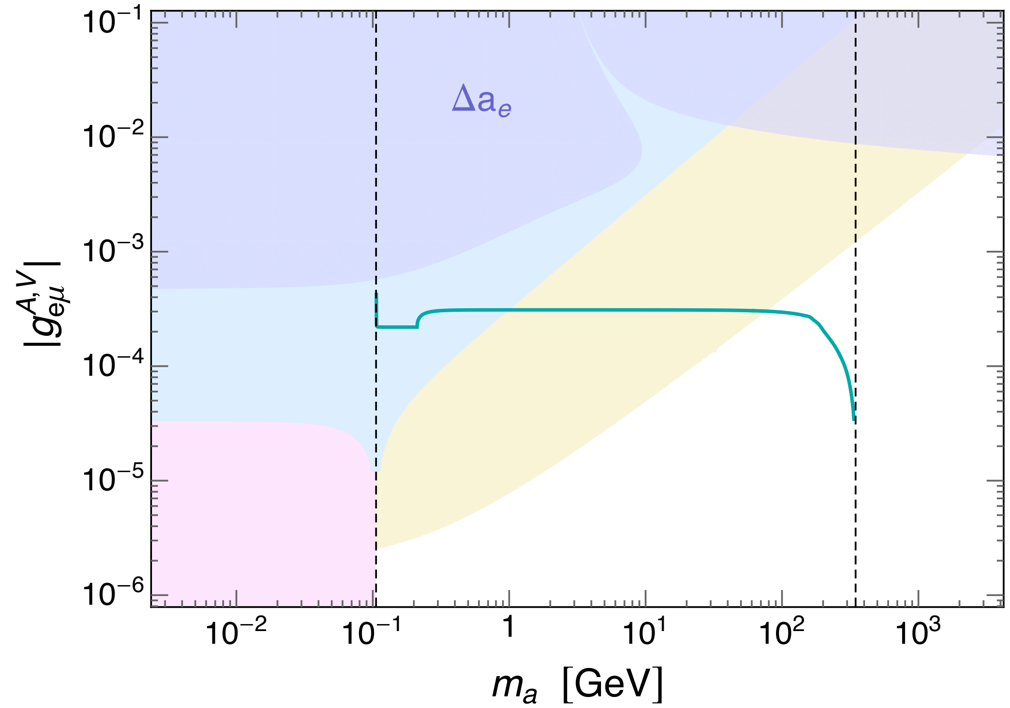


(b) LFV (μ-τ) and LFC couplings

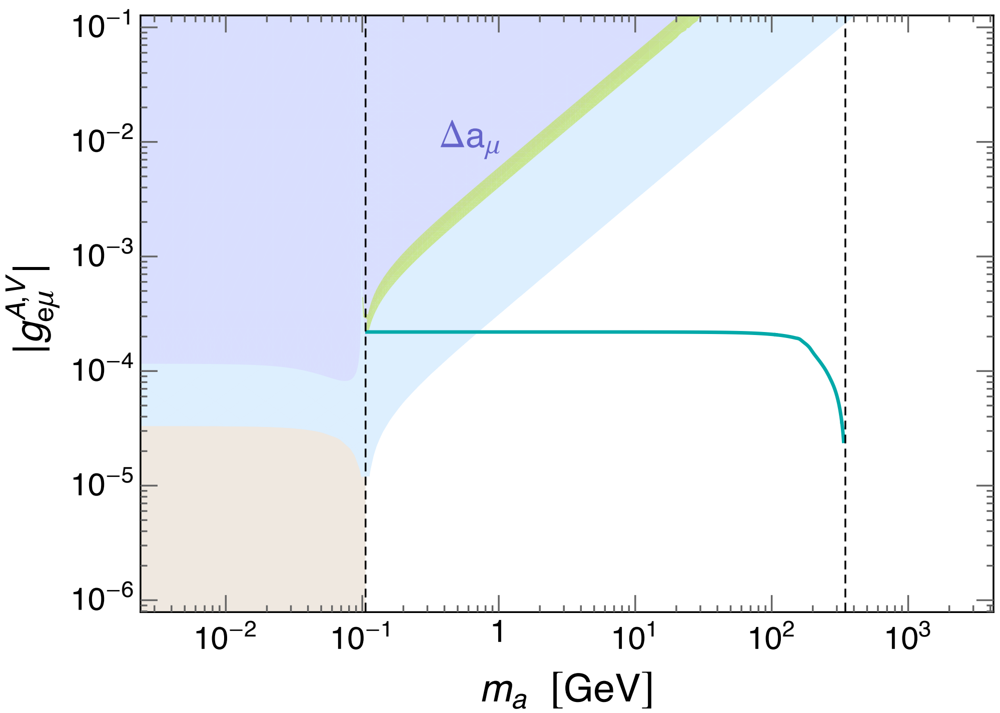
LC Li Mukherjee Yang '24



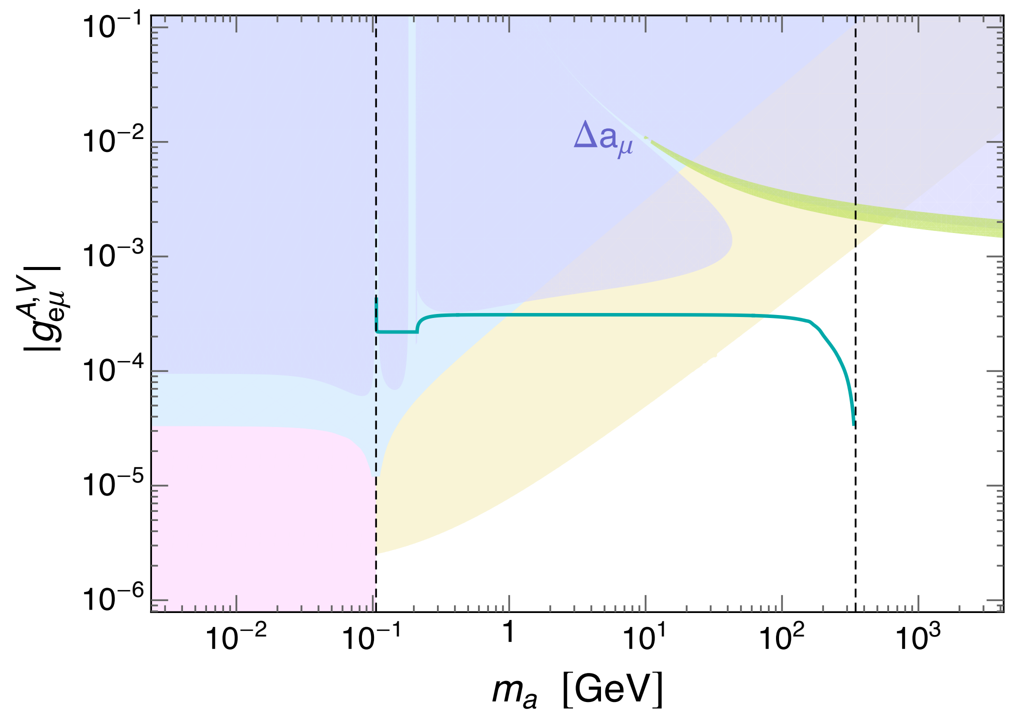
(a) LFV (e-μ) couplings only



(b) LFV (e-μ) and LFC couplings



(c) LFV (e-μ) couplings only



(d) LFV (e-μ) and LFC couplings