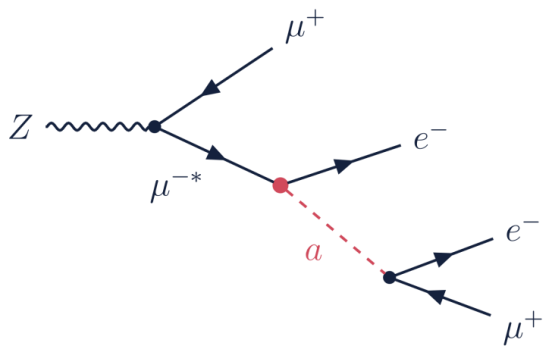
CEPC2026 · Flavour parallel session · Shanghai, 24 October 2026

Lepton-flavour-violating ALPs above the muon threshold

Production in meson, τ and gauge-boson decays — and why a Tera-Z can see it



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

Marco Fedele
PRISMA^{++} & MITP, Johannes Gutenberg University Mainz

with M. Ardu (IFIC Valencia), L. Calibbi (Nankai), F. Mescia (INFN LNF)
based on arXiv:2604.11889

Why lepton-flavour-violating ALPs?

- ALPs are pseudo-Goldstone bosons of a spontaneously broken global symmetry, with scale $\mathbf{f_a}$
- Coupled to leptons when the symmetry acts on them: lepton number, leptonic flavour symmetries, PQ
- In many models the ALP–lepton couplings are **generically flavour-violating** (loops, non-universal charges, non-Abelian structure)
- Exotic decays $\mu \to e\, a$, $\tau \to \ell\, a$ are then among the most sensitive probes of new light physics

Why leptophilic?

Quark FCNC couplings are already crushed: $\mathrm{BR}(K \to \pi a) \lesssim \text{few} \times 10^{-11} \Rightarrow f_a/C_{ds} \gtrsim 10^{12}$ GeV. Lepton-only couplings arise from flavour symmetries acting on leptons, or at loop level (e.g. the majoron).

[NA62, 2507.17286] [Calibbi et al., 2006.04795] [Chikashige, Mohapatra, Peccei '81; Schechter, Valle '82; Heeck, Patel, 1909.02029]

Strong CP problem
QCD axion, Peccei–Quinn

Neutrino masses
majoron from lepton-number breaking

Flavour hierarchies
familon / flavon-axion

Dark sector
DM candidate or portal

Effective set-up

Shift-symmetric, derivative couplings to charged leptons (Hermitian C^V, C^A treated as free parameters):

$$\mathcal{L}_{a\ell\ell} = \sum_i \frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i\, C^A_{ii}\gamma^\mu\gamma_5\,\ell_i \;+\; \sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i\gamma^\mu\left(C^V_{ij}+C^A_{ij}\gamma_5\right)\ell_j$$

Equivalent (up to anomalies) to non-derivative couplings proportional to lepton masses:

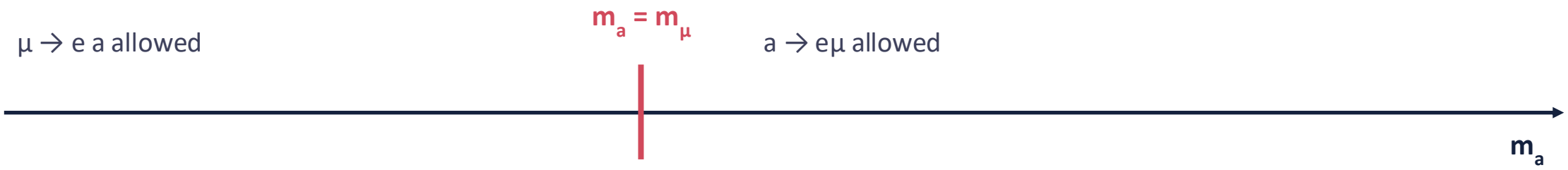
$$\mathcal{L}_{a\ell\ell} = i\,\frac{a}{2f_a}\,\bar{\ell}_i\Big[(m_i-m_j)\,C^V_{ij}+(m_i+m_j)\,C^A_{ij}\gamma_5\Big]\ell_j$$

Partial widths
$a \to \ell_i\ell_j \propto m_a\,(m_i \pm m_j)^2 / f_a^2$; $a \to \gamma\gamma$ via lepton loops

Once $m_a > m_\mu + m_e$
$a \to e\mu$ opens, coupling $\propto m_\mu \Rightarrow$ ALP typically decays promptly

$SU(2)_L$
$C^v_{ij} = C^V_{ij} - C^A_{ij}$ in the symmetric limit (matters for W, meson decays)

The muon threshold changes everything



Below: tightly constrained

- Intense muon beams: MEG II, Mu3e, Mu2e/COMET
- Invisible ALP (μ → e + inv.) and visible ALP (μ → e a → e ee, e γγ) both probed
- Reach: $f_a \gtrsim 10^9$–10^{10} GeV (μ → e a); $f_a \sim$ few × 10^6 GeV for τ → ℓ + inv. at Belle II

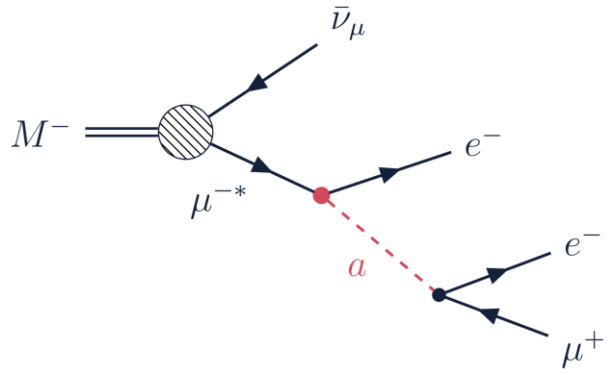
[Hill, Plestid, Zupan, 2310.00043] [Belle II, 2503.22195] [Calibbi et al., 2006.04795]

Above: a blind spot

- All bounds from production in μ decays disappear
- Left with muonium–antimuonium and g−2: **double insertion** of $C_{e\mu}/f_a$, weak
- Existing proposals (Belle II, μTRISTAN, eγ collisions) reach $f_a \lesssim 10$ TeV
- Here we propose: **produce on-shell ALPs from virtual muons**

[Endo, Iguro, Kitahara, 2002.05948] [Calibbi et al., 2406.13234] [Zhang, Zhang, Wang, 2603.26044]

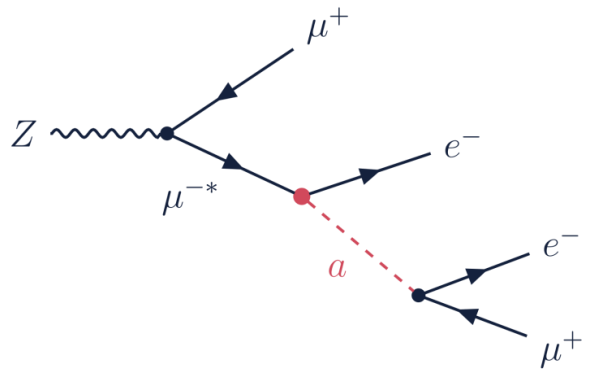
Idea: let a virtual muon radiate the ALP



Charged mesons & W

K, D_s, W → e^- $\bar{\nu}_\mu$ a

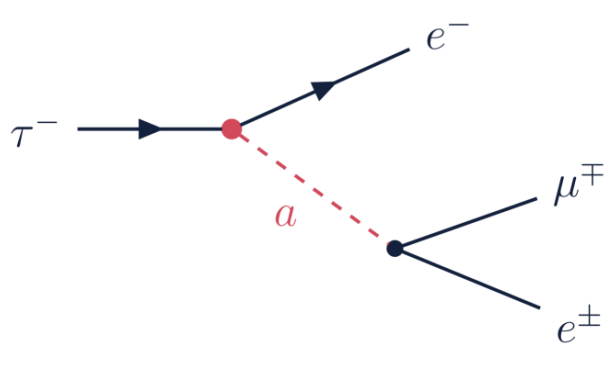
e^- e^- μ^+ + missing E



Z & vector quarkonia

Z, J/ψ, Υ → $e^\pm$ $\mu^\mp$ a

$e^\pm$ $e^\pm$ $\mu^\mp$ $\mu^\mp$, fully visible



τ decays (if $C_{e\tau} \neq 0$)

τ → ℓ a, two-body

prompt or displaced eμ vertex

Final states with **$|\Delta L_e| = |\Delta L_\mu| = 2$** plus a resonant eμ pair: no SM process gives them, whatever the neutrino flavour.
Background = misidentification and accidental overlaps only.

Mesons and W: chirality suppression vs $SU(2)_L$

$$\Gamma(M^- \to e^- \bar{\nu}_\mu a) \simeq \frac{f_M^2 G_F^2 |V_{ij}|^2 m_M^5}{3072\pi^3 f_a^2} \left[|C_L|^2 \, g_0(x) + \left(8|C_L|^2 + 4\,\mathrm{Re}(C_L C_{e\mu}^{\nu *}) + 4|C_R|^2\right) \frac{m_\mu^2}{m_M^2} \, g_1(x) \right]$$

$$\Gamma(W^- \to e^- \bar{\nu}_\mu a) \simeq \frac{g^2 m_W^3}{4096\pi^3 f_a^2} \left[|C_L|^2 + \frac{4}{9}\left(2|C_L|^2 + \mathrm{Re}(C_L C_{e\mu}^{\nu *}) + |C_R|^2\right) \frac{m_\mu^2}{m_W^2} \, g_2(x) \right]$$

$$C_L \equiv \frac{C_{e\mu}^V - C_{e\mu}^A - C_{e\mu}^\nu}{2}, \qquad C_R \equiv \frac{C_{e\mu}^V + C_{e\mu}^A}{2}$$

The role of C_L

- $SU(2)_L$ limit: $C_L = 0 \Rightarrow$ rate **suppressed by m_μ^2/m_M^2**
- $C_L \neq 0 \Leftrightarrow$ ALP–W–ℓ–ν contact vertex, not lepton-mass suppressed:

$$\mathcal{L}_{\text{gauge}} \supset \frac{ia}{2f_a} \frac{g}{\sqrt{2}} W_\alpha \, \bar{\ell}_i \left(C_{ij}^V - C_{ij}^A - C_{ij}^\nu\right) \gamma^\alpha P_L \nu_j$$

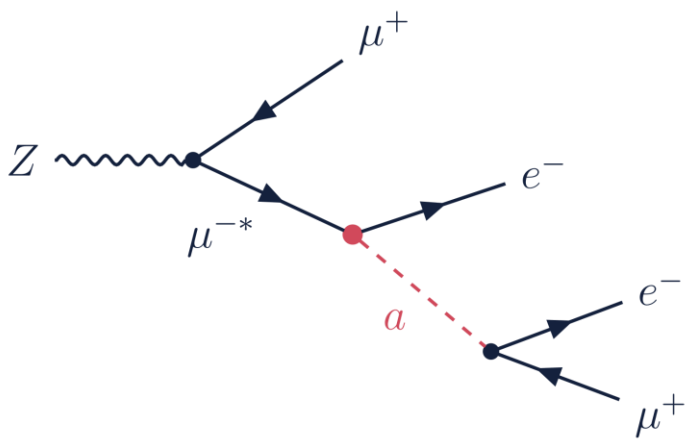
Where it matters

- **K → e ν a**: NA62 (prompt), SHiP (long-lived)
- **D_s → e ν a**: Tera-Z, ~10^{11} D_s; SHiP
- **W → e ν a**: WW threshold + 240 GeV runs
- D, B: CKM-suppressed; B_c: ~10^3 fewer than D_s

Z and quarkonium decays: four leptons, no neutrinos

$$\Gamma(Z \to e^{\pm}\mu^{\mp}a) \simeq \frac{g^2\, m_\mu^2\, M_Z}{36864\,\pi^3 c_W^2 f_a^2}\left[|C_{e\mu}^A|^2 + |C_{e\mu}^V|^2\right] g_3(x)\,, \qquad g_3(x \ll 1) \simeq -3\log x - 11$$

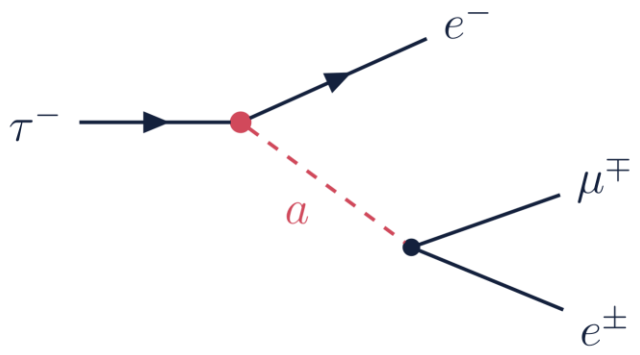
$$\Gamma(V \to e^{\pm}\mu^{\mp}a) \simeq \frac{\alpha^2 f_V^2 Q_Q^2\, m_\mu^2}{48\pi\, m_V f_a^2}\left[|C_{e\mu}^A|^2 + |C_{e\mu}^V|^2\right] g_4(x)\,, \qquad V = J/\psi,\ \Upsilon(nS)$$



Z → e⁻μ⁺ a(→ e⁻μ⁺)

- Always **chirally suppressed by m_μ^2**: the W-type contact term does not enter
- Log enhancement for light ALPs: $g_3 \simeq -3\log(m_a^2/M_Z^2) - 11$
- Signature $e^{\pm}\, e^{\pm}\, \mu^{\mp}\, \mu^{\mp}$ with $M(4\ell) = M_Z$ and a resonant eμ pair: **fully reconstructed**
- **J/ψ at STCF**: ~10^{13} in total ⇒ competitive with Tera-Z
- **Υ(1S–3S)**: ~10x smaller BR (m_V, Q_b) and 10^4–10^5 fewer events ⇒ not pursued

τ decays: a two-body ALP source with eμ-driven lifetime



$$\Gamma(\tau \to \ell a) = \frac{m_\tau^3}{64\pi f_a^2}\left(|C_{\ell\tau}^V|^2 + |C_{\ell\tau}^A|^2\right)\left(1 - \frac{m_a^2}{m_\tau^2}\right)^2$$

For $m_\mu \lesssim m_a \lesssim m_\tau$, the ALP decays through a → eμ (and a → μμ): its decay length measures the eμ couplings.

Prompt $l_a < 1$ mm

τ → e (μ e) resonance; bounded by τ → 3ℓ searches

Displaced 1 mm < l_a < 1 m

displaced eμ / μμ vertex in the inner detector: the new handle

Invisible $l_a > 1$ m

τ → ℓ + inv.; Belle (II) BR ≲ few x 10^{-4}, no eμ information

Two benchmarks, two kinds of indirect bound

Scenario A $C^{A}_{\mu\mu} \ll C^{V,A}_{e\mu}$

e.g. residual $\mathbb{Z}_4$ lepton flavour symmetry

Leading bound: muonium → antimuonium

$$P_{\mathrm{Mu}\overline{\mathrm{Mu}}} \propto \frac{m_\mu^4}{a_0^6\,\Gamma_\mu^2\,m_a^4\,f_a^4}\left|(C^V_{e\mu})^2 - \kappa_B\,(C^A_{e\mu})^2\right|^2$$

- $\propto 1/f_a^4$: **weak** (MACS: P < 8.3 x 10^{-11})
- MACE aims at 7 x 10^{-14}
- BR(a → $e^-\mu^+$) = BR(a → $e^+\mu^-$) = **1/2**

[Willmann et al., hep-ex/9807011] [MACE: Bai et al., 2410.18817]

Scenario B $C^{A}_{\mu\mu} \simeq C^{V,A}_{e\mu}$

generic non-universal U(1) with O(1) eμ rotations

Leading bound: μ → eγ at one loop

$$\Gamma(\mu \to e\gamma) = \frac{\alpha\, m_\mu^3}{2(64\pi^2)^2 f_a^4}\,|C^A_{\mu\mu}|^2\left[|C^A_{e\mu}|^2 + |C^V_{e\mu}|^2\right] h^2(m_a^2/m_\mu^2)$$

- MEG II: BR < 1.5 x 10^{-13}
- Mu3e (via dipole) ⇒ BR(μ → eγ) ≲ 1.6 x 10^{-14}; Mu2e/COMET ⇒ ≲ 2.3 x 10^{-14}
- a → μμ open too: BR(a → $e^{\mp}\mu^{\pm}$) ≃ **1/4**

[Cornella, Paradisi, Sumensari, 1911.06279] [MEG II, 2504.15711]

A Tera-Z run is the natural machine for this

4×10^{12}	1.8×10^{11}	2×10^{11}	2×10^{8}
Z bosons	**D_s mesons**	**τ leptons**	**W bosons**
$Z \to e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$	$D_s \to e^-e^-\mu^+\bar{\nu}$	$\tau \to e\, a(\to \mu e)$	$W \to e^-e^-\mu^+\bar{\nu}$

Event yields used in our projections (CEPC/FCC-ee, from the CEPC flavour white paper). Complementary: STCF with 10^{13} J/ψ, Belle II with 4.5×10^{10} τ. [CEPC: Ai et al., 2412.19743; STCF: Achasov et al., 2303.15790]

- **Clean environment**: excellent lepton ID, missing-energy reconstruction, closed kinematics at the Z pole
- **Charge selection**: pick the eμ charge combination so that the search is essentially background-free
- **Displaced vertices**: precise inner tracking for the τ-induced long-lived regime

Backgrounds and signal efficiency at the Z pole

Can anything fake $e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$?

$e^+e^- \to 4e, 4\mu, 2e2\mu$
$\sigma \approx$ few $\times 10^{-3}$ pb (MadGraph5)

x 100 ab^{-1}
$\approx$ few x 10^5 events

x two $e \leftrightarrow \mu$ mis-IDs
mis-ID < 0.1% ⇒ < 1 event

- $4\tau \to$ leptons: BR($\tau \to \ell\nu\nu$)^4 and no missing energy allowed ⇒ irrelevant
- $D_s \to K^+K^-e\nu$ with double hadron mis-ID: expected negligible

Signal efficiency

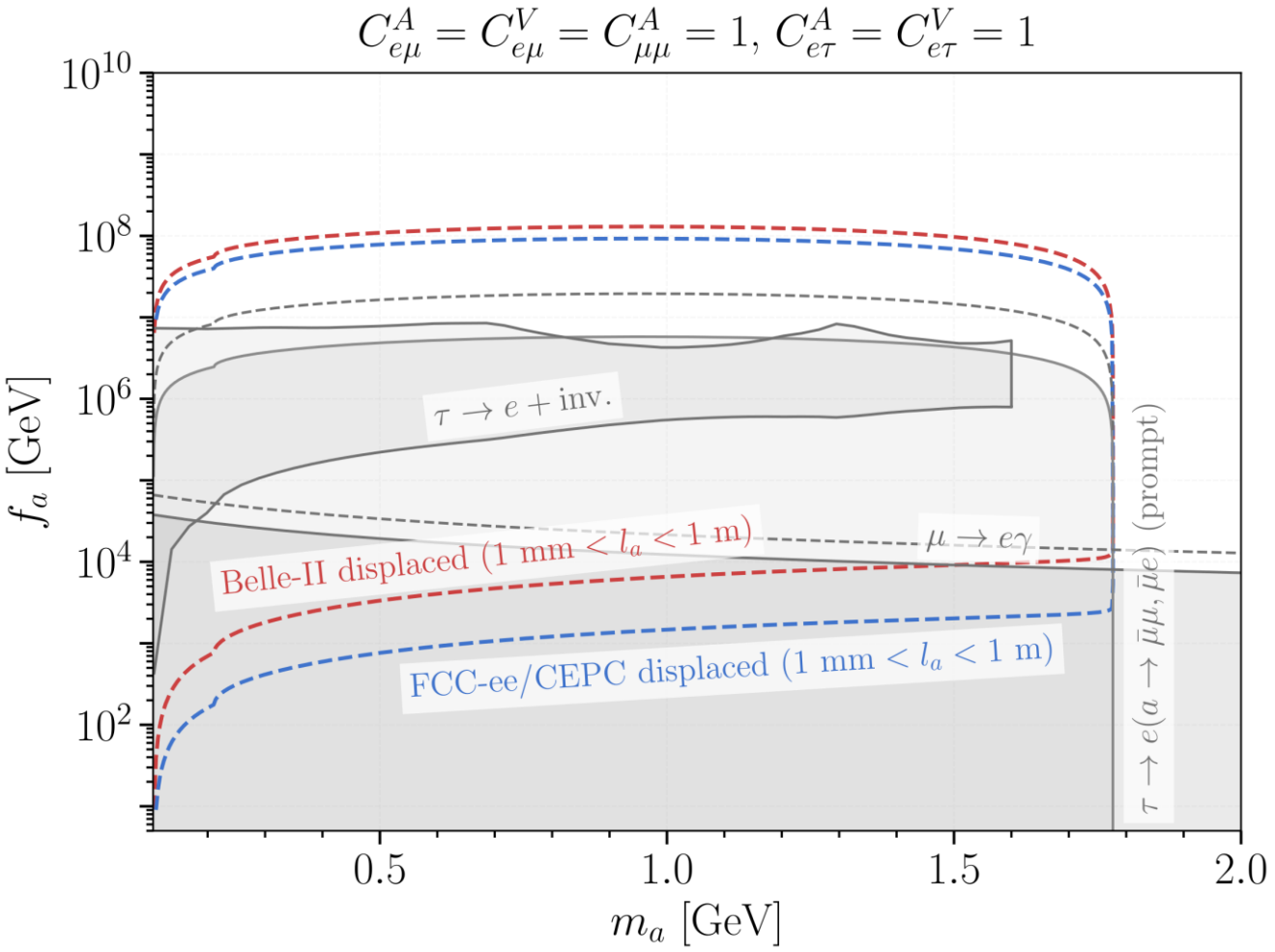
- MadGraph5 + Delphes with a CEPC-like detector card
- m_a = 0.12, 0.5, 1, 5, 10, 50 GeV (f_a = 1 TeV, $C^A_{e\mu}$ = 1)
- ≥ 50% of events correctly reconstructed in all cases ⇒ **$\varepsilon_{eff} \approx 0.5$**
- Same ε assumed for meson and W channels

$$N^Z_{\rm sig} = \epsilon_{\rm eff}\, N_Z\, {\rm BR}(Z \to e^\mp \mu^\pm a)\, {\rm BR}(a \to e^\mp \mu^\pm)$$

90% CL projection: N_{sig} = 2.3, zero background

Projections assume zero background; experimental input on mis-ID very welcome.

Displaced ALPs from τ → e a: Belle II vs Tera-Z



$$N_{\text{sig}} = N_\tau \, \text{BR}(\tau \to ea) \left[e^{-1\,\text{mm}/l_a} - e^{-1\,\text{m}/l_a} \right]$$

$l_a = \beta_a \gamma_a / \Gamma_a$

	Belle II	Tera-Z
N_τ	4.5 x 10^{10}	2 x 10^{11}
$\langle \gamma_a \rangle$	3.1	25.7

- Long-lived regime: P(decay in 1 m) ≃ 1 m / l_a ∝ $1/\gamma_a$
- Event ratio Tera-Z / Belle II ≃ (N_τ ratio) x (γ ratio)$^{-1}$ ≈ **0.54**
- ⇒ Belle II slightly better at large f_a; both go far beyond current bounds

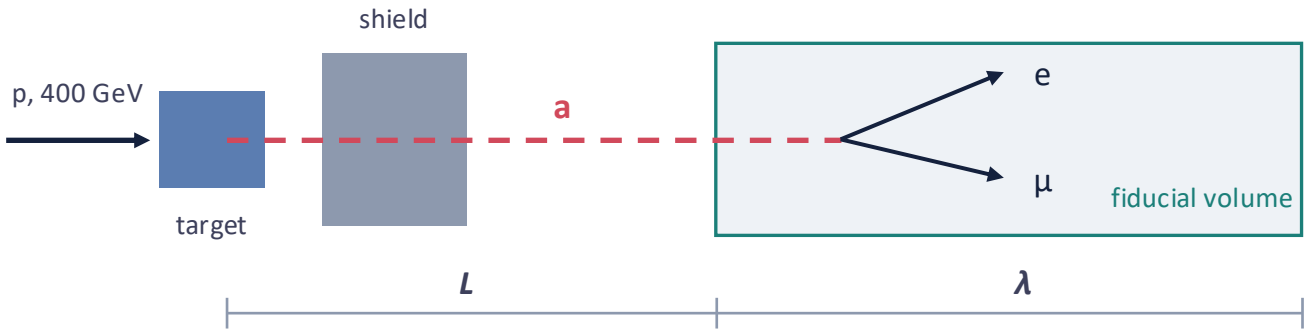
Fixed-target and beam-dump: NA62 and SHiP

NA62 **prompt**

$K^- \to e^- \bar{\nu}_\mu\, a(\to e^- \mu^+)$: the same background-free LFV signature; reach taken from LFV kaon searches, BR $\lesssim 10^{-11}$

SHiP **long-lived**

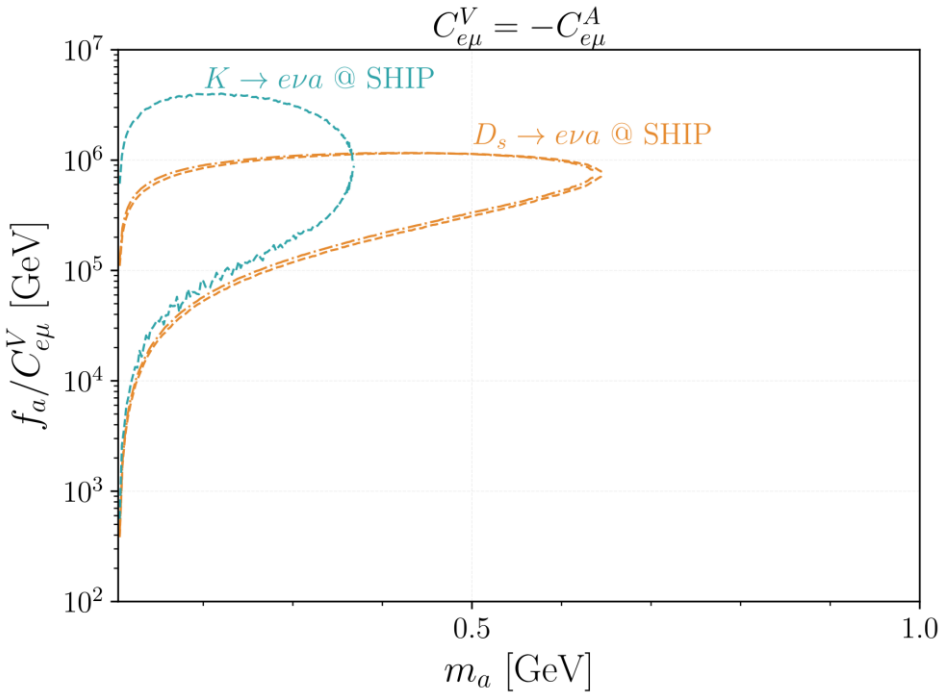
K, $D_s \to e\nu\, a$ in the target; the ALP crosses the shield and decays to eμ in the fiducial volume



$$N_{\rm sig} = N_M \int \frac{1}{\Gamma_M} \frac{d\Gamma_{M\to e\nu_\mu a}}{dE_a\, d\theta_a\, d\phi_a} P_a\, dE_a\, d\theta_a\, d\phi_a$$

$$P_a = \underbrace{\exp\left(-\frac{\Gamma_a L}{\gamma_a \beta_a}\right)}_{\text{survives to decay volume}} \underbrace{\left[1-\exp\left(-\frac{\Gamma_a \lambda}{\gamma_a \beta_a}\right)\right]}_{\text{decays inside it}}$$

[NA62, 1703.08501] [Bician, Nucl. Part. Phys. Proc. 318–323 (2022)] [SHiP, 2504.06692]

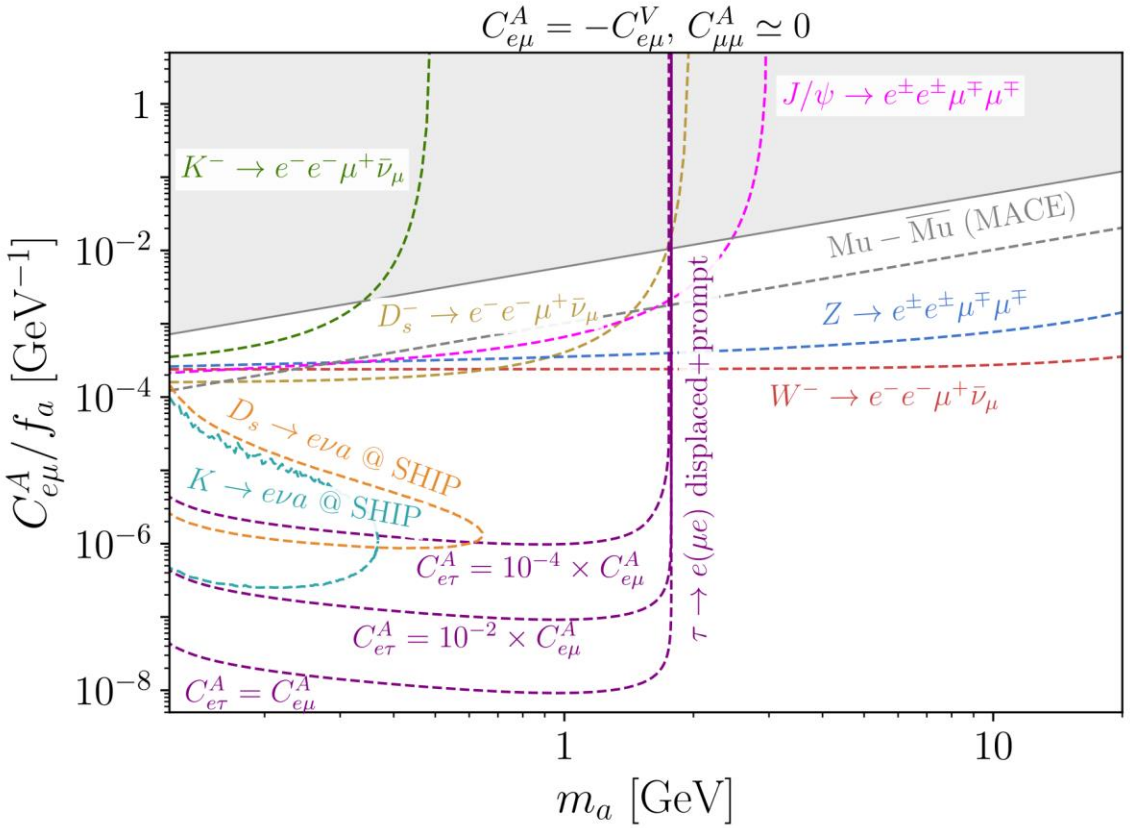


Left-handed eμ couplings; two D_s production spectra

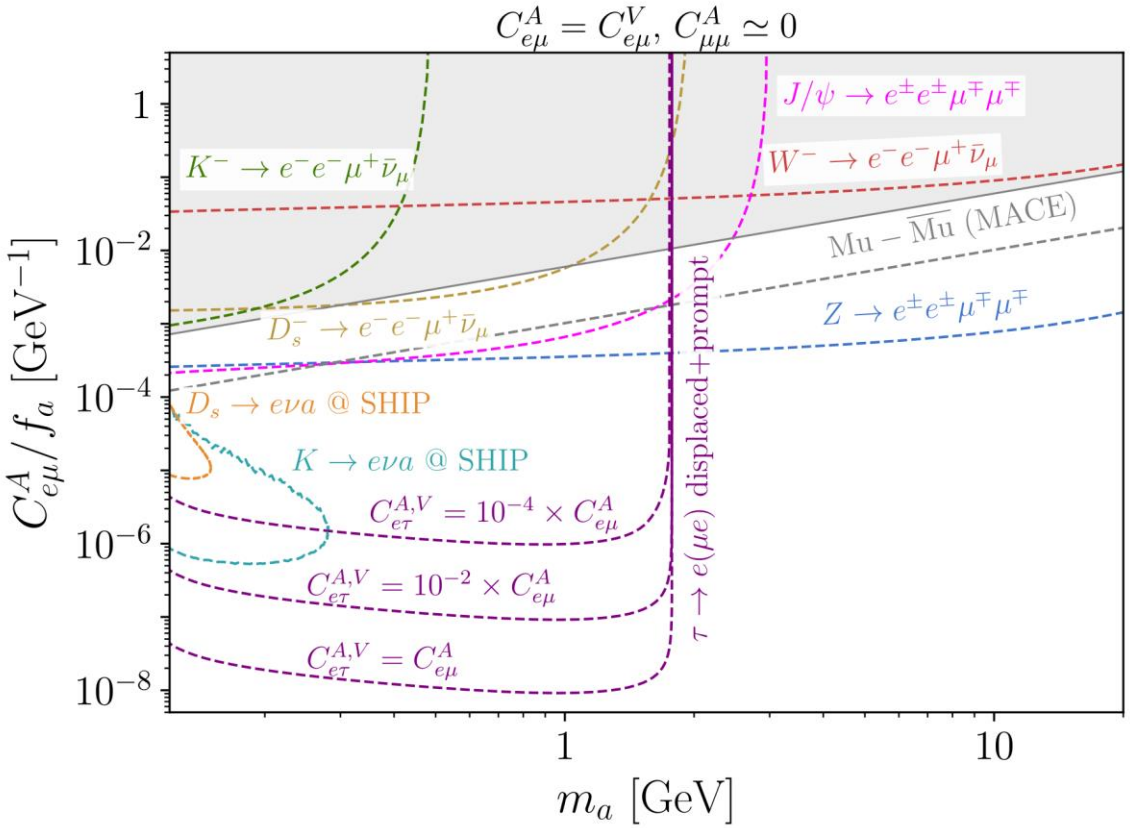
Reach $f_a/C^V_{e\mu} \sim 10^6$ GeV — far beyond collider and muonium reach

Only light ALPs: $m_a \lesssim 0.4$ GeV (K), 0.65 GeV (D_s) — three-body production is suppressed and heavier ALPs decay before the fiducial volume

Results — Scenario A (no diagonal muon coupling)



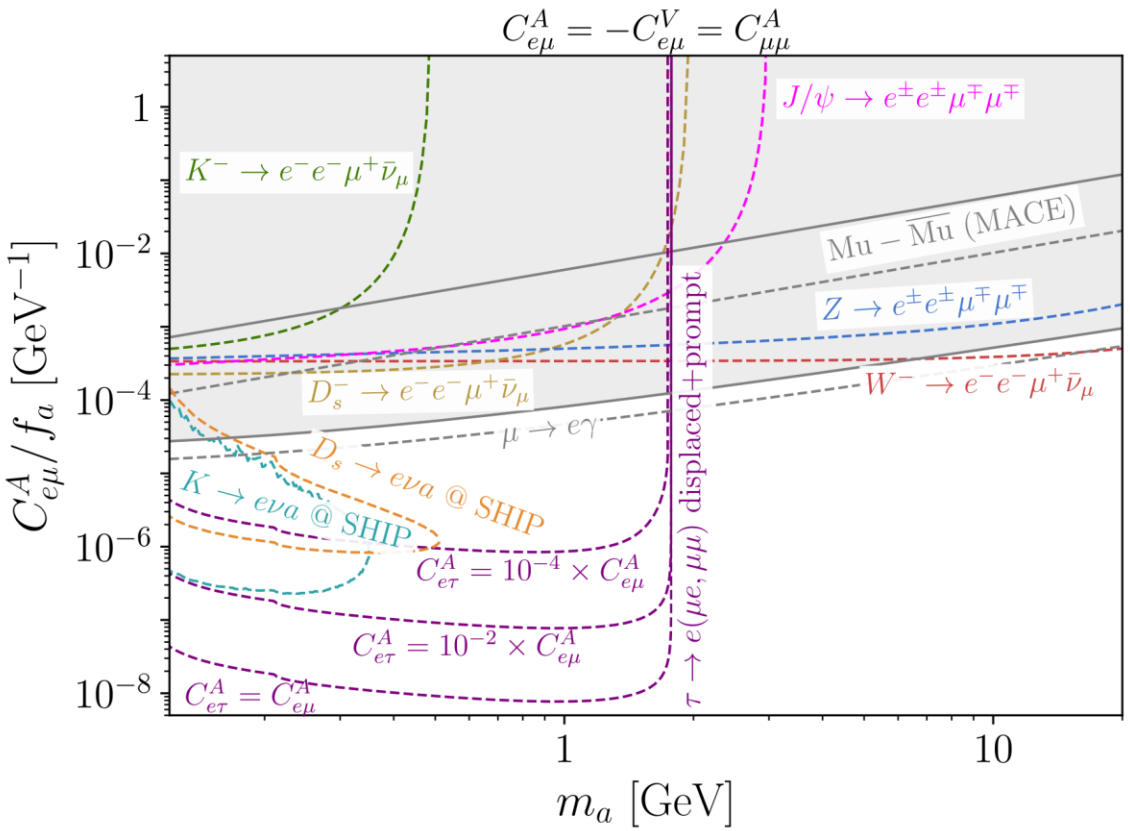
Left-handed couplings ($C^V_{e\mu} = 0$: maximal $SU(2)_L$ breaking)



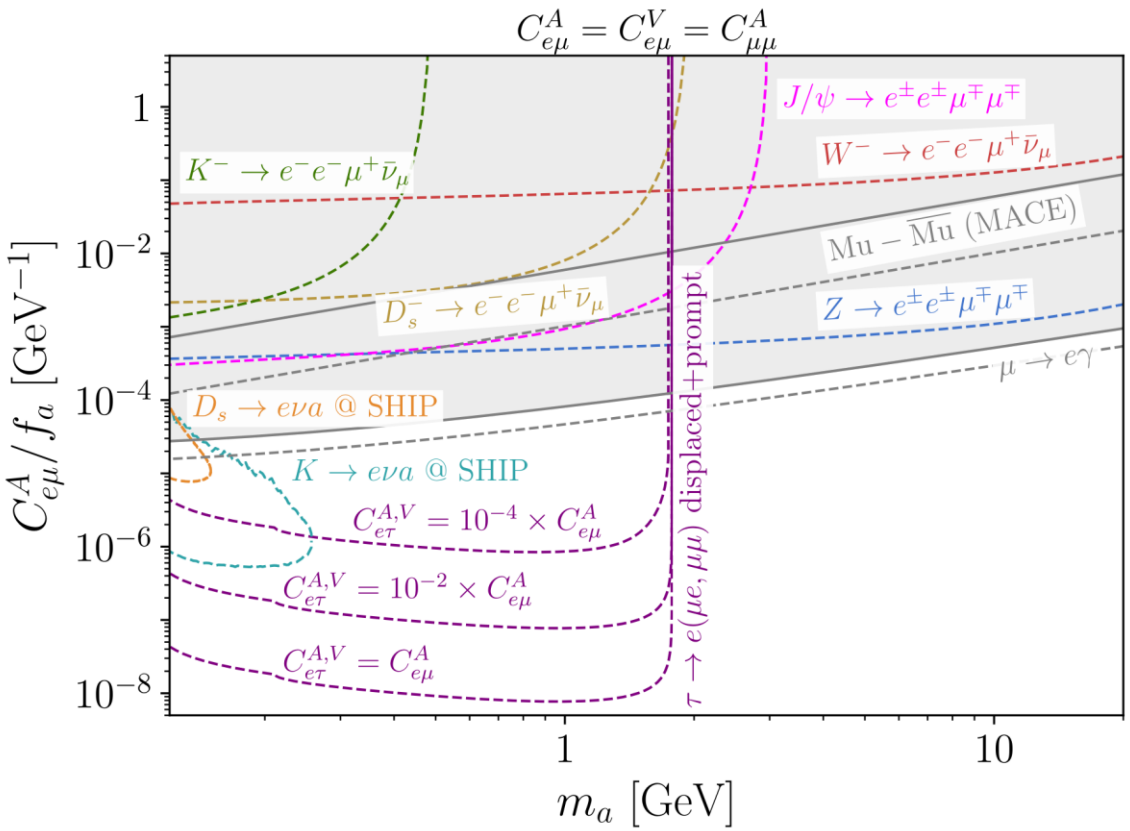
Right-handed couplings

Z, D_s, W at CEPC/FCC-ee: f_a up to ≈ 5 TeV, beyond today's muonium bound (grey); **τ route**: down to $C_{e\mu}/f_a \sim 10^{-8}$ GeV^{-1}; **SHiP**: long-lived corner

Results — Scenario B ($C_{\mu\mu} \simeq C_{e\mu}$)



Left-handed couplings ($C^V_{e\mu} = 0$: maximal $SU(2)_L$ breaking)



Right-handed couplings

Loop-induced μ → eγ, and in future μ → eee / μ → e conversion, **close most of the plane**; survivors: **W decays (LH, $m_a \gtrsim 10$ GeV)** and the τ route below m_τ

Summary

LFV ALPs with $m_a > m_\mu$: practically unconstrained, prompt $a \to e\mu$, background-free signatures

f_a reach

≈ 5 TeV

CEPC/FCC-ee

Z, D_s, W decays

f_a reach

≈ 5 TeV

STCF

$J/\psi \to e\mu\, a$

f_a reach

$\approx 10^6$ GeV

SHiP

K, $D_s \to e\nu\, a$

f_a reach

$\approx 10^8$ GeV

Belle II + Tera-Z

$\tau \to \ell\, a$, displaced

Proposal for the CEPC flavour programme

Add $Z \to e^\pm e^\pm \mu^\mp \mu^\mp$ (resonant $e\mu$), D_s / $W \to e^- e^- \mu^+ + E_{miss}$ and displaced $e\mu$ vertices in τ decays to the benchmark list of Tera-Z searches.

arXiv:2604.11889 · mfedele@uni-mainz.de

Backup

SHiP simulation · μ → e correlations

How large can $SU(2)_L$ breaking be?

$C_L \neq 0$ needs the operator $(\partial a/f_a)\,(\bar{L}H)\,\gamma\,(H^\dagger L)\,/\,\Lambda^2$ — e.g. from a vector-like lepton $E \sim (1, 1, -1)$ mixing with ℓ_L

1 **Mixing $\theta_i \simeq y_i\, v\,/\,(\sqrt{2}\, m_E)$** induces $\Delta C_L \propto c_E\, v^2\, y_e\, y_\mu^*\,/\,(2\, m_E^2)$

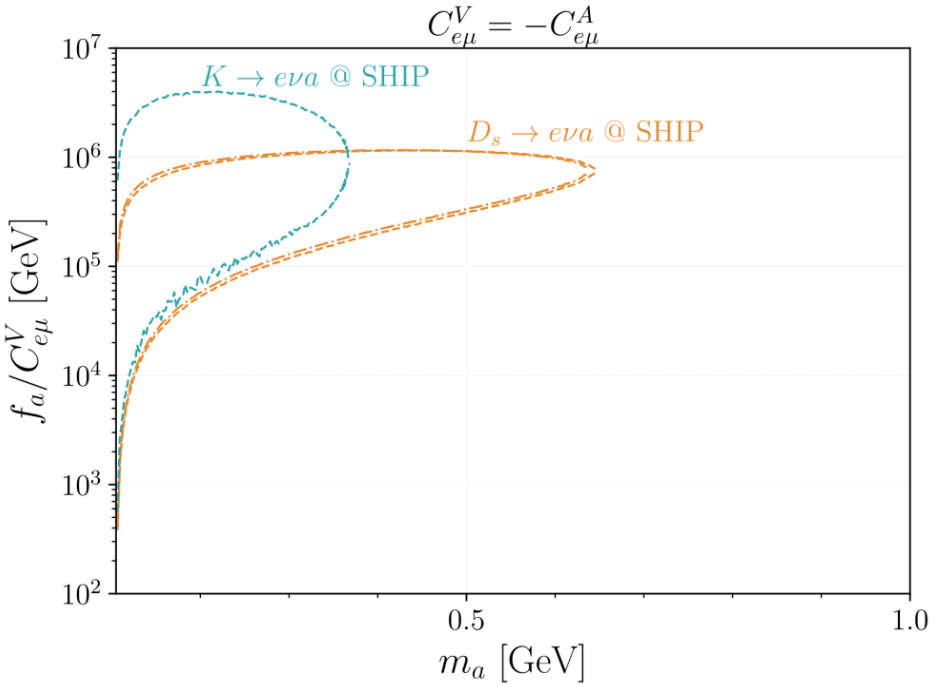
2 **Same spurion $y_e\, y_\mu^*$** also generates the e-μ dipole at one loop

3 **MEG II** $\Rightarrow v^2\, y_e\, y_\mu^*\,/\,(2\, m_E^2) \lesssim 10^{-4}$

- Couple E to electrons only: the dipole becomes m_e-suppressed ⇒ bound relaxed by $m_\mu/m_e \approx 200$, **not removed**
- Three generations of E with a dipole aligned to Y_e: possible, but needs tuning or an extra symmetry
- Take-home: **LH meson / W reach is optimistic**; RH results and Z, J/ψ, τ channels don't rely on it

Backup: SHiP sensitivity from K and $D_s \to e\,\nu\,a$

- 400 GeV SPS beam, 6 x 10^{20} POT; decay volume from ~34 m, ~50 m long
- D_s: $(1 - |x_F|)^n \exp(-b\, p_T^2)$, n = 5.8, b = 0.96 GeV^{-2} ⇒ $N_{Ds} \simeq 5 \times 10^{-5}\, N_{POT}$ (conservative)
- Cross-checked with the alternative D_s spectrum of Ema et al.: similar limits
- Kaons: GEANT4 on Mo/W target (~10 λ_{int}); ≈ 0.03 K/POT decay in flight with p_z > 1 GeV
- Stopped kaons dropped: isotropic emission rarely hits the decay volume
- $P_a = \exp(-\Gamma_a L/\gamma\beta)\,[1 - \exp(-\Gamma_a \lambda/\gamma\beta)]$, averaged over 10^5 MC ALPs



LH eμ couplings; two D_s spectra (dashed vs dot-dashed)

Backup: μ → e correlations in Scenario B

If μ → eee and μ → e conversion are dipole-dominated, their rates are tied to μ → eγ:

Observable	Relation	Future sensitivity	Implied BR(μ → eγ)
μ → eγ (MEG II)	—	6×10^{-14}	6×10^{-14}
μ → eee (Mu3e)	BR(eee)/BR(eγ) ≃ 6.1 $\times 10^{-3}$	10^{-16}	1.6×10^{-14}
μ Al → e Al (Mu2e, COMET)	BR(eγ)/CR ≃ 389	6×10^{-17}	2.3×10^{-14}

Current: BR(μ → eγ) < 1.5×10^{-13} (MEG II 2025). Muonium: MACS P < 8.3×10^{-11} at B = 0.1 T; MACE target 7×10^{-14}.