Same-sign dimuon probe of charged lepton flavor violation at electron–photon colliders

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Motivation

- cLFV is highly suppressed in the SM
- Observing cLFV $\Rightarrow$ unambiguous evidence for BSM physics
- Laser Compton backscattering (LCB) can induce $e\gamma$ scattering at e^+e^- colliders such as BEPC-II with BESIII, STCF, and ILC
- Identified a previously unexplored topology: $\gamma e^- \to e^+\mu^-\mu^-$
- A resonant ALP with a cLFV e–μ coupling
- Intrinsically clean, only residual backgrounds from detector effects
- Unique advantages compared to e^+e^- colliders or hadron colliders

Model framework – the ALP with an $e\mu$ coupling

- The QCD axion: pseudo–Nambu–Goldstone bosons of spontaneously broken global symmetries and well-motivated candidates for NP
- The ALPs appear in various extensions of the SM; unlike the QCD axion, their masses and couplings are largely independent parameters
- Their interactions need not respect the flavor structure of the SM, allowing for cLFV couplings
- Consider a real pseudoscalar ALP a with an e–μ coupling

$$\mathcal{L}_{\rm int} = -i g_{ae\mu}\, a\, \bar{e}\gamma_5 \mu + \text{h.c.}$$

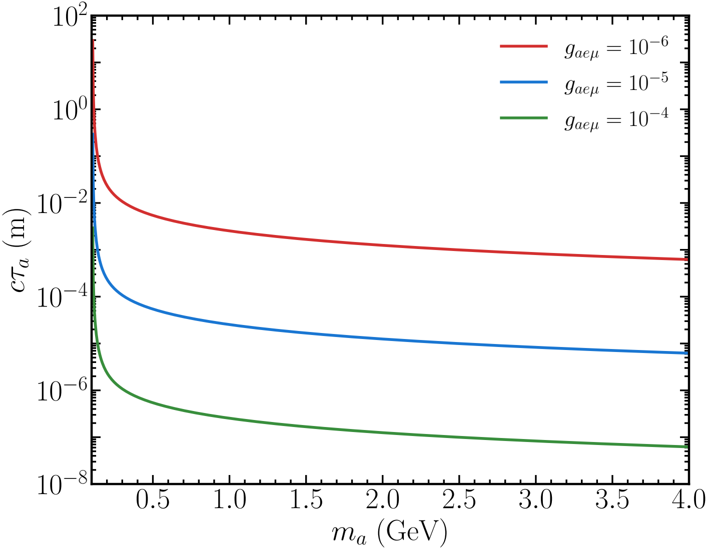
- Decay widths:

$$\Gamma(a \to e^\pm \mu^\mp) = \frac{g_{ae\mu}^2}{8\pi} m_a \left(1 - \frac{m_\mu^2}{m_a^2}\right)^2$$

- Lifetime:

$$c\tau_a = c\hbar / (2\,\Gamma(a \to e^\pm \mu^\mp))$$

Lifetime of the ALP



Existing constraints on $g_{ae\mu}$

- Muonium–antimuonium oscillations provide the most stringent bounds in the mass range of interest, as the ALP mediates a tree-level four-fermion interaction, leading to a constraint that scales linearly with m_a
- Loop-induced contributions to $(g-2)_{e/\mu}$, including recent lattice-QCD-based evaluations and Cs-based measurements: subdominant
- Collider bounds from LEP: subdominant

Electron–photon collider setup

- LCB: laser photons are scattered off the lepton beam to produce a high-energy photon beam

- Lepton-beam energy E_e and laser-beam energy $E_0 \Rightarrow E_\gamma = xE_e$, where x follows the distribution $f_{\gamma/e}(x)$ [Ginzburg et al 1983, Telnov 1990]:

$$f_{\gamma/e}(x) = \frac{1}{g(\zeta)}\left[1 - x + \frac{1}{1-x} - \frac{4x}{\zeta(1-x)} + \frac{4x^2}{\zeta^2(1-x)^2}\right]$$

  with
$$g(\zeta) = \left(1 - \frac{4}{\zeta} - \frac{8}{\zeta^2}\right)\ln(\zeta+1) + \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(\zeta+1)^2}$$

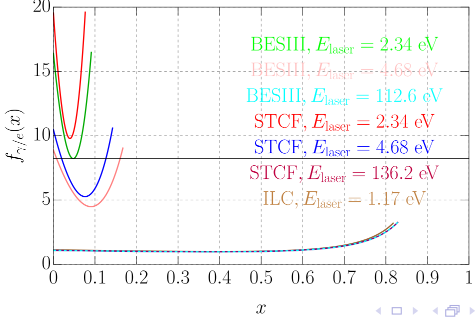
- $\zeta \equiv 4E_eE_0/m_e^2$ controls the kinematics

- Employed for precision beam-energy measurements at BESIII, and proposed for STCF and ILC

Benchmark parameters of e^+e^- colliders

Collider	$\sqrt{s}$ [GeV]	E_e [GeV]	E_0 [eV]	$\mathcal{L}$ [ab^{-1}]
BESIII	5.6	2.8	2.34, 4.68, 112.6	0.02
STCF	4.63	2.315	2.34, 4.68, 136.2	1
ILC	500	250	1.17	4

- Realistic E_0: 1.17 eV, 2.34 eV, 4.68 eV
- For $\zeta \simeq 4.83$, the energy transfer is maximized (a larger ζ would induce the pair-creation process: $\gamma_{\text{back}} + \gamma_{\text{laser}} \to e^+e^-$)

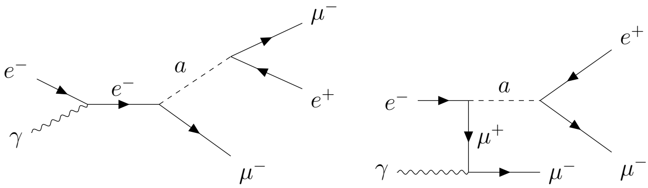


Cross sections and signal process

- The observable cross section is obtained by convoluting the partonic cross section with the photon spectrum

$$\frac{d\sigma}{d\cos\theta} = \int_0^{x_{\max}} dx\, f_{\gamma/e}(x)\, \frac{d\hat{\sigma}}{d\cos\theta}$$

- The maximal photon energy fraction given by $x_{\max} = \zeta/(1+\zeta)$
- $\gamma e^- \to e^+\mu^-\mu^-$: an on-shell ALP

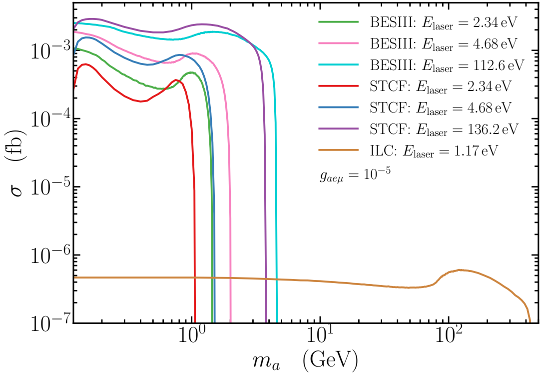


Detector acceptances and reconstruction efficiencies

- BESIII: require $|\cos\theta| < 0.93$ for both electrons and muons, and apply a flat identification efficiency of 90% for muons with $p > 0.5$ GeV
- STCF: require $|\cos\theta| < 0.93$ and apply momentum-dependent tracking efficiencies:
  - muons: the tracking efficiency is taken to be zero for $p < 0.4$ GeV, to increase linearly to 70% at 0.5 GeV and to 95% at 0.7 GeV, and to remain at 95% for $p > 0.7$ GeV
  - electrons: we require $p_T > 0.1$ GeV, with the efficiency rising linearly from 90% to 99% at 0.3 GeV and remaining at 99% thereafter
- ILC: require $|\cos\theta| < 0.95$ and $|p| > 0.1$ GeV, with flat efficiencies $\epsilon_e = 0.97$ and $\epsilon_\mu = 0.98$

Simulation and cross sections

- Model implementation with FeynRules
- Event generation with WHIZARD
- Detector acceptance is incorporated by requiring all visible leptons to satisfy basic kinematic criteria on the polar angle and momentum magnitude



  - Detector acceptance and reconstruction efficiencies included

Background discussion

- At the parton level, no SM process yields the same charge and flavor configuration, rendering the signal intrinsically clean
- Residual backgrounds mainly from charge misidentification
- We consider $m_a \gtrsim 0.12\ \mathrm{GeV}$ where the angular separation between the e^+ and the μ^- originating from the ALP decay remains sufficiently large
- SM process: $\gamma e^- \to e^- \mu^+ \mu^-$ constitutes a background if both e^- and μ^+ are charge-misidentified
- Assume single charge misidentification rate $\mathcal{O}(10^{-3})$

	Background events			
Collider	low E_0	medium E_0	high E_0	$\mathcal{L}$ [ab^{-1}]
BEPC-II (BESIII)	0.9	2.8	8.0	0.02
STCF	36.8	77.4	476.1	1
ILC	1.0	–	–	4

- Residual backgrounds from unconverted e^+e^- interactions are expected to be subleading and ignored

Search strategies

1. Prompt searches for a short-lived ALP $\Rightarrow$ prompt leptons $e^+\mu^-\mu^-$
2. Non-prompt searches for a long-lived ALP $\Rightarrow$ DV signatures
3. Missing-energy searches have no sensitivities

- The non-prompt searches realistically relevant for STCF only
- For the STCF setup, we treat the non-prompt search as effectively background-free

Fiducial volumes and decay treatment

- Prompt search:

$$P_{\text{prompt}} = 1 - \exp\left(-\frac{R_{\text{res}}}{L_T^a}\right)$$

  - BESIII: $R_{\text{res}} = 0.13$ mm
  - STCF: $R_{\text{res}} = 0.1$ mm
  - ILC: $R_{\text{res}} = 0$

- Non-prompt search:

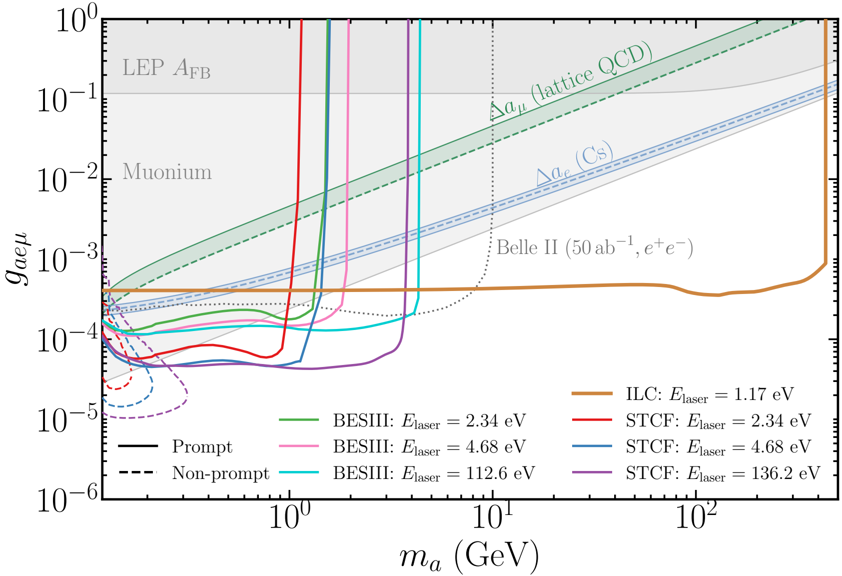
$$\begin{aligned} P_{\text{NP}} &= \frac{1}{L_T^a}\int_{R_{\text{min}}}^{L_T} dr\, e^{-r/L_T^a}\,\epsilon_{\text{vtx}}(r) \\ \epsilon_{\text{vtx}}(r) &= 1 - r/R_{\text{max}} \\ L_T &\equiv \min(\max(R_{\text{min}}, |L_d \tan\theta|), R_{\text{max}}) \end{aligned}$$

L_d: half length of the MDC θ: the ALP polar angle

  - STCF:

$$L_d = 1400 \text{ mm} \qquad R_{\text{min}} = 0.1 \text{ mm} \qquad R_{\text{max}} = 850 \text{ mm}$$

Numerical results



- 95% C.L. exclusion limits

Summary

- A previously unexplored and intrinsically clean same-sign dimuon signature in γe collisions, $\gamma e^- \to e^+\mu^-\mu^-$, mediated by $g_{ae\mu}$
- Absence of irreducible SM backgrounds & resonant production of the mediator: exceptionally sensitive & only small residual backgrounds
- γe collisions at STCF and ILC can probe $g_{ae\mu}$ values one to two orders of magnitude below existing bounds
- Improves upon conventional e^+e^- searches such as Belle II by up to one order of magnitude, despite their much larger integrated luminosities $\Rightarrow$ the unique advantage of the γe collision mode
- γe collisions provide a qualitatively new and uniquely powerful framework for probing cLFV
- This strategy can be extended to other flavor structures and mediator types, opening a new direction for flavor-violating searches at future colliders

Thank You! 谢谢!

Back-up slides