



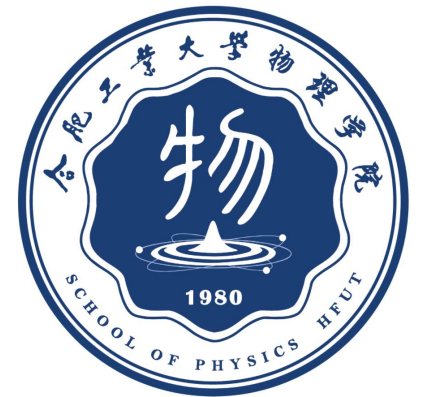
Same-sign dimuon probe of charged lepton flavor violation at electron–photon colliders

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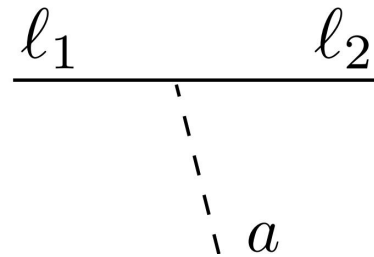
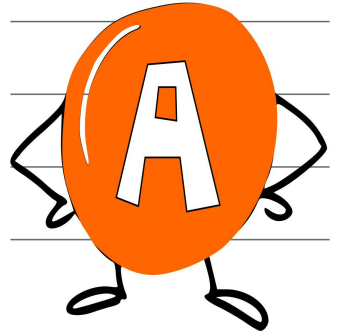
With Zhong Zhang (张忠), and Zeren Simon Wang (王泽人)



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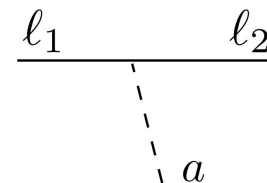
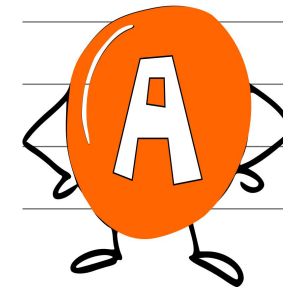


- cLFV is highly suppressed in the SM
- Observing cLFV $\Rightarrow$ unambiguous evidence for BSM physics
- Laser Compton backscattering (LCB) can induce $e\gamma$ scattering at e^+e^- colliders such as BEPC-II with BESIII, STCF, CEPC, and ILC
- Identified a previously unexplored topology: $\gamma e^-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





- 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 $e\mu$ coupling



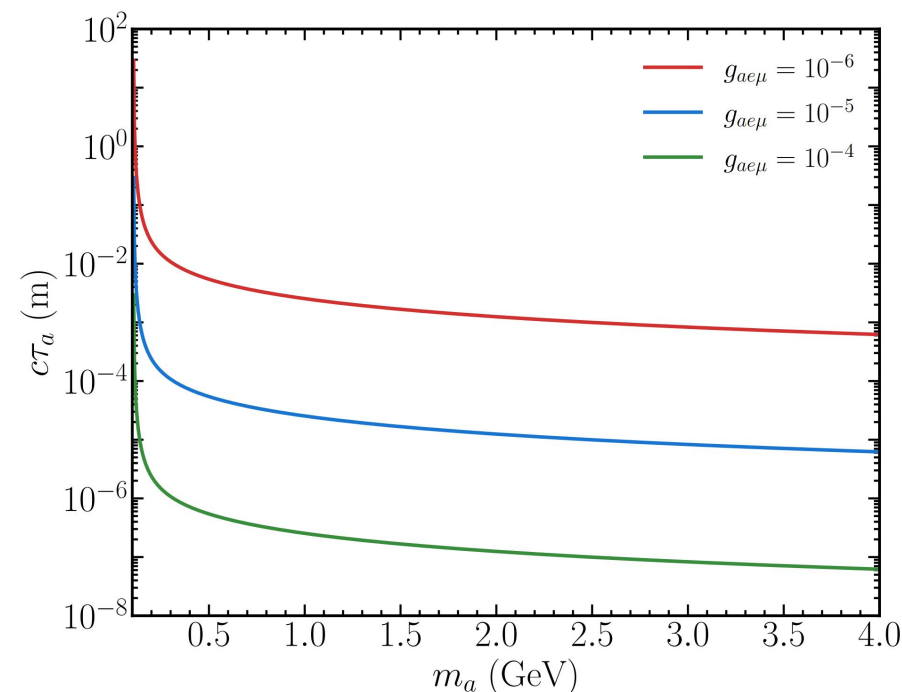
$$\mathcal{L}_{\text{int}} = -ig_{ae\mu} a \bar{e}\gamma_5\mu + \text{h.c.}$$

- Decay widths:

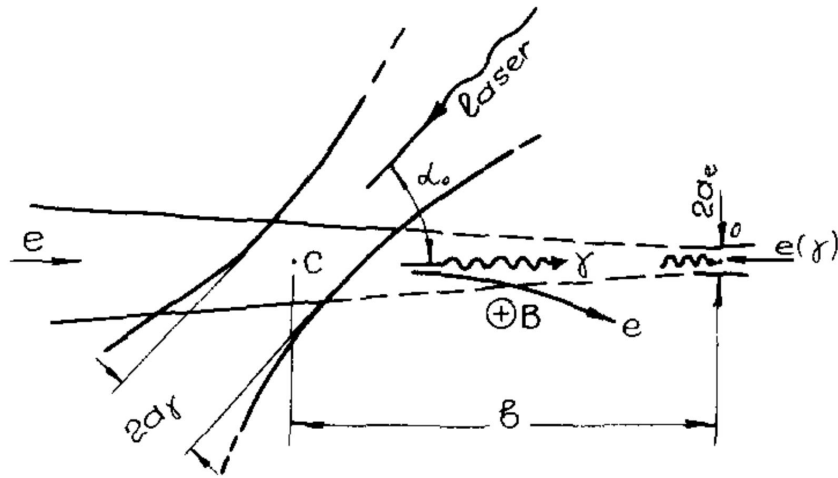
$$\Gamma(a \rightarrow e^\pm \mu^\mp) = \frac{g_{ae\mu}^2}{8\pi} m_a \left(1 - \frac{m_\mu^2}{m_a^2}\right)^2$$

- Lifetime:

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



laser Compton backscattering



[Ginzburg et al 1983](#)

- **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

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

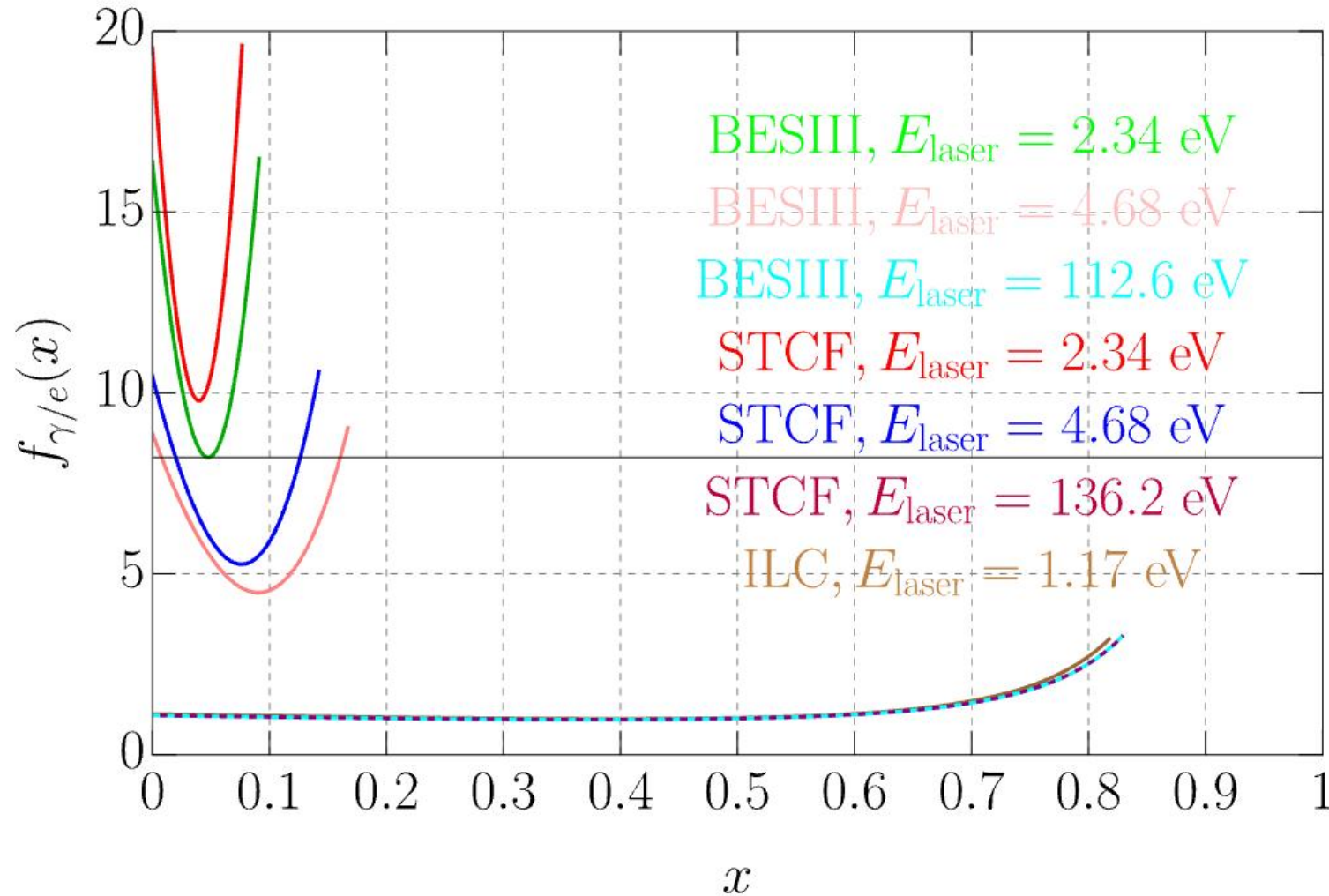
- $\zeta \equiv 4E_e E_0 / m_e^2$ controls the kinematics
- Employed for **precision beam-energy measurements** at BESIII, and proposed for STCF, CEPC and ILC



Collider	$\sqrt{s}$ [GeV]	E_e [GeV]	E_0 [eV]	$\mathcal{L}$ [ab $^{-1}$]
BESIII	5.6	2.8	<u>2.34</u> , <u>4.68</u> , 112.6	0.02
STCF	4.63	2.315	<u>2.34</u> , <u>4.68</u> , 136.2	1
CEPC	240	120	<u>2.34</u>	20
ILC	500	250	<u>1.17</u>	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: $\gamma_{\text{back}} + \gamma_{\text{laser}} \rightarrow e^+ e^-$)

$$\zeta \equiv 4E_e E_0 / m_e^2$$



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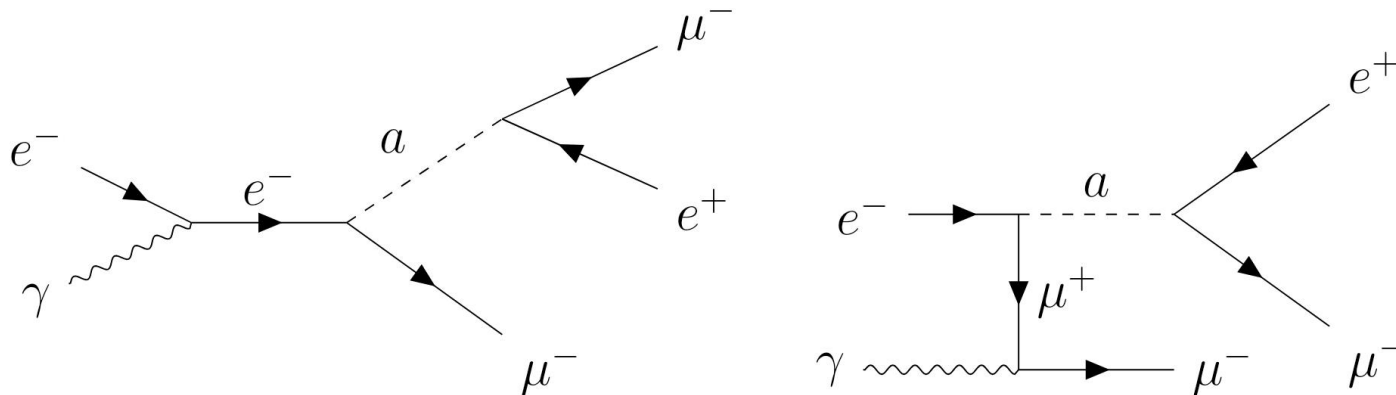
$$x_{\text{max}} = \zeta / (1 + \zeta)$$



- 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 $x_{\max} = \zeta/(1 + \zeta)$
- $\gamma e^- \rightarrow e^+ \mu^- \mu^-$: an **on-shell** ALP





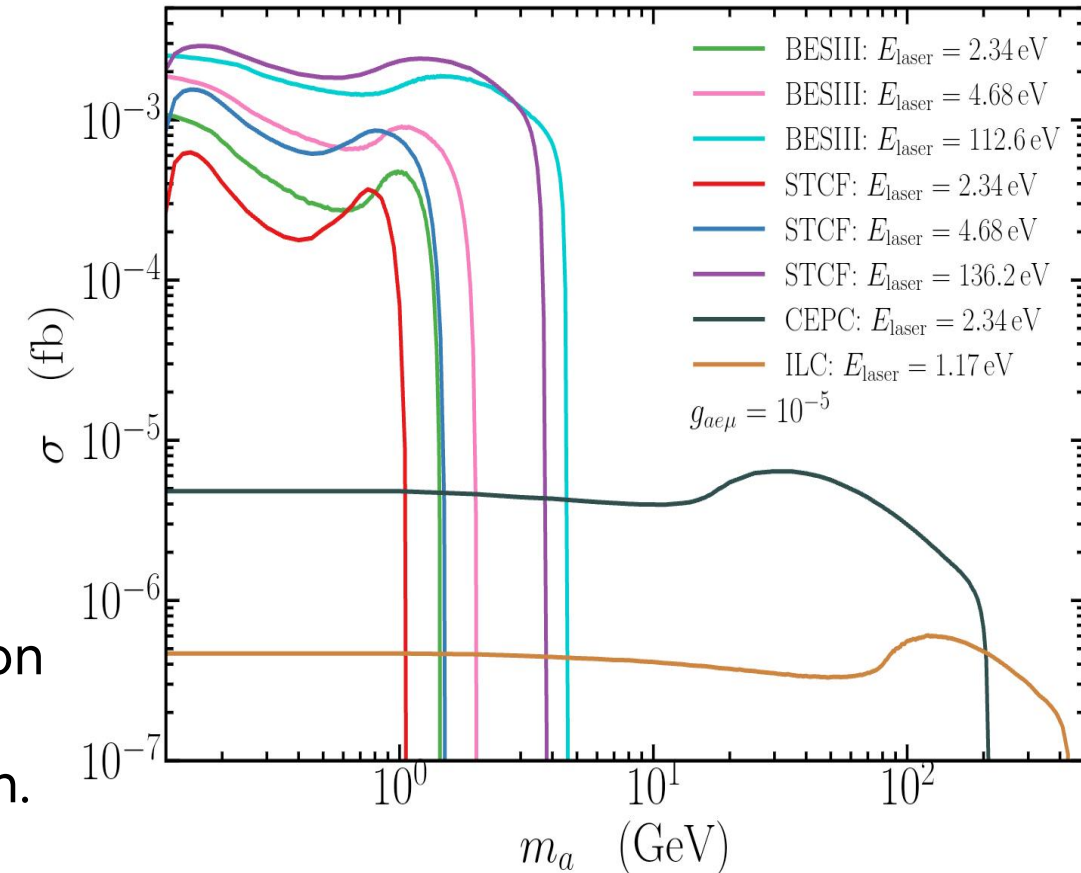
- **BESIII**: require $|\cos \theta| < 0.93$ for both electrons and muons, and apply a flat identification efficiency of 90% for muons with $p > 0.5$ GeV
- **STCF**: require $|\cos \theta| < 0.93$ and apply momentum-dependent tracking efficiencies:
 - muons: the tracking efficiency is taken to be zero 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
- **CEPC**: require $|\cos \theta| < 0.99$ and $|p| > 5$ GeV with a tracking efficiency of 0.99, and a lepton identification efficiency of 0.99,
- **ILC**: require $|\cos \theta| < 0.95$ and $|p| > 0.1$ GeV, with flat efficiencies $\epsilon_e = 0.97$ and $\epsilon_\mu = 0.98$



- 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

The cross sections exhibit a **nonmonotonic** dependence on m_a , reflecting the interplay between the LCB photon spectrum and the kinematic threshold for ALP production.

In the low-mass regime, the signal is enhanced by the peak of the photon spectrum. As m_a increases, larger photon energies are required and the cross section decreases, before rising again when the relevant kinematics approach the endpoint region where the photon spectrum is also enhanced.





- 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 $m_a \gtrsim 0.12 \text{ GeV}$ where **the angular separation** between the e^+ and the μ^- originating from the ALP decay remains **sufficiently large**
- **SM process:** $\gamma e^- \rightarrow e^- \mu^+ \mu^-$ constitutes a background if both e^- and μ^+ are **charge-misidentified**



- Assume single charge misidentification rate $\mathcal{O}(10^{-3})$

Collider	Background events			$\mathcal{L}$ [ab $^{-1}$]
	low E_0	medium E_0	high E_0	
BEPC-II (BESIII)	0.9	2.8	8.0	0.02
STCF	36.8	77.4	476.1	1
CEPC	100.1	—	—	20
ILC	1.0	—	—	4

The prompt searches remain effectively in the near-zero-background regime for the ILC setup and for the lower-laser-energy BESIII configurations, while nonzero residual backgrounds are expected for STCF and CEPC, and for the highest-laser-energy BESIII benchmark.

E_0 [eV]
<u>2.34</u> , <u>4.68</u> , 112.6
<u>2.34</u> , <u>4.68</u> , 136.2
<u>2.34</u>
<u>1.17</u>



- 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**



- Prompt search:

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

effective prompt-decay scale, characterizing the typical spatial/vertex resolution of the tracking system.

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

- Non-prompt search:

$$P_{\text{NP}} = \frac{1}{L_T^a} \int_{R_{\text{min}}}^{L_T} dr e^{-r/L_T^a} \epsilon_{\text{vtx}}(r)$$

$$\epsilon_{\text{vtx}}(r) = 1 - r/R_{\text{max}}$$

$$L_T \equiv \min(\max(R_{\text{min}}, |L_d \tan \theta|), R_{\text{max}})$$

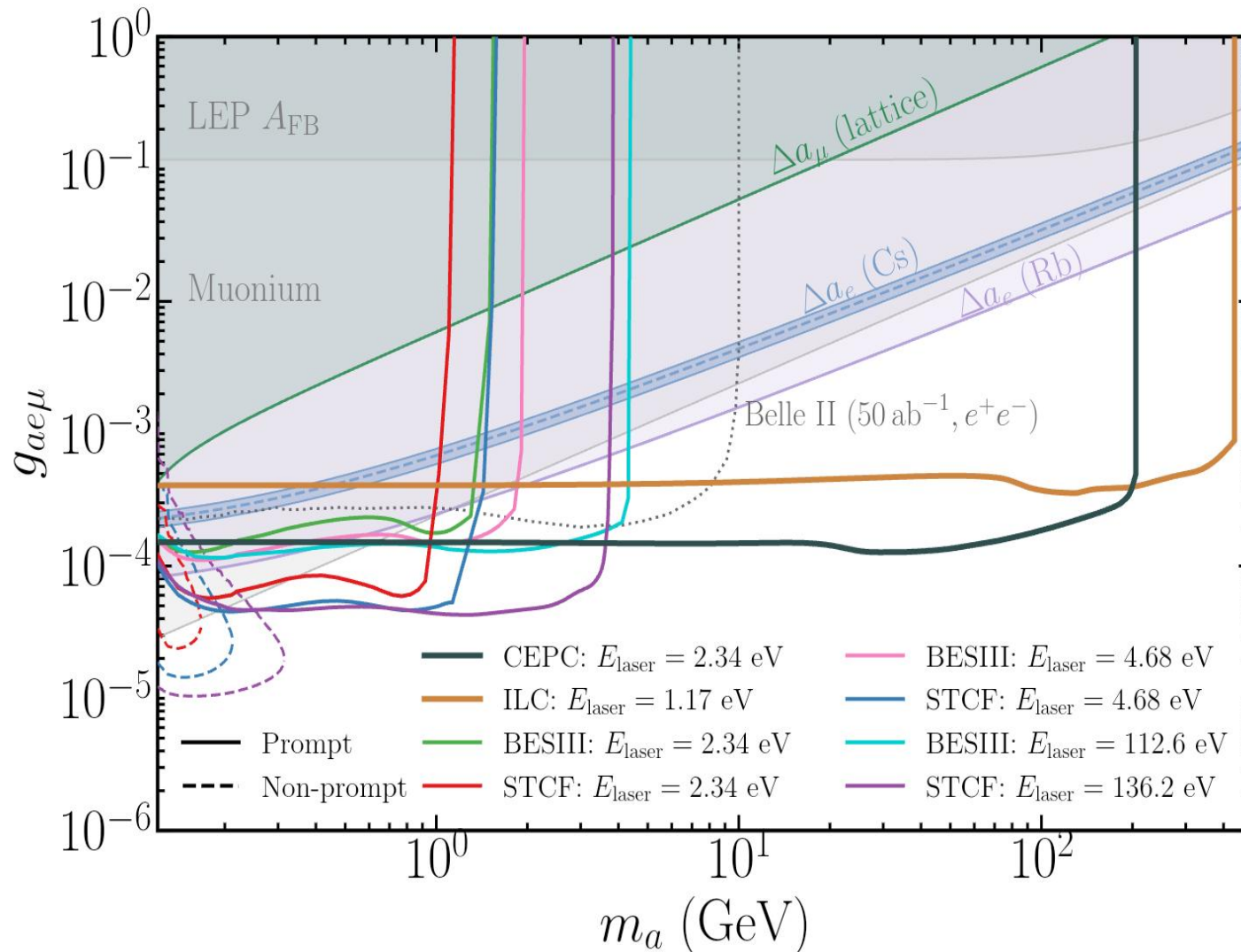
$$L_T^a = \beta_T \gamma c \tau_a$$

boosted transverse decay length

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

- STCF:

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



The γe collider setups, despite operating at much lower integrated luminosities, can probe values of $g_{ae\mu}$ that are more than one order of magnitude smaller over a wide mass range, demonstrating the clear advantage of the γe collision mode.

For STCF, a non-prompt (displaced) search provides additional sensitivity in part of the parameter space, leading to complementary coverage.



- A previously unexplored and intrinsically clean same-sign dimuon signature in γe collisions, $\gamma e^- \rightarrow e^+ \mu^- \mu^-$, 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, CEPC 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



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谢谢观看

Thank you!



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