Search for Lepton Flavor Violation at FASER

Takashi Shimomura
(Miyazaki U.)

based on

"Search for lepton flavor violating decay at FASER", JHEP01 (2023)

"Electron beam dump constraints on light bosons with LFV coupling", JHEP11 (2021)

"Dark photon from light scalar boson decays at FASER", JHEP06 (2021)

in collaboration with

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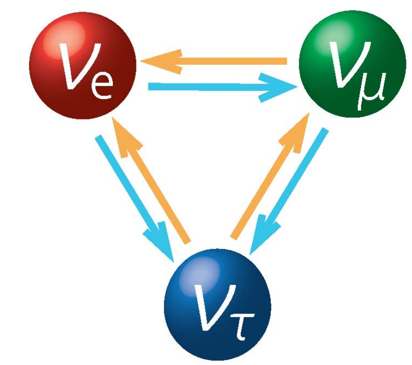
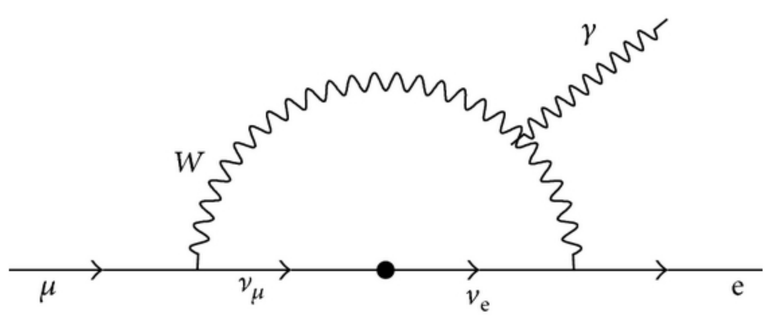
June 8th, 2023 @ Higgs as a Probe of New Physics 2023

Introduction

- Lepton Flavor is not conserved due to neutrino mass and mixing
  - Lepton flavor is conserved in the SM.
  - Lepton flavor violation is found in neutrino oscillation.



  - Charged lepton flavor is also not conserved via neutrino mass&mixing.



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m^2_W}\right|^2 < 10^{-54}$$

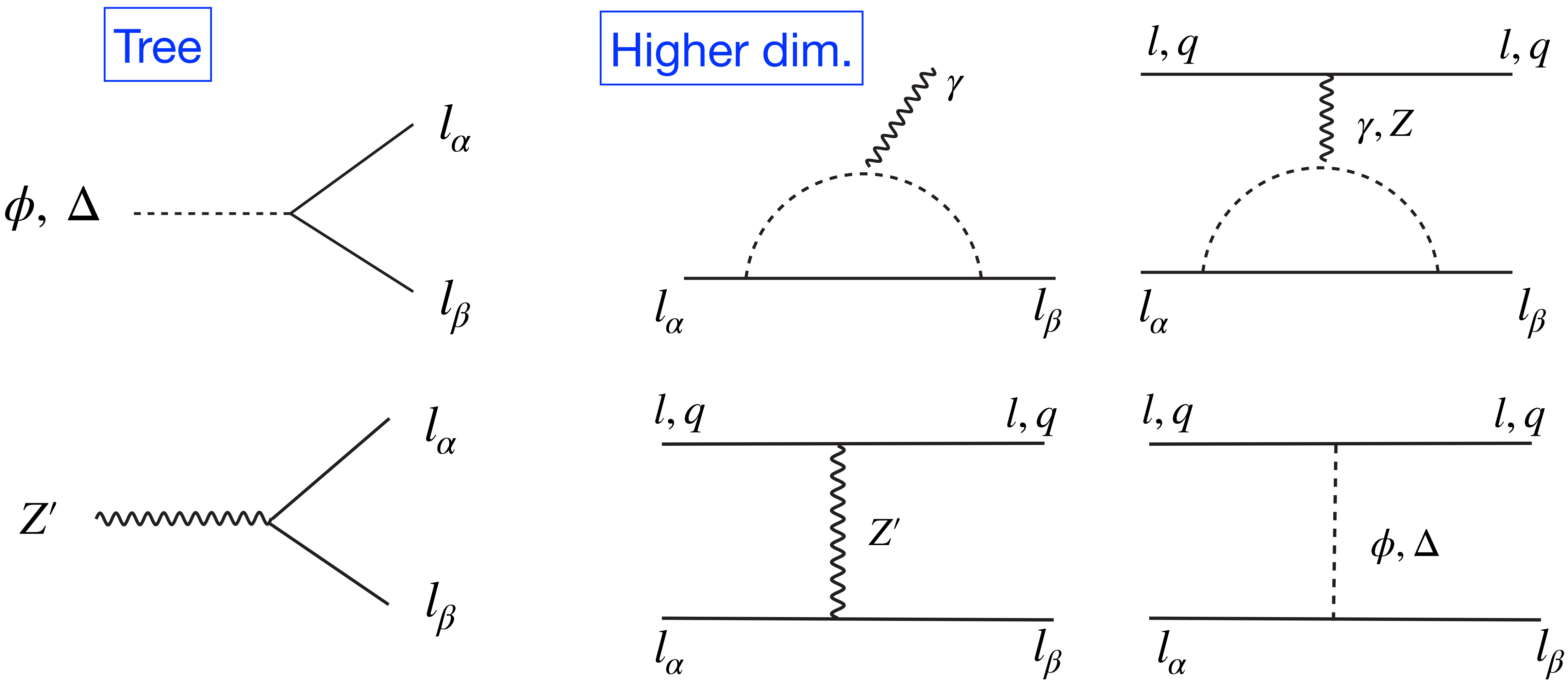
much suppressed by the GIM mechanism

- There are no reasons that charged lepton flavor is conserved in other NP.
- The above CLFV is very small due to tiny neutrino mass.

Sizable charged lepton flavor violation is a clear signature

Introduction

- CLFV is predicted in models of neutrino mass generation and other NP.
  - Seesaw mechanism (type-II, III, inverse, linear, etc)
  - Two Higgs doublet models (type-I, II, X(leptophilic), Y)
  - Radiative seesaw (many variants)
  - Flavor symmetry (gauged $L_\alpha - L_\beta$)



Introduction

- New particles that mediate the flavor violation are heavy.
  - CLFV is suppressed by its mass or new physics scale.

$$\mathscr{L}_{EFT} = \mathscr{L}_4 + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}} \mathscr{O}_d$$

- The new particles can be light when the couplings are tiny.

ex) $\frac{C^{(6)}}{\Lambda^2} \sim 10^{-10}\ /\mathrm{GeV}^2 \longrightarrow C^{(6)} \sim 10^{-12}$ for $\Lambda \sim 0.1$ GeV

  - Such light and feebly interacting particles are motivated by $(g\text{-}2)_\mu$, dark matter (portal), strong QCD problem (axion/ALPs).
  - These particles can have CLFV couplings.

Cornella, et al., JHEP 2020, Endo, et al., JHEP 2020, Calibbi et al, JHEP 2021

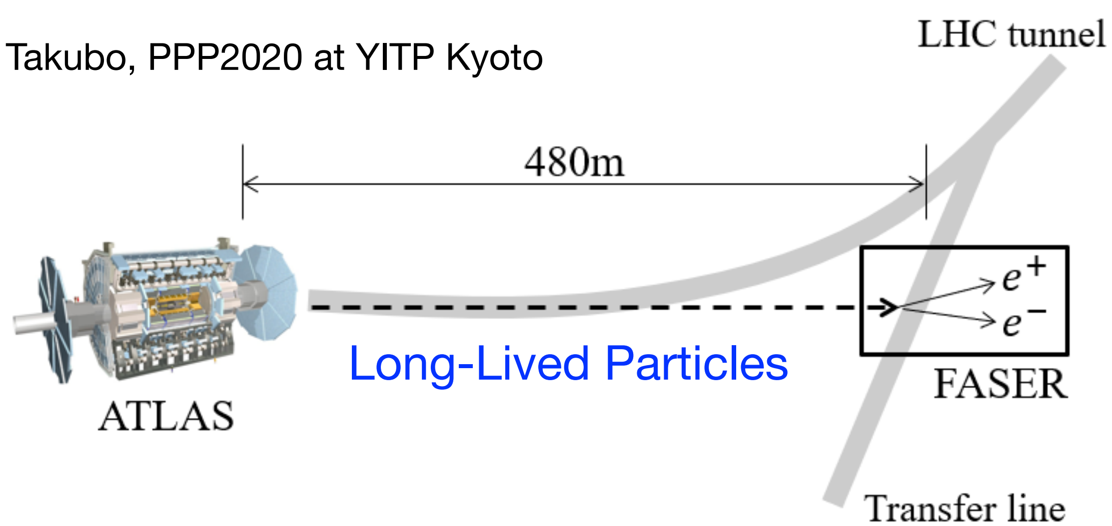
  - These light new particles are inevitably long-lived.
  - Experiments with high luminosity/statistics will explore these CLFV decays. (NA62, Belle-II, NA64, FASER, etc.)

FASER experiment

Feng, Galon, Kling, Trojanowski, PRD97 (2018)
"The FPF at HL-LHC", arXiv:2203.05090

- ForwArd Search ExpeRiment (FASER) at LHC, started from 2022.
- Aims to search for long lived particles such as dark photon, dark Higgs, Axion-like particle, etc.
- Detector is placed 480m downstream from the ATLAS interaction point.

Takubo, PPP2020 at YITP Kyoto



	length of decay volume		radius	integrated luminosity
	$L_{\rm min}$ (m)	$L_{\rm max}$ (m)	R (m)	$\mathcal{L}$ (ab^{-1})
FASER	478.5	480	0.1	0.15
FASER 2	475	480	1.0	3.0

FASER : LHC run3, FASER2 : LH-LHC

- CLFV decays of LLP will be identified.
  - separation of e and μ with opposite charges (τ diificult).
  - two tracks with the same momentum, originated from the same vertex.
  - half of energy deposit compared to the total energy of two tracks.

Introduction

In this talk,

Study of the sensitivity to CLFV couplings at FASER2

for scalar and vector bosons in some simple setups.

Contents

Feng, et al, PRD 97, 2018

Interaction Lagrangians

- Yukawa-type CLFV int. by extra scalar boson, ϕ
  - Leptophilic extra doublet Higgs
  - Tiny contribution to charged lepton mass generation (misalignment of Yukawa)
  - Mix with the SM Higgs ($\theta_{h\phi}$)

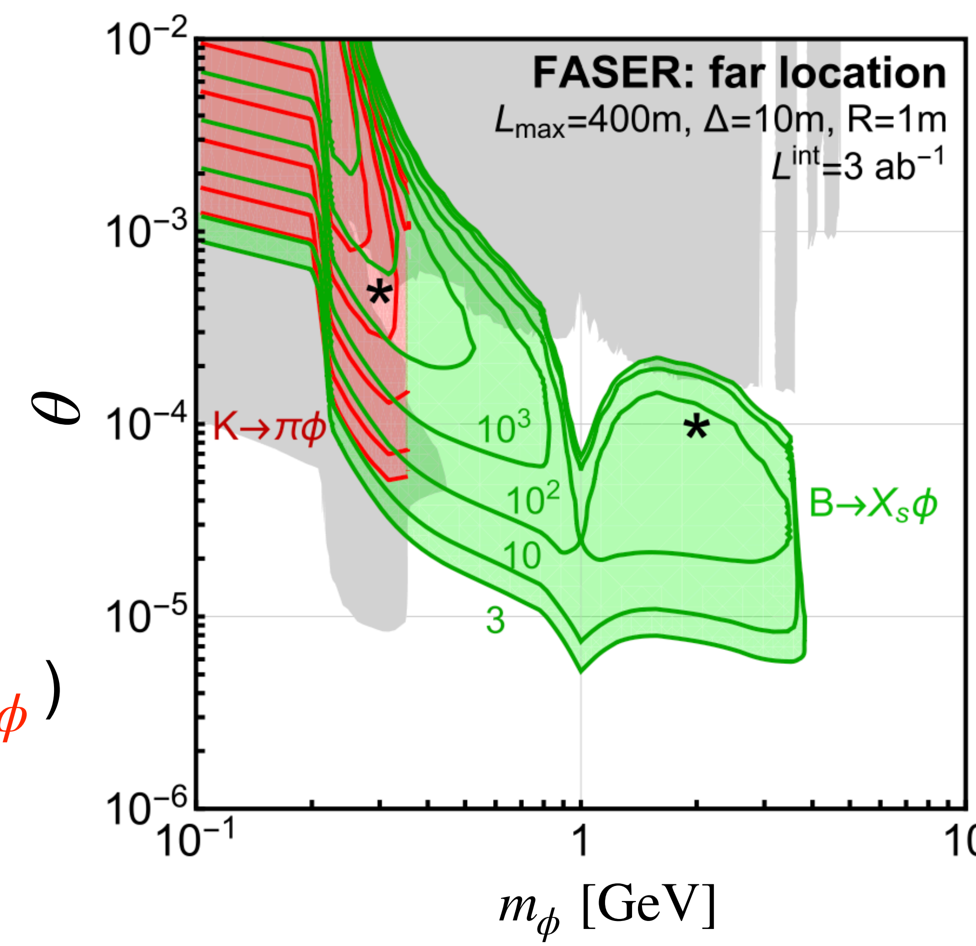
- Lagrangian $\mathscr{L}_{\rm scalar} = \frac{\theta_{h\phi}}{v}\sum_f m_f \bar{f}\phi_l f + \left(y_{e\mu}\overline{e_L}\phi_l \mu_R + y_{\mu e}\overline{\mu_L}\phi_l e_R + \mathrm{h.c.} \right)$

- Decay $\phi \to$ hadrons, $l\bar{l} \propto \theta^2_{h\phi}$

  $\phi \to e\bar{\mu},\ \bar{e}\mu \propto y^2_{e\mu}$

- Production (@ 3 /ab)

$B \to X_s\phi$	dominant ($10^{15}B$, Br ~ $\theta^2_{h\phi}$)
$K \to \pi\phi$	sub domi.($10^{17}K$, Br ~ $10^{-3}\theta^2_{h\phi}$)
η, η', π	negligible



Interaction Lagrangians

- Vectrial CLFV int. by extra gauge boson, Z'
  - $L_\mu - L_\tau$ model (different charge assignment for flavors, $\mu : +1,\ \tau : -1$)
  - Extra Higgs doublet ϕ for charged lepton mass (Z' mass & misalignment)
  - Mix with the SM Higgs

- Lagrangian

$$\mathscr{L}_{\mathrm{vector}} = g_{Z'} Z'_\rho (s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu - \bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$
$$+ g_{Z'} Z'_\rho (sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu)$$

where $s = \sin\theta_{LFV},\ c = \cos\theta_{LFV}$

$$\mathscr{L}_\phi = g_{Z'} m_{Z'} \phi Z'_\mu Z'^\mu + \frac{\theta_{h\phi}}{v} \sum_f m_f \phi \bar{f} f$$

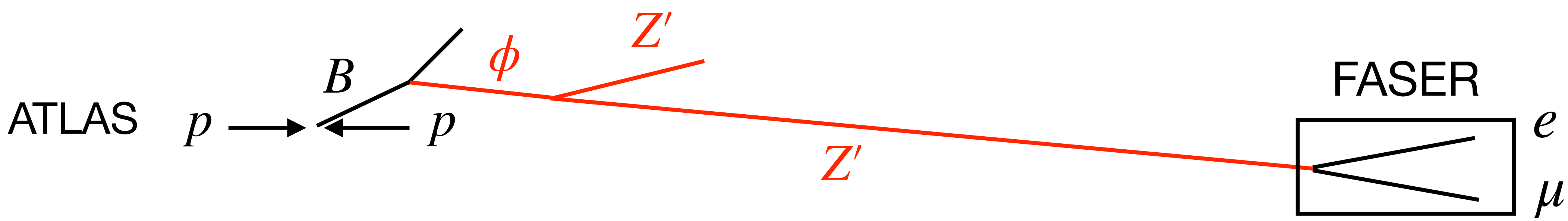
- Decay

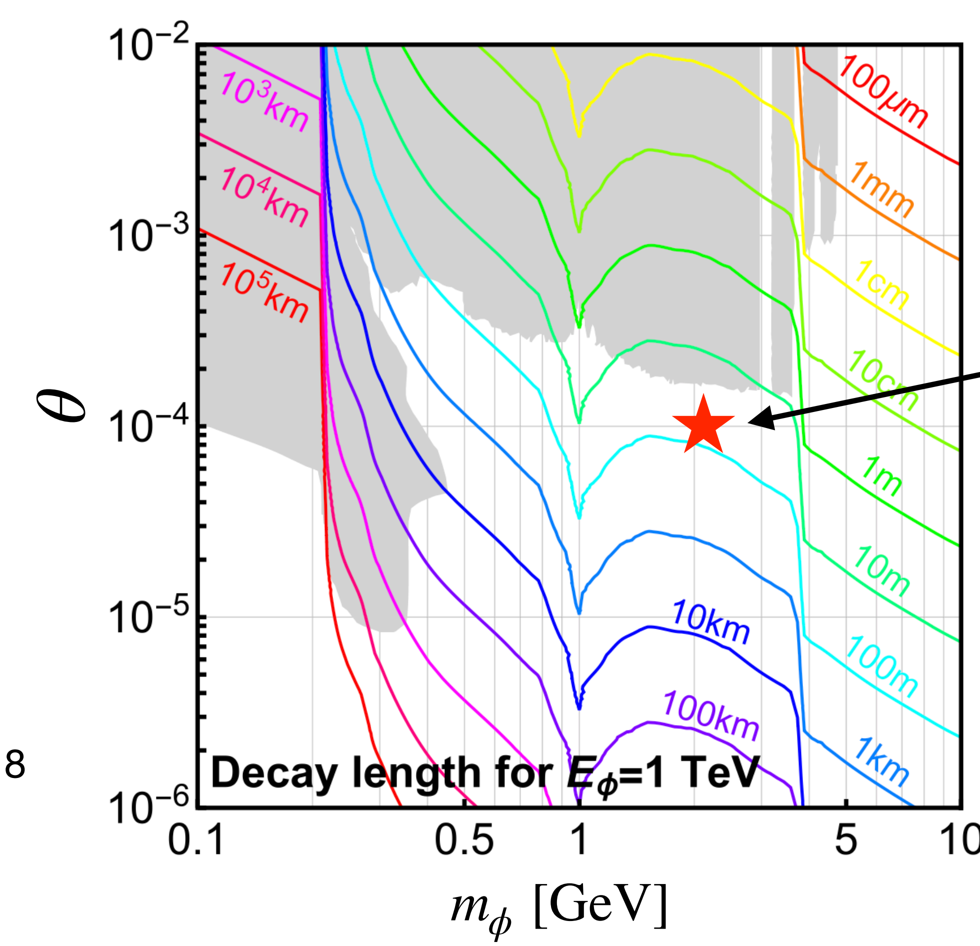
$Z' \to l\bar{l},\ \nu\bar{\nu}$ and $e\mu$ — only leptonic. ignore loop kinetic mixing

$\phi \to Z'Z'$ — almost 100% due to longitudinal mode enhancement

Production of Z’

- The vector bosons Z' can not be produced from meson decays and brems. due to no direct couplings to quarks. (different from the dark photon)
- The extra scalar ϕ can be produced from mesons similarly to the dark Higgs.
- ϕ can be a dominant source of Z'.



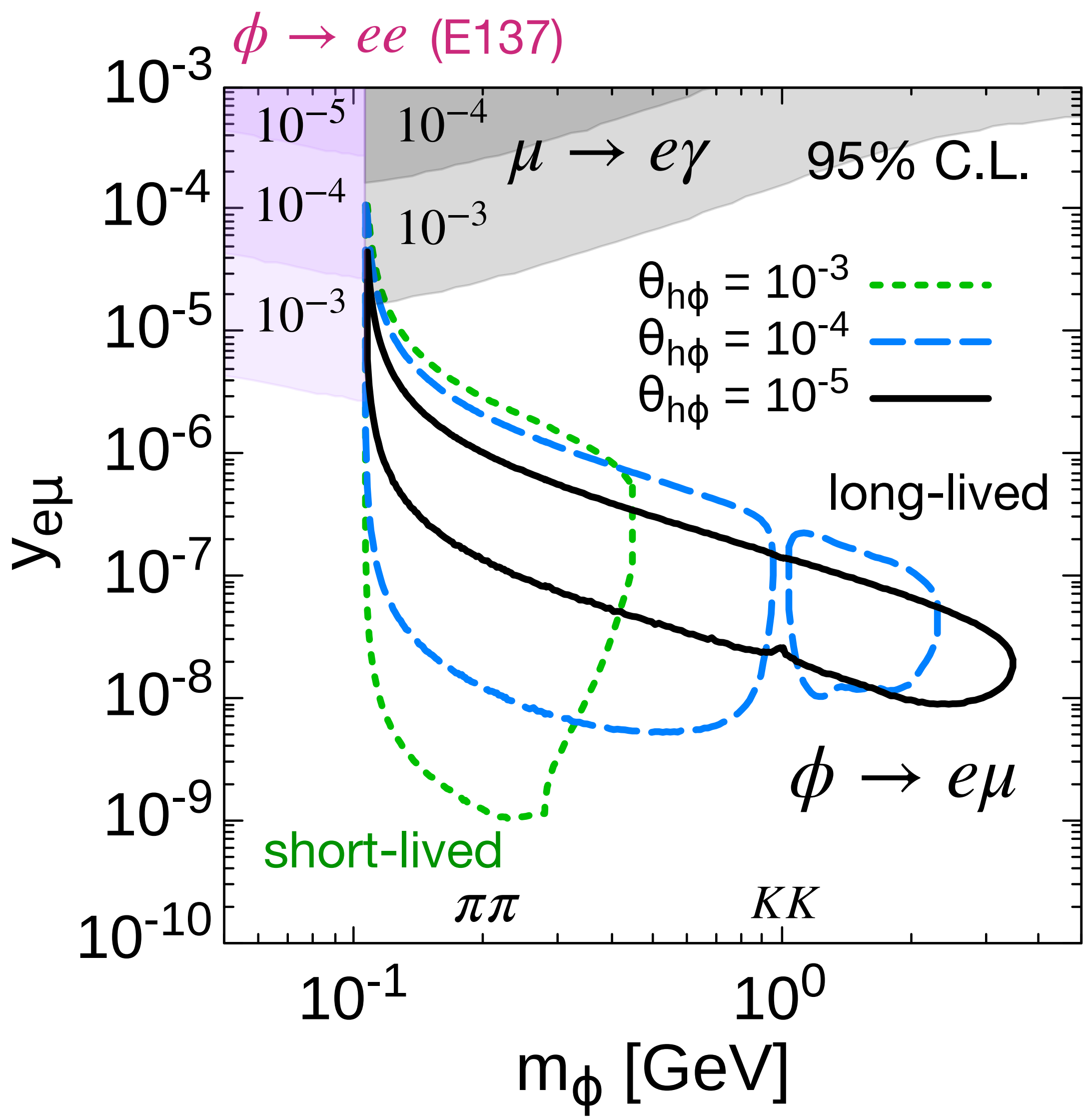


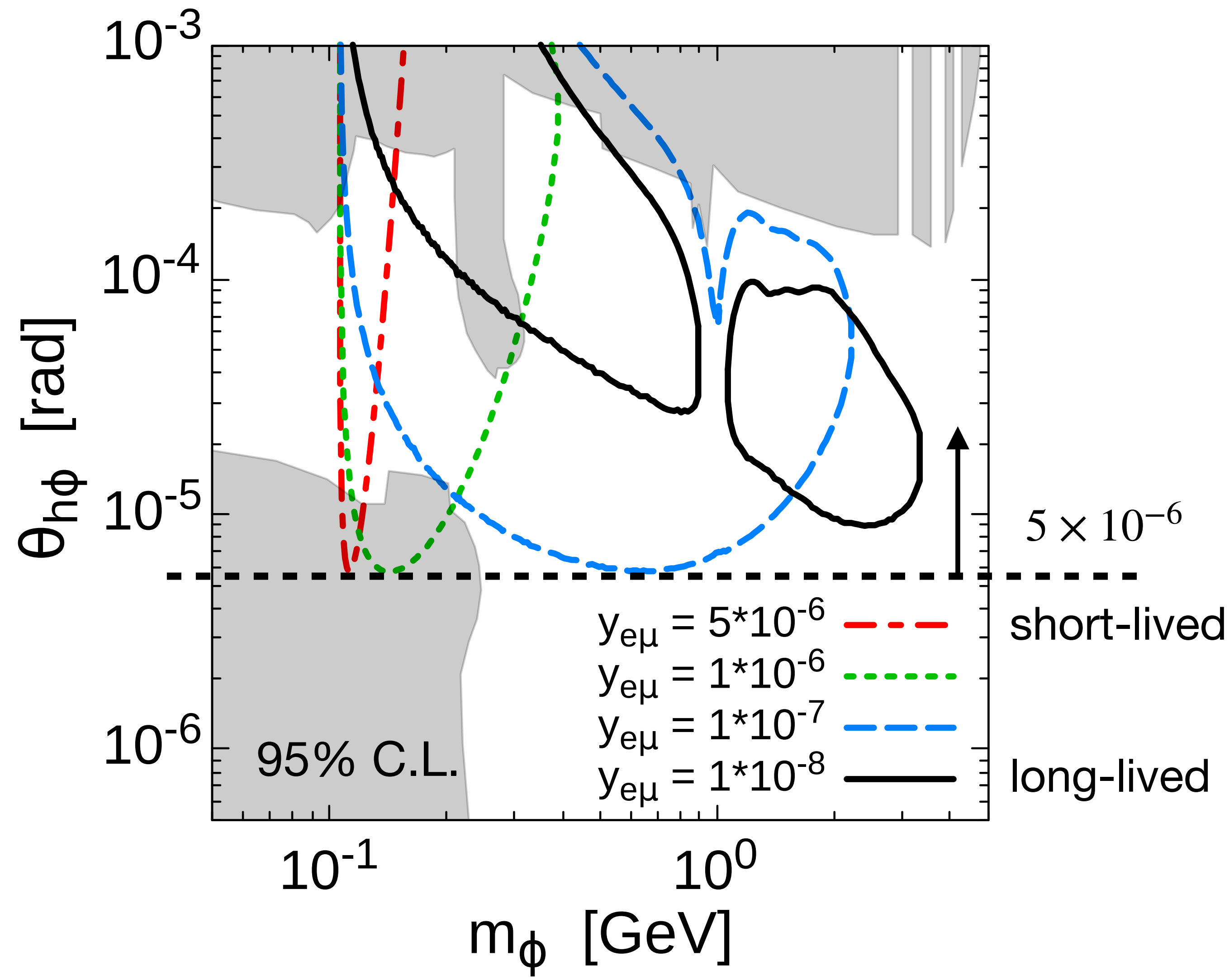
ϕ can travel over several m @ $\theta = 10^{-4}$, $m_\phi = 2$ GeV

Feng, et al, PRD 97, 2018

Yukawa-type int.

$$\mathcal{L}_{\text{scalar}} = \frac{\theta_{h\phi}}{v} \sum m_f \overline{f} \phi f + (y_{e\mu} \overline{e_L} \phi \mu_R + y_{\mu e} \overline{\mu_L} \phi e_R + \text{h.c.})$$





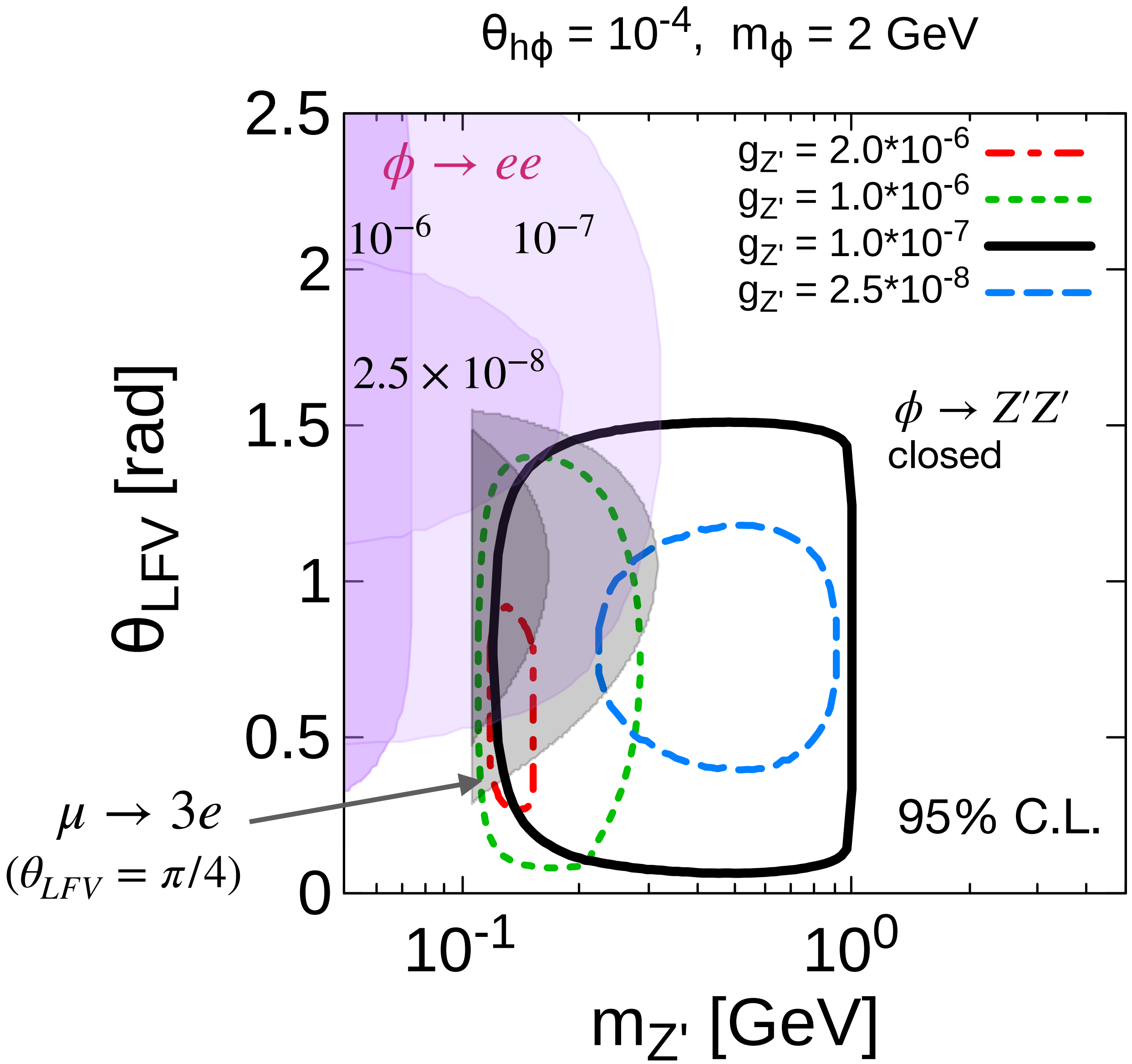
- $y_{e\mu} > 10^{-9}$ explored for $\theta_{h\phi} = 10^{-3}$
- $m_\phi < 4$ GeV explored for $\theta_{h\phi} = 10^{-5}$

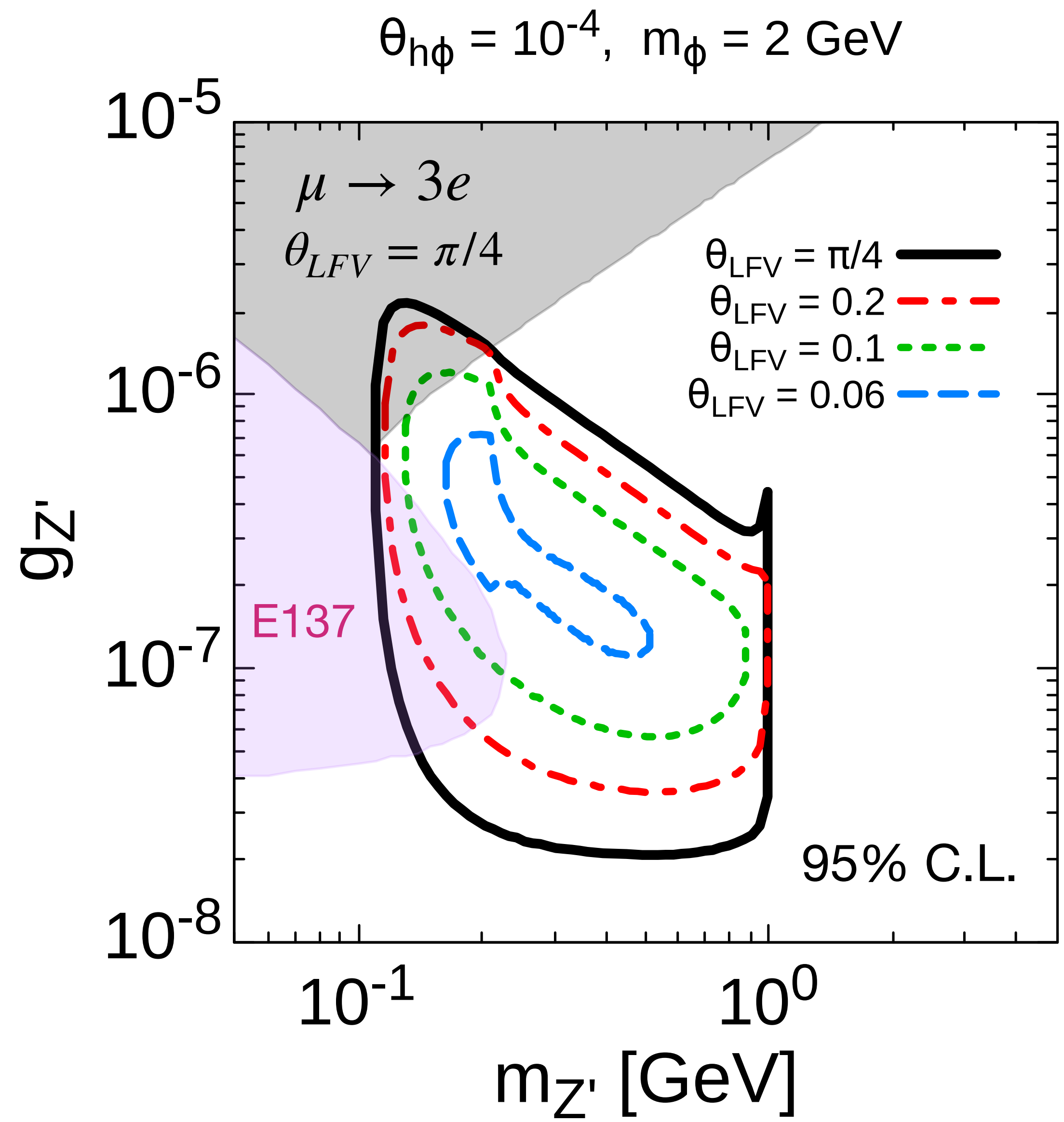
- Sensitive to $\theta_{h\phi} > 5 \times 10^{-6}$

Vector-type int.

$s = \sin\theta_{LFV},\ c = \cos\theta_{LFV}$

$$\mathcal{L}_{\rm vector} = g_{Z'} Z'_\rho (s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu + sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu)$$
$$+ g_{Z'} Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$

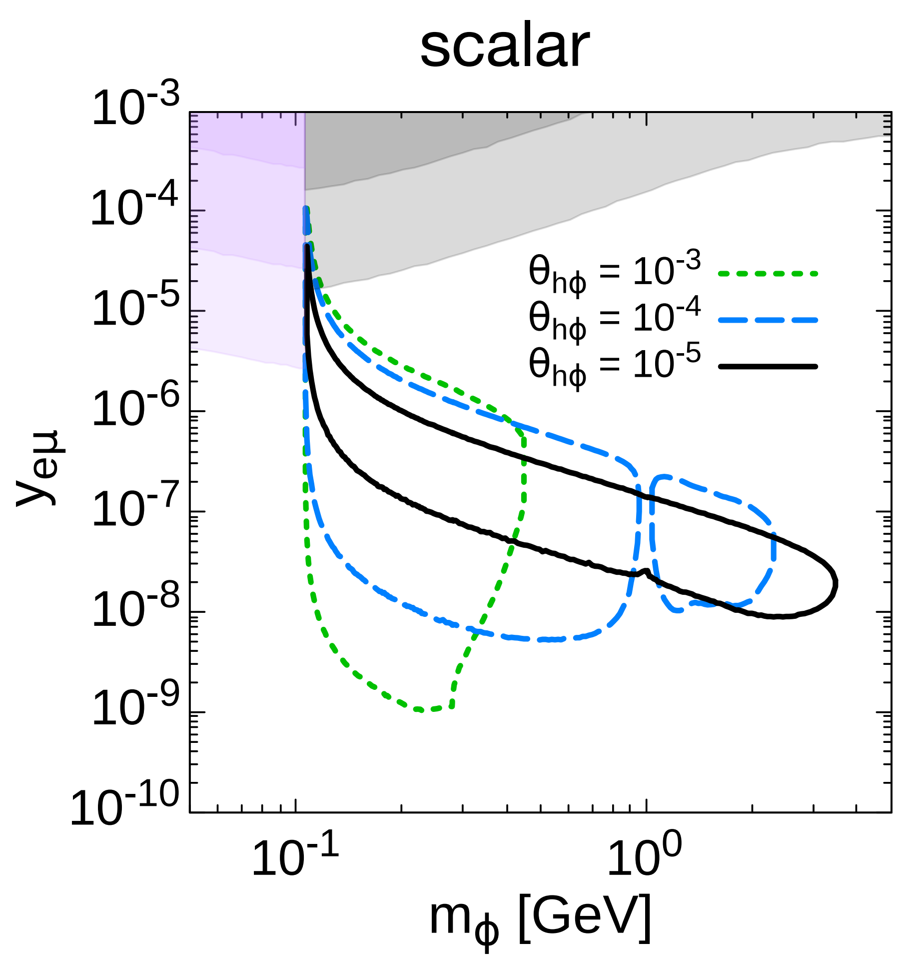


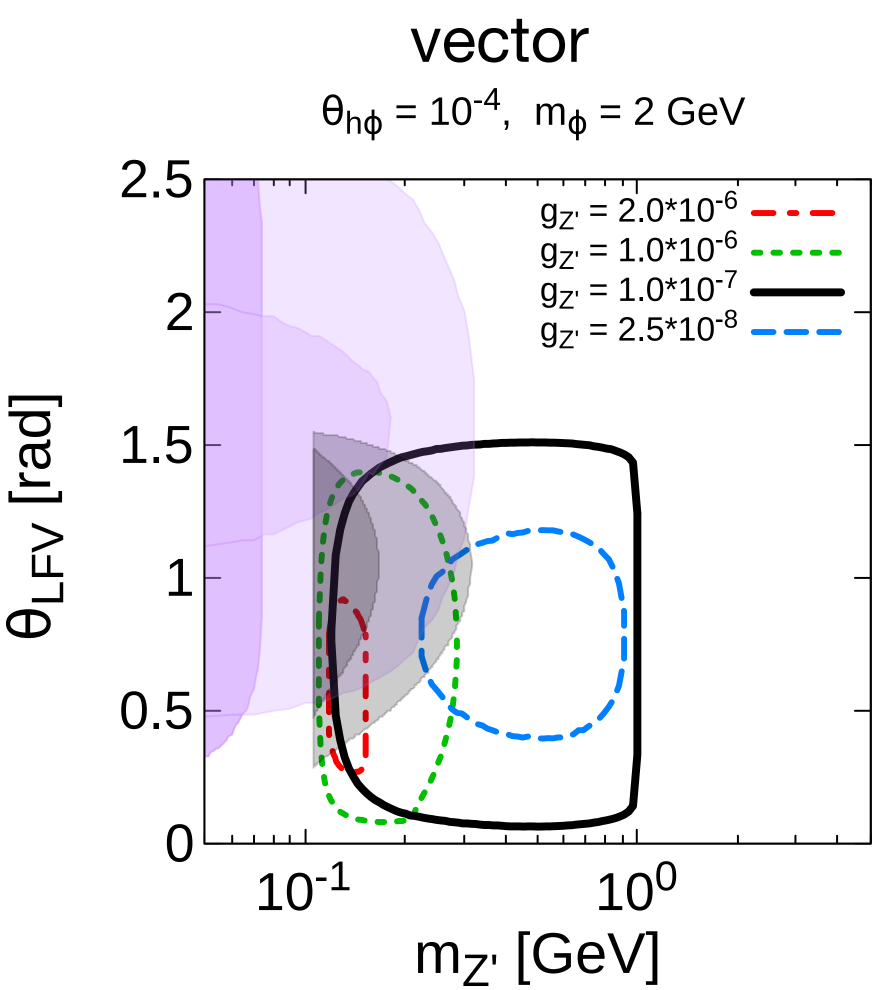


- $0.05 < \theta_{LFV} < 1.5$ can be explored
- $10^{-8} < g_{Z'} < 10^{-6}$ can be explored

Summary

- We have studied the possibility of searching for CLFV decays of light bosons at FASER.
  - Yukawa- and Vector-type interactions were considered.
  - FASER 2 can explore new CLFV coupling region.





Back-Up Slides

Feng, et al, PRD 97, 2018

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- Production (@ 3 /ab)

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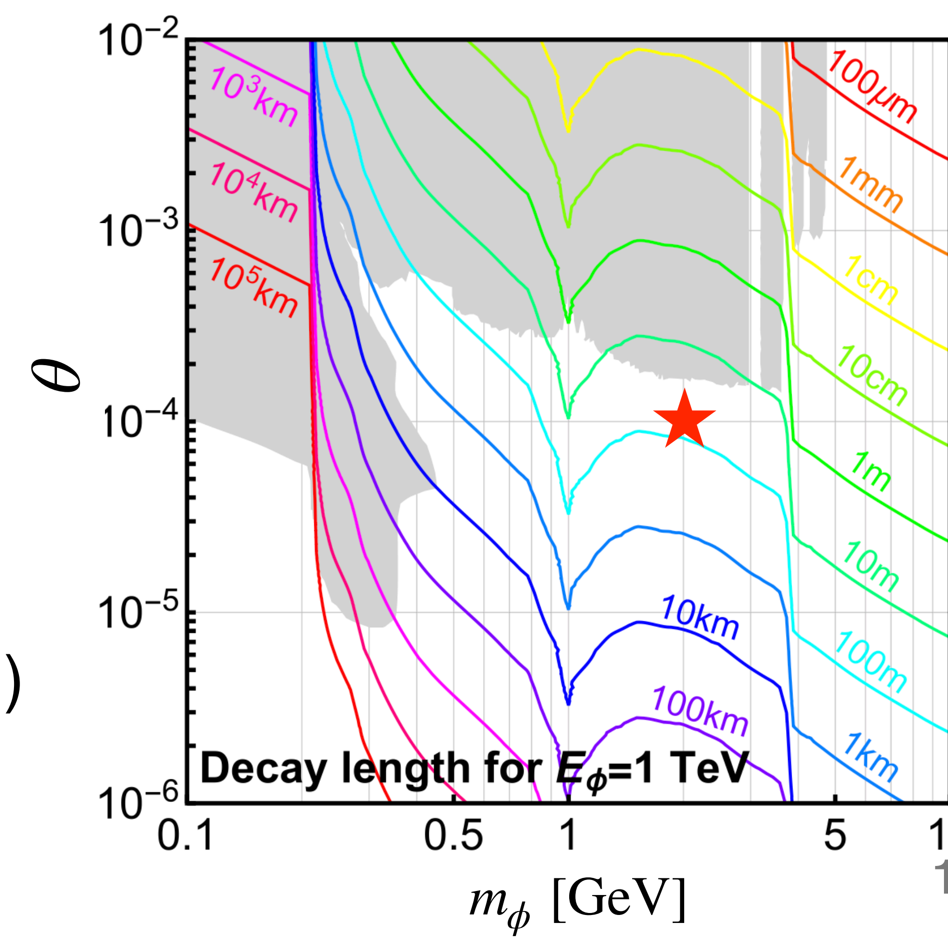


Scalar-type int.

$$\mathcal{L}_{\text{scalar}} = \frac{\theta_{h\phi}}{v} \sum \underbrace{m_f \overline{f} \phi f}_{\text{CLFC int.}} + \underbrace{(y_{e\mu} \overline{e_L} \phi \mu_R + y_{\mu e} \overline{\mu_L} \phi e_R + \text{h.c.})}_{\text{CLFV int.}}$$

$\theta_{h\phi}$: mixing with the SM higgs

m_f : mass of the SM fermions

$y_{e\mu,\mu e}$: CLFV coupling

Pseudoscalar-type int.

$$\mathcal{L}_{\text{pseudoscalar}} = \frac{\partial_\rho a}{\Lambda} \left(\sum \underbrace{c_{ff} \overline{f} \gamma^\rho \gamma_5 f}_{\text{CLFC int.}} + \underbrace{c_{e\mu} \overline{e} \gamma^\rho \gamma_5 \mu + c^*_{e\mu} \overline{\mu} \gamma^\rho \gamma_5 e}_{\text{CLFV int.}} \right)$$

Λ : a cutoff scale

c_{ff} : CLFC coupling

$c_{e\mu}$: CLFV coupling

Vector-type int.

$$\mathcal{L}_{\text{vector}} = g_{Z'} Z'_\rho (\underbrace{s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu}_{\text{CLFC int.}} + \underbrace{sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu)}_{\text{CLFV int.}}$$
$$+ g_{Z'} Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$

$g_{Z'}$: gauge coupling

$s = \sin\theta,\ c = \cos\theta$

θ : LFV mixing

Dipole-type int.

$$\mathcal{L}_{\text{dipole}} = \frac{1}{2} \sum_{\ell = e, \mu, \tau} \underbrace{\mu_\ell \bar{\ell} \sigma^{\rho\sigma} \ell A'_{\rho\sigma}}_{\text{CLFC int.}} + \frac{\mu'}{2} \underbrace{(\bar{\mu}\sigma^{\rho\sigma} e + \bar{e}\sigma^{\rho\sigma}\mu) A'_{\rho\sigma}}_{\text{CLFV int.}}$$

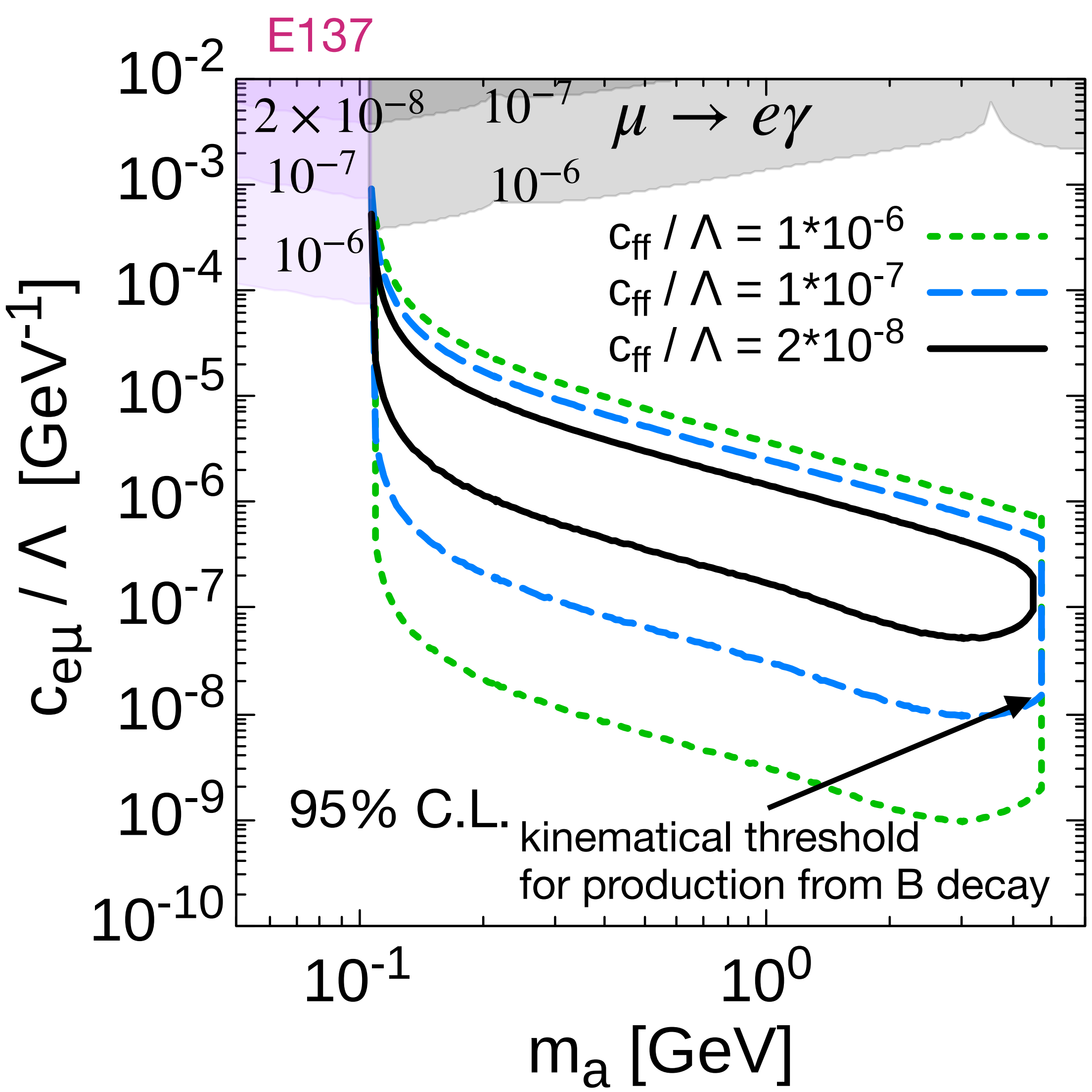
μ_l : CLFC dipole coupling

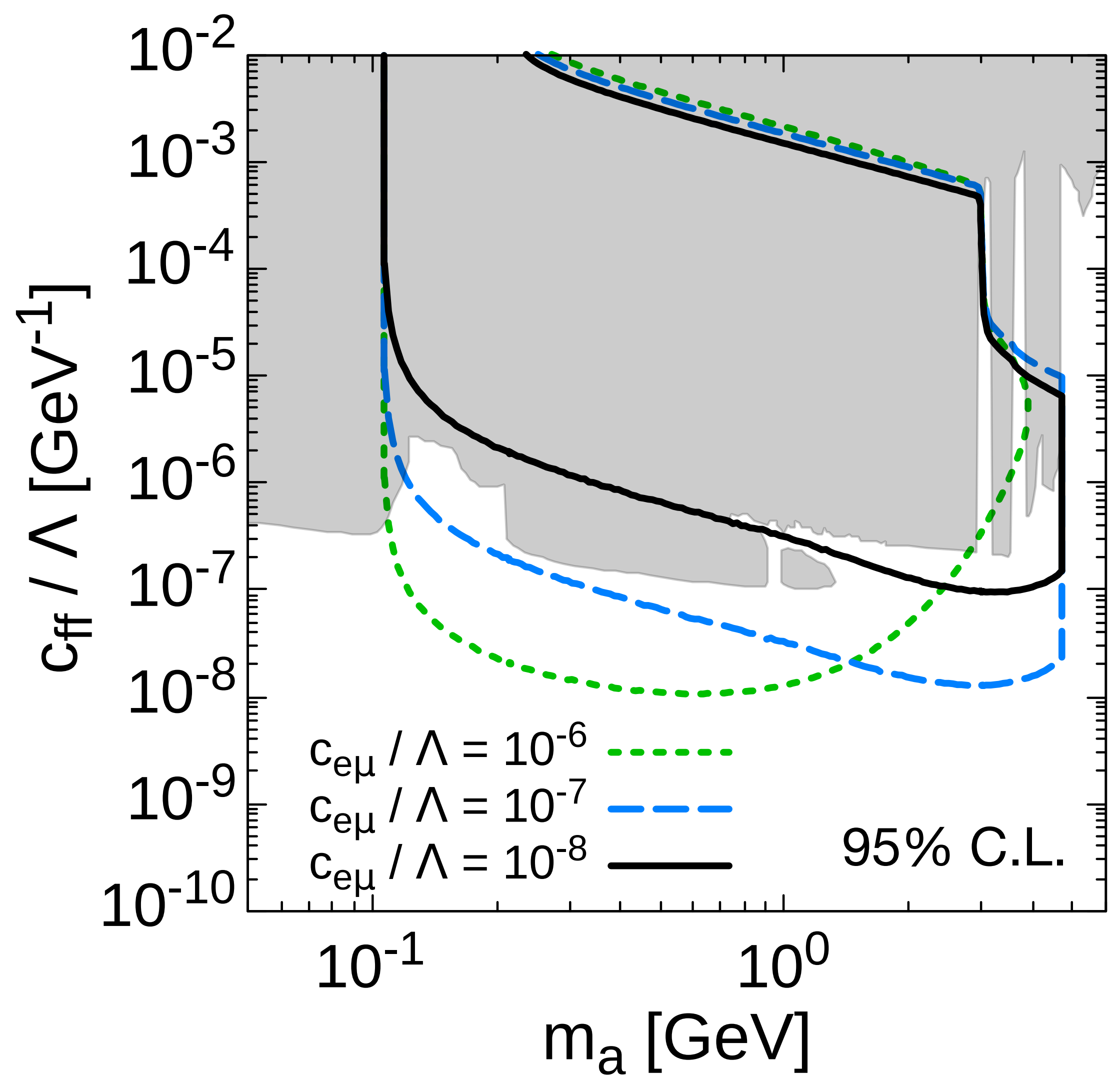
μ' : CLFV dipole coupling

Pseudoscalar-type int.

$$\mathcal{L}_{\text{pseudoscalar}} = \frac{\partial_\rho a}{\Lambda}\left(\sum c_{ff}\overline{f}\gamma^\rho\gamma_5 f + c_{e\mu}\overline{e}\gamma^\rho\gamma_5\mu + c^*_{e\mu}\overline{\mu}\gamma^\rho\gamma_5 e\right)$$

(c_{ff} is common)

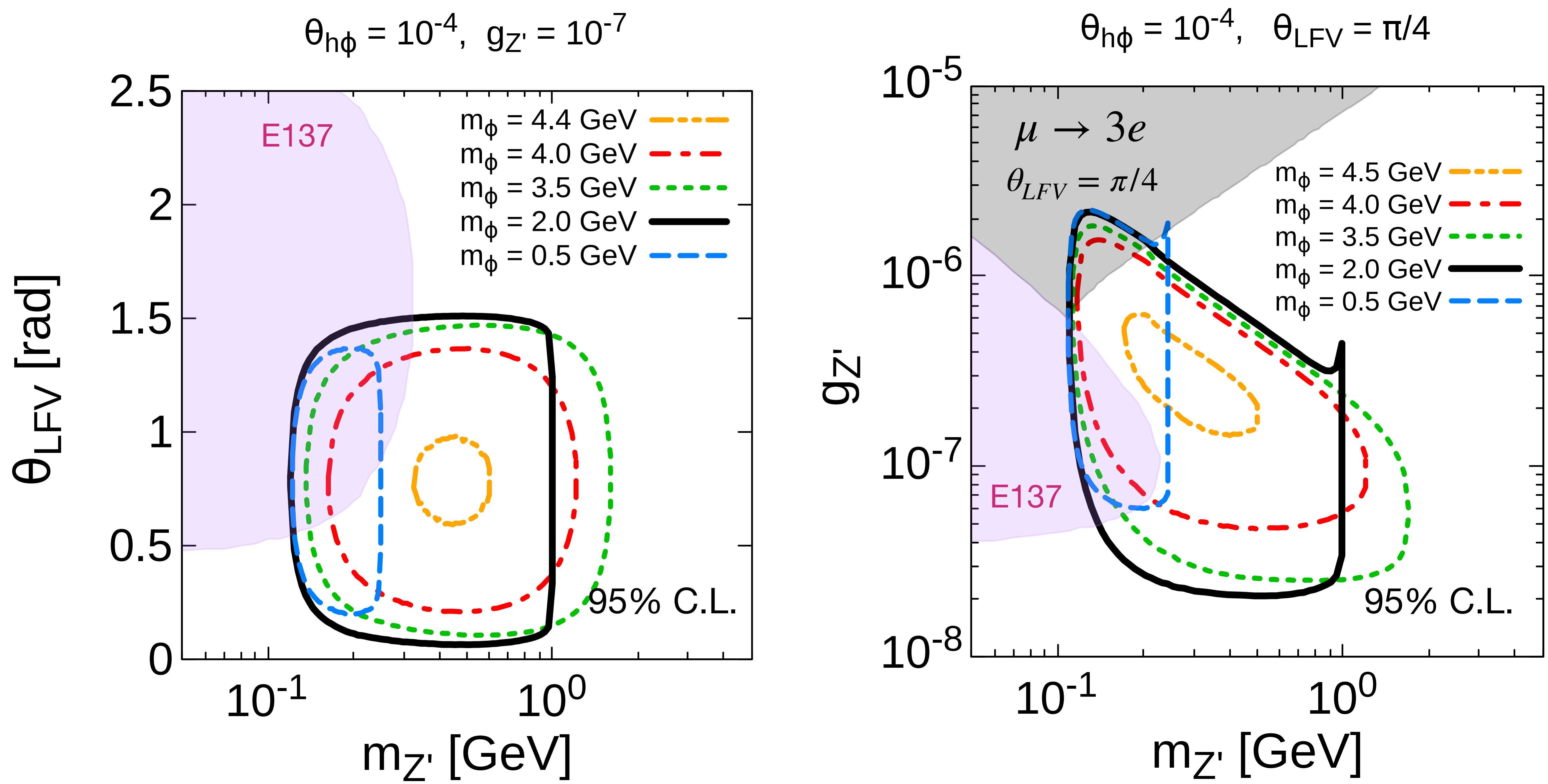




- longer-lived than scalar boson (decay into 2 mesons is forbidden)

Vector-type int.

$$\mathcal{L}_{\text{vector}} = g_{Z'} Z'_\rho (s^2\, \bar{e}\gamma^\rho e + c^2\, \bar{\mu}\gamma^\rho \mu + sc\, \bar{\mu}\gamma^\rho e + sc\, \bar{e}\gamma^\rho \mu)$$
$$+ g_{Z'} Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$

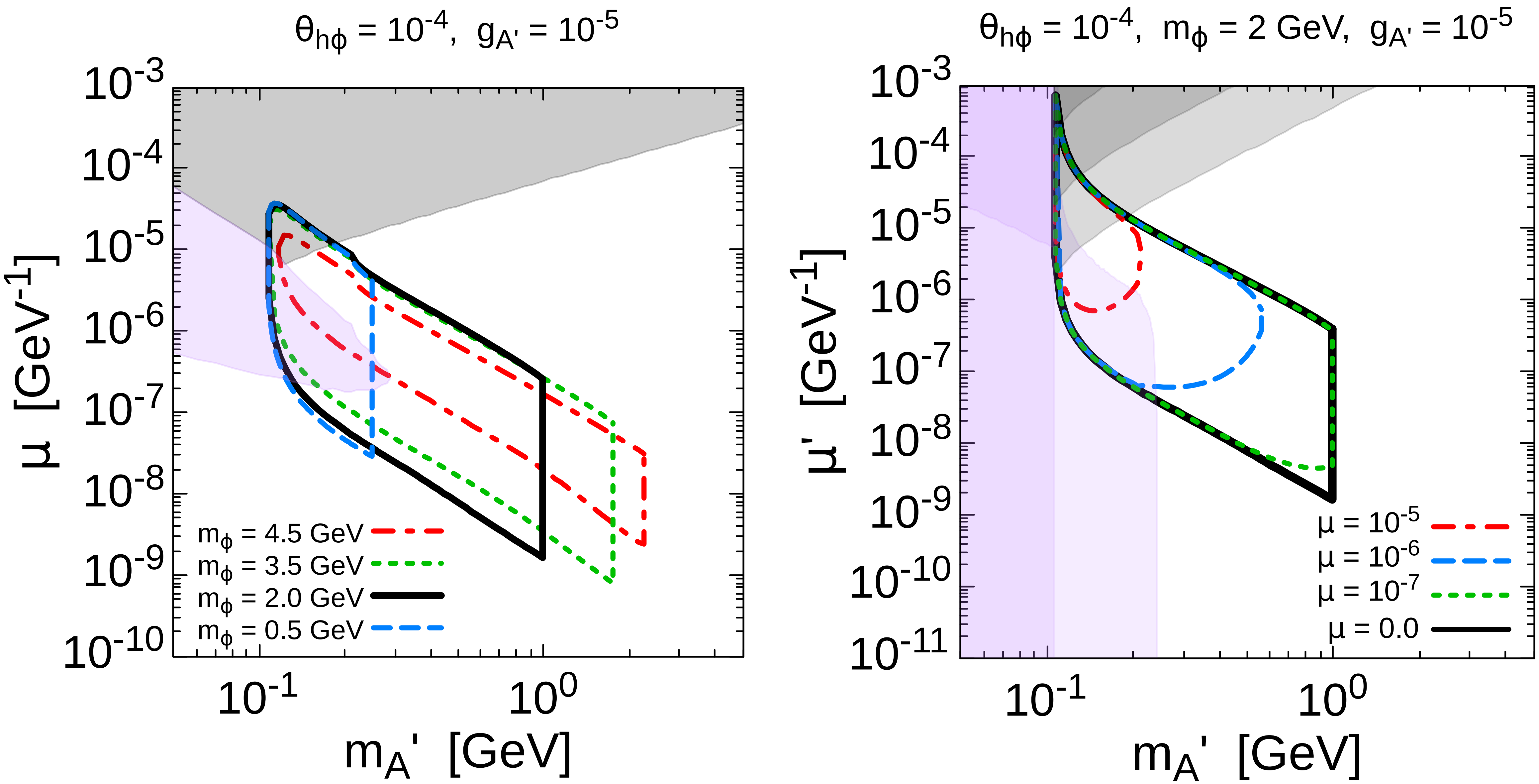


- $\tau\tau$ channel open for $m_\phi > 3.5$ GeV

→ # of Z' from B decay reduced

Dipole-type int.

$$\mathcal{L}_{\rm dipole} = \frac{1}{2}\sum_{\ell=e,\mu,\tau} \mu_\ell \bar{\ell}\sigma^{\rho\sigma}\ell A'_{\rho\sigma} + \frac{\mu'}{2}\left(\bar{\mu}\sigma^{\rho\sigma}e + \bar{e}\sigma^{\rho\sigma}\mu\right)A'_{\rho\sigma}$$



Dipole-type int.

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