# Search for Lepton Flavor Violating Decay at FASER

Kento ASAI (Saitama Univ.)

2nd Forward Physics Facility Meeting

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Based on ongoing work

in collaboration with T. Araki (Ohu Univ.), H. Otono (Kyushu Univ.),
T. Shimomura (Miyazaki Univ.), Y. Takubo (KEK)

# Introduction

# Introduction

## Charged Lepton Flavor Violation (cLFV)



### In the SM

Neutrino Oscillation

➡ cLFV is violating

Prediction : $\sim 10^{-50}$

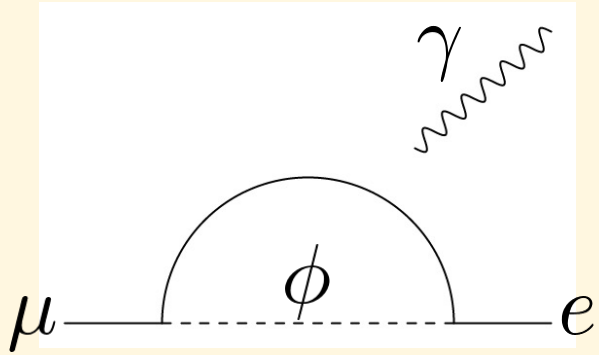
$\ll$

Experiements : $< 10^{-12}$

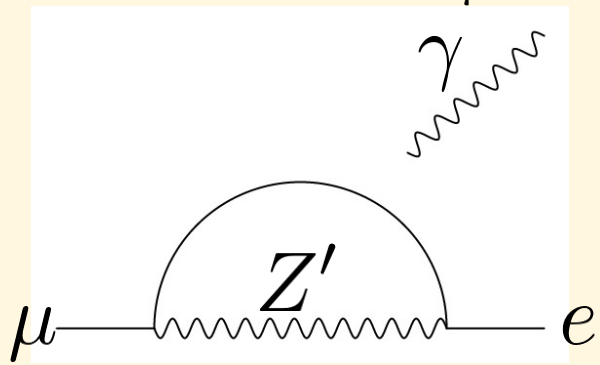
➡ It is impossible to detect cLFV process

### Beyond the SM

- Leptophilic scalar




- Extra gauge boson (ex: $\mathrm{U}(1)_{L_\mu - L_\tau}$)




- Dark Photon w/ dipole LFV coupling

# Introduction

## Charged Lepton Flavor Violation (cLFV)



In the SM

Neutrino Oscillation

➡ cLFV is violating

Prediction : $\sim 10^{-50}$

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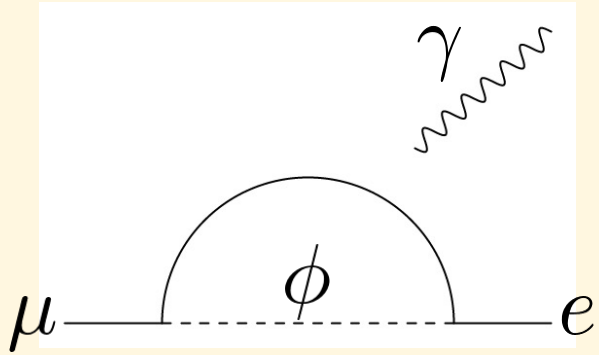
Expe

➡ It is cLFV process

Beyond the SM

- Leptophilic scalar

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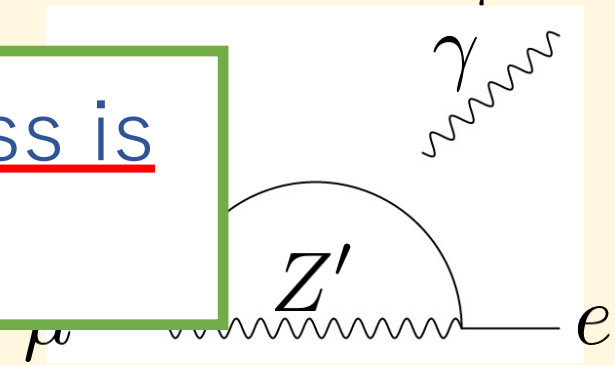



- Dark Photon w/ dipole LFV coupling

Charged lepton flavor violation process is a smoking gun signal of new physics

# Introduction



## Charged Lepton Flavor Violation (cLFV)

Ex) $U(1)_{L_\mu - L_\tau}$ gauge boson

Non-universal charge

$$g_{\mu\tau} Z'_\mu \bar{\ell}_\alpha \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & +1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \ell_\beta \qquad \text{[flavor basis]}$$

Diagonalization of charged lepton mass matrix

$$\ell_\alpha = V_{\alpha i} \ell_i$$

$$g_{\mu\tau} Z'_\mu \bar{\ell}_i \gamma^\mu V^\dagger_{i\alpha} \begin{pmatrix} 0 & 0 & 0 \\ 0 & +1 & 0 \\ 0 & 0 & -1 \end{pmatrix} V_{\beta j} \ell_j \qquad \text{[mass basis]}$$

**cLFV interaction**

# Introduction

## Gauge Boson Mass



Origin of gauge boson mass

➡ Spontaneous symmetry breaking by VEV of $\mathrm{U}(1)_{L_\mu - L_\tau}$-charged scalar

Interaction between $\mathrm{U}(1)_{L_\mu - L_\tau}$-charged scalar and gauge boson

$$\mathcal{L} \supset g'^2 \phi^\dagger \phi Z'_\mu Z'^\mu \xrightarrow[\text{SSB}]{\langle \phi \rangle = v_\phi/\sqrt{2}} \underbrace{\frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu}_{A' \text{ mass term}} + \boxed{\underbrace{g_{\mu\tau} m_{Z'} \phi Z'_\mu Z'^\mu}_{\phi A' A' \text{ coupling}}}$$

➡ $\phi Z' Z'$ coupling

# Introduction

## Dark Photon Mass



Interaction between $\mathbf{U(1)}_{L_\mu - L_\tau}$-charged scalar and gauge boson

$$\mathcal{L} \supset g_{\mu\tau} m_{Z'} \phi Z'_\mu Z'^\mu$$ ➡ $\boldsymbol{\phi}$ decay into $\mathbf{Z'}$ pair

We assume that$\mathbf{U(1)}_{L_\mu - L_\tau}$-charged scalar is much heavier than dark photon $(m_{Z'} \ll m_\phi)$

➡ Almost all $\boldsymbol{\phi}$ decay into dark photon

$$\Gamma(\phi \to Z'Z') = \frac{g_{\mu\tau}}{8\pi} \frac{m_{Z'}^2}{m_\phi} \sqrt{1 - \frac{4m_{Z'}^2}{m_\phi^2}} \left[ 2 + \frac{m_\phi^4}{4m_{Z'}^2} \left( 1 - \frac{2m_{Z'}^2}{m_\phi^2} \right)^2 \right]$$

enhancement factor $\gg 1$

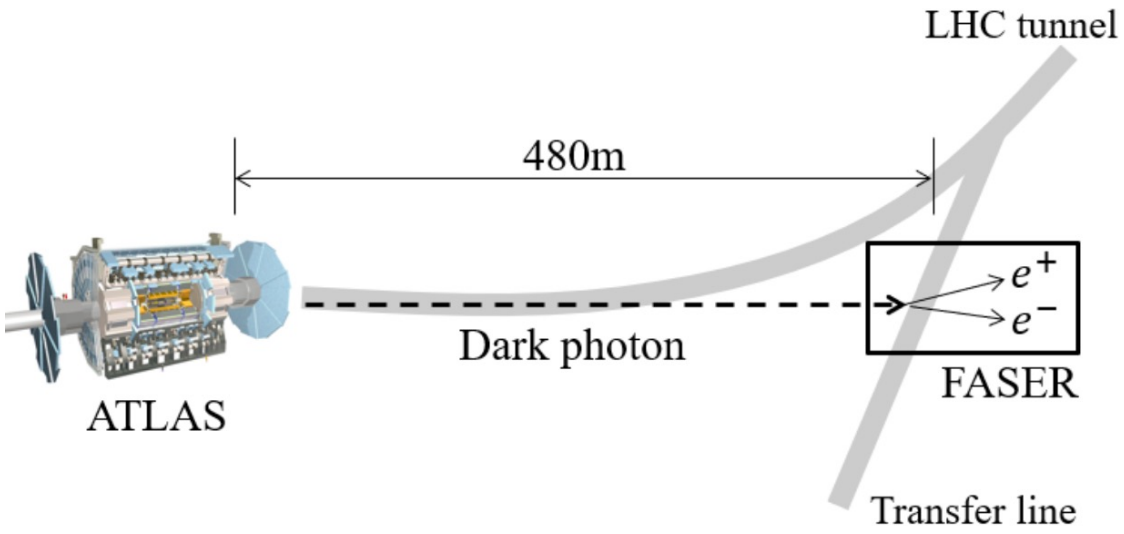
# Introduction

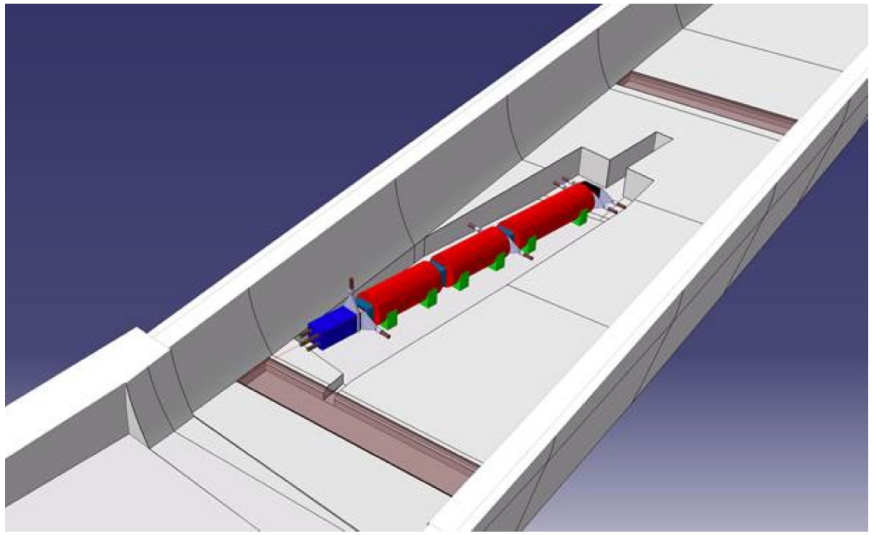


## FASER experiment

FASER (ForwArd Search ExpeRiment at the LHC)

- New experiment to search new light, weakly interacting, neutral particle
- Sensitive to long-lived particles



# Calculation

# Calculation



## Charged Lepton Flavor Violation (cLFV)

Ex) $U(1)_{L_\mu - L_\tau}$ gauge boson

$$g_{\mu\tau} Z'_\mu \bar{\ell}_i \gamma^\mu V^\dagger_{i\alpha} \begin{pmatrix} 0 & 0 & 0 \\ 0 & +1 & 0 \\ 0 & 0 & -1 \end{pmatrix} V_{\beta j} \ell_j \qquad \text{[mass basis]}$$

**cLFV interaction**

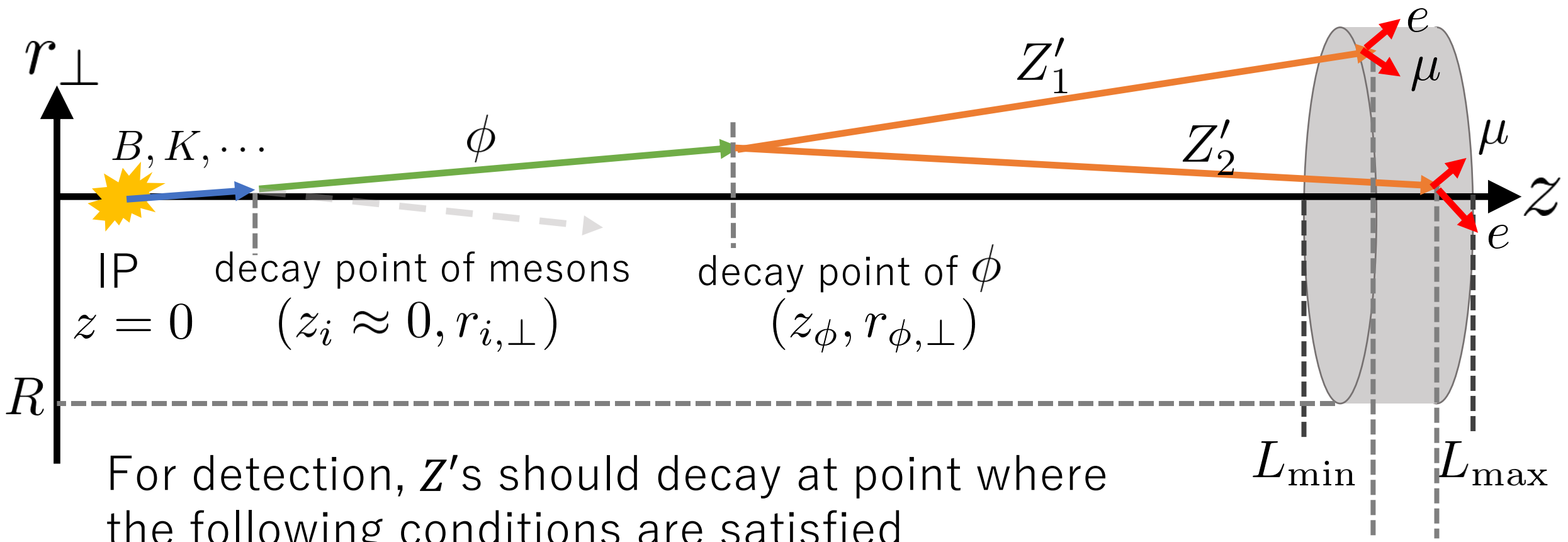
$$\begin{pmatrix} 0 & \lambda & \lambda \\ \lambda & 1 & \lambda \\ \lambda & \lambda & -1 \end{pmatrix}$$

$\lambda (\leq 1)$ : Ratio of strength of interaction (LFV / LFC)

# Calculation



## LFV decay at FASER




For detection, $Z'$s should decay at point where the following conditions are satisfied

Distance

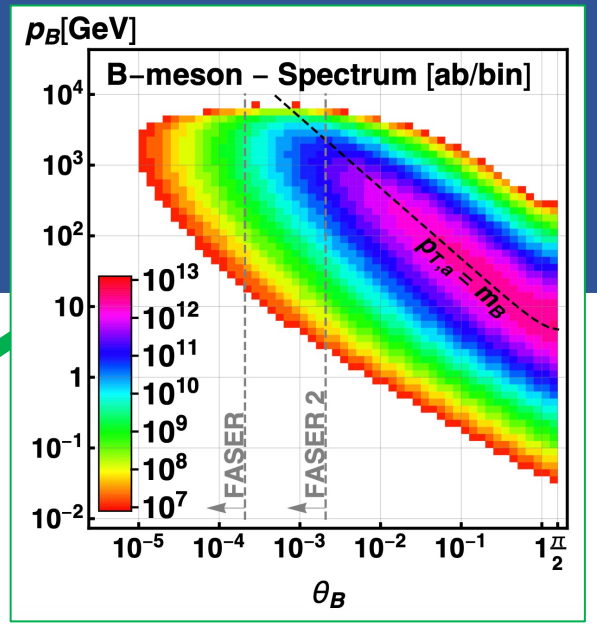
$$L_{\min} < z_{Z'_{1,2}} < L_{\max},$$

Angular

$$r_{Z'_{1,2},\perp} < R$$

# Calculation

## Event number of LFV decay at FASER




$$N = \mathcal{L} \int d\boldsymbol{p}_{A'} \frac{d\sigma_{pp\to A'X}}{dp_{A'}d\theta_{A'}} \mathcal{P}^{\rm det}_{A'}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi)$$

$$= \mathcal{L} \sum_{i:\text{meson}} \sum_{j=1,2} \int dp_i d\theta_i \int d\boldsymbol{p}_{A'} \int d\boldsymbol{p}_\phi \frac{d\sigma_{pp\to iX}}{dp_i d\theta_i} \mathrm{Br}(i \to \tilde{X}\phi)\mathrm{Br}(\phi \to A'_1 A'_2)$$

$$\times \mathcal{P}^{\rm det}_{A'_j}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi) \times \mathrm{BR}(Z' \to e\mu)$$

$\mathcal{L}$ : integrated luminosity

Assumption & Setup

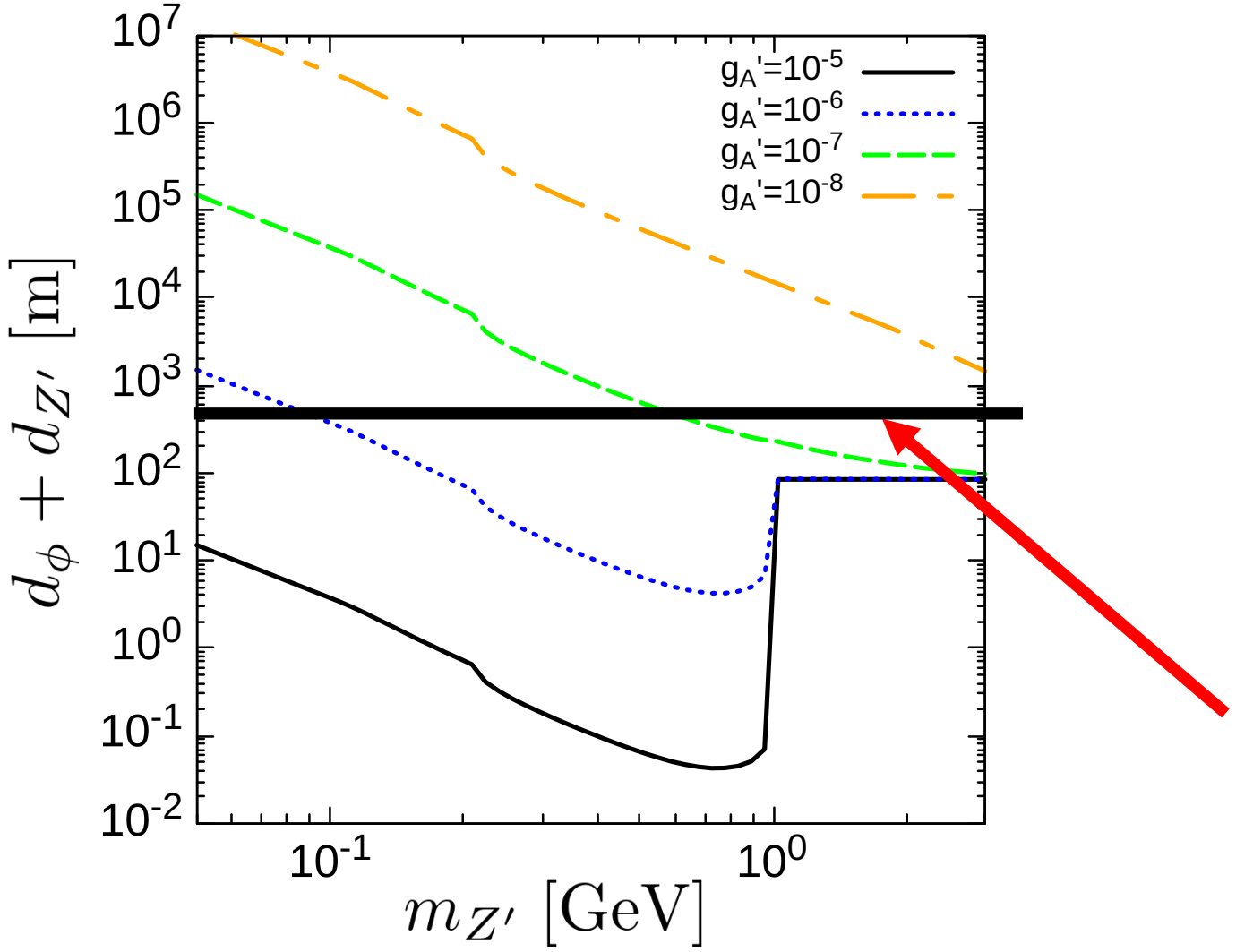
- Calculated for FASER2 case
- Background free

# Result

# Result



## Decay length ($U(1)_{L_\mu - L_\tau}$ gauge boson)




Parameters

$$m_\phi = 2.0\ [\mathrm{GeV}]$$

$$\theta = 1 \times 10^{-4}$$

$$\lambda = 0.5$$

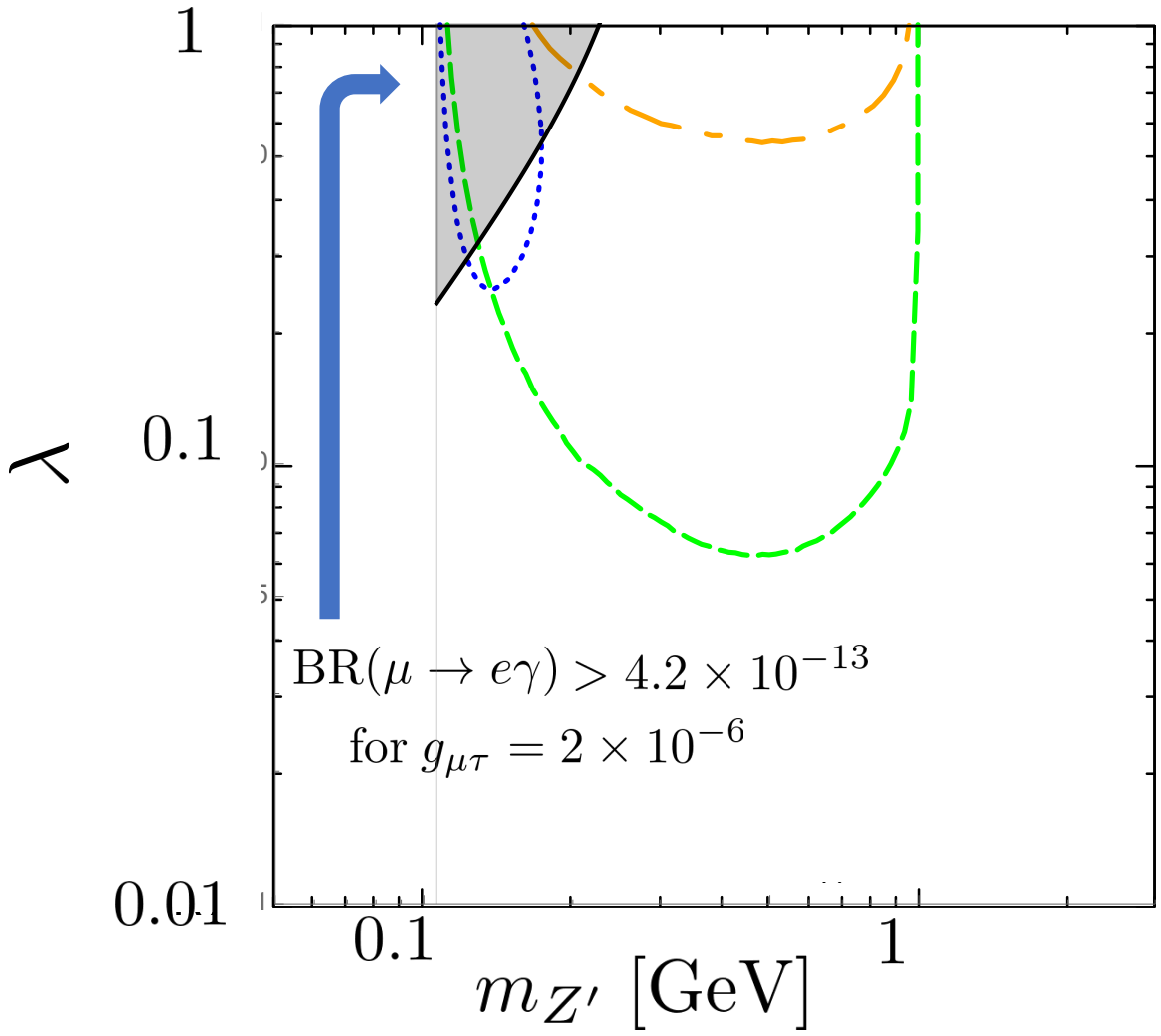
$$p_\phi = 2p_{Z'} = 1.0\ [\mathrm{TeV}]$$

$$d_\phi + d_{Z'} = 480\ [\mathrm{m}]$$

# Result

## # of signal events ($U(1)_{L_\mu - L_\tau}$ gauge boson)






95% C.L. exclusion contour @ FASER2

Parameters

$$m_\phi = 2.0\ [\mathrm{GeV}]$$

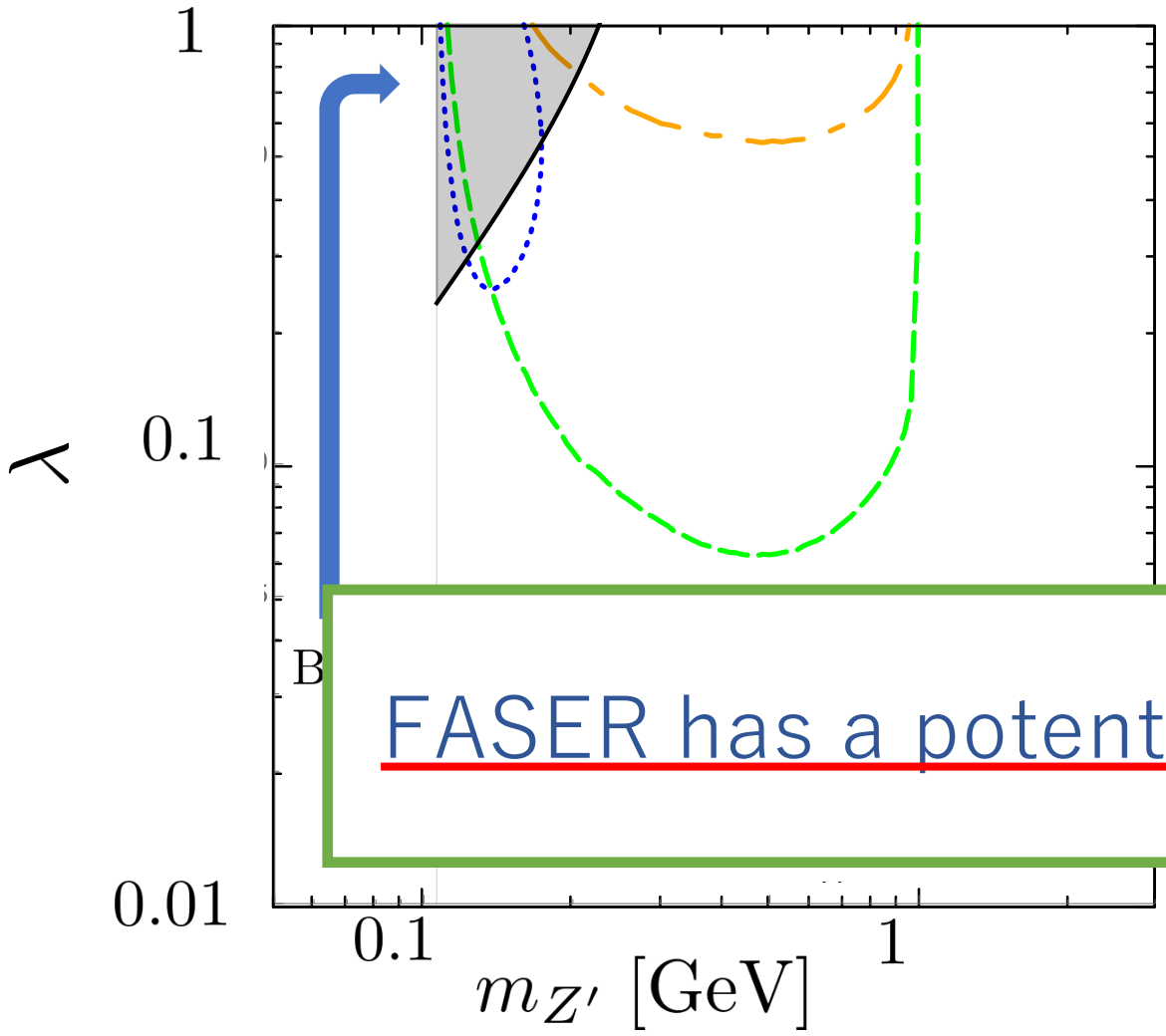
$$\theta = 10^{-4}$$

$$g_{\mu\tau} = \begin{cases} 2 \times 10^{-6} & \text{----------} \\ 1 \times 10^{-7} & \text{- - - - -} \\ 2 \times 10^{-8} & \text{-·-·-·-} \end{cases}$$

# Result

## # of signal events ($U(1)_{L_\mu - L_\tau}$ gauge boson)






95% C.L. exclusion contour
@ FASER2

Parameters

$$m_\phi = 2.0\ [\mathrm{GeV}]$$

$$\left\{ \begin{array}{l} \\ \\ 2 \times 10^{-8} \end{array} \right.$$

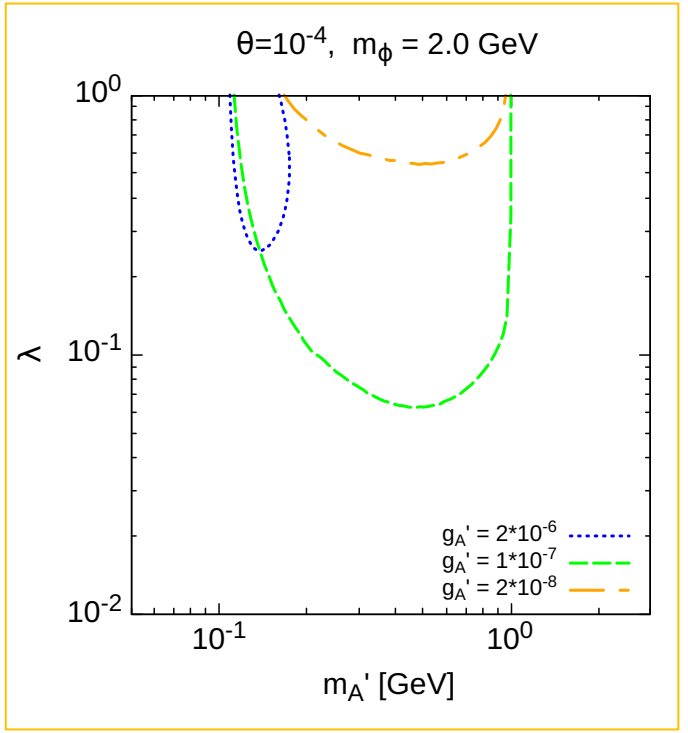
FASER has a potential to find cLFV decay

# Summary

Charged lepton flavor violating process
is a smoking gun signal of BSM

CLFV interaction is highly constrained
& FASER can search small coupling region

FASER has a potential to find cLFV decay



# Appendix

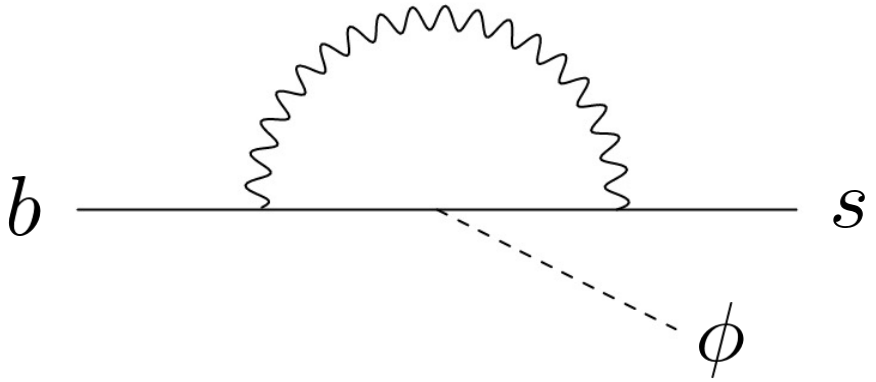
# Introduction

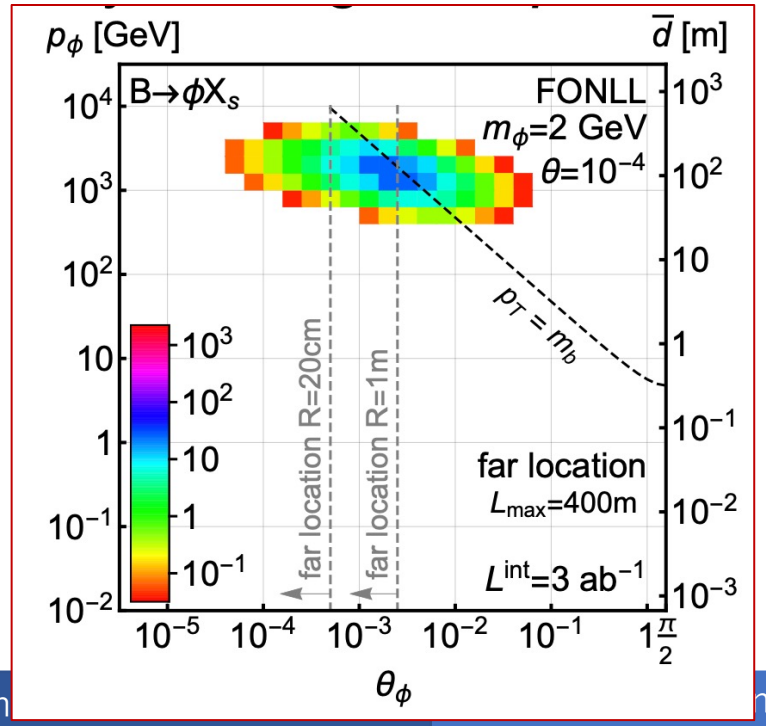
## New light particle production

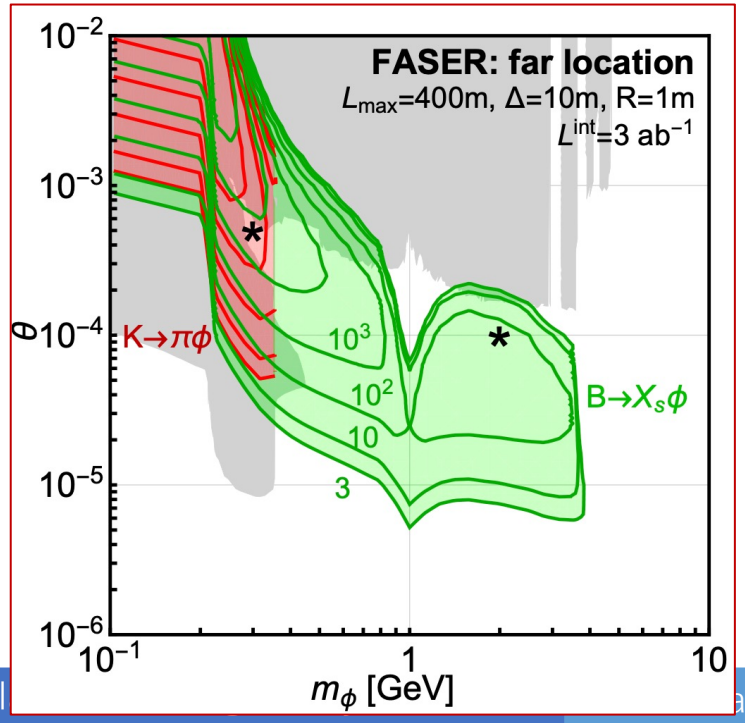


### Ex) Extra scalar

Extra scalar is produced by meson decays through $h - \phi$ mixing




J. L. Feng, I. Garon, F. Kling, S. Trojanowski, PRD **97** (2018) 5, 055034

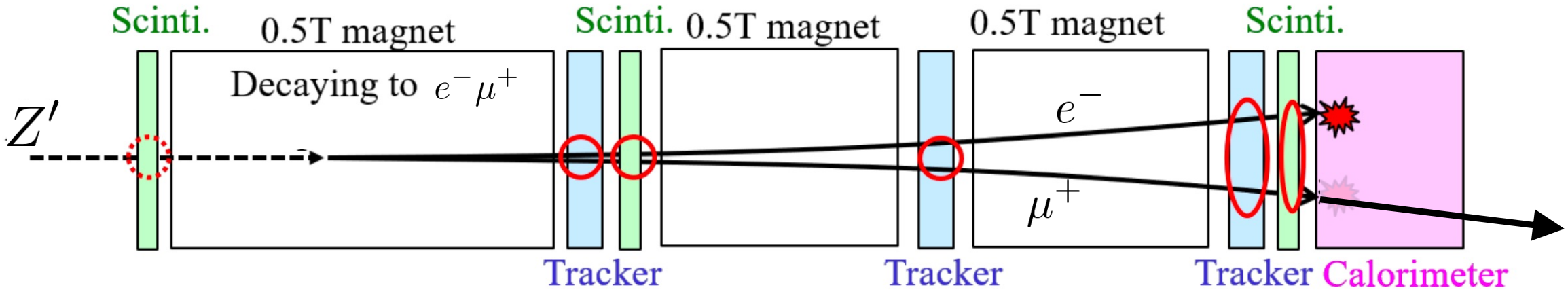
# Appendix

## CLFV decay detection



### Event detection

From Takubo san's slide




Visible charged particles are produced by Z' decays

$$Z' \to e^-\mu^+,\ e^+\mu^-$$

➡ They are separated by magnetic field and detected

# Appendix

## Background



- Rock & LHC infrastructure eliminate most background

Main background $[150\ \mathrm{fb}^{-1}$ @ LHC Run3]

- Muon brems. → photon
  : 80000 events
- CC / NC interactions of neutrinos $(E_\nu \gtrsim 100\ [\mathrm{GeV}])$
  : O(1) events

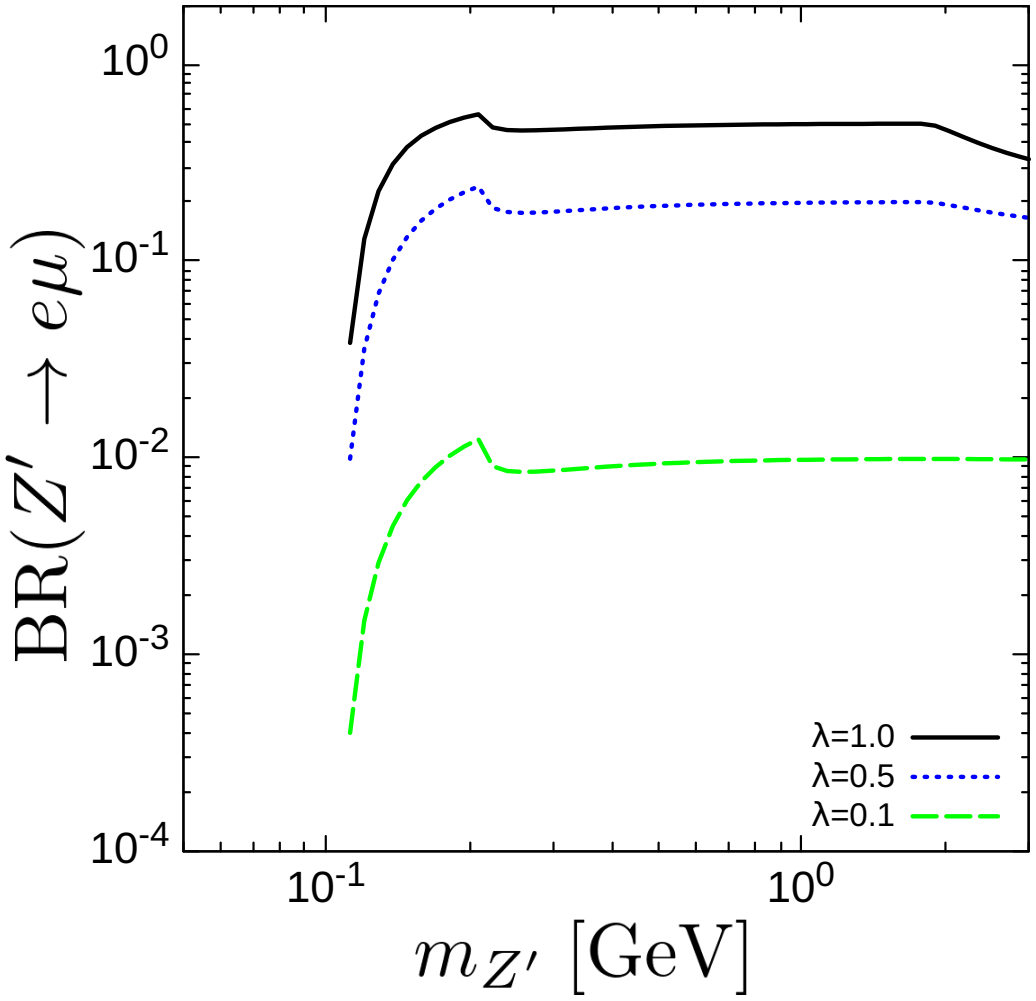
Veting entering charged particles
with an efficiency of 99.99%

Almost background free

# Appendix

## Branching ratio of LFV decay ($U(1)_{L_\mu - L_\tau}$ gauge boson)






### Decay width

$$\Gamma(Z' \to \ell\bar{\ell'}) = \frac{V^2}{24\pi} m_{Z'}\, \lambda\left(1, \frac{m_\ell^2}{m_{Z'}^2}, \frac{m_{\ell'}^2}{m_{Z'}^2}\right) \times \left[2 - \frac{m_\ell^2 - 6m_\ell m_{\ell'} + m_{\ell'}^2}{m_{Z'}^2} - \frac{(m_\ell^2 - m_{\ell'}^2)^2}{m_{Z'}^4}\right]$$

$$\lambda(1, a, b) = \sqrt{1 + a^2 + b^2 - 2a - 2b - 2ab}$$

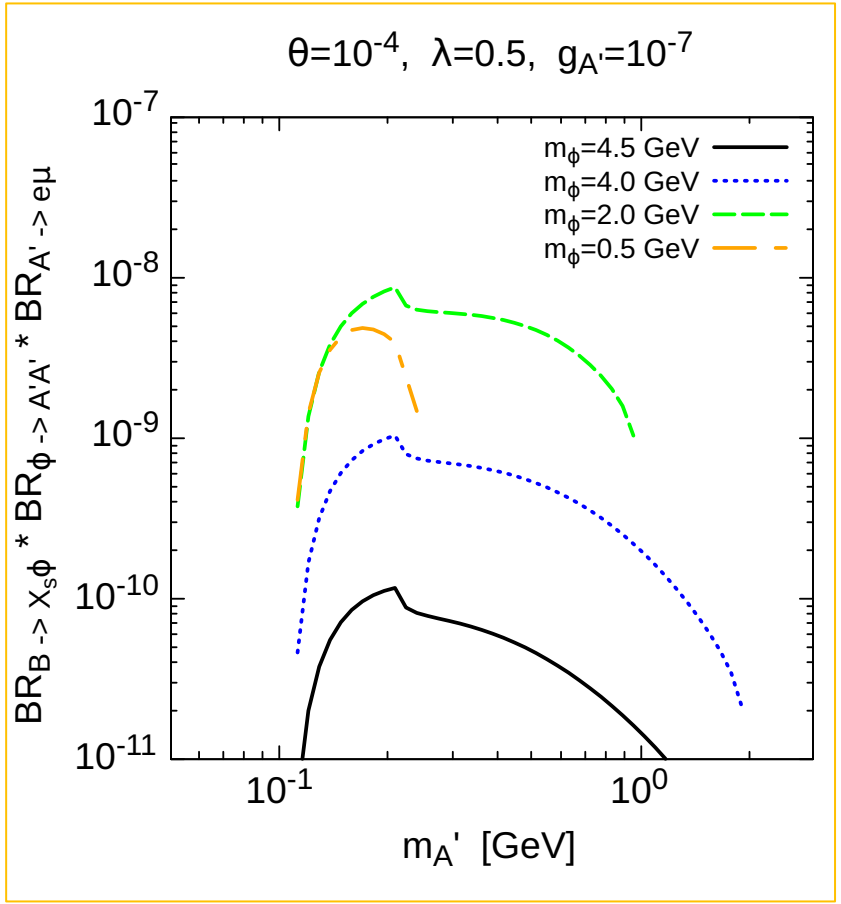
where

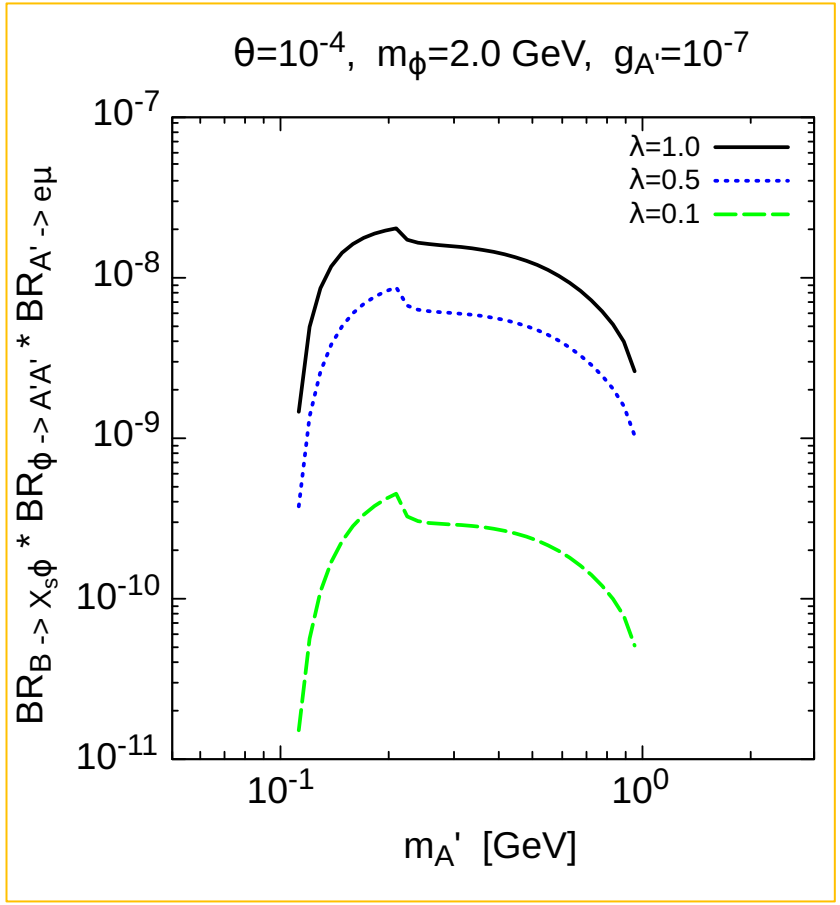
$$V = \begin{cases} g_{\mu\tau} & [\mathrm{LFC}] \\ \lambda g_{\mu\tau} & [\mathrm{LFV}] \end{cases}$$

# Appendix



## Branching ratio of LFV decay ($U(1)_{L_\mu - L_\tau}$ gauge boson)




## Decay width

$$\mathrm{Br}(B \to X_s \phi) \simeq 5.7 \left(1 - \frac{m_\phi^2}{m_b^2}\right)^2 \theta^2$$

$$Br(\phi \to A'A') = \frac{\Gamma_{\phi \to A'A'}}{\Gamma_{\phi \to A'A'} + \Gamma_{SM}}$$

$$\simeq 1 \ (\text{for } g_{A'} > 10^{-6})$$

# Appendix

## Toy model



Ex) Leptophilic scalar

$$\phi\, \bar{e}_{L,i} \begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} e_{R,j} + h.c. \qquad \text{[mass basis]}$$

**cLFV interaction**

SM Higgs - $\phi$ mixing : $\theta$

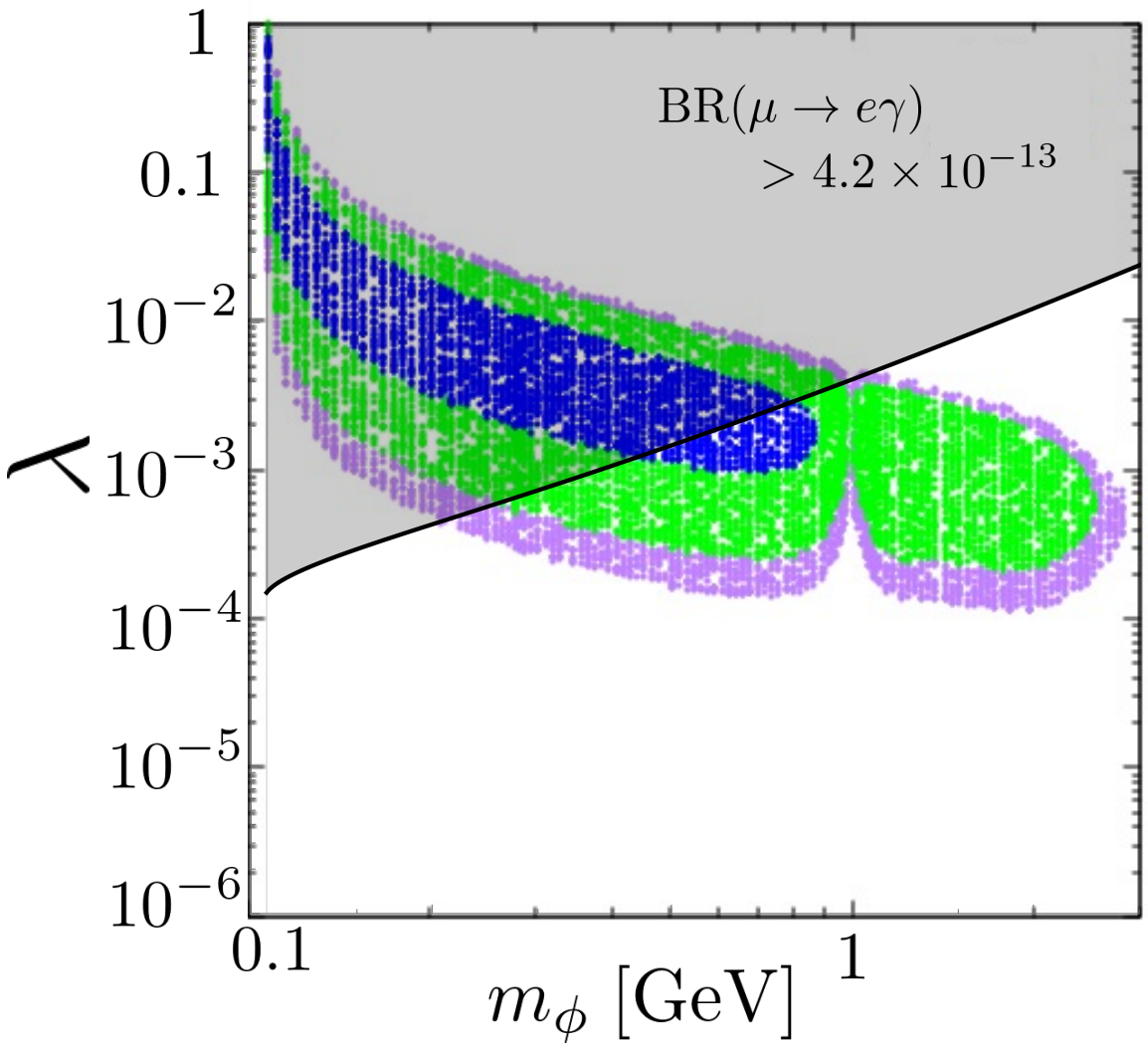
Couplings with the other SM fermions

$$\theta \sum_f \frac{m_f}{v} \phi \bar{f} f$$

# Appendix

## LFV decay at FASER (Leptophilic scalar)






Parameters

$$\theta = 5 \times 10^{-5}$$

# of LFV decay signals

$3 \sim 9$

$10 \sim 99$

$100 \leq$