Search for lepton flavor violating decay at long-lived particle search experiment

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Workshop on Muon LFV and Beyond
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August 7, 2026

Based on T. Araki, **KA**, T. Shimomura, JHEP 11 (2021) 082, arXiv : 2107.07487 [hep-ph]
T. Araki, **KA**, H. Otono, T. Shimomura, Y. Takubo, JHEP 01 (2023) 145, arXiv : 2210.12730 [hep-ph]

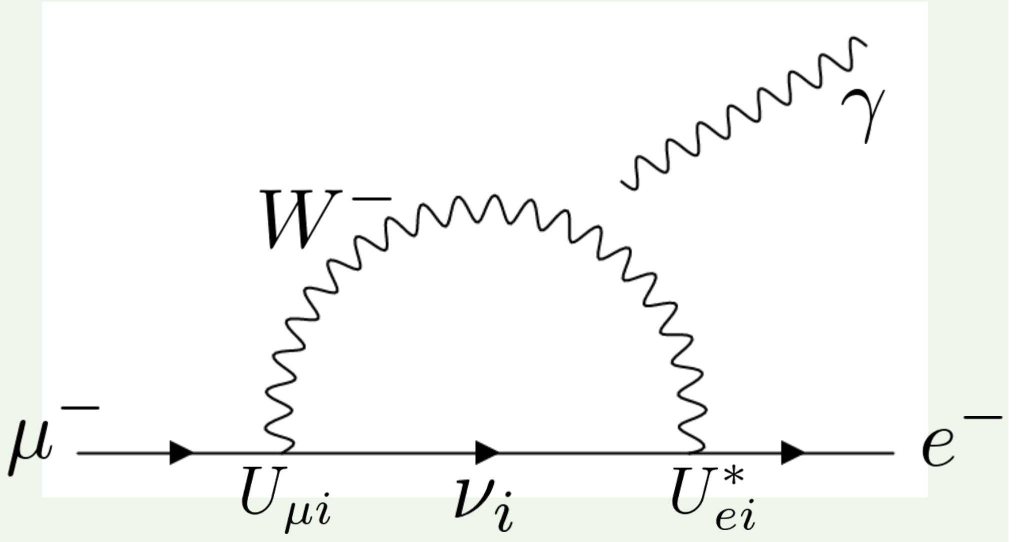
Introduction

Introduction

Charged Lepton Flavor Violation (cLFV)

In the Standard Model (SM)

Charged lepton flavor violating (cLFV) processes occur through neutrino oscillation



Theoretical prediction ：

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i} - m^2_{\nu_1}}{M_W^2}\right|^2 < 10^{-54}$$

Li ('77), Petcov ('77), Sandra ('77), Lee ('77)

Huge gap

Experimental bound ：

$$\mathrm{BR}(\mu^- \to e^-\gamma) < 4.2 \times 10^{-13}$$

MEG Collaboration (2016)

It is impossible to detect cLFV process

Introduction

Charged Lepton Flavor Violation (cLFV)

Beyond the SM

Supersymmetric model

Extra bosons

- Leptophilic scalar
- Extra gauge boson (ex: $U(1)_{L_\mu - L_\tau}$)
- Axion-like particle
- Dark Photon w/ dipole LFV coupling

⋮

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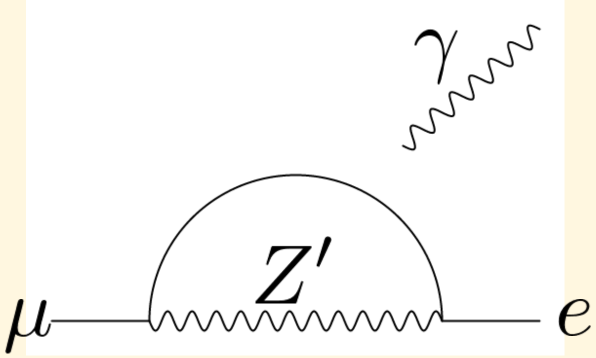


Because of no suppression from GIM mechanism, branching ratios of cLFV processes are not suppressed

Introduction

Charged Lepton Flavor Violation (cLFV)

Beyond the SM

Supersymmetric model

Extra bosons

We focus on light bosons

・・・

⇒ New physics makes cLFV processes observable

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

Introduction

Constraints on cLFV

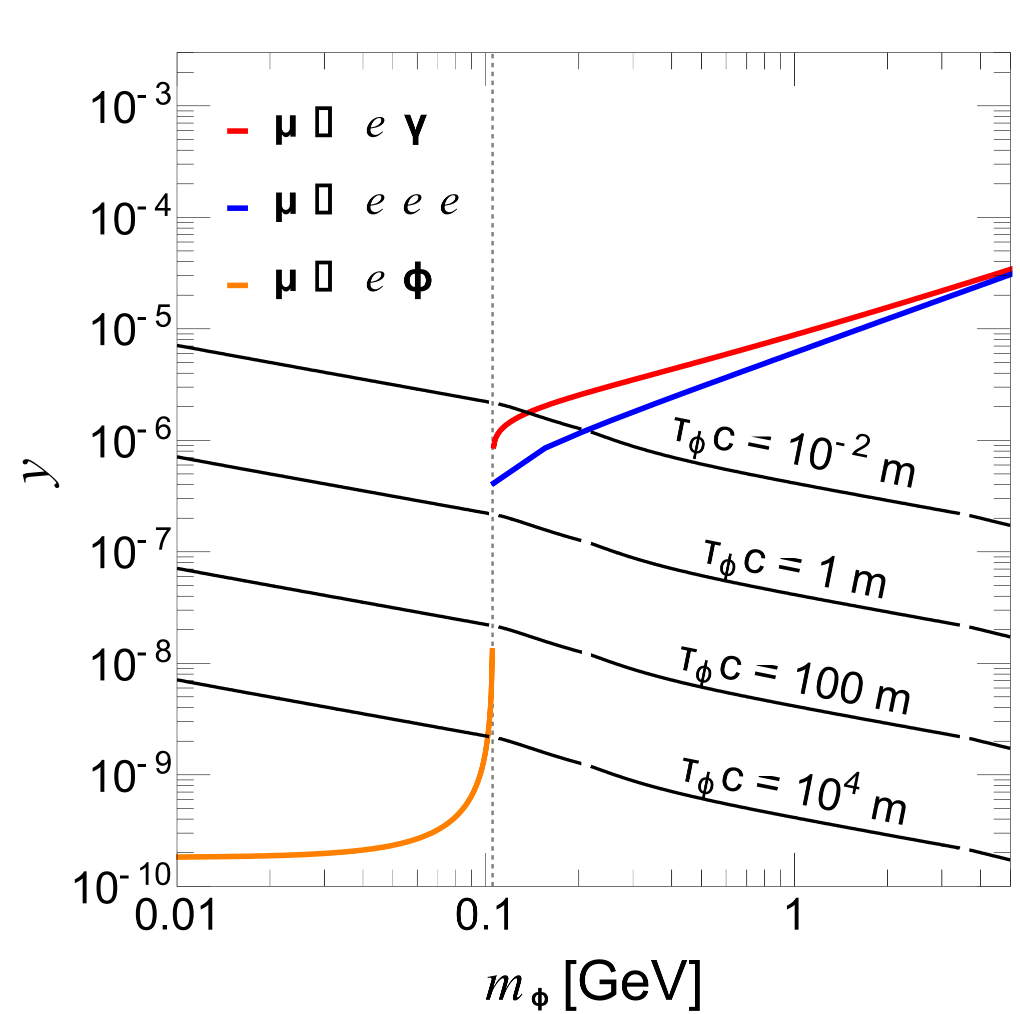
Ex) Leptophilic scalar model

$$\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} y\bar{\ell}_L \phi \ell_R + y\bar{\mu}_L \phi e_R + y\bar{e}_L \phi \mu_R$$

In light-mass & small-coupling region
($m_\phi \sim 0.01 - 1$ GeV & $y_e \sim 10^{-8} - 10^{-5}$)

1, CLFV coupling can be as large as CLFC one

2, New particles with CLFV coupling are long-lived



Introduction

Constraints on cLFV

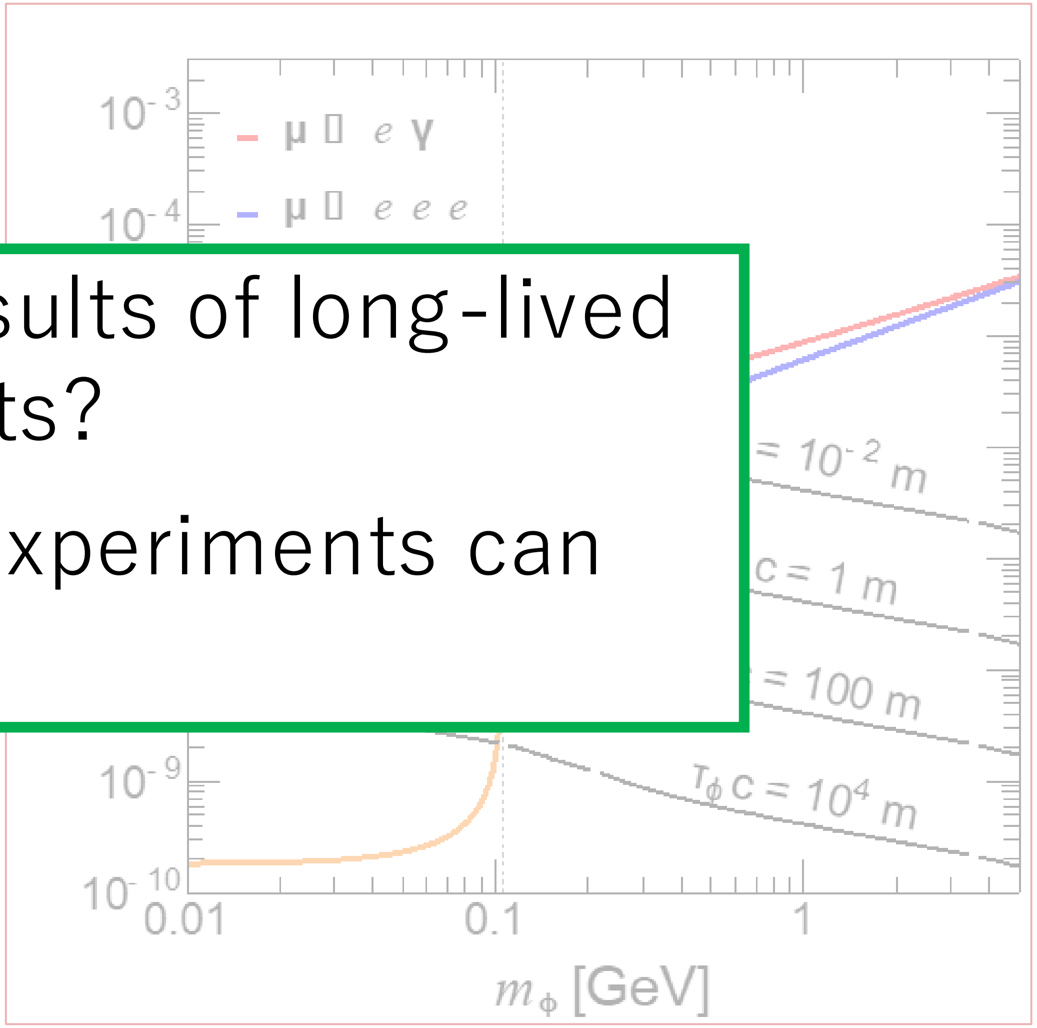
Ex) Leptophilic scalar model

$$\mathcal{L} \supset \sum y\bar{\ell}_L \phi \ell_R + y\bar{\mu}_L \phi e_R + y\bar{e}_L \phi \mu_R$$

In light
(m_ϕ~0

1, CL
CLFC one

2, New particles with CLFV coupling
are long-lived



- CLFV interactions affect results of long-lived particle search experiments?
- Long-lived particle search experiments can detect CLFV decays ?

Long-lived particle search experiments

LLP Search Experiments

Experiments in past, present, & future

Fixed target

	Place	Year	Beam	Shield length
CHARM	CERN	1979	p, 400GeV	480m
ν-Cal I	Serpkhov	1989	p, 68.6GeV	64m
E137	SLAC	1988	e^-, 20GeV	179m
NA64e$^\pm/\mu^-$	CERN	2016-	100GeV e^-/ 40-100GeV e^+ 160GeV μ^-	-
SHiP	CERN	2033	p, 400GeV	50m
ILC beam dump	Iwate	?	e^-/ e^+, 125GeV	70m

Beam-beam

	Place	Year	Beam $\sqrt{s}$	Distance
FASER	ATLAS	2022-	p, 13.6TeV	480m
FASER2	ATLAS	HL-LHC	p, 14TeV	650m

LLP Search Experiments

Experiments in past, present, & future

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Thick-target experiment

- Target is longer than radiation length
- Long shield behind target
- Decay volume & detector behind shield

LLP Search Experiments

Thick target experiment

High-energy beam is dumped into dense target and produces secondly particles

➡ High intensity

- Production of large number of new particles

Detector is placed behind long shield

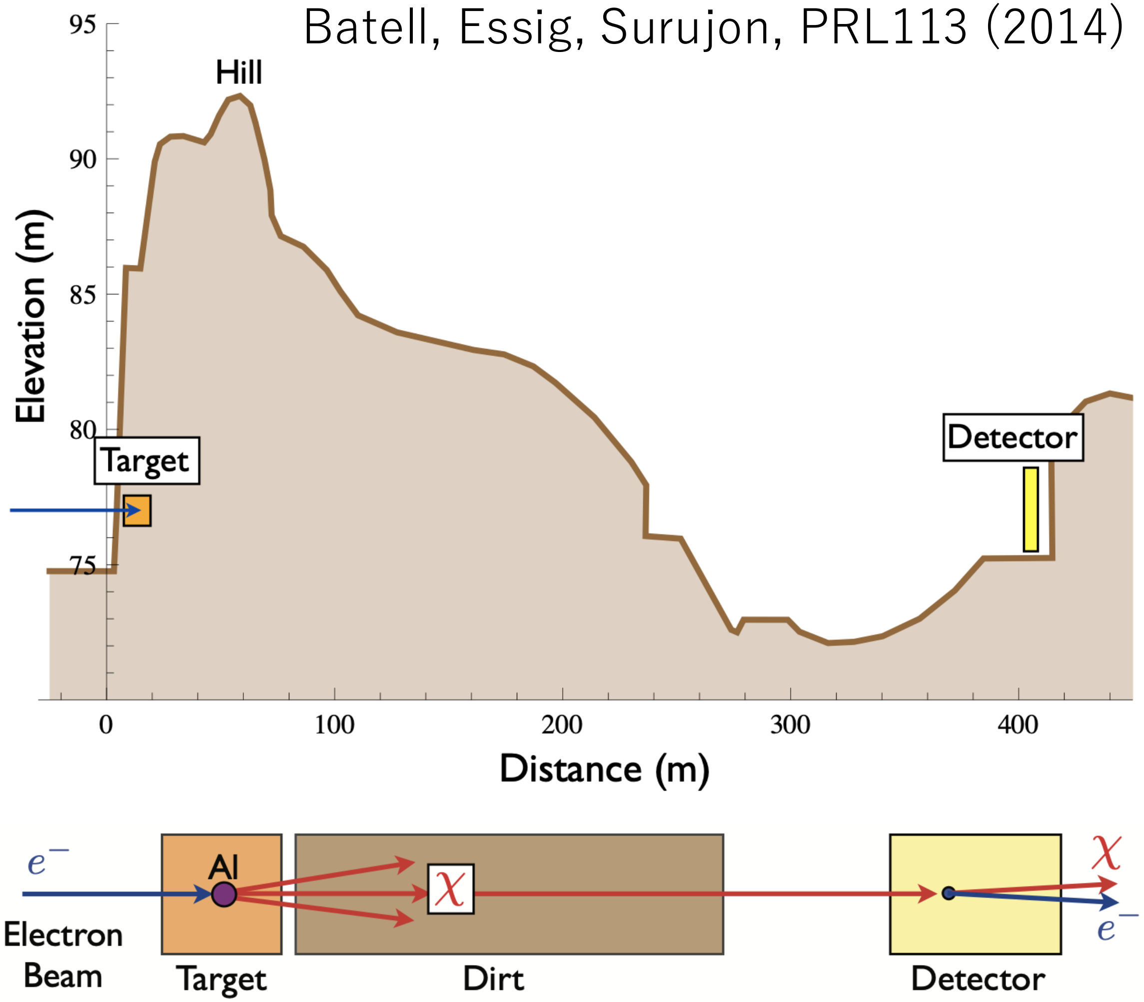
➡ Low background

- Most of background events are removed by shield

Sensitive to small coupling region

- New particles should be long-lived to reach detector

Batell, Essig, Surujon, PRL113 (2014)



LLP Search Experiments

Experiments in past, present, & future

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ILC beam dump	Iwate ?	?	e^-/ e^+, 125GeV	70m

Thin-target experiment

- Target is shorter than radiation length
- Target = detector in some cases

Not discuss in this talk

LLP Search Experiments

Thin target experiment

High-energy beam is dumped into dense target ~~and produces secondly particles~~

→ High intensity

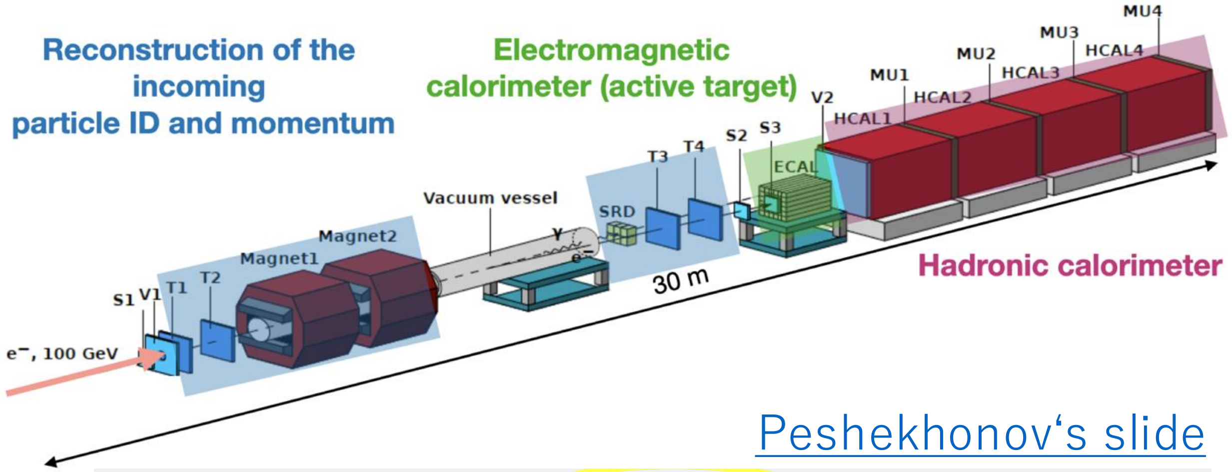
- Production of large number of new particles

No multiple reaction and measurement of visible final state

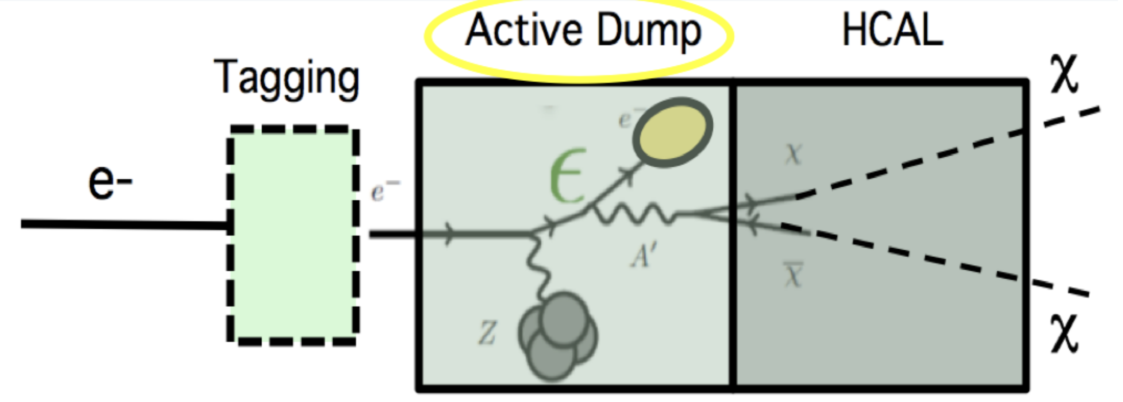
→ High sensitivity

- No necessity to measure produced BSM particles

P. Crivelli, 2301.09905 [hep-ex]



Peshekhonov's slide



LLP Search Experiments

Experiments in past, present, & future

Beam-beam		Place	Year	Beam $\sqrt{s}$	Distance
	FASER	ATLAS	2022-	p, 13.6TeV	480m
	FASER2	ATLAS	HL-LHC	p, 14TeV	650m

Beam-beam collision experiment

- Target is high-energy beam

LLP Search Experiments

Beam-beam collision experiment

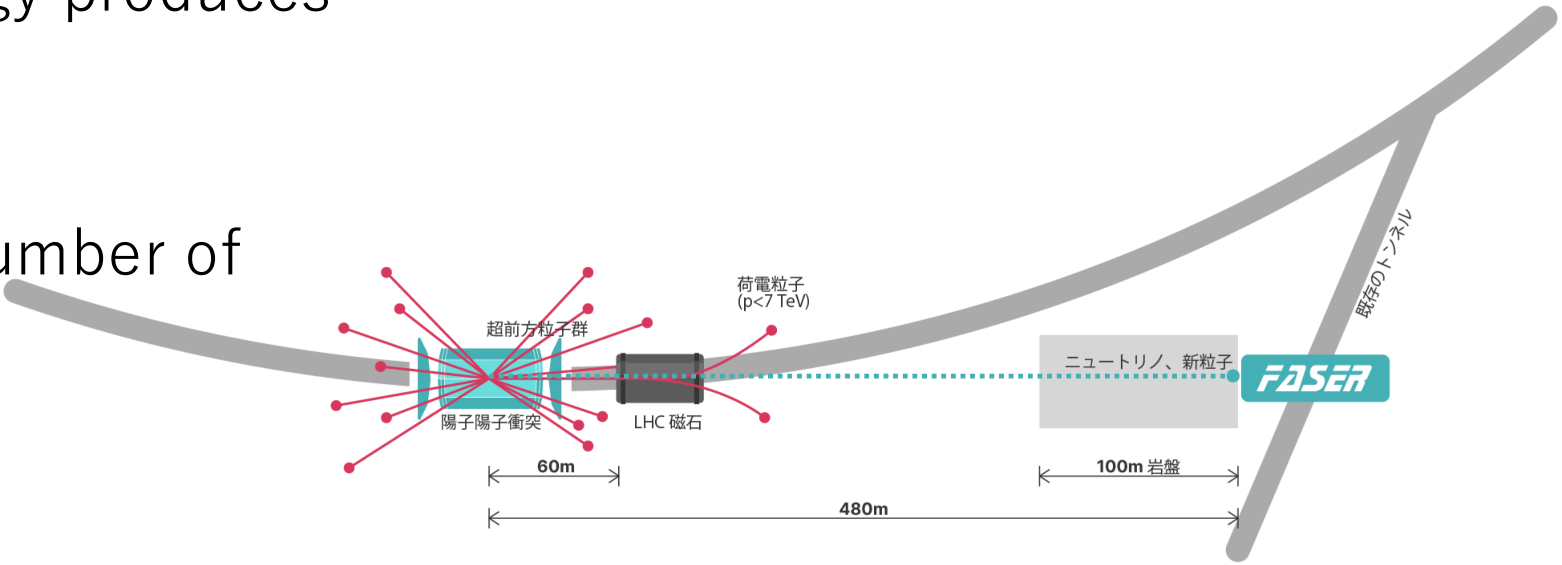
Collision with large COM energy produces huge number of hadrons

High intensity
- Production of large number of new particles

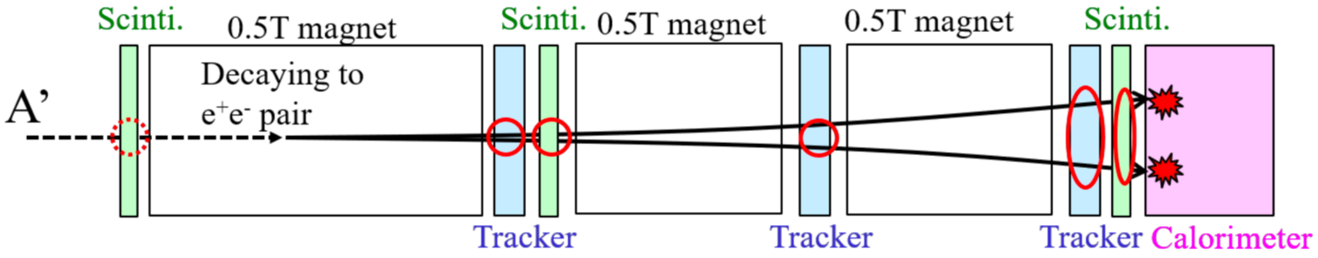
Large COM energy reactions

Sensitivity to heavy BSM
- Heavy BSM particles can be produced in comparison with fixed target experiments

FASER Japan web page



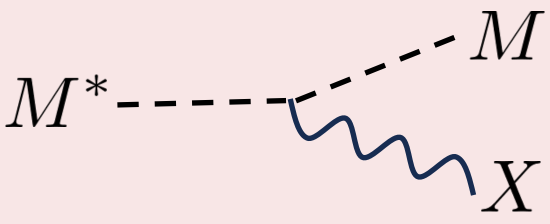
Takubo san's slide



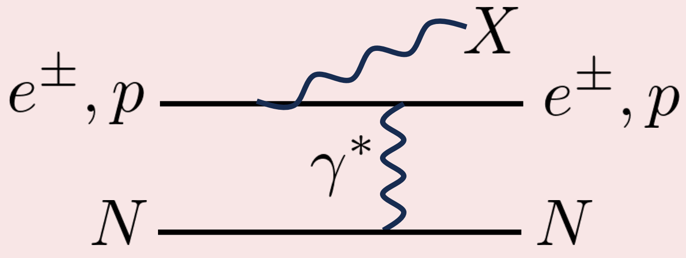
LLP Search Experiments

LLP production process

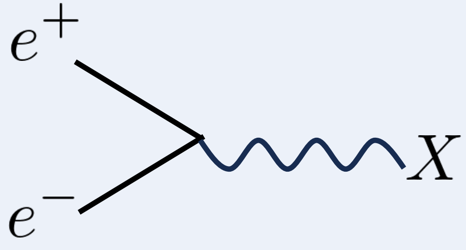
- Meson decay



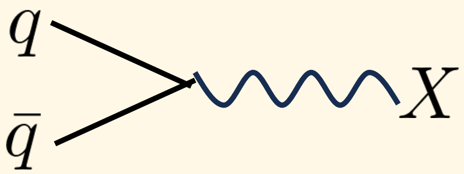
- Bremsstrahlung



- Pair annihilation



- Drell-Yan process



Proton beam

meson decay
bremsstrahlung
Drell-Yan

Lepton beam

bremsstrahlung
pair-annihilation
(meson decay)

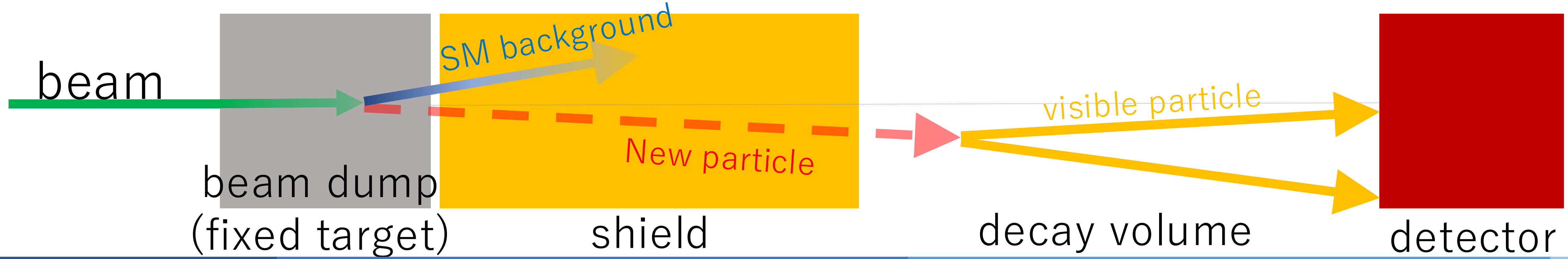
Significant production process depends on beam

LLP Search Experiments

Strategy of LLP search

Thick target experiment

1, LLPs are produced and fly in forward direction
2, LLPs pass through long shied
3, LLPs decay into SM visible particles in decay volume
4, Visible particles are detected at detectors



LLP Search Experiments

Strategy of LLP search

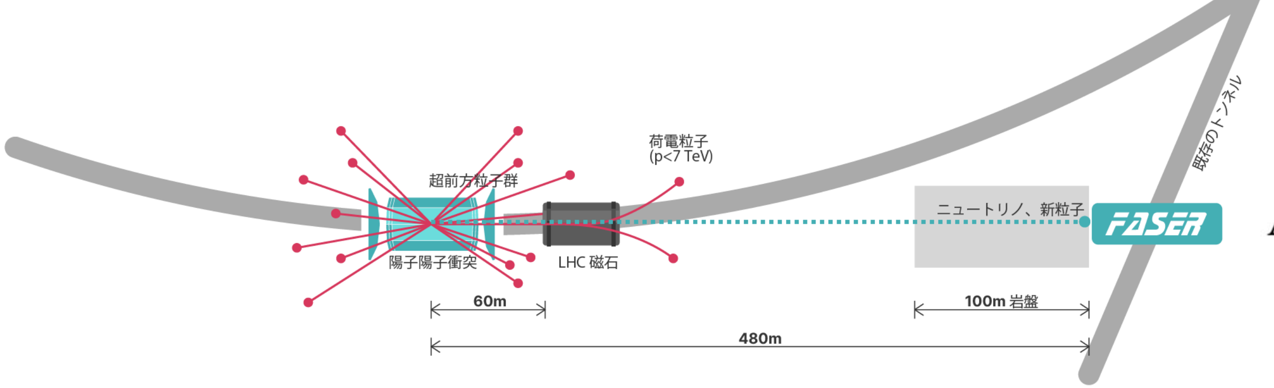
Beam-beam collision experiment (FASER)

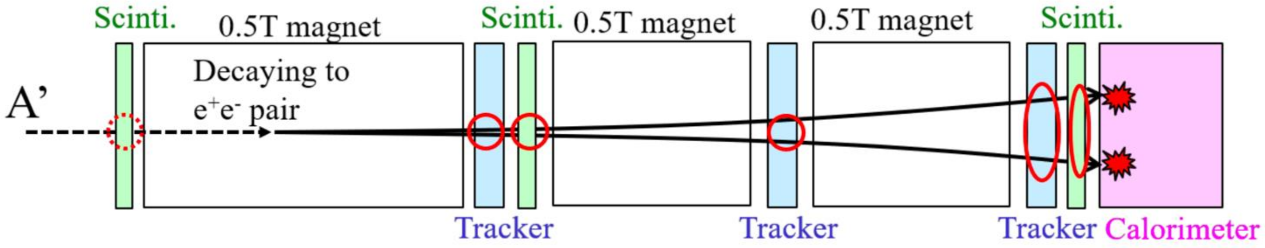
1, LLPs are produced and fly in forward direction

2, LLPs pass through long shied

3, LLPs decay into SM visible particles in decay volume

4, Visible particles are detected at detectors





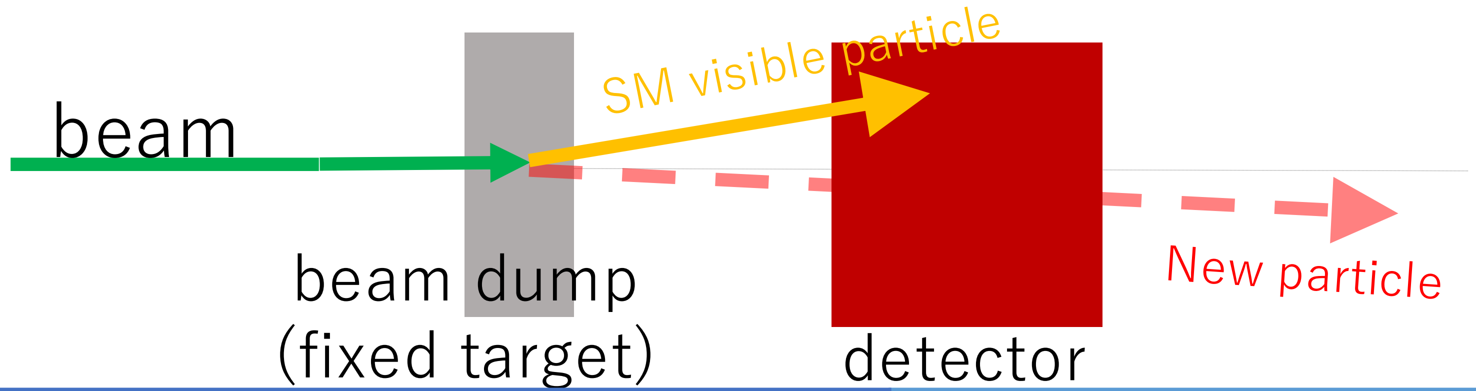
Strategy of LLP search

Thin target experiment

1, LLPs are produced and take away energy & momentum

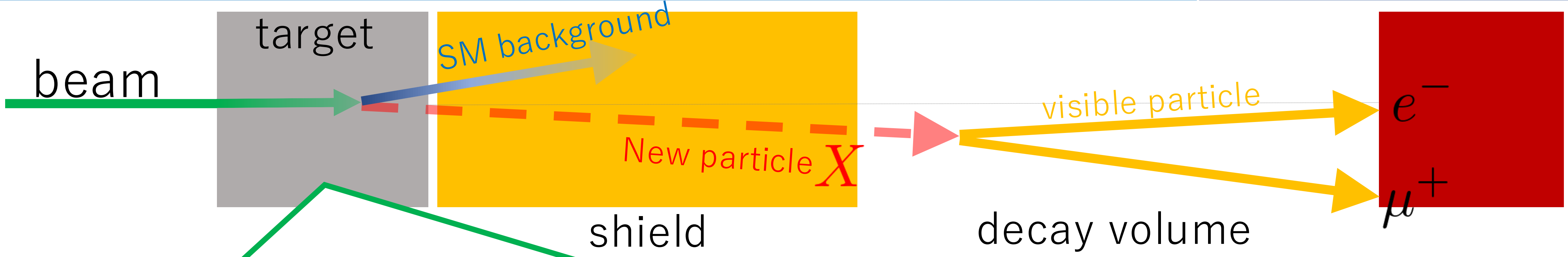
2, Energies & momenta of SM visible final-state particles are measured

3, LLPs are detected as missing energy & momentum



LLP Search Experiments

LLP production with LFV coupling

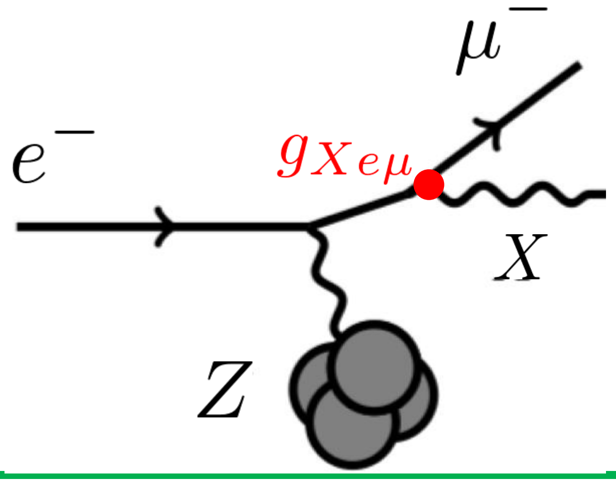


Lagrangian

Coupling with $\boldsymbol{e}$ & $\boldsymbol{\mu}$

$$\mathcal{L} \supset g_{Xe\mu} X_\rho \bar{e} \gamma^\rho \mu$$

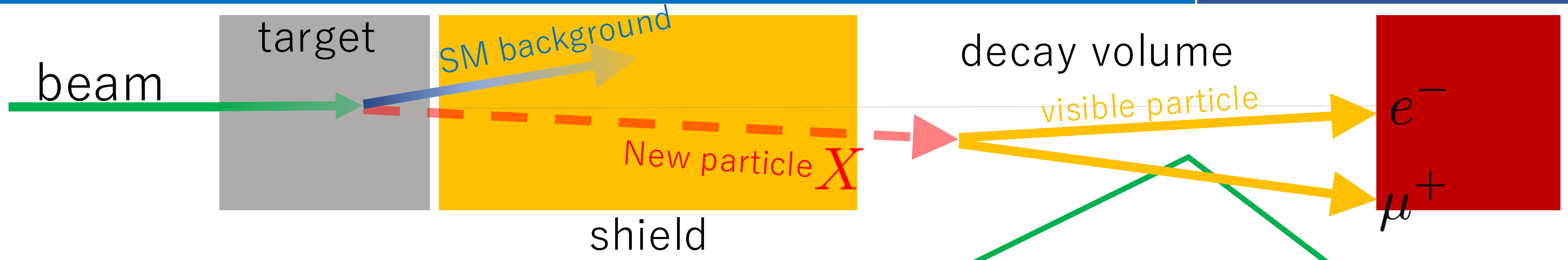
Bremsstrahlung production



Possibly LFV interactions contribute to bremsstrahlung production

LLP Search Experiments

LLP detection with LFV coupling

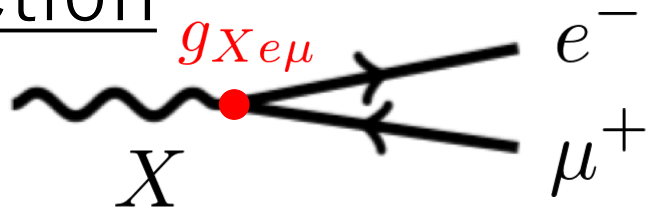


Lagrangian

Coupling with e & μ

$$\mathcal{L} \supset g_{Xe\mu} X_\rho \bar{e} \gamma^\rho \mu$$

Detection

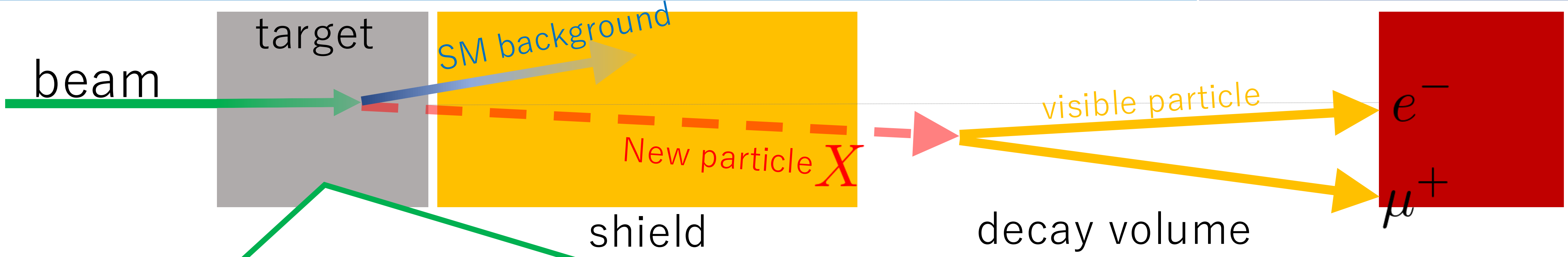


Decay into $\mu^+ e^-$ pair → Detection

LFV decay can be searched by LLP search experiment

LLP Search Experiments

LLP production & detection with LFV coupling

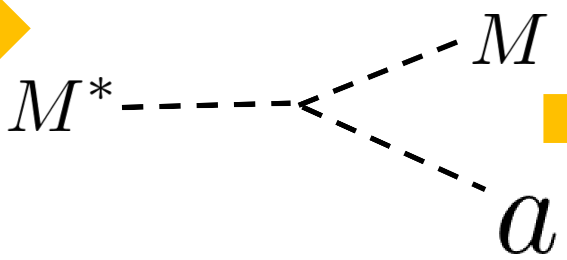


Lagrangian

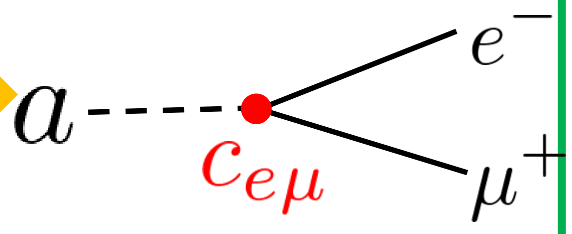
Coupling with $f\bar{f}$ & $e\mu$

$$\mathcal{L} \supset \frac{\partial_\rho a}{\Lambda}\left\{\sum_f c_{ff}\bar{f}\gamma^\rho\gamma_5 f + c_{e\mu}\bar{e}\gamma^\rho\gamma_5\mu + c_{e\mu}^*\bar{\mu}\gamma^\rho\gamma_5 e\right\}$$

Meson decay



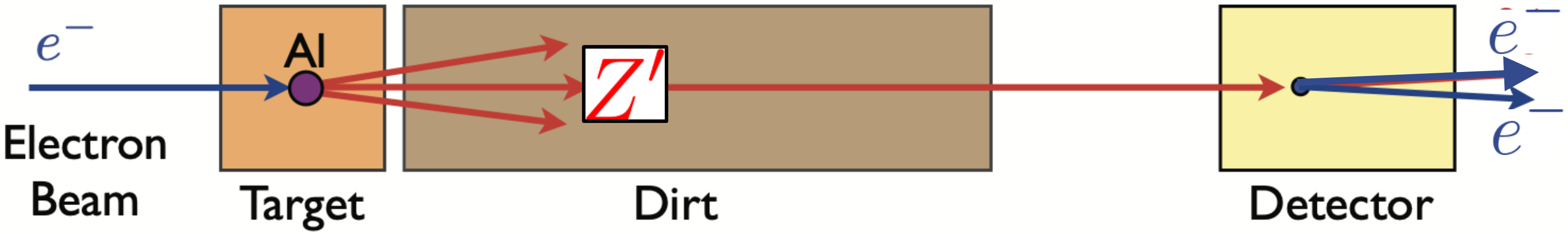
Detection



LFV decay can be searched by LLP search experiment

LLP Search Experiments

Number of signal events



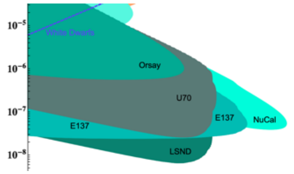
(# of events) = (# of produced Z') × (Acceptance) × (Branching ratio)

$$= N_e \frac{N_{\rm avo} X_0}{A} \sum_{\ell=e,\mu} \int_{m_X}^{E_0 - m_\ell} dE_X \int_{E_X+m_\ell}^{E_0} dE_e \int_0^{T_{\rm sh}} dt$$

$$\times \left[I_e(E_0, E_e, t) \frac{1}{E_e} \left. \frac{d\sigma_{\rm brems}}{dx} \right|_{x=\frac{E_X}{E_e}} e^{-L_{\rm sh}/L_X} \left(1 - e^{-L_{\rm dec}/L_X}\right) \right] {\rm Br}(X \to e\mu)$$

Coupling to SM ⟶ # of production ⤴ Acceptance (lifetime)

# of signals is defined by competition of two effects
(belt-shaped sensitivity region)



LFV search @ e^- beam dump experiment

Based on
"Electron beam dump constraints on light bosons with lepton flavor violating coupling", T. Araki **K. Asai**, and T. Shimomura, JHEP 11 (2021) 082

LFV search @ e^--BD Exp.

E137 experiment

Experiment parameters

Beam : 20 GeV e^- beam
$\cong 2 \times 10^{20}$ EOT

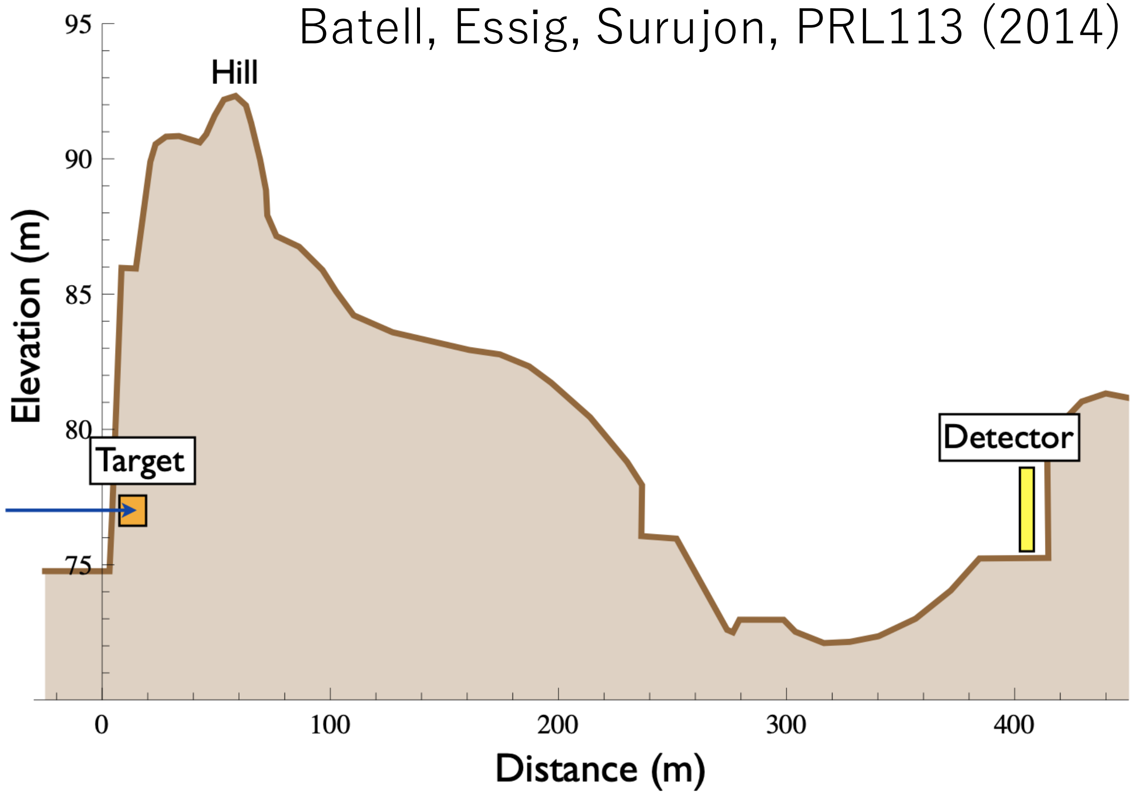
Target : Aluminum beam dump

Shielding : 179m ground (hill)

Decay volume : 204m open air

Detector : EM calorimeter + MWPC

Batell, Essig, Surujon, PRL113 (2014)



LFV search @ e^--BD Exp.

E137 experiment with LFV coupling

Unfortunately, E137 experiment can detect only electron

We have explored constraints on LFV couplings of new particles by E137 experiment

Result

Production through LFV coupling

For $E_\phi = E_e \ (x=1)$,

LFC

$$\frac{d\sigma^{\rm LFC}_{\rm brems}}{dx} \sim \frac{\alpha^2 y_{ee}^2}{2\pi}\xi\beta_\phi \times \boxed{\frac{1}{2m_e^2}}$$

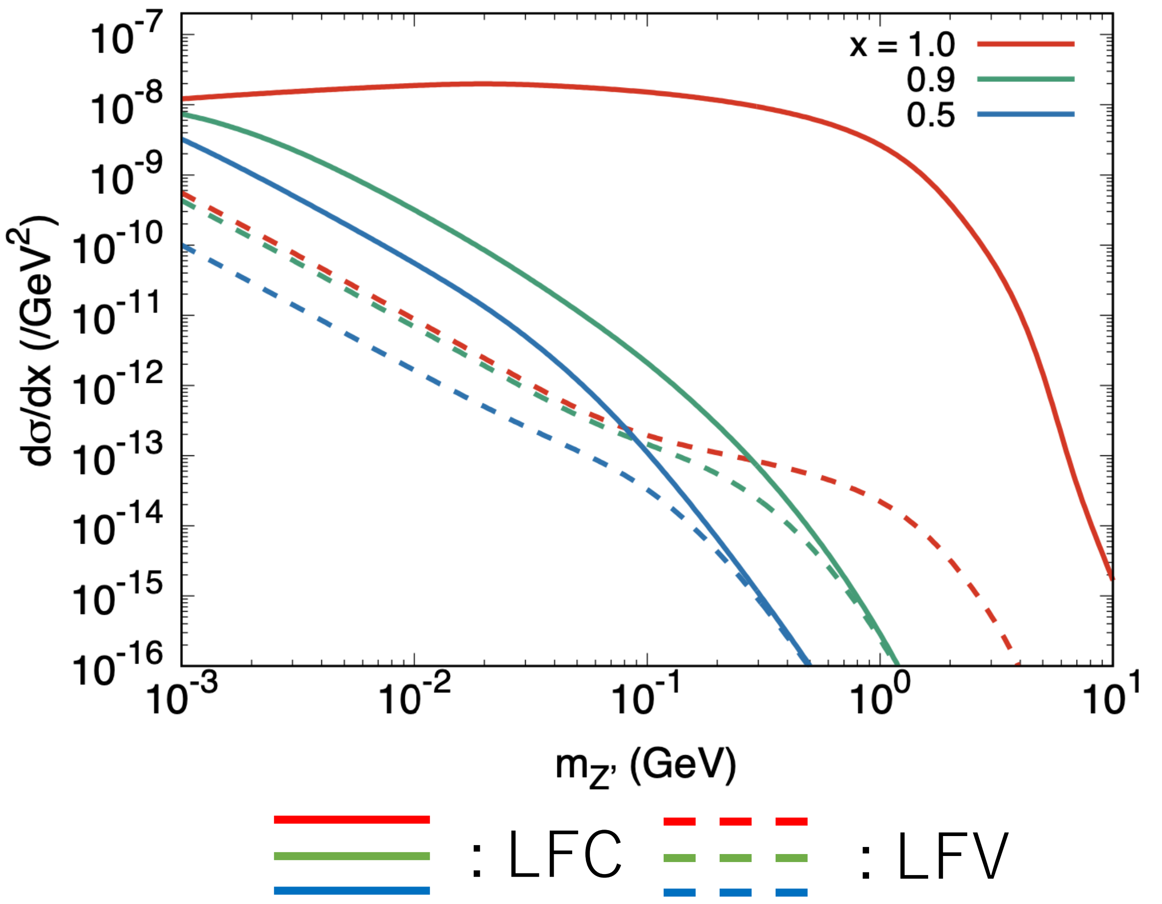
$\gg$

LFV

$$\frac{d\sigma^{\rm LFV}_{\rm brems}}{dx} \sim \frac{\alpha^2 y_{e\mu}^2}{2\pi}\xi\beta_\phi \times \boxed{\frac{\theta_{\rm max}^2 E_e^2}{2m_\mu^4}}$$

ϕ production through LFV coupling is negligible

Production cross section



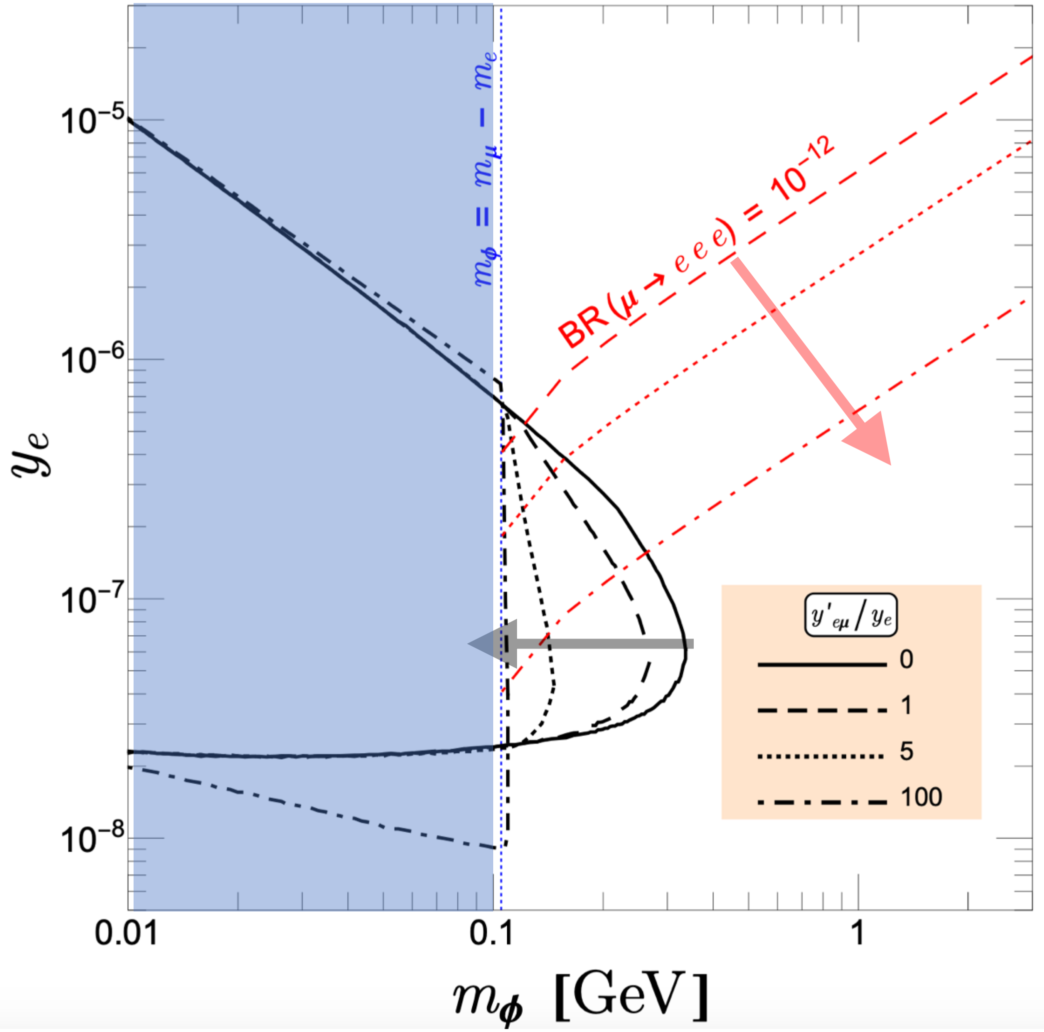
LFV search @ e^--BD Exp.

Result

Scalar-type int.

$$\mathcal{L}_{\rm scalar} = \sum_{\ell=e,\mu,\tau} y_\ell \overline{\ell_L}\phi \ell_R + y'_{e\mu}\overline{e_L}\phi\mu_R + y'_{\mu e}\overline{\mu_L}\phi e_R + h.c.$$

- Larger LFV/LFC ratio
  - Larger $\mu^+ e^-$ coupling
  - Shorter decay length for $m_\phi > m_e + m_\mu$ & smaller ${\rm BR}(\phi \to e^+e^-)$
  - Sensitivity region is covered with constraints from $\mu \to e\phi$



LFV search @ e^--BD Exp.

Result

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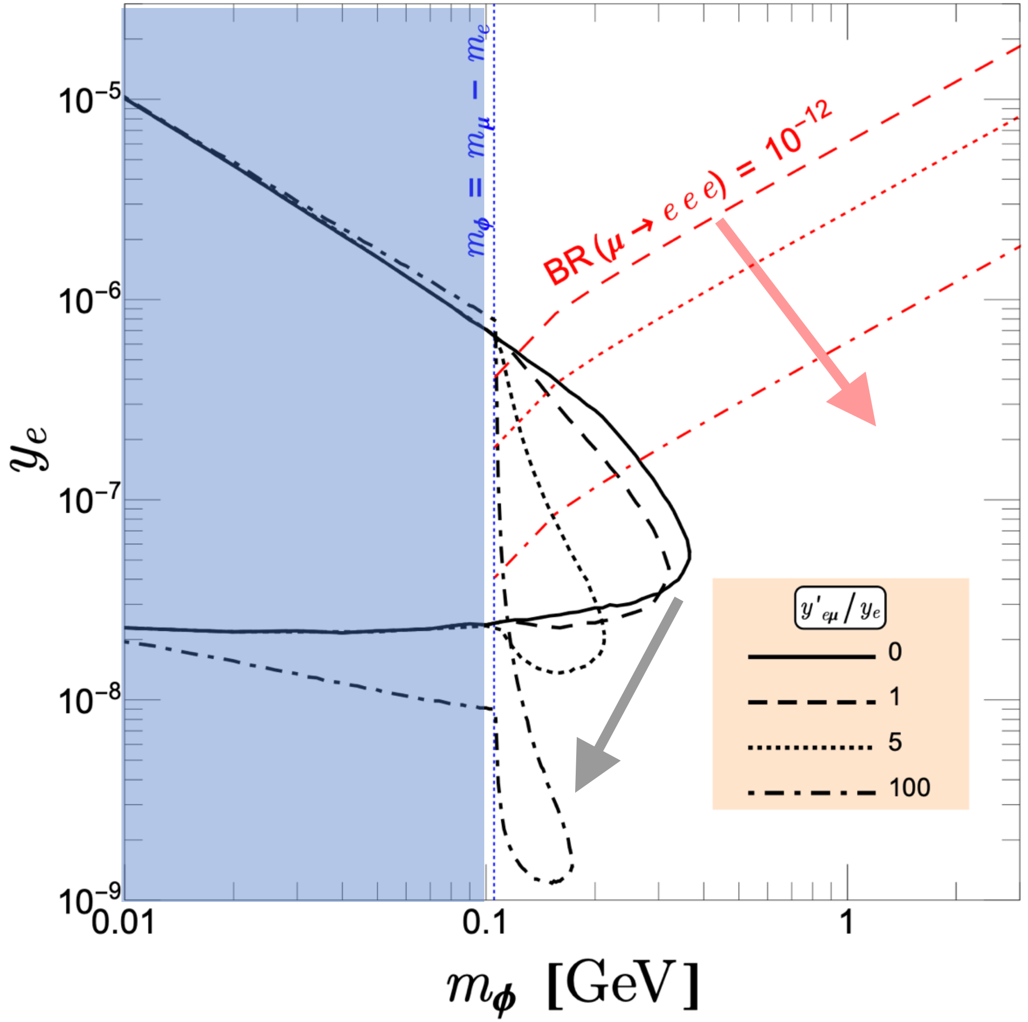
If E137 experiment can detect muon,

signal : $\phi \to ee$ ➡ $\phi \to ee,\ \mu\mu,\ e\mu$

e^- beam dump with muon detector can search unexplored LFV coupling and perhaps detect LFV decay



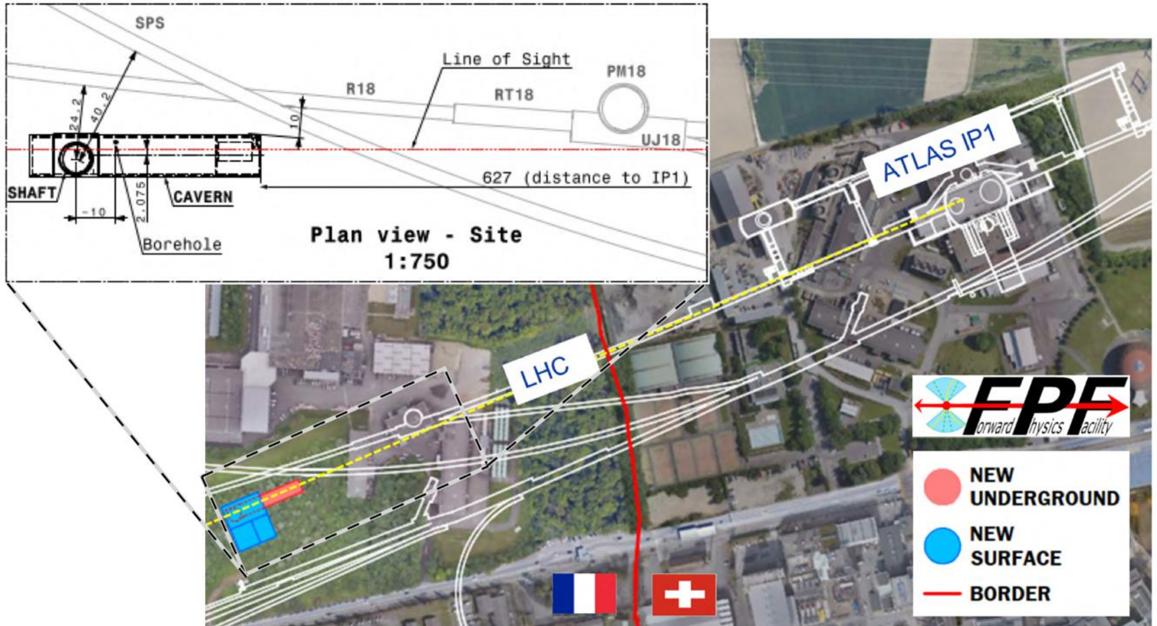
LFV search @ FASER2

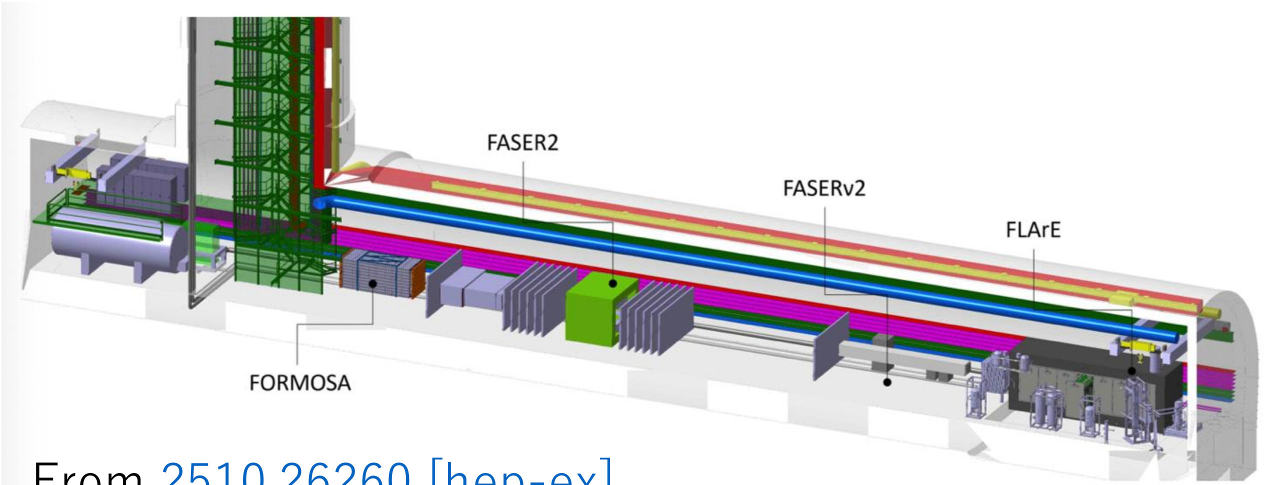
Based on
"Search for lepton flavor violating decay at FASER",
T. Araki **K. Asai**, H. Otono, T. Shimomura, and Y. Takubo, JHEP 01 (2023) 145

LFV search @ BBC Exp.

FASER2 detector

- Upgraded detector of FASER
- Detector is placed at 650m downstream from ATLAS interaction point
- Data taking will start at the beginning of Run5 in 2036





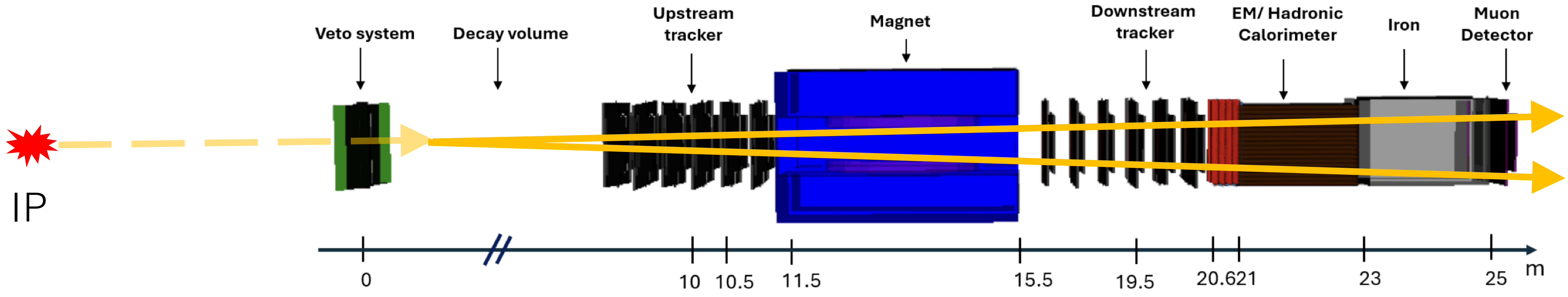
From 2510.26260 [hep-ex]

LFV search @ BBC Exp.

Detector design of FASER2

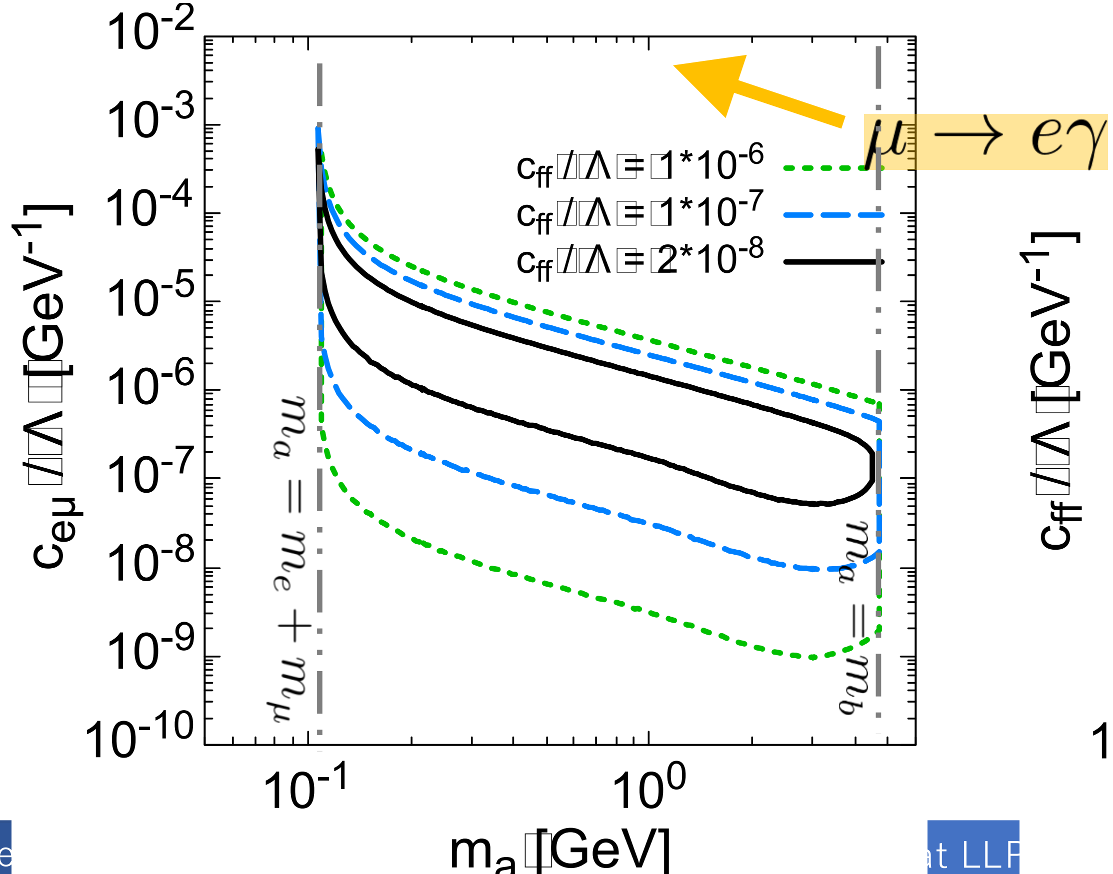
- Decay volume : $2.6 \times 1.0 \times 10\ \mathrm{m}^3$ rectangular parallelepiped
- Magnet : 2 Tm integrated magnetic field
- Upstream & downstream trackers, EM/hadronic calorimeter, and muon detector

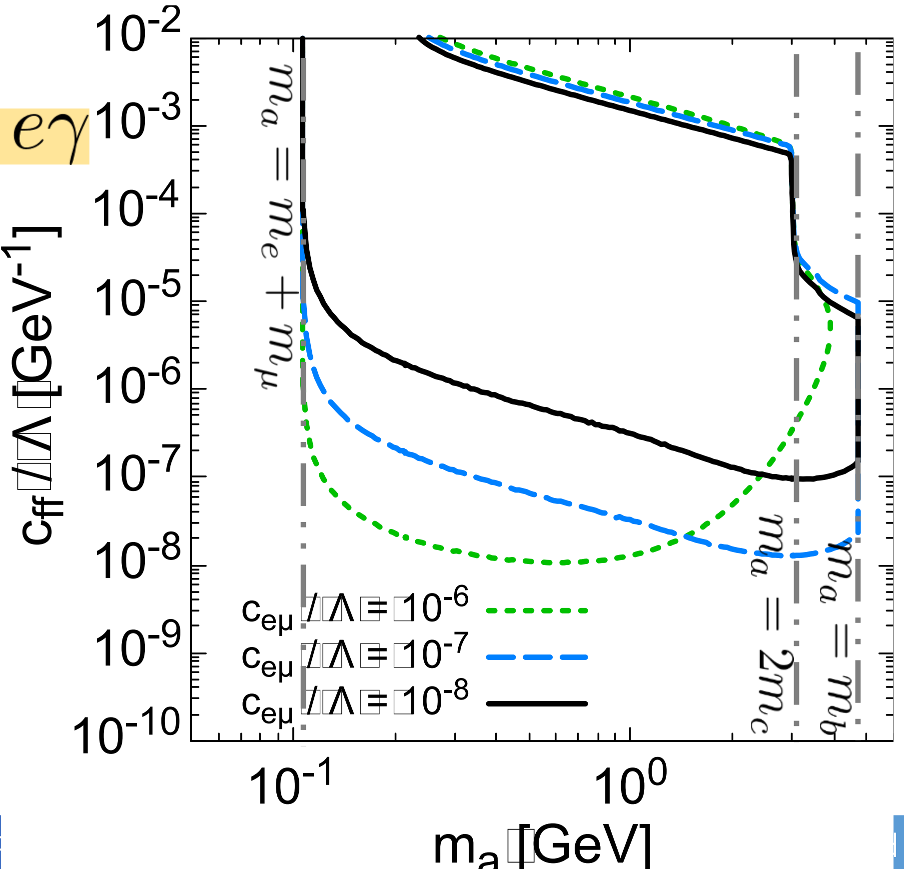
From 2510.26260 [hep-ex]



Pseudoscalar-type int.

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





Excluded by E137

95% C.L. sensitivity contour @ FASER2

Summary

○ Long-lived particle search experiments have sensitivity to light new physics interacting very weakly

○ In such small coupling regions, light BSM particle is long-lived and can escape from current LFV constraints

○ We considered several benchmark LFV interactions and studied sensitivity to LFV interaction ($X \to e\mu$ decay) by LLP search experiment

Thank you for your attention !