Search for Lepton Flavor Violating Decay at FASER

Kento Asai (ICRR, Univ. of Tokyo)

Flavor Physics Workshop 2022

Nov. 9, 2022 @ New Hakkeien, Izunokuni

Based on
T. Araki, **KA**, H. Otono, T. Shimomura, Y. Takubo, arXiv : [2210.12730 [hep-ph]]

Summary

- FASERは，標準模型粒子との相互作用がとても小さな軽い領域に感度がある

  ➡ 新物理が隠れている可能性がある

- そのような領域ではCLFV相互作用がCLFC相互作用と同程度の大きさでも既存のCLFVの制限を回避しており，FASERで新粒子のCLFV崩壊が見えるかもしれない (CLFV相互作用の探索)

これまでのCLFV探索(荷電レプトンの崩壊, 加速器 …)

➡ CLFV相互作用の大きな領域から徐々に小さな領域へ

FASER & 他の長寿命粒子探索実験

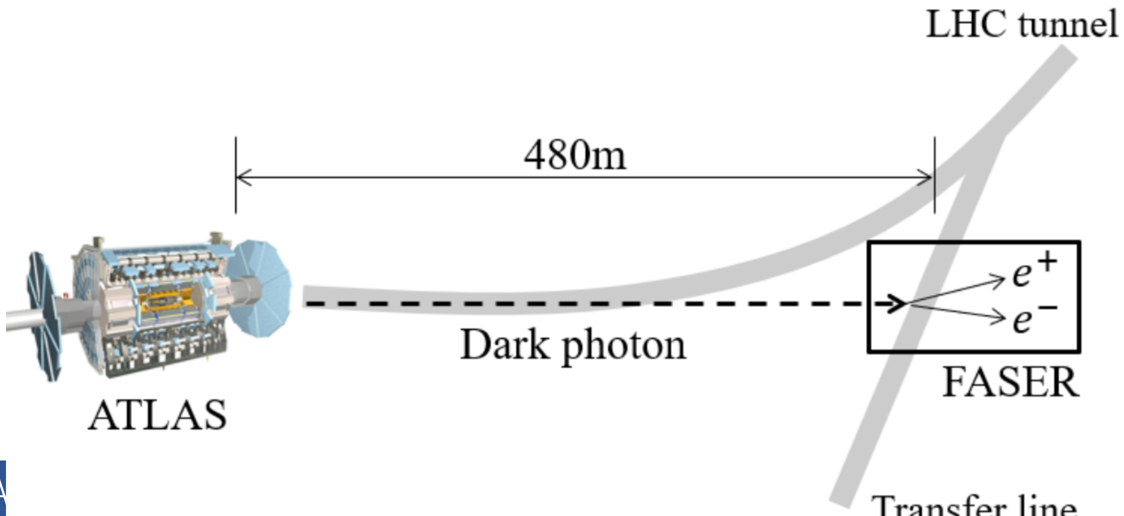
➡ CLFV相互作用の小さな領域をいきなり探索

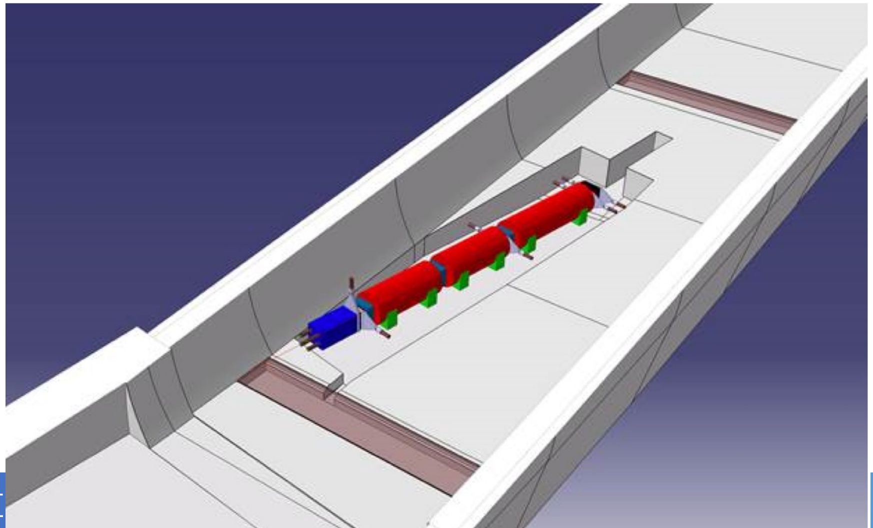
Introduction
- FASER -

FASER

FASER (ForwArd Search ExpeRiment at the LHC)

- Experiment to search for new light particles (dark photon, dark Higgs, ALP, sterile neutrino…), started from April 2022
- Detector is placed at 480m from ATLAS collision point





Introduction - FASER

FASER

Advantage

1) pp-reaction cross section @ LHC is very large in the direction of beam axis

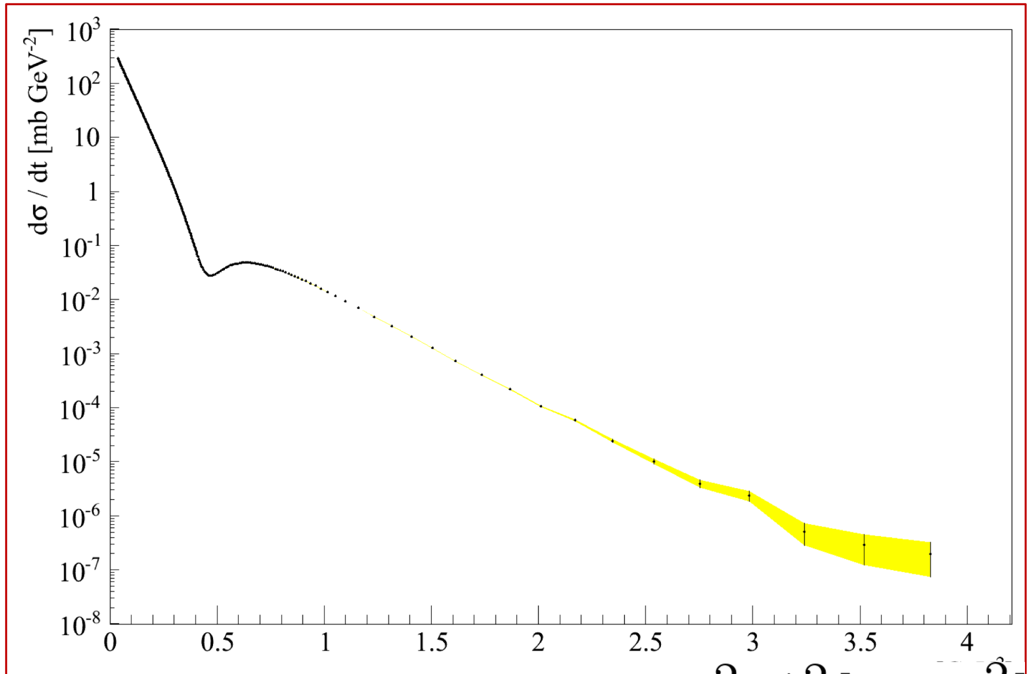
➡ Large production number of BSM particles

2) 480m from ATLAS

→ Long decay width

➡ FASER can search small interaction region

Inelastic scattering cross section of pp collision @ 13TeV LHC



$-t = p^2\theta^{*2}$ [GeV^2]

TOTEM Collaboration, EPJC 79 (2019) 10, 861

Introduction - FASER

FASER

Advantage

3) FASER is placed in far-forward region

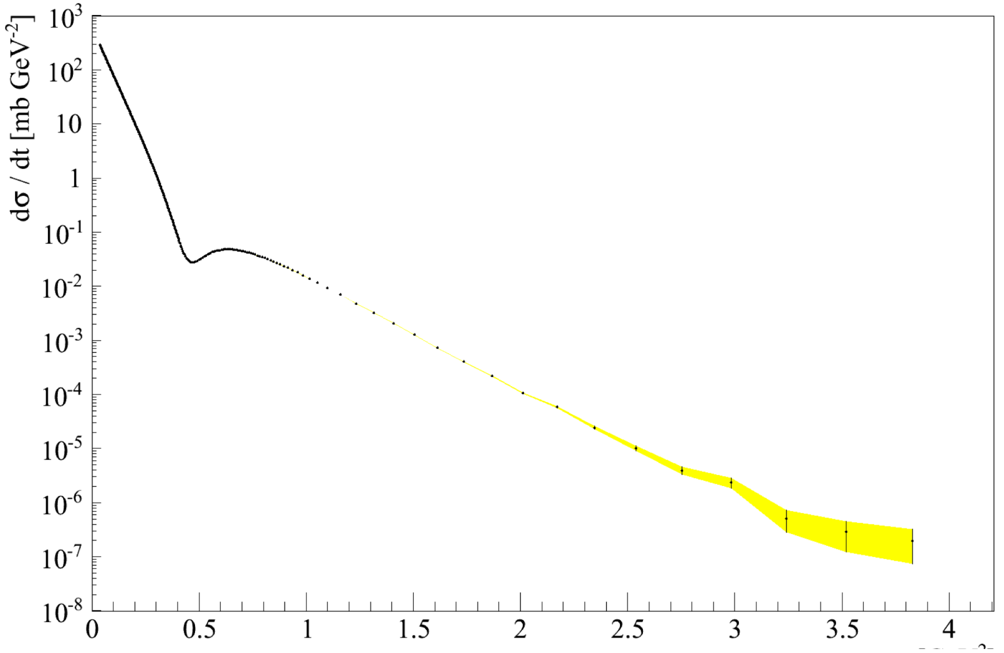
➡ FASER can search light BSM particles

cf.) LHC

New physics searches @ LHC focus on high p_T

➡ LHC can search heavy BSM particles

Inelastic scattering cross section of pp collision @ 13TeV LHC



New physics searches @ LHC focus on high p_T

TOTEM Collaboration, EPJC 79 (2019) 10, 861

Introduction - FASER

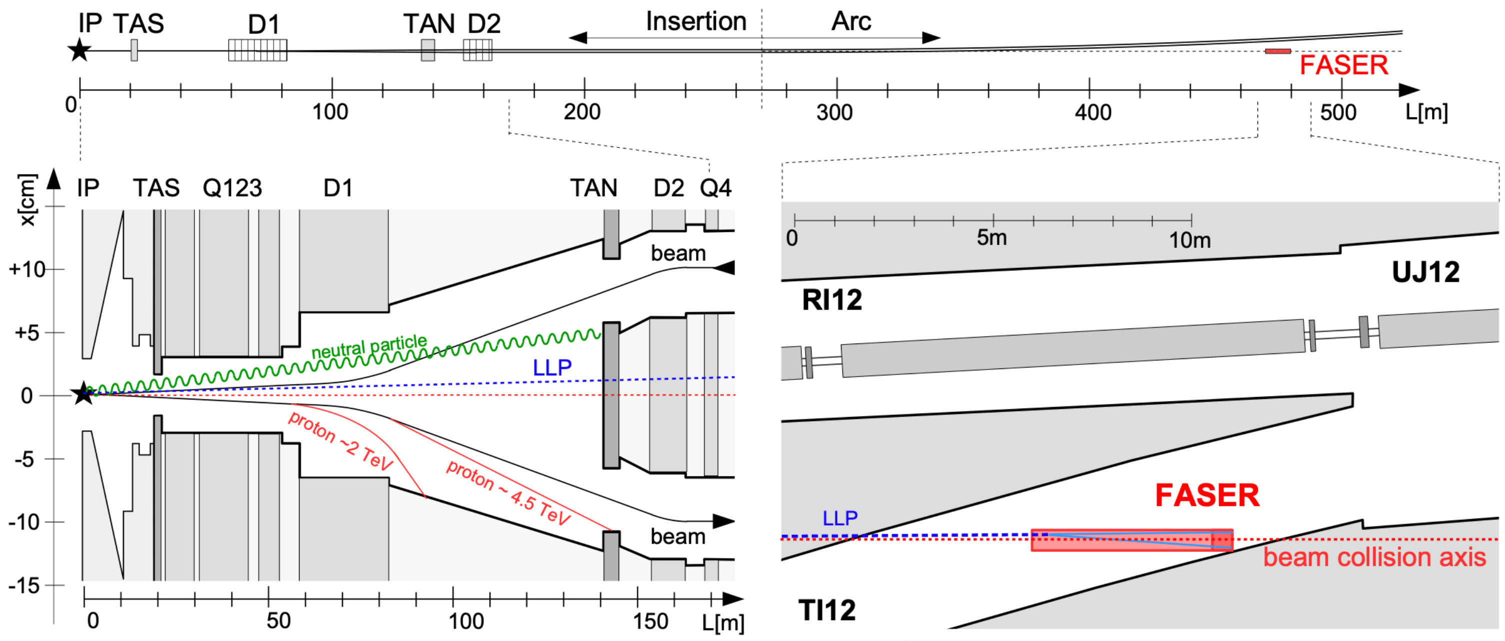
FASER location

FASER detector is situated along the beam collision axis line of sight

Between ATLAS IP and FASER detector, there are LHC materials and natural rock

They eliminate most potential backgrounds

From 1901.04468 [hep-ex]



Introduction - FASER

FASER detector

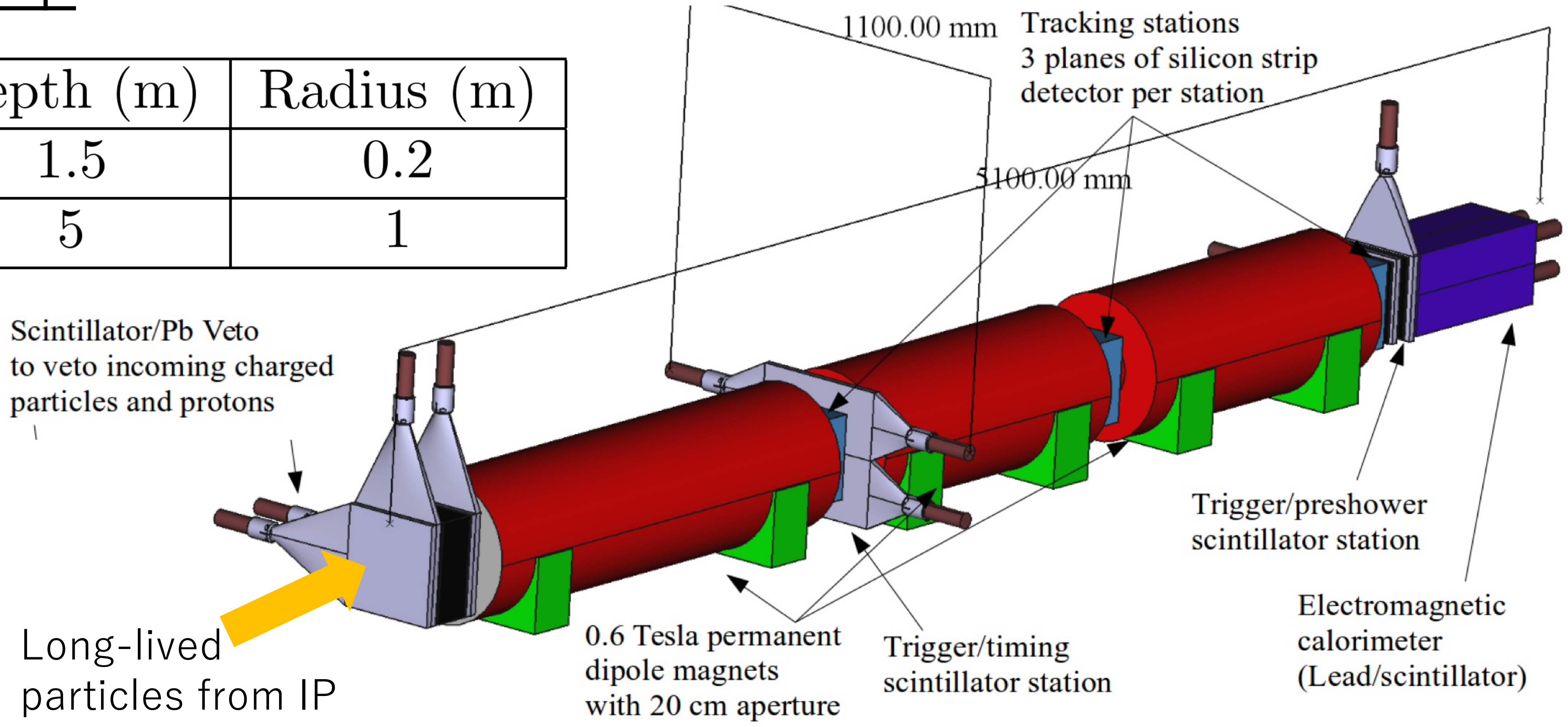
Detector setup

	Depth (m)	Radius (m)
FASER	1.5	0.2
FASER2	5	1

FASER
➡ 150 fb^{-1}
@ LHC Run3

FASER2
➡ 3 ab^{-1}
@ HL-LHC

From 1901.04468 [hep-ex]



Introduction - FASER

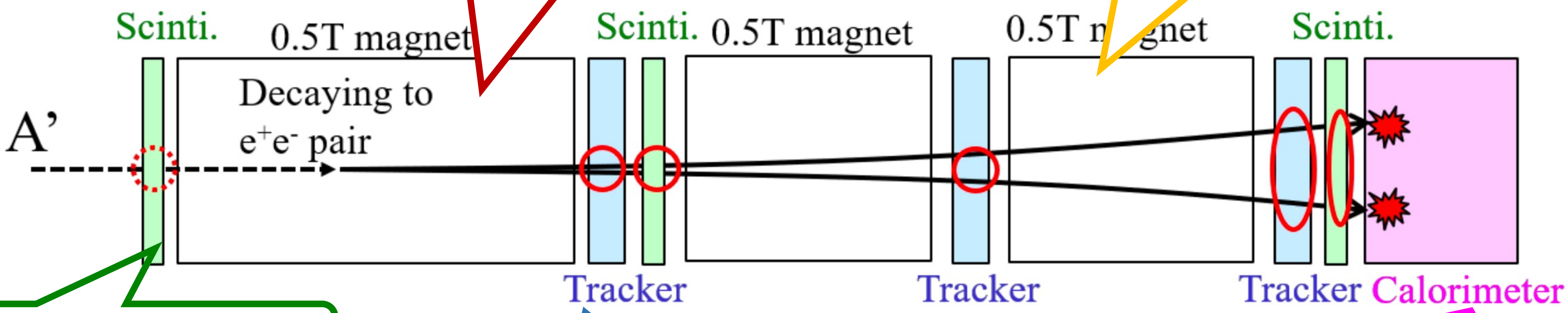
FASER detector

Detector setup

1.5m decay volume

Spectrometer : separating daughter particles by magnets

From Takubo san's slide



Scintillator veto

Calorimeter : measurement of energies of daughter particles

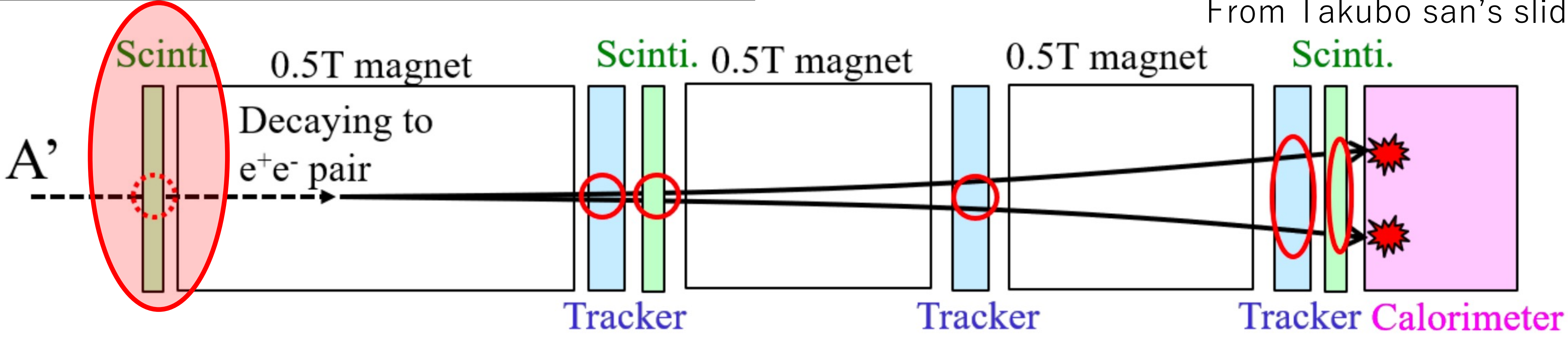
Tracker : Measurement of two oppositely charged particle and their momenta

Introduction - FASER

FASER detector

Benchmark signal (dark photon)

From Takubo san's slide



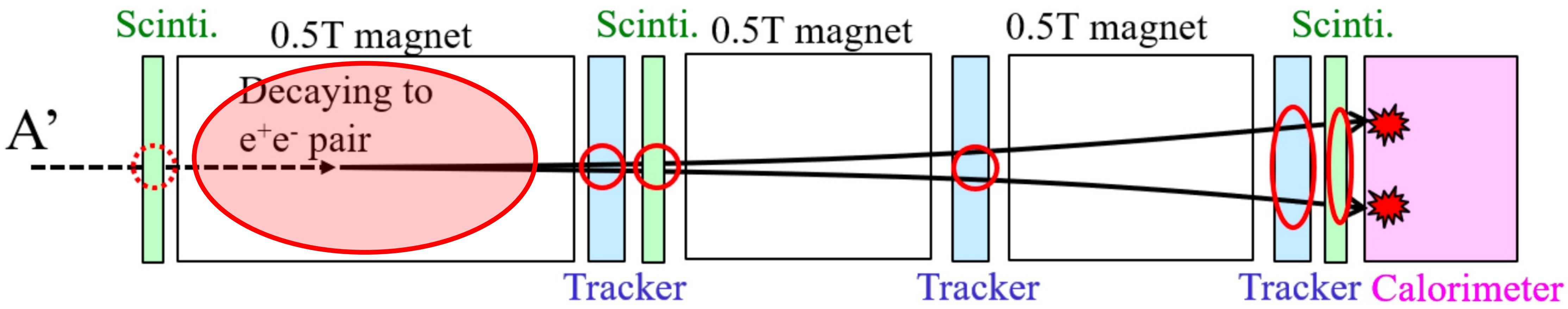
1, No signal in veto scintillator

Introduction - FASER

FASER detector

Benchmark signal (dark photon)

From Takubo san's slide



1, No signal in veto scintillator
2, Decay into e^+ and e^-

Introduction - FASER

FASER detector

Benchmark signal (dark photon)

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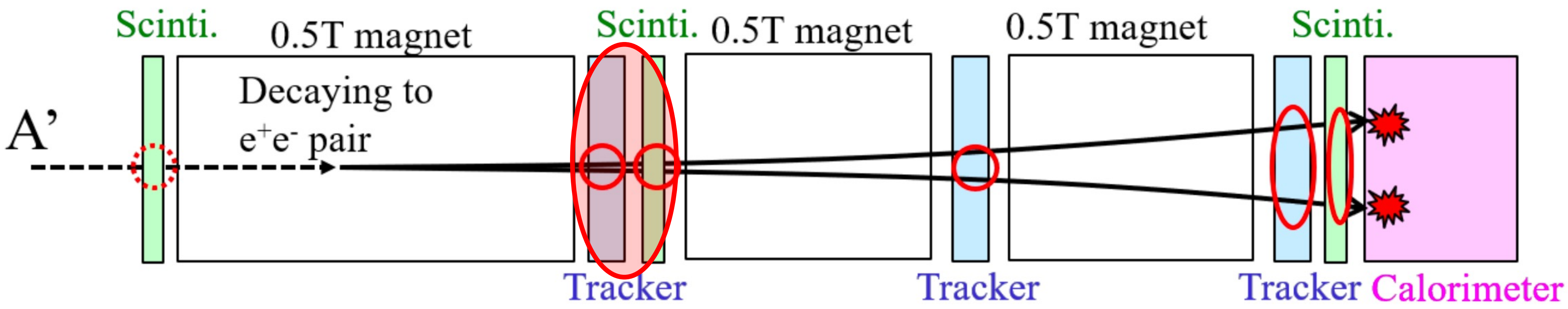

1, No signal in veto scintillator
2, Decay into e^+ and e^-
3, Detection of two high energy charged tracks
that emanate from a common vertex

Introduction - FASER

FASER detector

Benchmark signal (dark photon)

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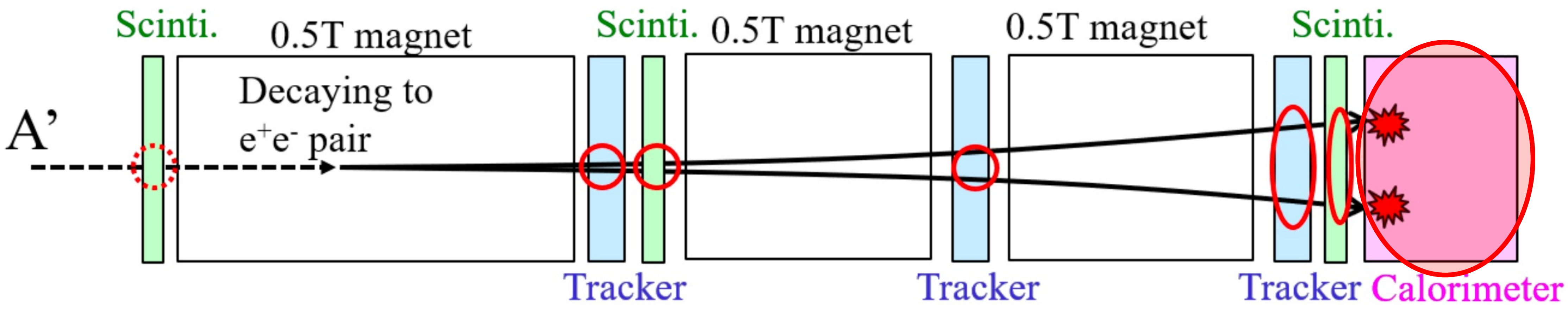


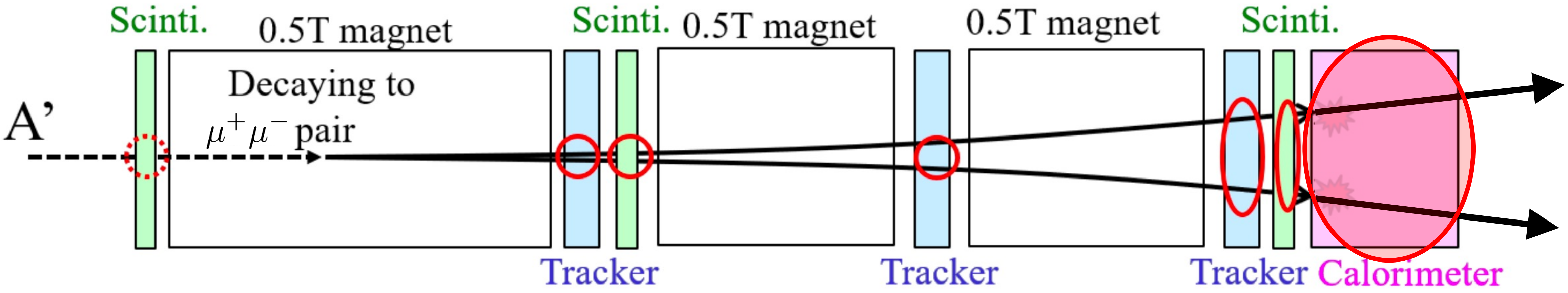
1, No signal in veto scintillator
2, Decay into e^+ and e^-
3, Detection of two high energy charged tracks
that emanate from a common vertex
4, Measurement of large EM energy in calorimeter

Introduction - FASER

FASER detector

Benchmark signal (dark photon)

From Takubo san's slide



1, No signal in veto scintillator
2, Decay into μ^+ and μ^-
3, Detection of two high energy charged tracks
that emanate from a common vertex
4, Muons pass through calorimeter as minimum ionizing particles (MIP)

Introduction

- Charged Lepton Flavor Violation-

Introduction – CLFV

Charged Lepton Flavor Violation (cLFV)

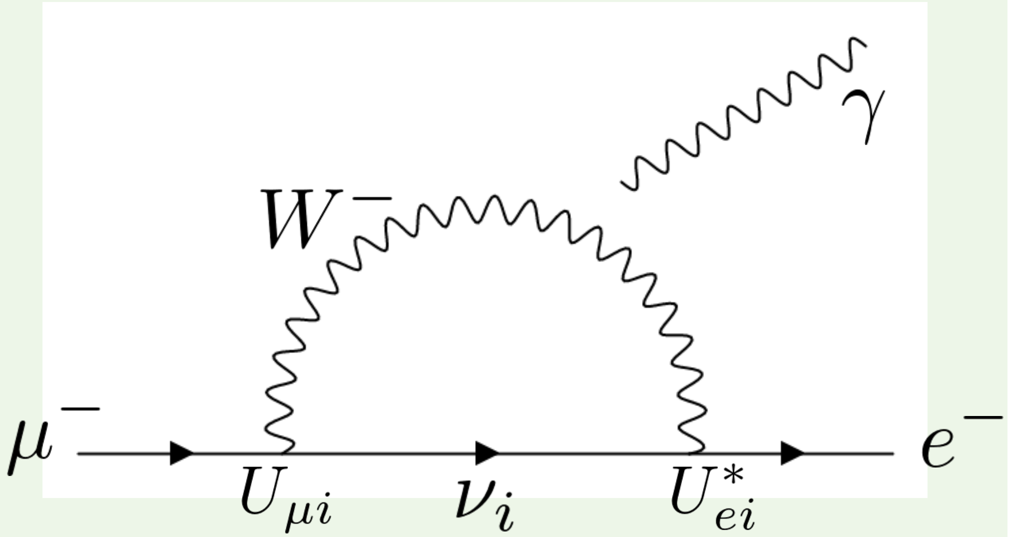
In the Standard Model (SM)

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

Theoretical prediction ：

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

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 – CLFV

Charged Lepton Flavor Violation (CLFV)

Beyond the SM

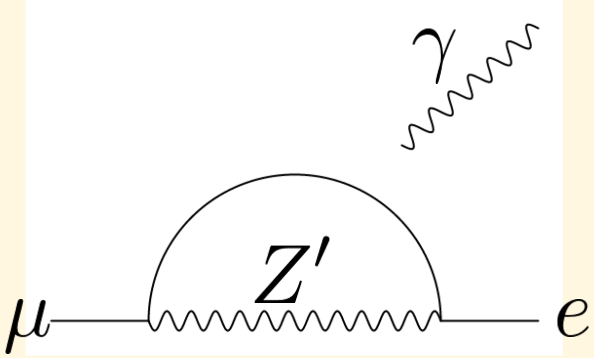
Supersymmetric model

Extra bosons

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

⋮

. . .



Because of no suppression from GIM mechanism, branching ratios of CLFV processes are enhanced

Introduction – CLFV

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 – CLFV

Constraints on CLFV

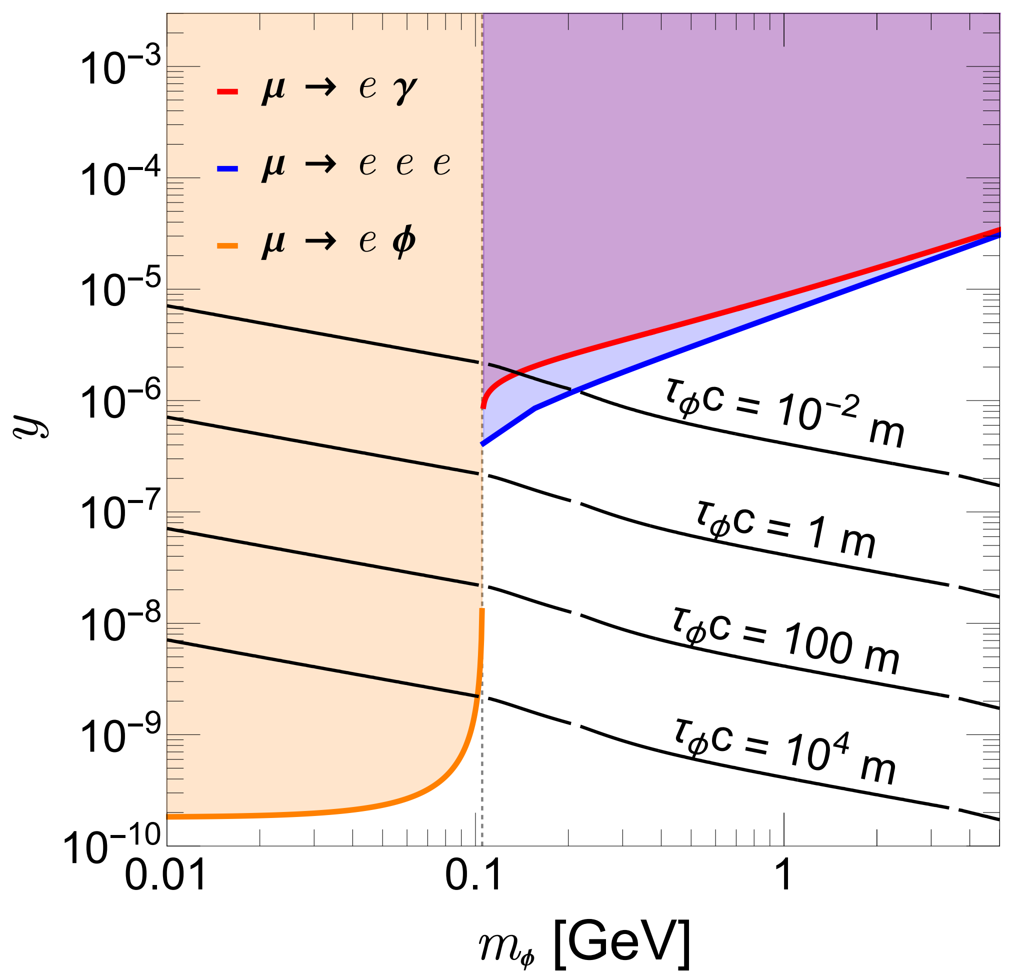
Ex) Leptophilic scalar model

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

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 – CLFV

Constraints on cLFV

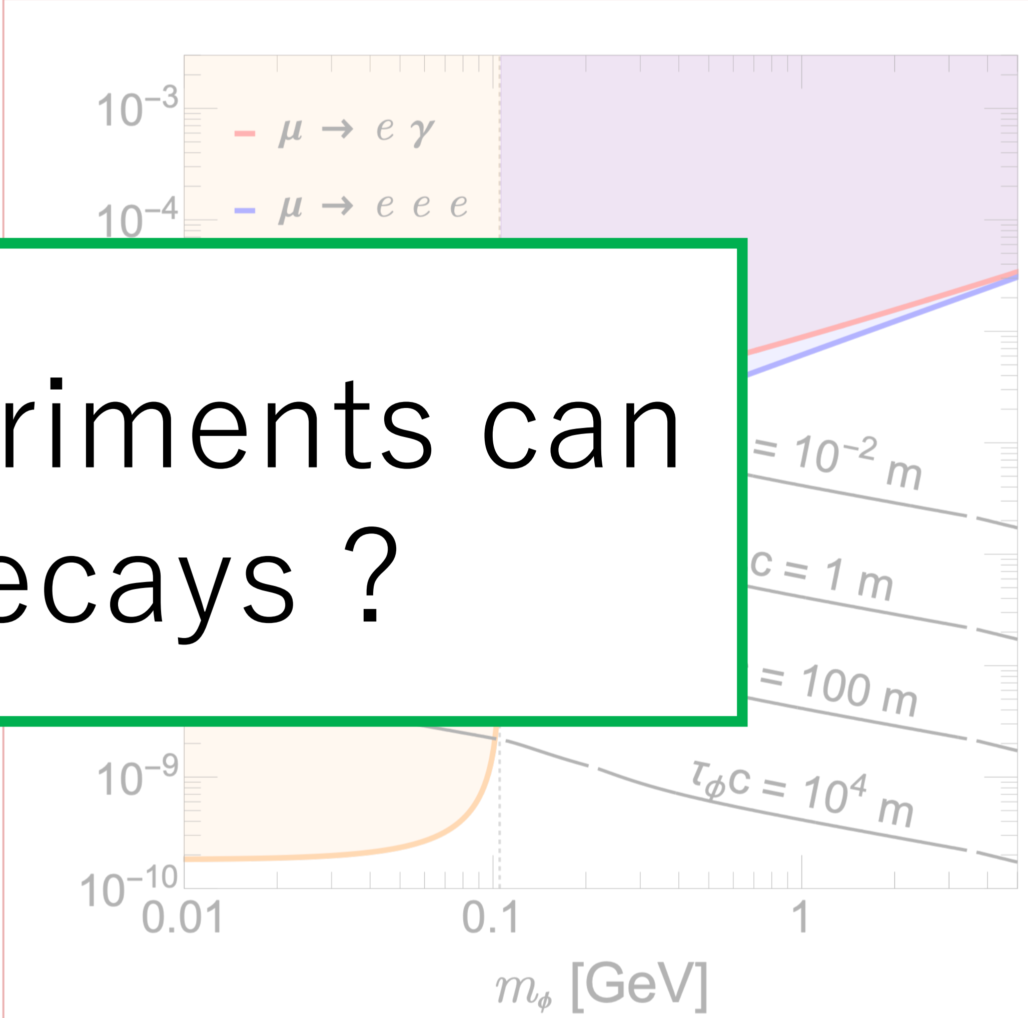
Ex) Leptophilic scalar model

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

In light
(m_ϕ~0

1, CL
CLFC one

2, New particles with CLFV coupling are long-lived



FASER search experiments can detect CLFV decays ?

Calculation

Benchmark Interactions

○ Scalar interaction

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

➡ Scalars are produced by meson rare decays

○ Pseudoscalar interaction

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

➡ Pseudoscalars are produced by meson rare decays

Calculation

Benchmark Interactions

Detail in
"Dark photon from light scalar decays at FASER",
T.Araki, **KA**, H.Otono, T.Shimomura, Y.Takubo,
JHEP 03 (2021) 072, 2008.12765 [hep-ph]

○ Vector-type interaction

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

➡ Gauge bosons are produced by meson -> scalar decays

○ Dipole-type interaction

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

➡ Gauge bosons are produced by meson -> scalar decays

Calculation

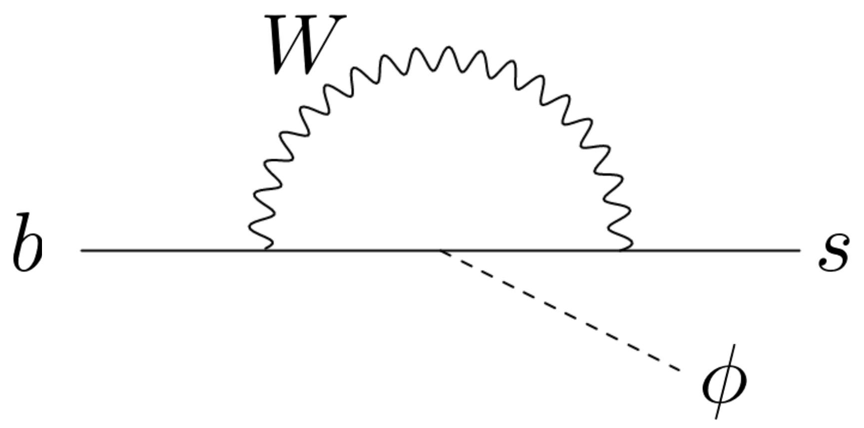
Scalar production

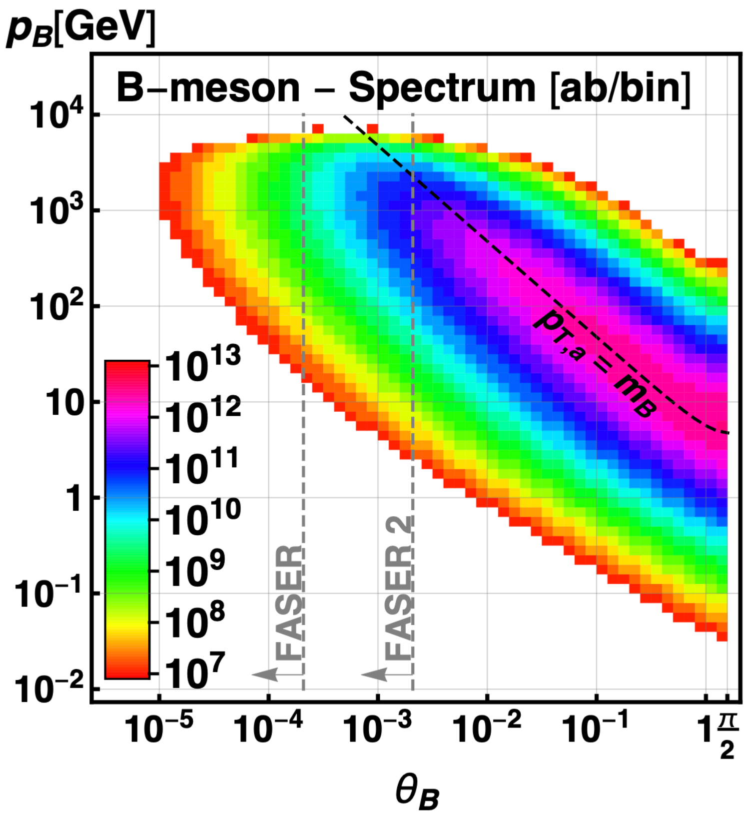
Light scalar boson ϕ is mainly produced by rare decays of B mesons

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

FASER collaboration, PRD 99 (2019) 9, 095011

$$B \to K + \phi$$





Calculation

Gauge boson production

Origin of BSM gauge boson mass

➡ Spontaneous symmetry breaking by VEV of $\mathrm{U(1)_X}$-charged scalar

Interaction between $\mathrm{U(1)_X}$-charged scalar and gauge boson

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

➡ $\phi Z' Z'$ coupling

Calculation

Gauge boson production

Interaction between $\mathrm{U(1)_X}$-charged scalar and dark photon

$$\mathcal{L} \supset g' m_{A'} \phi A'_\mu A'^\mu$$

→ ϕ decay into A' pair

We assume that $\mathrm{U(1)_X}$-charged scalar is much heavier than dark photon $(m_{A'} \ll m_\phi)$

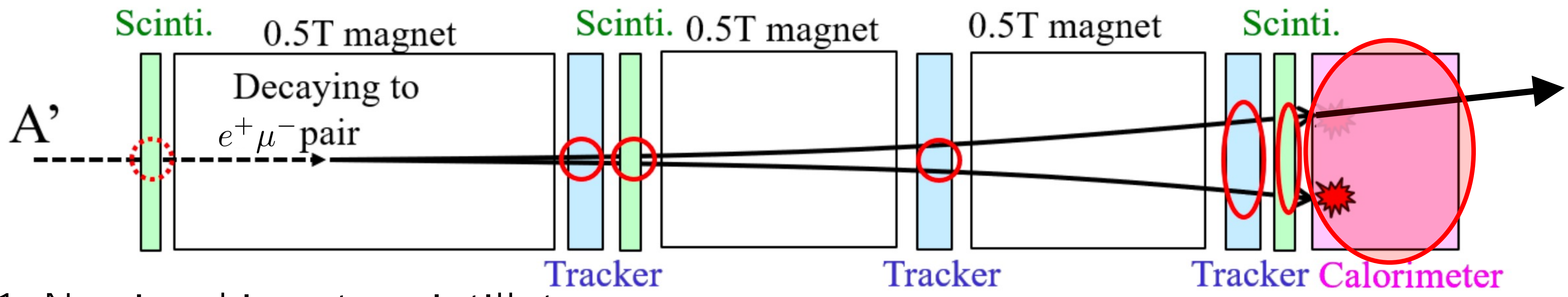
→ Almost all ϕ decay into dark photon

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

enhancement factor $\gg 1$

Signal of CLFV decay

Benchmark signal



1, No signal in veto scintillator
2, Decay into e^+ and μ^-
3, Detection of two high energy charged tracks
that emanate from a common vertex
4, Electron leaves EM energy in calorimeter, and on the other hand muon passes through calorimeter as minimum ionizing particles (MIP)

Calculation

Number of events

Detail in
"Dark photon from light scalar decays at FASER",
T.Araki, **KA**, H.Otono, T.Shimomura, Y.Takubo,
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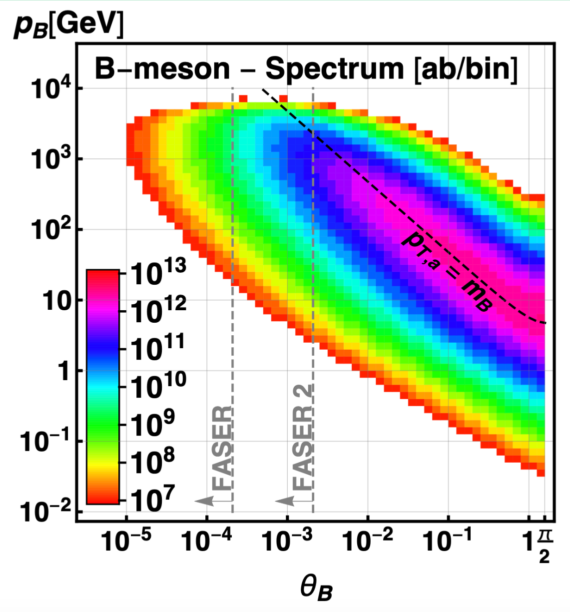
Number of LFV decays in FASER detector

$$N_{\rm cLFV} = \mathcal{L} \sum_{i:\rm meson} \sum_{j=1,2} \int dp_i d\theta_i \int d\boldsymbol{p}_{A'} \int d\boldsymbol{p}_\phi \frac{d\sigma_{pp\to iX}}{dp_i d\theta_i} {\rm Br}(i \to \tilde{X}\phi){\rm Br}(\phi \to A'_1 A'_2)$$
$$\times \mathcal{P}^{\rm det}_{A'_j}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi) \times {\rm BR}(Z' \to e\mu)$$



Assumption & Setup

- Calculated for FASER2 case
- Background free

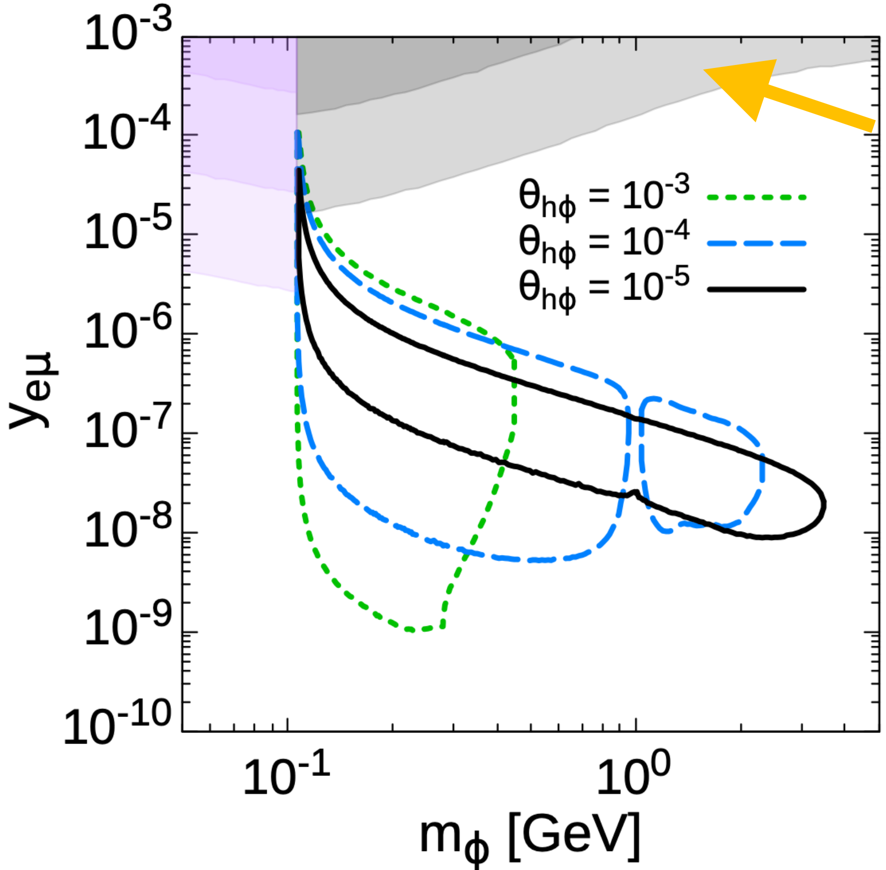
Result

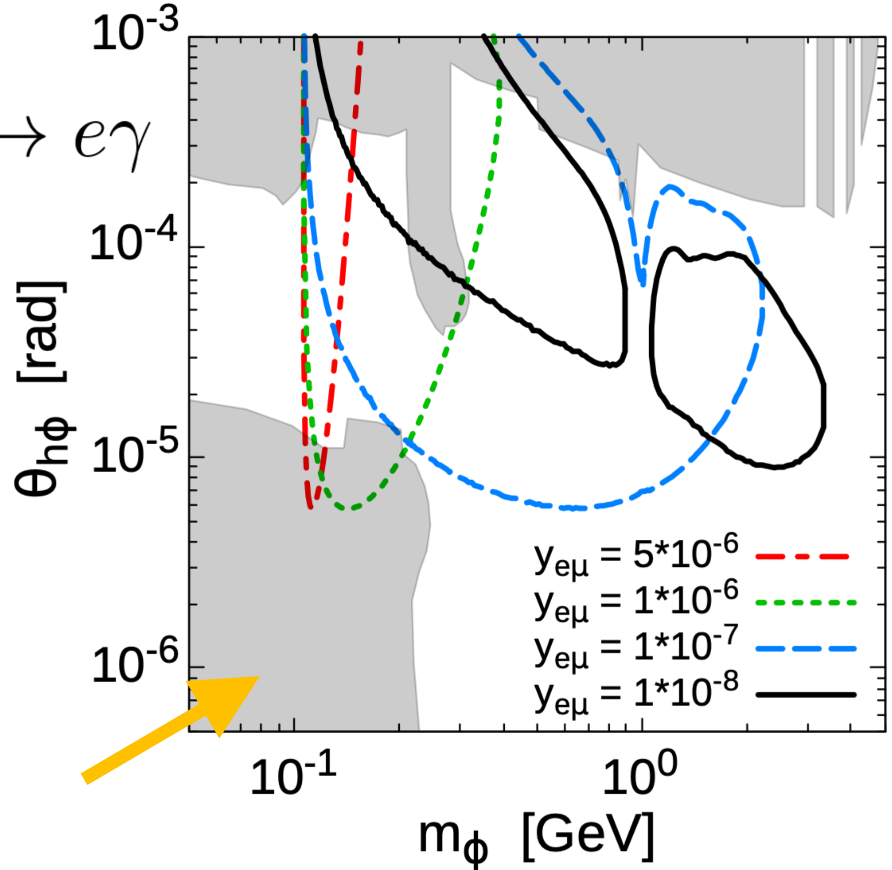
Result

Constraint on LFV coupli

Detail in
"Electron beam dump constraints on light boson with lepton flavor violating couplings",
T.Araki, **KA**, T.Shimomura, JHEP 11 (2021) 082,
2107.07487 [hep-ph]

Scalar-type int. $\mathcal{L}_{\text{scalar}} = \frac{\theta_{h\phi}}{v}\sum_f m_f \bar{f}\phi_l f + (y_{e\mu}\overline{e_L}\phi_l\mu_R + y_{\mu e}\overline{\mu_L}\phi_l e_R + h.c.)$





Excluded by E137

95% C.L. sensitivity contour @ FASER2

Result

Constraint on LFV coupli

Detail in
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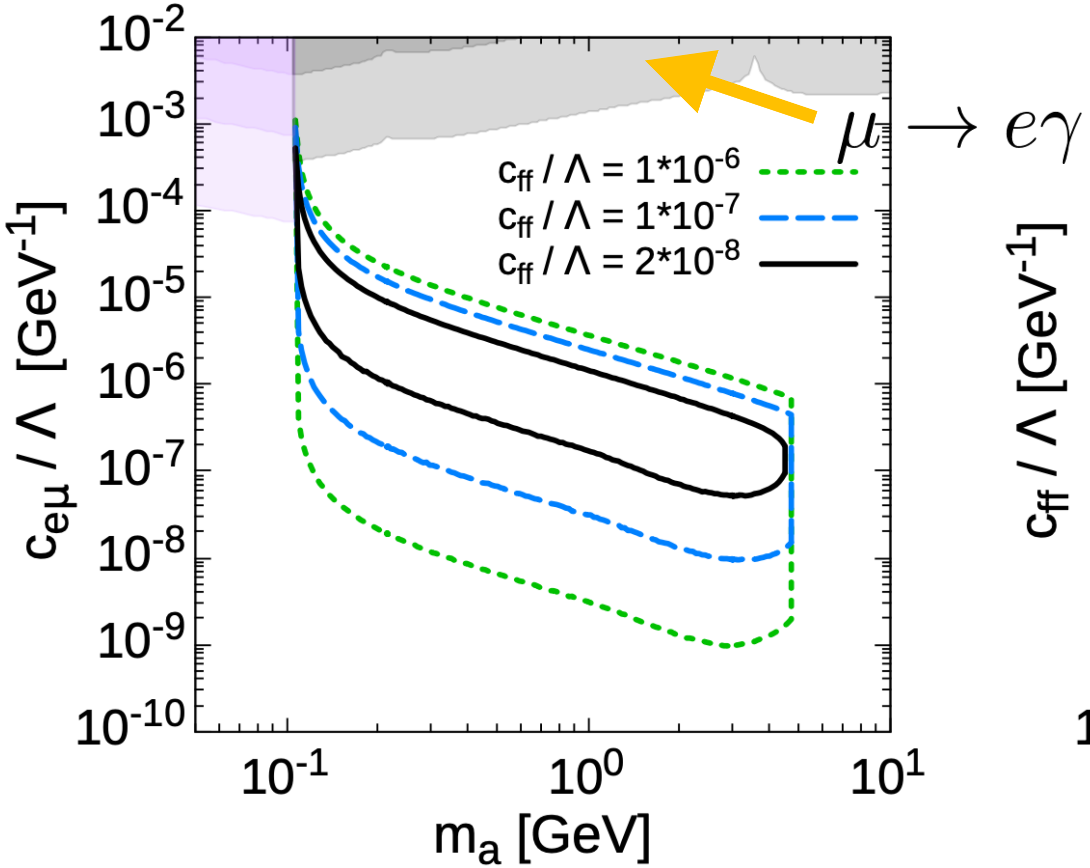
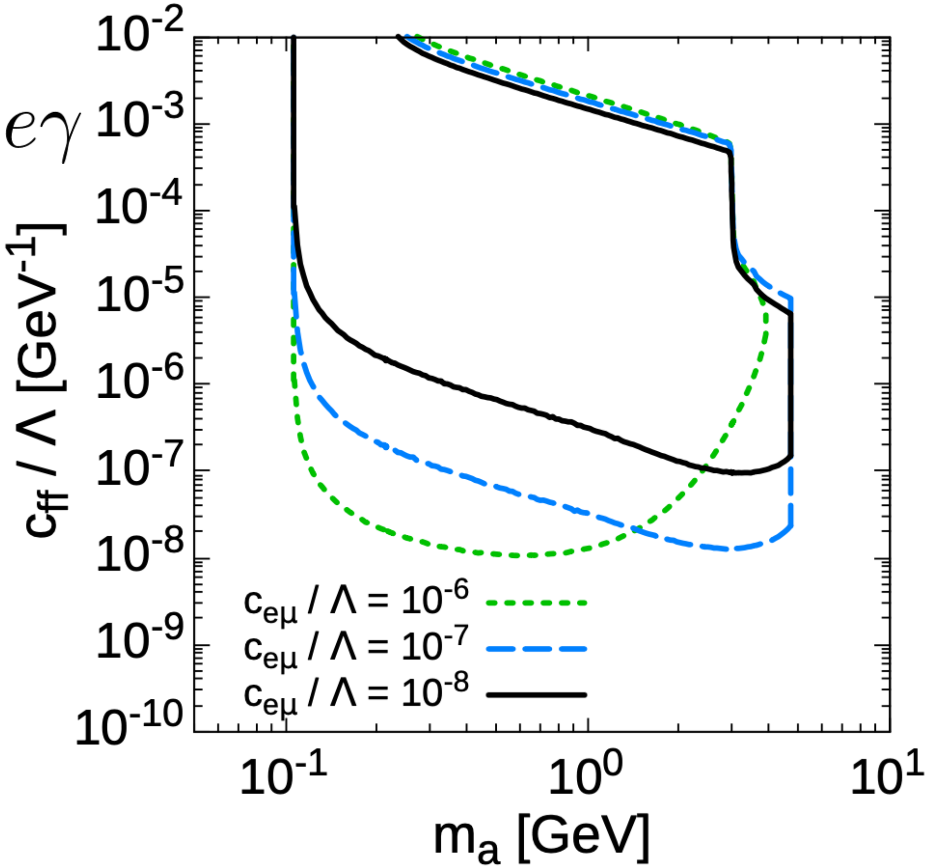
Pseudoscalar-type int. $\mathcal{L}_{\text{pseudoscalar}} = \frac{\partial_\rho a}{\Lambda} \left\{ \sum_f c_{ff} \bar{f} \gamma^\rho \gamma_5 f + c_{e\mu} \bar{e} \gamma^\rho \gamma_5 \mu + c_{e\mu}^* \bar{\mu} \gamma^\rho \gamma_5 e \right\}$





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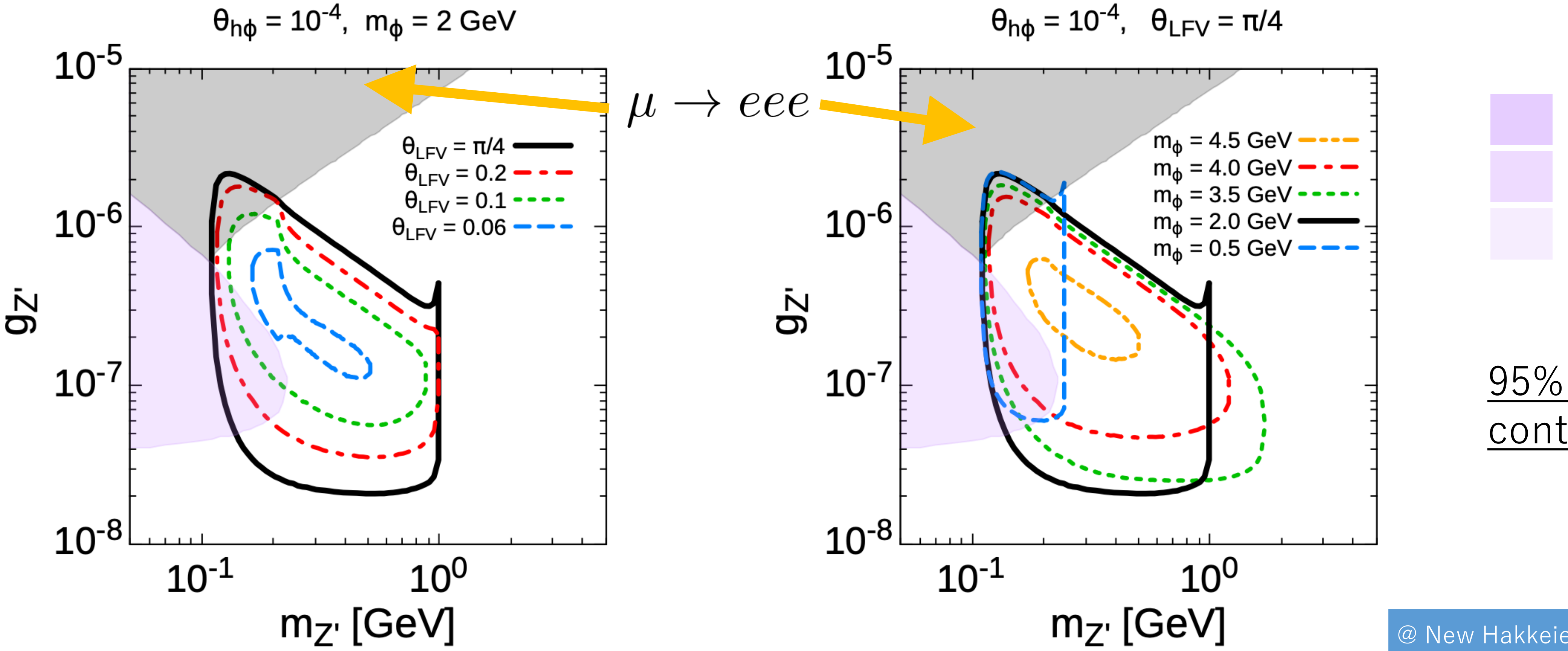
Vector-type int.

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



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Result

Constraint on LFV coupli

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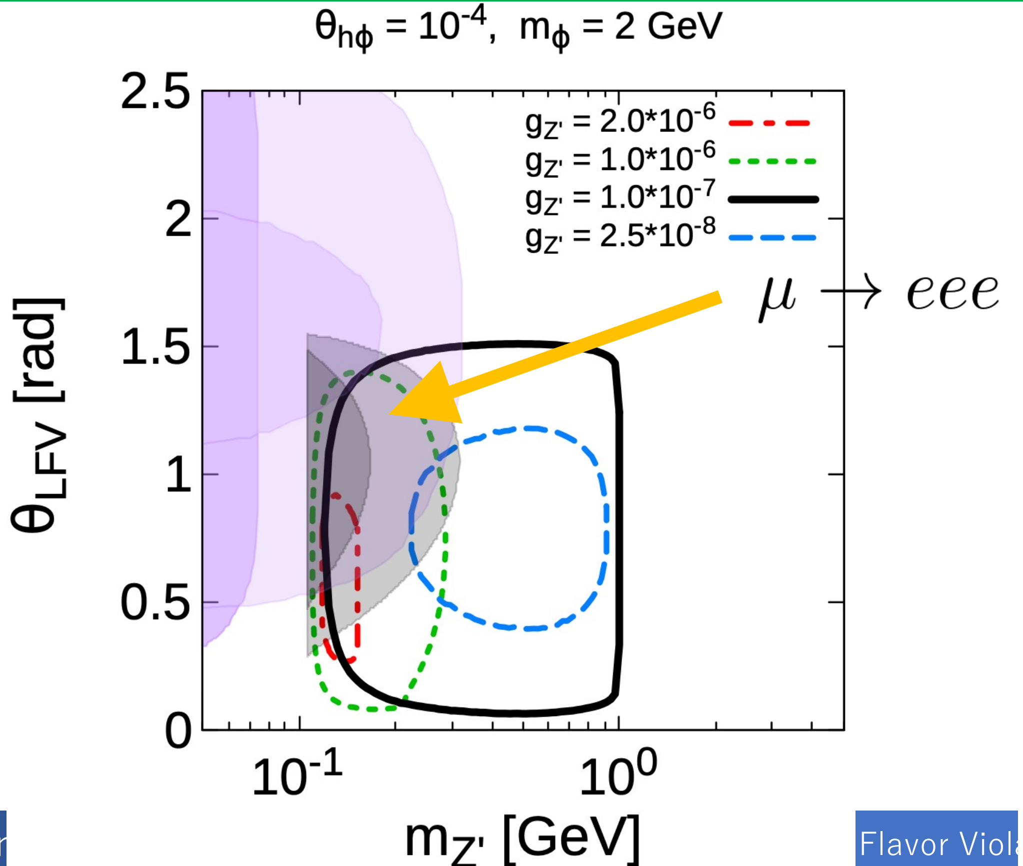

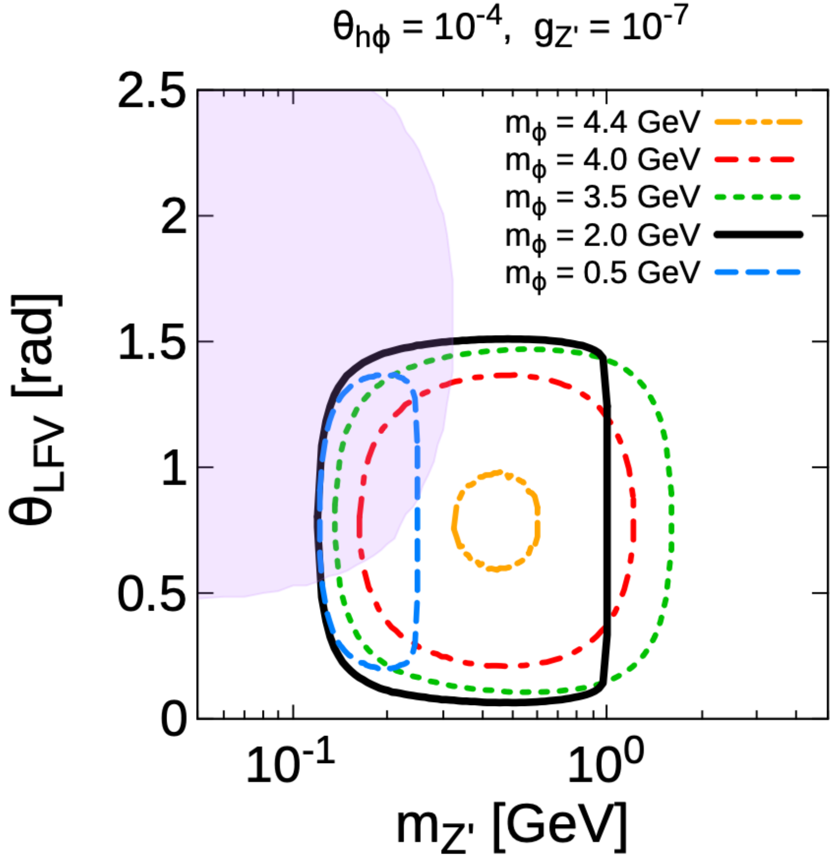

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Result

Constraint on LFV coupli

Detail in
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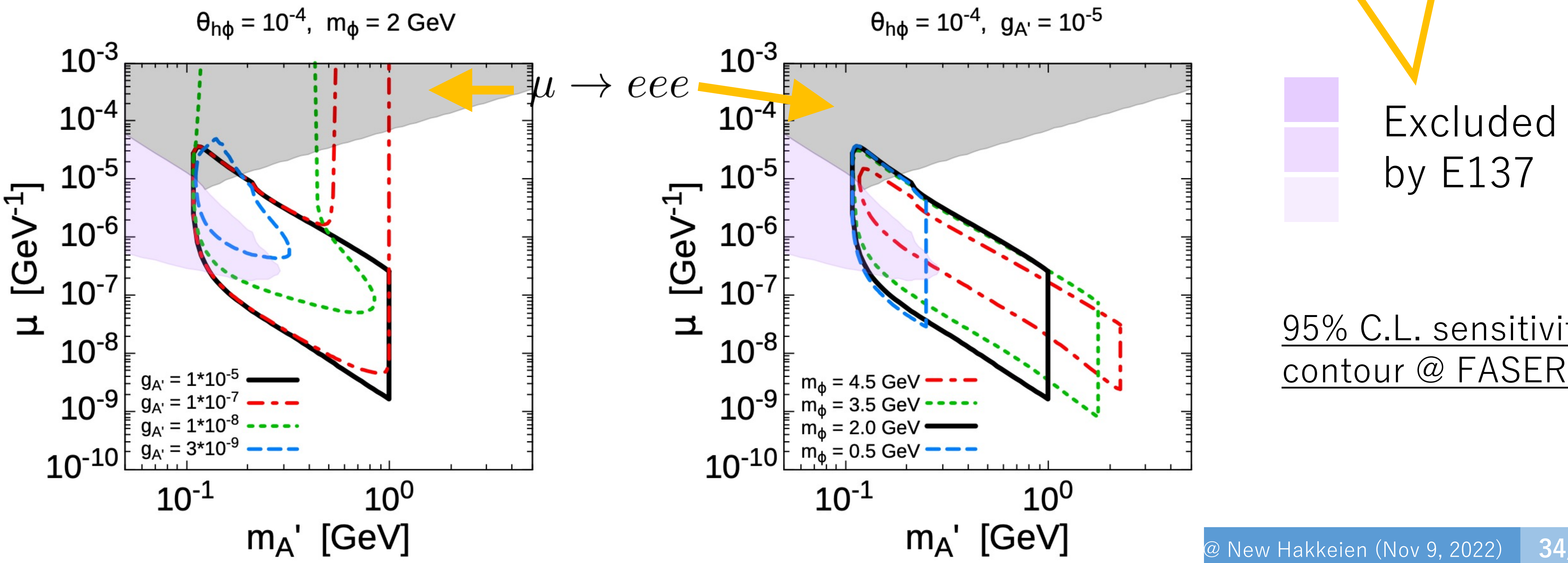
2107.07487 [hep-ph]

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



95% C.L. sensitivity contour @ FASER2

Result

Constraint on LFV coupli

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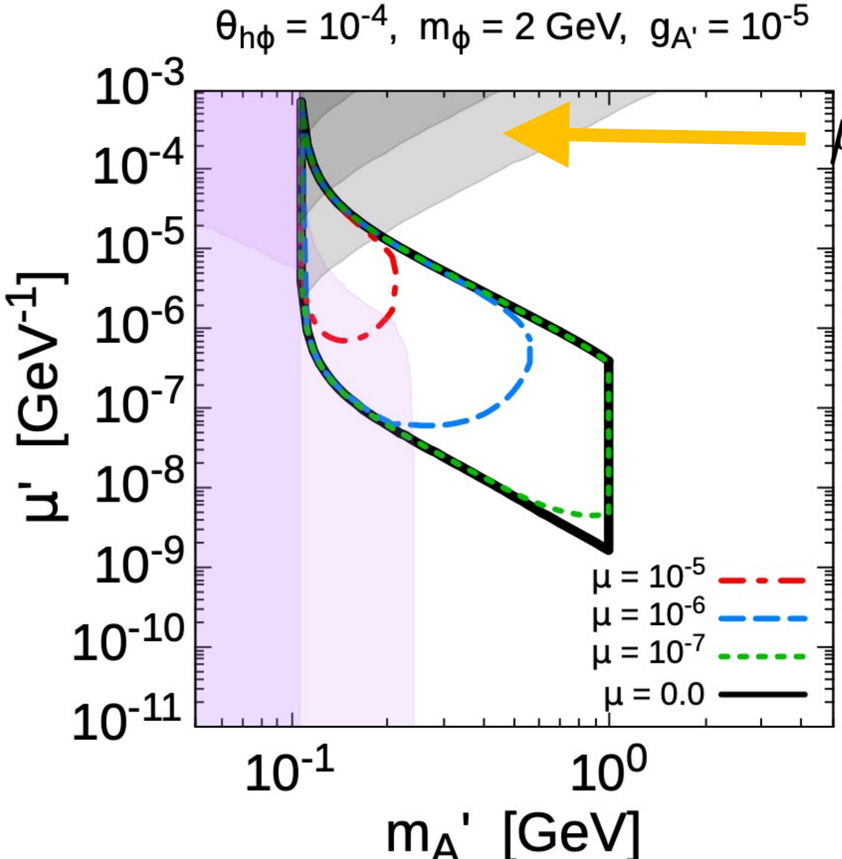
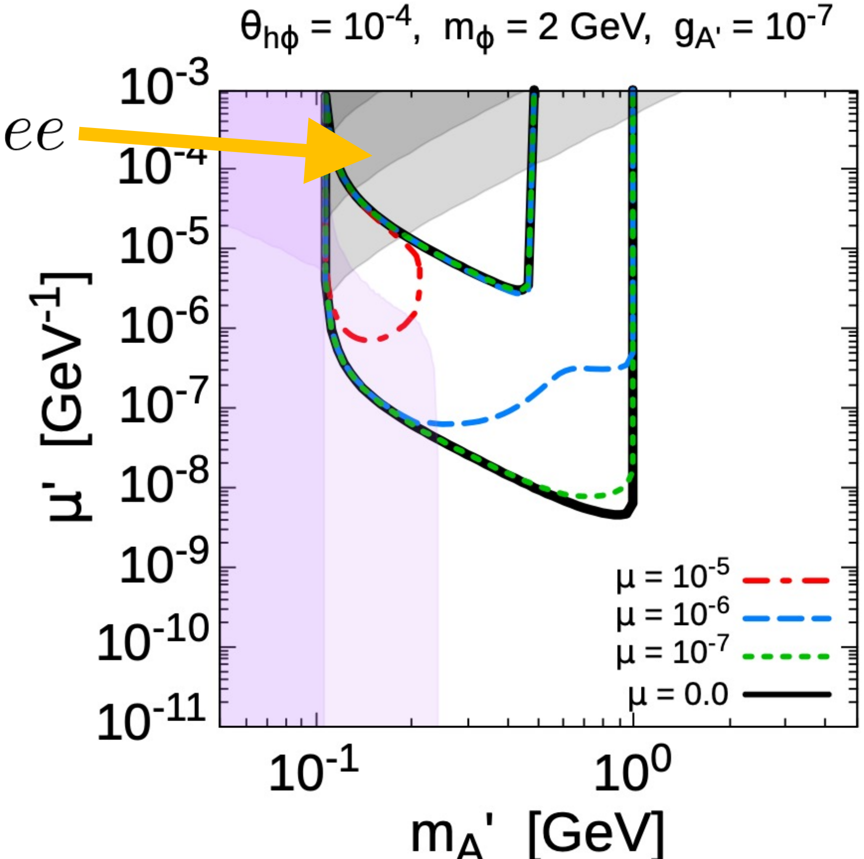
Dipole-type int. $\mathcal{L}_{\rm dipole} = \frac{1}{2}\sum_{\ell=e,\mu,\tau} \mu_\ell \bar{\ell}\sigma^{\rho\sigma}\ell A'_{\rho\sigma} + \frac{\mu'}{2}\left(\bar{\mu}\sigma^{\rho\sigma}e + \bar{e}\sigma^{\rho\sigma}\mu\right)A'_{\rho\sigma}$



$\mu \to eee$



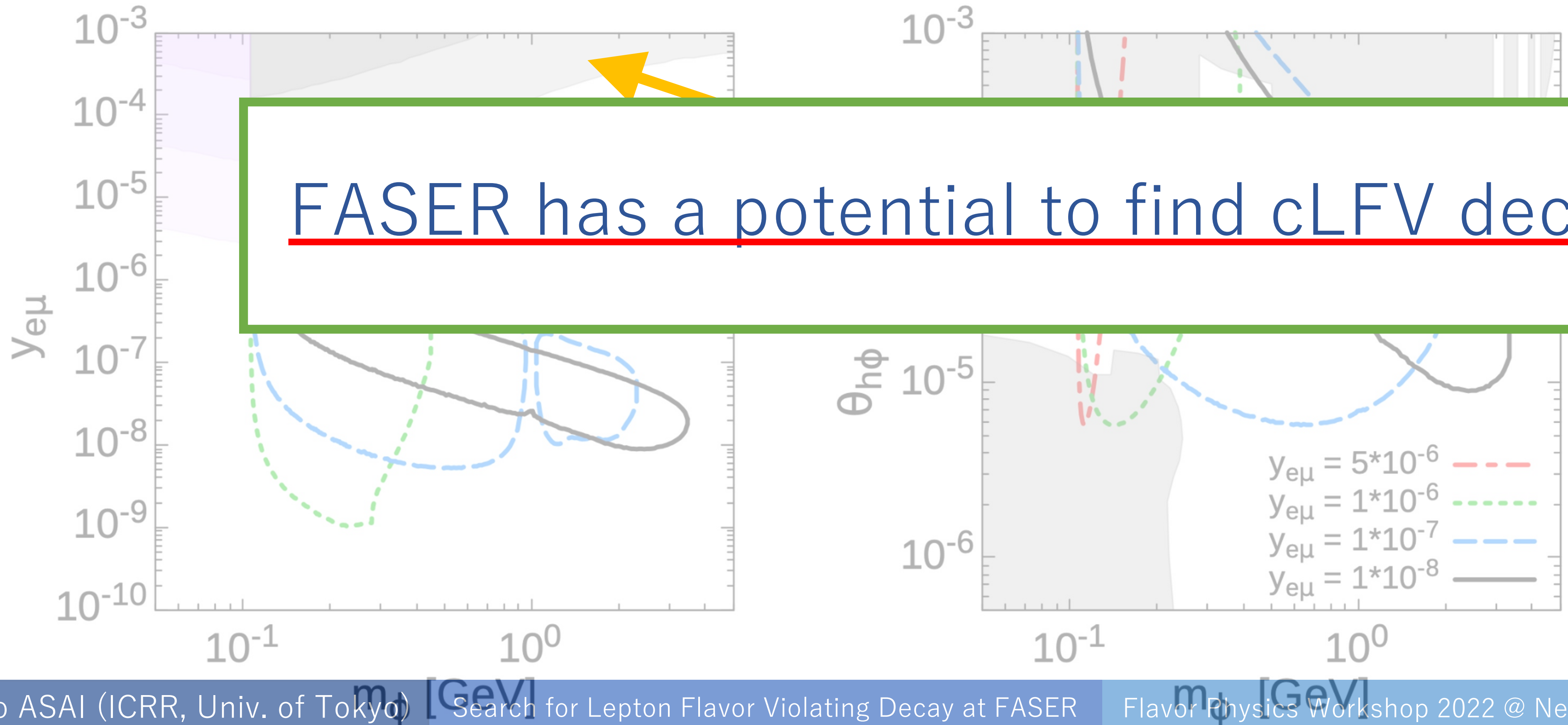
Excluded by E137

95% C.L. sensitivity contour @ FASER2

Result

Constraint on LFV coupling

Scalar-type int. $\mathcal{L}_{\rm scalar} = \frac{\theta_{h\phi}}{v} \sum_f m_f \bar{f} \phi_l f + (y_{e\mu} \overline{e_L} \phi_l \mu_R + y_{\mu e} \overline{\mu_L} \phi_l e_R + h.c.)$



FASER has a potential to find cLFV decay

Excluded by E137

95% C.L. sensitivity contour @ FASER2

Summary

- FASERは，標準模型粒子との相互作用がとても小さな軽い領域に感度がある

  ➡ 新物理が隠れている可能性がある

- そのような領域ではCLFV相互作用がCLFC相互作用と同程度の大きさでも既存のCLFVの制限を回避しており，FASERで新粒子のCLFV崩壊が見えるかもしれない (CLFV相互作用の探索)

これまでのCLFV探索(荷電レプトンの崩壊, 加速器 …)
➡ CLFV相互作用の大きな領域から徐々に小さな領域へ

FASER & 他の長寿命粒子探索実験
➡ CLFV相互作用の小さな領域をいきなり探索

Appendix

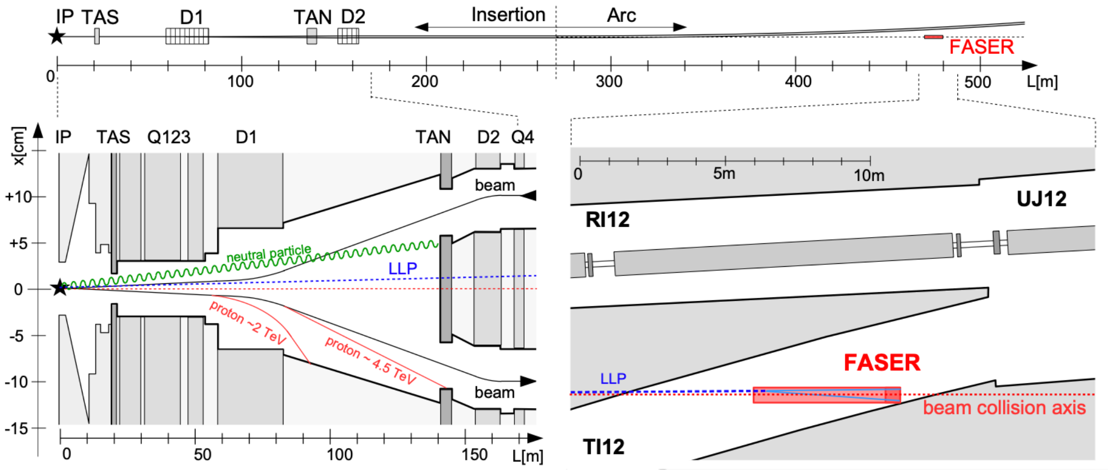
Schedule of FASER

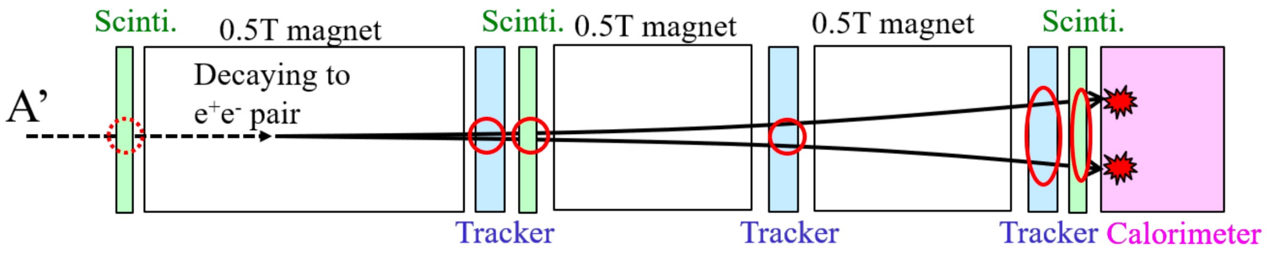
FASER実験の歴史と今後の予定

- 2018年8月、LOI (Letter Of Intent)をLHC委員会に提出 (arXiv:1811.10243).
- 2018年11月、TP (Technical Proposal)をLHC委員会に提出 (arXiv:1812:09139)
- 2019年3月、CERNに公式に承認された
- 検出器の建設と運転費用は、Simons財団とHeising-Simons財団が提供
- 2020年秋に検出器を実験サイトに設置する予定
- 2021年はコミッショニング作業
- データ取得はLHC Run3が始まる2022年に開始

From Takubo san's slide

Background @ FASER





Almost all potential backgrounds are eliminated by rock and LHC materials

Main background

- EM/HD shower from muon bremsstrahlung : 8×10^3 events @ LHC Run3
- CC/NC neutrino events : A few (~100 GeV) events @ LHC Run3

➡ Can be eliminated by charged particle veto with efficiency of 99.99%

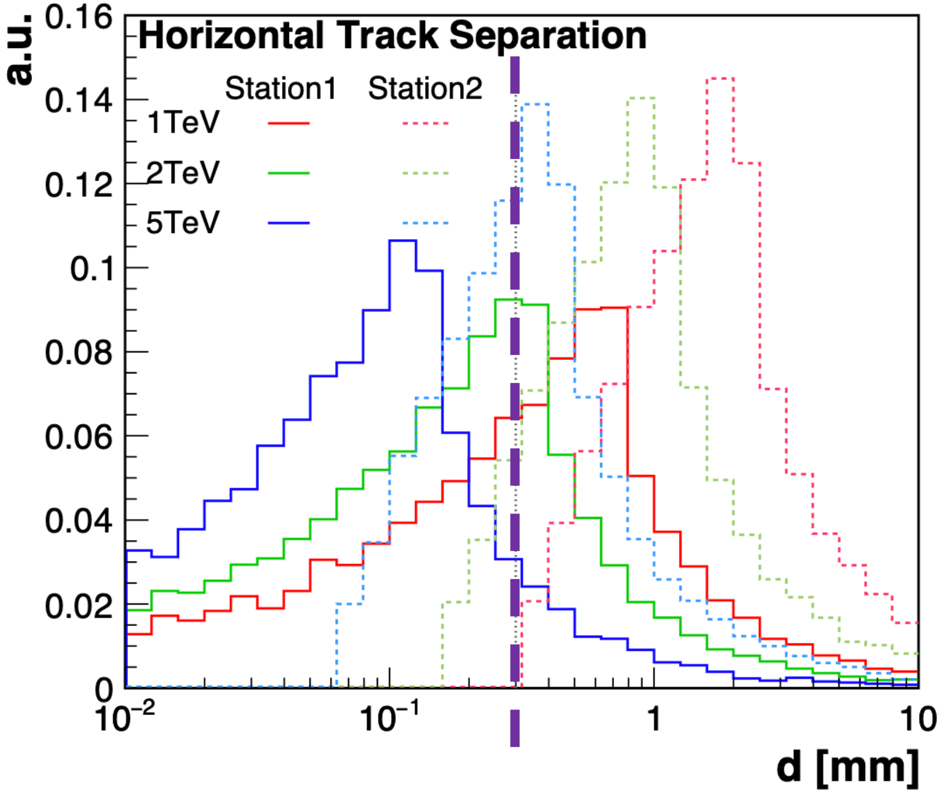
Introduction - FASER

Spectrometer

Ex) e^+e^- pair from decay of 100 MeV dark photon are separated by 0.5T magnet

➡ Can identify two tracks

From 1811.10243 [hep-ex]



threshold : 300 μ m

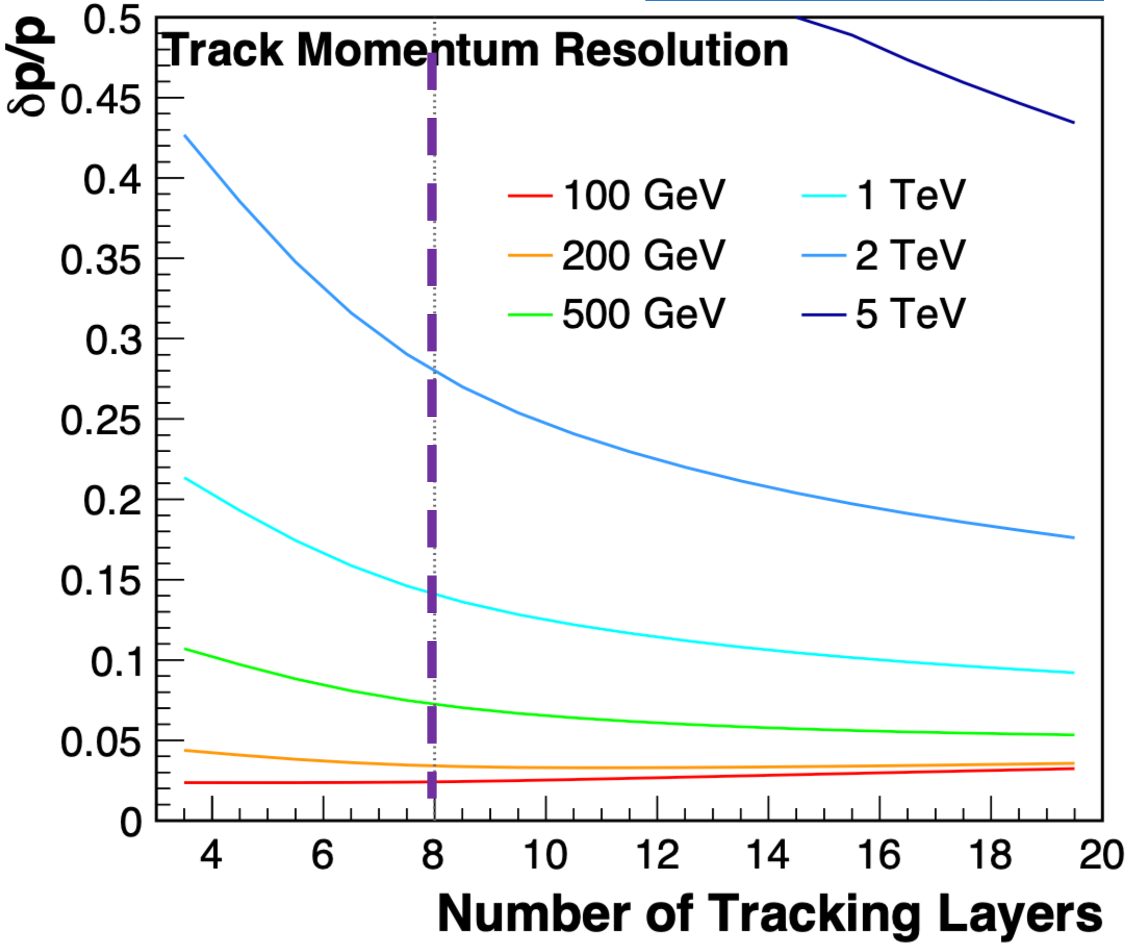
Introduction - FASER

Spectrometer

From [1811.10243 [hep-ex]]

Momentum resolution

The lower energy e^+e^- have,
the better momentum resolution is.



Introduction – FASER

Dark Photon Model

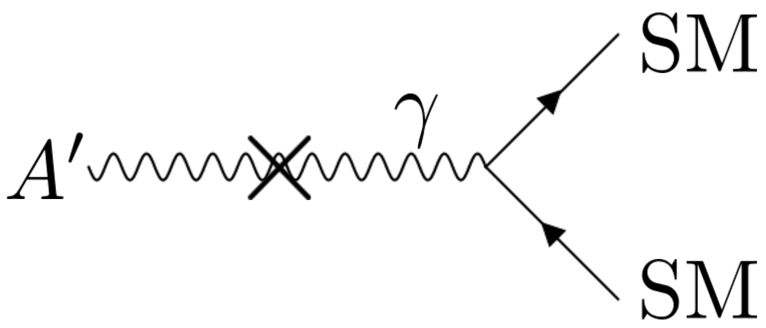
Extension of the Standard Model by a dark U(1) gauge symmetry

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{\mathrm{dark}}$$

Mixing between SM photon and dark photon appears through gauge kinetic mixing

$$\mathcal{L}_{\mathrm{mix}} = -\frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$$

$$\mathcal{L}_{\mathrm{int}} = \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

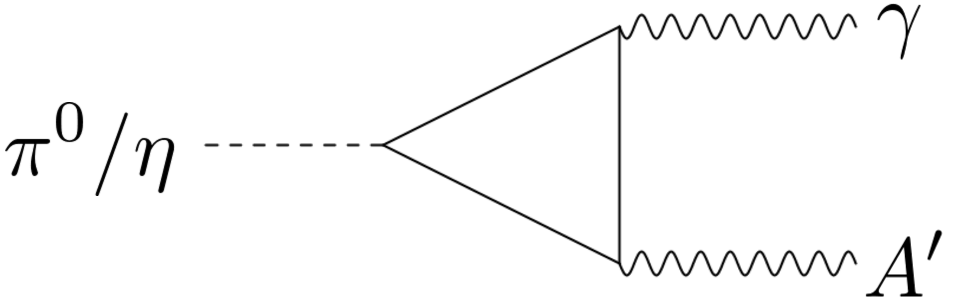


Introduction – FASER

Dark Photon Model

Production @ ATLAS

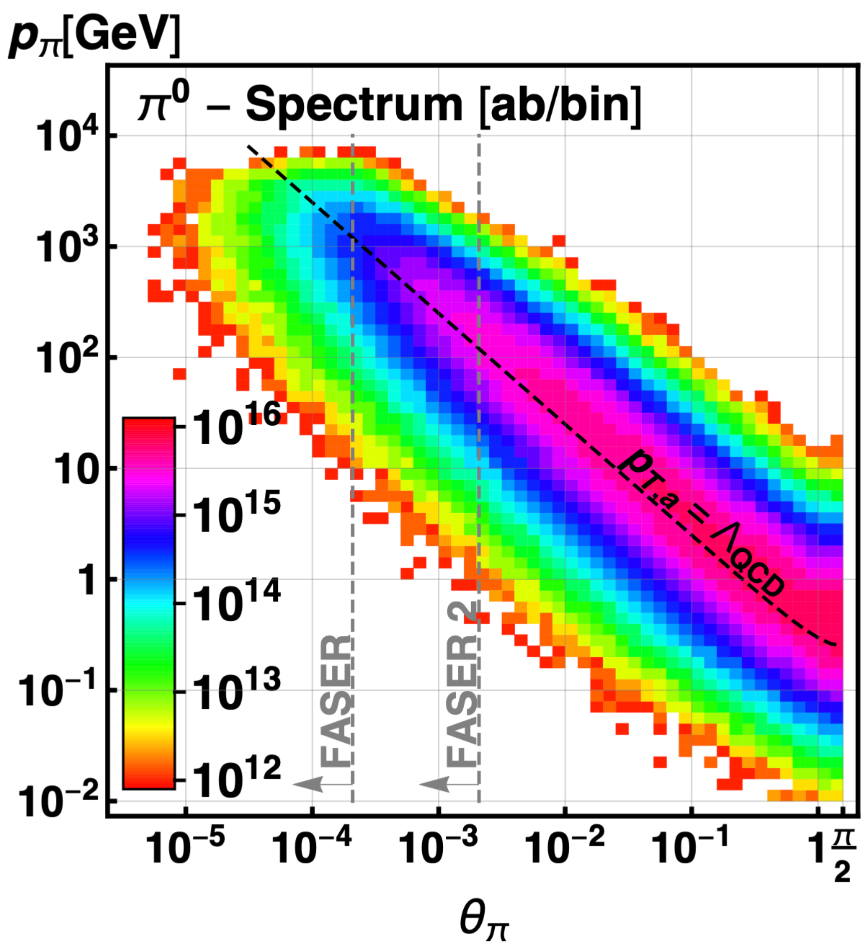
π^0 and η are produced at ATLAS collision point



Dark photons are produced by rare decays of π^0 and η

$$\mathrm{BR}(\pi^0 \to \gamma A') \sim 2\epsilon^2 \times \underbrace{\mathrm{BR}(\pi^0 \to \gamma\gamma)}_{\approx 1}$$

FASER collaboration, PRD 99 (2019) 9, 095011



Introduction – FASER

Decay length

Dark photon decays into SM particles through $\gamma - A'$ mixing

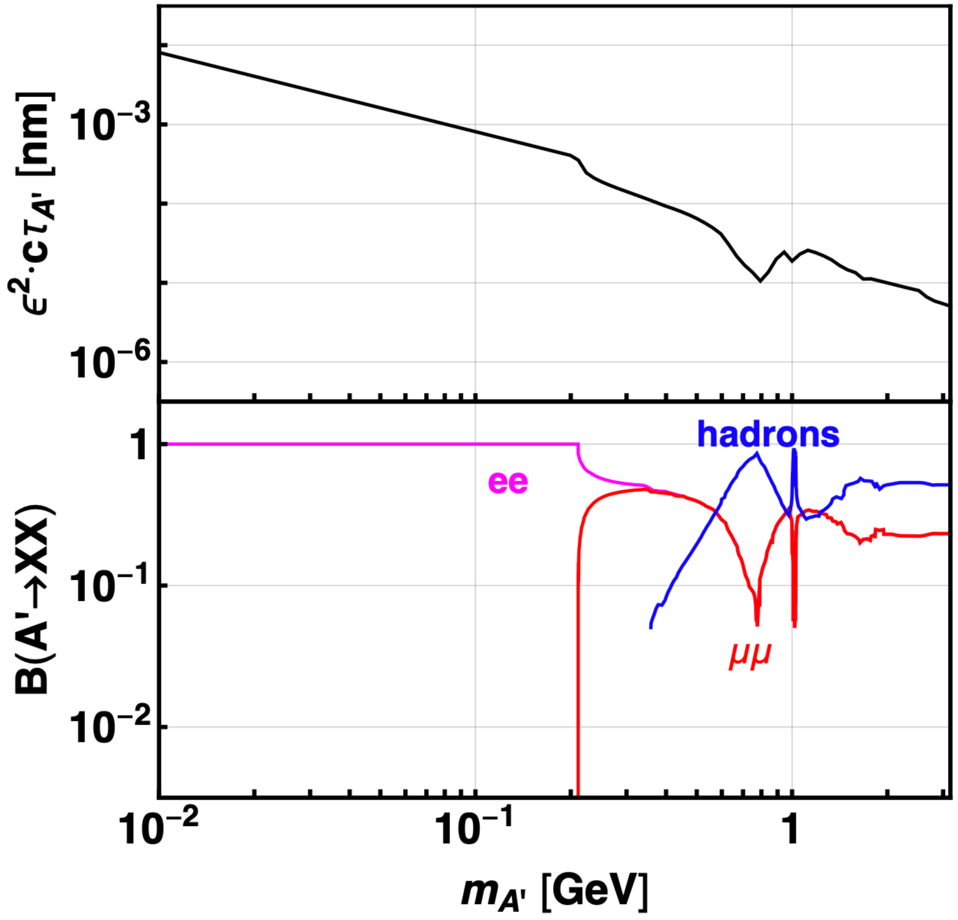
<u>Decay length</u>

$$d = c\tau_{A'}^{\text{rest}}\beta\gamma = c\tau_{A'}^{\text{rest}}\frac{p_{A'}}{m_{A'}}$$

$$\sim 10^{-2}\ \text{m}\cdot\frac{10^3\ \text{GeV}}{0.1\ \text{GeV}} = 100\ \text{m}$$

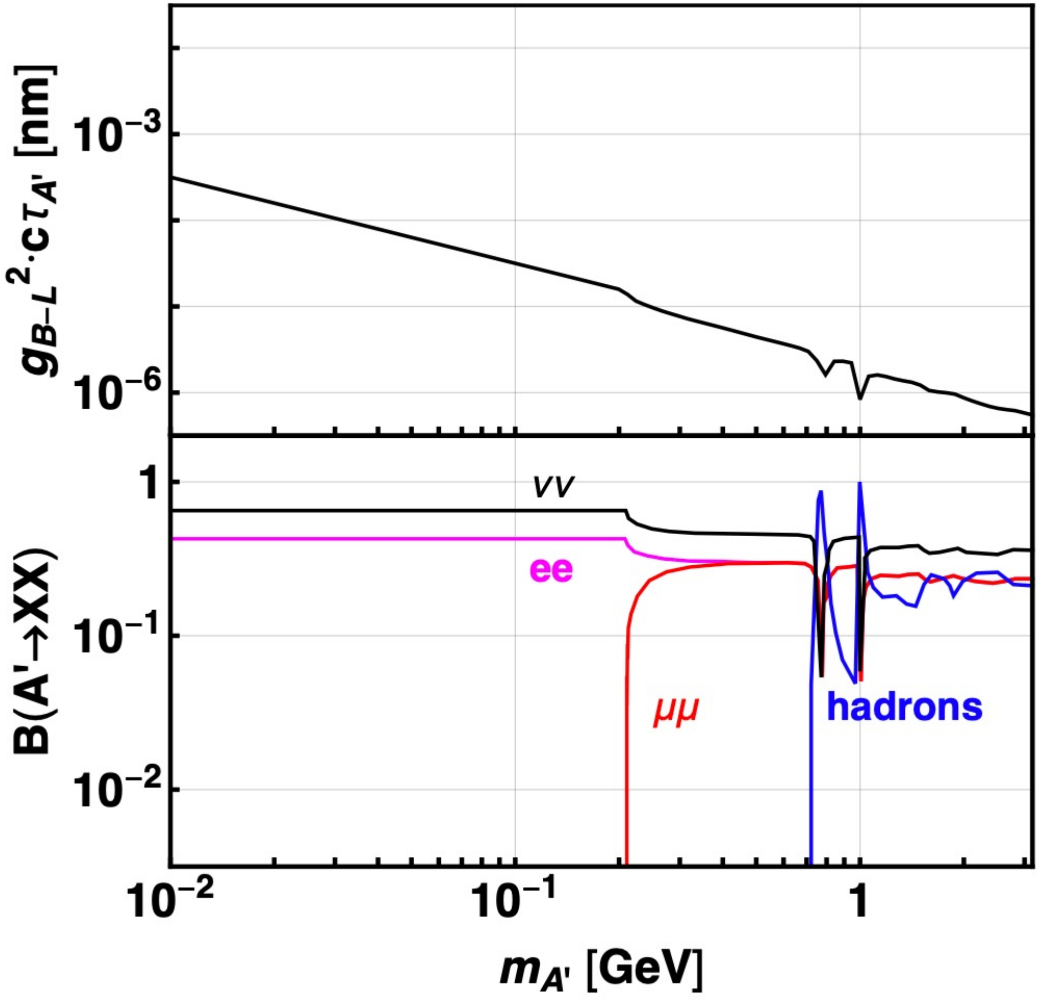
for $m_{A'} = 0.1\ \text{GeV},\ \epsilon = 10^{-5}$

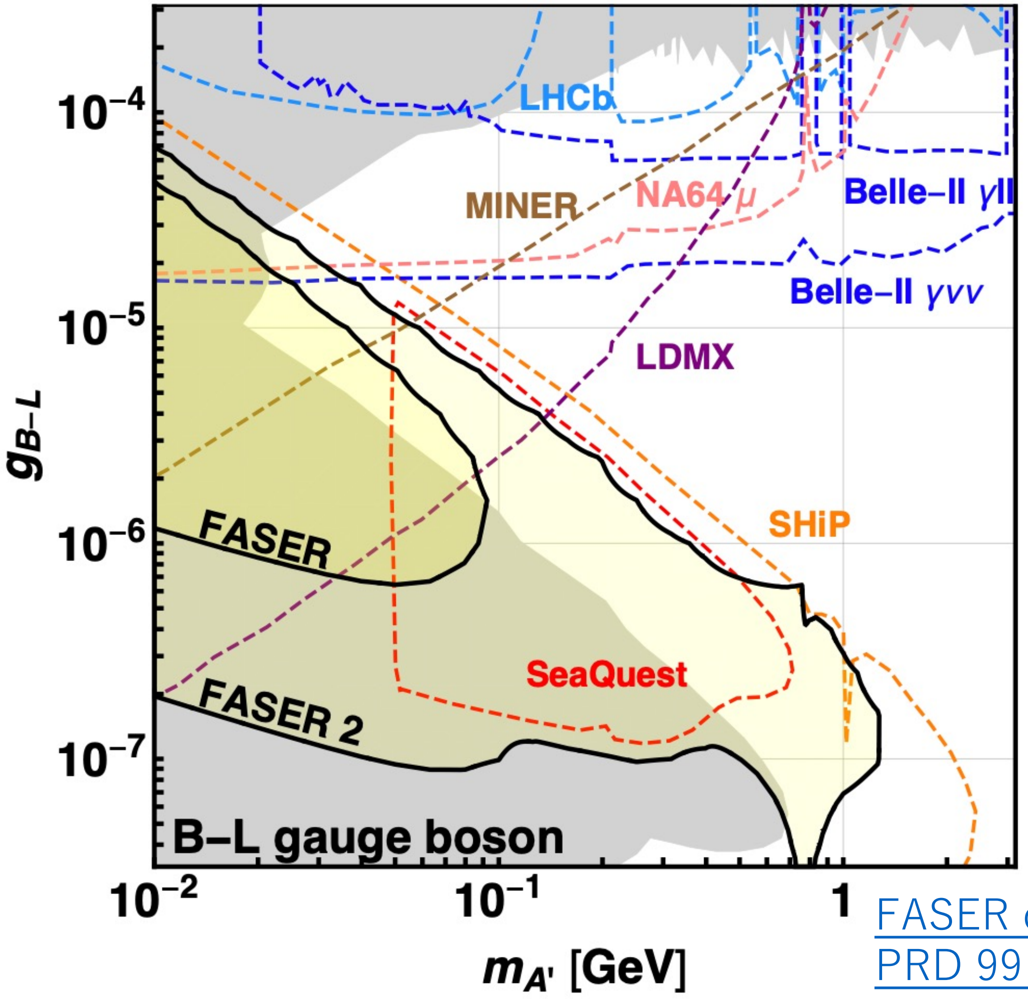
FASER collaboration, PRD 99 (2019) 9, 095011



Introduction – FASER

Expected sensitivity (Dark photon)

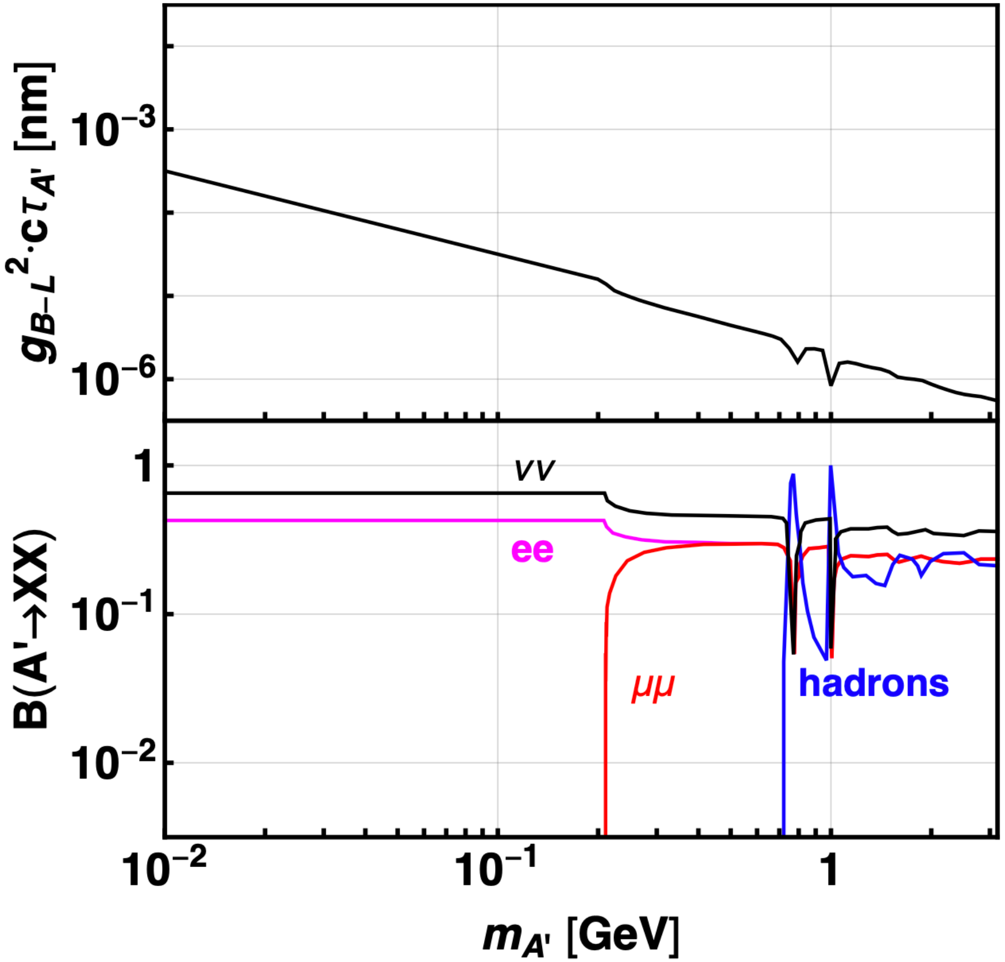


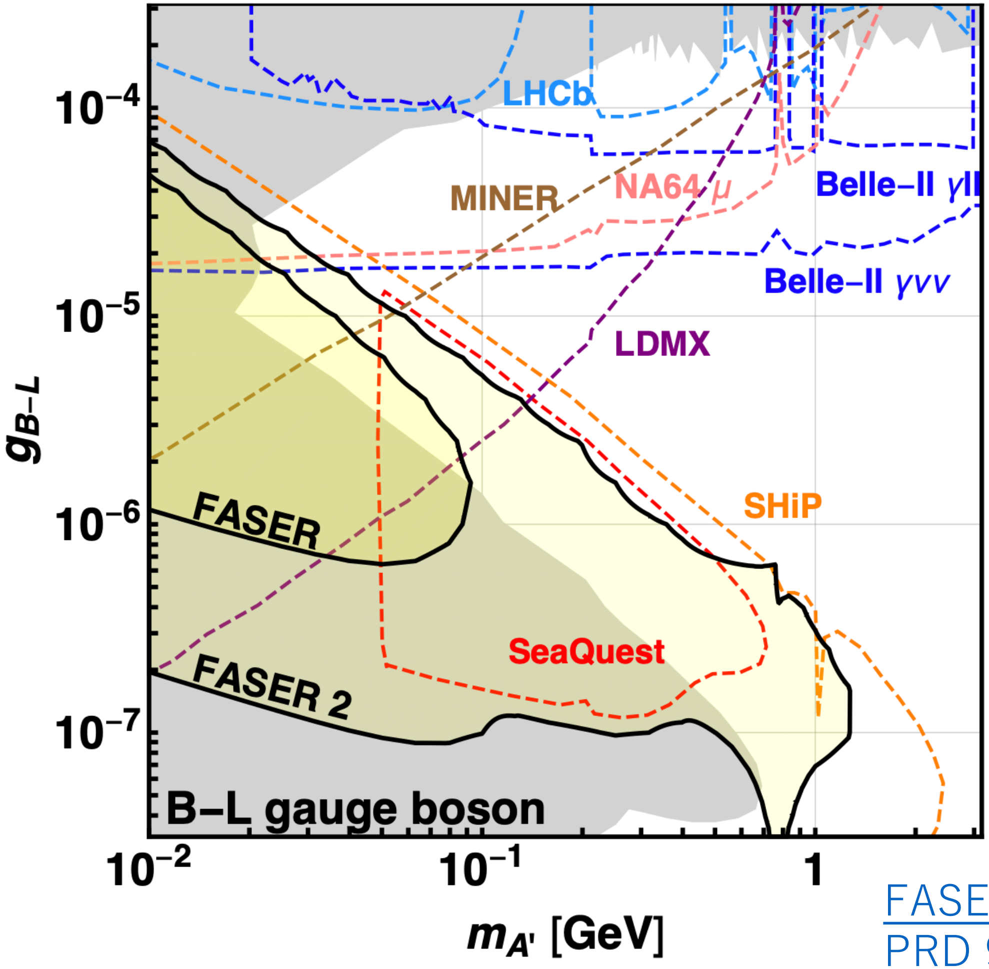


FASER collaboration, PRD 99 (2019) 9, 095011

Introduction – FASER

Expected sensitivity ($U(1)_{B-L}$ gauge boson)

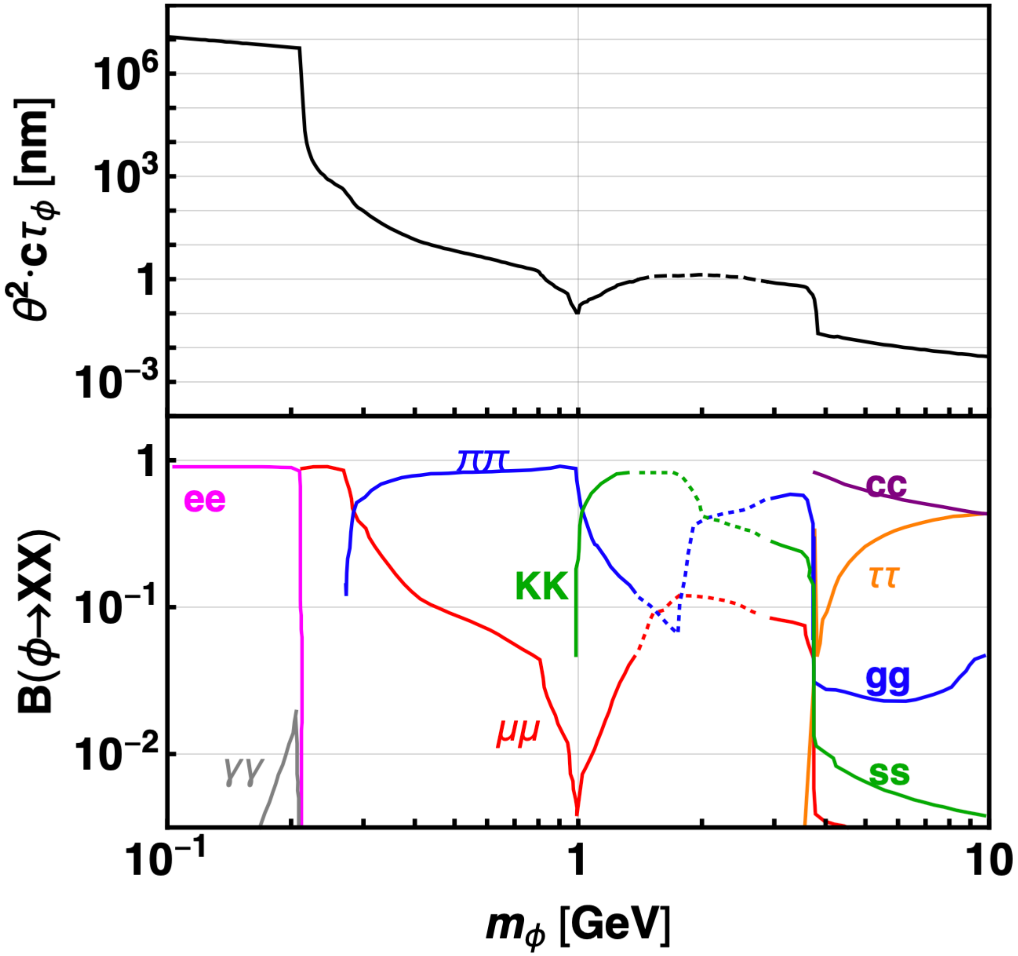


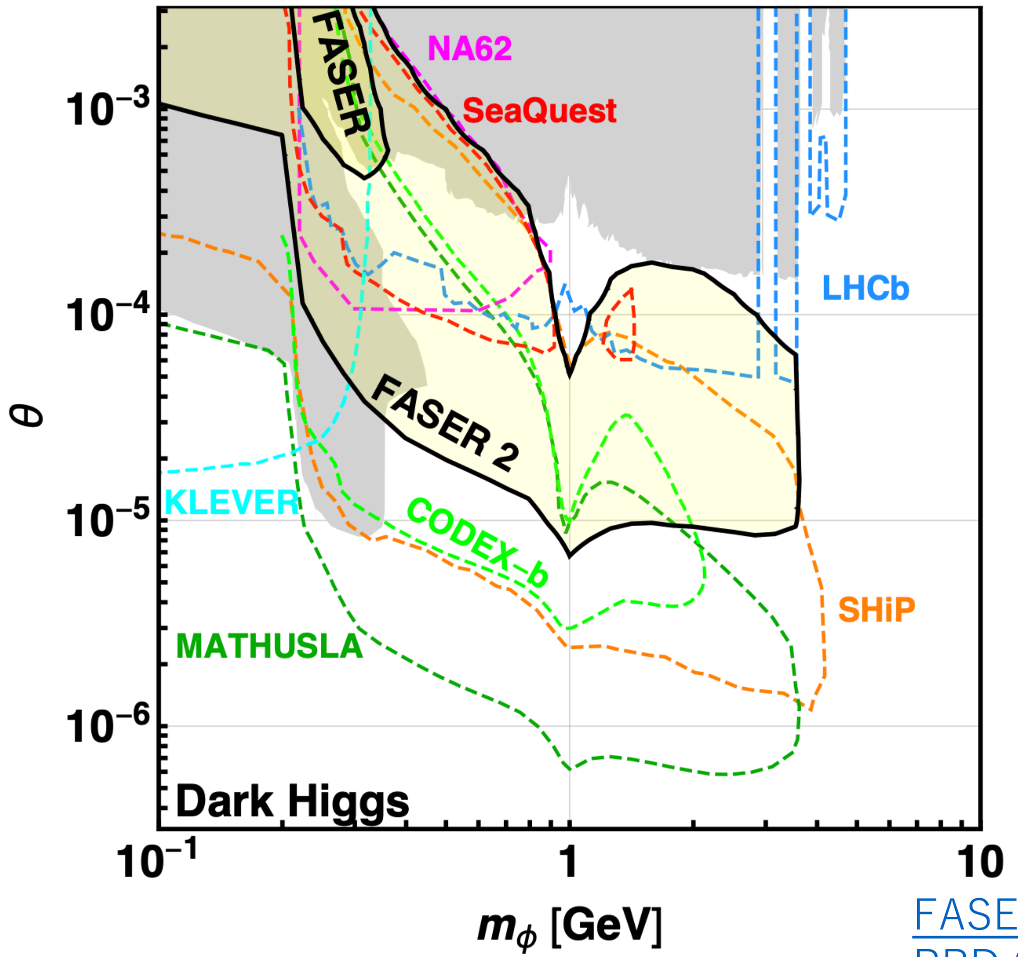


FASER collaboration, PRD 99 (2019) 9, 095011

Introduction – FASER

Expected sensitivity (Dark Higgs boson)

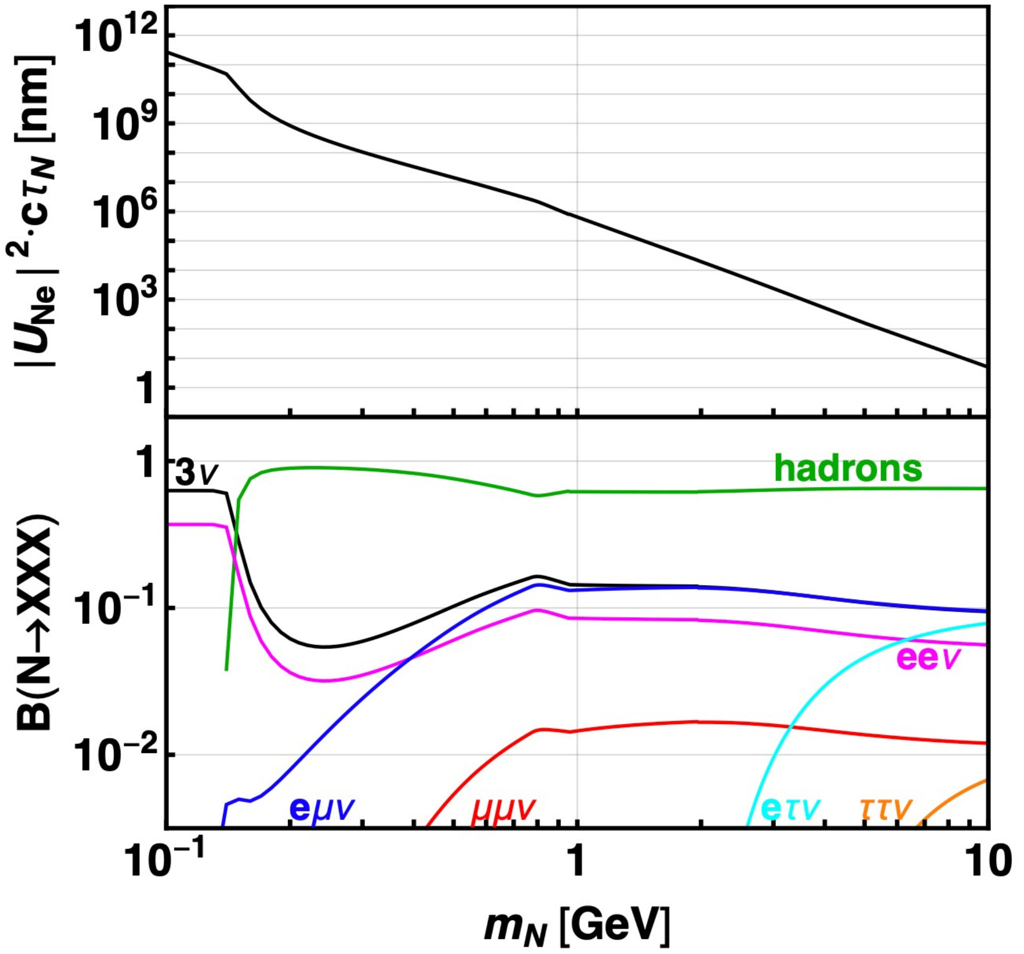


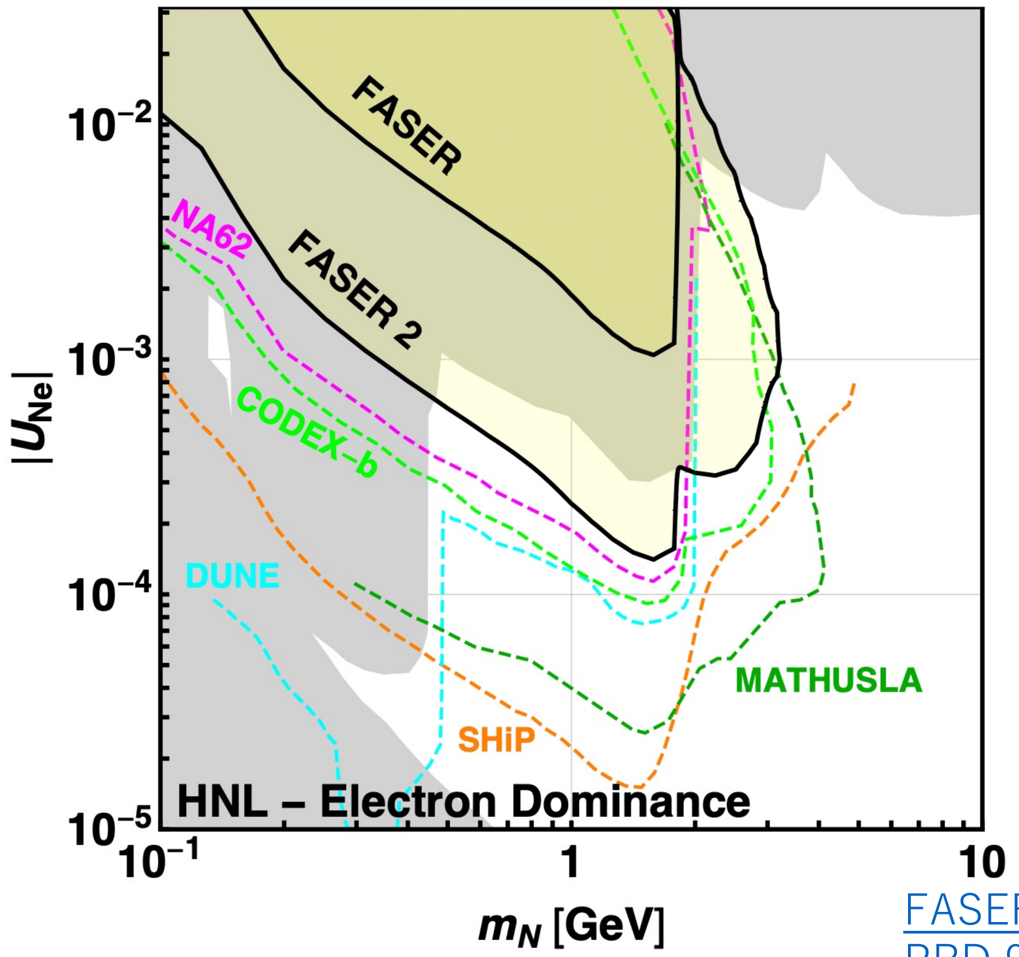


FASER collaboration, PRD 99 (2019) 9, 095011

Introduction – FASER

Expected sensitivity (Heavy neutral lepton)

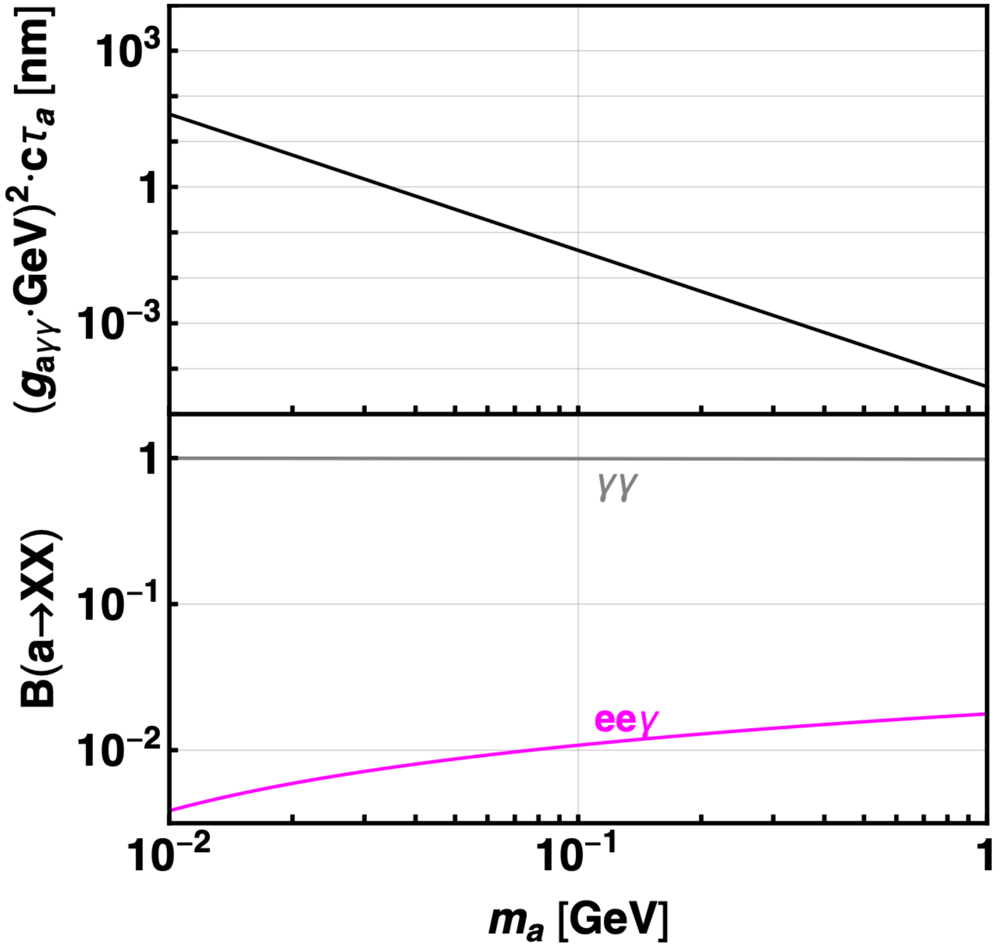


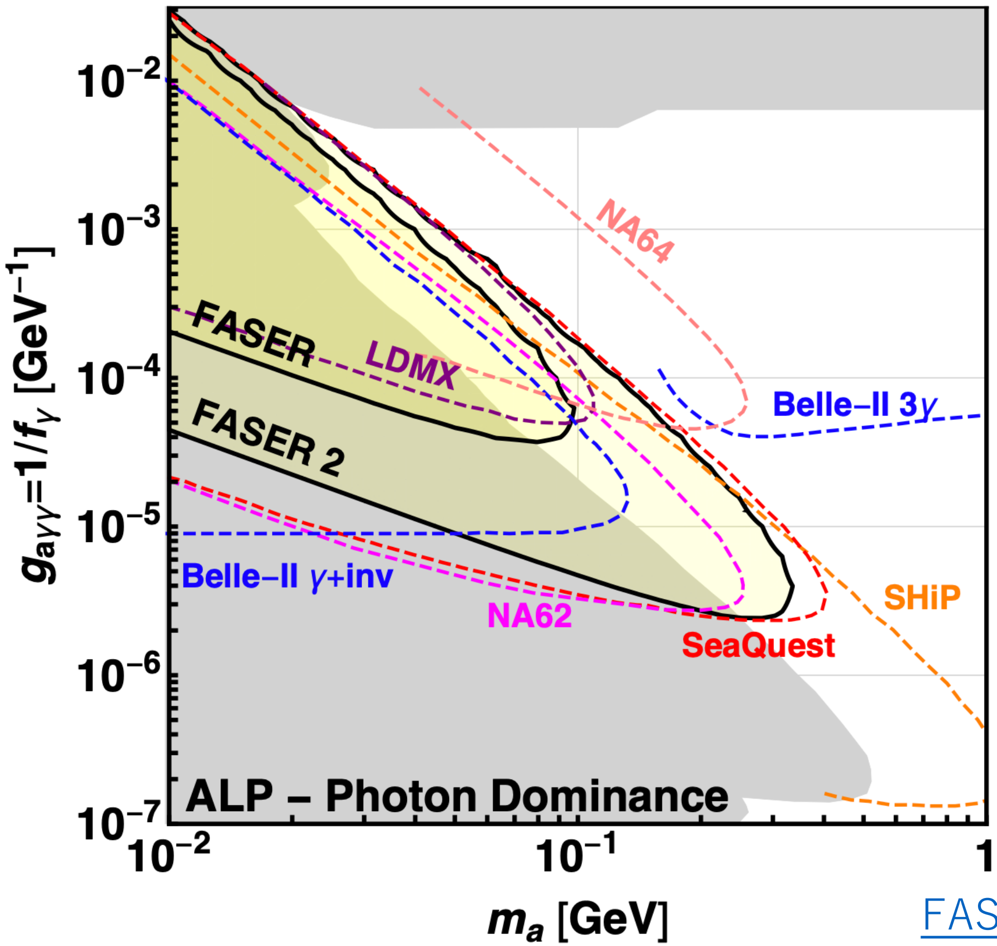


FASER collaboration, PRD 99 (2019) 9, 095011

Introduction – FASER

Expected sensitivity (Axion-like particle)





FASER collaboration, PRD 99 (2019) 9, 095011

Introduction – FASER

Background

- Rock & LHC infrastructure eliminate most background

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

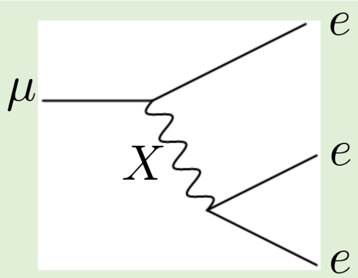
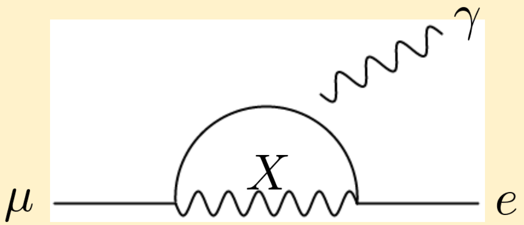
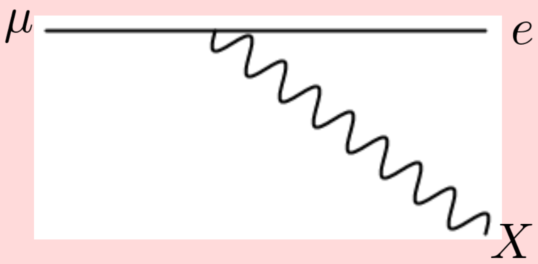
- Muon brems. → photon
  : 80000 events
- CC / NC interactions of neutrinos ($E_\nu \gtrsim 100$ [GeV])
  : O(1) events

Veting entering charged particles with an efficiency of 99.99%

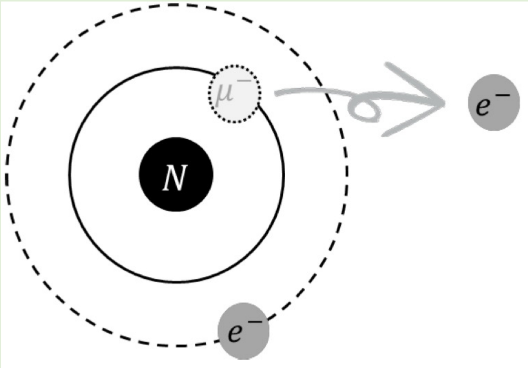
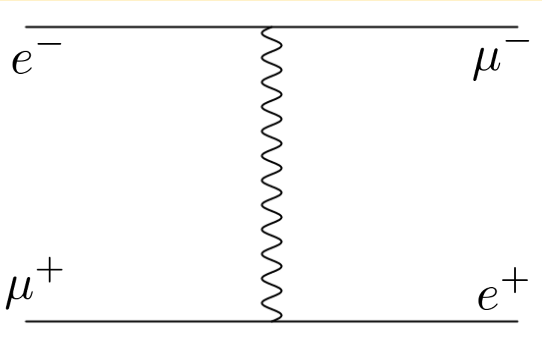
Almost background free

Introduction – CLFV

Constraints on CLFV

CLFV process		Exp. limit on BR	Future prospect
$\mu \to eee$		1.0×10^{-12} SINDRUM Collaboration (1988)	$\approx 10^{-16}$ Mu3e Collaboration (2013)
$\mu \to e\gamma$		4.2×10^{-13} MEG Collaboration (2016)	$\approx 6 \times 10^{-14}$ MEGII Collaboration (2018)
$\mu \to eX$		$\approx 10^{-5}$ TWIST Collaboration (2015)	—

Constraints on CLFV

CLFV process		Exp. limit on BR	Future prospect
$\mu N \to eN$		7×10^{-13} (Au) SINDRUM II Collaboration (2006)	7×10^{-15} [Phase -I] 2.6×10^{-17} [Phase -II] (Al) COMET Collaboration (2020)
$\mathrm{Mu} \leftrightarrow \overline{\mathrm{Mu}}$		Oscillation probability 8.3×10^{-11} $(B = 0.1\ \mathrm{Tesla})$ MACS Experiment (1999)	$\mathcal{O}(10^{-13})$ J. Tang et al., MACE working group collaboration (2021)

Introduction – CLFV

Decay of scalar boson

Almost all ϕ decay into dark photon

Nonzero ϕ-Higgs mixing : θ

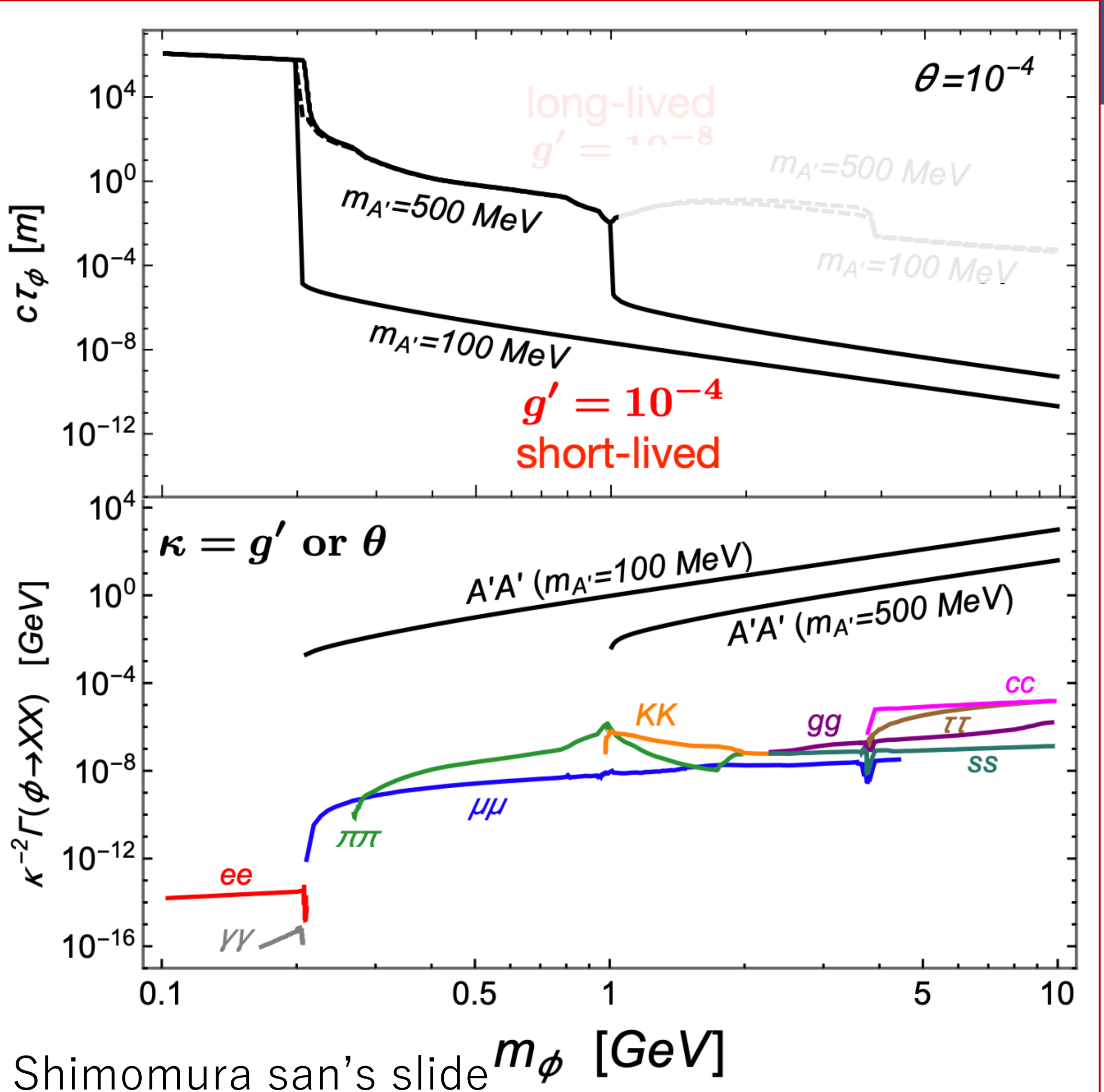
➡ A small number of ϕ can decay into SM particles

for $g' > \theta$

ϕ : short-lived, A' : long-lived

for $g' \ll \theta$

ϕ : long-lived



From Shimomura san's slide

Dark photon from scalar decay

Decay of scalar boson

Almost all ϕ decay into dark photon

Nonzero ϕ-Higgs mixing : θ

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for $g' > \theta$

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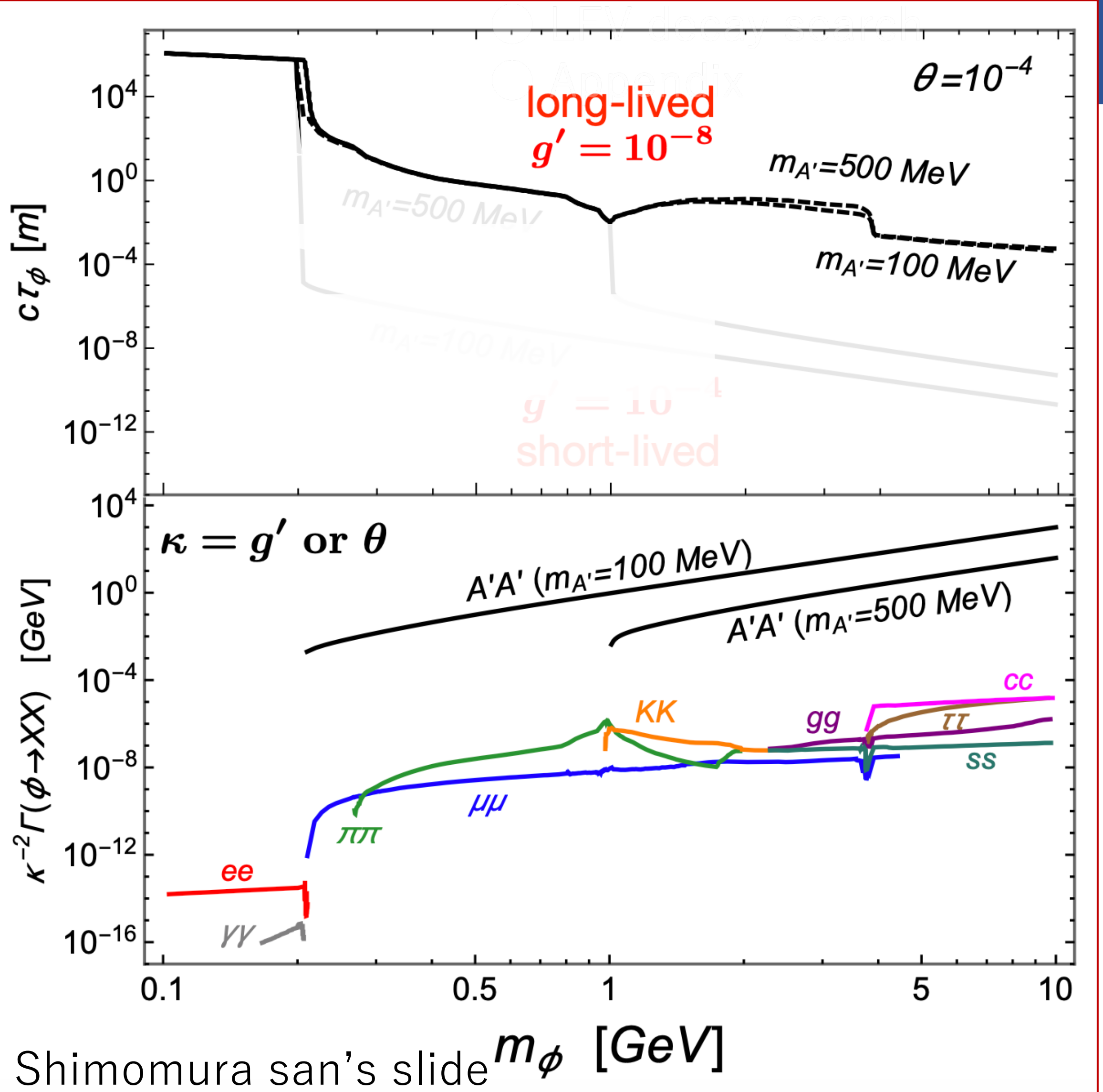

From Shimomura san's slide

Dark photon from scalar decay

Decay of scalar boson

Almost all ϕ decay into dark photon

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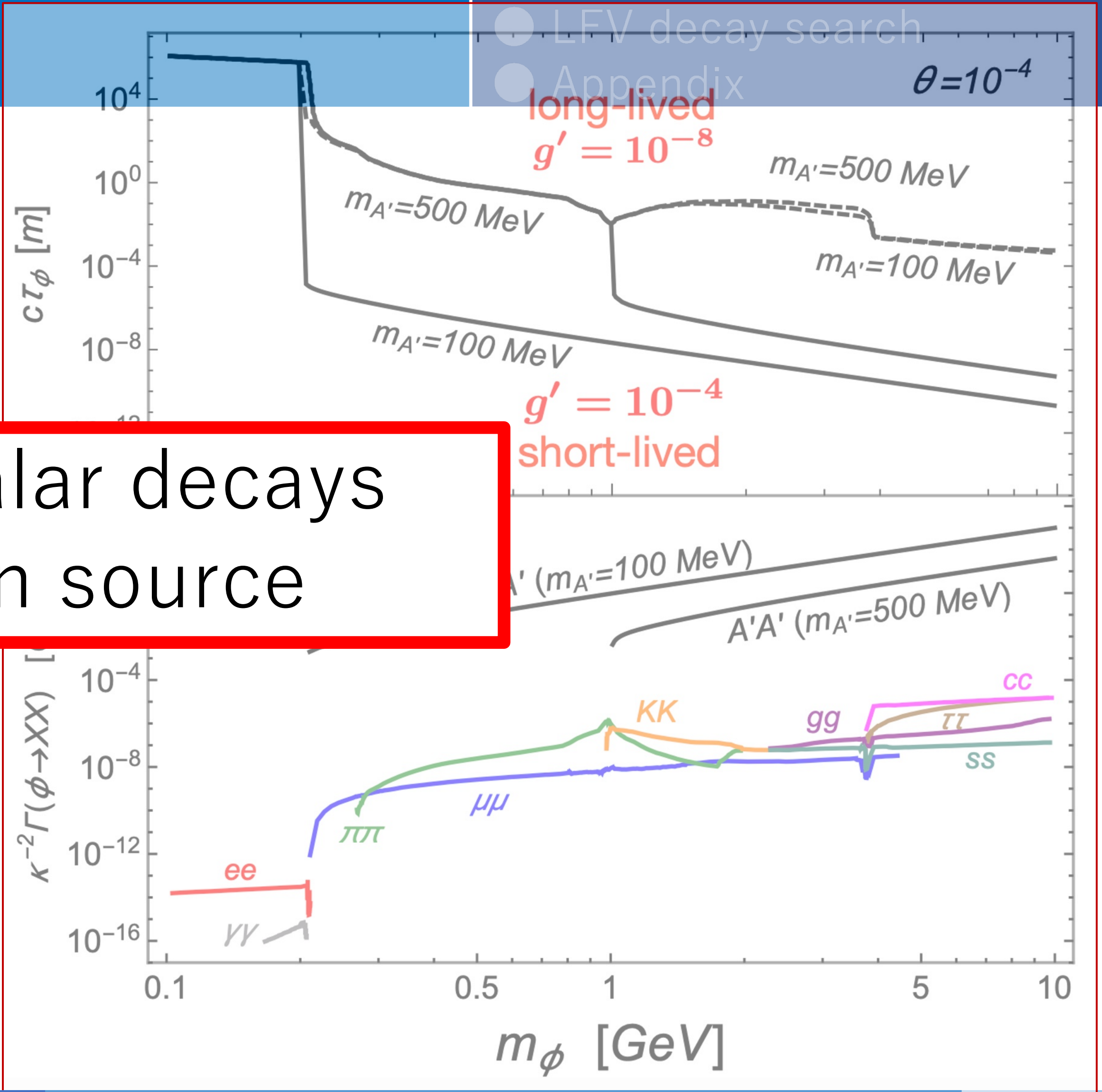


We consider scalar decays as dark photon source

for $g' > \theta$

ϕ : short-lived, A' : long-lived

for $g' \ll \theta$

ϕ : long-lived

Dark photon from scalar decay

Scalar production

Production processes

$$B \to X_s \phi\,, \quad K^\pm \to \pi^\pm \phi\,,$$

$$K_{L(S)} \to \pi^0 \phi\,, \quad \eta' \to \eta\phi$$

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

$$\mathrm{Br}(K^\pm \to \pi^\pm \phi) = 2.0 \times 10^{-3} \frac{2p_\phi^0}{m_K} \theta^2\,,$$

$$\mathrm{Br}(K_L \to \pi^0 \phi) = 7.0 \times 10^{-3} \frac{2p_\phi^0}{m_K} \theta^2\,,$$

$$\mathrm{Br}(K_S \to \pi^0 \phi) = 2.2 \times 10^{-6} \frac{2p_\phi^0}{m_K} \theta^2\,,$$

$$\mathrm{Br}(\eta' \to \eta \phi) = 7.2 \times 10^{-5} \frac{2p_\phi^0}{m_{\eta'}} \theta^2\,,$$

Number of scalars

7.1×10^{13} B mesons are produced in LHC Run3 ($150\ \mathrm{fb}^{-1}$)

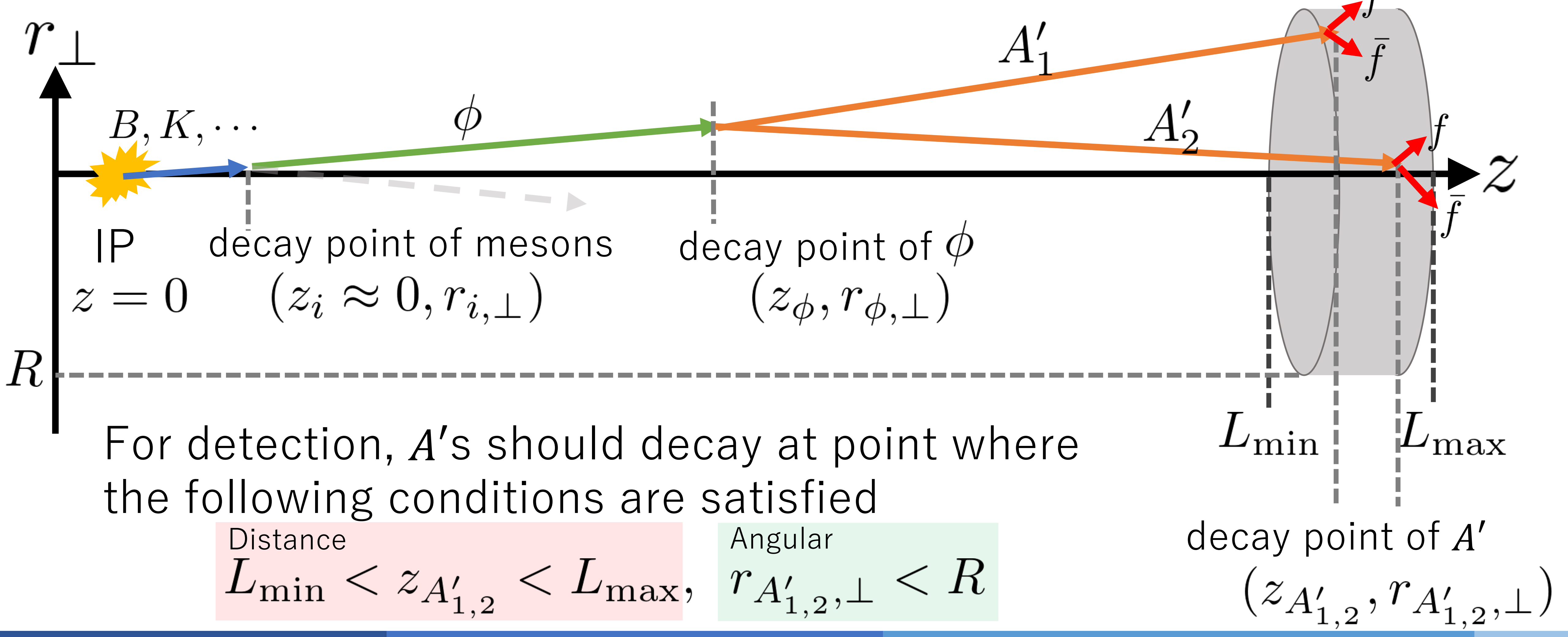
➡ Scalars ϕ are produced by rare decays of B mesons

$$\mathrm{BR}(B \to X_s \phi) \sim \theta^2$$

$$\Rightarrow N_{B\to\phi} \sim 10^6 \quad (\text{for } \theta = 10^{-4})$$

Dark photon from scalar decay

Geometrical acceptance



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

Distance
$$L_{\rm min} < z_{A'_{1,2}} < L_{\rm max},$$

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

Geometrical acceptance

Probability of dark photon decay in detector

$$\mathcal{P}^{\rm det}_{A'}(\boldsymbol{p}_{A'},\boldsymbol{p}_\phi) = \frac{1}{\bar{d}_\phi \cos\theta_\phi}\int_{z_{\phi,\rm min}}^{z_{\phi,\rm max}} dz_\phi e^{-\frac{z_\phi}{\bar{d}_\phi\cos\theta_\phi}} \frac{1}{\bar{d}_{A'}\cos\theta_{A'}}\int_{z_{A',\rm min}}^{L_{\rm max}} dz_{A'} e^{-\frac{z_{A'}-z_\phi}{\bar{d}_{A'}\cos\theta_{A'}}}$$

Distance

$$\times\,\Theta(R - r_{A',R})\Theta(R - r_{A',F})$$

Angular

$\bar{d}_{\phi(A')}$: decay length of ϕ (A') in lab frame

$\Theta(x)$: Heaviside step function

$\theta_{\phi(A')}$: angular of ϕ (A') with respect of beam axis (z-axis)

$r_{A',F(R)}$: distance of A' from beam axis at $z_{A'} = L_{\rm min}$ ($L_{\rm max}$)

Dark photon from scalar decay

Number of events

Number of dark photons which decay in detector

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

$$\times \mathcal{P}^{\det}_{A'_j}(\boldsymbol{p}_\phi, \boldsymbol{p}_{A'})$$

$$\sim 150\ \mathrm{fb}^{-1} \times 10^{11}\ \mathrm{ab} \times 10^{-7} \times 1 \times 10^{-2}$$

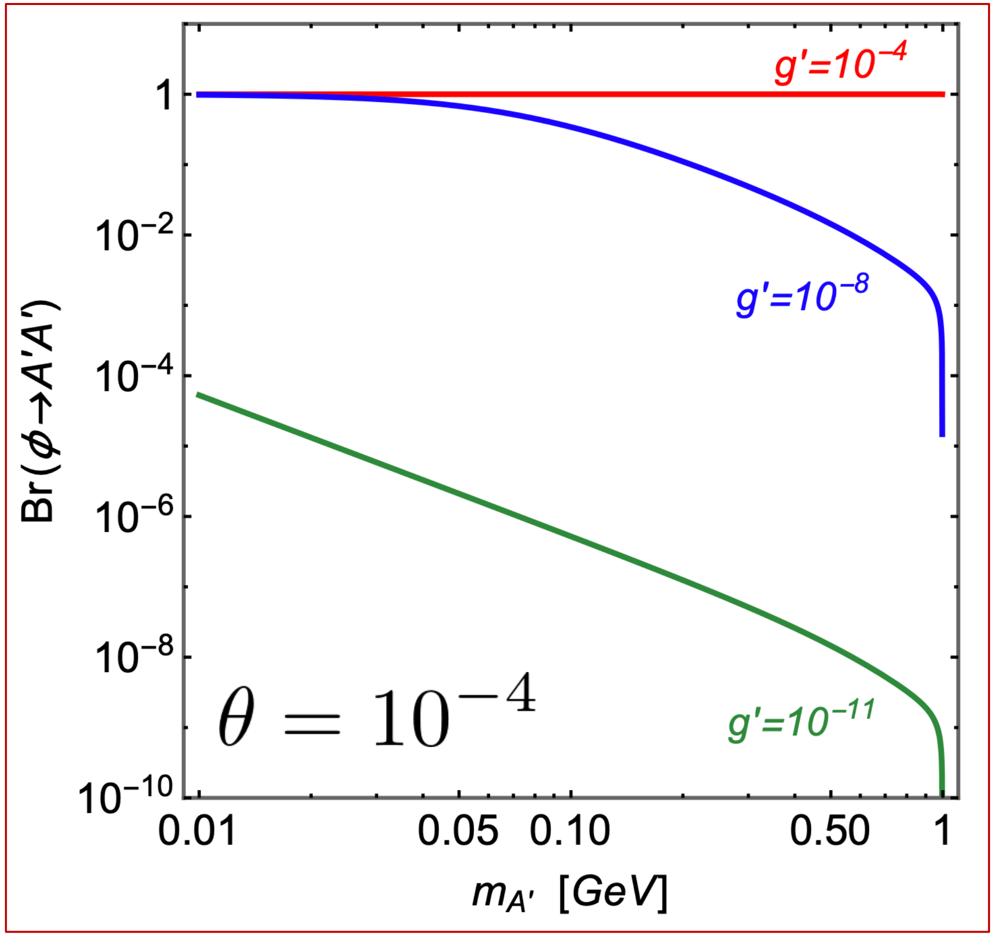
$$\sim 10$$

$\mathcal{L}$: integrated luminosity

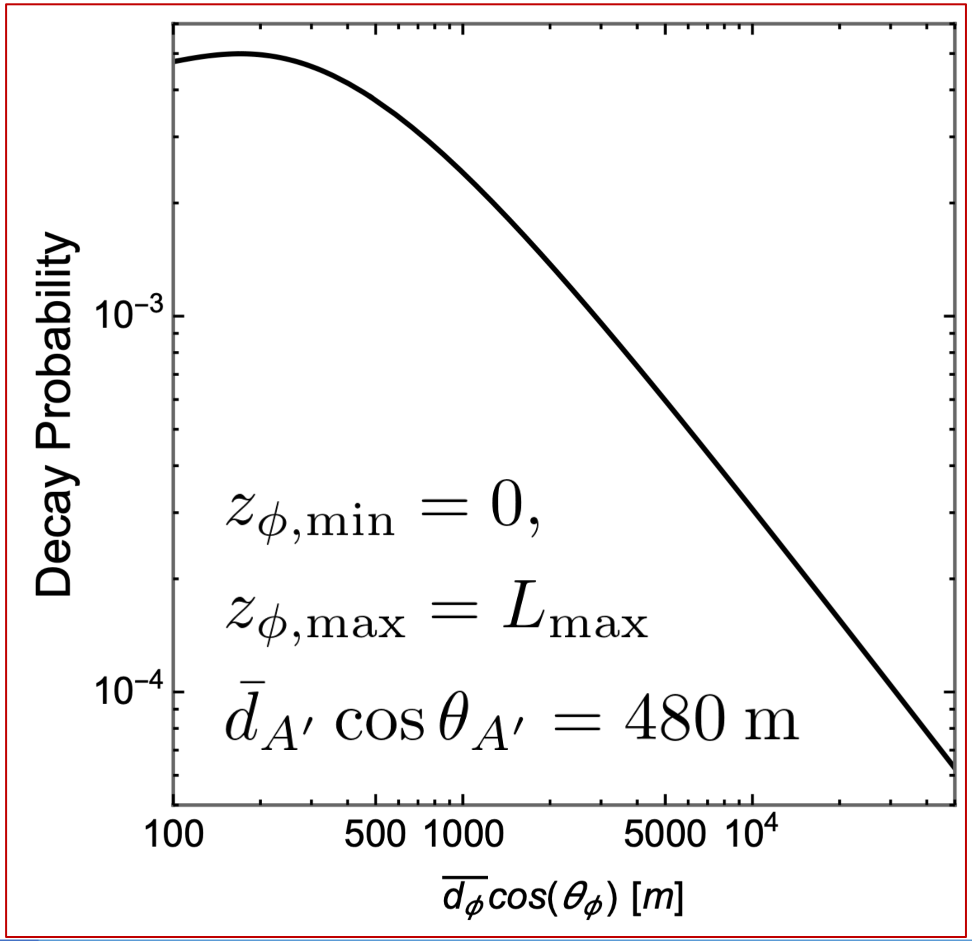
for FASER (LHC Run3)

Dark photon

Branching fraction of $\phi \to A'A'$

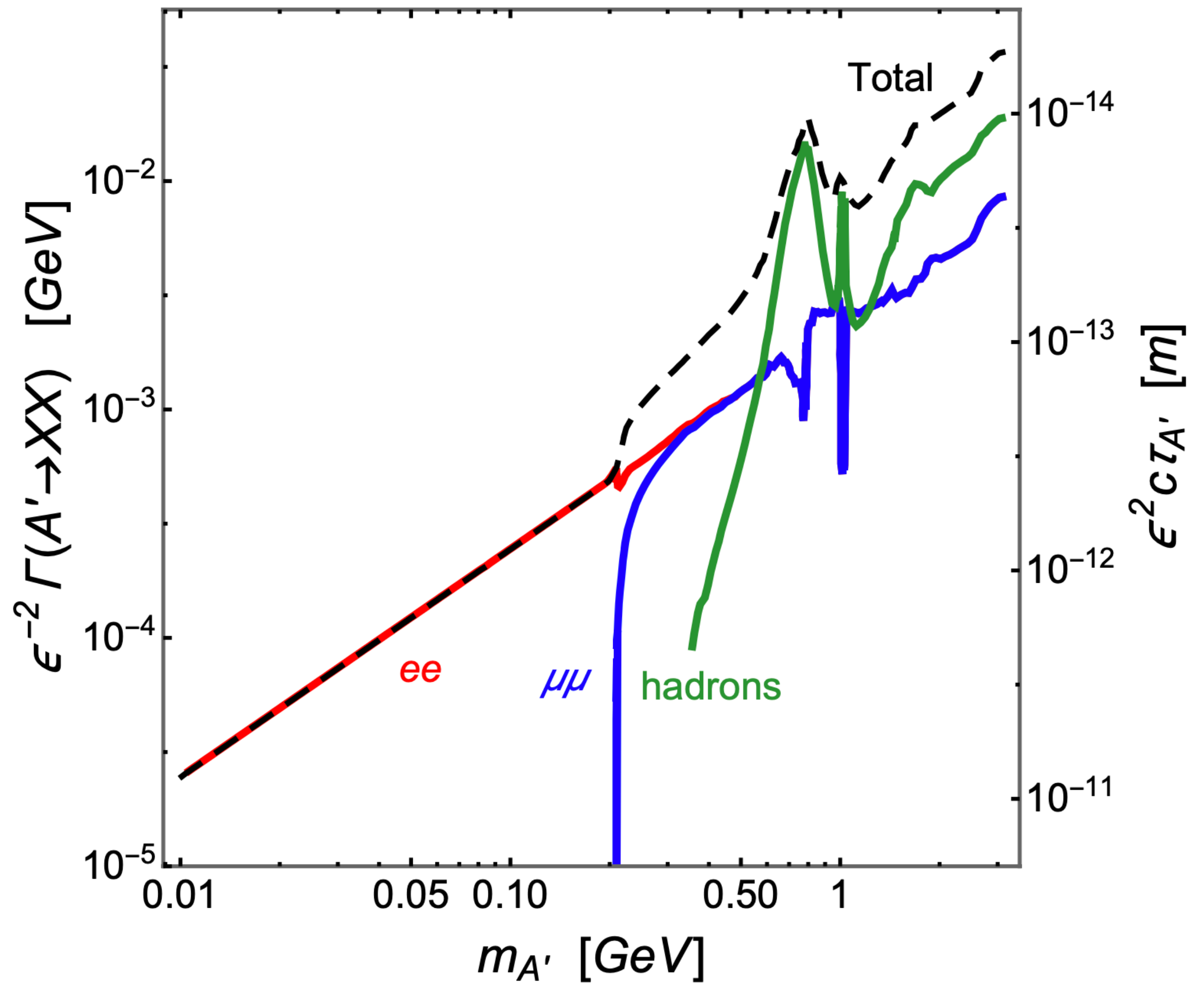


Decay probability of ϕ



Dark photon

Decay length of A'



Charged LFV decay search

Constraints from past experiments

Not only FASER experiment, but also past beam dump experiments can search for LFV decays ?

→ Parameter region where FASER can observe LFV decays is alive or already excluded ?

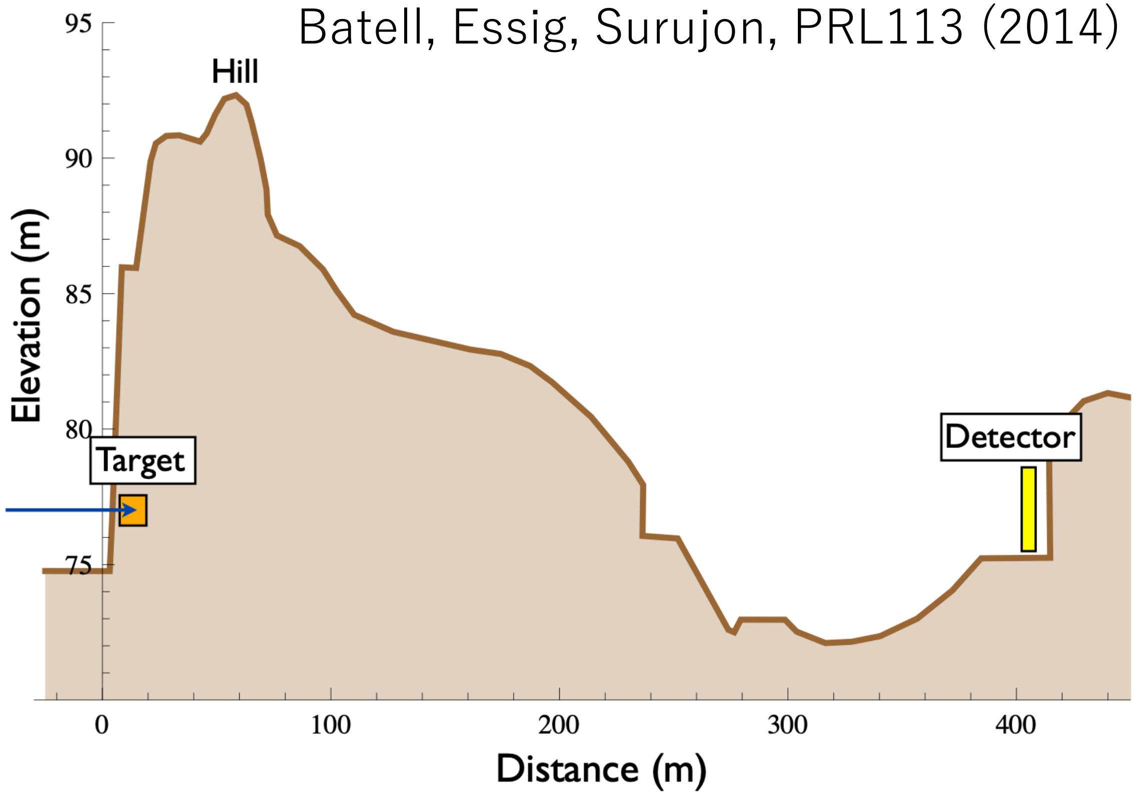
↓

We have explored possibility of observation of LFV decays by E137 experiment

e^- Beam Dump Experiment

E137 experiment

Batell, Essig, Surujon, PRL113 (2014)



Experiment parameters

Beam : 20 GeV e^- beam
$\cong 2\times10^{20}$ EOT

Target : Aluminum beam dump

Shielding : 179m ground (hill)

Decay volume : 204m open air

Detector : EM calorimeter + MWPC

e^- Beam Dump Experiment

New particle production

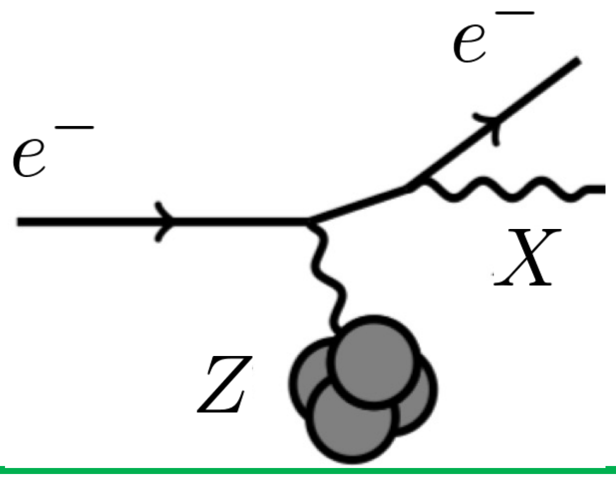
Batell, Essig, Surujon, PRL113 (2014)

Lagrangian

Coupling with electrons

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

Bremsstrahlung production

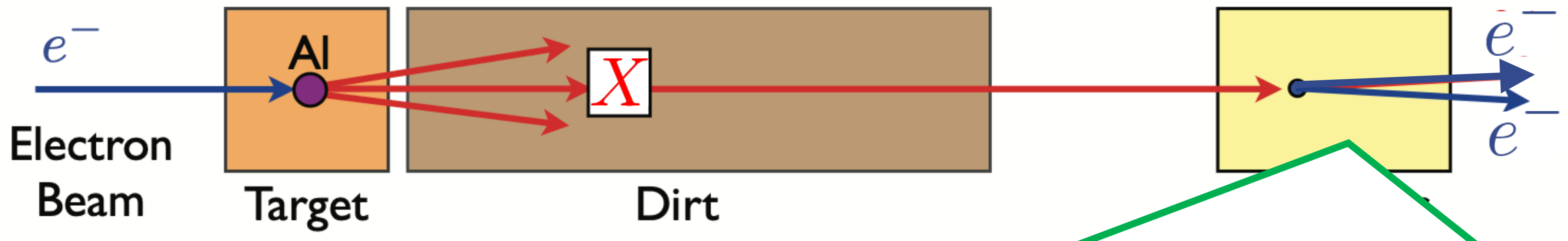


New particles are produced through bremsstrahlung process

e^- Beam Dump Experiment

New particle detection

Batell, Essig, Surujon, PRL113 (2014)
Batell, Essig, Surujon, PRL113 (2014)



Lagrangian

Coupling with electrons

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

Detection

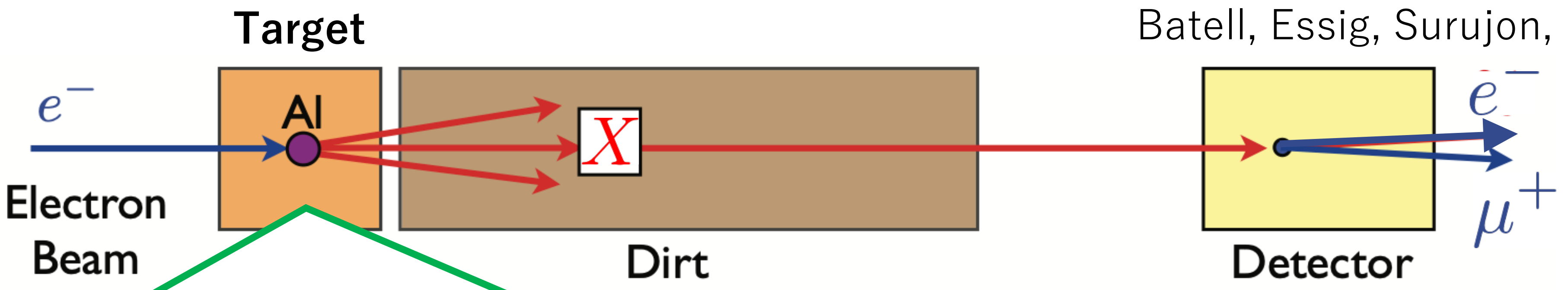
Decay into e^+e^- pair → Detection

After passing through shield, new particles decay into e^+e^- pair in decay volume and are detected

e^- Beam Dump Experiment

New particle production with LFV coupling

Batell, Essig, Surujon, PRL113 (2014)

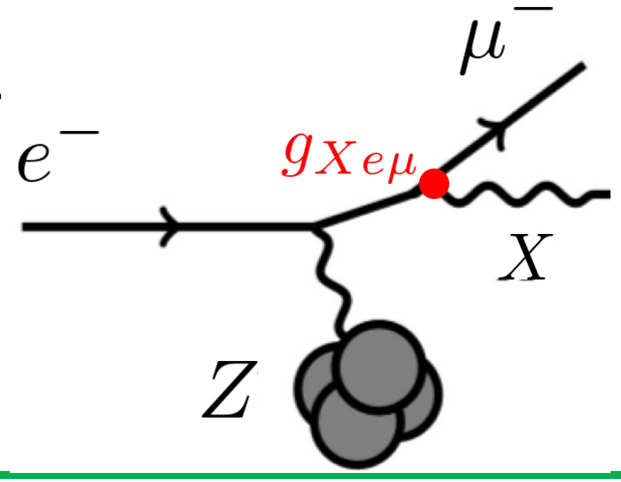


Lagrangian

Coupling with e & μ

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

Bremsstrahlung production

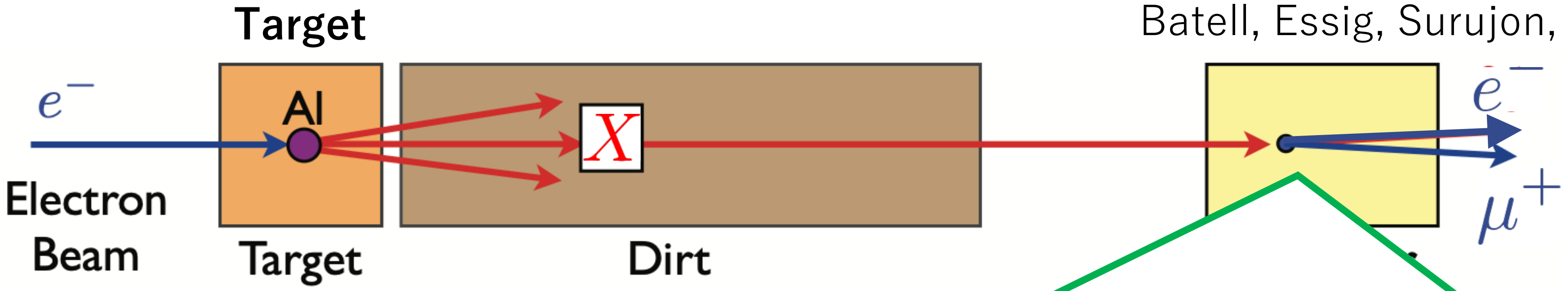


Possibly LFV interactions contribute to bremsstrahlung production

e^- Beam Dump Experiment

New particle detection with LFV coupling

Batell, Essig, Surujon, PRL113 (2014)

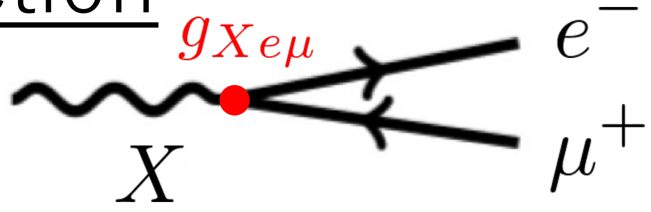


Lagrangian

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 beam dump experiment

e^- Beam Dump Experiment

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

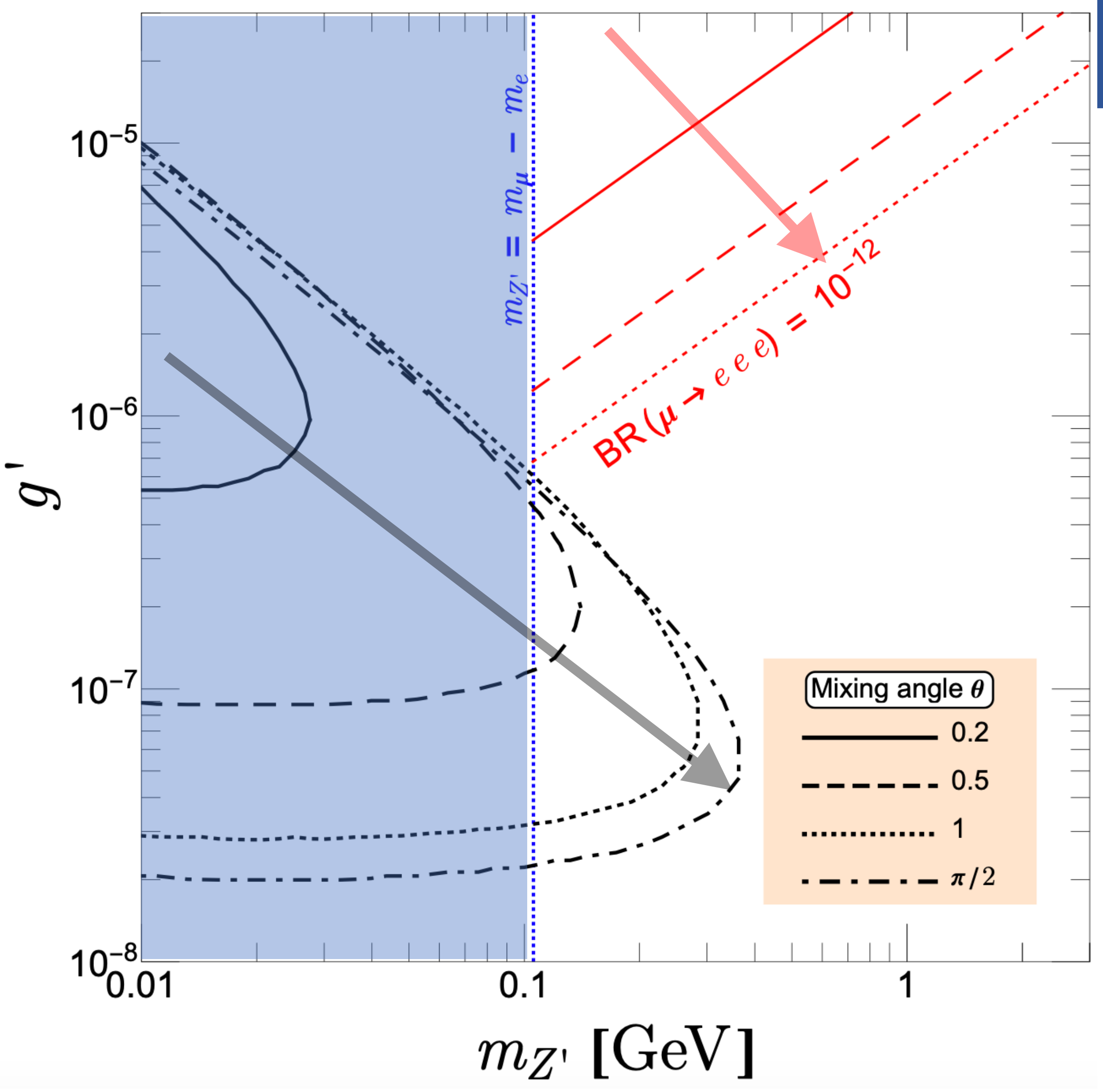
Result

Constraint on LFV coupling

$U(1)_{L_\mu - L_\tau}$ model

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

- ○ Large mixing angle
  - ➡ Larger e^+e^- coupling
    (More Z' production & signals)
  - ➡ Larger μ^+e^- coupling
    (More Z' production ?
    & Stronger constraint from $\mu \to eee$)
- ○ For $\theta \gtrsim 0.4$ rad , E137 experiment can give stronger bound on LFV coupling than $\mu \to e$



Result

Production through LFV coupling

For $E_{Z'} = E_e \, (x = 1)$,

LFC

$$\frac{d\sigma^{\rm LFC}_{\rm brems}}{dx} \sim \frac{\alpha^2 g'^2}{2\pi} \xi \beta_{Z'} \times \frac{1}{E_e^2}$$

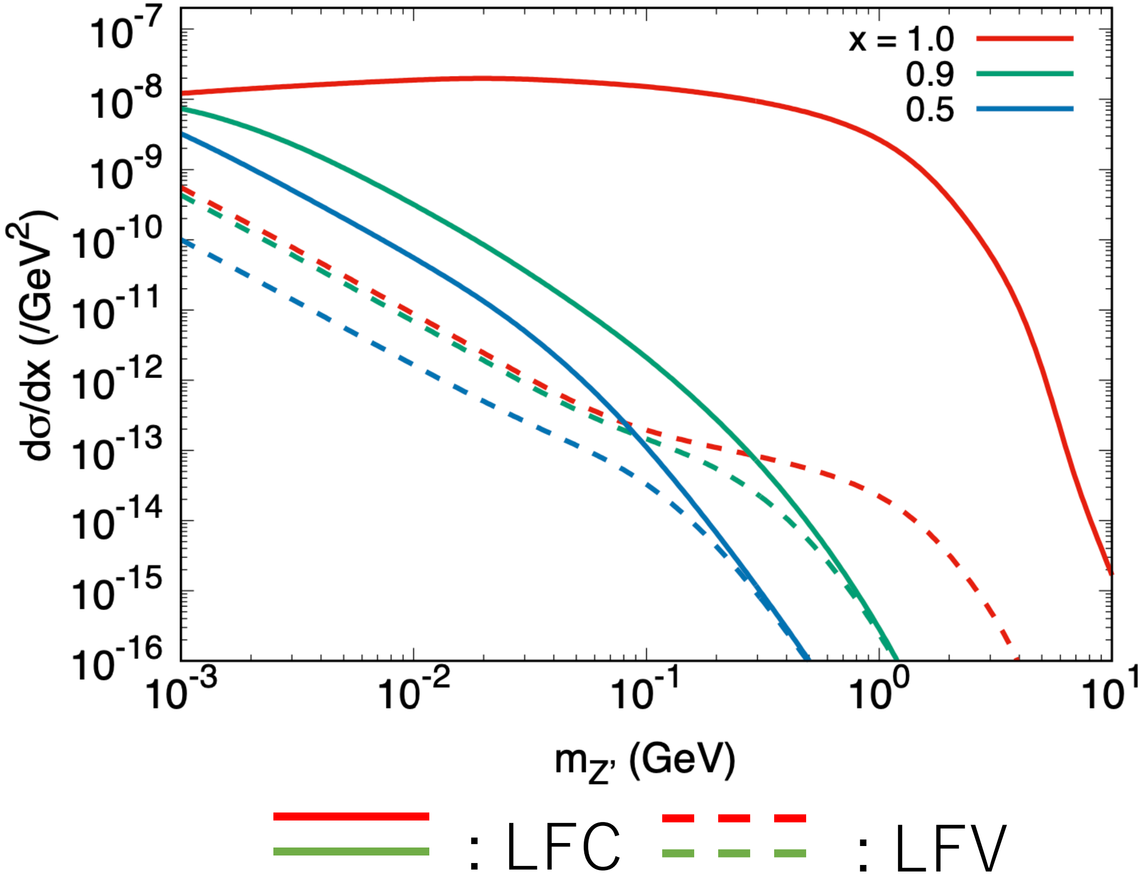
$\gg$

LFV

$$\frac{d\sigma^{\rm LFV}_{\rm brems}}{dx} \sim \frac{\alpha^2 g'^2}{2\pi} \xi \beta_{Z'} \times \frac{E_e^2 \theta_{\rm max}^2}{m_\mu^2 m_{Z'}^2}$$

Z' production through LFV coupling is negligible

Production cross section



Result

Constraint on LFV coupling

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 μ^+e^- coupling
- Shorter decay length for $m_\phi > m_e + m_\mu$ & smaller $\mathrm{BR}(\phi \to e^+e^-)$
- Sensitivity region is covered with constraints from $\mu \to e\phi$