Search for Lepton Flavor Violating Decay at FASER

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素粒子物理学の進展2021

09/07/2021 @ オンライン

Based on
T. Araki, **KA**, H. Otono, T. Shimomura, Y. Takubo (ongoing work)

Summary

- FASER can search for the regions where interactions with SM particles are small, and in such regions, new physics may be hidden
- In the region where FASER has a sensitivity, charged lepton flavor violating (CLFV) couplings can be as large as charged lepton flavor conserving (CLFC) couplings
- FASER can explore unsearched region of LFV coupling by search for LFV decays

Introduction

Introduction

Charged Lepton Flavor Violation (cLFV)

In the SM

Neutrino Oscillation

➡ cLFV is violating

Prediction : $\sim 10^{-54}$

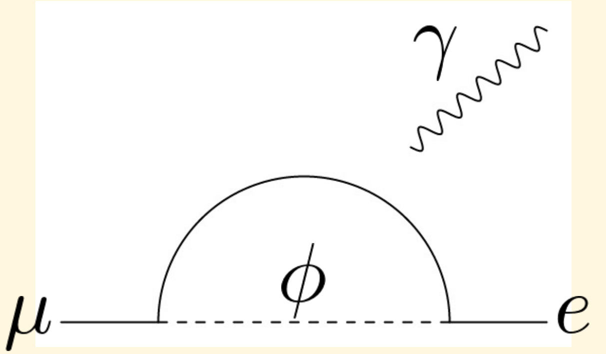
$\wedge\!\!\wedge$

Experiements : $< 10^{-12}$

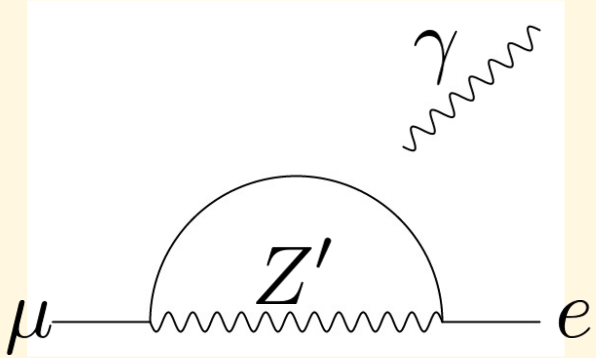
➡ It is impossible to detect cLFV process

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 : $\sim 10^{-50}$

$\gg$

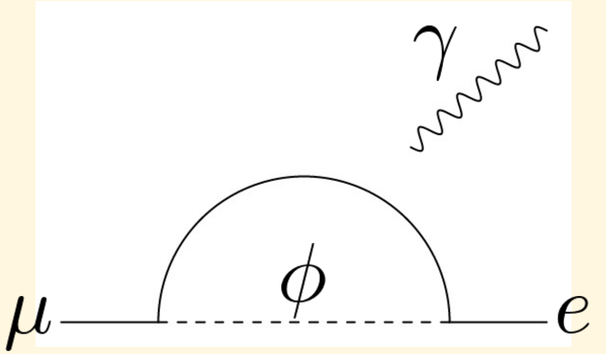
Expe

It is

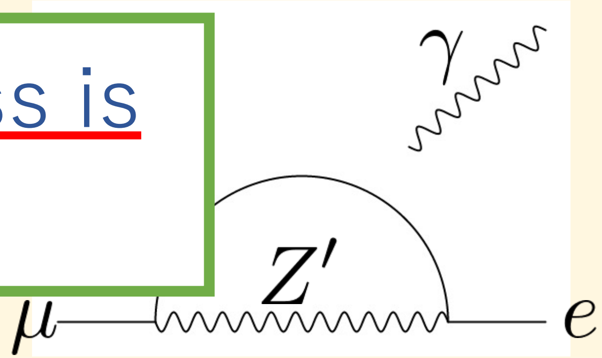
cLFV process

Beyond the SM

- Leptophilic scalar



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



- Dark Photon w/ dipole LFV coupling

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

Origin of cLFV interaction

Ex) Leptophilic scalar boson

$$y_{\alpha\beta}\bar{\ell}_{L,\alpha}\phi\ell_{R,\beta} + \text{h.c.}$$ [flavor basis]

Diagonalization of charged lepton mass matrix

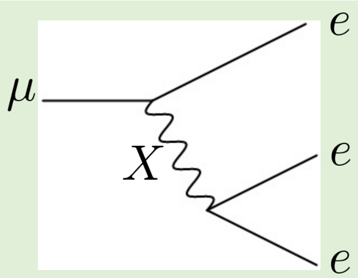
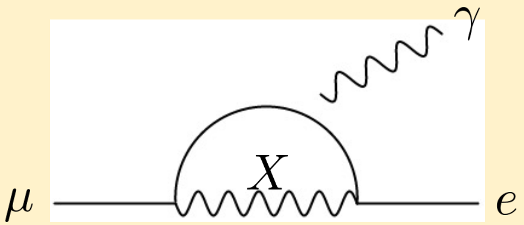
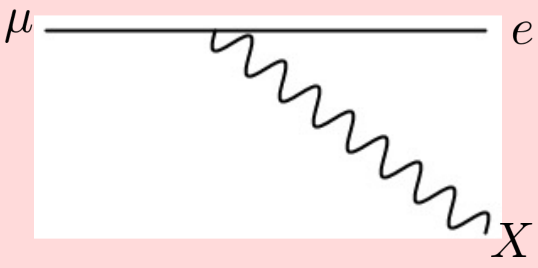
$$\ell_\alpha = V_{\alpha i}\ell_i$$

$$\underline{V^\dagger_{i\alpha}y_{\alpha\beta}V_{\beta j}}\bar{\ell}_{L,i}\phi\ell_{R,j} + \text{h.c.}$$ [mass basis]

cLFV interaction

Introduction

Constraints on cLFV

cLFV process		Exp. limit on BR	Future prospect
$\mu \to eee$		1.0×10^{-12} SINDRUM Collaboration (1988)	$\approx 10^{-16}$ PDG (2020)
$\mu \to e\gamma$		4.2×10^{-13} MEG Collaboration (2016)	$\approx 6 \times 10^{-14}$ PDG (2020)
$\mu \to eX$		$\approx 10^{-5}$ TWIST Collaboration (2015)	—

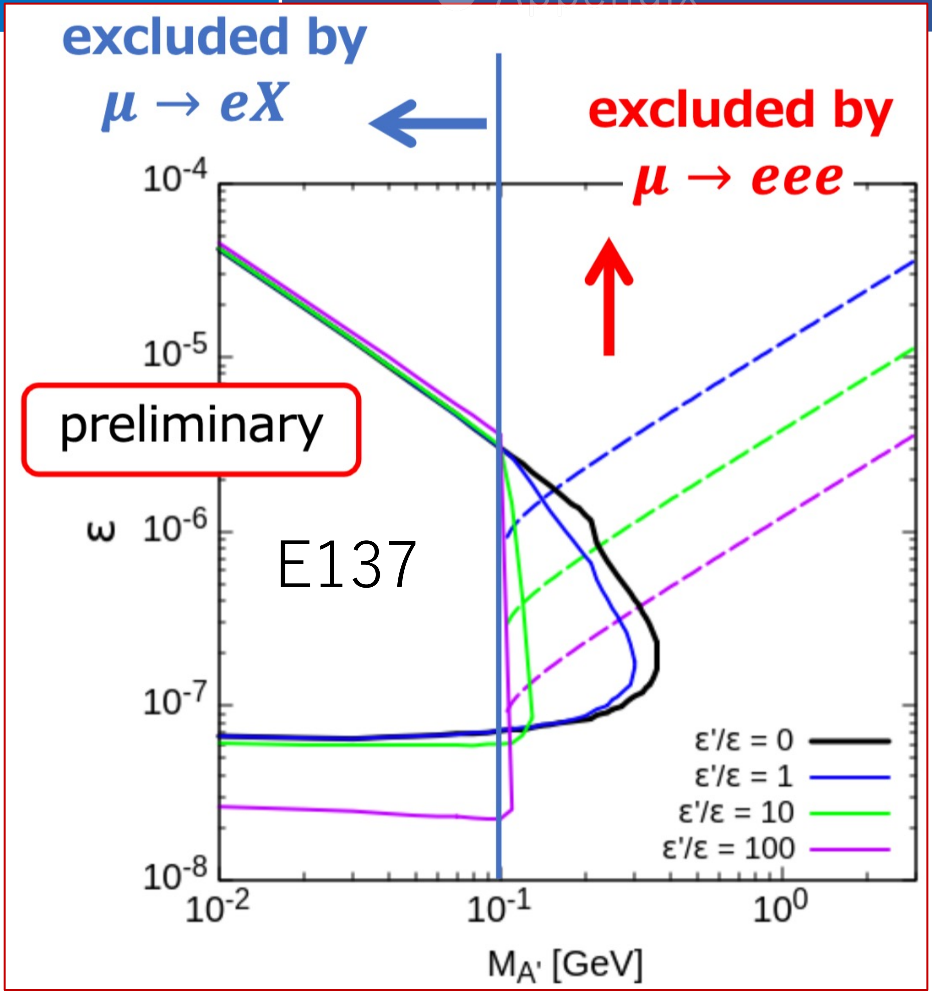
Introduction

Constraints on cLFV

Ex) Dark photon model

In light mass region ($m_{A'} \sim 0.01 - 1$ GeV), cLFV decay of muon gives upper bound as shown in right figure

CLFV coupling can be as large as CLFC one in such a region ($m_\phi \sim 0.01 - 1$ GeV & $y_e \sim 10^{-8} - 10^{-5}$)



From Araki san's slide

Introduction

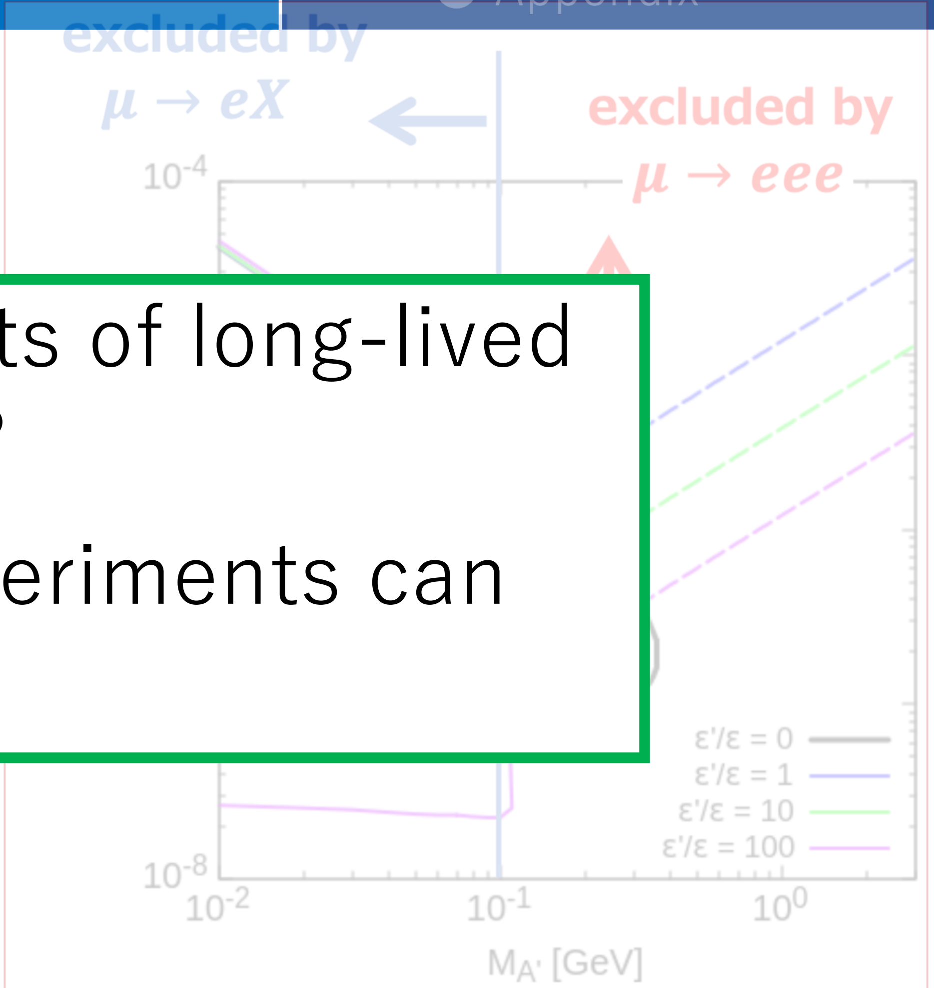
Constraints on cLFV

Ex) Dark photon model

In light mass region ($m_{A'} \sim 0.01 - 1$ GeV),
cLFV
as sh

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

CLFV
one in such a region ($m_\phi \sim 0.01 - 1$ GeV &
$y_e \sim 10^{-8} - 10^{-5}$)



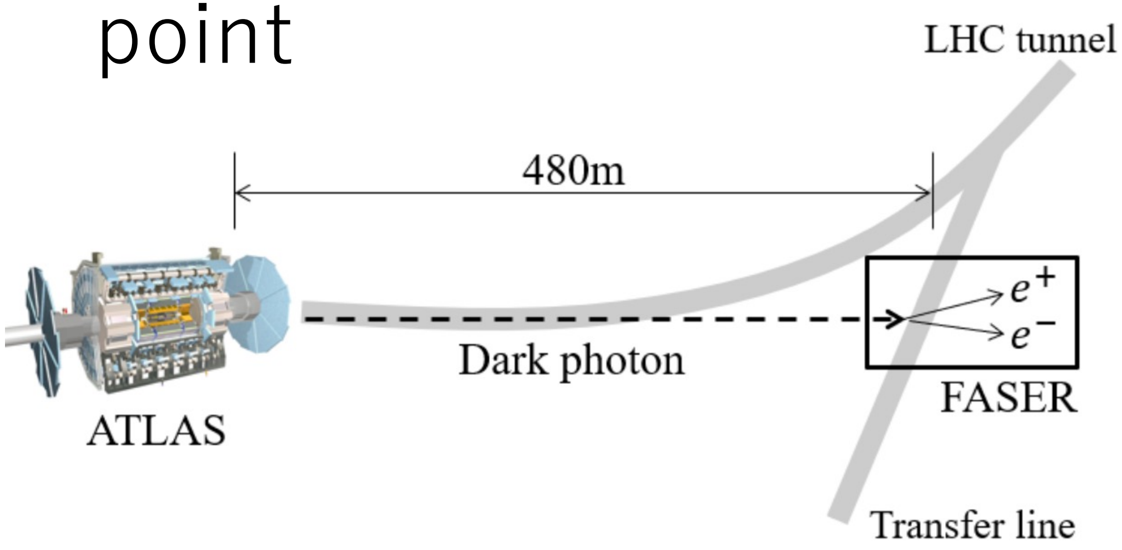
From Araki san's slide

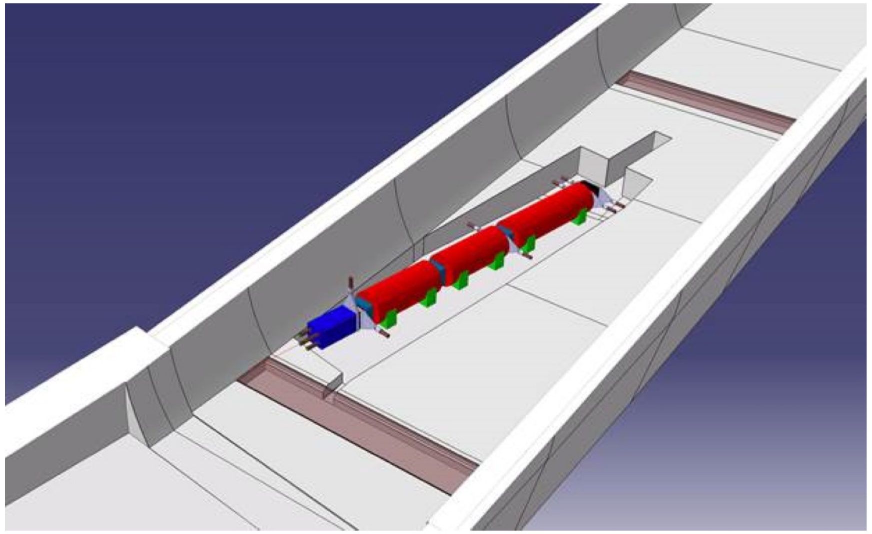
FASER

FASER

FASER (ForwArd Search ExpeRiment at the LHC)

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





Advantage

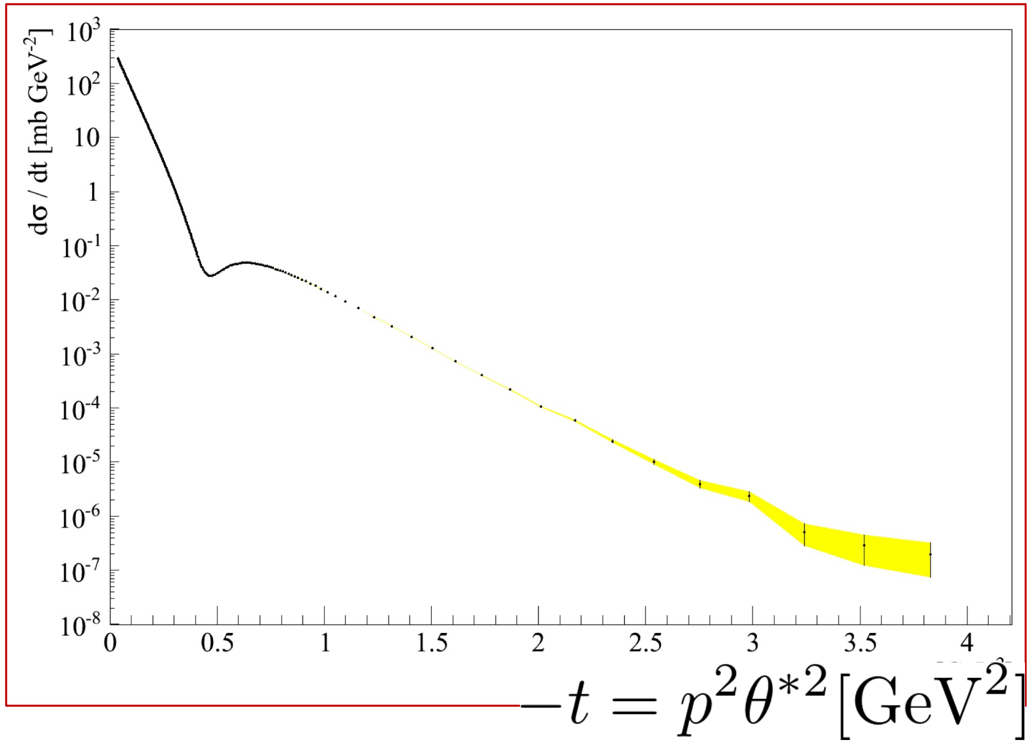
1) pp-reaction cross section @ LHC is very large in the direction of beam axis

➡ 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



TOTEM Collaboration, EPJC 79 (2019) 10, 861

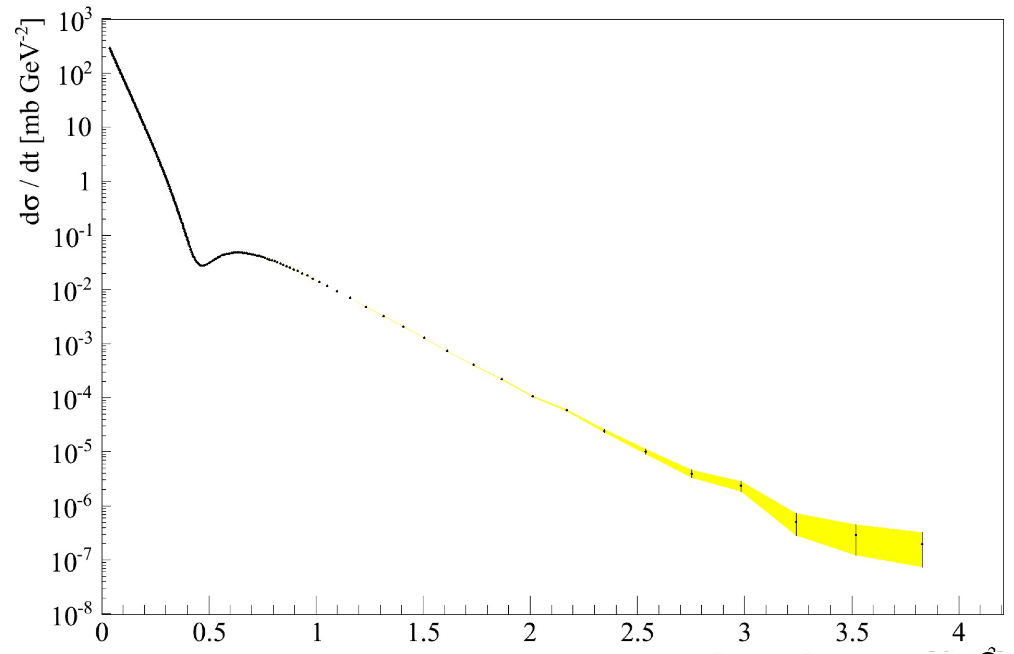
FASER

Advantage

3) FASER is placed in far-forward region

➡ FASER can search light BSM particles

Inelastic scattering cross section of pp collision @ 13TeV LHC



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

TOTEM Collaboration, EPJC 79 (2019) 10, 861

cf.) LHC

New physics searches @ LHC focus on high p_T

➡ LHC can search heavy BSM particles

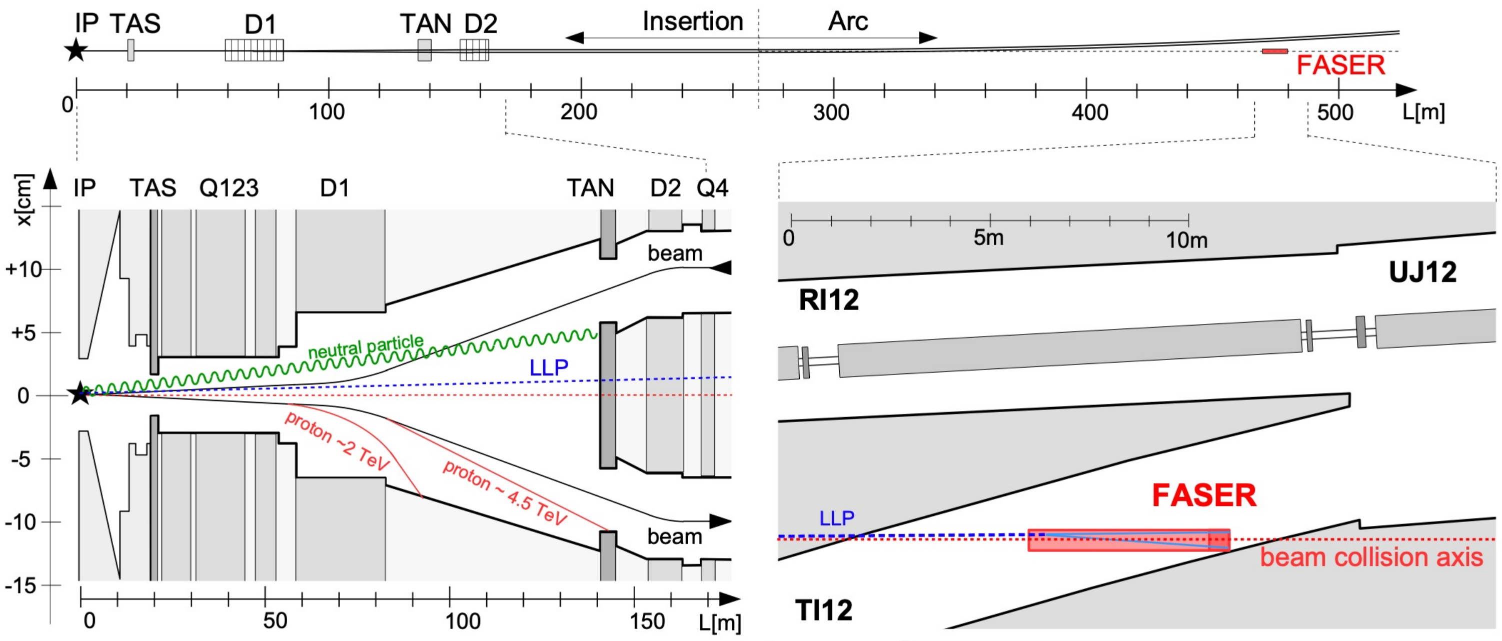
Location

FASER detector will be 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]



FASER

Detector

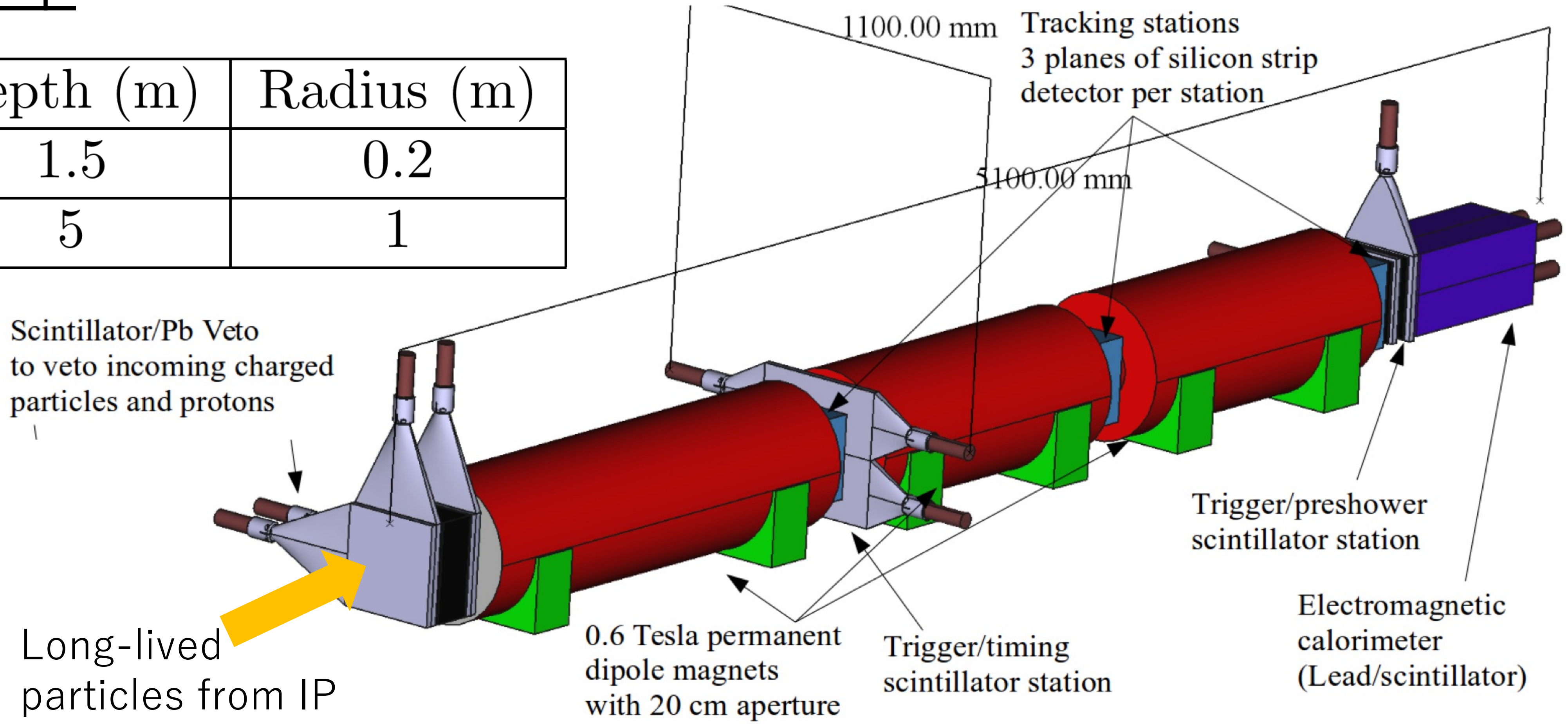
Detector setup

From 1901.04468 [hep-ex]

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

FASER
$150\ \mathrm{fb}^{-1}$
@ LHC Run3

FASER2
$3\ \mathrm{ab}^{-1}$
@ HL-LHC



FASER

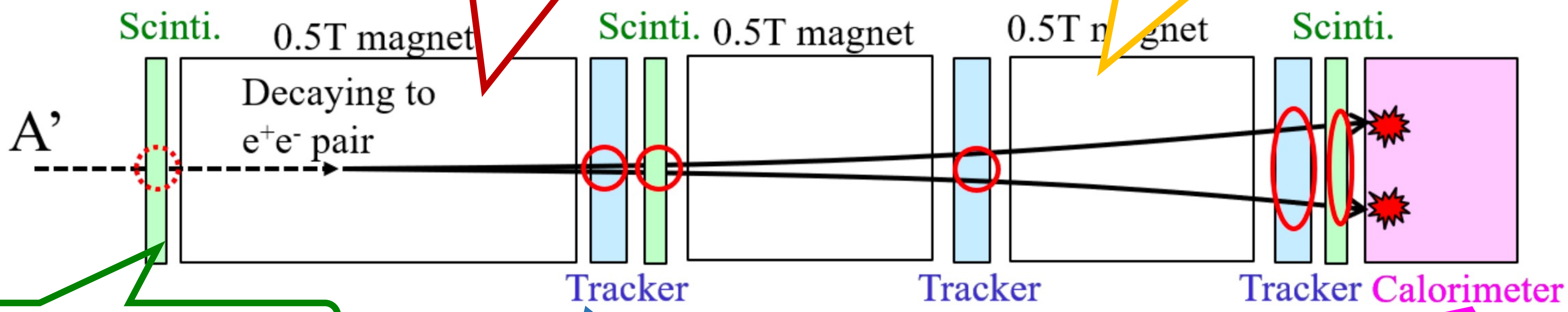
Detector

Detector setup

1.5m decay volume

Spectrometer : separating daughter particles by magnets

From Takubo san's slide



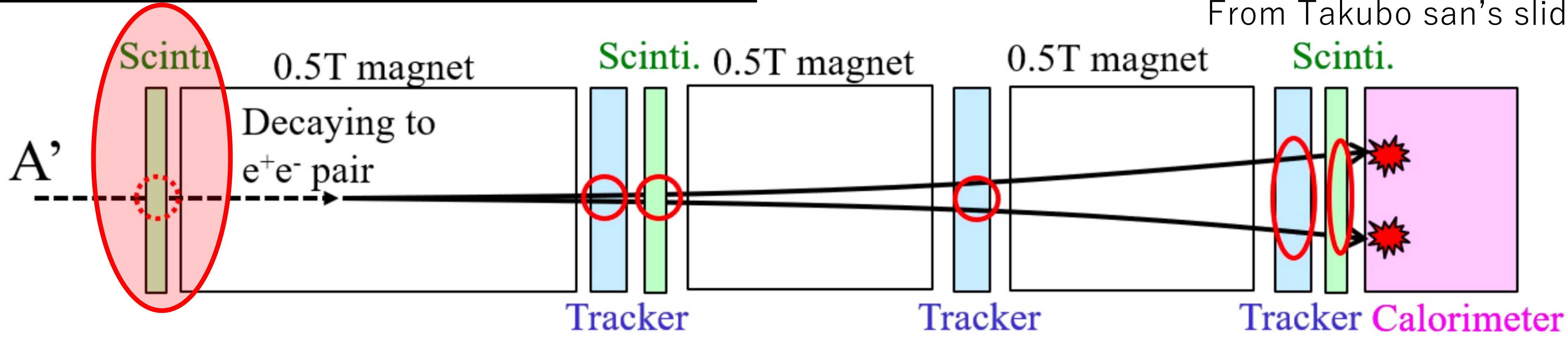
Scintillator veto

Calorimeter : measurement of energies of daughter particles

Tracker : Measurement of two oppositely charged particle and their momenta

Benchmark signal (dark photon)

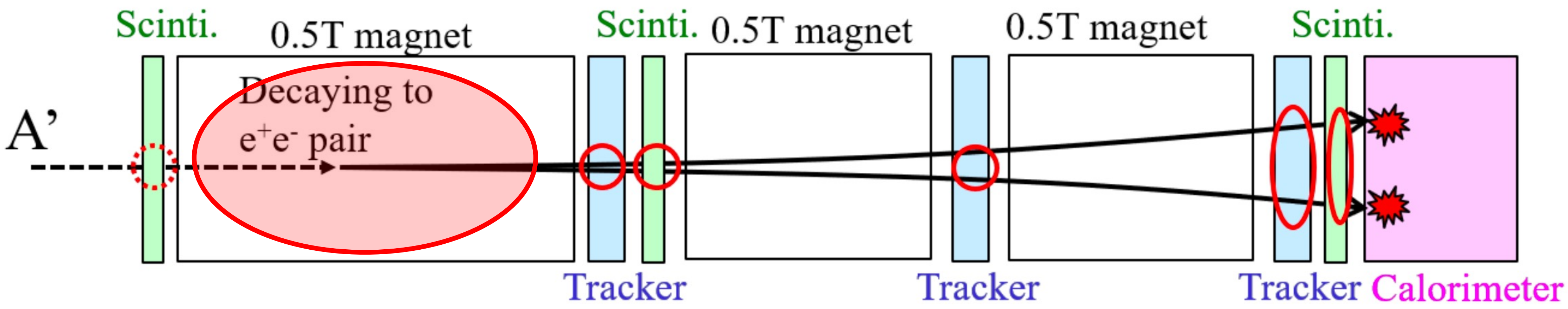
From Takubo san's slide



1, No signal in veto scintillator

Benchmark signal (dark photon)

From Takubo san's slide



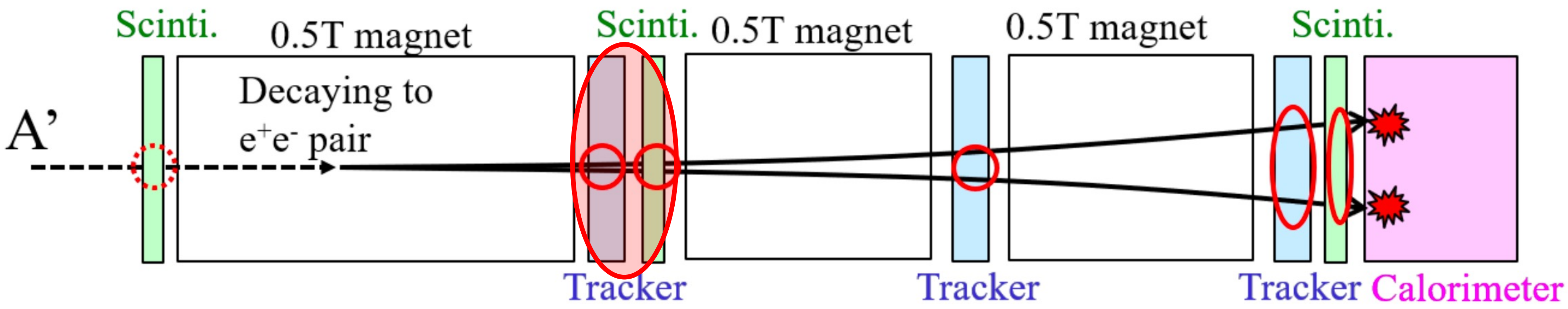
1, No signal in veto scintillator

2, Decay into e^{+} and e^{-}

Detector

Benchmark signal (dark photon)

From Takubo san's slide

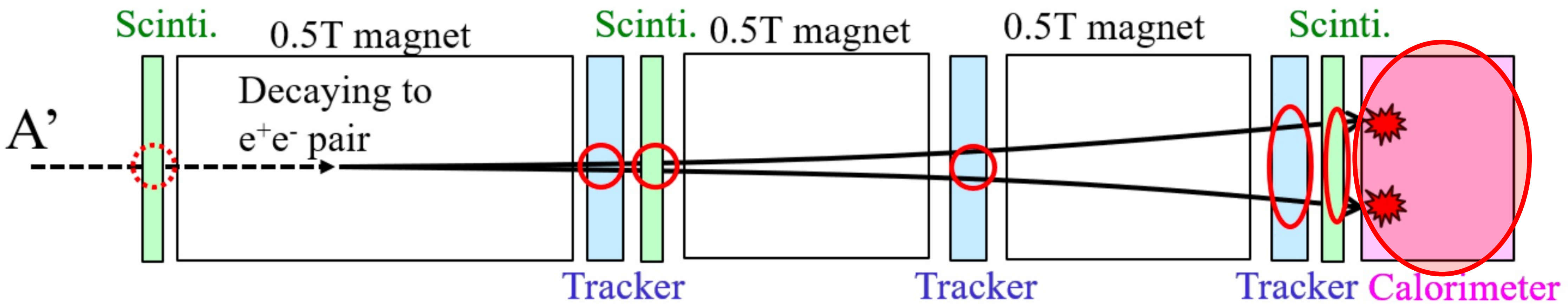


1, No signal in veto scintillator
2, Decay into e^+ and e^-
3, Detection of two high energy charged tracks
that emanate from a common vertex

Detector

Benchmark signal (dark photon)

From Takubo san's slide

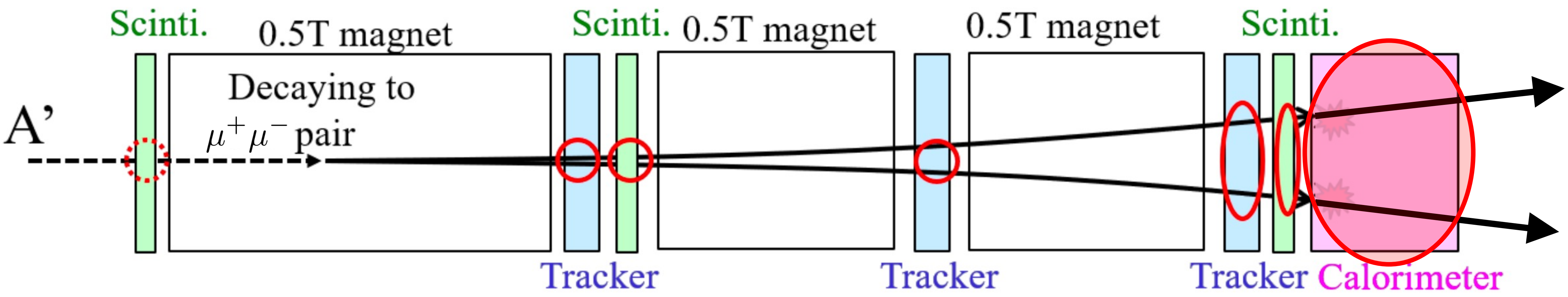


1, No signal in veto scintillator
2, Decay into e^+ and e^-
3, Detection of two high energy charged tracks
that emanate from a common vertex
4, Measurement of large EM energy in calorimeter

Detector

Benchmark signal (dark photon)

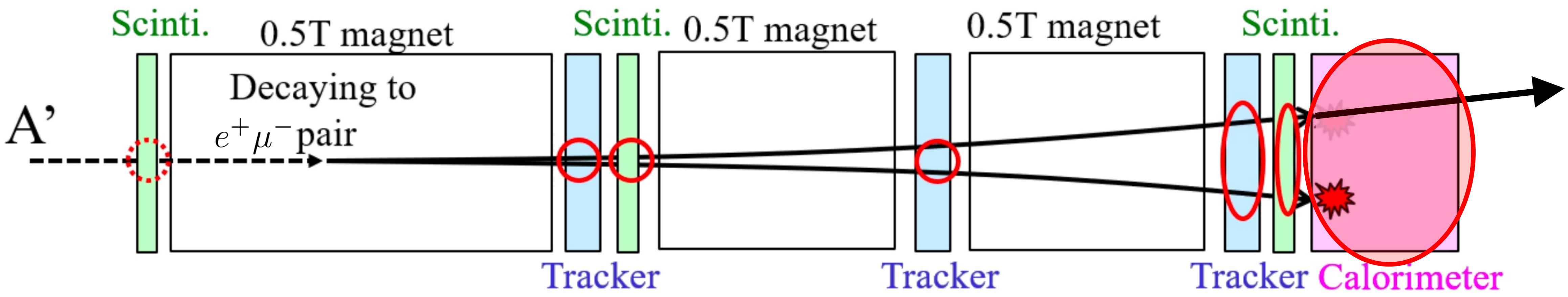
From Takubo san's slide



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)

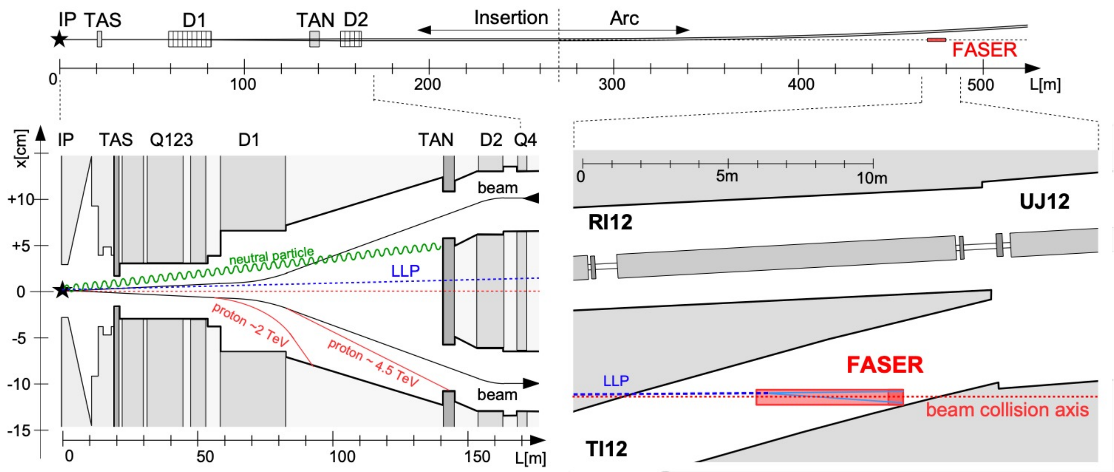
Benchmark signal (dark photon)

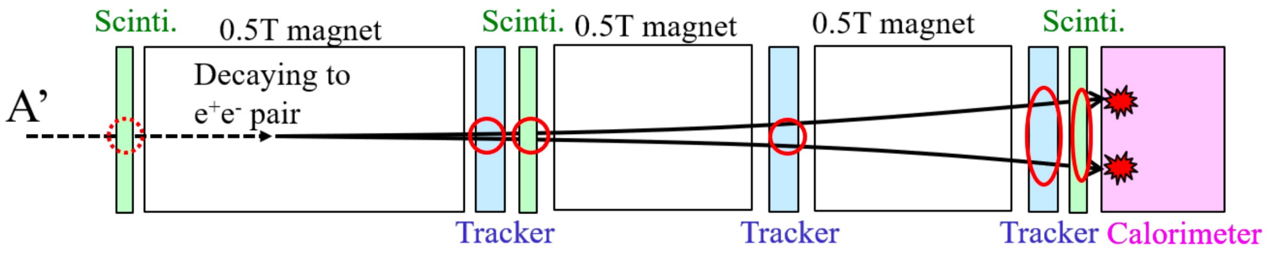
From Takubo san's slide



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, Muon passes through calorimeter as minimum ionizing particle (MIP), and electron leaves a large EM energy in calorimeter

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

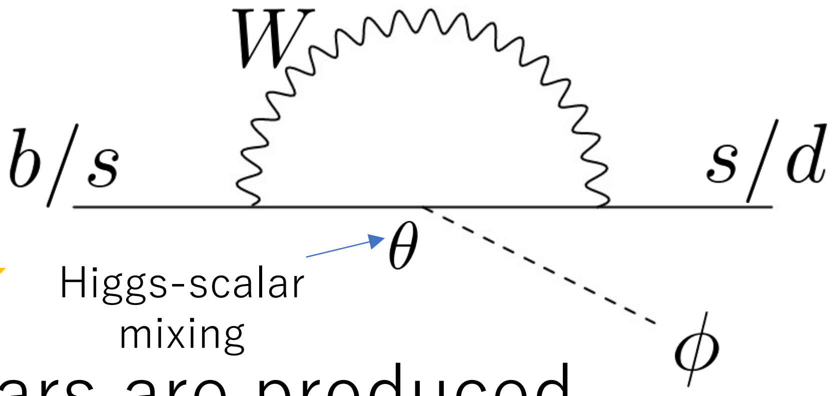
➡ Can be eliminated by charged particle veto with efficiency of 99.99%

Production of BSM particles

Production @ ATLAS

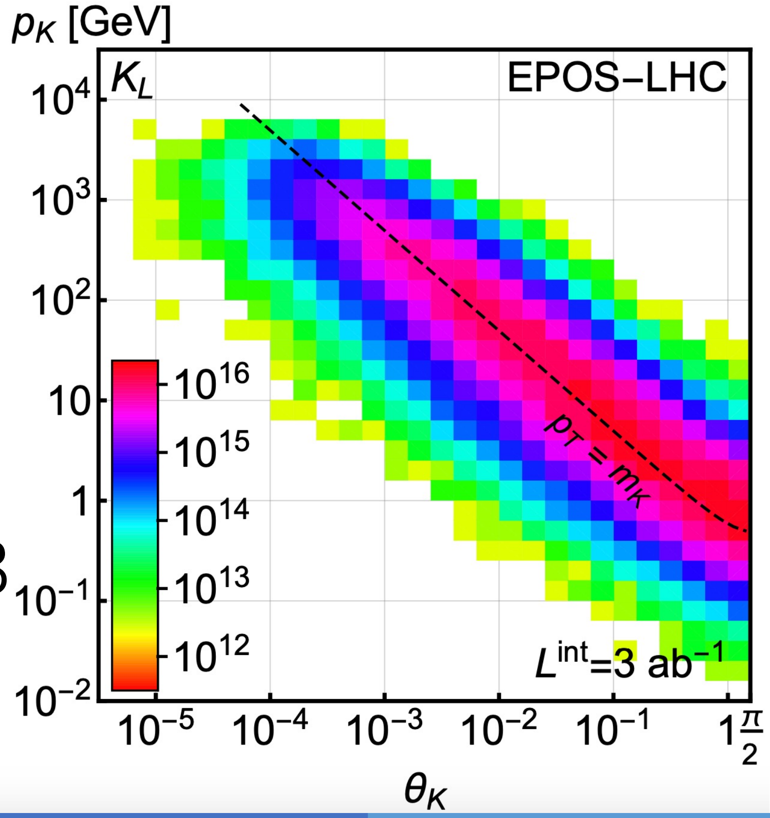
[J. L. Feng, I. Galon, F. Kling, S. Trojanowski, PRD 97 (2018) 5, 055034](#) ; [FASER collaboration, PRD 99 (2019) 9, 095011](#)

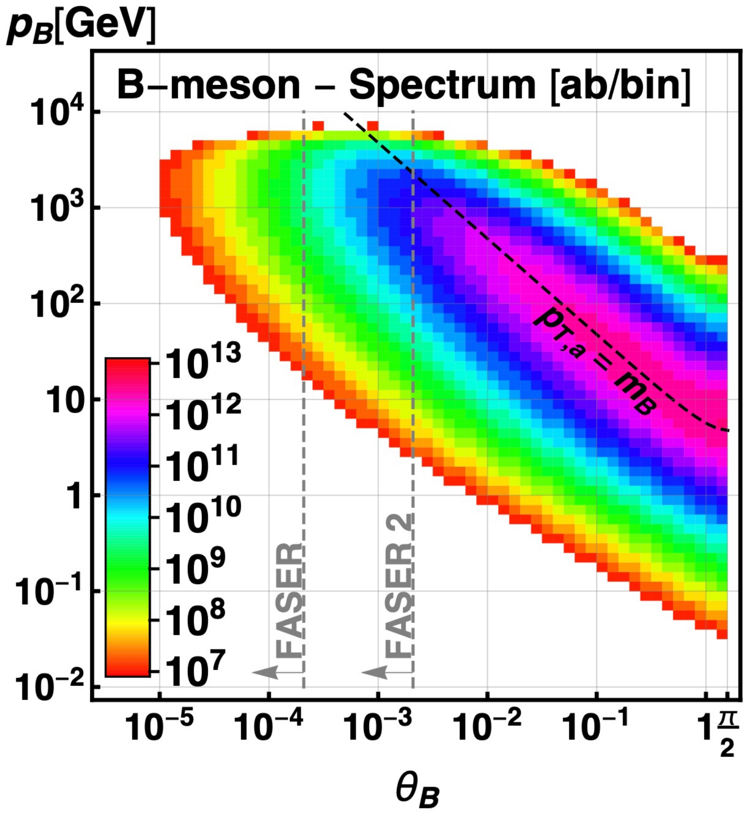
B and K mesons are produced at ATLAS IP



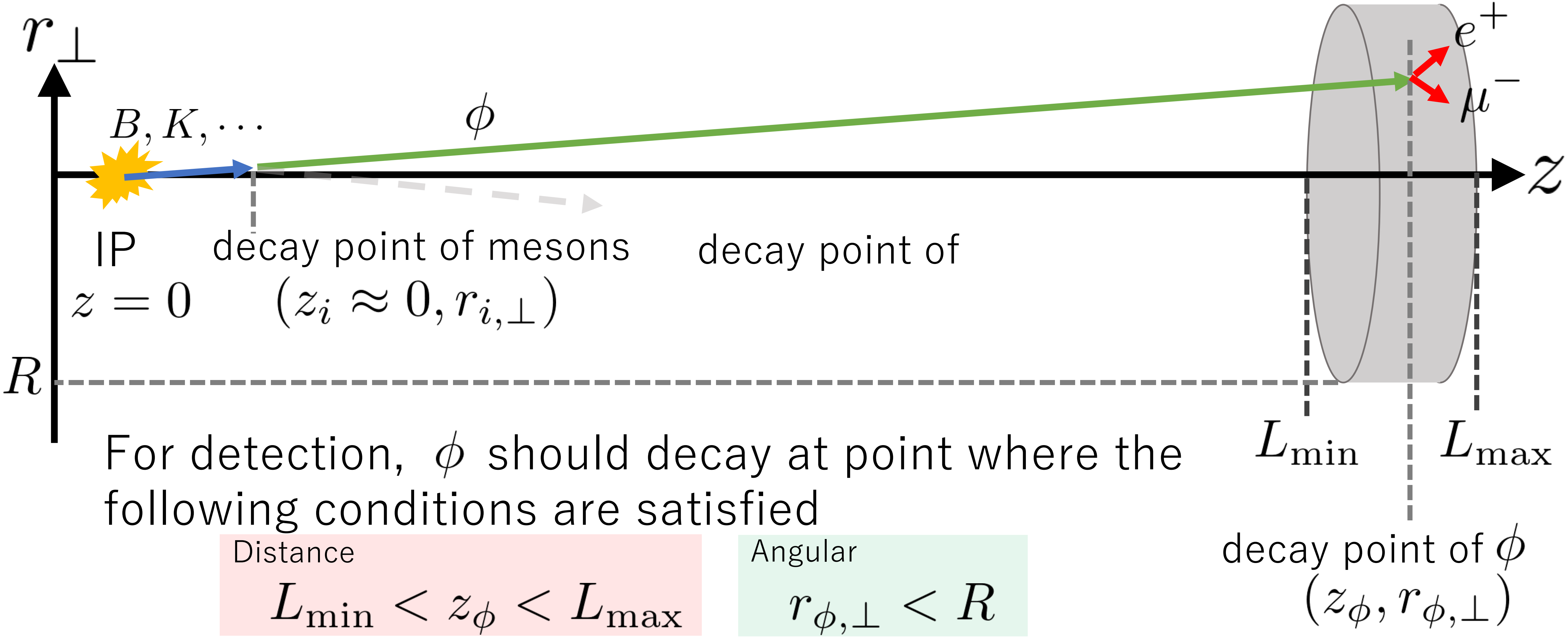
Scalars are produced by rare decays of K and B

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





Geometrical acceptance



For detection, ϕ should decay at point where the following conditions are satisfied

Distance

$$L_{\min} < z_\phi < L_{\max}$$

Angular

$$r_{\phi,\perp} < R$$

Geometrical acceptance

Probability of dark photon decay in detector

$$\mathcal{P}_{\phi}^{\det}(\boldsymbol{p}_{\phi}) = \frac{1}{\bar{d}_{\phi}\cos\theta_{\phi}} \int_{z_{\phi,\min}}^{z_{\phi,\max}} dz_{\phi} e^{-\frac{z_{\phi}}{\bar{d}_{\phi}\cos\theta_{\phi}}} \times \Theta(R - r_{\phi,R})\Theta(R - r_{\phi,F})$$

Distance　　Angular

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

$\Theta(x)$: Heaviside step function

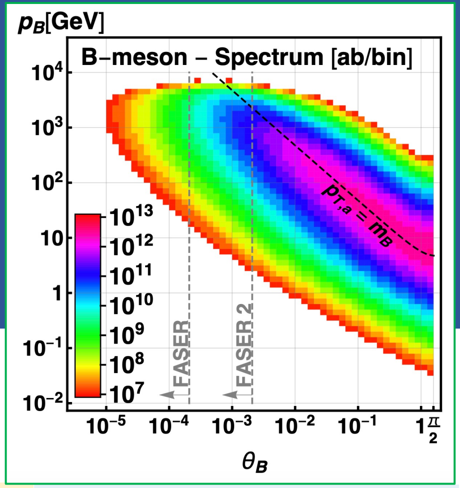
θ_{ϕ} : angular of ϕ with respect of beam axis (z-axis)

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

FASER

Number of events

Number of dark photons which decay in detector



$$N_{\rm cLFV} = \mathcal{L} \sum_{i:\rm meson} \int dp_i d\theta_i \int d\boldsymbol{p}_\phi \frac{d\sigma_{pp\to iX}}{dp_i d\theta_i} {\rm Br}(i \to X\phi){\rm Br}(\phi \to e\mu)$$

$$\times \mathcal{P}_\phi^{\rm det}(\boldsymbol{p}_\phi)$$

$$\sim 150 \text{ fb}^{-1} \times 10^{11} \text{ ab} \times 10^{-7} \times \mathcal{O}(0.1) \times 10^{-2}$$

$$\sim \mathcal{O}(1)$$

for FASER (LHC Run3)

Result

Origin of cLFV interaction

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

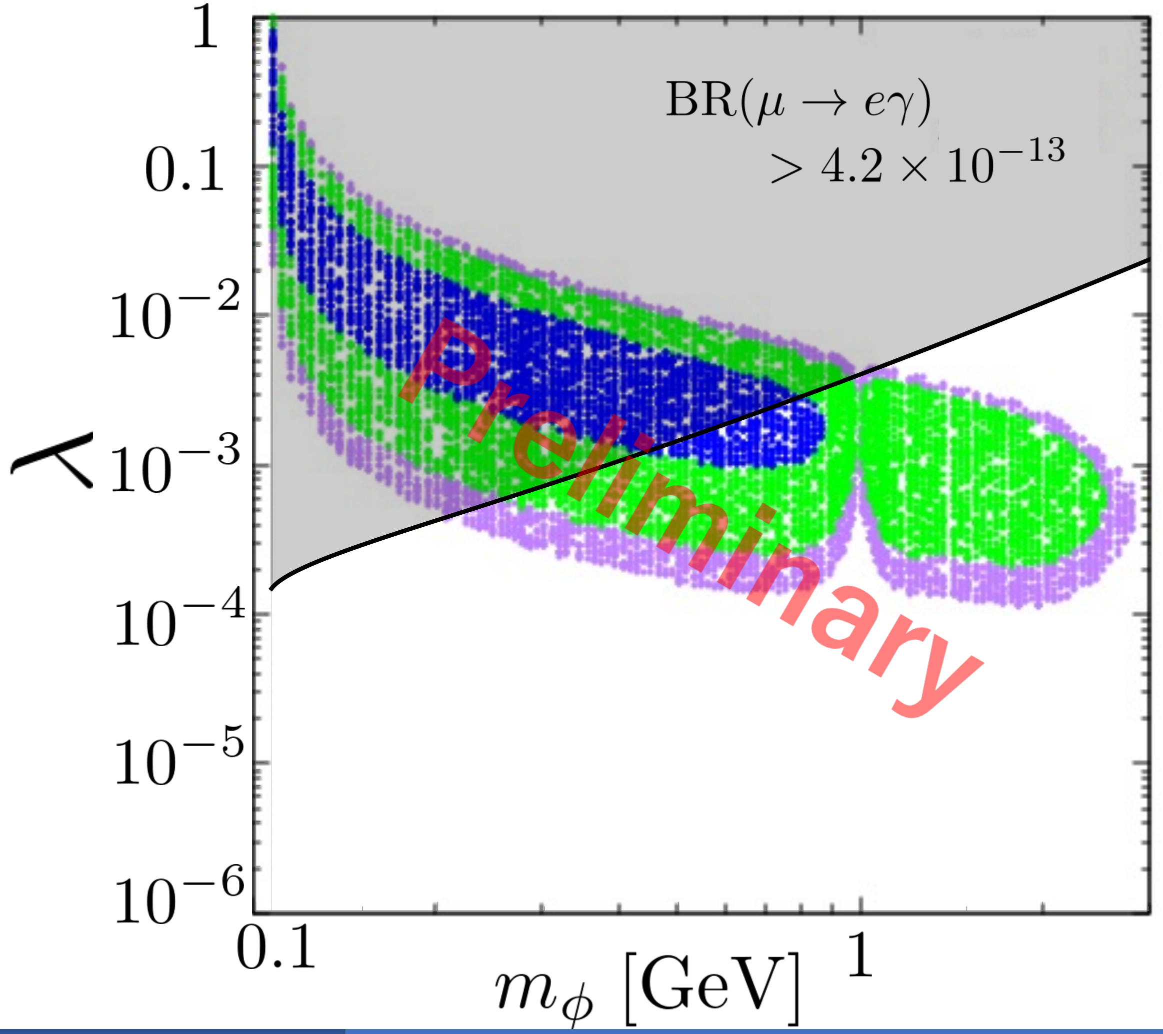
SM Higgs - ϕ mixing : θ

Couplings with the other SM fermions

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

Result

of signal events (Leptophilic scalar)



Parameters

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

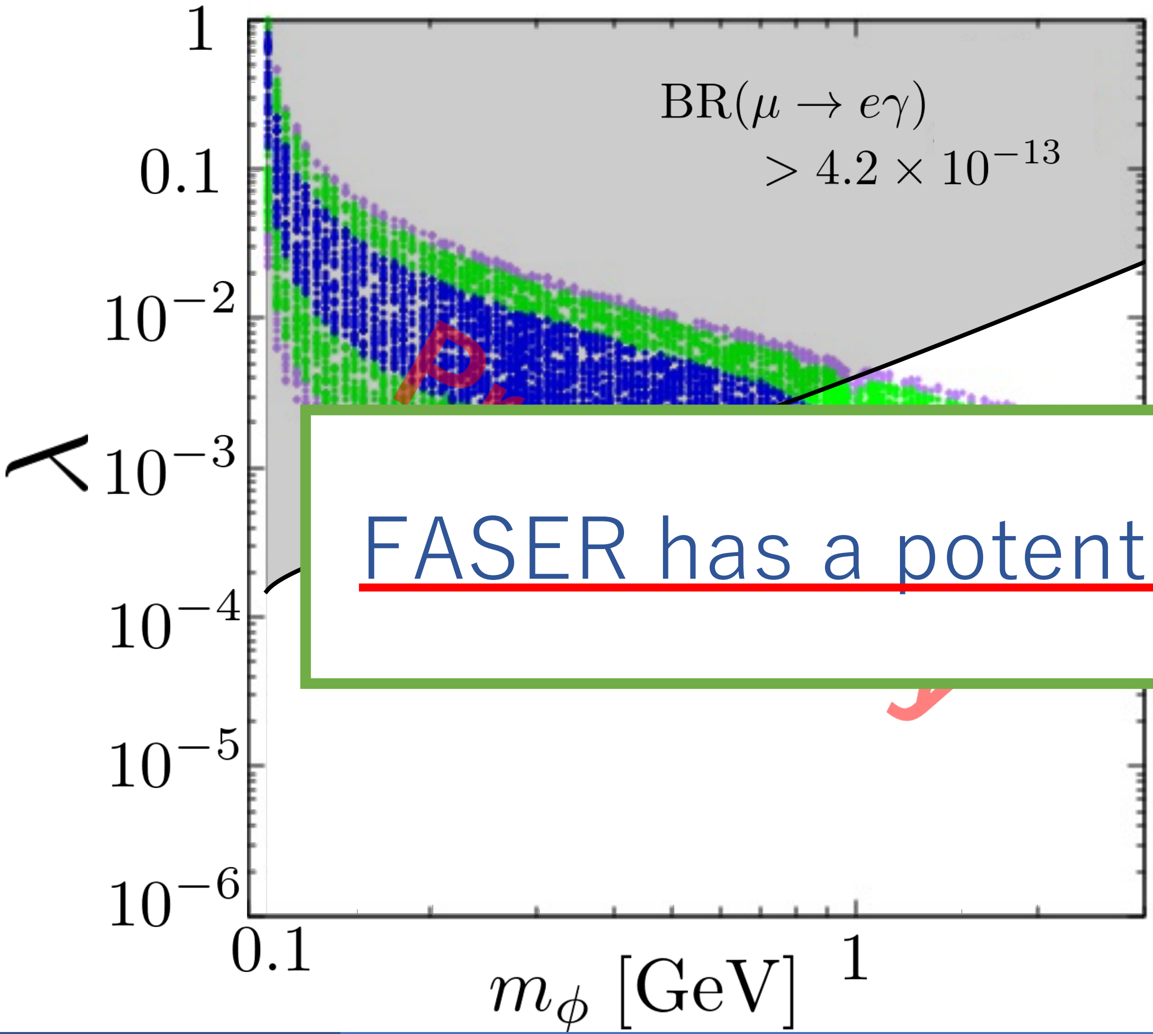
# of LFV decay signals

$3 \sim 9$ (purple)

$10 \sim 99$ (green)

$100 \leq$ (blue)

of signal events (Leptophilic scalar)



Parameters

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

# of LFV decay signals

FASER has a potential to find cLFV decay

Summary

- FASER can search for the regions where interactions with SM particles are small, and in such regions, new physics may be hidden
- In the region where FASER has a sensitivity, charged lepton flavor violating (CLFV) couplings can be as large as charged lepton flavor conserving (CLFC) couplings
- FASER can explore unsearched region of LFV coupling by search for LFV decays

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

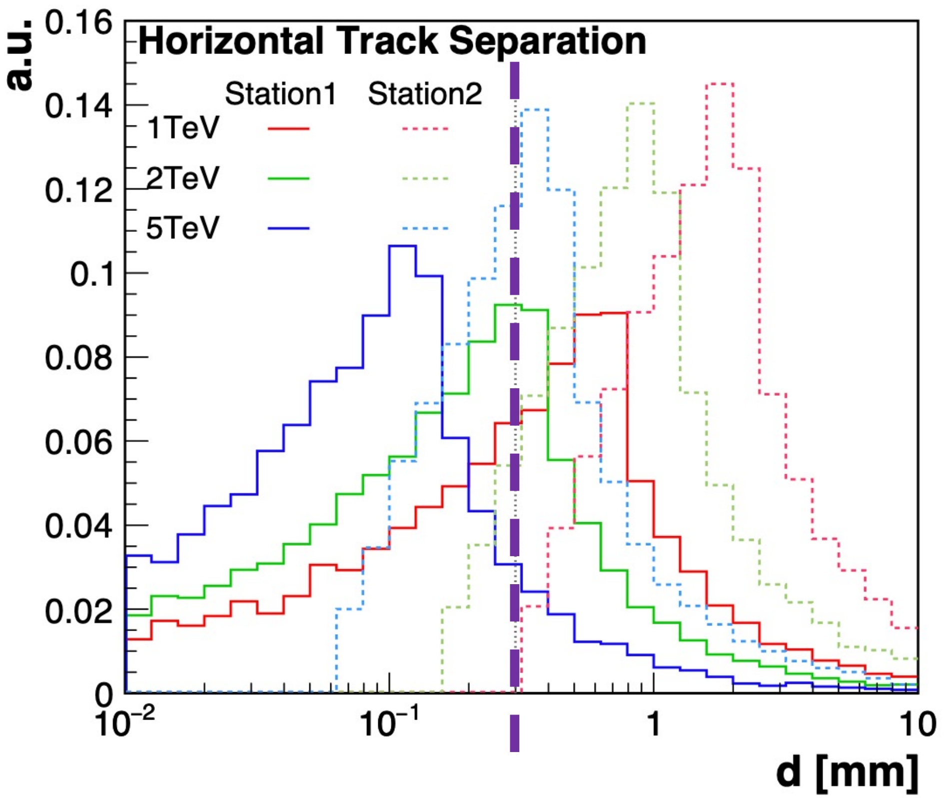
From Takubo san’s slide

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]



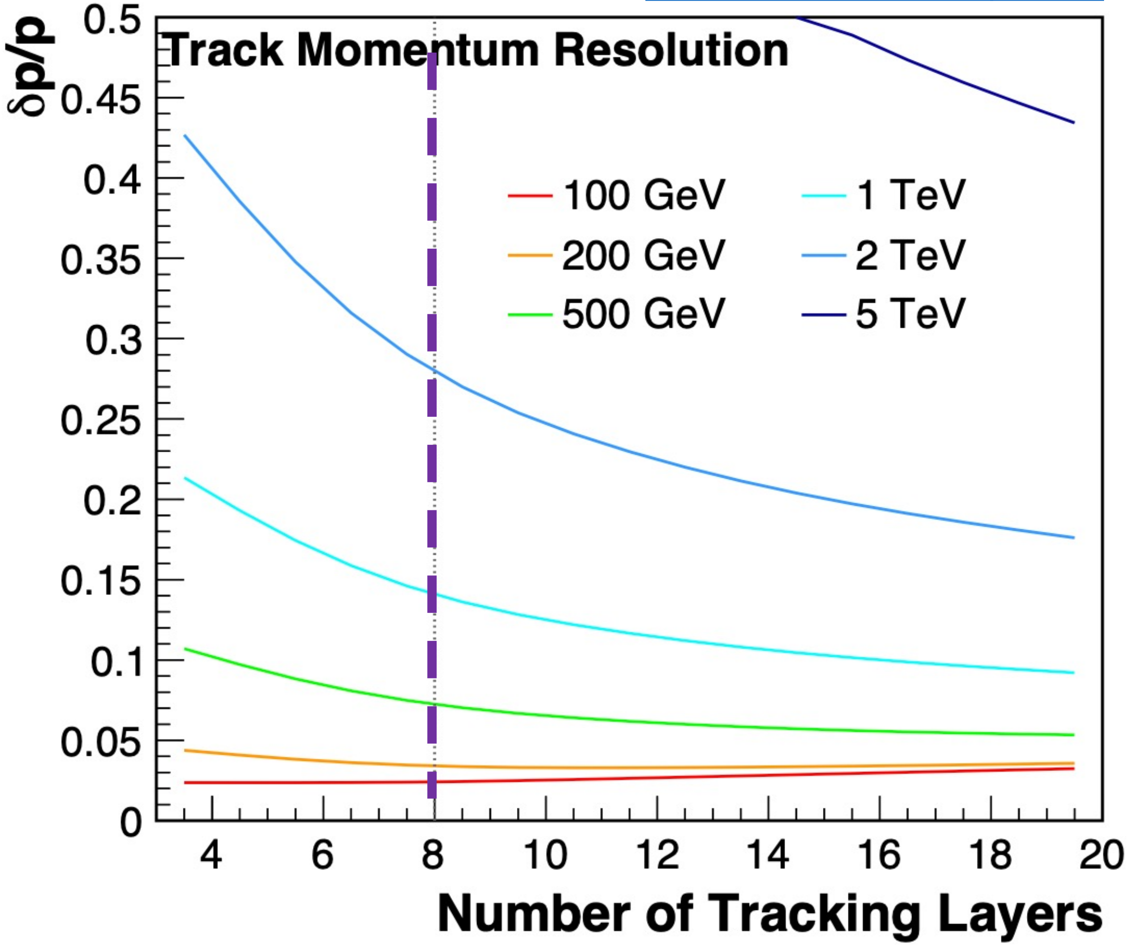
threshold : 300 μm

Spectrometer

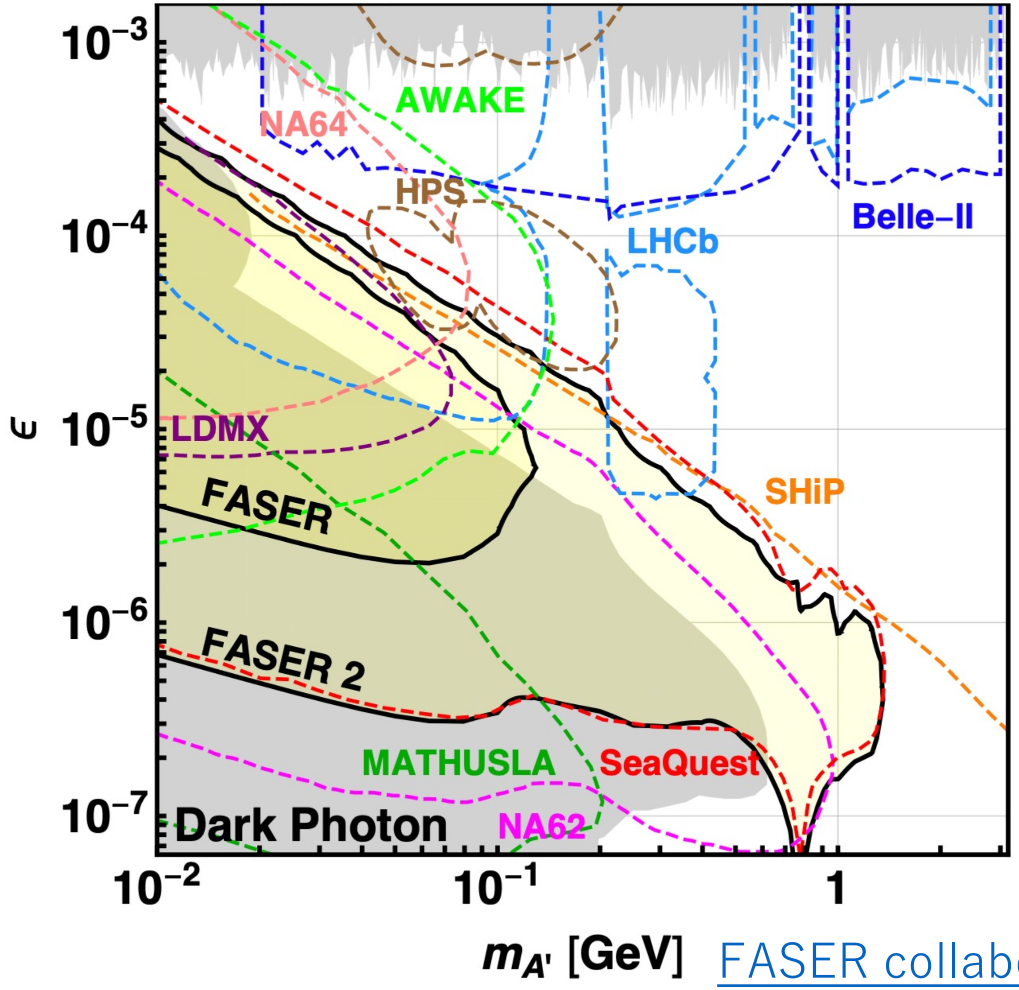
Momentum resolution

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

From 1811.10243 [hep-ex]



Expected sensitivity

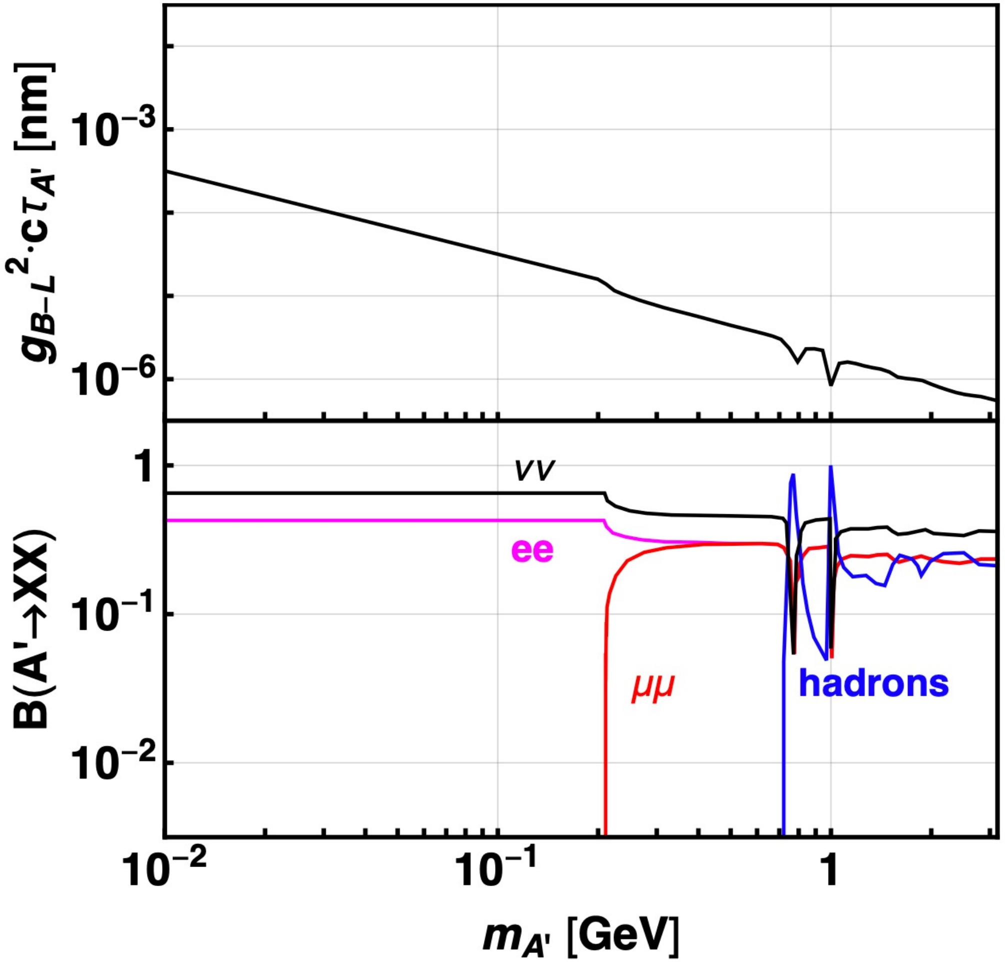


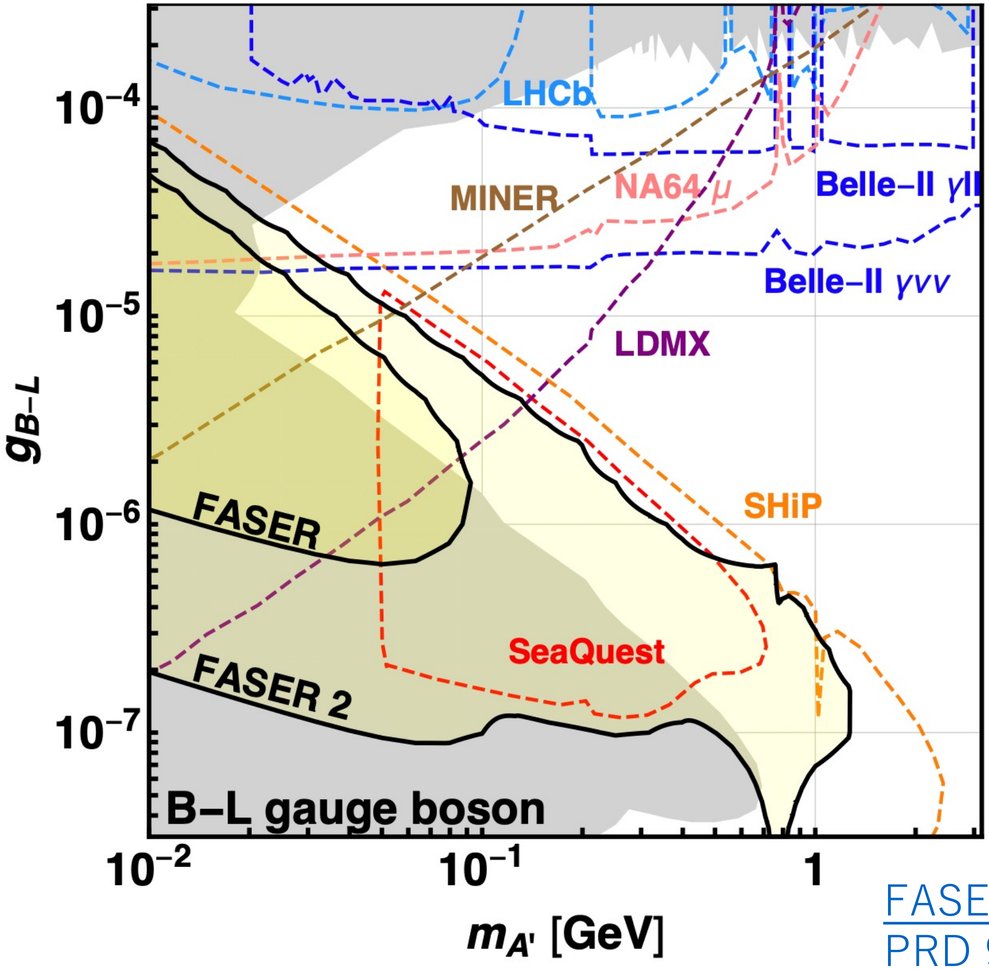
Dark photon

FASER(2) can explore parameter region with $\epsilon \sim 10^{-5} - 10^{-4}$ $(10^{-7} - 10^{-4})$

[FASER collaboration, PRD 99 (2019) 9, 095011]

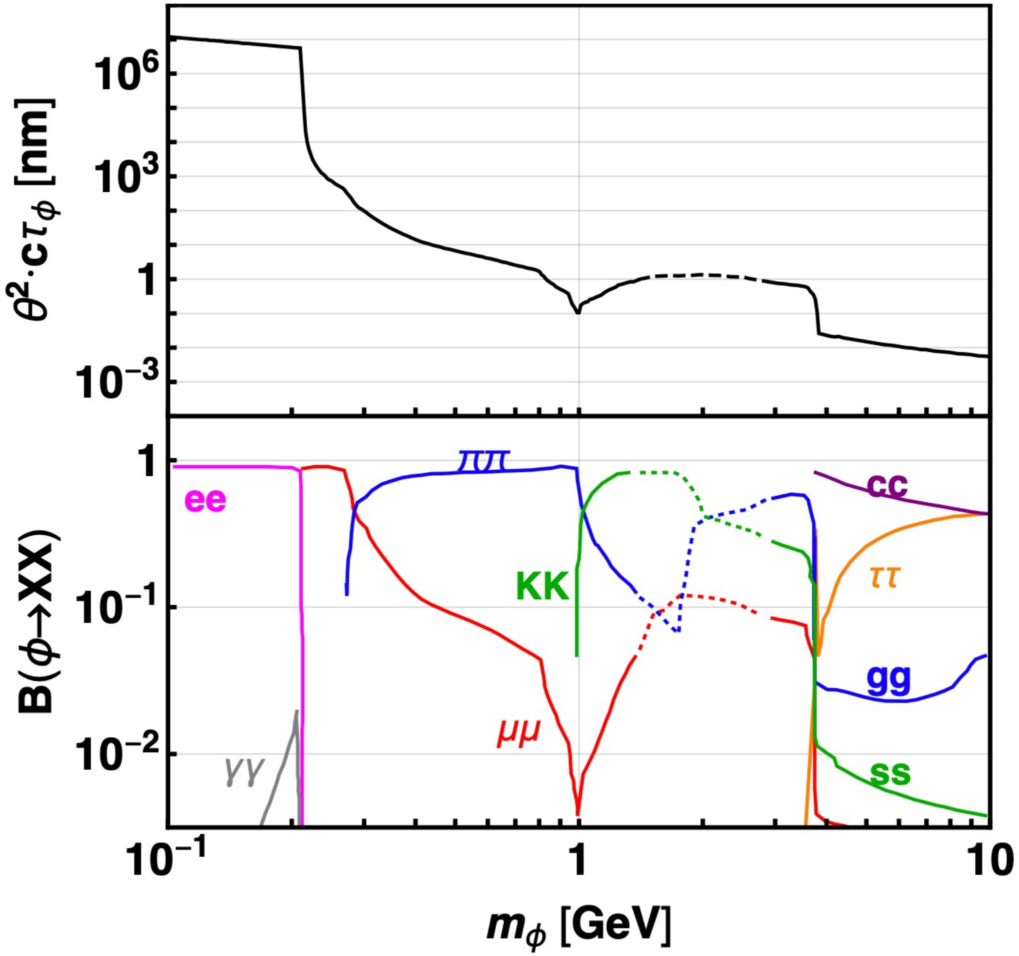
Expected sensitivity ($U(1)_{B-L}$ gauge boson)

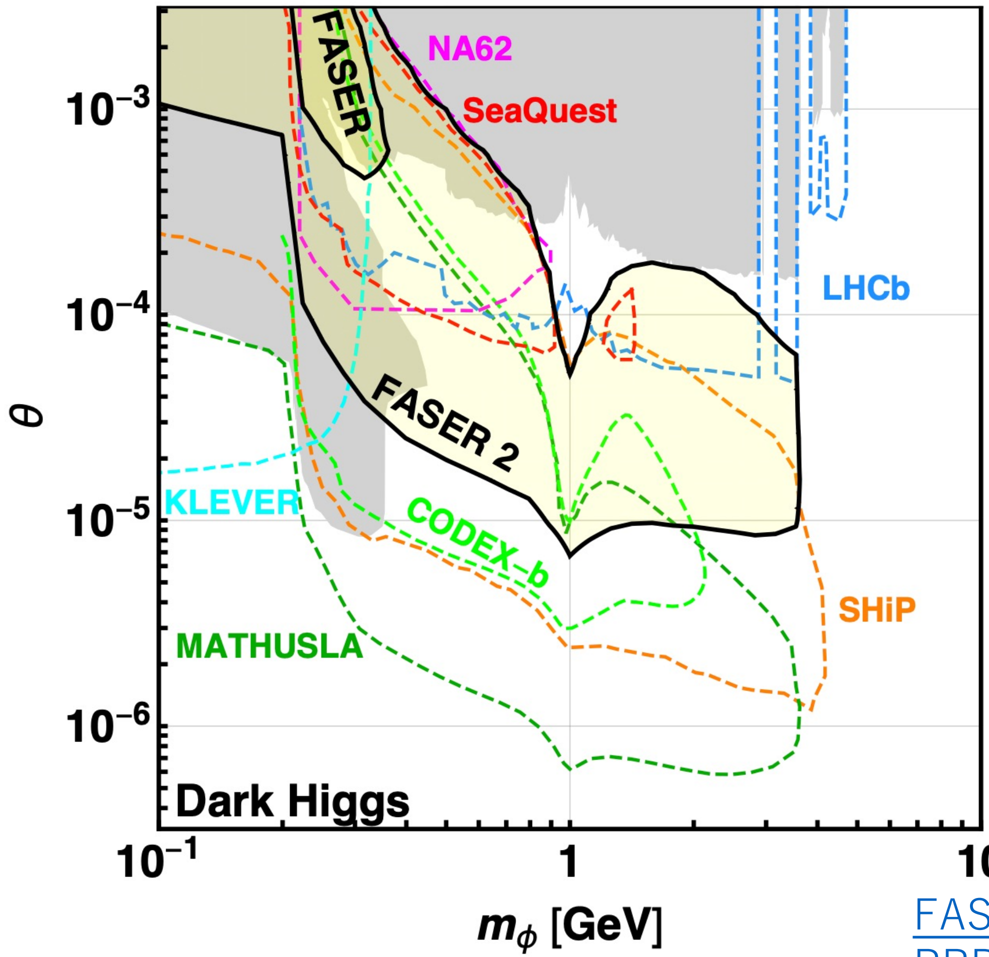




FASER collaboration, PRD 99 (2019) 9, 095011

Expected sensitivity (Dark Higgs boson)

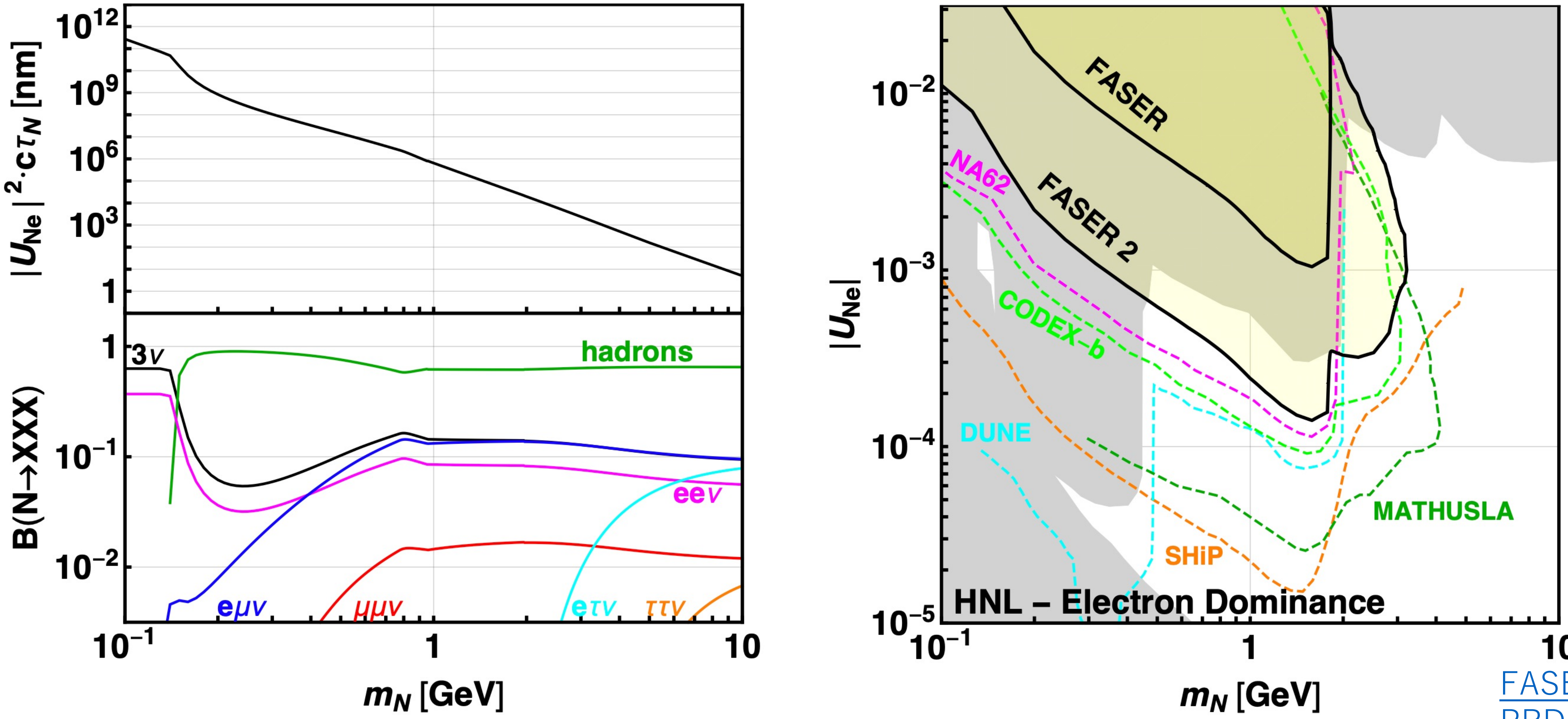




FASER collaboration, PRD 99 (2019) 9, 095011

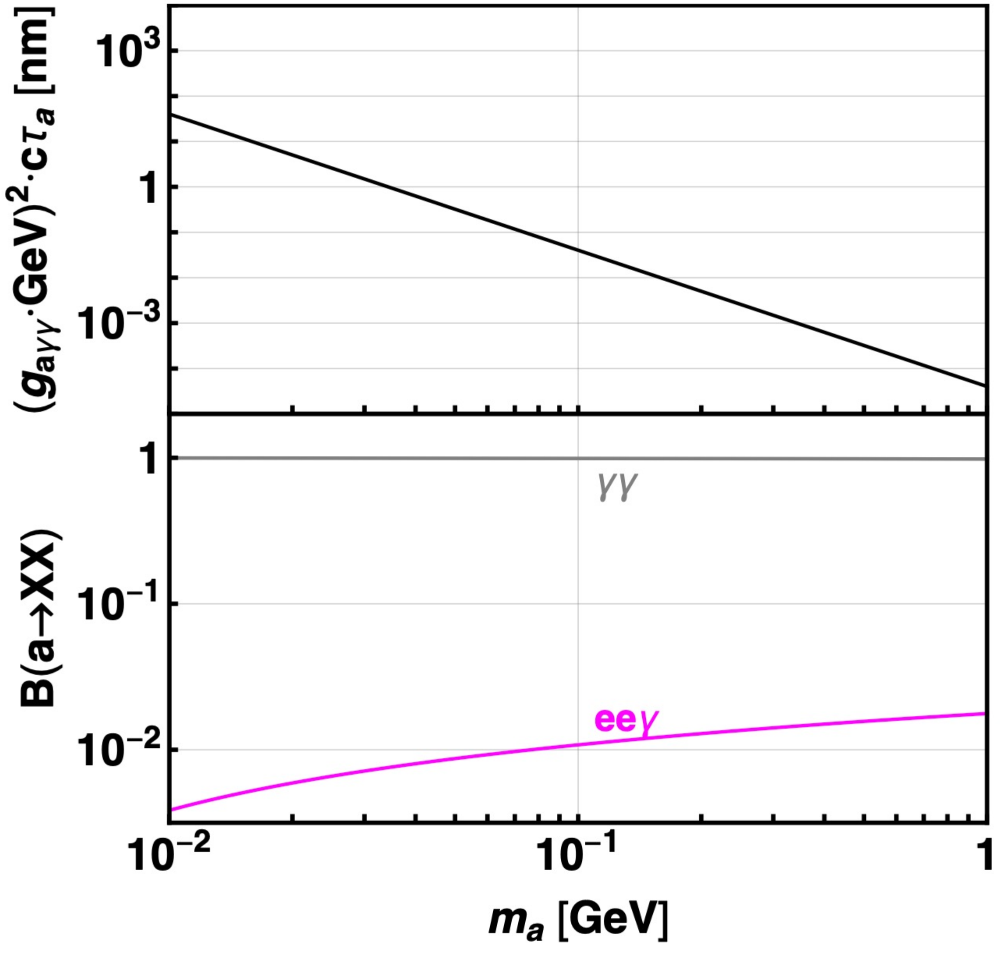
Appendix

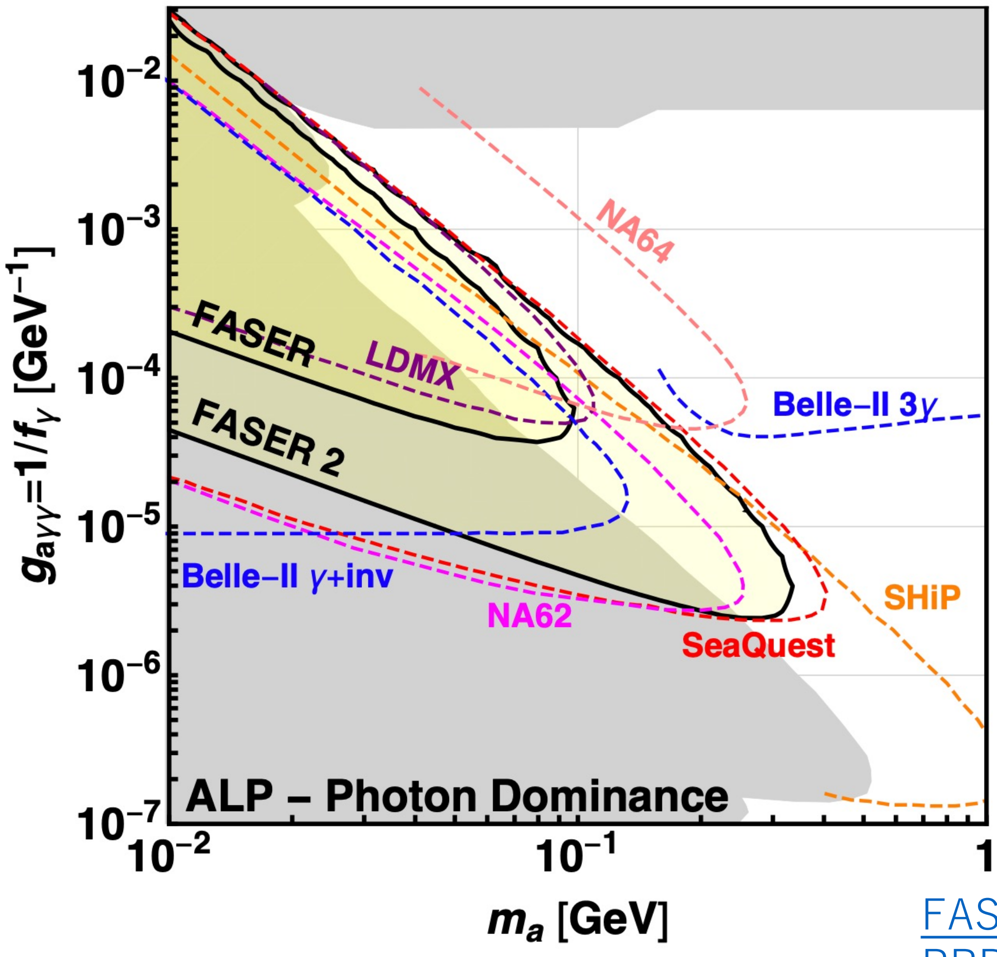
Expected sensitivity (Heavy neutral lepton)



[FASER collaboration, PRD 99 (2019) 9, 095011]

Expected sensitivity (Axion-like particle)





[FASER collaboration, PRD 99 (2019) 9, 095011]

Origin of cLFV interaction

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

Non-universal charge

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

[flavor basis]

Diagonalization of charged lepton mass matrix

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

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

[mass basis]

cLFV interaction

Dark Photon Model

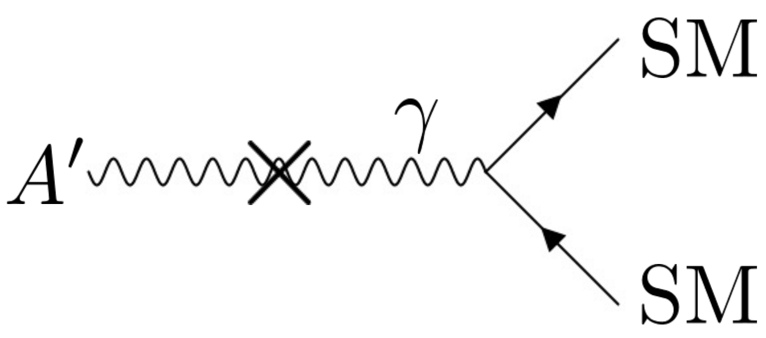
Extension of the Standard Model by a dark U(1) gauge symmetry

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

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

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

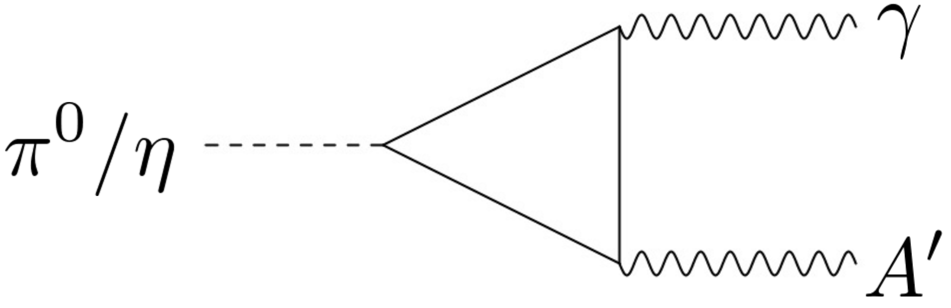
$$\mathcal{L}_{\mathrm{int}} = \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$



Production of BSM particles

Production @ ATLAS

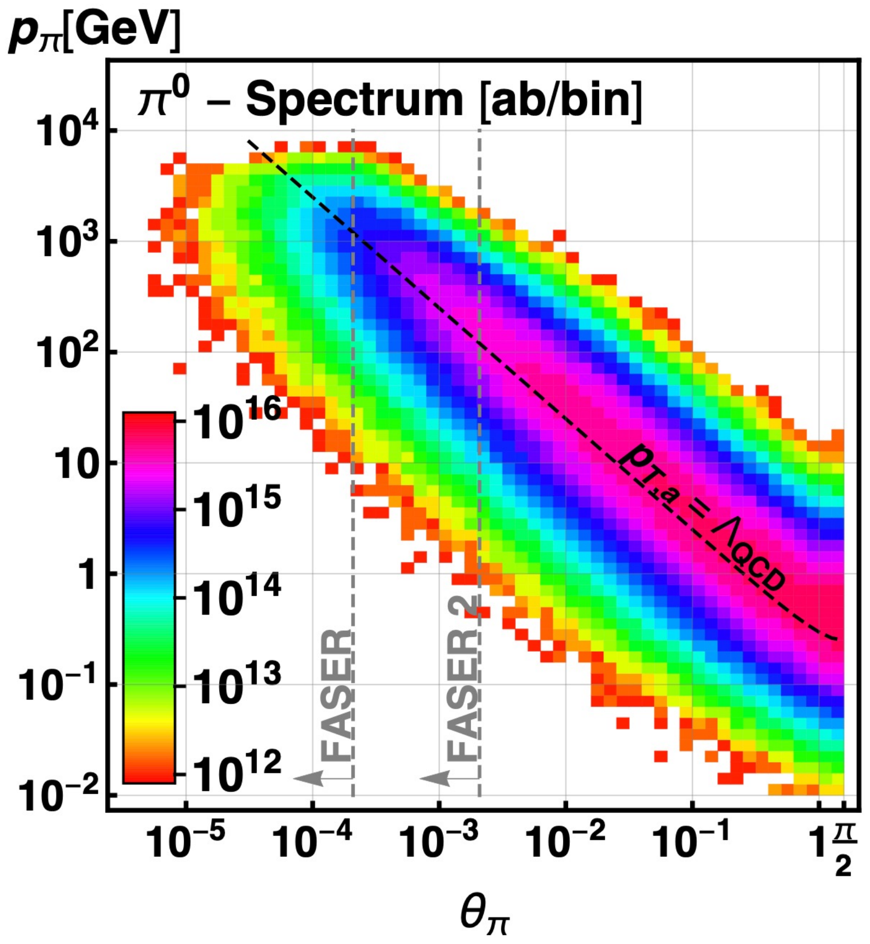
π^0 and η are produced at ATLAS interaction point



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



Decay length

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

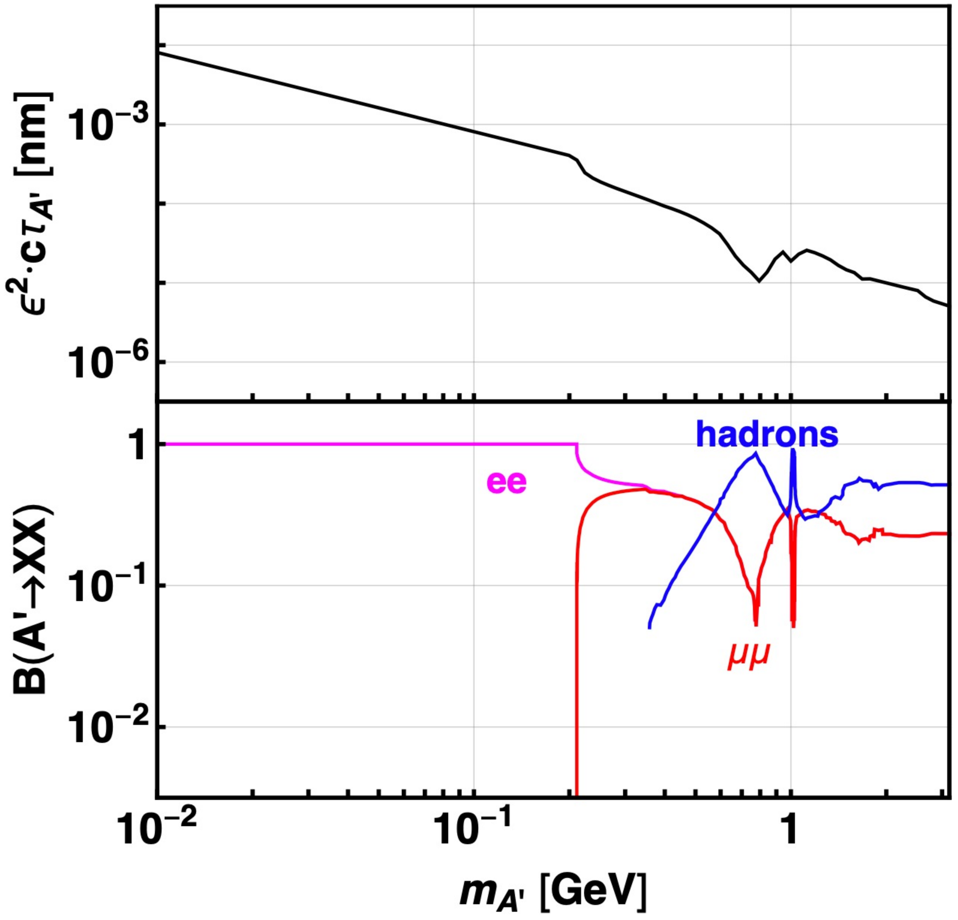
Decay length

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

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

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

FASER collaboration, PRD 99 (2019) 9, 095011



Dark photon mass

Origin of dark photon mass

→ Spontaneous symmetry breaking by VEV of $\mathrm{U(1)}_{\mathrm{dark}}$-charged scalar

Interaction between $\mathrm{U(1)}_{\mathrm{dark}}$-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

Appendix

Dark photon mass

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

$$\mathcal{L} \supset g' m_{A'} \phi A'_{\mu} A'^{\mu}$$ ➡ ϕ decay into A' pair

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

➡ Almost all ϕ decay into dark photon

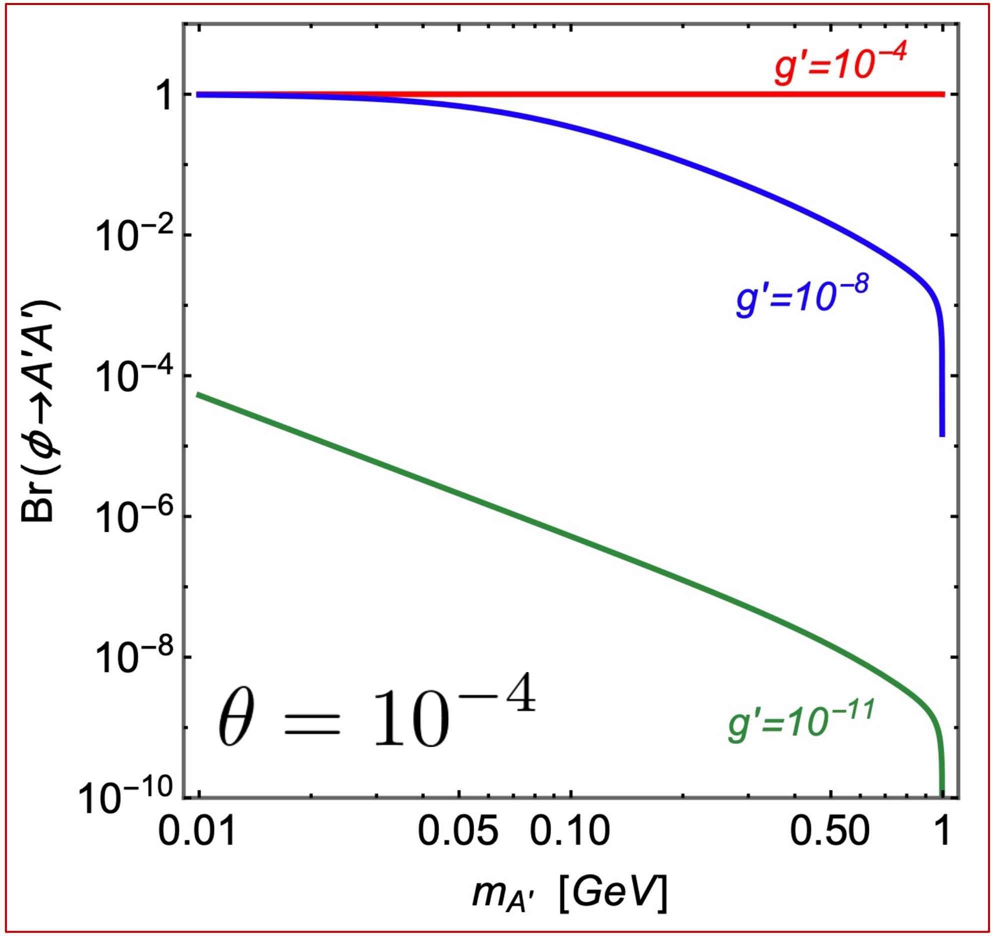
$$\Gamma(\phi \to A'A') = \frac{g'}{8\pi} \frac{m_{A'}^2}{m_\phi} \sqrt{1 - \frac{4m_{A'}^2}{m_\phi^2}} \left[2 + \frac{m_\phi^4}{4m_{A'}^4} \left(1 - \frac{2m_{A'}^2}{m_\phi^2}\right)^2 \right]$$

enhancement factor ≫ 1

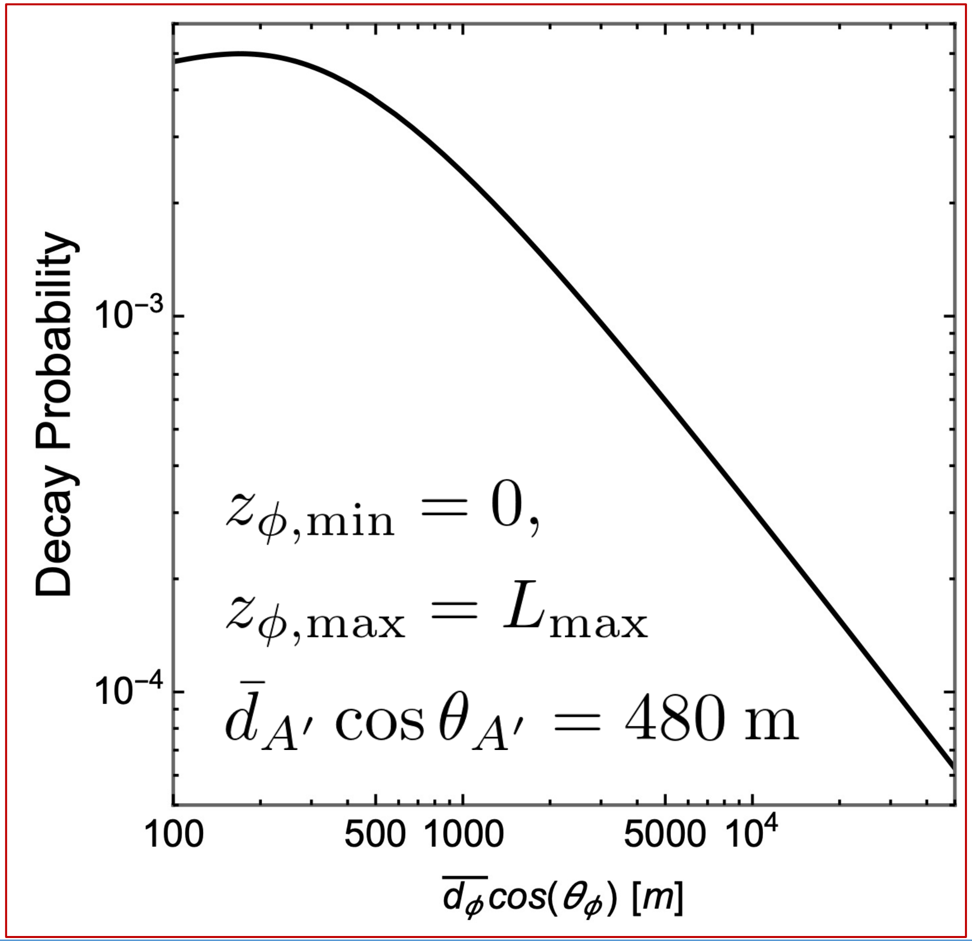
Appendix

Dark photon

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

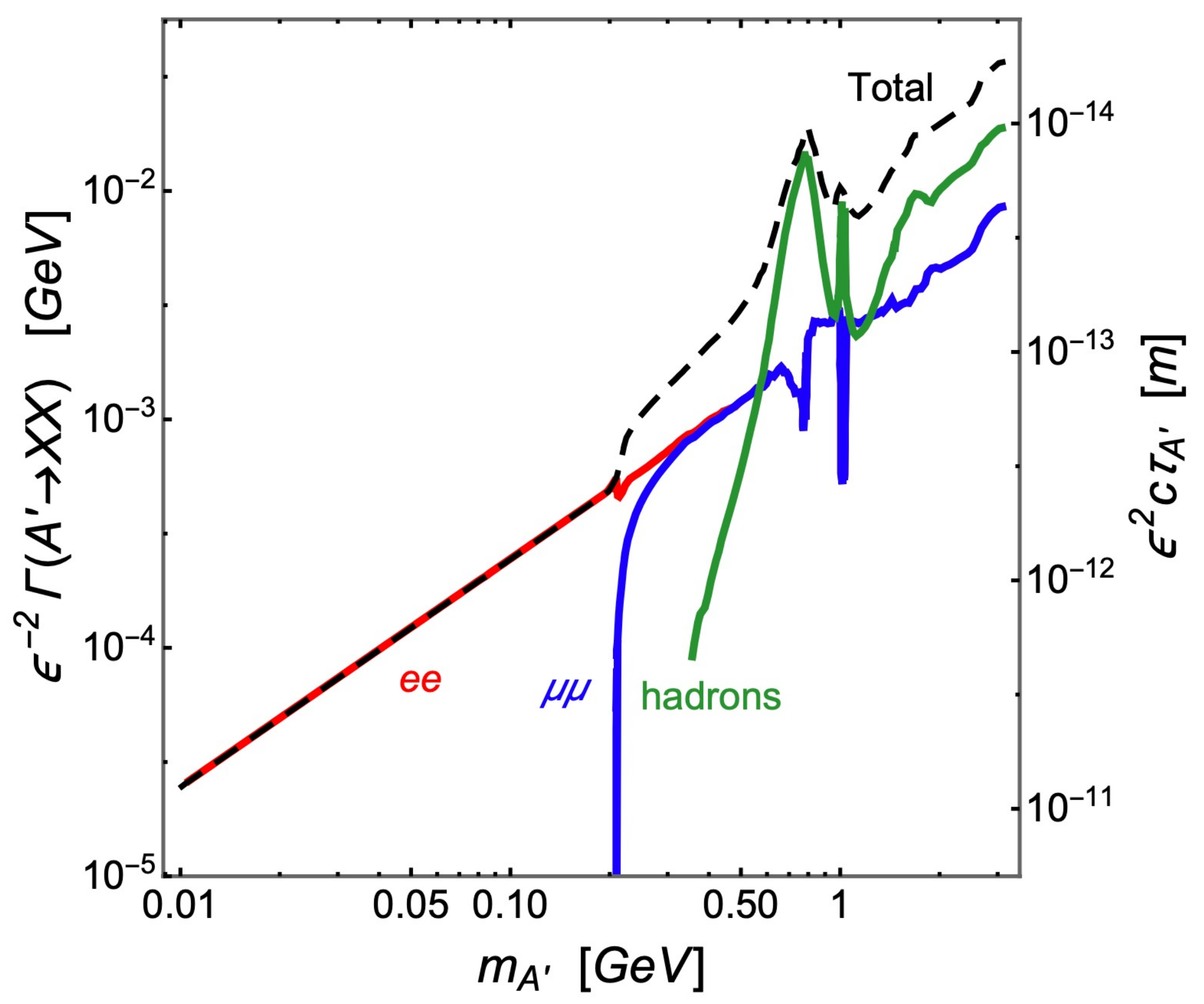


Decay probability of ϕ



Dark photon

Decay length of A'



Decay of scalar boson

Almost all ϕ decay into dark photon

Nonzero ϕ-Higgs mixing : θ

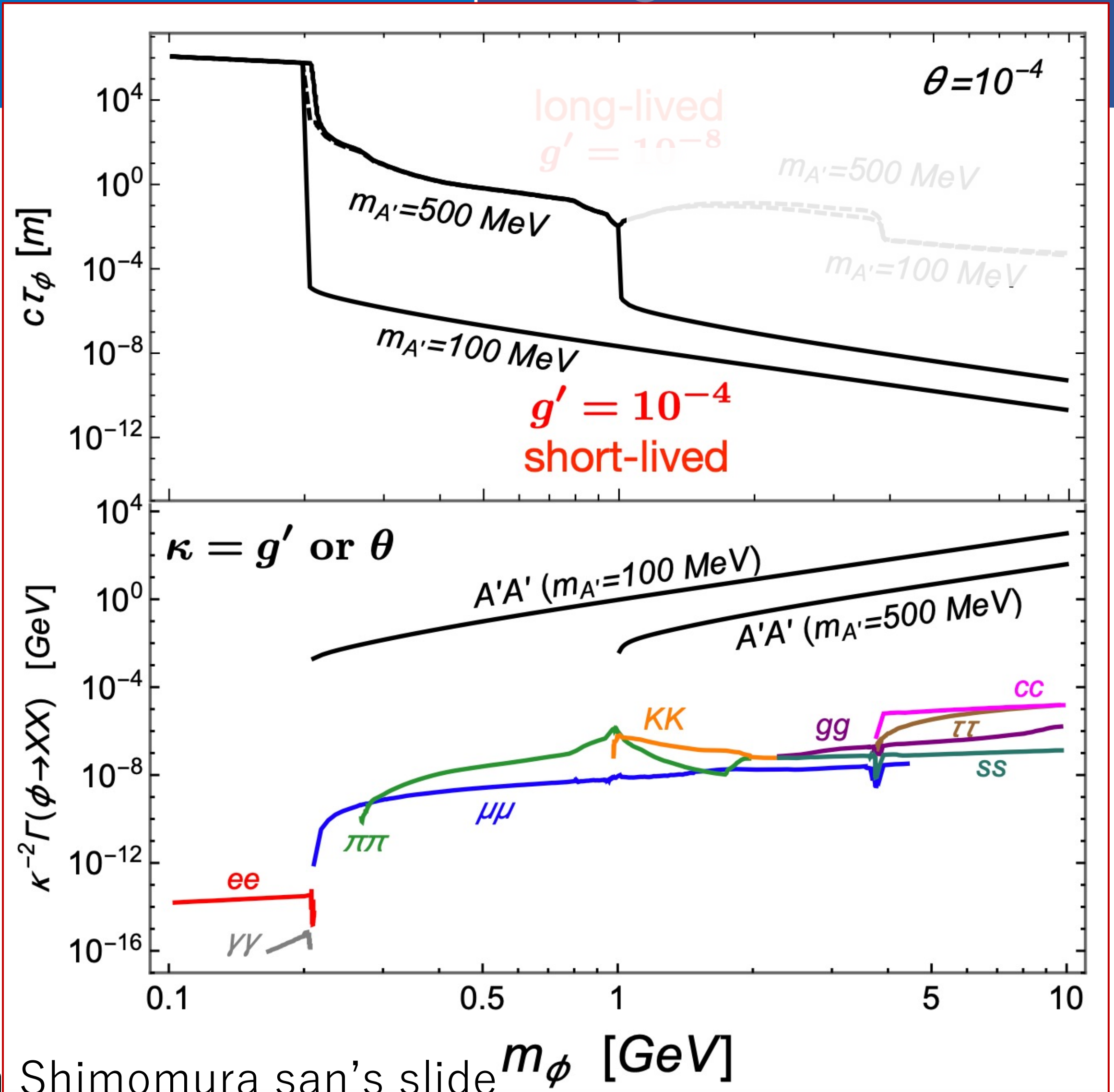
➡ A small number of ϕ can decay into SM particles

for $g' > \theta$

ϕ : short-lived, A' : long-lived

for $g' \ll \theta$

ϕ : long-lived



From Shimomura san's slide

Decay of scalar boson

Almost all ϕ decay into dark photon

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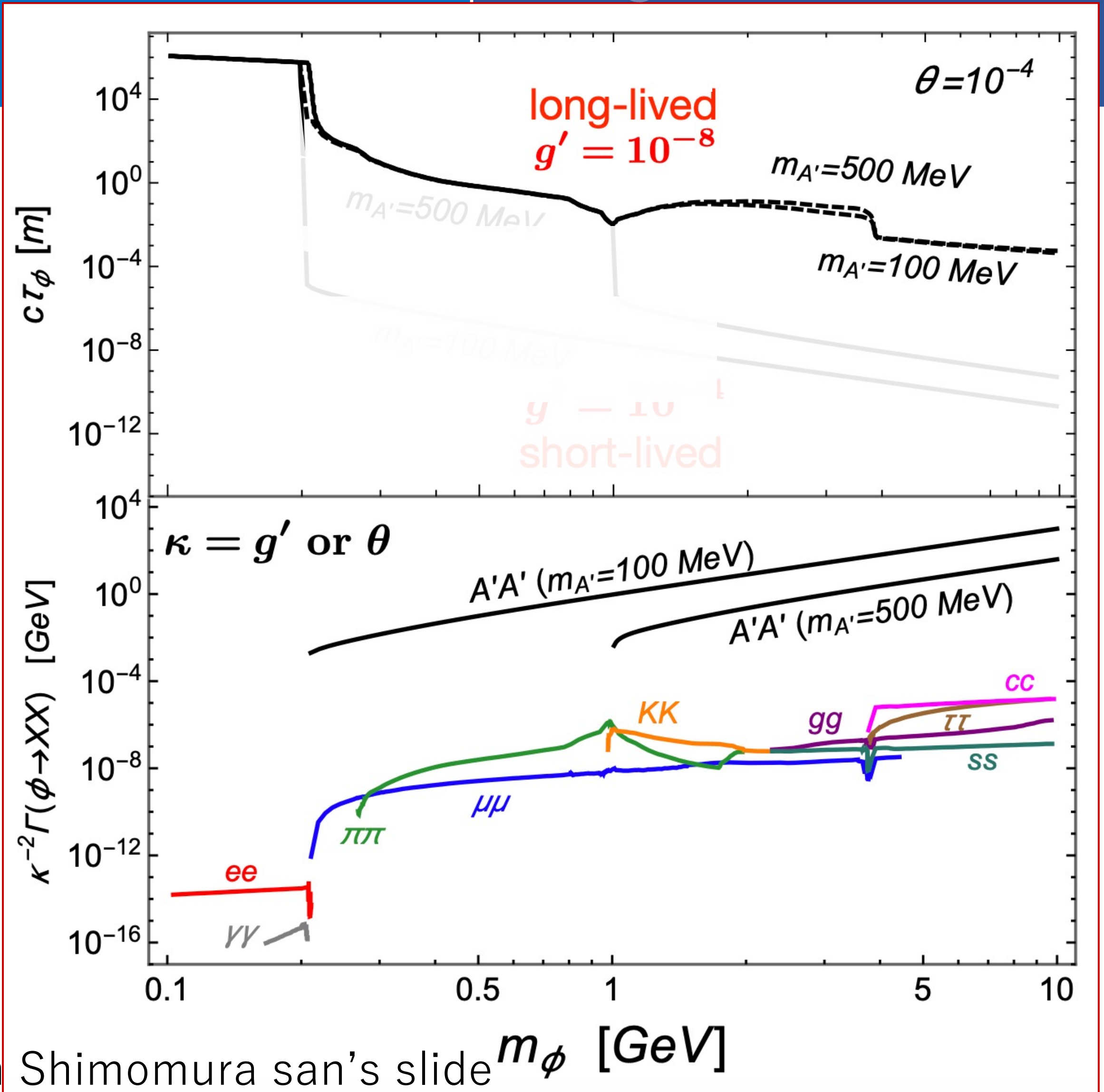

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Appendix

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 pa

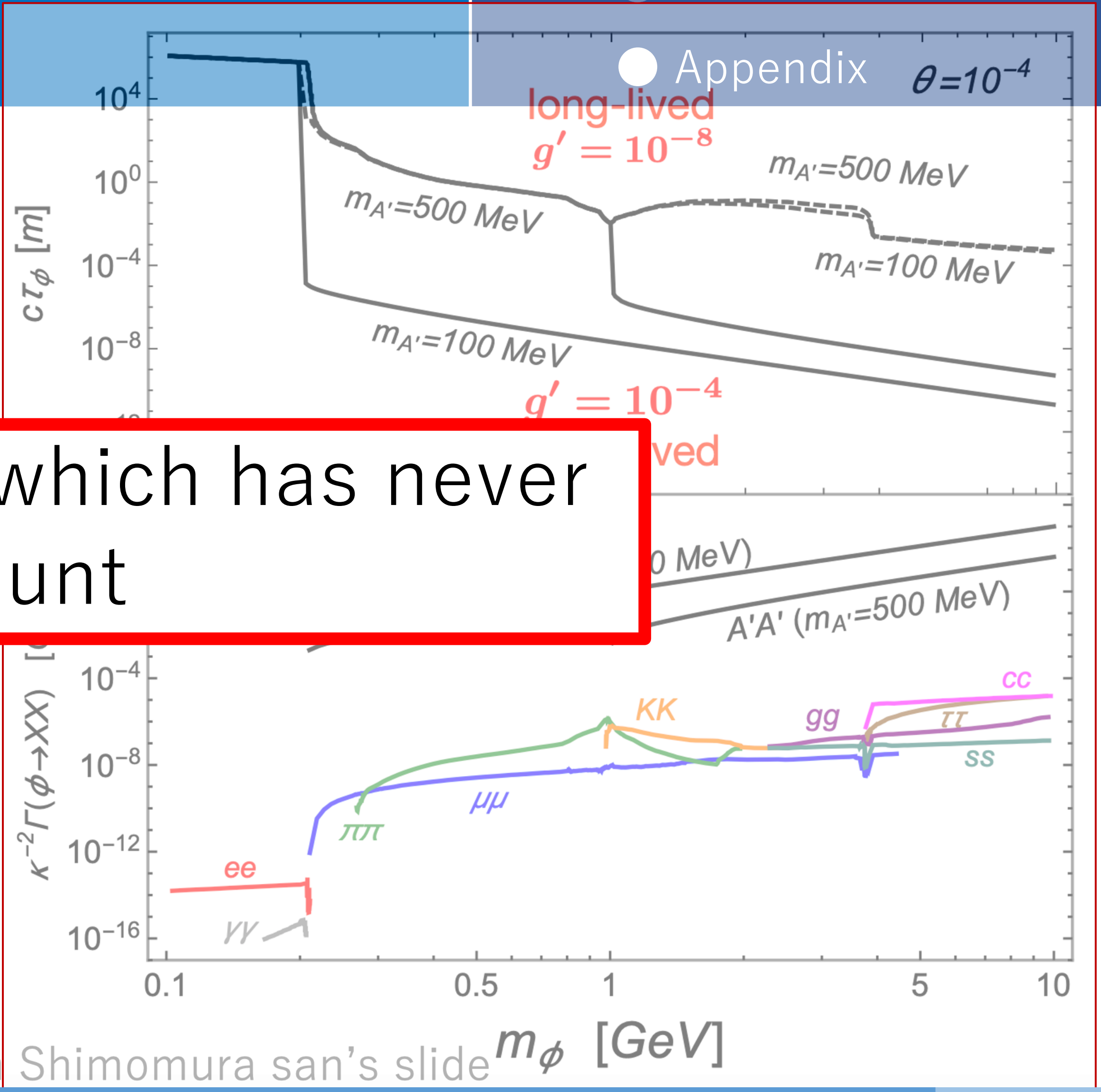
Dark photon source which has never been taken into account

for $g' > \theta$

ϕ : short-lived, A' : long-lived

for $g' \ll \theta$

ϕ : long-lived



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Appendix

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

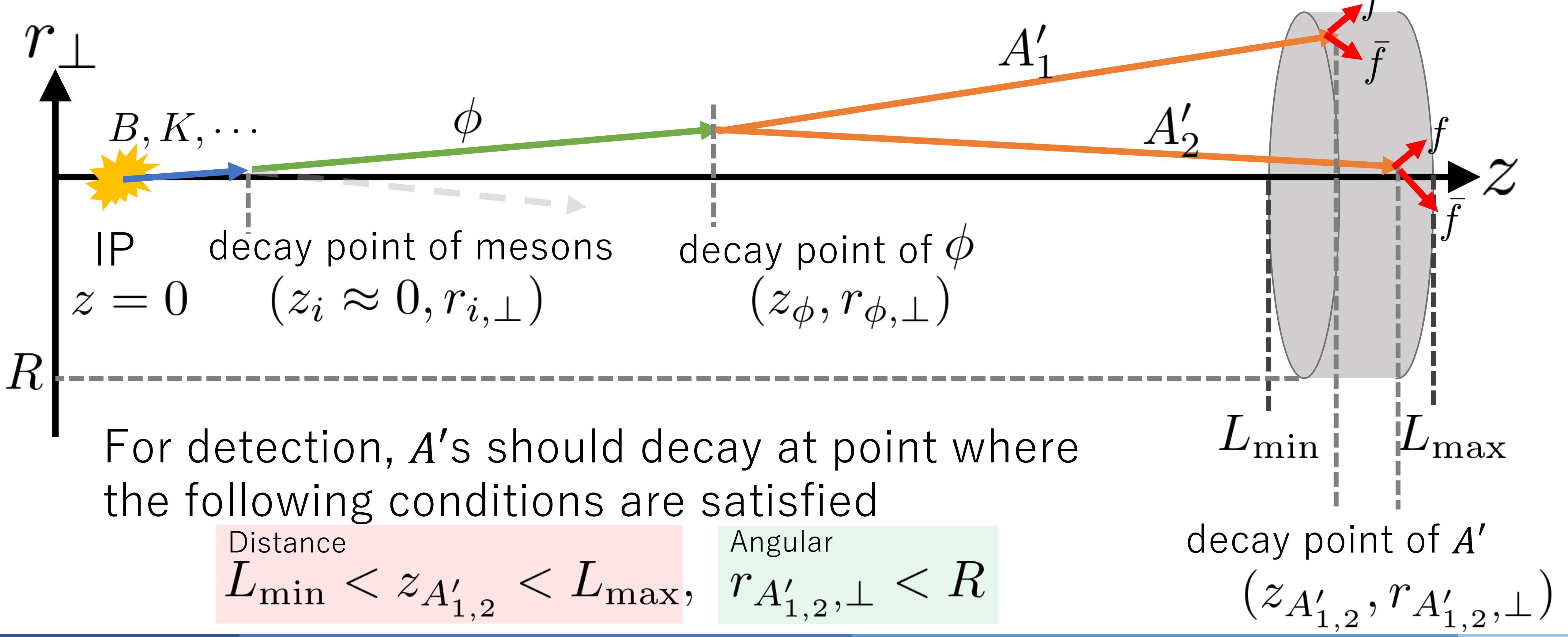
7.1×10^{13} B mesons are produced in LHC Run3 ($150\ \mathrm{fb}^{-1}$)

Scalars ϕ are produced by rare decays of B mesons

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

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

Geometrical acceptance



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

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

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

Geometrical acceptance

Probability of dark photon decay in detector

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

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

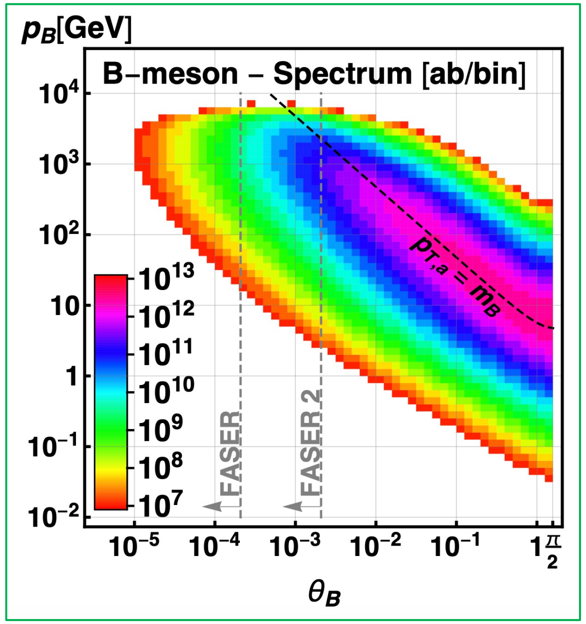
$\theta_{\phi(A')}$: angular of ϕ (A') with respect of beam axis (z-axis)

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

Number of LFV decays in FASER detector

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

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



Assumption & Setup

- Calculated for FASER2 case
- Background free

Parameters

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

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

cLFV interaction

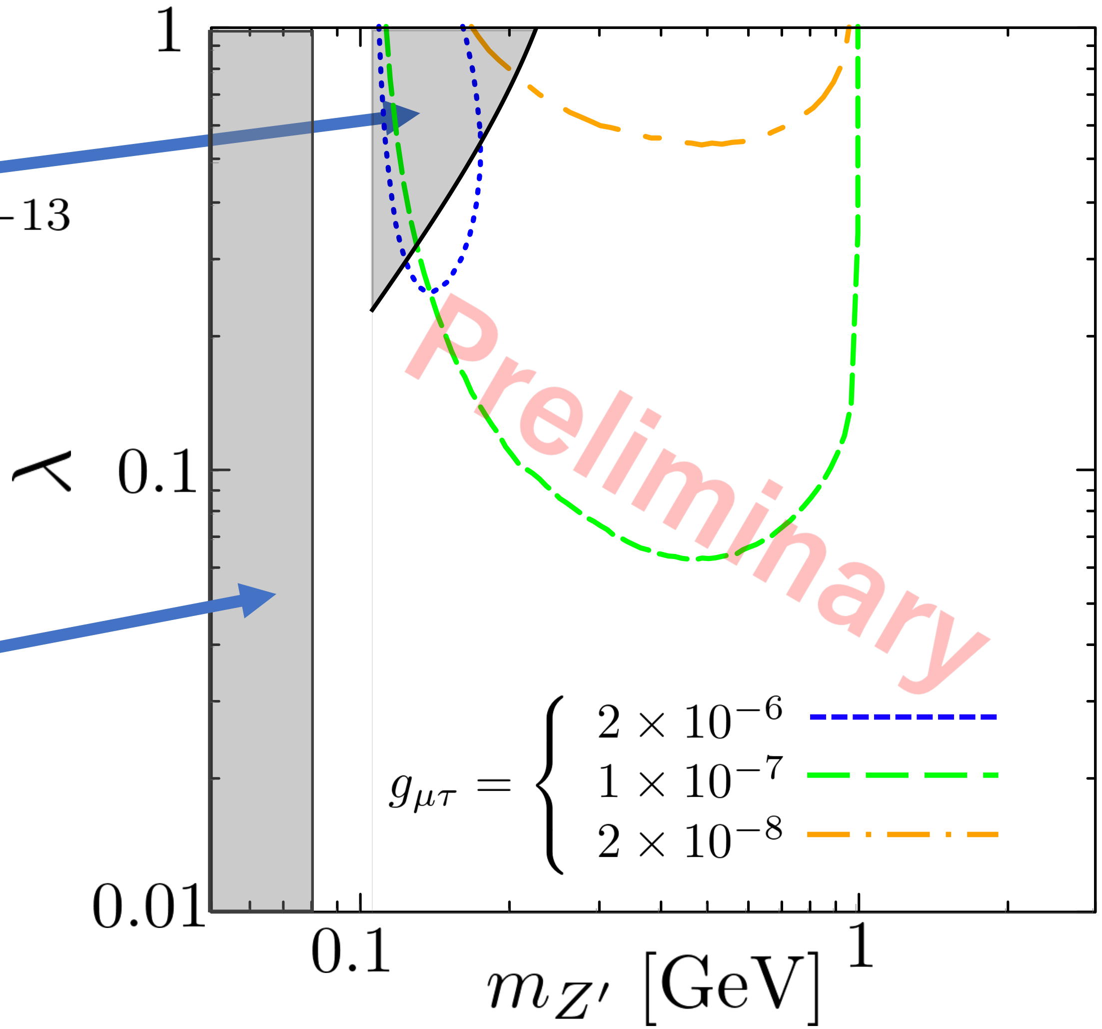
$$\begin{pmatrix} 0 & \lambda & \lambda \\ \lambda & 1 & \lambda \\ \lambda & \lambda & -1 \end{pmatrix}$$

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

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

$\mathrm{BR}(\mu \to e\gamma) > 4.2 \times 10^{-13}$
for $g_{\mu\tau} = 2 \times 10^{-6}$

$\mathrm{BR}(\mu \to eZ') > 10^{-5}$



95% C.L. exclusion contour @ FASER2

Parameters

$m_\phi = 2.0$ [GeV]

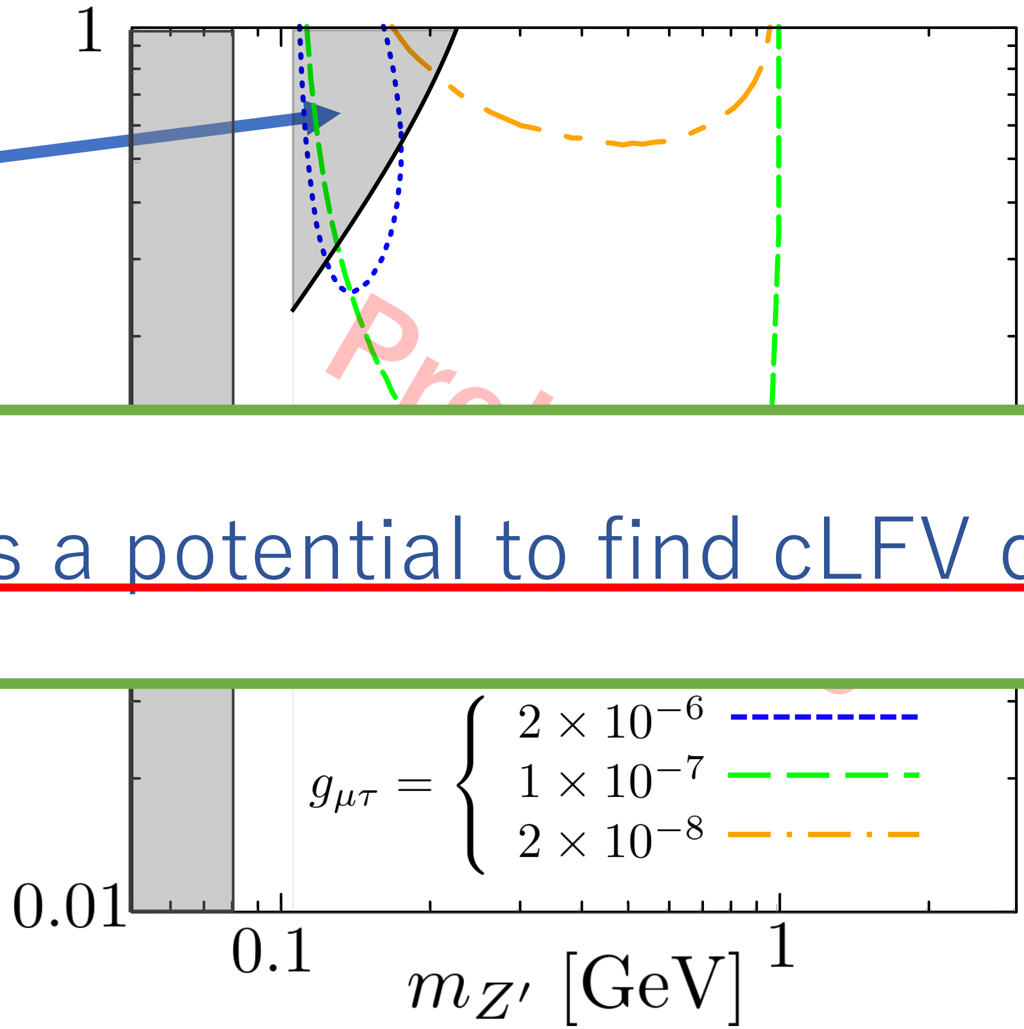
$\theta = 10^{-4}$

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

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

for $g_{\mu\tau} = 2 \times 10^{-6}$

$\mathrm{BR}(\mu \to eZ') > 10^{-5}$



95% C.L. exclusion contour @ FASER2

...meters

$m_\phi = 2.0$ [GeV]

$\theta = 10^{-4}$

FASER has a potential to find cLFV decay

Background

- Rock & LHC infrastructure eliminate most background

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

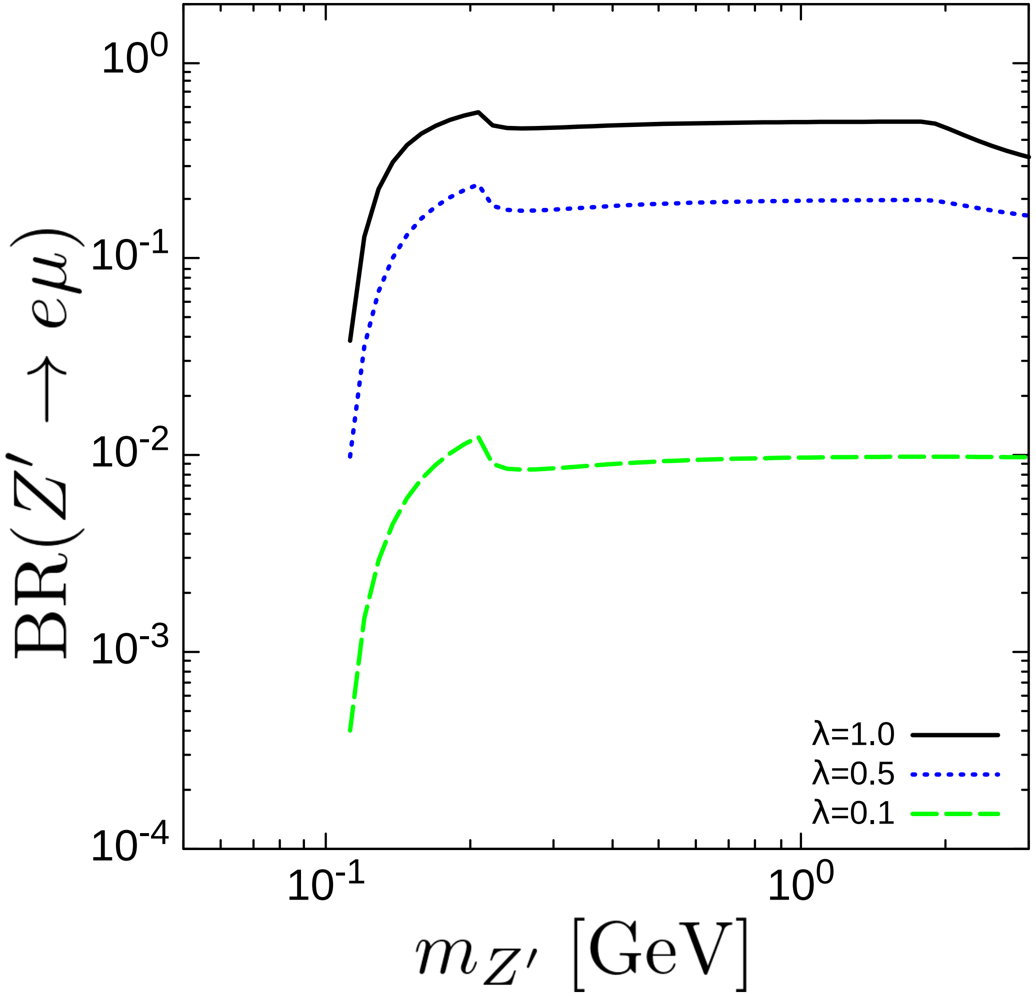
- Muon brems. → photon
  : 80000 events
- CC / NC interactions of neutrinos ($E_\nu \gtrsim 100$ [GeV])
  : O(1) events

Veting entering charged particles
with an efficiency of 99.99%

Almost background free

Appendix

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



Decay width

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

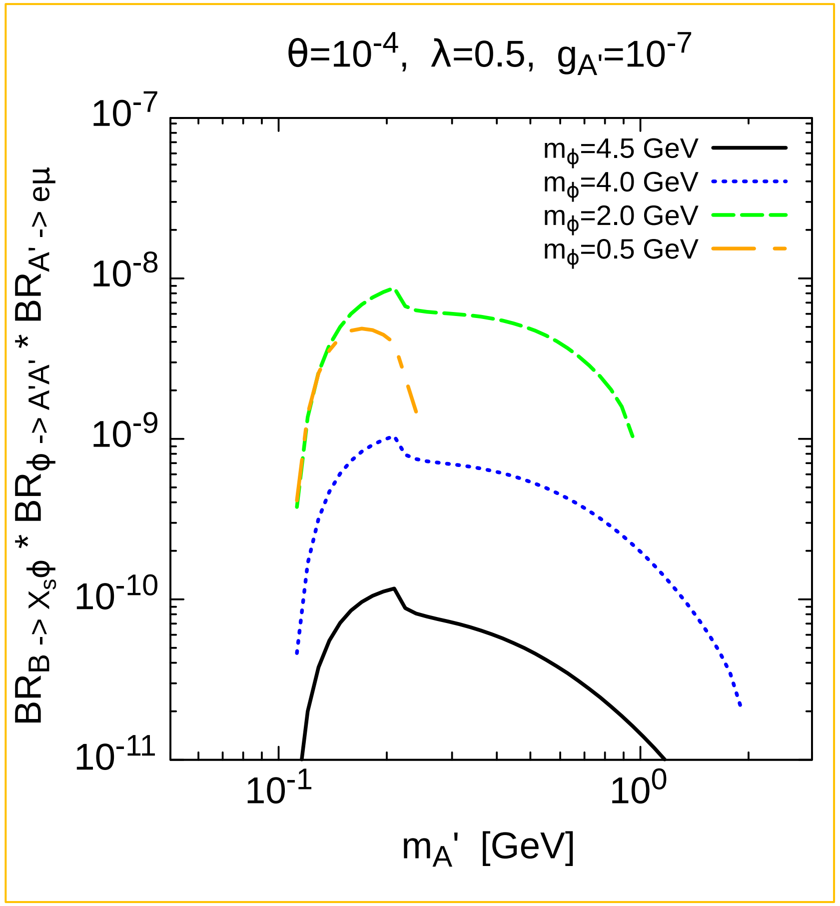
$$\lambda(1, a, b) = \sqrt{1 + a^2 + b^2 - 2a - 2b - 2ab}$$

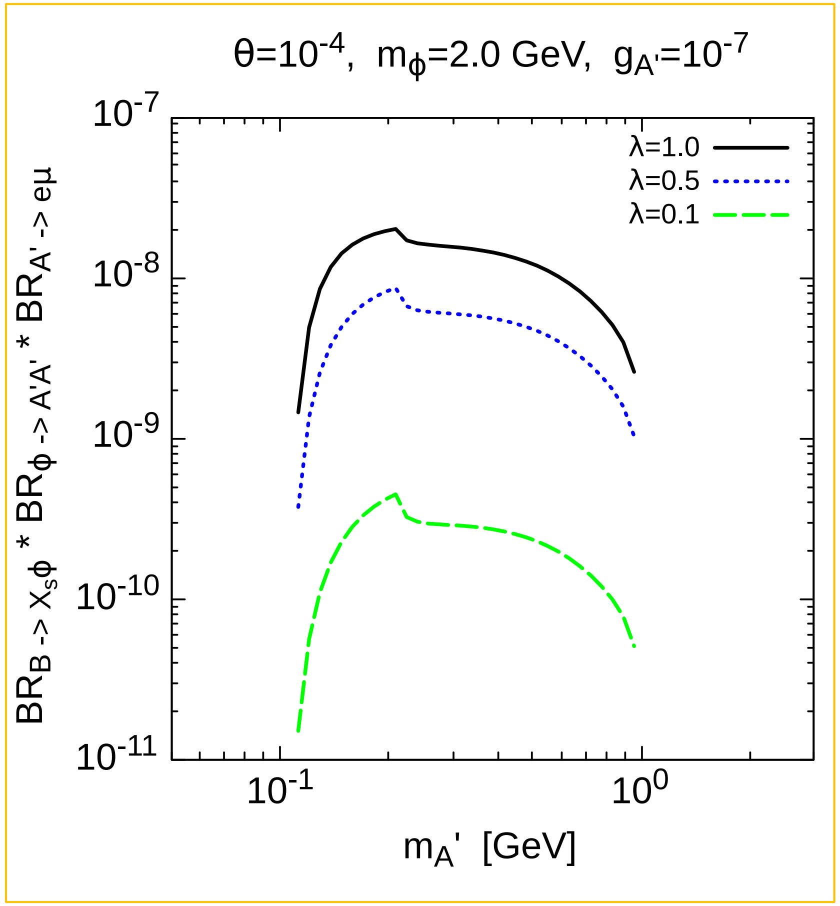
where

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

Appendix

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





Decay width

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

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

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