Search for lepton flavor violating decay at lepton beam dump experiment

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@ University of Tokyo

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Based on T. Araki, **KA**, T. Shimomura, JHEP 11 (2021) 082, arXiv : 2107.07487 [hep-ph]
& ongoing work

Introduction

Introduction

Charged Lepton Flavor Violation (cLFV)

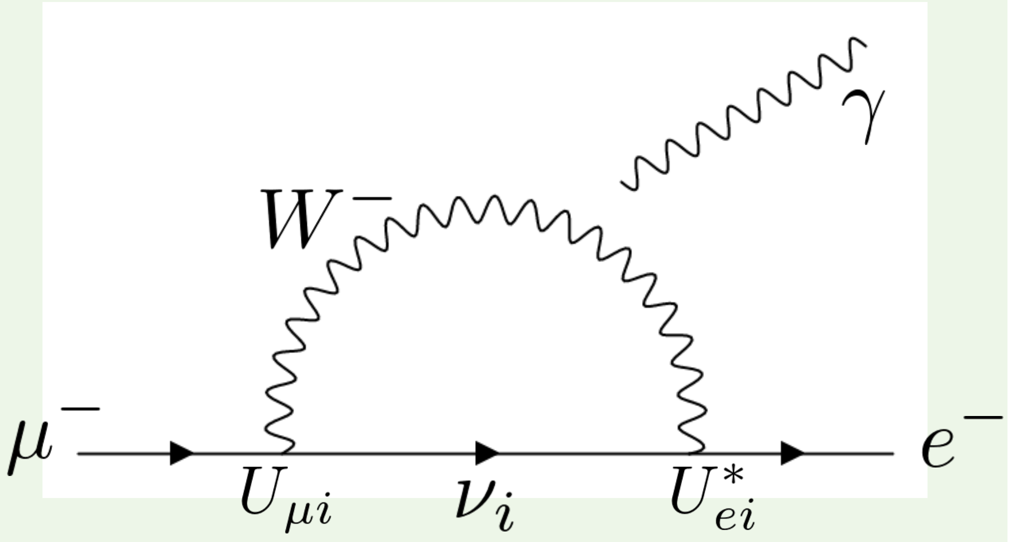
In the Standard Model (SM)

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

⋮

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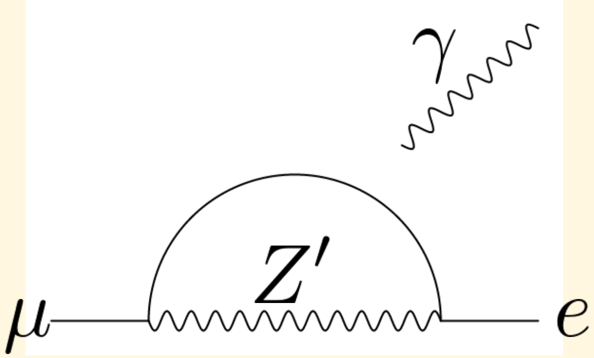


Because of no suppression from GIM mechanism, branching ratios of cLFV processes are not suppressed

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

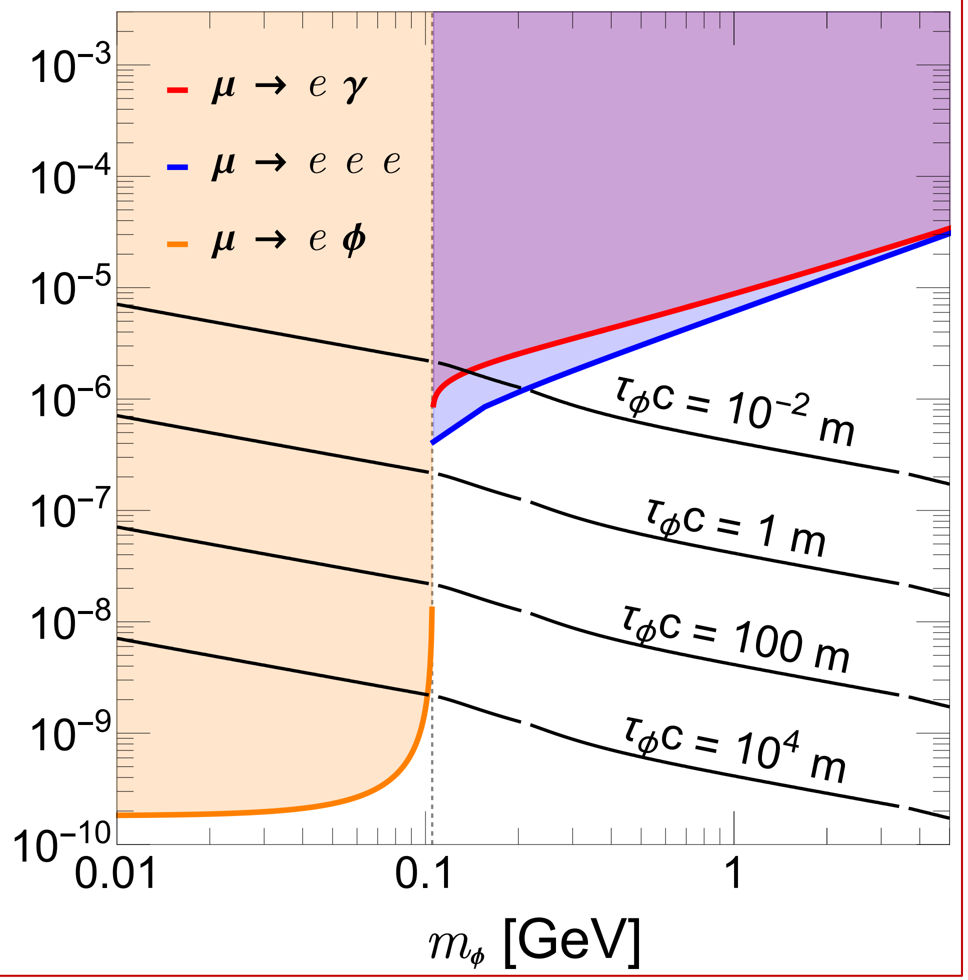
Ex) Leptophilic scalar model

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

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

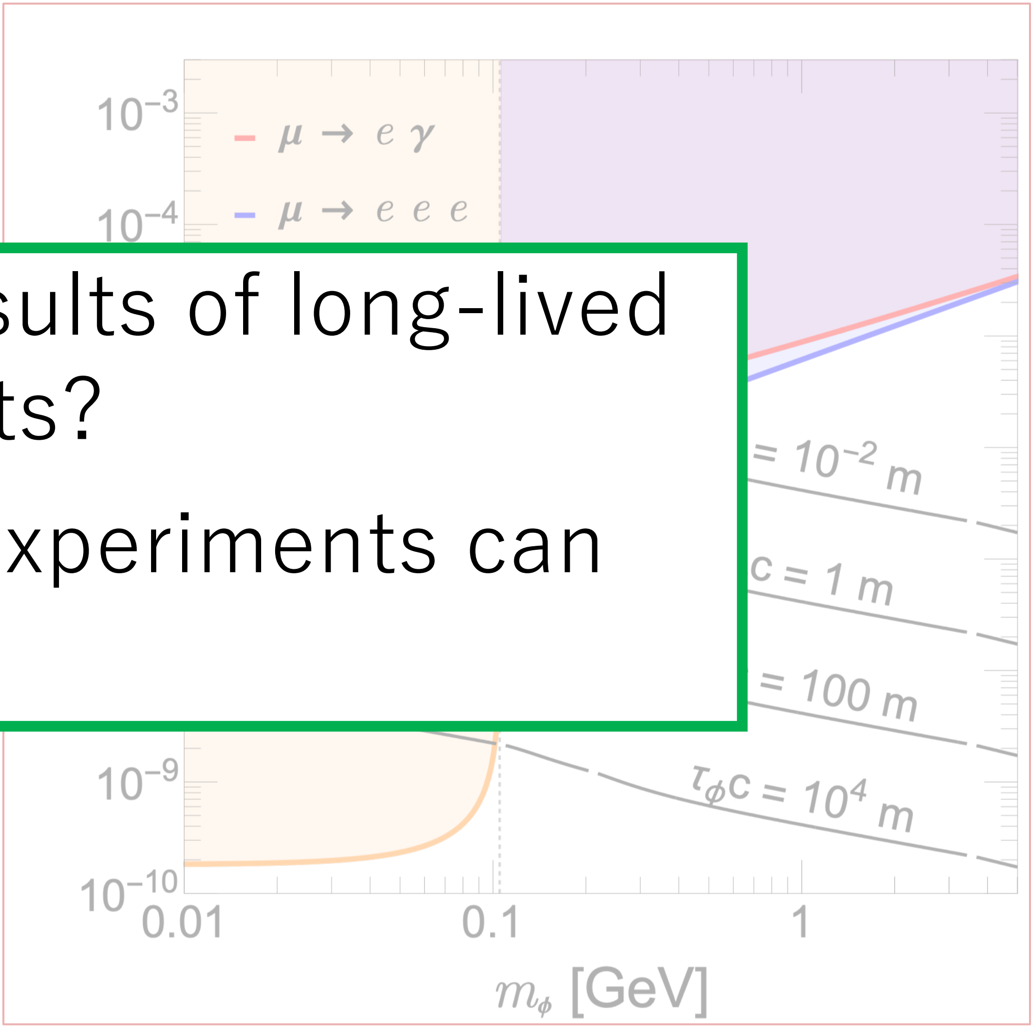
$(m_\phi \sim 0$

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 ?



Electron Beam Dump Experiment

Based on T. Araki, **KA**, T. Shimomura, JHEP 11 (2021) 082, arXiv : 2107.07487 [hep-ph]

e^- Beam Dump Experiment

Overview

Beam of high-energy e^- is dumped into dense target

→ High intensity

- Production of large number of new particles

Detector is placed behind long shield

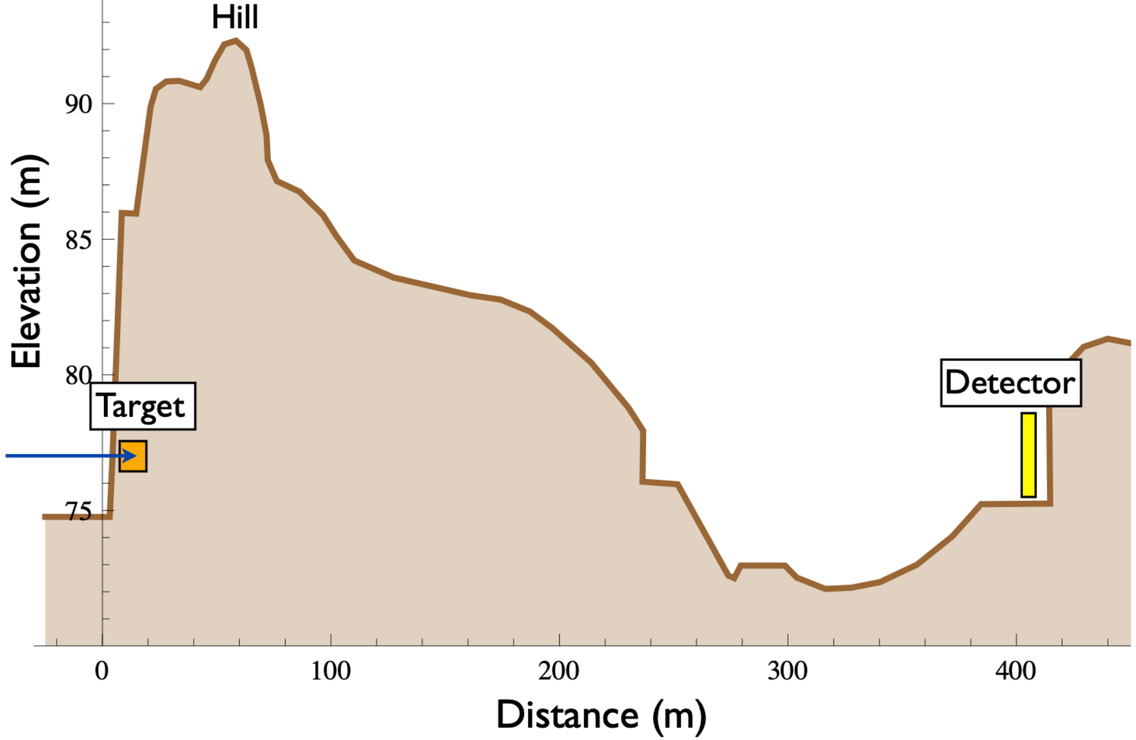
→ Low background

- 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)



e^- Beam Dump Experiment

E137 experiment

Experiment parameters

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

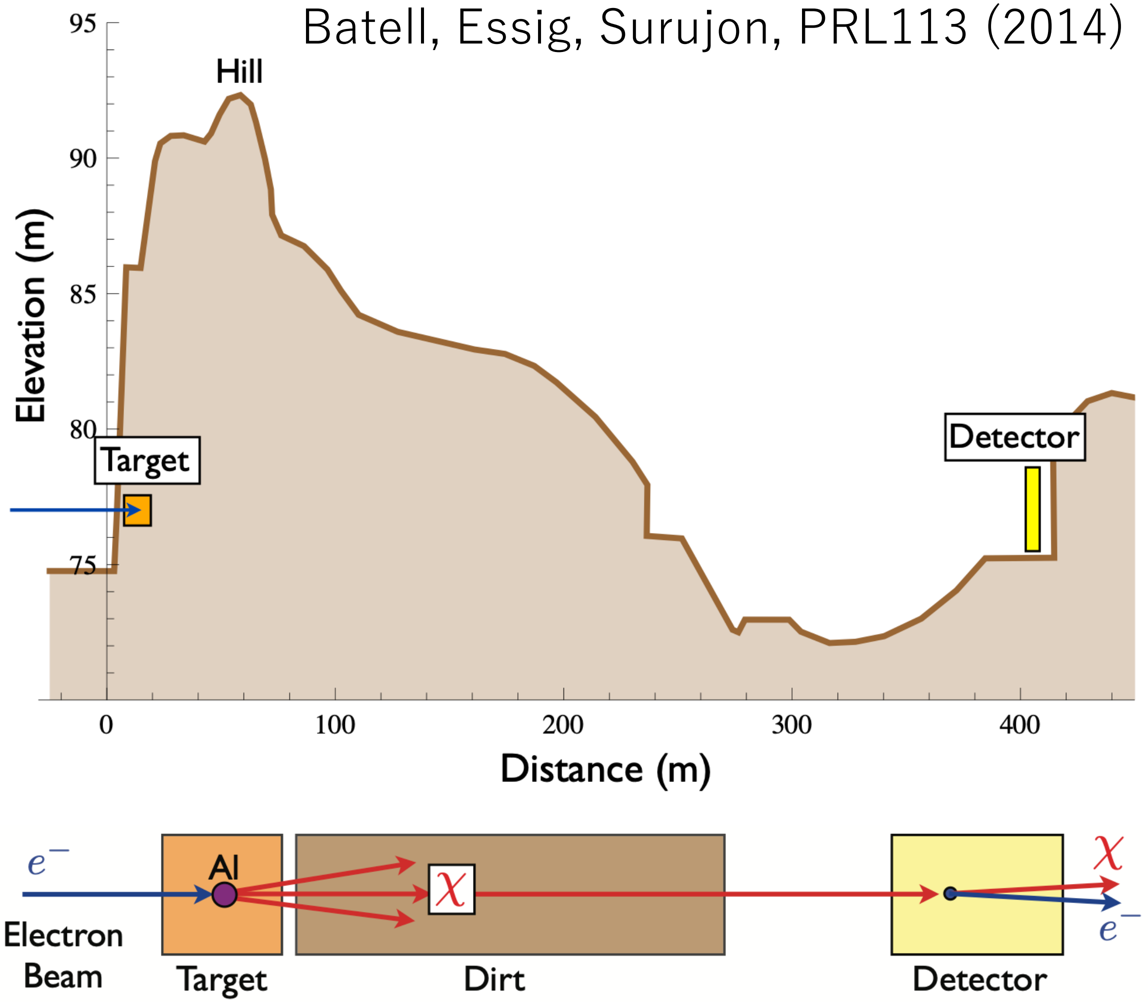
Target : Aluminum beam dump

Shielding : 179m ground (hill)

Decay volume : 204m open air

Detector : EM calorimeter + MWPC

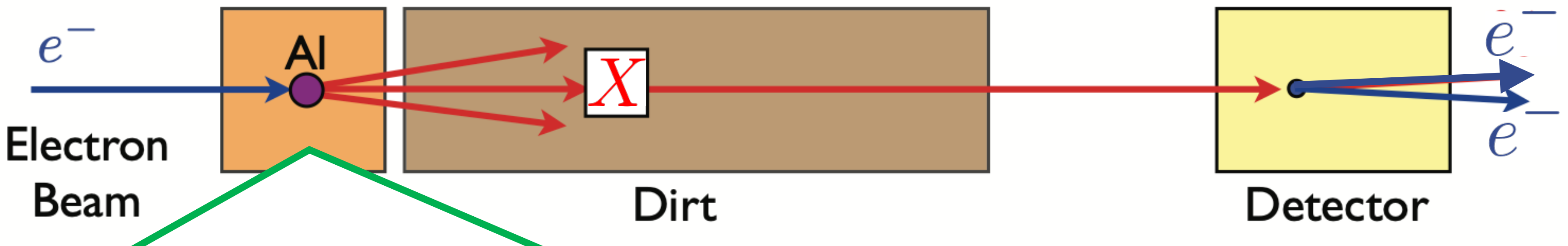
Batell, Essig, Surujon, PRL113 (2014)



e^- Beam Dump Experiment

New particle production

Batell, Essig, Surujon, PRL113 (2014)

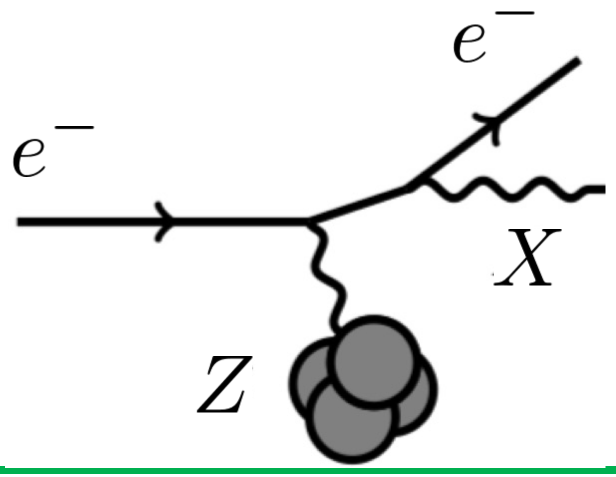


Lagrangian

Coupling with electrons

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

Bremsstrahlung production

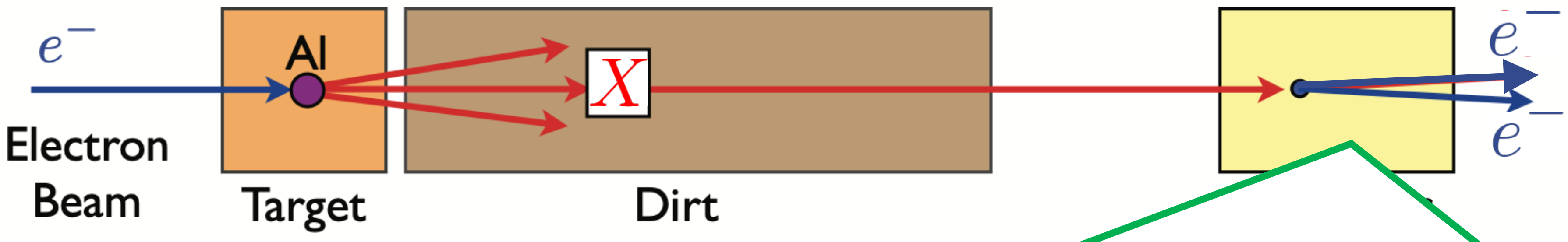


New particles are produced through bremsstrahlung process

e^- Beam Dump Experiment

New particle detection

Batell, Essig, Surujon, PRL113 (2014)



Lagrangian

Coupling with electrons

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

Detection

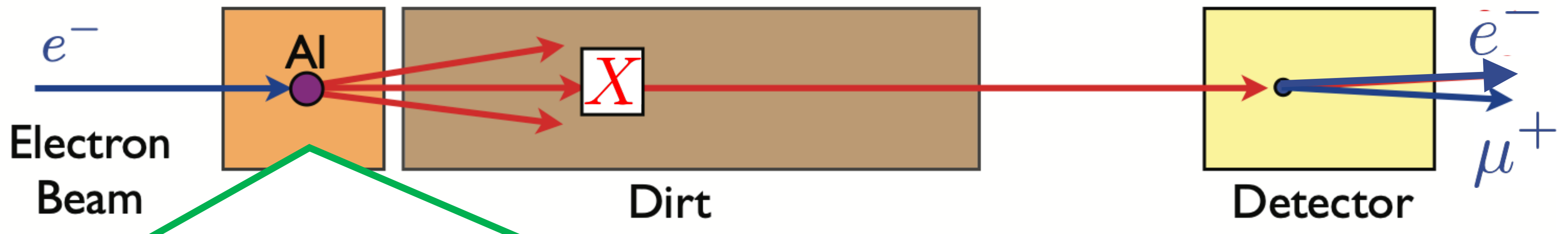
Decay into e^+e^- pair → Detection

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)

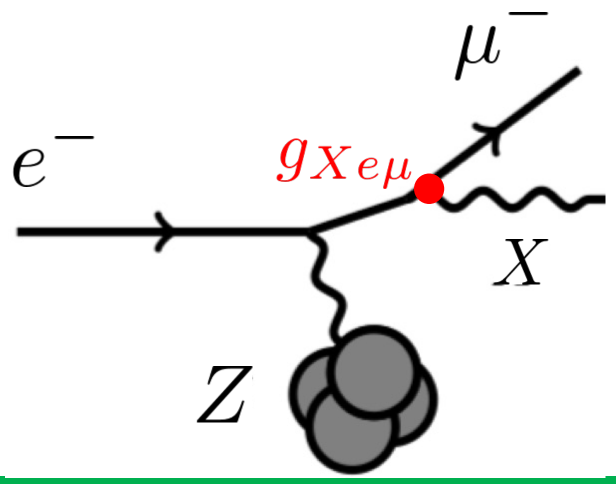


Lagrangian

Coupling with e & μ

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

Bremsstrahlung production

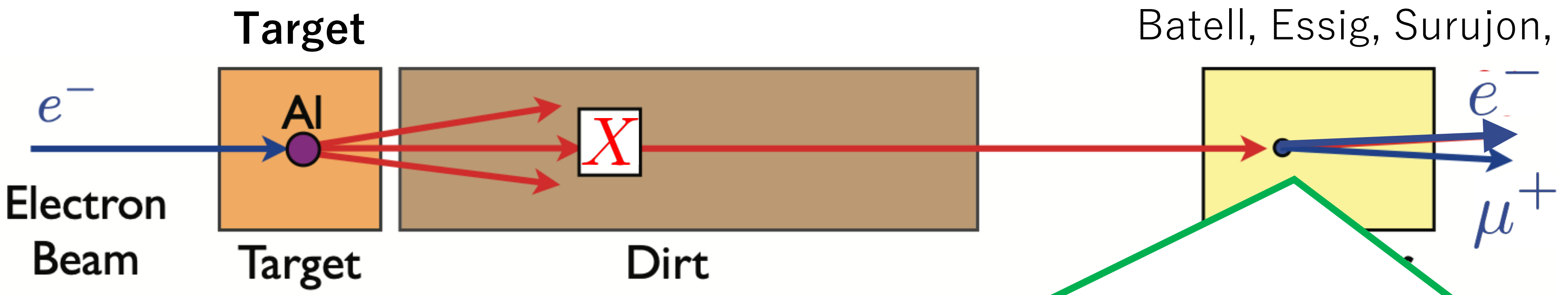


Possibly LFV interactions contribute to bremsstrahlung production

e^- Beam Dump Experiment

New particle detection with LFV coupling

Batell, Essig, Surujon, PRL113 (2014)

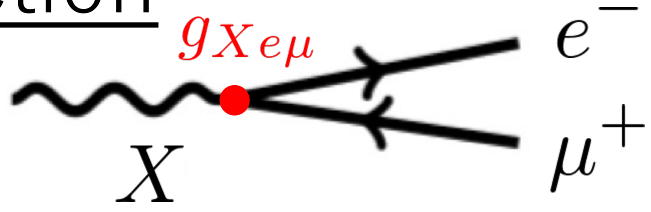


Lagrangian

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)

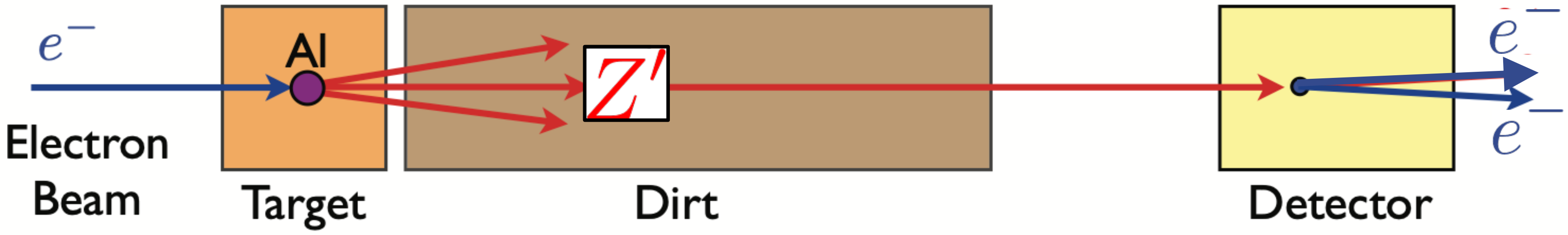
Unfortunately, E137 experiment can detect only electron

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

Calculation

Calculation

Number of signals

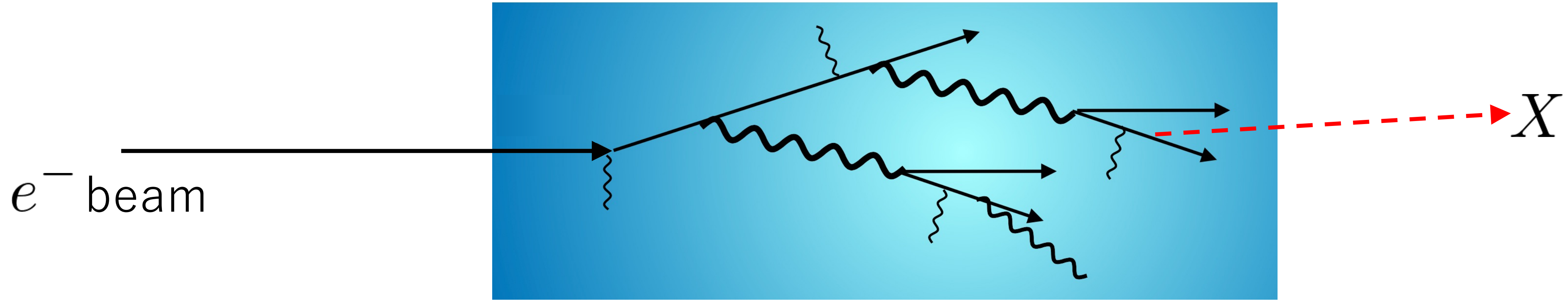


(# of signal detection)

= (# of produced new particle) × (Acceptance)

Calculation

of produced new particle



(# of produced new particle)

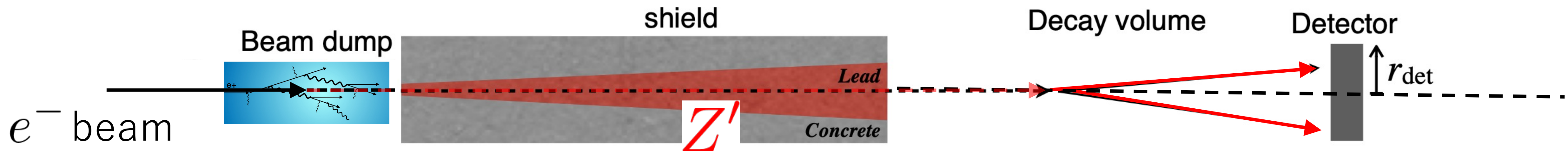
$= $ (Luminosity) $\times$ (Production cross section)

Dependent on beam and beam dump

Dependent on particle species

Calculation

Number of signals

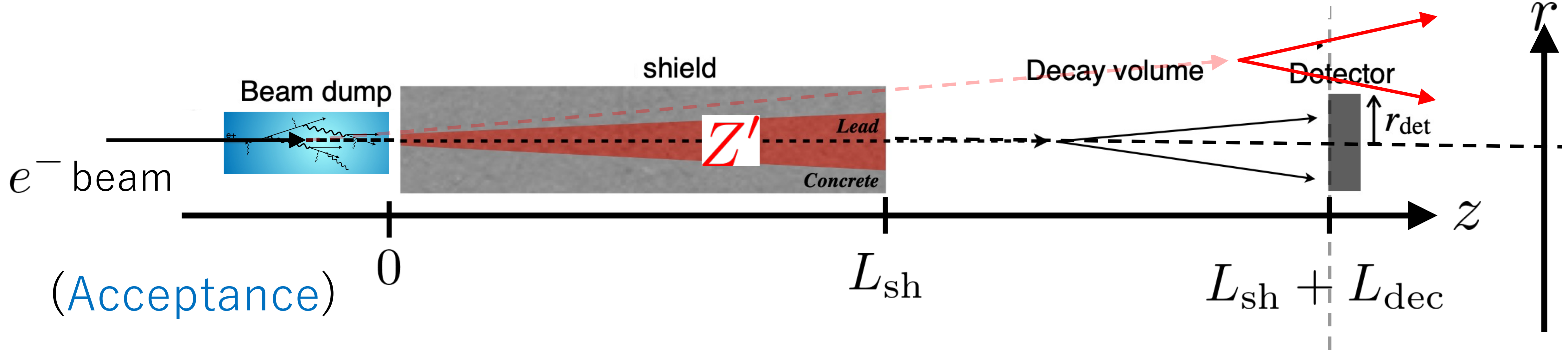


(Acceptance)

= (Probability of decaying in decay volume) × (Angular cut)

Calculation

Number of signals



(Acceptance)

= (Probability of decay in decay volume) × (Angular cut)

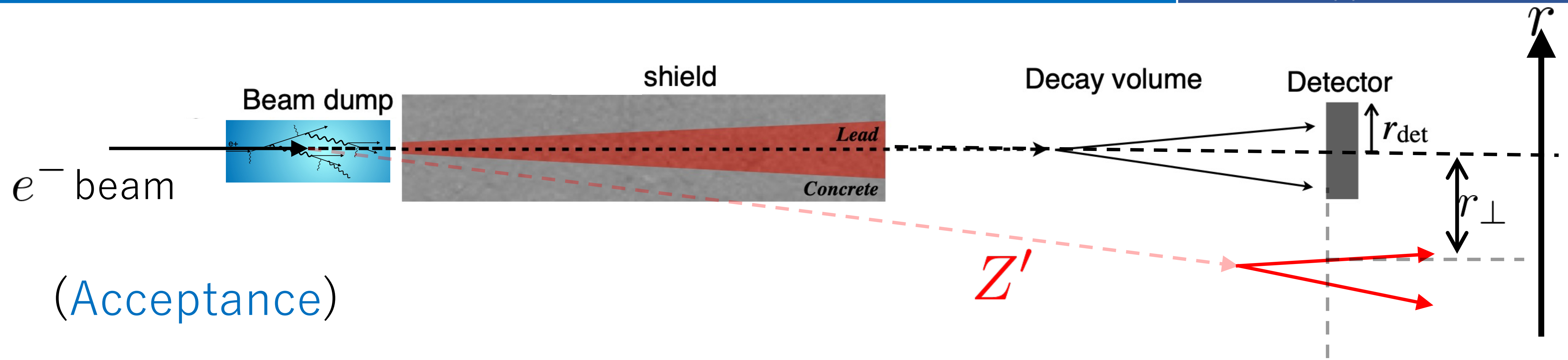
New particles reach decay volume and are detected by decay into visible particles

➡ Probability of decay between $L_{\rm sh} \sim L_{\rm sh} + L_{\rm dec}$

$$P_{\rm dec} = \int \frac{dz}{l_X} e^{-z/l_X} = e^{-L_{\rm sh}/l_X}\left(1 - e^{-L_{\rm dec}/l_X}\right)$$

l_X : Decay length in laboratory frame

Number of signals



(Acceptance)

= (Probability of decay in decay volume) × (Angular cut)

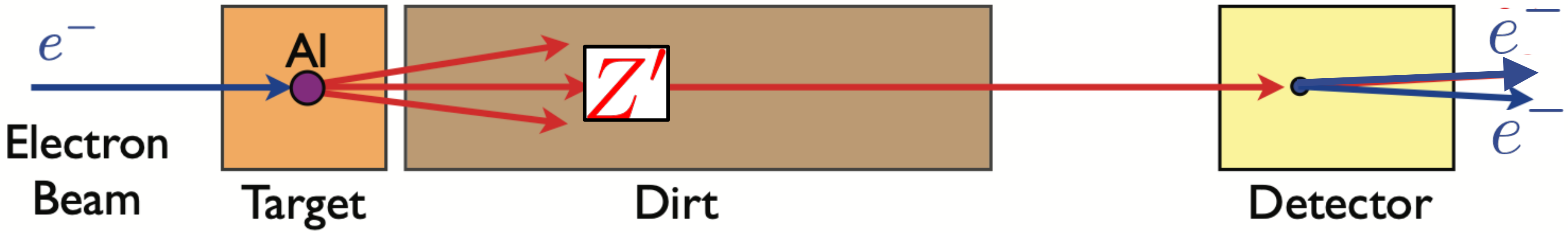
Produced particles have angles with respect to initial particles

➡ For large angle (deviation from beam axis $r_\perp$), visible particles in decay volume do not hit detector

➡ Angular cut : $\Theta(r_{\mathrm{det}} - r_\perp)$

Calculation

Number of signal events



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

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

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

Coupling to SM → # of production, Acceptance (lifetime)

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

Result

Result

Production through LFV coupling

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

LFC

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

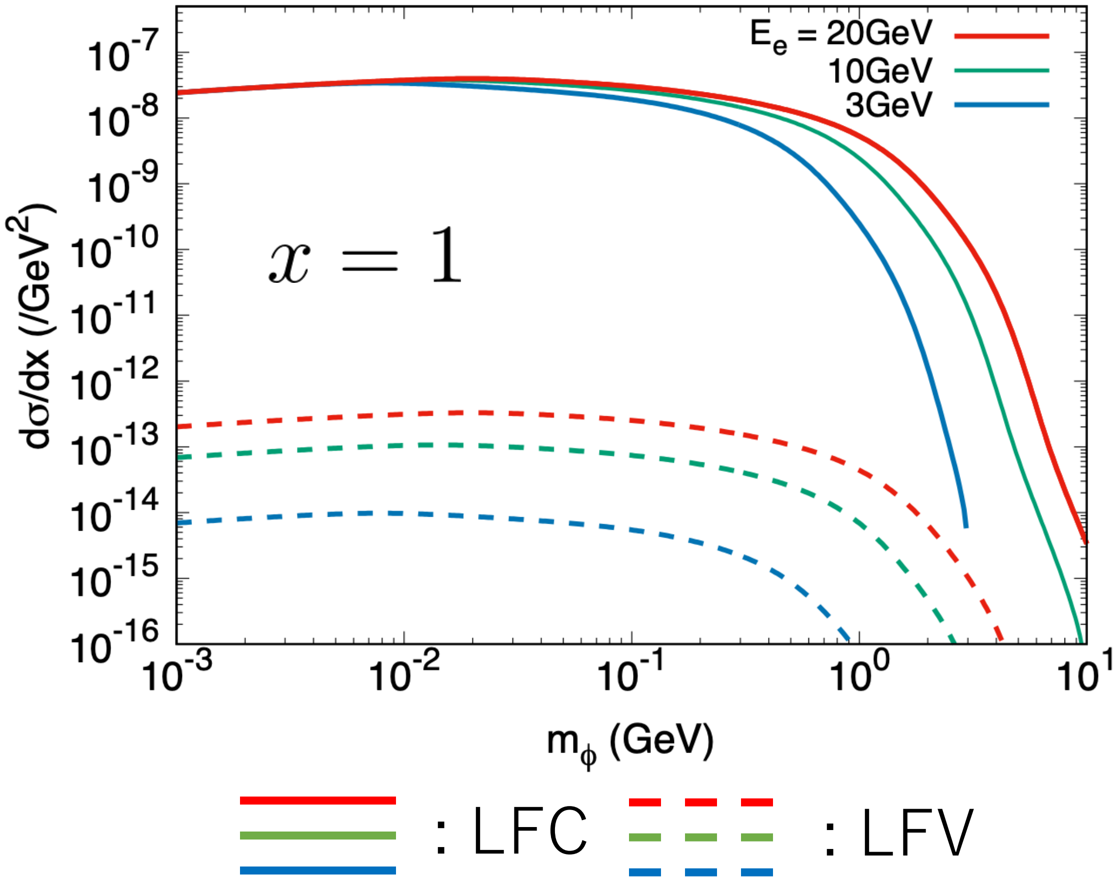
$\gg$

LFV

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

ϕ production through LFV coupling is negligible

Production cross section



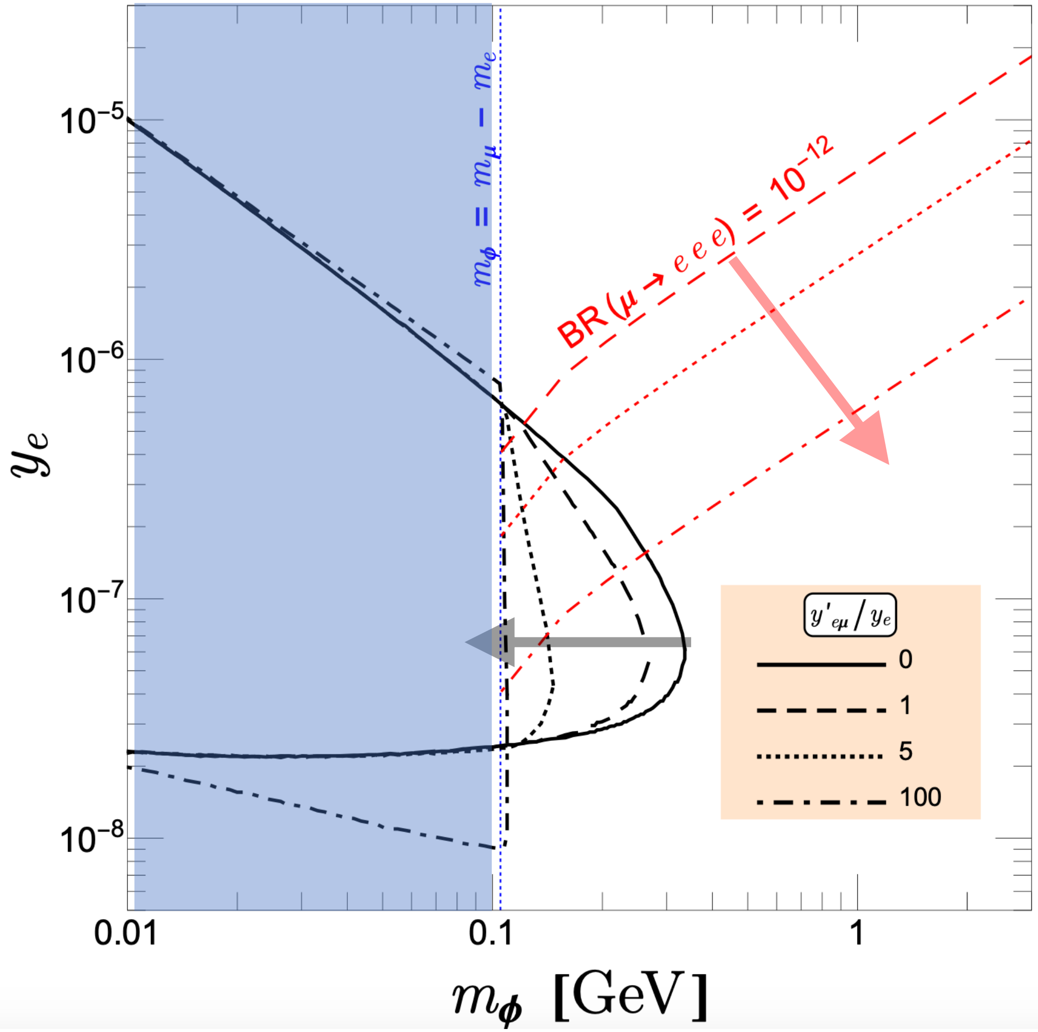
Constraint on LFV coupling

Scalar-type int.

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

○ 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 $\mu \to e\phi$



Result

Constraint on LFV coupling

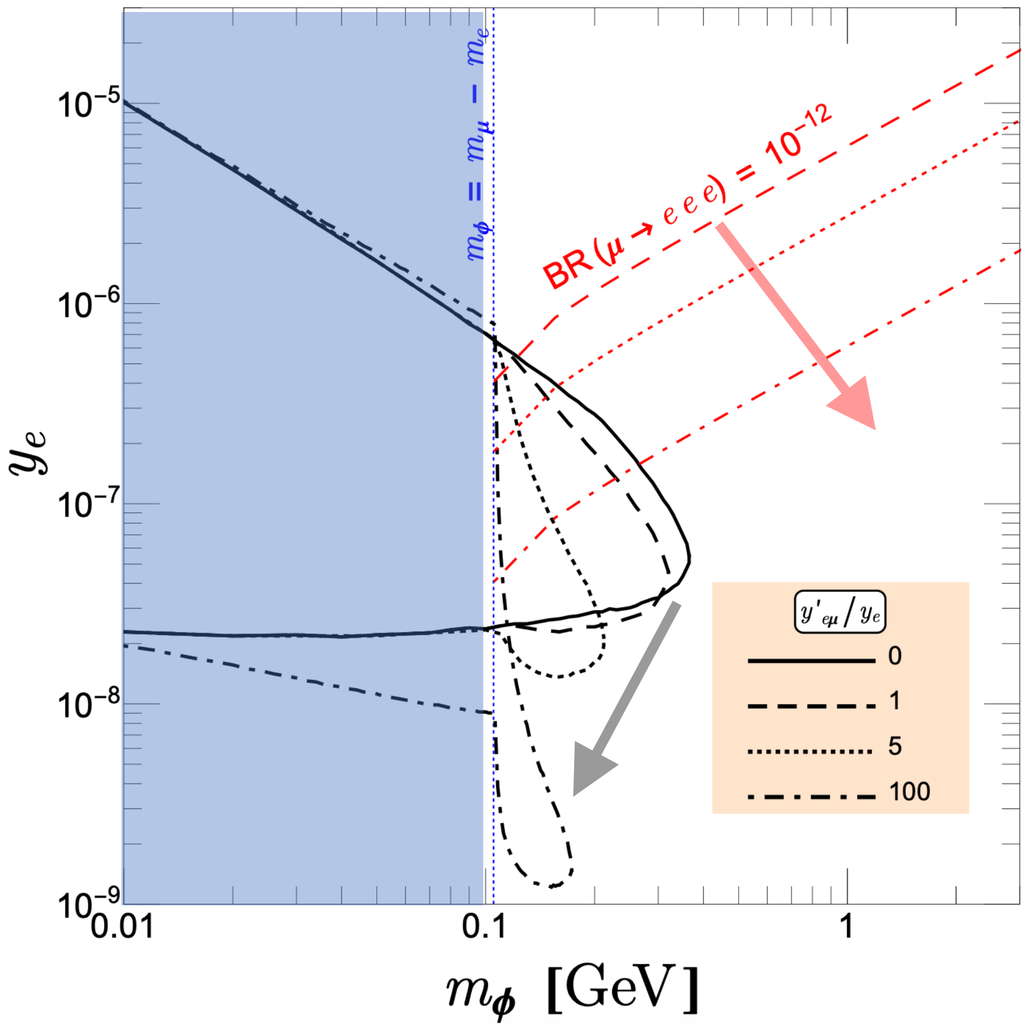
<u>Scalar-type int.</u>

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

If E137 experiment could 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



Question

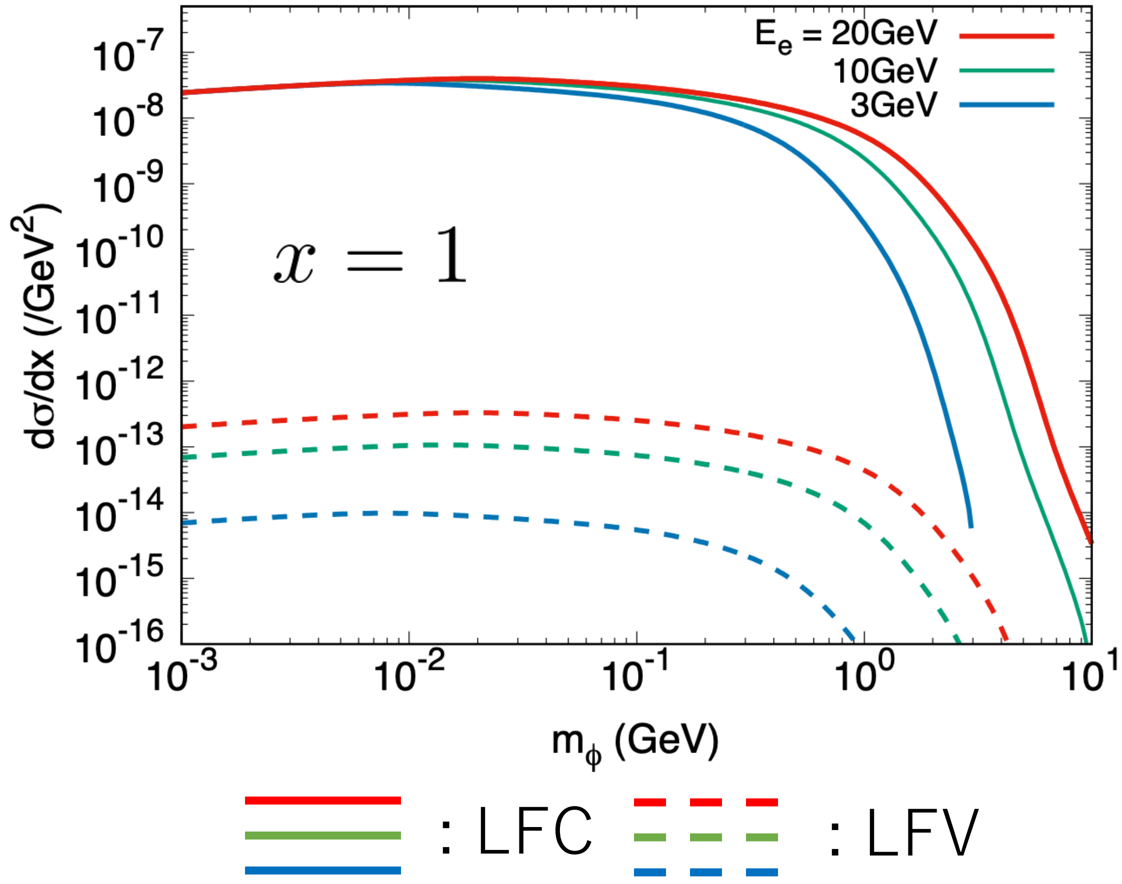
Production through LFV coupling

ϕ production through LFV coupling is negligible

ϕ production by muon beam through LFV bremsstrahlung is larger than LFC one ?

Muon beam dump experiment

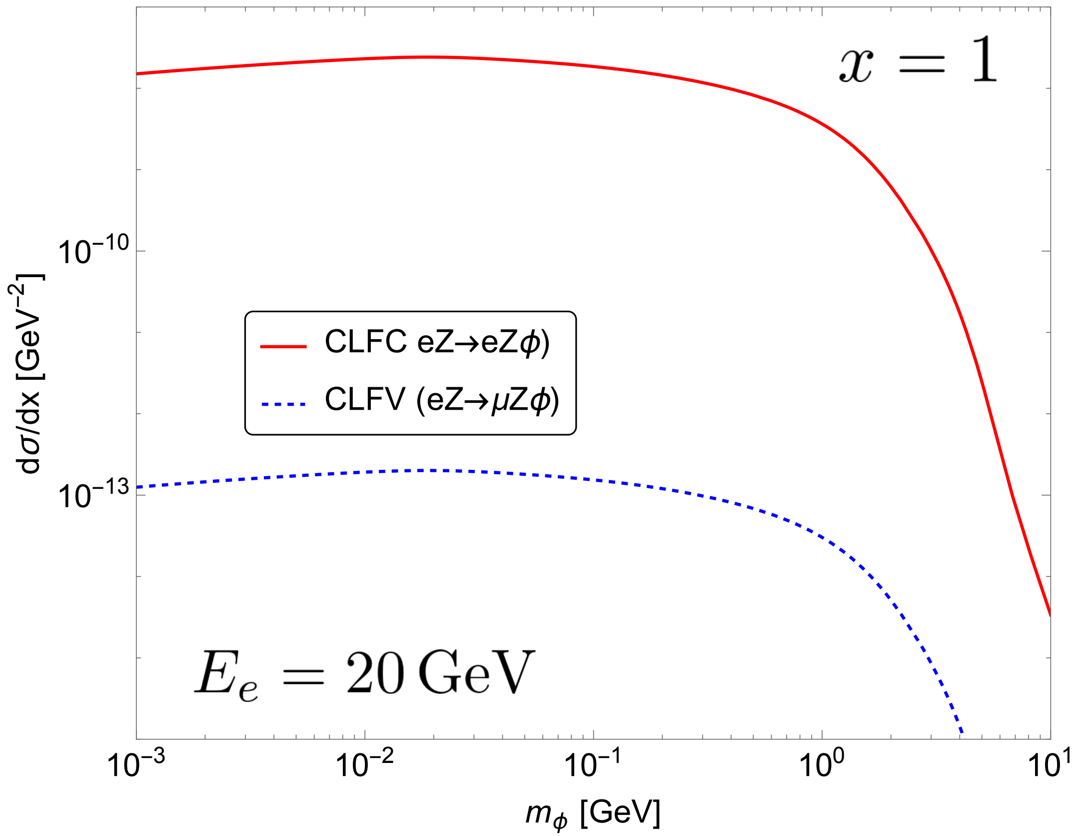
Production cross section



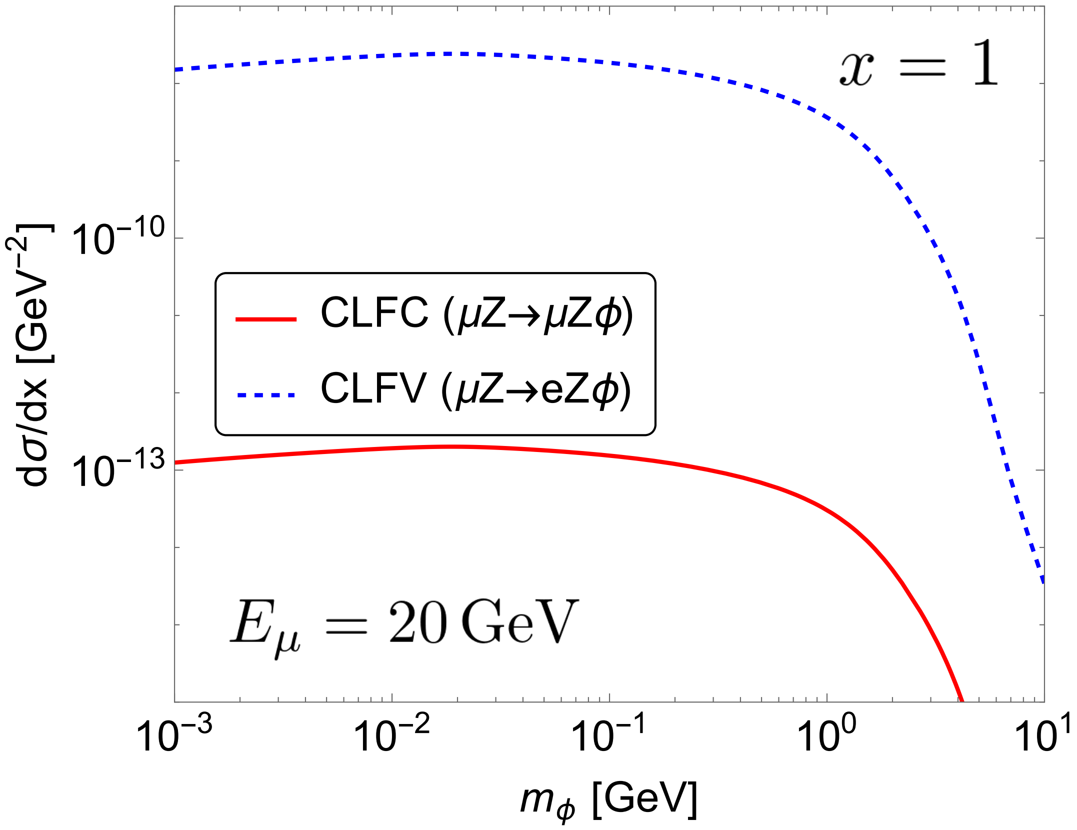
Question

Bremsstrahlung cross section

Electron beam dump



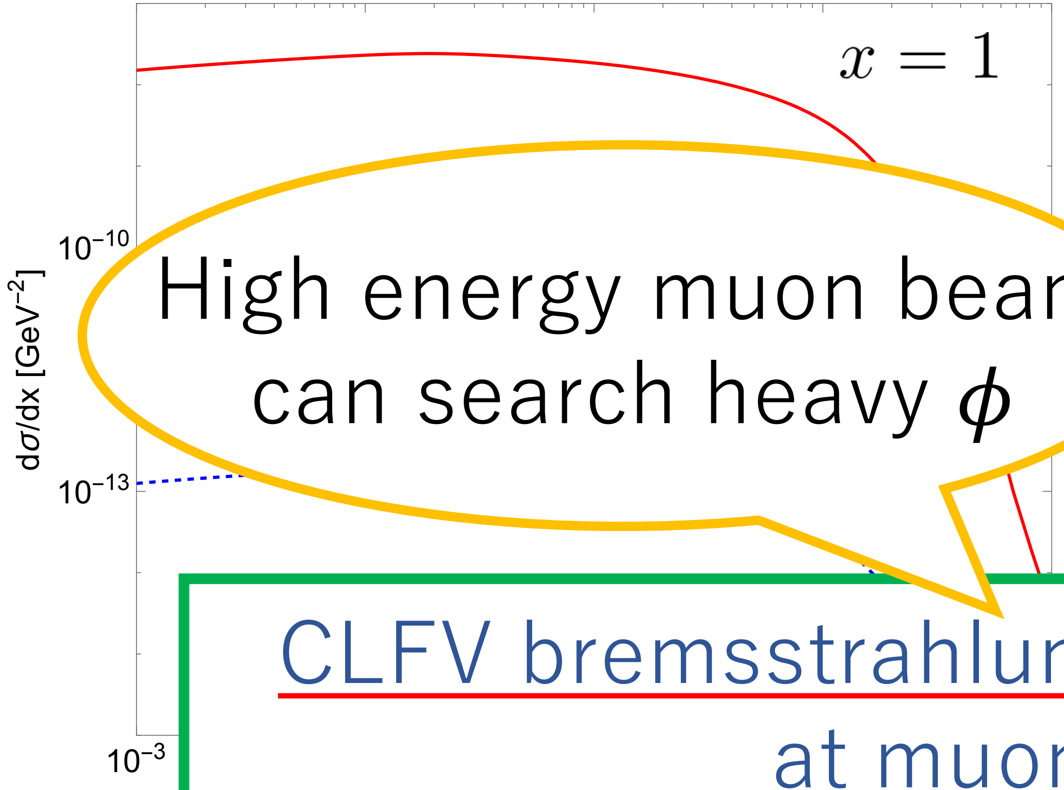
Muon beam dump



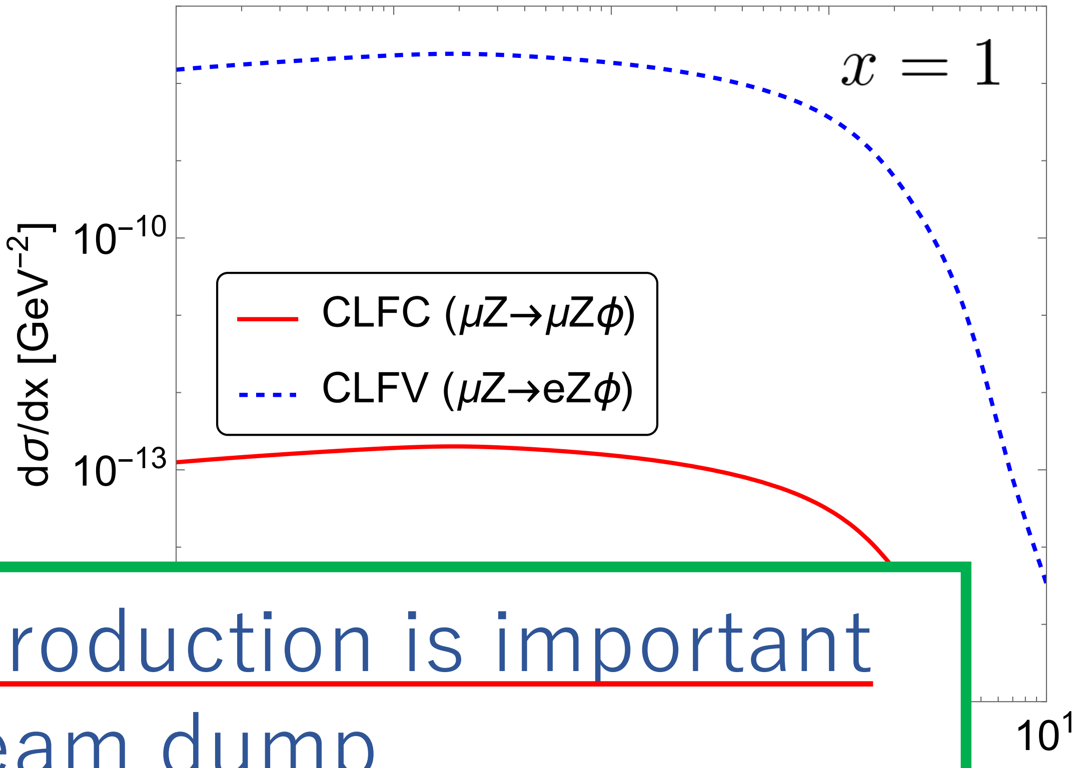
Question

Bremsstrahlung cross section

Electron beam dump



Muon beam dump



High energy muon beam can search heavy ϕ

CLFV bremsstrahlung production is important at muon beam dump

LFV decay search @ muon beam dump

Based on T. Araki, **KA**, T. Shimomura, ongoing

μ Beam Dump Experiment

Experimental setup

<u>Experiment parameters</u>

Beam : 1.5 TeV μ beam
$= 10^{18}, 10^{22}$ MOT

Target : Liquid water, 10m

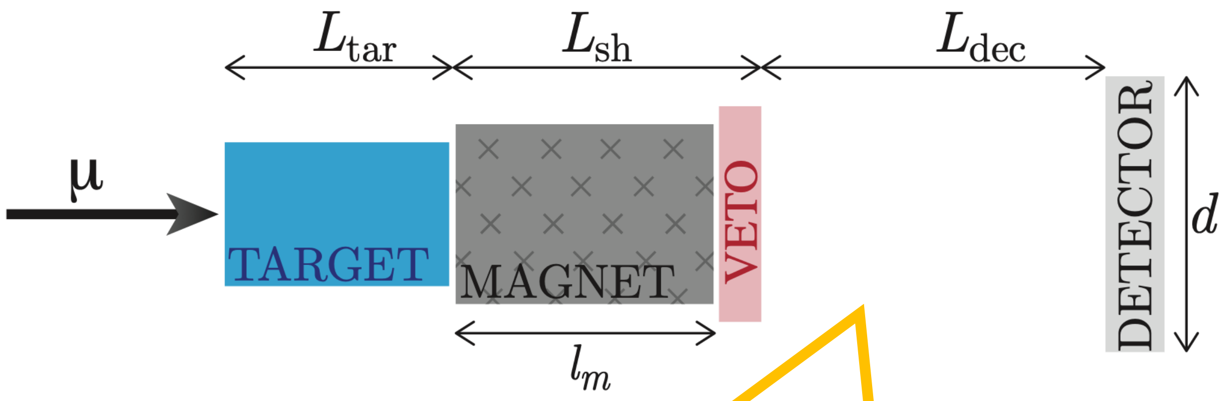
Shielding : 10m active shield

(magnetic field applied)

Decay volume : 100m

Detector : EM calorimeter + muon detector, 2m radius

C. Cesarotti, S. Homiller, R. K. Mishra, M. Reece,
<u>PRL 130 (2023) 7, 071803</u>



We follow the setup
in the above PRL paper

Calculation

Number of signal events

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

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

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

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

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

$$I_\mu(E_0, E_\mu, t) = \delta(E_\mu - E_0)$$

for thin beam dump

Result

Sensitivity to LFV coupling

Scalar-type int.

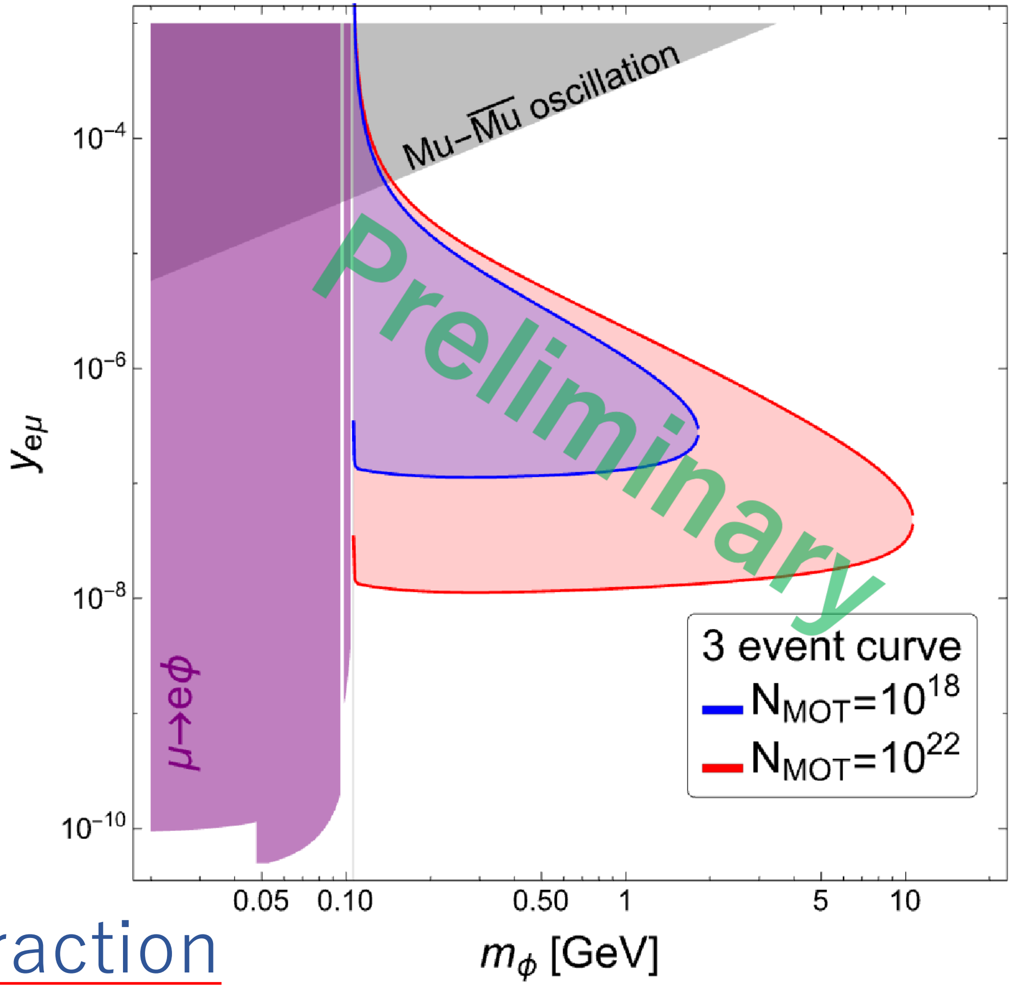
$$\mathcal{L}_{\rm scalar} = y_{e\mu}\overline{e_L}\phi\mu_R + y_{e\mu}\overline{\mu_L}\phi e_R + {\rm H.c.}$$

$m_\phi > m_\mu - m_e$

➡ Sensitivity region is below Mu-$\overline{\rm Mu}$ oscillation bound

$m_\phi < m_\mu - m_e$

➡ Bound on ${\rm Br}(\mu \to e\phi)$ is stronger



Muon beam dump experiment can search unexplored parameter region of CLFV interaction

Summary

○ Lepton beam dump 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

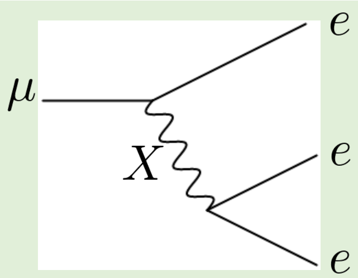
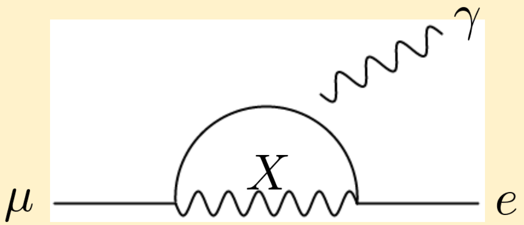
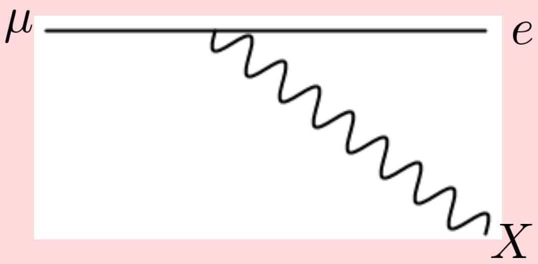
○ We considered scalar-type LFV interaction and are studying sensitivity to LFV interaction ($\phi \to e\mu$ decay) by muon beam dump experiment

Thank you for your attention !

Appendix

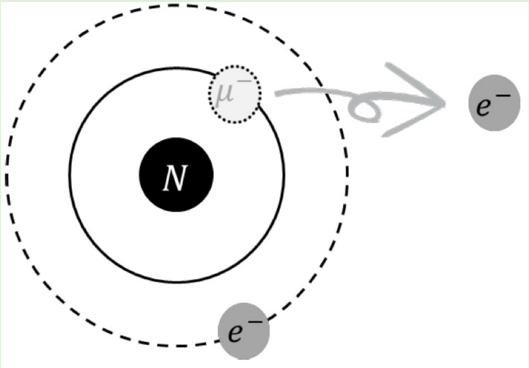
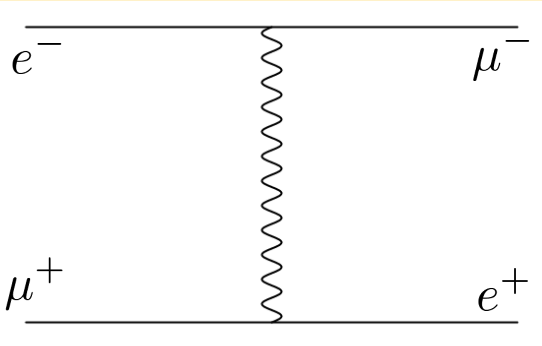
Introduction

Constraints on cLFV

cLFV process		Exp. limit on BR	Future prospect
$\mu \to eee$		1.0×10^{-12} SINDRUM Collaboration (1988)	$\approx 10^{-16}$ 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)	—

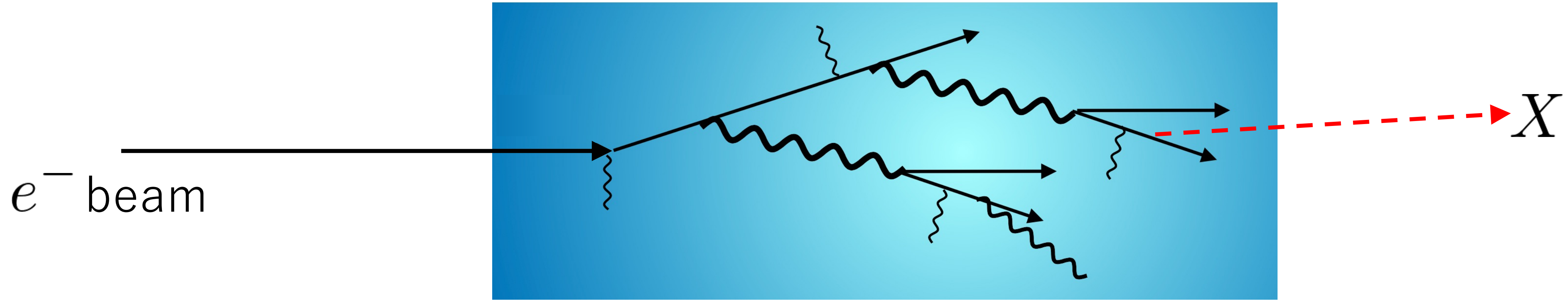
Introduction

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)

Calculation

Luminosity



(# of produced new particle)

= (Luminosity) × (Production cross section)

||

(# of incident particles into beam dump) ← $N_e = 1.86 \times 10^{20}$

× (# density of target particles in beam dump) ← $n_N = \rho_{\mathrm{sh}} N_{\mathrm{avo}}/A \simeq 6 \times 10^{22}$

× (Track length of shower particles)

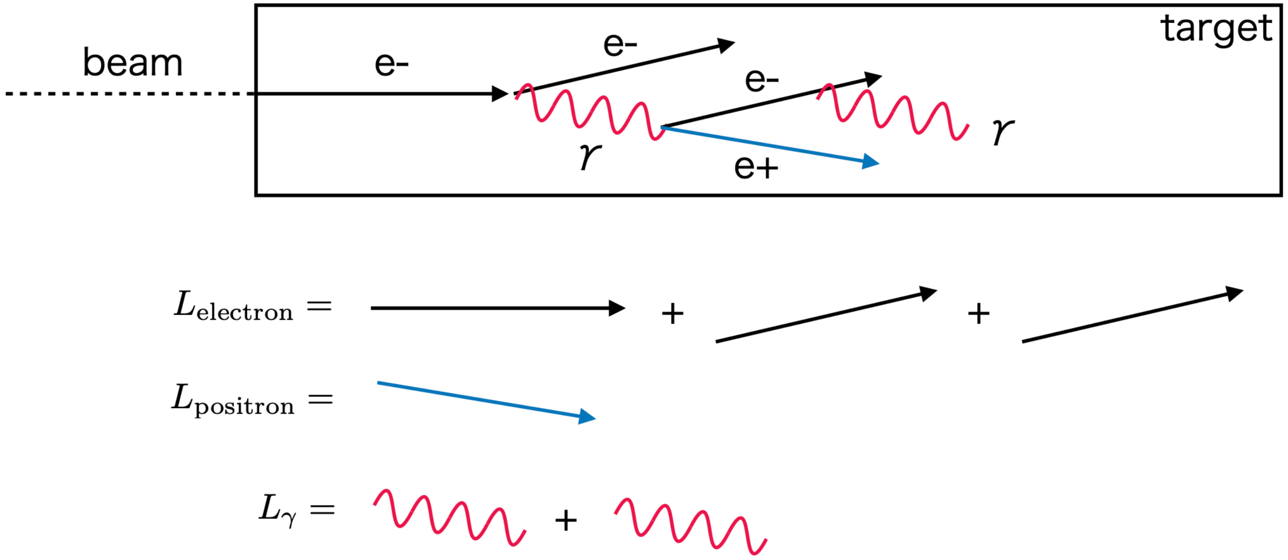
Calculation

Luminosity

Track length

- Integral of particle fluence over beam dump volume
- Used Tsai's formula
  [Y.-S. Tsai, PRD **34** (1986) 1326]

From Sakaki san's slide



=

(# of incident p... to beam dump)

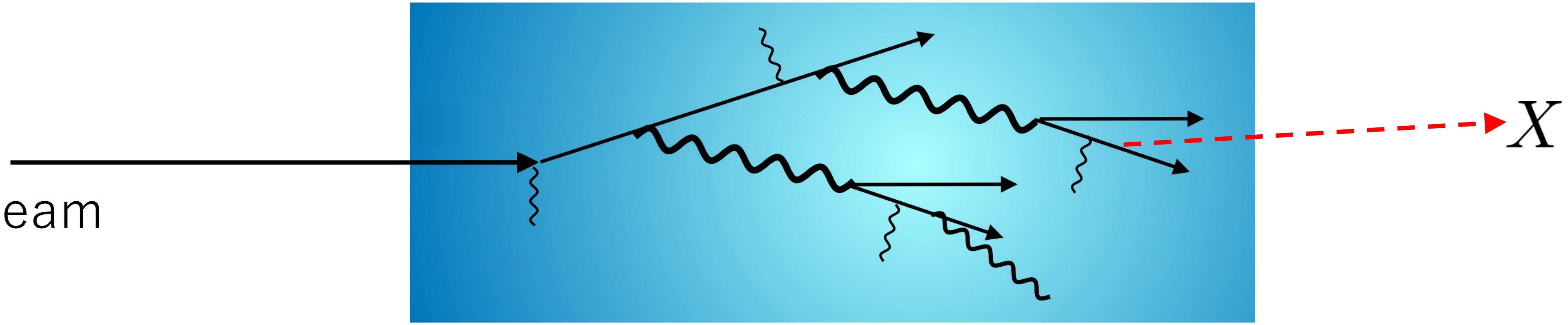
× (# density of ta...t particles in beam dump)

× (Track length of shower particles)

Calculation

Production cross section

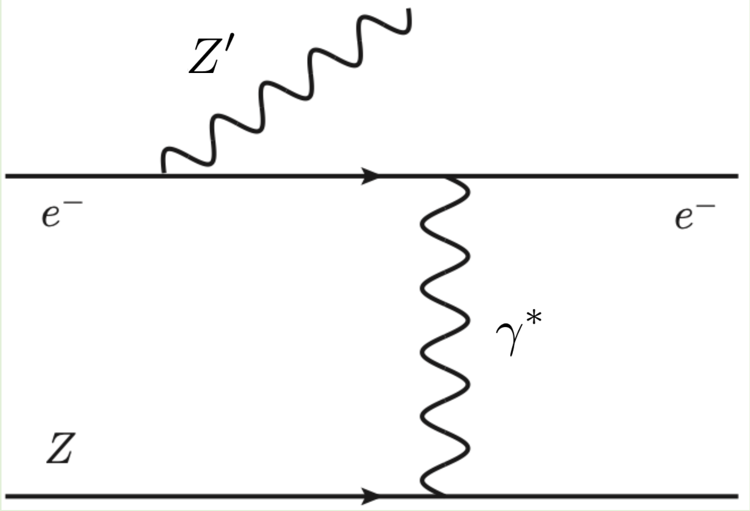
e^- beam



(# of produced new particle)

= (Luminosity) × (Production cross section)

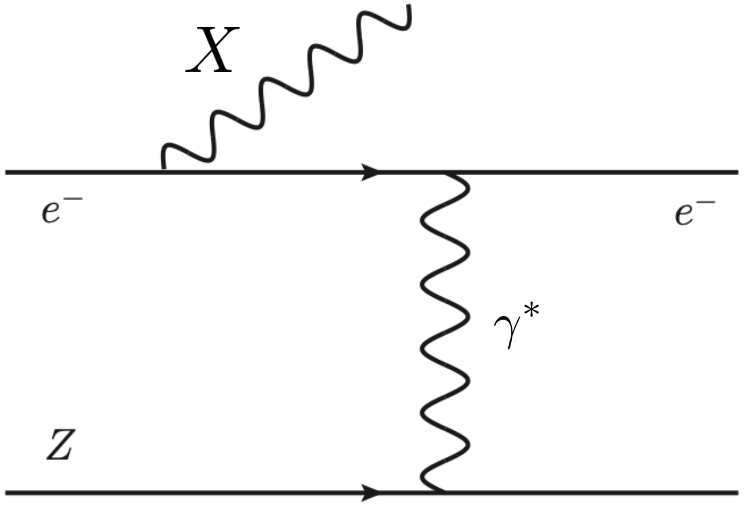
||

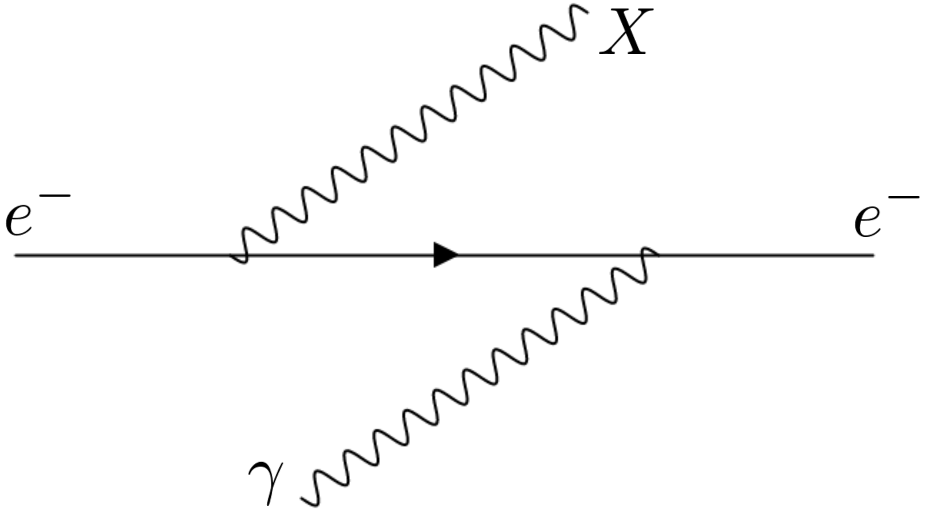


Bremsstrahlung process

$$\frac{d\sigma(e(p)+Z(P_i)\to e(p')+Z(P_f)+X(k))}{dE_X\,d\cos\theta_X}$$

Production cross section





C. F. von Weizsäcker (1934);
E. J. Williams (1935)

<u>Weizsäcker-Williams approximation</u>

- Approximation for simplifying phase space integral
- Electromagnetic field generated by fast moving charged particle is nearly transverse
  → can be approximated by real photon

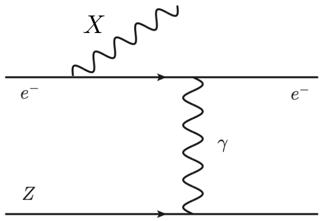
cf) 2-to-2 scattering

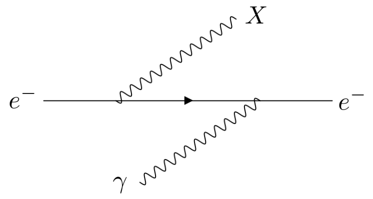
$$q^2 = -2p^0 p'^0 (1 - \cos\theta) \simeq 0$$

Production cross section

Weizsäcker-Williams approximation

$$\frac{d\sigma(e(p)+Z(P_i)\to e(p')+Z(P_f)+X(k))}{dx\,d\cos\theta_X}=\frac{\alpha\xi}{\pi}\frac{E_0 x\beta_X}{1-x}\frac{d\sigma(e(p)+\gamma(q)\to e(p')+X(k))}{dx\,d\cos\theta_X}$$





where

E_0 : beam energy $\quad x = E_X/E_0 \quad \beta_X = \sqrt{1-m_X^2/E_0^2}$

Production cross section

Weizsäcker-Williams approximation

$$\frac{d\sigma(e(p)+Z(P_i)\to e(p')+Z(P_f)+X(k))}{dx\,d\cos\theta_X}=\frac{\alpha\xi}{\pi}\frac{E_0 x\beta_X}{1-x}\frac{d\sigma(e(p)+\gamma(q)\to e(p')+X(k))}{dx\,d\cos\theta_X}$$

where

effective photon flux

$$\xi=\int_{t_{\rm min}}^{t_{\rm max}}dt\frac{t-t_{\rm min}}{t^2}G_2(t)$$

$t=-q^2$

general electron form factor

Calculation

Production cross section

Improved Weizsäcker-Williams approximation   K. J. Kim & Y.-S. Tsai (1973)

$$\frac{d\sigma(e(p)+Z(P_i)\to e(p')+Z(P_f)+X(k))}{dx\,d\cos\theta_X}=\frac{\alpha\xi}{\pi}\frac{E_0 x\beta_X}{1-x}\frac{d\sigma(e(p)+\gamma(q)\to e(p')+X(k))}{dx\,d\cos\theta_X}$$

where

effective photon flux

$$\xi=\int_{t_{\min}}^{t_{\max}}dt\frac{t-t_{\min}}{t^2}G_2(t)\simeq\int_{(m_X^2/2E_X)^2}^{m_X^2}dt\frac{t-t_{\min}}{t^2}G_2(t)$$

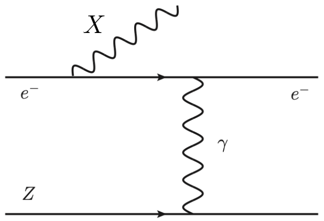
Integral interval is independent of x and θ_X

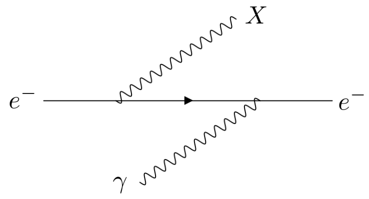
Calculation

Production cross section

Weizsäcker-Williams approximation

$$\frac{d\sigma(e(p)+Z(P_i)\to e(p')+Z(P_f)+X(k))}{dx\,d\cos\theta_X} = \frac{\alpha\xi}{\pi}\frac{E_0 x\beta_X}{1-x}\frac{d\sigma(e(p)+\gamma(q)\to e(p')+X(k))}{dx\,d\cos\theta_X}$$





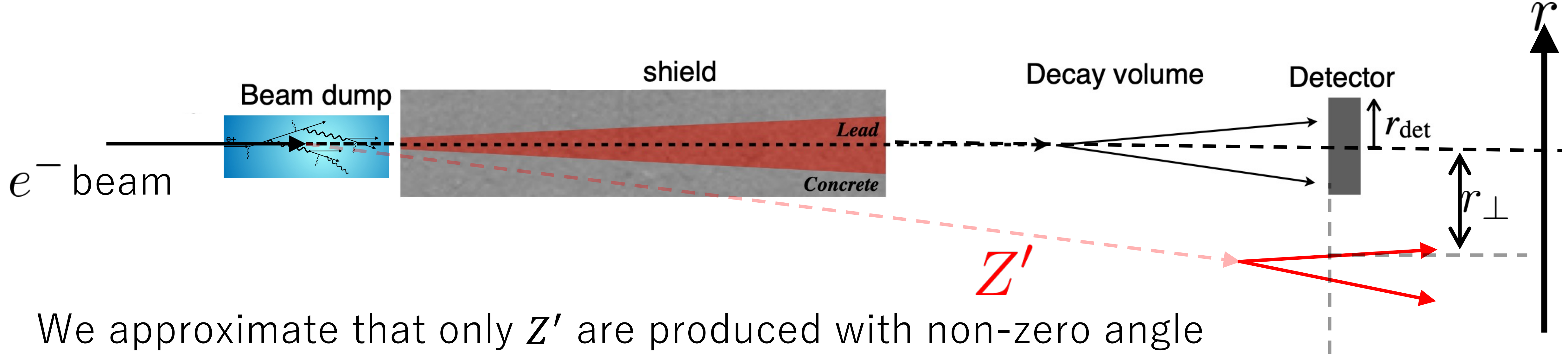
where

$$E_0 \ :\ \text{beam energy} \qquad x = E_X/E_0 \qquad \beta_X = \sqrt{1-m_X^2/E_0^2}$$

$$\xi = \int_{t_{\min}}^{t_{\max}} dt\frac{t-t_{\min}}{t^2}G_2(t) \simeq \int_{(m_X^2/2E_X)^2}^{m_X^2} dt\frac{t-t_{\min}}{t^2}G_2(t)$$

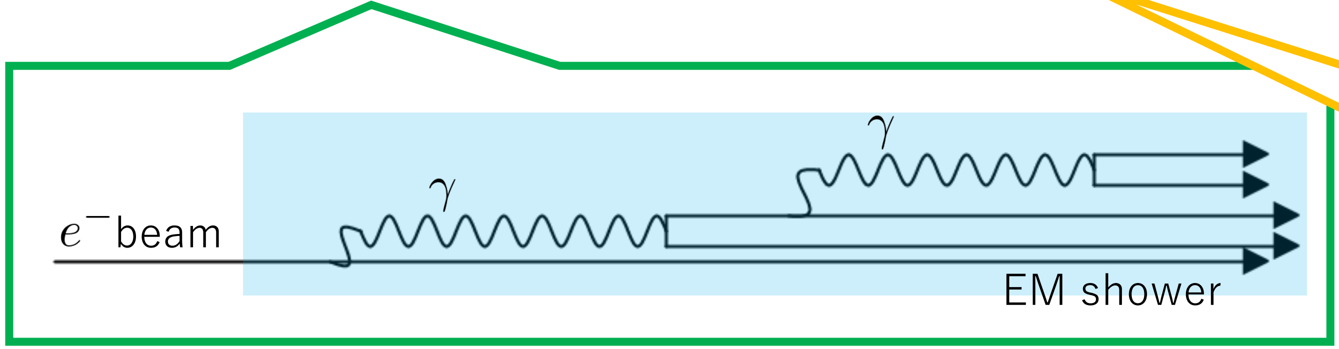
Production cross section can be calculated more simply

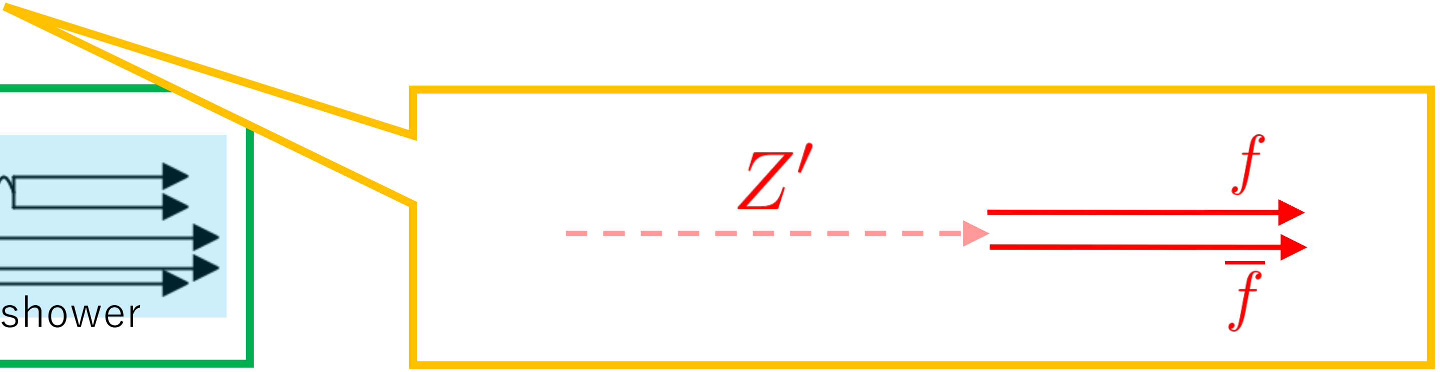
Number of signals



We approximate that only Z' are produced with non-zero angle

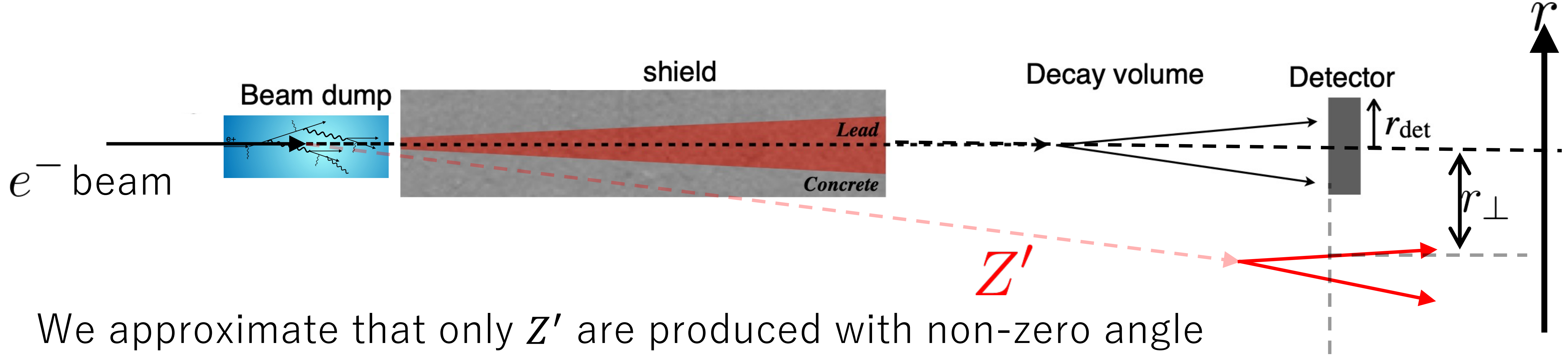
$$\theta_e = 0,\ \theta_X \neq 0,\ \theta_f = 0$$





Calculation

Number of signals



We approximate that only Z' are produced with non-zero angle

$$\theta_e = 0,\ \theta_X \neq 0,\ \theta_f = 0$$

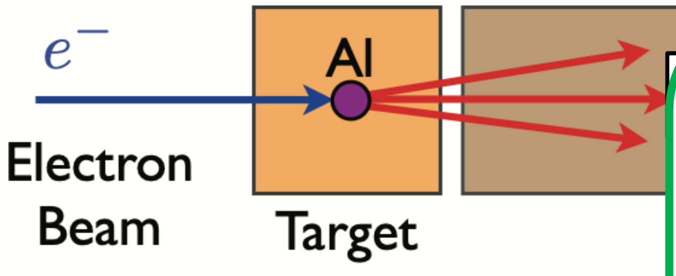
$$\Rightarrow \int d\theta_e d\theta_X d\theta_f (\#\,\mathrm{of}\,Z') \times P_{\rm dec}\,\Theta(r_{\rm det} - r_\perp)$$

$$= \int_0^{\theta_{\max}} d\theta_X (\#\,\mathrm{of}\,Z') \times P_{\rm dec}$$

θ_X dependent

Calculation

Number of signal events



(# of events) = (# of produc

$$= N_e \frac{N_{\rm avo} X_0}{A} \sum_{\ell = e, \mu} \int_{m_X} \qquad \int_0$$

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

Production cross section

$$\frac{d\sigma_{\rm brems}}{dx} = \frac{\alpha \xi}{\pi} \frac{E_0 x \beta_X}{1 - x} \frac{d\sigma_{\rm scat}}{dx}$$

$$\frac{d\sigma_{\rm scat}}{dx} = \int_0^{\theta_X^{\rm max}} d\theta_X \frac{d\sigma_{\rm scat}}{dx \, d\cos\theta_X}$$

with $\tan \theta_X^{\rm max} \equiv r_{\rm det} / (L_{\rm sh} + L_{\rm dec})$

Result

Constraint on LFV coupling

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

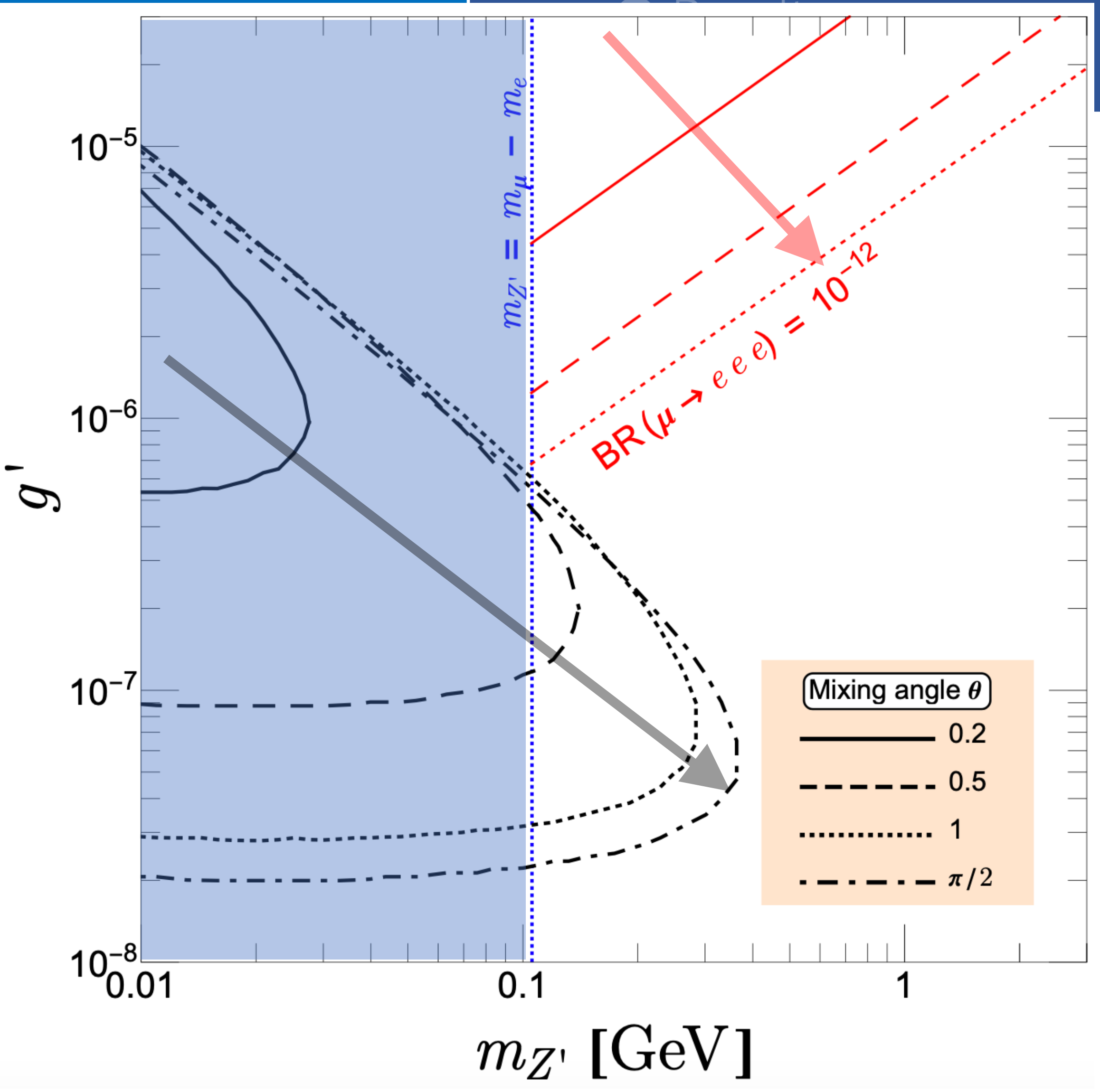
$$\mathcal{L}_{\text{vector}} = g' Z'_\rho (s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu + sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu) + g' Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)\ ,$$

○ 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 $\mu \to e$



Appendix

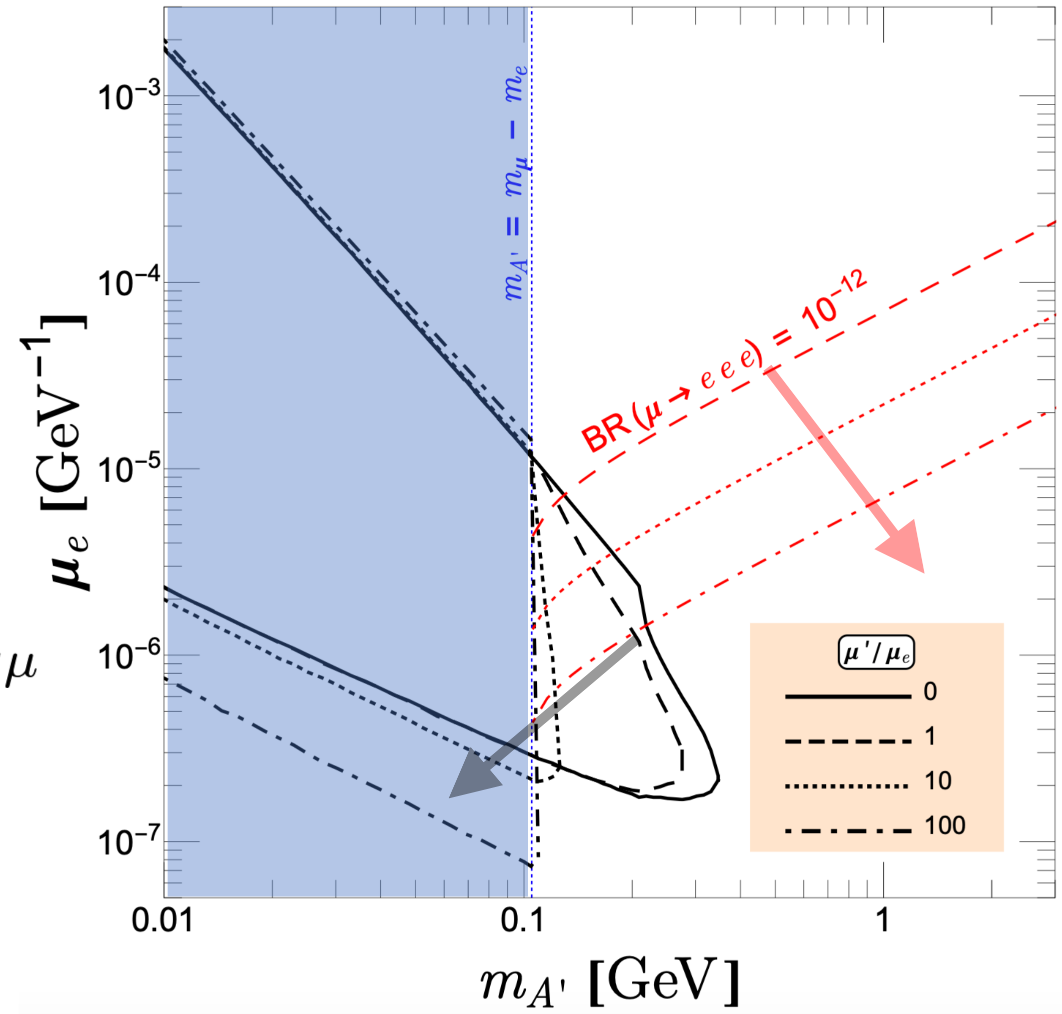
Constraint on LFV coupling

dipole-type int.

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

○ Larger LFV/LFC ratio

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



Appendix

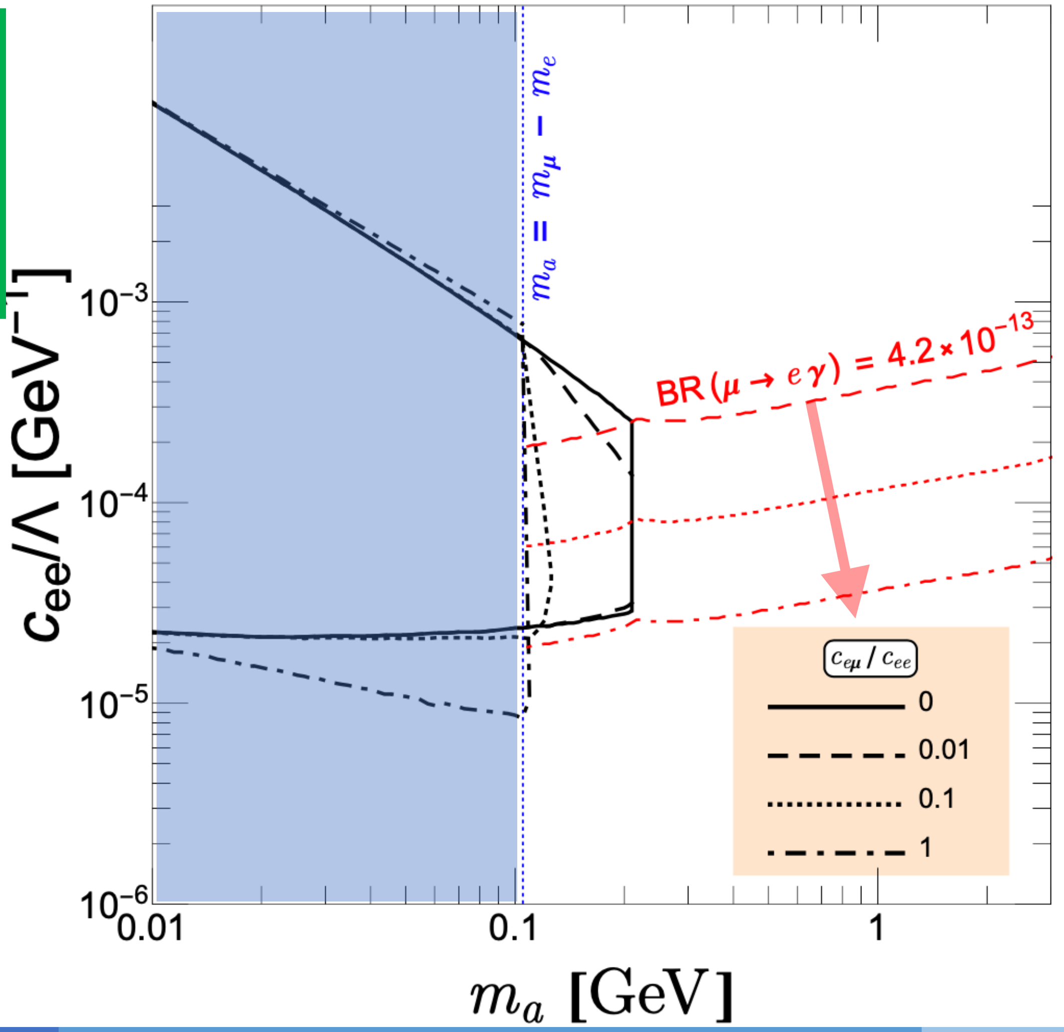
Constraint on LFV coupling

pseudoscalar int.

$$\mathcal{L}_{\text{pseudoscalar}} = \frac{\partial_\mu a}{\Lambda}\left\{\sum_{\ell=e,\mu,\tau} c_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + c_{e\mu}\bar{e}\gamma^\mu\gamma_5\mu + c_{\mu e}\bar{\mu}\gamma^\mu\gamma_5 e\right\}$$

○ Larger LFV/LFC ratio

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



Appendix

Scattering cross section

$$\frac{d\sigma_{\rm scat}}{dx} = \frac{\alpha g_X^2}{2E_0}\frac{1-x}{x}\left[f_1(x)\frac{\tilde{U}_1^\ell}{m_X^2} + f_2(x)\frac{\tilde{U}_2^\ell}{E_e^2 x} - f_3(x)\left(x\frac{m_X^2\tilde{U}_3^\ell}{(E_e^2 x)^2} - (1-a_1 x + r_e x^2)\frac{m_X^4\tilde{U}_4^\ell}{(E_e^2 x)^3}\right)\right]$$

with

$$\eta_\ell = \frac{m_X^2}{E_e^2}\frac{1-x}{x^2} + \frac{m_e^2}{E_e^2} + \frac{m_\ell^2 - m_e^2}{E_e^2 x} \qquad r_\ell = \frac{m_\ell^2}{m_X^2}$$

$$a_1 = 1 + r_e - r_\ell\ ,$$

$$a_2 = 1 - r_e - r_\ell\ ,$$

$$a_3 = 2 + r_e + r_\ell - 2\sqrt{r_e r_\ell}\ ,$$

$$a_4 = 2 - r_e - r_e^2 - r_\ell - r_\ell^2 + 6\sqrt{r_e r_\ell} + 2 r_e r_\ell$$

<u>scalar int.</u>

$$f_1(x) = 0\ ,\quad f_2(x) = S_1\frac{x^2}{2}\ ,\quad f_3(x) = (a_2 S_1 - 4\sqrt{r_e r_\ell}S_2)(1-x)$$

<u>pseudoscalar int.</u>

$$f_1(x) = 0\ ,\quad f_2(x) = x^2\ ,\quad f_3(x) = 2\left(a_2 + 2\sqrt{r_e r_l}\right)(1-x)$$

<u>vector int.</u>

$$f_1(x) = 0\ ,\quad f_2(x) = 4 - 4x + a_3 x^2\ ,\quad f_3(x) = 2a_4(1-x)$$

<u>dipole int.</u>

$$f_1(x) = 4x\ ,\quad f_2(x) = x(x + 2(r_\ell - r_e)(x-2))\ ,\quad f_3(x) = 2a_4(1-x)$$