将来レプトンビームダンプ実験による
レプトンフレーバーを破る相互作用の探索

浅井 健人
(宇宙線研究所, 東京大学)

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荒木氏 (奥羽大) & 下村氏 (宮崎大)との現在進行中の共同研究に基づく

Take home message

サブMeV ~ 数MeV程度の軽い新粒子が荷電レプトンフレーバーの破れ(CLFV)を引き起こすという模型を仮定するならば

将来レプトンビームダンプ実験は
既存のCLFV探索実験($\mu \to e\gamma$など)よりも
はるかに小さなCLFV結合定数に感度をもつ

Introduction

Charged Lepton Flavor Violation (cLFV)

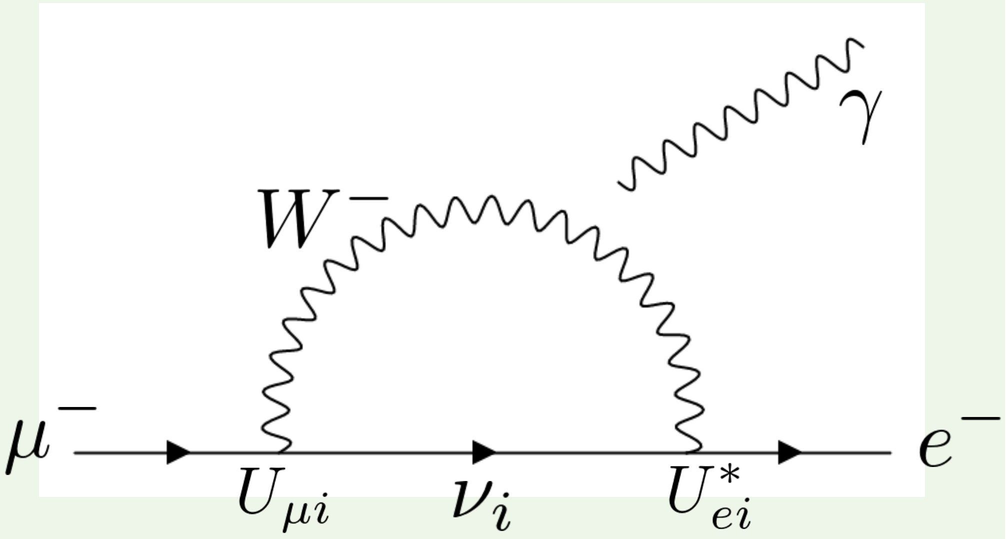
In the Standard Model (SM)

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

Theoretical prediction ：

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

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

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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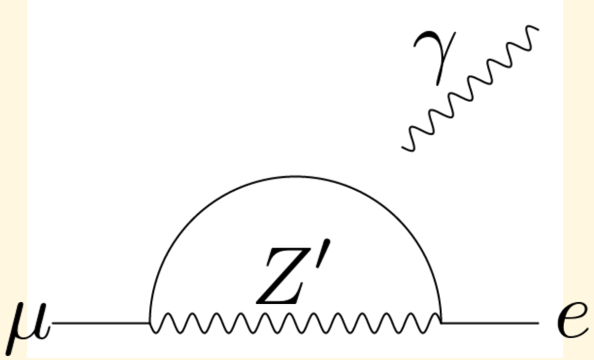


Because of no suppression from GIM mechanism, branching ratios of cLFV processes are not suppressed

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

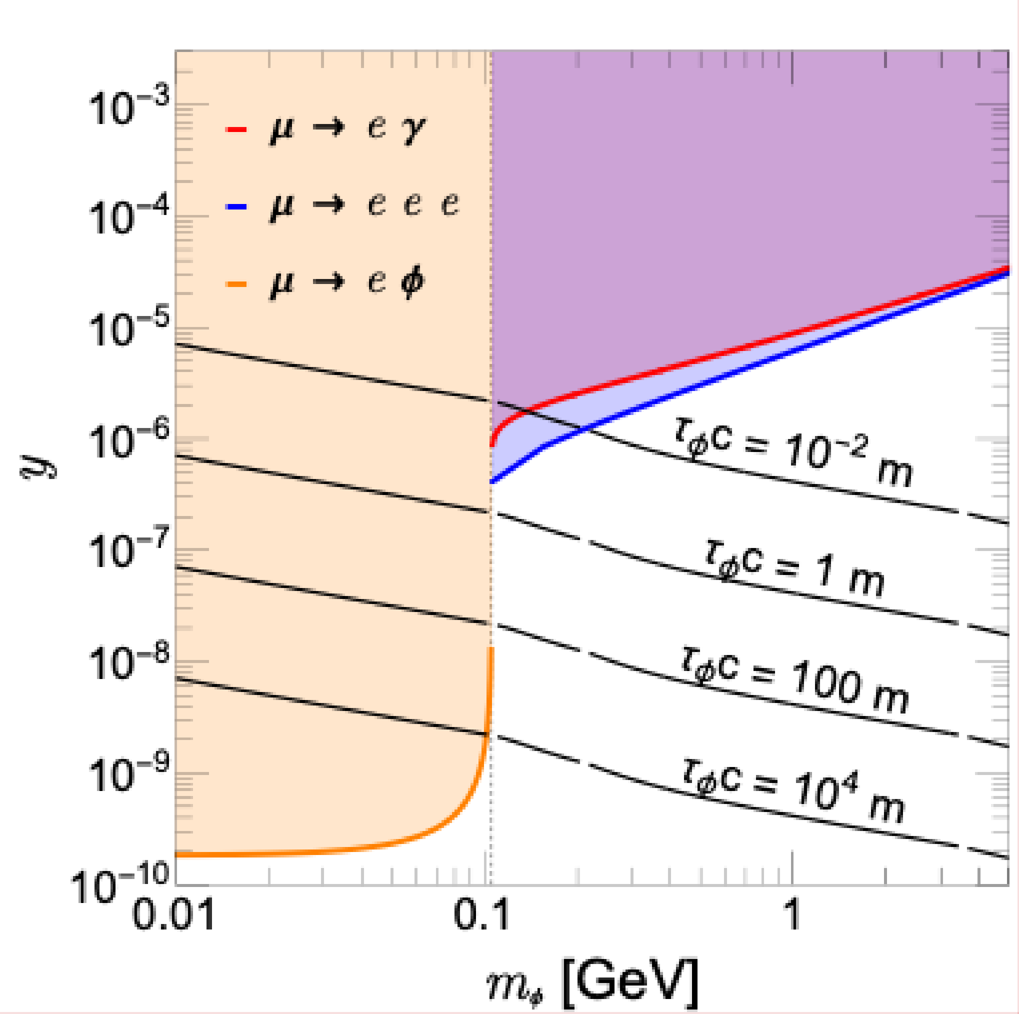
Ex) Leptophilic scalar model

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

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

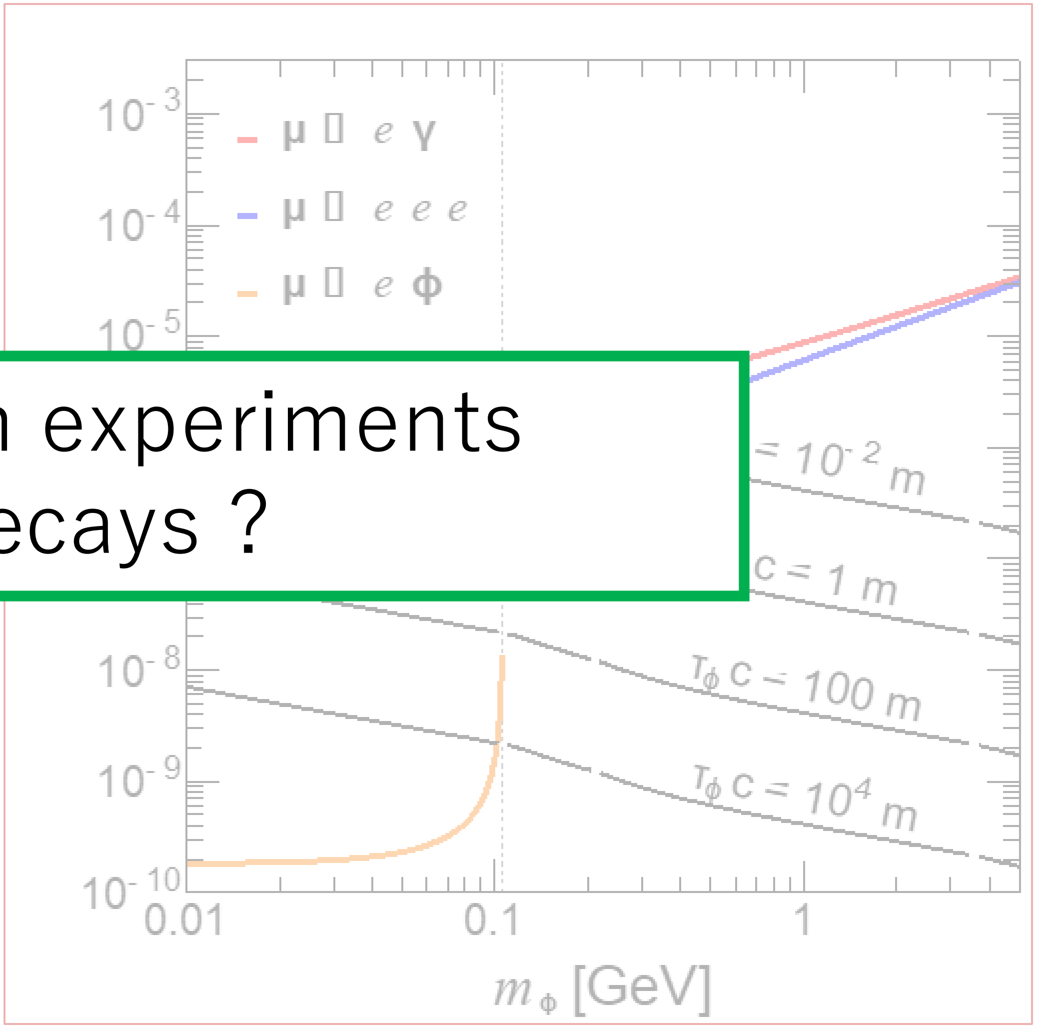
$$\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} y\bar{\ell}_L\phi\ell_R + y\bar{\mu}_L\phi e_R + y\bar{e}_L\phi\mu_R$$

In light
$(m_\phi \sim 0$

Long-lived particle search experiments can detect CLFV decays ?

1, CLFV coupling can be as large as CLFC one

2, New particles with CLFV coupling are long-lived



Electron Beam Dump Experiment

e^- Beam Dump Experiment

Overview

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

➡ High luminosity

- Production of large number of new particles

Detector is placed behind long shield

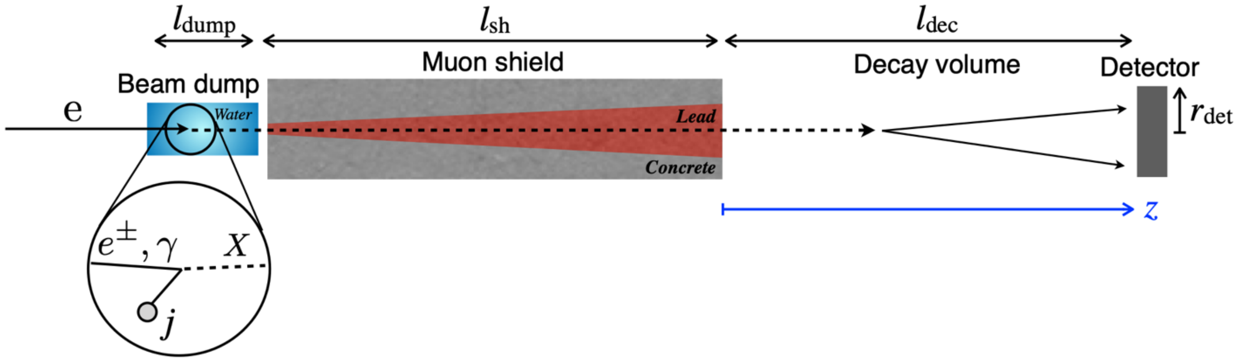
➡ Low background

- Most of background events are removed by shield

Sensitive to small coupling region

- New particles should be long-liv to reach detector

ILC加速器の構成模式図
Schematic illustration of ILC



e^- Beam Dump Experiment

New particle production

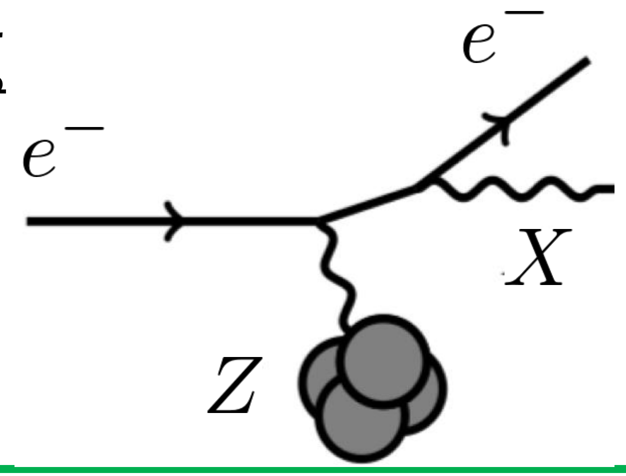
Batell, Essig, Surujon, PRL113 (2014)

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

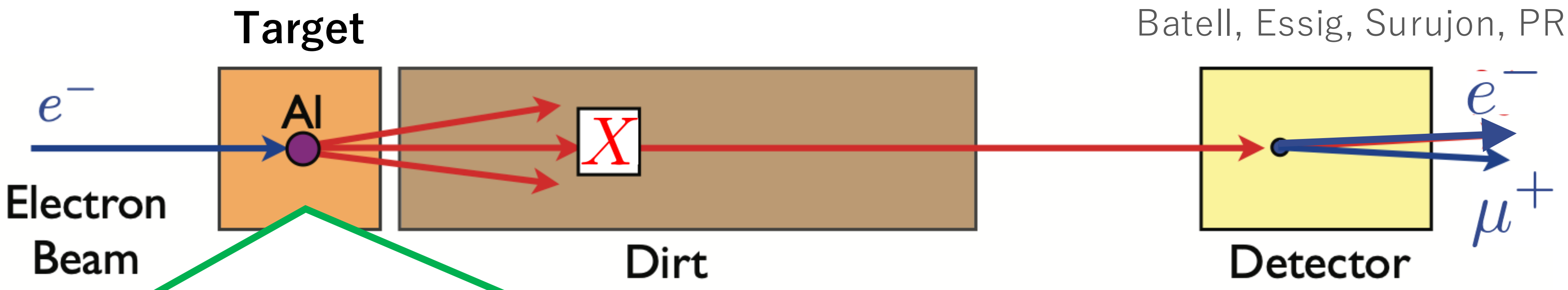
Decay into e^+e^- pair → Detection

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)

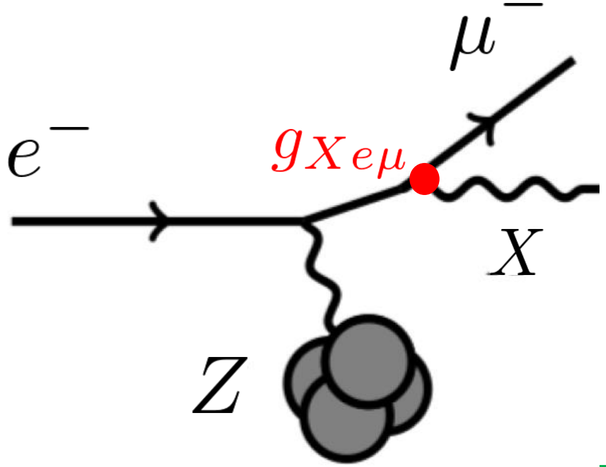


Lagrangian

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

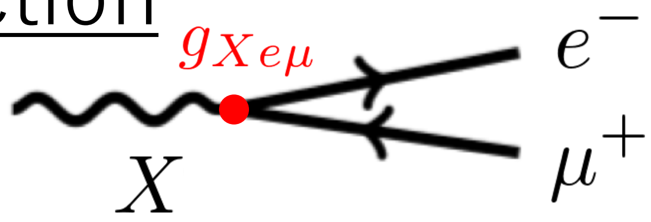
Batell, Essig, Surujon, PRL113 (2014)

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

ILC beam dump experiment

Experiment parameters

Kanemura, Moroi, Tanabe, PLB 751 (2015) 25-28;
Sakaki, Ueda, PRD 103 (2021) 3, 035024;

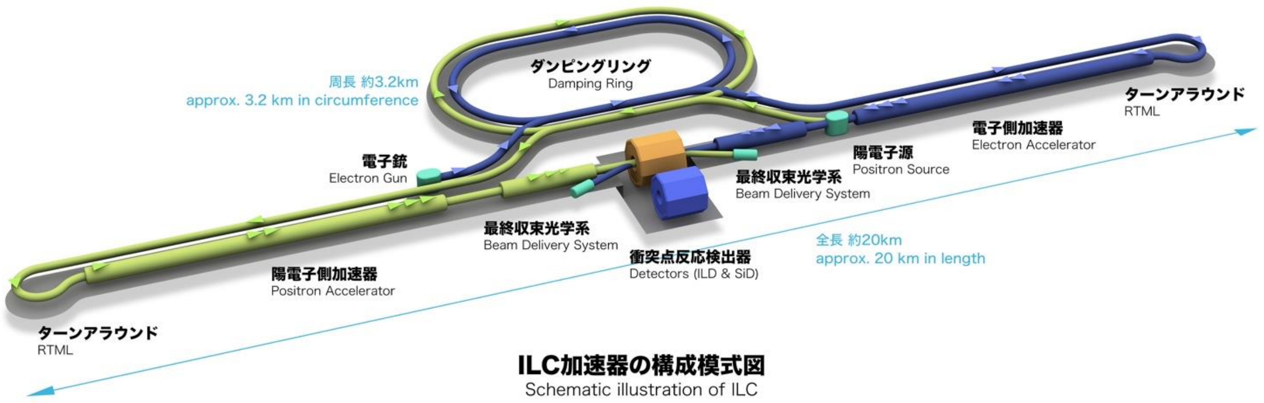
Beam : 125 GeV $e^{\pm}$ beam, $250\ \mathrm{fb}^{-1}$

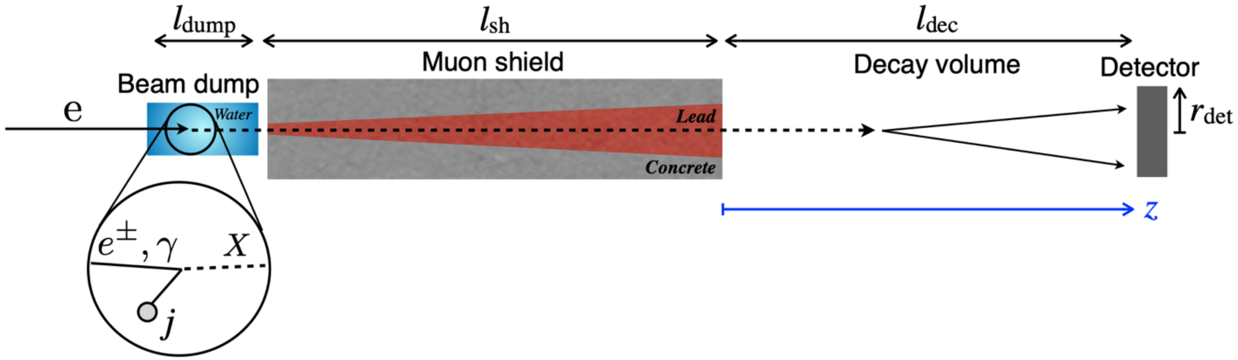
Target : liquid water

Shielding : 70m lead

Decay volume : 50m

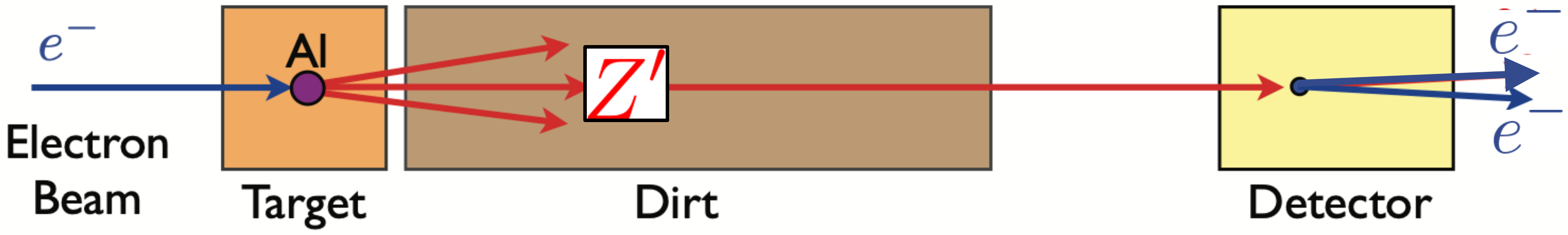
Detector : EM calorimeter + MWPC + muon detector





Calculation

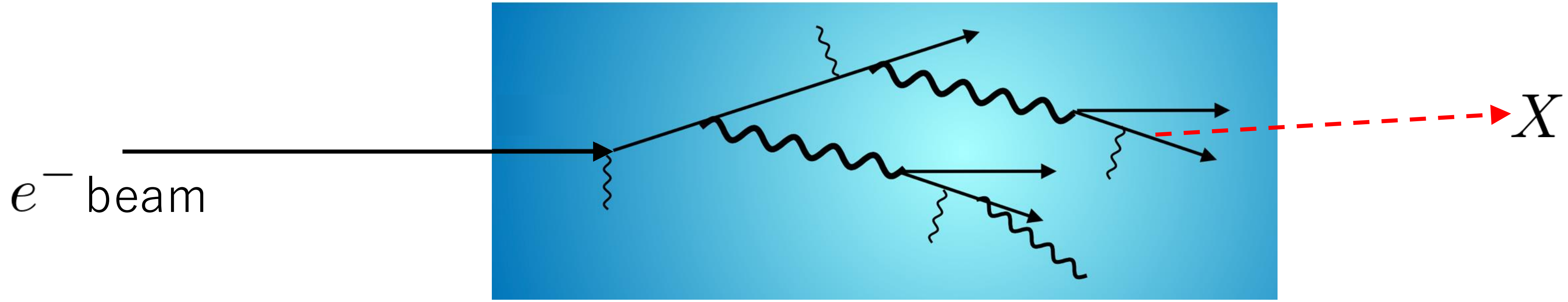
Number of signals



(# of signal detection)

$=$ (# of produced new particle) $\times$ (Acceptance)

of produced new particle



(# of produced new particle)

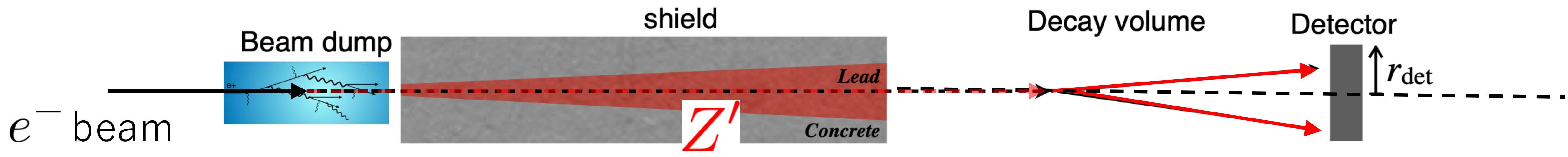
= (Luminosity) × (Production cross section)

Dependent on beam and beam dump

Dependent on particle species

Calculation

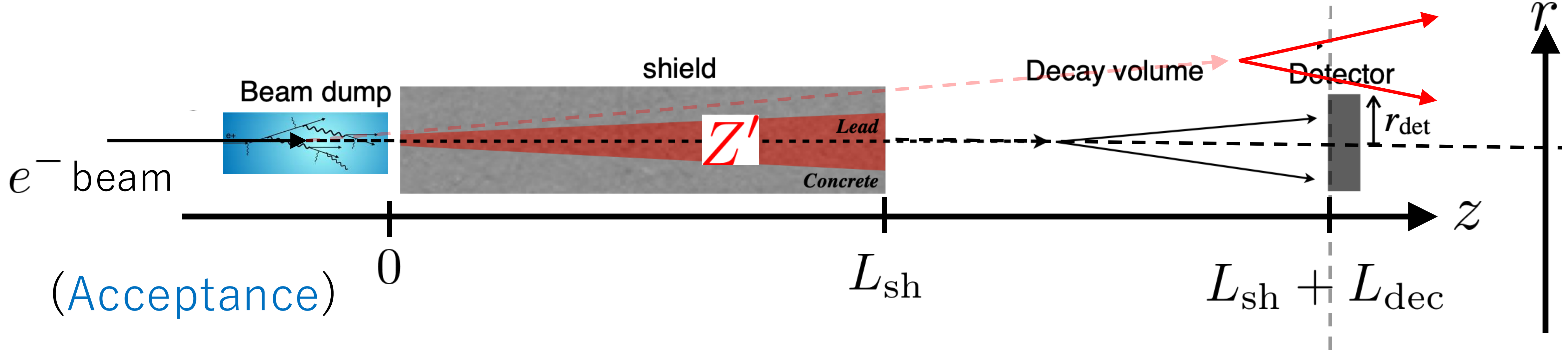
Number of signals



(Acceptance)

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

Number of signals



(Acceptance)

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

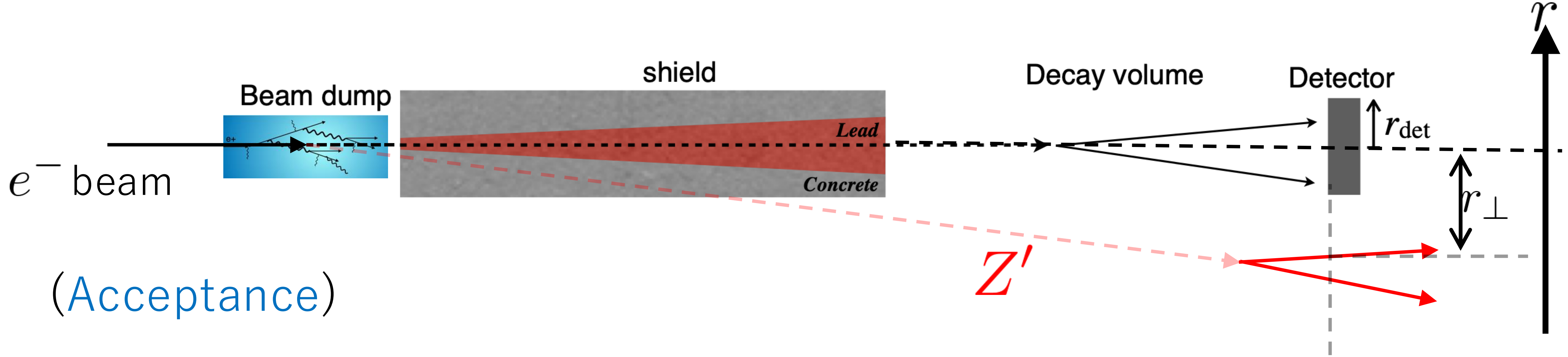
New particles reach decay volume and are detected by decay into visible particles

➡ 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)

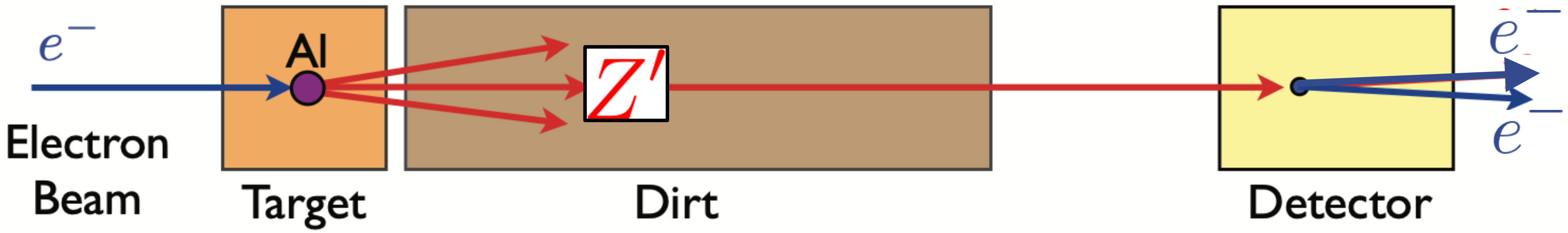
= (Probability of decay in decay volume) × (Angular cut)

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 : $\Theta(r_{\rm det} - r_\perp)$

Calculation

Number of signal events



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

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

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

Coupling to SM ↑ ⟶ # of production ↑ Acceptance (lifetime) ↓

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

Result

Result

Sensitivity to LFV coupling

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

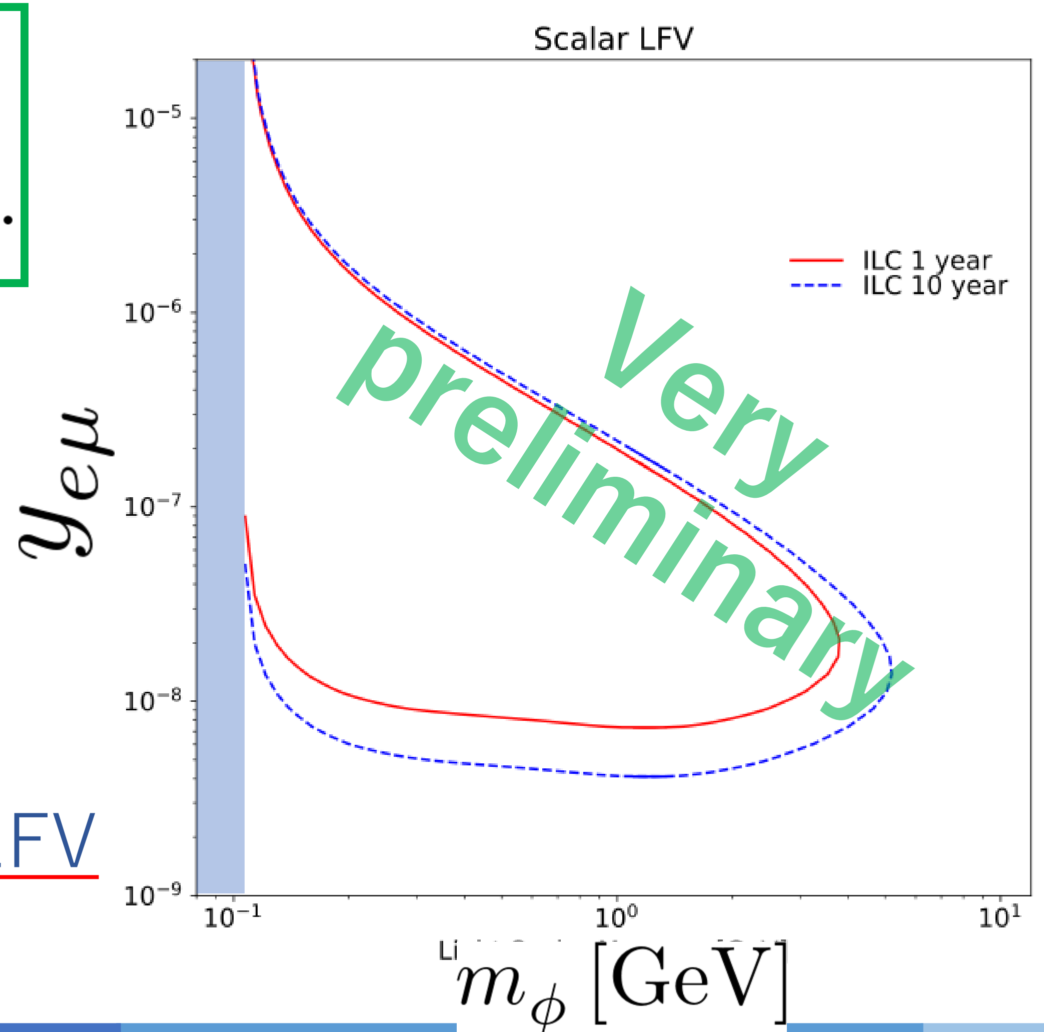
$$\mathcal{L}_{\text{scalar}} = y_{e\mu}\overline{e_L}\phi\mu_R + y_{e\mu}\overline{\mu_L}\phi e_R + \text{H.c.}$$

<u>LFV decay search @ ILC</u>

\# of LFV decay signals ($\phi \to e\mu$) = 3

➡ red solid line : 1 year   blue dashed line : 10 years

<u>ILC beam dump can search unexplored LFV coupling and perhaps detect LFV decay</u>



Question

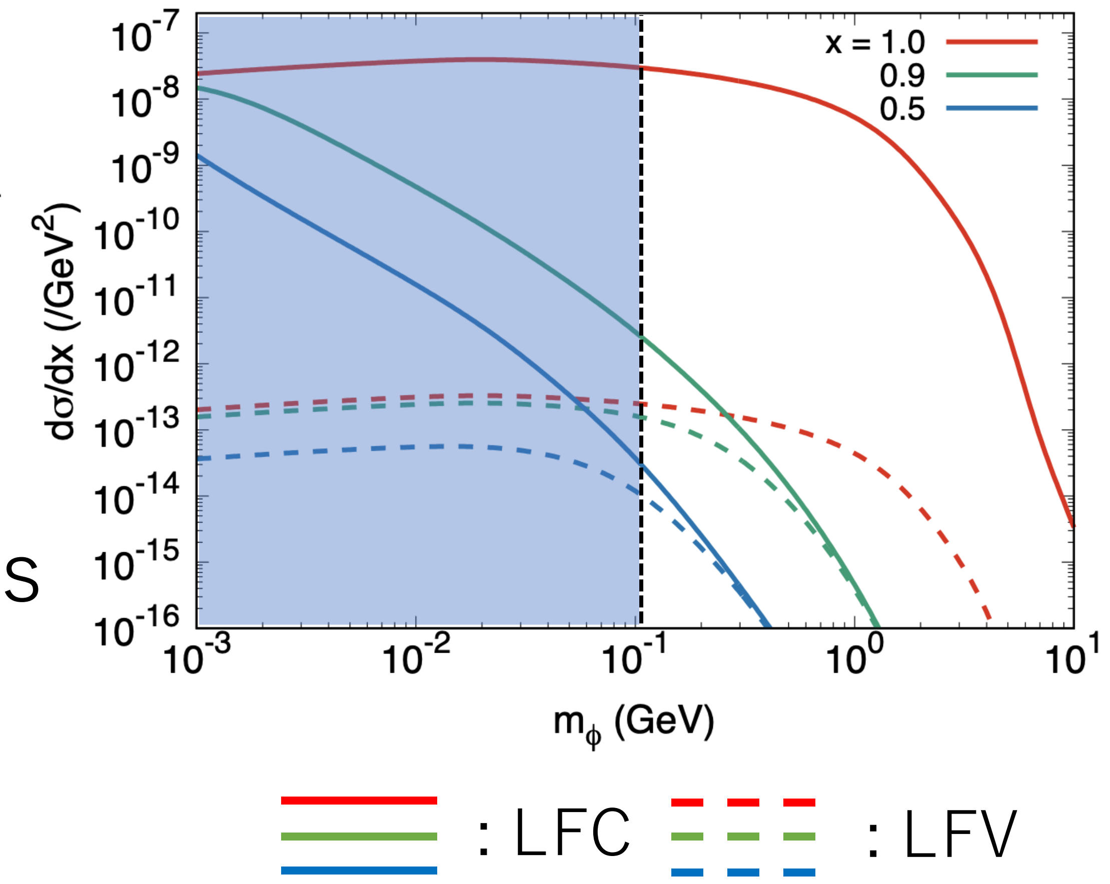
Production through LFV coupling

ϕ production cross section through LFC & LFV coupling is almost same for $m_\phi > m_\mu$ & $x < 1$

Muon beam dump experiment

- High energy beam → heavy mass
- Contribution from LFV brems for $x \lesssim 1$

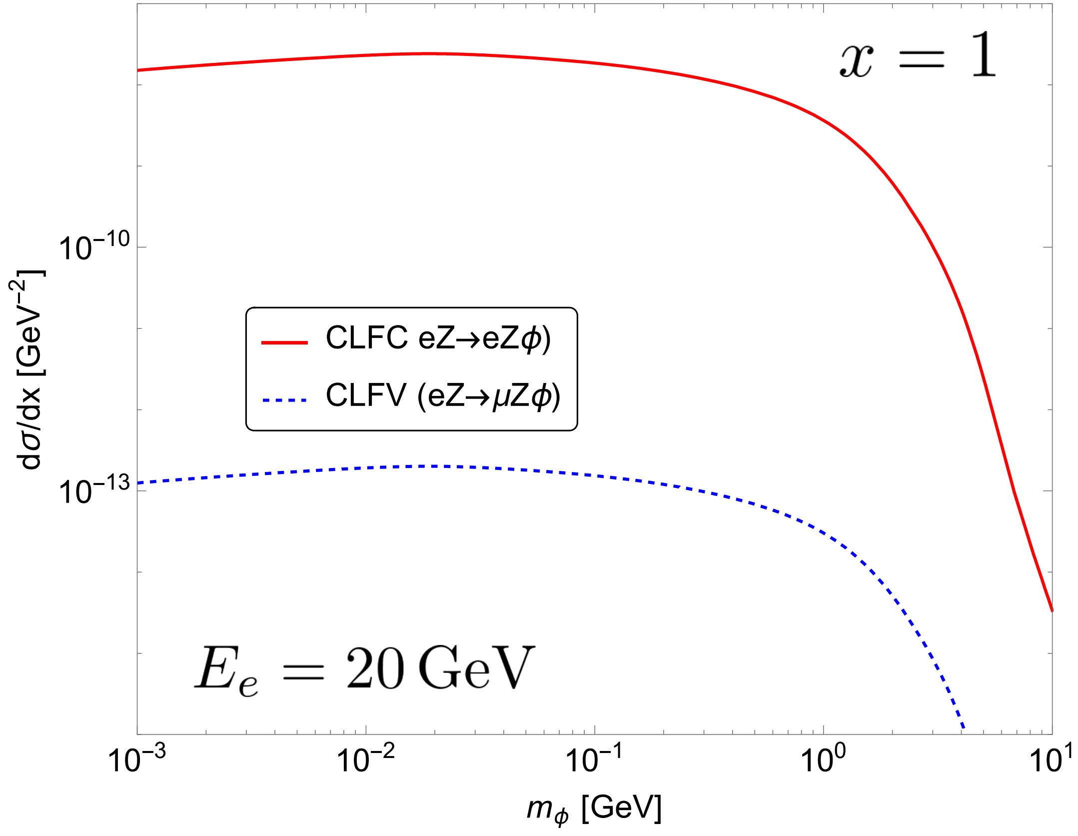
$$x \equiv E_\phi / E_e = E_\phi / 20\,\mathrm{GeV}$$



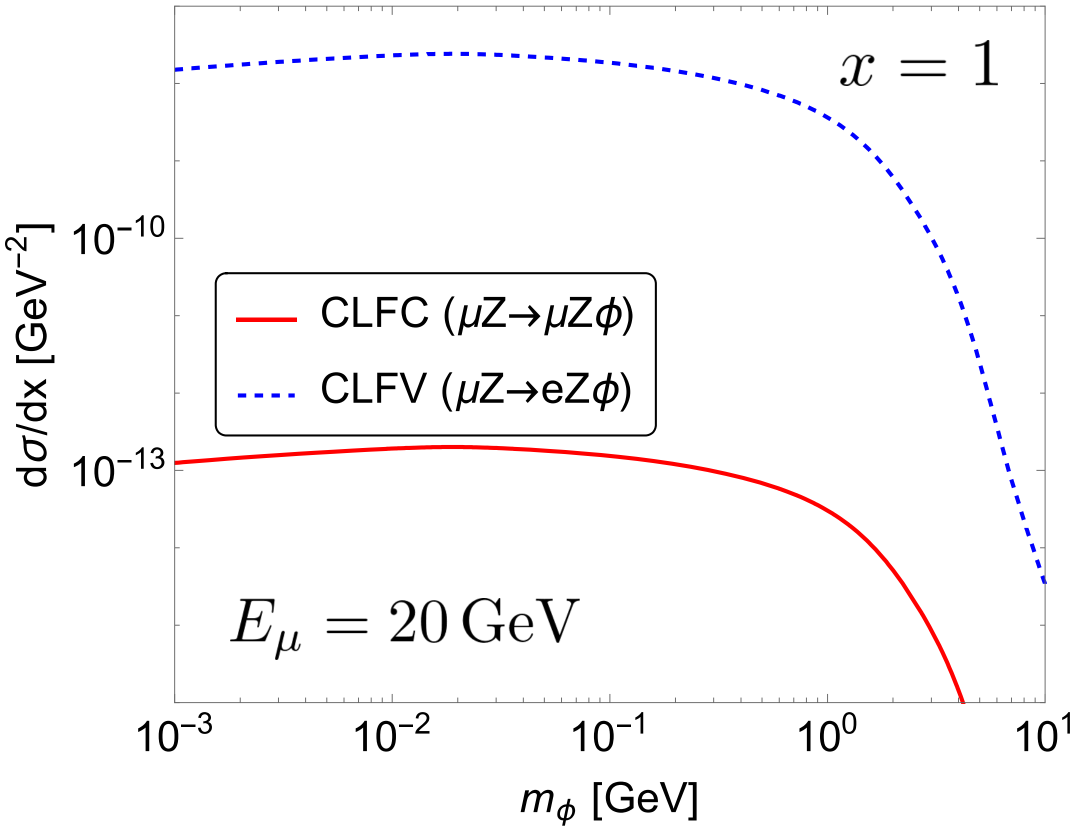
Question

Bremsstrahlung cross section

Electron beam dump



Muon beam dump



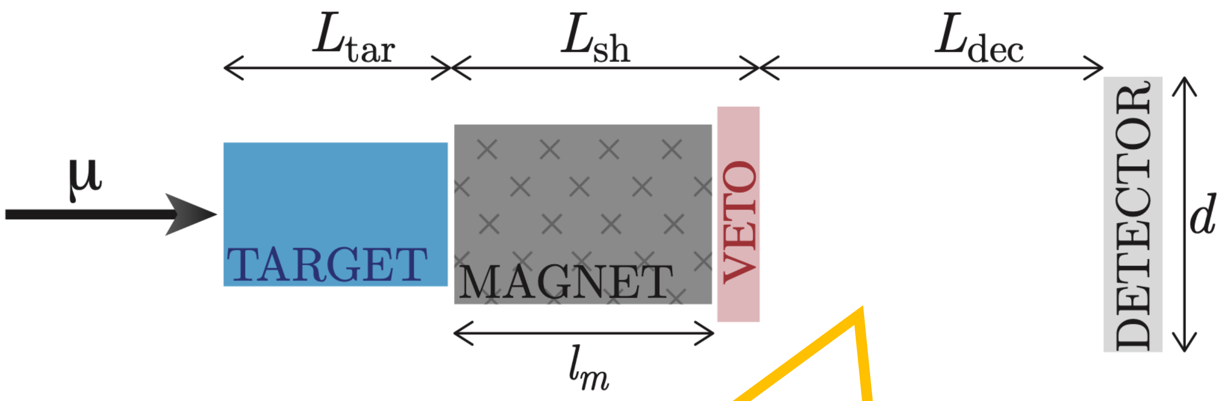
LFV decay search @ muon beam dump

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

μ Beam Dump Experiment

Experimental setup

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



We follow the setup
in the above PRL paper

Experiment parameters

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

Number of signal events

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

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

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

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

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

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

for thin beam dump

Sensitivity to LFV coupling

Scalar-type int.

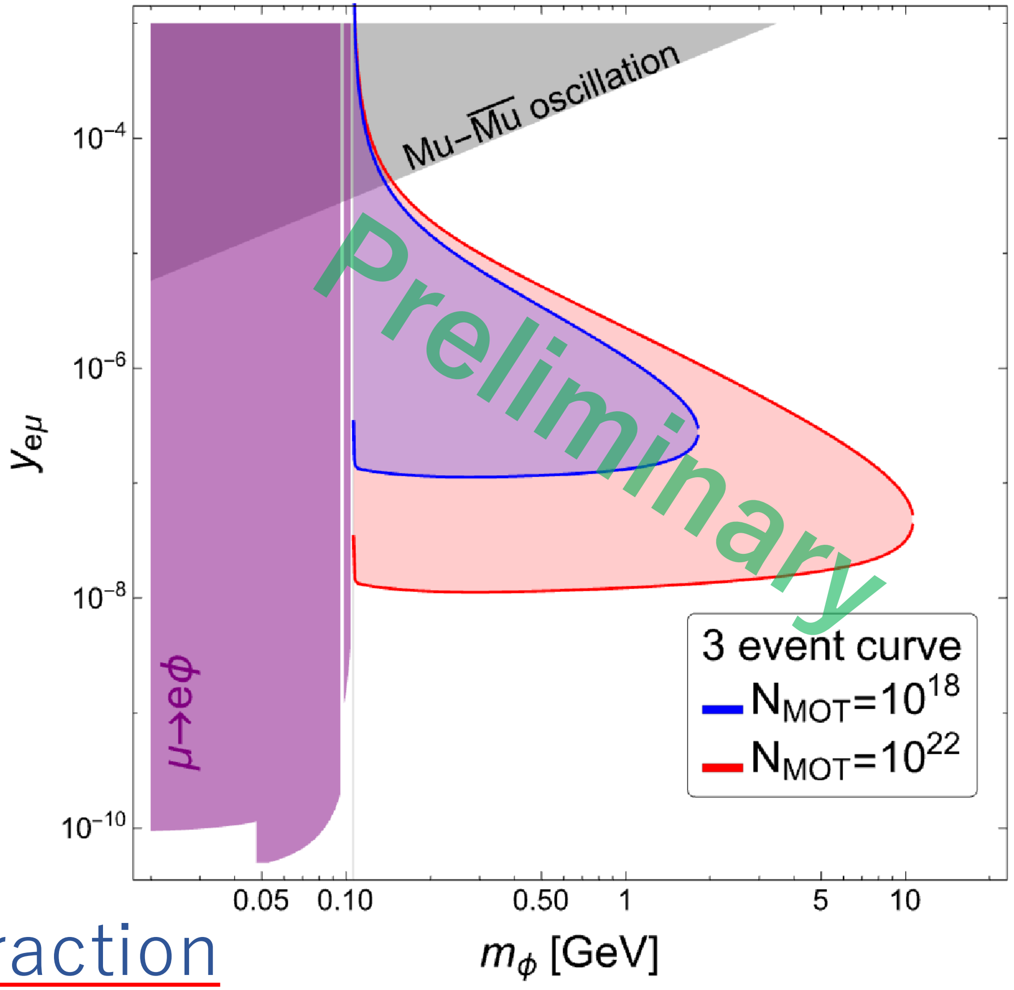
$$\mathcal{L}_{\rm scalar} = y_{e\mu}\overline{e_L}\phi\mu_R + y_{e\mu}\overline{\mu_L}\phi e_R + \text{H.c.}$$

$$m_\phi > m_\mu - m_e$$

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

$$m_\phi < m_\mu - m_e$$

➡ Bound on $\text{Br}(\mu \to e\phi)$ is strong



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 with SM particles
- ○ In such small coupling regions, light BSM particle is long-lived and can have LFV coupling comparable to LFC one
- ○ We consider scalar-type LFV interaction and are studying sensitivity to LFV interaction ($\phi \to e\mu$ decay) by future lepton beam dump experiment

Thank you for your attention !

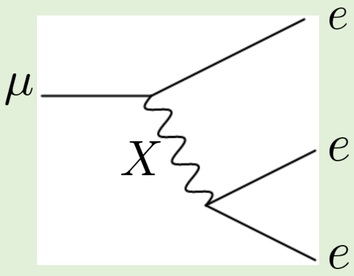
Back up

Introduction

Constraints on cLFV

cLFV process | Exp. limit on BR | Future prospect

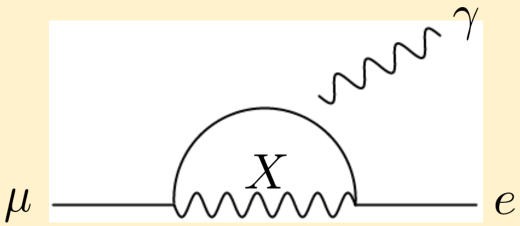
$\mu \to eee$



1.0×10^{-12}
SINDRUM Collaboration (1988)

$\approx 10^{-16}$
Mu3e Collaboration (2013)

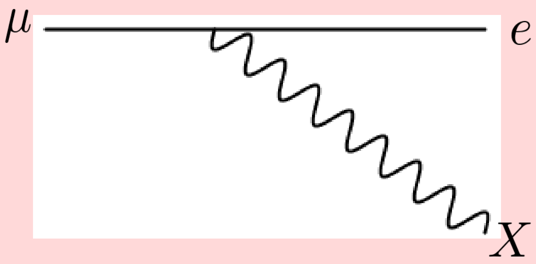
$\mu \to e\gamma$



4.2×10^{-13}
MEG Collaboration (2016)

$\approx 6 \times 10^{-14}$
MEGII Collaboration (2018)

$\mu \to eX$



$\approx 10^{-5}$
TWIST Collaboration (2015)

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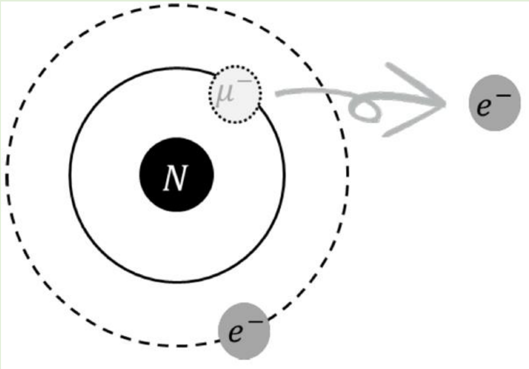
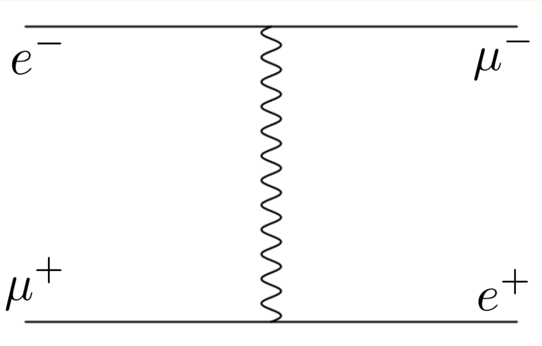
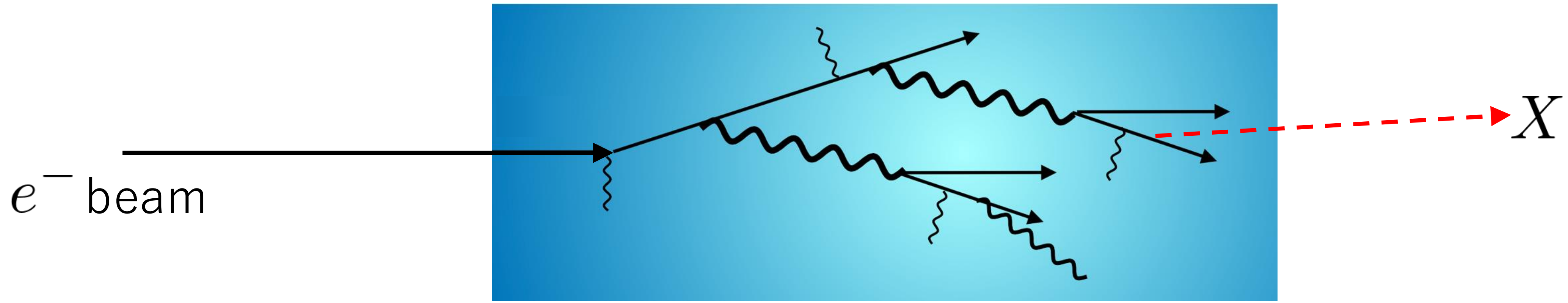
Constraints on cLFV

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) ← $n_N = \rho_{\rm sh} N_{\rm avo}/A \simeq 6 \times 10^{22}$

× (Track length of shower particles)

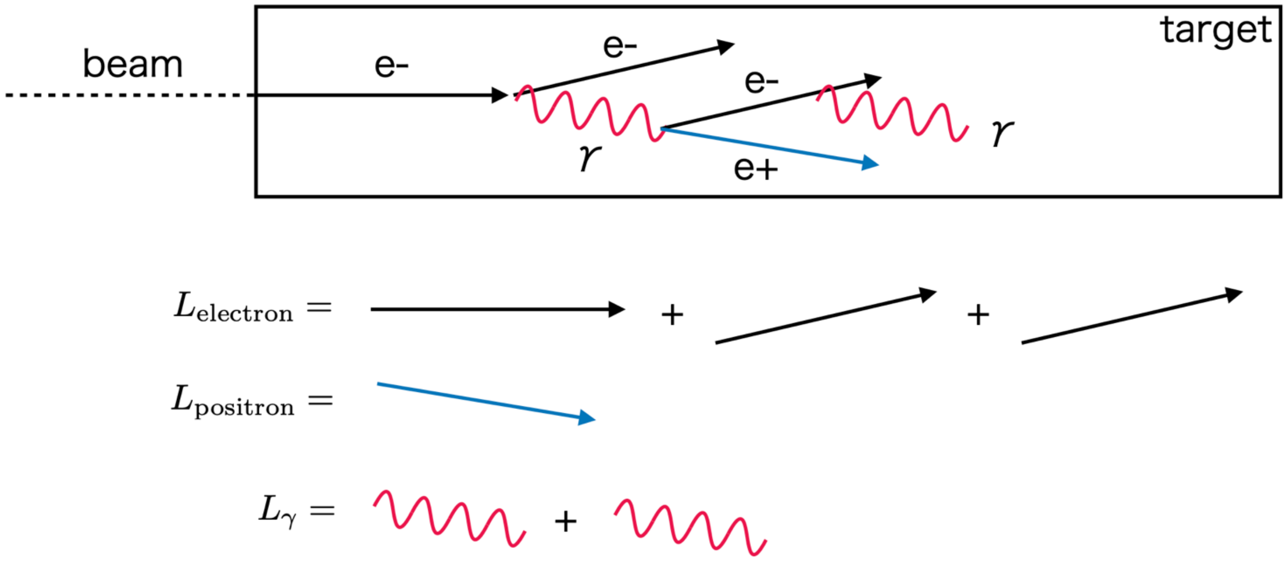
Calculation

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



=

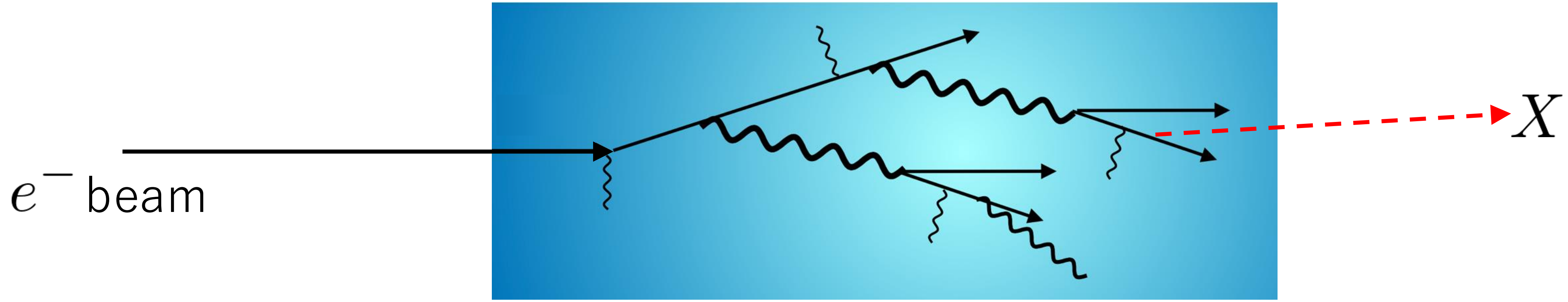
(# of incident p… …to beam dump)

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

× (Track length of shower particles)

Calculation

Production cross section



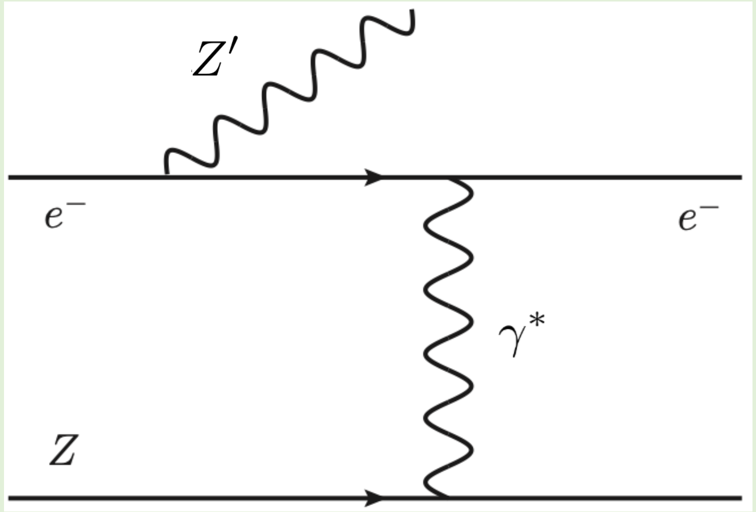
(# of produced new particle)

= (Luminosity) × (Production cross section)

||

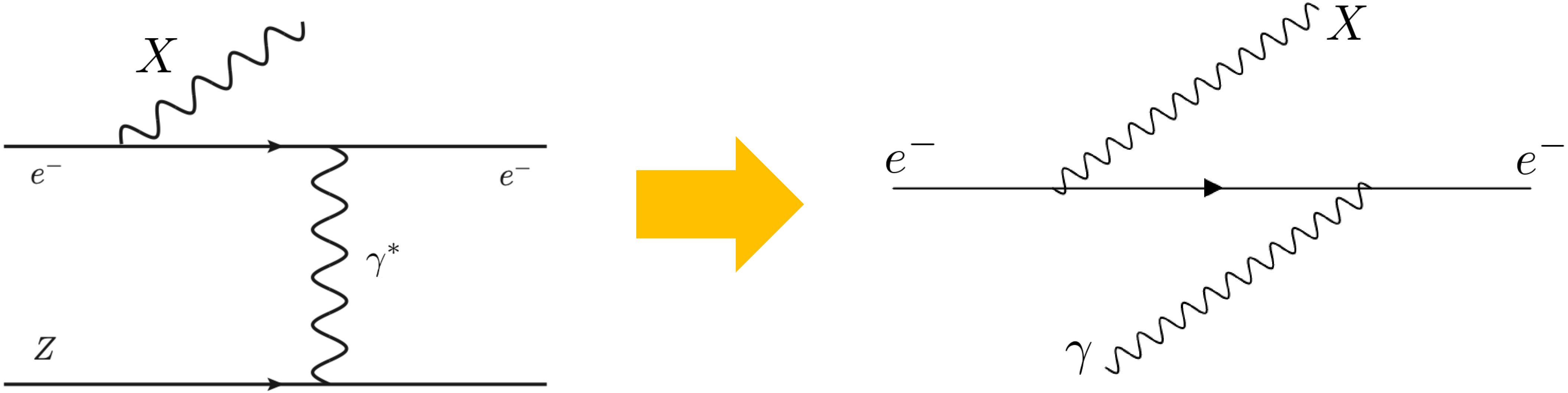
Bremsstrahlung process

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



Calculation

Production cross section



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

Weizsäcker-Williams approximation

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

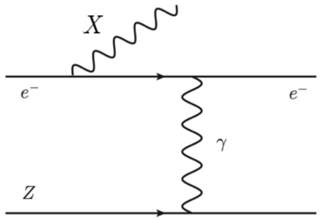
cf) 2-to-2 scattering

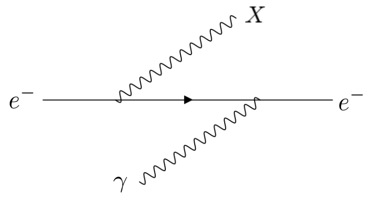
$$q^2 = -2p^0p'^0(1 - \cos\theta) \simeq 0$$

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

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

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

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

$t=-q^2$

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

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

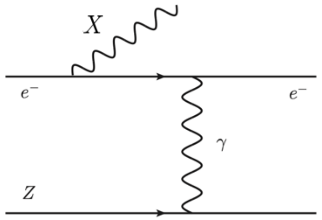
Integral interval is independent of x and θ_X

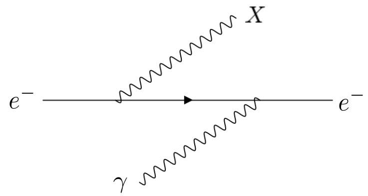
Calculation

Production cross section

Weizsäcker-Williams approximation

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





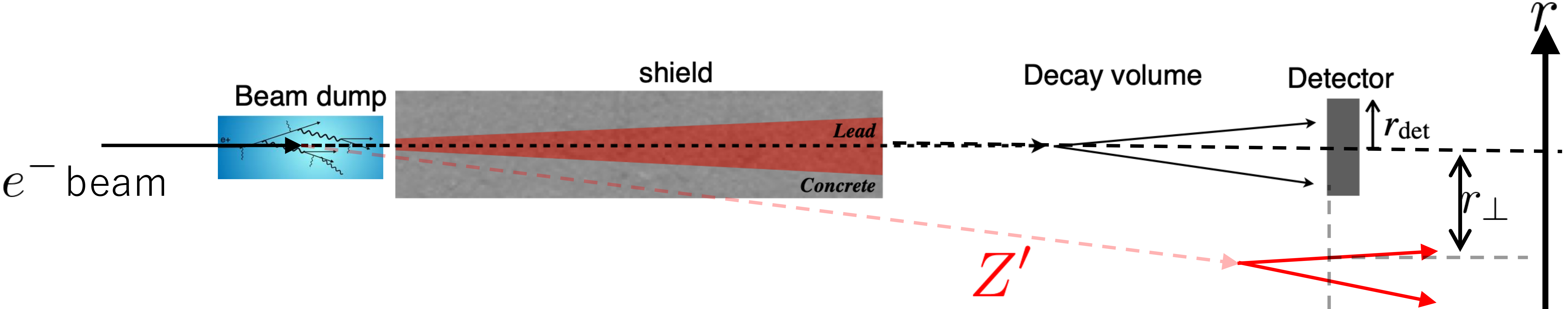
where

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

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

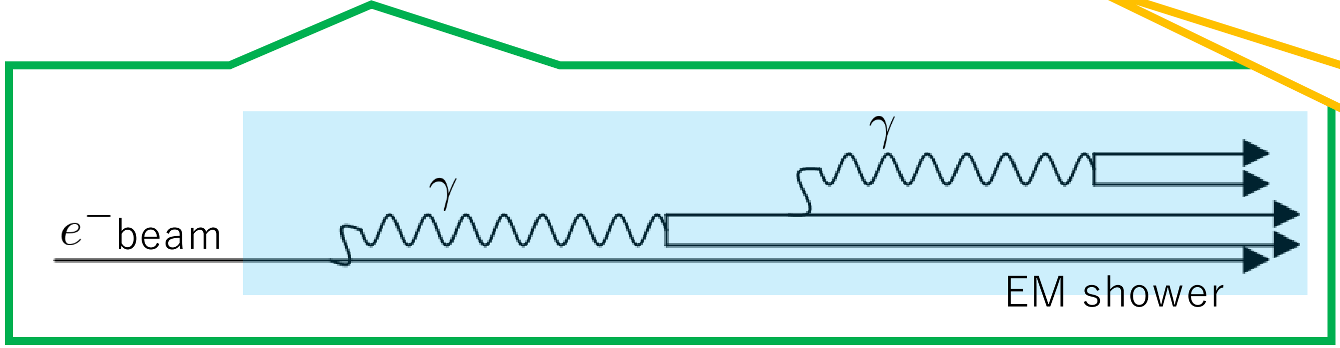
Production cross section can be calculated more simply

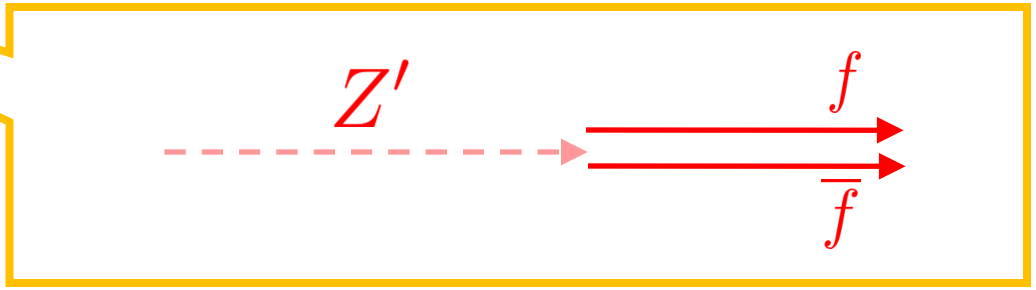
Number of signals



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

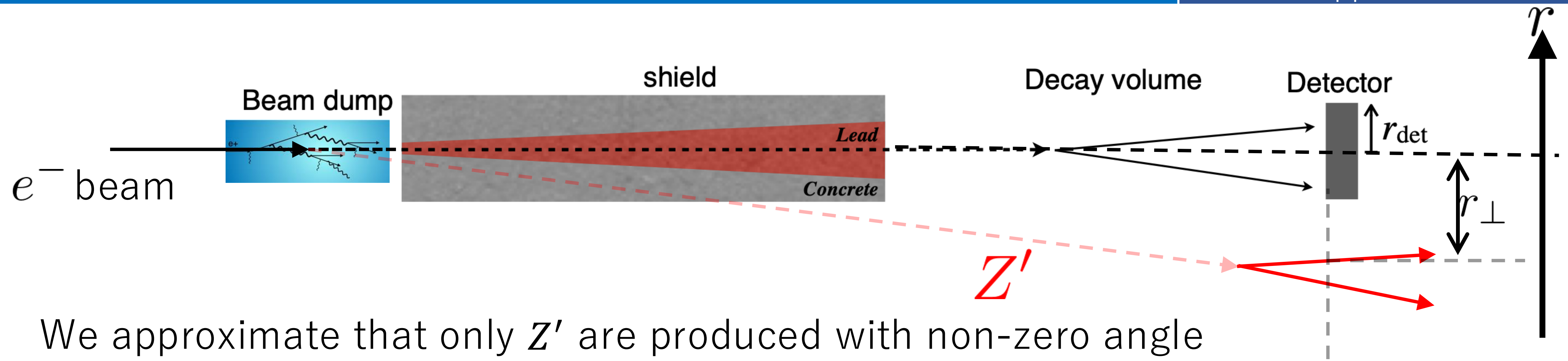
$$\theta_e = 0,\ \theta_X \neq 0,\ \theta_f = 0$$





Calculation

Number of signals



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

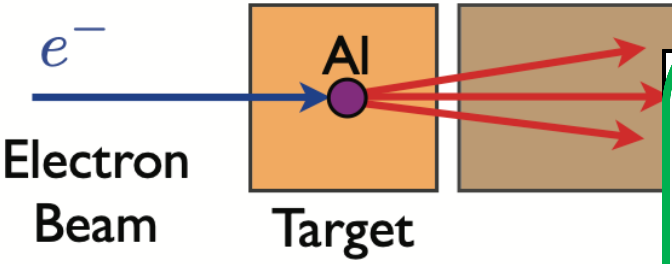
$$\theta_e = 0,\ \theta_X \neq 0,\ \theta_f = 0$$

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

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

θ_X dependent

Number of signal events



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

(# of events) = (# of produc

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

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