Future beam dump experiments constraint on lepton flavor violating coupling

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

Introduction

Charged Lepton Flavor Violation (cLFV)

In the Standard Model (SM)

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

Theoretical prediction ：

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

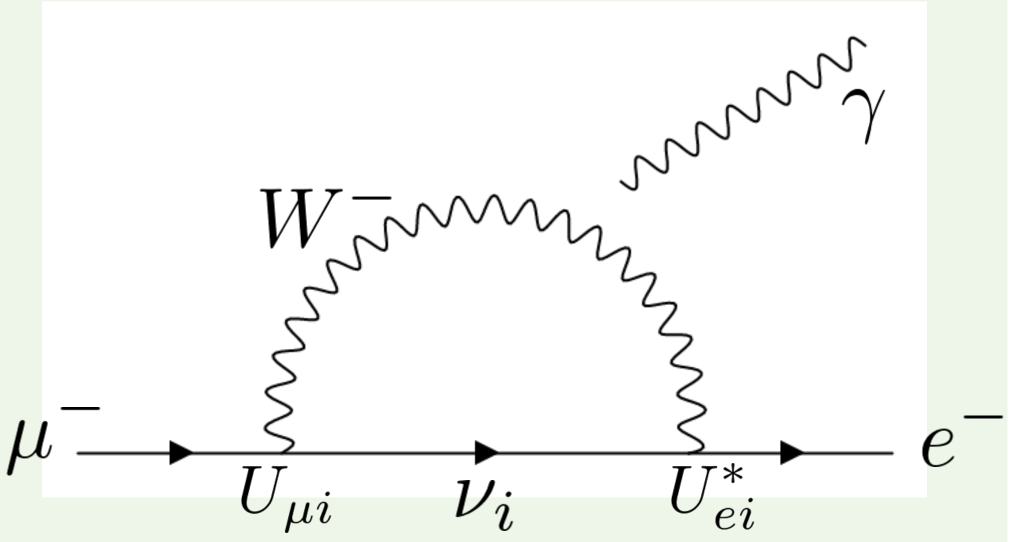
Li ('77), Petcov ('77), Sandra ('77), Lee ('77)

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

We focus on light bosons

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New physics makes cLFV processes observable

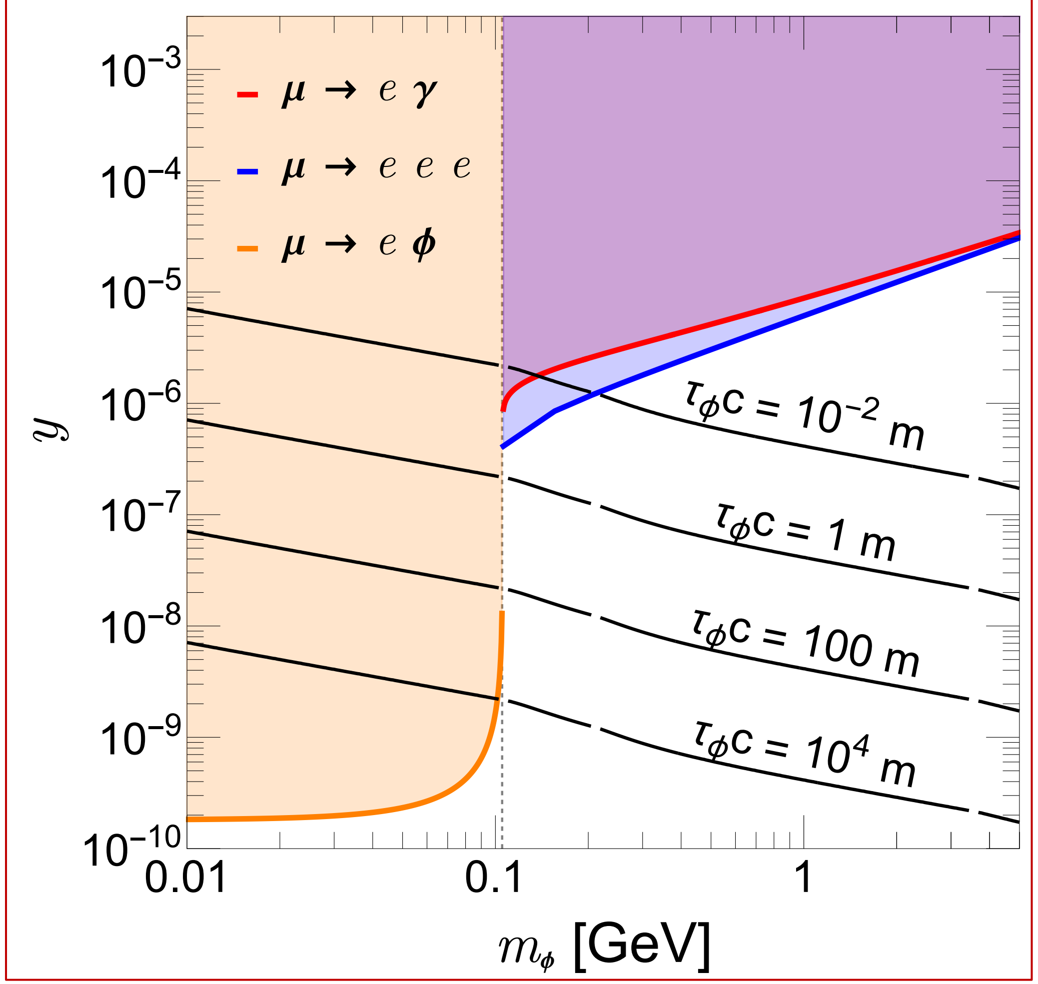
Charged lepton flavor violation process is a smoking gun signal of new physics

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

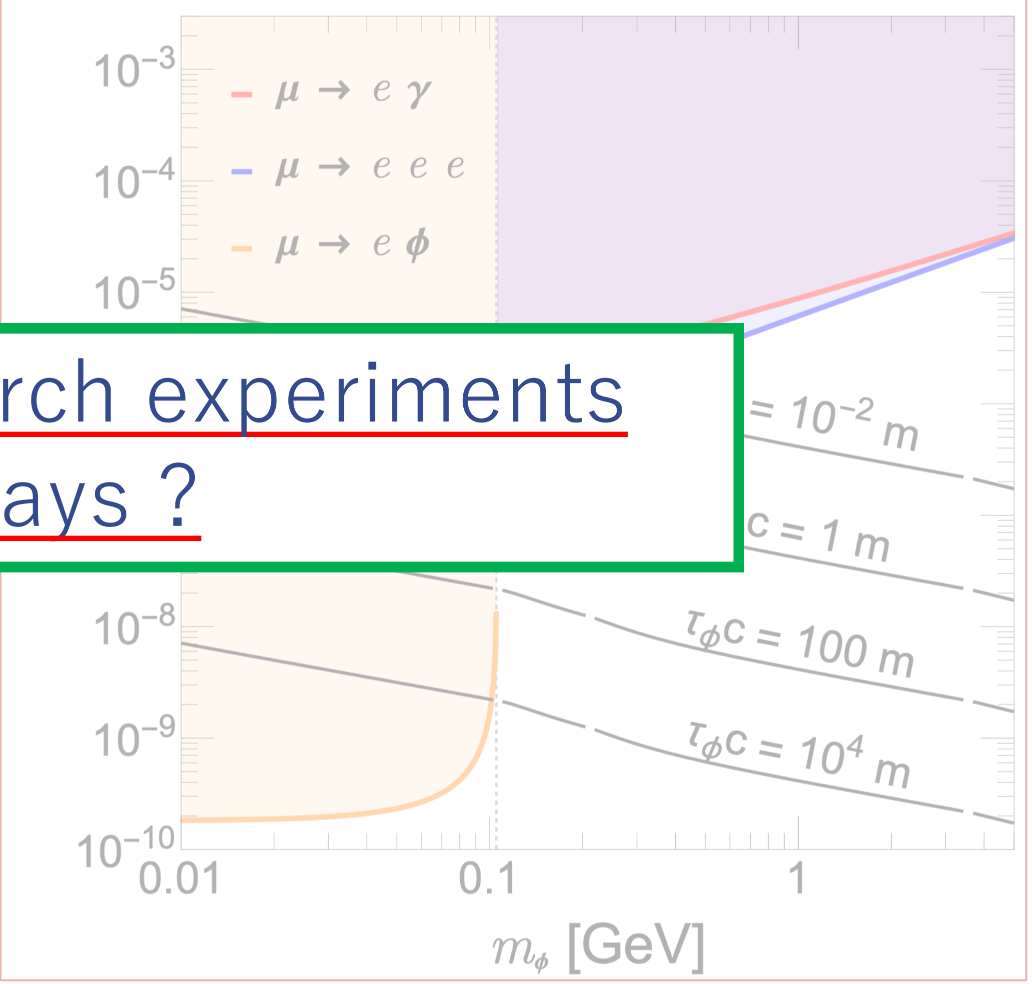
$$\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} y\bar{\ell}_L\phi\ell_R + y\bar{\mu}_L\phi e_R + y\bar{e}_L\phi\mu_R$$

In light
$(m_\phi \sim 0$

Can Long-lived particle search experiments detect CLFV decays ?

1, CLFV coupling can be as large as CLFC one

2, New particles with CLFV coupling are long-lived



Beam Dump Experiment

Overview

High-energy beam is dumped into dense target

➡ High intensity

- Production of large number of new particles

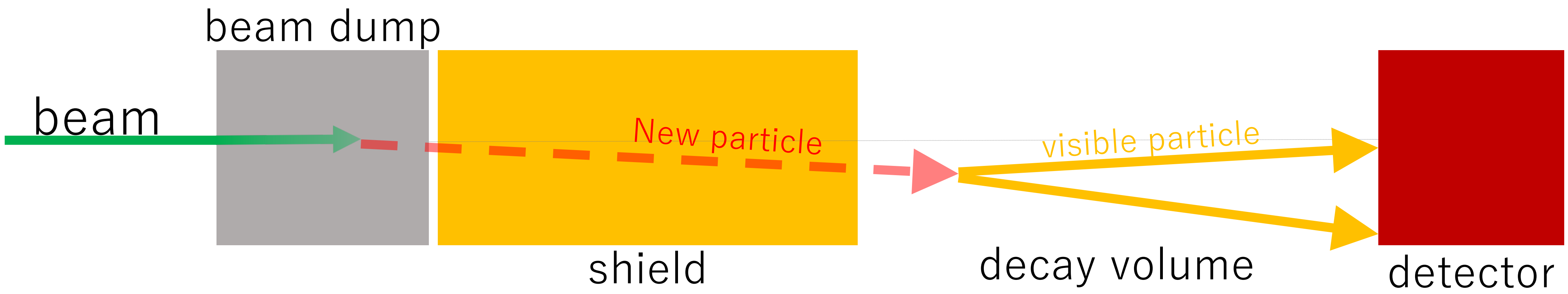
Detector is placed behind long shield

➡ Low background

- Most of background events are removed by shield

Sensitive to small coupling region

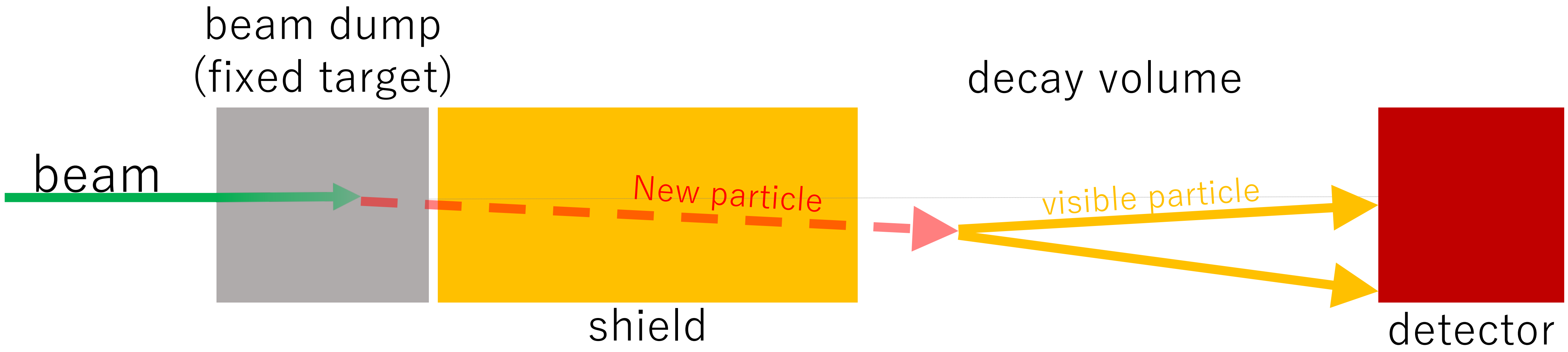
- New particles should be long-lived to reach detector



Beam Dump Experiment

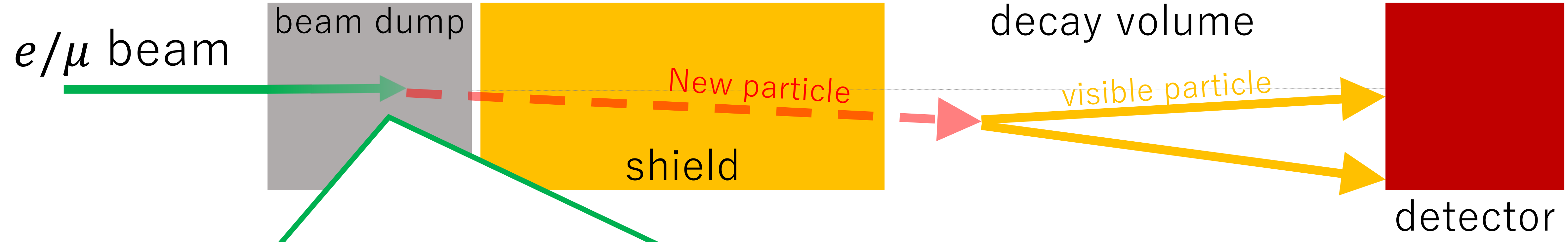
Basic strategy

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



Beam Dump Experiment

New particle production



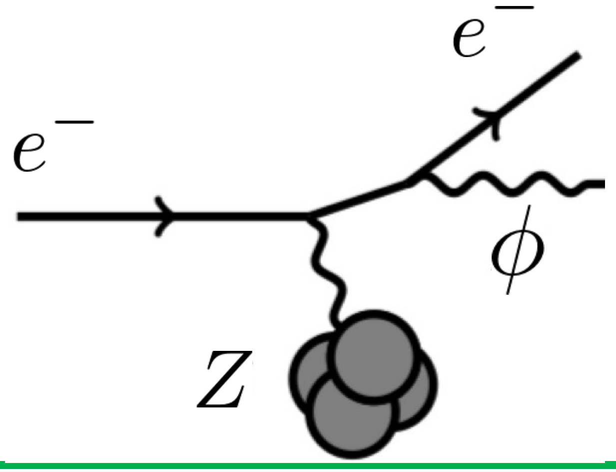
Lagrangian

Coupling with ee / $\mu\mu$

$$\mathcal{L} \supset y_{ee}\phi\bar{e}e$$

$$/ y_{\mu\mu}\phi\bar{\mu}\mu$$

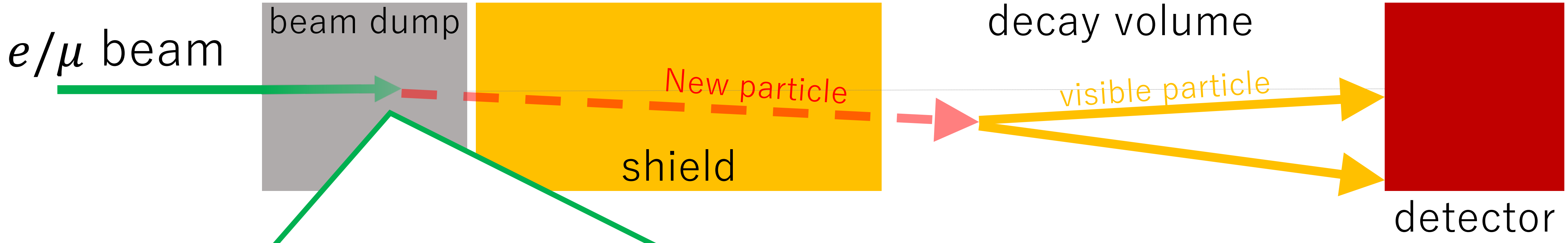
Bremsstrahlung production



New particles are produced through bremsstrahlung process

Beam Dump Experiment

New particle production with LFV coupling

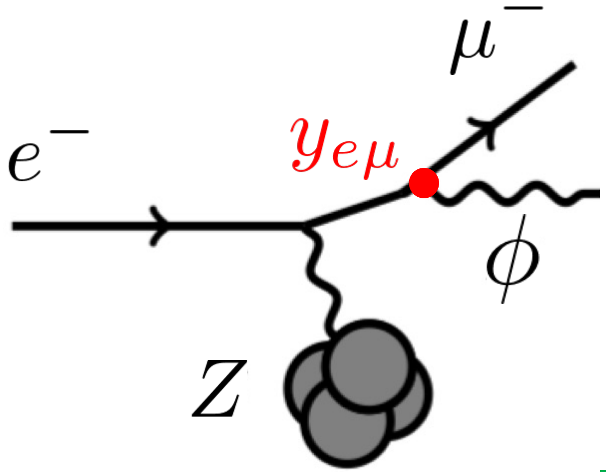


Lagrangian

Coupling with e & μ

$$\mathcal{L} \supset y_{e\mu}\phi\bar{e}\mu + y_{\mu e}\phi\bar{\mu}e$$

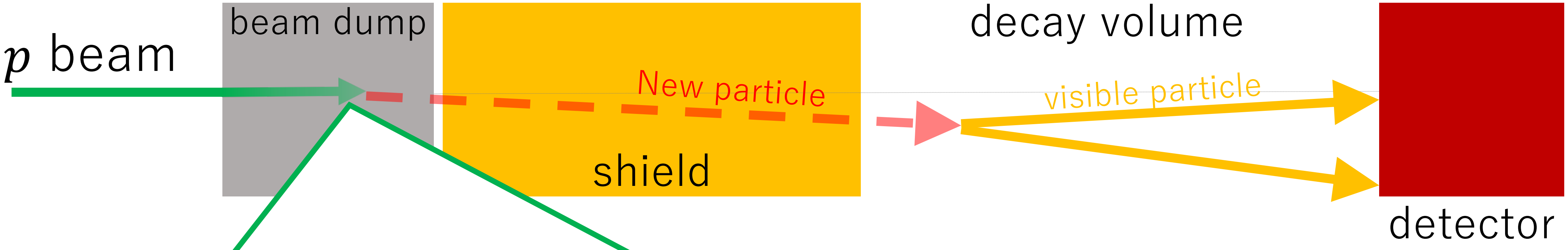
Bremsstrahlung production



Possibly LFV interactions contribute to bremsstrahlung production

Beam Dump Experiment

New particle production

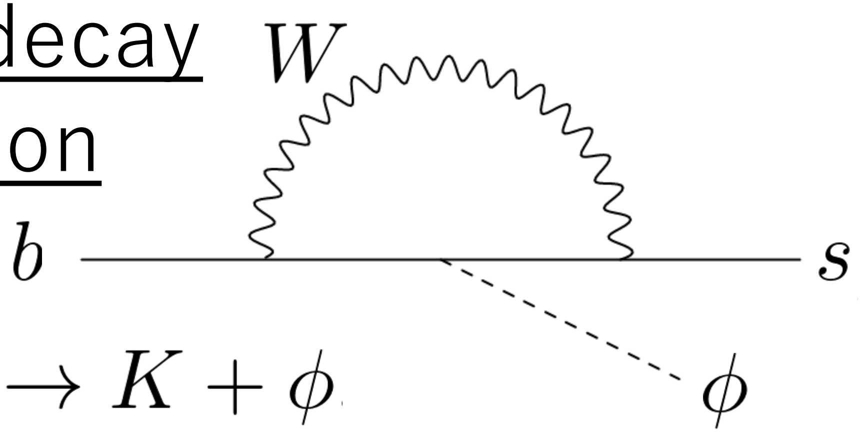


Lagrangian

Mixing SM Higgs and scalar

$$\mathcal{L} \supset \sum_f \theta_{h\phi} \frac{m_f}{v} \phi \bar{f} f + y_{e\mu} \phi \bar{e} \mu + y_{\mu e} \phi \bar{\mu} e$$

Meson decay production

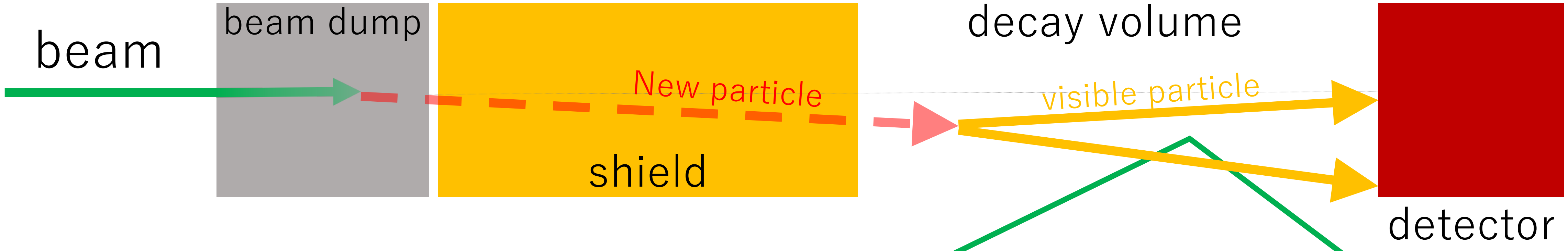


$B \to K + \phi$

New particles are produced through bremsstrahlung process

Beam Dump Experiment

New particle detection with LFV coupling

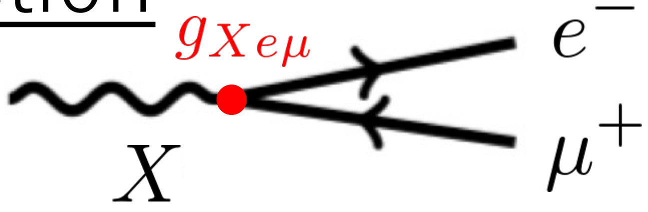


Lagrangian

Coupling with e & μ

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

Detection

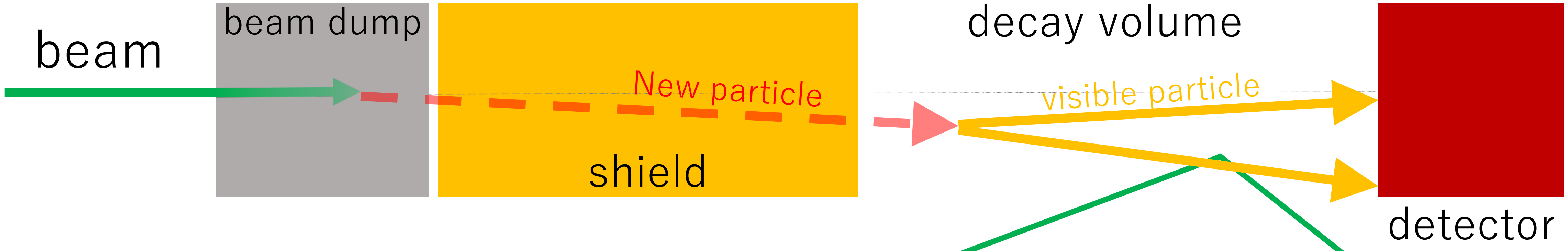


Decay into $\mu^+ e^-$ pair → Detection

LFV decay can be searched by beam dump experiment

Beam Dump Experiment

New particle detection



Lagrangian

Coupling with electrons

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

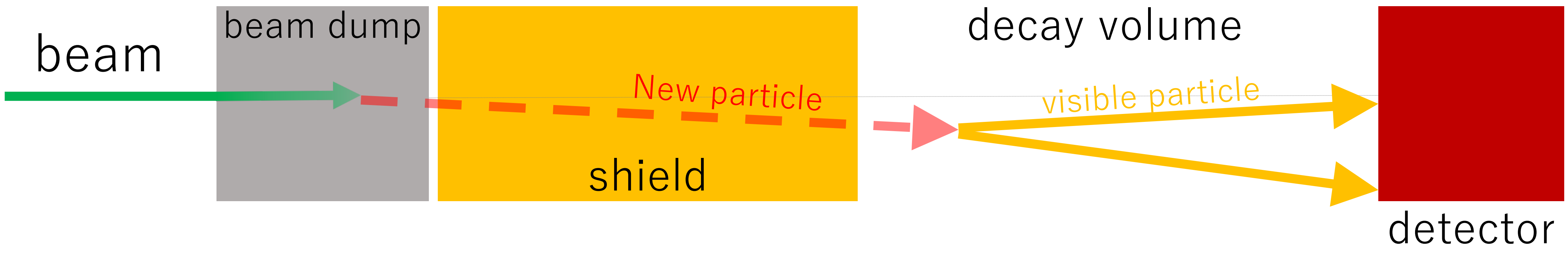
Detection

Decay into e^+e^- pair → Detection

Branching fractions of decay processes
give information of couplings

Calculation

Number of signals

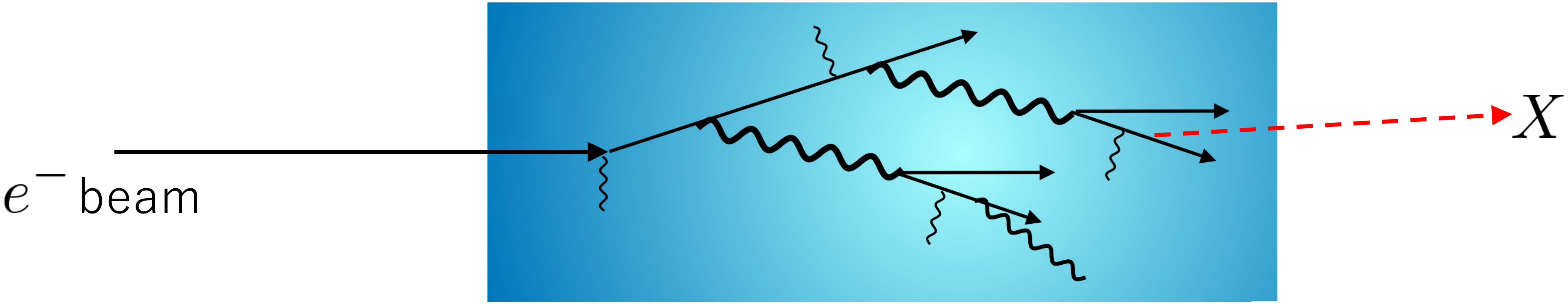


(# of signal detection)

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

Calculation

of new particles

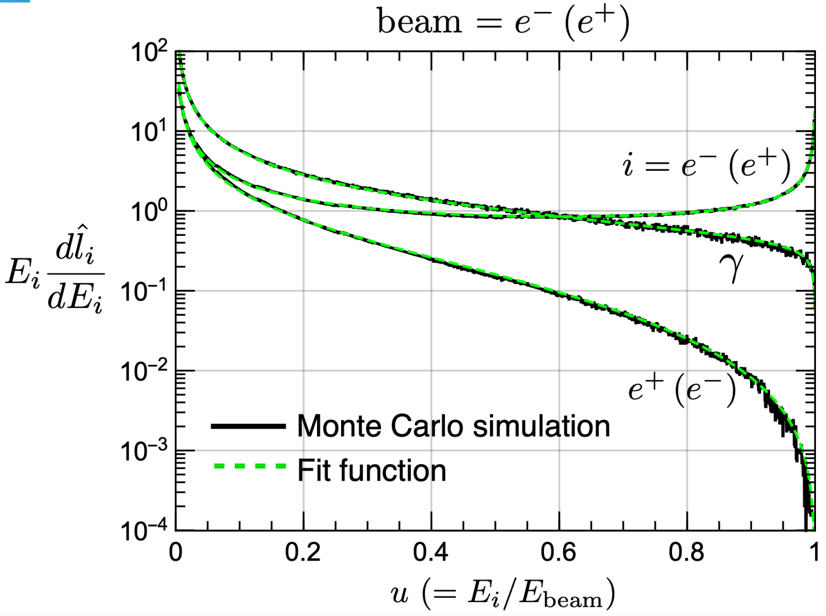


(# of produced new particles)

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

$\|$

(# of incident particles into beam dump)
$\times$ (# density of target particles in beam dump)
$\times$ (Track length of shower particles)



Calculation

of new particles

(# of produced new particles)

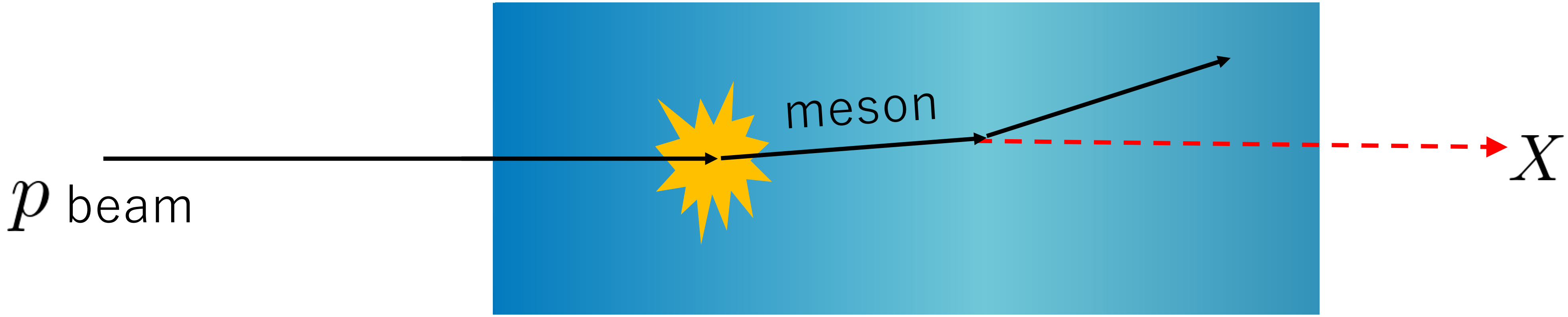
= (Luminosity) × (Production cross section)

||

(# of incident particles into beam dump)
× (# density of target particles in beam dump)
× (Track length of shower particles) = (Length of beam dump)

Calculation

of new particles



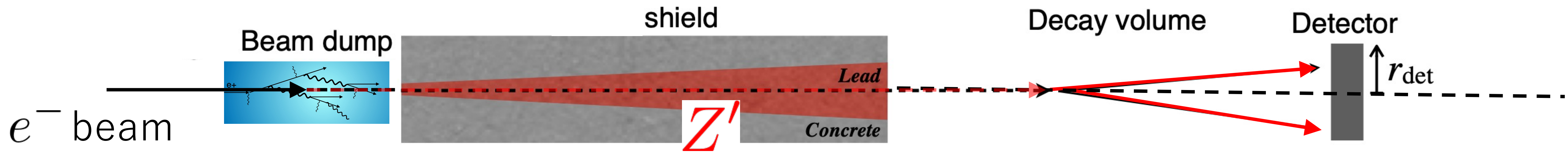
(# of produced new particles)

$=$ (# of produced mesons) $\times$ (Branching ratio of $M \to M'X$)

||

(# of incident particles into beam dump)
$\times$ (# of produced mesons per one beam proton injection)

Number of signals

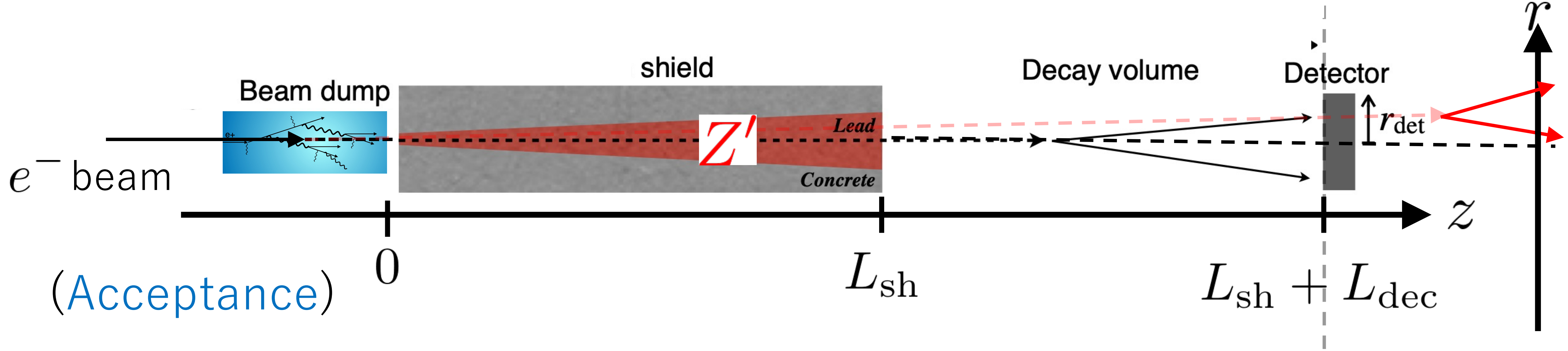


(Acceptance)

$=$ (Probability of decaying in decay volume) $\times$ (Angular cut)

Calculation

Number of signals



(Acceptance)

$=$ (Probability of decay in decay volume) $\times$ (Angular cut)

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

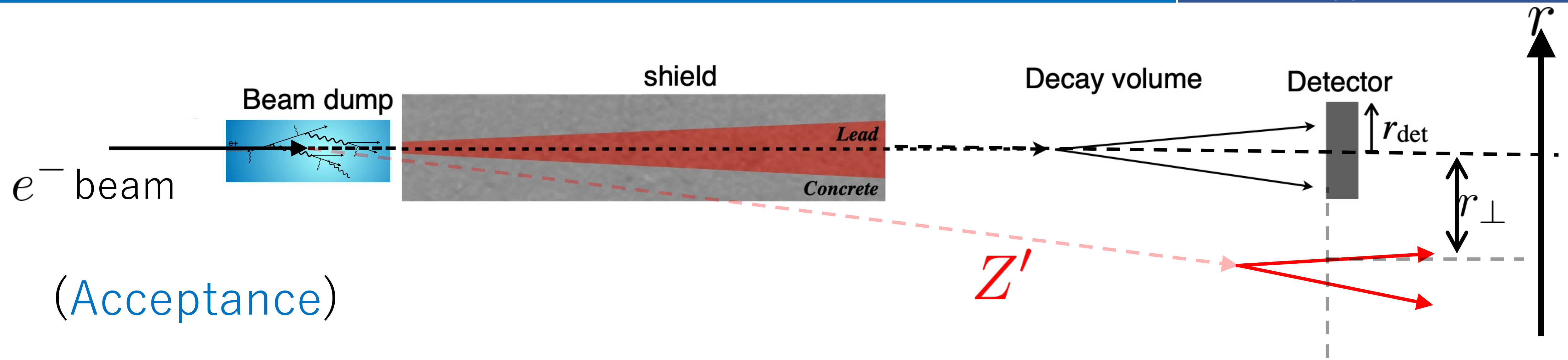
➡ Probability of decay between $L_{\rm sh} \sim L_{\rm sh} + L_{\rm dec}$

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

l_X : Decay length in laboratory frame

Calculation

Number of signals



(Acceptance)

$=$ (Probability of decay in decay volume) $\times$ (Angular cut)

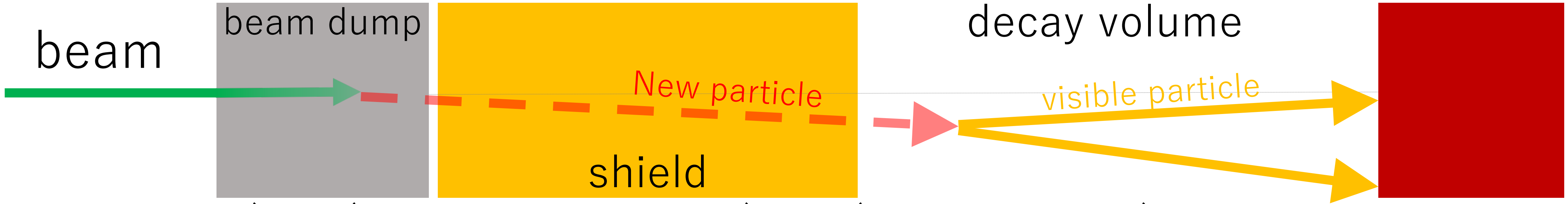
Produced particles have angles with respect to initial particles

➡ 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)

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

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

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

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

Beam Dump Experiment

Electron & muon & proton beams

<u>Electron beam dump</u>

@ ILC main beam dump

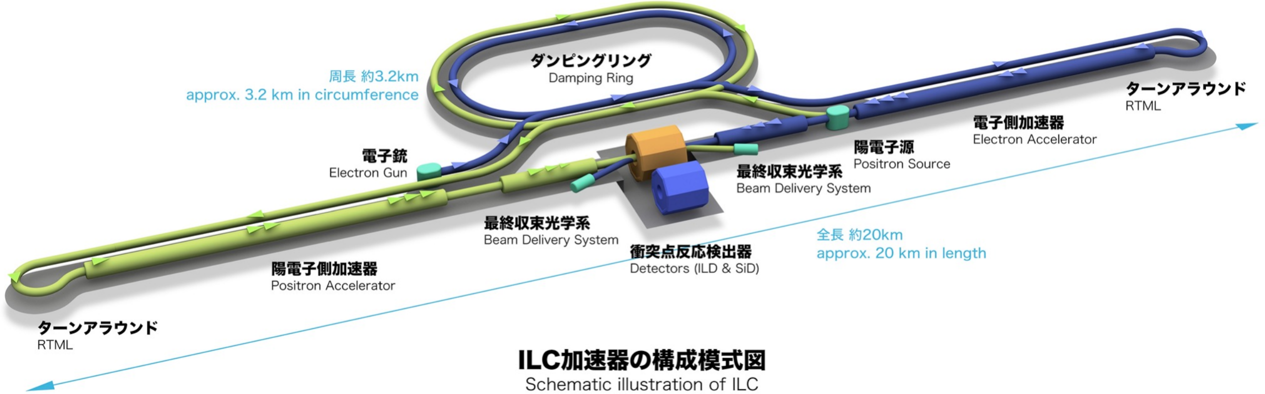
Beam : 125 GeV e^- beam

$\cong 4\times10^{21}$ EOT/year

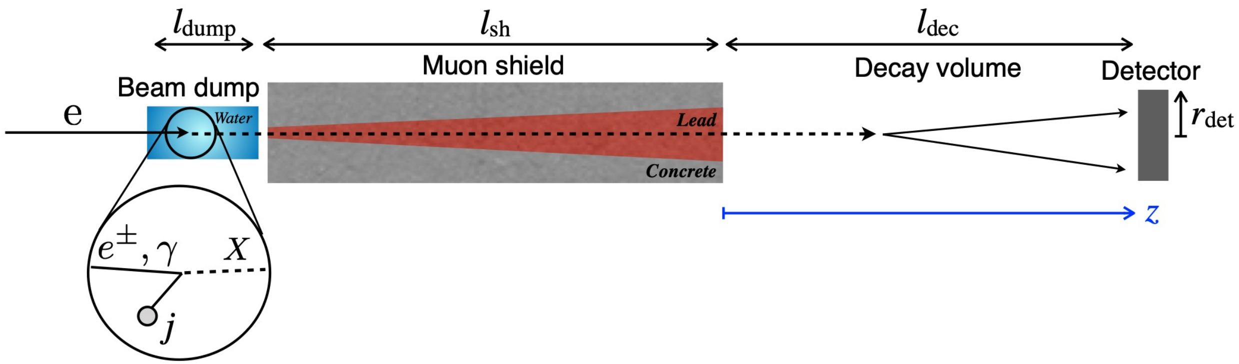
Target : Liquid water

Shielding : 70m lead

Decay volume : 50m



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



S. Kanemura, T. Moroi, and T. Tanabe, PLB 751 (2015) 25-28;
Y. Sakaki and D. Ueda, PRD 103 (2021) 035024;
KA, S. Iwamoto, Y. Sakaki, D. Ueda, JHEP 09 (2021) 183

Beam Dump Experiment

Electron & muon & proton beams

Muon beam dump

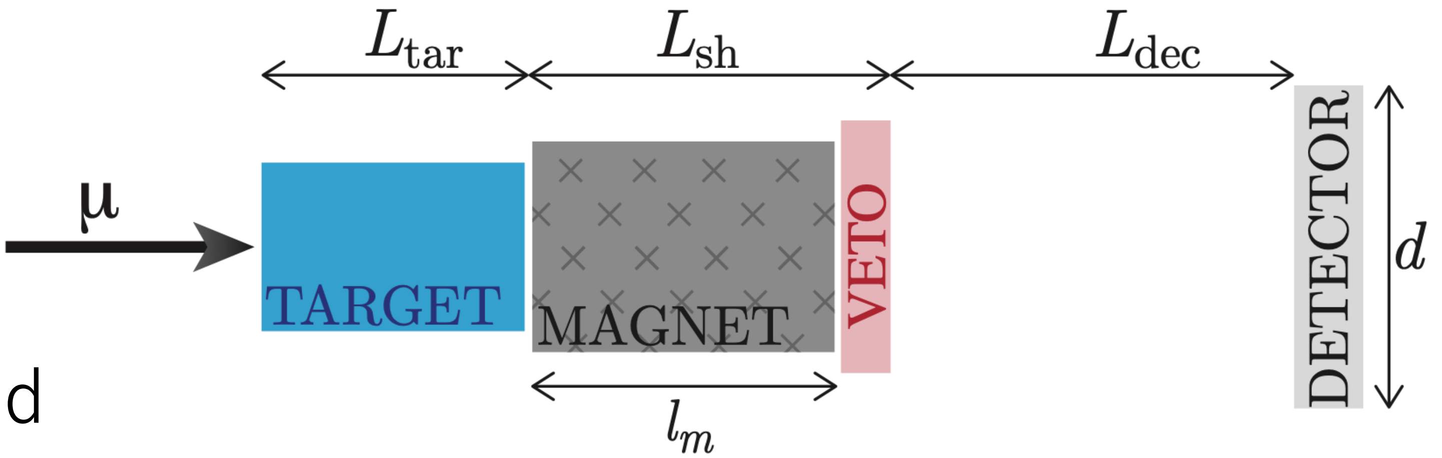
C. Cesarotti, S. Homiller, R.K. Mishra, and M. Reece,
PRL 130 (2023) 7, 071803

Beam : 1.5 TeV μ beam
$= 10^{18}, 10^{20}$ MOT

Target : 10m liquid water

Shielding : 10m active shield

Decay volume : 100m



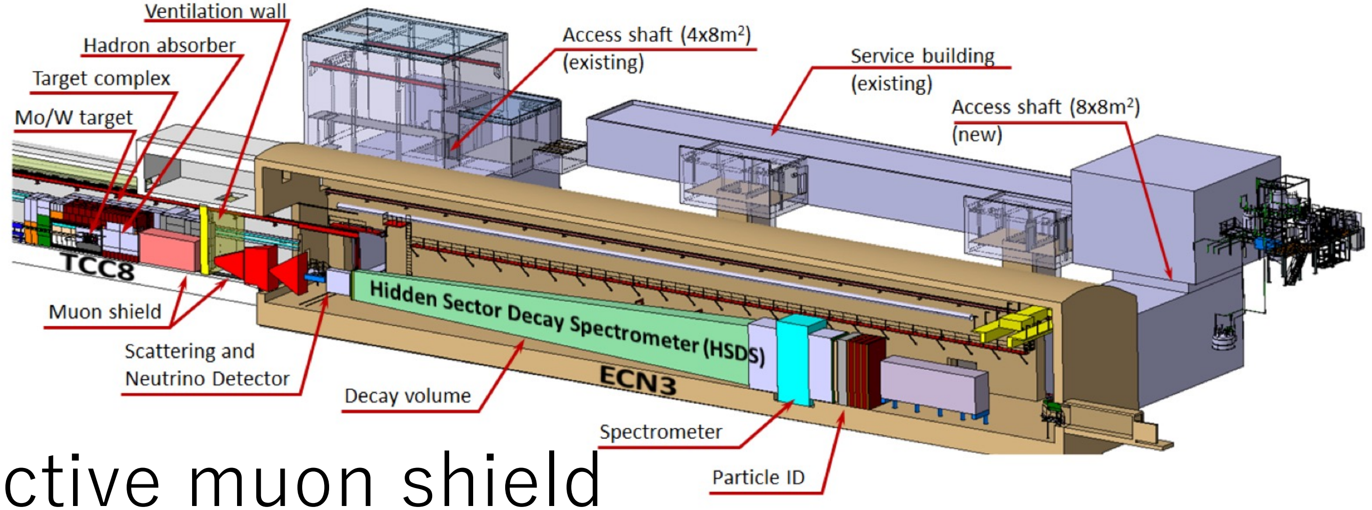
Beam Dump Experiment

Electron & muon & proton beams

SHiP collaboration (2023)
CERN-SPSC-2023-033/SPSC-P-369

Proton beam dump

@ SHiP experiment (CERN)



Beam : SPS 400 GeV p beam
$= 4\times10^{19}$ POT/year

Target : Ti-Zr-Mo alloy, etc.

Shielding : hadron absorber + active muon shield

Decay volume : 50m

Decay : 6m × 4m (originally 10m × 5m)

Result

Sensitivity to LFV coupling

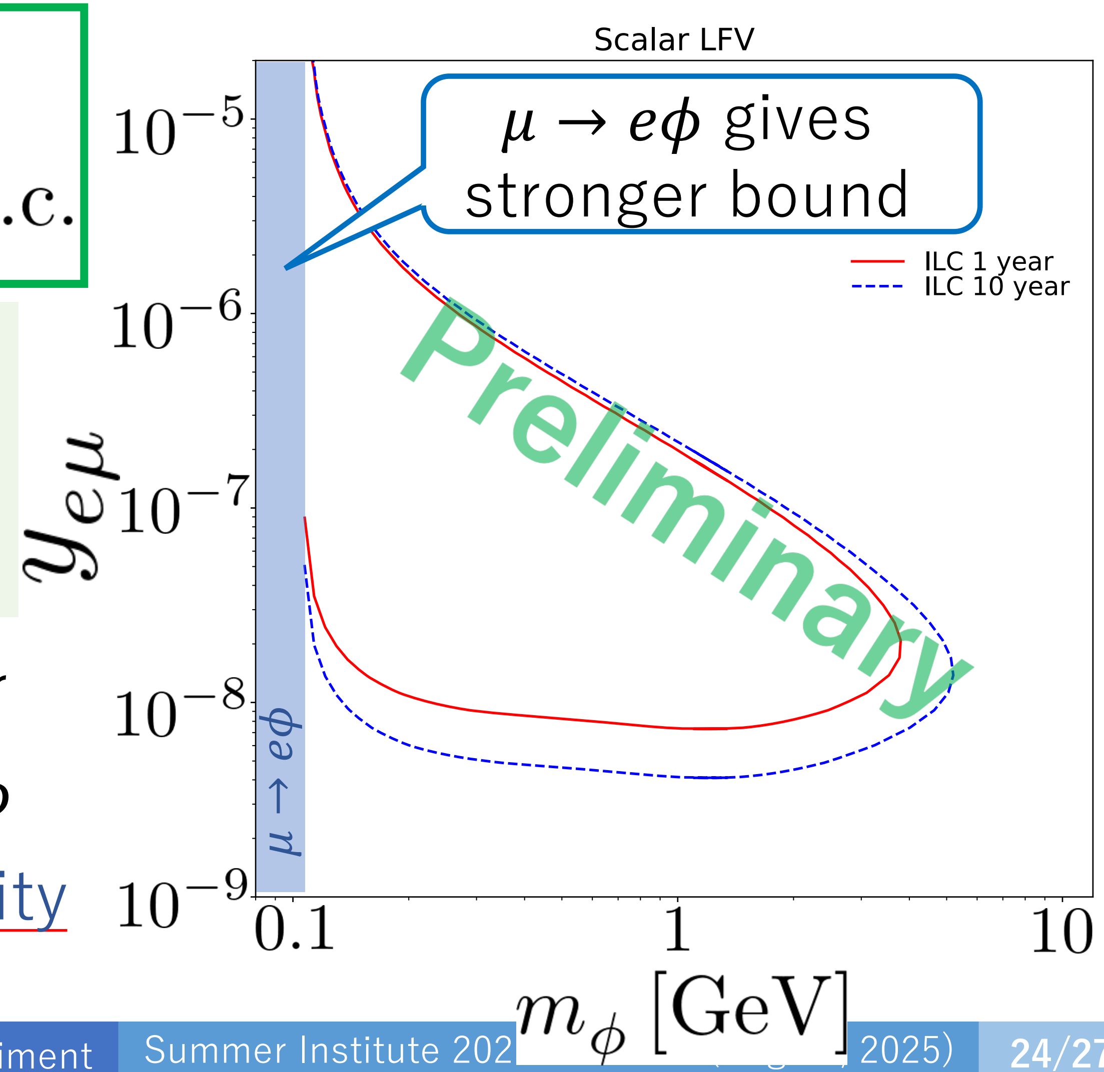
Scalar-type int.

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

CLFV search @ ILC beam dump

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

→ red solid line : 1 year, blue dashed line : 10 years



Huge # of lower energy $e^\pm$ from EM shower

→ More low energy (small boost factor) ϕ

$e^\pm$ beam dump exp. (ILC-BD) has sensitivity in smaller CLFV interaction region

Result

Sensitivity to LFV coupling

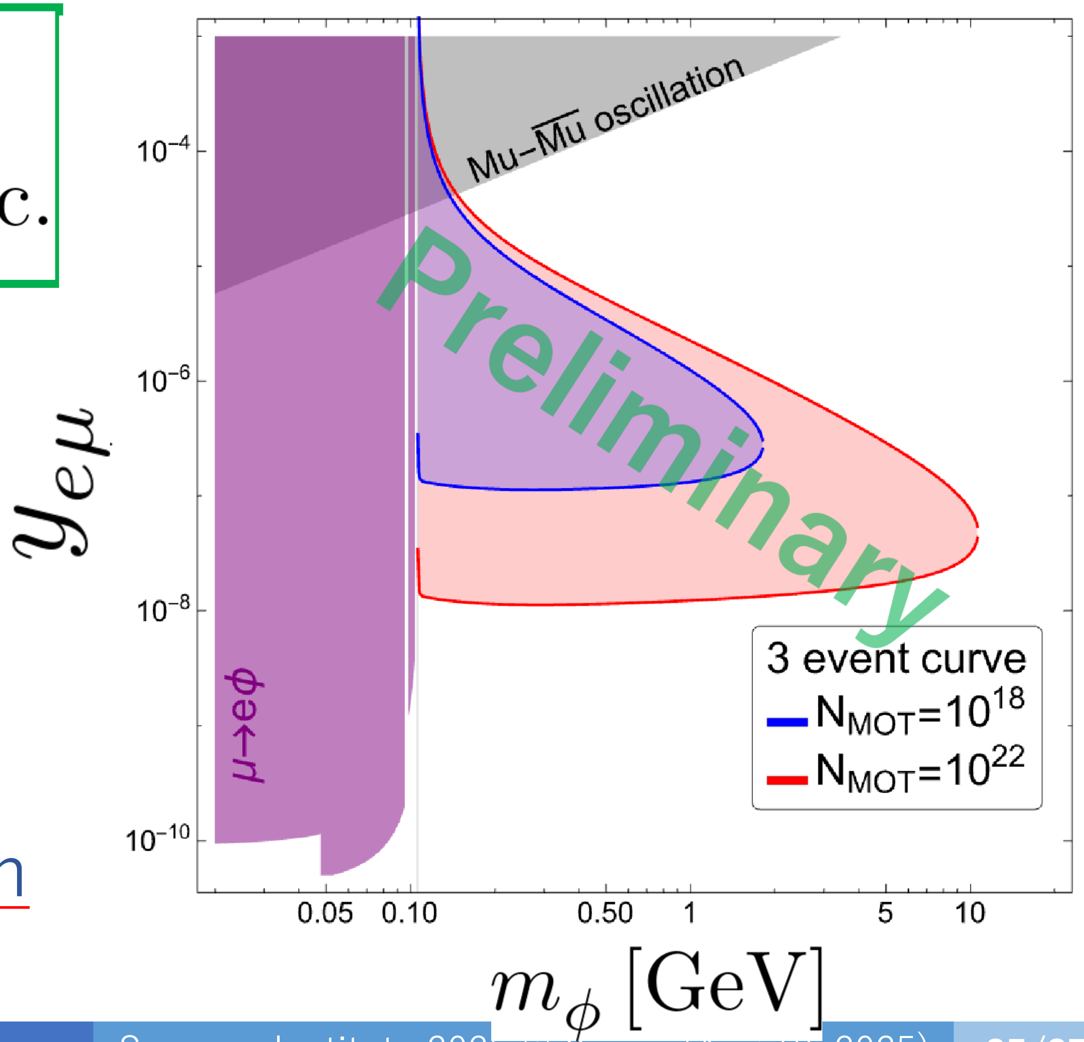
Scalar-type int.

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

CLFV search @ muon beam dump

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

➡ —— : 10^{18}MOT - - - - : 10^{20}MOT



Beam particles with higher energy

➡ Higher COM energy

Muon beam dump experiment can search heavier scalar with CLFV interaction

Result

Sensitivity to LFV coupling

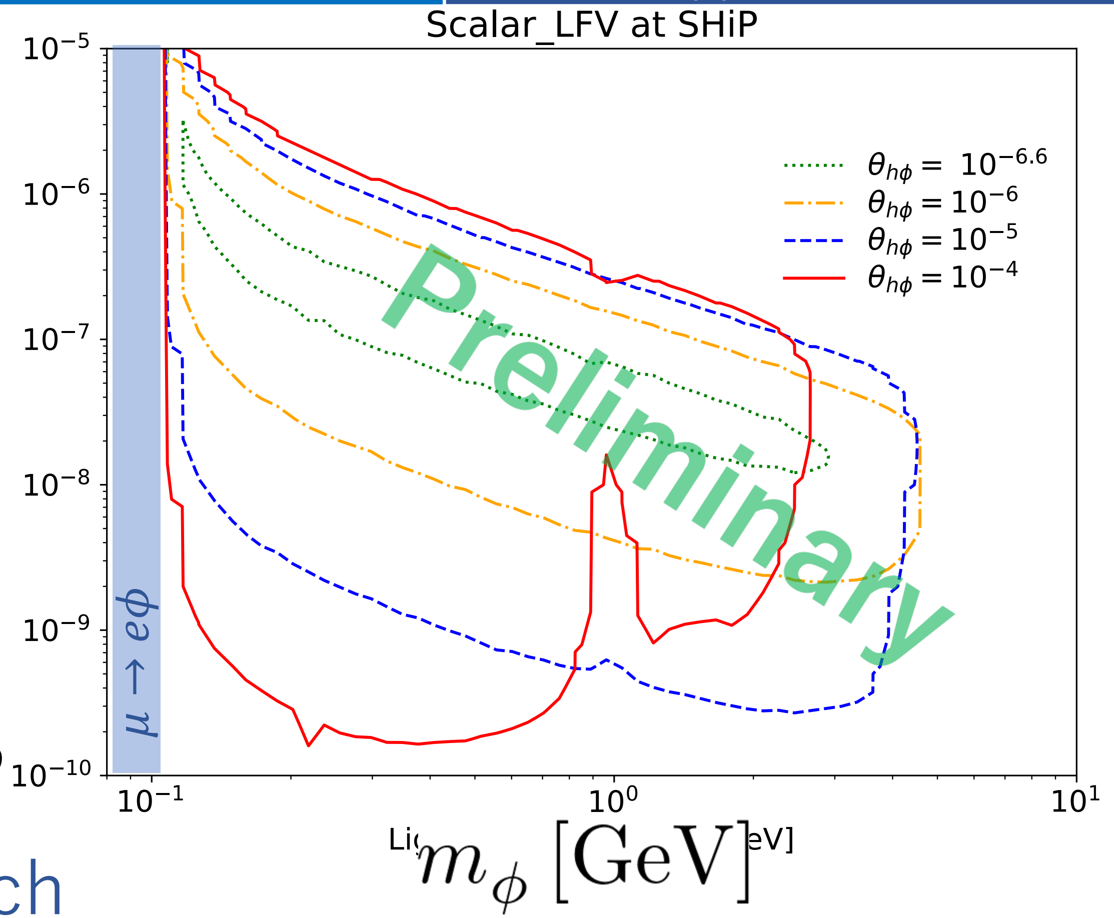
Scalar-type int.

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

CLFV search @ SHiP experiment

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

→ $\theta_{h\phi} = 10^{-4,-5,-6,-6.6}$ $(6\times10^{20}$POT$)$



Huge # of B meson
& ϕ production rate is large → Huge # of ϕ

Proton beam dump experiment can search
smaller CLFV interaction if scalar mixes with SM Higgs boson

Summary

○ Sub-/several-GeV bosons with CLFV interaction is facing on stringent constraints and only tiny coupling region is alive

○ In such small coupling regions, light BSM boson is long-lived and beam dump experiments have advantage and sensitivity

○ We consider light bosons with CLFV interaction and study sensitivity to CLFV interaction ($\phi \to e\mu$ decay) by future beam dump experiment

○ By comparison with several kinds of experiments, we can know not only existence of CLFV int., but also information about flavor, SM Higgs-scalar mixing, etc…

Thank you for your attention !