New Physics Searches at the ILC positron and electron beam dumps

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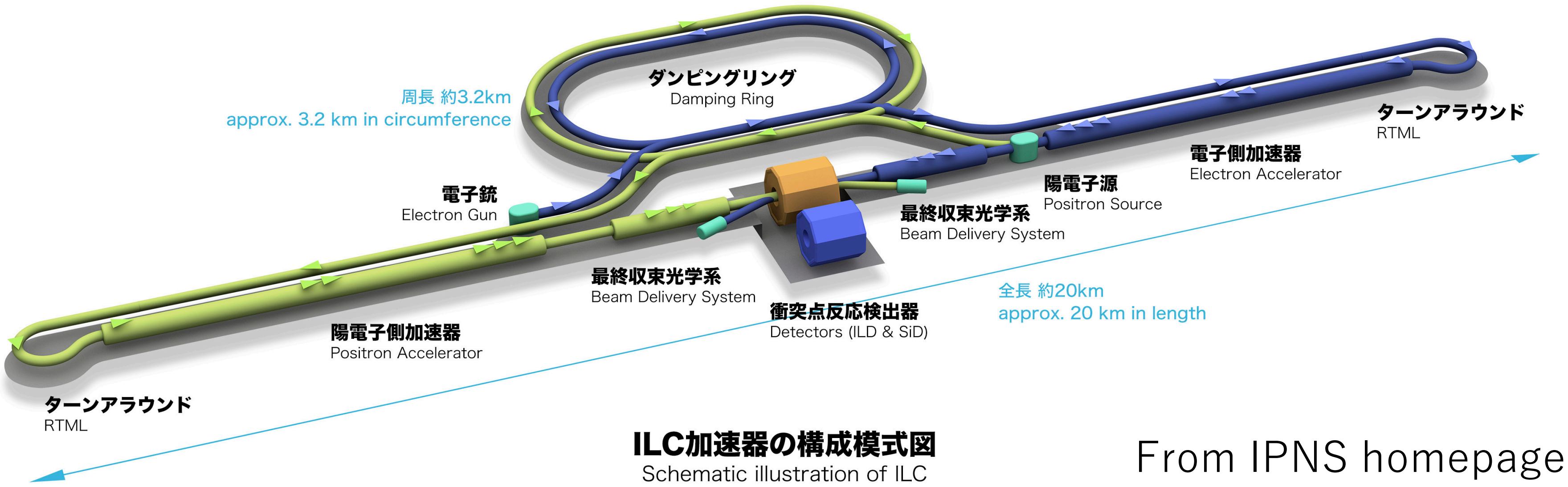
Based on
KA, S. Iwamoto, Y. Sakaki, D. Ueda, JHEP **09** (2021) 183, arXiv : 2105.13768 [hep-ph]

Introduction

International Linear Collider

ILC (International Linear Collider)

- Electron-positron linear collider
- 250 GeV center-of-mass energy (-> upgrade to 500 GeV, 1TeV)
- 250 fb^{-1} integrated luminosity



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

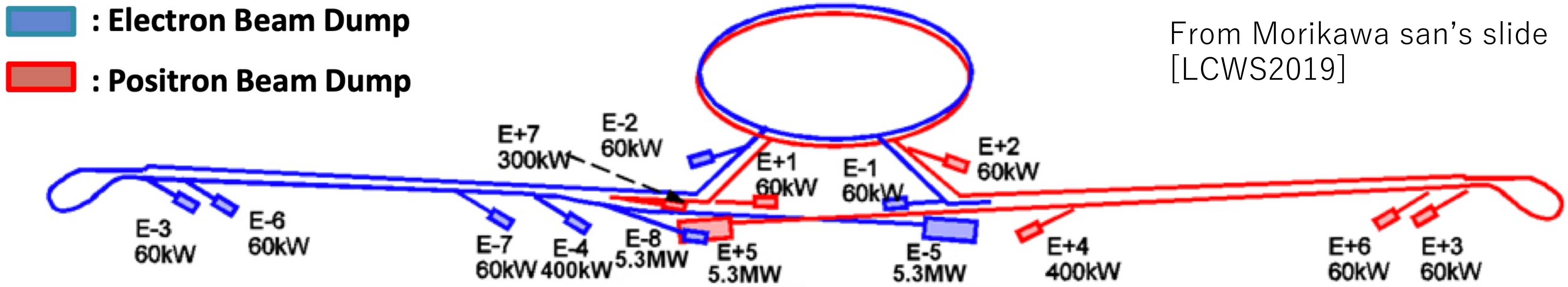
From IPNS homepage

Introduction

Beam dumps in ILC

Total 15 beam dumps in ILC

- for electron, positron, and photon
- Absorber (water, graphite, aluminum alloy)
- Energy (5, 15, 125 GeV e^-& e^+, average 8 MeV γ)
- Normal operation → E-5, E-8 (e^-), E+5 (e^+), E+7 (γ)



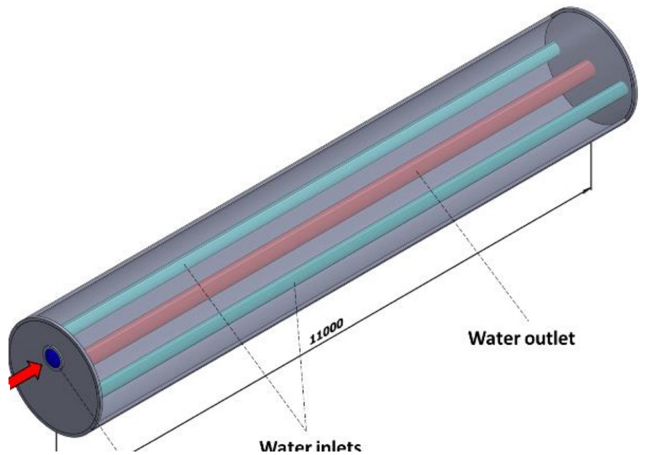
From Morikawa san's slide [LCWS2019]

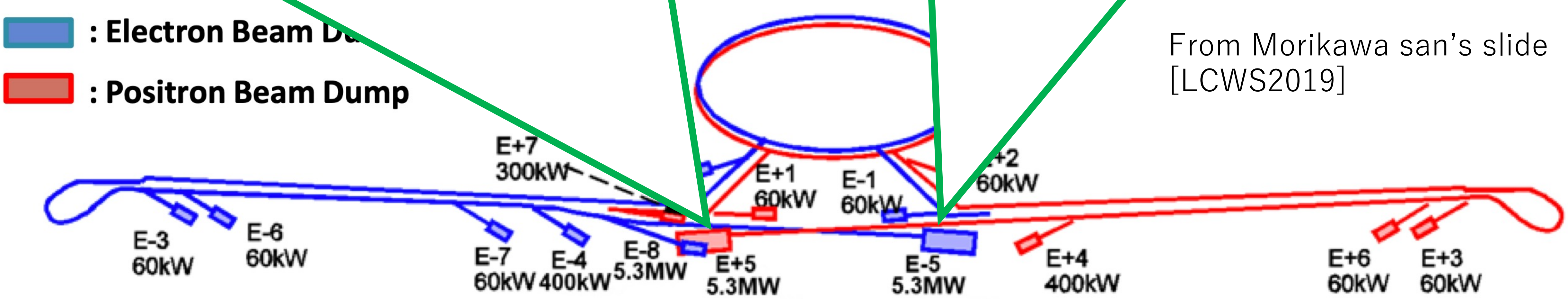
Introduction

Beam dumps in ILC

Main beam dump

- Absorber : liquid water
- Covered by iron shield and concrete
- 11 m length





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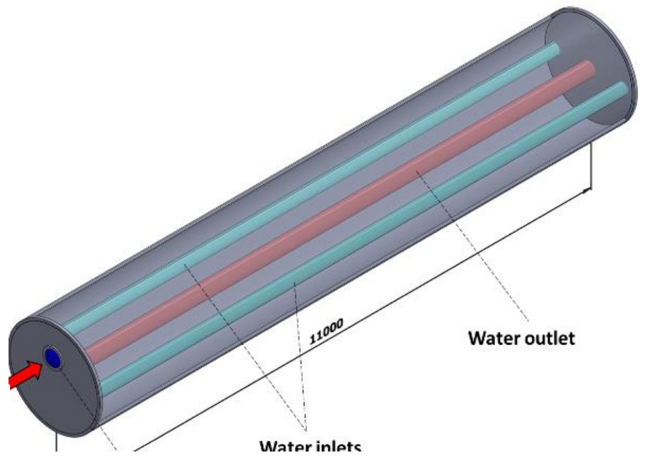
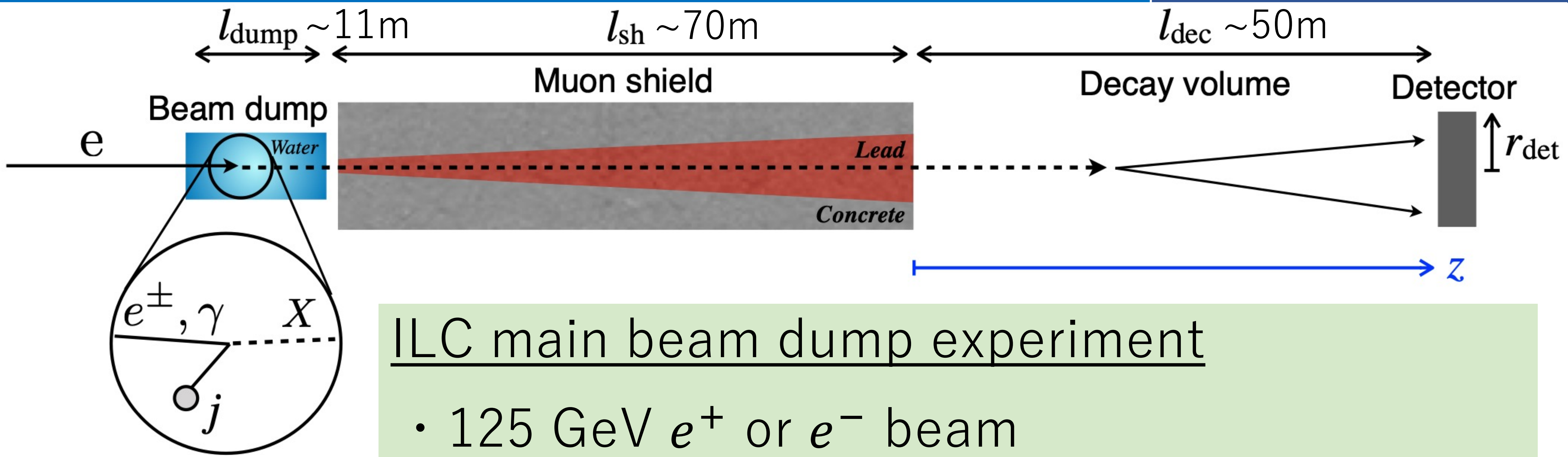


What a waste !!

Almost all e^+ & e^- are dumped at main beam dump

⇒ Use them for beam dump experiment

Beam dump experiment in ILC



ILC main beam dump experiment

- 125 GeV e^+ or e^- beam
- Liquid water target
- Thick muon shield for removing background

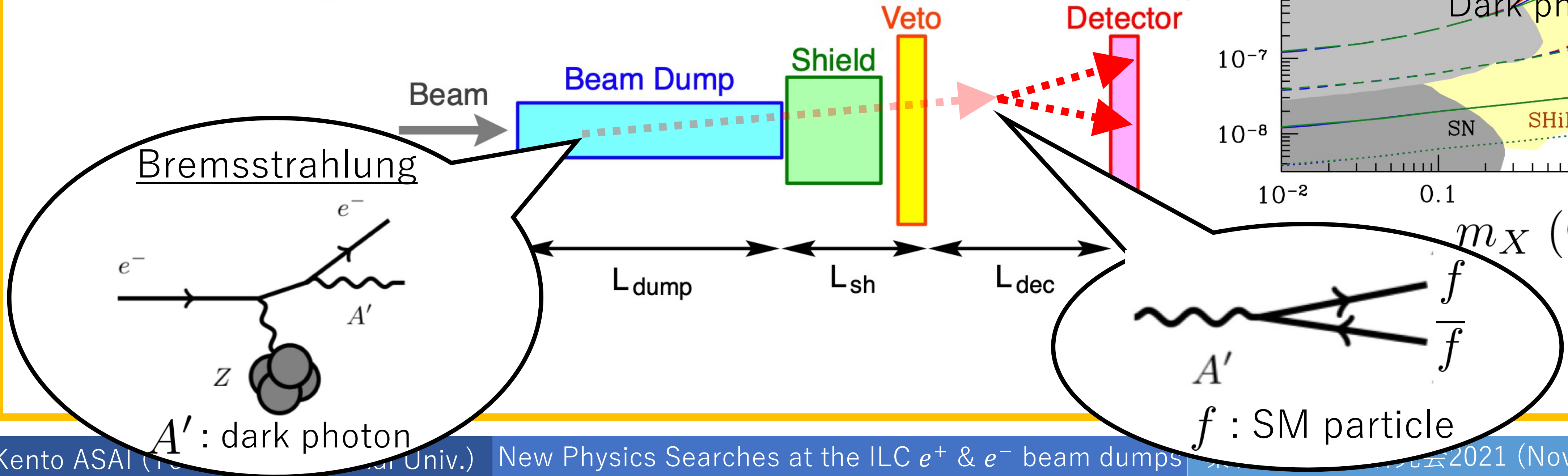
Beam dump experiment in ILC

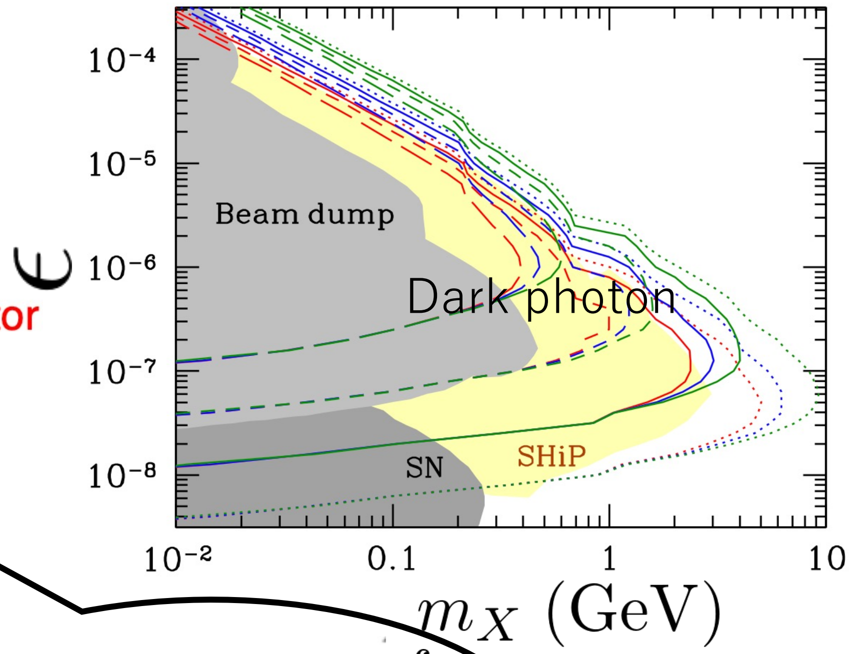
Previous work

S. Kanemura, T. Moroi, T. Tanabe, PLB 751 (2015) 25-28, arXiv : 1507.02809 [hep-ph]

Dark photon search by ILC electron beam

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F^{(X)}_{\mu\nu} F^{(X)}_{\mu\nu} - \frac{\epsilon}{2} F^{(\rm em)}_{\mu\nu} F^{(X)}_{\mu\nu} + \frac{m_X^2}{2} X_\mu X_\mu$$





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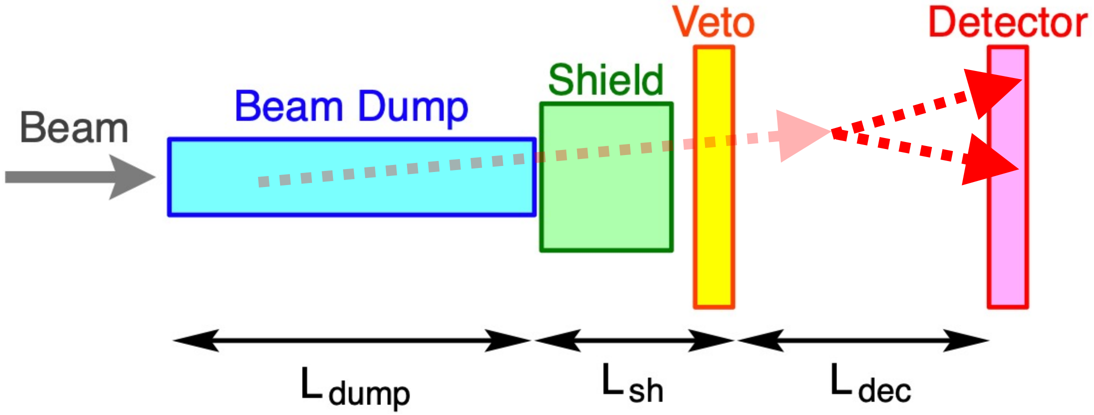
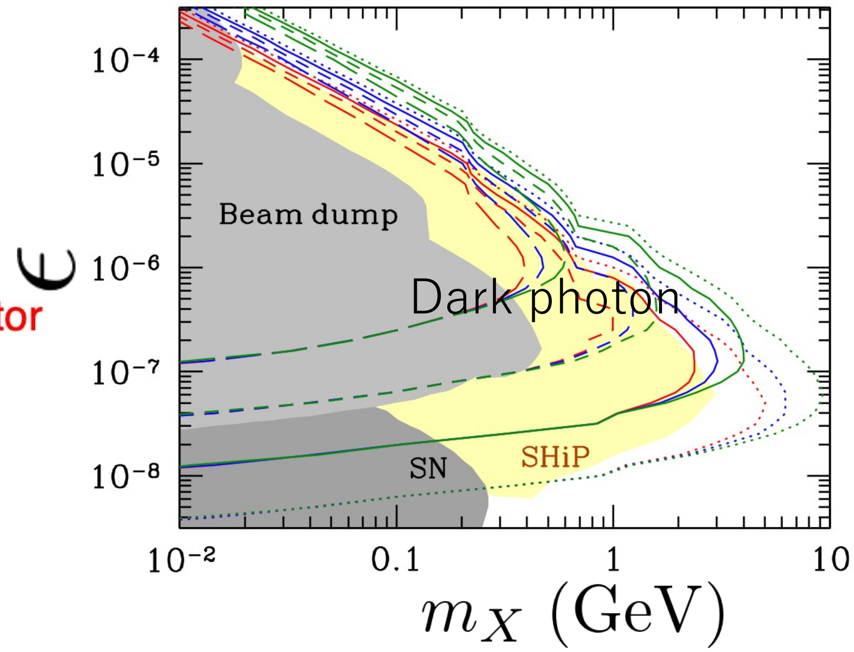




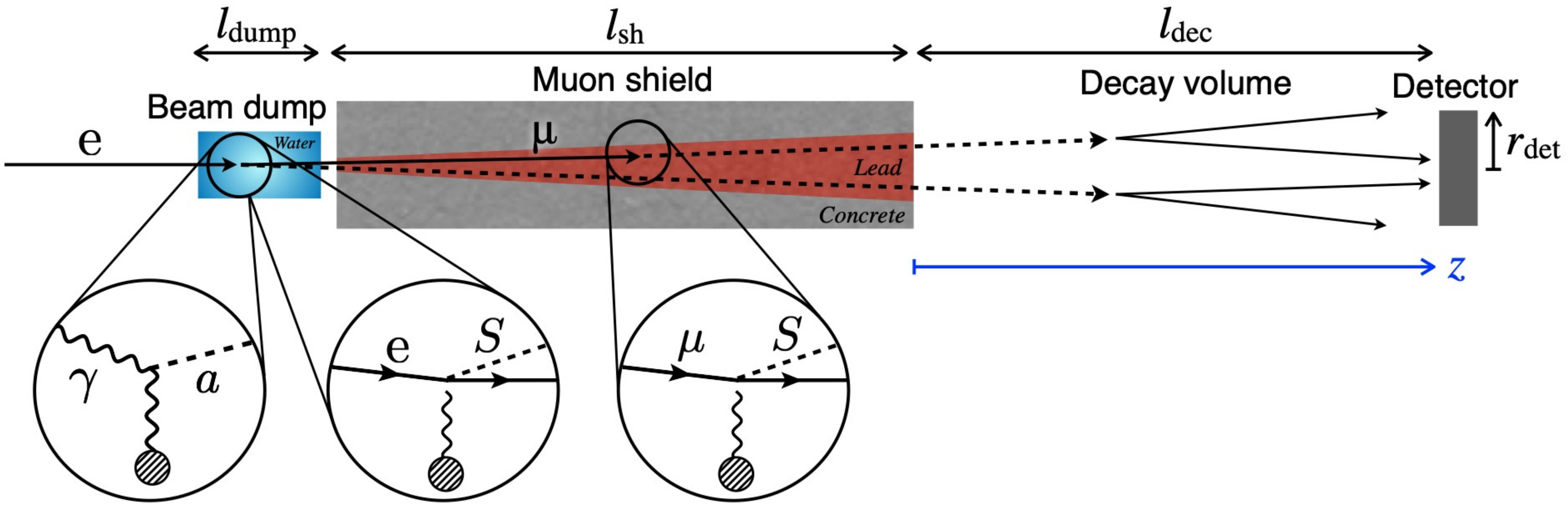
Sensitivity of ILC beam dump experiment to light particles is much higher than those of past beam dump experiments and comparable to that of SHiP experiment

Beam dump experiment in ILC

Previous work

Y. Sakaki, D. Ueda, PRD 103 (2021) 3, 035024 arXiv : 2009.13790 [hep-ph]

- Electromagnetic shower (e & μ & γ) in ILC electron beam dump
- Production of Axion-like particle and light scalar by remsstrahlung process from e & μ, Primakoff process from γ



Introduction

Beam dump experiment in

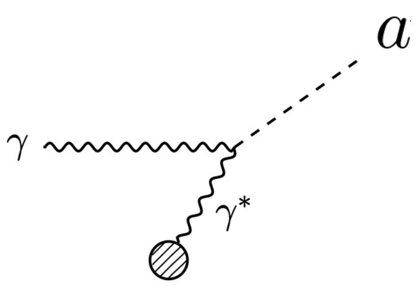
Other work

KA, T. Moroi, A. Niki, *Leptophilic Gauge Bosons at ILC Beam Dump Experiment*, PLB 818 (2021) 136374

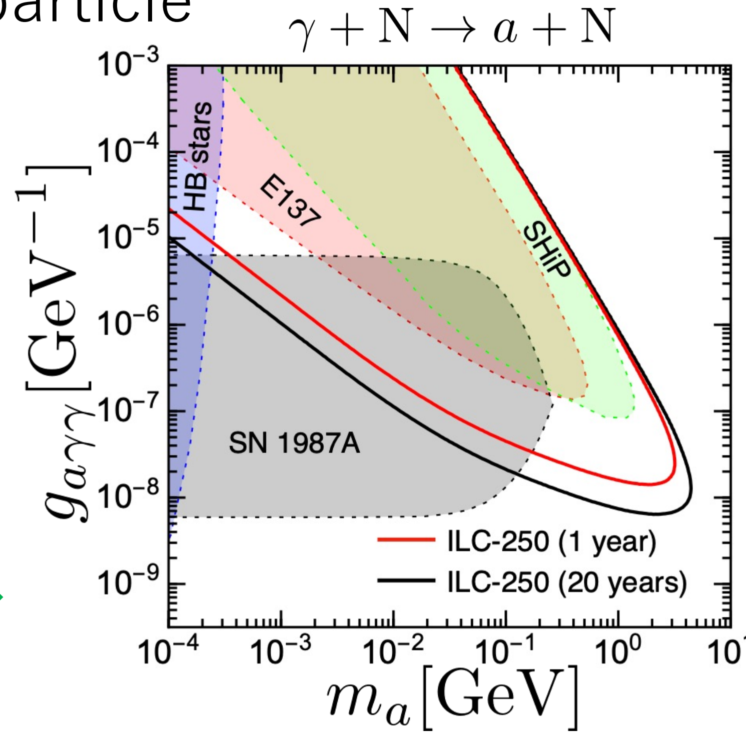
Previous work

Y. Sakaki, D. Ueda, PRD 103 (2021) 3, 035024 arXiv : 2009.13790 [hep-ph]

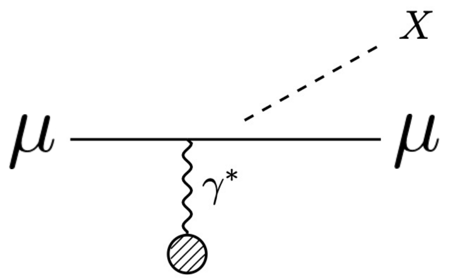
○ Axion-like particle



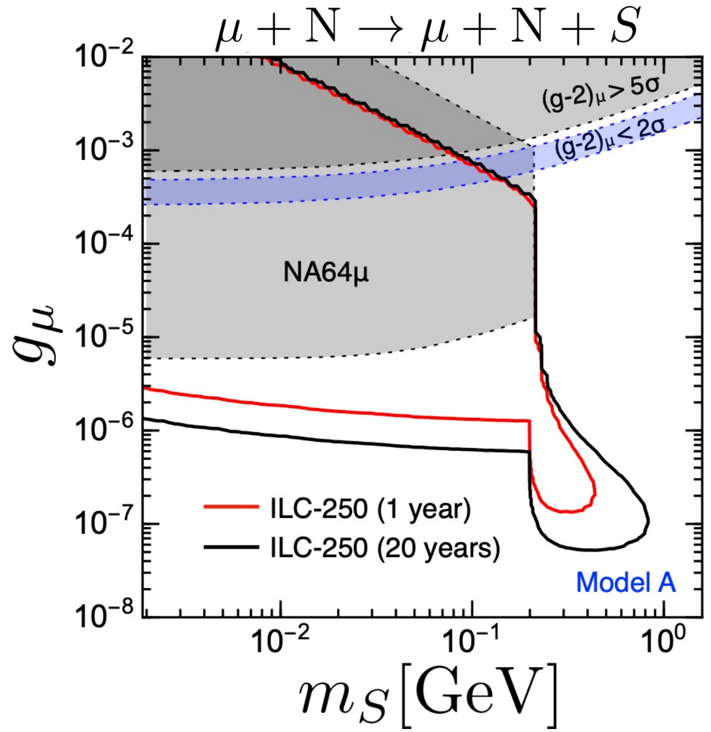
Primakoff



○ Light scalar



Bremsstrahlung



Productions by secondary particles are important

Beam dump experiment in ILC

Advantage

○ Intensity frontier

- Produce large number of light weakly-interacting BSM particles by high-intensity beam & fixed target

ILC beam dump experiment and ILC main experiment are in complementary relation

ILC experiment

○ Energy frontier

- Produce heavy interactive BSM particle by high energy beam

○ Low cost of construction and operation

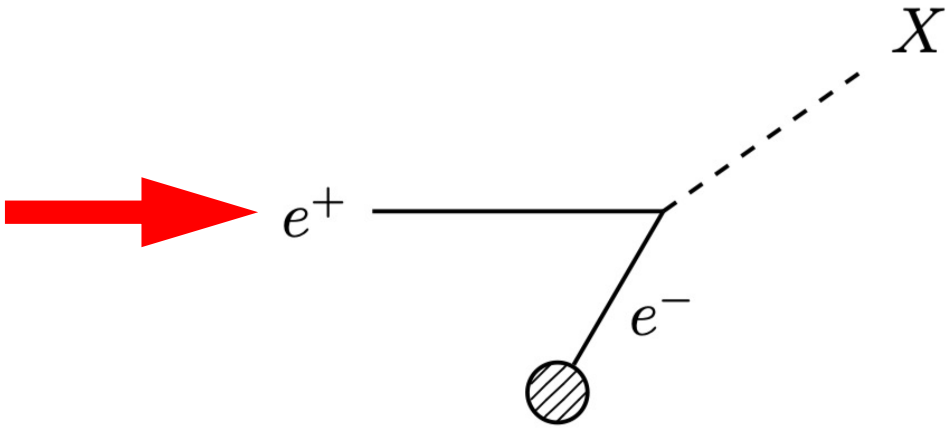
- Possible to use beams and beam dumps for ILC main experiment

Beam dump experiment in ILC

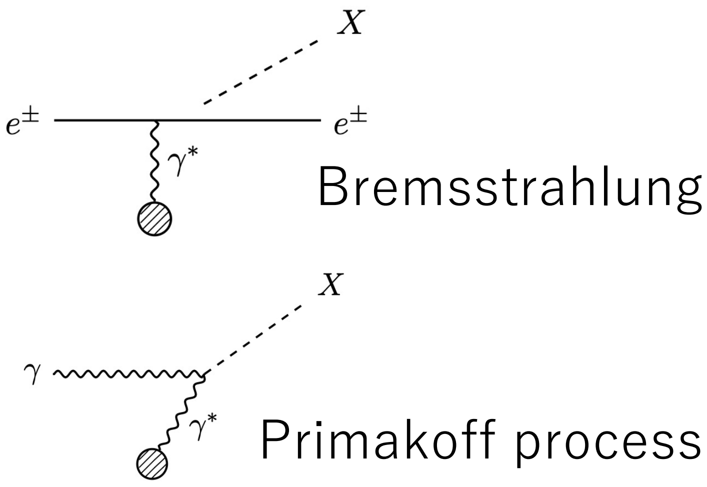
Advantage

- Can use positron beam
  - Production by pair annihilation between e^+ beam and e^- in $\mathrm{H_2O}$

→ Proton beam dump has higher sensitivity than electron one



Other process



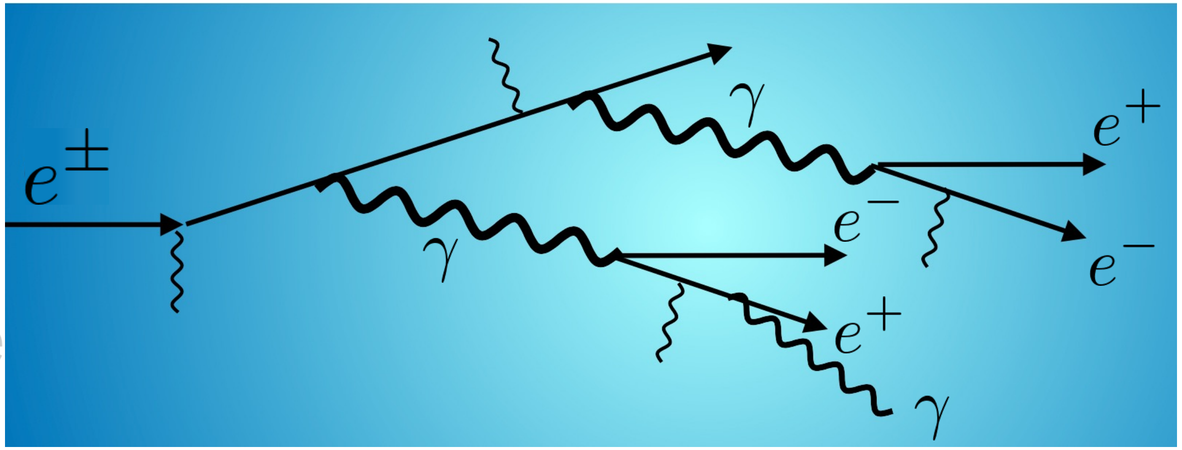
Introduction

Beam dump experiment in ILC

Advantage

- Can use positron beam
  - Production by pair annihilation

➡ Proton beam dump has higher ... than electron one



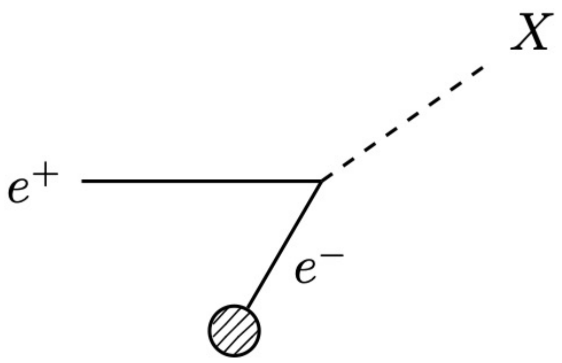
Large number of positrons are produced by electromagnetic shower in both electron and positron beam dumps

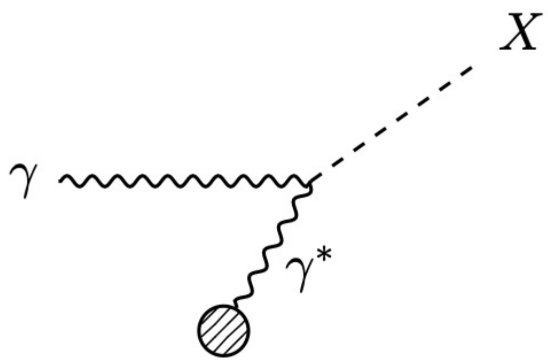
➡ Annihilation process occurs in positron beam dump

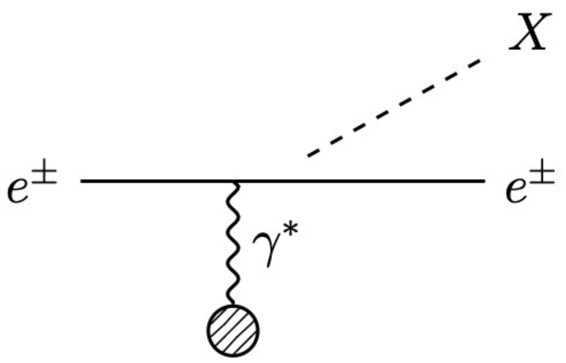
➡ How much better sensitivity of positron beam dump to search for new light particles than that of electron one ?

Introduction

Production Process



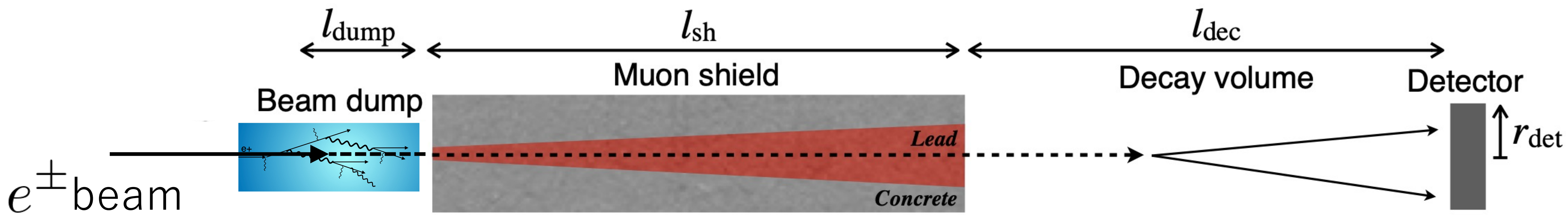




	(a) Pair-annihilation	(b) Primakoff process	(c) Bremsstrahlung
dark photon	✓		✓
ALP	✓	✓	✓
scalar	✓	✓	✓

Beam Dump Experiment

Number of signals

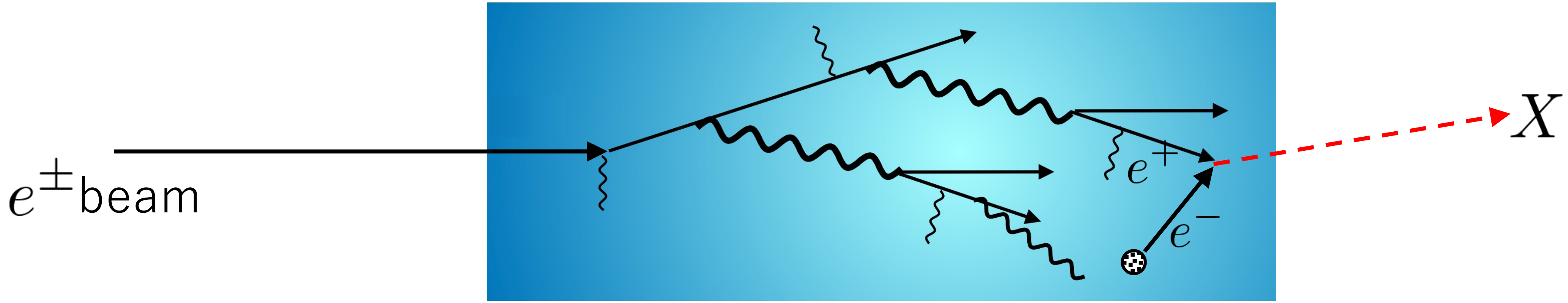


(# of signal detection)

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

Beam Dump Experiment

Number of signals



(# of produced new particle)

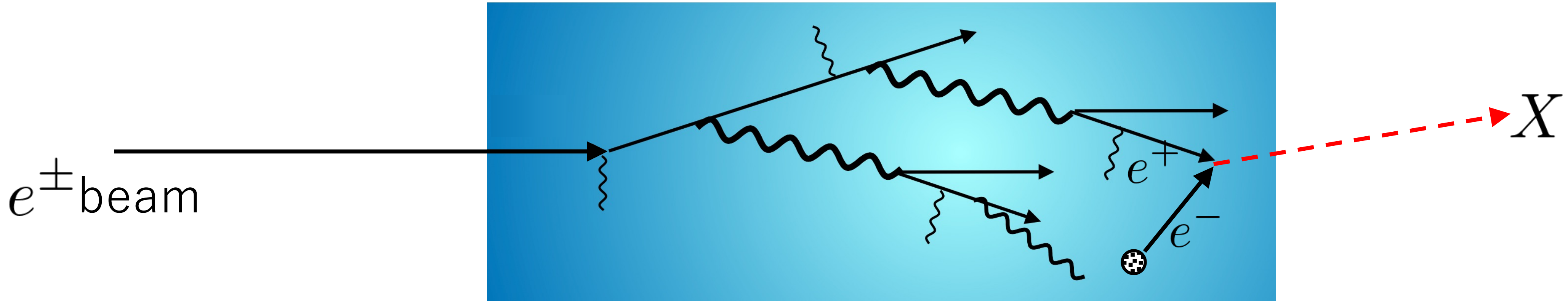
= (Luminosity) × (Production cross section)

Dependent on beam and beam dump

Dependent on particle species

Beam Dump Experiment

Number of signals



(# of produced new particle)

= (Luminosity) × (Production cross section)

||

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

$N_{e^\pm} = 4 \times 10^{21}/\mathrm{yr}$

$n_{\mathrm{N}} = \rho_{\mathrm{H_2O}} N_A / A_{H_2O} \simeq 4 \times 10^{22}$

$n_{e^-} = \rho_{\mathrm{H_2O}} N_A Z_{H_2O} / A_{H_2O} \simeq 3 \times 10^{23}$

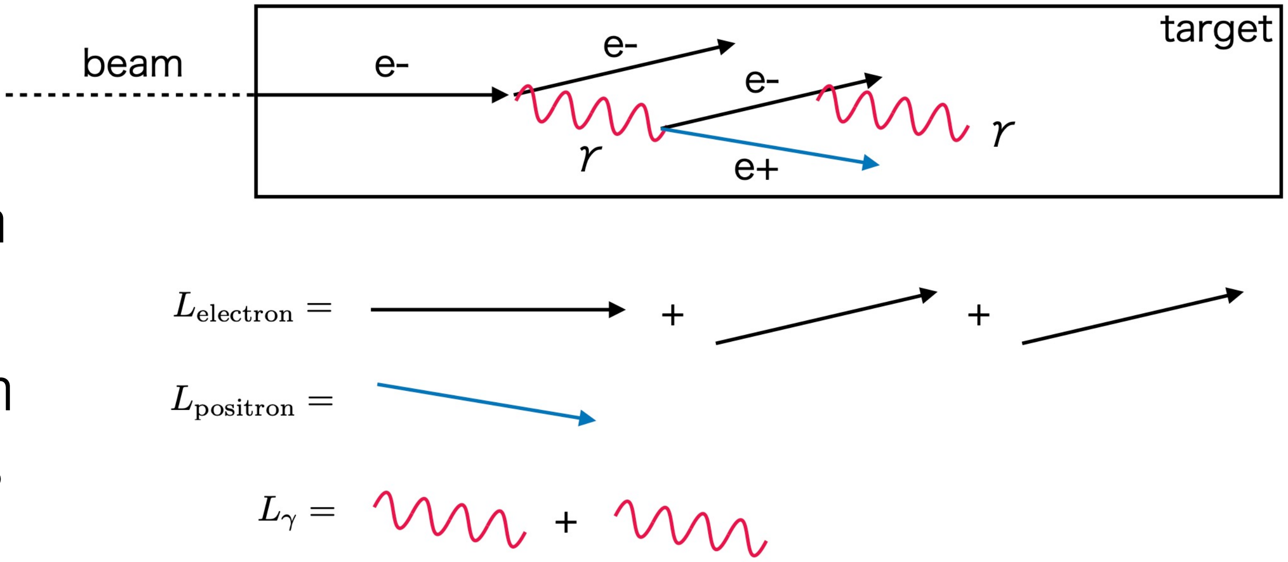
Beam Dump Experiment

Number of signals

Track length

- Integral of particle fluence over beam dump volume
- Calculated by Monte Carlo simulation [Geant4 & PHITS in our study]
- Beam particles have longer TL in high energy region, and every particle has comparable TL in low energy region

From Sakaki san's slide



||

(# of incident p to beam dump)

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

× (Track length of shower particles)

Beam Dump Experiment

Number of signals

Track length

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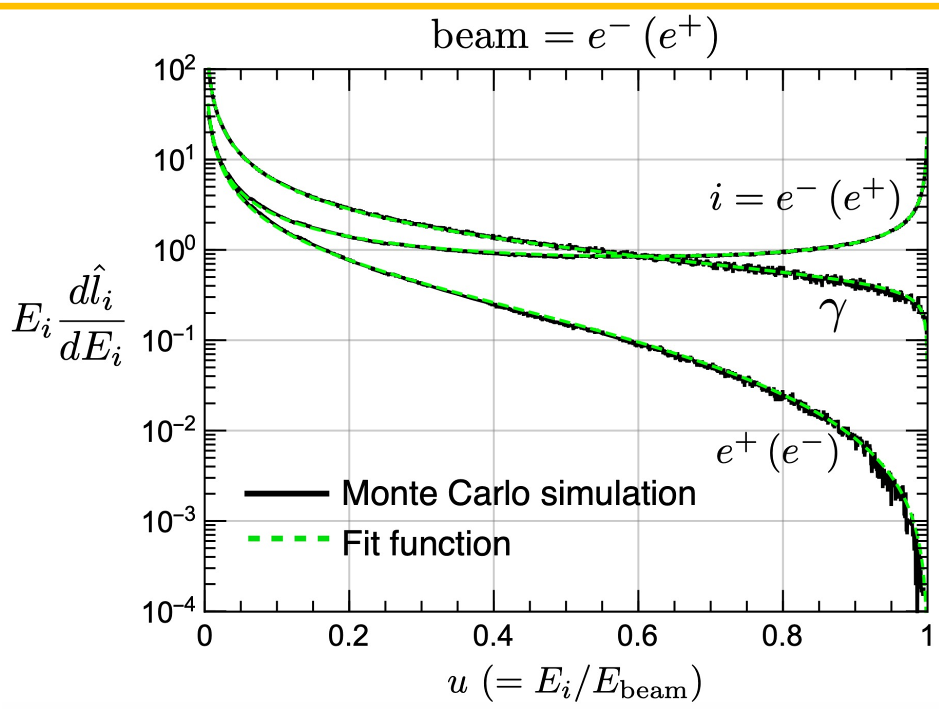


||

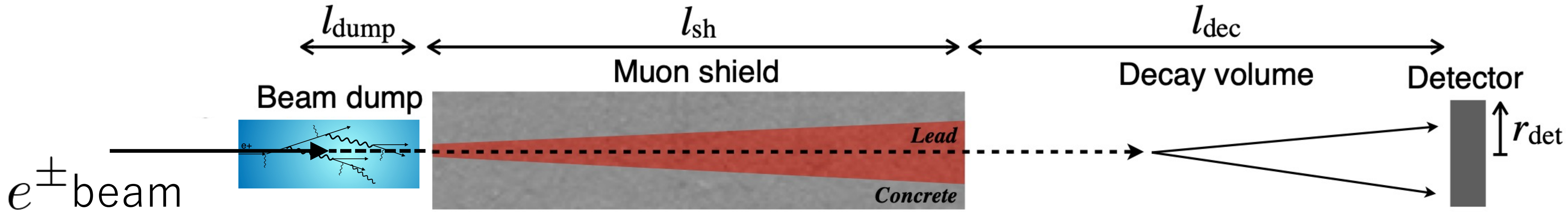
(# of incident p... to beam dump)

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

× (Track length of shower particles)

Beam Dump Experiment

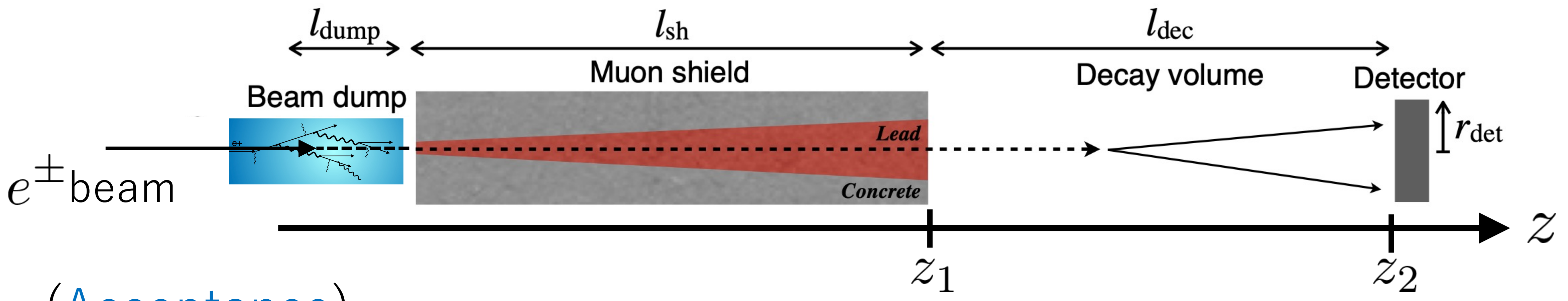
Number of signals



(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

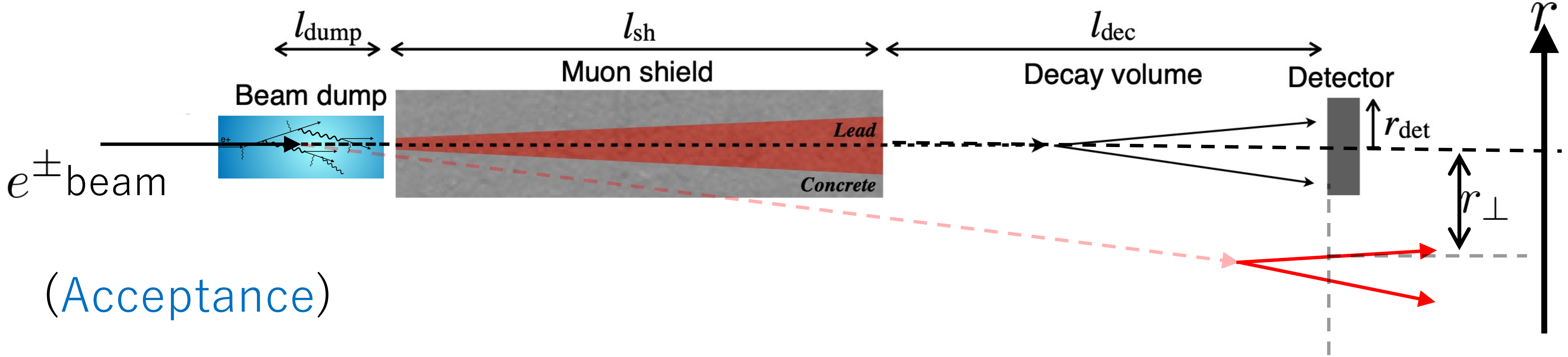
⇒ Probability of decay between $z_1 \sim z_2$

$$P_{\rm dec} = \int_{z_1}^{z_2} \frac{1}{l_{\rm dec}} e^{-z/l_{\rm dec}}$$

$l_{\rm dec}$: Decay length in laboratory frame

Beam Dump Experiment

Number of signals



(Acceptance)

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

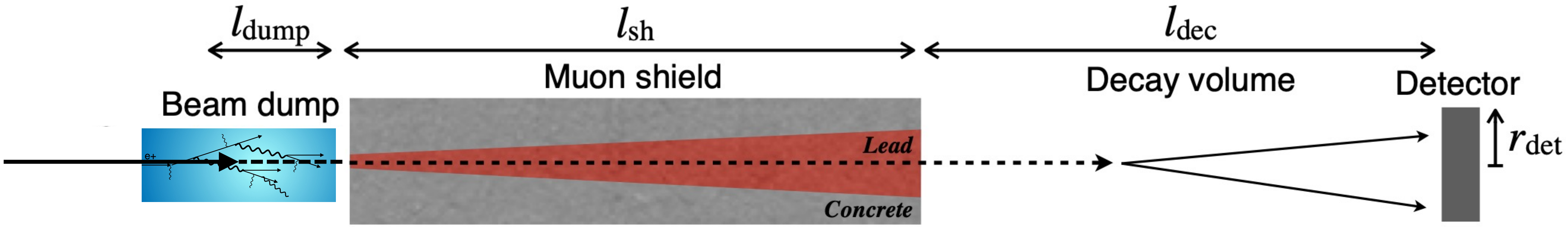
Produced particles have angles with respect to initial particles

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

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

Beam Dump Experiment

Number of signals



(Number of signals)

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

$$= N_{e^\pm} n_j \int^{E_{\rm beam}} dE_i \frac{dl_i}{dE_i} \int_0^{\pi} d\theta_X \frac{d\sigma(i+j \to X \text{ prod})}{d\theta_X} \int_{z_1}^{z_2} dz \frac{1}{l_{\rm dec}} e^{-z/l_{\rm dec}} \Theta(r_{\rm det} - r_\perp)$$

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

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

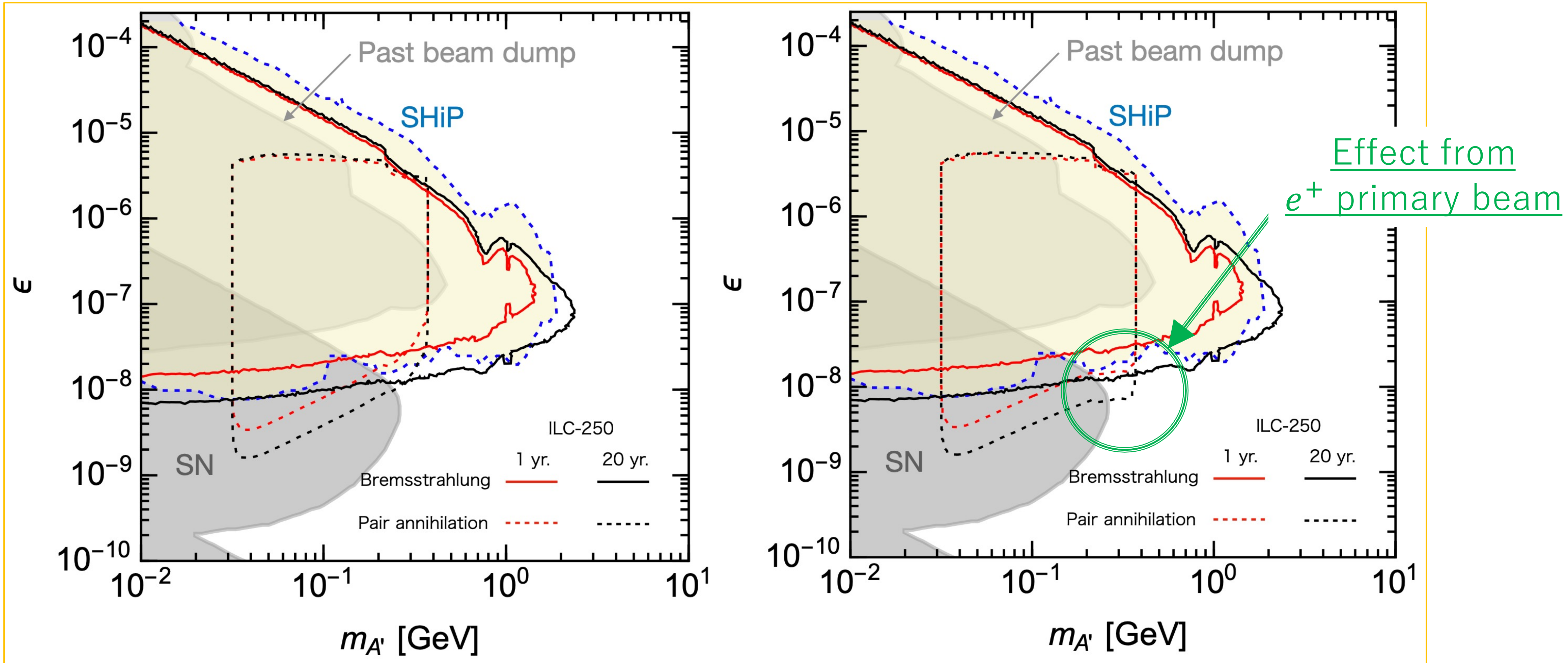
Result

Result

Sensitivity

Dark photon

$$\mathcal{L} \supset -\frac{1}{4}F^{(A')}_{\mu\nu}F^{(A')\mu\nu} - \frac{\epsilon}{2}F^{(\mathrm{em})}_{\mu\nu}F^{(A')\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu}$$



Electron beam

Positron beam

Result

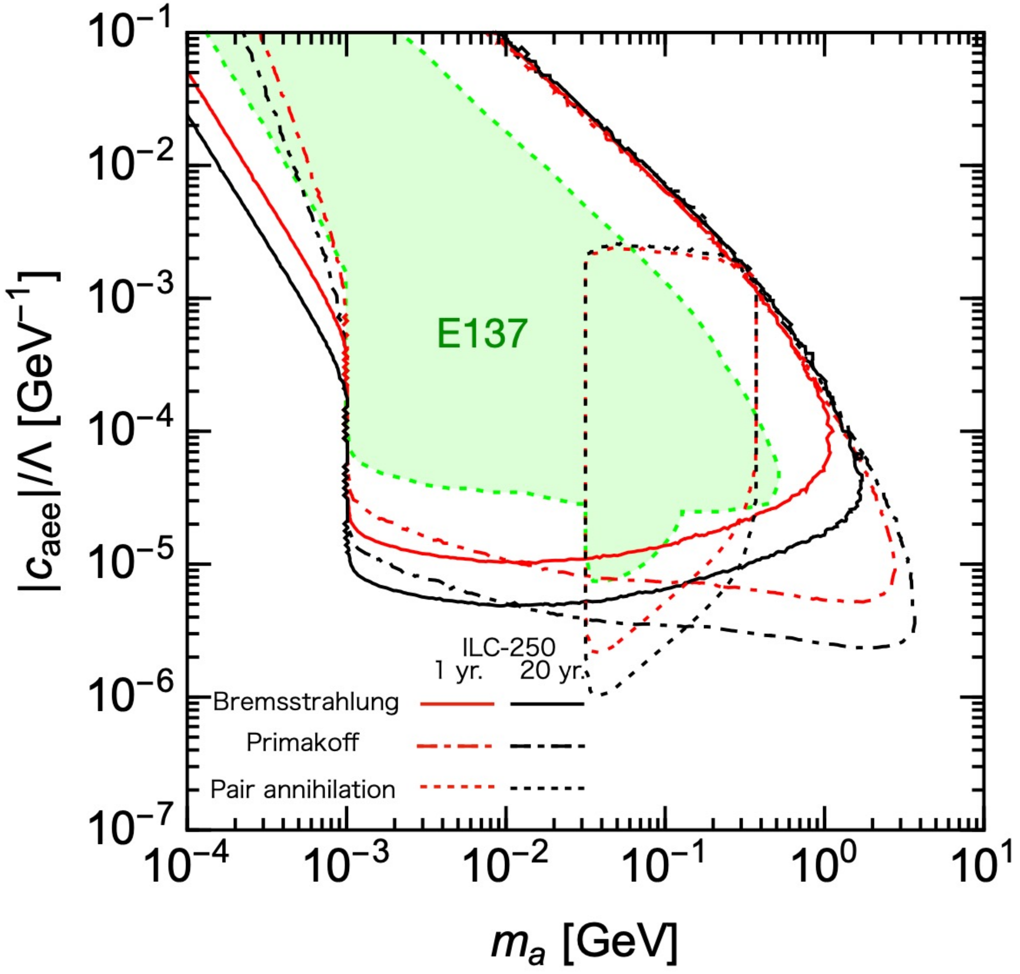
Sensitivity

Axion-like particle

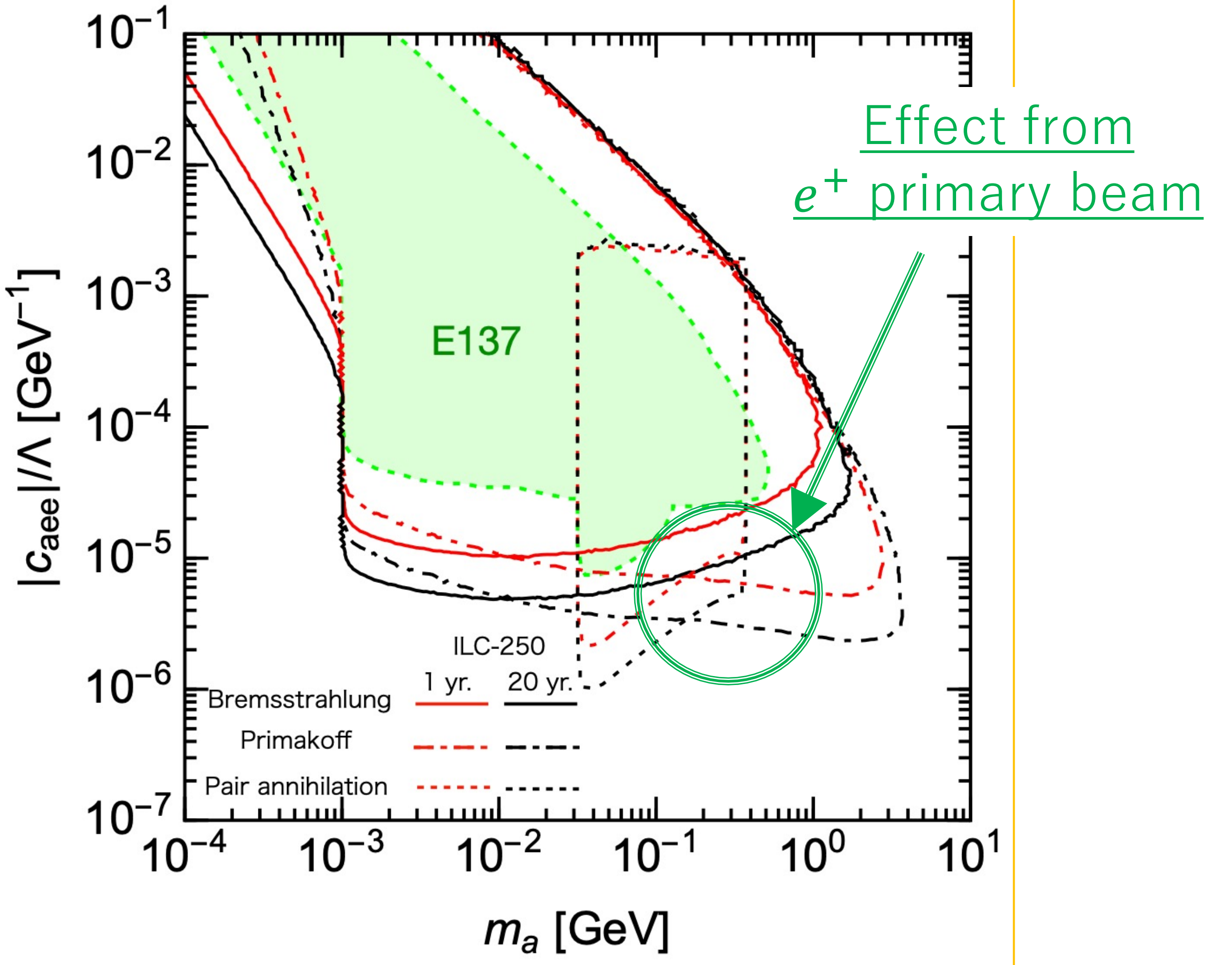
$c_{aee} \neq 0, c_{a\mu\mu} = c_{a\tau\tau} = 0$

loop induced

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + \sum_{\ell=e,\mu,\tau} \frac{1}{2} c_{a\ell\ell} \frac{\partial_\mu a}{\Lambda} \bar{\ell}\gamma^\mu\gamma_5 \ell - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Electron beam



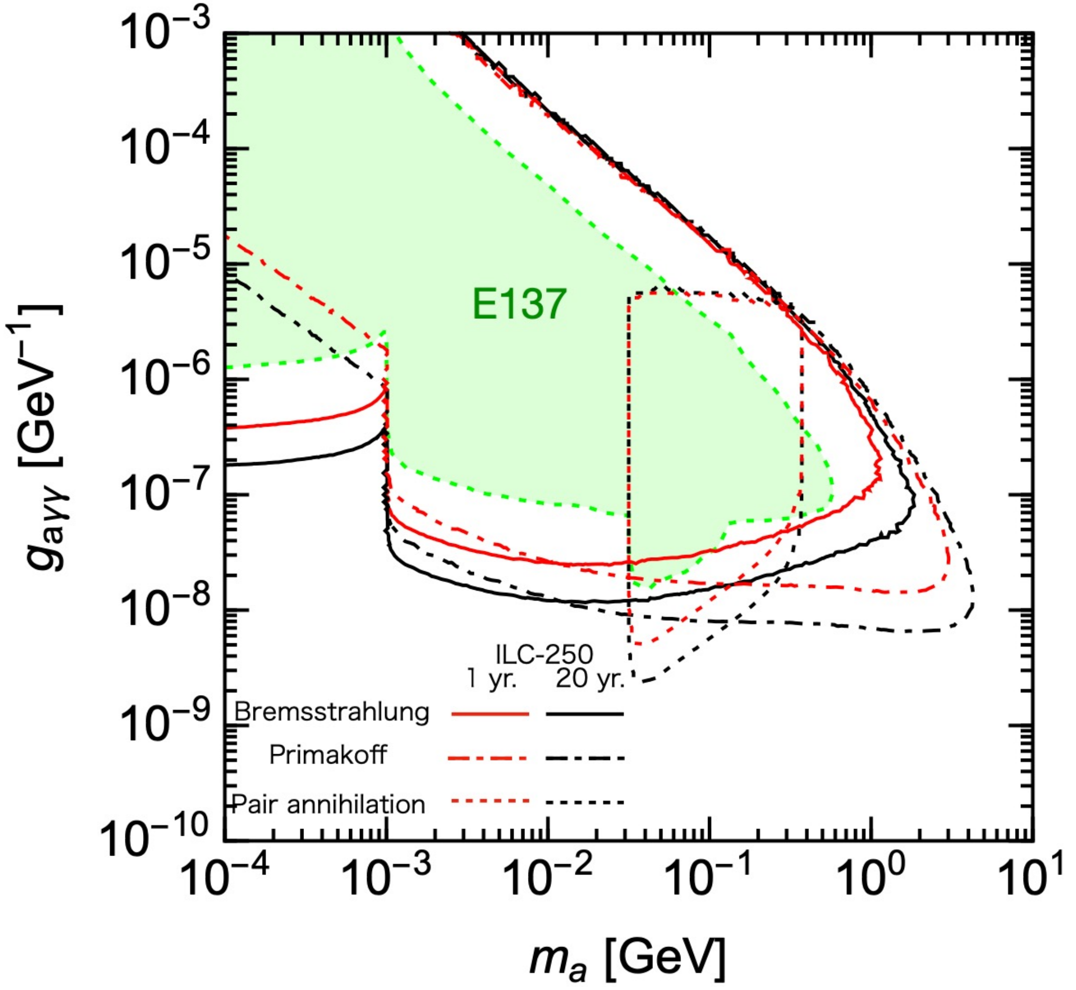
Positron beam

Result

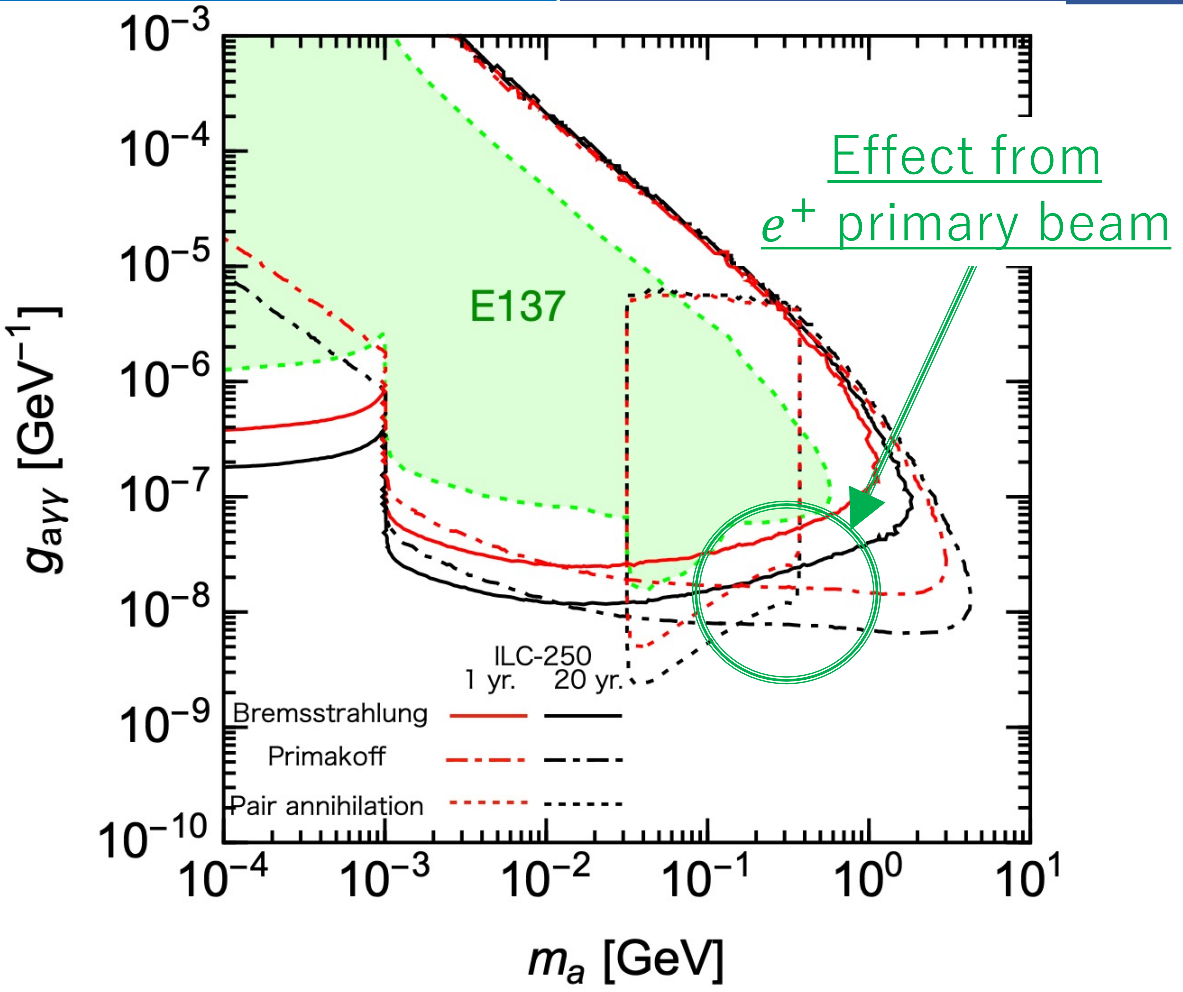
Sensitivity

Axion-like particle $c_{aee} \neq 0, c_{a\mu\mu} = c_{a\tau\tau} = 0$ loop induced

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \sum_{\ell=e,\mu,\tau} \frac{1}{2} c_{a\ell\ell} \frac{\partial_\mu a}{\Lambda} \bar{\ell}\gamma^\mu \gamma_5 \ell - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Electron beam



Positron beam

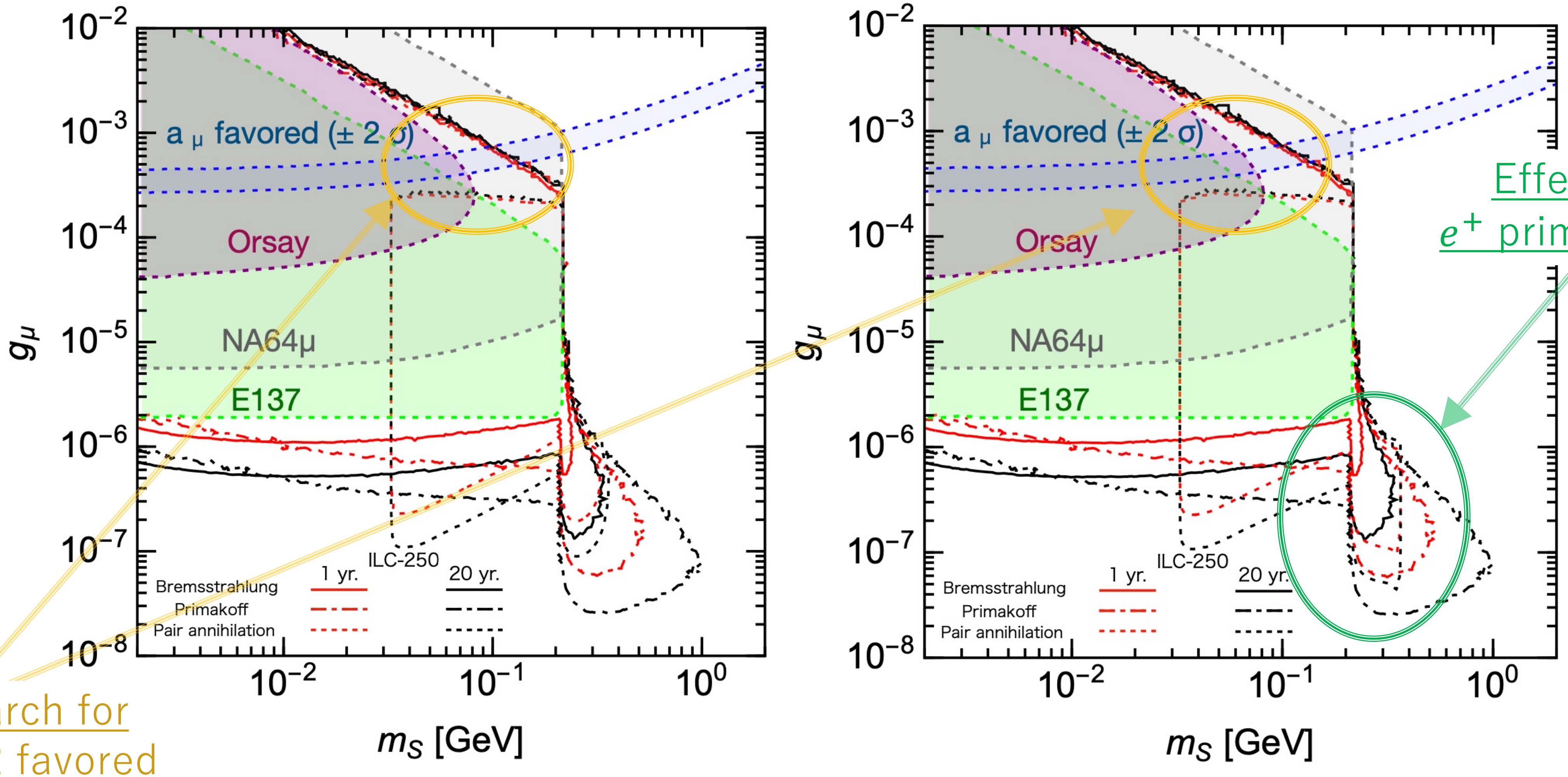
Result
Sensitivity

Scalar particle

$g_e/m_e = g_\mu/m_\mu = g_\tau/m_\tau$

loop induced

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell - \frac{1}{4}g_{S\gamma\gamma}SF_{\mu\nu}F^{\mu\nu}$$



Can search for muon g-2 favored region

Electron beam

Effect from e^+ primary beam

Positron beam

Summary

- ILC $e^{\pm}$ beam dump experiment has higher sensitivity to light ($\lesssim 1\,\mathrm{GeV}$) weakly-interacting particles than past beam dump experiments
- We take account of productions by bremsstrahlung, Primakoff, and pair annihilation processes for dark photon, ALP, and light scalar models
- Although pair annihilation processes occur in both electron and positron beam dumps, positron case is more sensitive to heavy mass region because of primary e^{+} beam
- ILC beam dump experiments are necessary to exploit the full ability of the high-energy $e^{\pm}$ beams, which are not inexpensive

Appendix

Model

Lagrangian

Dark photon model

$$\mathcal{L} \supset -\frac{1}{4}F^{(A')}_{\mu\nu}F^{(A')\mu\nu} - \frac{\epsilon}{2}F^{(\mathrm{em})}_{\mu\nu}F^{(A')\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$$

$$\mathcal{L}_{\mathrm{int}} \simeq -\epsilon e A'_\mu j^\mu_{\mathrm{em}}$$

Light scalar boson model

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell - \frac{1}{4}g_{S\gamma\gamma}SF_{\mu\nu}F^{\mu\nu}$$

$$g_e/m_e = g_\mu/m_\mu = g_\tau/m_\tau$$

Loop induced

Lagrangian

ALP model

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + \sum_{\ell=e,\mu,\tau} \frac{1}{2} c_{a\ell\ell} \frac{\partial_\mu a}{\Lambda} \bar{\ell}\gamma^\mu \gamma_5 \ell - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Case 1

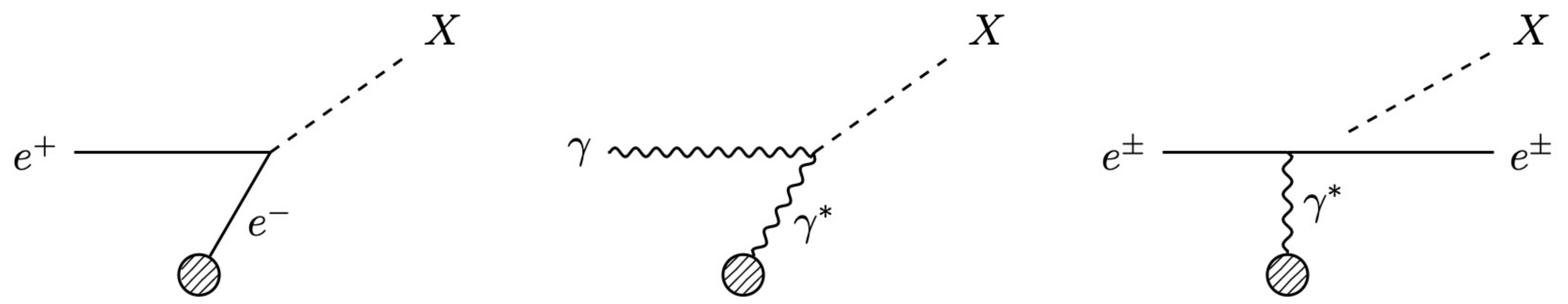
$$c_{aee} \neq 0, \ c_{a\mu\mu} = c_{a\tau\tau} = 0$$

Case 2

$$c_{aee} = c_{a\mu\mu} = c_{a\tau\tau}$$

Loop induced

Number of signal events



(a) Pair-annihilation (b) Primakoff process (c) Bremsstrahlung

$$N_{\text{signal}}^{(\text{a})} = N_{e^\pm} \int \mathrm{d}E_{e^+} \frac{\mathrm{d}l_{e^+}}{\mathrm{d}E_{e^+}} \cdot n_{e^-} \cdot \sigma(e^+e^- \to X) \cdot \mathrm{Acc}(X)\,,$$

$$N_{\text{signal}}^{(\text{b})} = N_{e^\pm} \int \mathrm{d}E_{\gamma} \frac{\mathrm{d}l_{\gamma}}{\mathrm{d}E_{\gamma}} \cdot n_{\text{N}} \int_0^{\pi} \mathrm{d}\theta_X \frac{\mathrm{d}\sigma(\gamma\text{N} \to X\text{N})}{\mathrm{d}\theta_X} \cdot \mathrm{Acc}(X)\,,$$

$$N_{\text{signal}}^{(\text{c})} = N_{e^\pm} \sum_{i=e^-,e^+} \int \mathrm{d}E_i \frac{\mathrm{d}l_i}{\mathrm{d}E_i} \cdot n_{\text{N}} \int \mathrm{d}E_X \int_0^{\pi} \mathrm{d}\theta_X \frac{\mathrm{d}^2\sigma(i\text{N} \to iX\text{N})}{\mathrm{d}E_X\,\mathrm{d}\theta_X} \cdot \mathrm{Acc}(X)$$

Production cross section

Pair annihilation

$$\sigma(e^+e^- \to A') \simeq \frac{2\pi^2\alpha\epsilon^2}{m_e} \, \delta\left(E_i - \frac{m_{A'}^2}{2m_e} + m_e\right) \; ,$$

$$\sigma(e^+e^- \to a) \simeq \frac{\pi m_e}{4} \left(\frac{c_{aee}}{\Lambda}\right)^2 \, \delta\left(E_i - \frac{m_a^2}{2m_e} + m_e\right) \; ,$$

$$\sigma(e^+e^- \to S) \simeq \frac{\pi g_e^2}{4m_e} \, \delta\left(E_i - \frac{m_S^2}{2m_e} + m_e\right)$$

Production cross section

Primakoff process

$$\frac{\mathrm{d}\sigma\left(\gamma \mathrm{N} \to a\mathrm{N}\right)}{\mathrm{d}\theta_a} \simeq \frac{\alpha g_{a\gamma\gamma}^2 E_i^4 \theta_a^3}{4t^2} G_2(t),$$

$$\frac{\mathrm{d}\sigma\left(\gamma \mathrm{N} \to S\mathrm{N}\right)}{\mathrm{d}\theta_S} \simeq \frac{\alpha g_{S\gamma\gamma}^2 E_i^4 \theta_S^3}{4t^2} G_2(t),$$

where

$G_2(t)$: electric form factor

$t = -q^2 \simeq E_i^2 \theta_X^2 + \frac{m_X^4}{4E_i^2}$ (q : momentum transfer)

Bremsstrahlung

$$\frac{d^2\sigma(e^\pm N \to e^\pm X N)}{dx\, d\theta_X} = \frac{g_{Xee}^2 \alpha^2}{2\pi} x(1-x) E_i^2 \beta_X \frac{\mathcal{A}^X|_{t=t_{\min}}}{\tilde{u}^2} \chi \,,$$

where $x = E_X / E_i$ $\qquad \tilde{u} = -x E_i^2 \theta_X^2 - m_X^2 \frac{1-x}{x} - m_e^2 x$

$\beta_X = \sqrt{1 - m_X^2 / E_i^2}$ $\qquad \chi$: effective flux of photon

$$\mathcal{A}^{A'}|_{t=t_{\min}} = 2\frac{2-2x+x^2}{1-x} + 4(m_{A'}^2 + 2m_e^2)\frac{\tilde{u}x + m_{A'}^2(1-x) + m_e^2 x^2}{\tilde{u}^2} \,,$$

$$\mathcal{A}^{a}|_{t=t_{\min}} = \frac{x^2}{1-x} + 2m_a^2 \frac{\tilde{u}x + m_a^2(1-x) + m_e^2 x^2}{\tilde{u}^2} \,,$$

$$\mathcal{A}^{S}|_{t=t_{\min}} = \frac{x^2}{1-x} + 2(m_S^2 - 4m_e^2)\frac{\tilde{u}x + m_S^2(1-x) + m_e^2 x^2}{\tilde{u}^2} \,,$$

Angular acceptance

Angle of initial particle i

$$\theta_1 = \begin{cases} 16\ \mathrm{mrad} \cdot \mathrm{GeV}/E_{e^\pm} & \text{(for shower electrons and positrons)}, \\ 8\ \mathrm{mrad} \cdot \mathrm{GeV}/E_\gamma & \text{(for shower photons)} \end{cases}$$

Production angle of new light particle

$$\theta_2 = \begin{cases} \theta_X & \text{(for Primakoff process \& bremsstrahlung)} \\ 0 & \text{(for pair annihilation)} \end{cases}$$

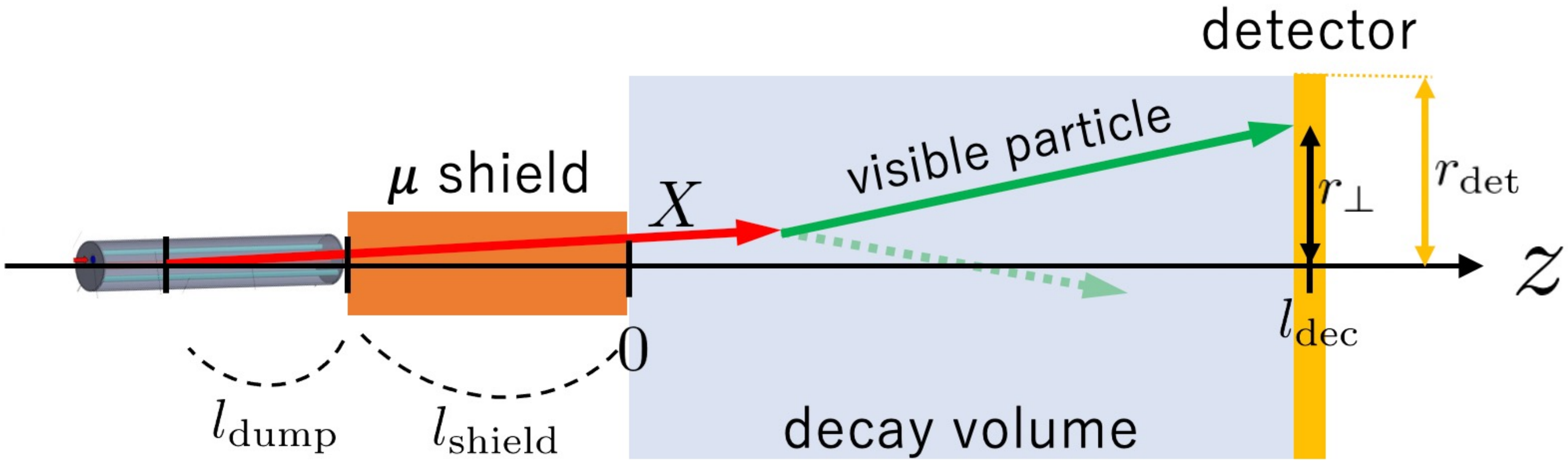
Decay angle of SM particle from X

$$\theta_3 = \frac{\pi m_X}{2E_X}$$

Angular acceptance

Typical deviation of emitted SM particle from beam axis

$$r_\perp(z) = \sqrt{\theta_1^2(l_{\text{dump}} + l_{\text{shield}} + l_{\text{dec}})^2 + \theta_2^2(l_{\text{dump}} + l_{\text{shield}} + l_{\text{dec}})^2 + \theta_3^2(l_{\text{dec}} - z)^2}$$



Angular acceptance

Averaged angled of initial particles

$$\theta_1 = \begin{cases} 16\ \mathrm{mrad} \cdot \mathrm{GeV}/E_{e^\pm} & \text{(for shower electrons and positrons),} \\ 8\ \mathrm{mrad} \cdot \mathrm{GeV}/E_\gamma & \text{(for shower photons)} \end{cases}$$

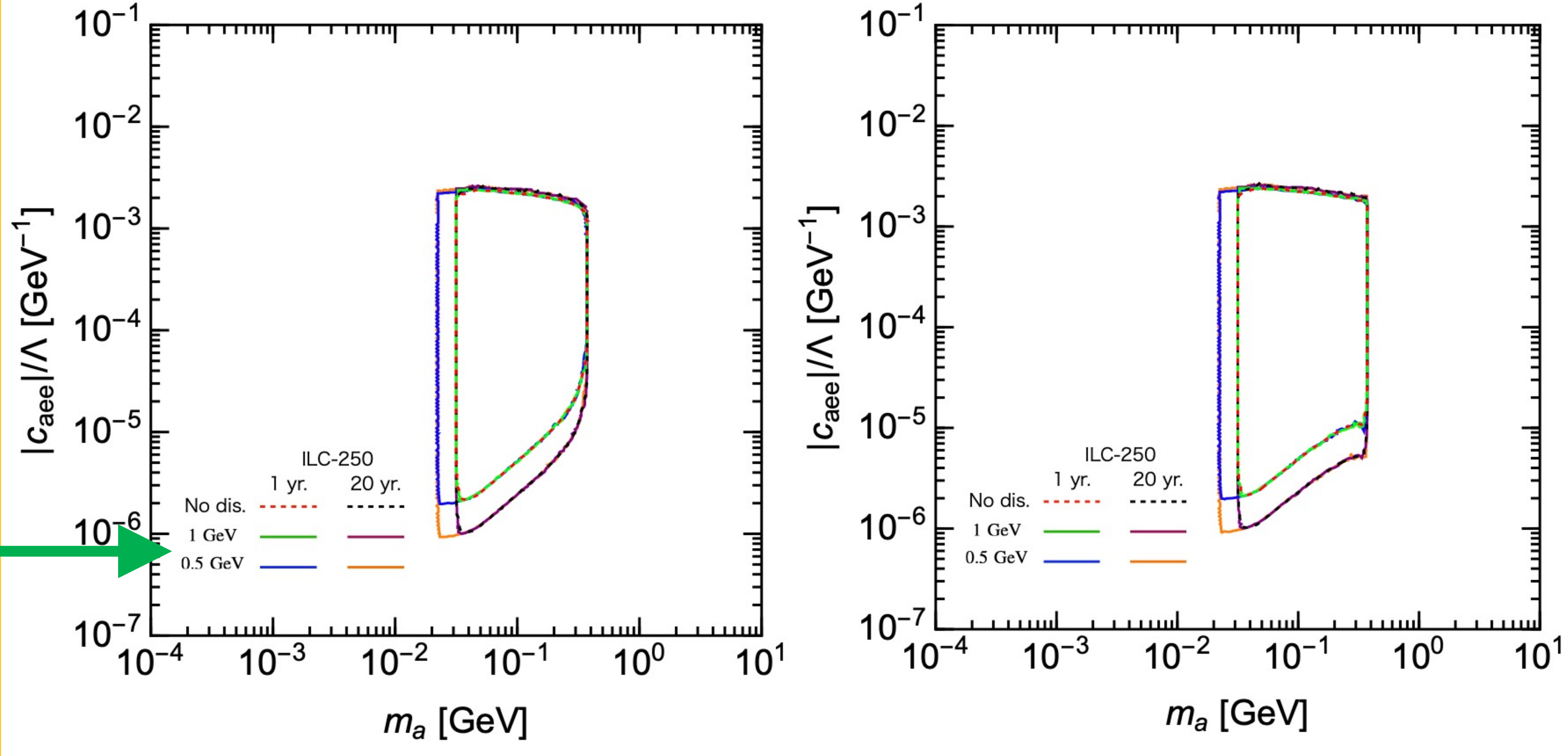
Shower γ ($e^\pm$) with $E_\gamma < 0.52$ GeV ($E_{\gamma\,(e^\pm)} < 1.05$ GeV) always result in $r_\perp > r_{\mathrm{det}}$

In reality, θ_1 has a distribution, and shower particles with smaller momentum may pass the angular cut

Angular acceptance

ALP model (Case 1)

$E_{\rm th}$: minimal energy for detection



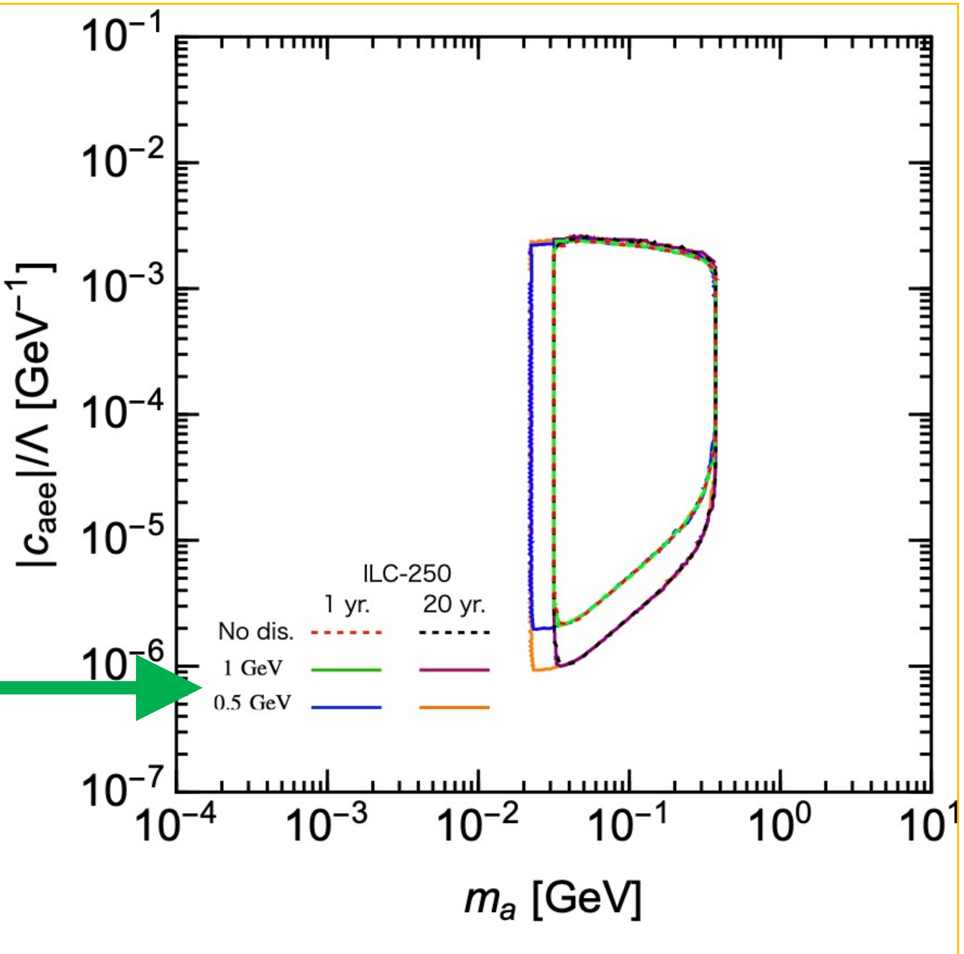
(a) electron beam dump

(b) positron beam dump

Angular acceptance

ALP model (Case 1)

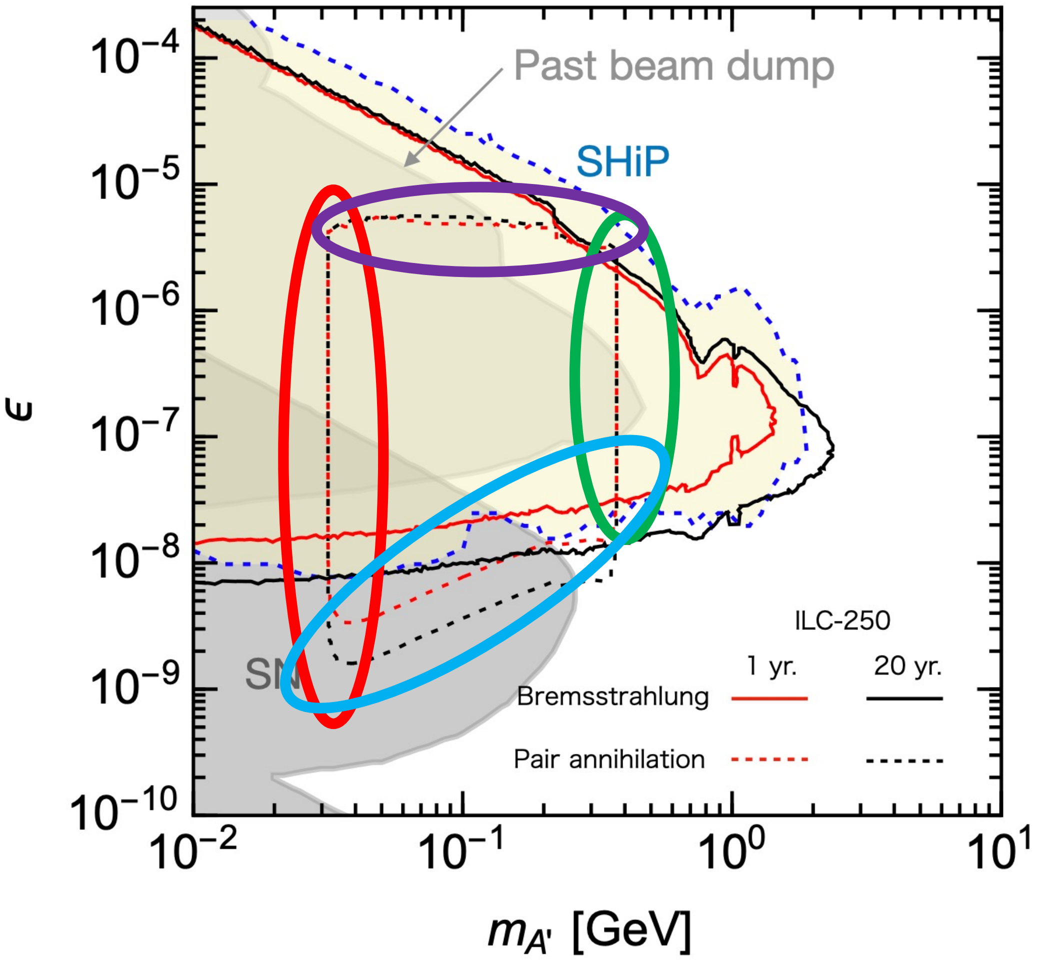
E_{th} : minimal energy for detection



(a) electron beam dump

Low mass boundary is sensitive to energy threshold

Dark photon case



(b) positron beam dump

Pair annihilation

Low-mass boundary

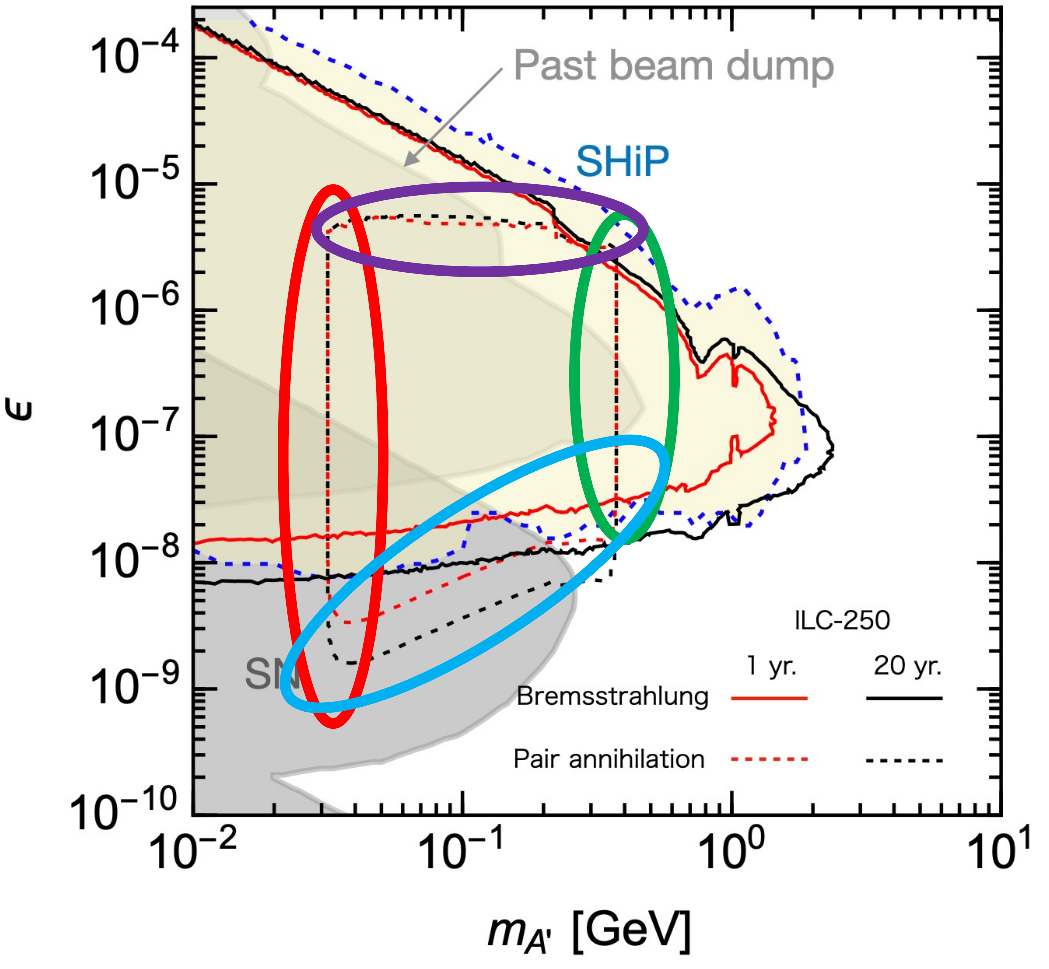
Angular acceptance
(energy threshold for detection)

High-mass boundary

Center-of–mass energy

$$m_{A'} < \sqrt{s} = \sqrt{2\,E_{\text{beam}}\,m_e} \simeq 0.35\ \text{GeV}$$

Dark photon case



(b) positron beam dump

Pair annihilation

Large coupling boundary

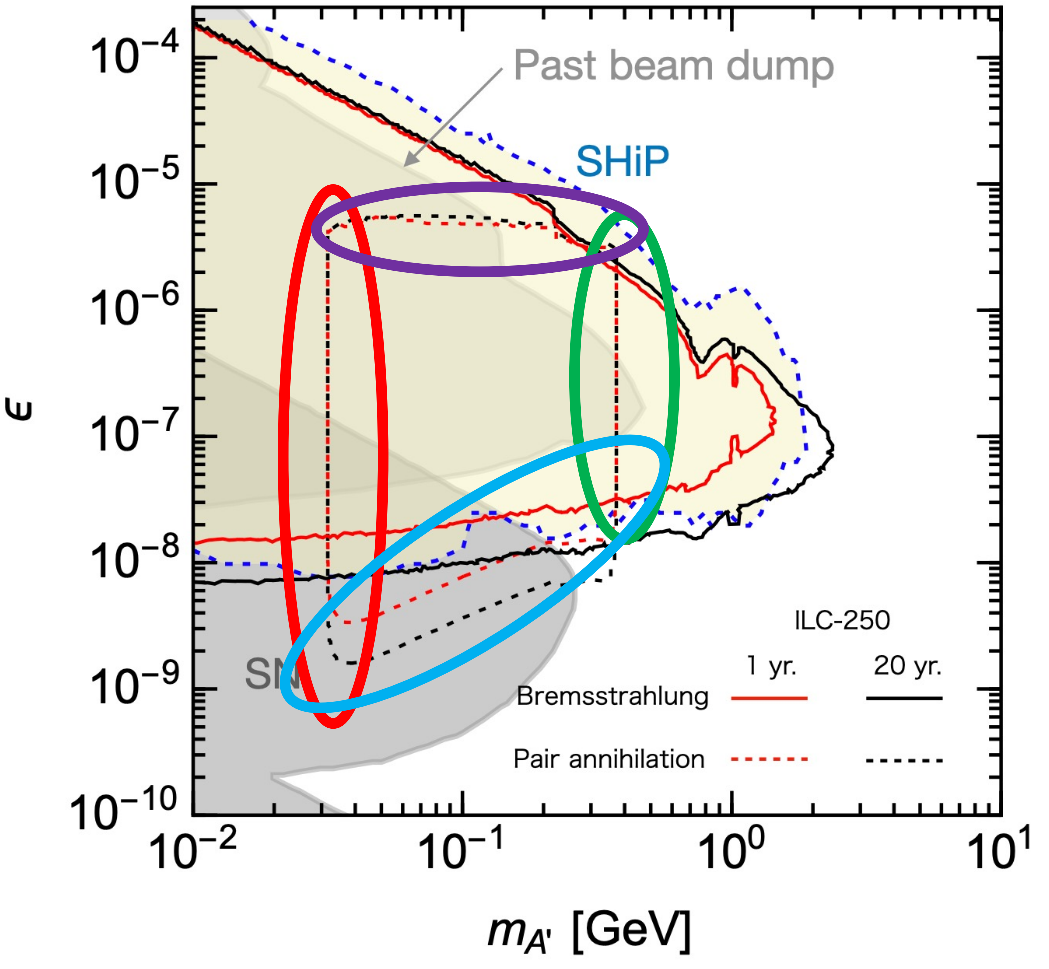
Decay probability

$$\frac{m_{A'}\Gamma_{A'}}{E_{A'}^{(\mathrm{lab})}}(l_{\mathrm{dump}} + l_{\mathrm{sh}}) \sim \mathrm{const}$$

$$\Longrightarrow \epsilon^2 \sim \mathrm{const}$$

Upper side of boundary does not depend on mass $m_{A'}$

Dark photon case



(b) positron beam dump

Pair annihilation

Small coupling boundary

$$\frac{dl_{e^-}}{dE_{e^-}} \simeq \left(\frac{dl_{e^-}}{dE_{e^-}}\right)_{\text{shower}} \propto \frac{E_{\text{beam}}}{E_{e^-}^2}$$

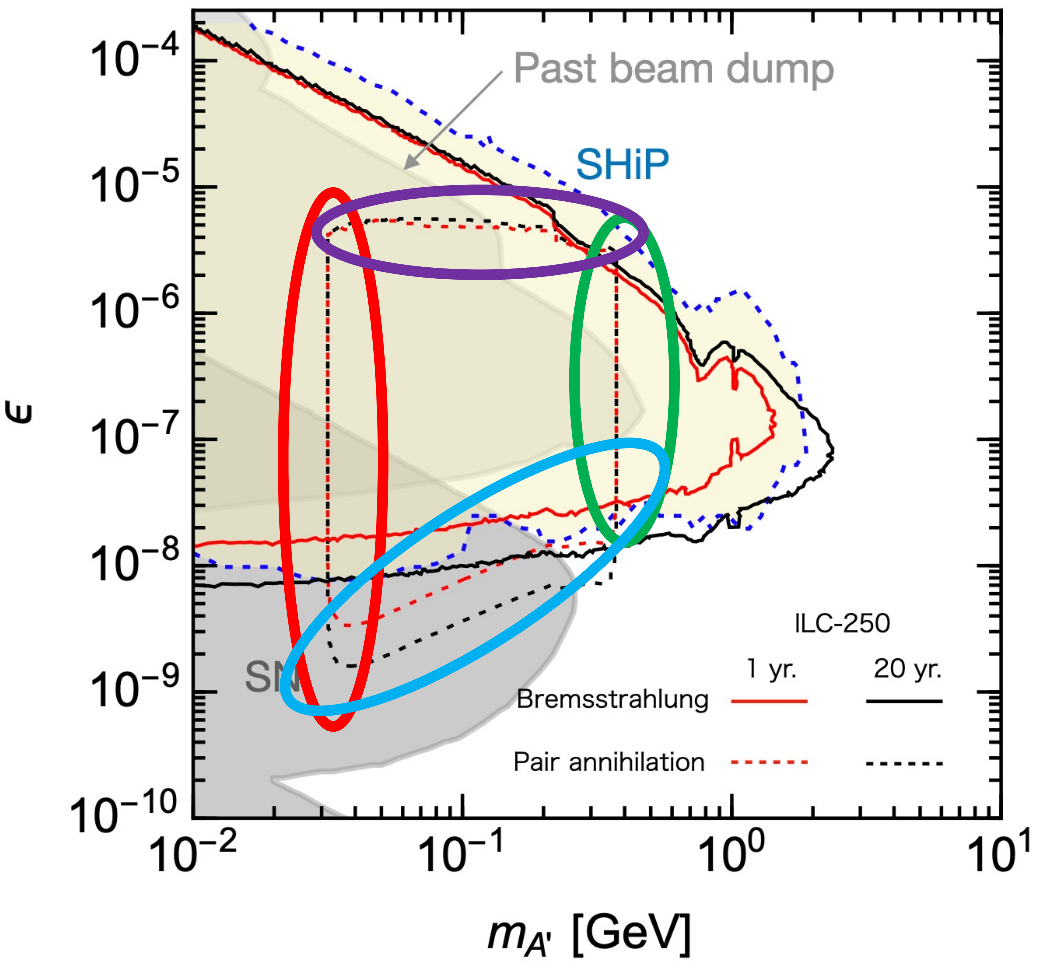
$$\sigma(e^+ + e^- \to A') \propto \epsilon^2$$

$$\left(l_{A'}^{(\text{lab})}\right)^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}}$$

for positron beam & $m_{A'} \lesssim \mathcal{O}(10^{-1})$ GeV

$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4\times 10^{21}}\right)\left(\frac{E_{\text{beam}}}{125\ \text{GeV}}\right)\left(\frac{l_{\text{dec}}}{50\ \text{m}}\right)\left(\frac{\epsilon}{8\times 10^{-9}}\right)^4\left(\frac{0.1\ \text{GeV}}{m_{A'}}\right)^4$$

Dark photon case



(b) positron beam dump

Pair annihilation

Small coupling boundary

$$\frac{dl_{e^-}}{dE_{e^-}} \simeq \left(\frac{dl_{e^-}}{dE_{e^-}}\right)_{\text{primary}} \propto \frac{1}{E_{e^-}}$$

$$\sigma(e^+ + e^- \to A') \propto \epsilon^2$$

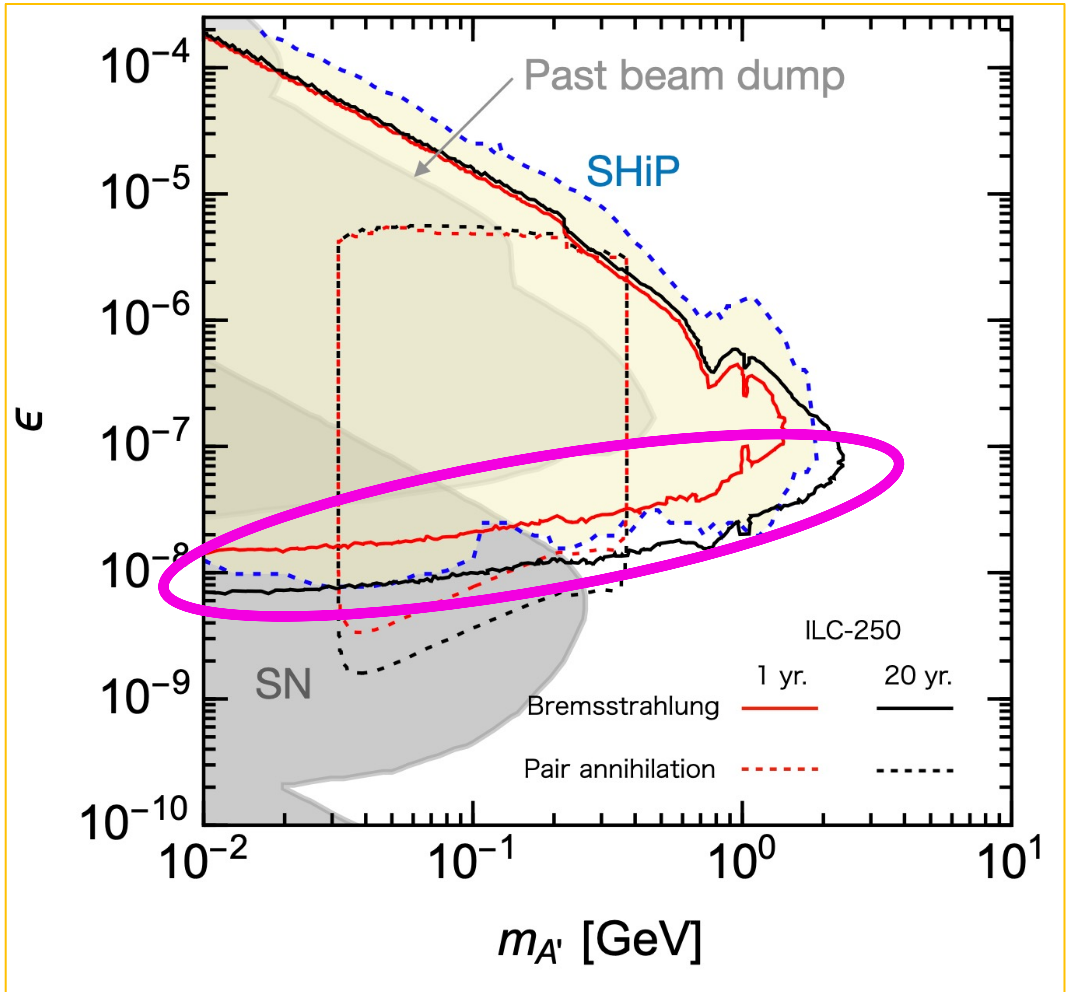
$$\left(l_{A'}^{(\text{lab})}\right)^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}}$$

for positron beam & $m_{A'} \gtrsim \mathcal{O}(10^{-1})$ GeV

$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4\times 10^{21}}\right)\left(\frac{l_{\text{dec}}}{50\ \text{m}}\right)\left(\frac{\epsilon}{10^{-8}}\right)^4\left(\frac{0.2\ \text{GeV}}{m_{A'}}\right)^2$$

Appendix

Dark photon case



(b) positron beam dump

Bremsstrahlung

Small coupling boundary

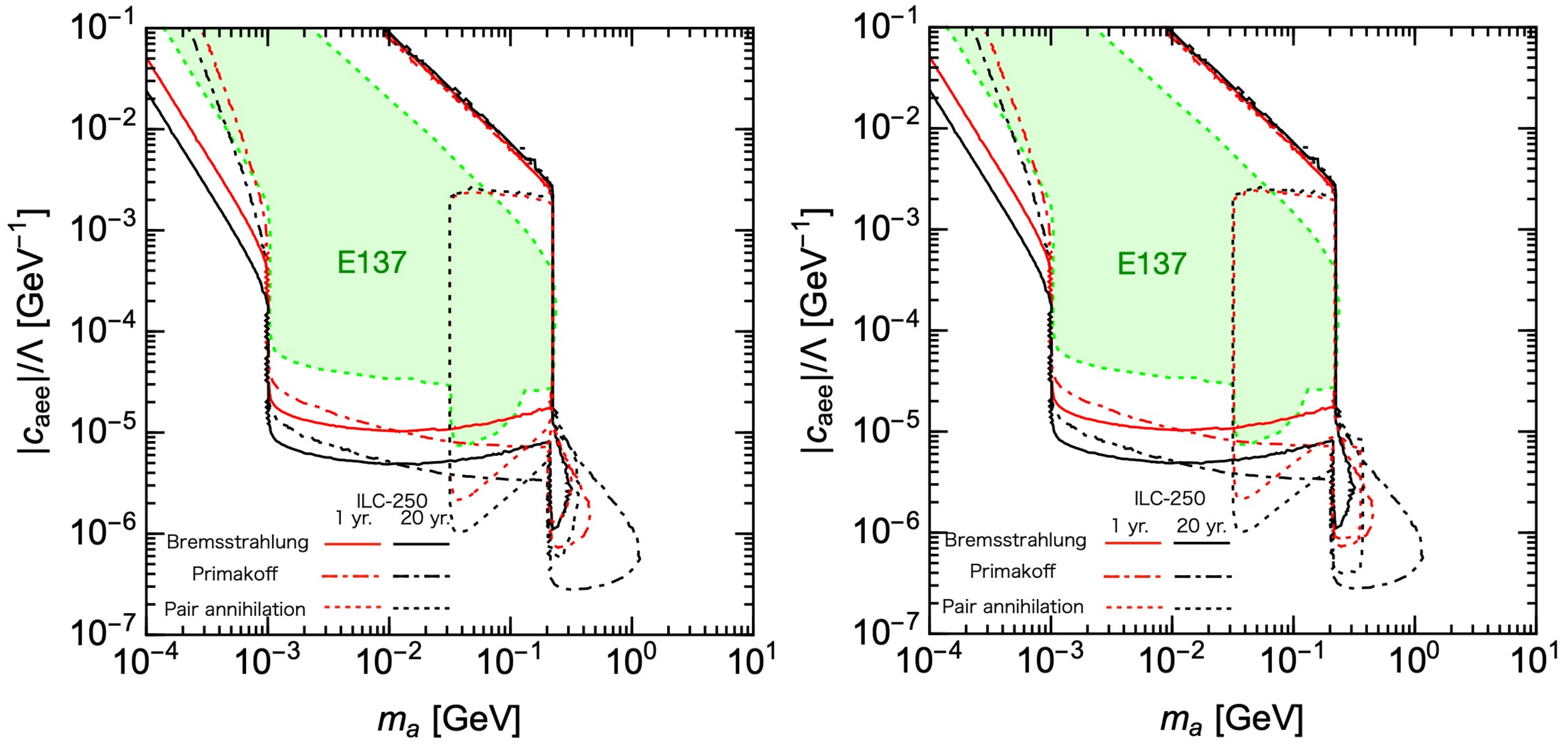
$$\frac{dl_{e^\pm}}{dE_{e^\pm}} \simeq \left(\frac{dl_{e^\pm}}{dE_{e^\pm}}\right)_{\text{shower}} \propto \frac{E_{\text{beam}}}{E_{e^\pm}^2}$$

$$\sigma(e^\pm \text{N} \to e^\pm \text{N}A') \propto \frac{\epsilon^2}{m_{A'}^2}$$

$$\left(l_{A'}^{(\text{lab})}\right)^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}}$$

$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4\times 10^{21}}\right)\left(\frac{E_{\text{beam}}}{125\text{ GeV}}\right)\left(\frac{l_{\text{dec}}}{50\text{ m}}\right)\left(\frac{r_{\text{det}}}{2\text{ m}}\right)\left(\frac{131\text{ m}}{l_{\text{dump}}+l_{\text{sh}}+l_{\text{dec}}}\right)\left(\frac{\epsilon}{10^{-8}}\right)^4$$

ALP case (model 2)



(a) electron beam dump

(b) positron beam dump