Beam-dump Experiments and New Physics Searches

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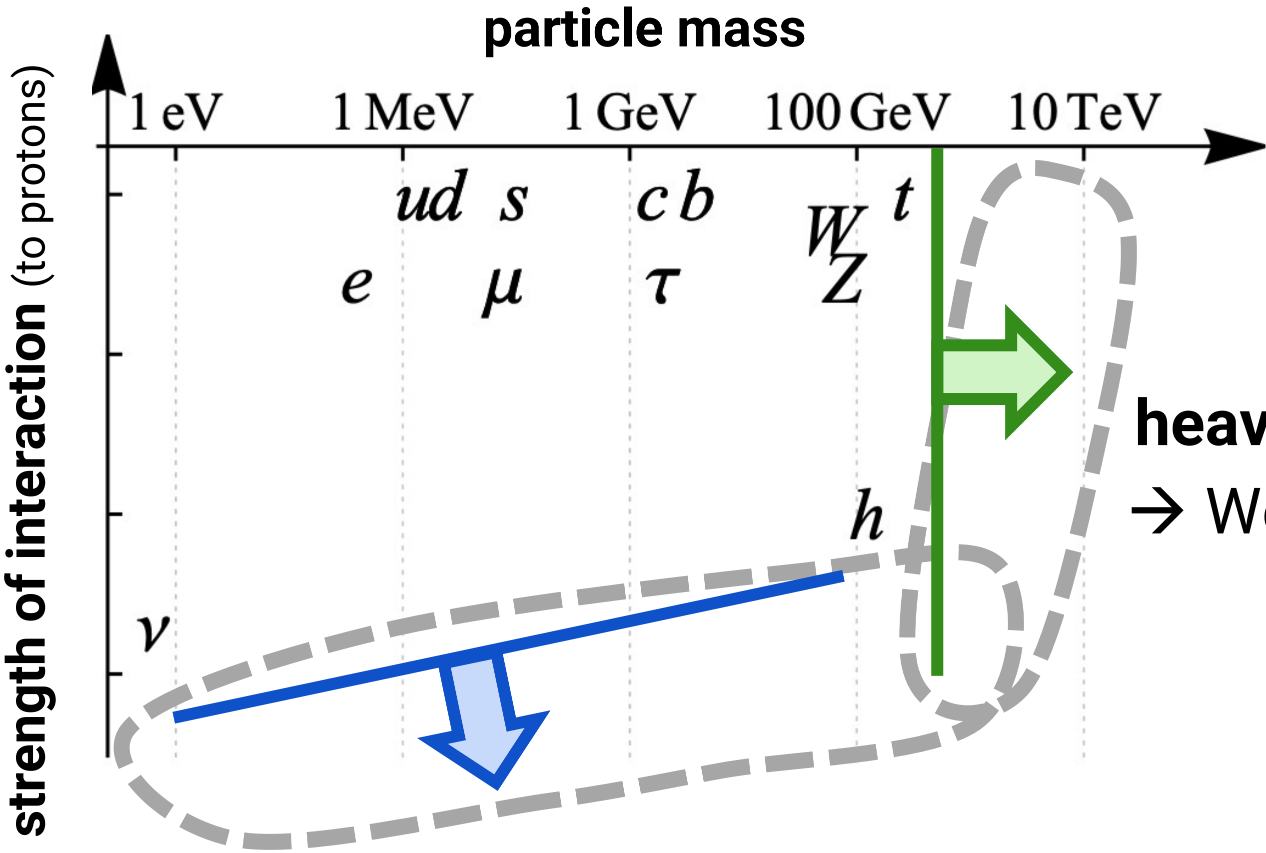
17 Dec. 2023

NCTS Annual Theory Meeting @ National Taiwan University

Based on

- Asai, Iwamoto, Sakaki, Ueda [2105.13768]
- Asai, Iwamoto, Perelstein, Sakaki, Ueda, [2301.03816]



heavier?

→ We need more energy!

"energy frontier"

(Also:
neutrino frontier,
precision frontier,
cosmic frontier,
theory frontier, ...)

weak and elusive?

→ We need more intensity!

"intensity frontier"

Thanks for the stable run of the LHC!

Run 2: 13 TeV, ~150/fb

2022: 13.6 TeV, 35/fb
2023: **13.6 TeV, 30/fb**

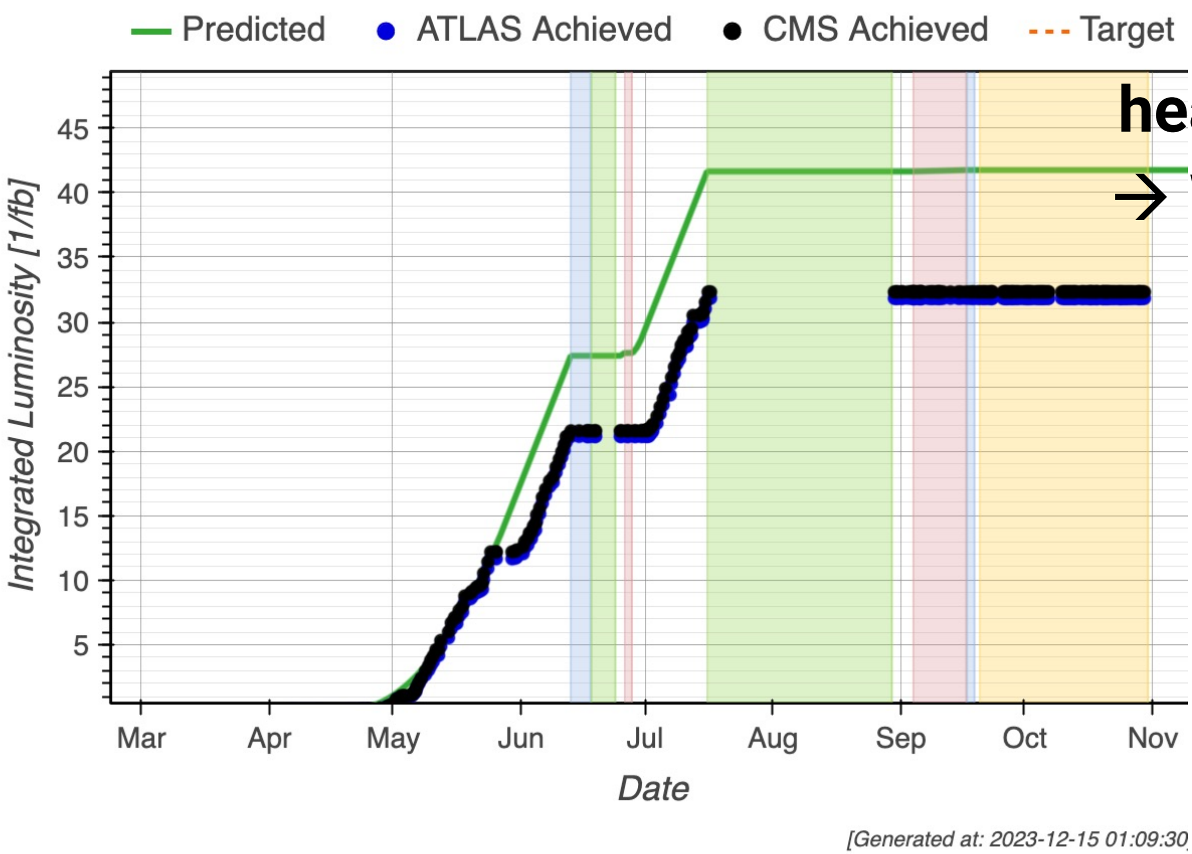


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Figure from Beam Performance Tracking in the CERN accelerator complex

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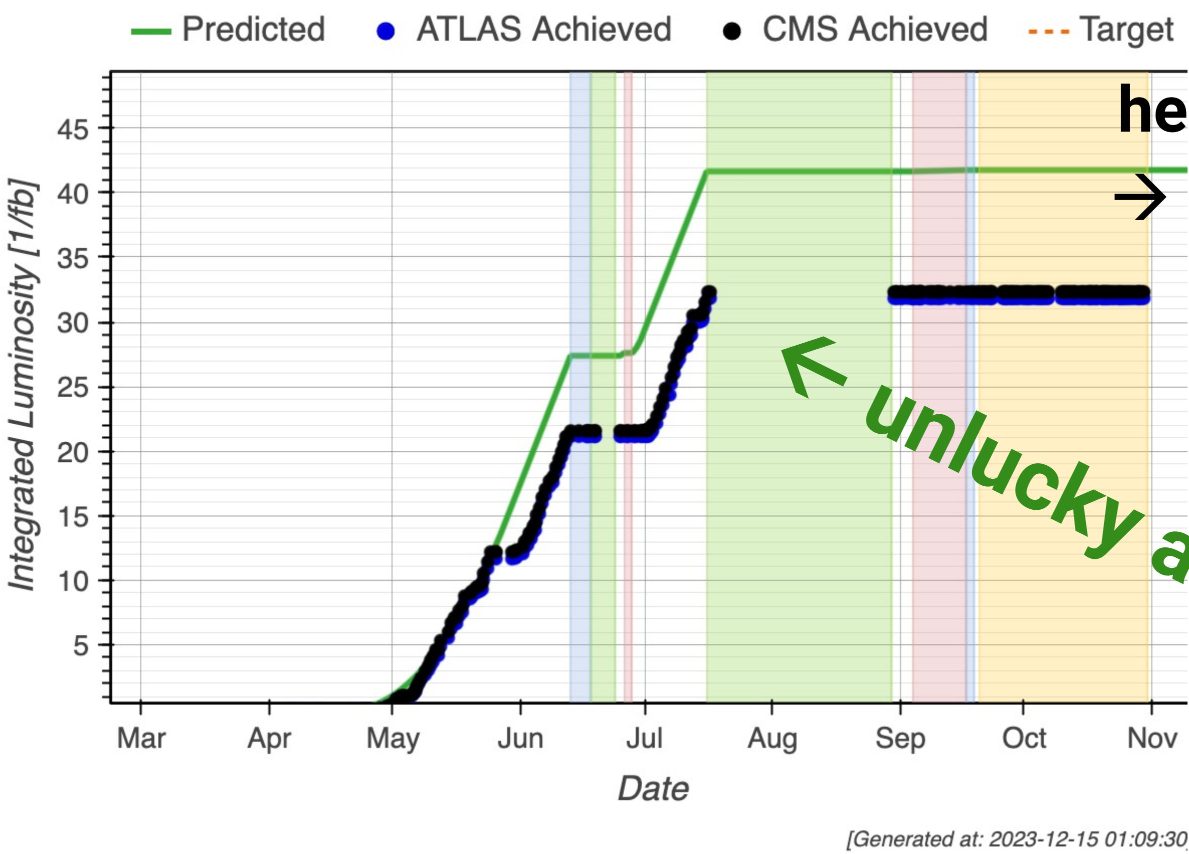

← unlucky accident

heavier?

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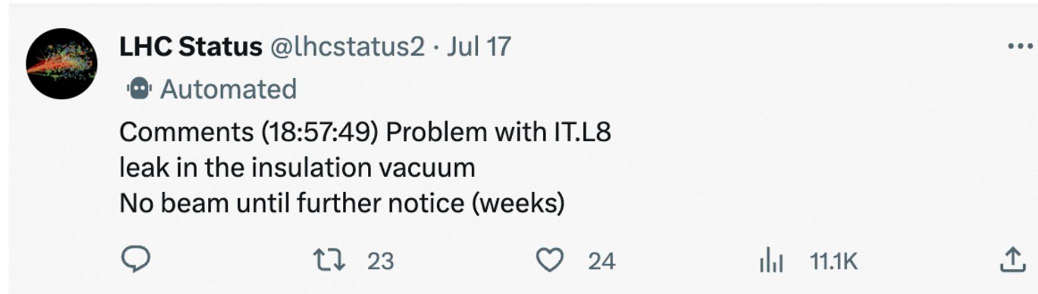
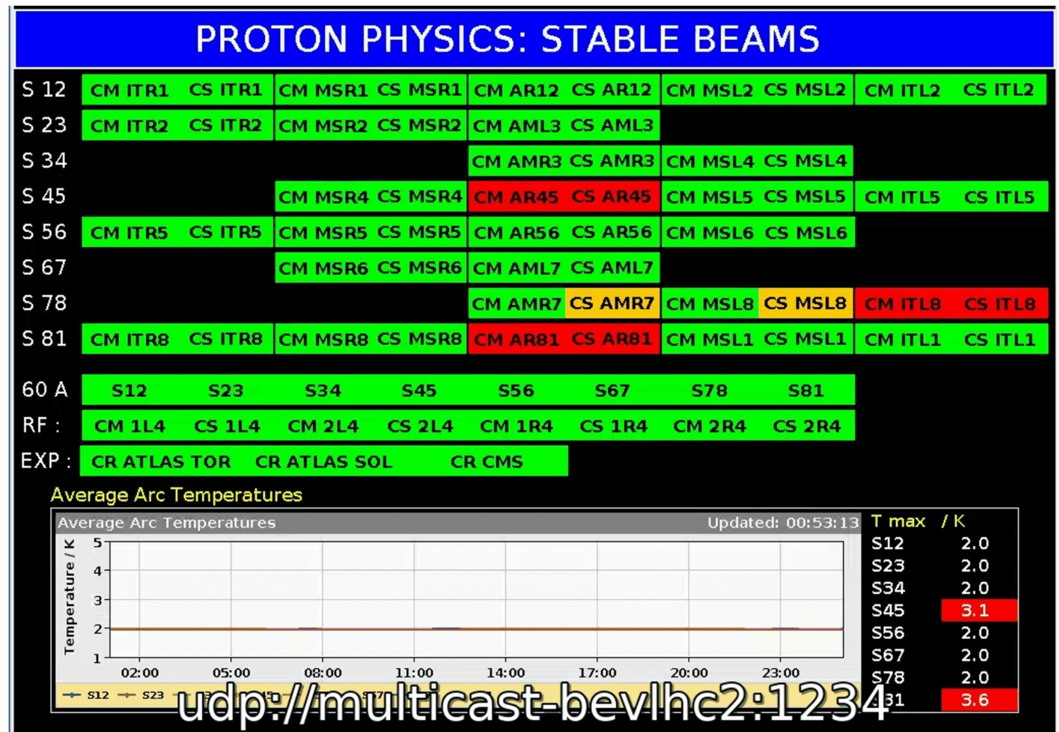
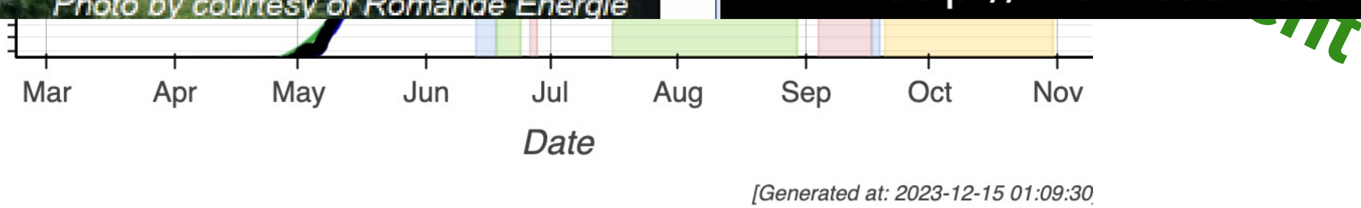
Figure from Beam Performance Tracking in the CERN accelerator complex

A tree fallen down on power cables (Swiss side, 55km from CERN) → … → … → helium leak







- Run 3 (2022–2025) 300/fb
- Run 4 (2029–2032) 600–1000/fb
  - ➢ Higgs precision:
    searches for *HH*-productions, couplings to 2nd-gen., …
  - ➢ Non-colored TeV-scale new physics: (i.e., non-colored SUSY particles)
    closing the parameter space for muon $g-2$ anoma….(????)

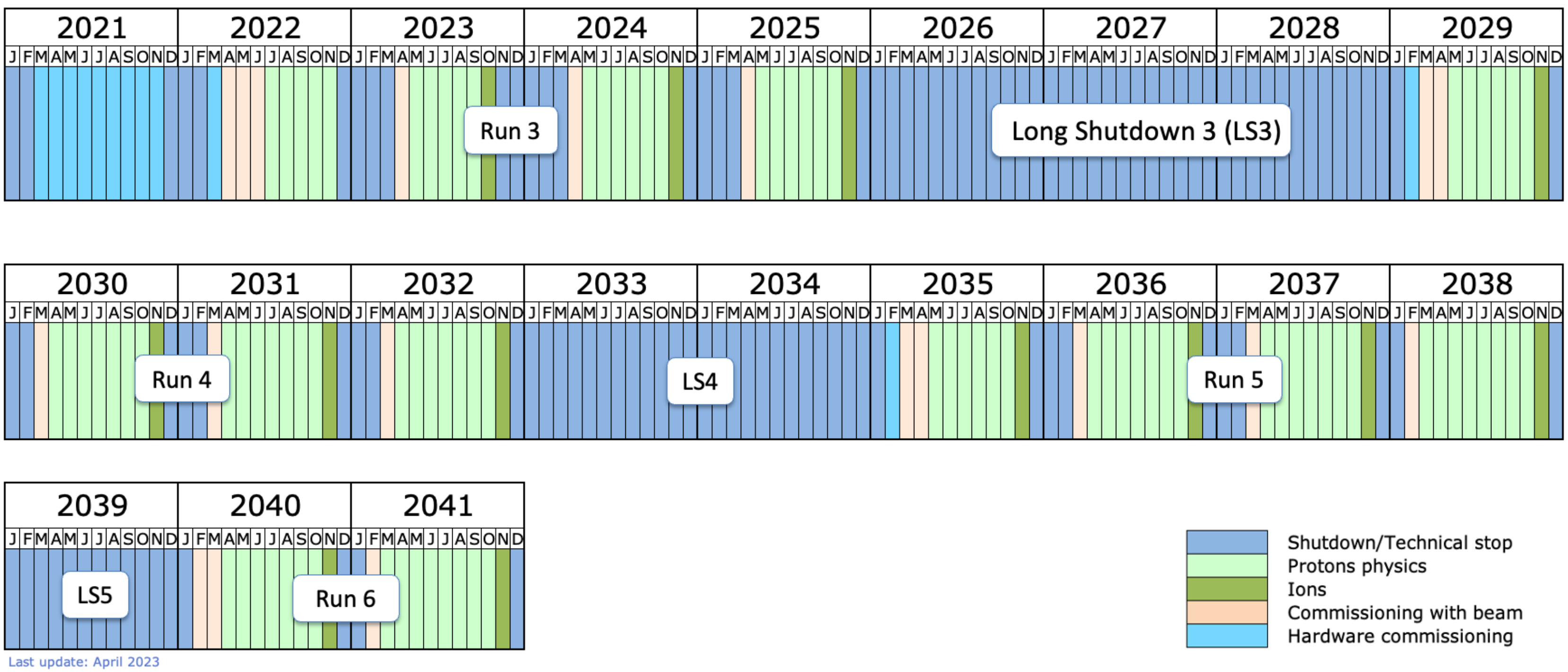
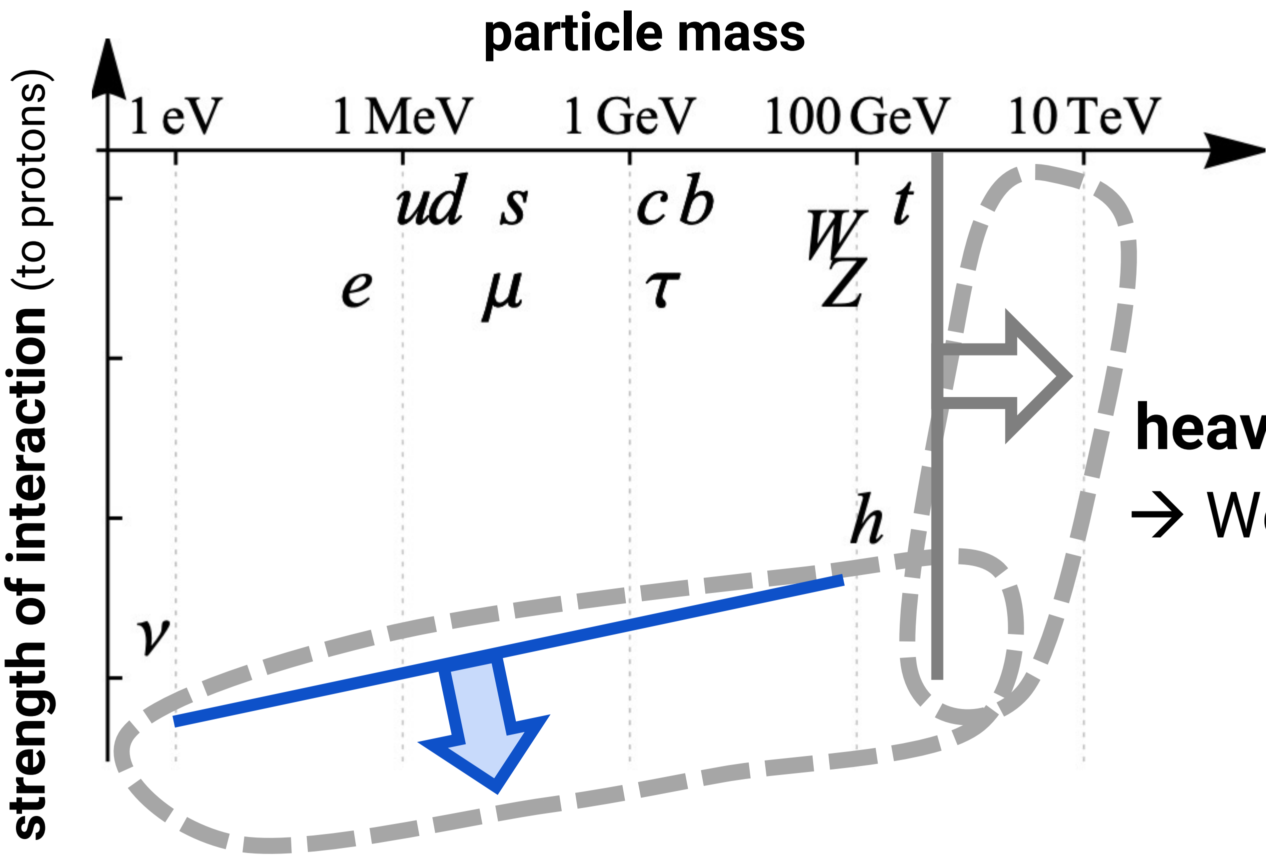


Figure from Longer term LHC schedule



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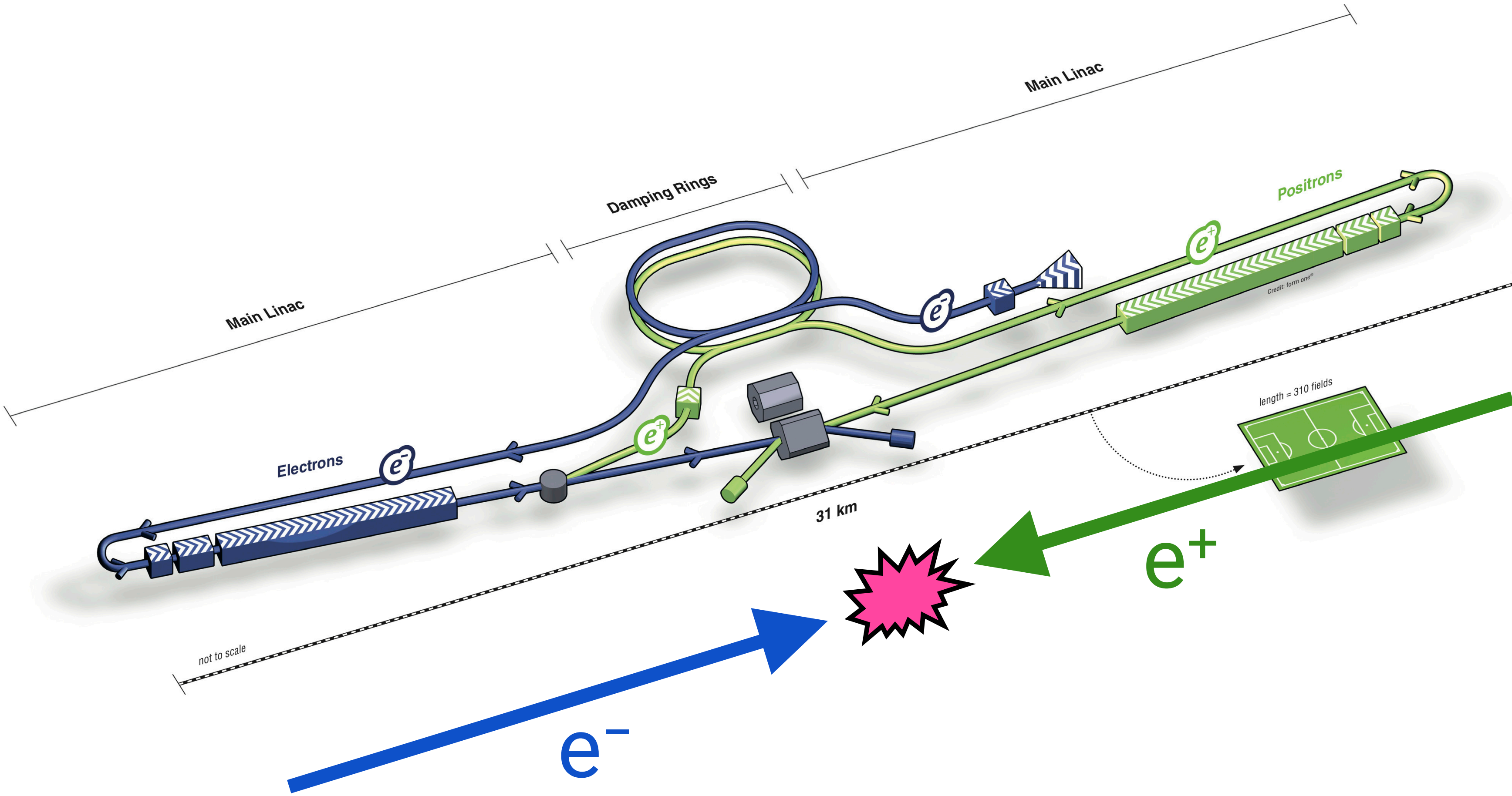
“ILC beam dump experiments”

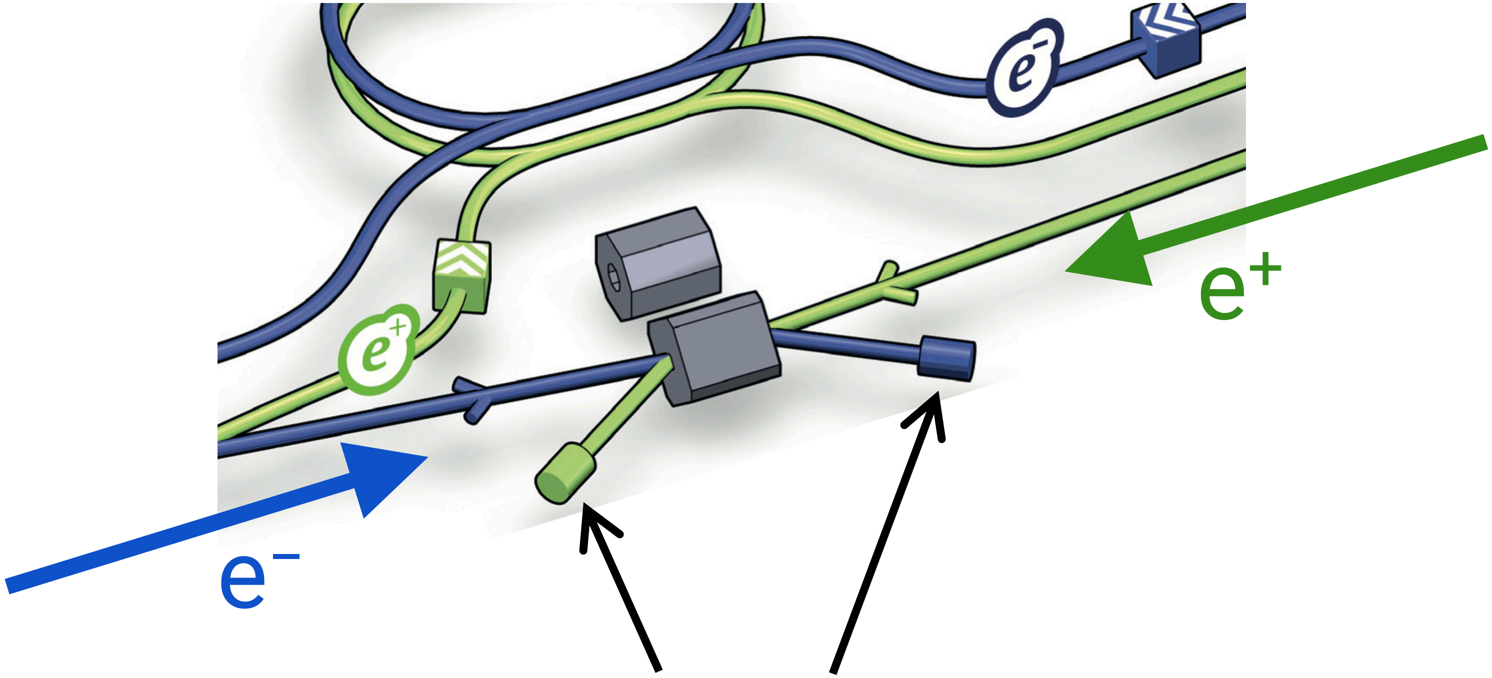
1. ILC
2. Merits of this proposal
3. Analysis
4. Physics Cases
   - ❖ Sub-GeV new particles (non-DM)
   - ❖ Sub-GeV DM

ILC (planned in Japan)

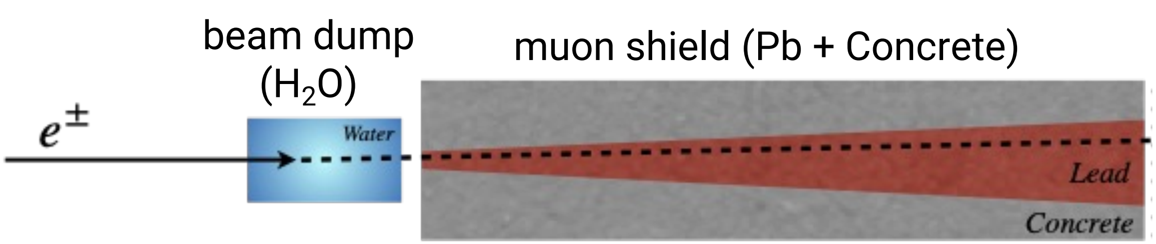
→ for Higgs precision etc.

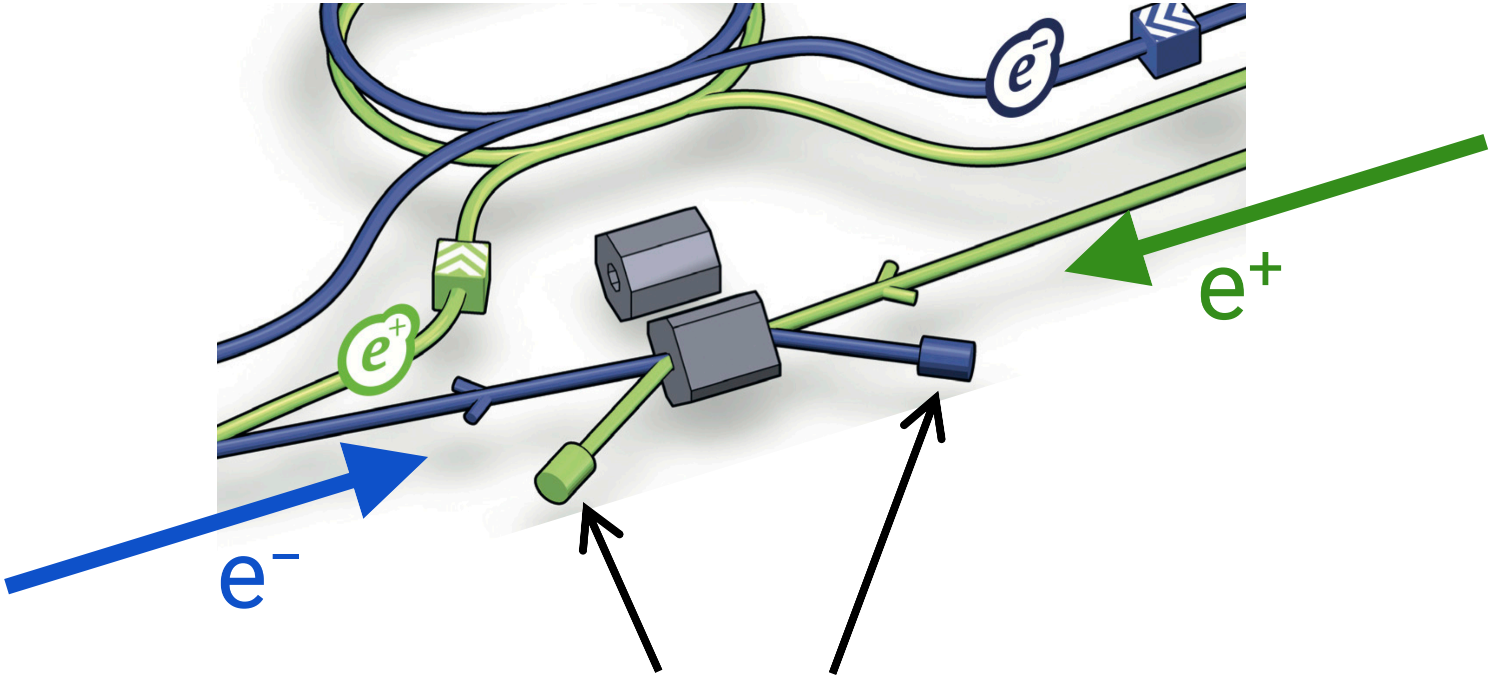
$$\boxed{E_{\text{beam}} = 125\,\text{GeV}} \; (\to 250\,\text{GeV?} \to 500\,\text{GeV?})$$





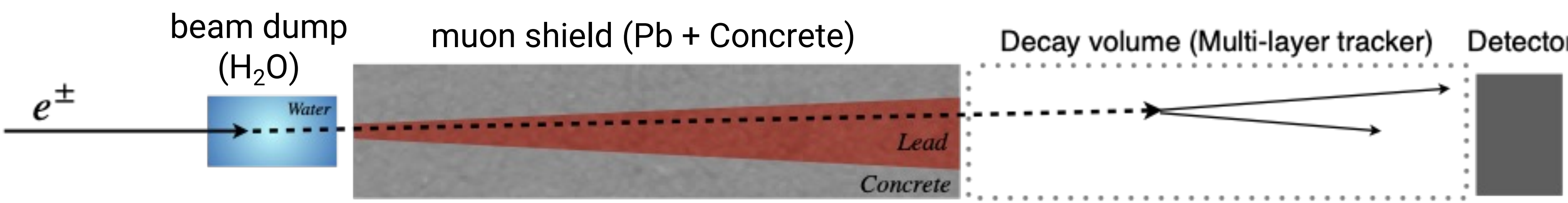
main beam dumps (束流垃圾桶)

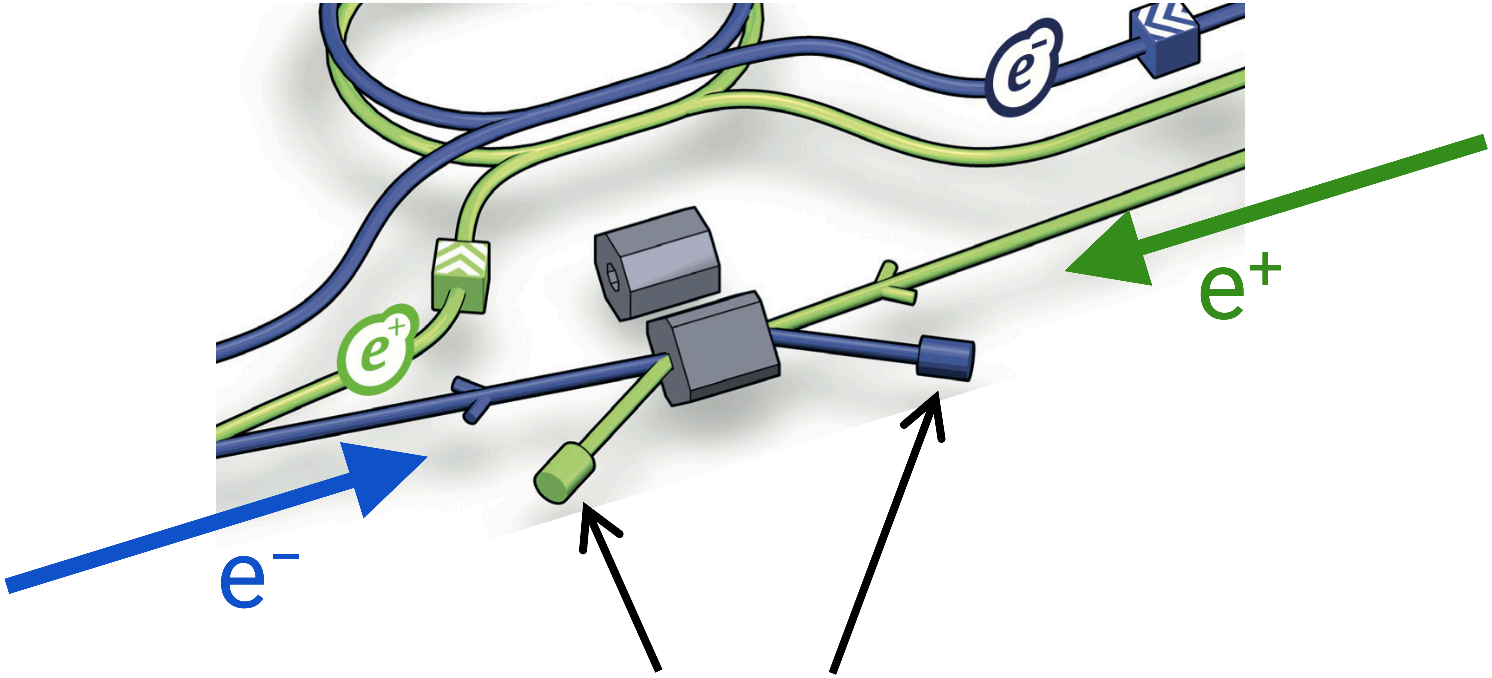




main beam dumps (束流垃圾桶)

Our proposal





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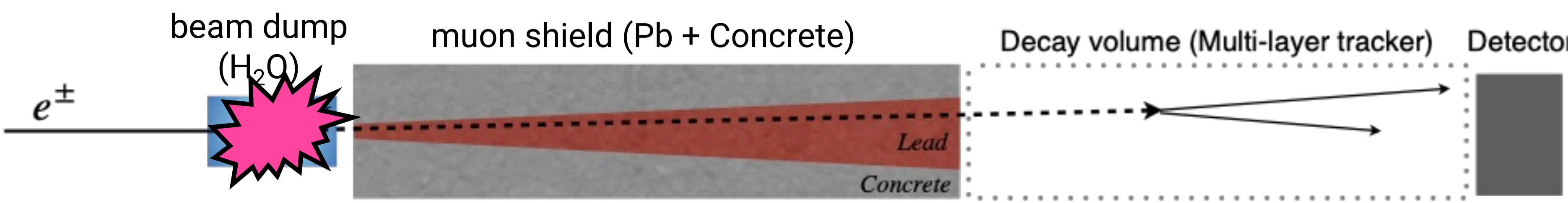

A fixed-target experiment: $e^{\pm}$ N / $e^{\pm}$ e^{-} scattering

Earlier work: Kanemura, Moroi, Tanabe [1507.02809]

"ILC beam dump experiments"

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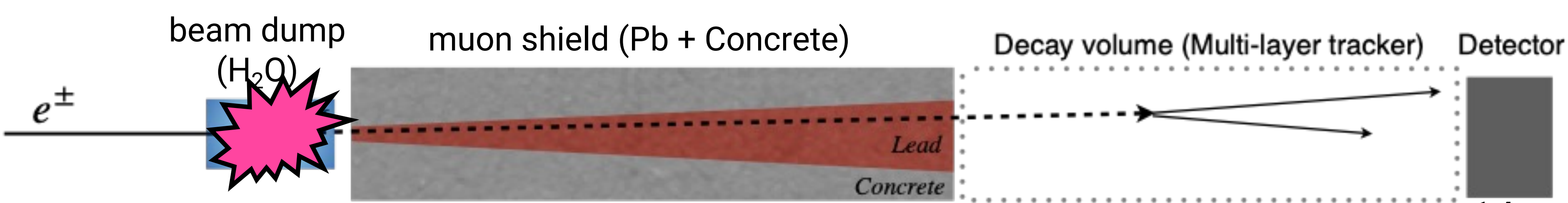
   - Sub-GeV new particles (non-DM)
   - Sub-GeV DM

- Less cost. ($$$ for detectors; **recycling** the beams.)
- 125 GeV positron beam. → **e^+ e^-** collision.
- Higher intensity. … **"linear" collider** = always dumps. (↔ circular collider)
- ❑ Fixed-target: Lower E_{CM}.

$$E_{\rm CM} = \sqrt{2mE_{\rm beam}} = \begin{cases} 15\,{\rm GeV} & (e^\pm {\rm N}) \\ 0.36\,{\rm GeV} & (e^\pm e^-) \end{cases}$$

(↔ collider: $E = 2(E_1E_2)^{1/2}$)

→ Searches for sub-GeV tiny-interaction particles



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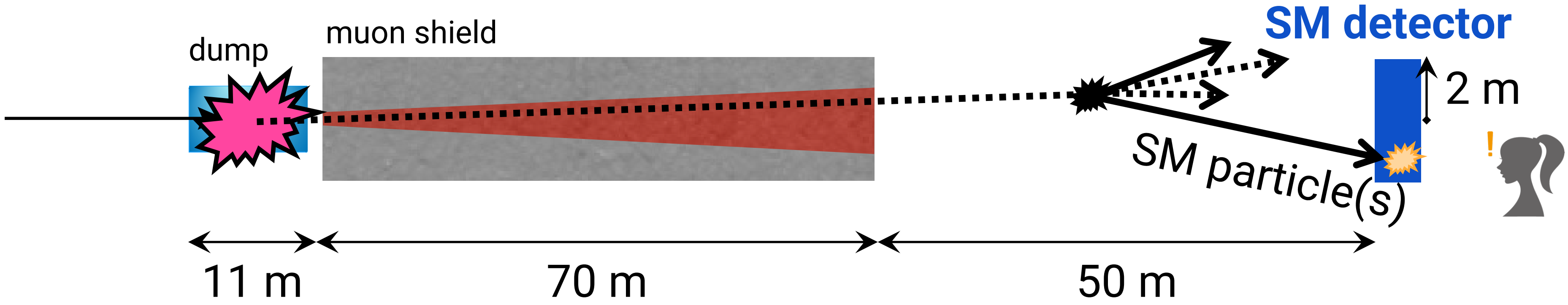
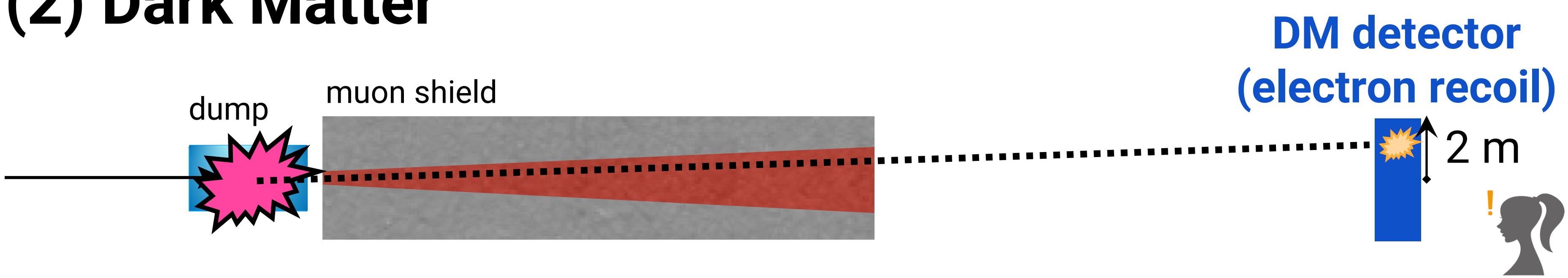
(1) Meta-stable, decaying into SM (and other) particles



Sakaki, Ueda [2009.13790]
Asai, Iwamoto, Sakaki, Ueda [2105.13768]

(2) Dark Matter



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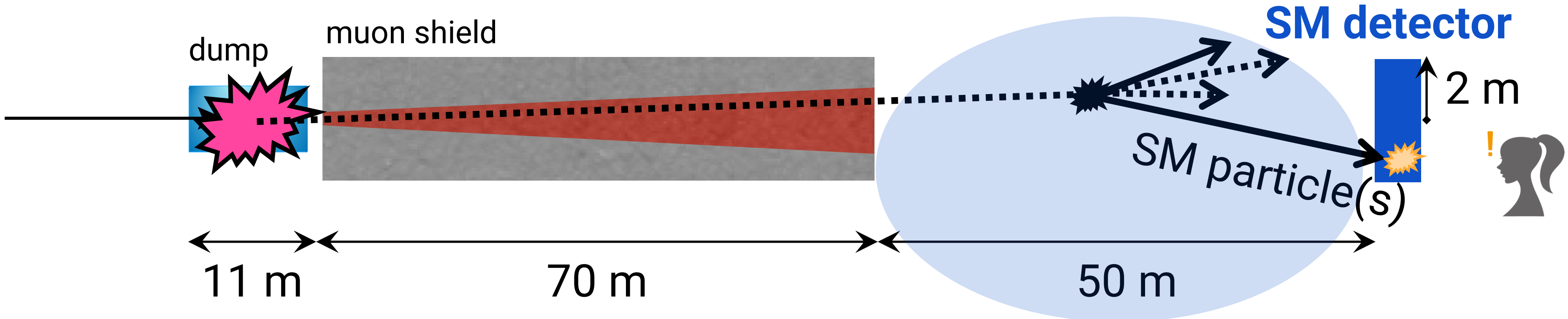

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$$N_{\text{signal}} = N_{\text{production}} \times \text{Acceptance} \times \mathcal{E}_{\text{detector}}$$

$\simeq 1$

model dependence

~ Angular acceptance
× Prob(decay inside the **50m**)

- Semi-analytic method ← our choice
- Monte Carlo simulation

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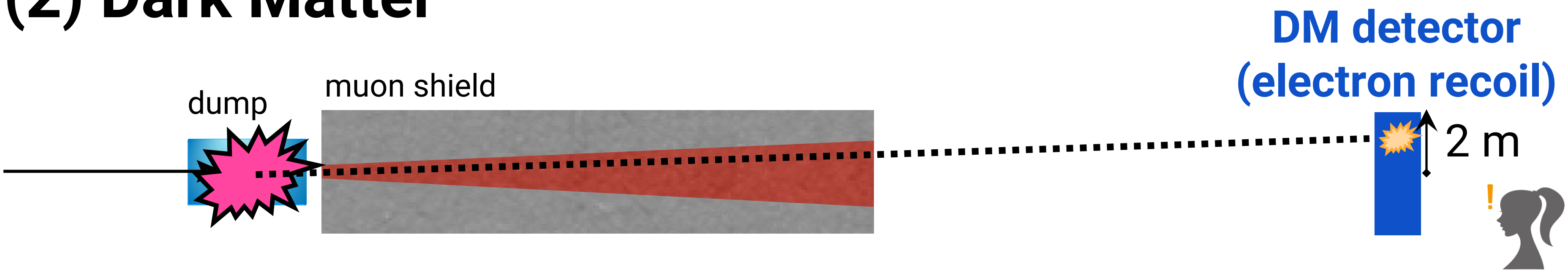

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Rough number is known.
/ Beyond theorists' capability.

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$\mathcal{E}_{\text{detector}} \simeq 1$

model dependence ($N_{\text{production}}$)

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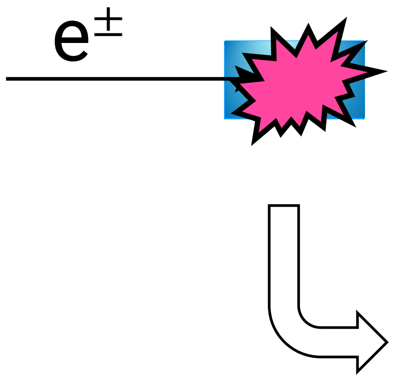
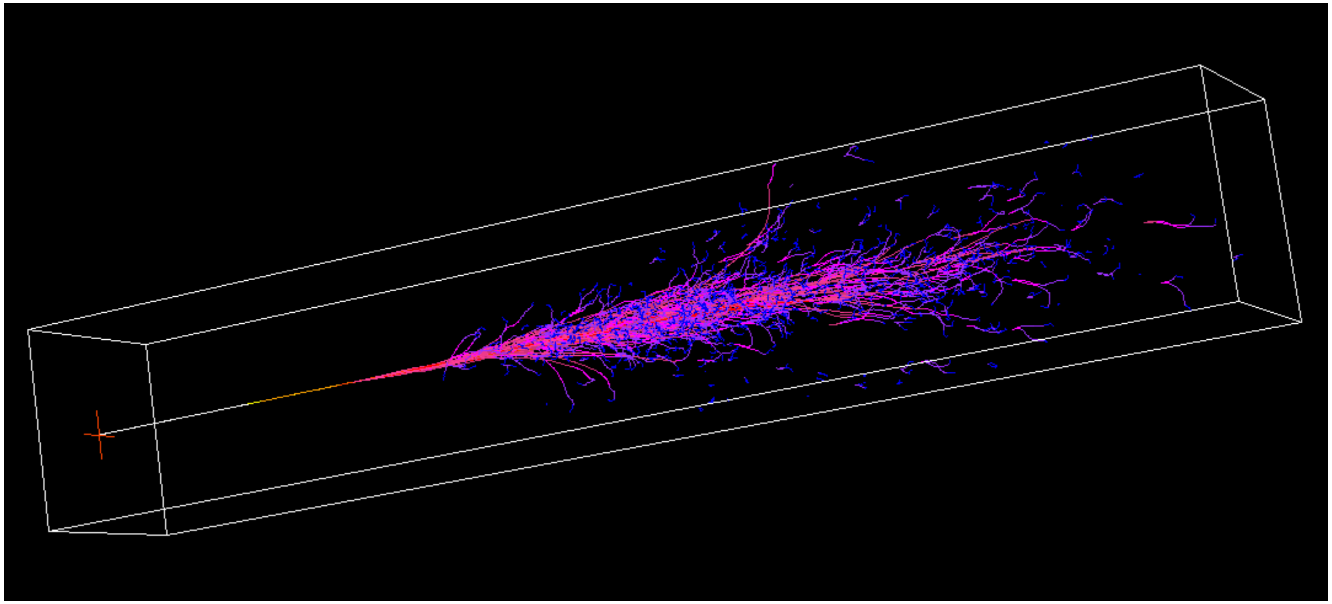
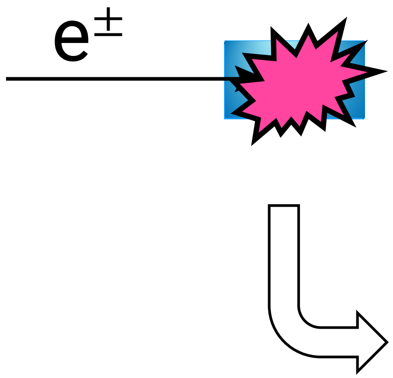
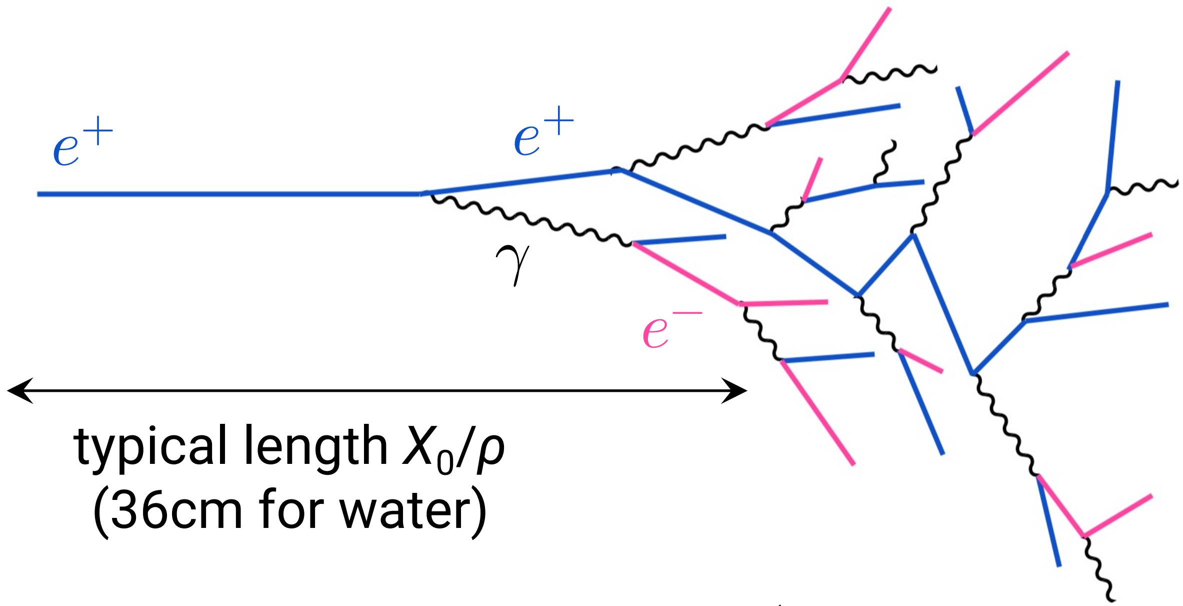
Elementary process at the beam dump





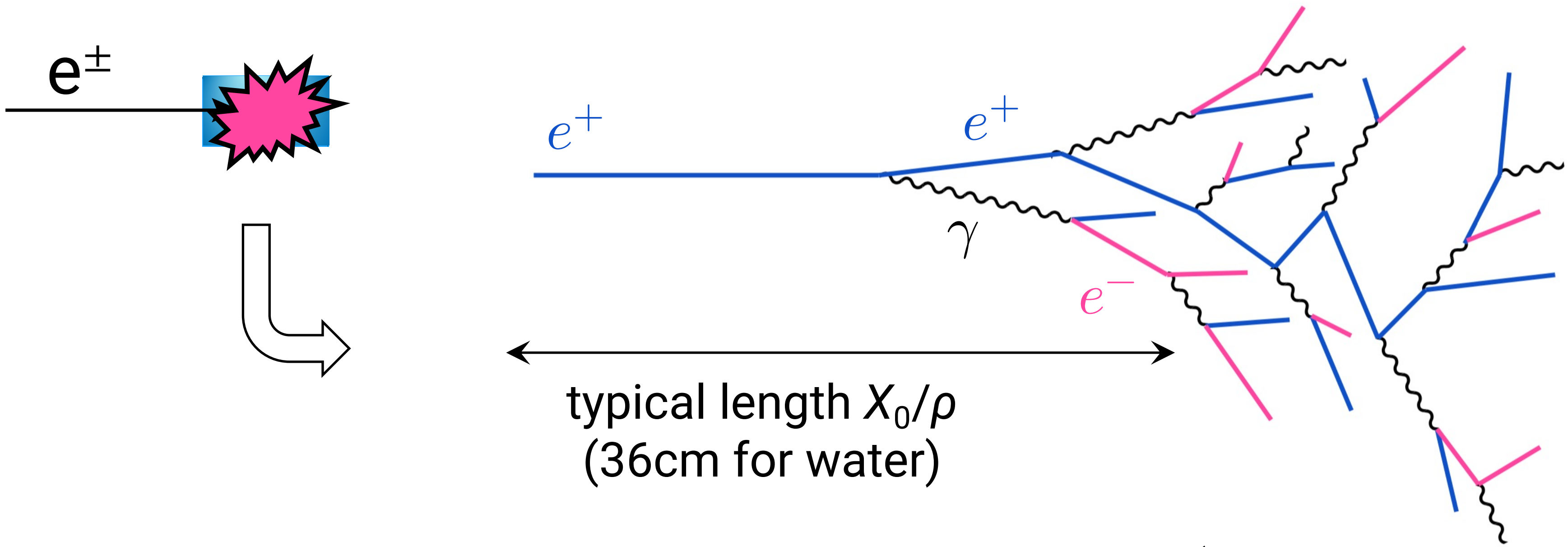
24 GeV e⁻ on iron, from the Electromagnetic Shower Simulator by Sven Menke.



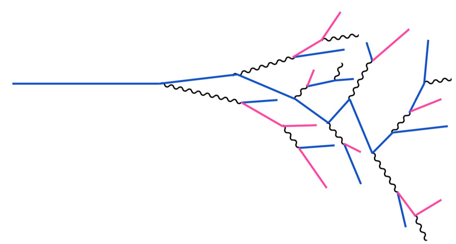


(and a bit of $\mu^{\pm}$ / hadron)

X_0: radiation length, ρ: density (of target material)



(and a bit of $\mu^{\pm}$ / hadron)

beam $\otimes$ target $=$  $\otimes(N, \mathrm{e}^-)$ from water

$=$

e^+ N,	e^+ e^-
e^- N,	e^- e^-
γ N,	γ e^-

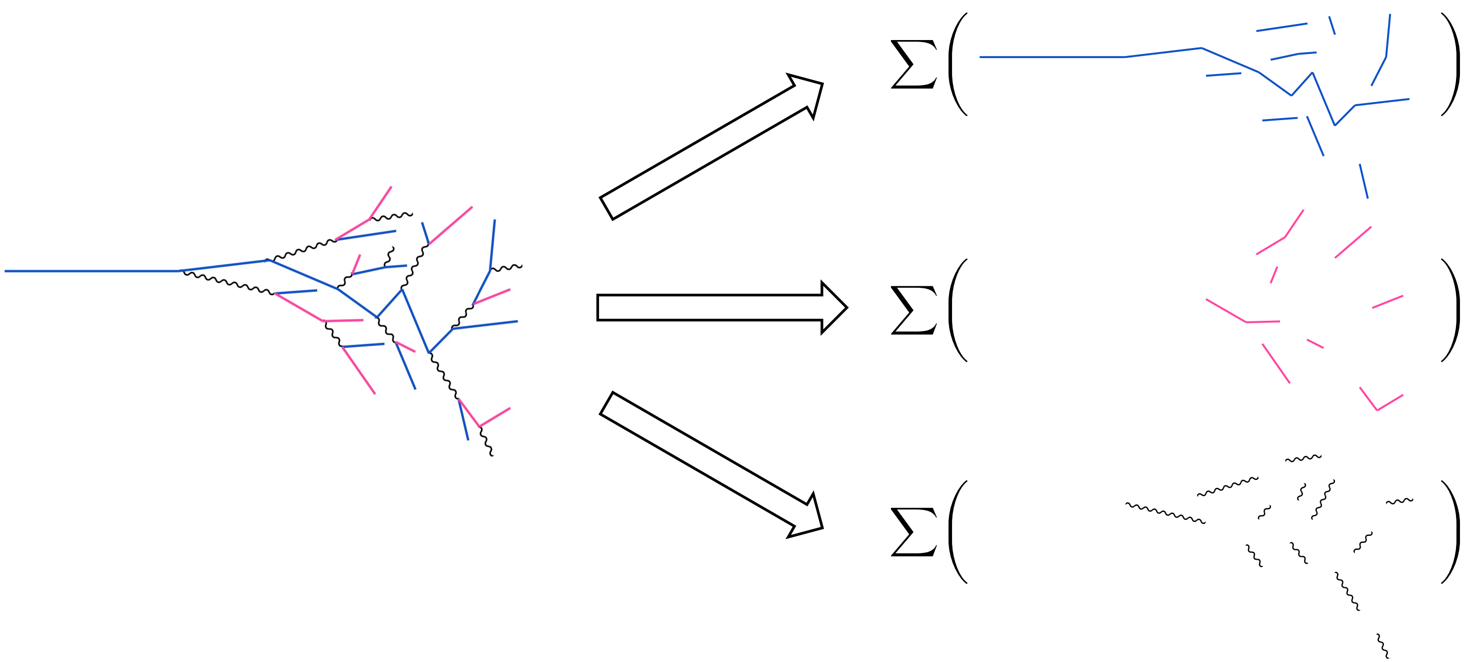
scatterings

X_0: radiation length, ρ: density (of target material)

$$\frac{N}{VT} = n_1 n_2 \sigma v$$ (definition of cross section σ)

$$\boxed{N = N_{\text{inject}}\, n_{\text{target}}\, L\, \sigma}$$ fixed-target version

L = **track length of the electromagnetic shower**



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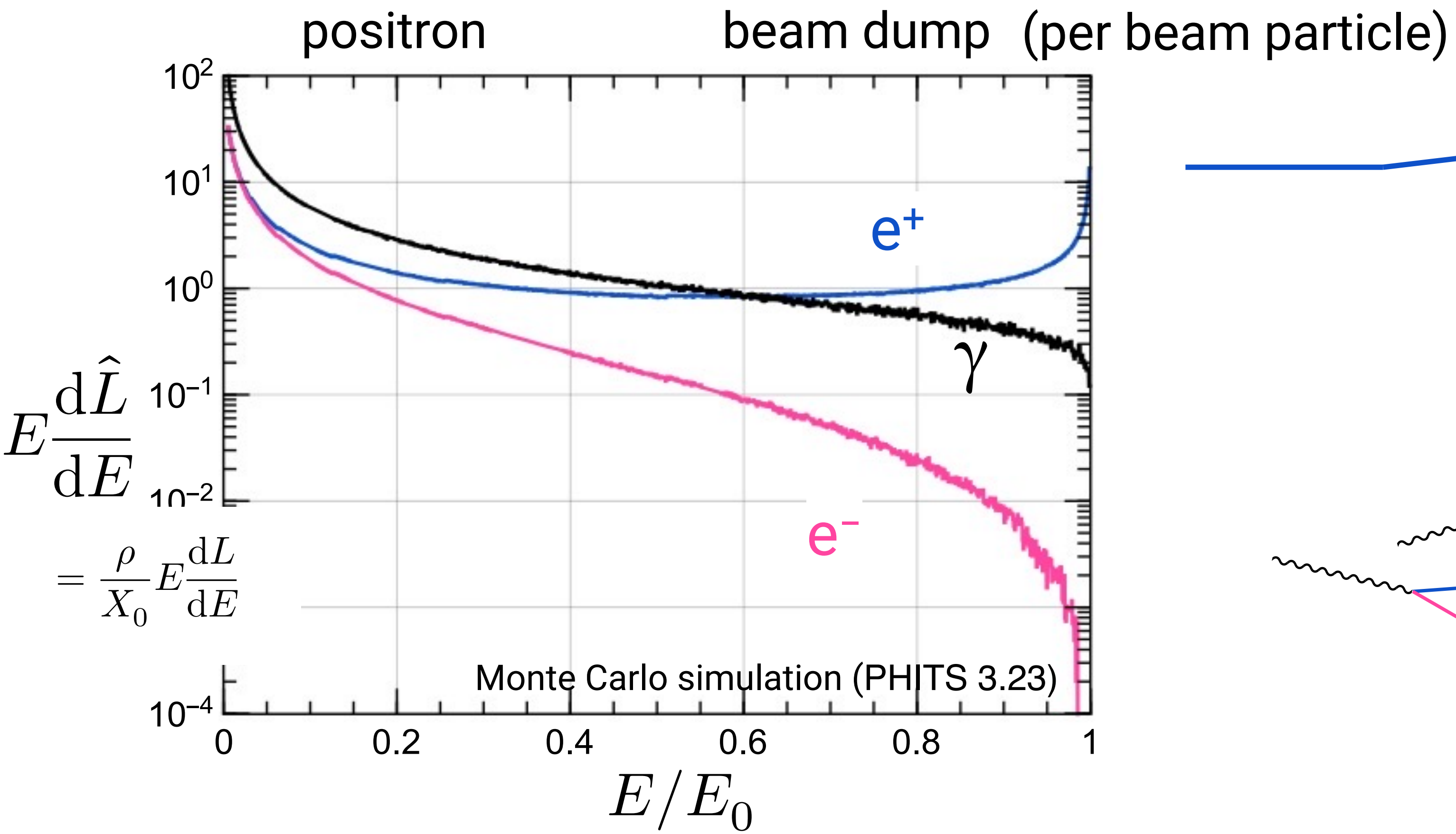
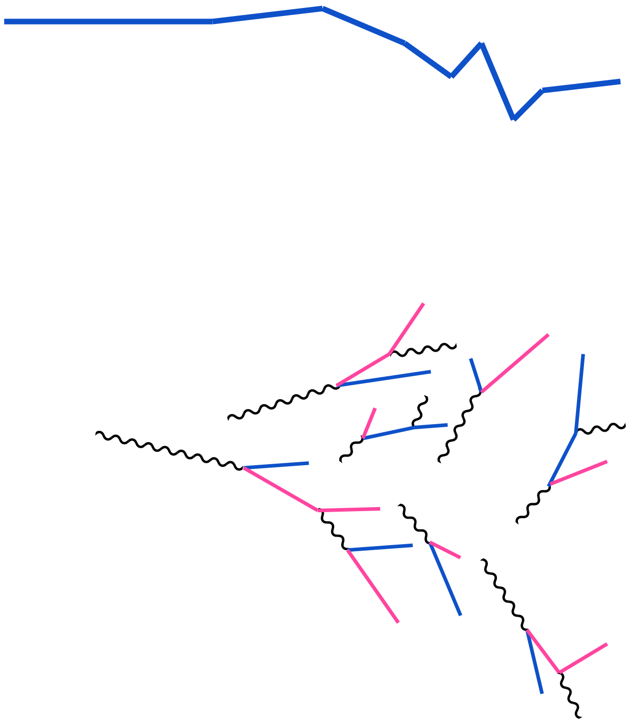
$$N_{\text{production}}(\text{e+ dump}) =$$

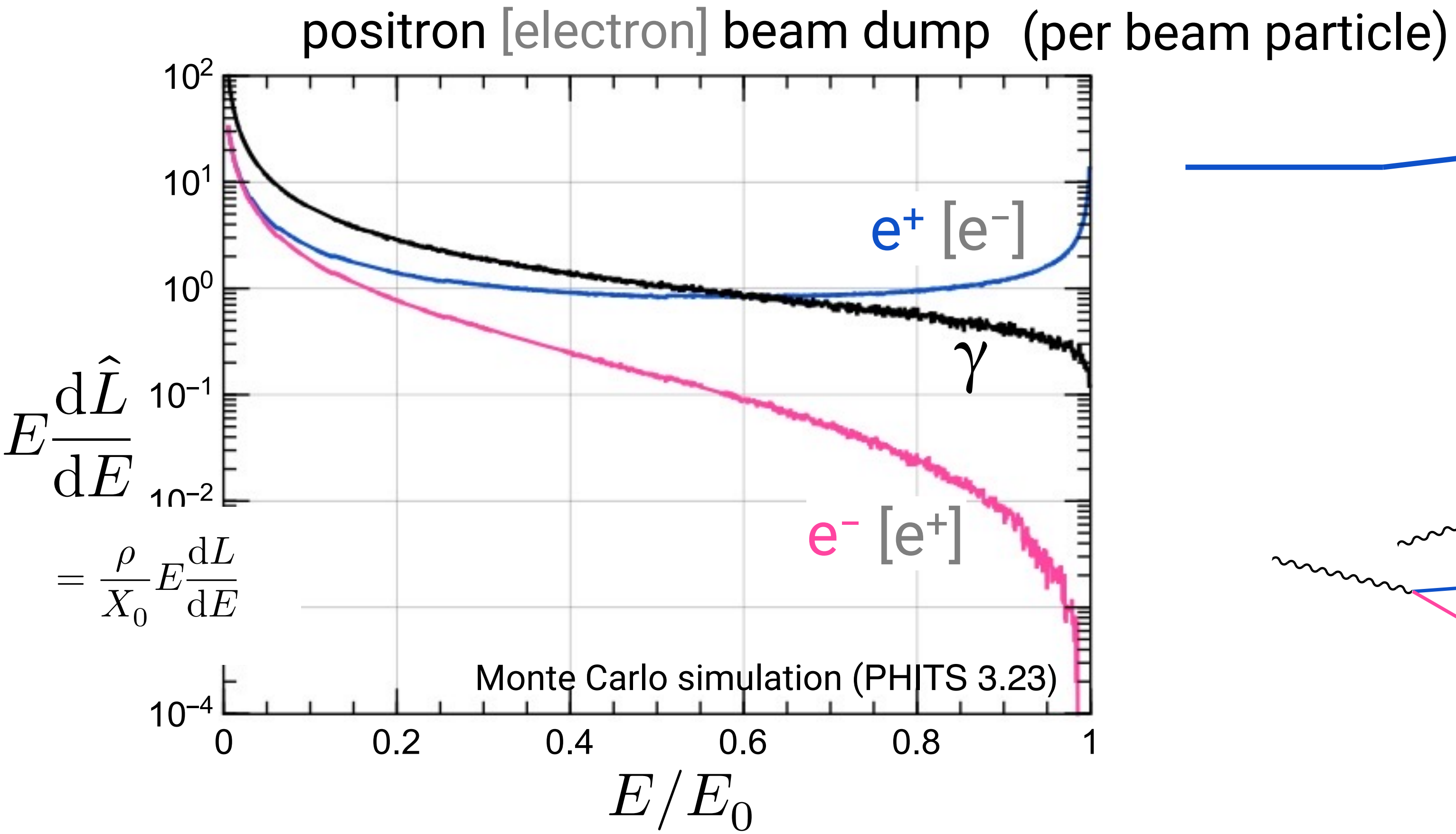
$$N_{\text{inject}} \times \sum_{\Phi=\{e^+,e^-,\gamma\}} \left[n_{e^-} \frac{\mathrm{d}L_\Phi^{\text{e+ beam}}}{\mathrm{d}E} \sigma(\Phi e^- \to \text{new physics}; E) + n_N \frac{\mathrm{d}L_\Phi^{\text{e+ beam}}}{\mathrm{d}E} \sigma(\Phi N \to \text{new physics}; E) \right]$$

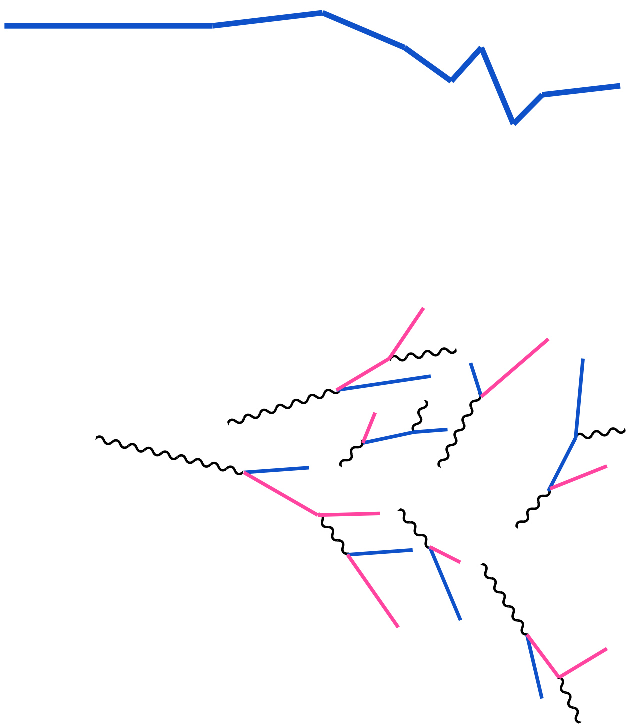
Track length?





- Beam-dependent contribution + beam-independent contribution.
- *L* mainly comes from low-energy shower.
- Low-energy side: independent of beam-type.
- High-energy side: mainly from the injected particle.





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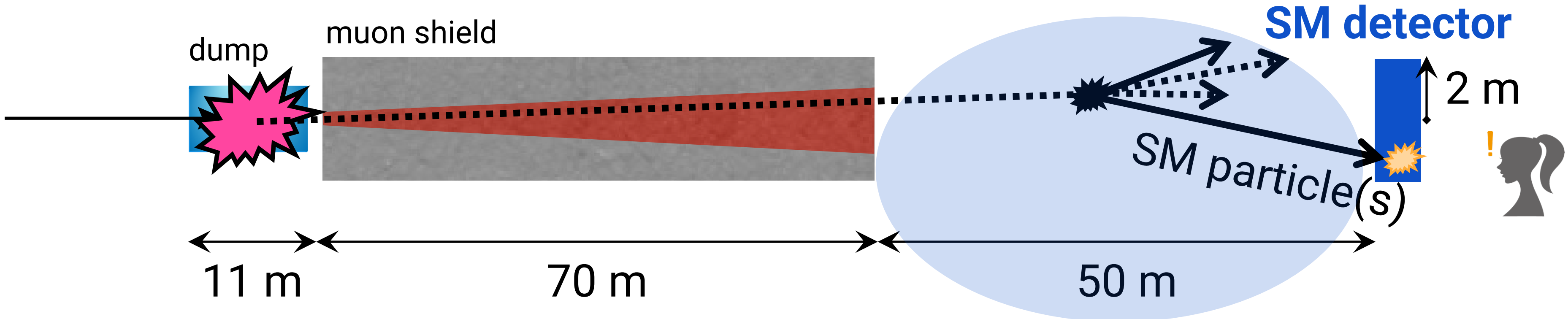

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vector

■ Dark photon

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

induce

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

CP-odd scalar

■ Axion-like particles (ALPs)

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

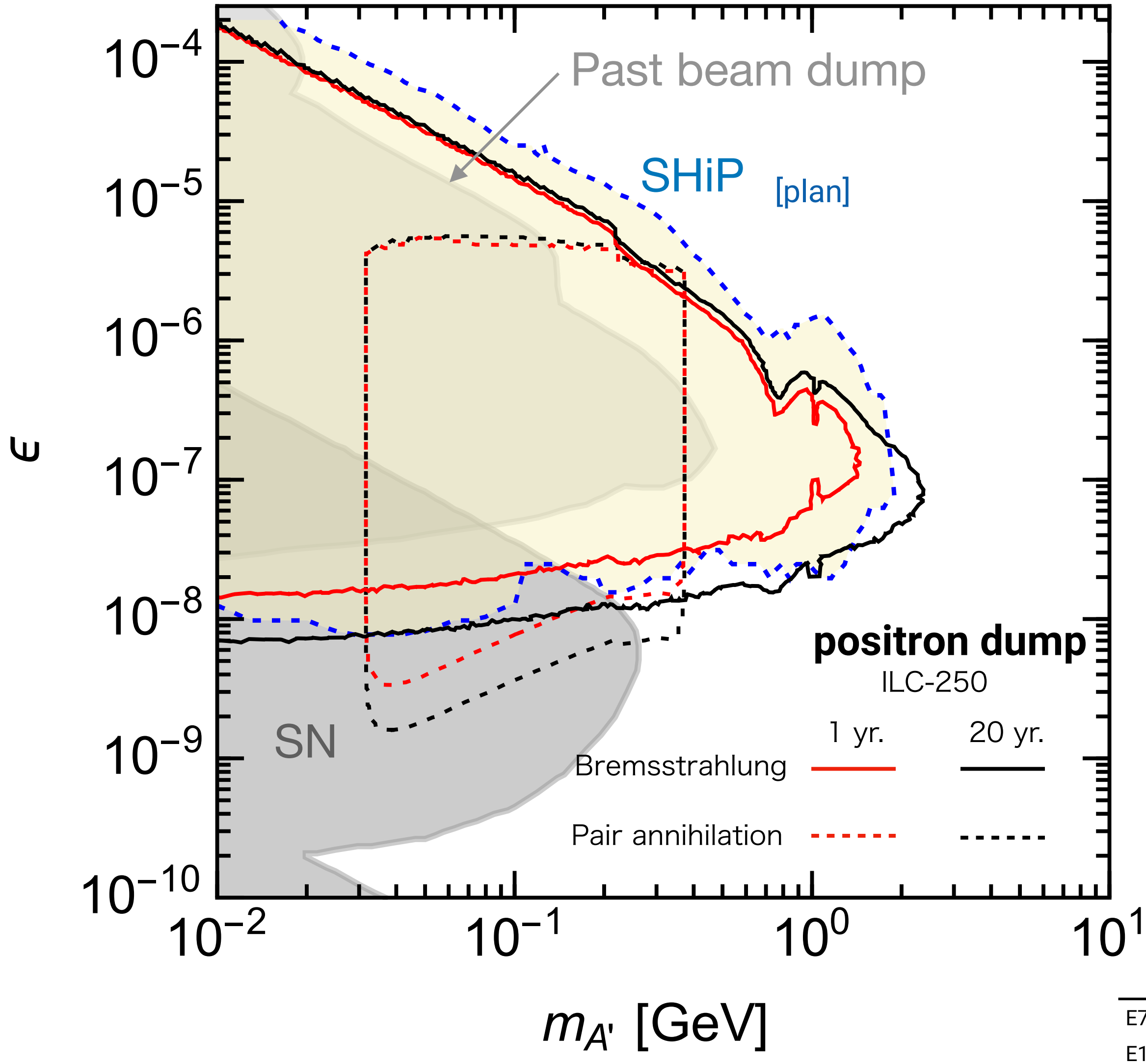
Leptonic couplings assumed, photon coupling induced

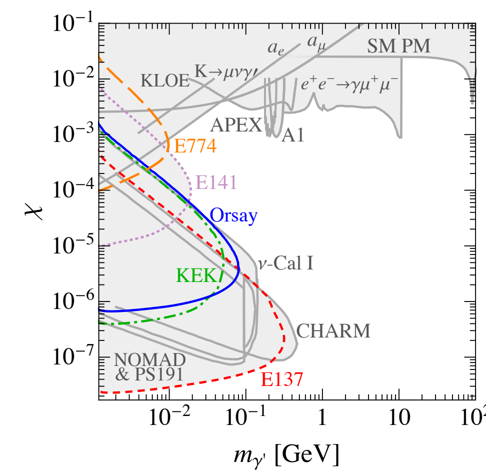
CP-even scalar

■ Extra scalar boson

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

Leptonic couplings assumed, photon coupling induced

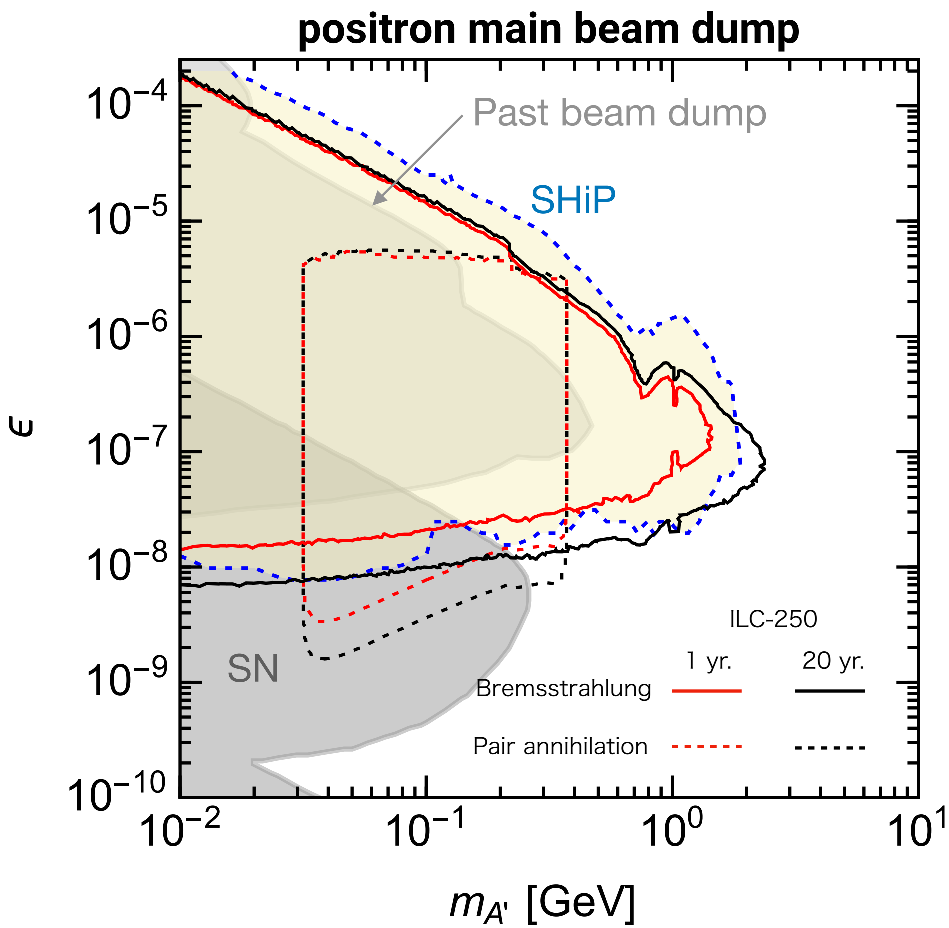


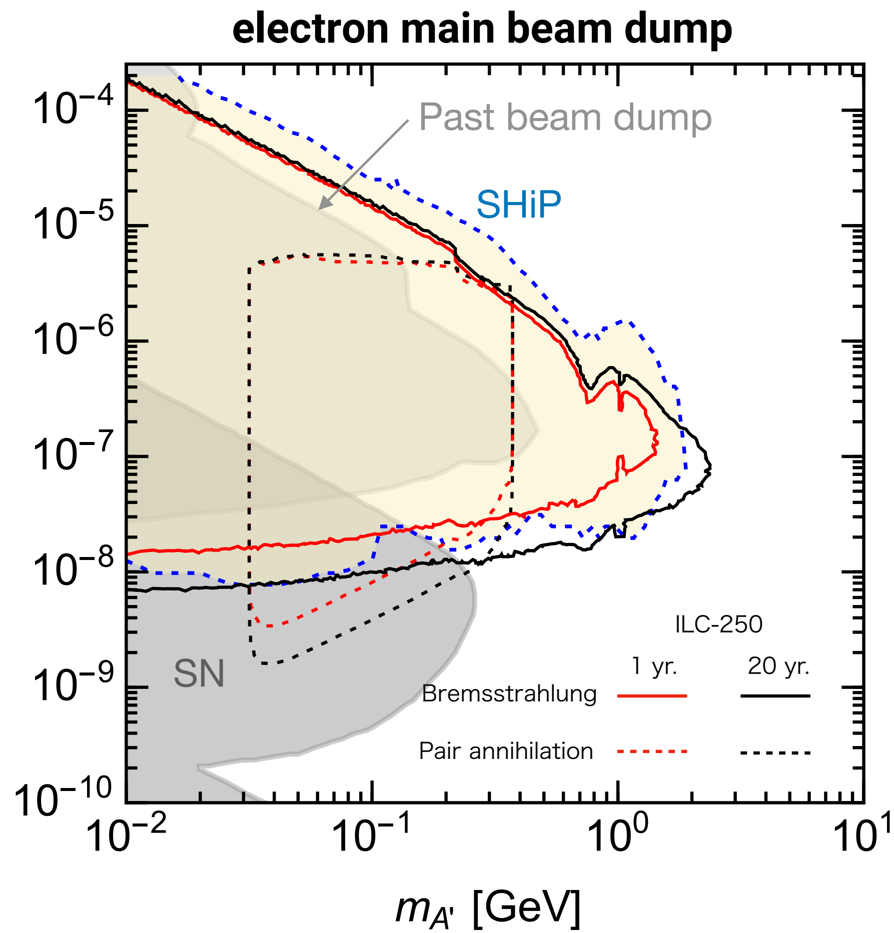


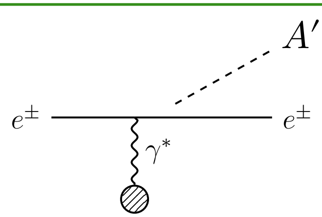
E774	1991, FNAL	e^-,	275 GeV,	10^{10} 個,	2 m
E141	1987, SLAC	e^-	9 GeV,	10^{15} 個,	40 m
Orsay	1989, Orsay	e^-,	1.6 GeV,	10^{16} 個,	3 m
KEK LBDX	1986, KEK	e^-,	2.5 GeV,	10^{17} 個,	5 m
CHARM II	1991, CERN	p,	450 GeV,	10^{19} 個,	870 m
E137	1988, SLAC	e^-,	20 GeV,	10^{20} 個,	400 m
ILC beam dump	????, Iwate	e^- / e^+,	125 GeV,	10^{21} 個/年,	120 m
SHiP	LHC Run 4, CERN	p,	400 GeV,	10^{19} 個/年,	120 m

Past beam dump: cf. Andreas, Niebuhr, Ringwald [1209.6083]

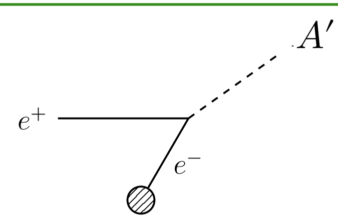
■ Spot the difference!







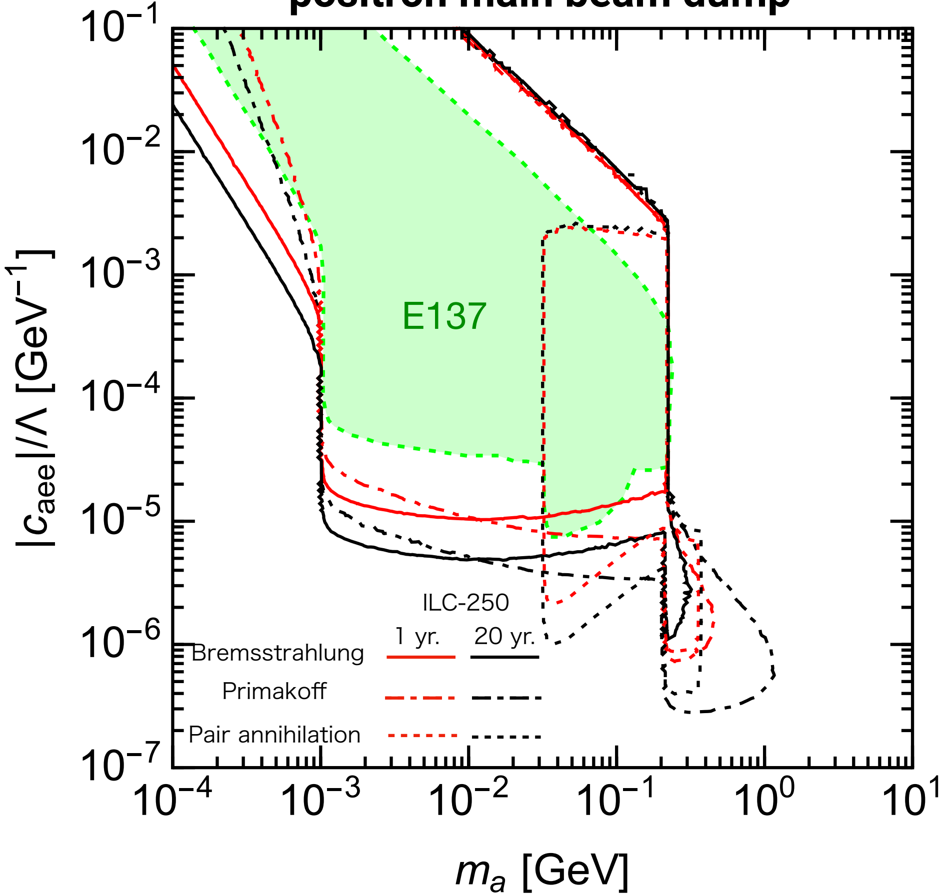
Bremsstrahlung



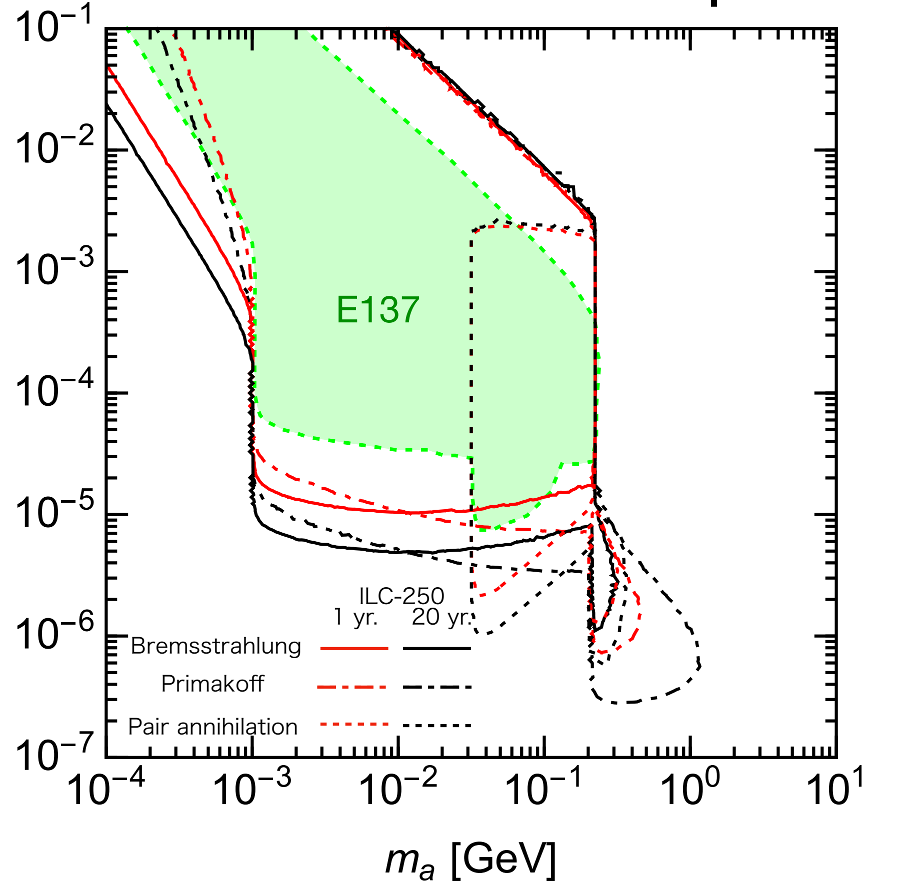
Pair annihilation

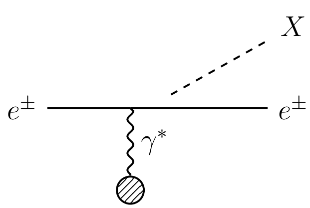
■ $\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \sum_{\ell=e,\mu,\tau} \frac{1}{2} \frac{c_{a\ell\ell}}{\Lambda} \partial_\mu a \bar{\ell} \gamma^\mu \gamma_5 \ell - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad c_{aee} = c_{a\mu\mu} =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

positron main beam dump

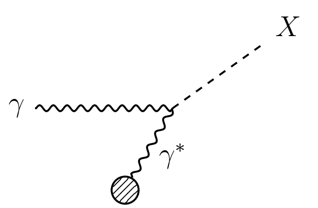


electron main beam dump

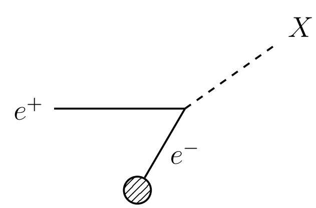




Bremsstrahlung



Primakoff process



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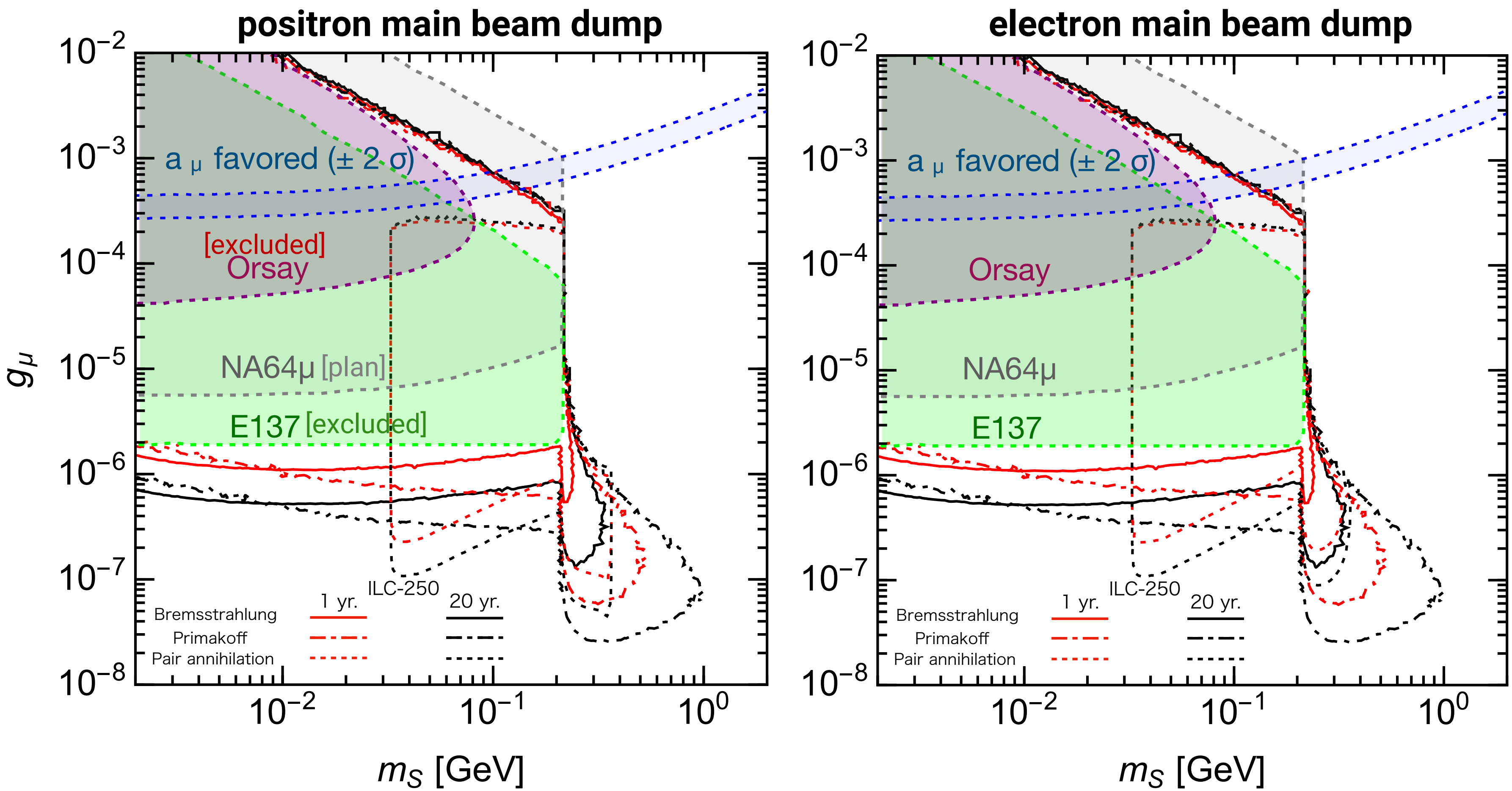
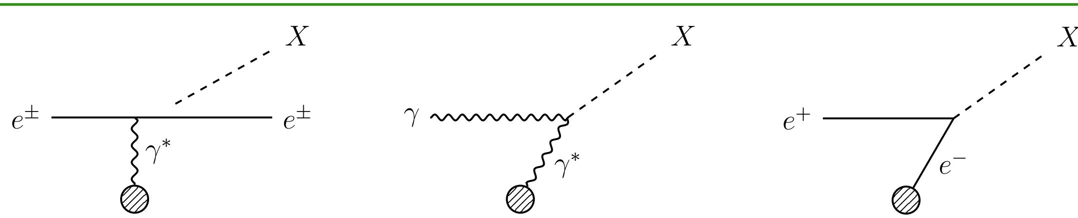
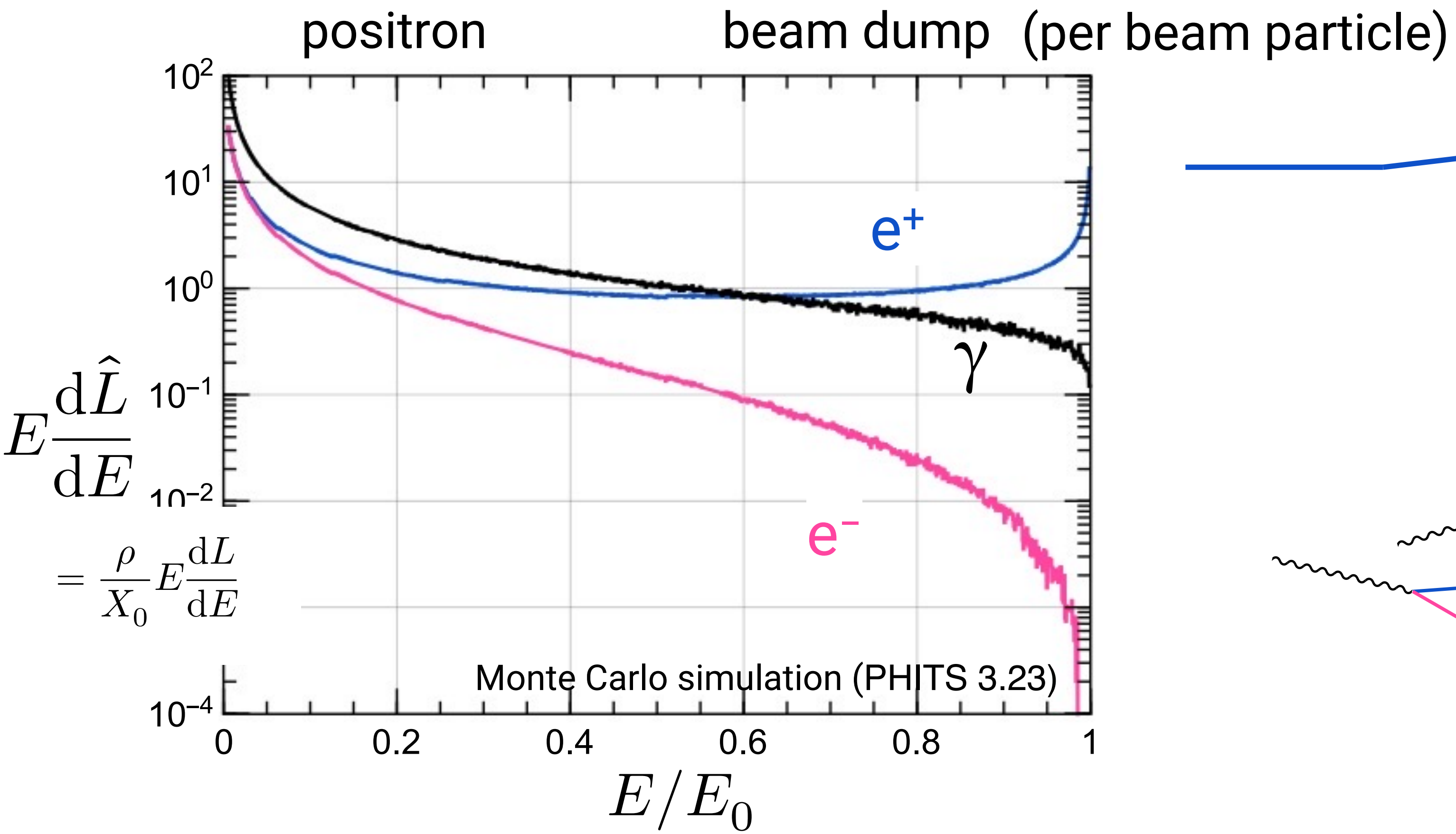
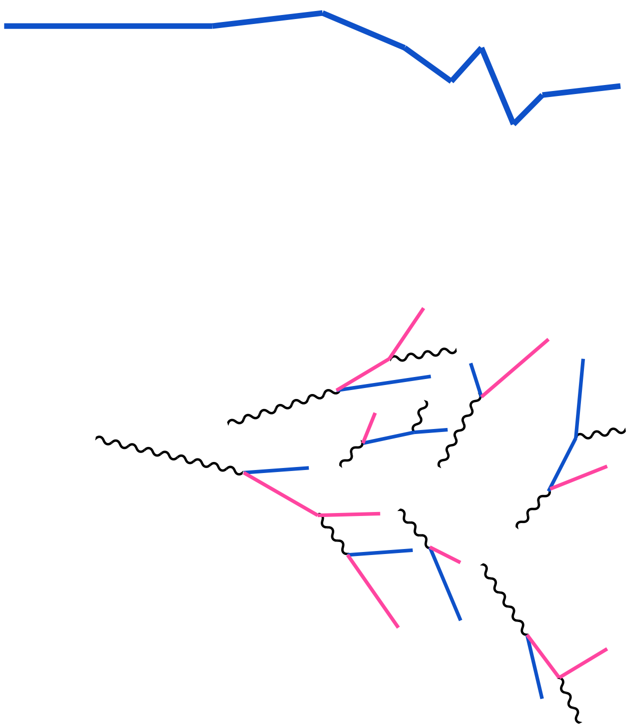




Bremsstrahlung　Primakoff process　Pair annihilation

 Asai, Iwamoto, Sakaki, Ueda [2105.13768]





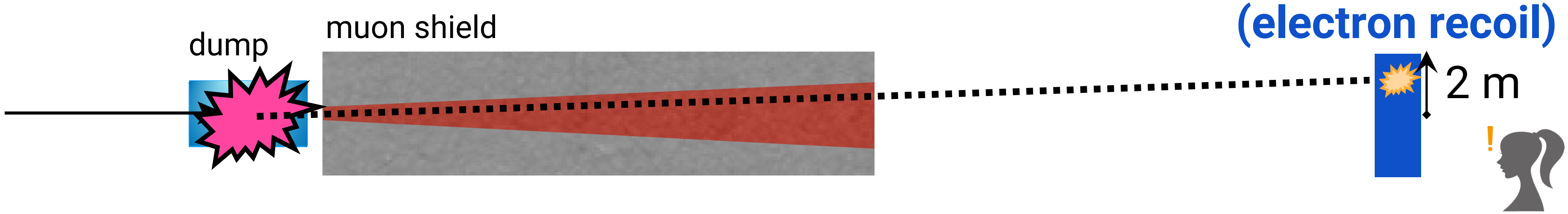
- Beam-dependent contribution + beam-independent contribution.
- *L* mainly comes from low-energy shower.
- Low-energy side: independent of beam-type.
- High-energy side: mainly from the injected particle.

“ILC beam dump experiments”

1. ILC
2. Merits of this proposal
3. Analysis
4. Physics Cases
    - Sub-GeV new particles (non-DM)
    - **Sub-GeV DM**

Asai, Iwamoto, Perelstein, Sakaki, Ueda [2301.03816]

(2) Dark Matter



Asai, Iwamoto, Perelstein, Sakaki, Ueda [2301.03816]

$$N_{\text{signal}} = N_{\text{production}} \times \text{Acceptance} \times \mathcal{E}_{\text{detector}}$$

~ angular acc.

model dependence

Rough number is known.
/ Beyond theorists' capability.

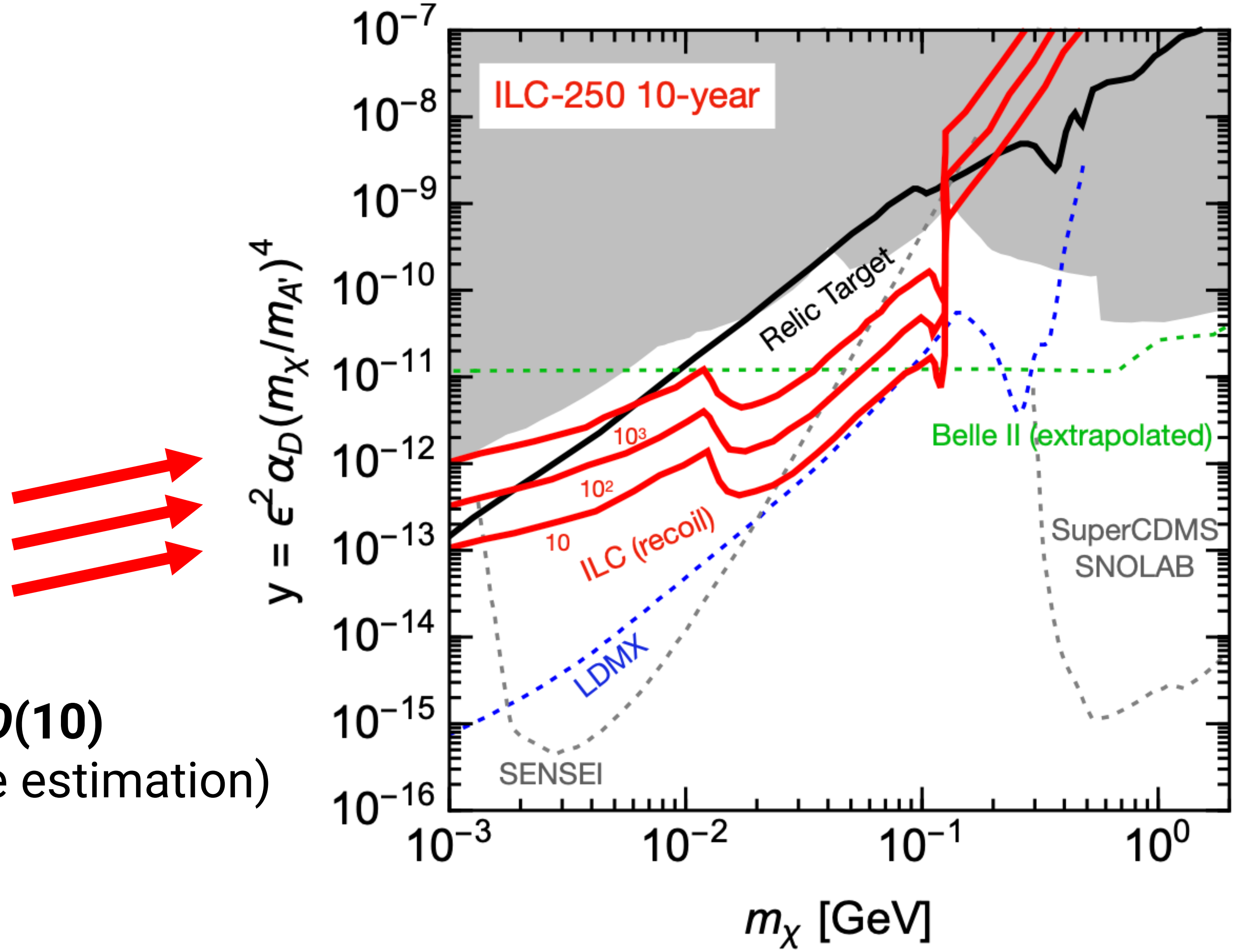
$$\mathcal{L}_{\rm int} = -i g_{\rm D} A'_\mu \left(\chi^* \partial^\mu \chi - \chi \partial^\mu \chi^*\right)$$

$\alpha_{\rm D} = 0.5,$

$m_{A'} = 3 m_{\rm DM}$

#(signal) = 1000
100
10

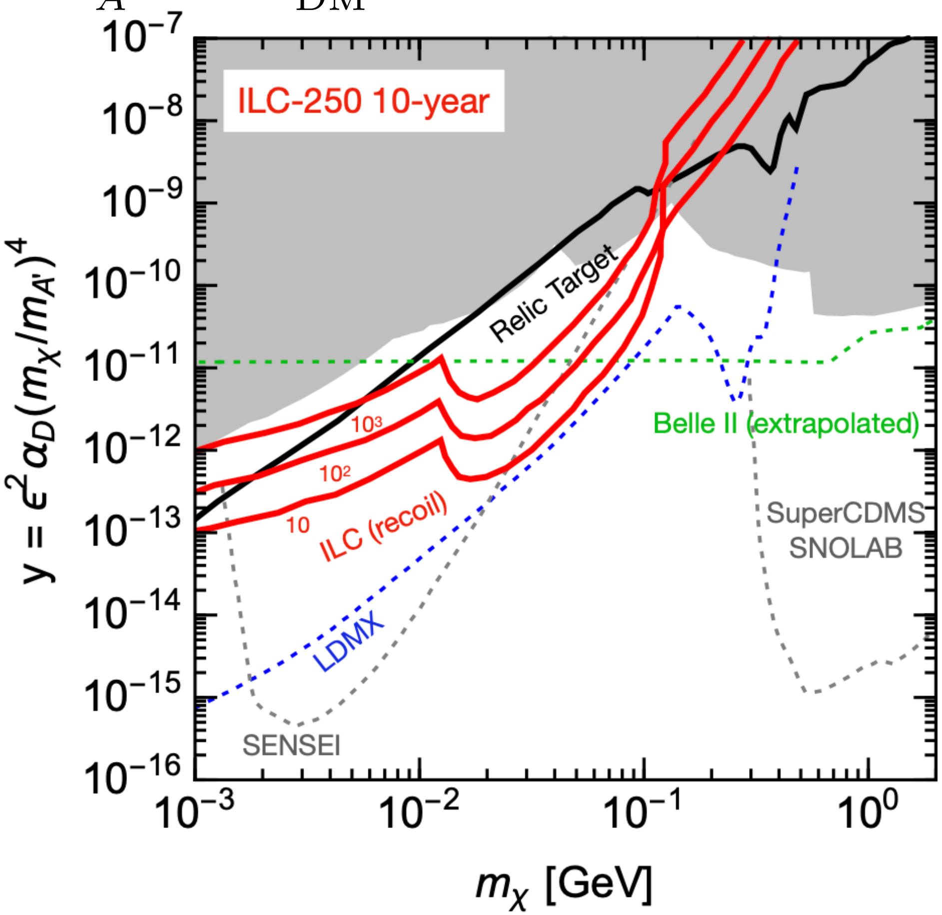
vs. #(BKG) ~ *O*(10)
(our crude estimation)



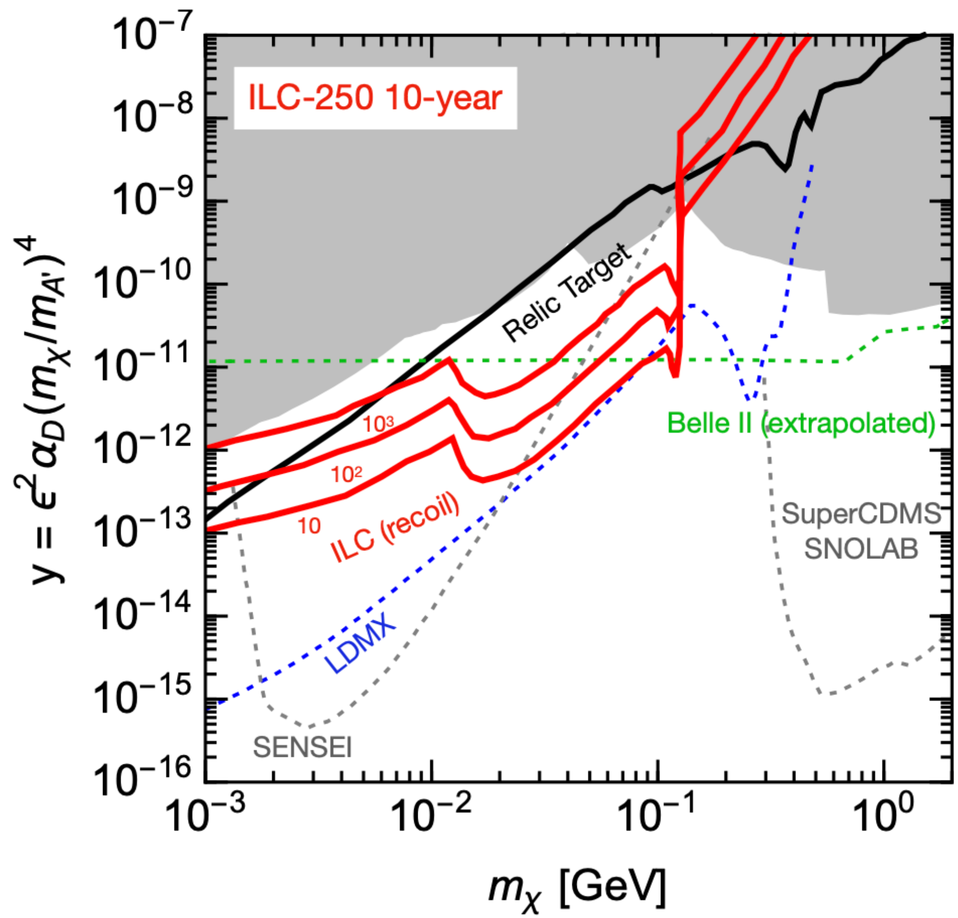
$$\mathcal{L}_{\rm int} = -{\rm i}g_{\rm D}A'_{\mu}\left(\chi^{*}\partial^{\mu}\chi - \chi\partial^{\mu}\chi^{*}\right)$$

$$\alpha_{\rm D} = 0.5,$$

$$m_{A'} = 3m_{\rm DM}$$



(a) electron beam dump



(b) positron beam dump

- Beam into water dump → neutrinos → background events.
  - neutrino-flux simulated by PYTHIA 8.3 + PHITS 3.25
- Event selection E_{recoil} > 1 GeV

electron recoil by neutrinos

$$\nu e^- \to \nu e^-, \quad \bar{\nu} e^- \to \bar{\nu} e^-$$

Nuclear recoil by neutrinos : mis-ID

$$\nu_\ell n \to \ell^- p, \quad \bar{\nu}_\ell p \to \ell^+ n,$$

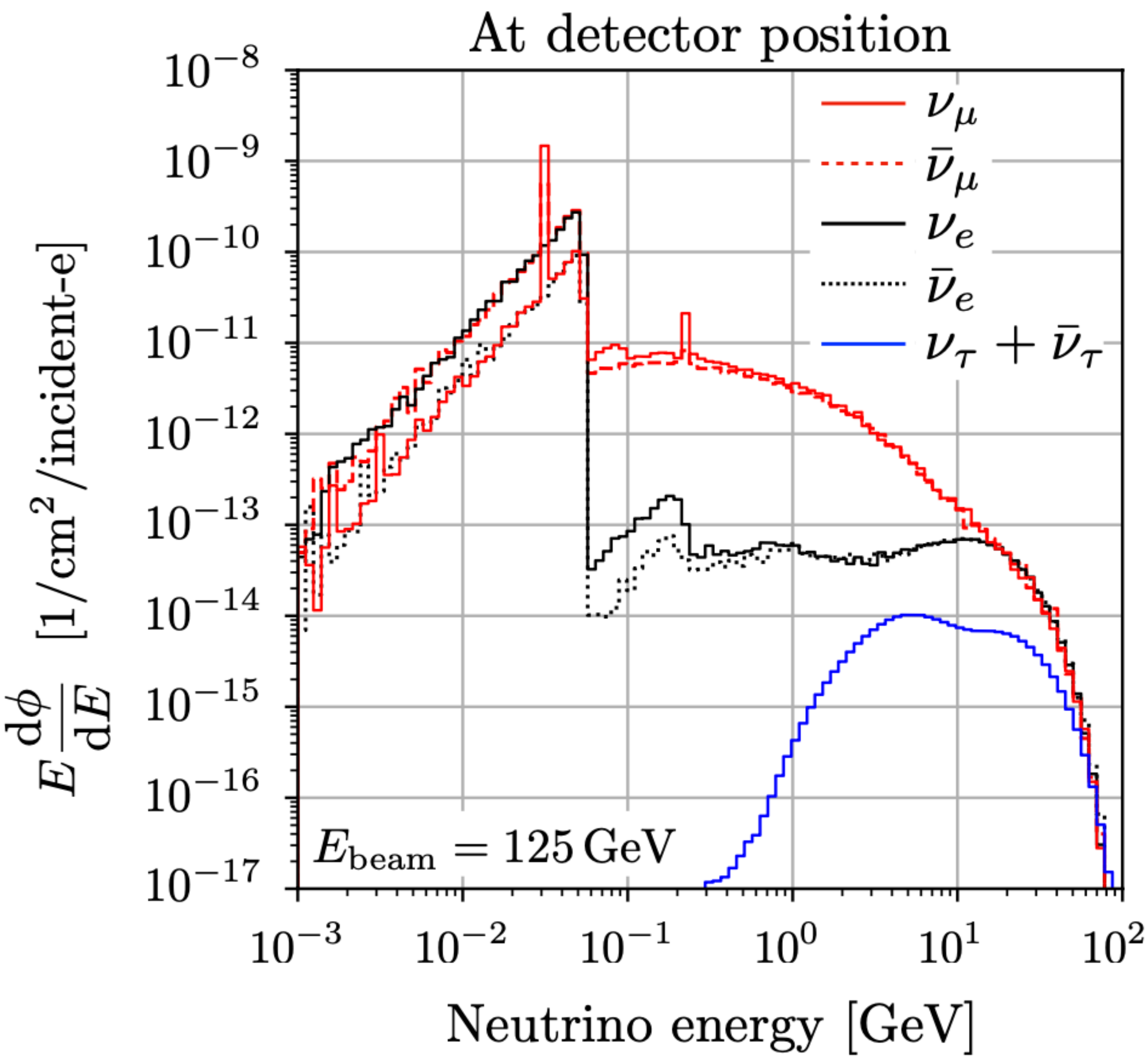
$$\nu p \to \nu p, \quad \bar{\nu} p \to \bar{\nu} p, \quad \nu n \to \nu n, \quad \bar{\nu} n \to \bar{\nu} n,$$

$$\nu_\mu n \to \mu^- p \pi^0, \quad \bar{\nu}_\mu p \to \mu^+ n \pi^0,$$

$$\nu_\mu p \to \nu_\mu p \pi^0, \quad \bar{\nu}_\mu p \to \bar{\nu}_\mu p \pi^0,$$

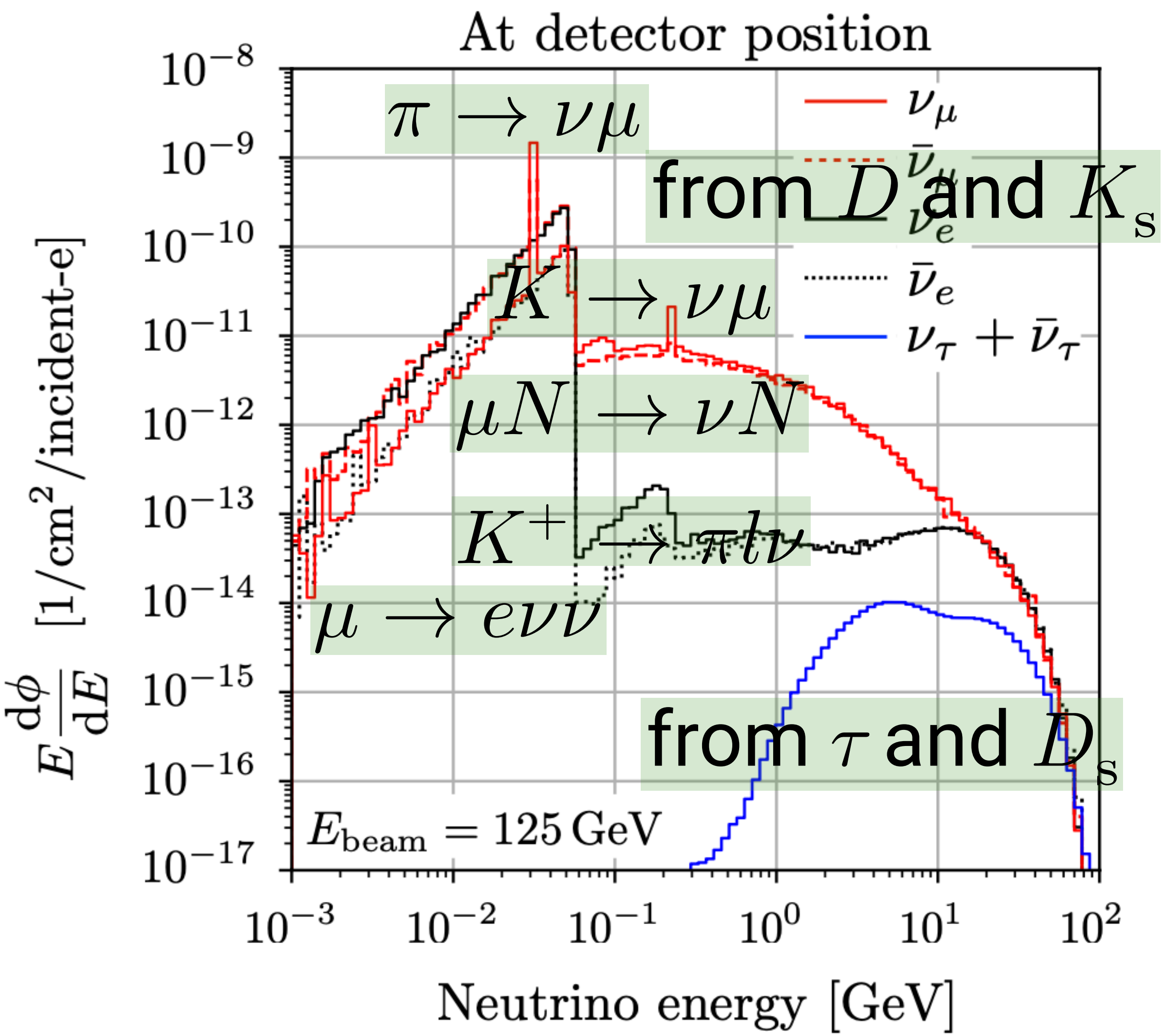
$$\nu_\mu n \to \nu_\mu n \pi^0, \quad \bar{\nu}_\mu n \to \bar{\nu}_\mu n \pi^0.$$

- Beam into water dump → neutrinos → background events.
  - neutrino-flux simulated by PYTHIA 8.3 + PHITS 3.25



■ Beam into water dump → neutrinos → background events.

- ➢ neutrino-flux simulated by PYTHIA 8.3 + PHITS 3.25



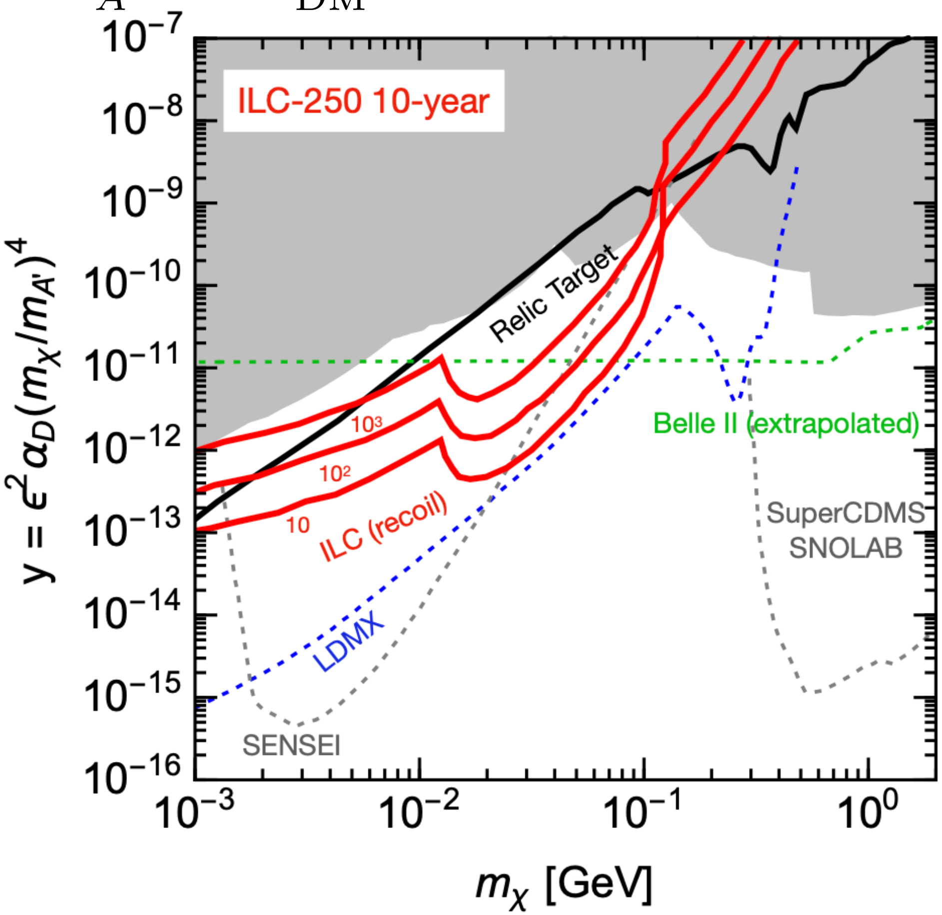
- Beam into water dump → neutrinos → background events.
  - neutrino-flux simulated by PYTHIA 8.3 + PHITS 3.25
- Event selection E_{recoil} > 1 GeV

  - **Neutrinos from dumped beam**
    - electron recoil ~ 10 / 10 years
    - nuclear recoil ~ 20000 × mis-ID rate / 10 years
  - **Neutrinos from cosmic rays** ~ O(10) / 10 years
  - **Noise** ~ ??

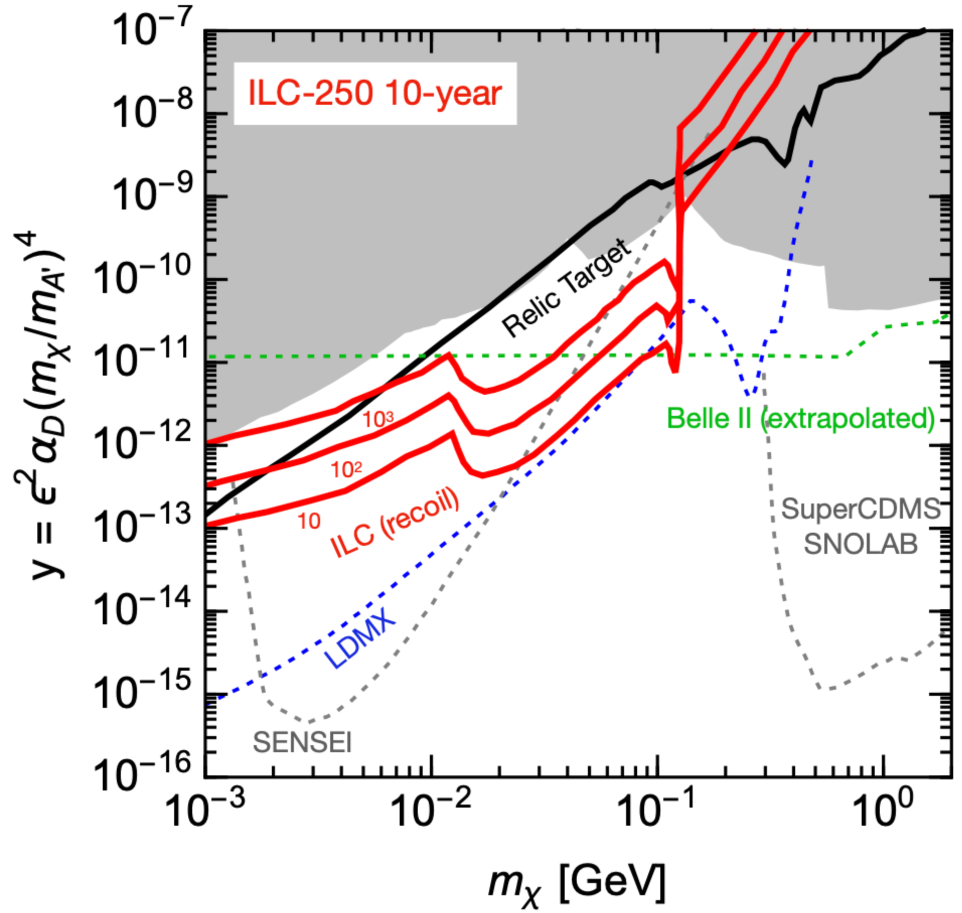
$$\mathcal{L}_{\rm int} = -{\rm i}g_{\rm D} A'_\mu \left(\chi^* \partial^\mu \chi - \chi \partial^\mu \chi^*\right)$$

$\alpha_{\rm D} = 0.5,$

$m_{A'} = 3m_{\rm DM}$



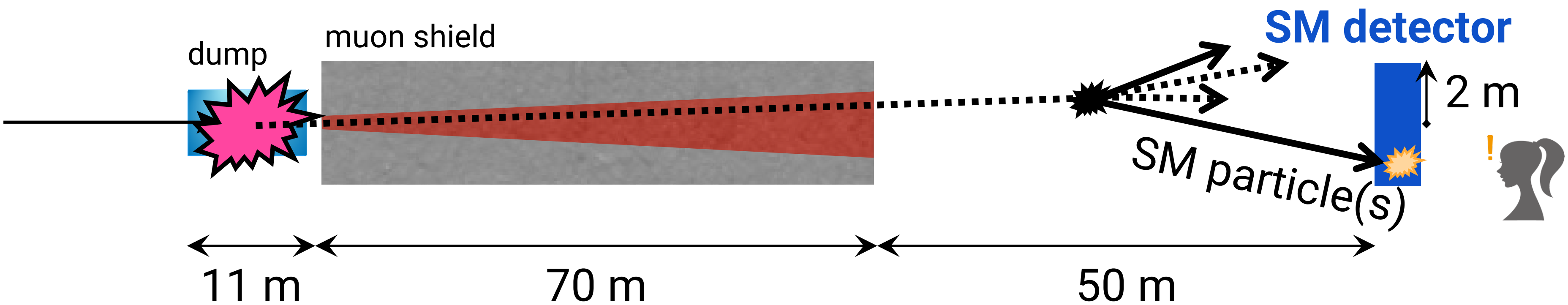
(a) electron beam dump



(b) positron beam dump

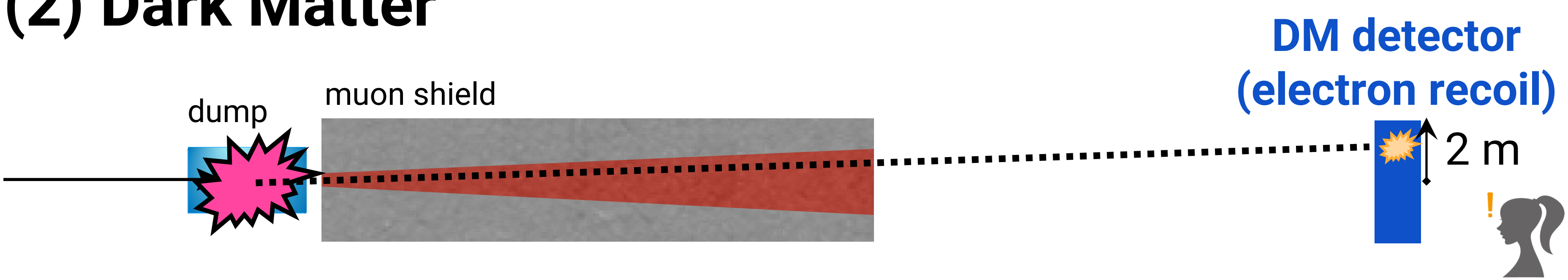
conclusion

(1) Meta-stable, decaying into SM (and other) particles

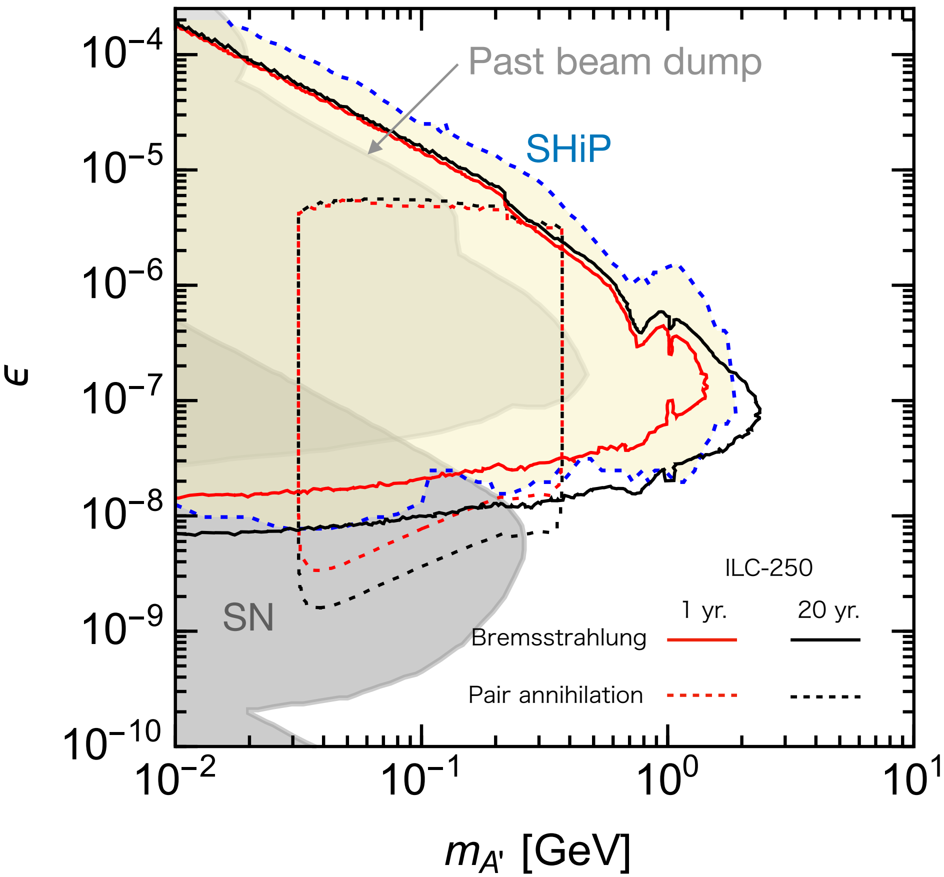


Sakaki, Ueda [2009.13790]
Asai, Iwamoto, Sakaki, Ueda [2105.13768]

(2) Dark Matter

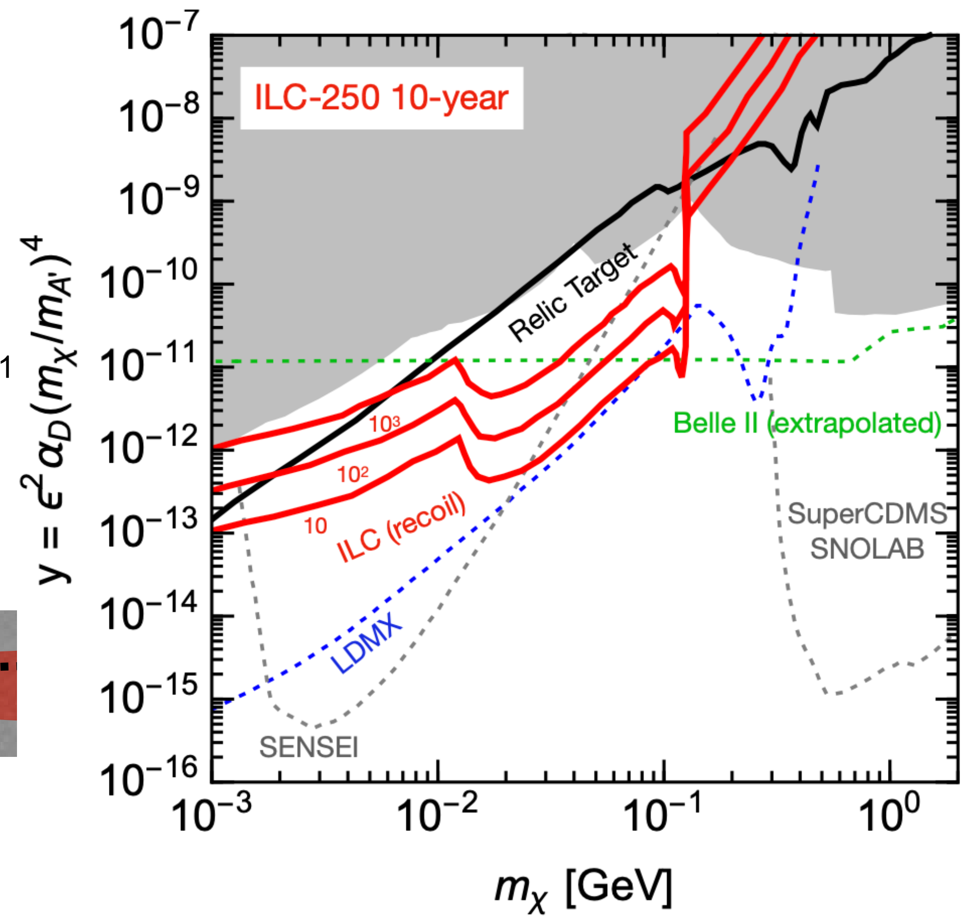


Asai, Iwamoto, Perelstein, Sakaki, Ueda [2301.03816]

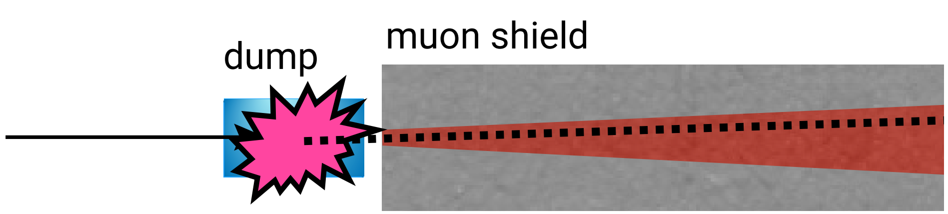


to SM (and other) particles

SM detector

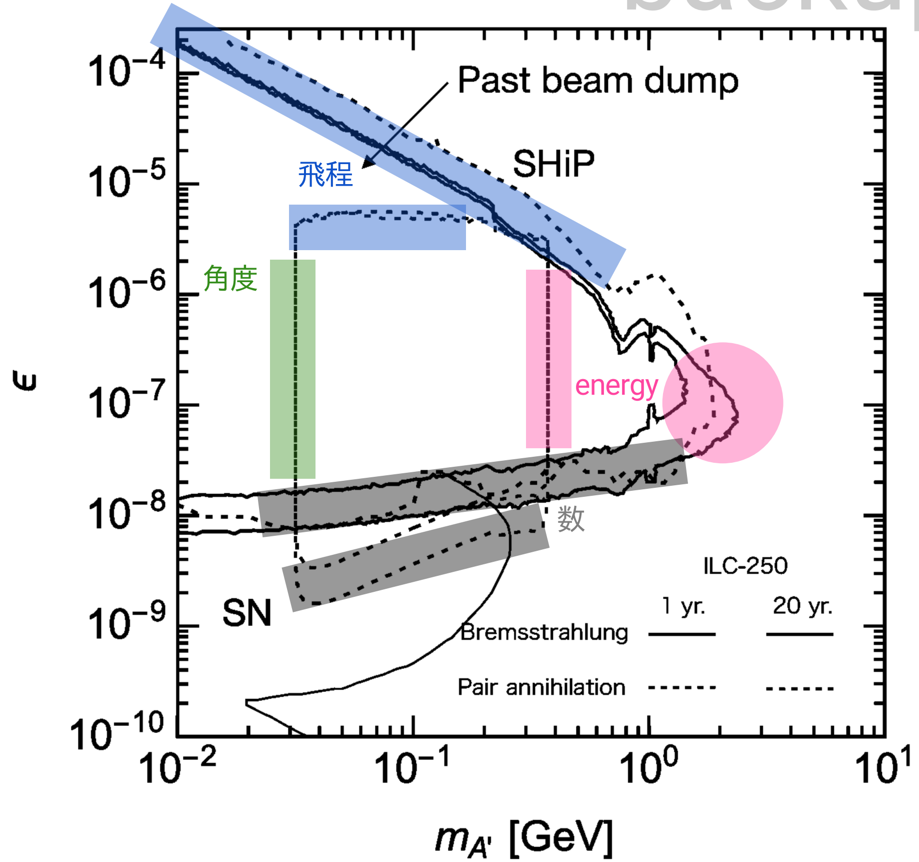


(2) Dark Matter



感度曲線の物理的解釈

backup slide



➤ Energy の限界

$$\sqrt{s} \sim m_{A'} < \sqrt{2mE_{\rm beam}} \simeq (360\,{\rm MeV}, 15\,{\rm GeV})$$

➤ 飛程の下限

$$\text{flight} = \frac{p_{A'}}{m_{A'}\Gamma} \overset{!}{\gtrsim} 70\,{\rm m}; \quad \Gamma \approx \frac{\alpha\epsilon^2 m_{A'}}{3}$$

- Pair-annihilation の場合

$$p_{A'} \sim E_{e^+}^{\rm shower} \sim \frac{m_{A'}^2}{2m_e} \longrightarrow \epsilon \lesssim 10^{-6}$$

- Bremsstrahlung の場合

$$p_{A'} \sim \mathcal{O}({\rm GeV}) \longrightarrow \epsilon m_{A'} \lesssim 10^{-7}\,{\rm GeV}$$

➤ 低 energy の shower 粒子は散らばりがち → 角度条件に引っかかる

（角度条件が実質的に
low-energy threshold になっている）

- $r_{\rm perp} < r_{\rm det} \iff \theta \lesssim (2\,{\rm m})/(120\,{\rm m}) = 1/60$
- our approx. $\theta^{-1} \approx (E_{e^\pm}/{\rm GeV})/0.008 \implies E_{e^\pm} \gtrsim 0.5\,{\rm GeV} \implies \sqrt{2m_e E_{e^+}} \simeq 23\,{\rm MeV}$

➤ Injection 強度（とdecay volume の長さ）