A New Probe for Long-Lived Particles at Higgs Factories: Displaced Photons in the Hadronic Calorimeter

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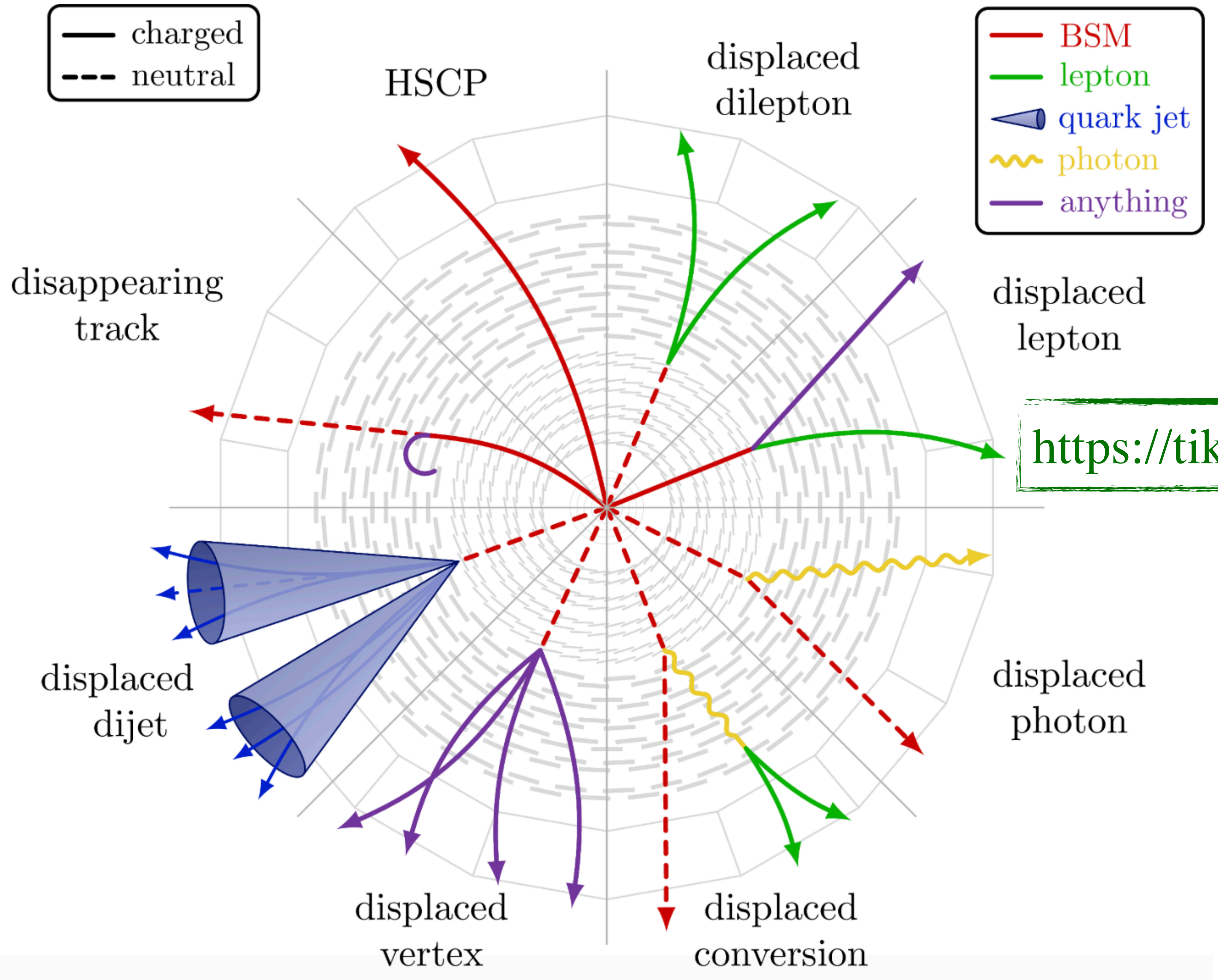
Outline

- Challenges in detecting displaced photons at future Higgs factories
- A new probe for displaced photons: the HCAL as a photon far detector
- Why the HCAL can serve as a photon detector, and the advantages of the new probe
- Sensitivities of the new probe for benchmark models

Long-lived particle (LLP) searches at colliders

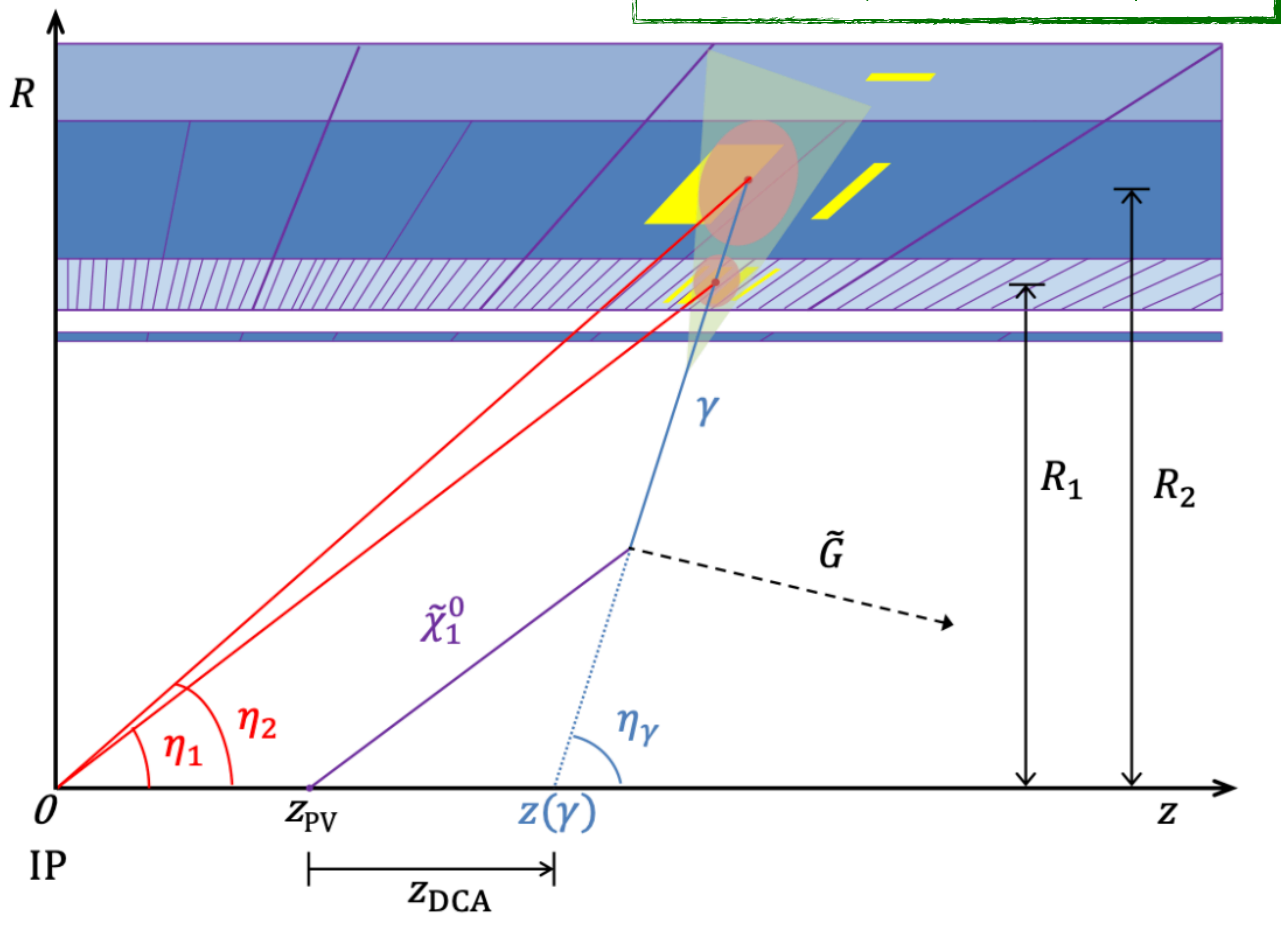
Decay into charged particles:
displaced dijet, displaced dilepton…
(vertex detector, tracker)
negligible backgrounds

Decay into neutral particles:
displaced photon (non-pointing photon)
(Multi-layer ECAL)
more backgrounds



https://tikz.net/bsm_longlived/

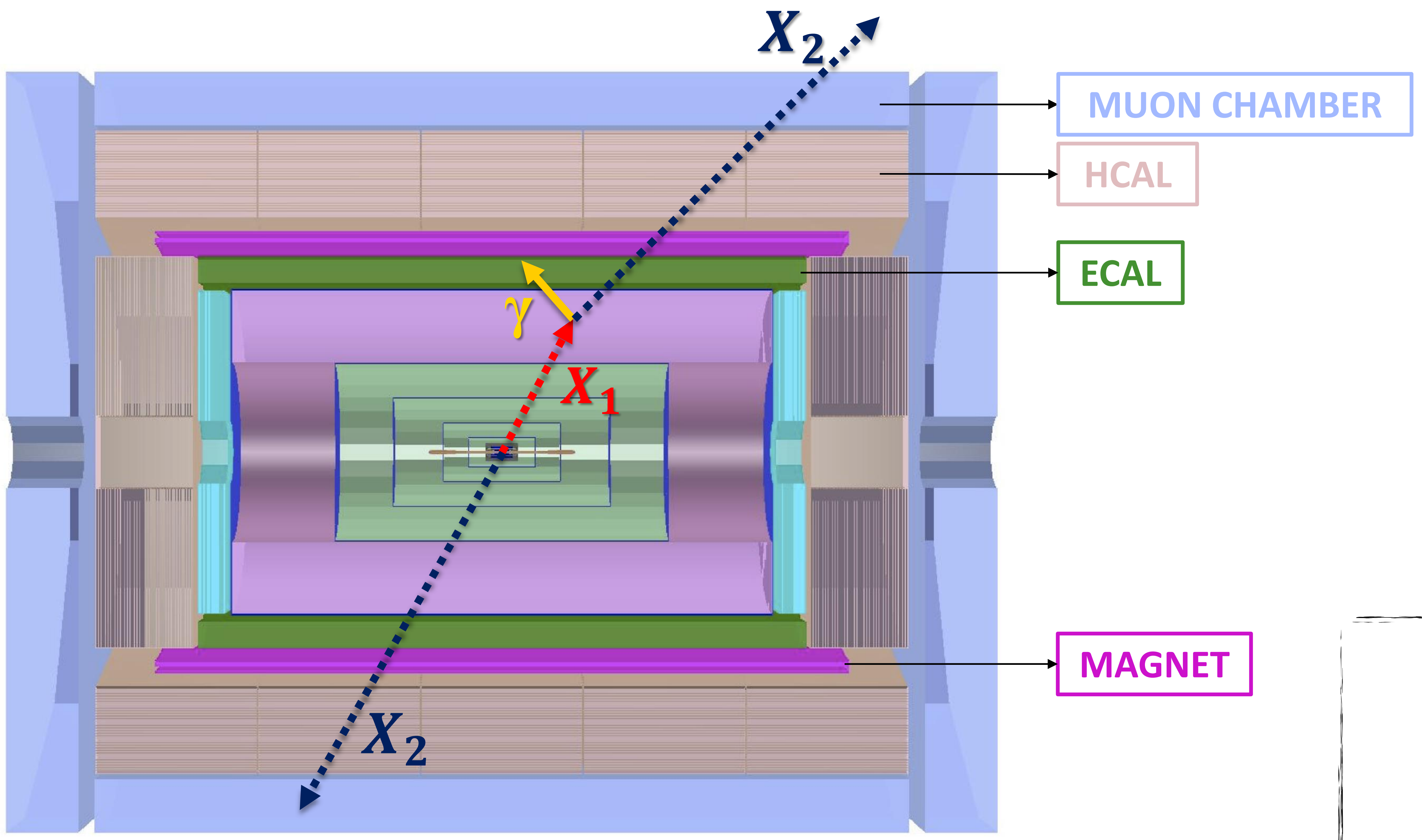
Nikiforou, PHD thesis, 2014



In general, displaced charged particles have cleaner backgrounds than displaced photons, thanks to the higher position resolution of the vertex detector and the tracker.

Large backgrounds for displaced mono-photon at future Higgs factories

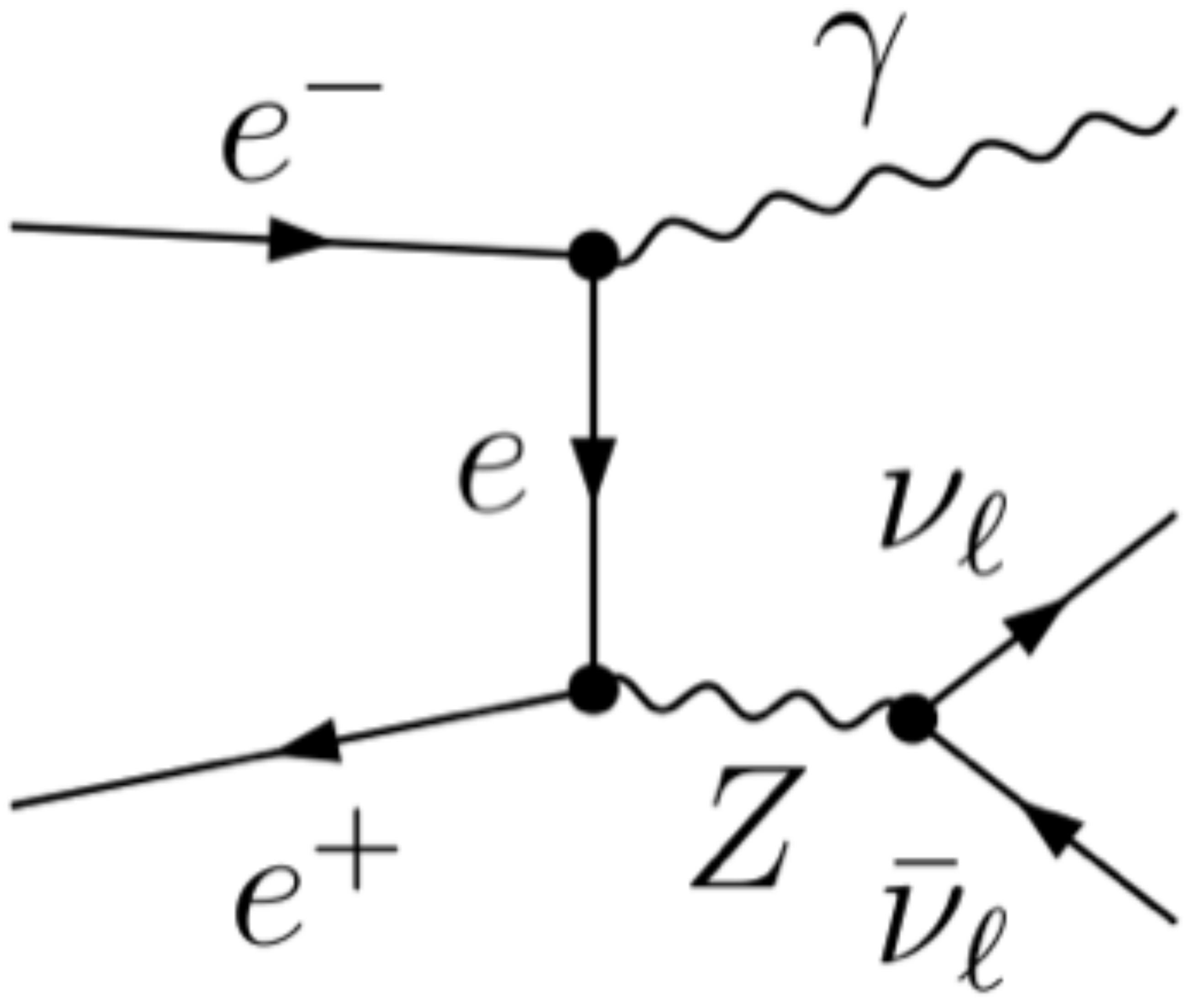
CEPC reference detector



$$e^+e^- \to X_1 X_2,\ X_1 \to X_2 \gamma$$

X_1: heavier dark sector particle

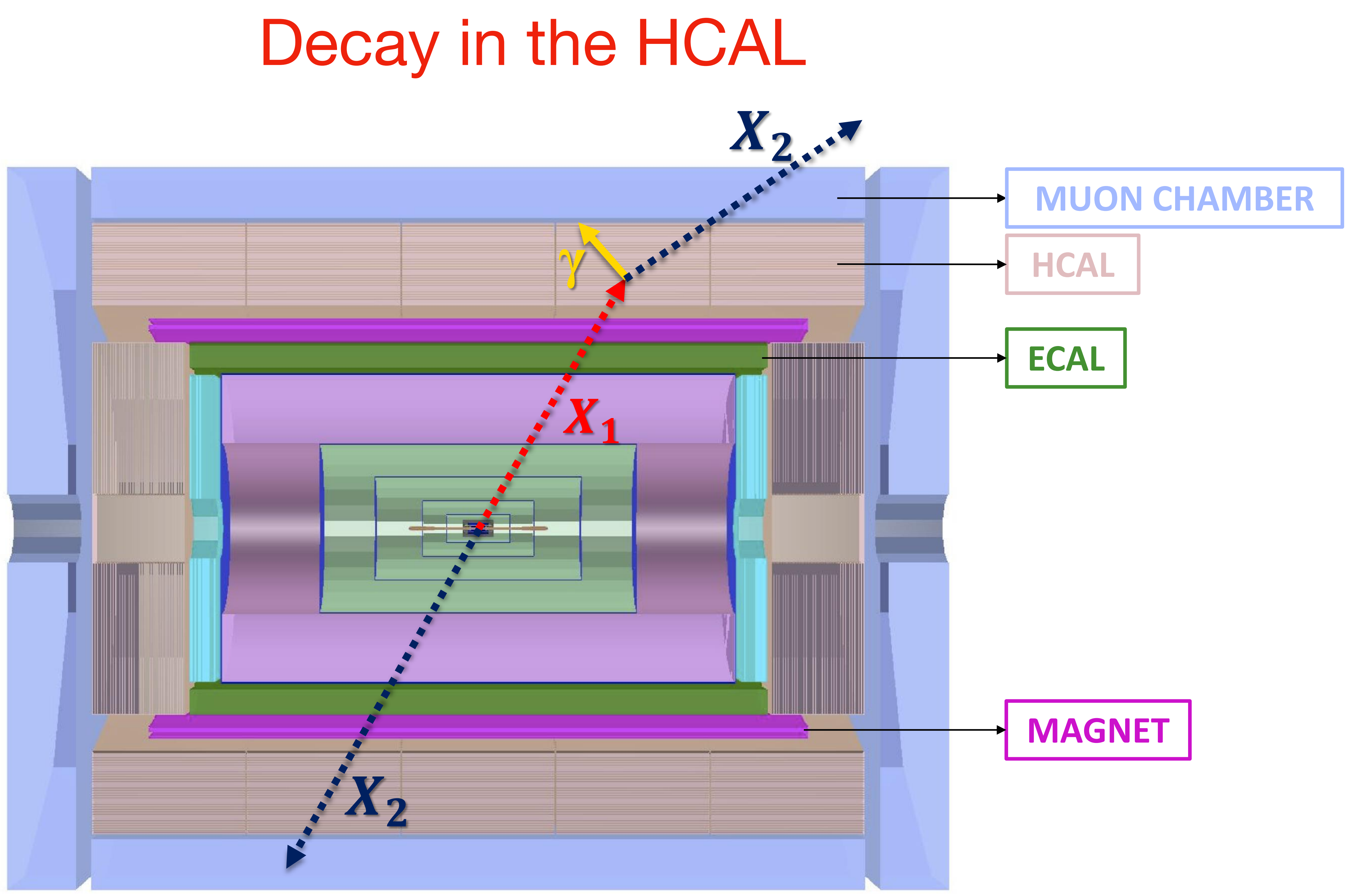
X_2: lighter dark sector particle or SM neutrino

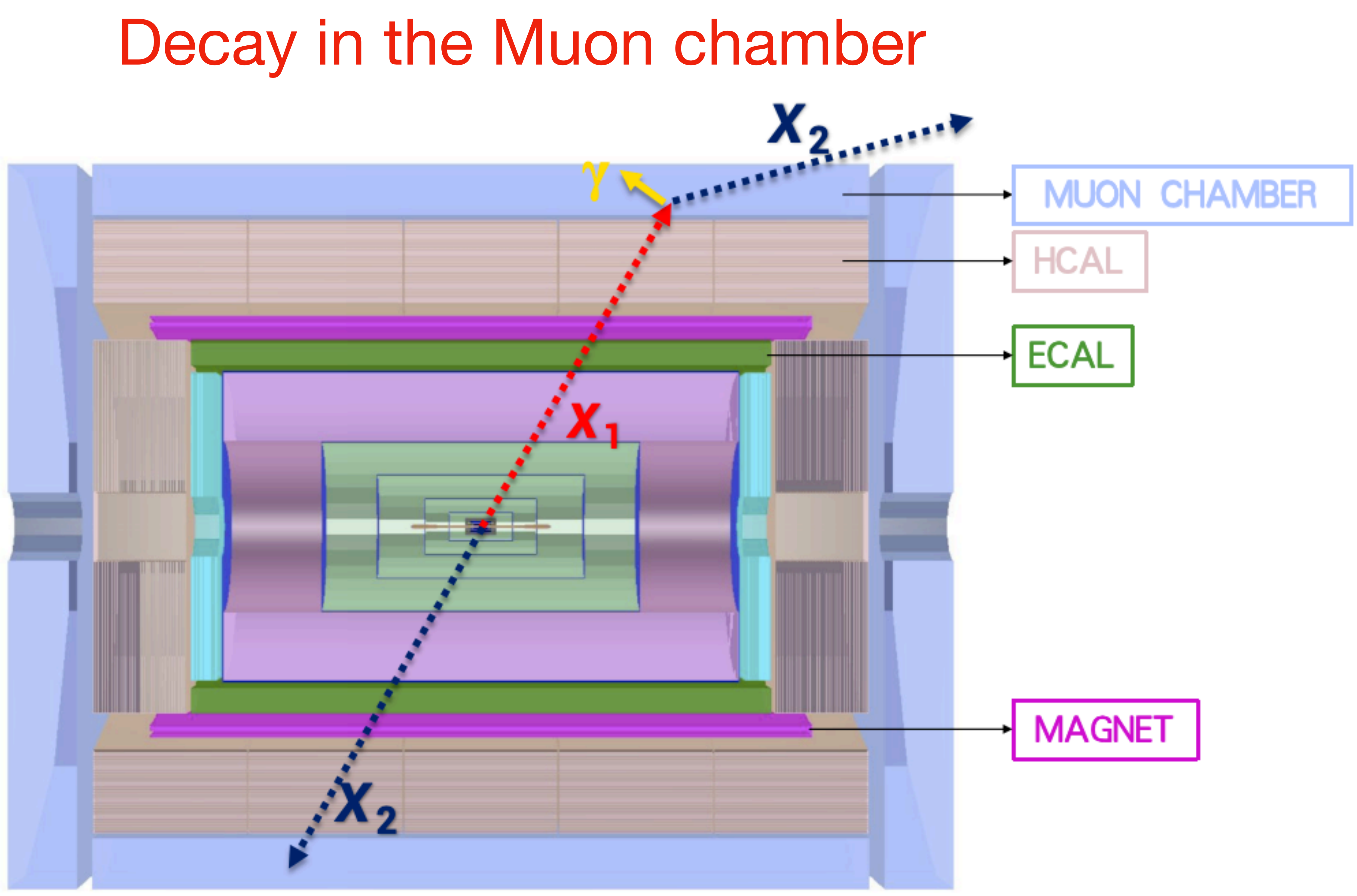


More than 10^{10} $e^+e^- \to \nu\bar{\nu}\gamma$ events with $E_\gamma > 1$ GeV for CEPC Z-mode with the luminosity of 100/ab

Displaced photons face large backgrounds at future Higgs factories

HCAL and the muon detector serving as photon far detectors





$$e^+e^- \to X_1 X_2,\ X_1 \to X_2 \gamma$$

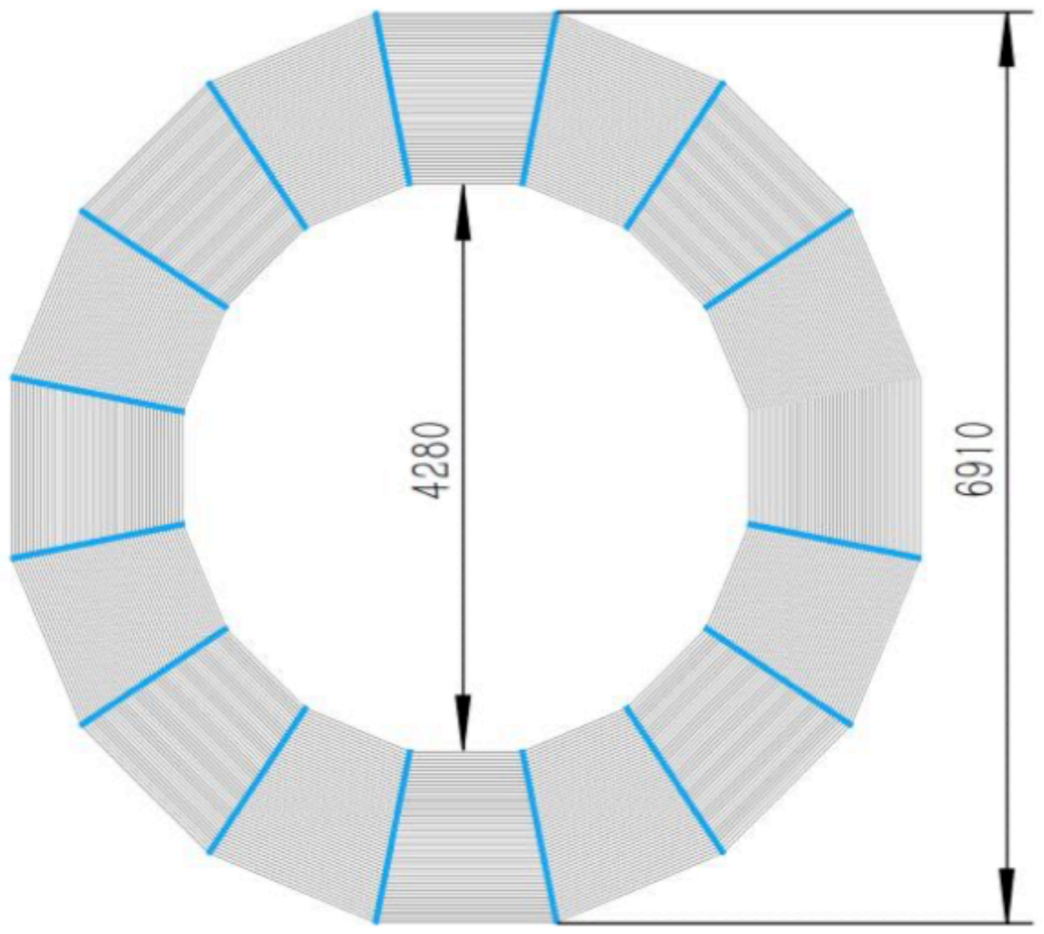
X_1: heavier dark sector particle

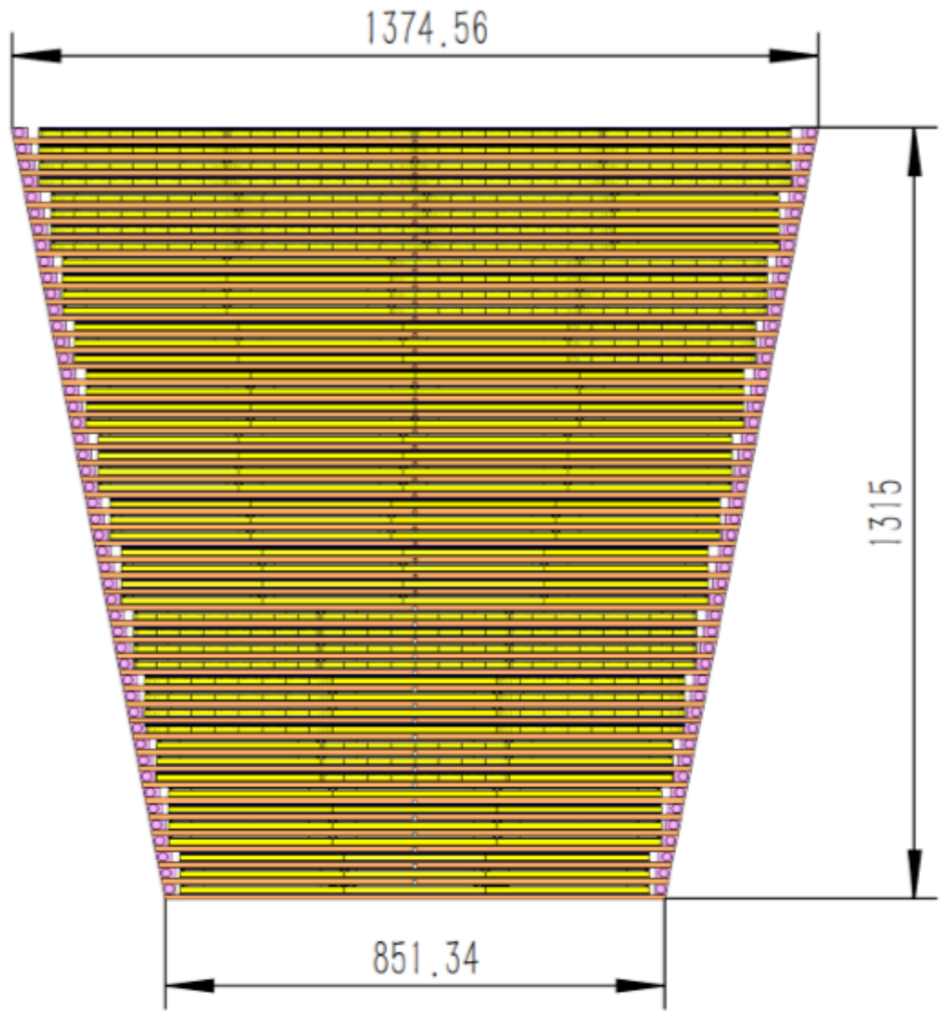
X_2: lighter dark sector particle or SM neutrino

Using the ECAL as a shield against mono-photon backgrounds from the primary vertex and detecting displaced photons in the HCAL or muon detector.

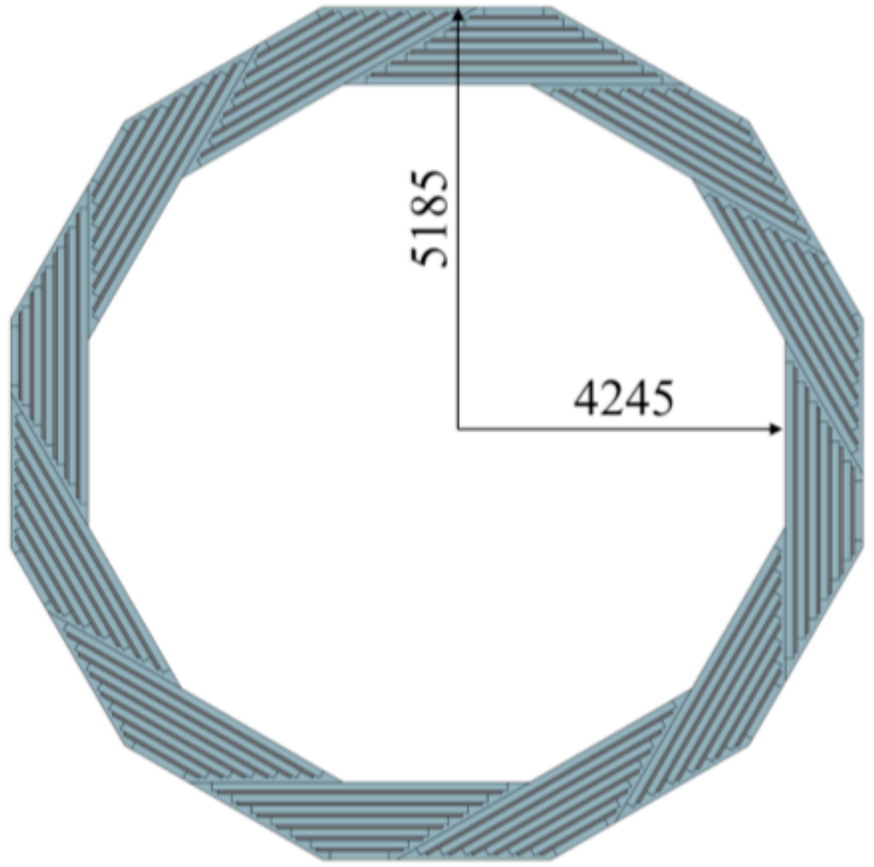
HCAL and the muon detector serving as photon far detectors

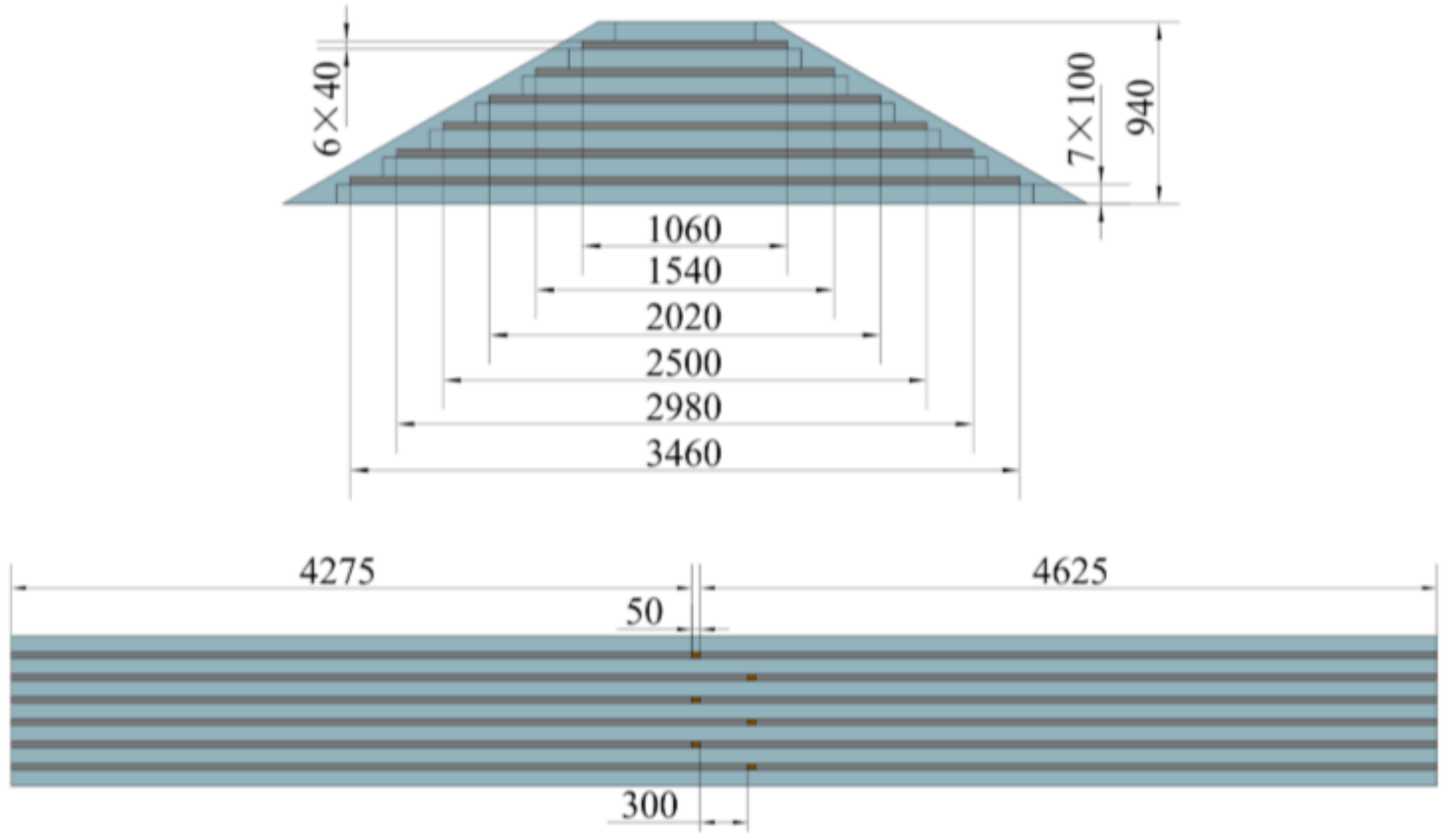
CEPC Ref-TDR



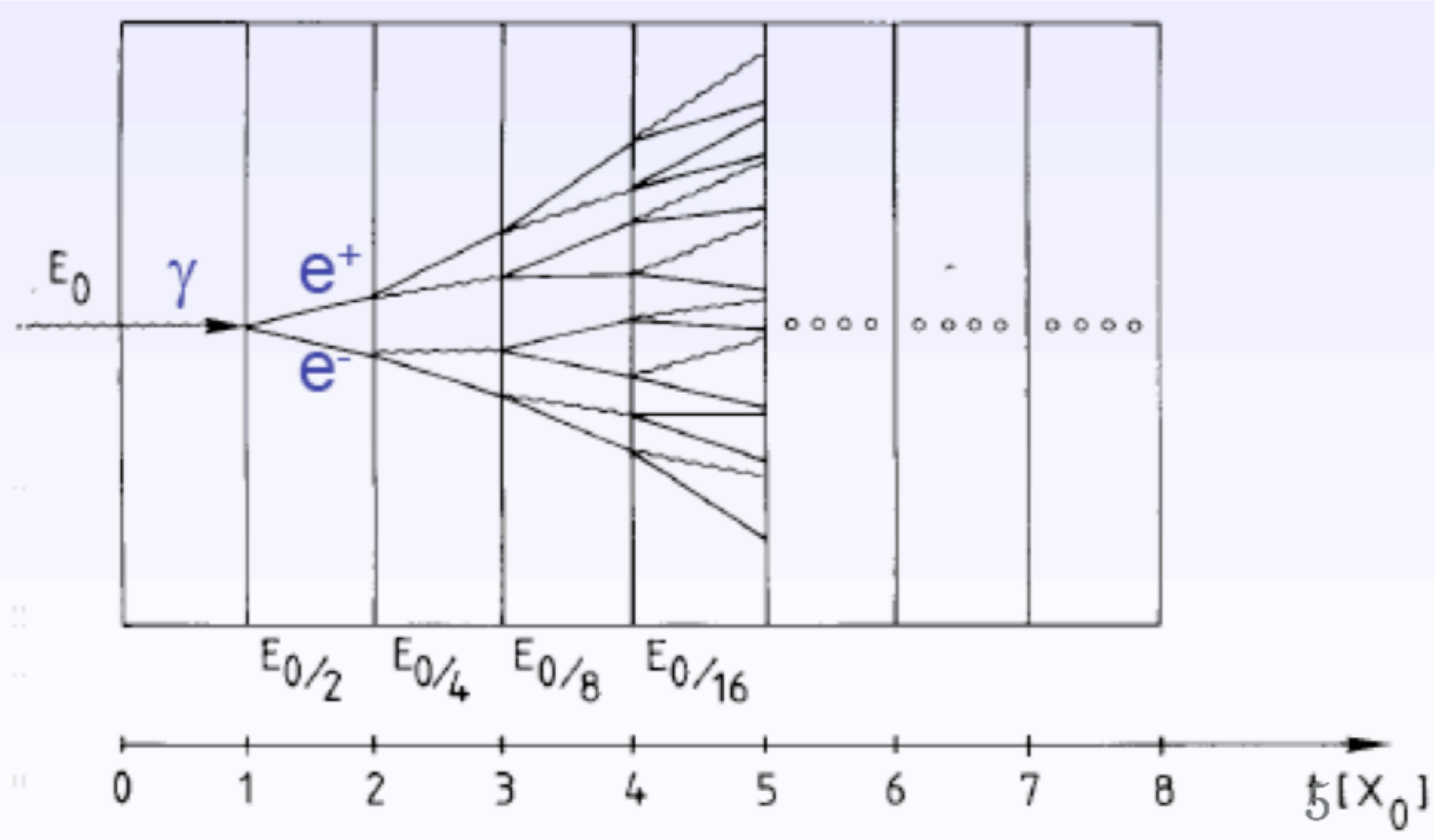


HCAL



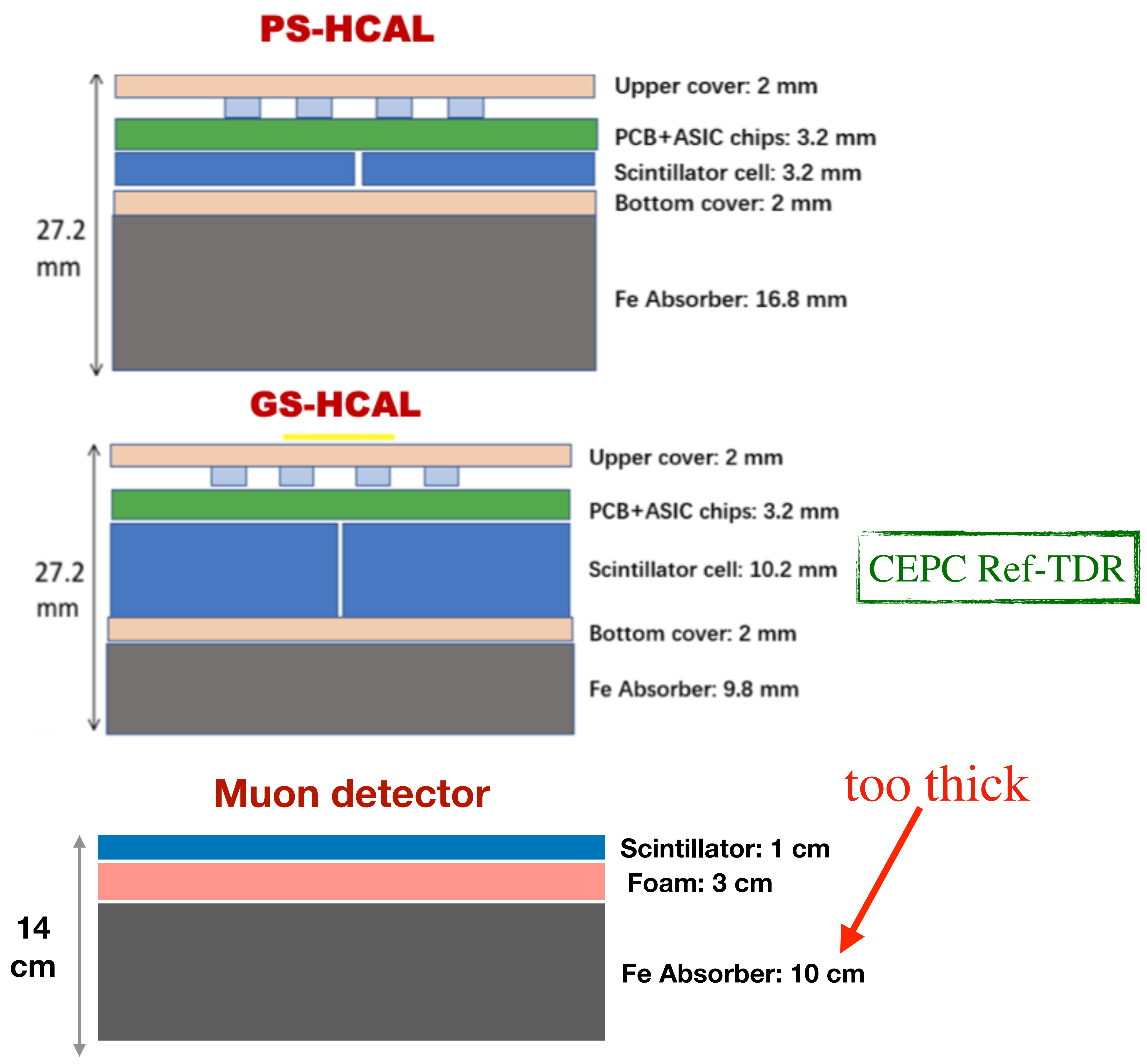


Muon detector



Both the HCAL and the muon detector are sampling detectors with a sandwich structure of iron plates and scintillators, when considered as detectors for photons.

The HCAL serving as a photon far detector

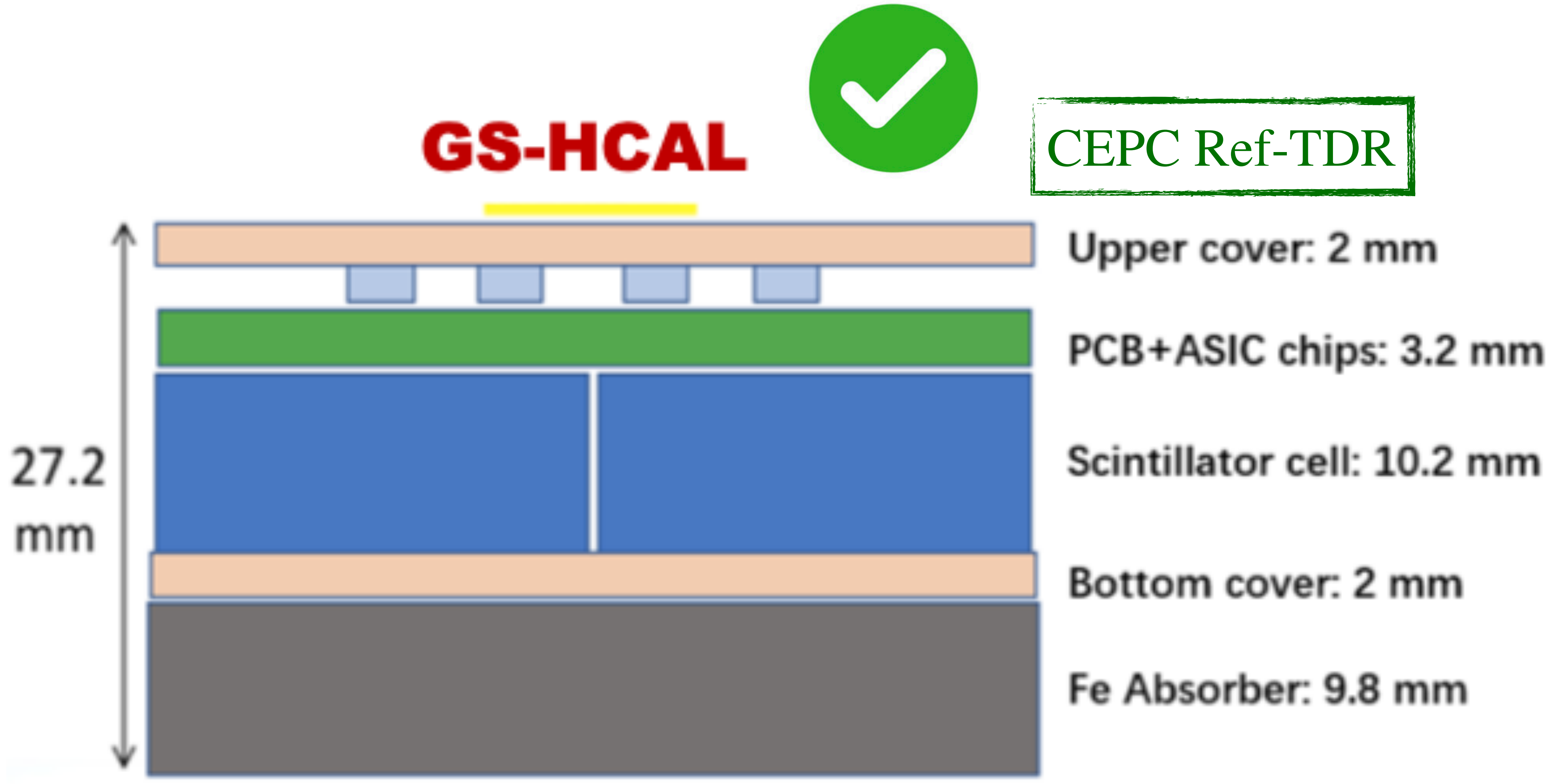


$$E_\gamma^{\min} = 2^t \times E_c, t = L/X_0$$

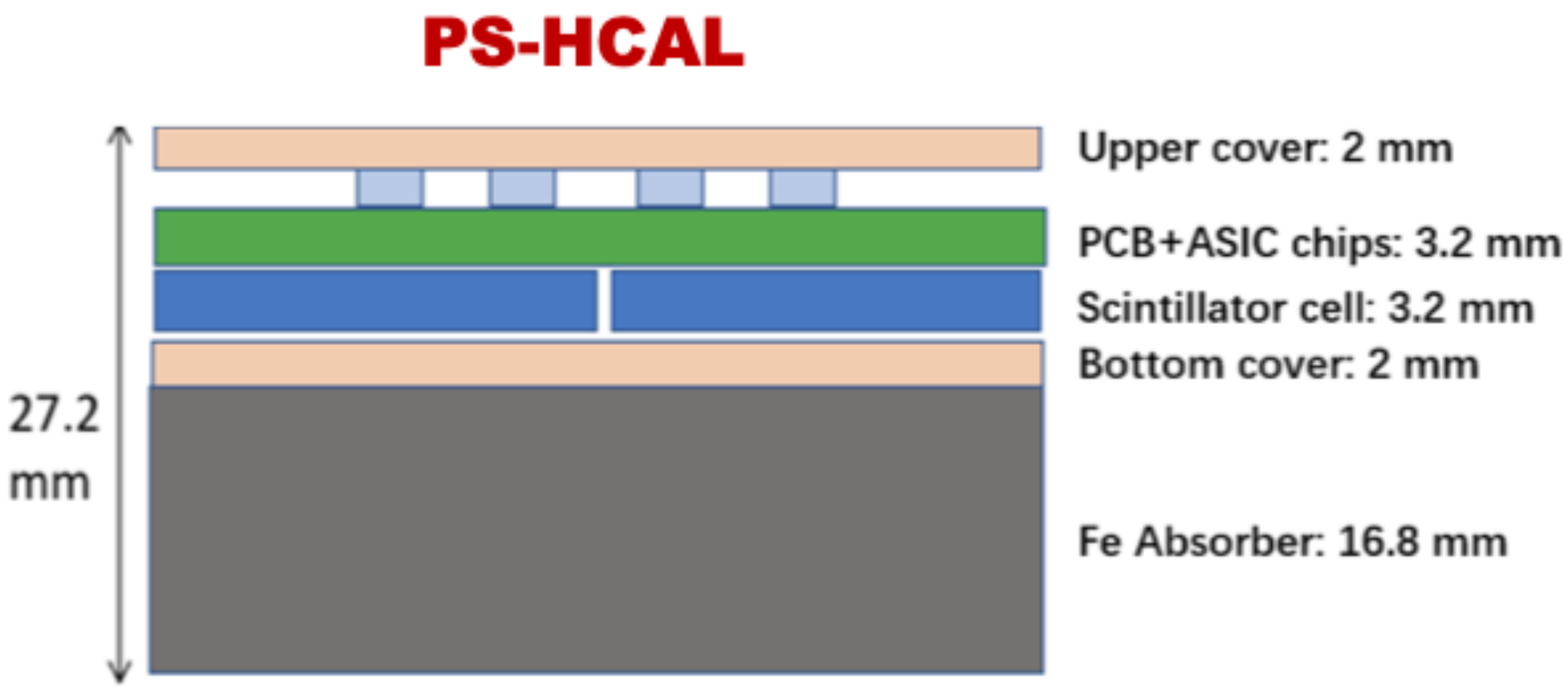
Detector	PS-HCAL	GS-HCAL	Muon detector
Main components per layer	20.8 mm Fe	13.8 mm Fe 10.2 mm GS	10 cm Fe
t (radiation length per layer)	1.21	1.44	5.68
Critical energy	~20.7 MeV	~15.7 MeV	~20.7 MeV
Energy threshold for five layers	1.37 GeV	2.30 GeV	7332 TeV
	✓	✓	✗

Only HCAL can be used to detect photons, either GS-HCAL or PS-HCAL, provided that energy is deposited in at least five active layers.

The GS-HCAL serving as photon far detectors



Sampling fraction ~31%



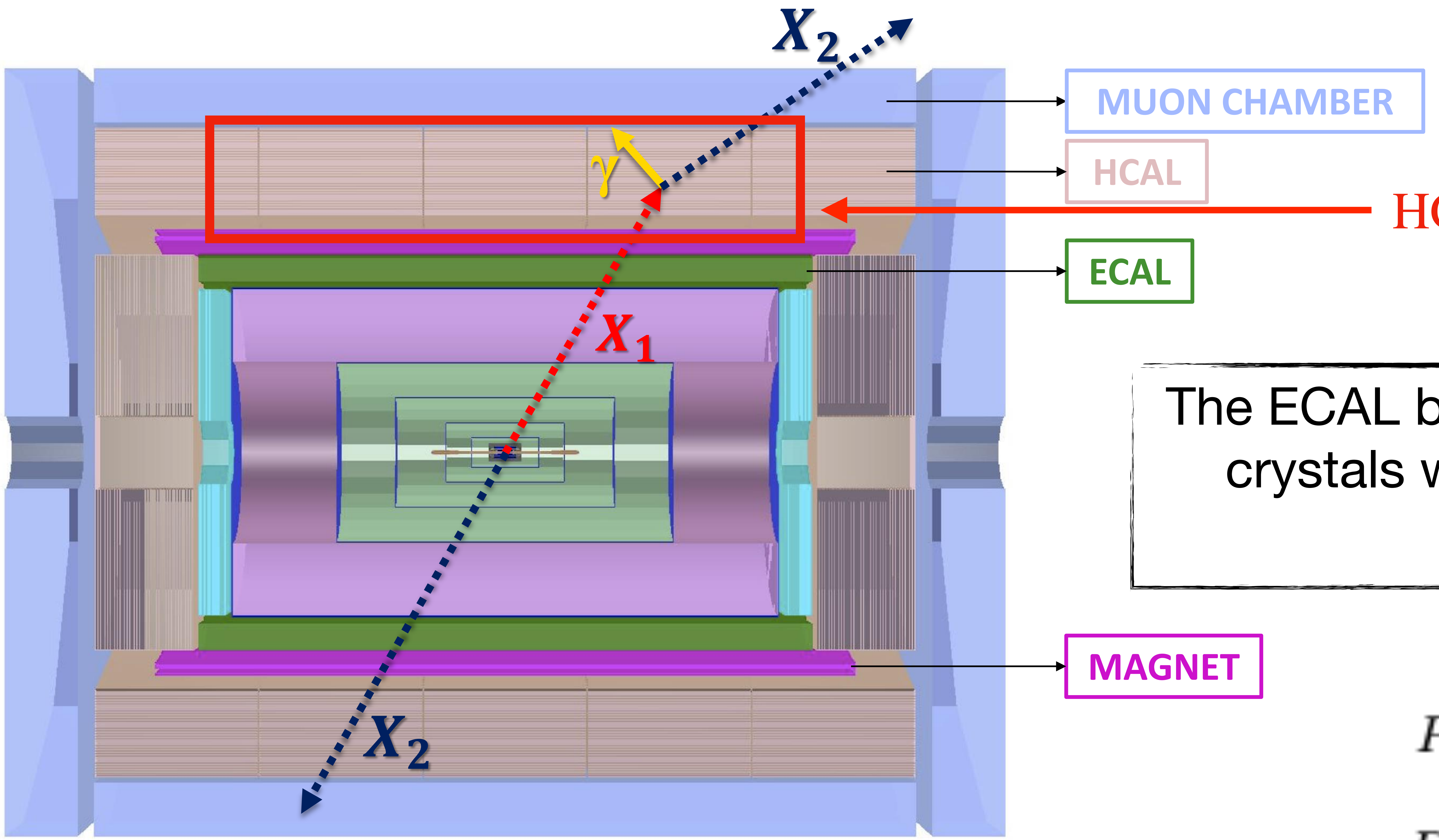
Sampling fraction ~1.6%

With high density and thick GS cell design, the sampling fraction of GS-HCAL can be increased by a factor of ~20 compared to that of PS-HCAL.

↓

We take the GS-HCAL as the benchmark detector for photons originating from LLP decays and assume a 50% reconstruction efficiency.

GS-HCAL barrel serving as a photon far detector



The ECAL barrel employs homogeneous BGO crystals with a total thickness of 300 mm (24 X_0, 1.35 λ_I).

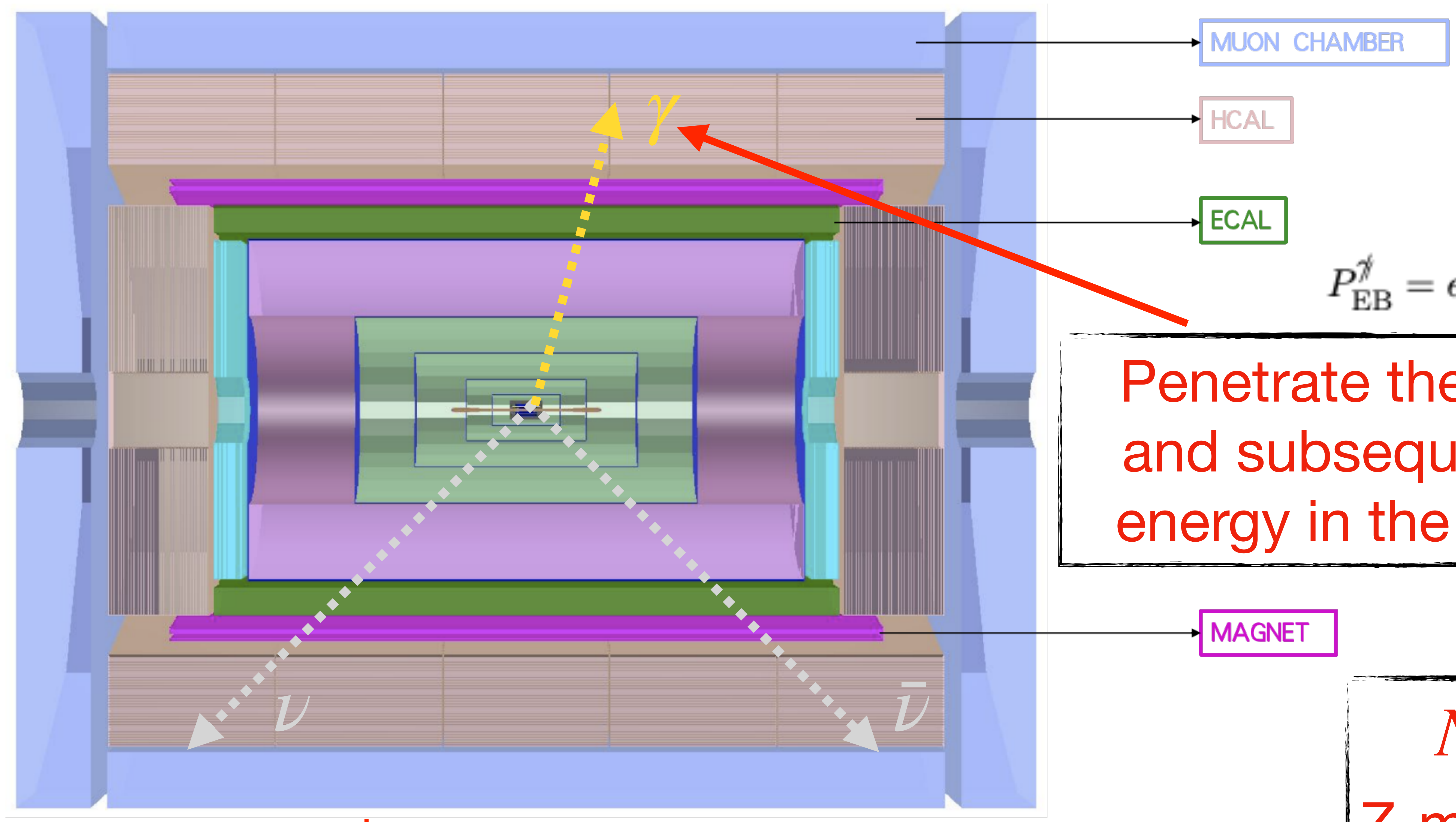
$$P_{\mathrm{EB}}^{\not\gamma} = e^{-7/9\times 24} = 7.8\times 10^{-9}$$

$$P_{\mathrm{EB}}^{\not h} = \exp(-1.35) = 0.26$$

The HCAL barrel is surrounded by ECAL, HCAL endcaps, and muon detector, which together provide strong veto capabilities against beam-related backgrounds, cosmic rays, and neutral particles from the primary interaction.

Backgrounds

- Photon backgrounds
- Neutrino backgrounds
- Neutral hadron backgrounds



$P_{\rm EB}^{\gamma} = e^{-7/9\times 24} = 7.8\times 10^{-9}$

Penetrate the ECAL barrel and subsequently deposit energy in the HCAL barrel.

$N_{\rm BG}^{\gamma} \sim 10$

Z-mode, 100/ab

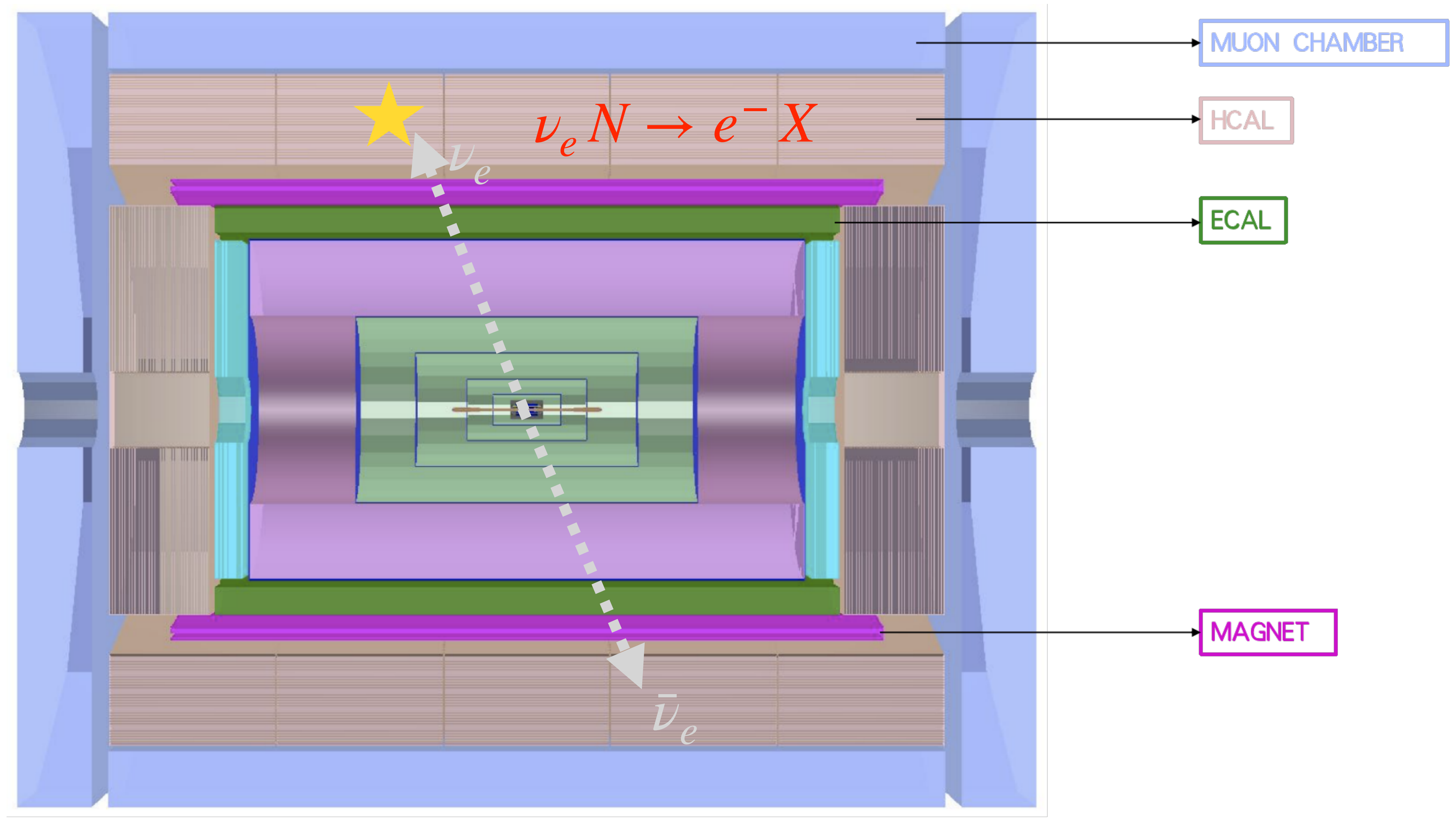
$e^+e^- \to \nu\bar{\nu}\gamma$

The dominant SM backgrounds for the HCAL mono-photon signature originate from neutral particles such as single photons, neutrinos, or neutral hadrons produced at the primary vertex without any accompanying detectable particles.

These neutral particles evade detection in the inner tracker and ECAL, and subsequently deposit energy in the HCAL barrel.

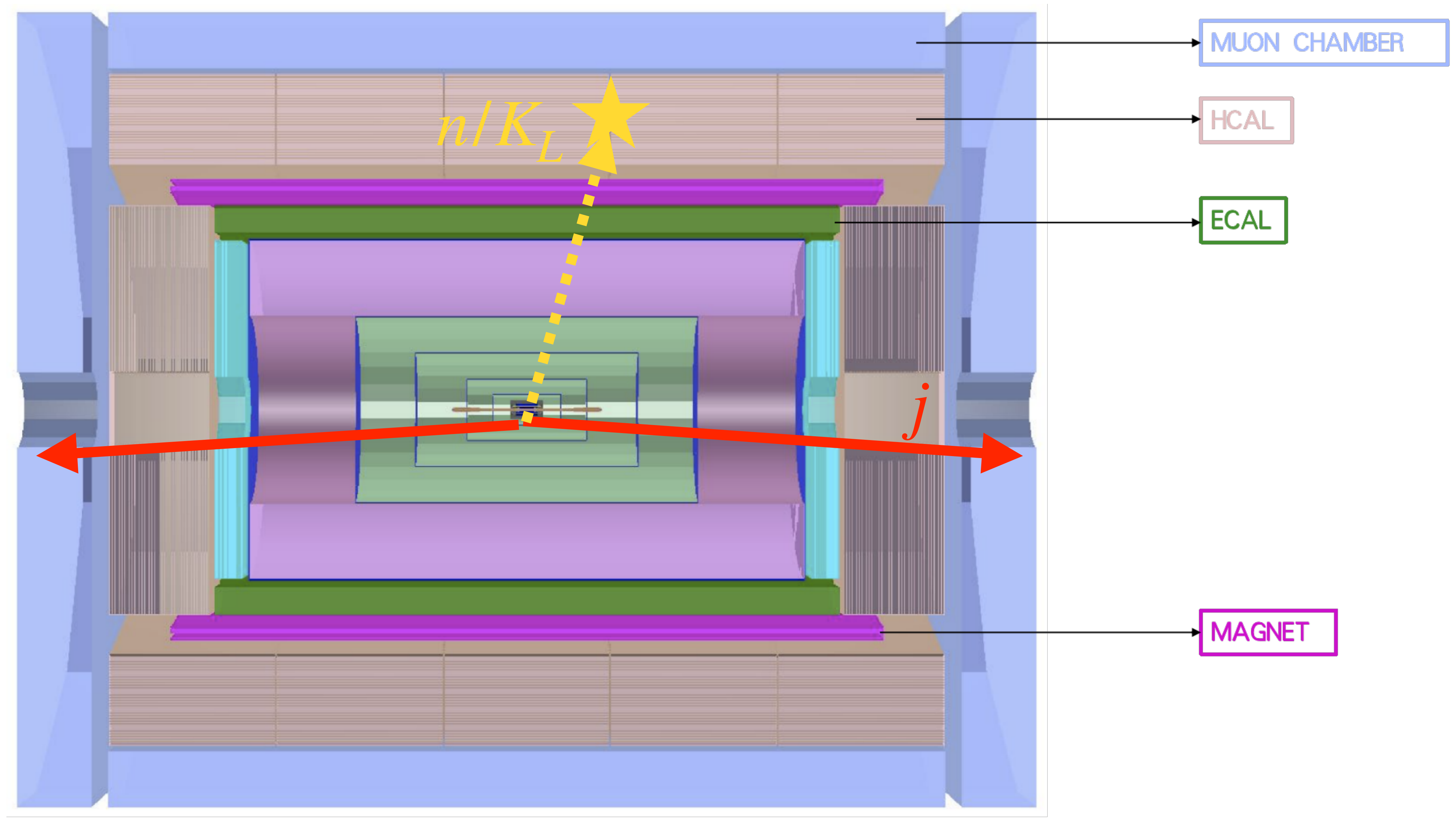
Neutrino and neutral hadron Backgrounds

Neutrino backgrounds



$$N^{\nu}_{\rm BG} \sim 1$$

Neutral hadron backgrounds



$$N^{n}_{\rm BG} \sim 10^3$$

The EM showers initiated by photons differ significantly from those produced by hadrons.
It is expected that neutral hadron backgrounds can be further suppressed by PFA.

Sensitivity estimation

$N_{\mathrm{BG}}^{\gamma} \sim 10,\ N_{\mathrm{BG}}^{\nu} \sim 1,\ N_{\mathrm{BG}}^{n,K_L} \sim 10^3$

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^3$

Optimistic estimation

(Particle flow algorithms can effectively distinguish neutron hadrons and photons in the HCAL)

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^2$

Conservative estimation

(Other potential backgrounds)

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^4$

2σ sensitivity: $N_s = 2\sqrt{N_{\mathrm{BG}}^{\mathrm{tot}}}$

Axion portal operator

$$\mathcal{O}_{a\gamma' B} \equiv g_B\, a\tilde{F}'_{\mu\nu}B^{\mu\nu}$$

a: axion like particle

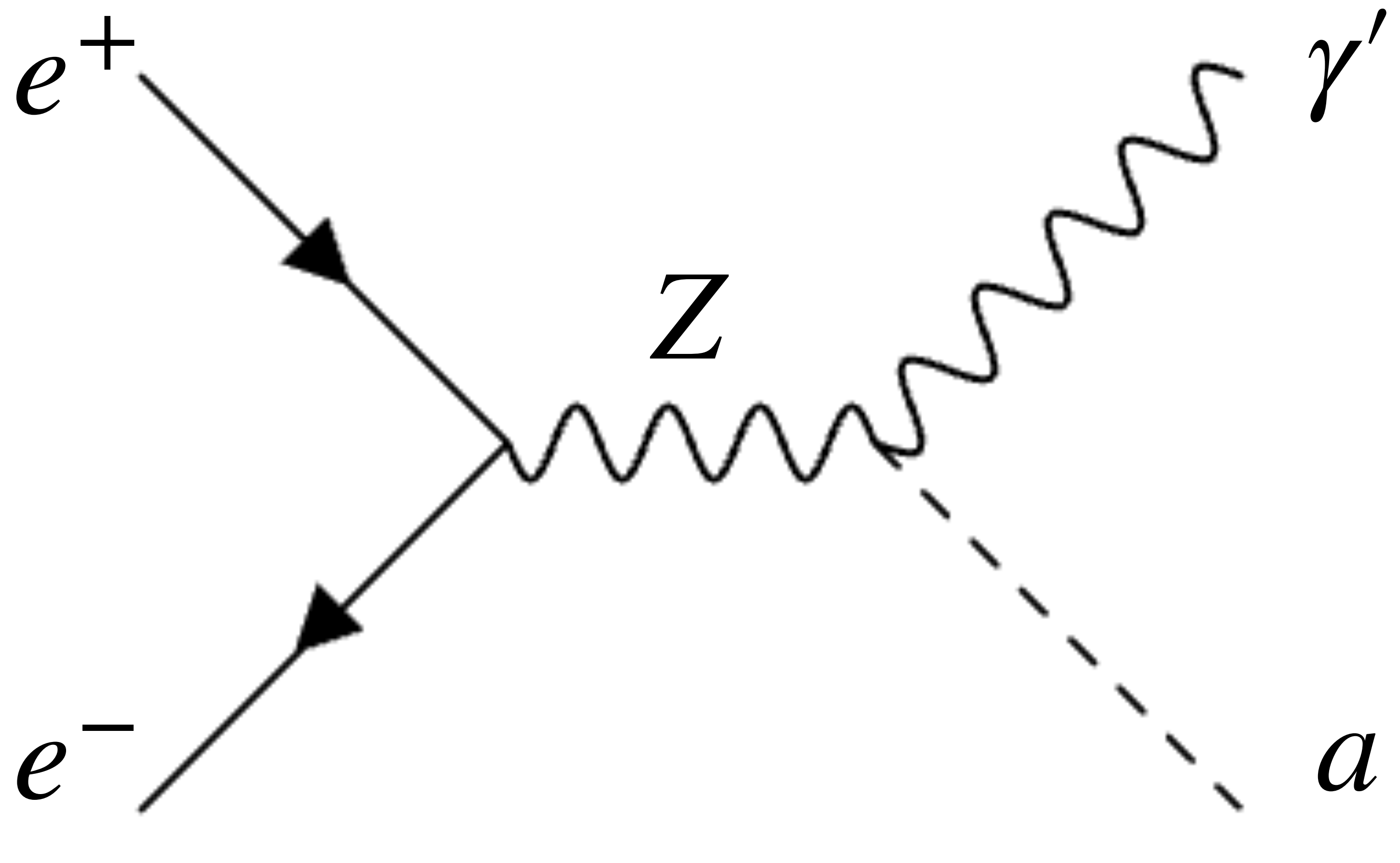
$F'_{\mu\nu}$: the field-strength tensor of the dark photon γ'

$B_{\mu\nu}$: the hypercharge field-strength tensor

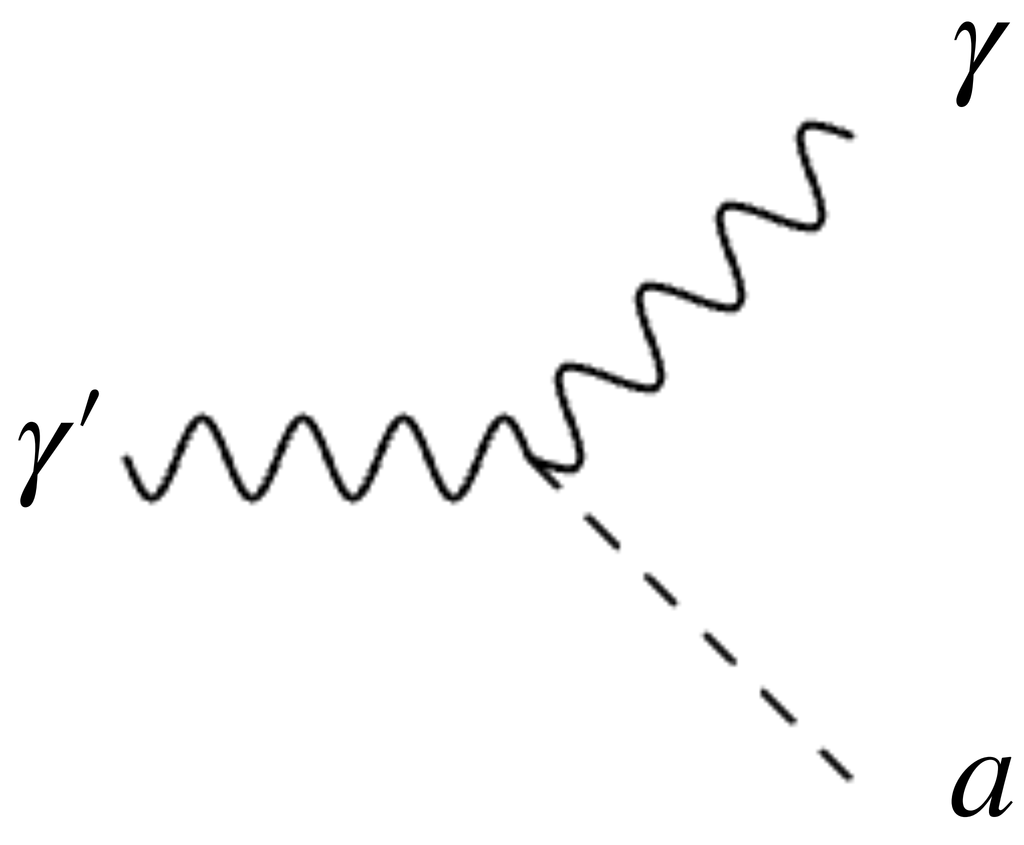
$$m_Z > m_{\gamma'} > m_a$$

$$\Gamma_{\gamma'\to a\gamma} = \frac{1}{24\pi}\, g_B^2\, c_W^2\, m_{\gamma'}^3\,(1 - r_m^2)^3,\, r_m = m_a/m_{\gamma'}$$

$$L_D \simeq \mathcal{O}(\mathrm{m}) \times \left(\frac{g_B \mathrm{GeV}}{10^{-4}}\right)^{-2} \times (1 - r_m^2)^{-2} \times (\frac{m_{\gamma'}}{0.1\,\mathrm{GeV}})^{-4}$$



Generation process

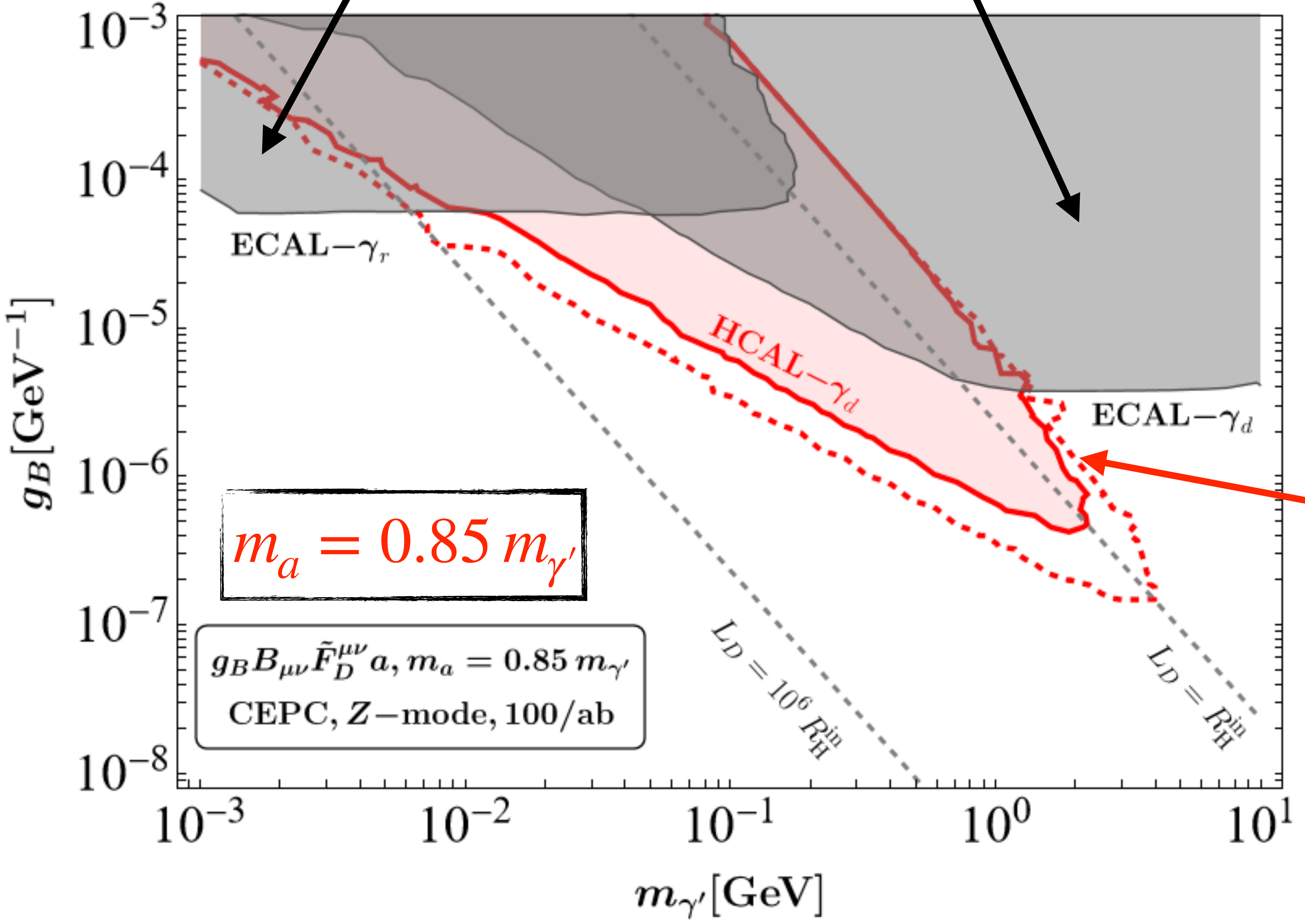


Decay process

CEPC sensitivities on the axion portal operator

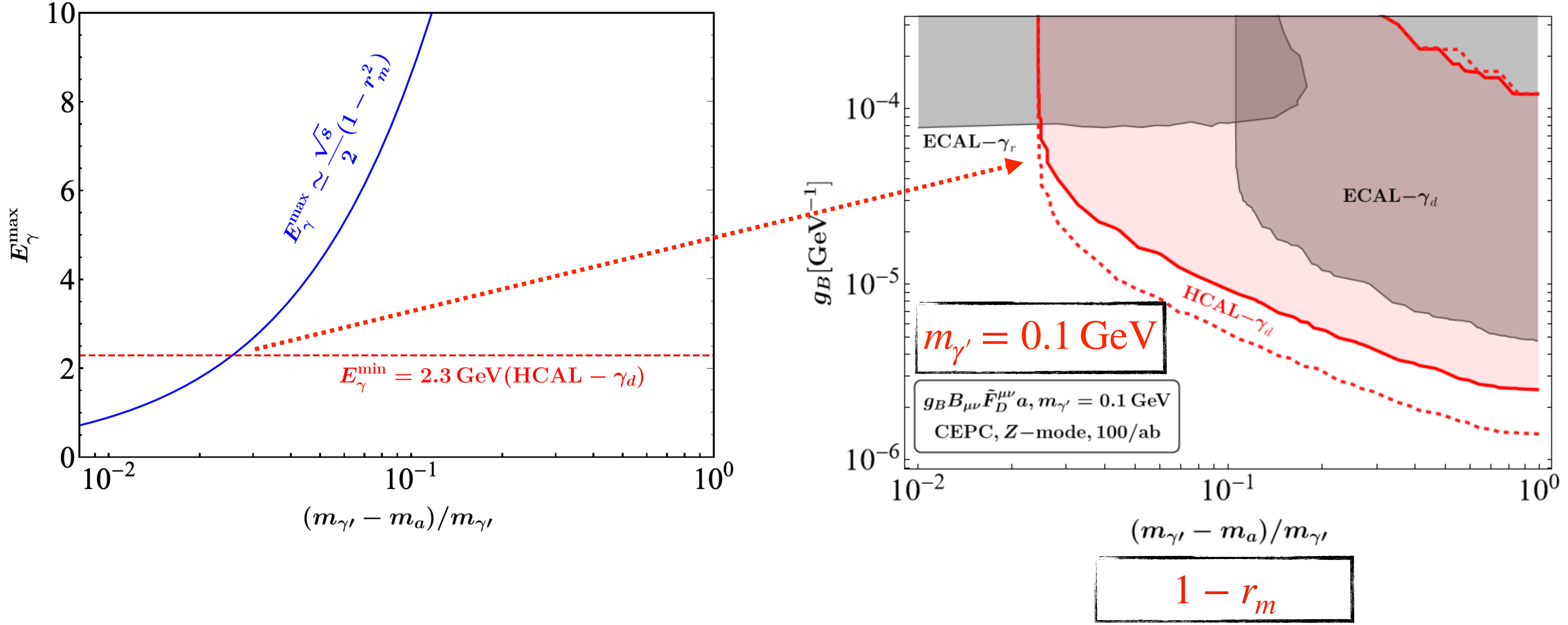
Convertional ECAL mono-photon signatures

Inner radius of the HCAL
$R_{\rm H}^{\rm in} = 2.14\,\mathrm{m}$



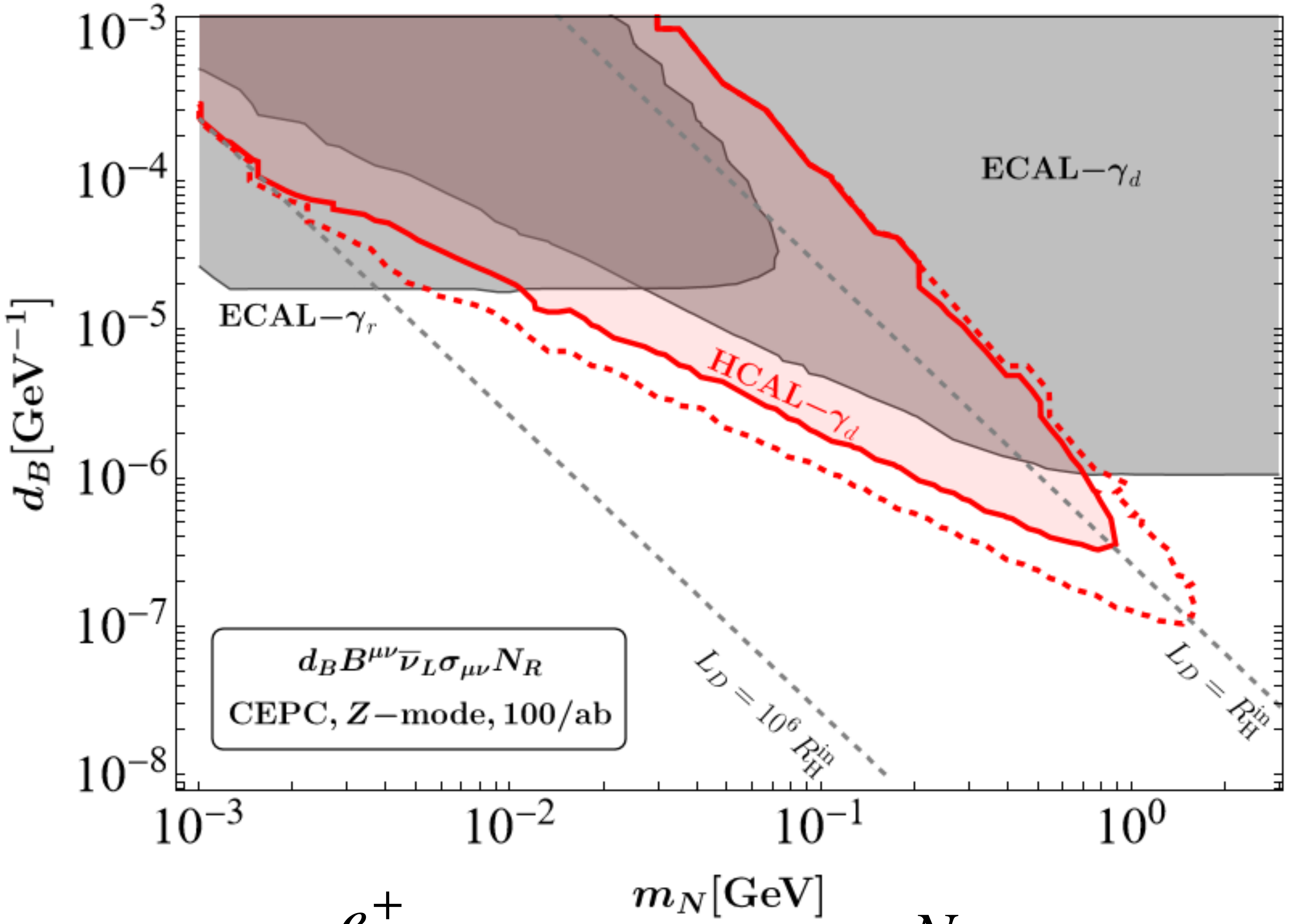
The HCAL mono-photon signature provides exceptional sensitivity to LLPs with decay lengths between ~1 and 10^6 meters and achieves the best sensitivity when $L_D = R_{\rm H}^{\rm in}$.

CEPC sensitivities on the axion portal operator



The HCAL mono-photon signature shows better sensitivity by about one order of magnitude when $0.1 \lesssim r_m \lesssim 0.97$,
but loses sensitivity when $r_m \gtrsim 0.97$ due to the photon energy threshold of the HCAL.

CEPC sensitivities on neutrino dipole portal operator



$r_m = 0$

$$(\bar{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$$

$$\downarrow$$

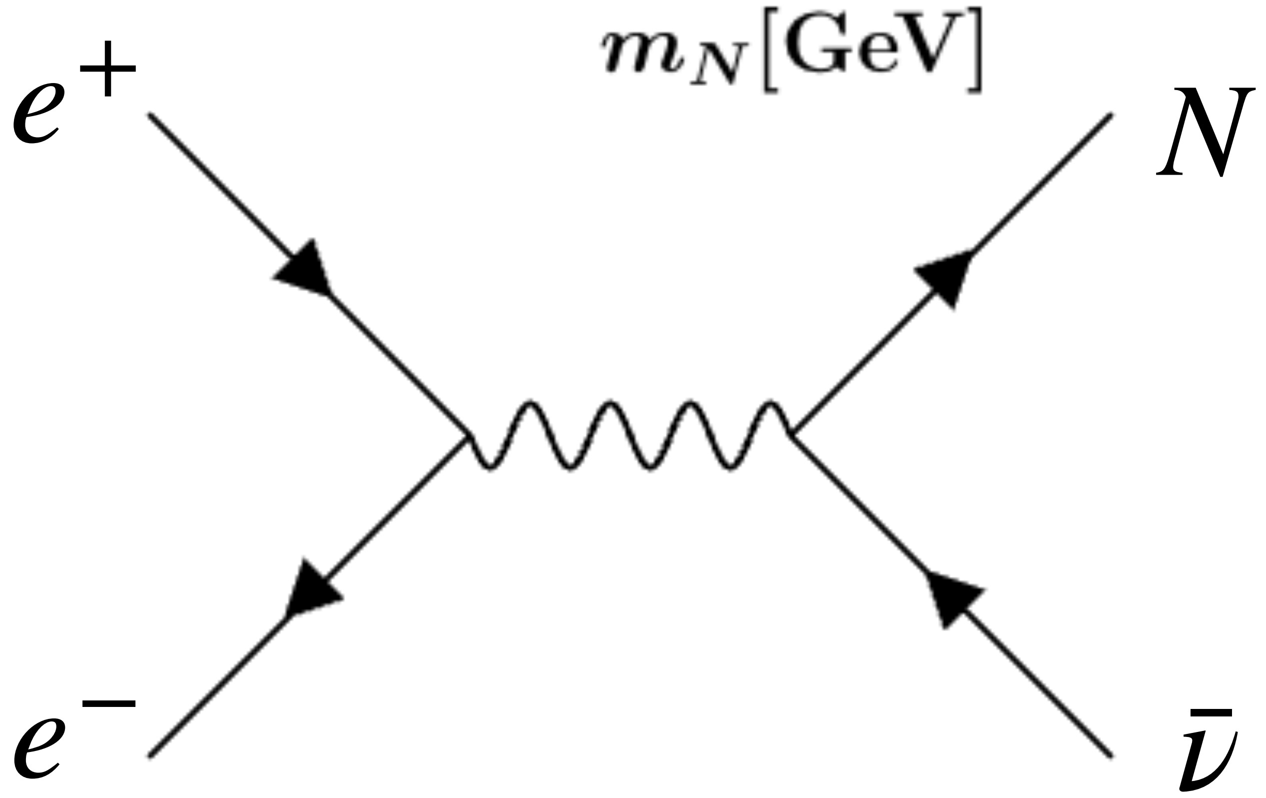
$$\mathcal{O}_{\nu NB} \equiv d_B\bar{\nu}_L\sigma_{\mu\nu}NB^{\mu\nu}$$

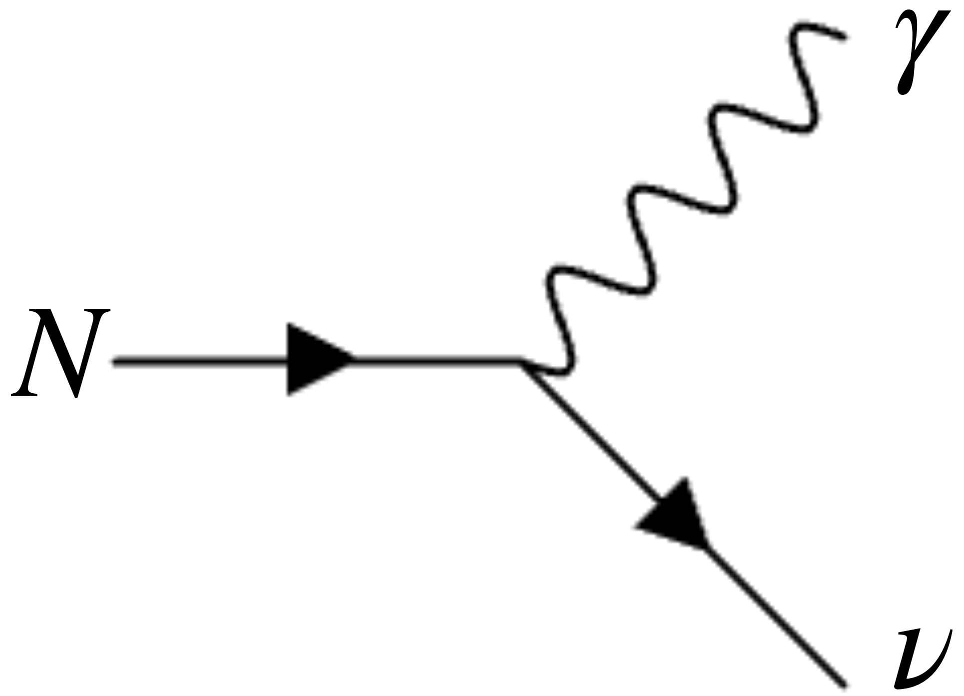
N: sterile neutrino

H: Higgs doublet

$B_{\mu\nu}$: hypercharge field-strength tensor

$$\Gamma_{N\to\nu\gamma} = \frac{1}{4\pi}d_B^2 c_W^2 m_N^3$$





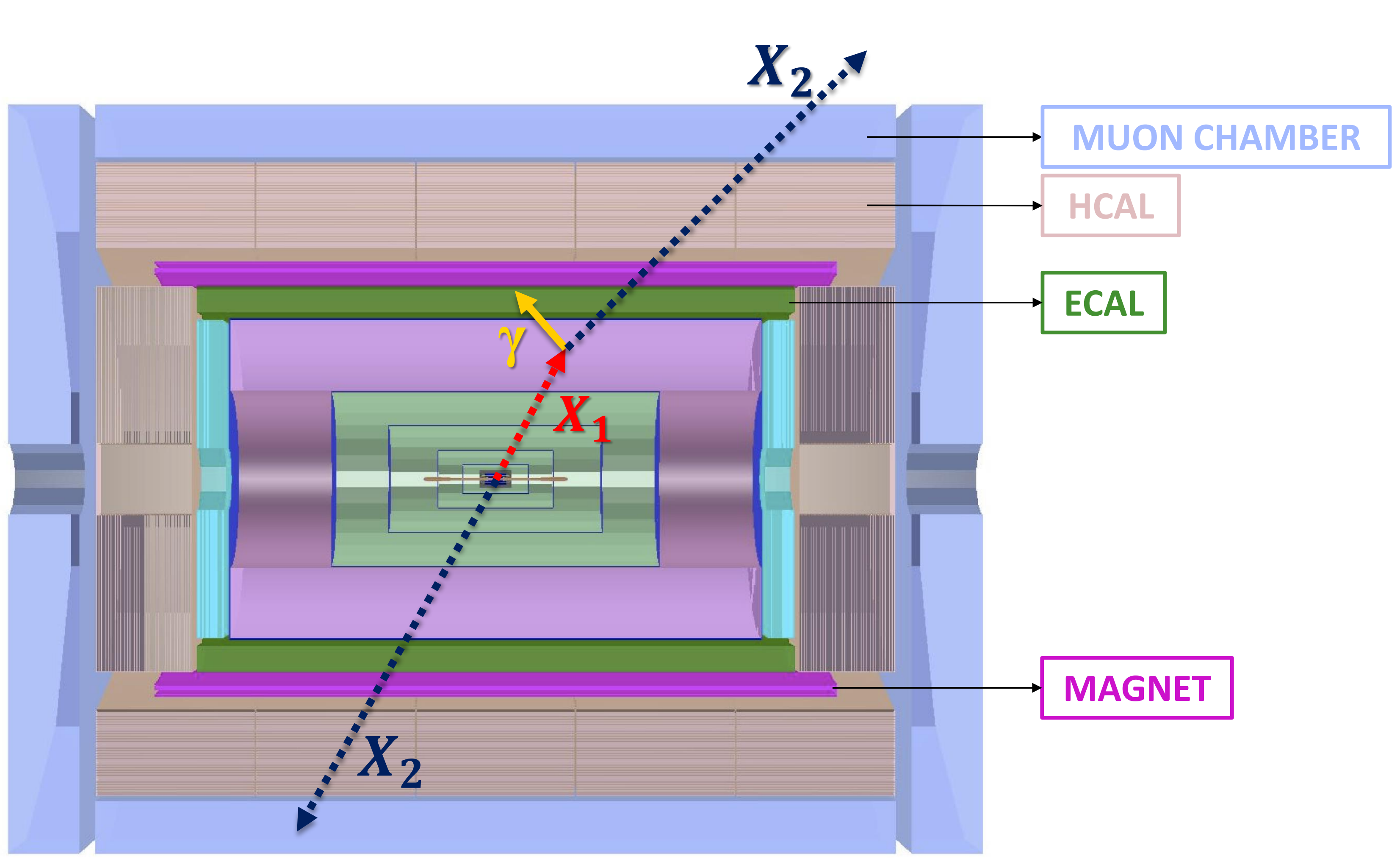
Summary

- We propose using the HCAL barrel as a far detector for displaced photons from LLP decays at future Higgs factories. The surrounding subdetectors are considered as shields against SM particles from the primary vertex, beam, and cosmic rays.
- The HCAL mono-photon signature provides excellent sensitivity to photon-portal LLPs with decay lengths between $\sim$1 and 10^6 meters.
- The dominant backgrounds originate from neutral hadrons produced at the primary vertex. They are expected to be efficiently suppressed by the particle flow algorithm in future work.

Backup

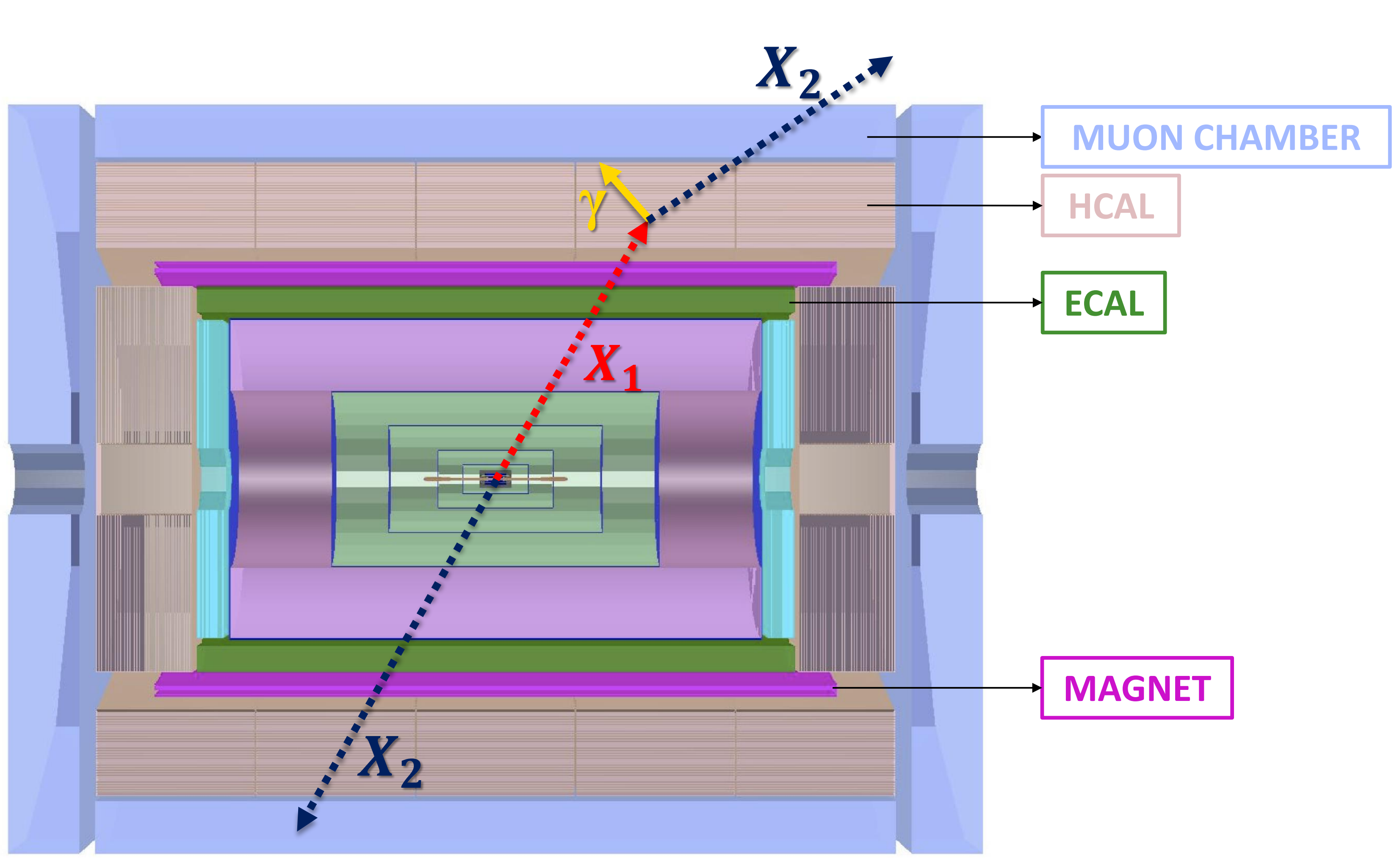
Three mono-photon signatures

$L_D \ll R_{\rm HCAL}$



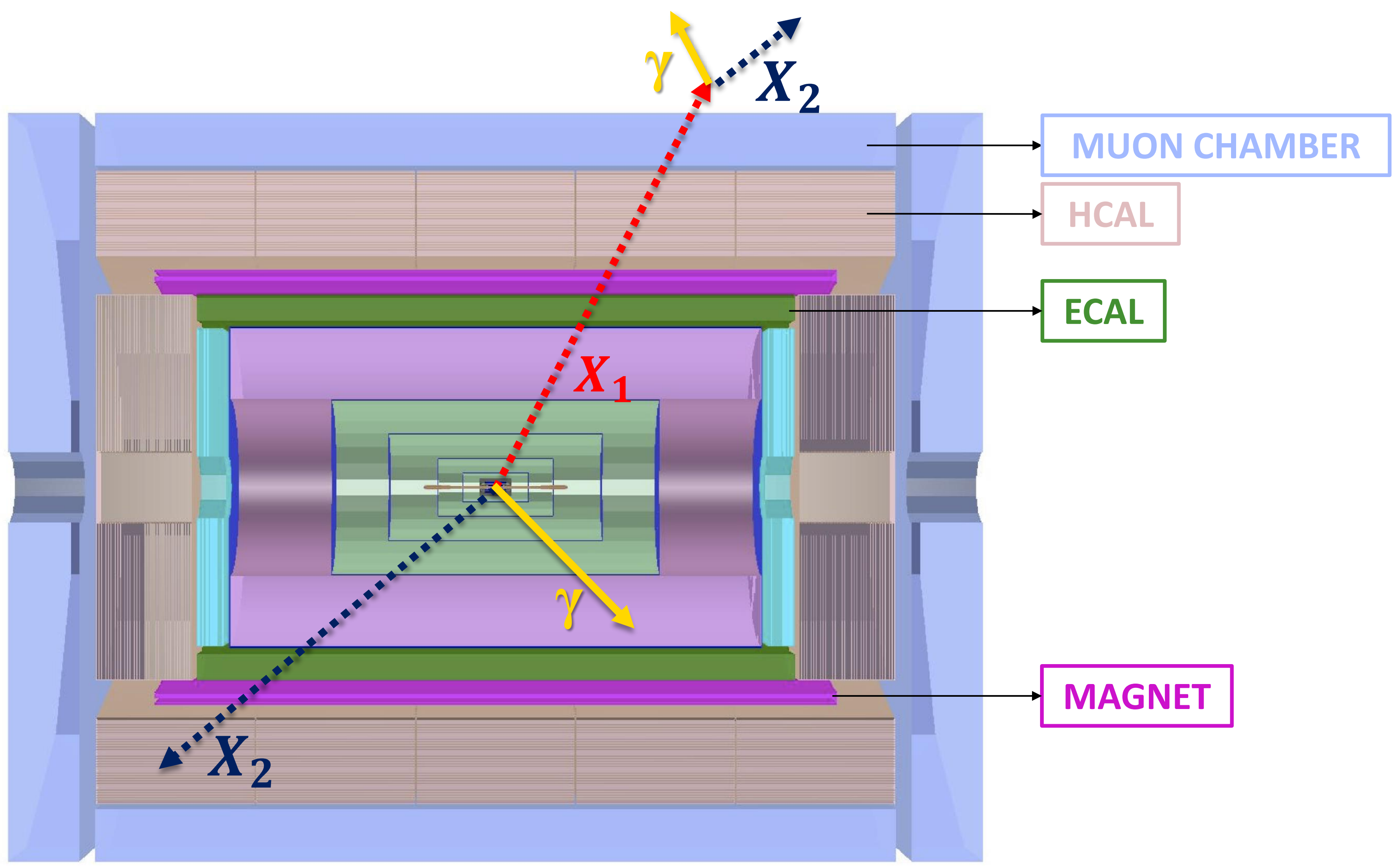
ECAL-γ_d

$L_D \sim R_{\rm HCAL}$



HCAL-γ_d (This work)

$L_D \gg R_{\rm HCAL}$



ECAL-γ_r

$$e^+e^- \to X_1X_2, X_1 \to X_2\gamma_d$$

γ_d: generated by X_1 decay

$$e^+e^- \to X_1X_2\gamma_r, X_1 \to X_2\gamma_d$$

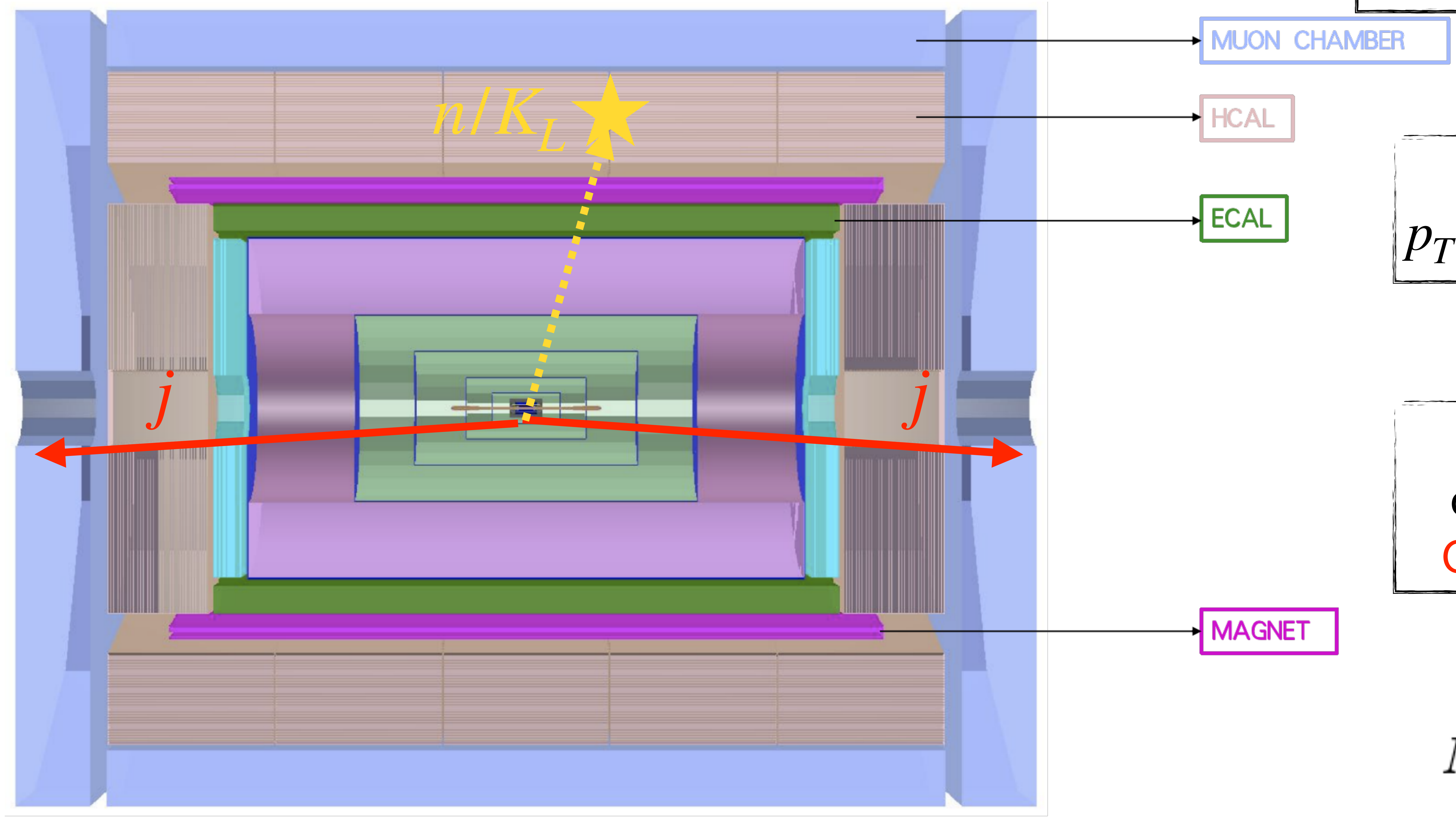
γ_r: generated by ISR

Three mono-photon signatures give complementary sensitivities on photon portal LLPs.

Neutral hadron Backgrounds

Simulate 10^8 $e^+e^- \to jjj$ events with $p_T^{j_1} > 1\,\mathrm{GeV}$, $p_T^{j_2,j_3} < 10\,\mathrm{GeV}$, and $\Delta R_{2j} > 0.4$

$\sigma_{3j} = 3300$ pb



Veto events if there are trakcs with $p_T > 0.1\,\mathrm{GeV}$ or photons with $E_\gamma > 0.1\,\mathrm{GeV}$

Select events with only one neutron or K_L within the HCAL barrel.

Only one event is found (large uncertainty).

$$N_{\mathrm{BG}}^{n,K_L} \simeq \frac{1}{10^8} \times \sigma_{3j} \times \mathcal{L} \times P_{\mathrm{EB}}^{\not\gamma} = 858$$

The electromagnetic showers induced by photons differ markedly from those of hadrons. Hence, with full exploitation of the high granularity and high sampling fraction of the GS-HCAL, neutral hadron backgrounds can be effectively suppressed.