

Exotic channels for probing dark sector particles at electron-positron colliders

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JHEP 05 (2024) 273 and arXiv:2510.26649



对撞机上新物理寻找研讨会，南京大学（苏州）

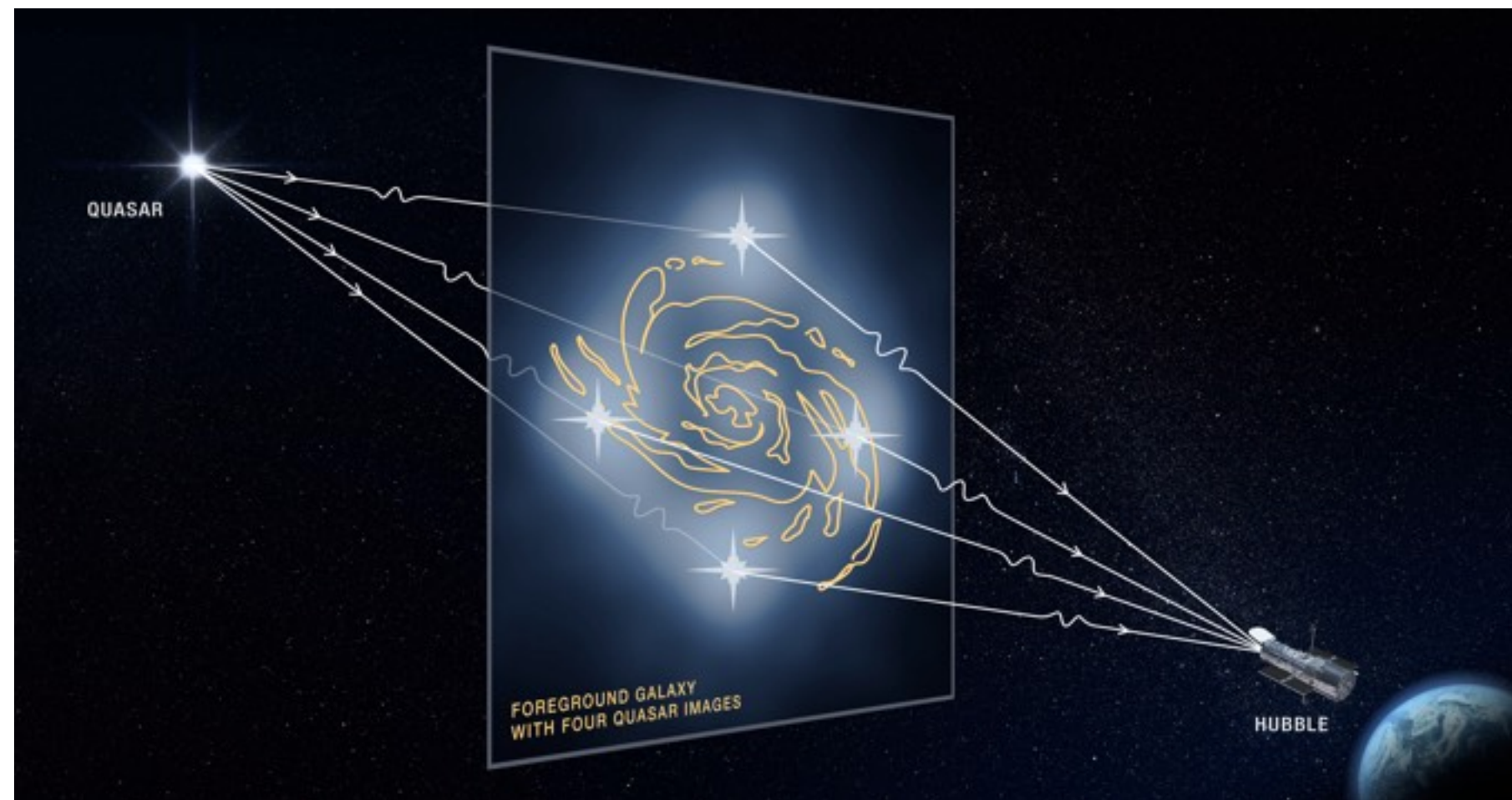
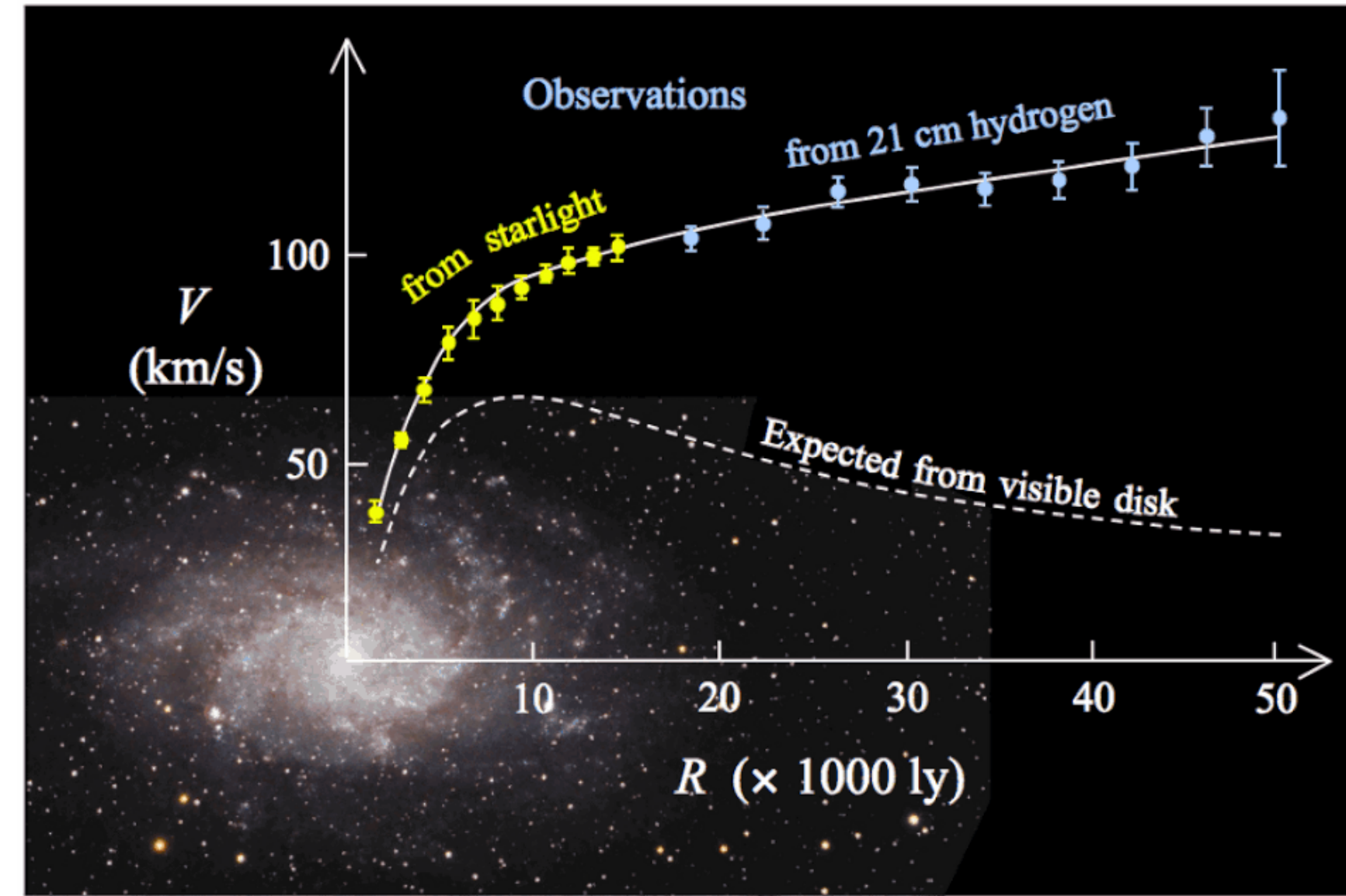
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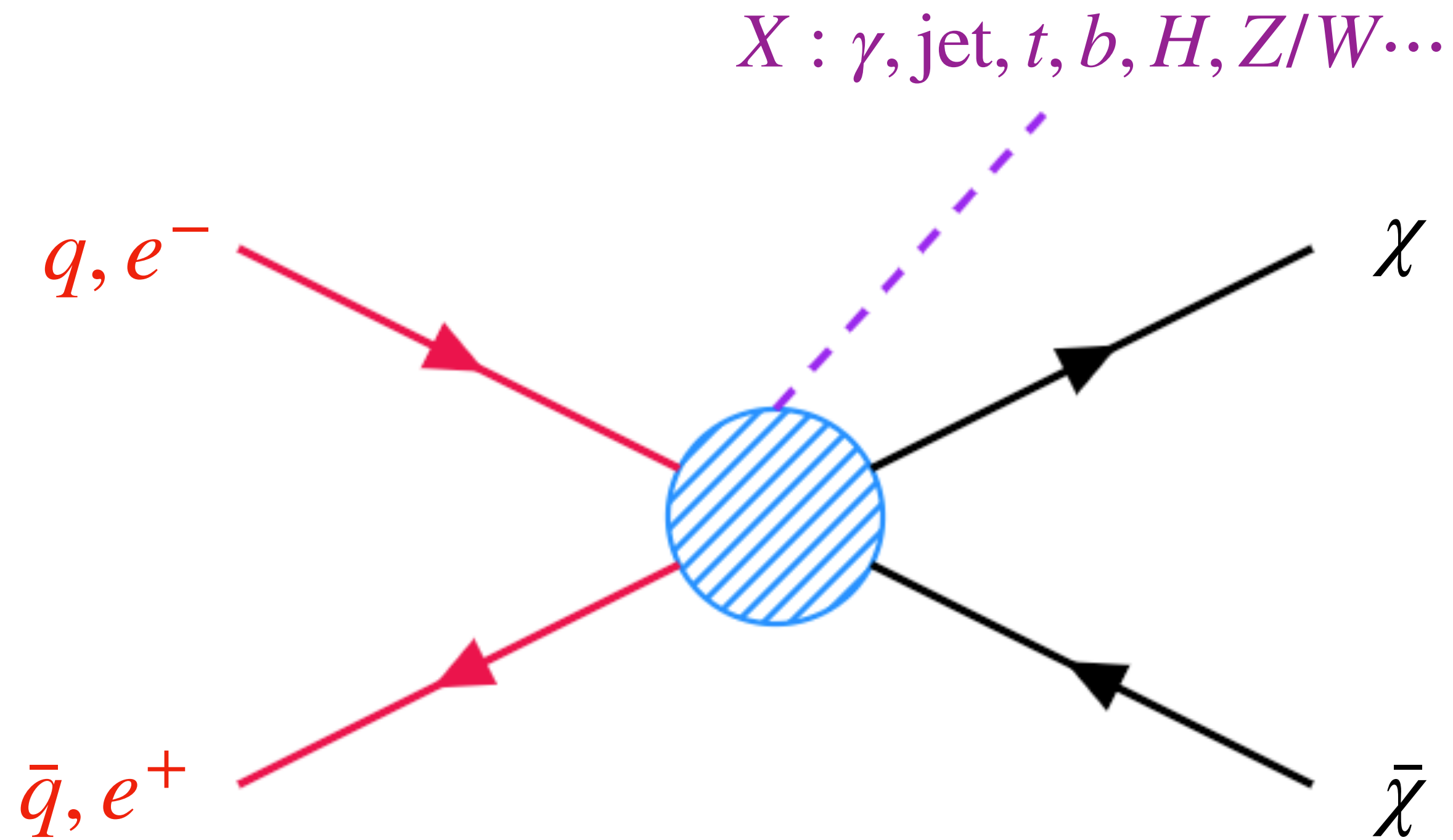
Outline

- Introduction to dark matter
- CEPC HCAL as a photon far detector for photon-portal long-lived particles
- Belle II as a fixed-target experiment for dark photon searches
- Summary

Dark matter evidences



Mono-X channel at collider



DMs are produced at the primary vertex
and performed as missing energy

γ : Birkedal+ 2004, Fox+ 2011...

Jet: Feng+ 2005, Bai+ 2010...

t : Andrea+ 2011, Agram+ 2013...

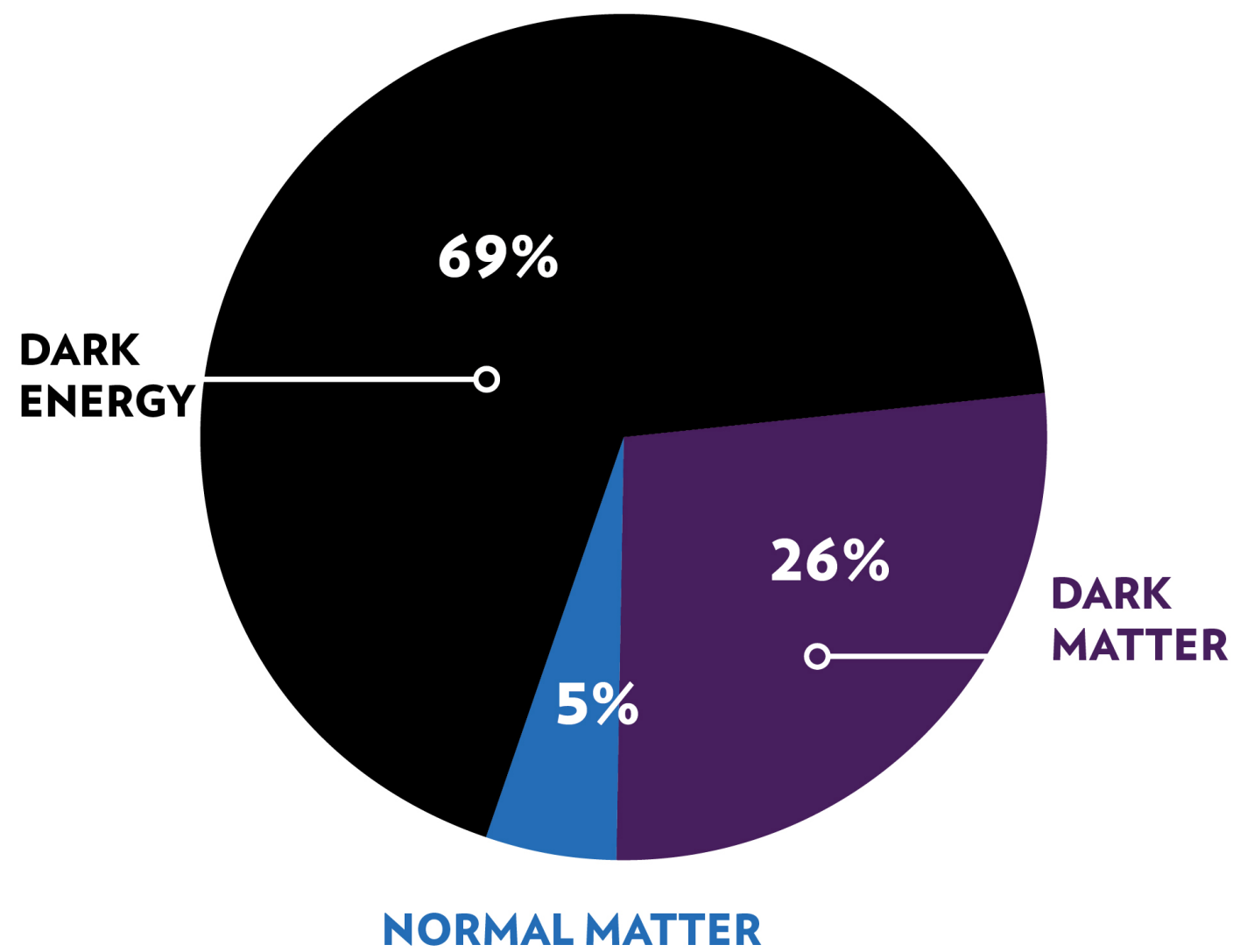
b : Lin+ 2013, Izaguirre+ 2014...

Z/W : Petriello+ 2008, Bell+ 2012...

H : Petrov+ 2013, Carpenter+ 2013...

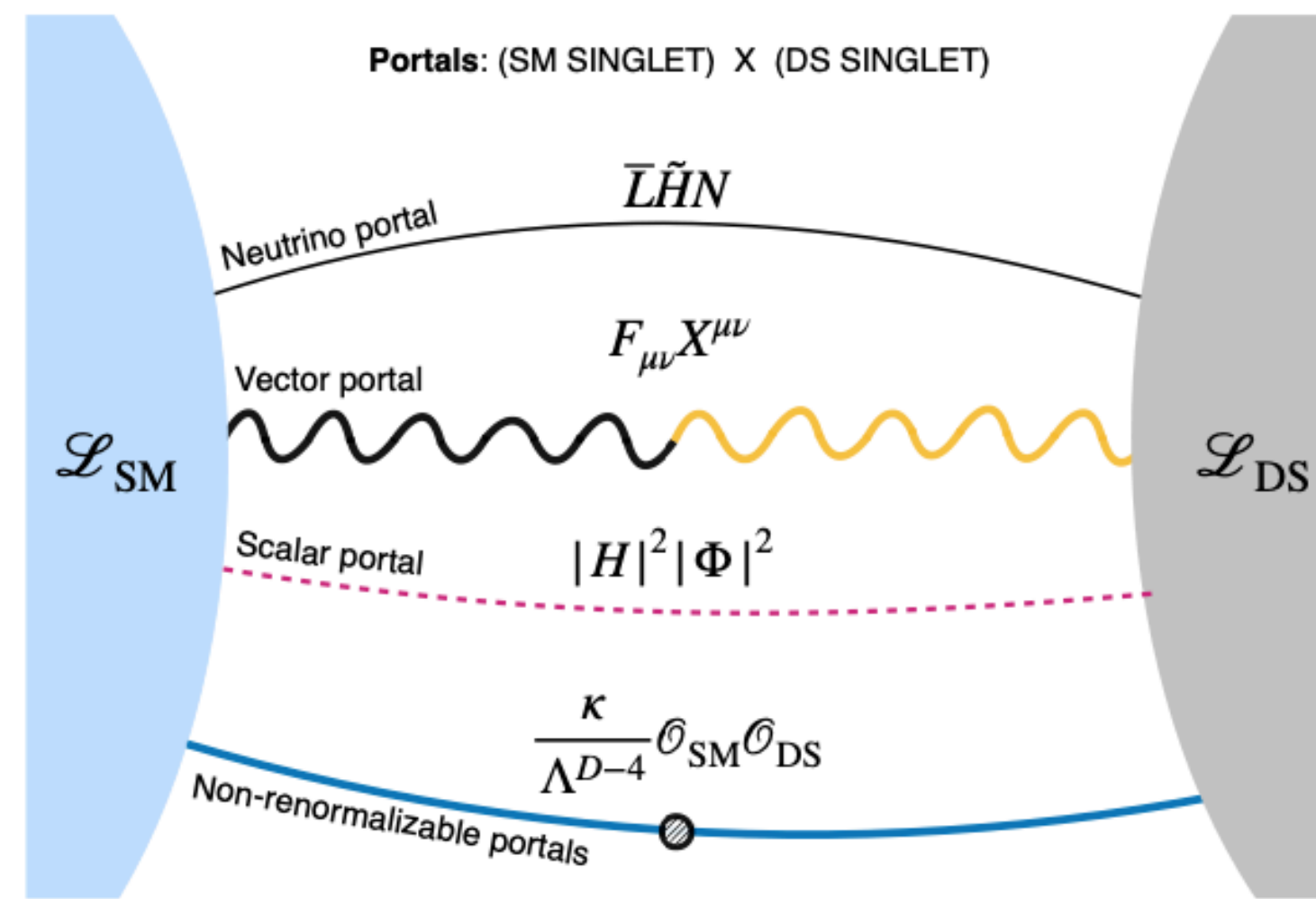
Interactions between DM and SM

ENERGY DISTRIBUTION OF THE UNIVERSE



Abdullah et al., Nucl.Phys.B 1020 (2025) 117148

JL, Liao, Ma, Wang, JHEP 12 (2023) 172



Portal interactions

Operator	Specific form	#	Operator	Specific form	#
dim-5: $(\bar{\chi}\psi)F$					
$\mathcal{O}_{\chi\psi F}^{T1}$	$(\bar{\chi}i\sigma^{\mu\nu}\psi)F_{\mu\nu}$		$\mathcal{O}_{\chi\psi F}^{T2}$	$(\bar{\chi}\sigma^{\mu\nu}\gamma_5\psi)F_{\mu\nu}$	
dim-6: $(\bar{\chi}\psi)(\bar{\Psi}\Psi)$					
$\mathcal{O}_{\nu\chi\psi}^{SS} + \text{h.c.}$	$(\bar{L}_{L,p}^c\nu_{L,r})(\bar{\chi}\psi)$	$n_\nu(n_\nu + 1)$	$\mathcal{O}_{\nu\chi\psi}^{PS} + \text{h.c.}$	$(\bar{L}_{L,p}^c\nu_{L,r})(\bar{\chi}i\gamma_5\psi)$	$n_\nu(n_\nu + 1)$
$\mathcal{O}_{\nu\chi\psi}^{VV}$	$(\bar{L}_{L,p}\gamma_\mu\nu_{L,r})(\bar{\chi}i\gamma^\mu\psi)$	n_ν^2	$\mathcal{O}_{\nu\chi\psi}^{VA}$	$(\bar{L}_{L,p}\gamma_\mu\nu_{L,r})(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_ν^2
$\mathcal{O}_{\nu\chi\psi}^{TT} + \text{h.c.}$	$(\bar{L}_{L,p}\sigma_{\mu\nu}\nu_{L,r})(\bar{\chi}\sigma^{\mu\nu}\psi)$	$n_\nu(n_\nu - 1)$			
$\mathcal{O}_{\ell\chi\psi}^{SS}$	$(\bar{\ell}_p\ell_r)(\bar{\chi}\psi)$	n_ℓ^2	$\mathcal{O}_{\ell\chi\psi}^{SP}$	$(\bar{\ell}_p\ell_r)(\bar{\chi}i\gamma_5\psi)$	n_ℓ^2
$\mathcal{O}_{\ell\chi\psi}^{PS}$	$(\bar{\ell}_p i\gamma_5\ell_r)(\bar{\chi}\psi)$	n_ℓ^2	$\mathcal{O}_{\ell\chi\psi}^{PP}$	$(\bar{\ell}_p i\gamma_5\ell_r)(\bar{\chi}i\gamma_5\psi)$	n_ℓ^2
$\mathcal{O}_{\ell\chi\psi}^{VV}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{\chi}i\gamma^\mu\psi)$	n_ℓ^2	$\mathcal{O}_{\ell\chi\psi}^{VA}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_ℓ^2
$\mathcal{O}_{\ell\chi\psi}^{AV}$	$(\bar{\ell}_p\gamma_\mu\gamma_5\ell_r)(\bar{\chi}i\gamma^\mu\psi)$	n_ℓ^2	$\mathcal{O}_{\ell\chi\psi}^{AA}$	$(\bar{\ell}_p\gamma_\mu\gamma_5\ell_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_ℓ^2
$\mathcal{O}_{\ell\chi\psi}^{T1}$	$(\bar{\ell}_p\sigma_{\mu\nu}\ell_r)(\bar{\chi}\sigma^{\mu\nu}\psi)$	n_ℓ^2	$\mathcal{O}_{\ell\chi\psi}^{T2}$	$(\bar{\ell}_p\sigma_{\mu\nu}\ell_r)(\bar{\chi}\sigma^{\mu\nu}\gamma_5\psi)$	n_ℓ^2
$\mathcal{O}_{u\chi\psi}^{SS}$	$(\bar{u}_p u_r)(\bar{\chi}\psi)$	n_u^2	$\mathcal{O}_{u\chi\psi}^{SP}$	$(\bar{u}_p u_r)(\bar{\chi}i\gamma_5\psi)$	n_u^2
$\mathcal{O}_{u\chi\psi}^{PS}$	$(\bar{u}_p i\gamma_5 u_r)(\bar{\chi}\psi)$	n_u^2	$\mathcal{O}_{u\chi\psi}^{PP}$	$(\bar{u}_p i\gamma_5 u_r)(\bar{\chi}i\gamma_5\psi)$	n_u^2
$\mathcal{O}_{u\chi\psi}^{VV}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{\chi}i\gamma^\mu\psi)$	n_u^2	$\mathcal{O}_{u\chi\psi}^{VA}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_u^2
$\mathcal{O}_{u\chi\psi}^{AV}$	$(\bar{u}_p\gamma_\mu\gamma_5 u_r)(\bar{\chi}i\gamma^\mu\psi)$	n_u^2	$\mathcal{O}_{u\chi\psi}^{AA}$	$(\bar{u}_p\gamma_\mu\gamma_5 u_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_u^2
$\mathcal{O}_{u\chi\psi}^{T1}$	$(\bar{u}_p\sigma_{\mu\nu}u_r)(\bar{\chi}\sigma^{\mu\nu}\psi)$	n_u^2	$\mathcal{O}_{u\chi\psi}^{T2}$	$(\bar{u}_p\sigma_{\mu\nu}u_r)(\bar{\chi}\sigma^{\mu\nu}\gamma_5\psi)$	n_u^2
$\mathcal{O}_{d\chi\psi}^{SS}$	$(\bar{d}_p d_r)(\bar{\chi}\psi)$	n_d^2	$\mathcal{O}_{d\chi\psi}^{SP}$	$(\bar{d}_p d_r)(\bar{\chi}i\gamma_5\psi)$	n_d^2
$\mathcal{O}_{d\chi\psi}^{PS}$	$(\bar{d}_p i\gamma_5 d_r)(\bar{\chi}\psi)$	n_d^2	$\mathcal{O}_{d\chi\psi}^{PP}$	$(\bar{d}_p i\gamma_5 d_r)(\bar{\chi}i\gamma_5\psi)$	n_d^2
$\mathcal{O}_{d\chi\psi}^{VV}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{\chi}i\gamma^\mu\psi)$	n_d^2	$\mathcal{O}_{d\chi\psi}^{VA}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_d^2
$\mathcal{O}_{d\chi\psi}^{AV}$	$(\bar{d}_p\gamma_\mu\gamma_5 d_r)(\bar{\chi}i\gamma^\mu\psi)$	n_d^2	$\mathcal{O}_{d\chi\psi}^{AA}$	$(\bar{d}_p\gamma_\mu\gamma_5 d_r)(\bar{\chi}\gamma^\mu\gamma_5\psi)$	n_d^2
$\mathcal{O}_{d\chi\psi}^{T1}$	$(\bar{d}_p\sigma_{\mu\nu}d_r)(\bar{\chi}\sigma^{\mu\nu}\psi)$	n_d^2	$\mathcal{O}_{d\chi\psi}^{T2}$	$(\bar{d}_p\sigma_{\mu\nu}d_r)(\bar{\chi}\sigma^{\mu\nu}\gamma_5\psi)$	n_d^2

Dark sector EFT

DM contributes four times more energy density than SM particles



Multi-component dark sector

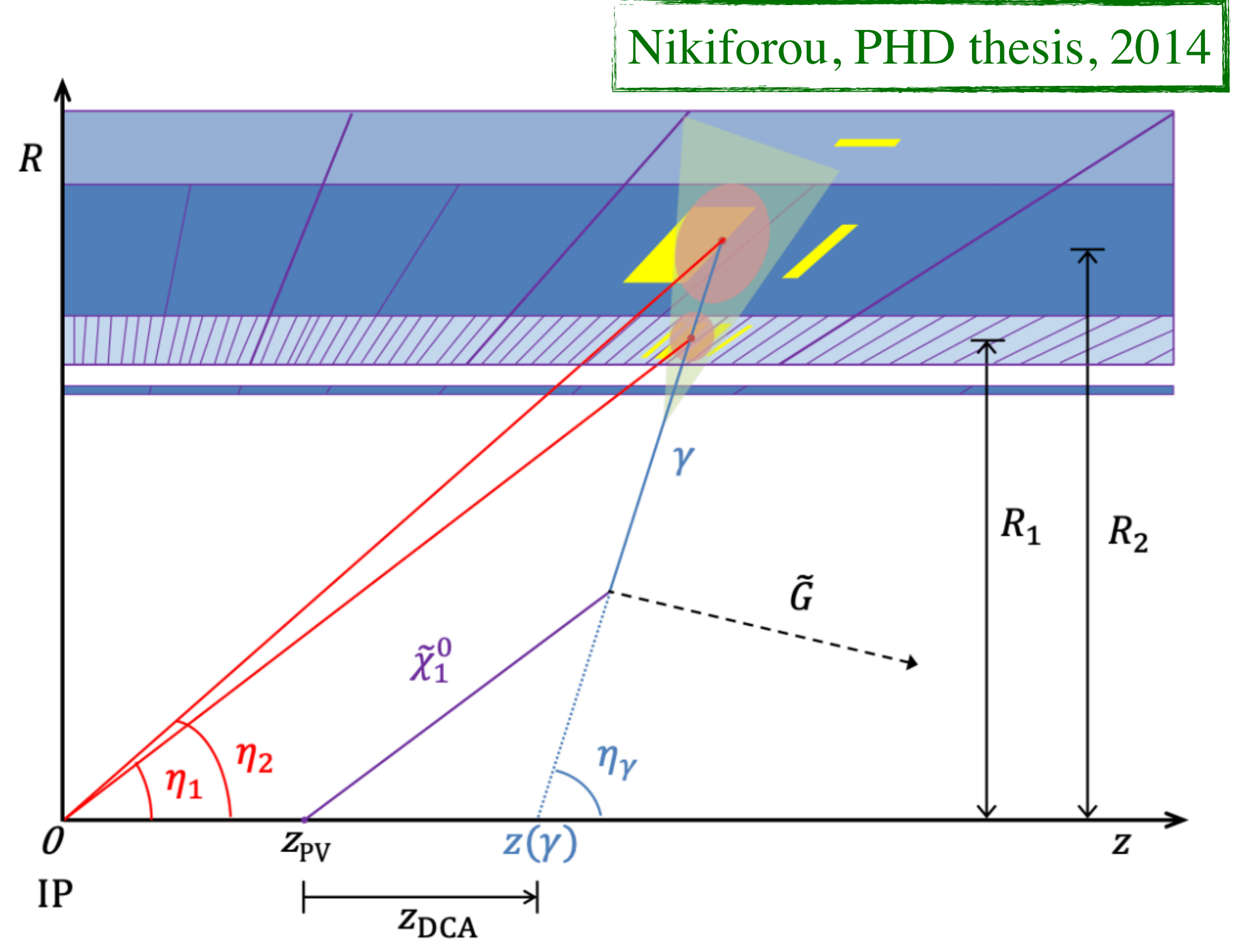
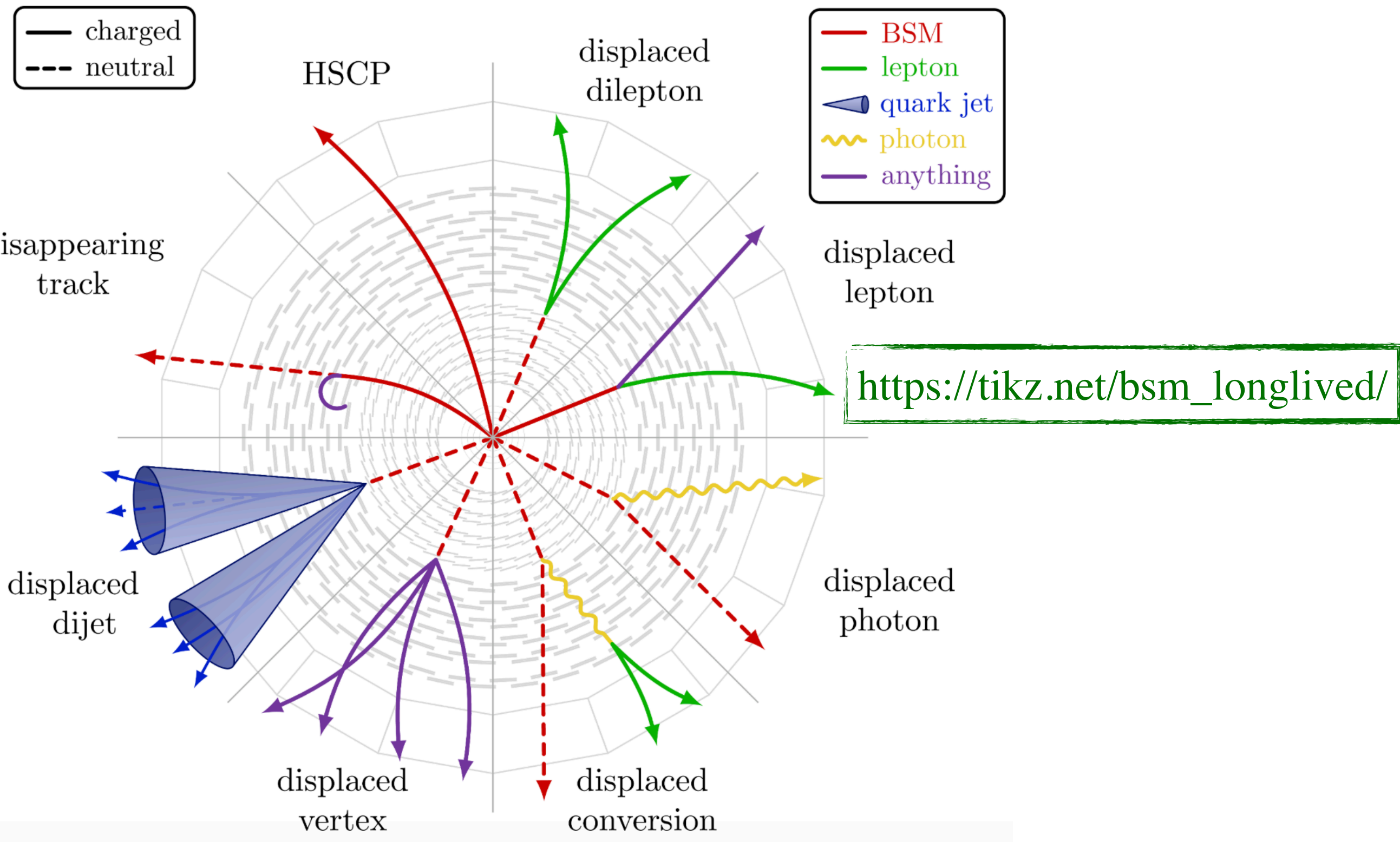


Long-lived particle (LLP)

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



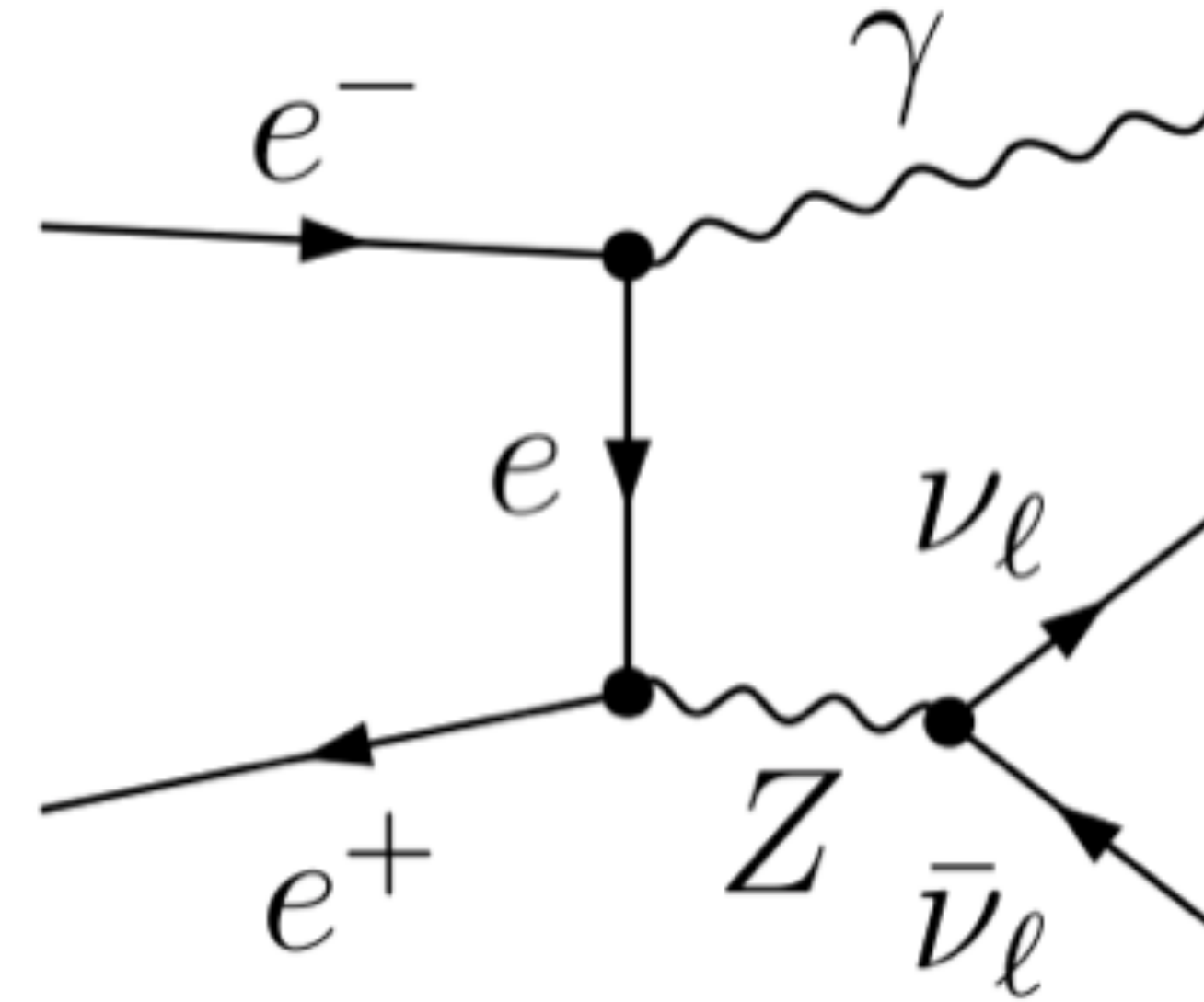
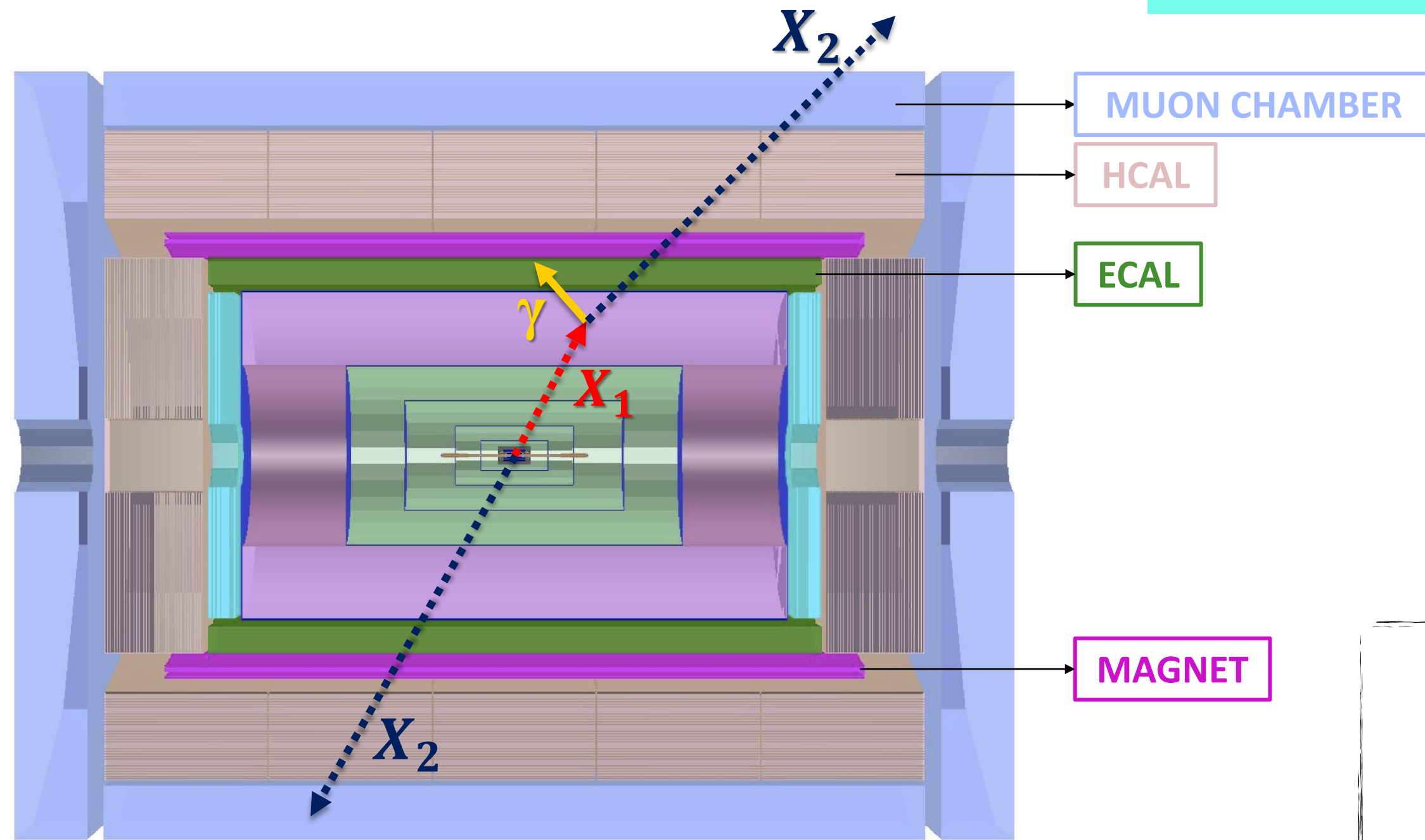
In general, displaced charged particles have cleaner backgrounds than displaced photons, thanks to the higher position resolution of the vertex detector and the tracker.

CEPC HCAL as a photon far detector

Large backgrounds for displaced mono-photon at future Higgs factories

CEPC reference detector

Far detector?



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

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

X_1 : heavier dark sector particle (long-lived)

X_2 : lighter dark sector particle or SM neutrino

Displaced photons face large backgrounds at future Higgs factories

HCAL barrel as a photon far detector

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

X_1 : heavier dark sector particle

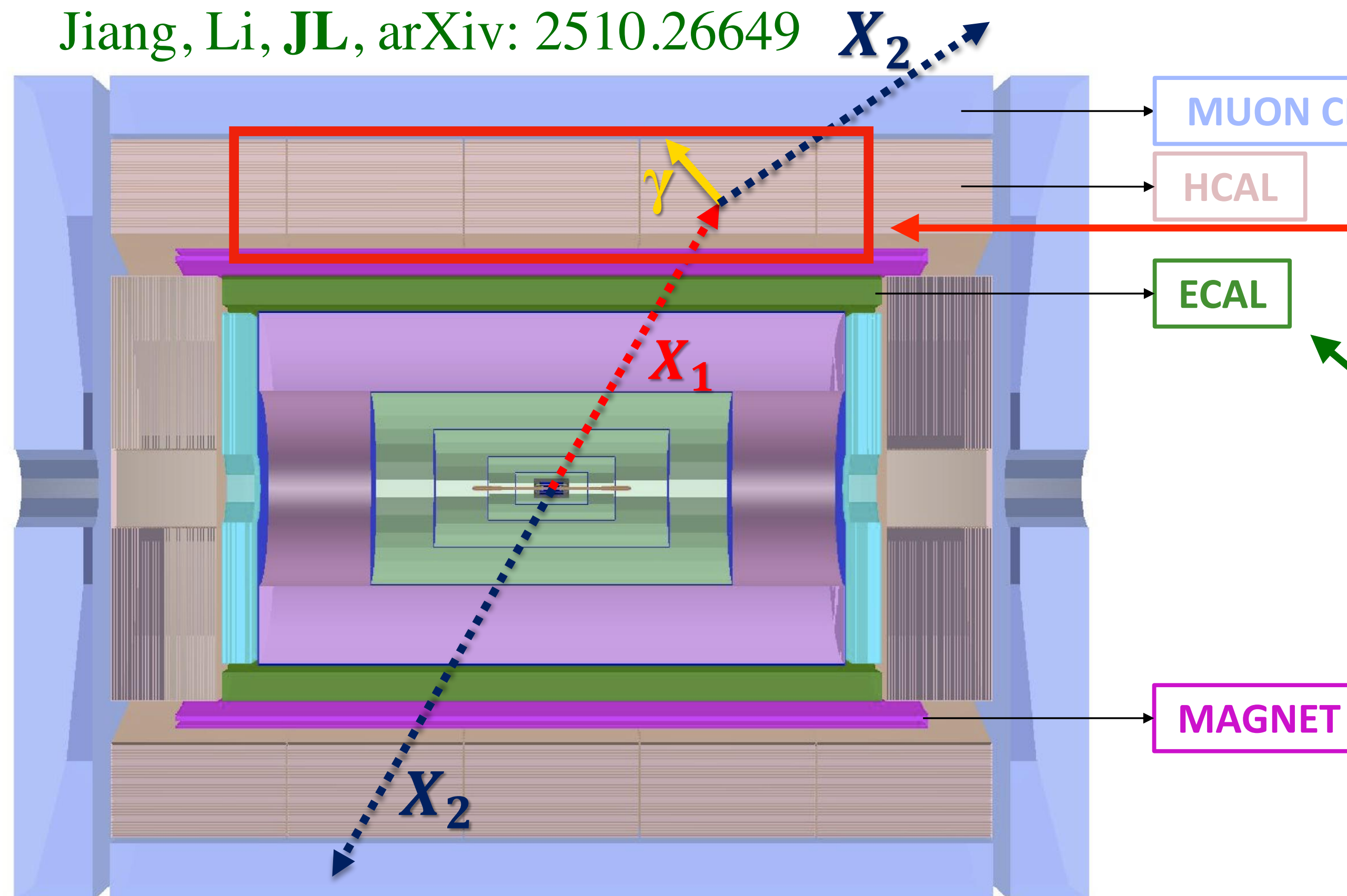
X_2 : lighter dark sector particle or SM neutrino

Jiang, Li, JL, arXiv: 2510.26649

Muon chamber as a shield for beam-related backgrounds and cosmic rays

HCAL barrel as a photon far detector

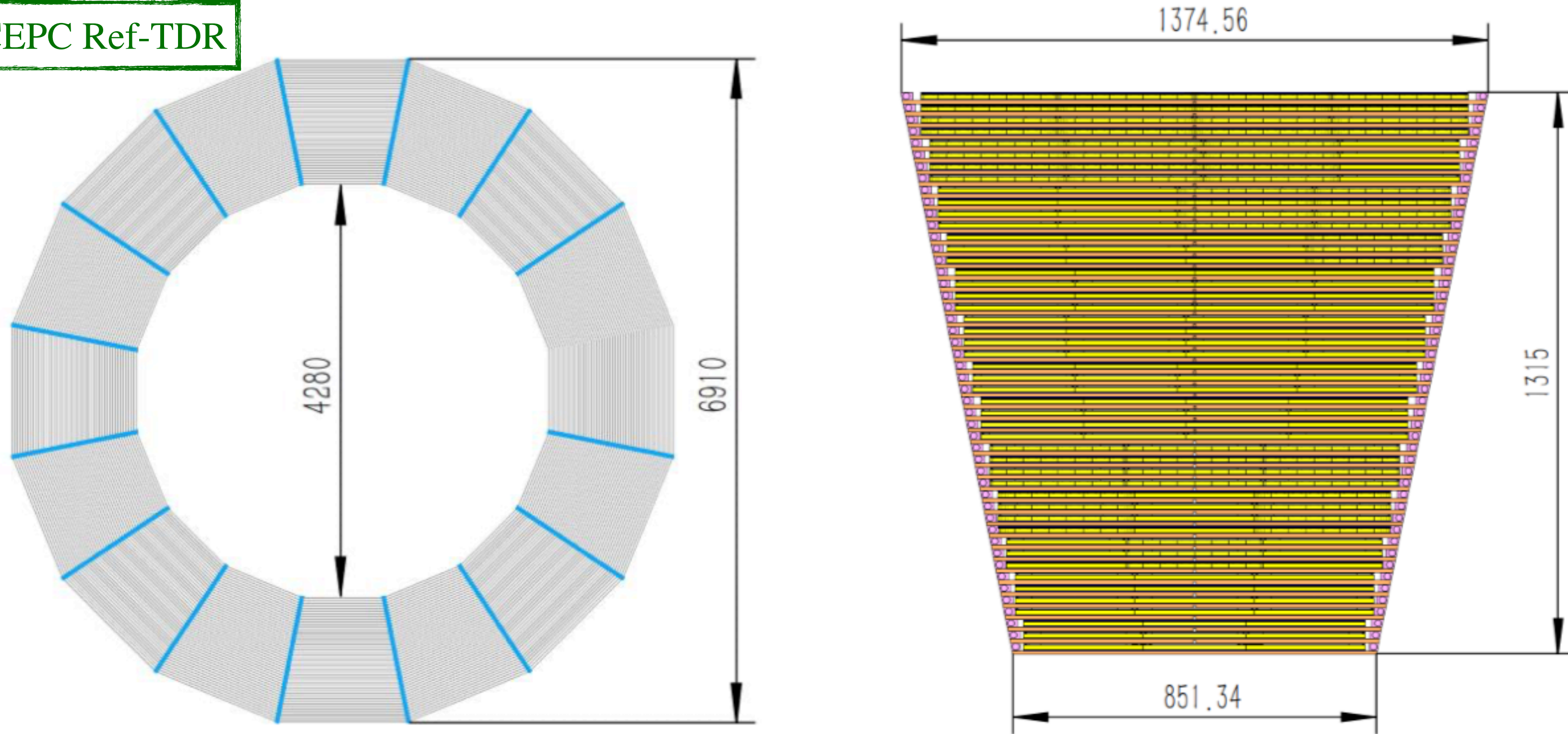
ECAL as a shield for neutral particles from the primary vertex



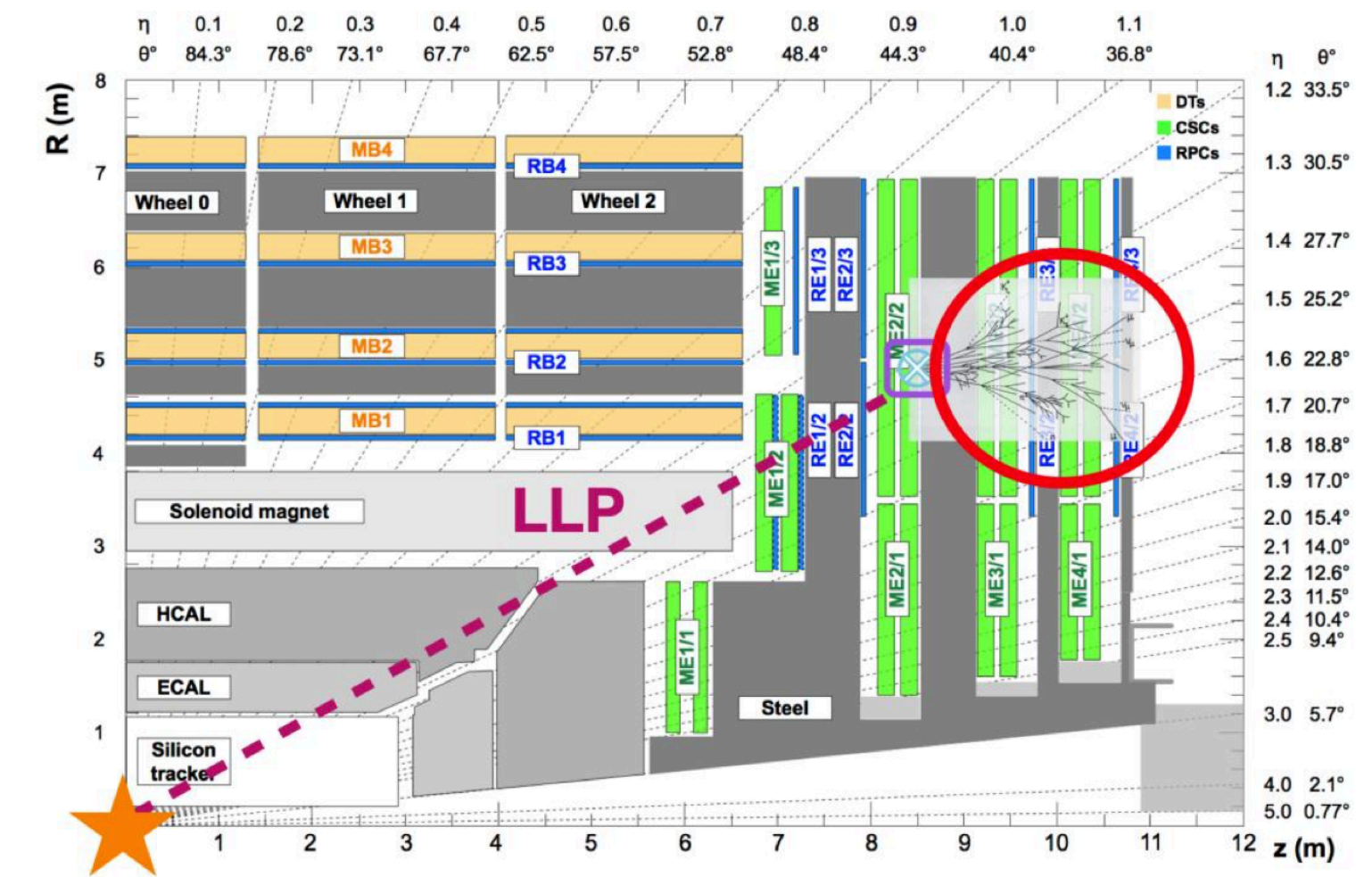
Why CEPC HCAL?

- (1) High-Granularity HCAL with small radiation length per layer
- (2) Much cleaner environment than the hadron colliders

CEPC Ref-TDR



CMS collaboration, PRL. 127 (2021) 26, 261804

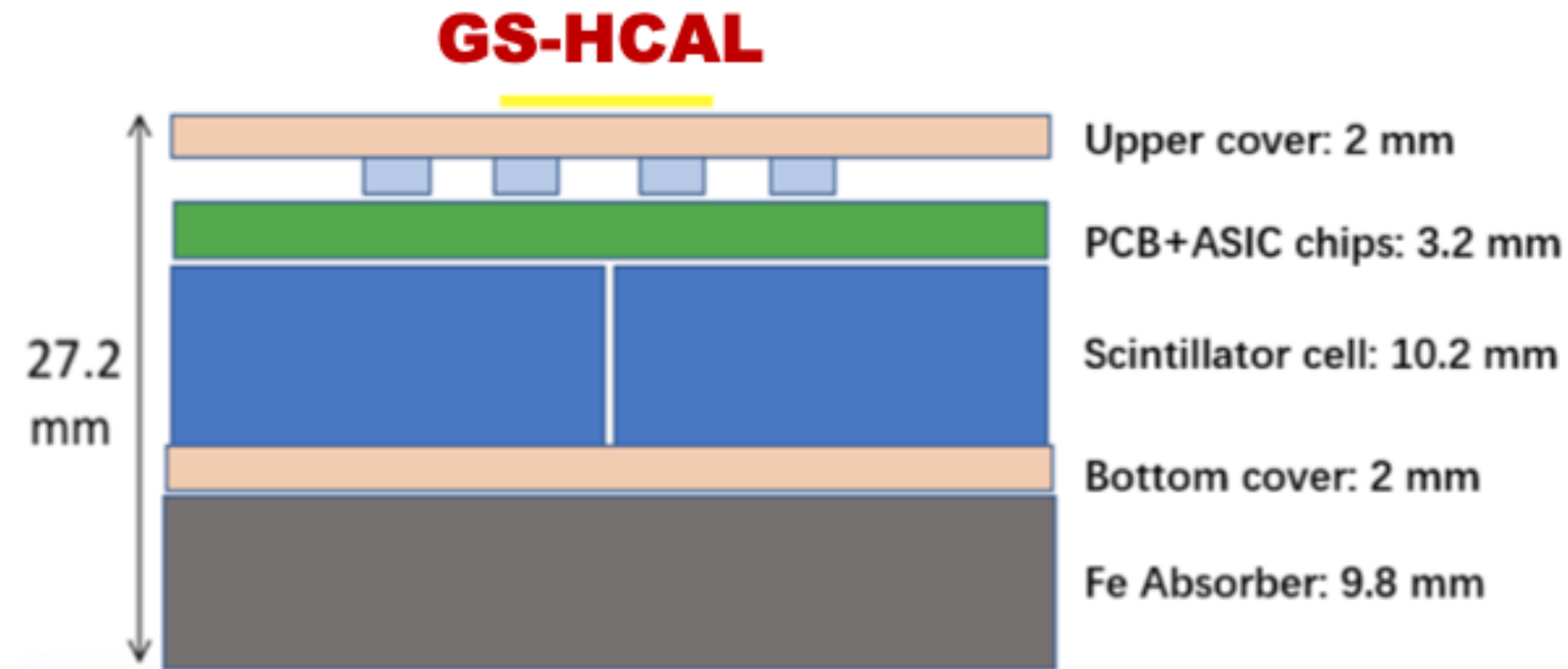
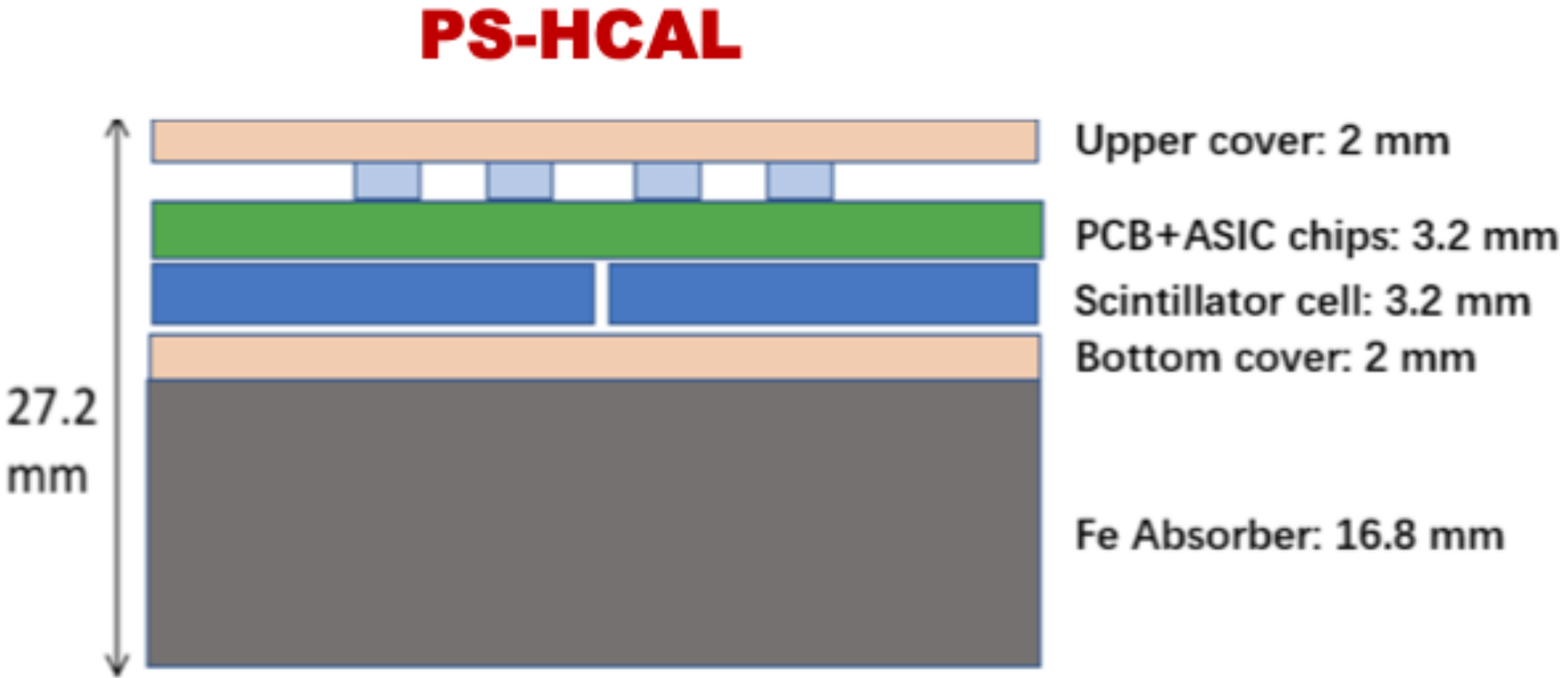


Muon endcap as a far detector for jets at CMS

A 48-layer sandwich structure of iron plates and scintillators

PS-HCAL or GS-HCAL?

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

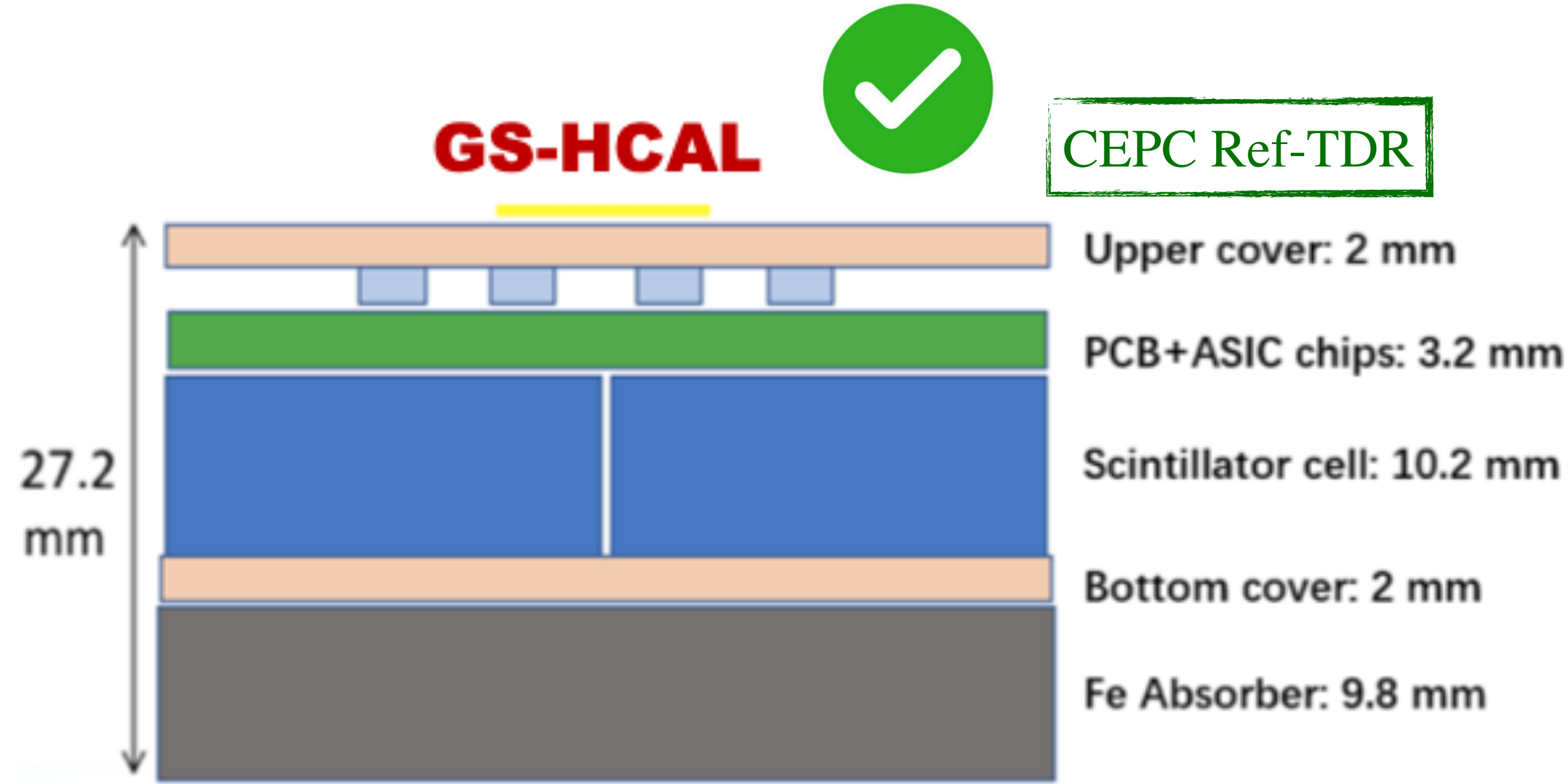


Detector	PS-HCAL	GS-HCAL
Main components per layer	20.8 mm Fe	13.8 mm Fe 10.2 mm GS
t (radiation length per layer)	1.21	1.44
Critical energy	~20.7 MeV	~15.7 MeV
Energy threshold for five layers	1.37 GeV	2.30 GeV

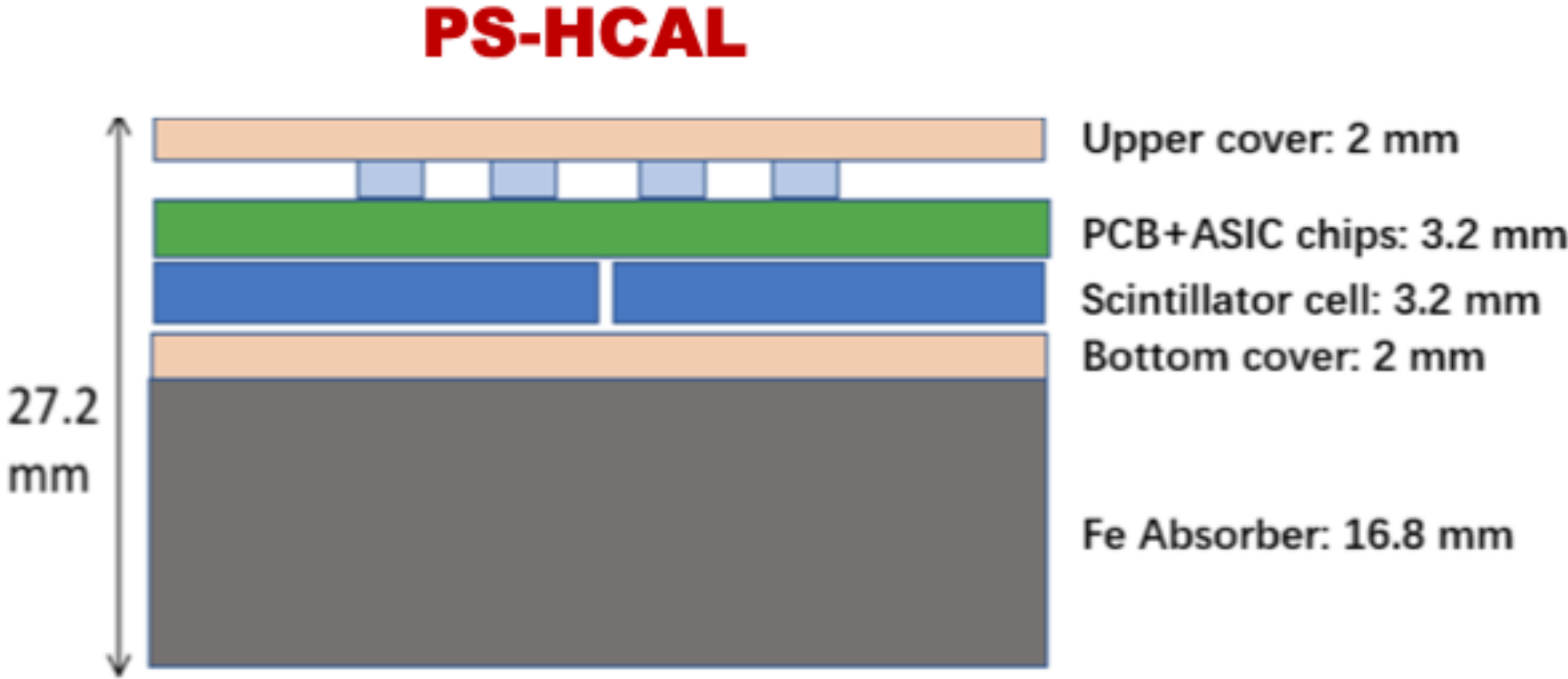
CEPC Ref-TDR

We require that the photon can induce energy deposition in at least five layers.
 The PS-HCAL has a lower photon energy threshold.

PS-HCAL or GS-HCAL?



Sampling fraction ~31%



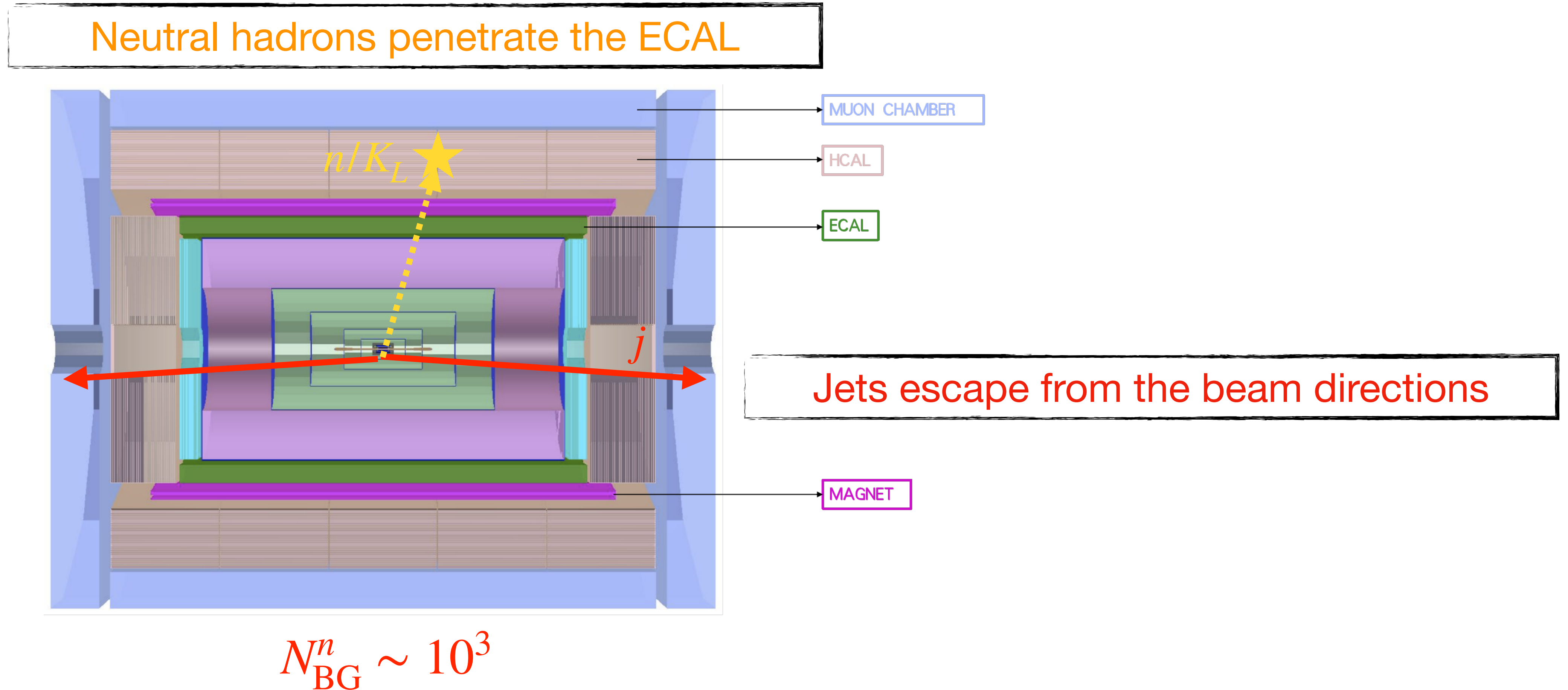
Sampling fraction ~1.6%

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.

Main SM Backgrounds



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.

Axion portal operator

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

a : axion like particle

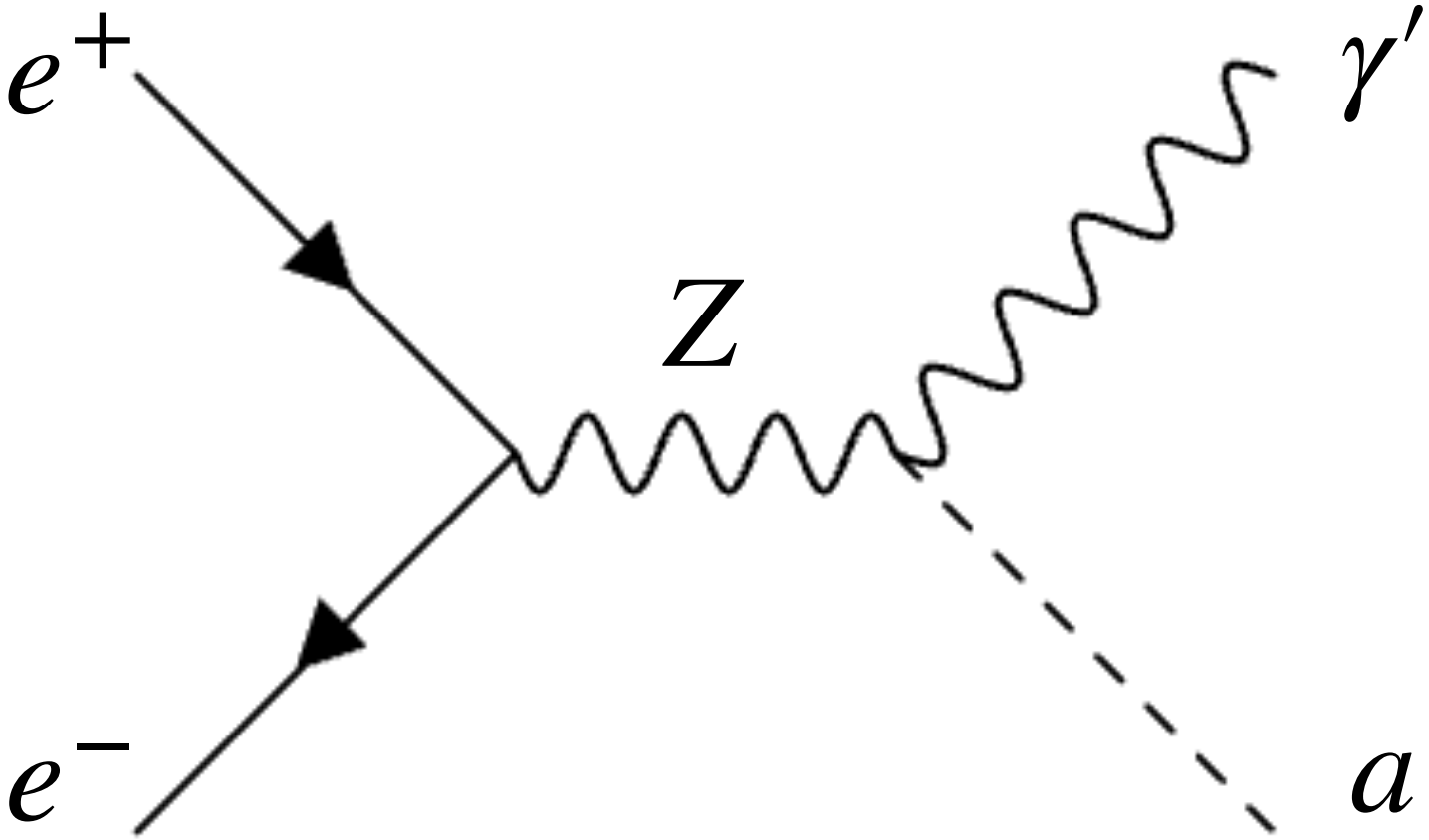
$F'_{\mu\nu}$: the field-strength tensor of the dark photon γ'

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

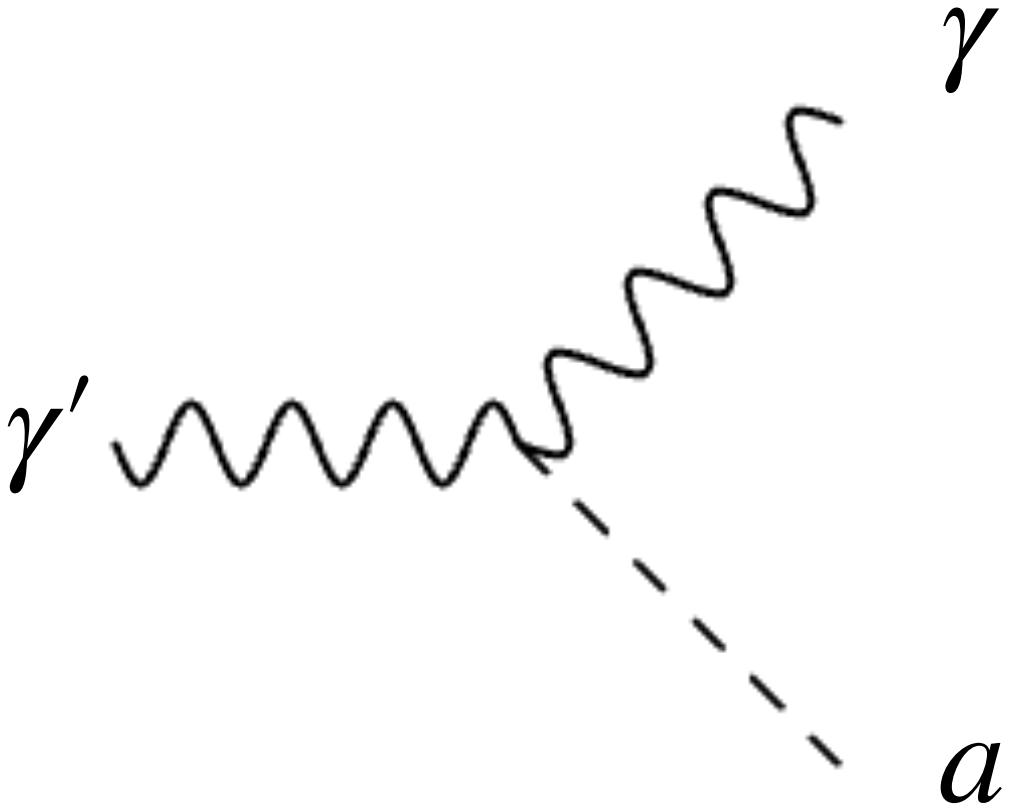
$$m_Z > m_{\gamma'} > m_a$$

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

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

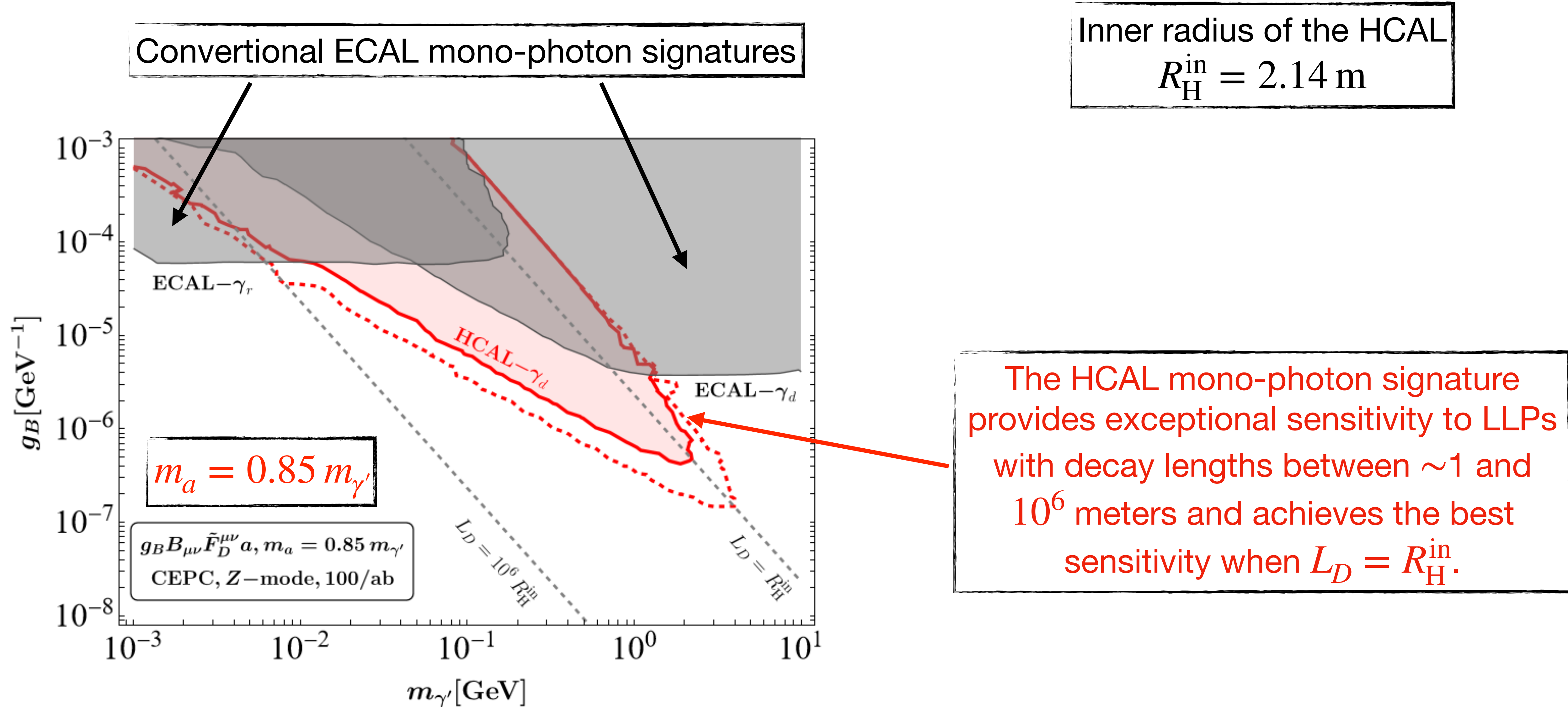


Generation process



Decay process

CEPC sensitivities on the axion portal operator

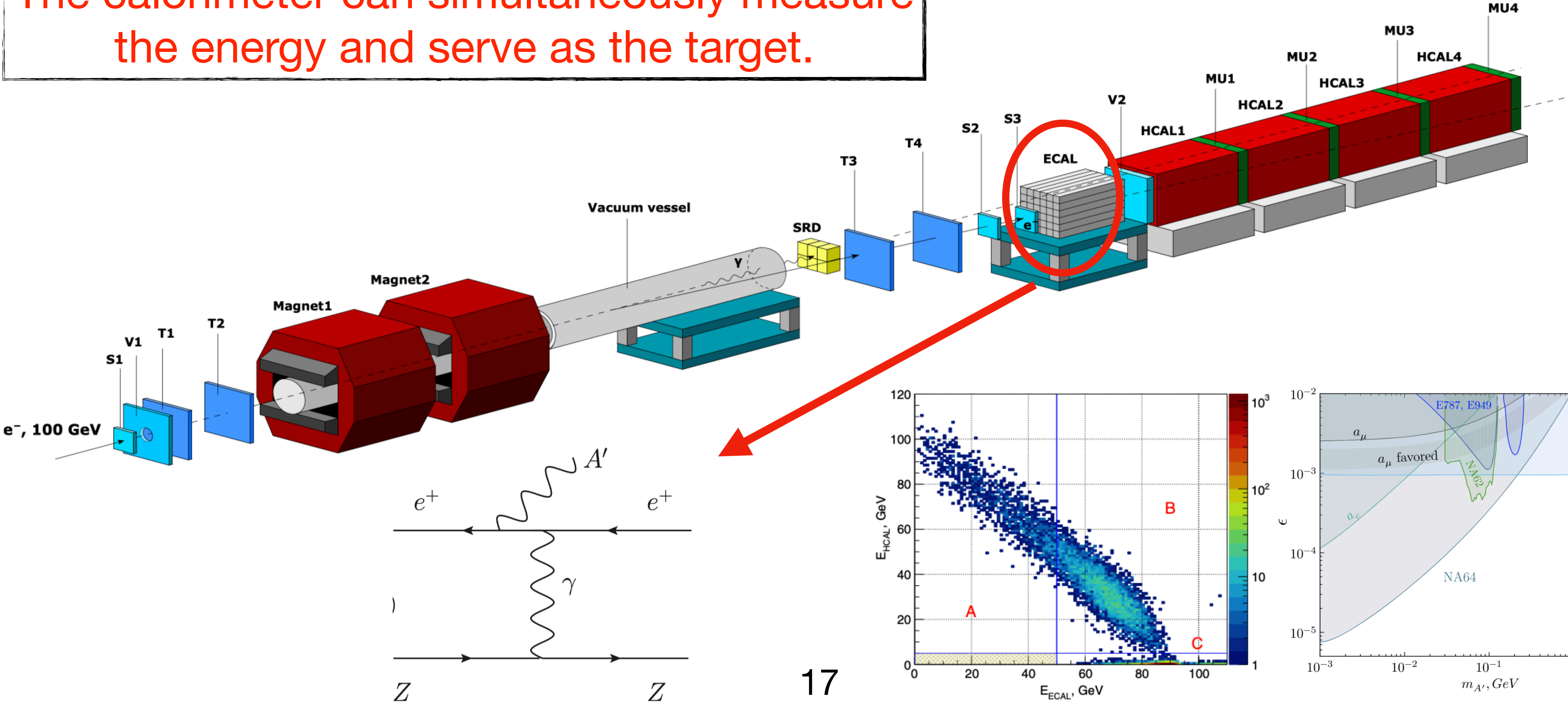


Disappearing positron track signature at Belle II

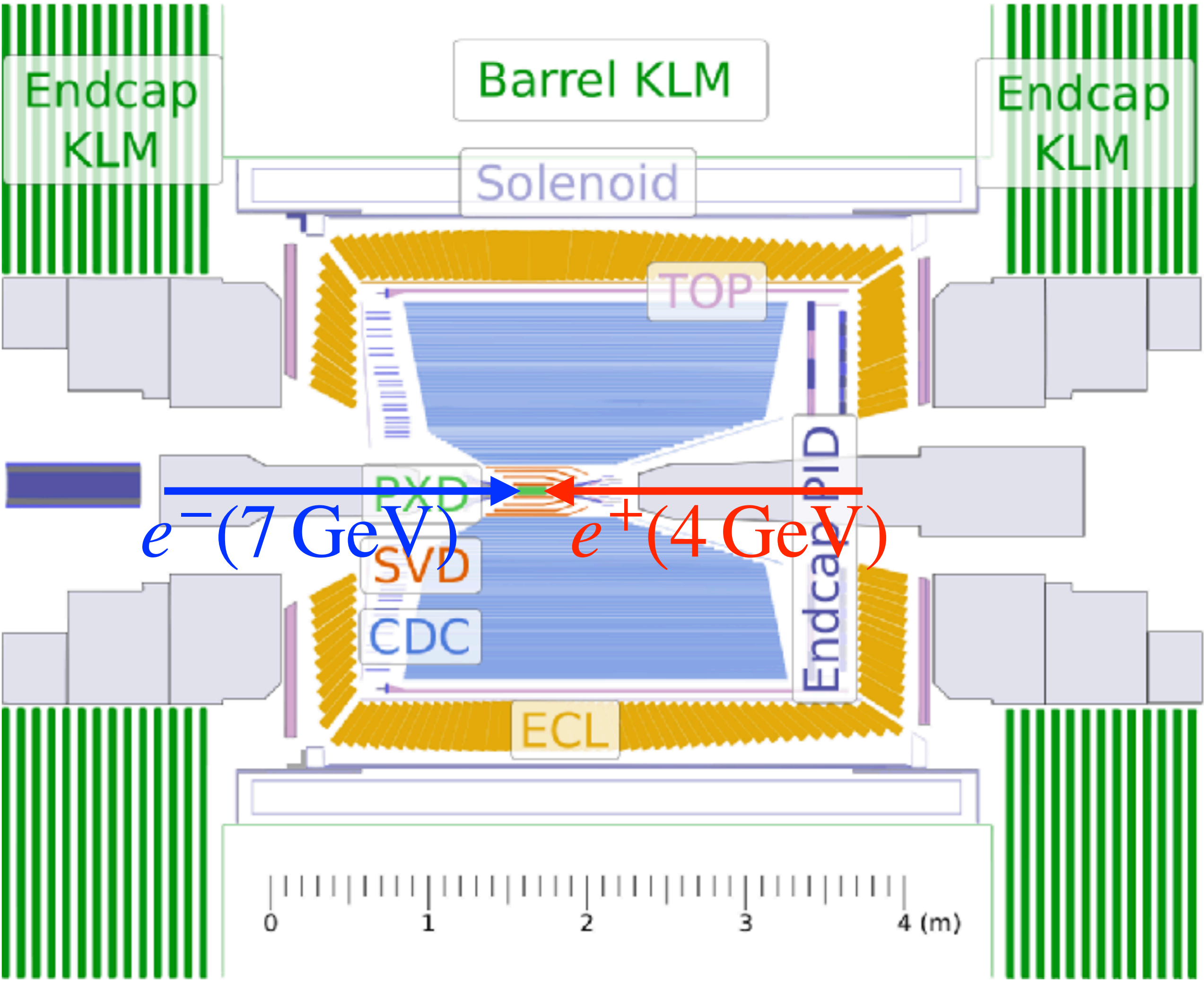
Large missing energy search at NA64 experimet

NA64 Collaboration, PRL 123, 121801 (2019)

The calorimeter can simultaneously measure the energy and serve as the target.



Belle II detectors



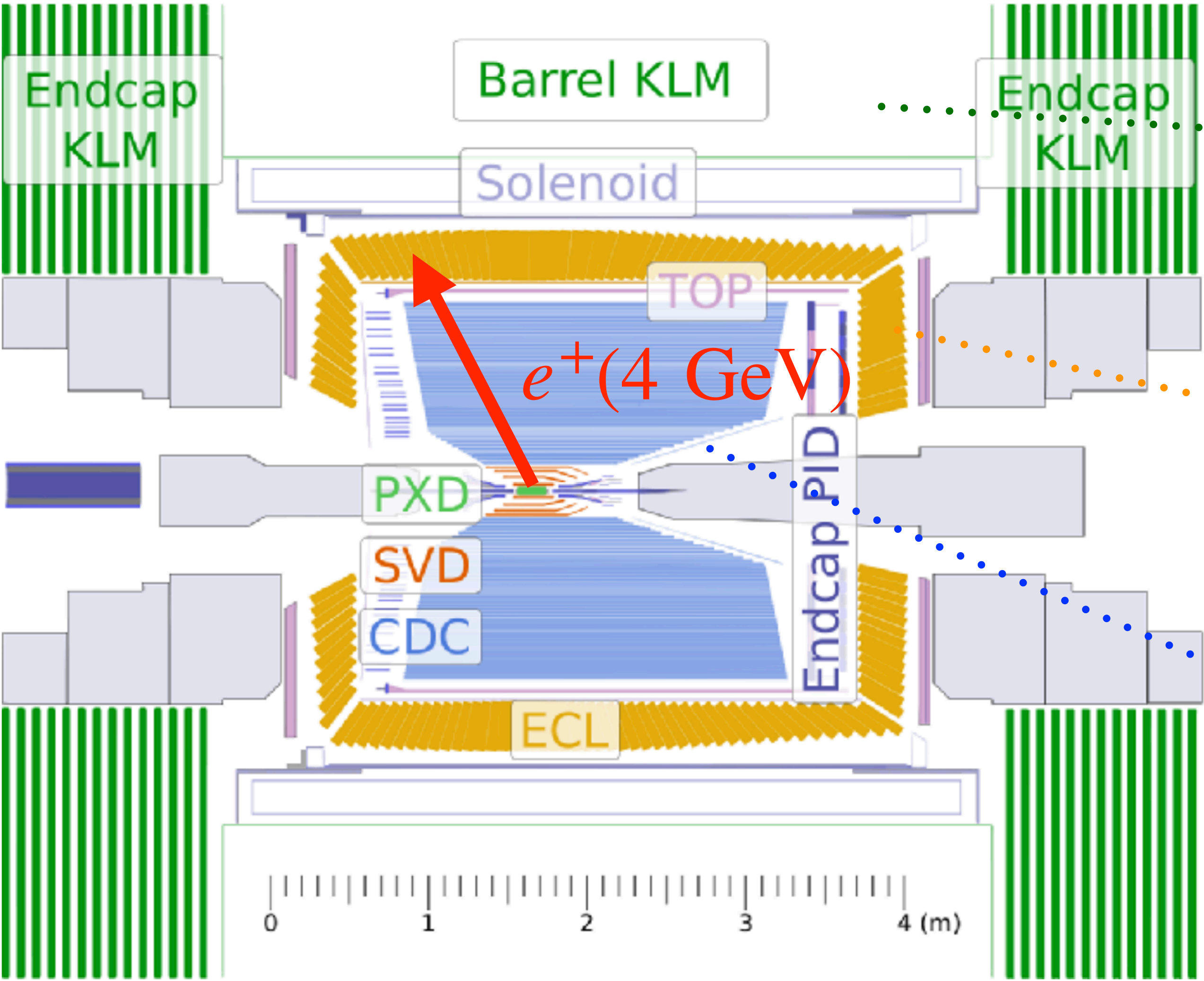
$\mathcal{L} = 50/\text{ab}, \sqrt{s} = 10.58 \text{ GeV}$

CDC:
 $\delta p_T/p_T \simeq 0.4 \%$ for $p_T \simeq 3 \text{ GeV}$

ECL:
 16 X_0 CsI crystals,
 $\sigma_E/E = 1.6 \%$ for $E \simeq 8 \text{ GeV}$

KLM:
 Alternating sandwich of iron plates
 and active detector elements (RPC
 and scintillator strips)

Belle II detectors

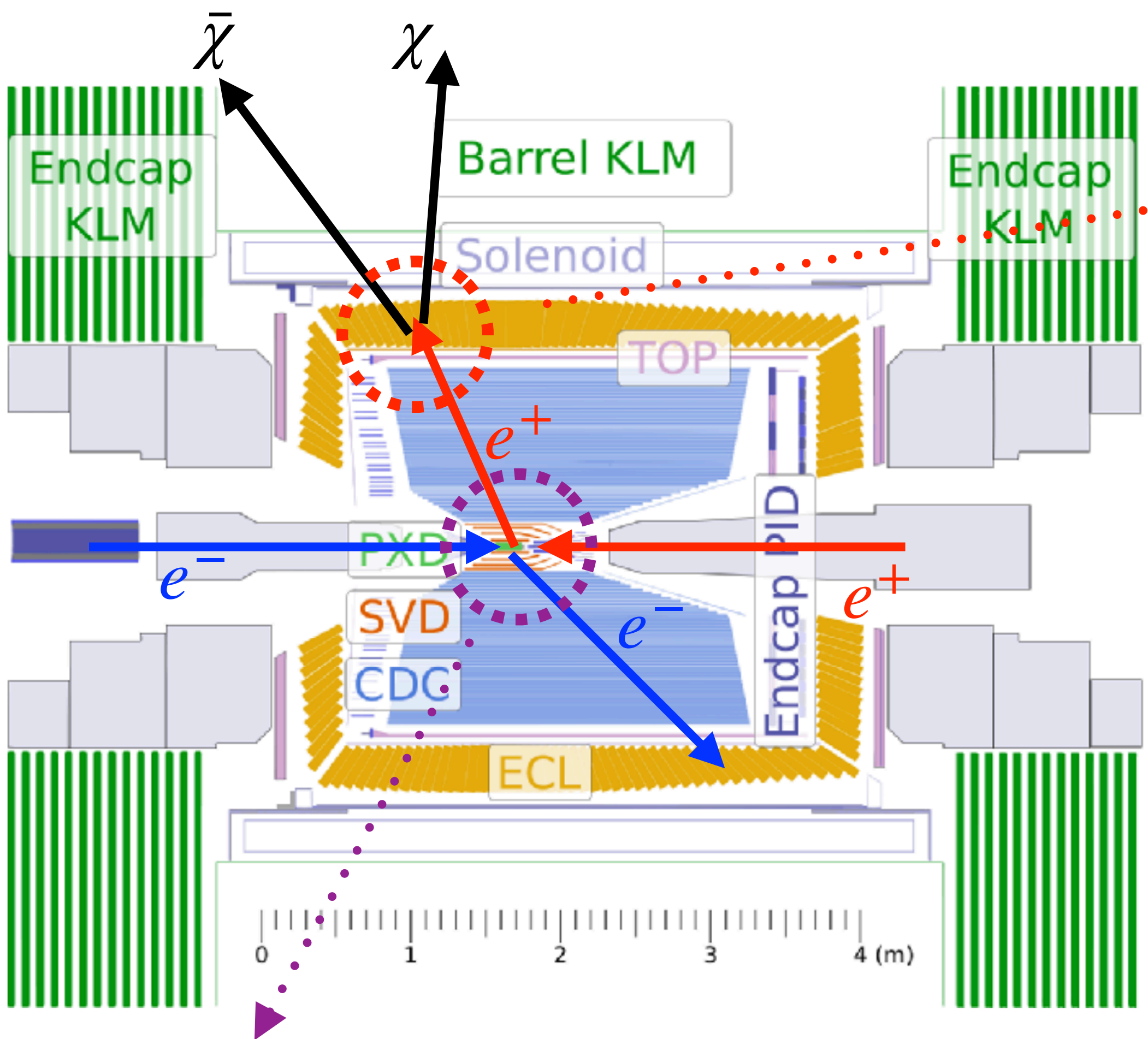


KLM:
No significant activity at KLM

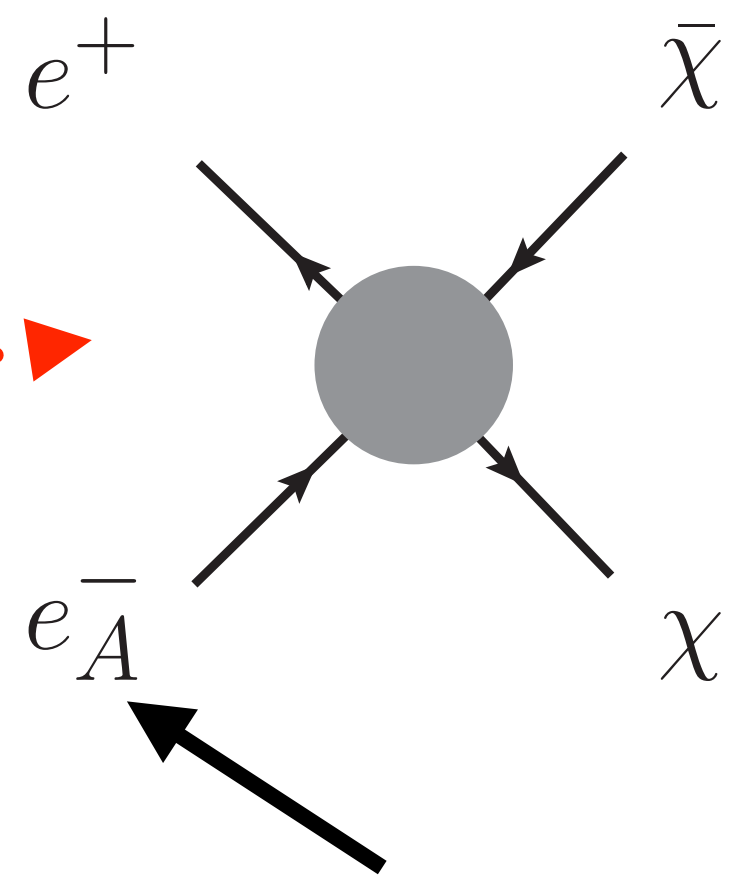
ECL:
4 GeV deposited energy

CDC:
A charged track with $p = 4 \text{ GeV}$

Disappearing positron track signature

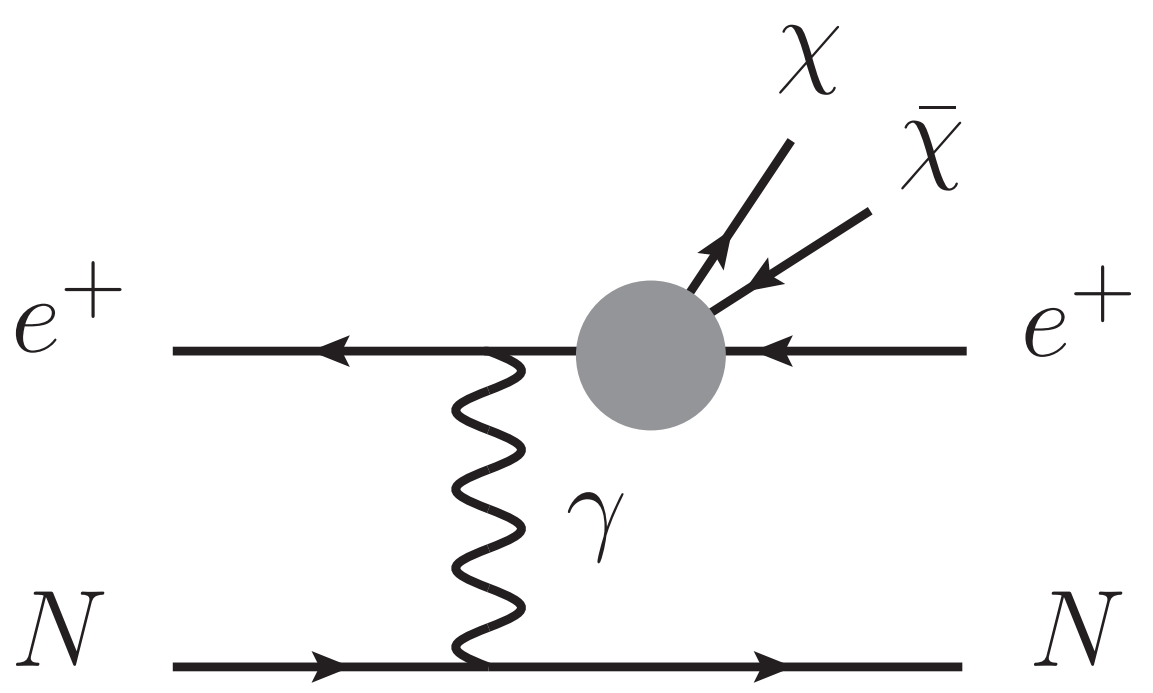


Annihilation



Atomic electron in the ECL

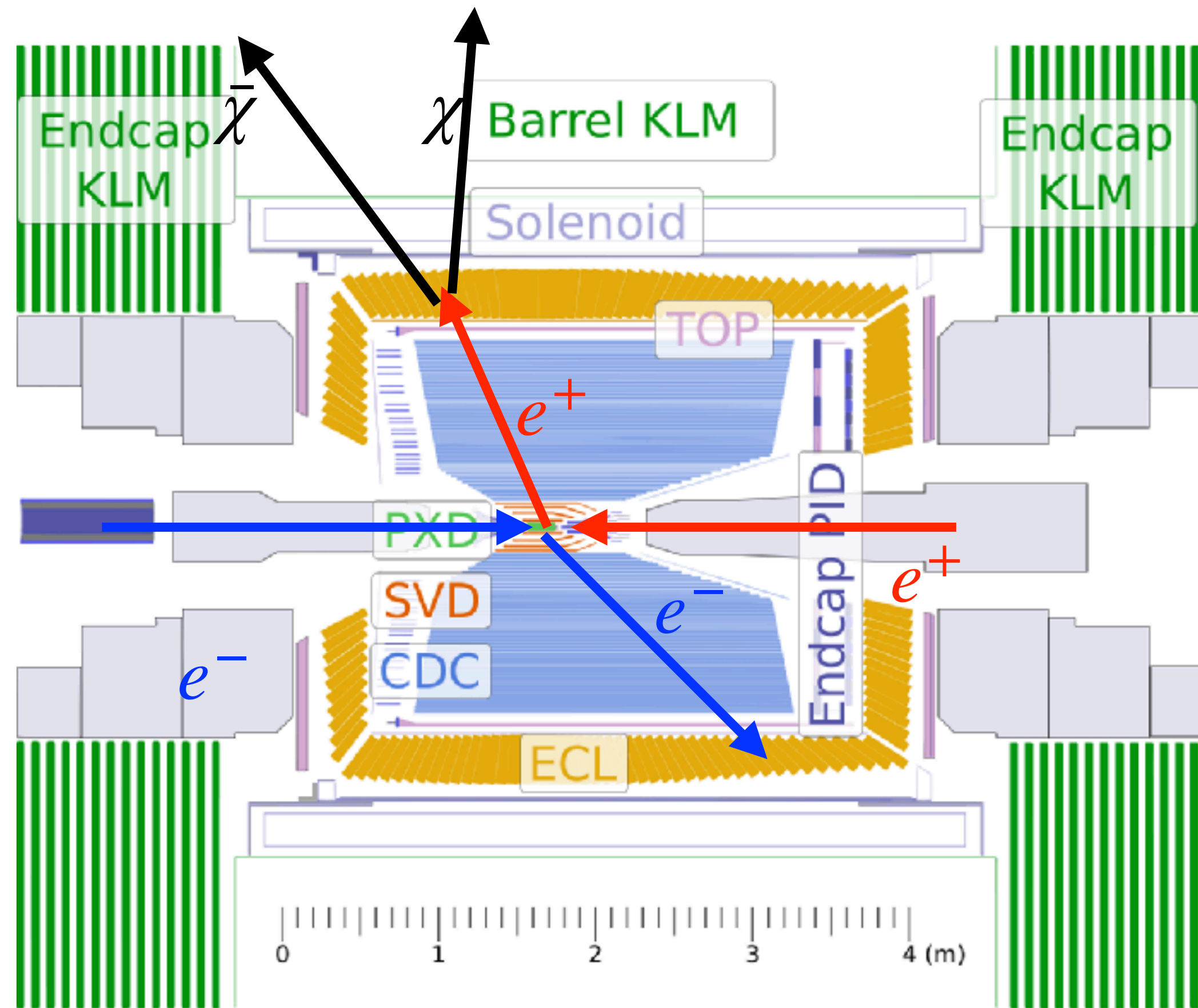
Bremsstrahlung



DMs are generated in collisions between the positron and the atomic electron in the ECAL.

Bhabha scattering: 6×10^{11} positrons

Disappearing positron track signature

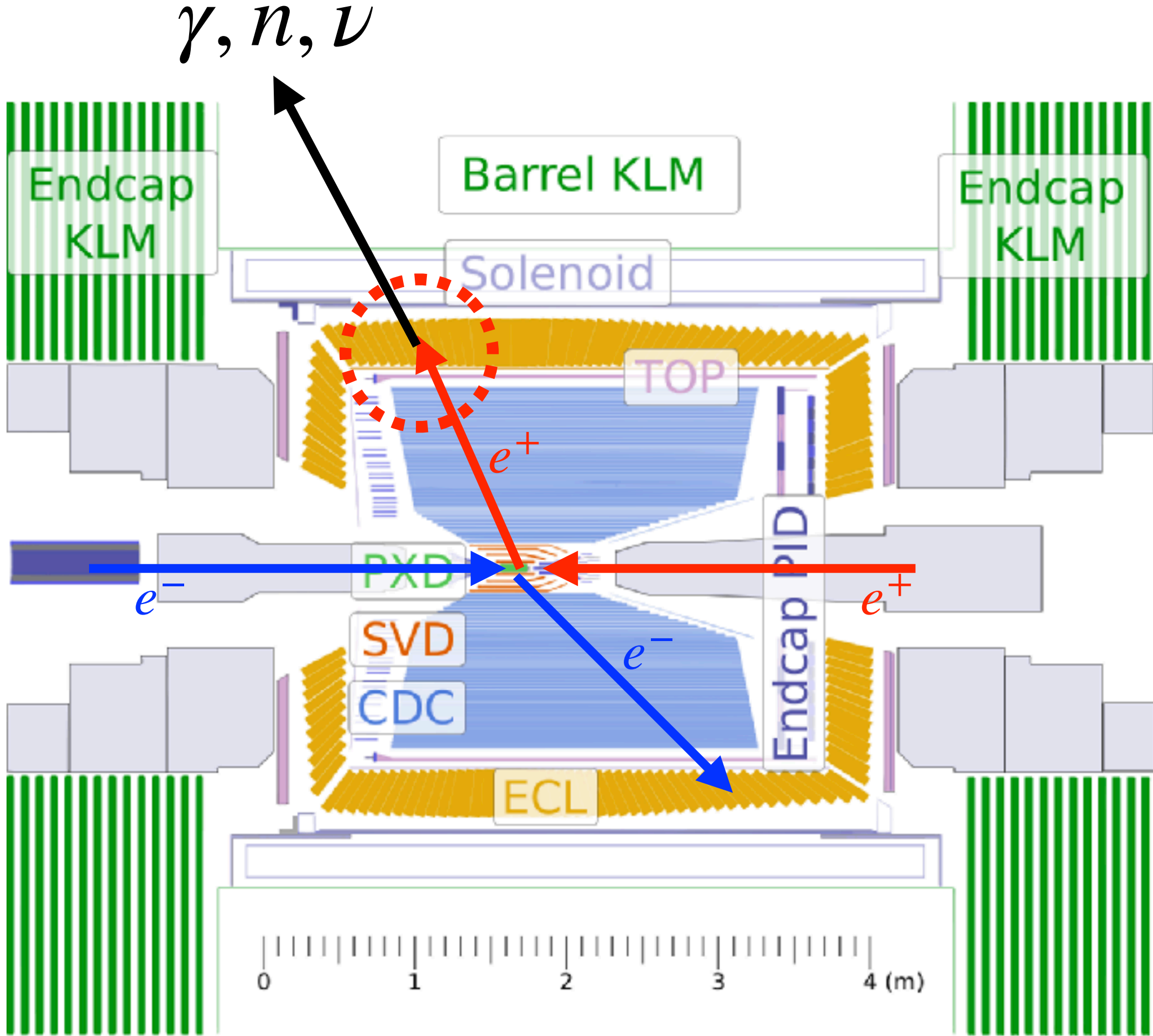


Signature:

- (1) Positron: a clear track in the CDC, very little energy deposited in the ECL
- (2) Electron: a clear track in the CDC, full energy deposited in the ECL
- (3) No tracks or clusters in the KLM

We treat Belle II as a positron fixed target experiment with the ECL as the target.

SM Backgrounds

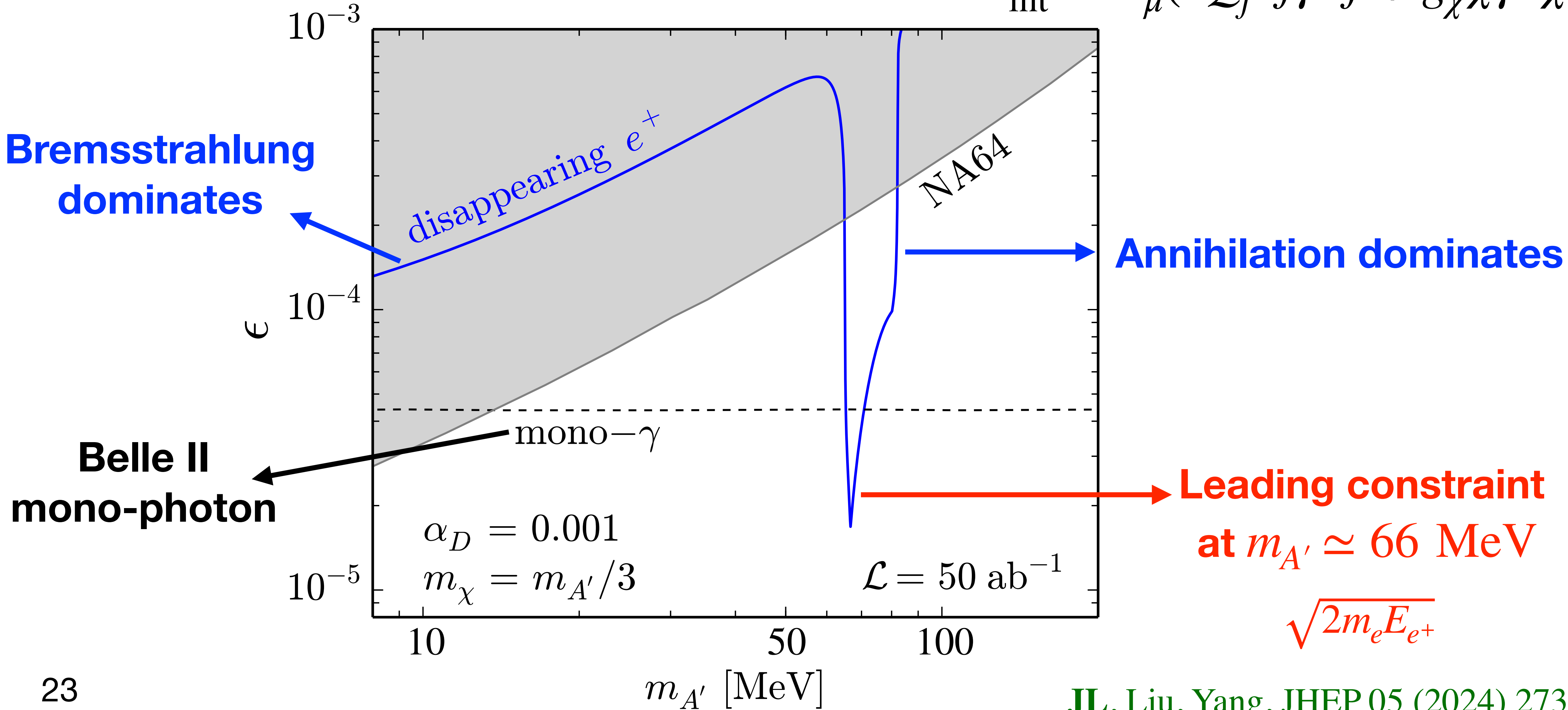


- Cuts:
- (1) Less than 5% of the positron energy deposited in the ECL barrel
 - (2) No clusters or tracks in the KLM

$$N_\gamma \simeq 13, N_n \simeq 81$$

Constraints on the dark photon model

$$\mathcal{L}_{\text{int}} = A'_\mu (e Q_f \epsilon \bar{f} \gamma^\mu f + g_\chi \bar{\chi} \gamma^\mu \chi)$$

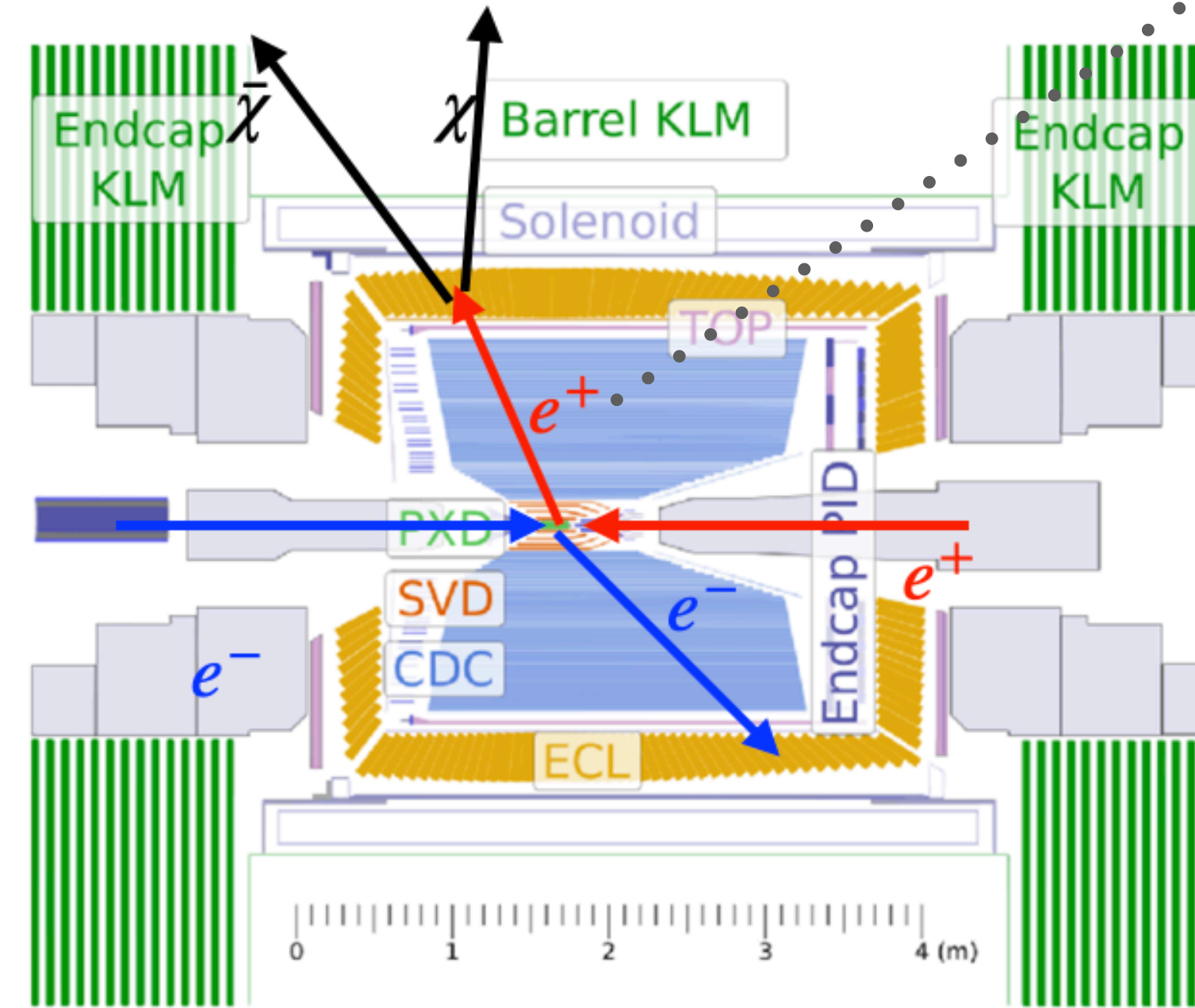
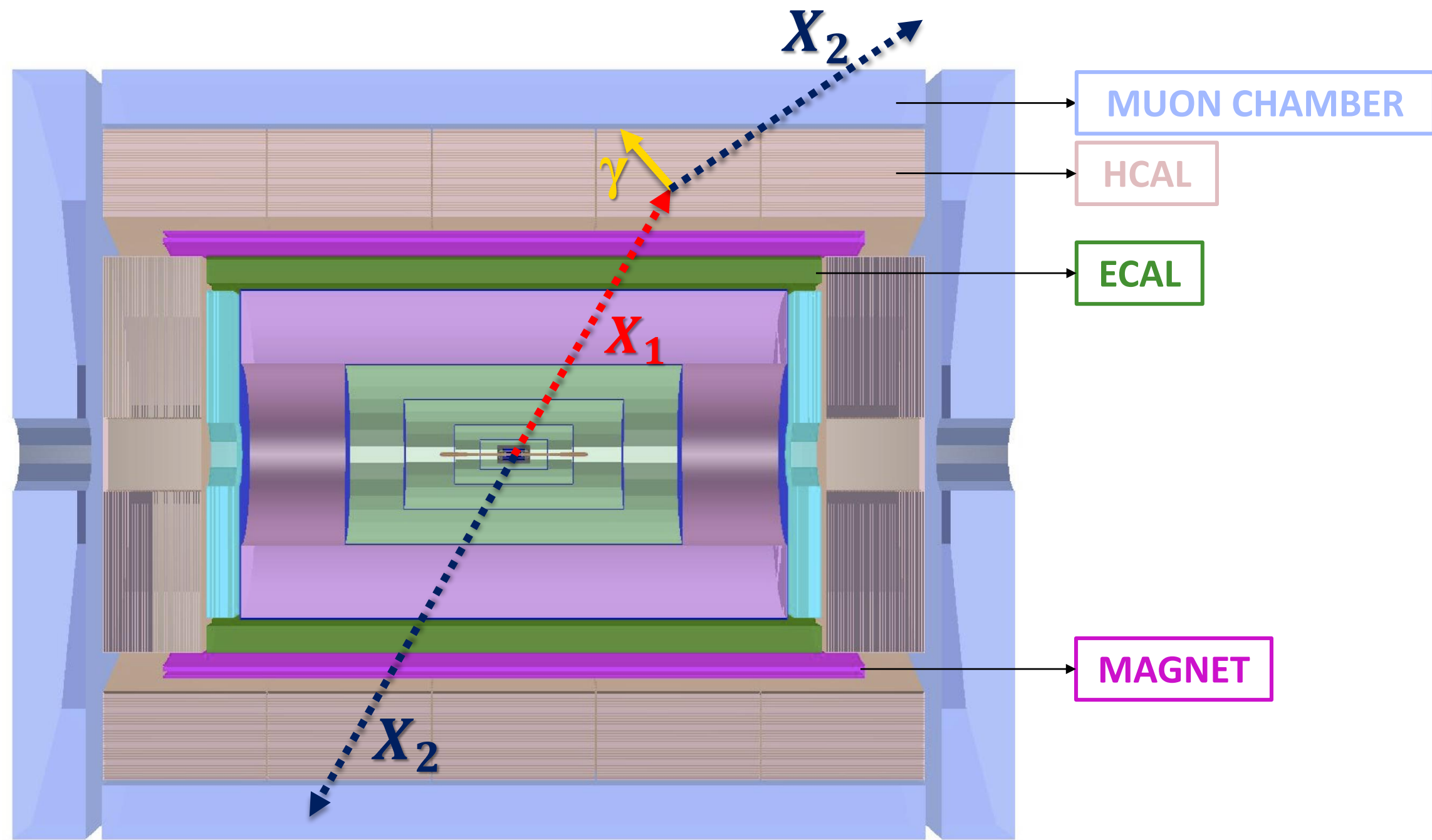


Summary: two exotic channels

$$4 \times 10^{10} e^+e^- \rightarrow \mu^+\mu^-$$

$$\mu^+e^- \rightarrow a$$

for the LFV axion?



CEPC HCAL barrel as a photon far detector for long-lived particles

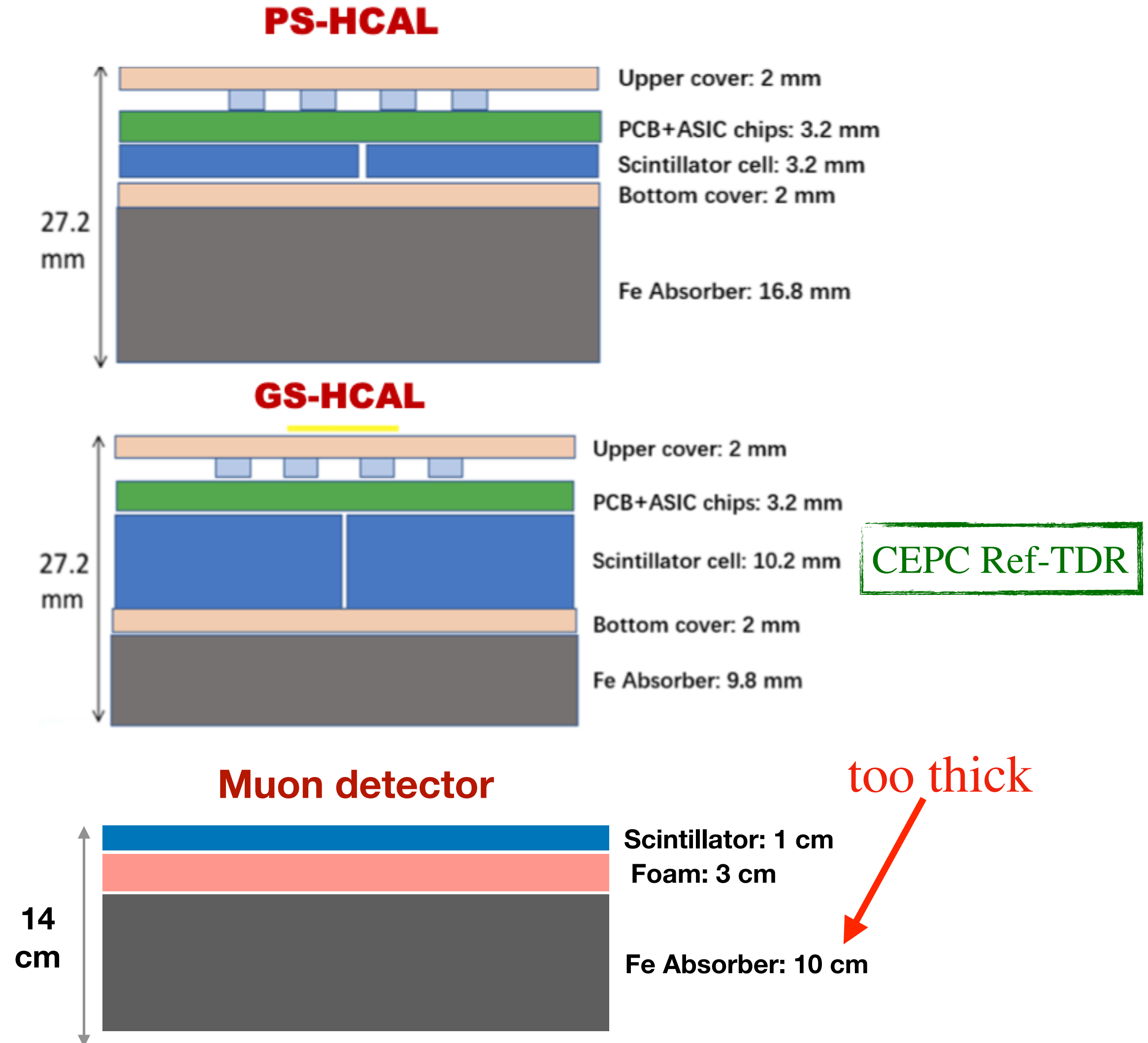
Belle II as a fixed-target experiment: disappearing positron track signature

Background analysis: large uncertainty, trusting experimentalists

Backup

The HCAL serving as a photon far detector

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



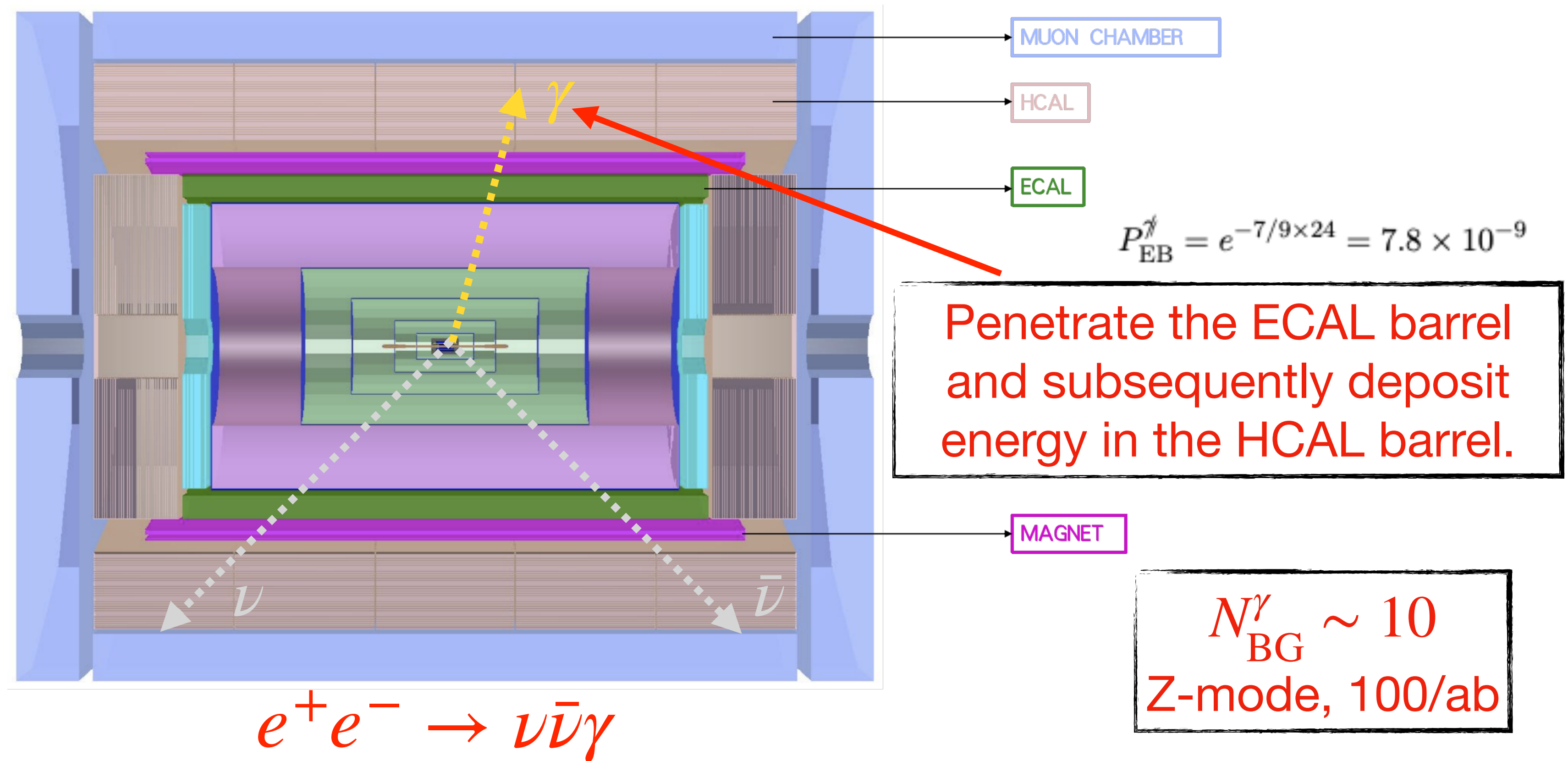
Detector	PS-HCAL	GS-HCAL	Muon detector
Main components per layer	20.8 mm Fe	13.8 mm Fe 10.2 mm GS	10 cm Fe
t (radiation length per layer)	1.21	1.44	5.68
Critical energy	~20.7 MeV	~15.7 MeV	~20.7 MeV
Energy threshold for five layers	1.37 GeV	2.30 GeV	7332 TeV



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.

Backgrounds

- Photon backgrounds
- Neutrino backgrounds
- Neutral hadron backgrounds

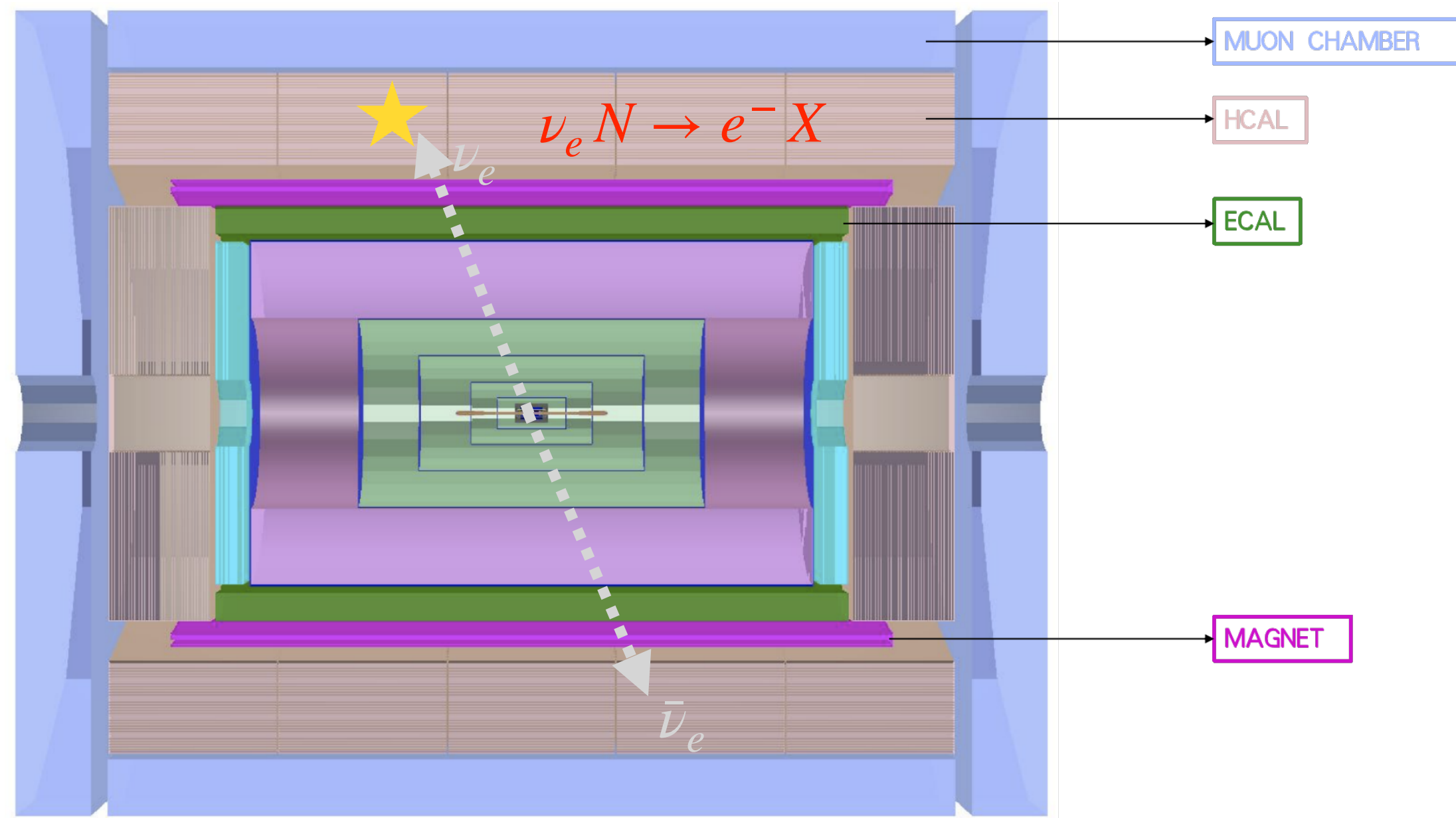


The dominant SM backgrounds for the HCAL mono-photon signature originate from **neutral particles** such as single photons, neutrinos, or neutral hadrons produced at the primary vertex without any accompanying detectable particles.

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

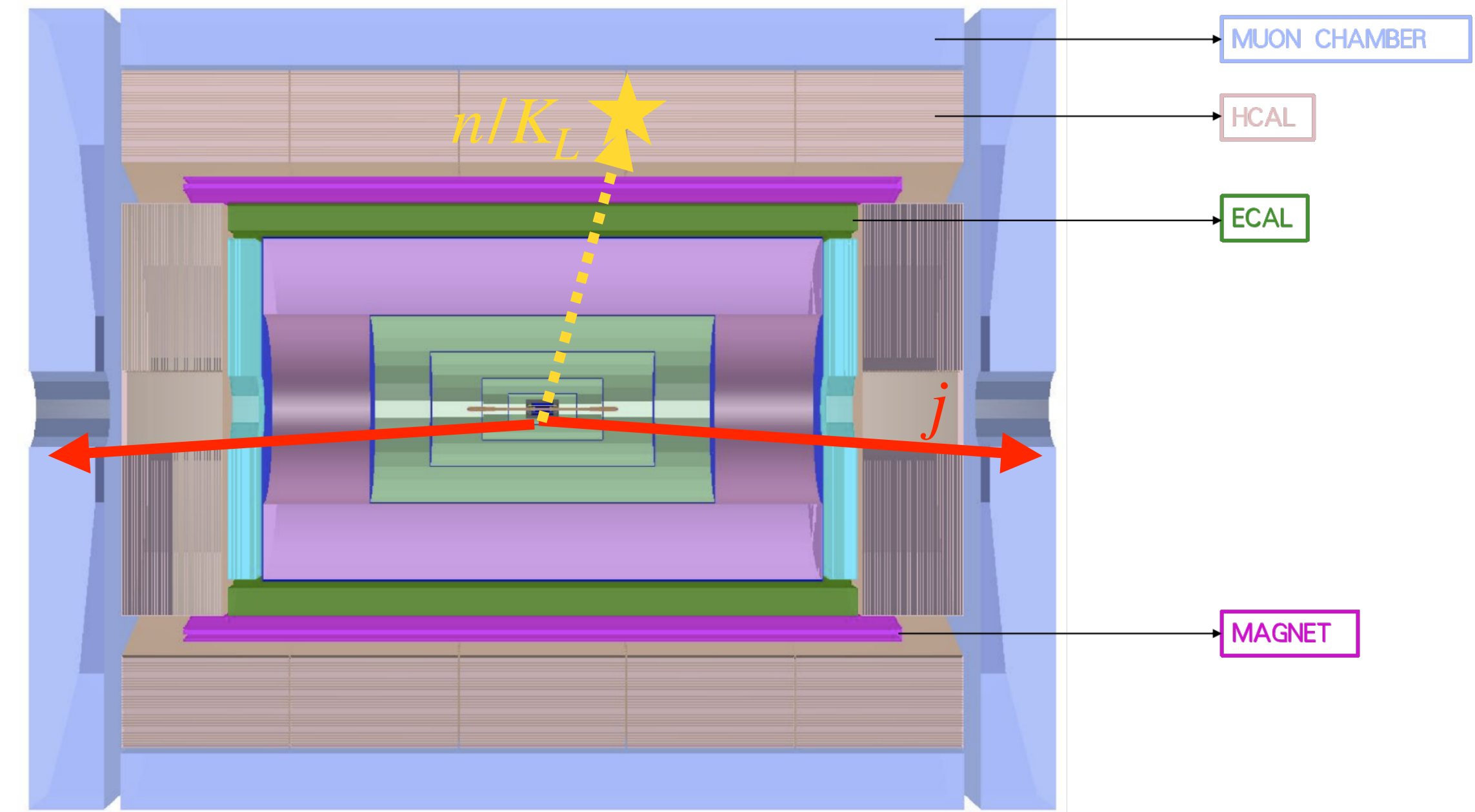
Neutrino and neutral hadron Backgrounds

Neutrino backgrounds



$$N_{BG}^{\nu} \sim 1$$

Neutral hadron backgrounds



$$N_{BG}^n \sim 10^3$$

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

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

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

Optimistic estimation

Conservative estimation

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

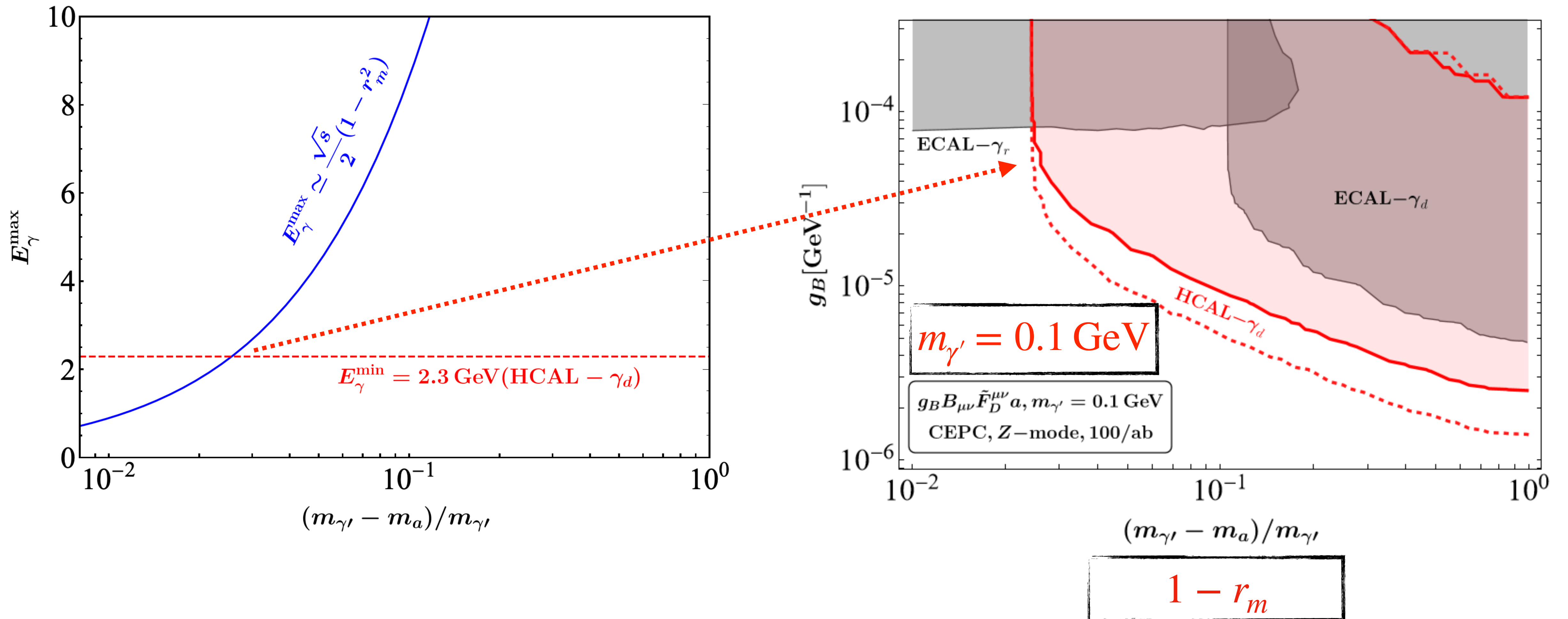
(Other potential backgrounds)

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

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

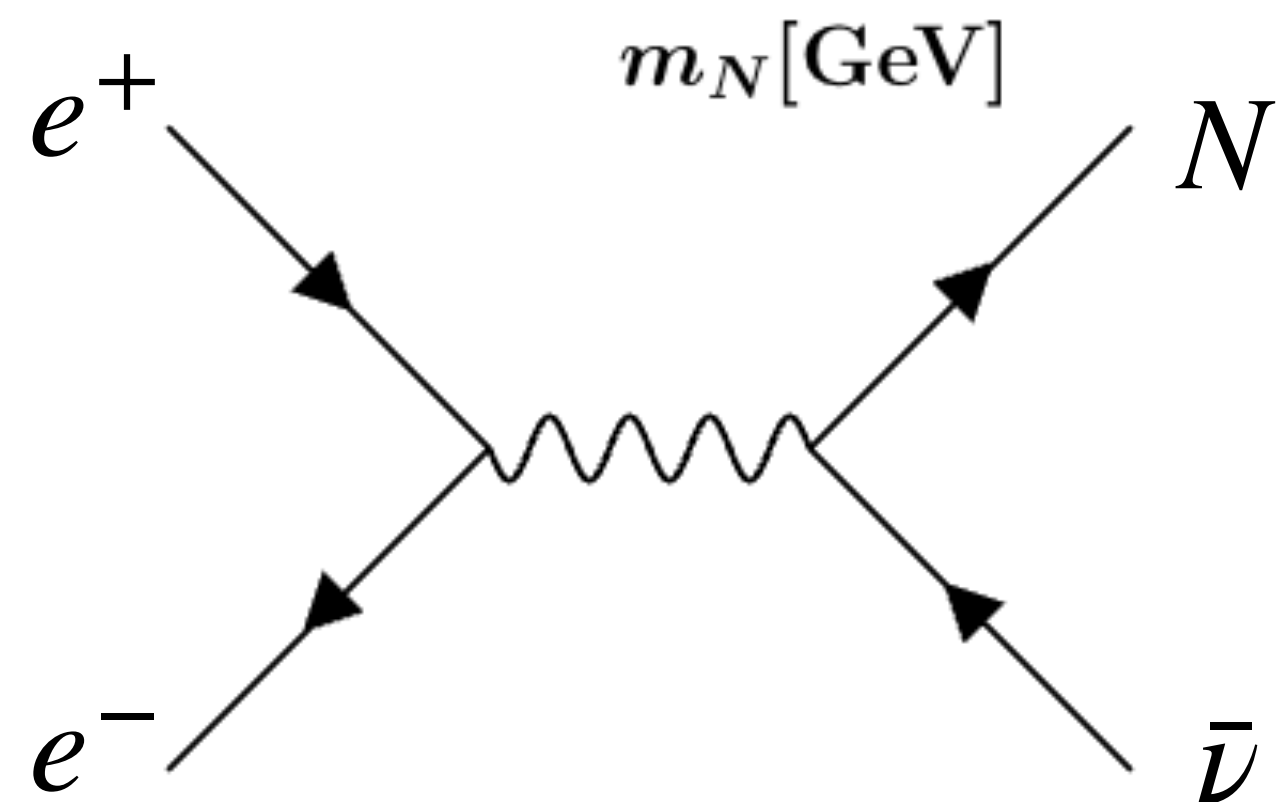
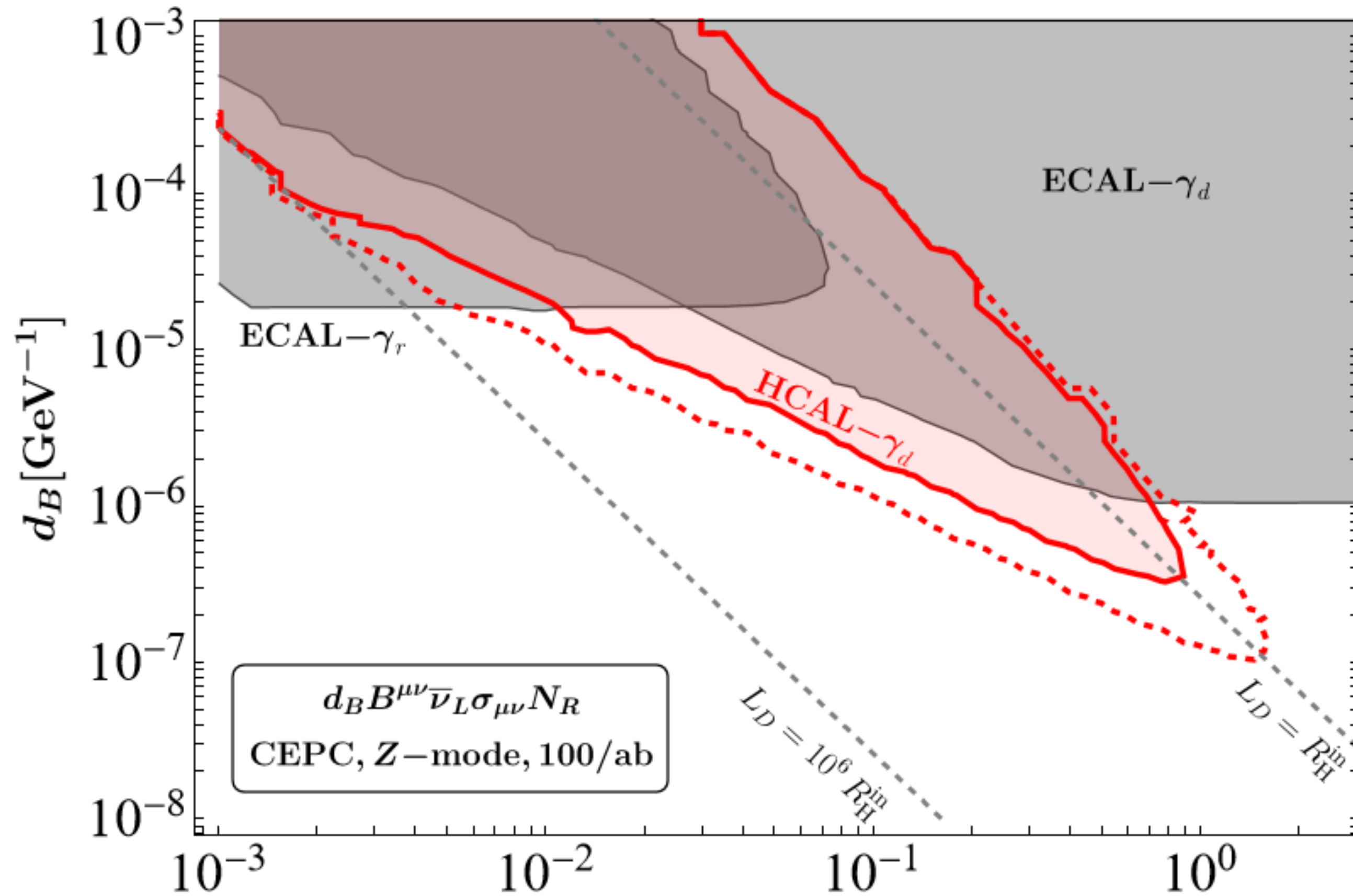
$$2\sigma \text{ sensitivity: } N_s = 2\sqrt{N_{\text{BG}}^{\text{tot}}}$$

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



31

$r_m = 0$

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

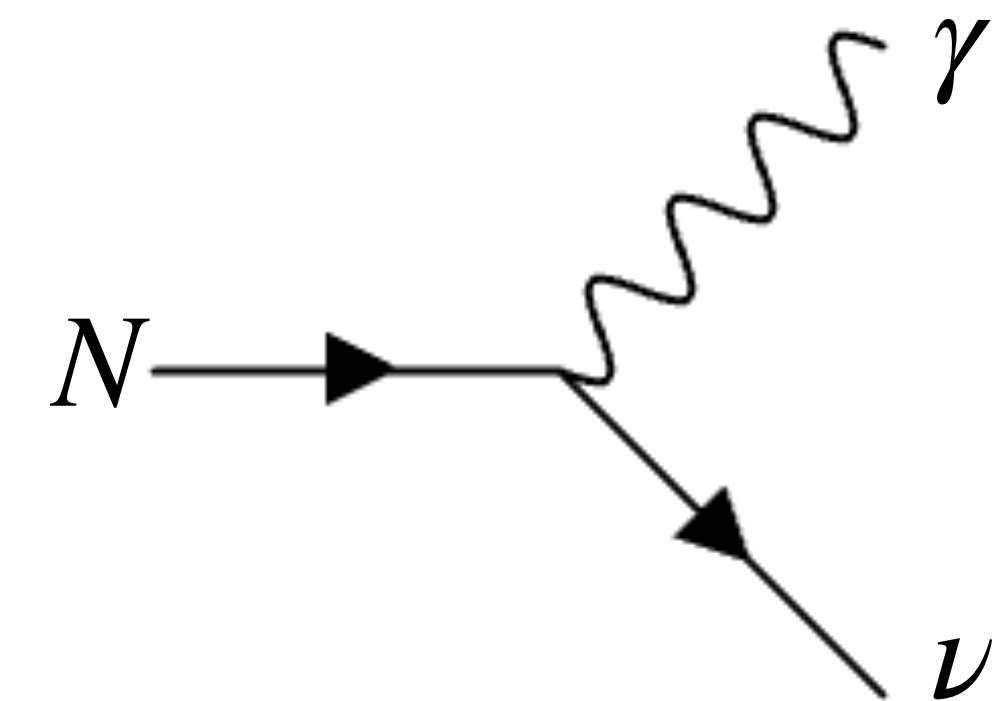
↓

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

N : sterile neutrino
 H : Higgs doublet

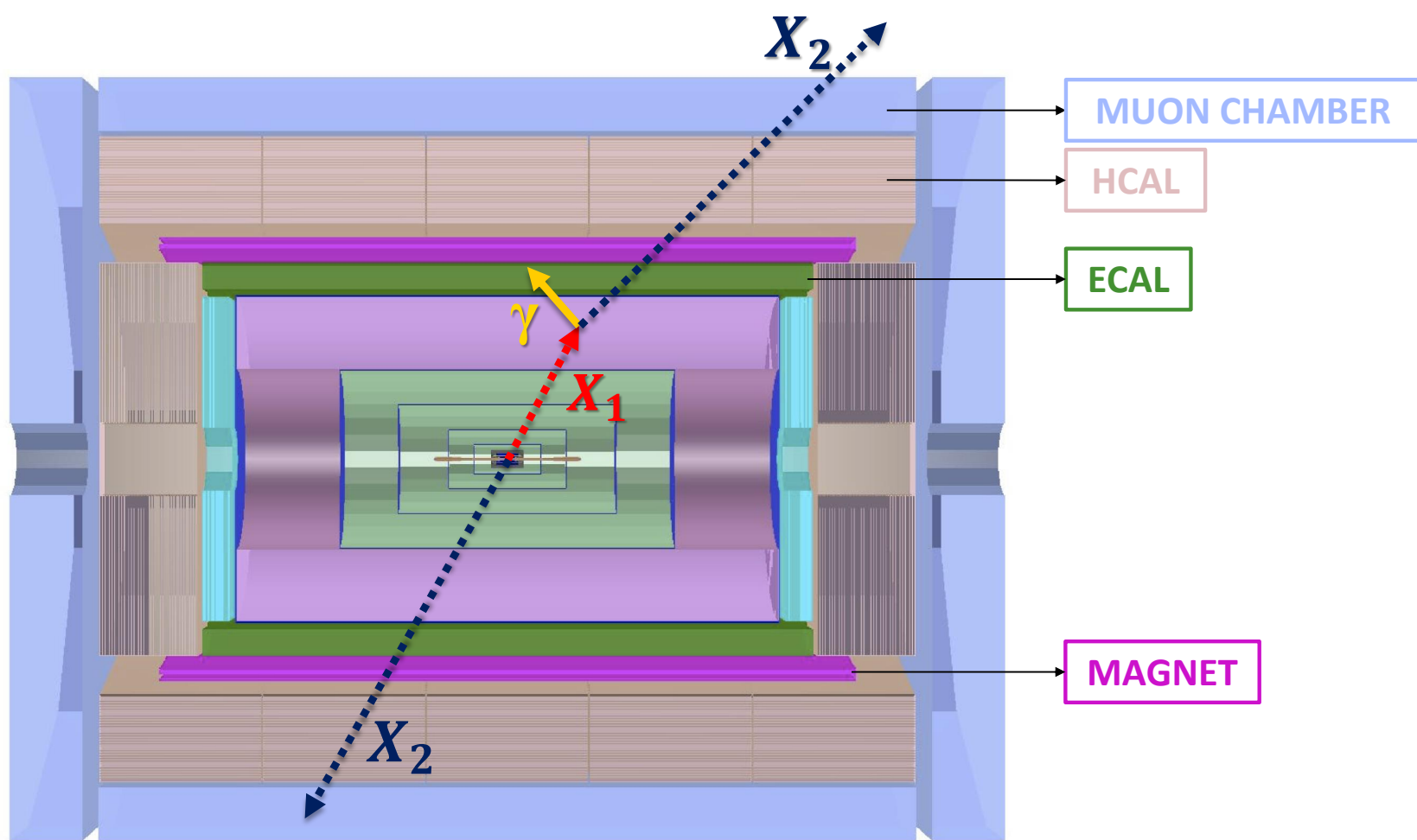
$B_{\mu\nu}$: hypercharge field-strength tensor

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



Three mono-photon signatures

$$L_D \ll R_{\text{HCAL}}$$

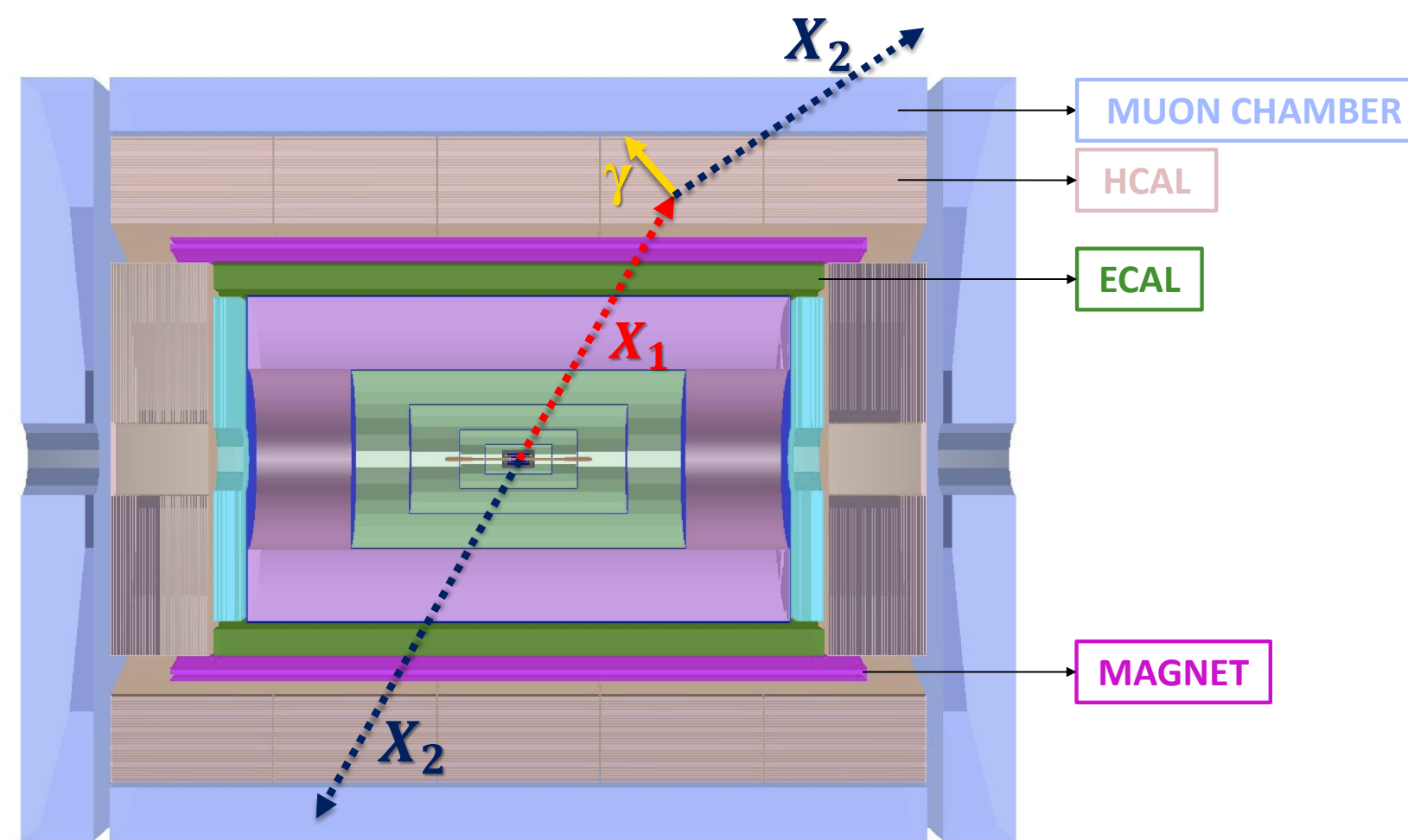


ECAL- γ_d

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

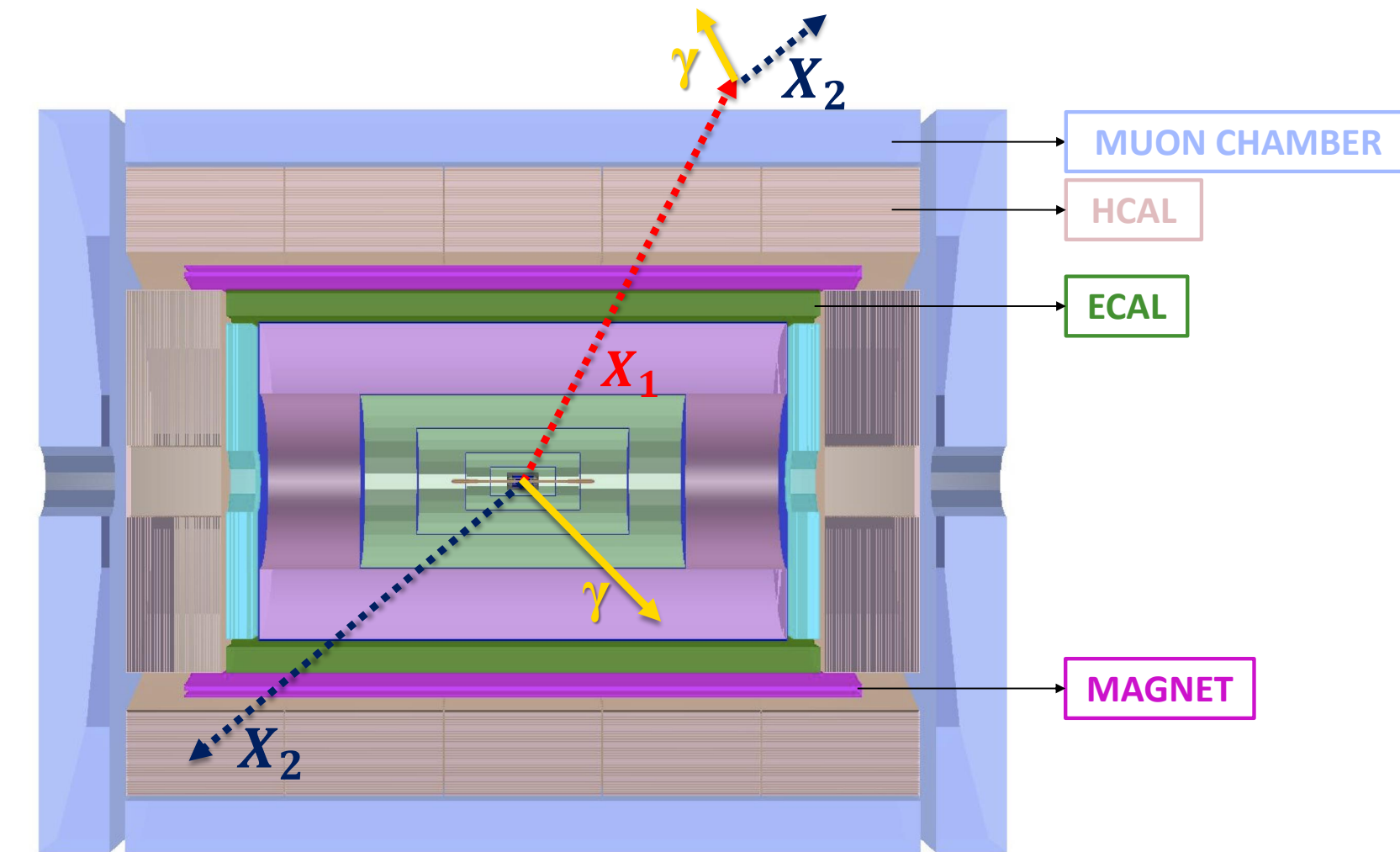
γ_d : generated by X_1 decay

$$L_D \sim R_{\text{HCAL}}$$



HCAL- γ_d (This work)

$$L_D \gg R_{\text{HCAL}}$$



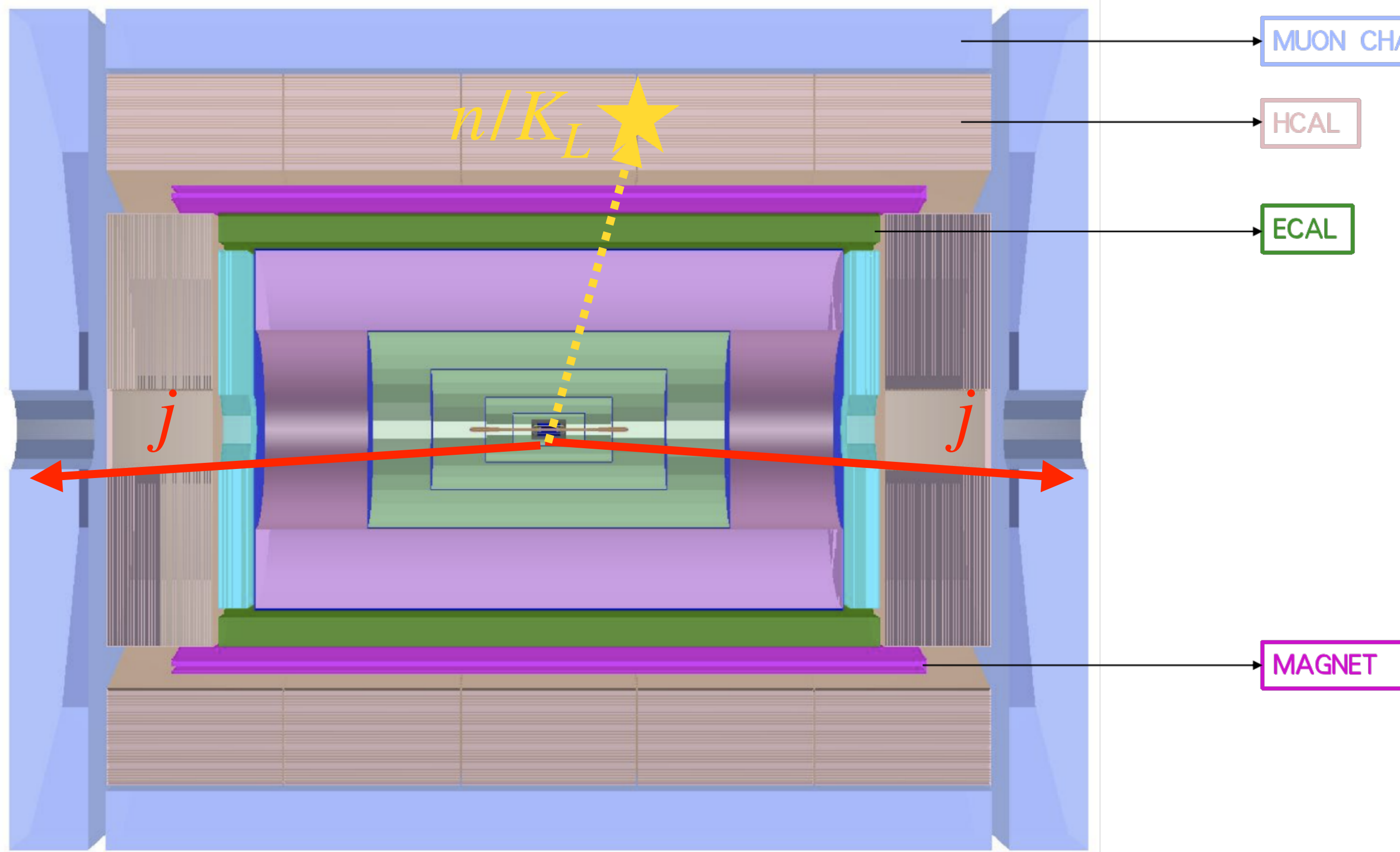
ECAL- γ_r

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

γ_r : generated by ISR

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

Neutral hadron Backgrounds



Simulate $10^8 e^+e^- \rightarrow jjj$ events with
 $p_T^{j_1} > 1 \text{ GeV}$, $p_T^{j_2, j_3} < 10 \text{ GeV}$, and $\Delta R_{2j} > 0.4$
 $\sigma_{3j} = 3300 \text{ pb}$

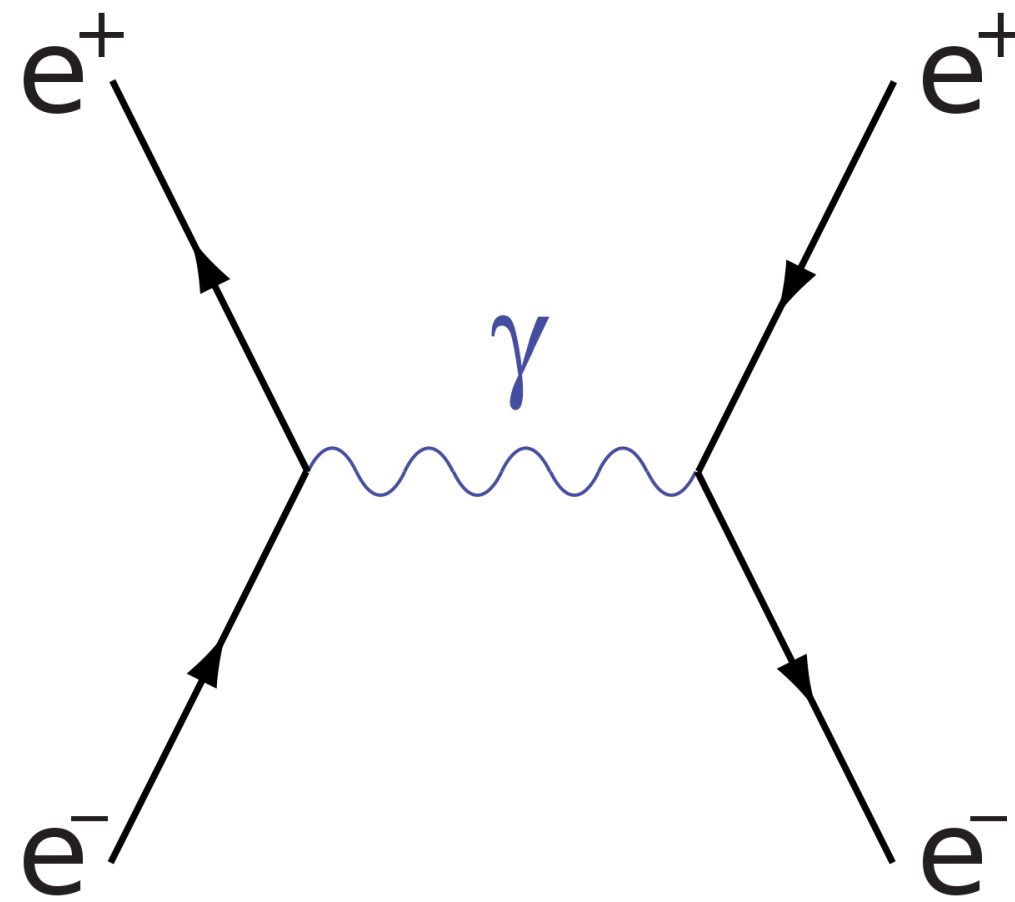
Veto events if there are tracks with
 $p_T > 0.1 \text{ GeV}$ or photons with $E_\gamma > 0.1 \text{ GeV}$

Select events with only
 one neutron or K_L within the HCAL barrel.
 Only one event is found (large uncertainty).

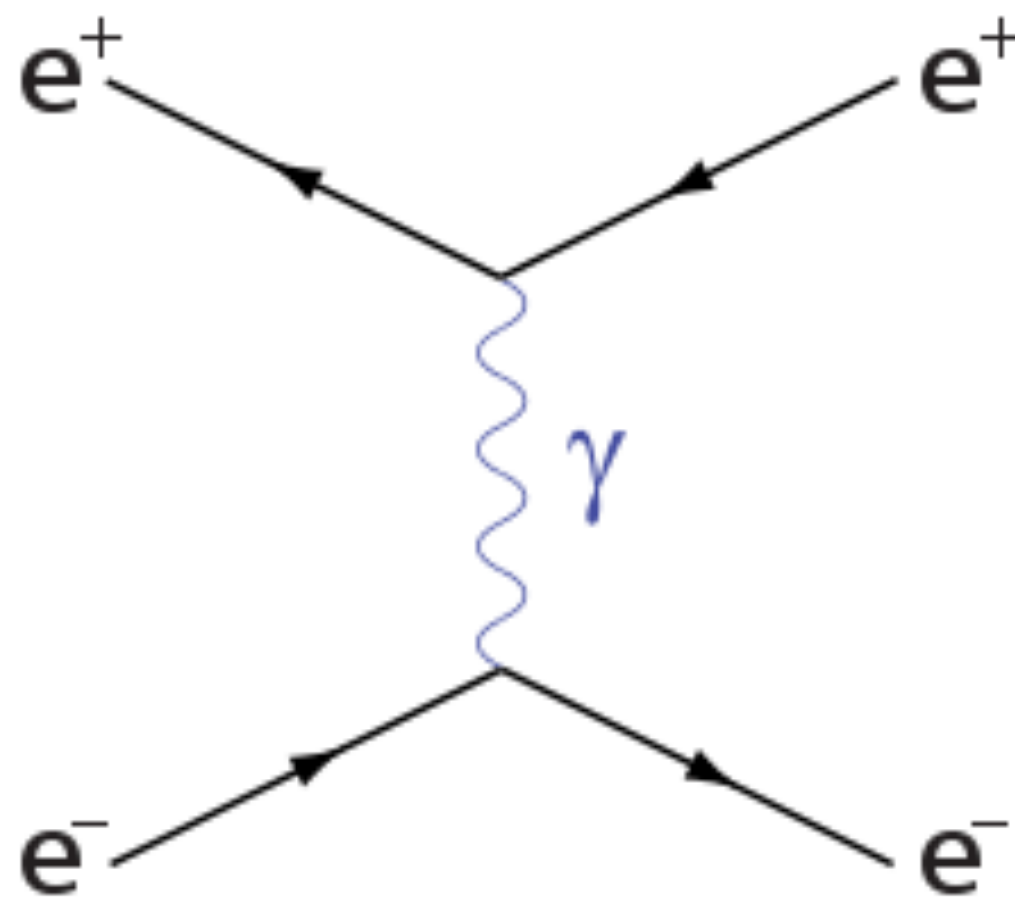
$$N_{\text{BG}}^{n, K_L} \simeq \frac{1}{10^8} \times \sigma_{3j} \times \mathcal{L} \times P_{\text{EB}}^{\eta} = 858$$

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.

Positron flux from Bhabha scattering



$$\frac{d\sigma_B}{d\cos\theta^*} = \frac{\pi\alpha^2}{2s} \frac{(3 + \cos^2\theta^*)^2}{(1 + \cos\theta^*)^2},$$



$$N_{e^+} \simeq 6 \times 10^{11} \quad (\mathcal{L} = 50/ab)$$

for the ECL barrel region

New channel constraints on dark photon model

$$\mathcal{L}_{\text{int}} = A'_\mu (eQ_f \epsilon \bar{f} \gamma^\mu f + g_\chi \bar{\chi} \gamma^\mu \chi)$$

A'_μ : dark photon

χ : Dirac dark matter

f : SM fermion with charge Q

ϵ, g_χ : coupling constants