A new channel to search for dark matter at Belle II

刘佐伟

南京大学

第十二届新物理研讨会

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Outline

1. New dark matter channel
2. Background
3. Sensitivity on invisible dark photon models

in collaboration with Jinhan Liang and Lan Yang [2212.04252]

1 New dark matter channel

Previous dark matter detection channels at colliders

Most studies focus on mono-X channel with SM X produced at the primary vertex

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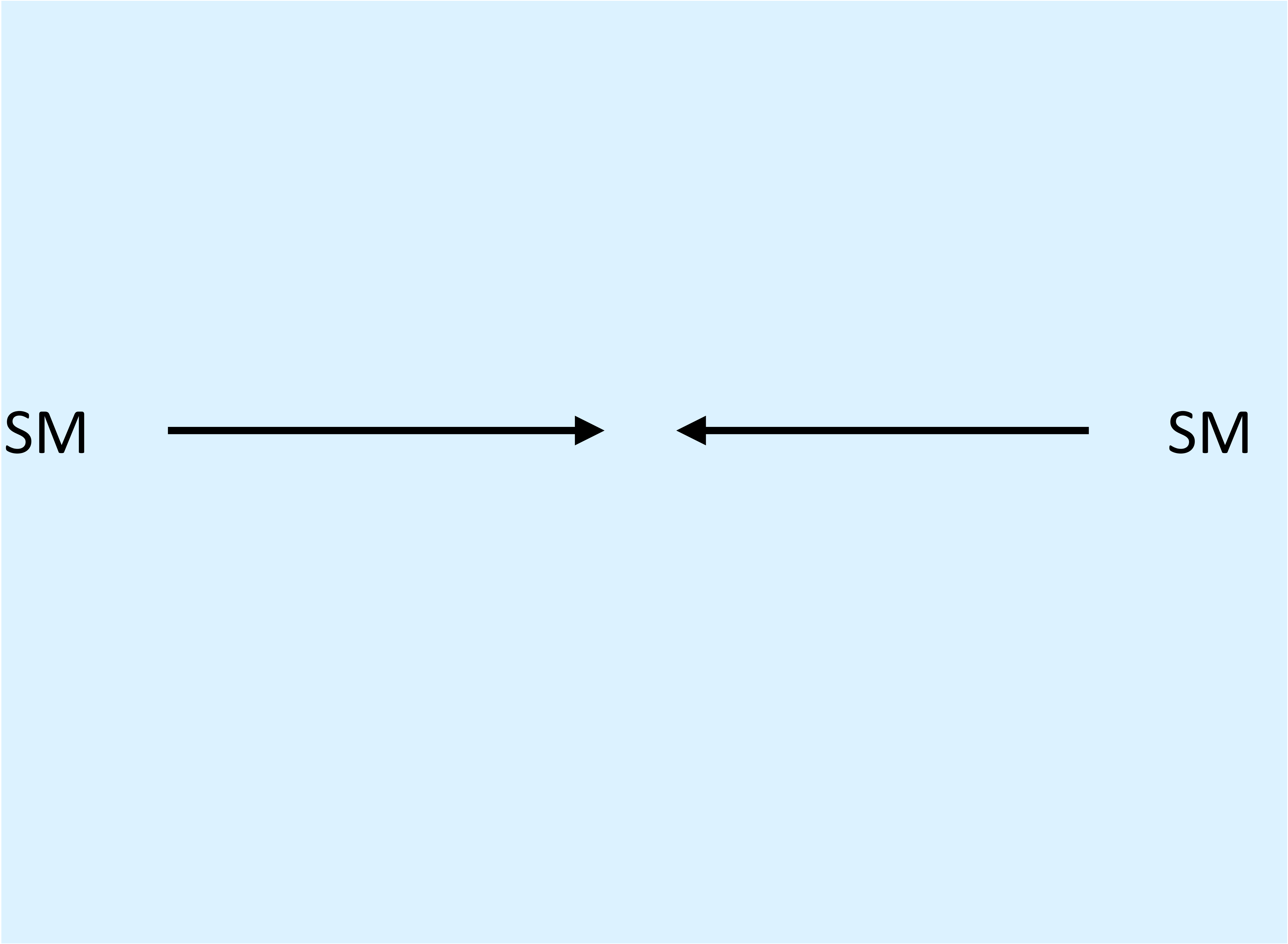

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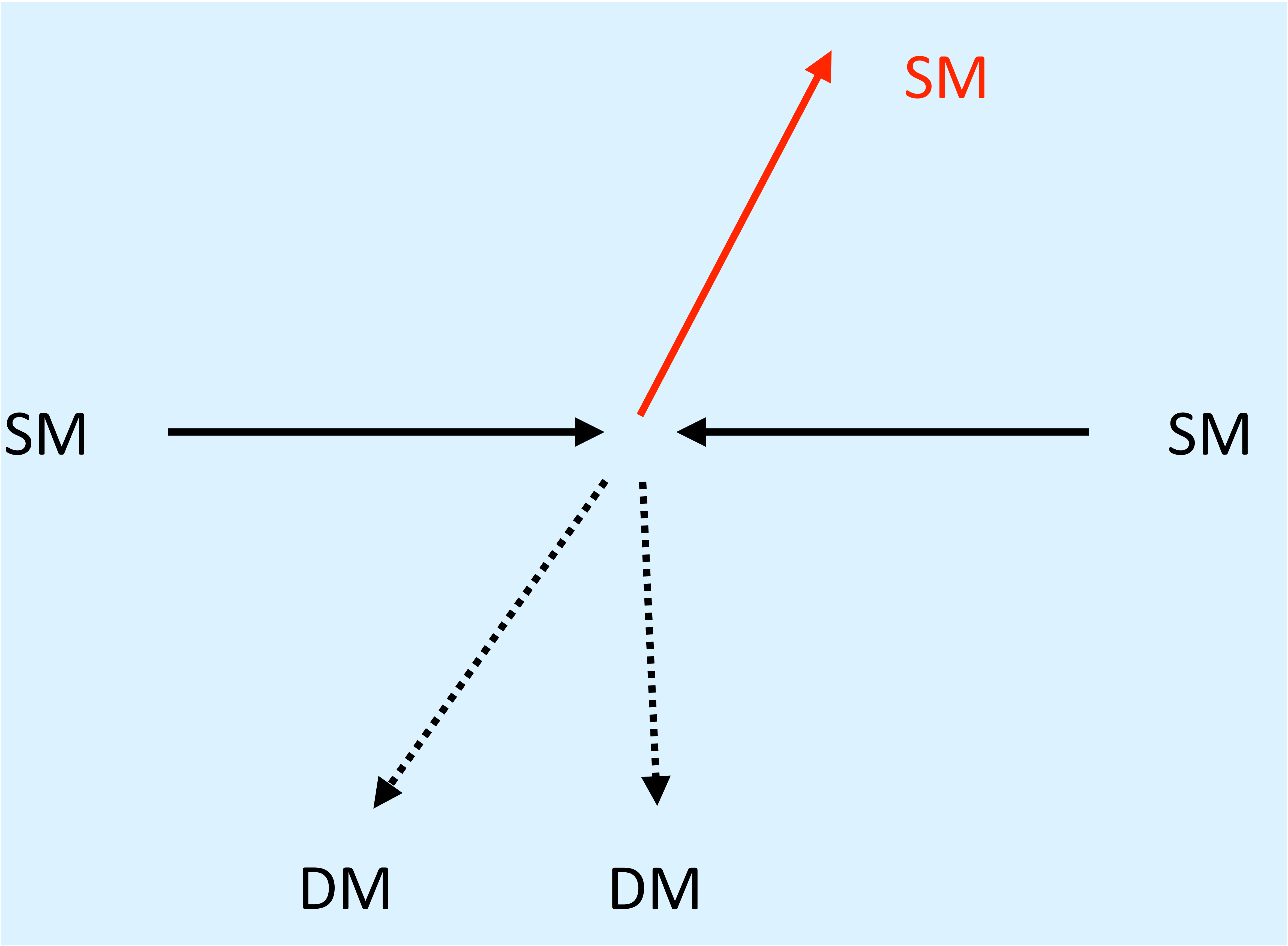

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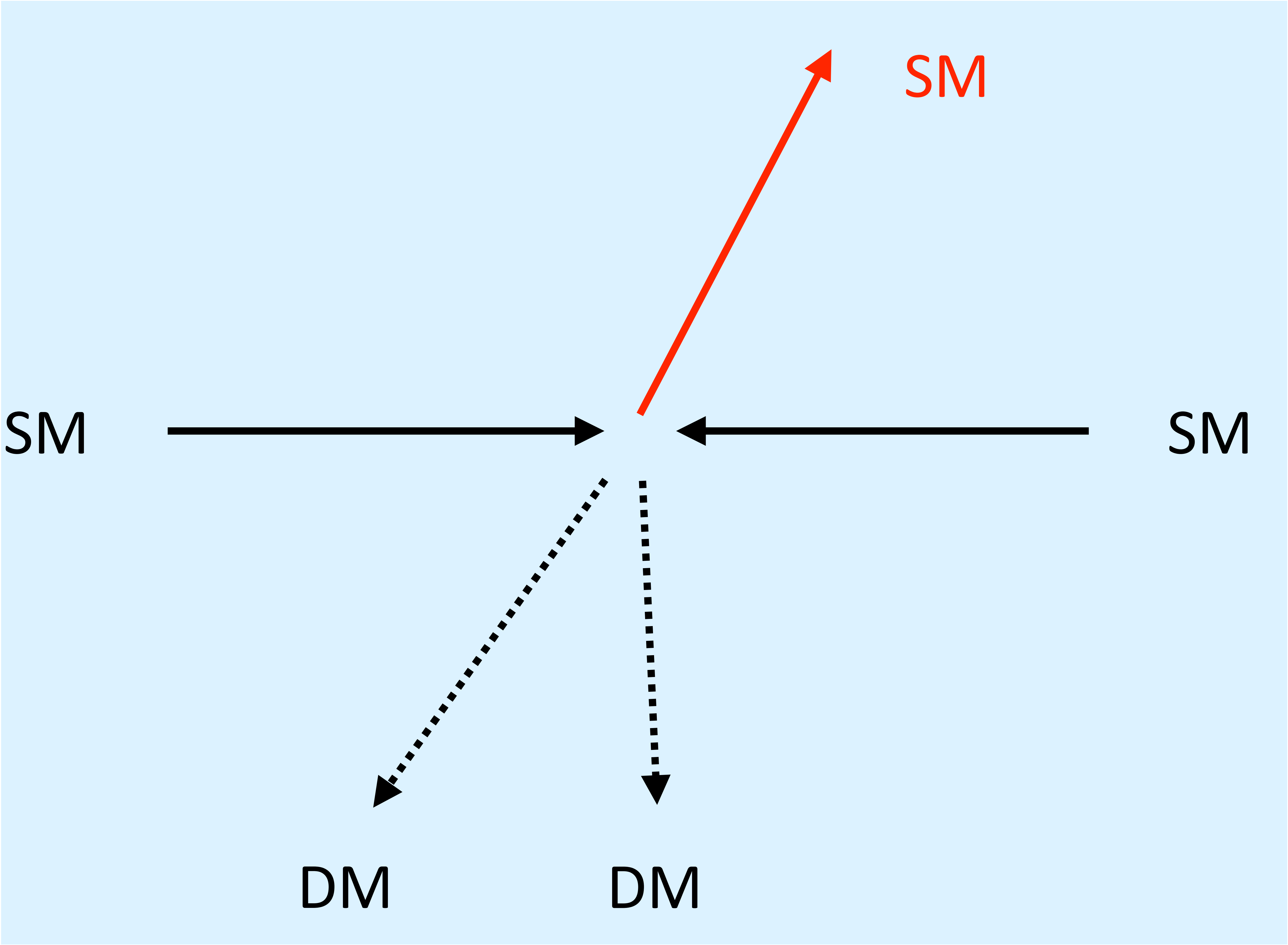

Different mono-X channels

- mono-photon
- mono-jet
- mono-Higgs
- mono-Z
- mono-top

We propose a new dark matter channel at colliders

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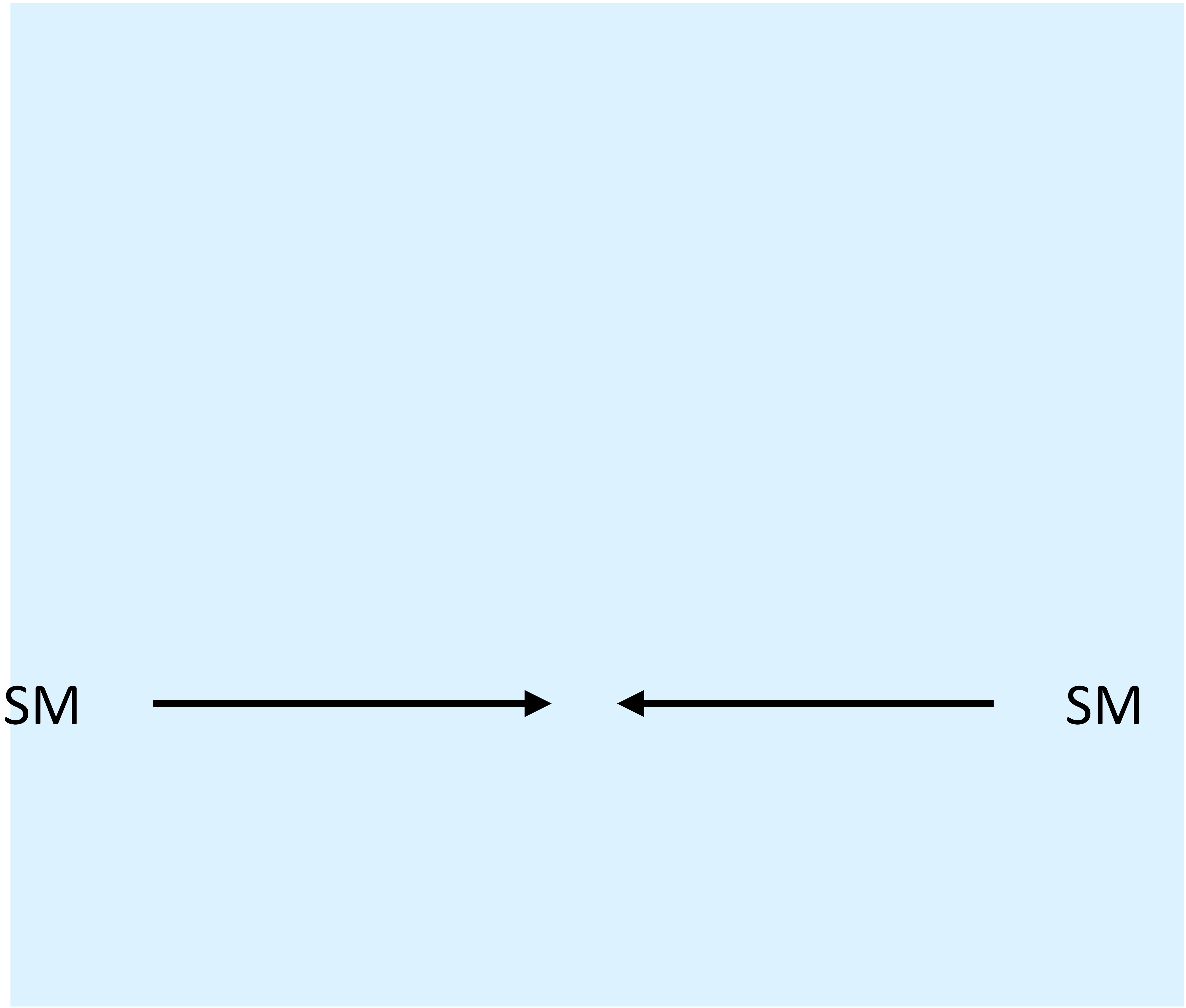

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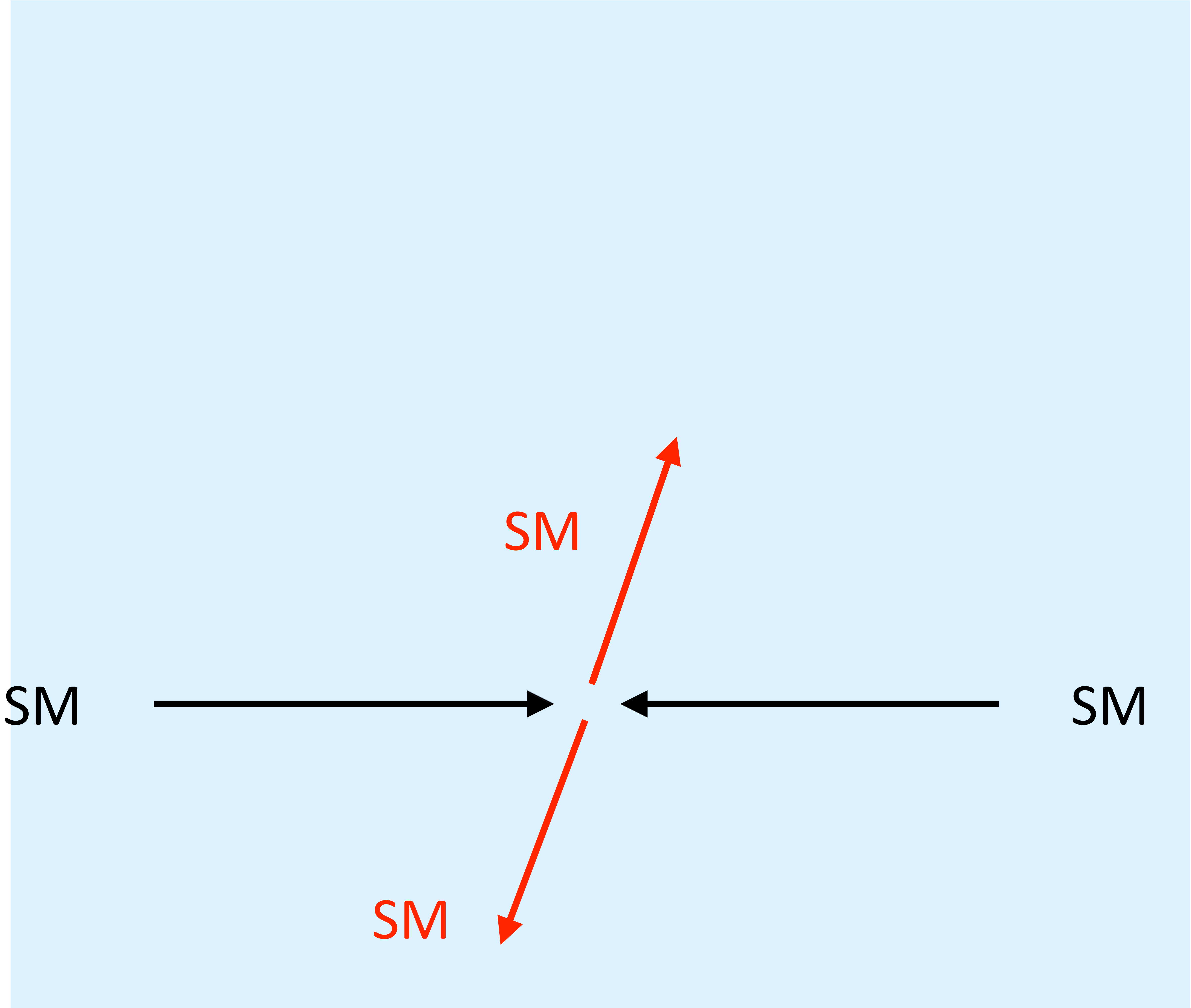

A pair of SM particles produced at the primary vertex

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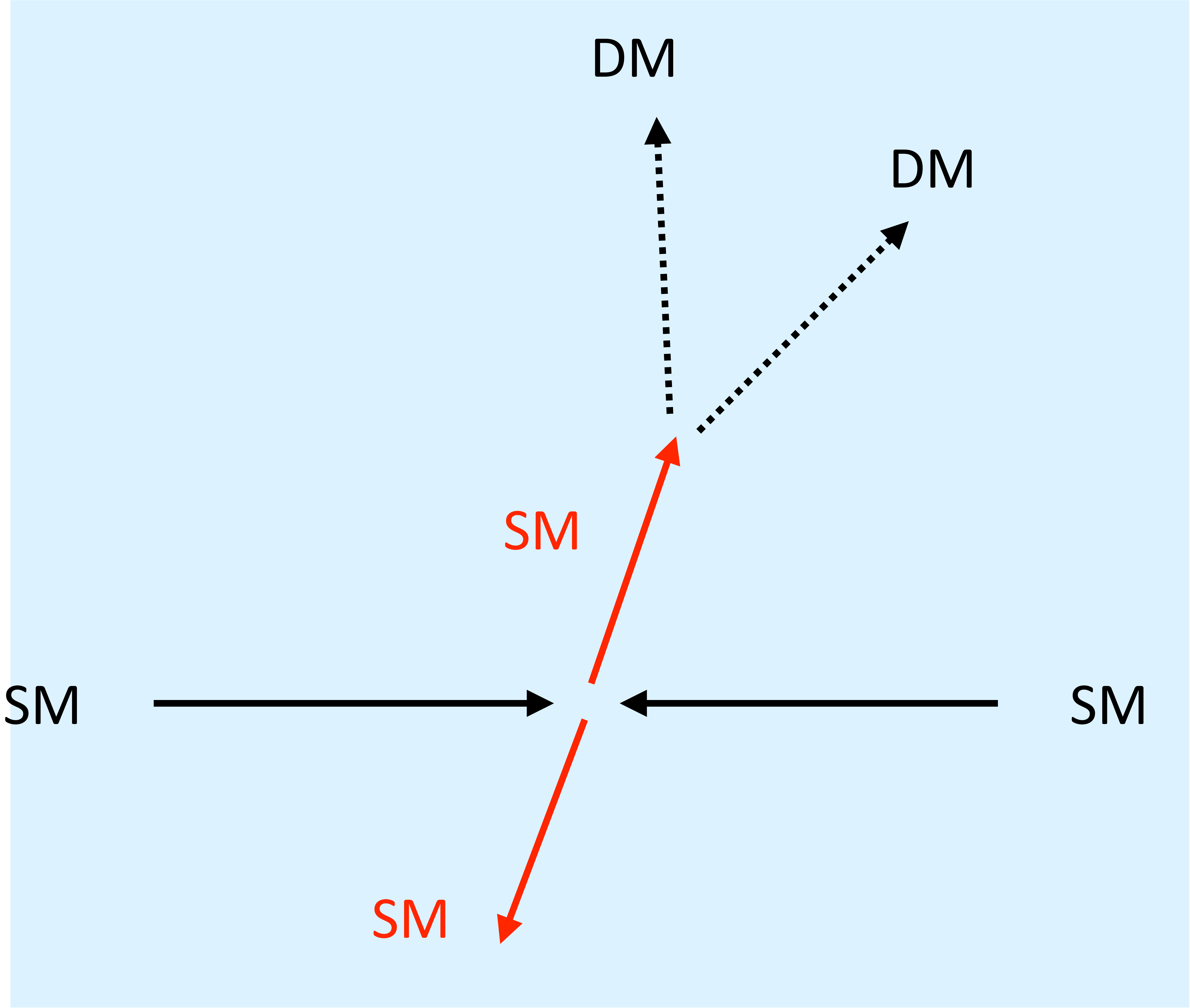

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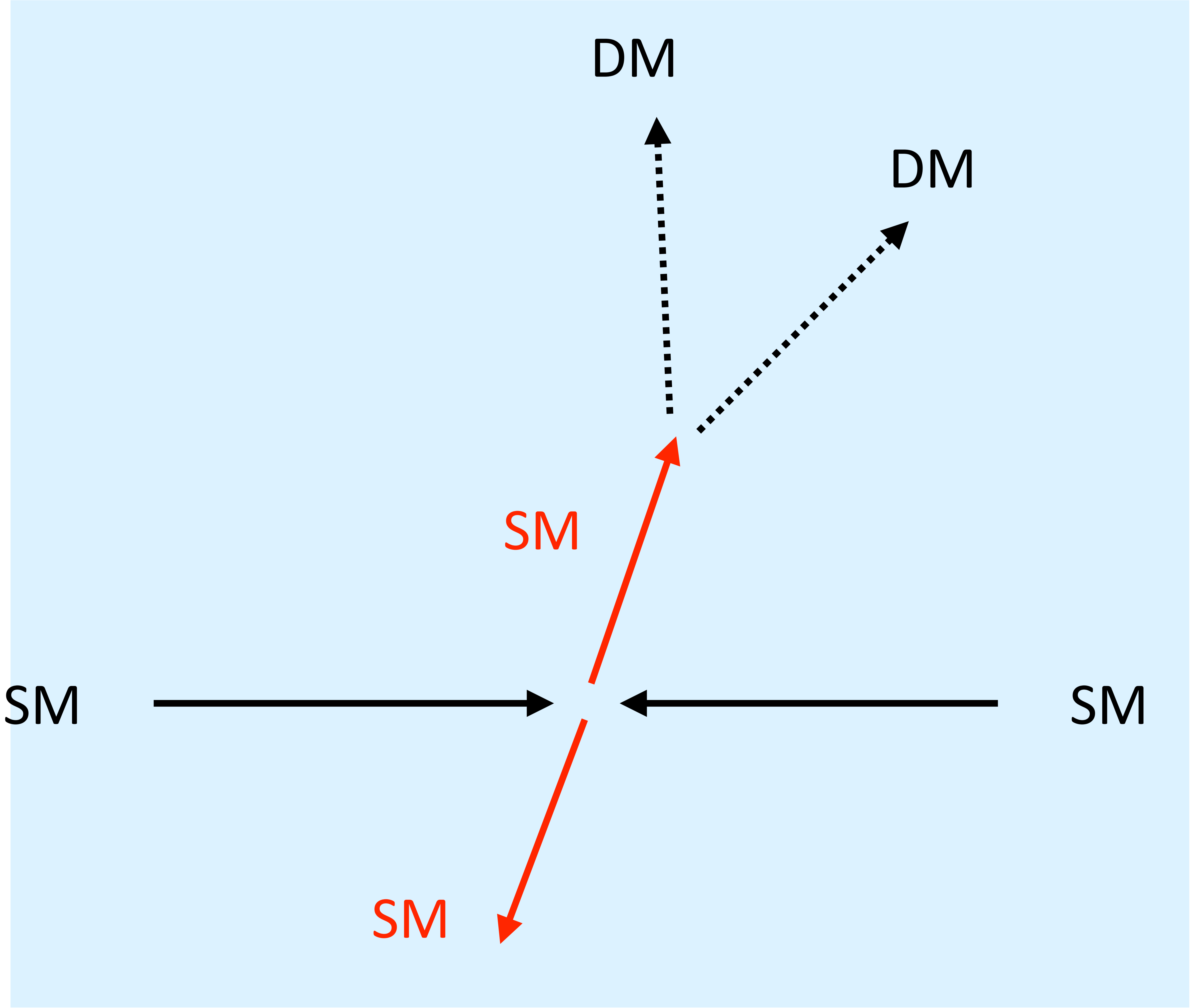

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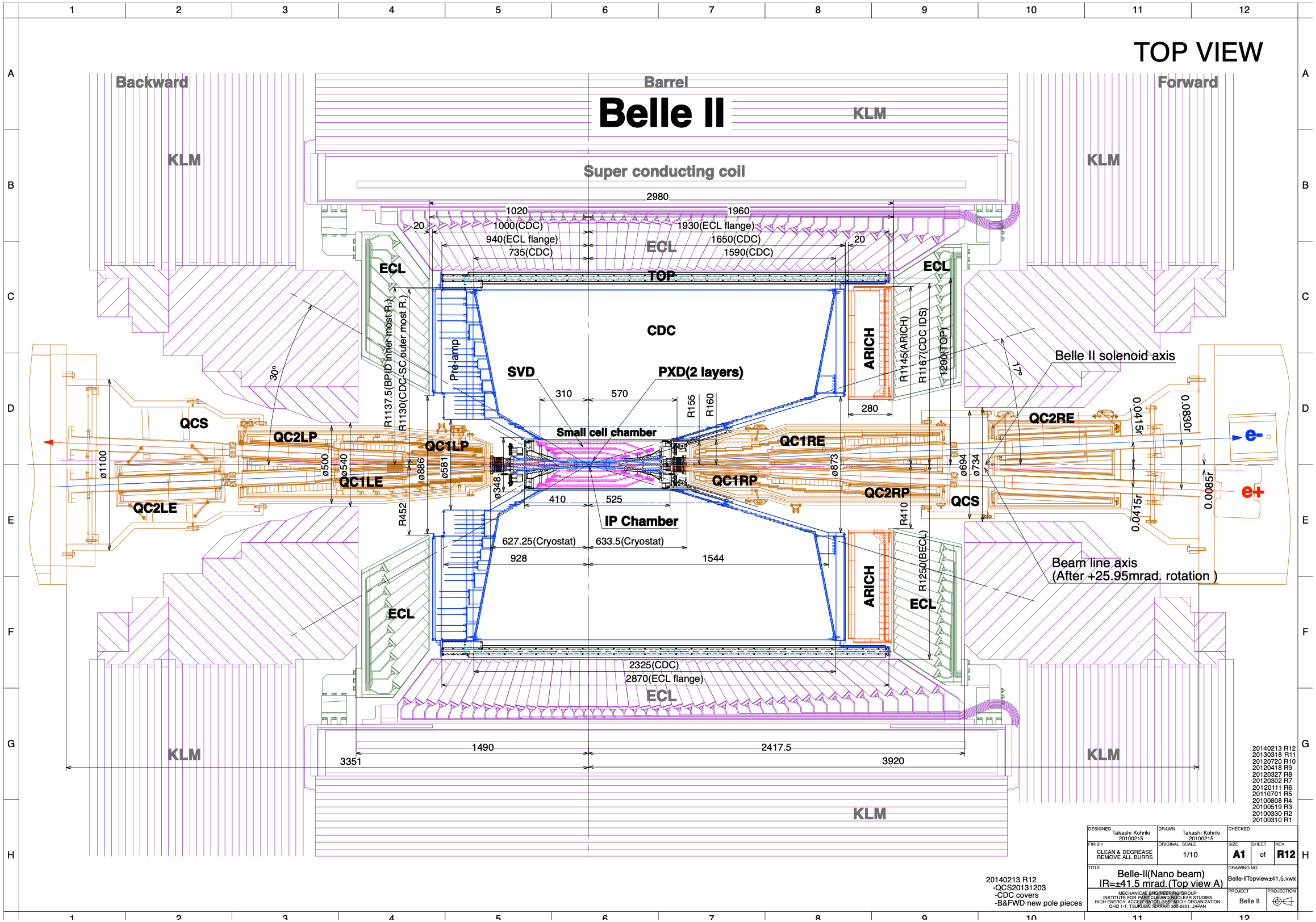
fixed target in collider


TOP VIEW
Backward
Barrel
Forward
Belle II
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Super conducting coil
ECL
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CDC
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SVD
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-CDC covers
-B&FWD new pole pieces
DESIGNED Takashi Kohriki 20100215
DRAWN Takashi Kohriki 20100215
CHECKED
FINISH CLEAN & DEGREASE REMOVE ALL BURRS
ORIGINAL SCALE 1/10
SIZE A1
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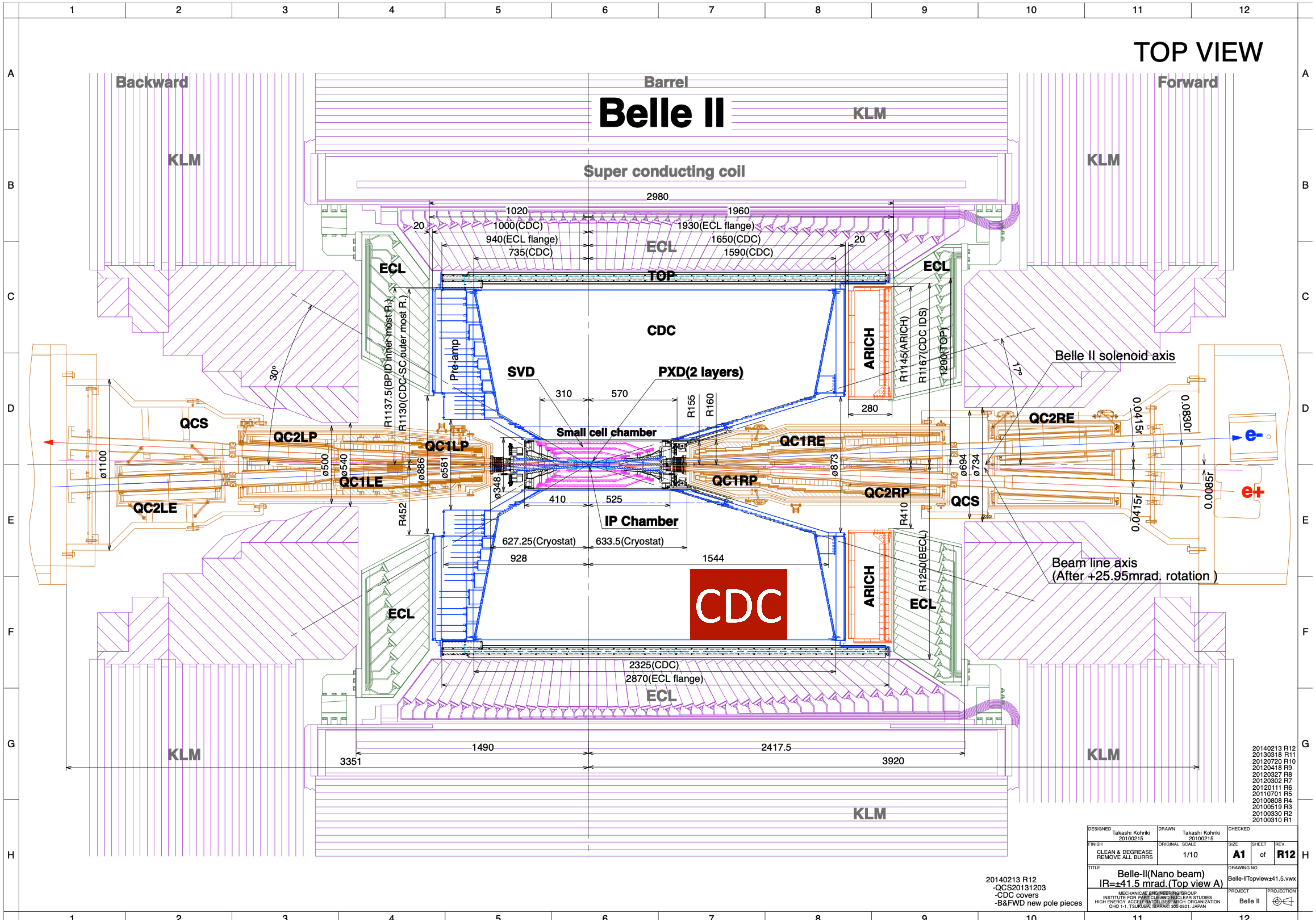
TITLE Belle-II(Nano beam) IR=±41.5 mrad.(Top view A)
DRAWING NO. Belle-IITopview±41.5.vwx
MECHANICAL ENGINEERING GROUP
INSTITUTE FOR PARTICLE AND NUCLEAR STUDIES
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION
OHO 1-1, TSUKUBA, IBARAKI 305-0801, JAPAN
PROJECT Belle II
PROJECTION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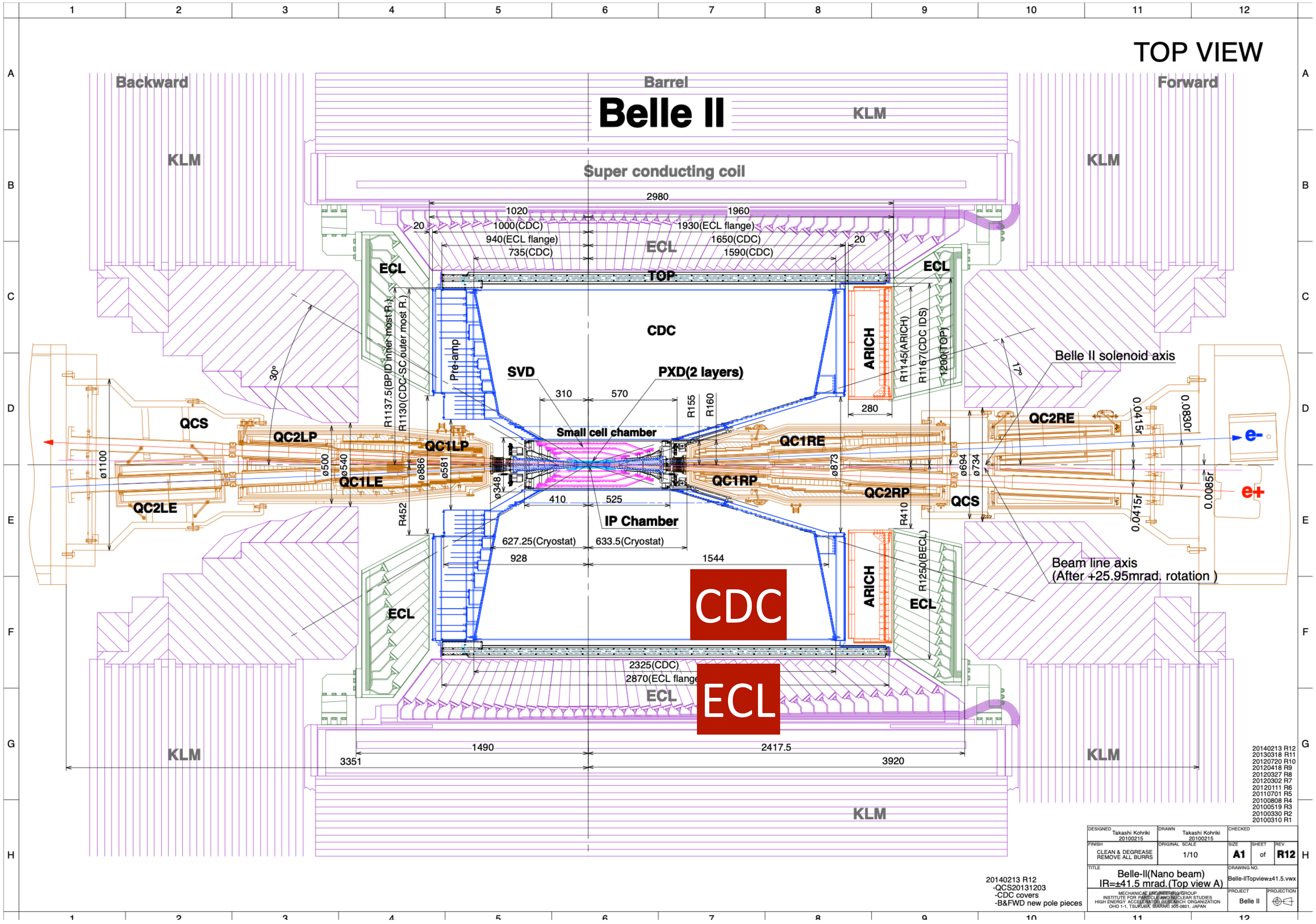
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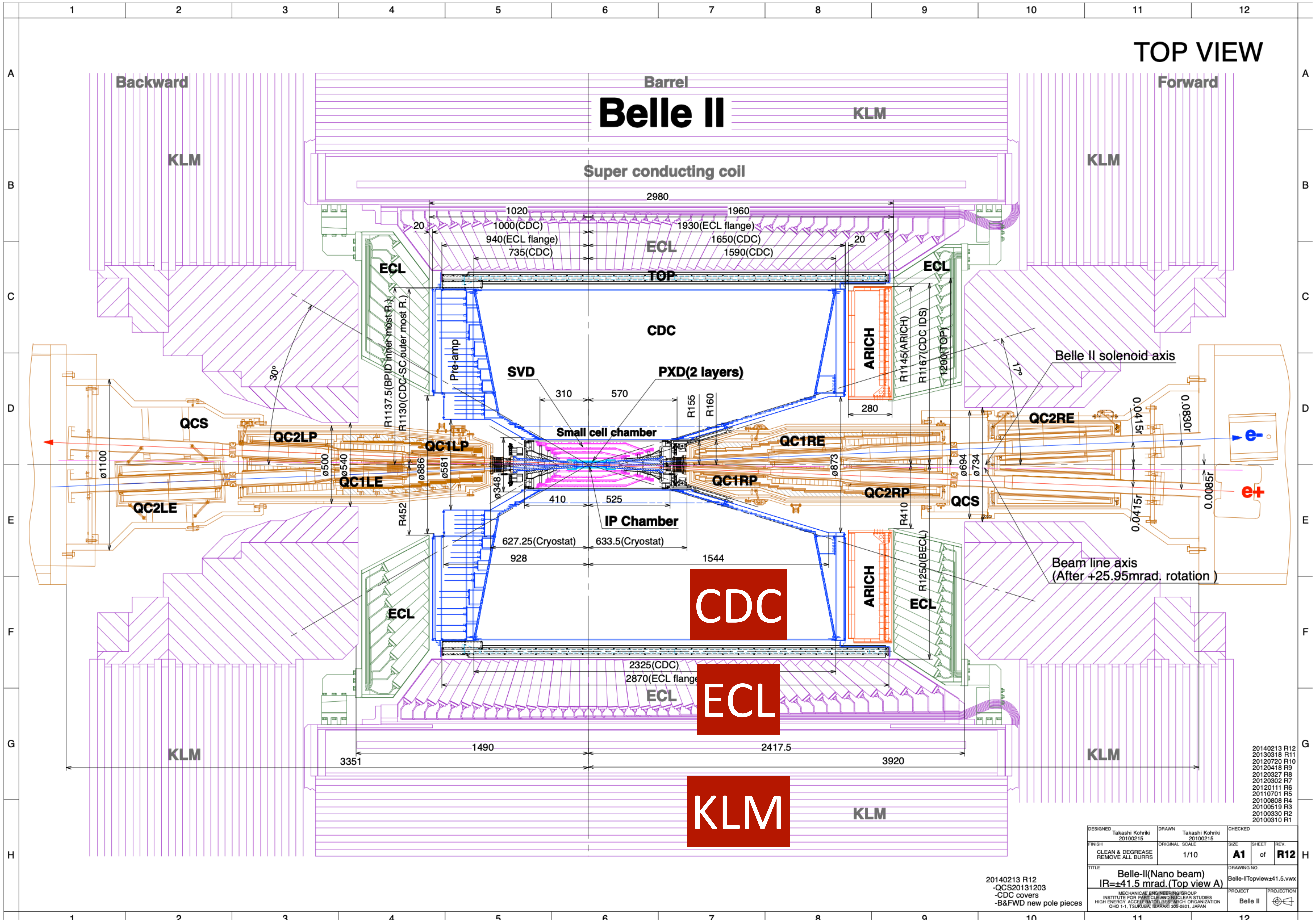
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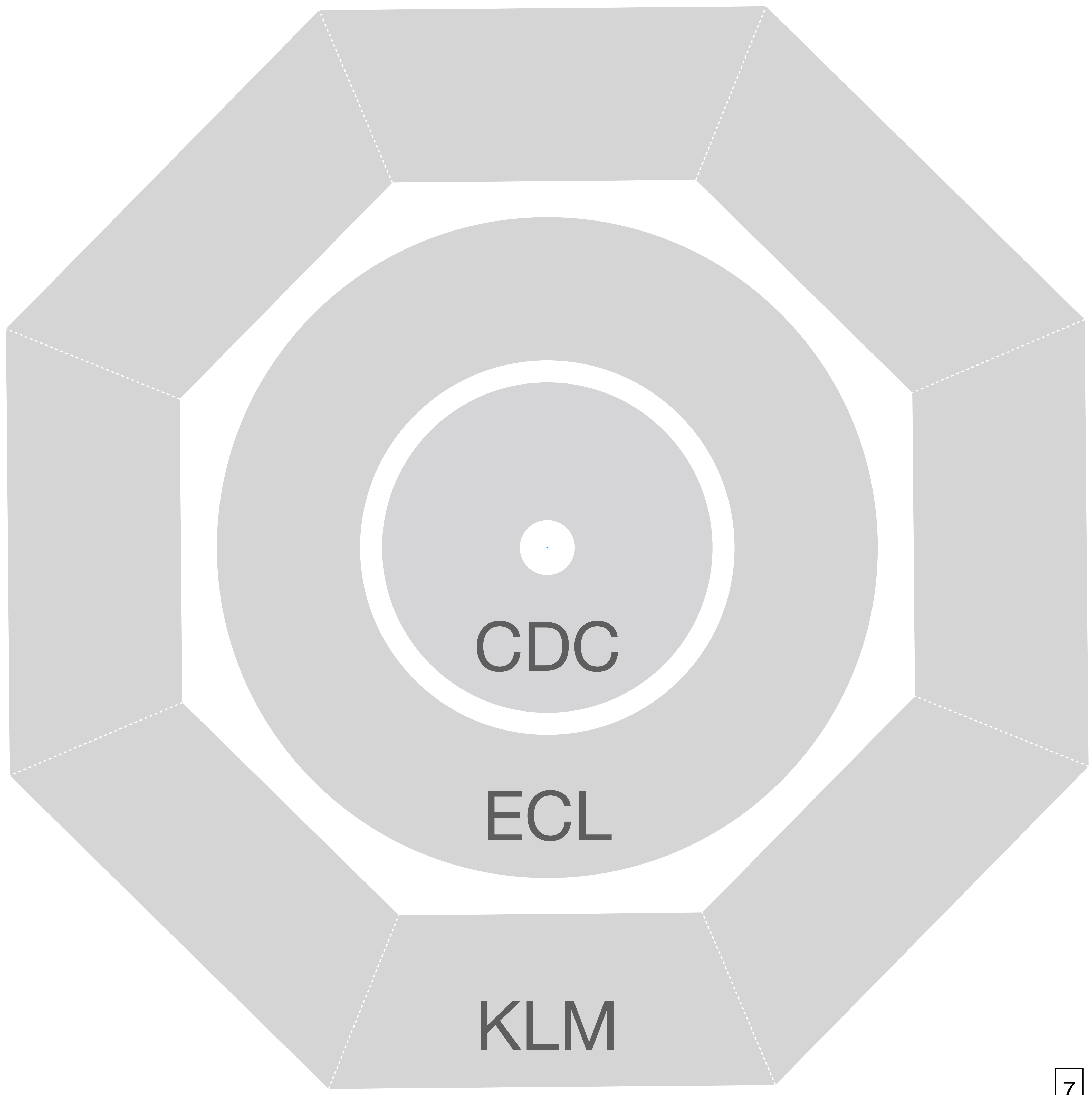
New DM channel @ Belle II (x-y plane)



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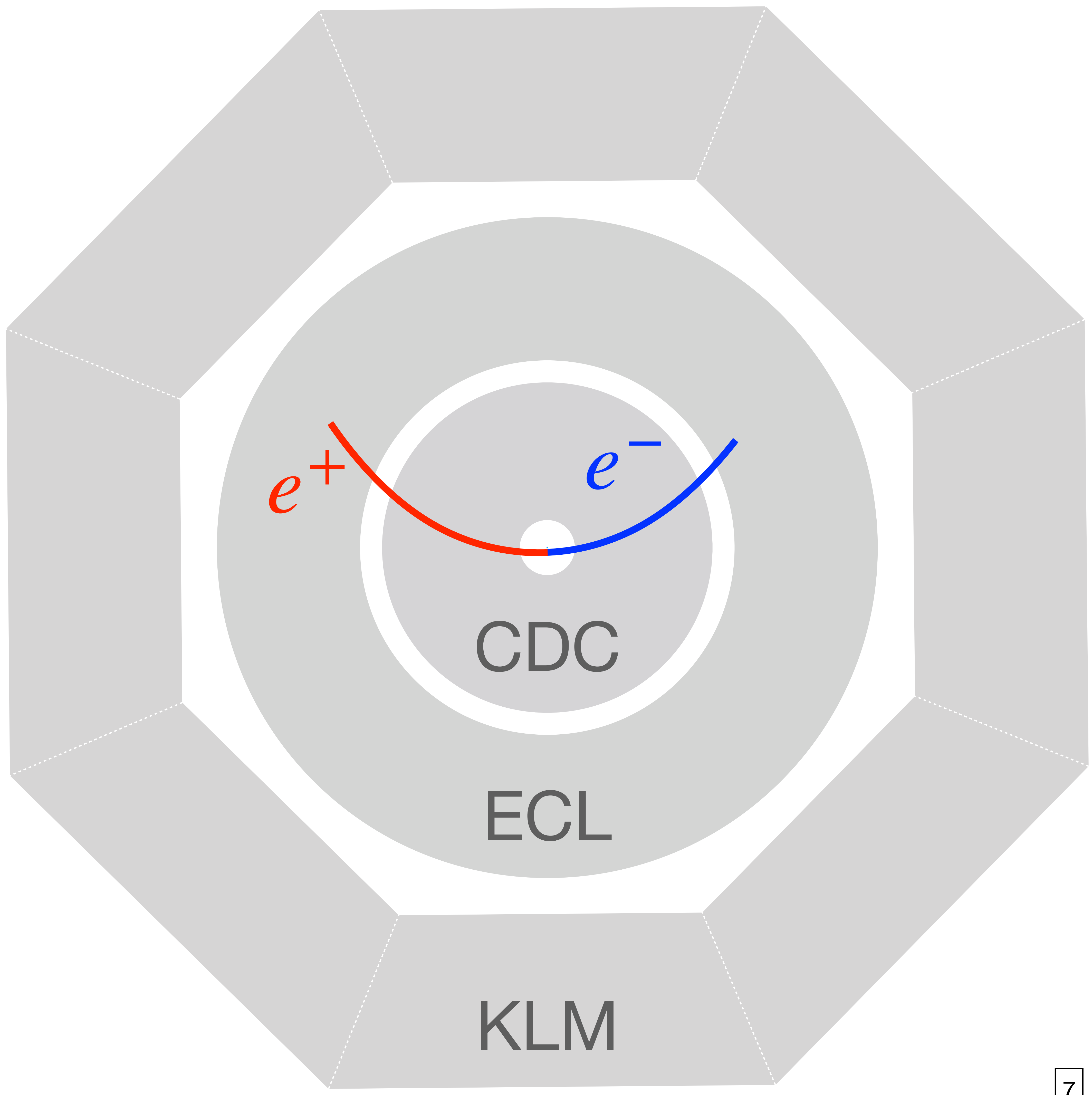

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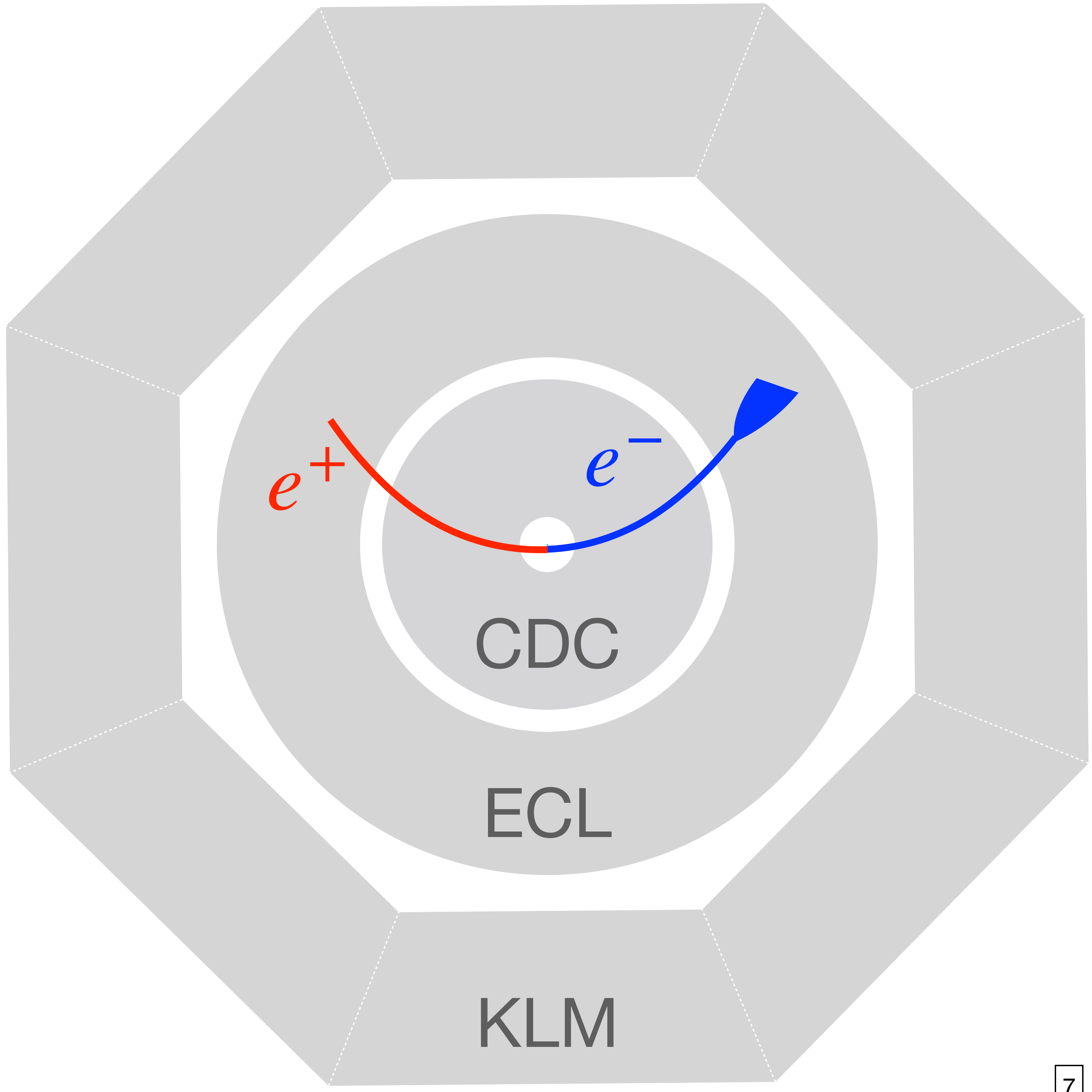

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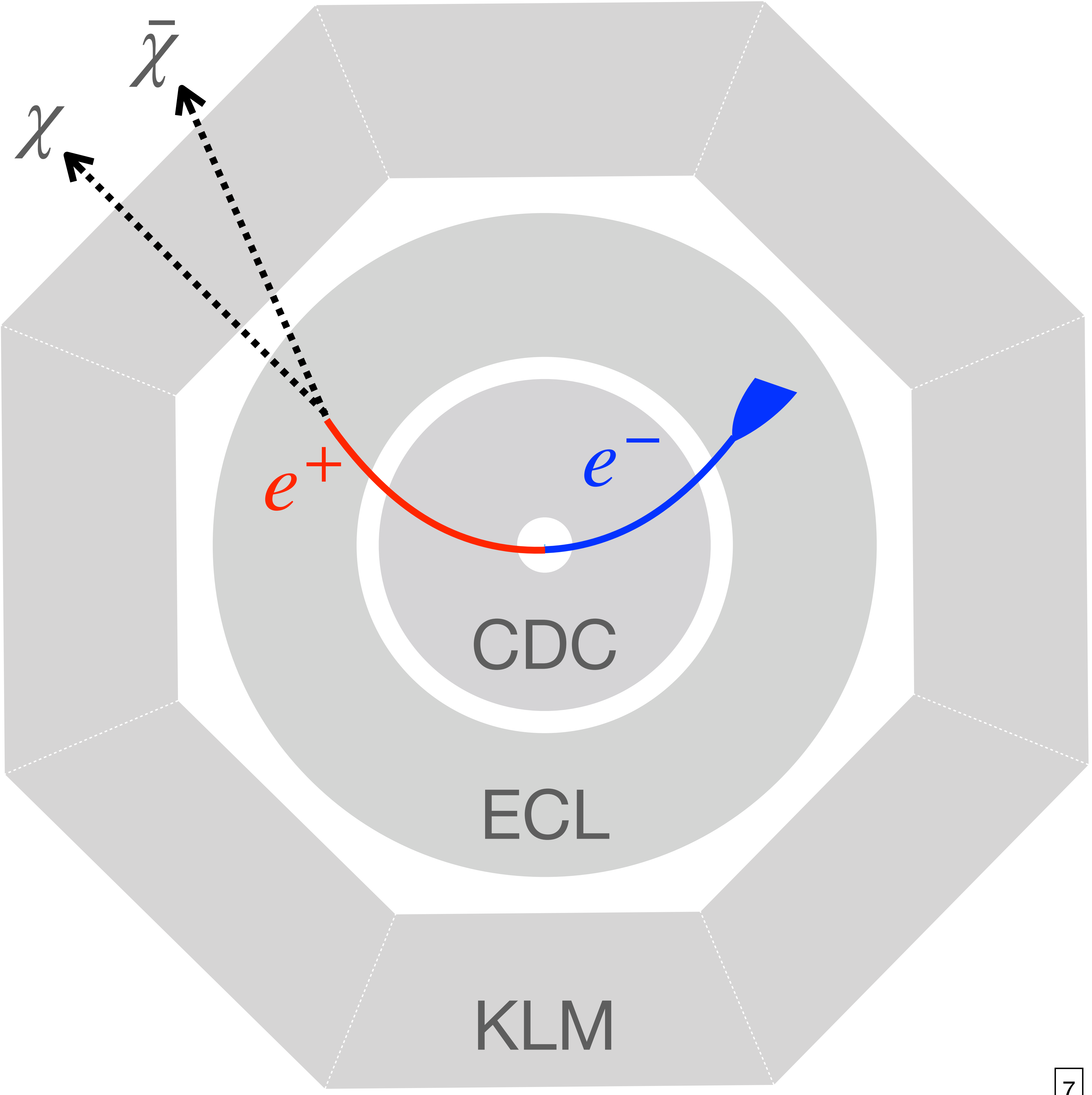

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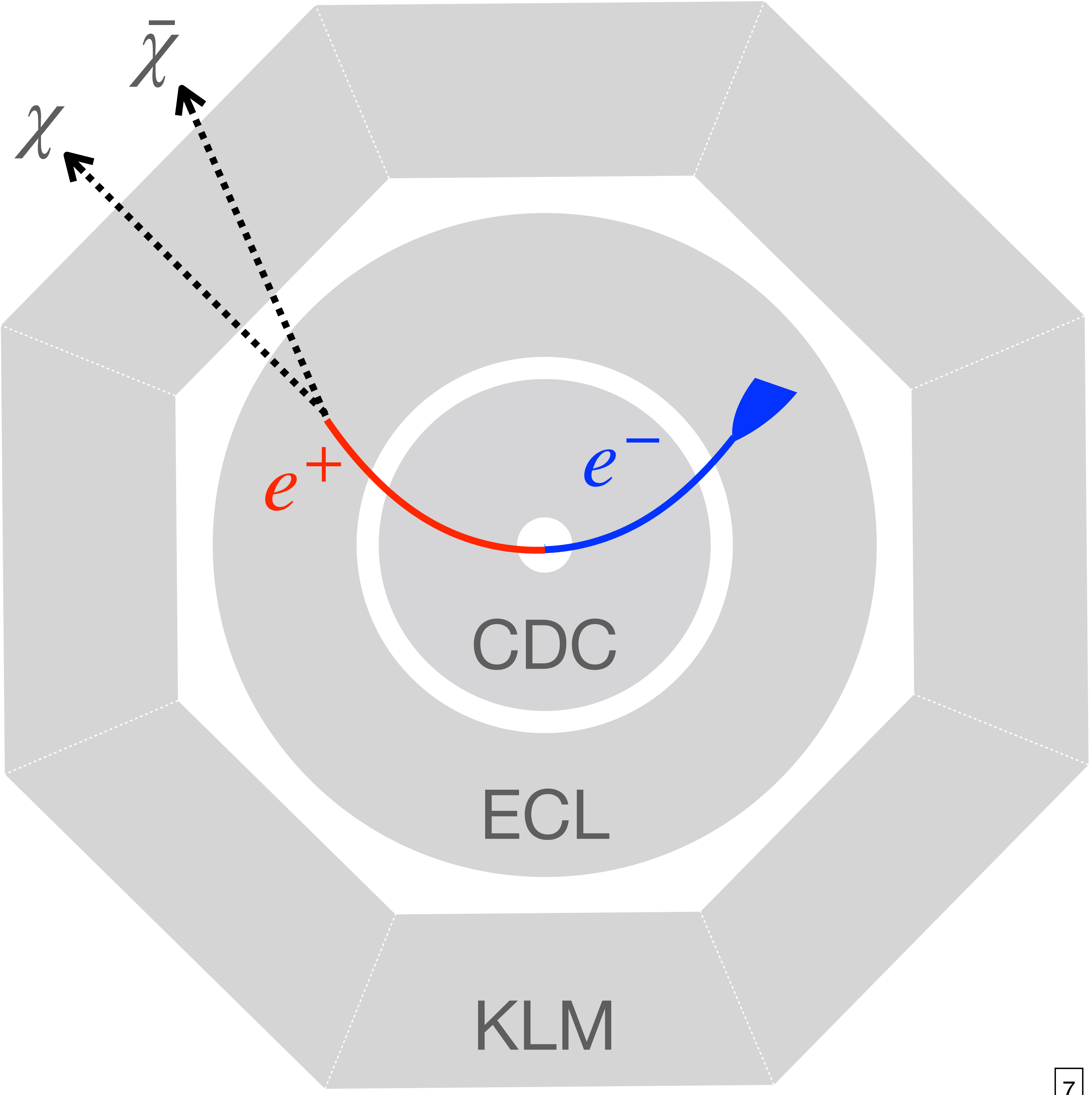
disappearing positron track



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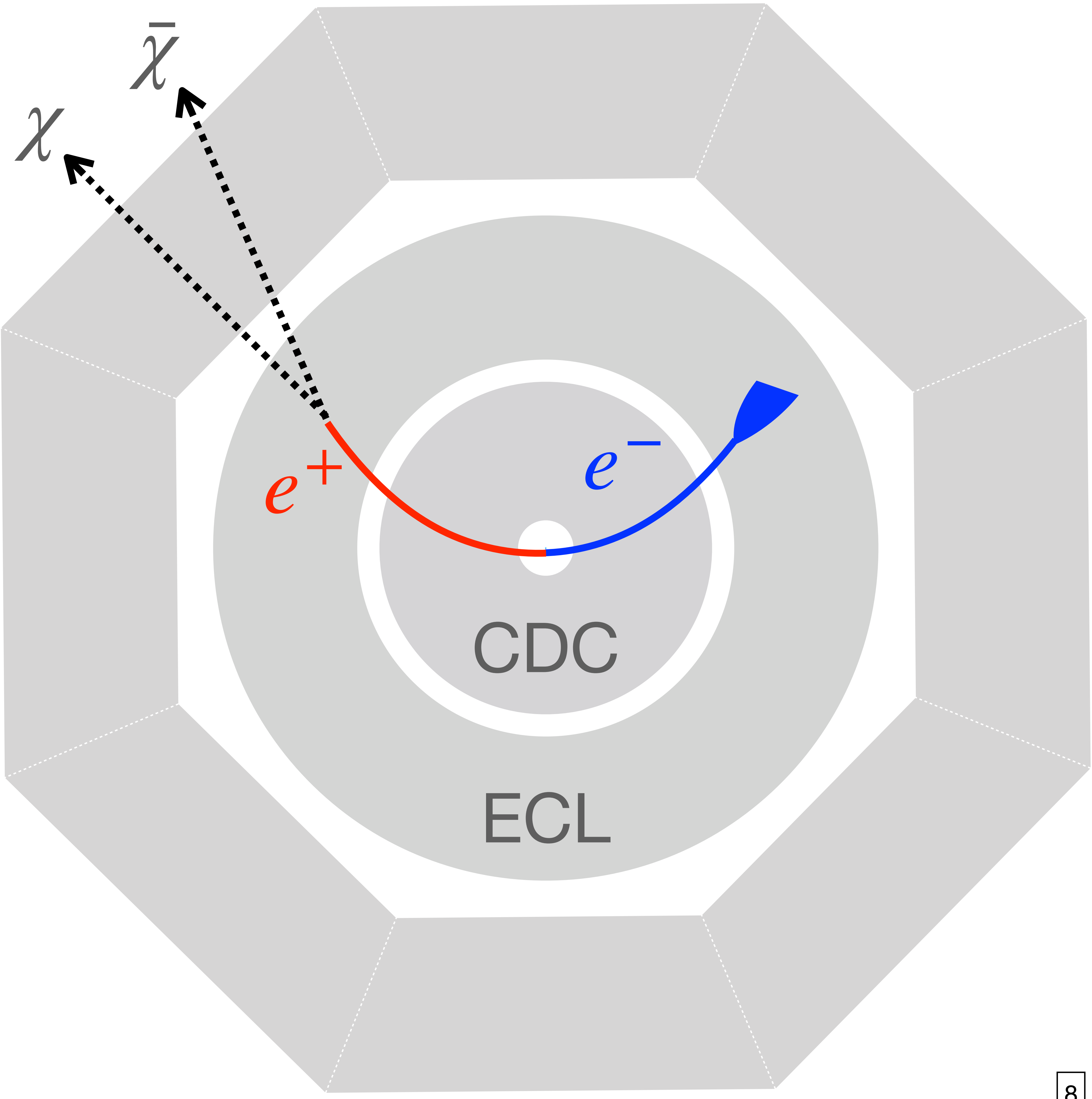
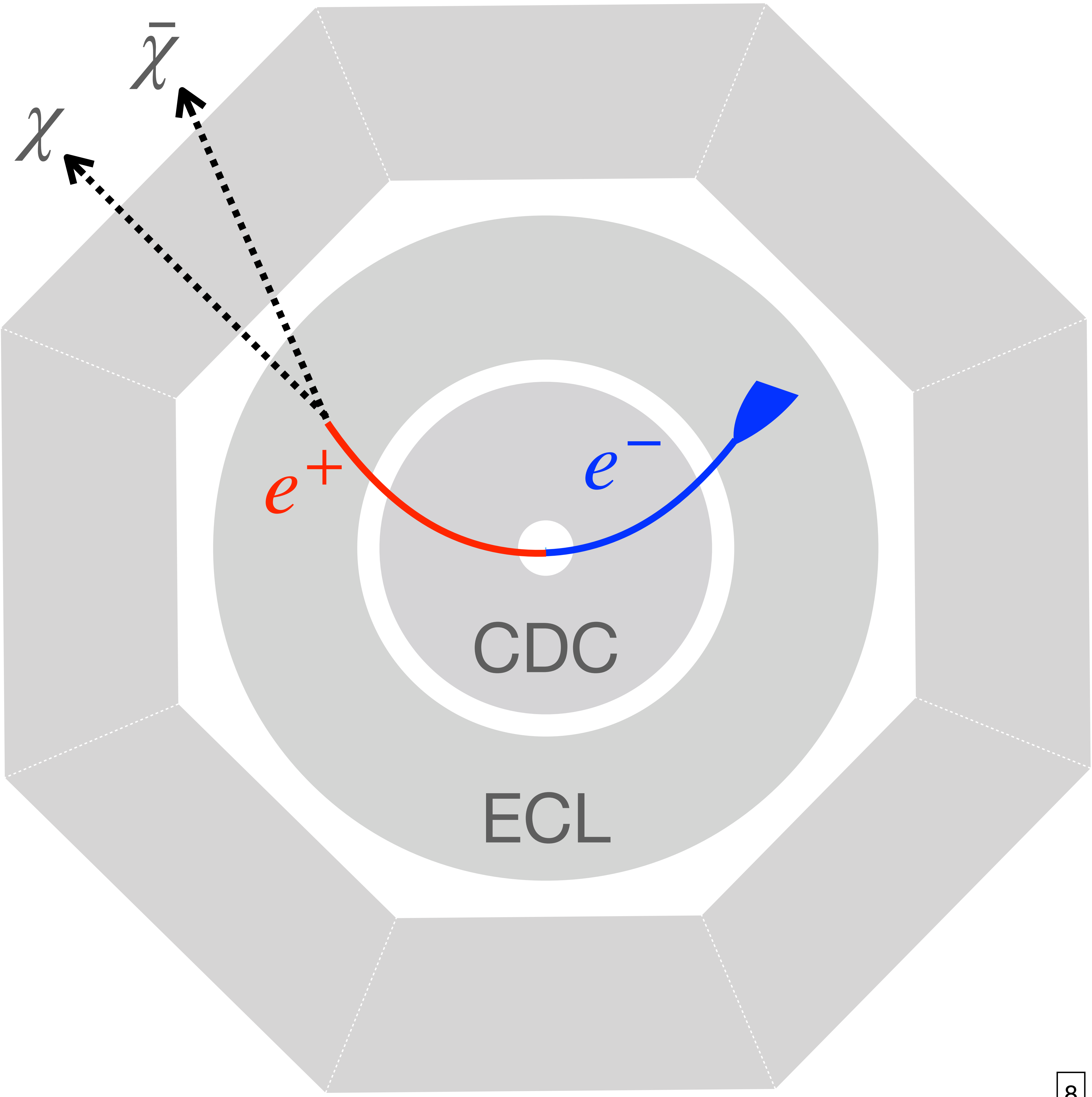


Signature

- e^-: CDC & ECL



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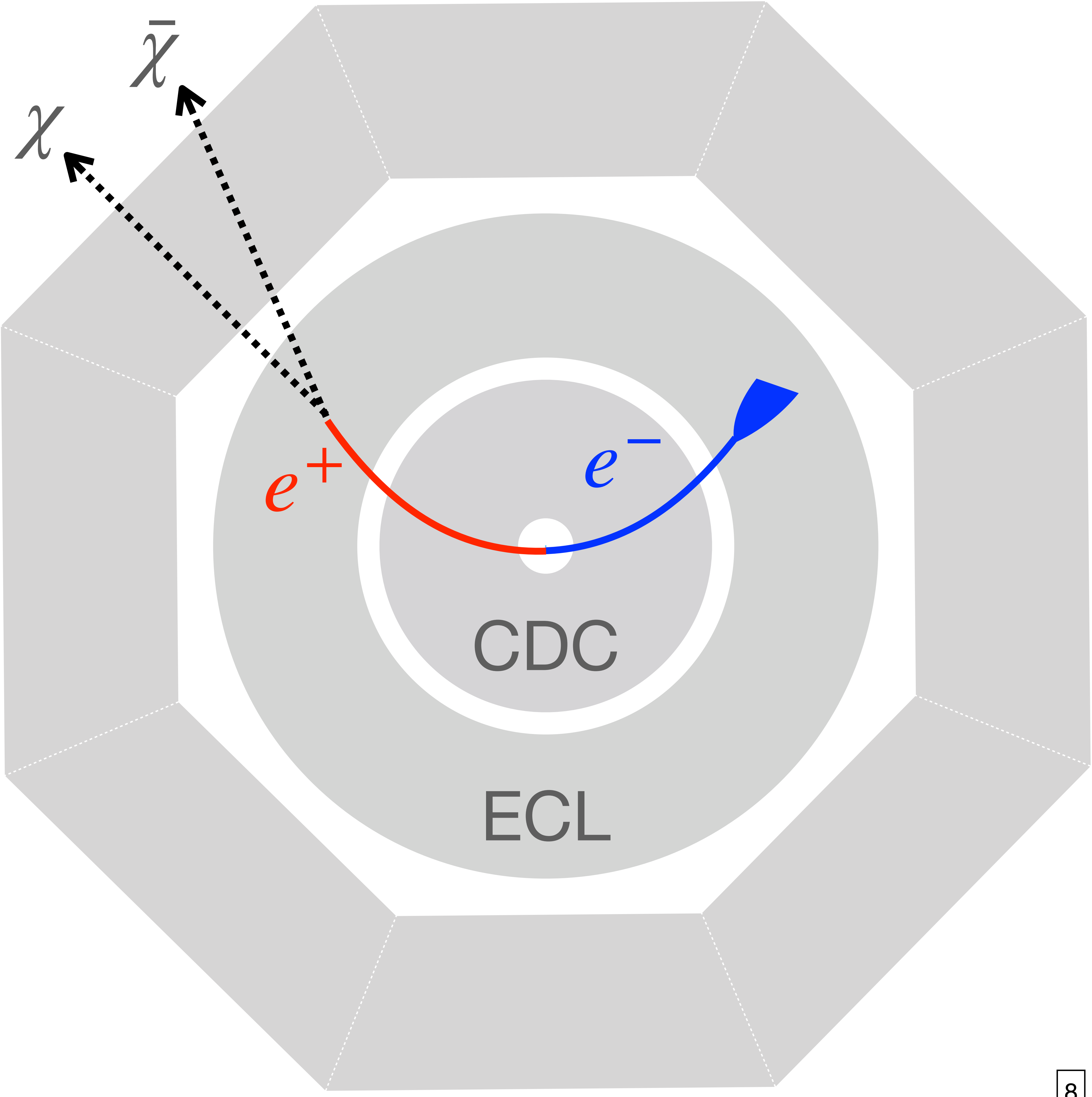

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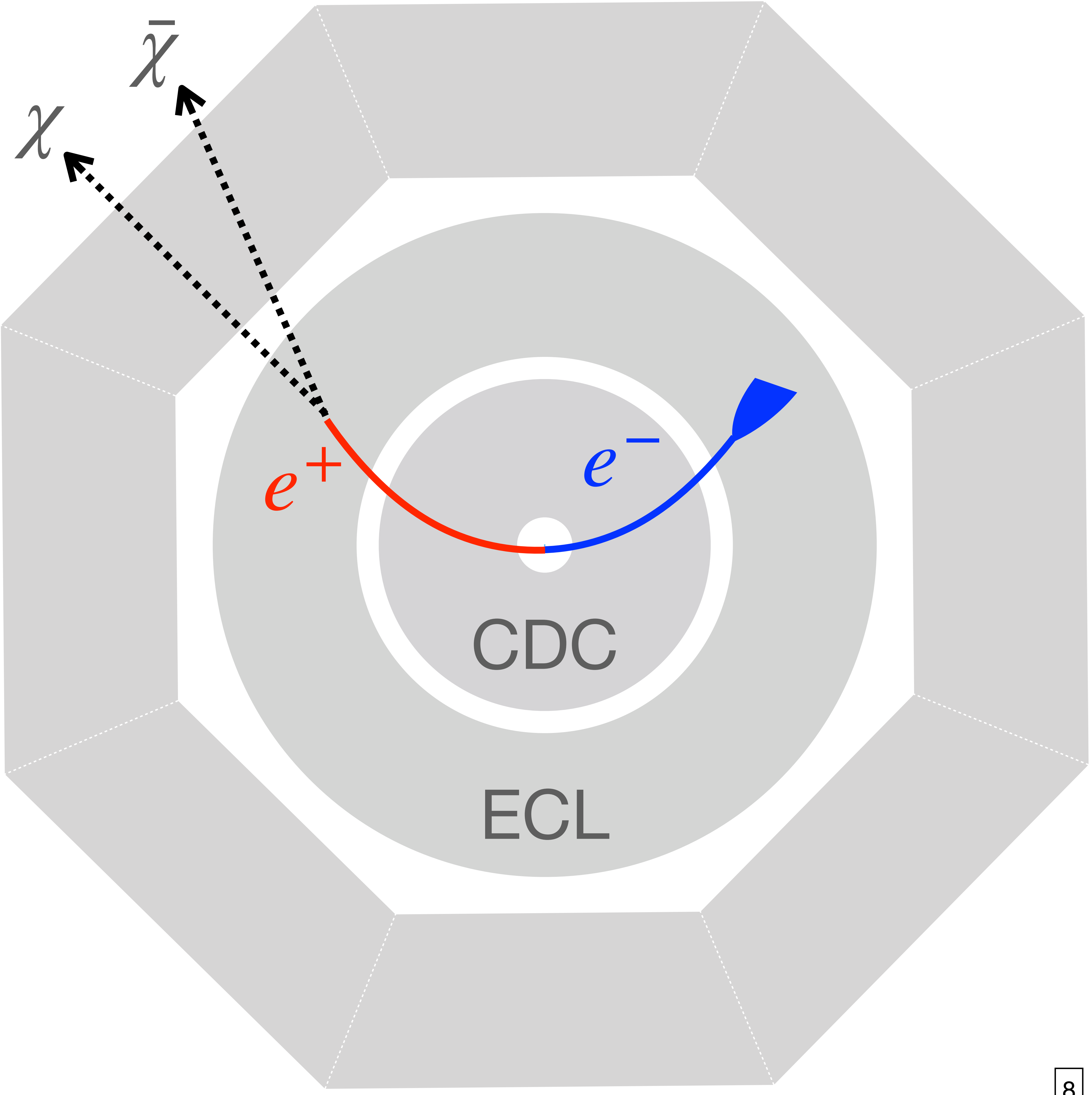
CDC: $\frac{\delta p_T}{p_T} \simeq 0.4\,\%$ for $p_T \simeq 3$ GeV



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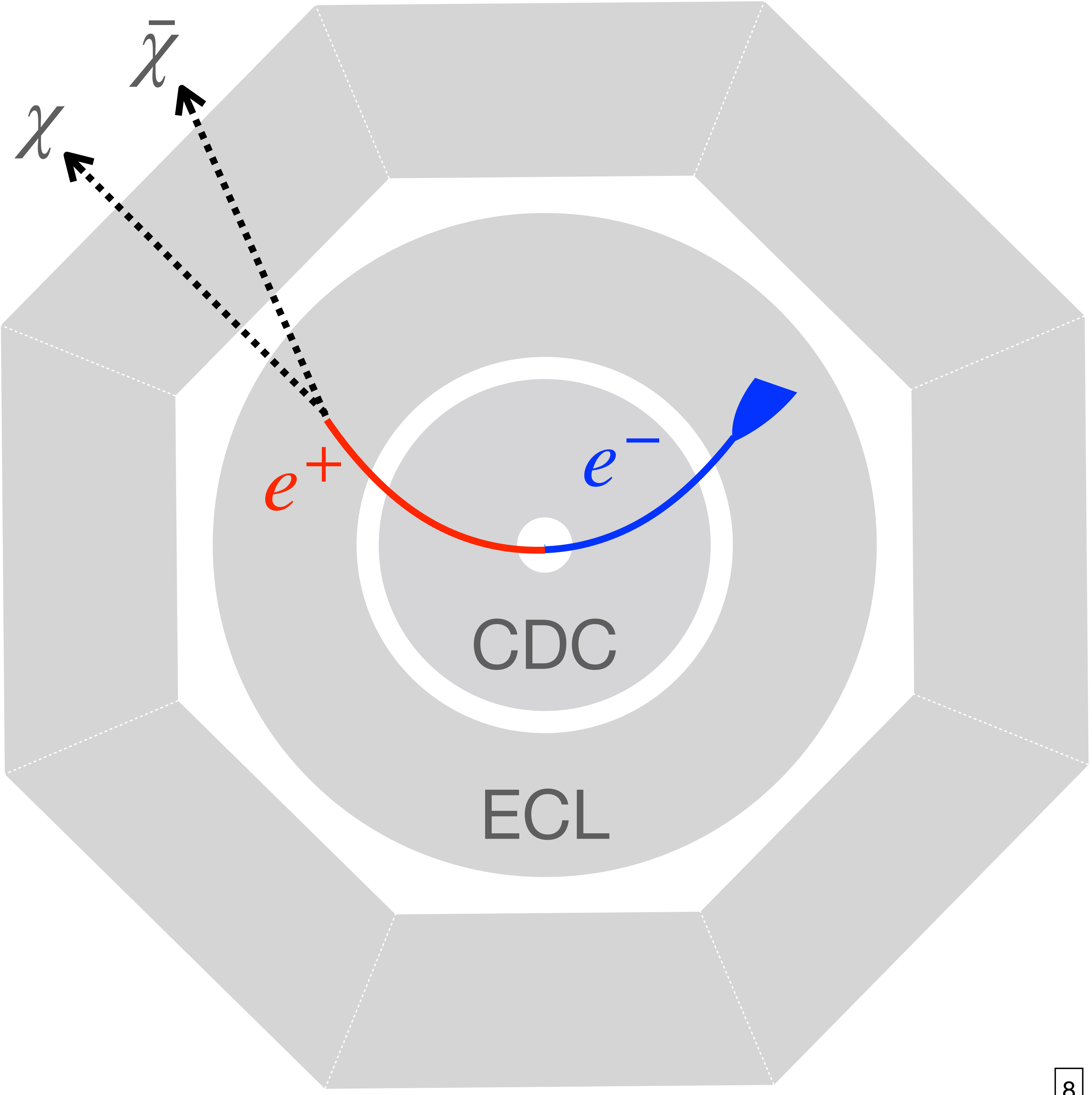
Equal & opposite momenta for e^- & e^+ in the CM frame



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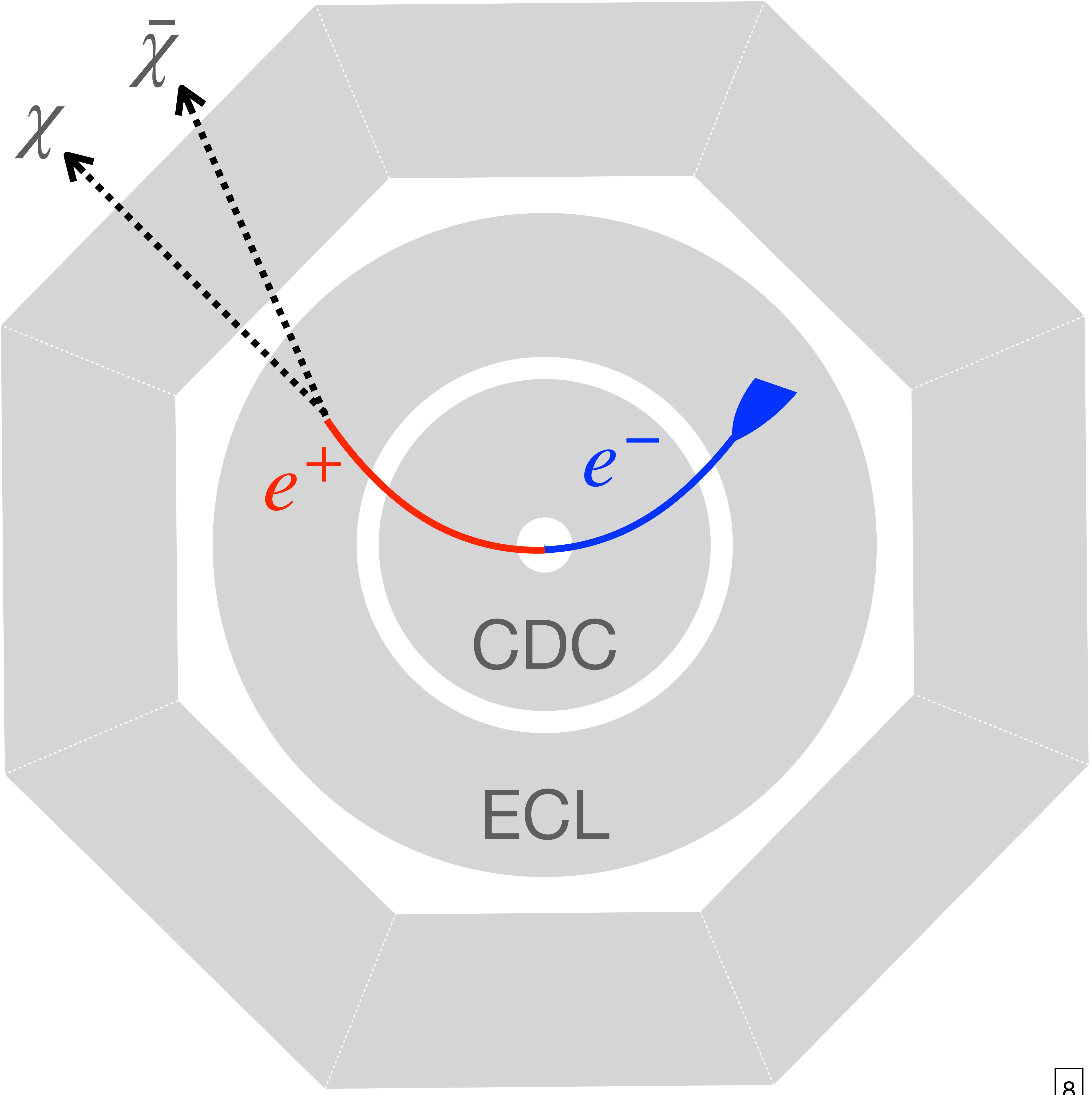
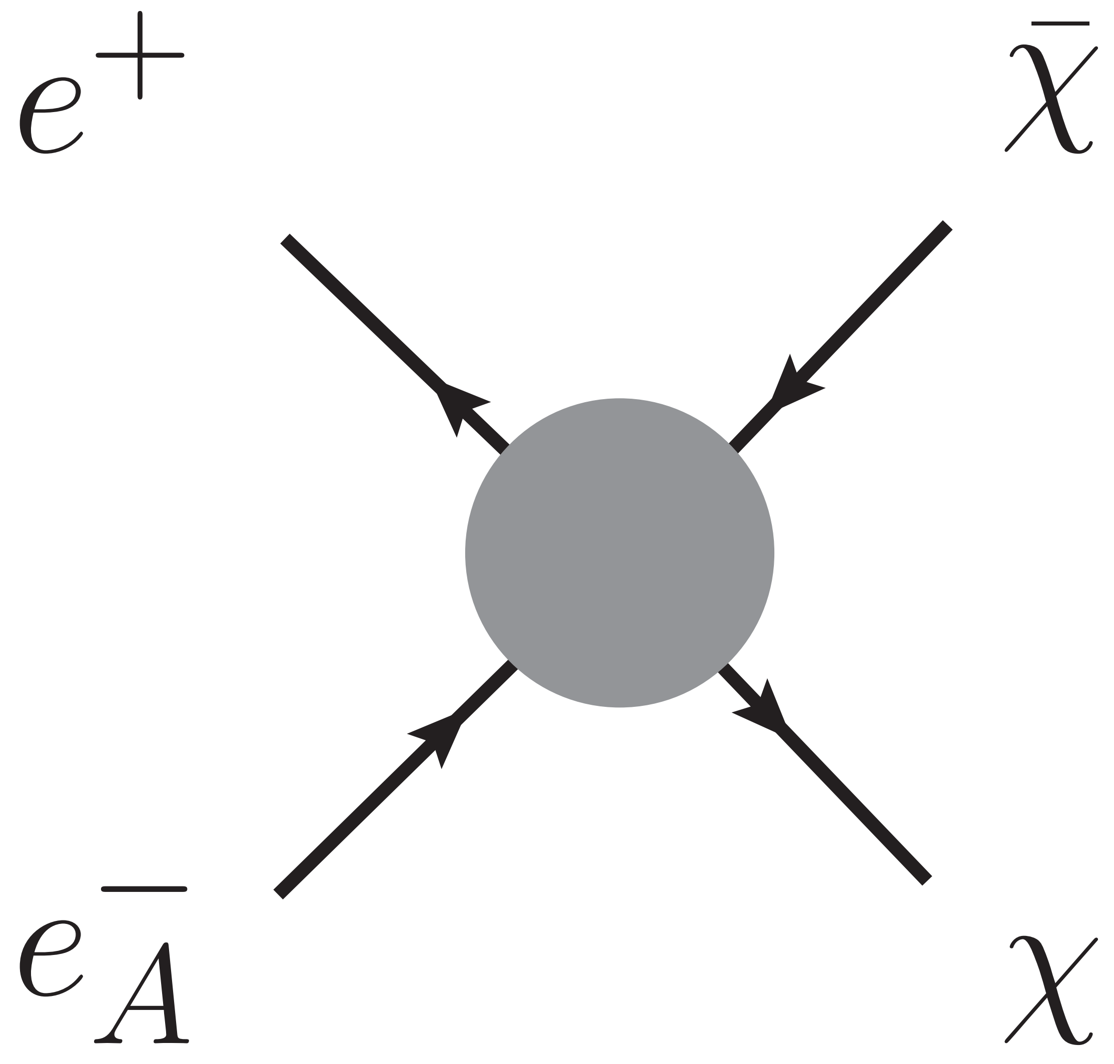
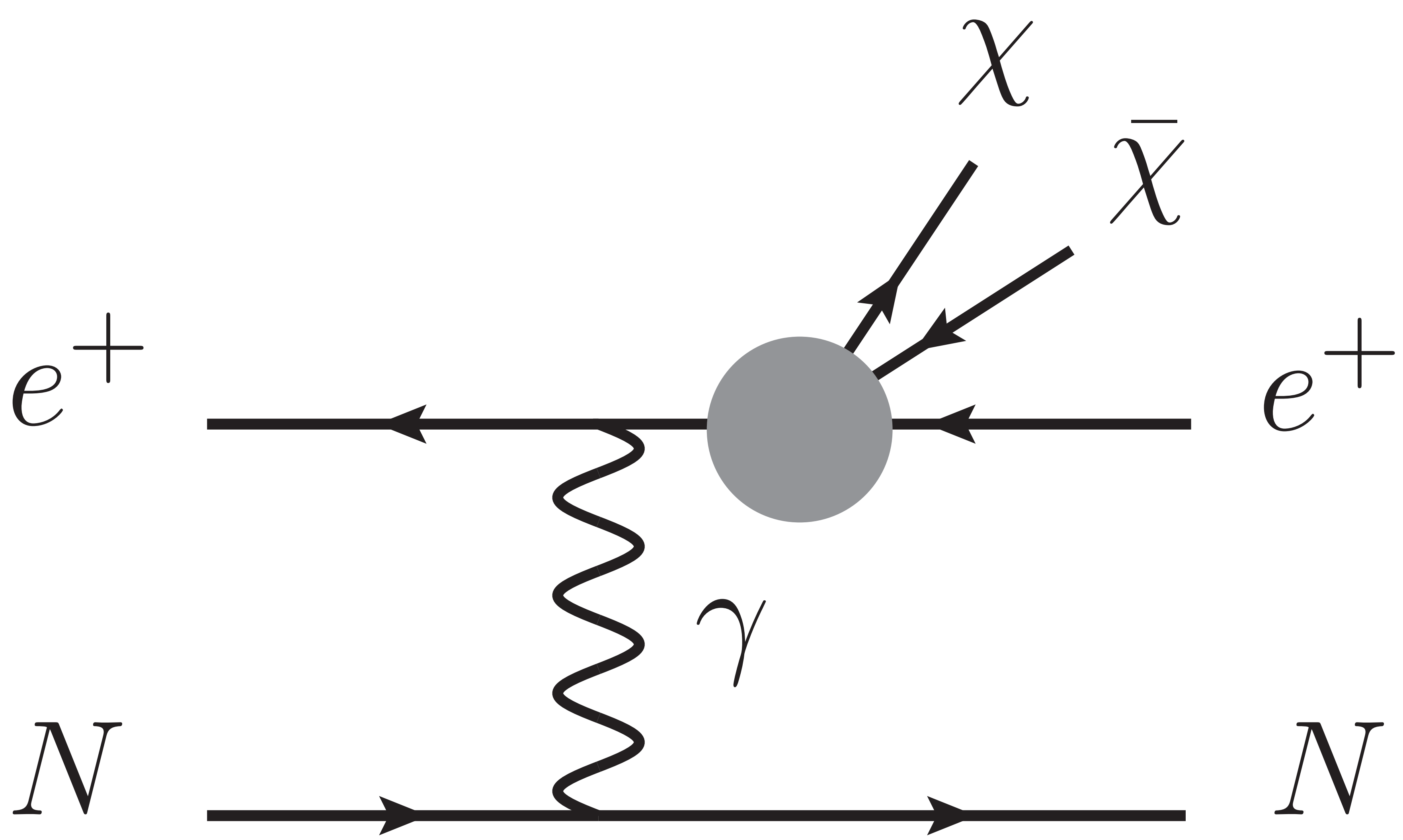
- missing energy: <5% e^+ energy in ECL



Positron interaction with ECL



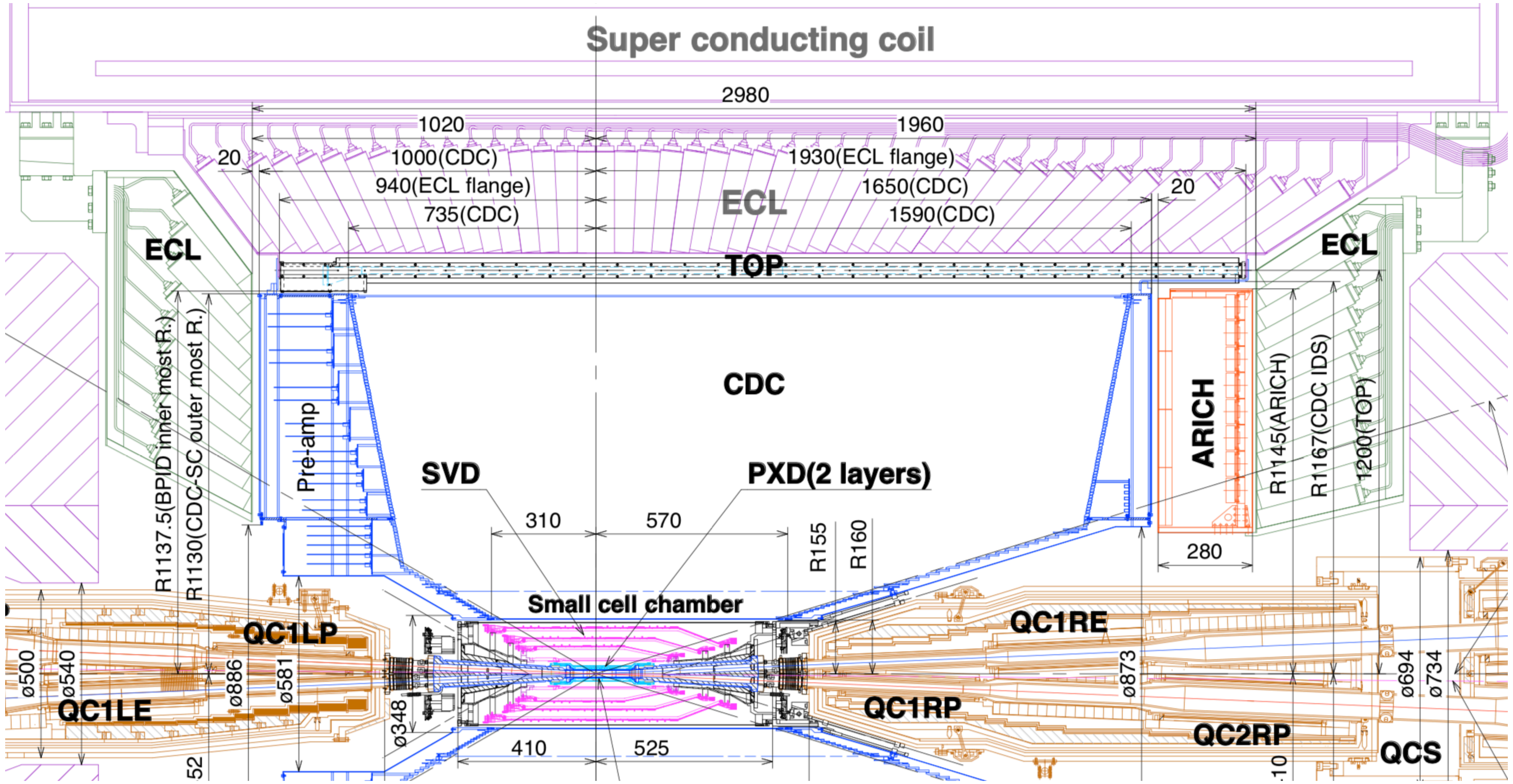
annihilation w/
atomic electrons



bremsstrahlung w/
target nucleus

Use the ECL barrel region as the fixed target

ECL barrel: $32.2^{\circ} < \theta < 128.7^{\circ}$



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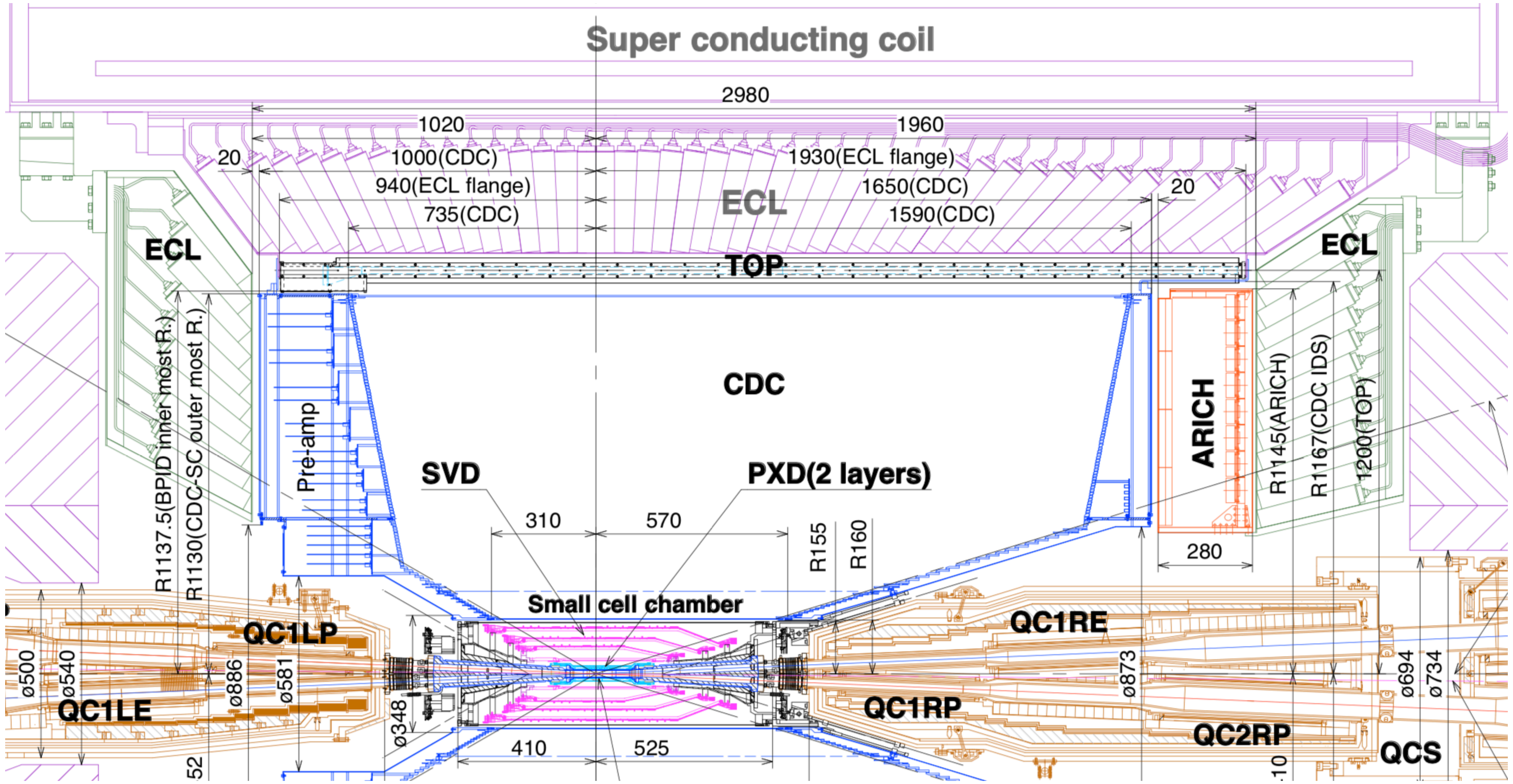

Less non-instrumented setups (e.g., magnetic wires) between ECL & KLM

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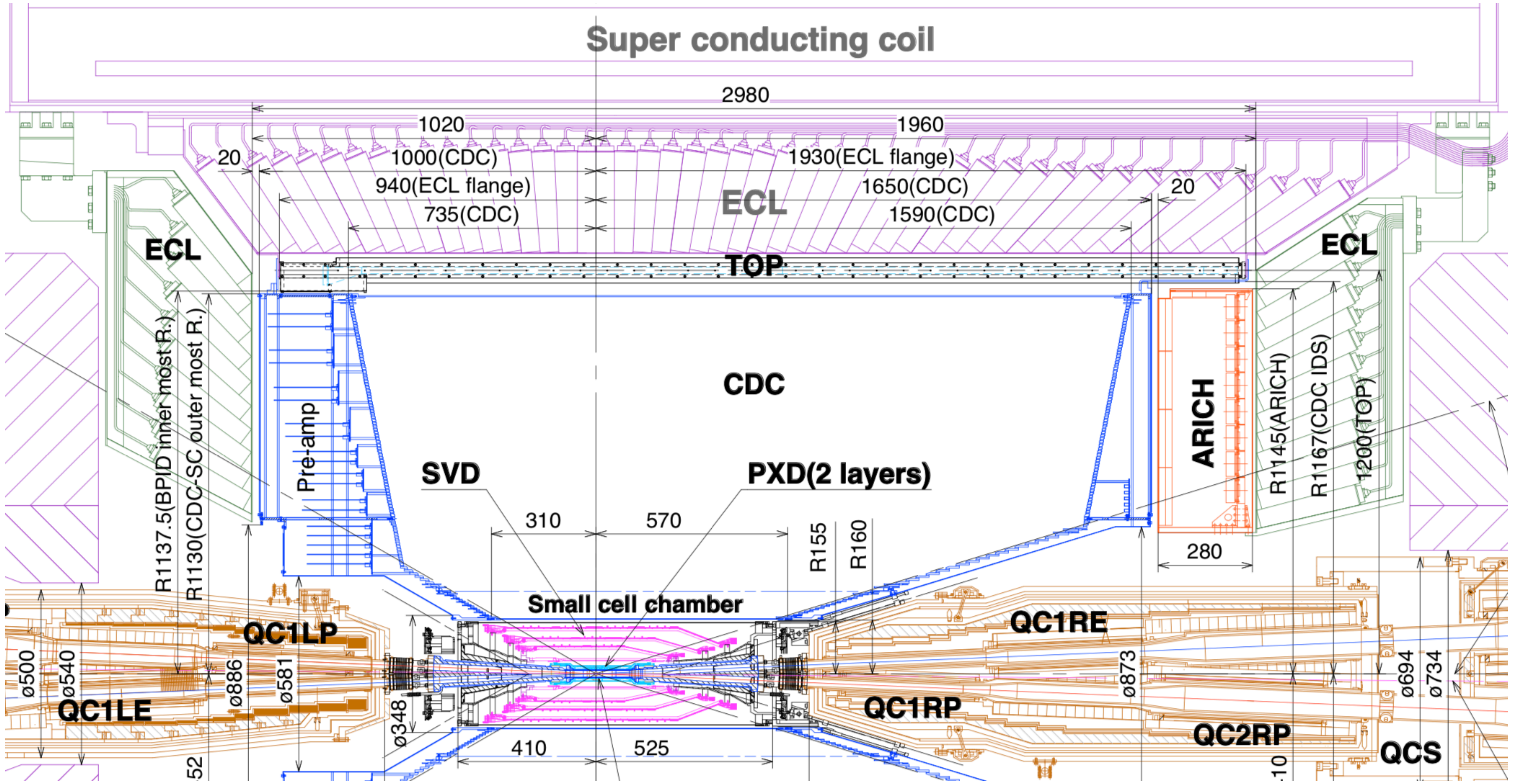

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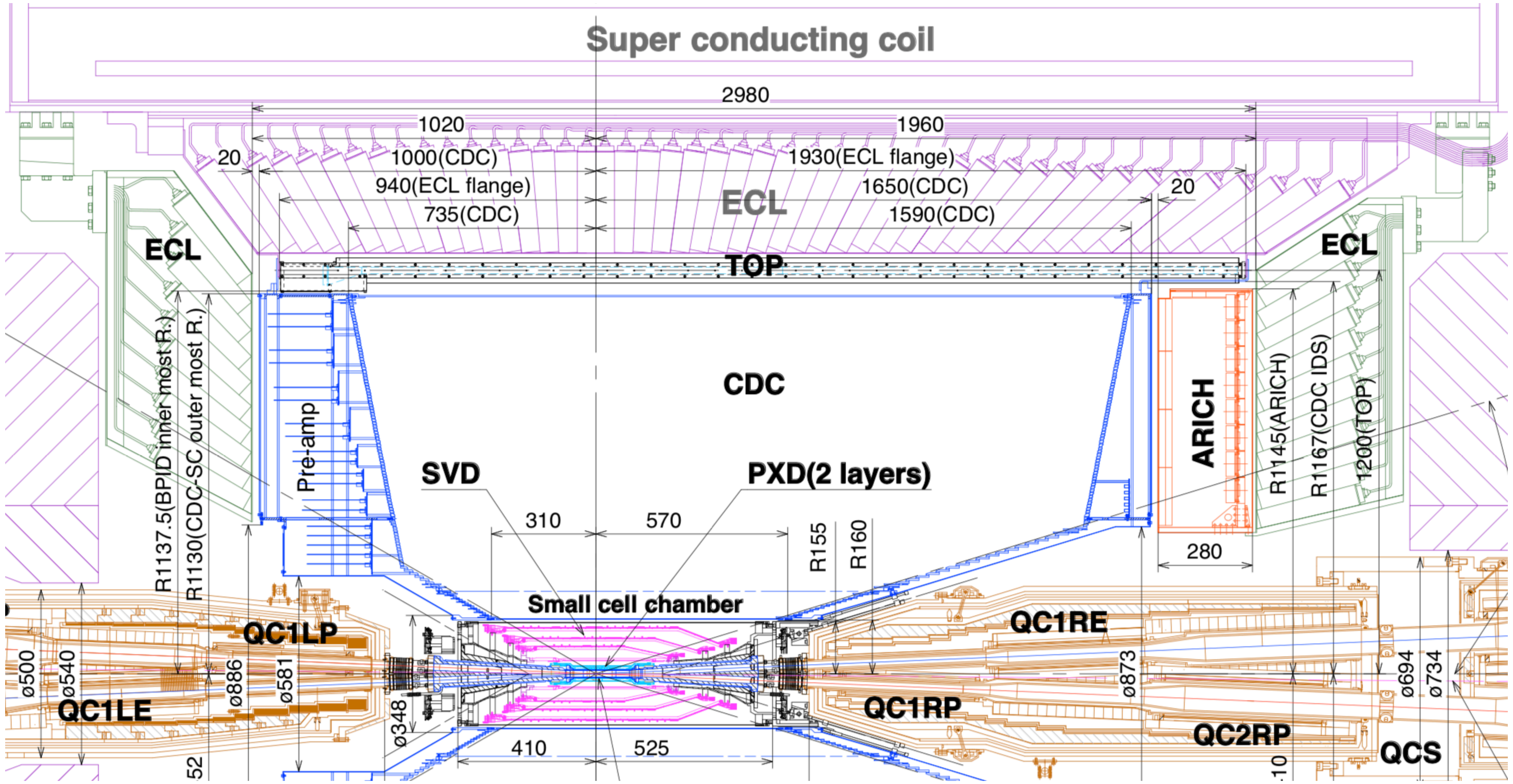

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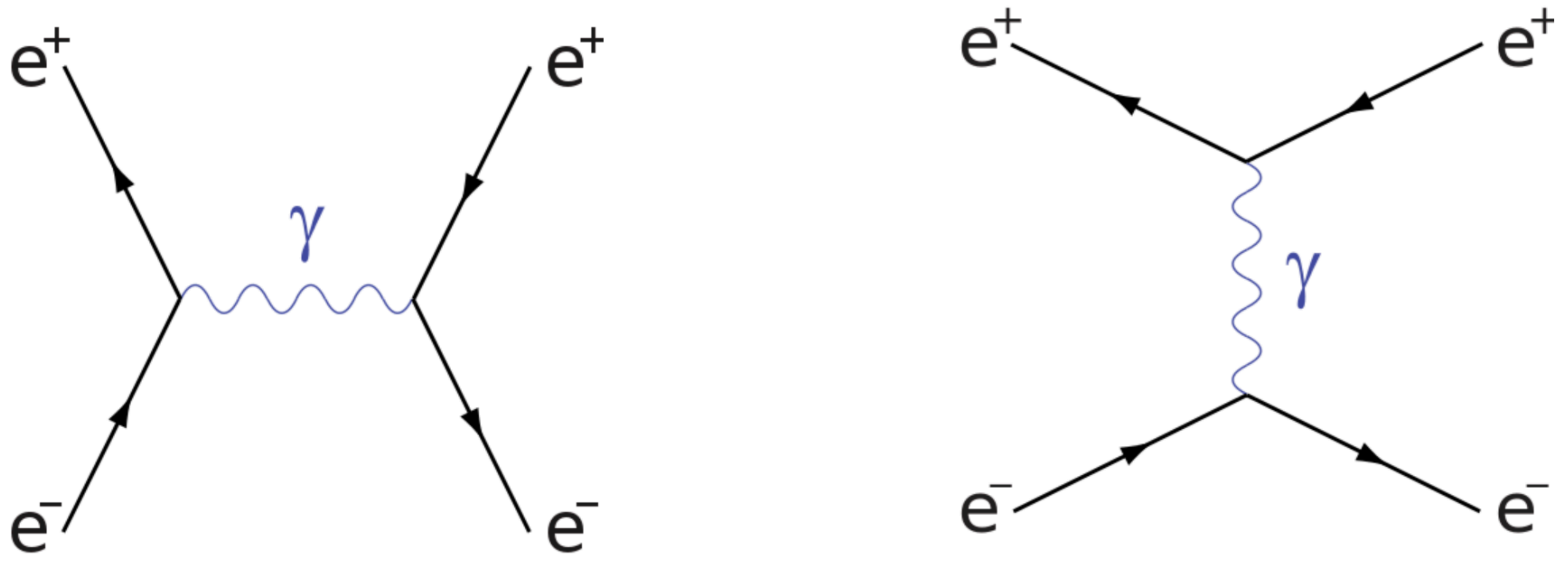
More beam BG in Endcaps

Bhabha scattering

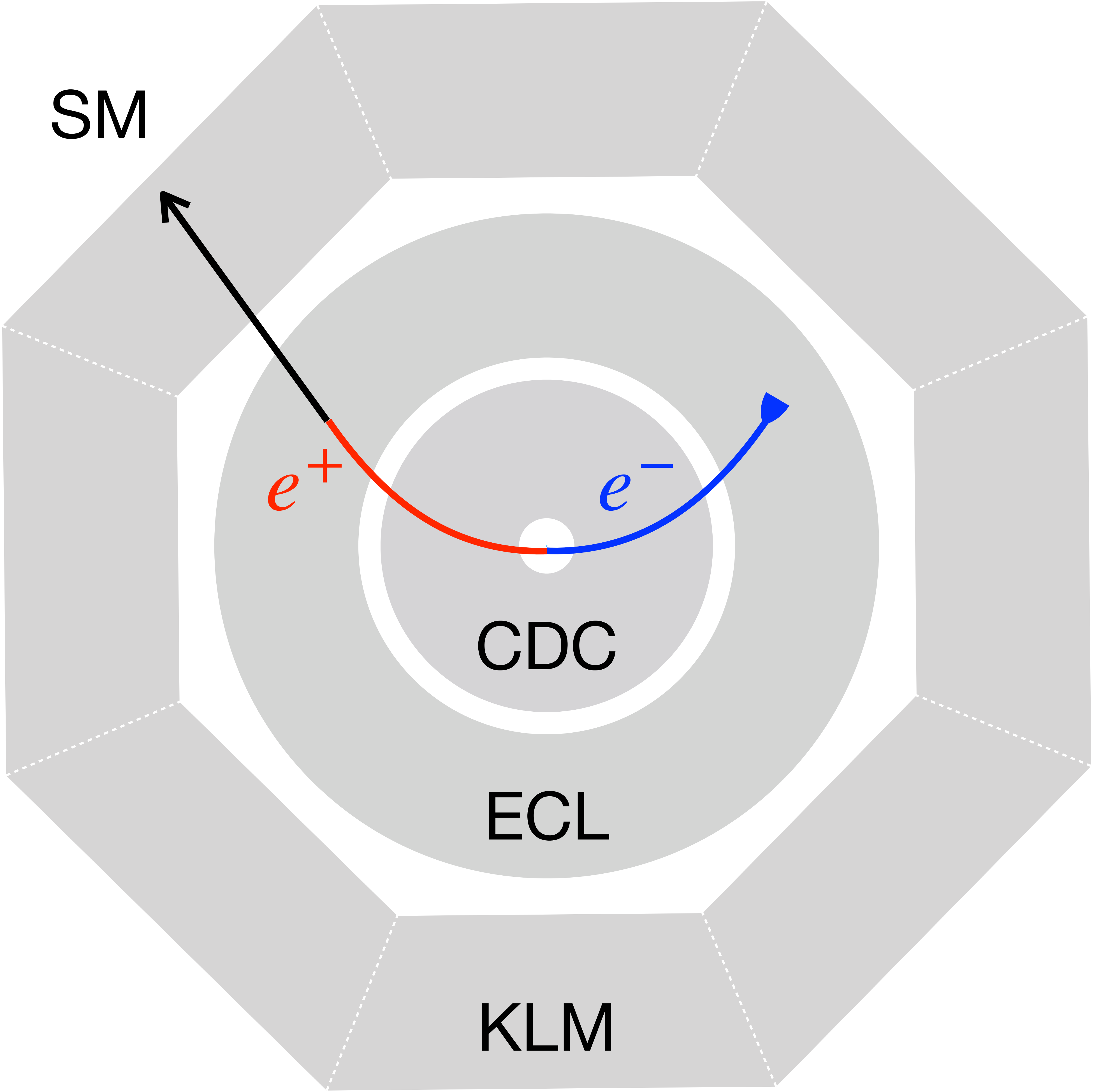


$6 \times 10^{11}\, e^+e^-$ in the barrel region with 50/ab

2 Background

Background

BG: e^+ + ECL $\rightarrow$ SM
which then escape detection



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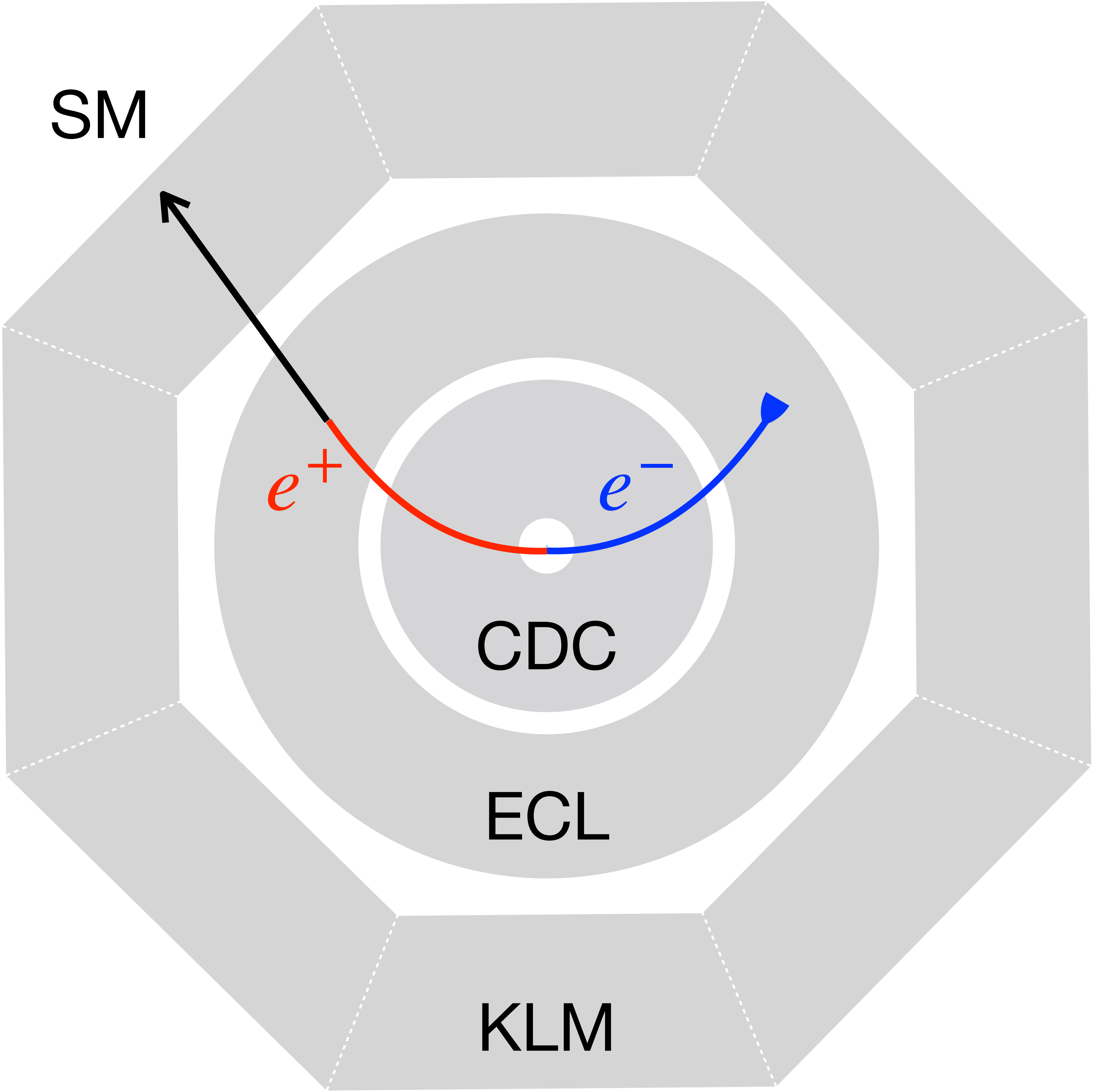
- Charged particles (e, μ, $\pi^\pm$): likely detected by ECL and/or KLM



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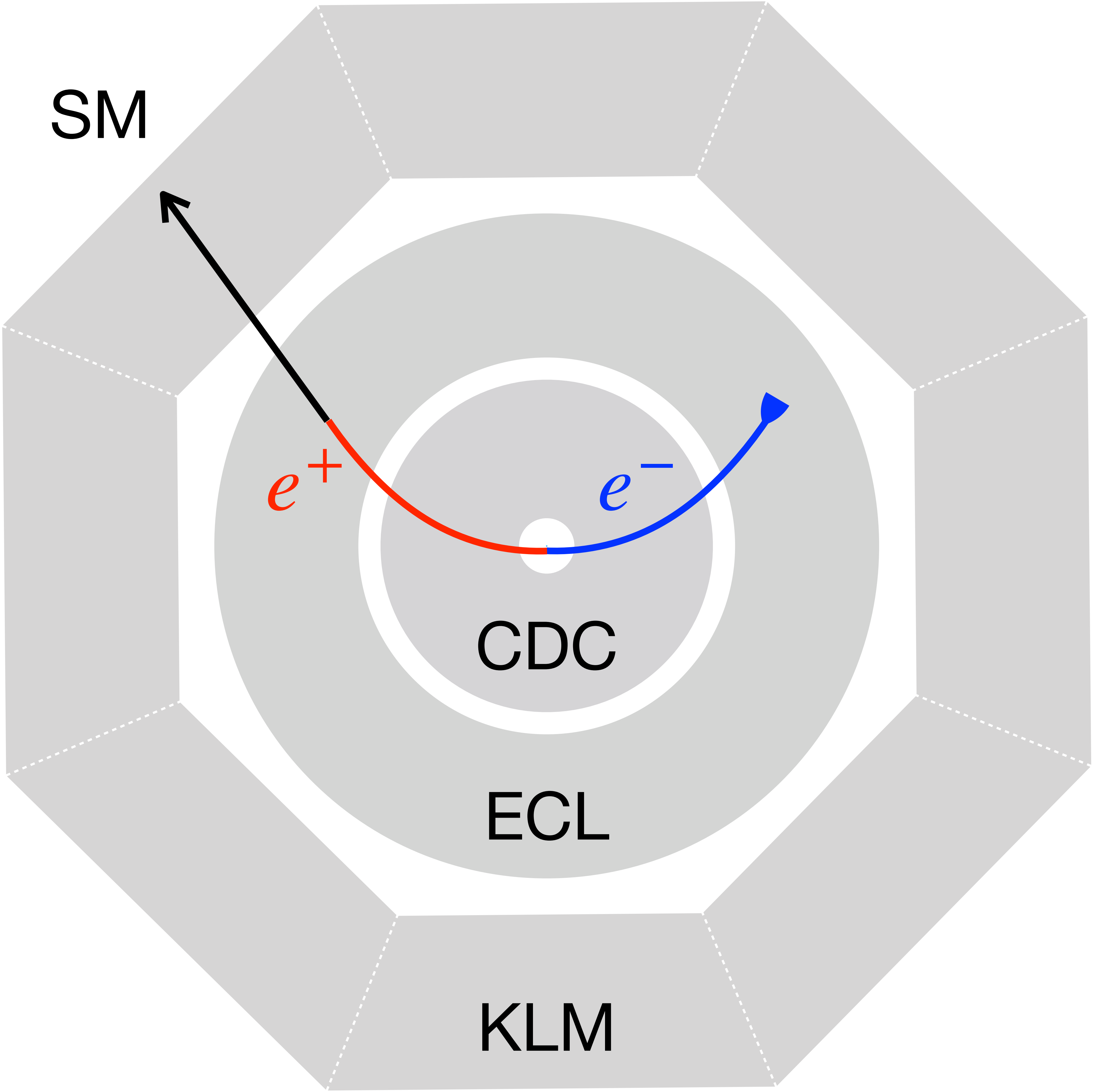

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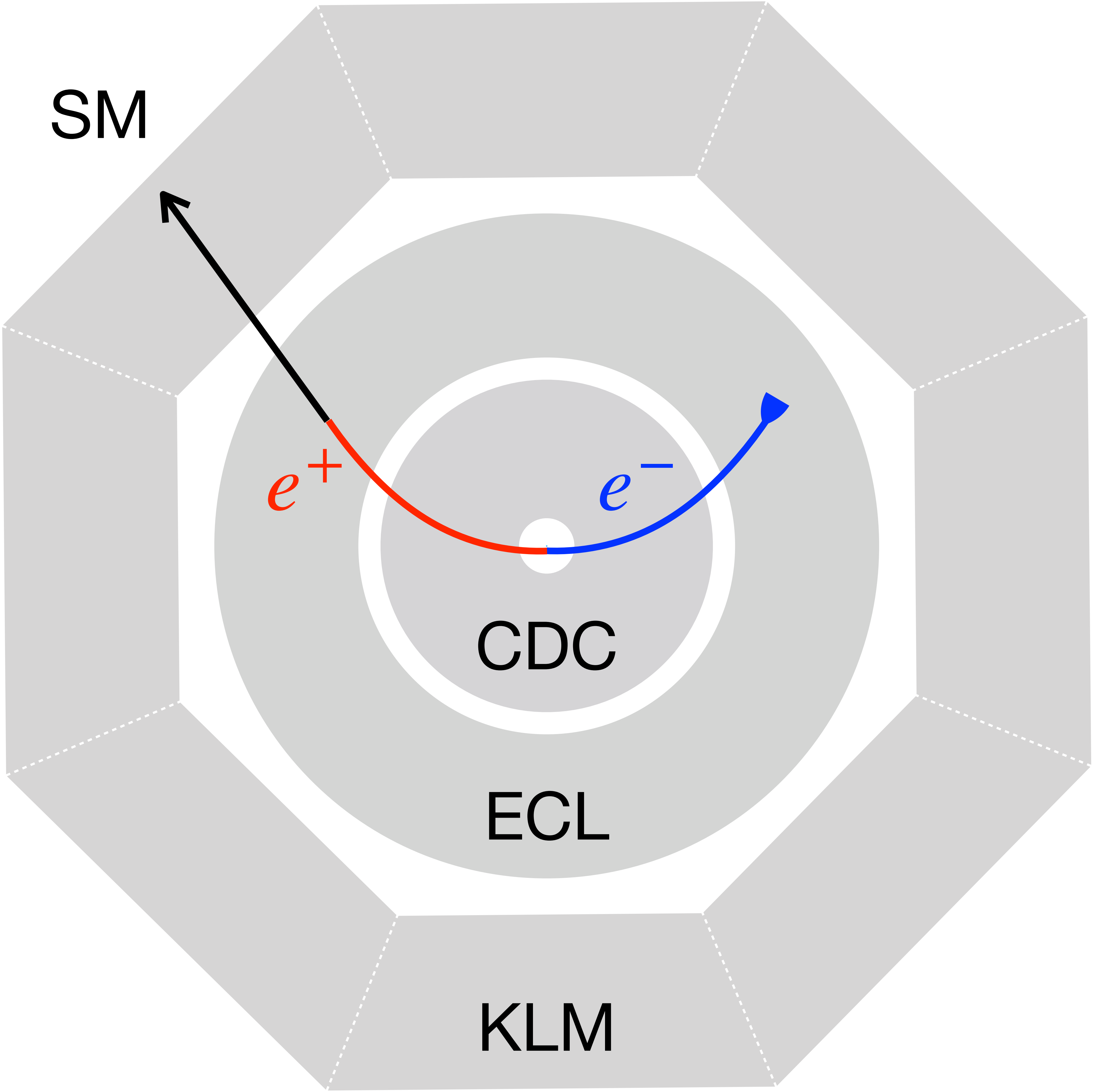
Neutrino BG is negligible (xsec is small)



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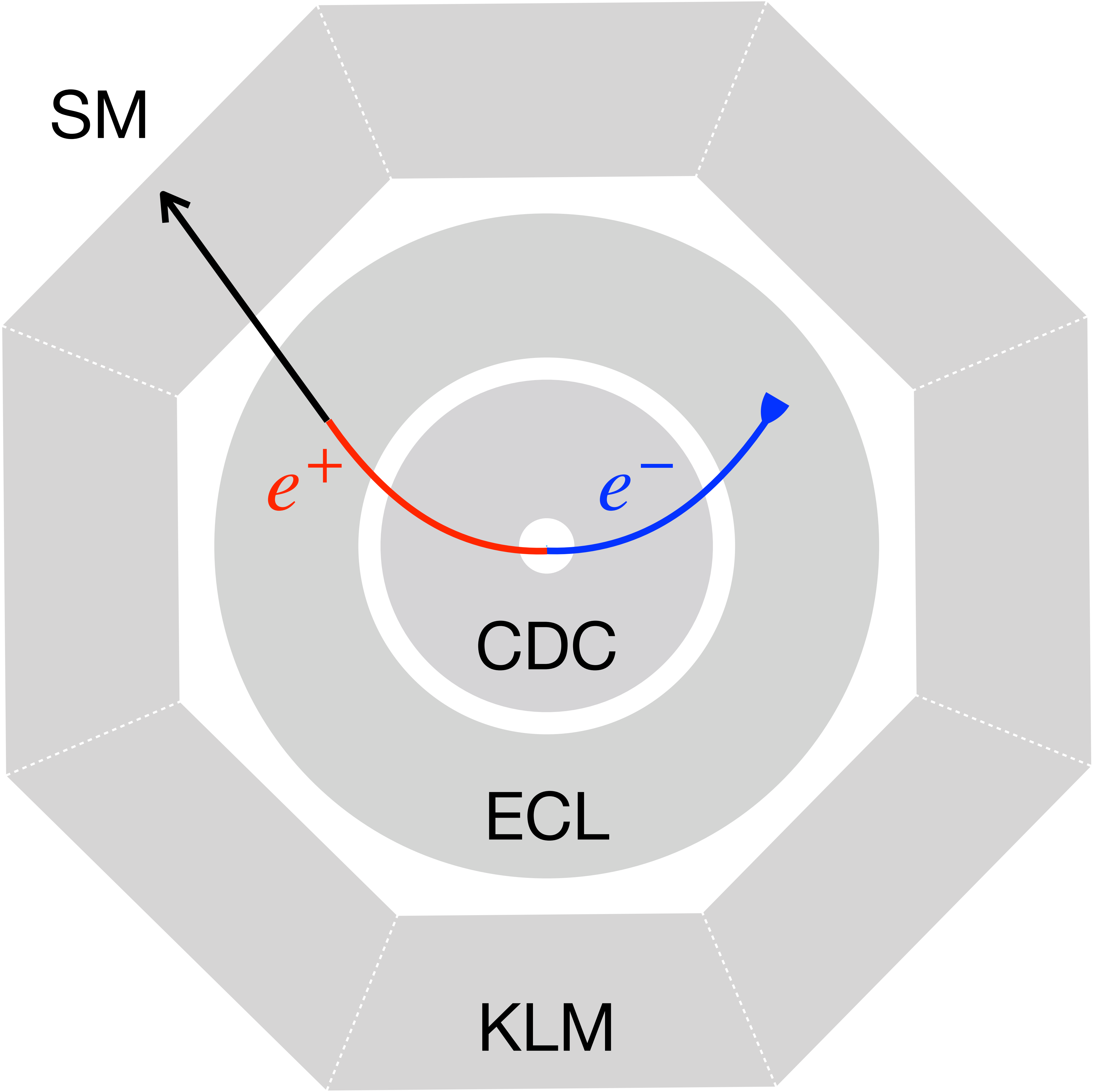
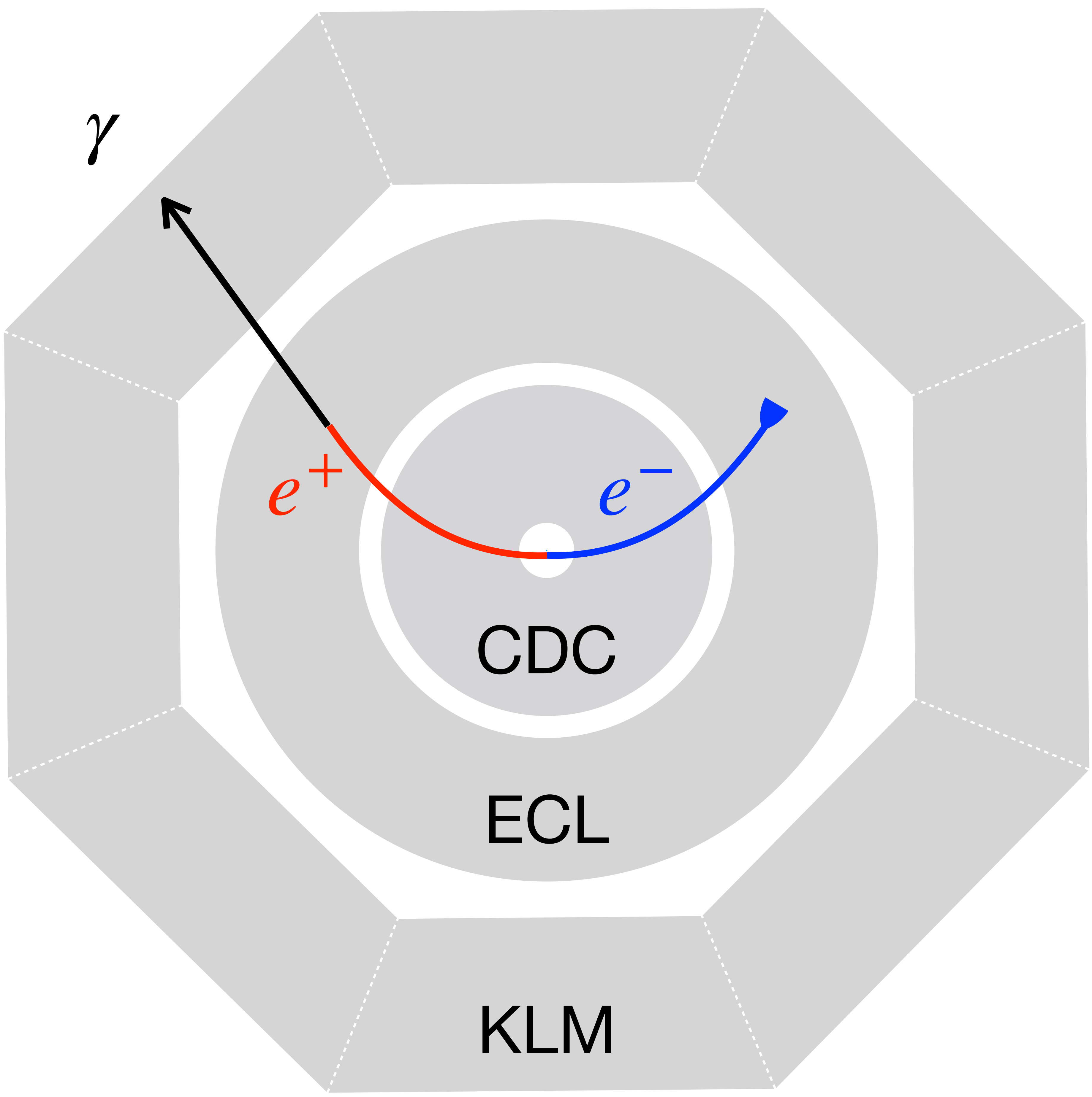
Main BG is due to n/γ

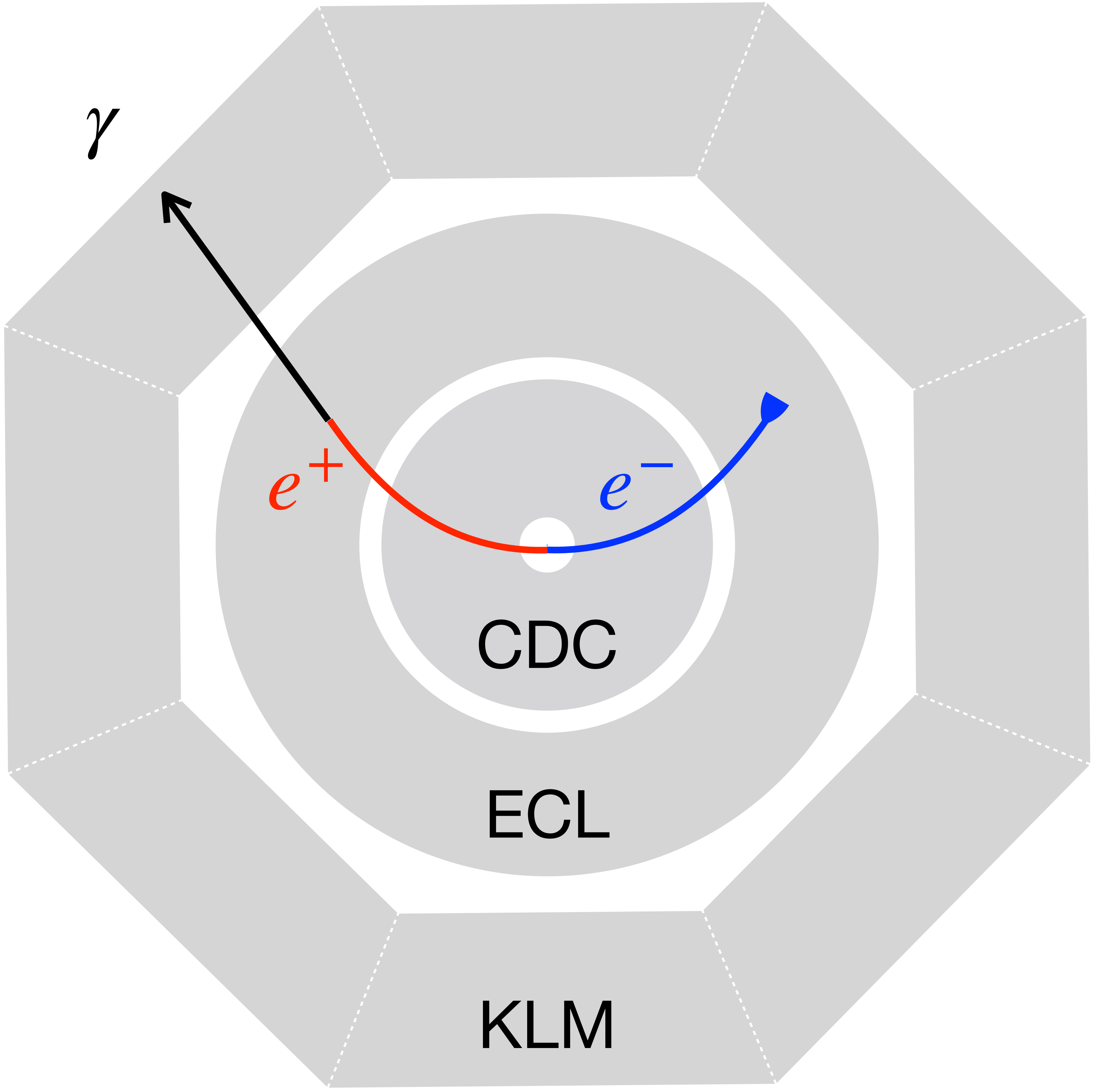


Photon background



Photon background

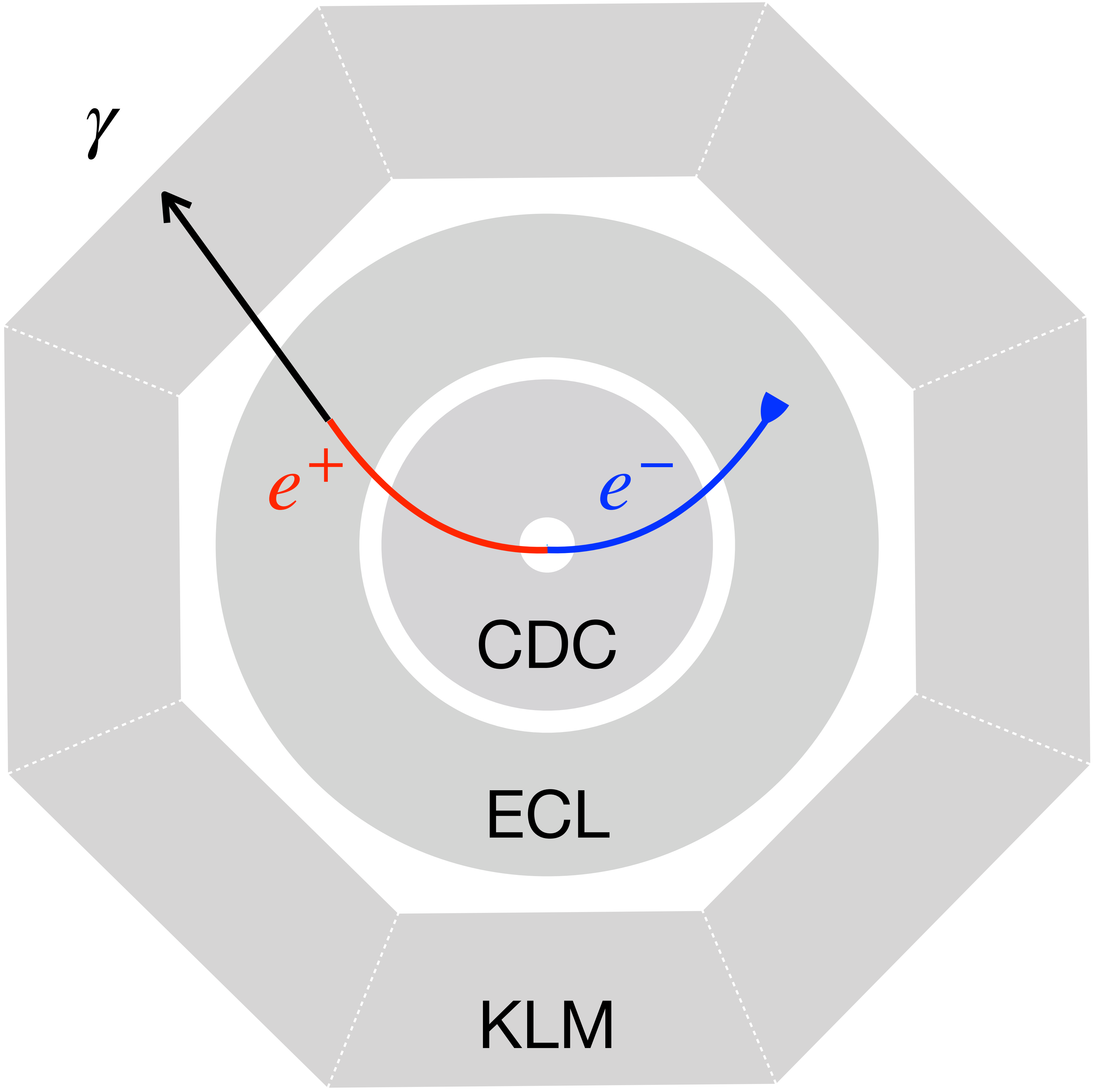
Photon energy measured in ECL



Photon background

Photon energy measured in ECL

ECL = 16-X_0 CsI crystals, w/ $X_0 = 1.86$ cm



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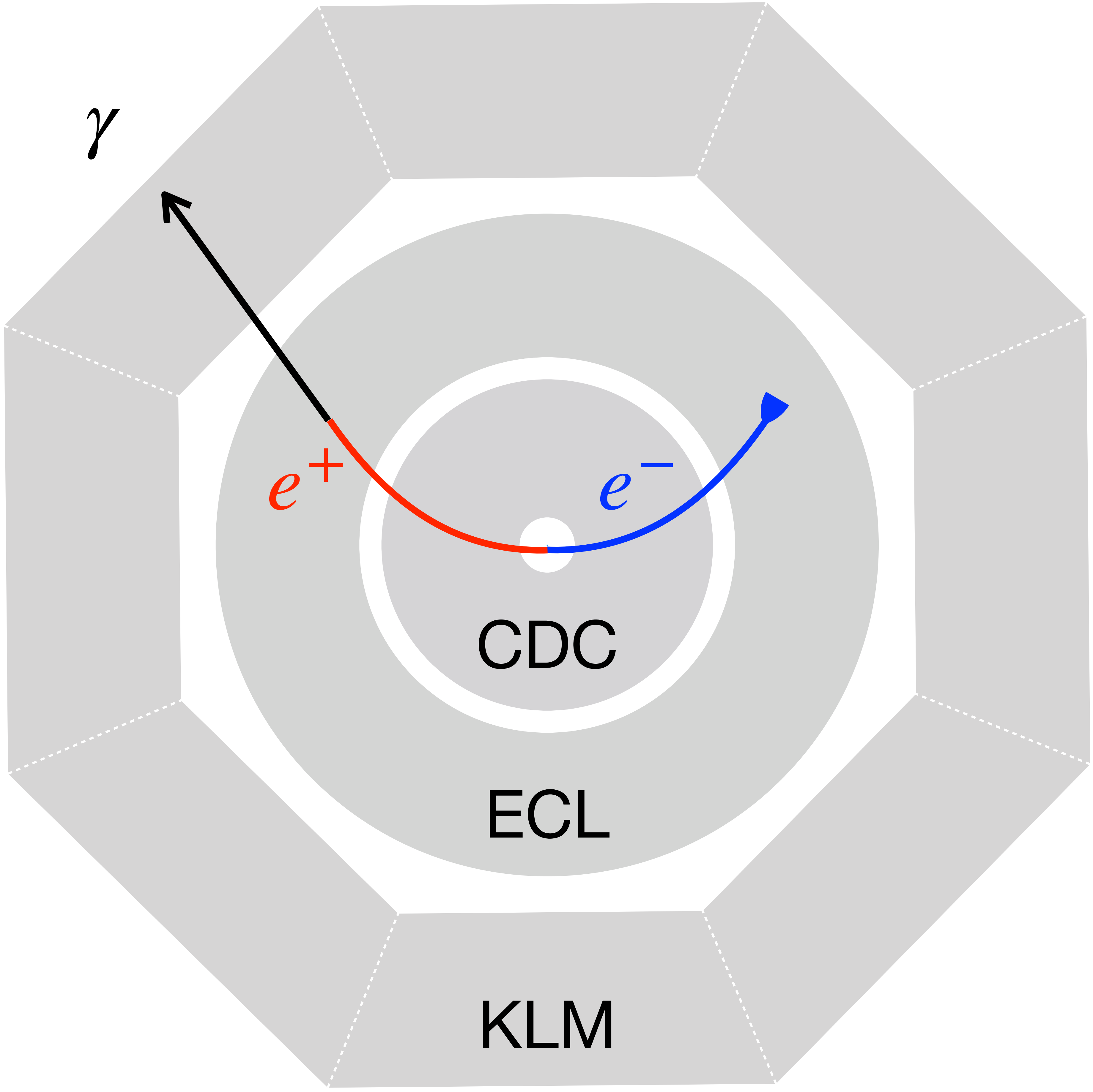

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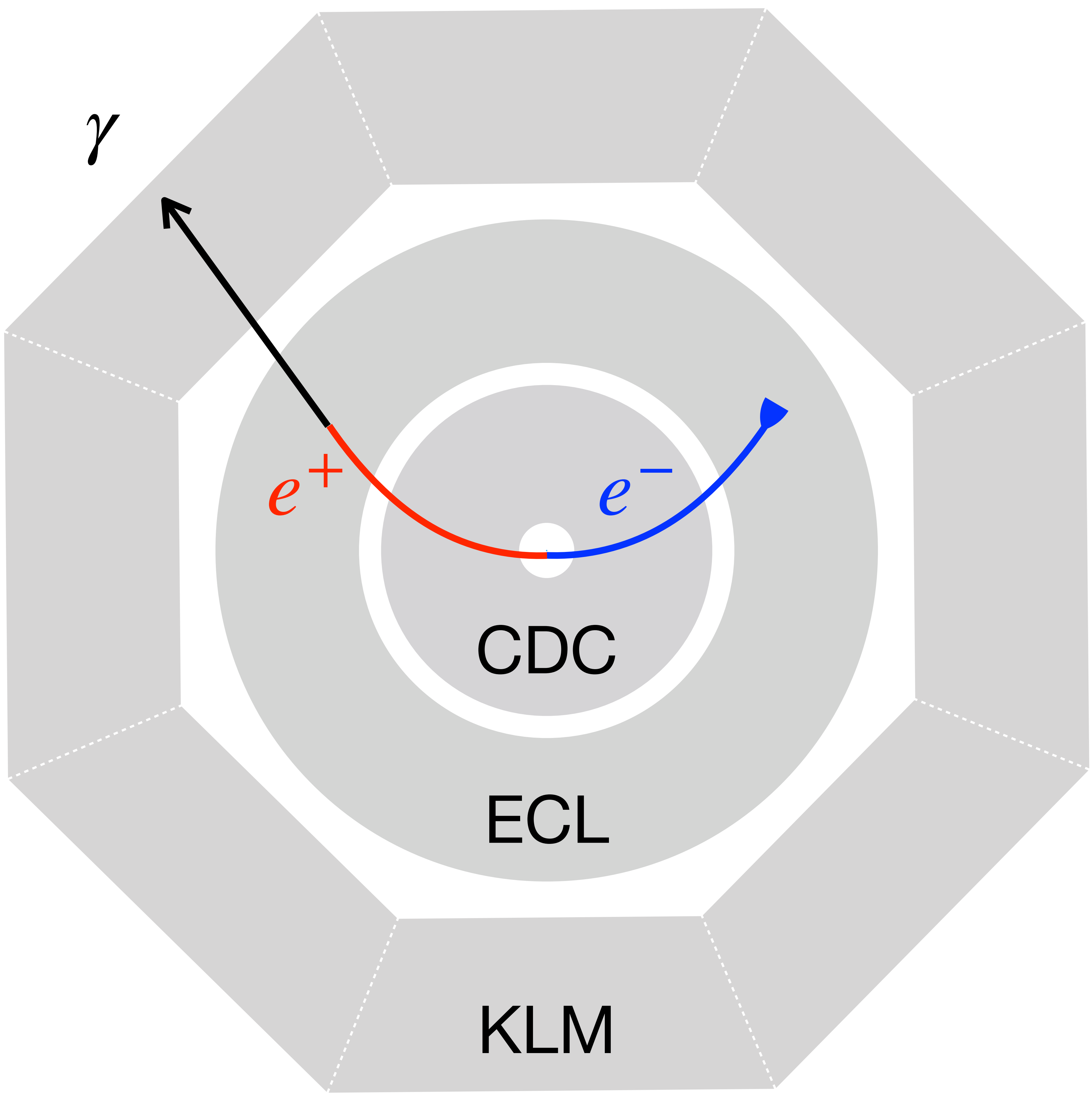
KLM = alternating sandwich of 4.7-cm iron plates and active detectors



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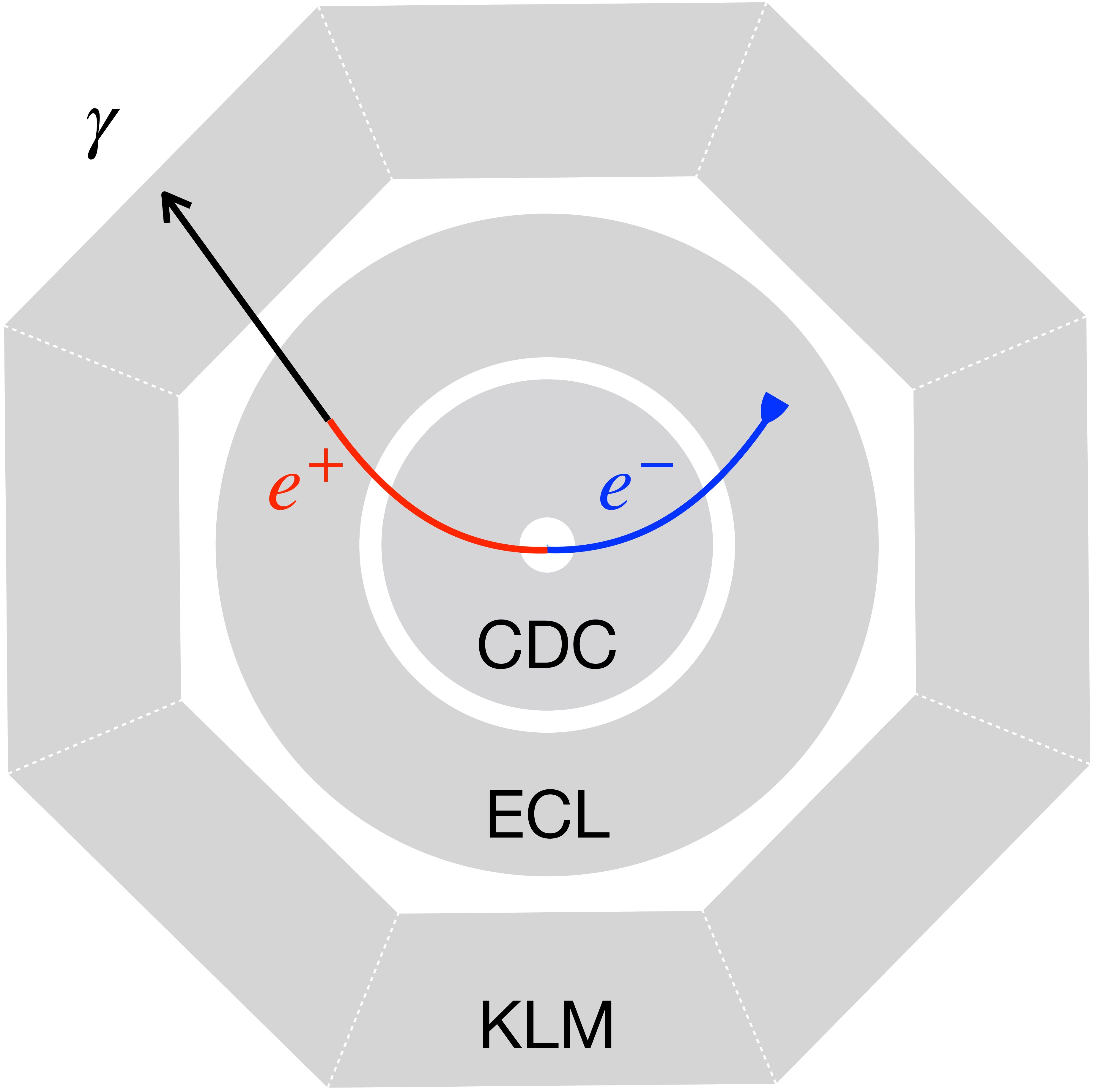


Photon escapes ECL

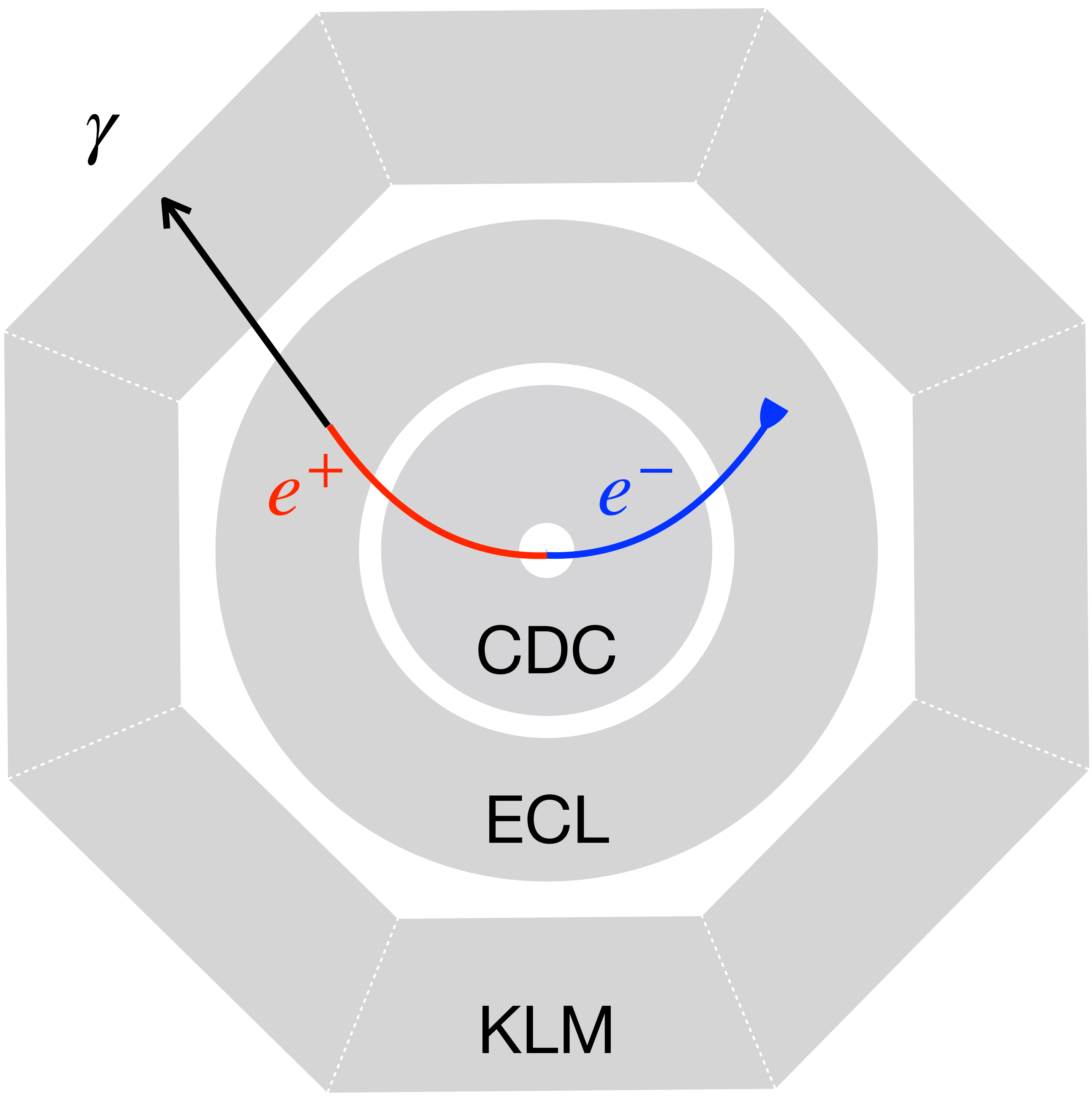
Photon energy spectrum due to e^+ collision with ECL

[Tsai & Whitis 1966]

$$\frac{dN_\gamma}{dx_\gamma}(t, x_\gamma) \simeq \frac{1}{x_\gamma}\frac{(1 - x_\gamma)^{(4/3)t} - e^{-(7/9)t}}{7/9 + (4/3)\ln(1 - x_\gamma)}$$

$x_\gamma = E_\gamma / E_e$

tX_0 is the distance



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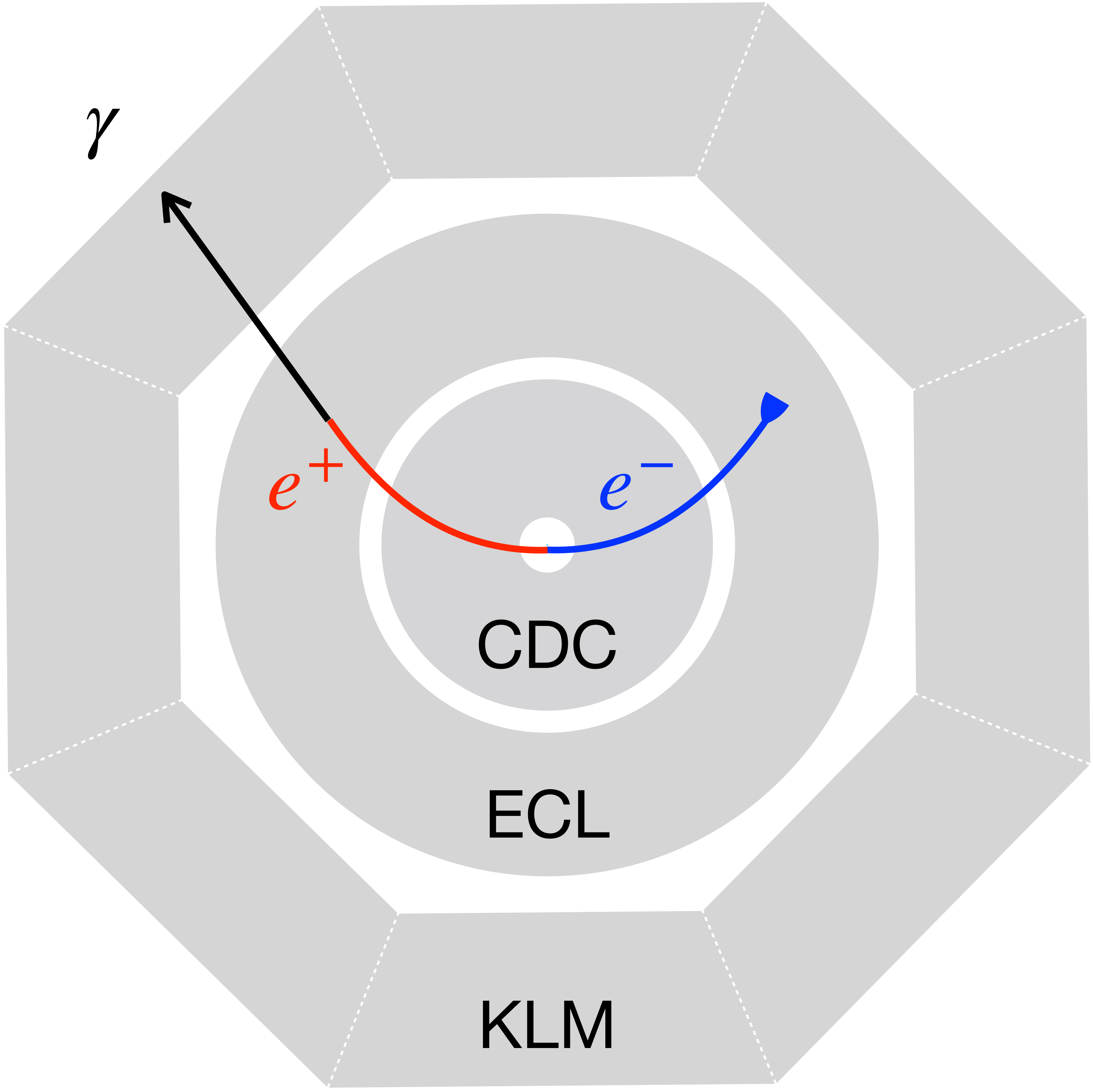
$$\frac{dN_\gamma}{dx_\gamma}(t, x_\gamma) \simeq \frac{1}{x_\gamma} \frac{(1-x_\gamma)^{(4/3)t} - e^{-(7/9)t}}{7/9 + (4/3)\ln(1-x_\gamma)}$$

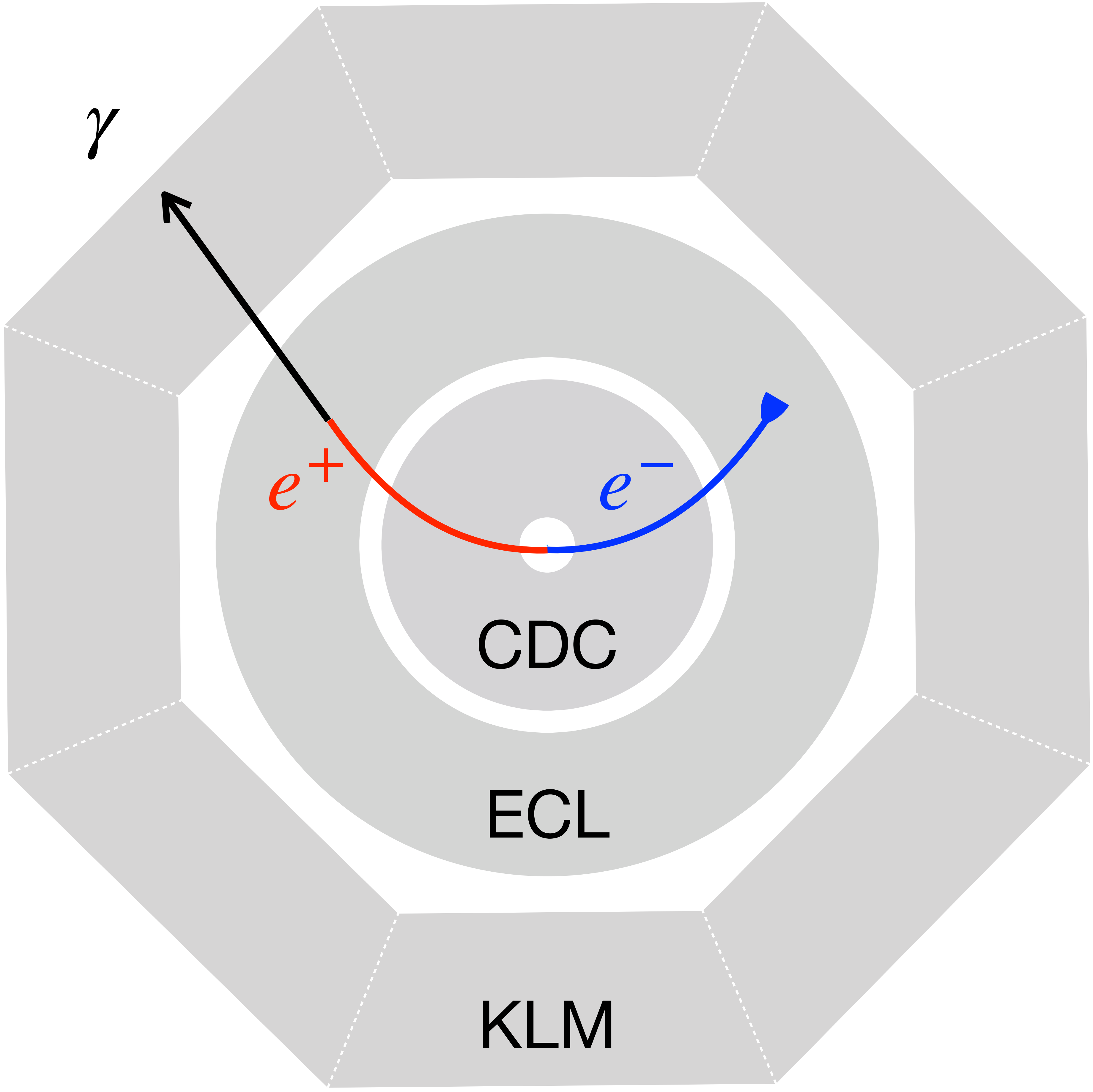
$x_\gamma = E_\gamma / E_e$ $\qquad$ tX_0 is the distance

$$\int_{0.95}^{1} dx_\gamma \frac{dN_\gamma}{dx_\gamma}(t = 16, x_\gamma) \simeq 4.7 \times 10^{-8}$$

$\sim 2.8 \times 10^4$ γ-BG after ECL for 6×10^{11} e^+

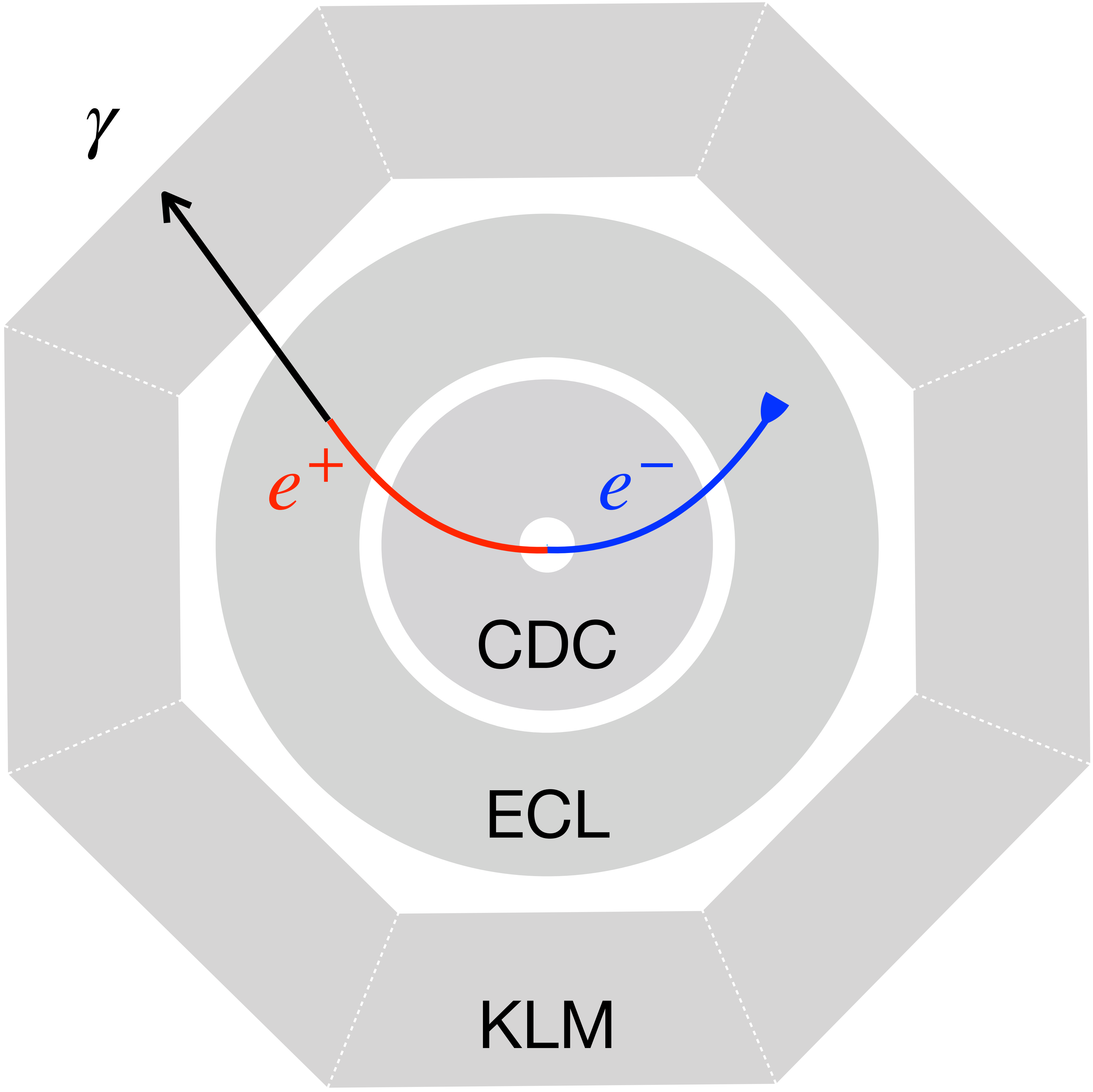


KLM veto capability on photon



KLM veto capability on photon

GeV γ is unlikely to penetrate the KLM



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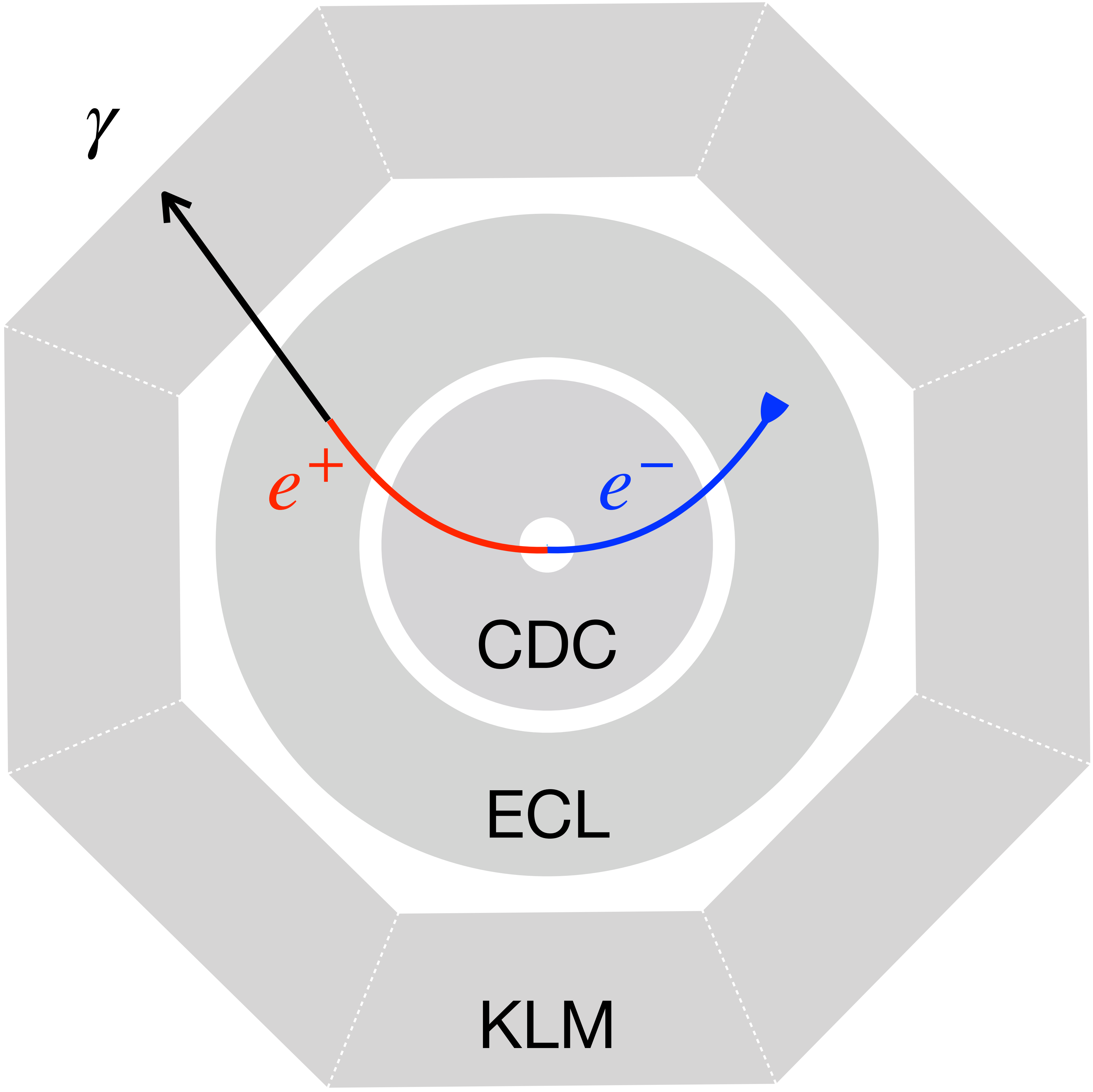

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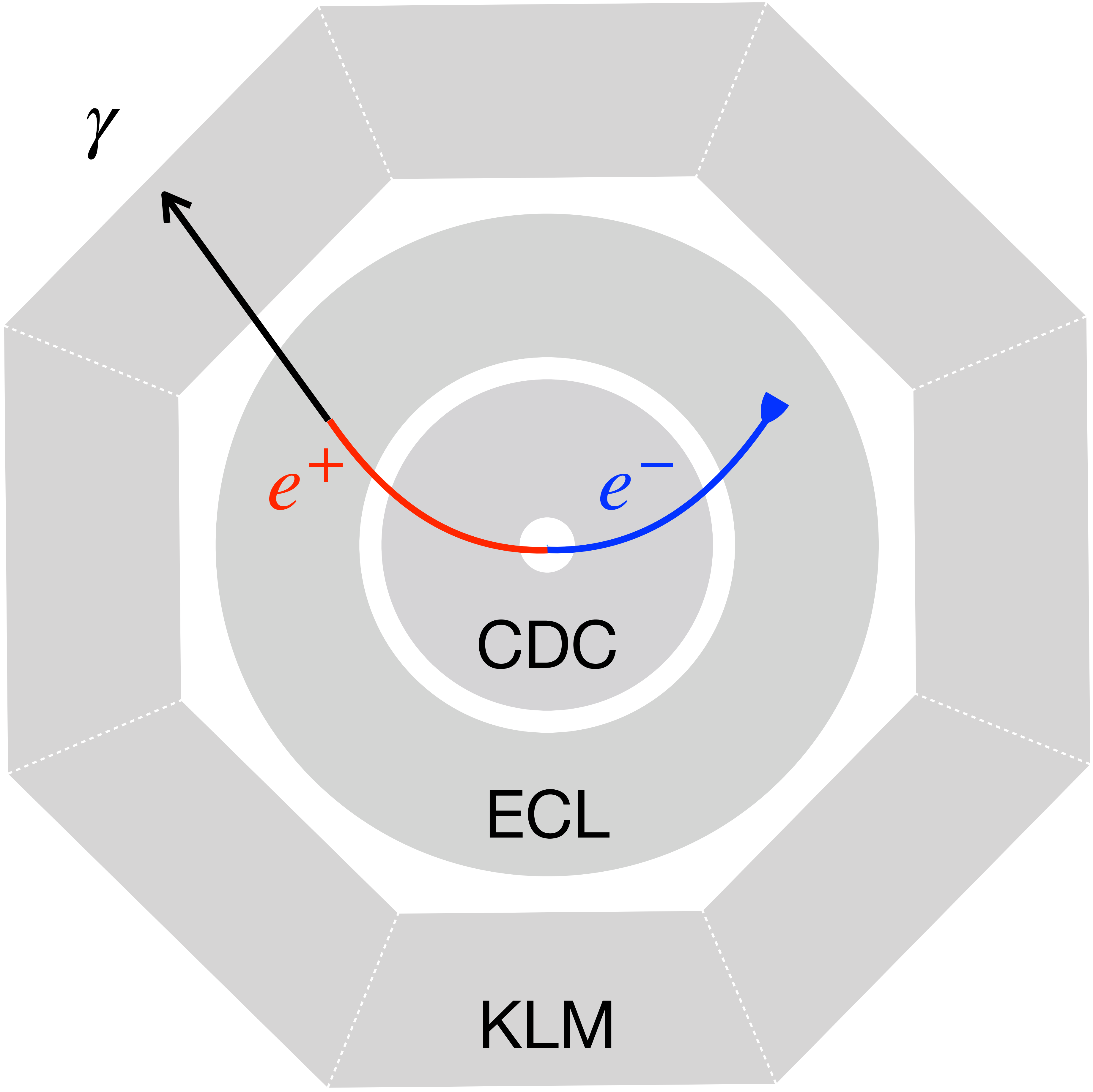

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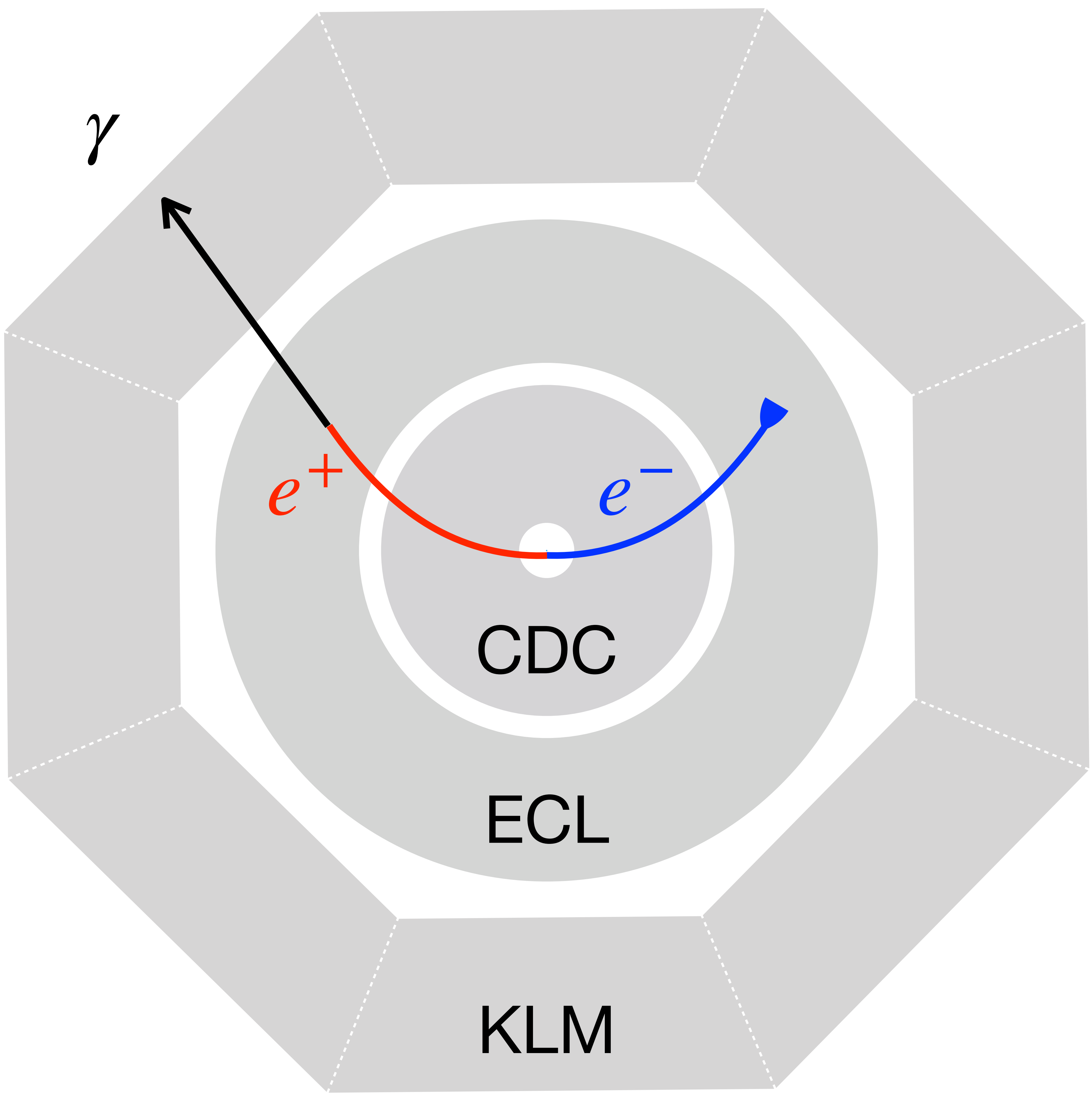

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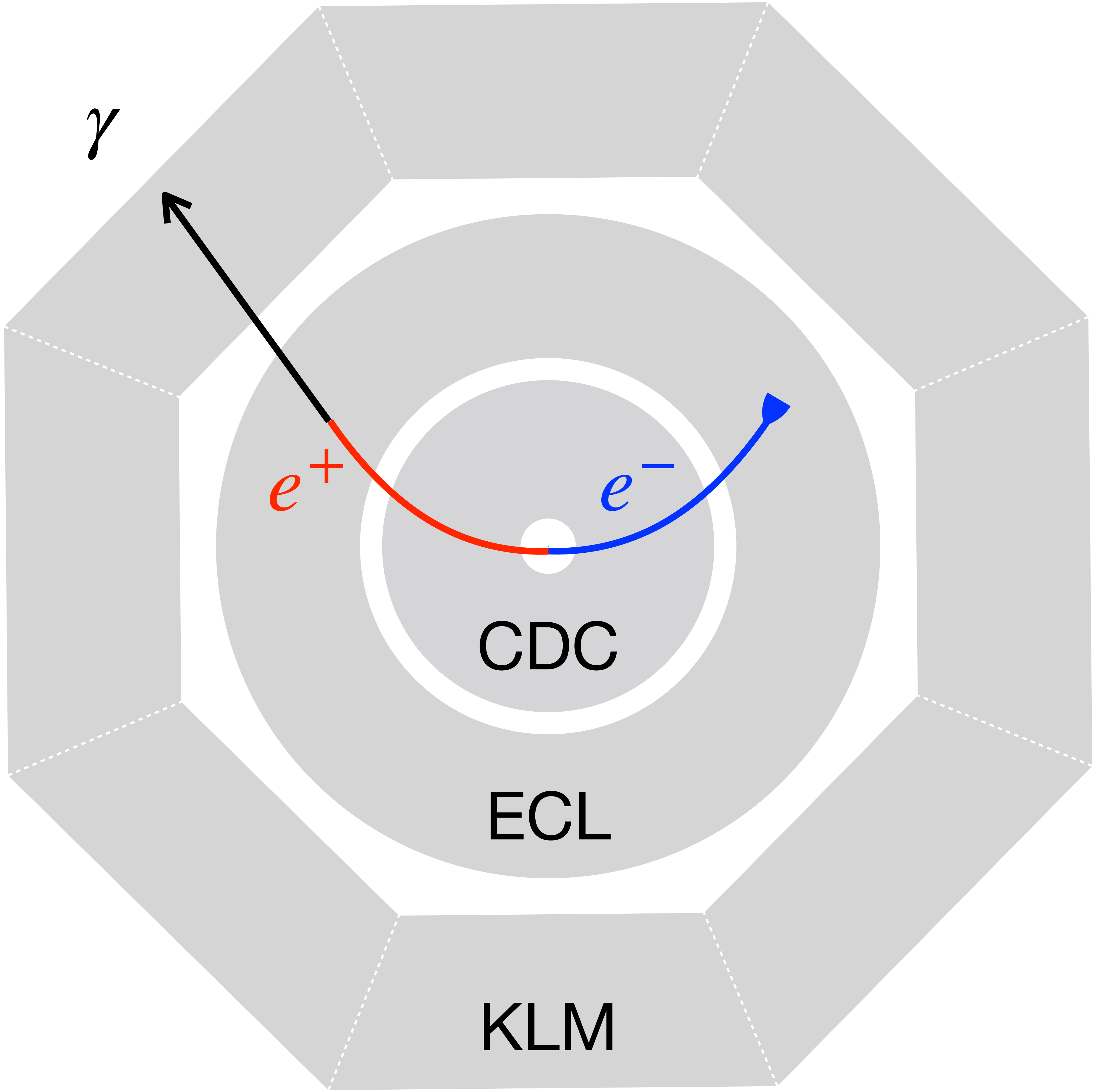
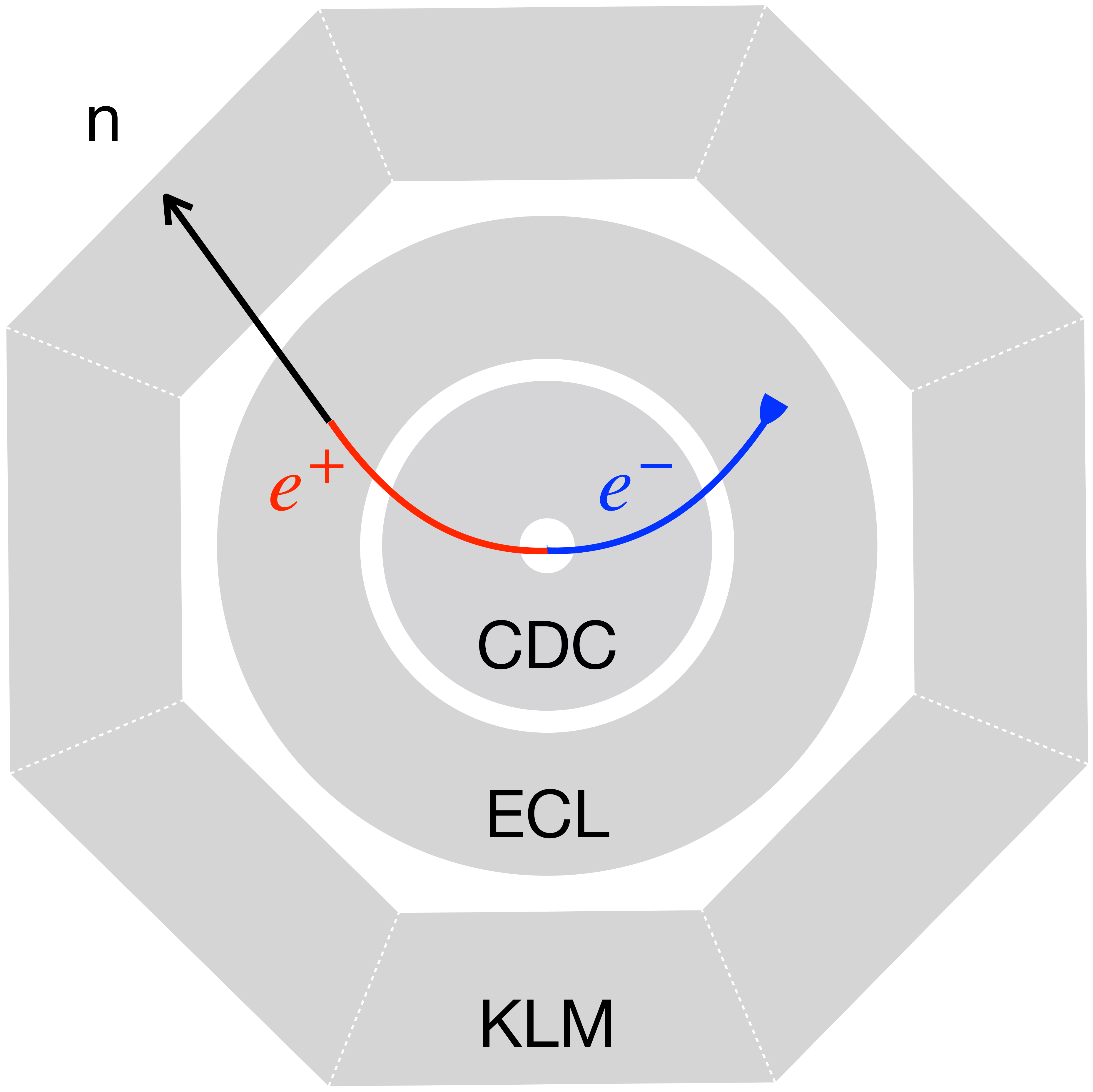
13 photon BG (conservative)

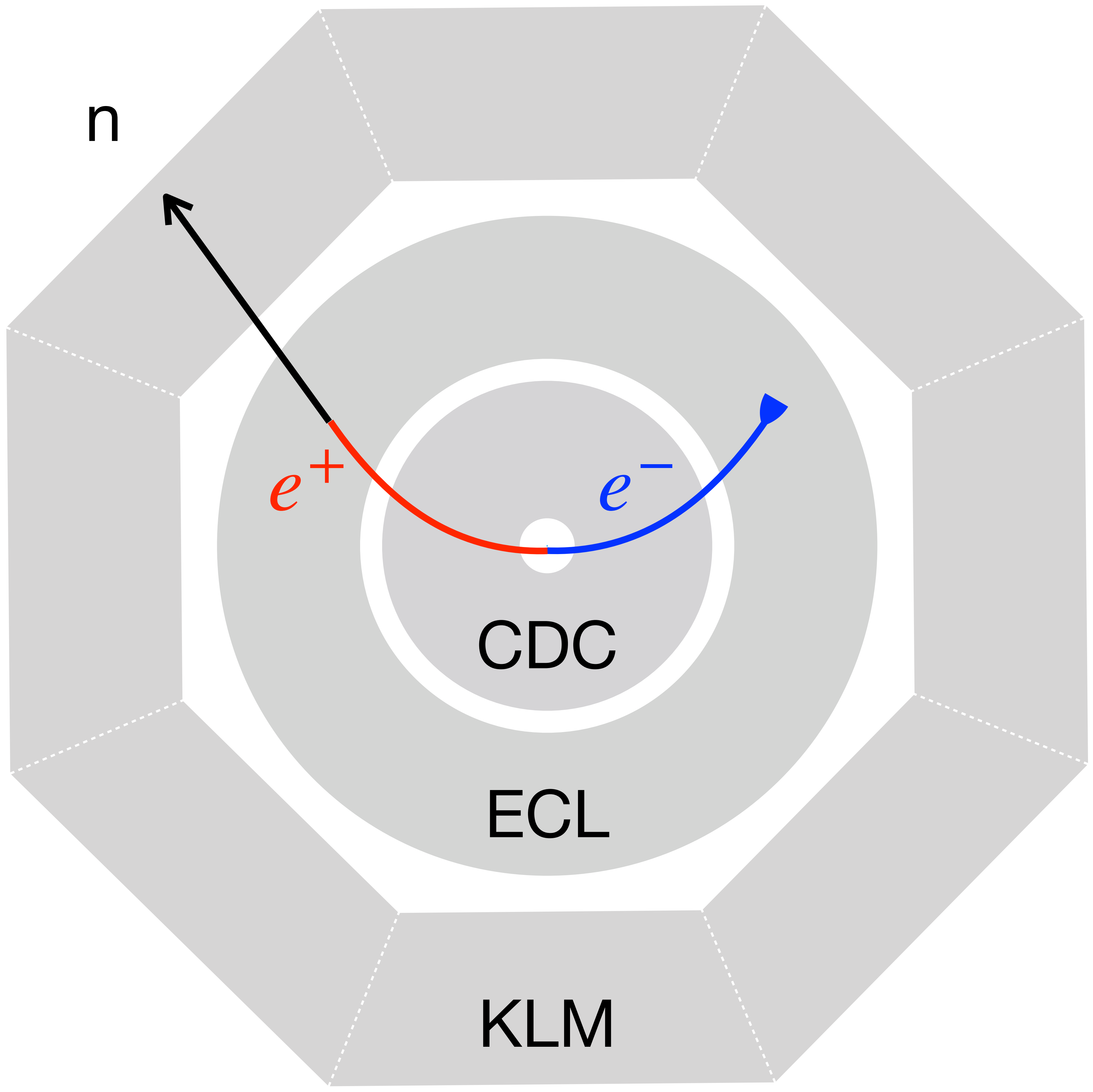


Neutron background simulation



Neutron background simulation

GEANT4 simulation of $10^9\ e^+$ with 4.35 GeV onto a CsI target with 1 X_0



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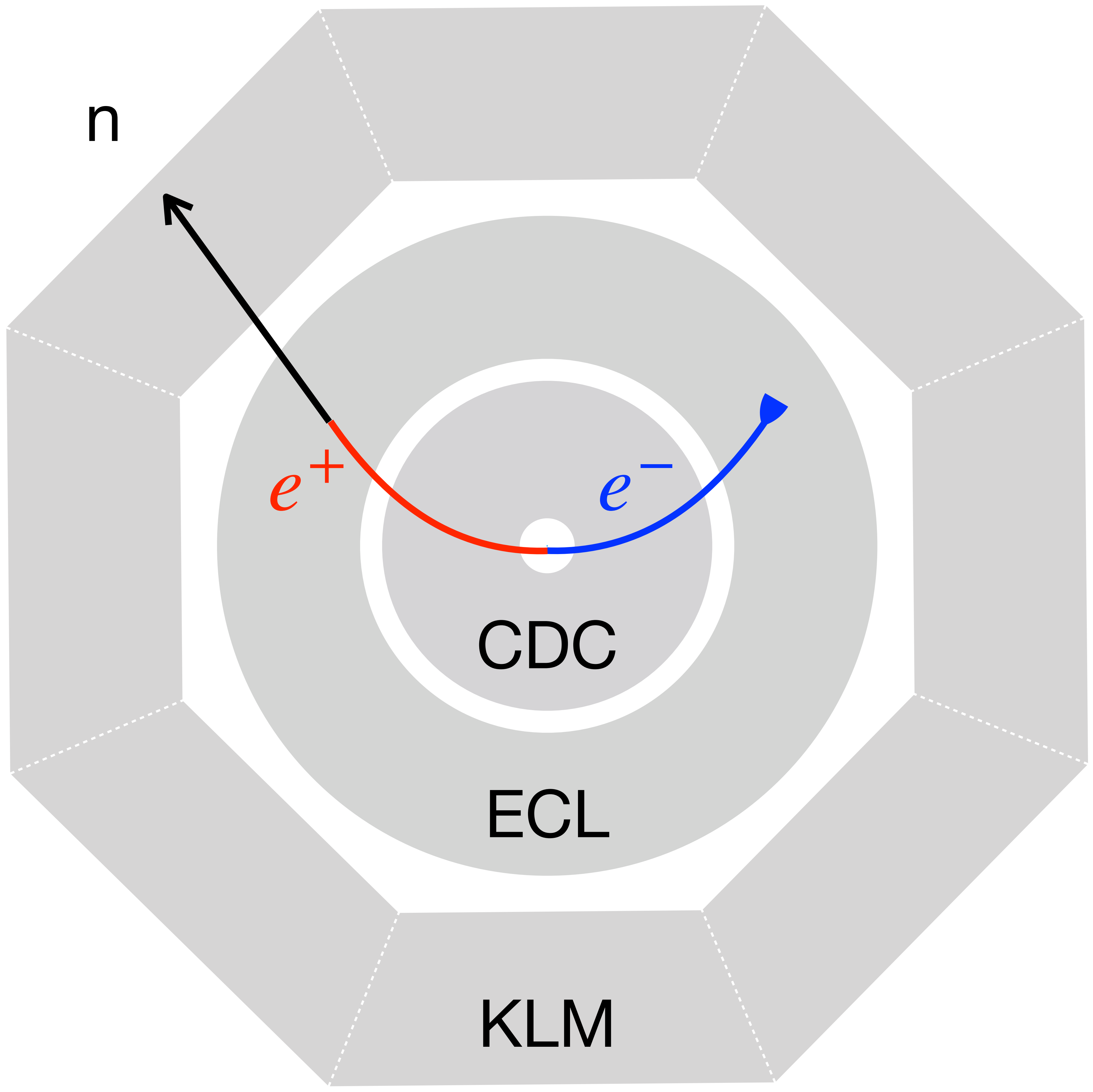
Full simulation with 16 X_0 is time-consuming

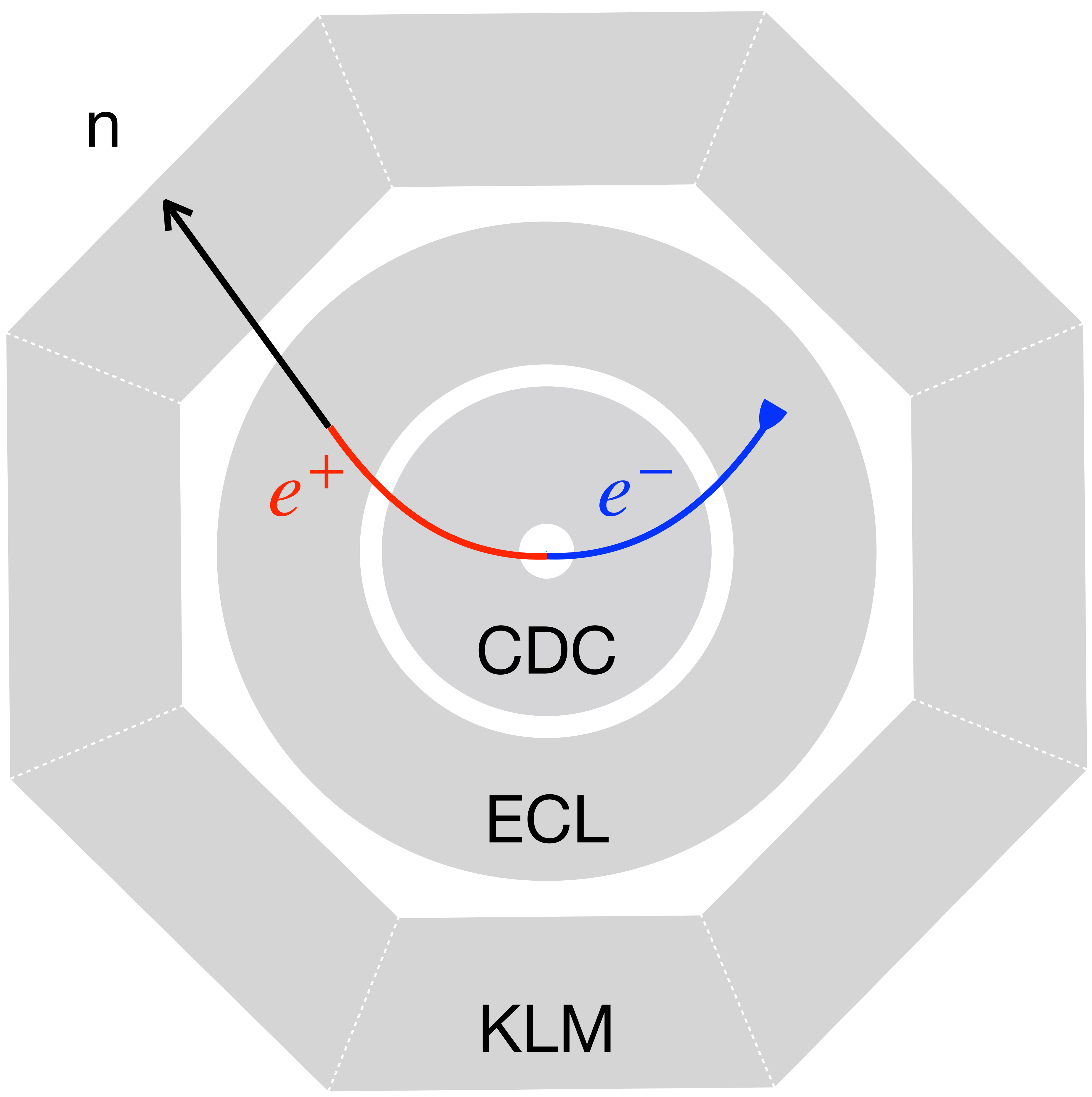


Neutron background simulation

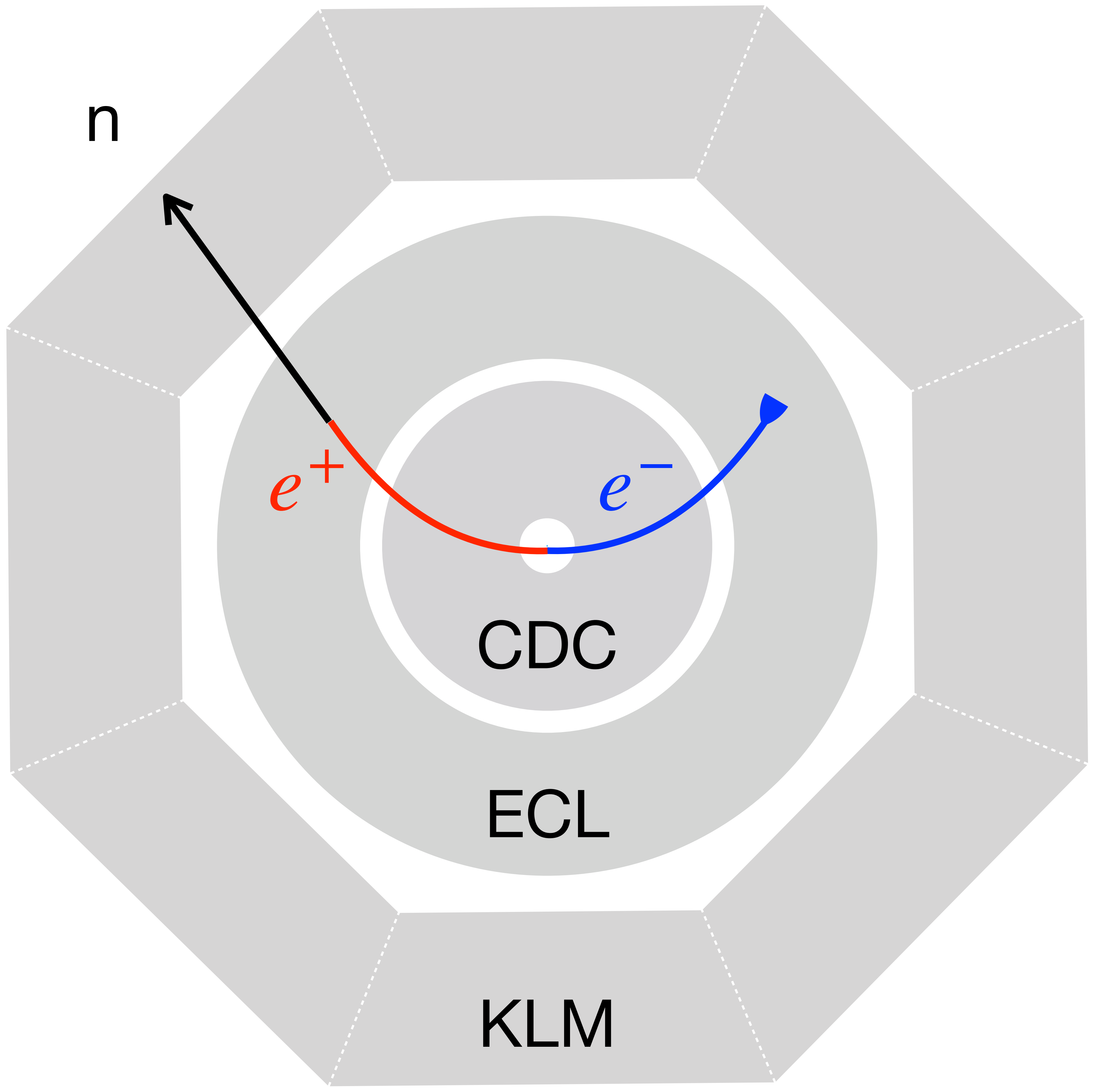
GEANT4 simulation of 10^9 e^+ with 4.35 GeV onto a CsI target with 1 X_0

Full simulation with 16 X_0 is time-consuming

Neutrons with significant energy are likely to be produced in the 1st X_0 (confirmed in simulations with 2-X_0)

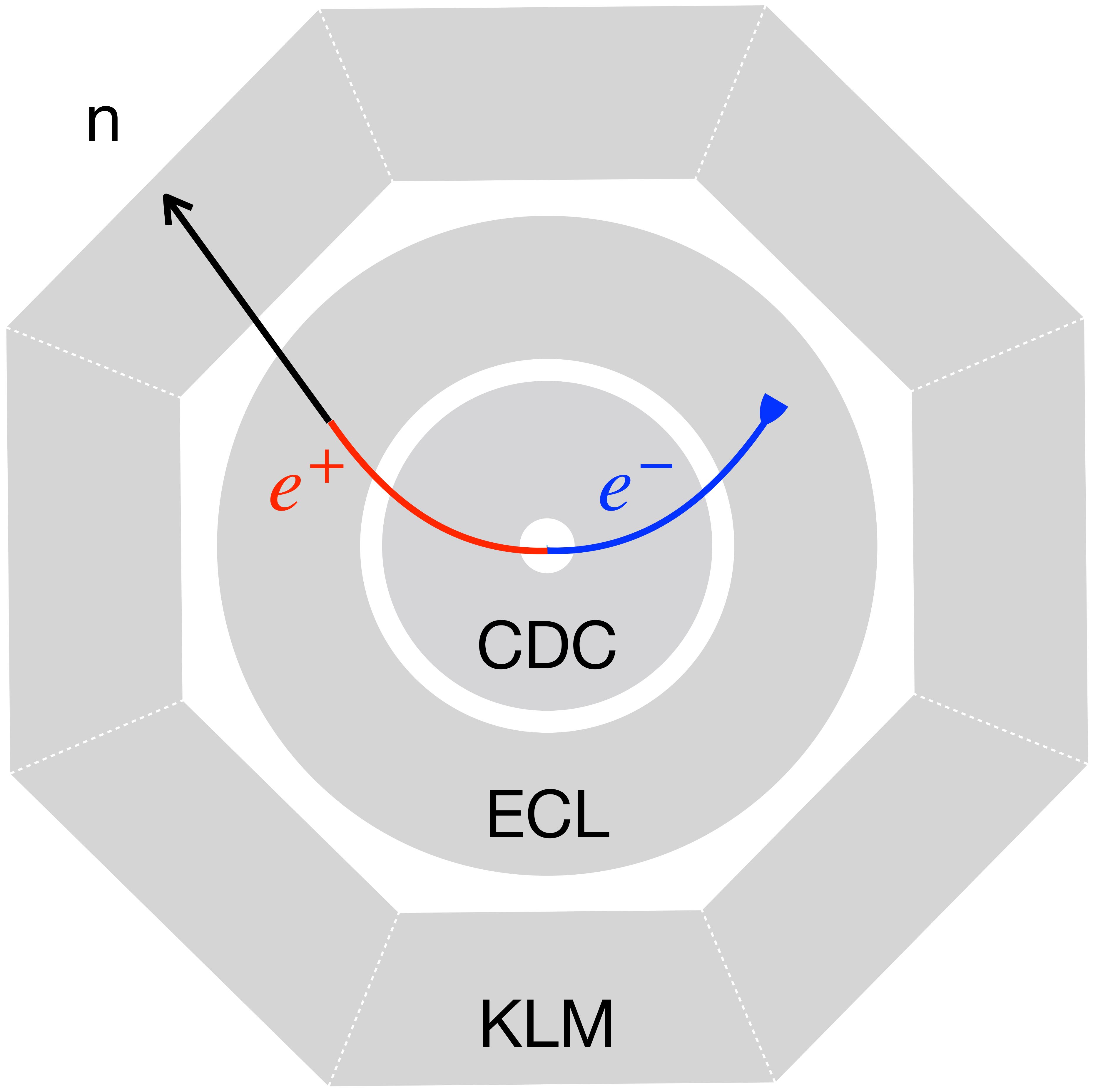


Selection in GEANT4 simulation



Selection in GEANT4 simulation

At least 1 neutron with energy > 3 GeV



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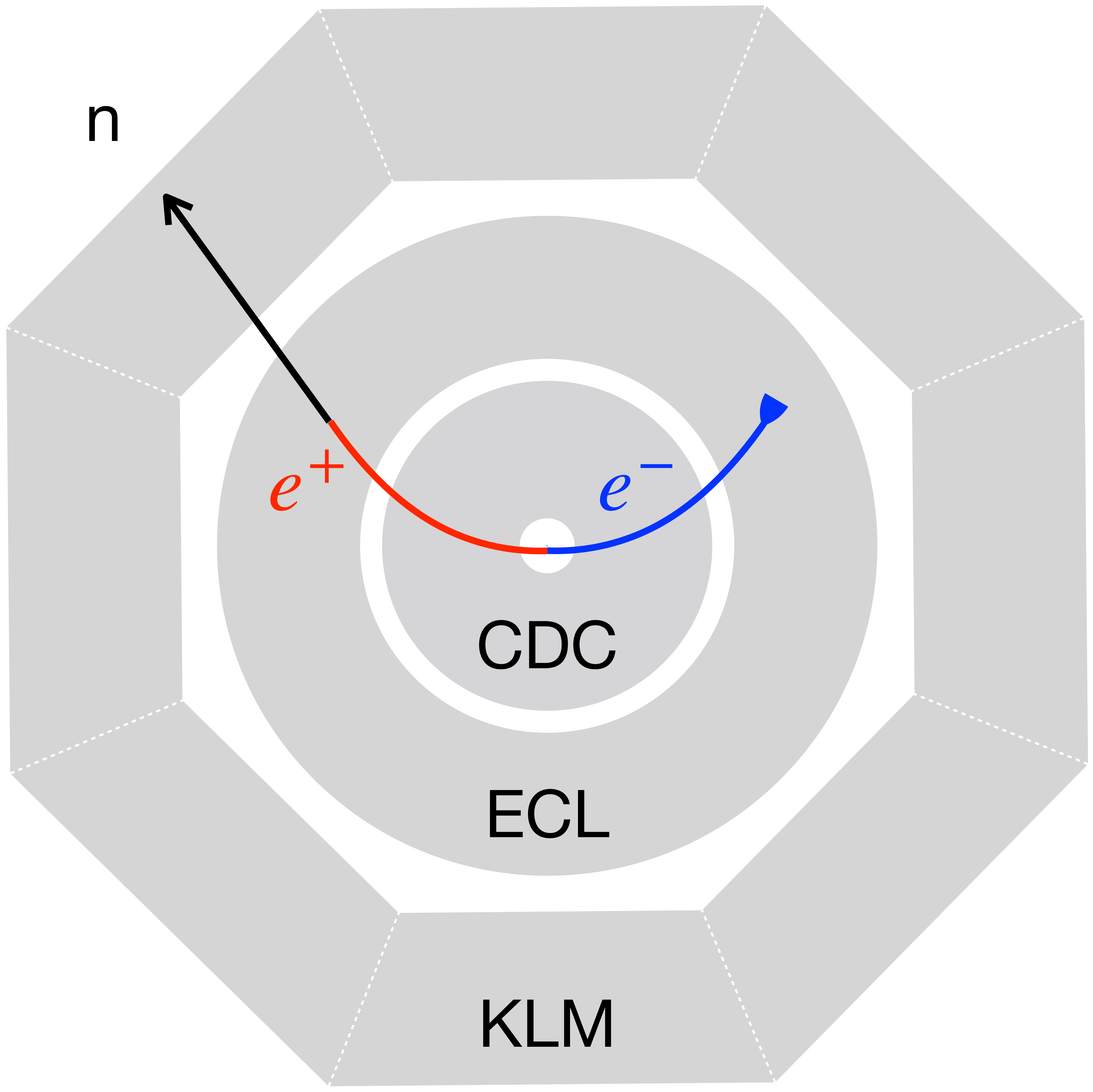
At least 1 neutron with energy > 3 GeV

Energy deposition in ECL < 5%



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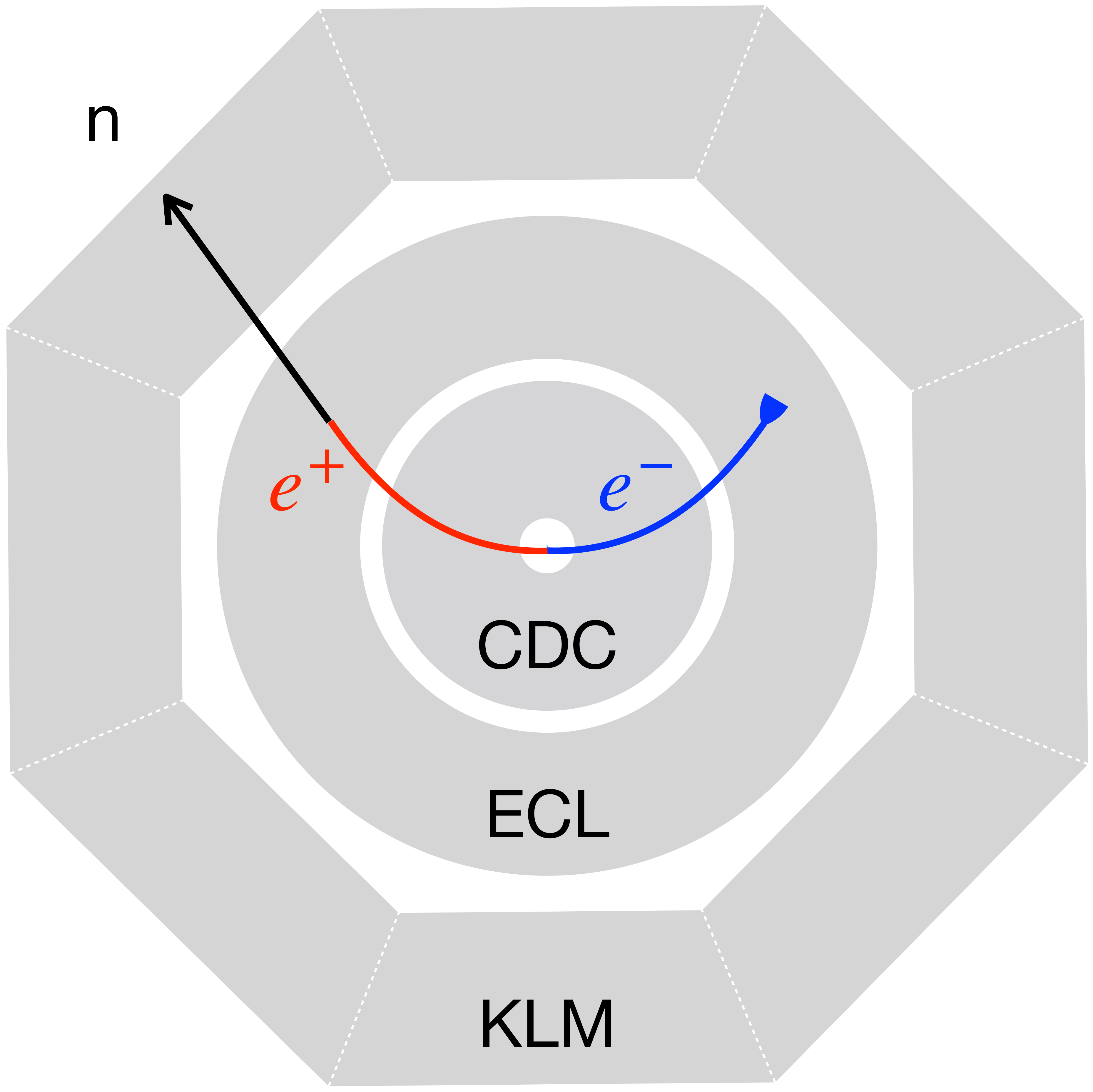
Veto $p/\pi^{\pm}$ with momentum > 0.6 GeV (either deposit energy in ECL or produce tracks in KLM)



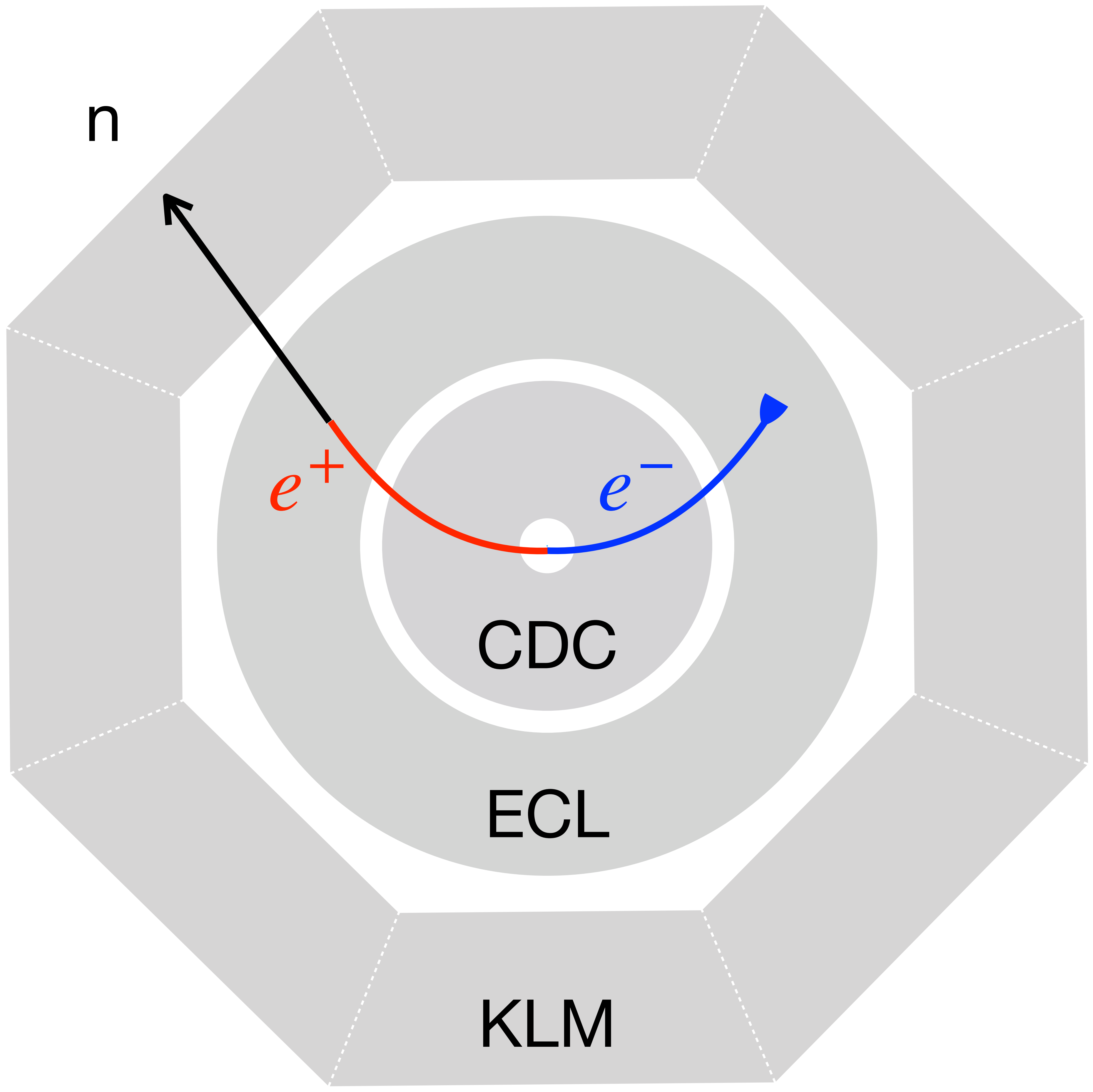
Selection in GEANT4 simulation

At least 1 neutron with energy > 3 GeV

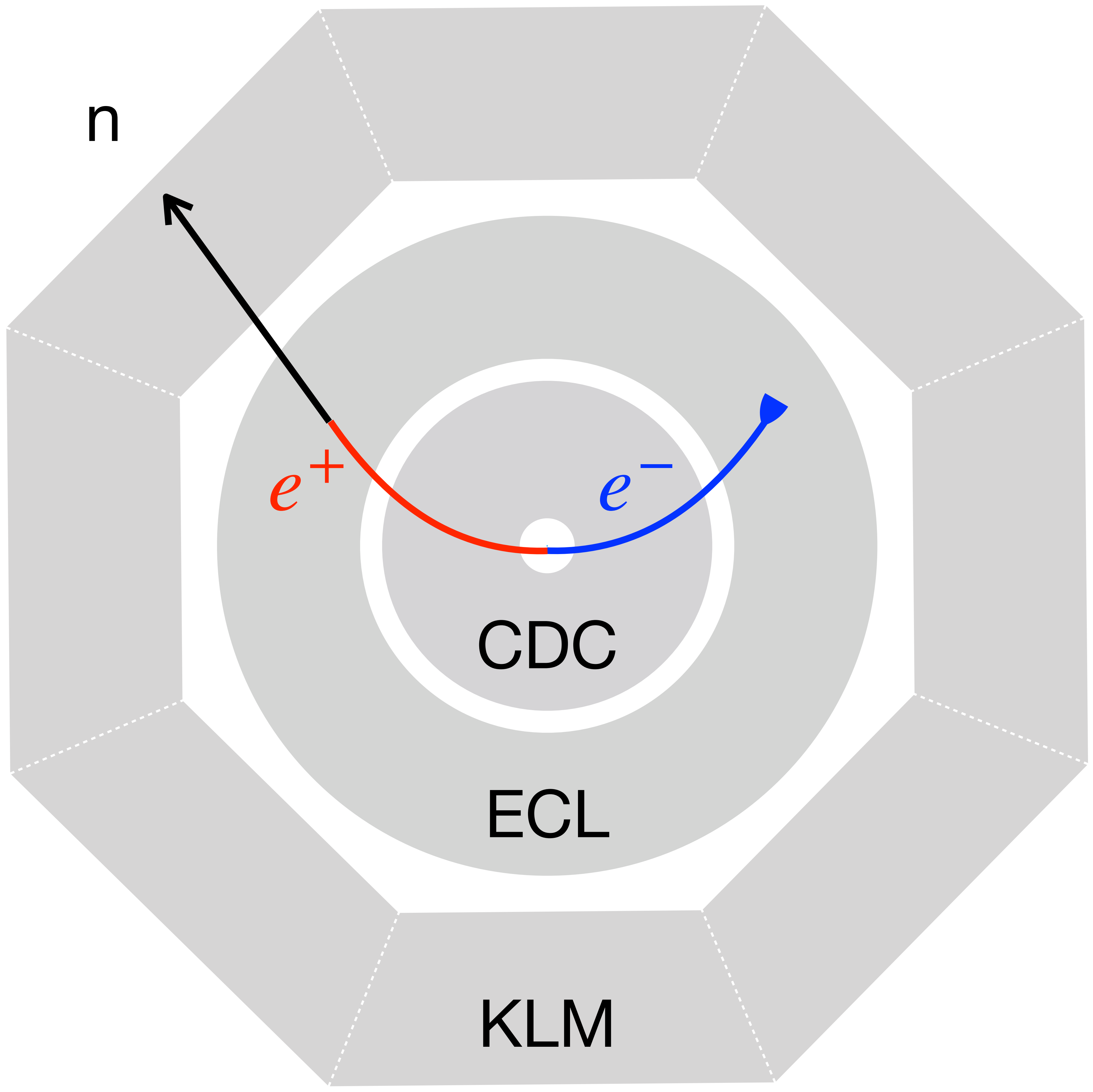
Energy deposition in ECL < 5%

Veto $p/\pi^{\pm}$ with momentum > 0.6 GeV (either deposit energy in ECL or produce tracks in KLM)

Count # of neutrons with K.E. > 280 MeV (hadronic shower threshold)



Probability for a neutron to penetrate ECL & KLM



Probability for a neutron to penetrate ECL & KLM

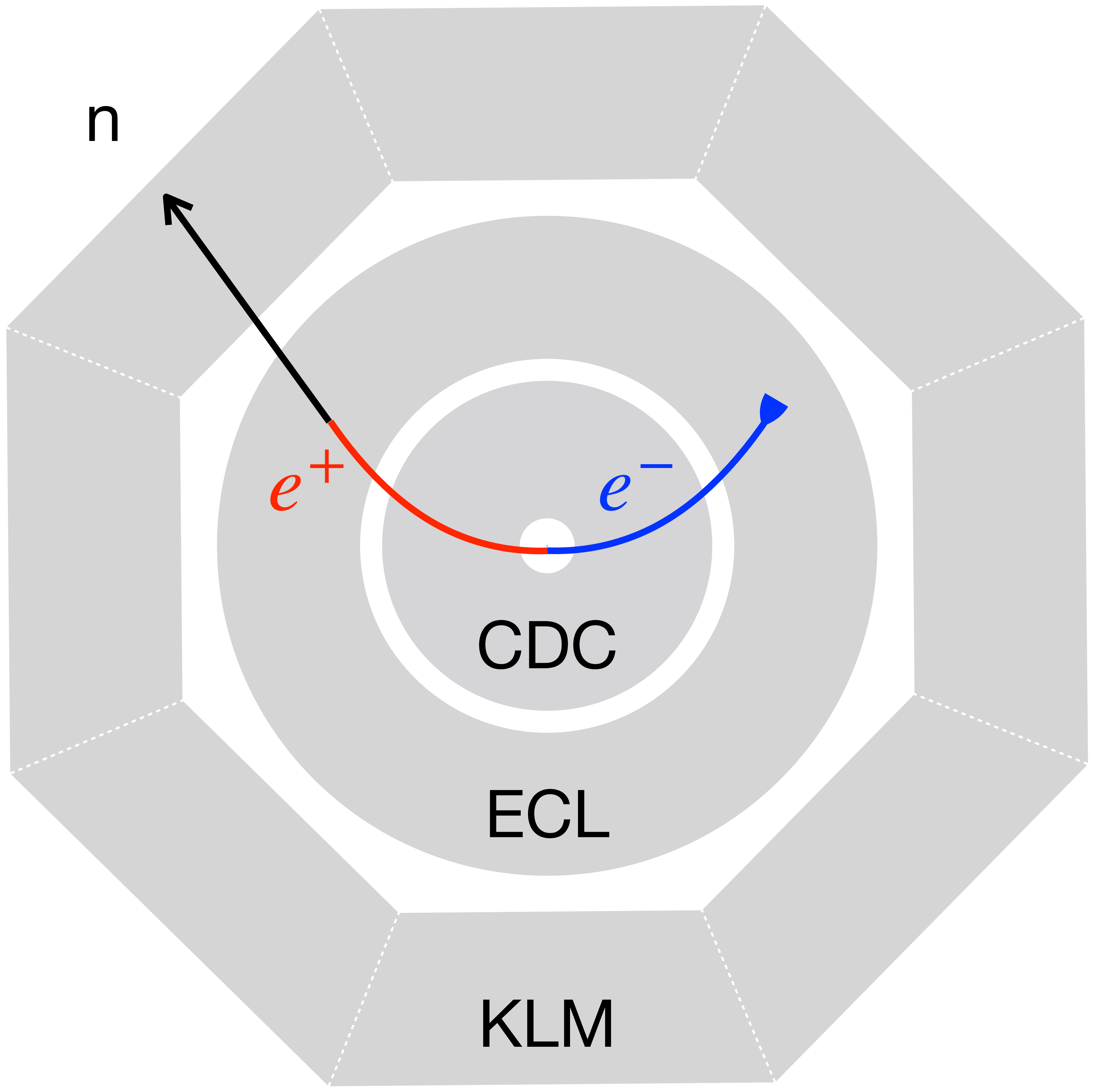
Prob to penetrate a target with length L

$$P = \exp(-L/\lambda_0)$$

λ_0 = hadronic interaction length

KLM has $\sim 3.9\,\lambda_0$

ECL has $\sim 0.8\,\lambda_0$



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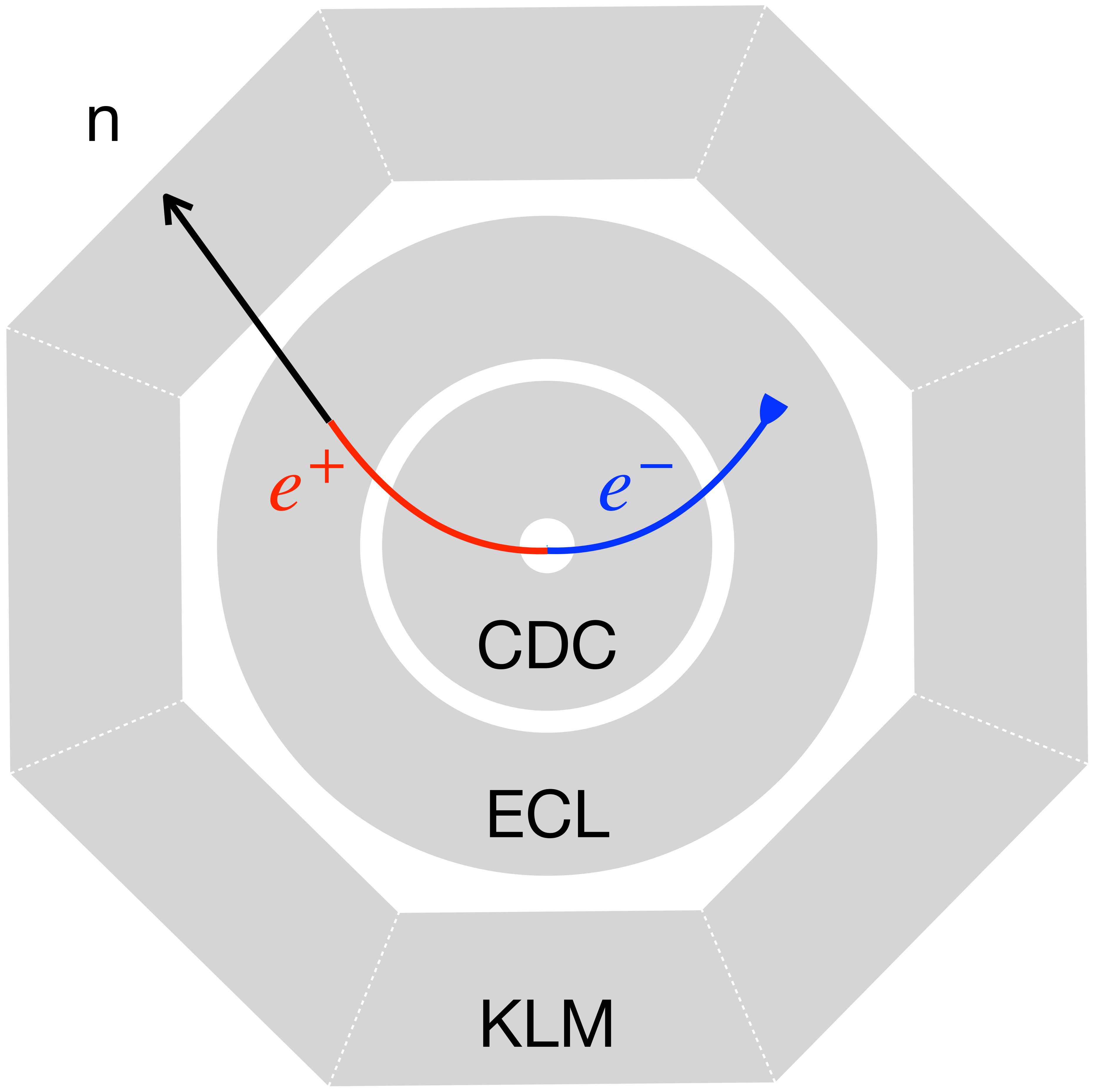

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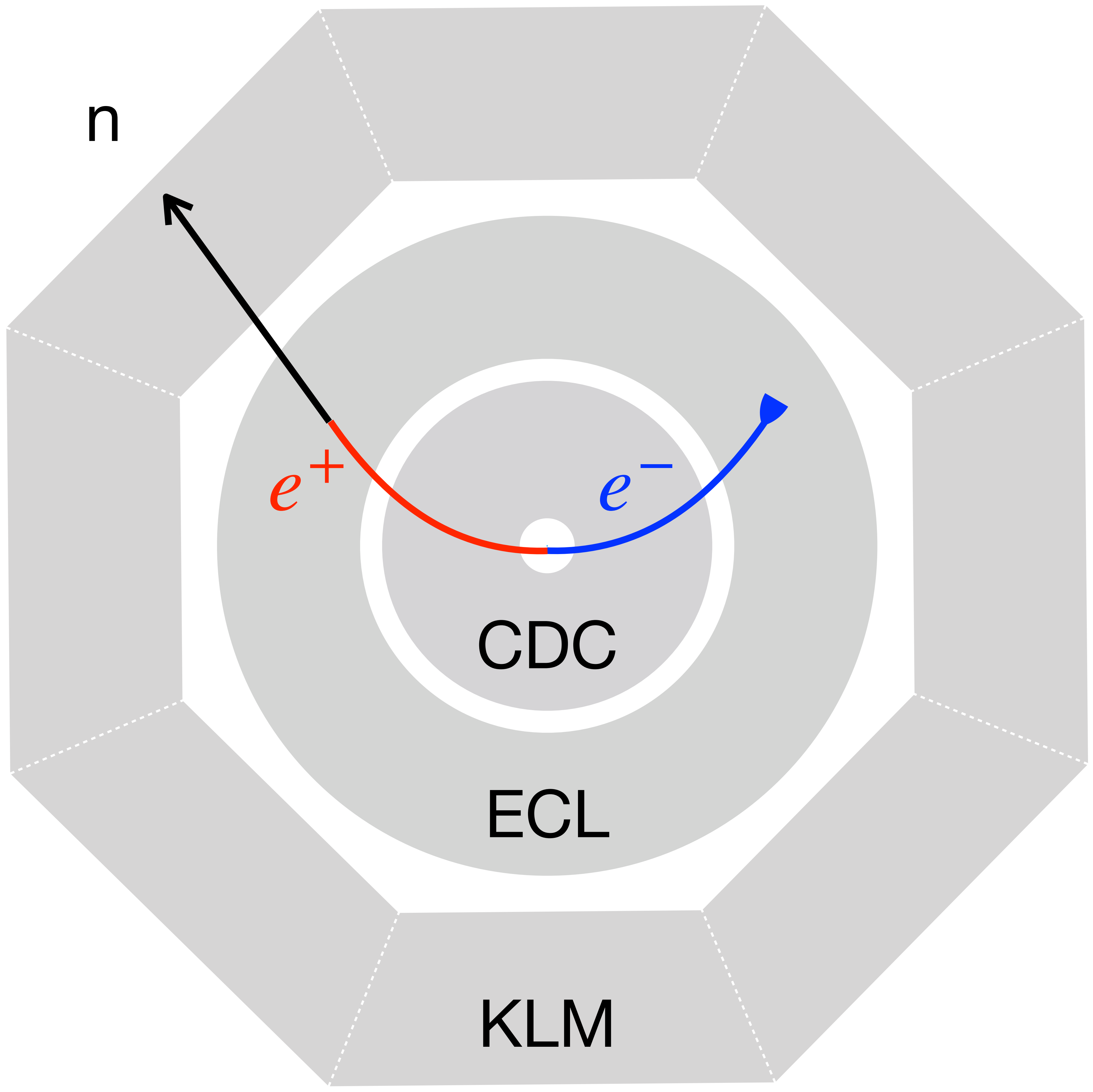
Prob to penetrate ECL & KLM is about 1%

about 81 neutron background in total



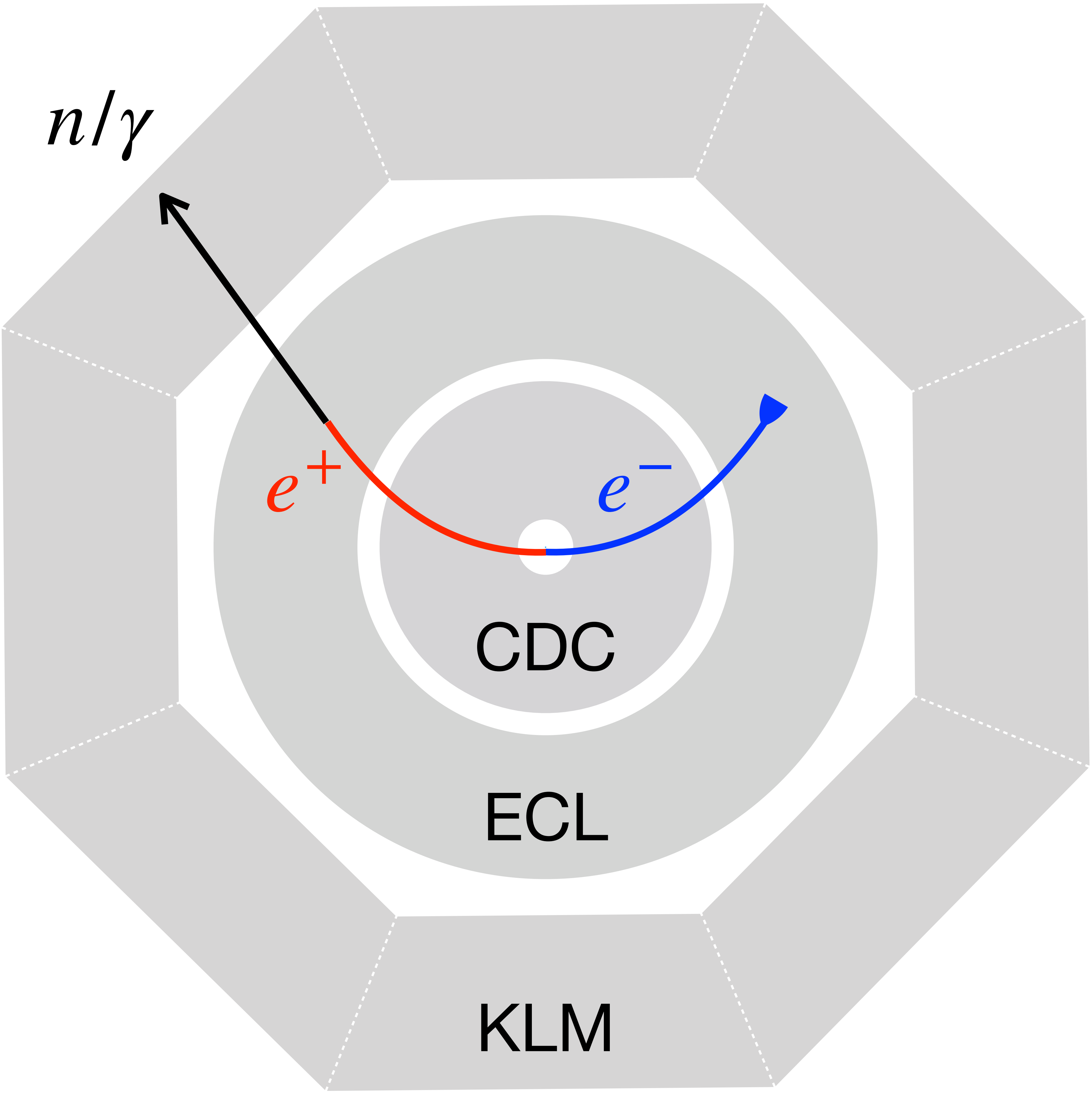
Summary on background estimation

BG: e^+ + ECL $\rightarrow \gamma/n$ which escape detection

Use KLM to veto such BG

- photon BG events: ~ 13
- neutron BG events: ~ 81

[Liang, ZL, Yang, 2212.04252]



3 Sensitivity on invisible dark photon

Invisible dark photon

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

dark photon A'_μ

suppressed coupling ϵ to SM fermion

gauge coupling to hidden fermion χ: $g_\chi \gg e\epsilon$

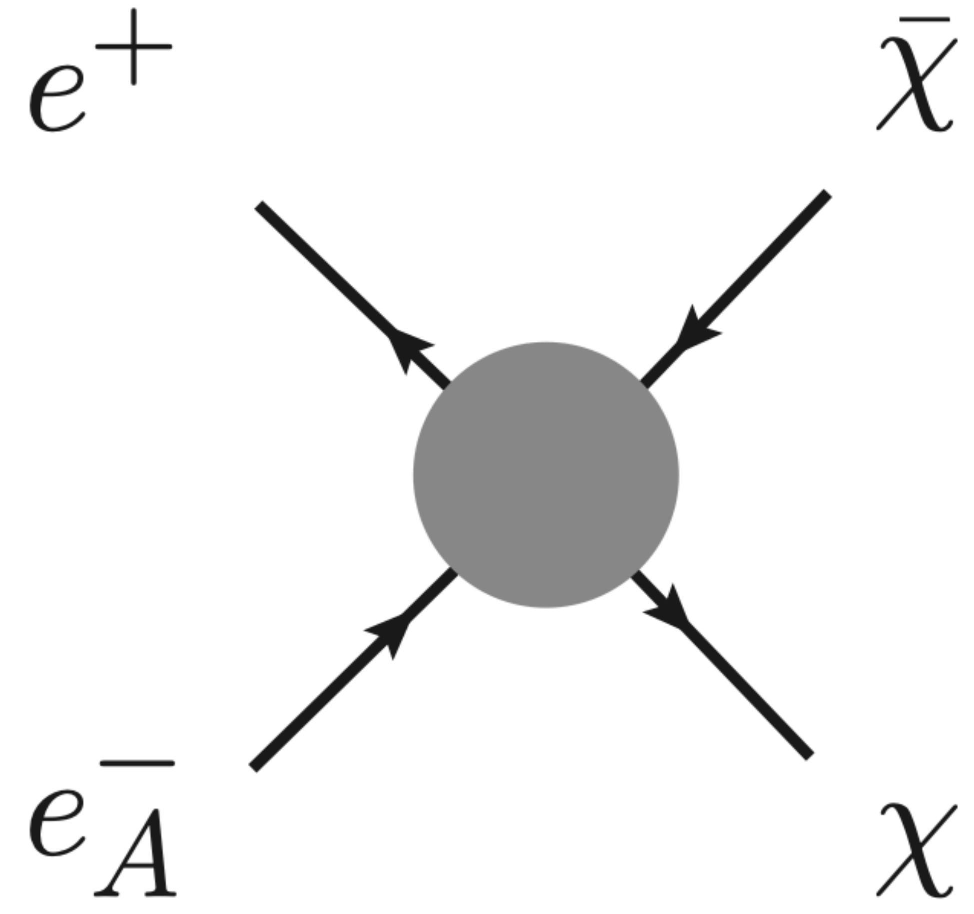
$m_{A'} = 3m_\chi$

Annihilation with atomic electrons

annihilation process: $e^+e^-_A \to A' \to \chi\bar{\chi}$

$$\sigma_{\text{ann}}(\sqrt{s}) = \frac{e^2\epsilon^2\alpha_D}{3}\frac{s+2m_\chi^2}{(s-m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2}\sqrt{1-\frac{4m_\chi^2}{s}}$$

$$\alpha_D = g_\chi^2/4\pi \qquad s = 2m_eE' + 2m_e^2 = 2m_eE_{A'}$$



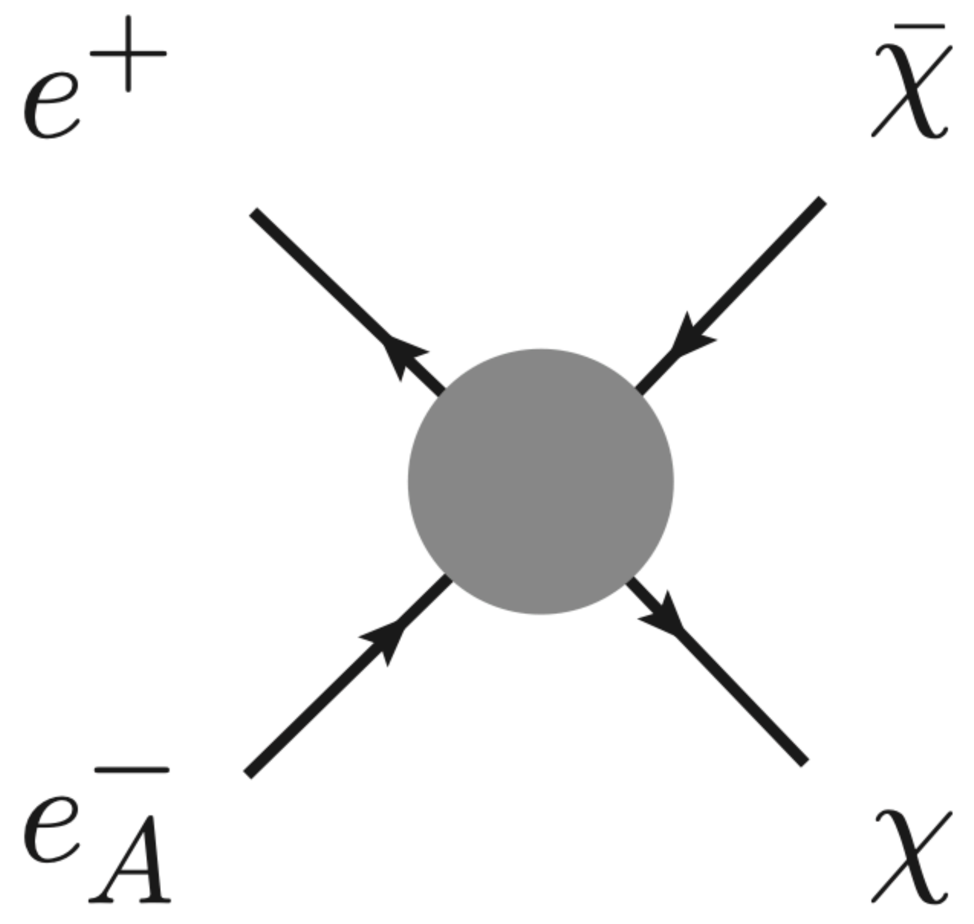
Annihilation with atomic electrons (continued)

$$N_{\text{ann}} = \mathscr{L} \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{d\sigma_B}{dE} \int_{0.95E}^{E+m_e} dE_{A'} n_e T_e(E' = E_{A'} - m_e, E, L_T) \sigma_{\text{ann}}(E_{A'})$$

$\frac{d\sigma_B}{dE}$ is the Bhabha xsec

n_e is the electron # density

$T_e(E', E, L_T)$ is the e^+ differential track length



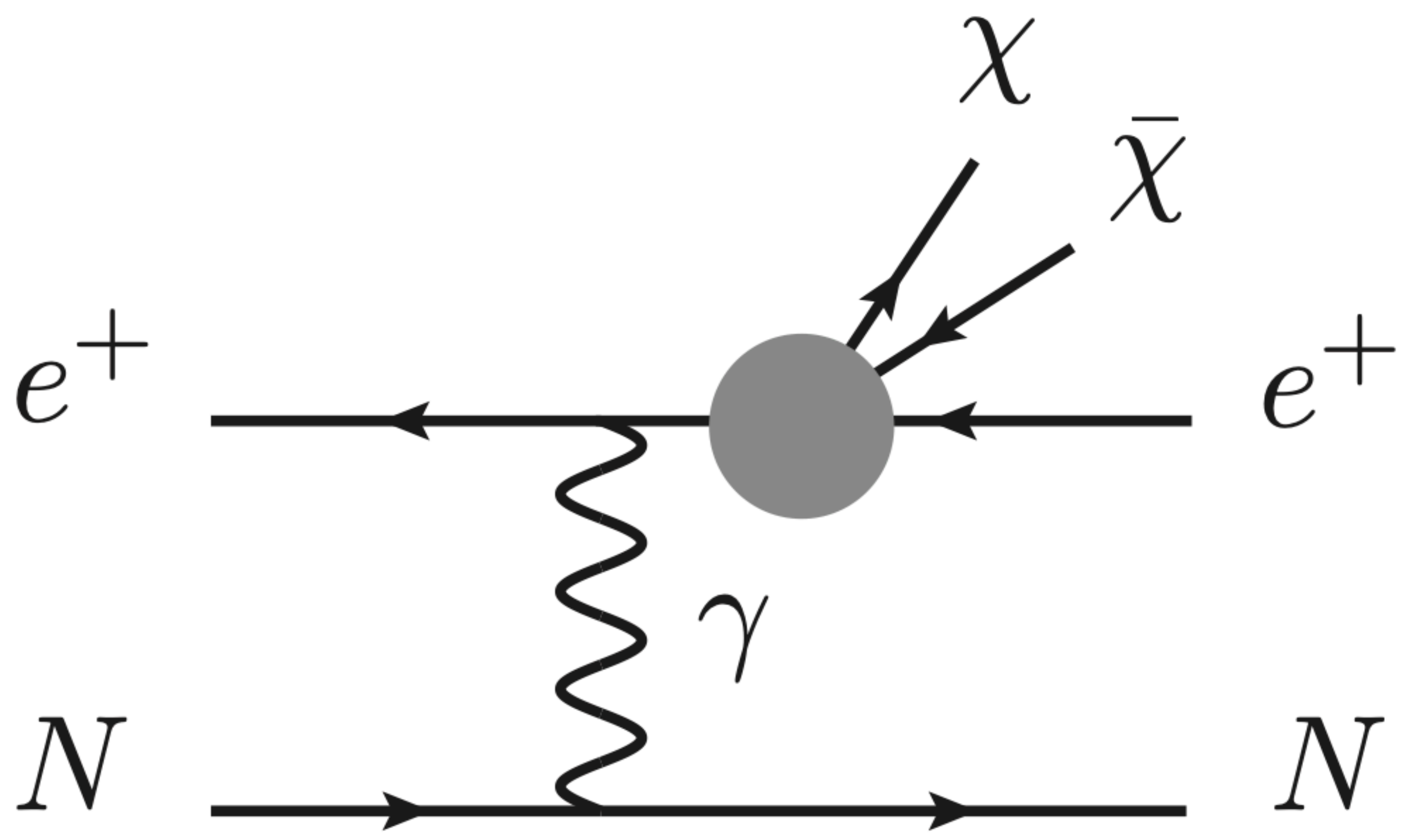
[Tsai & Whitis 1966] [Bjorken et al, 1988]

Bremsstrahlung with target nucleus

dominated by on-shell A' production

$$N_{\rm bre} = \mathscr{L} \int_{E_{\rm min}}^{E_{\rm max}} dE \frac{d\sigma_B}{dE} \int_{0.95E}^{E-m_e} dE_{A'} n_N T_e(E', E, X_0) \frac{d\sigma_{\rm bre}}{dE_{A'}}$$

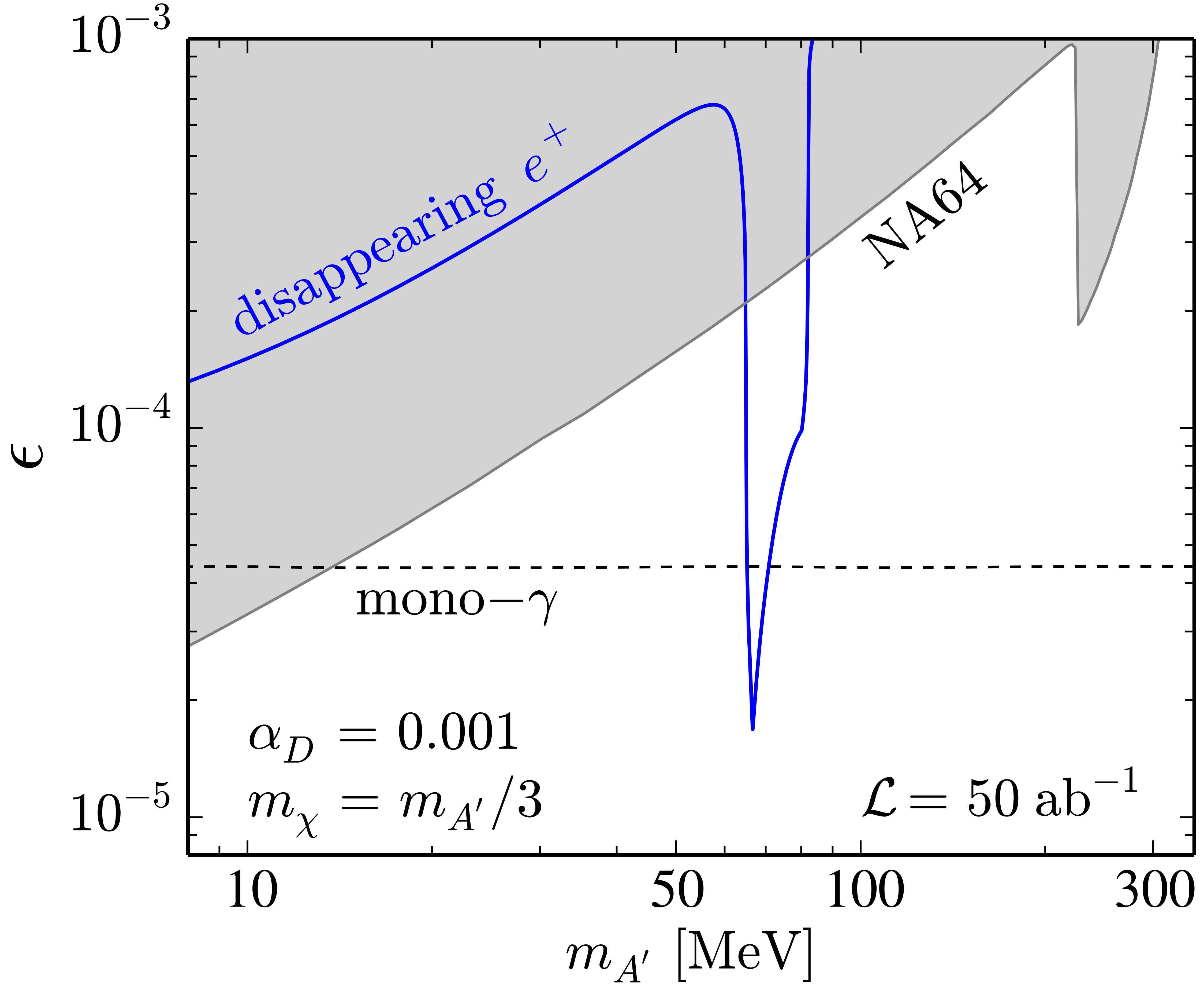
$\frac{d\sigma_{\rm bre}}{dE_{A'}}$ = xsec of on-shell produced A'



[Bjorken et al, 0906.0580]
[Gninenko et al, 171205706]
[Liu & Miller, 1705.01633]

Belle II sensitivity on invisible dark photon

[Liang, ZL, Yang, 2212.04252]



Summary

We propose a new dark matter channel at colliders, where one SM particle interacts with the detector to produce DM particles

The main background at Belle II are due to photon and neutron events that escape the detection

We find that this new DM channel @ Belle II can probe new parameter space of invisible dark photon, surpassing both the mono-photon channel and NA64

backup slides

Track length

For positrons with initial energy E to enter a target with thickness L_T, the differential track-length distribution as a function of the positron energy E' can be computed by [1, 2]

$$T_e(E', E, L_T) = X_0 \int_0^{L_T/X_0} I_e(E', E, t)dt, \quad (1)$$

where X_0 is the radiation length of the target. Here $I_e(E', E, t)$ is the energy distribution of E' at the depth tX_0, which can be computed iteratively such that $I_e = \sum_i I_e^{(i)}$ where $I_e^{(i)}$ denotes the i-th generation positrons [3]. We adopt the analytical model of Ref. [3] up to second-generation positrons, which are found to be in good agreement with simulations in Ref. [1]. The contributions from the first two generations are [3]

$$I_e^{(1)}(E', E, t) = \frac{1}{E}\frac{(\ln(1/v))^{b_1 t - 1}}{\Gamma(b_1 t)}, \quad (2)$$

$$I_e^{(2)}(E', E, t) = \frac{2}{E}\int_v^1 \frac{dx}{x^2}\frac{1}{b_2 + b_1\ln(1-x)}\left[\frac{(1-x)^{b_1 t} - (1-v/x)^{b_1 t}}{b_1 \ln\left[(x-x^2)/(x-v)\right]} + \frac{e^{-b_2 t} - (1-v/x)^{b_1 t}}{b_2 + b_1\ln(1-v/x)}\right], \quad (3)$$

where $b_1 = 4/3$, $b_2 = 7/9$, $v = E'/E$.

[1] 1802.03794
[2] 1807.05884
[3] Tsai & Whitis 1966

xsec of on-shell dark photon

where n_N is the number density of I (or Cs). Here $d\sigma_{\rm bre}/dE_{A'}$ is the differential cross section of the on-shell produced A' [71–73],

$$\frac{d\sigma_{\rm bre}}{dE_{A'}} = (\phi_I + \phi_{\rm Cs})\frac{4\alpha^3\epsilon^2}{E'}\frac{x(1-x+x^2/3)}{m_{A'}^2(1-x)+m_e^2x^2}, \qquad (13)$$

where $x \equiv E_{A'}/E'$, and ϕ_N denotes the effective flux of photons from nucleus N [71]:

$$\phi_N = \int_{t_{\rm min}}^{t_{\rm max}} dt \frac{t-t_{\rm min}}{t^2}\left[\frac{Za^2t}{(1+a^2t)(1+t/d)}\right]^2, \qquad (14)$$

with $t_{\rm min} = (m_{A'}^2/2E')^2$, $t_{\rm max} = m_{A'}^2 + m_e^2$, $a = 111m_e^{-1}Z^{-1/3}$, and $d = 0.164A^{-2/3}$ GeV^2. We use $Z = 53\,(55)$ and $A = 127\,(133)$ for I (Cs). Here we only consider the dominant elastic form factor.

[71] Bjorken et al, 0906.0580
[72] Gninenko et al, 171205706
[73] Liu & Miller, 1705.01633