New channel to search for dark matter at Belle II

刘佐伟（南京大学）

2023年紫金山暗物质研讨会

2023 年 12 月 30-31 日，南京师范大学

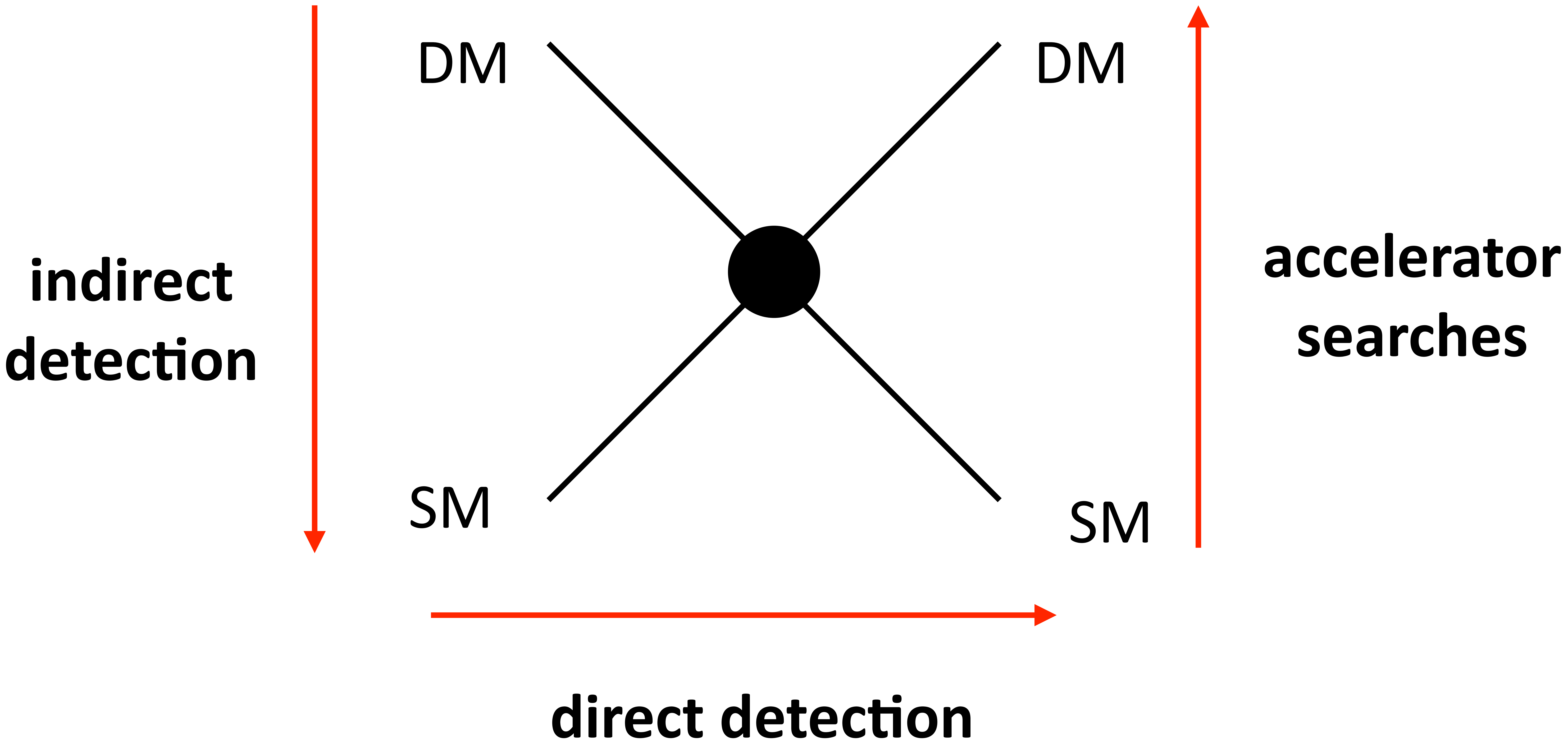
Outline

1. New dark matter channel @ Belle II
2. Standard model backgrounds
3. Sensitivity on invisible dark photon models

in collaboration with Jinhan Liang and Lan Yang [2212.04252]

1 New dark matter channel @ Belle II

Searches for dark matter in particle physics experiments

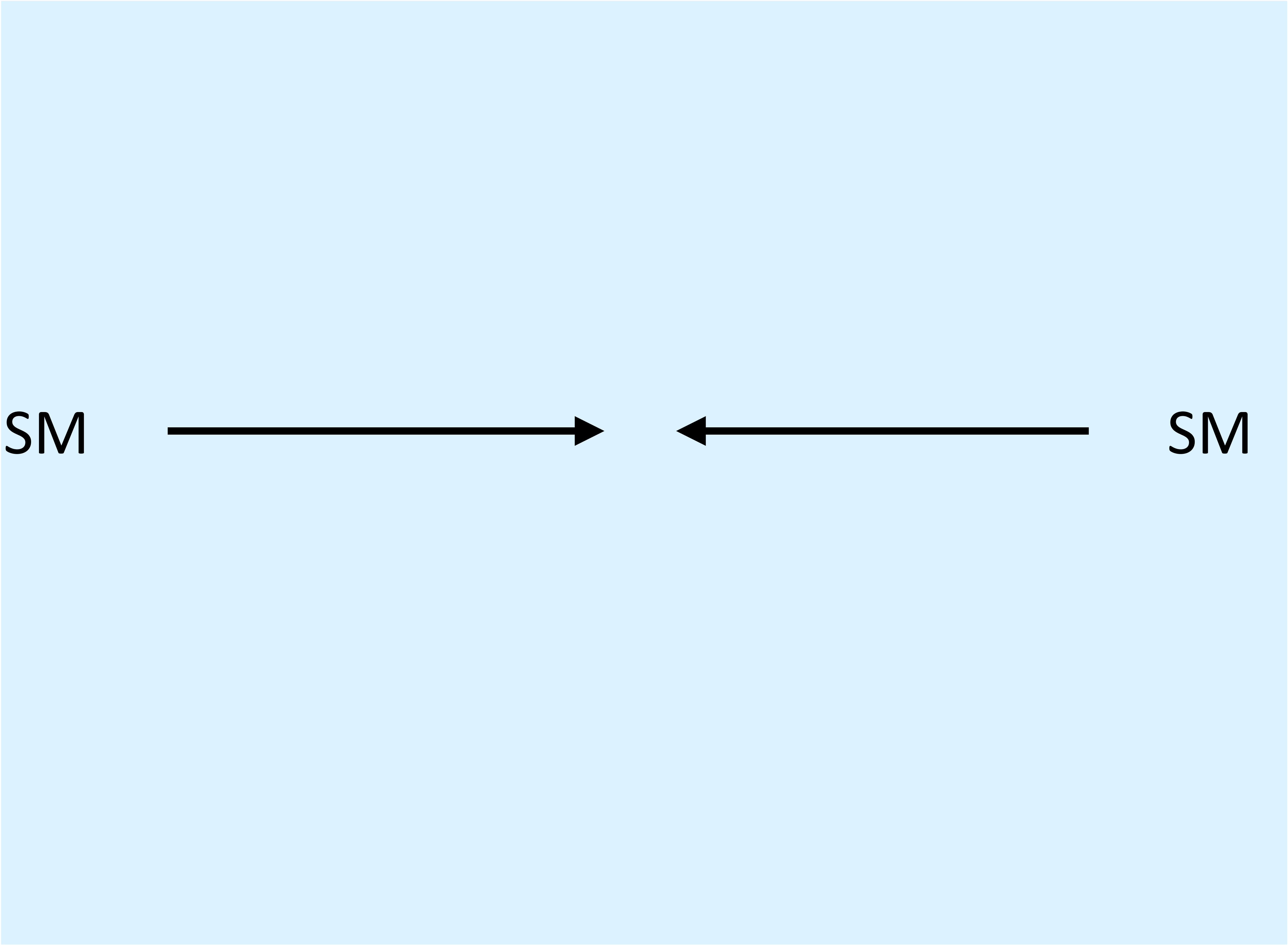


Previous dark matter detection channels at colliders

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

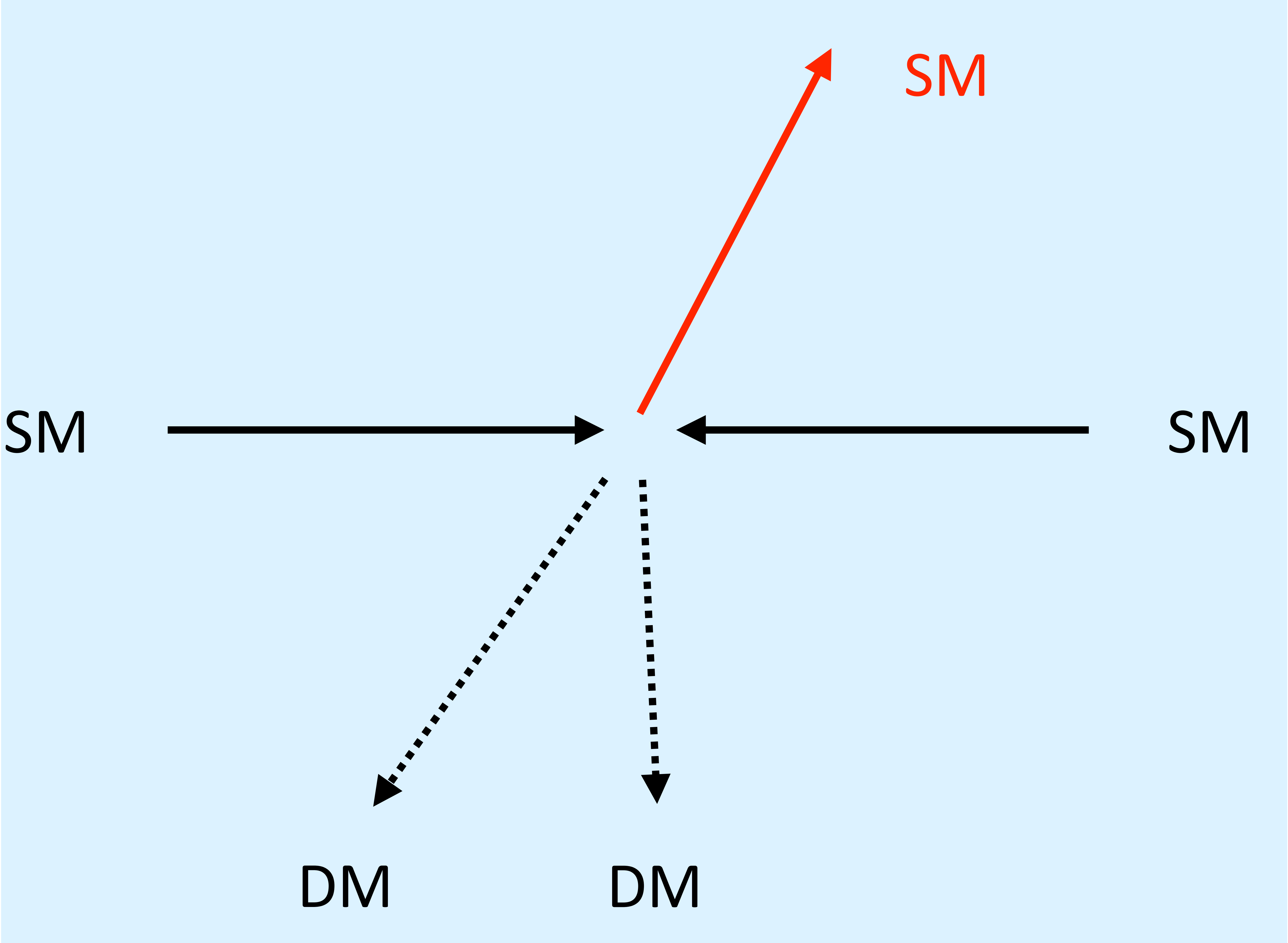
Previous dark matter detection channels at colliders

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



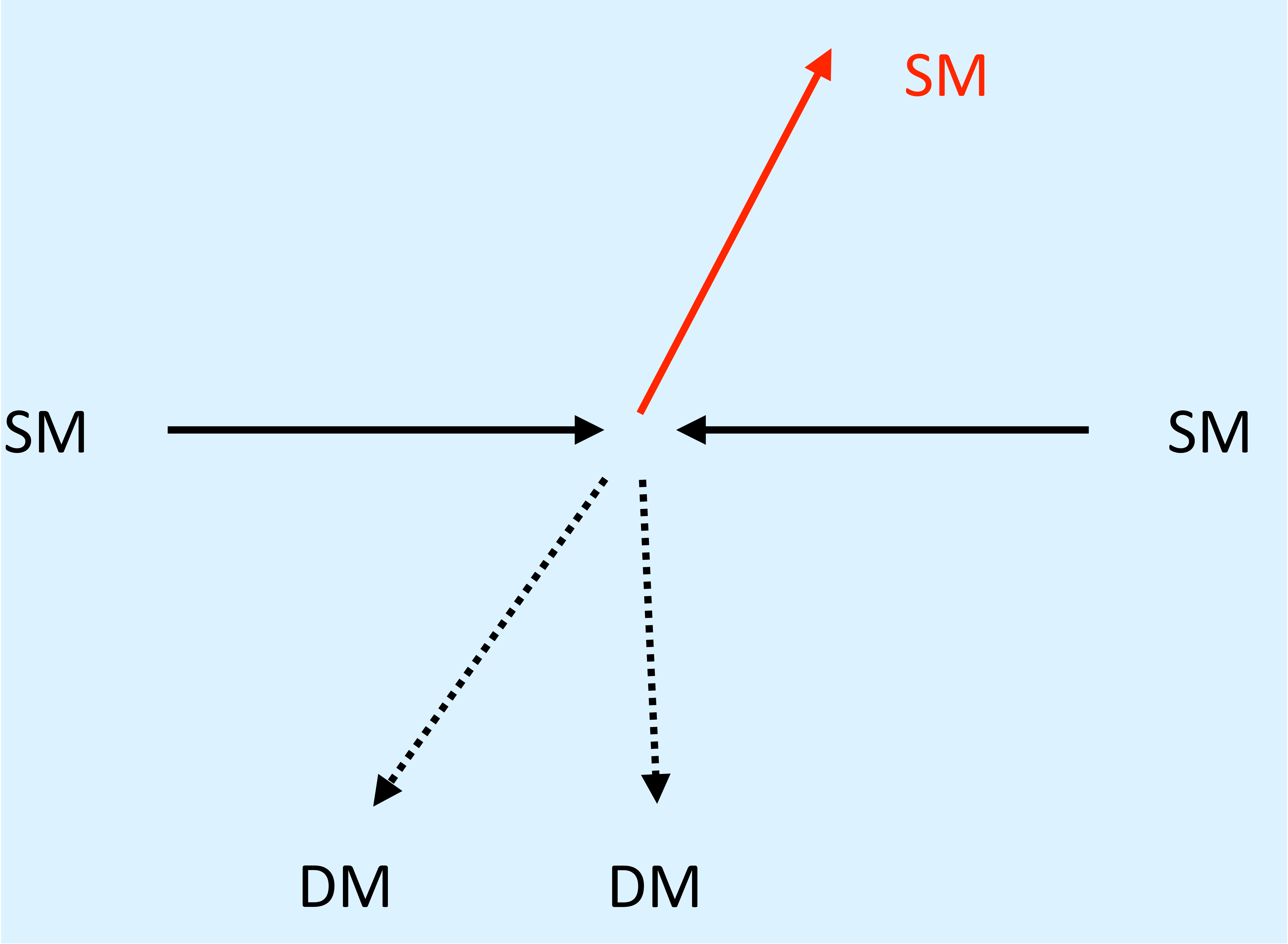
Previous dark matter detection channels at colliders

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



Previous dark matter detection channels at colliders

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

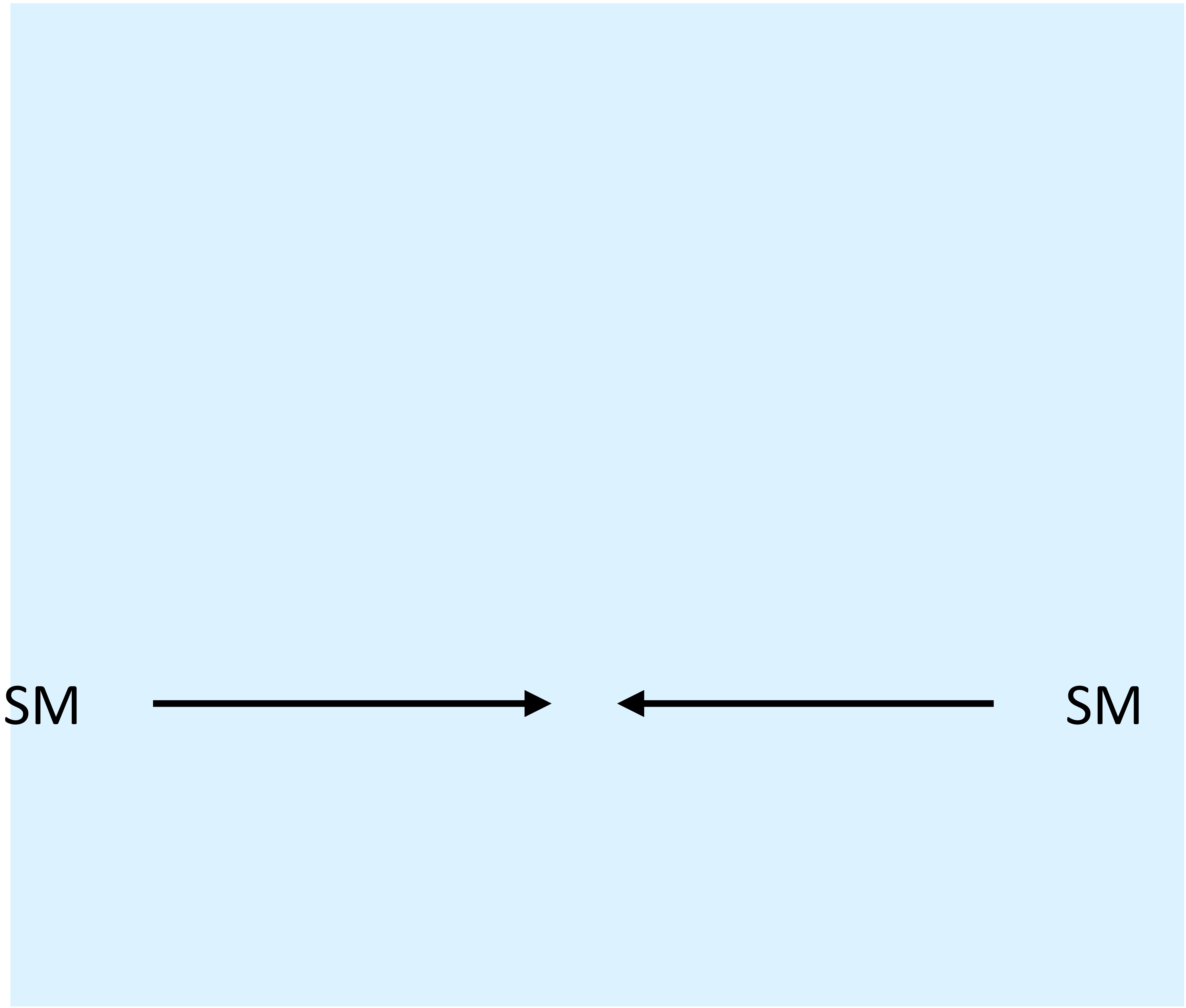


Different mono-X channels

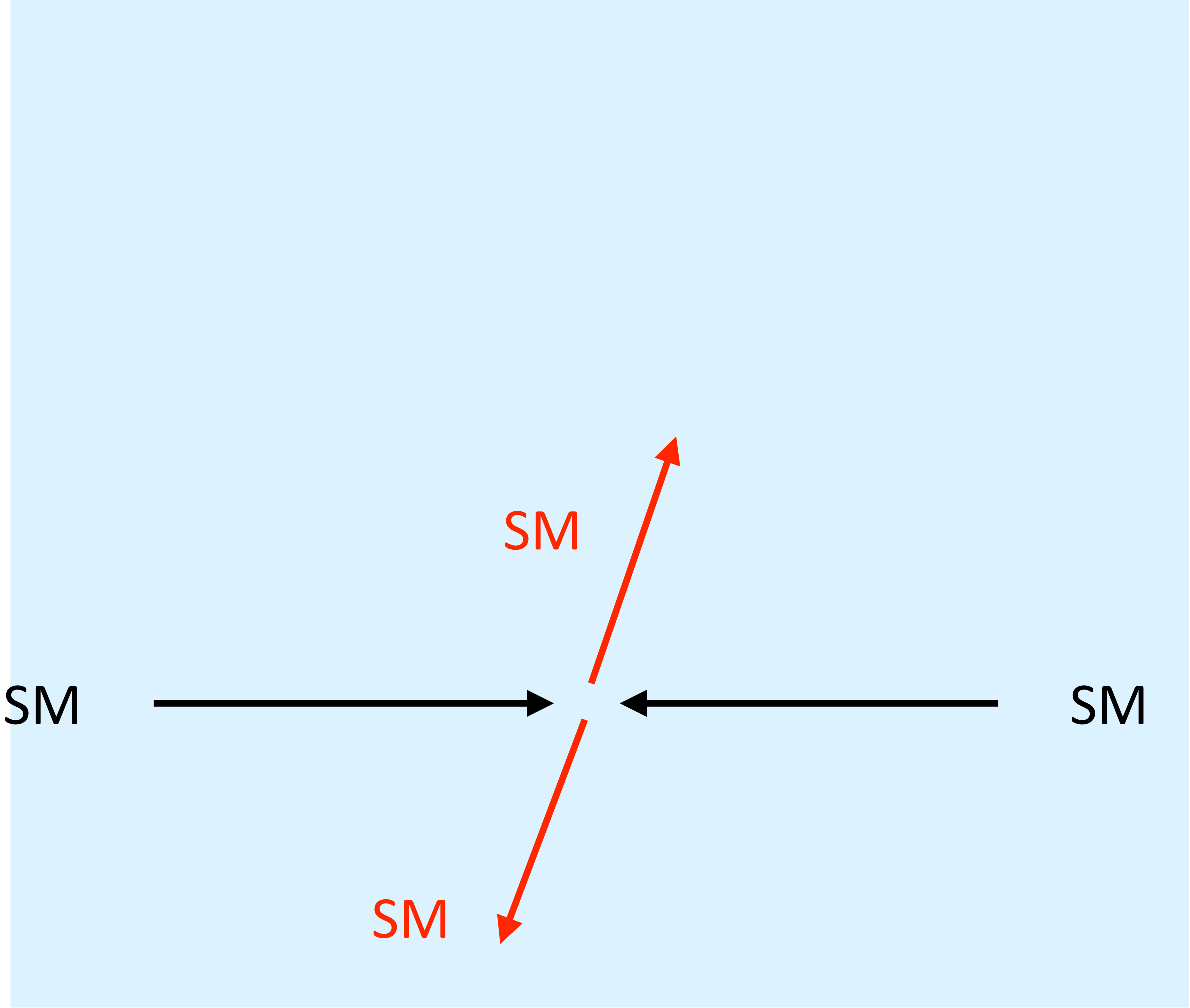
- mono-photon
- mono-jet
- mono-Higgs
- mono-Z
- mono-top

We propose a new dark matter channel at colliders

We propose a new dark matter channel at colliders

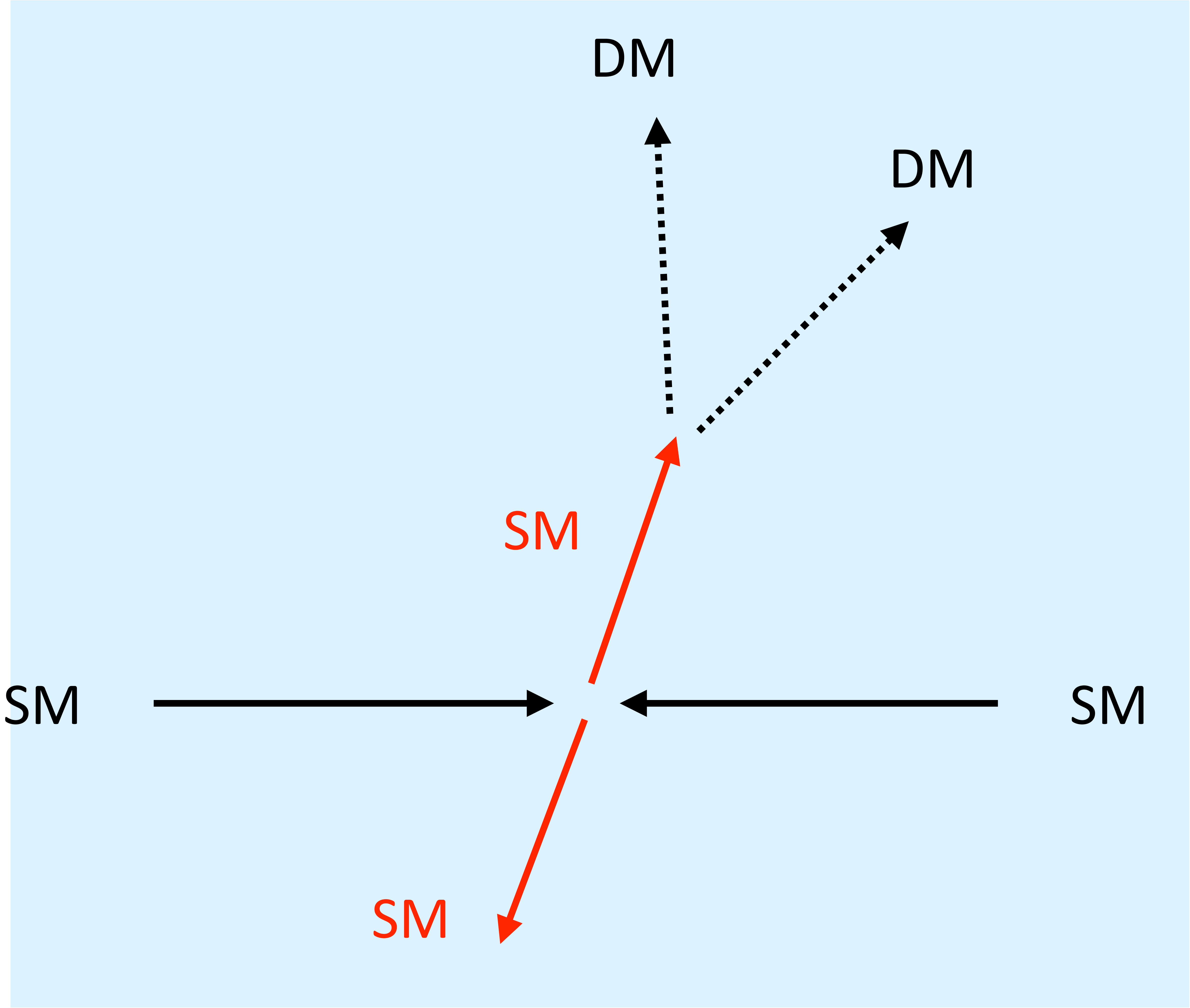


We propose a new dark matter channel at colliders



A pair of SM particles
produced at the primary vertex

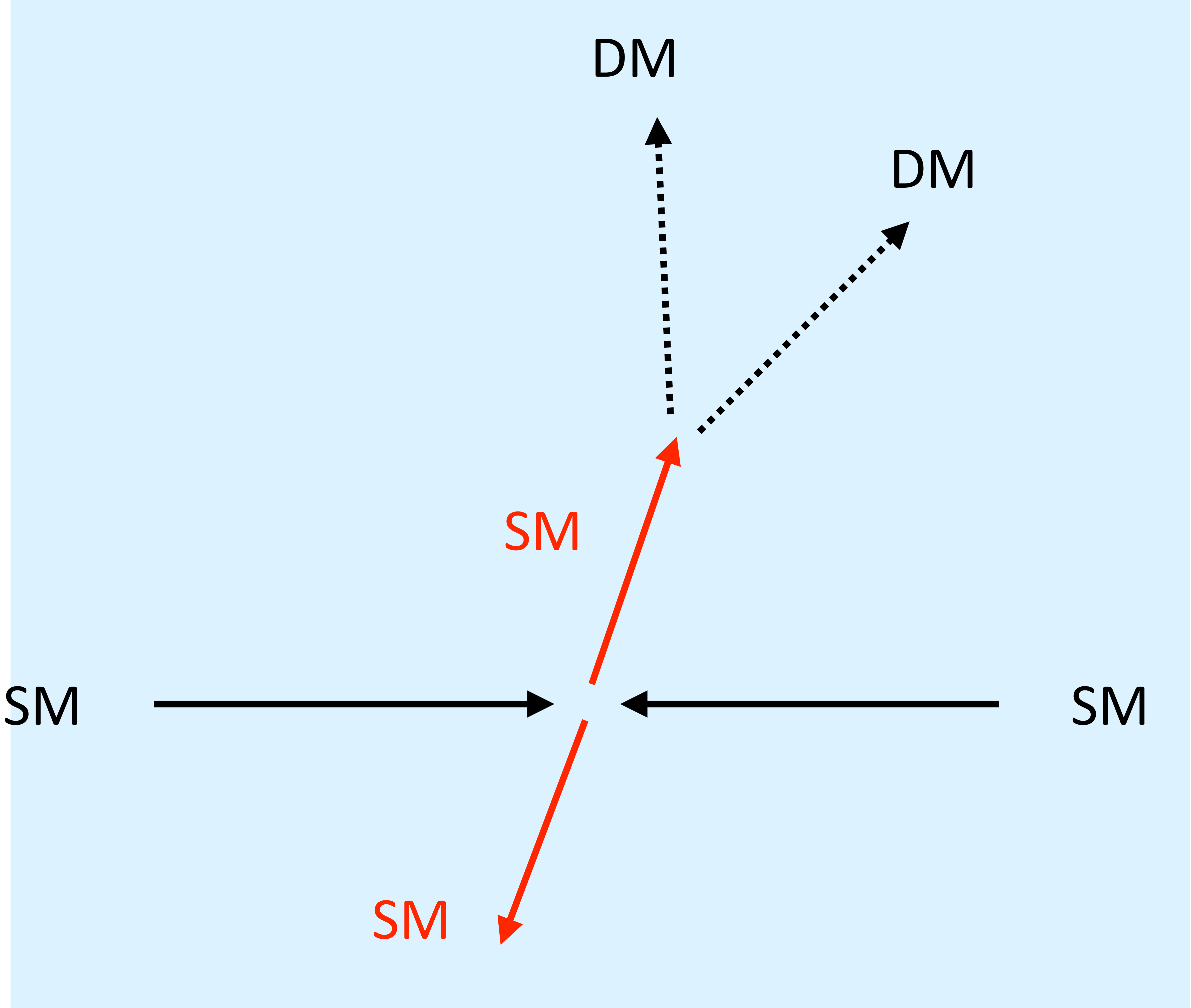
We propose a new dark matter channel at colliders



One SM particle interacts with the detector to produce a pair of DM particles

A pair of SM particles produced at the primary vertex

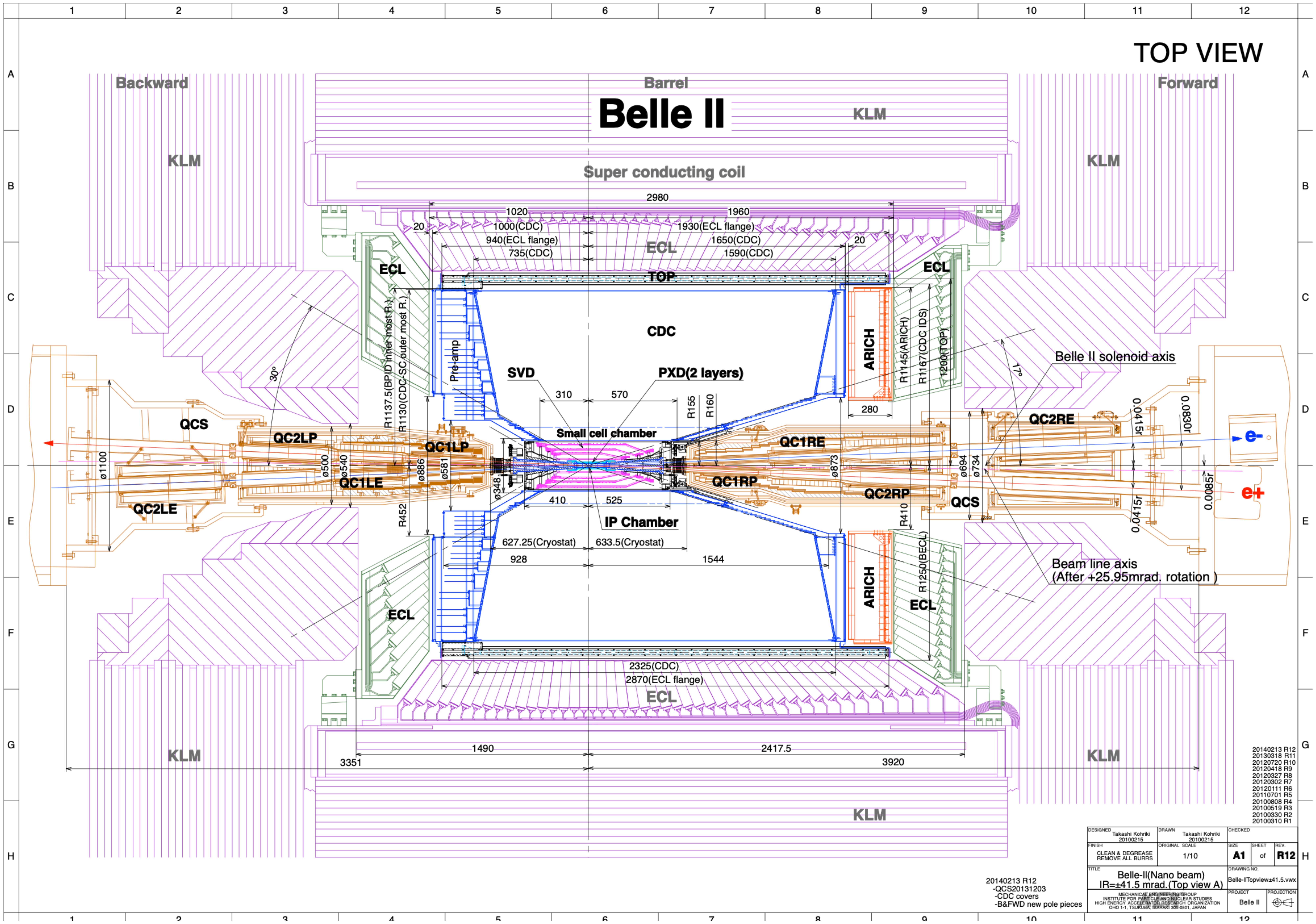
We propose a new dark matter channel at colliders

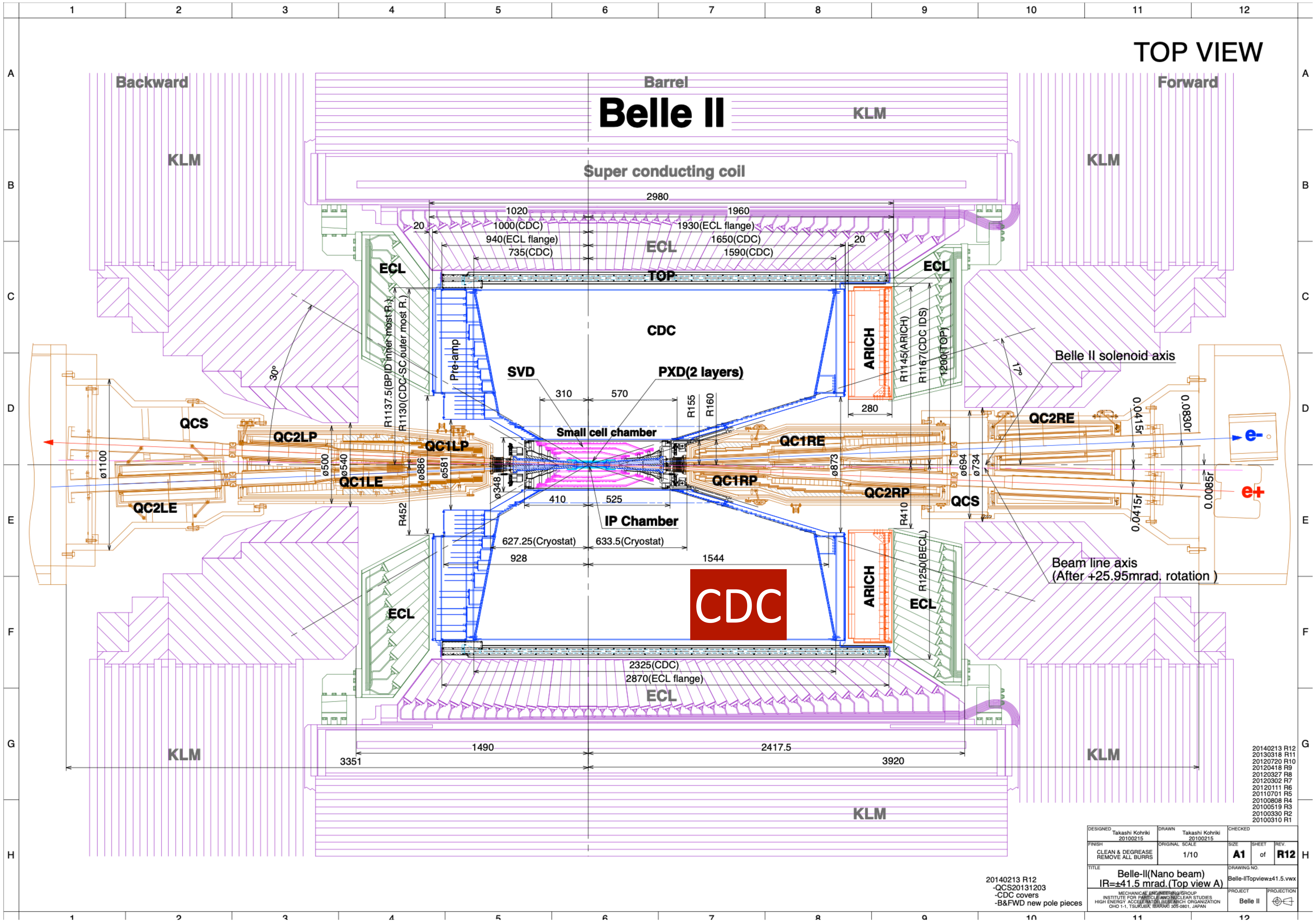


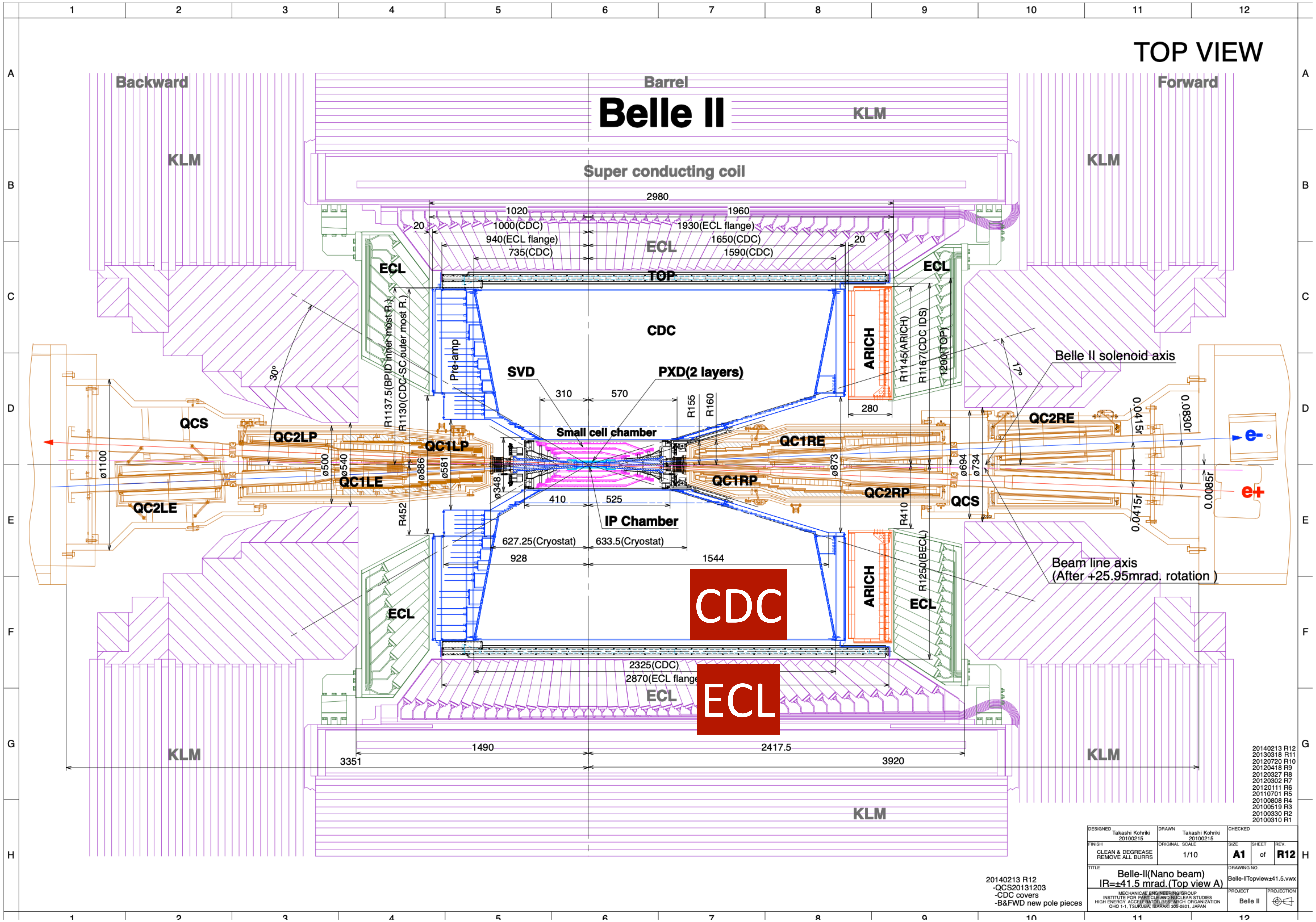
One SM particle interacts with the detector to produce a pair of DM particles

A pair of SM particles produced at the primary vertex

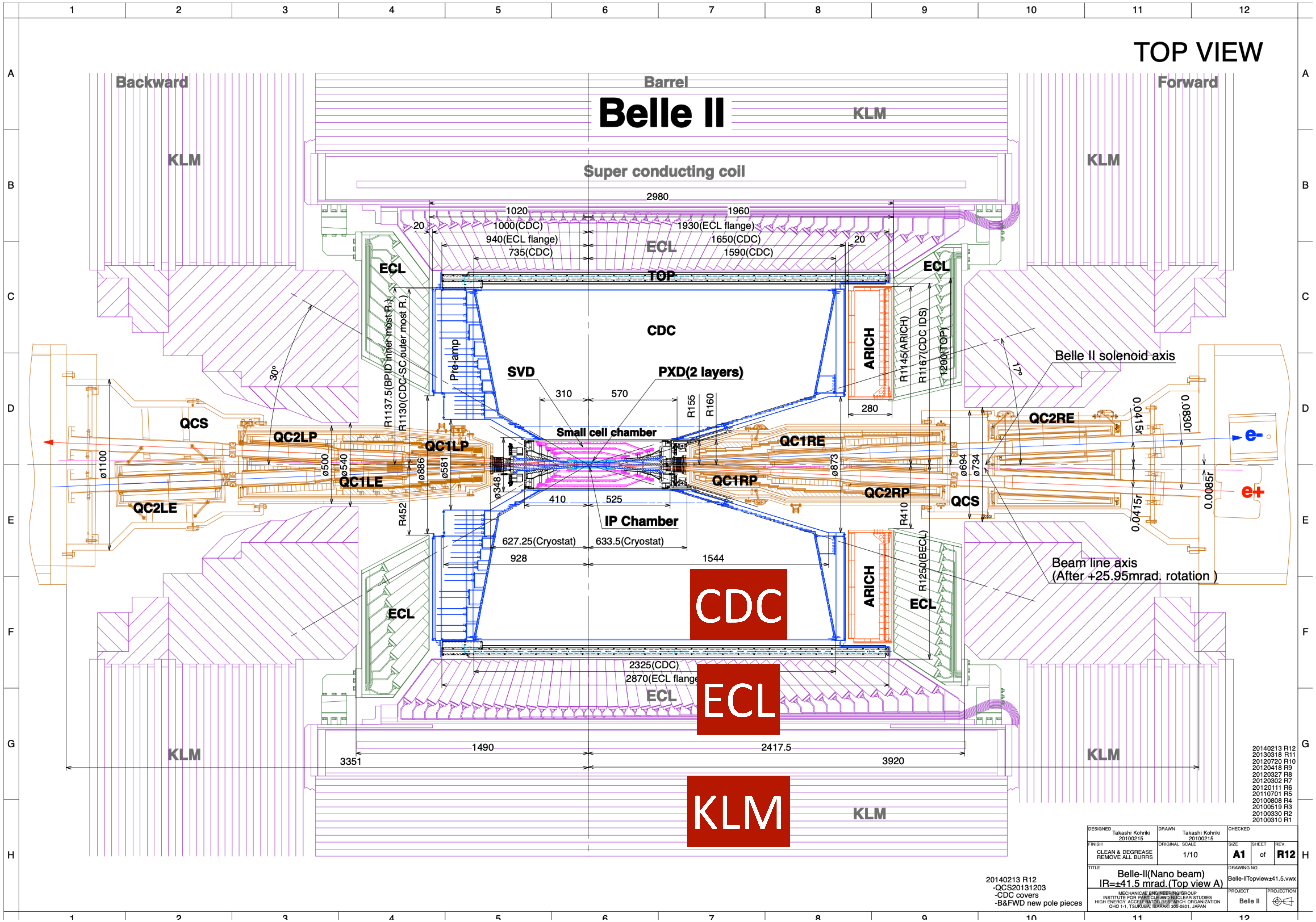
fixed target in collider


TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
ARICH
SVD
PXD(2 layers)
Pre-amp
Small cell chamber
IP Chamber
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RE
QC2RP
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
2980
1020
1960
1000(CDC)
1930(ECL flange)
940(ECL flange)
1650(CDC)
735(CDC)
1590(CDC)
20
310
570
410
525
627.25(Cryostat)
633.5(Cryostat)
928
1544
2325(CDC)
2870(ECL flange)
1490
2417.5
3351
3920
280
R1137.5(BPID inner most R.)
R1130(CDC-SC outer most R.)
R1145(ARICH)
R1167(CDC IDS)
1200(TOP)
R1250(BECL)
R155
R160
R452
R410
30°
17°
ø1100
ø500
ø540
ø886
ø581
ø348
ø873
ø694
ø734
0.0415r
0.0830r
0.0085r
20140213 R12
20130318 R11
20120720 R10
20120418 R9
20120327 R8
20120302 R7
20120111 R6
20110701 R5
20100808 R4
20100519 R3
20100330 R2
20100310 R1
20140213 R12
-QCS20131203
-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
SHEET of
REV. R12
TITLE Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)
DRAWING NO. Belle-IITopview±41.5.vwx
PROJECT Belle II
PROJECTION
MECHANICAL ENGINEERING GROUP
INSTITUTE FOR PARTICLE AND NUCLEAR STUDIES
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION
OHO 1-1, TSUKUBA, IBARAKI 305-0801, JAPAN


TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
ARICH
SVD
PXD(2 layers)
Small cell chamber
IP Chamber
Pre-amp
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RE
QC2RP
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
2980
1020
1960
1000(CDC)
1930(ECL flange)
940(ECL flange)
1650(CDC)
735(CDC)
1590(CDC)
2325(CDC)
2870(ECL flange)
627.25(Cryostat)
633.5(Cryostat)
928
1544
1490
2417.5
3351
3920
R1137.5(BPID inner most R.)
R1130(CDC-SC outer most R.)
R1145(ARICH)
R1167(CDC IDS)
R1200(TOP)
R1250(BECL)
R452
R410
R155
R160
17°
30°
CDC
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)
Takashi Kohriki
1/10
A1
R12
Belle II
20140213 R12
-QCS20131203
-CDC covers
-B&FWD new pole pieces



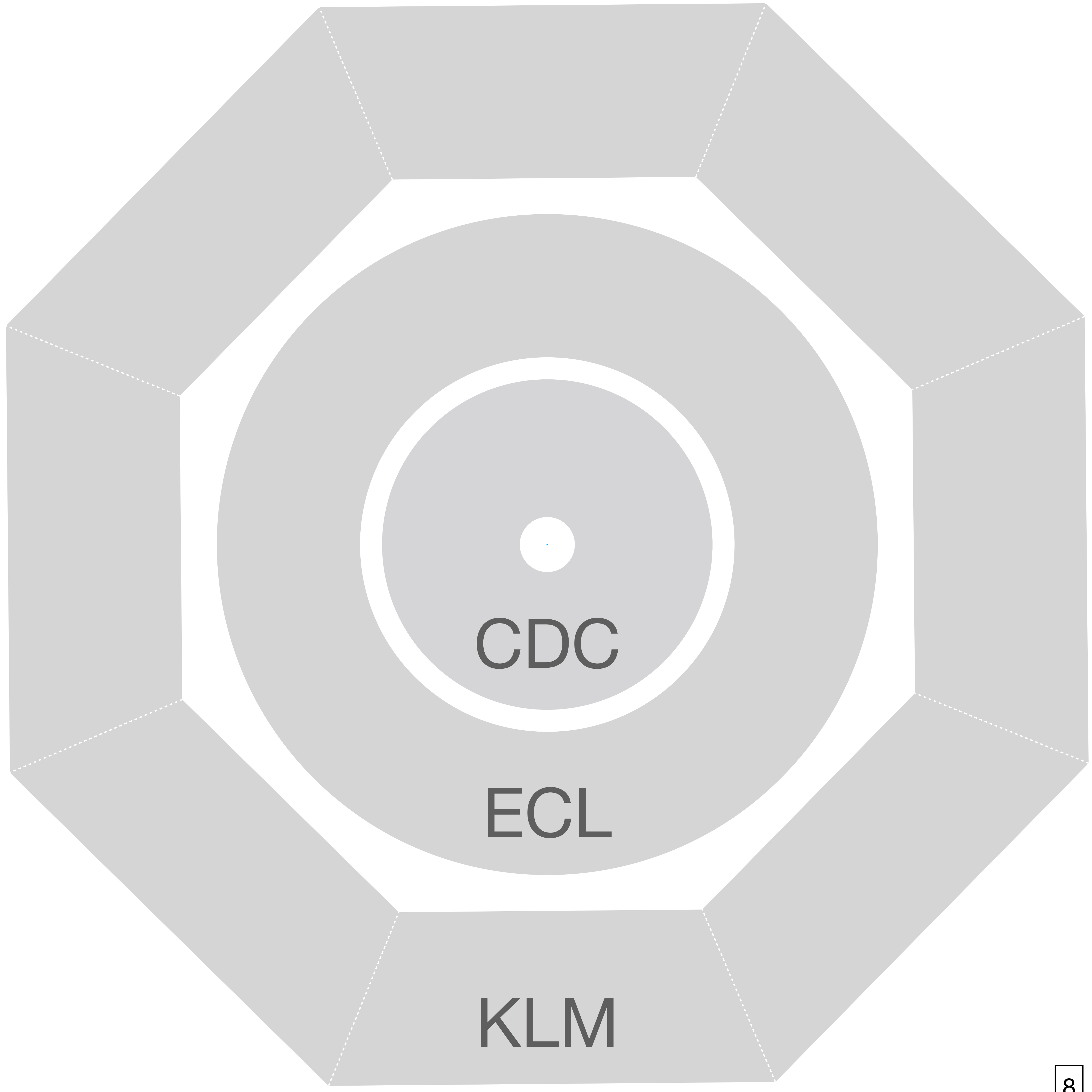
TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
SVD
PXD(2 layers)
Pre-amp
ARICH
Small cell chamber
IP Chamber
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC2RE
QC1RE
QC1RP
QC2RP
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
CDC
ECL
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)



TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
SVD
PXD(2 layers)
Small cell chamber
IP Chamber
ARICH
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RE
QC2RP
Pre-amp
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
CDC
ECL
KLM

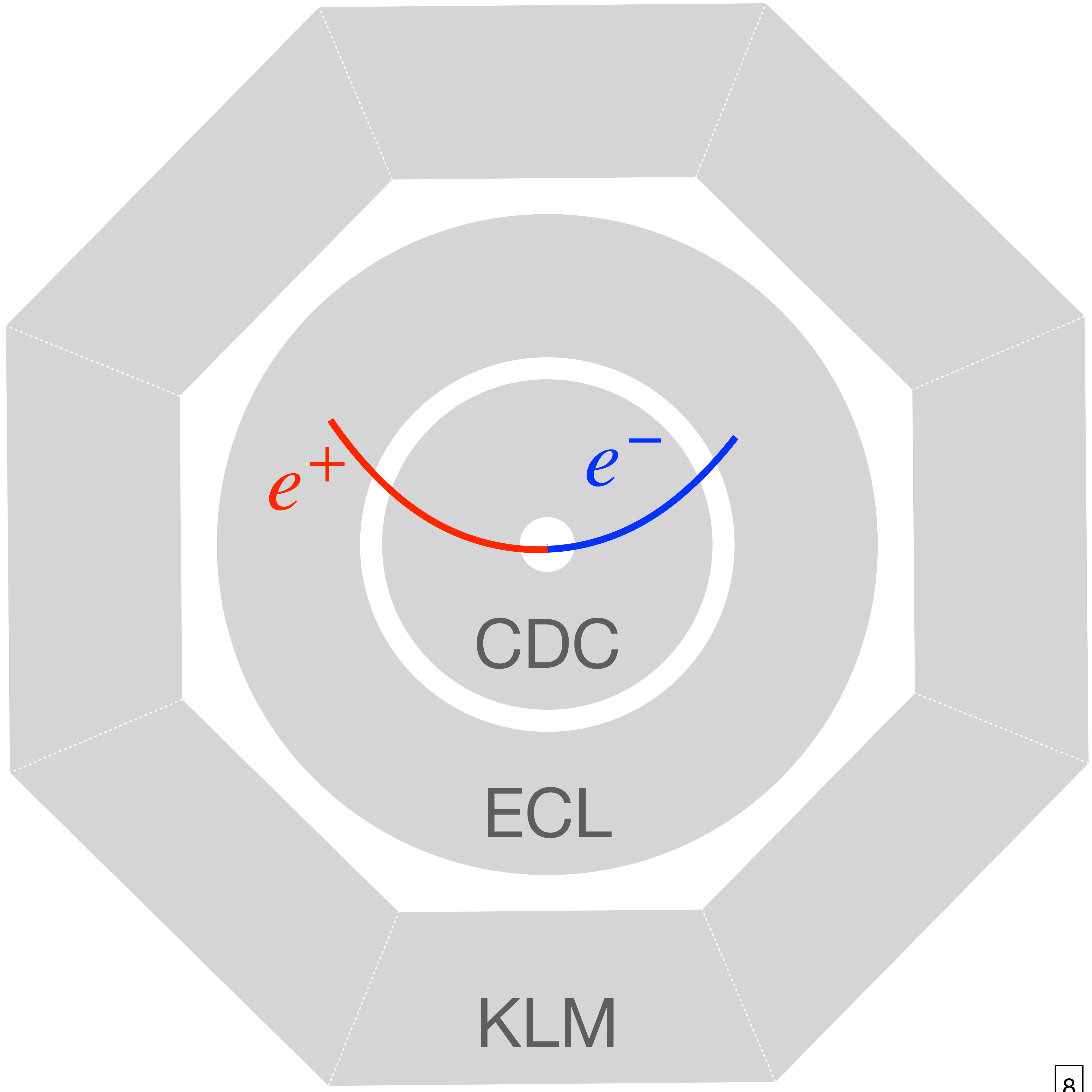
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)
Takashi Kohriki
A1
R12
1/10

New DM channel @ Belle II (x-y plane)



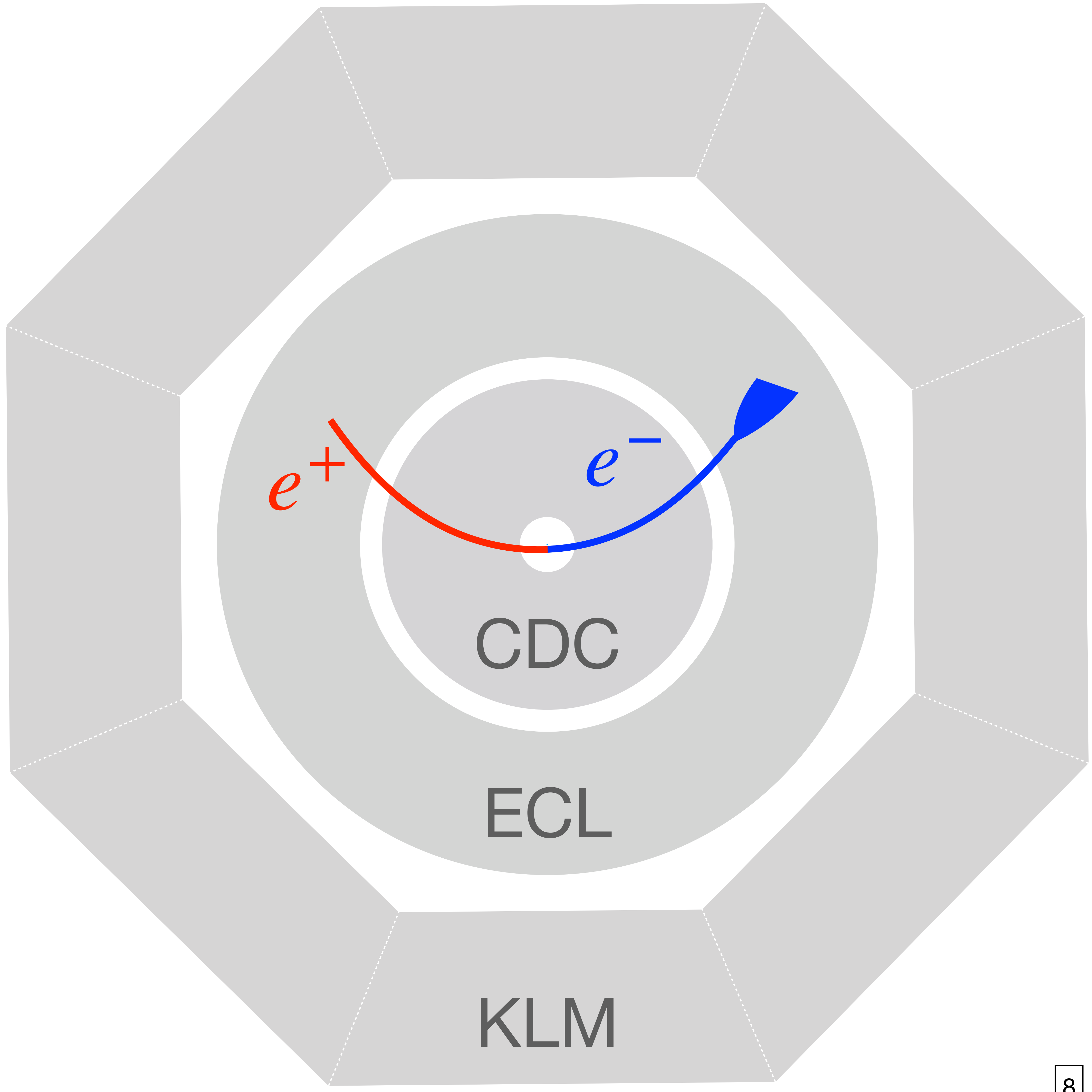
New DM channel @ Belle II (x-y plane)

- $e^+e^- \rightarrow e^+e^-$



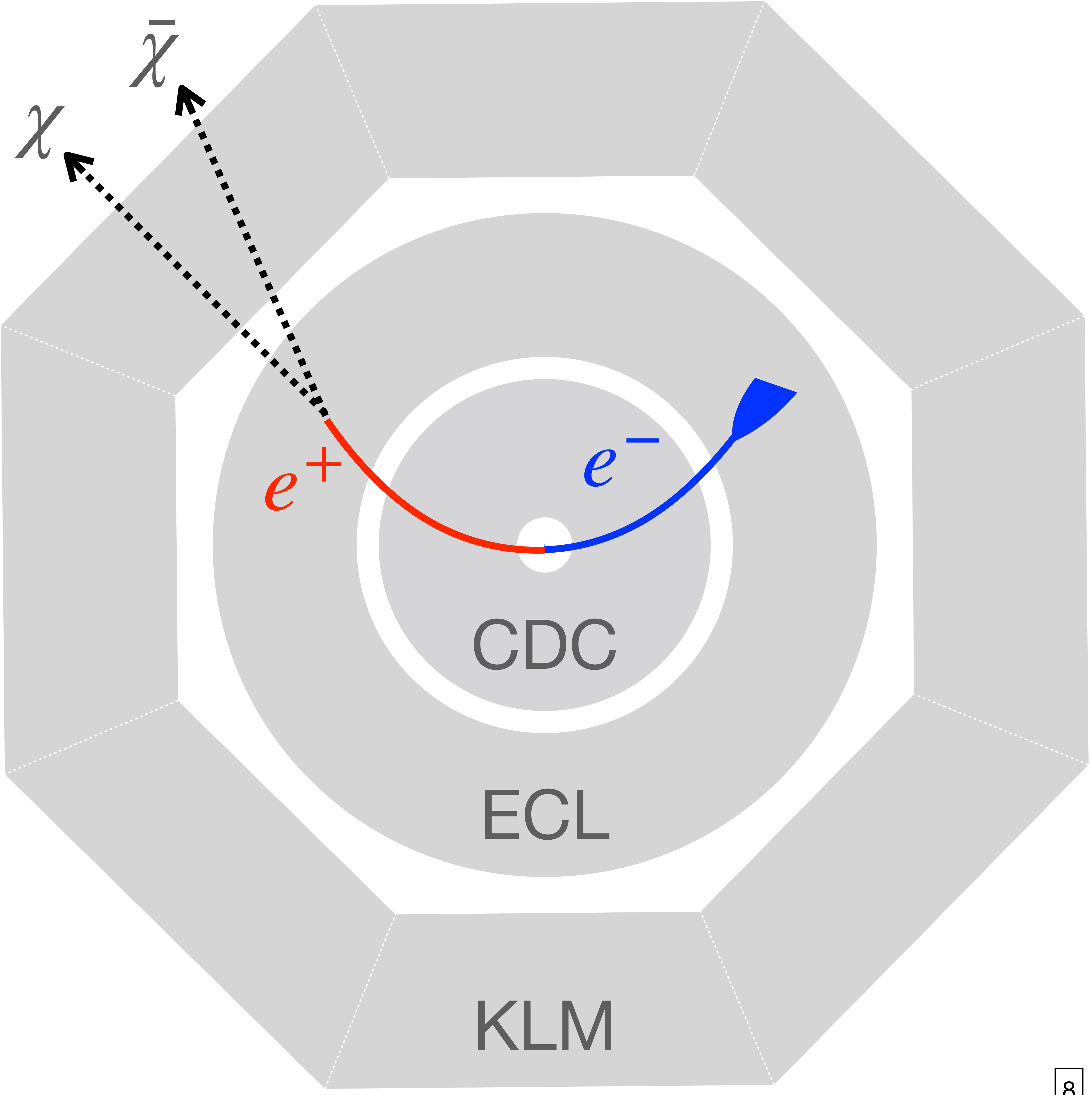
New DM channel @ Belle II (x-y plane)

- $e^+e^- \to e^+e^-$
- e^- deposit energy in ECL



New DM channel @ Belle II (x-y plane)

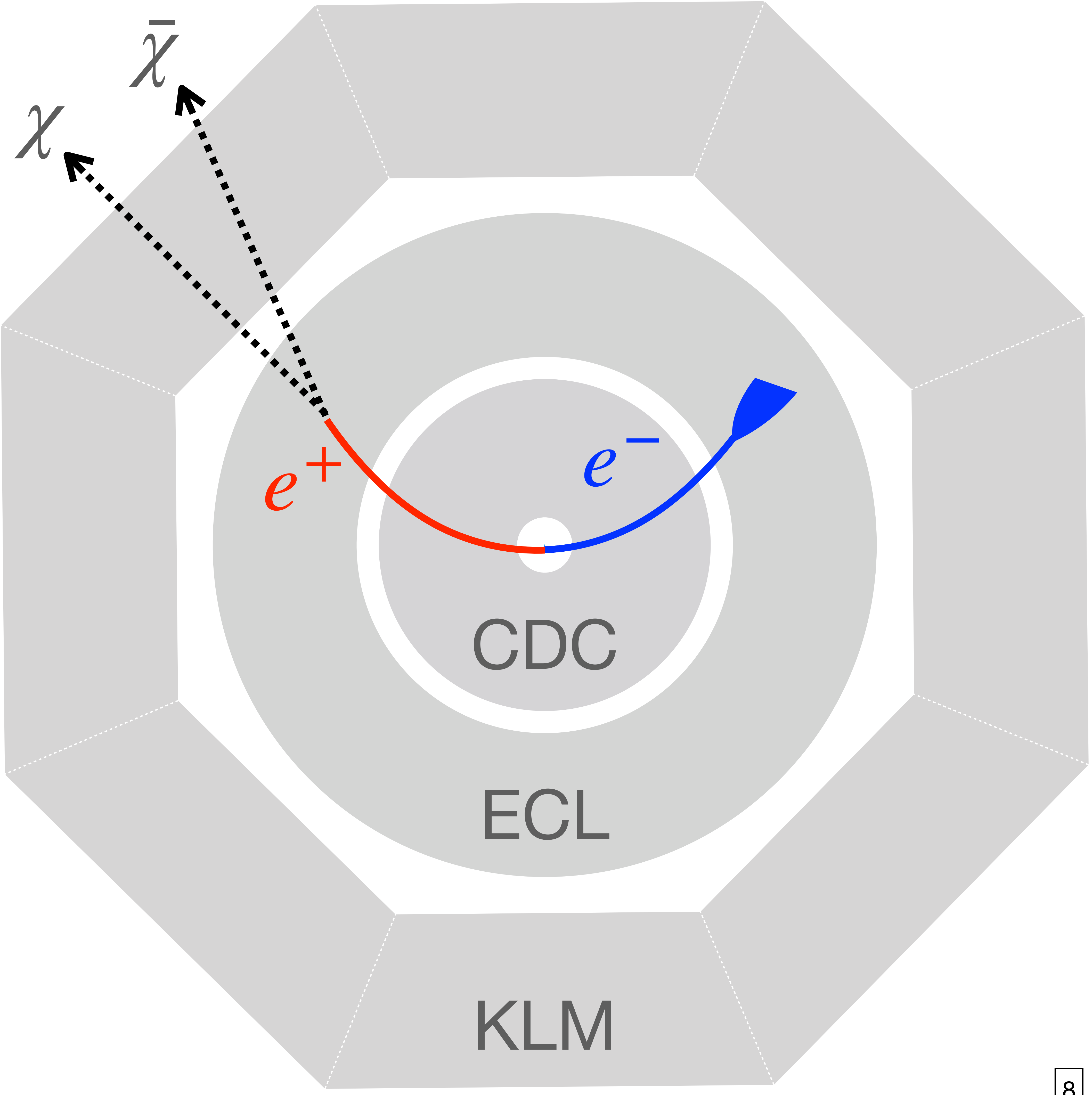
- $e^+e^- \rightarrow e^+e^-$
- e^- deposit energy in ECL
- e^+ interact with ECL to produce DM



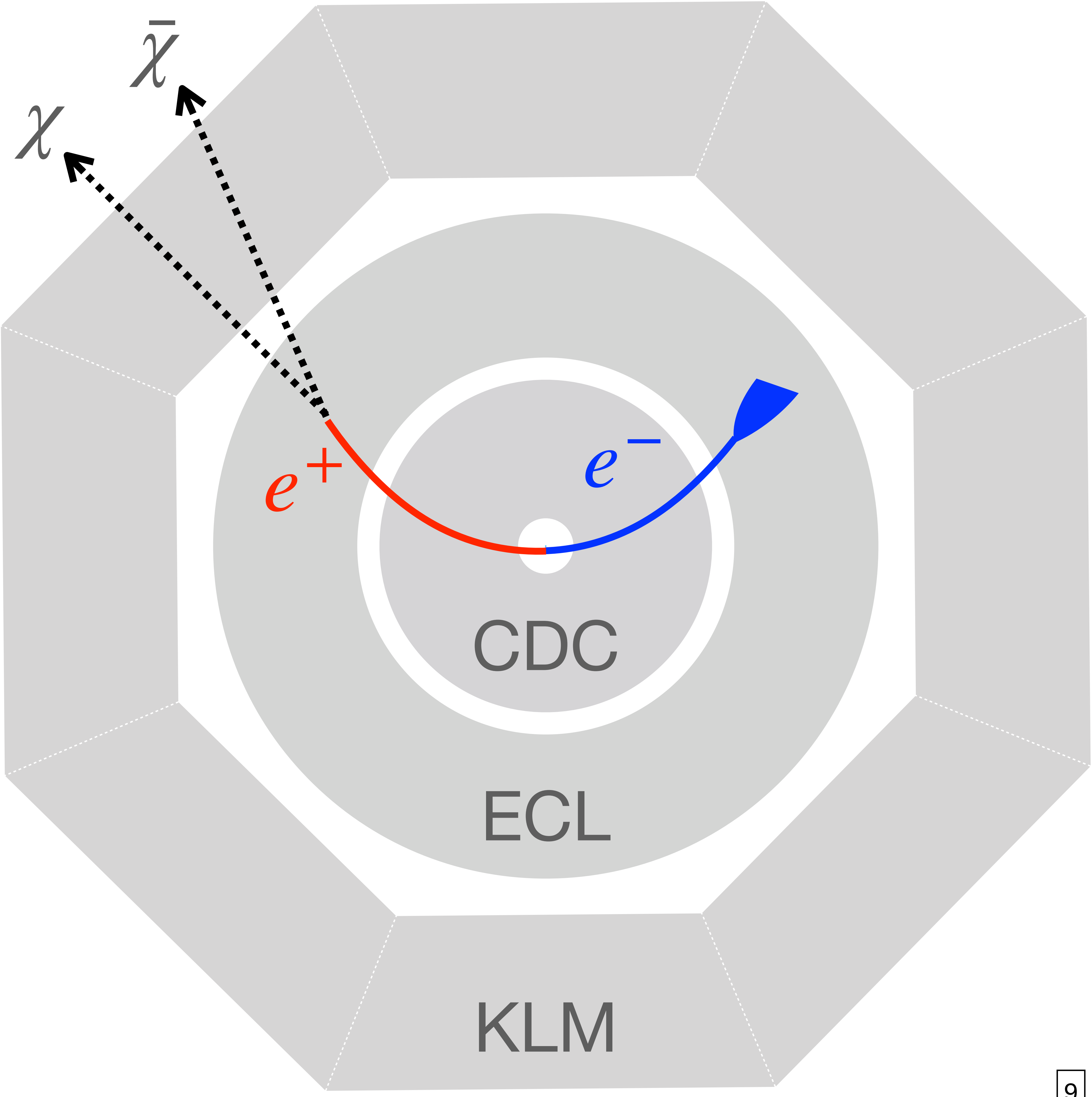
New DM channel @ Belle II (x-y plane)

- $e^+e^- \to e^+e^-$
- e^- deposit energy in ECL
- e^+ interact with ECL to produce DM

disappearing positron track



“disappearing positron track” signature

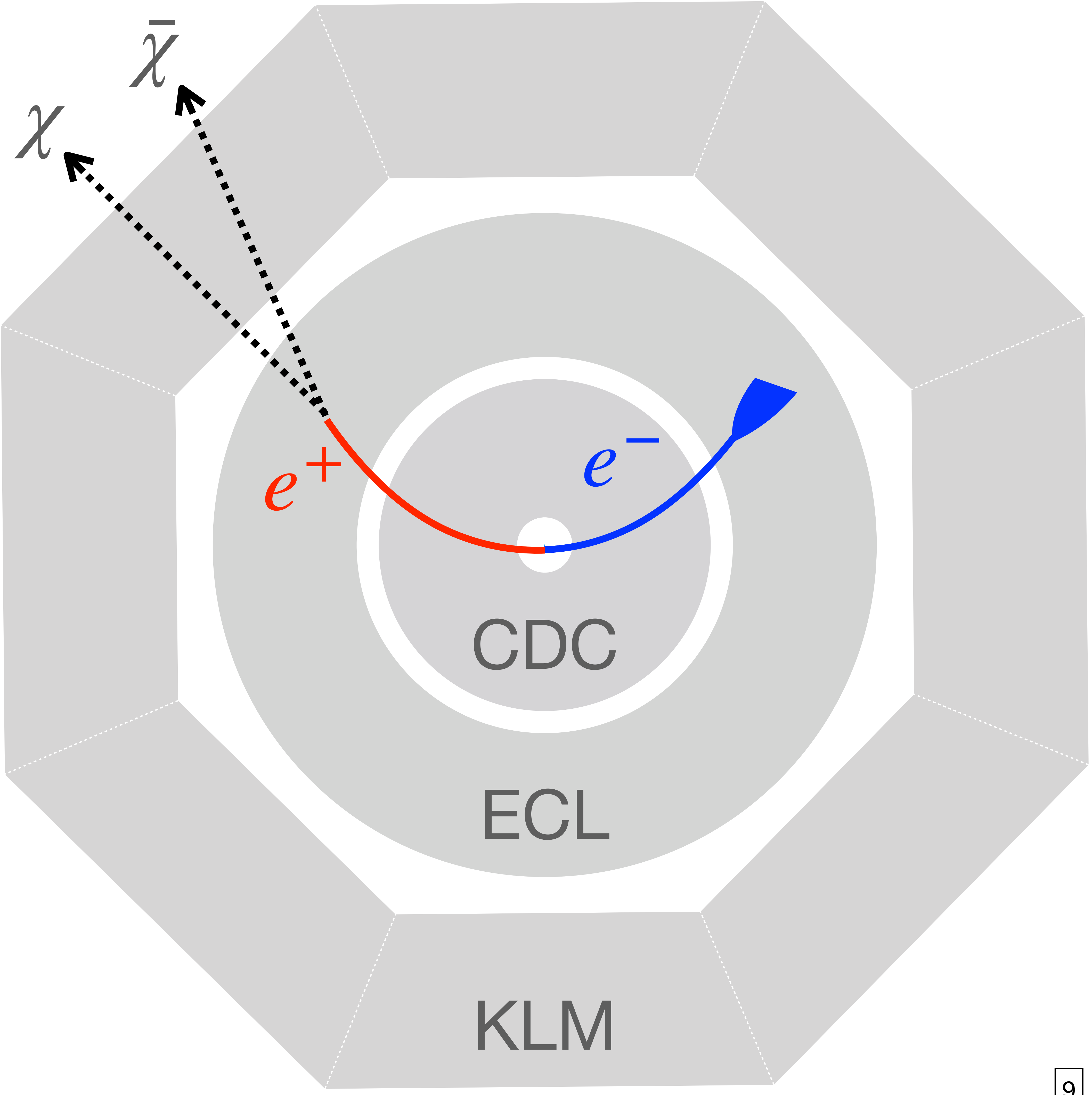


“disappearing positron track” signature

- CDC: e^- & e^+

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

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



“disappearing positron track” signature

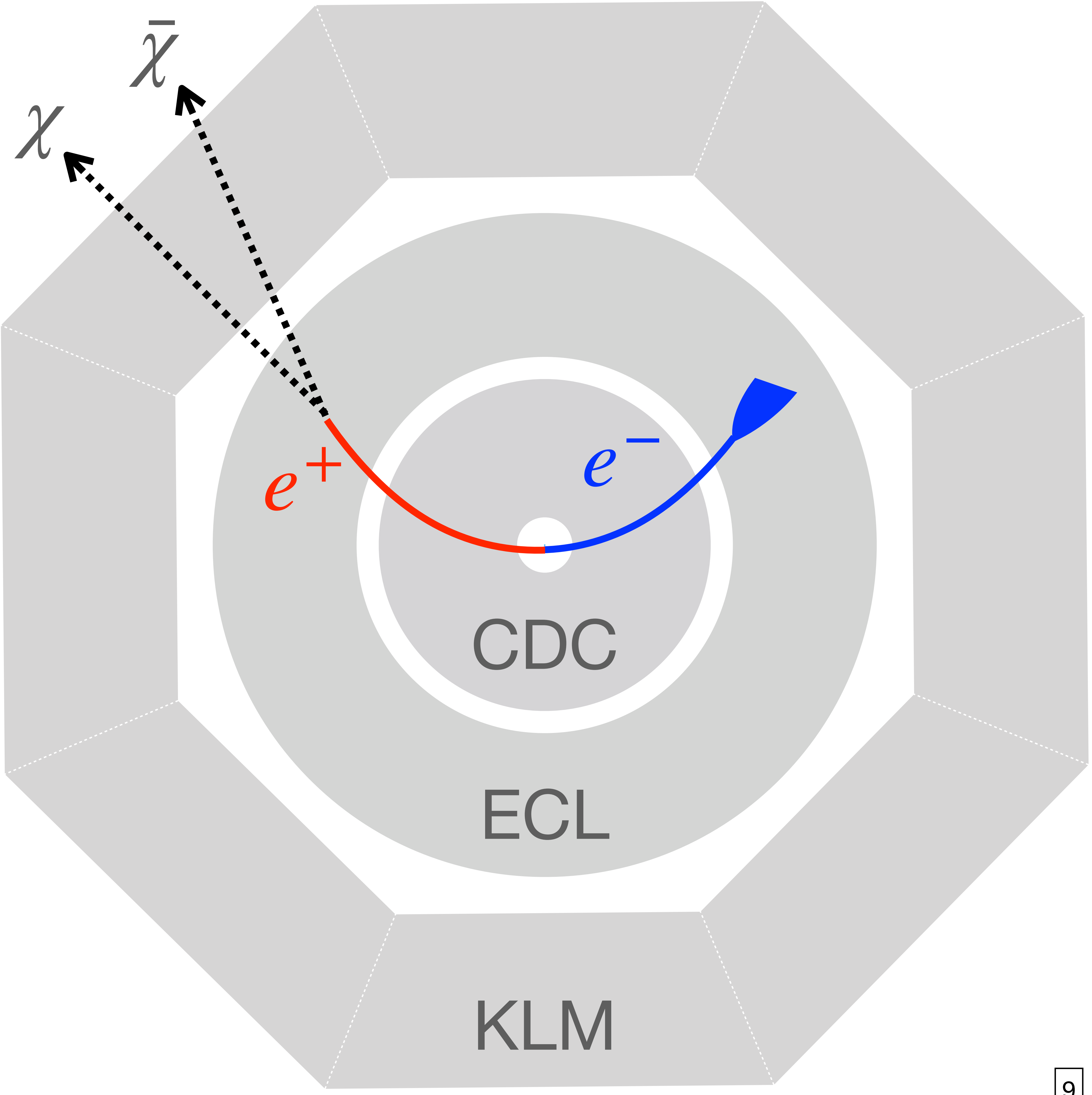
- CDC: e^- & e^+

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

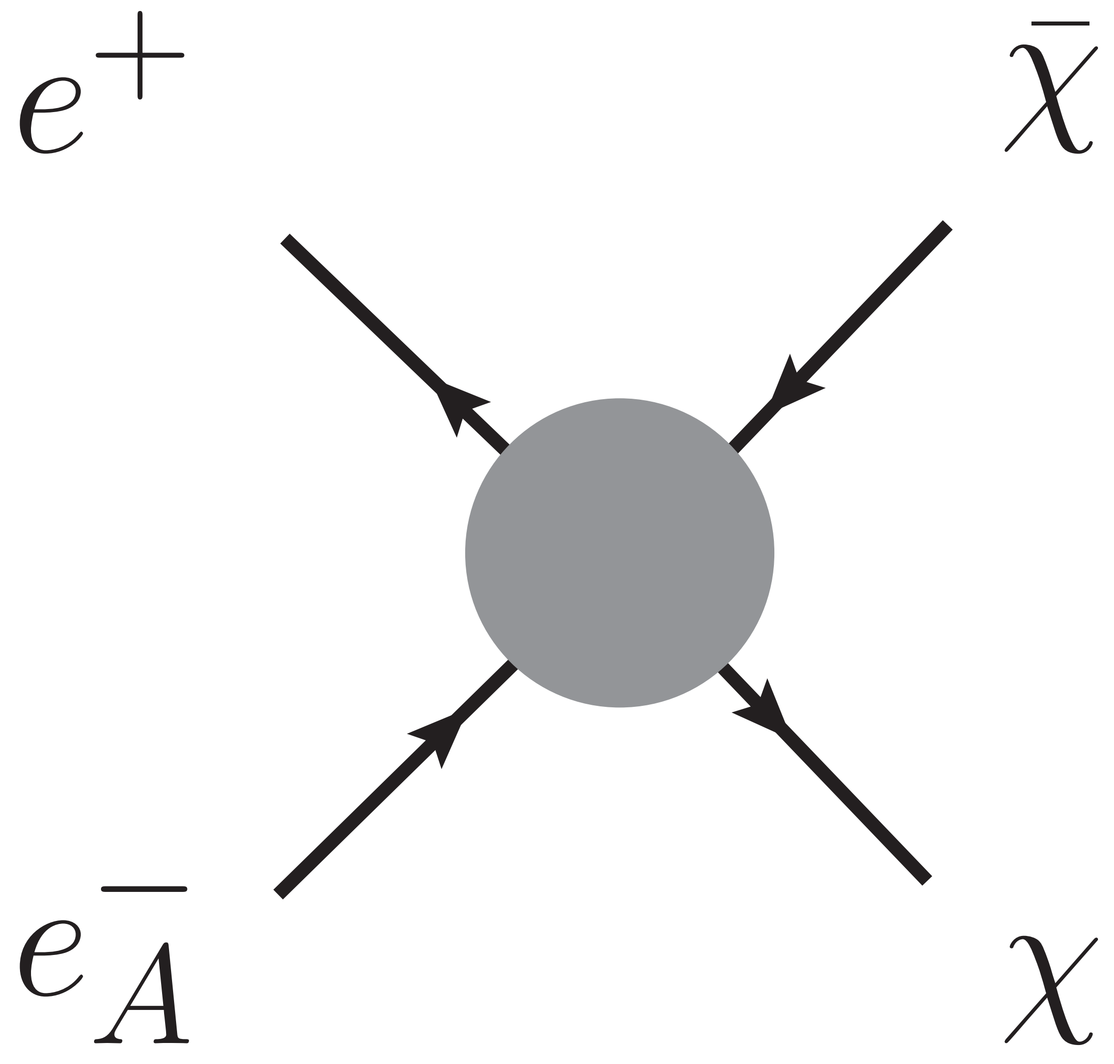
  Equal & opposite momenta for e^- & e^+ in the CM frame

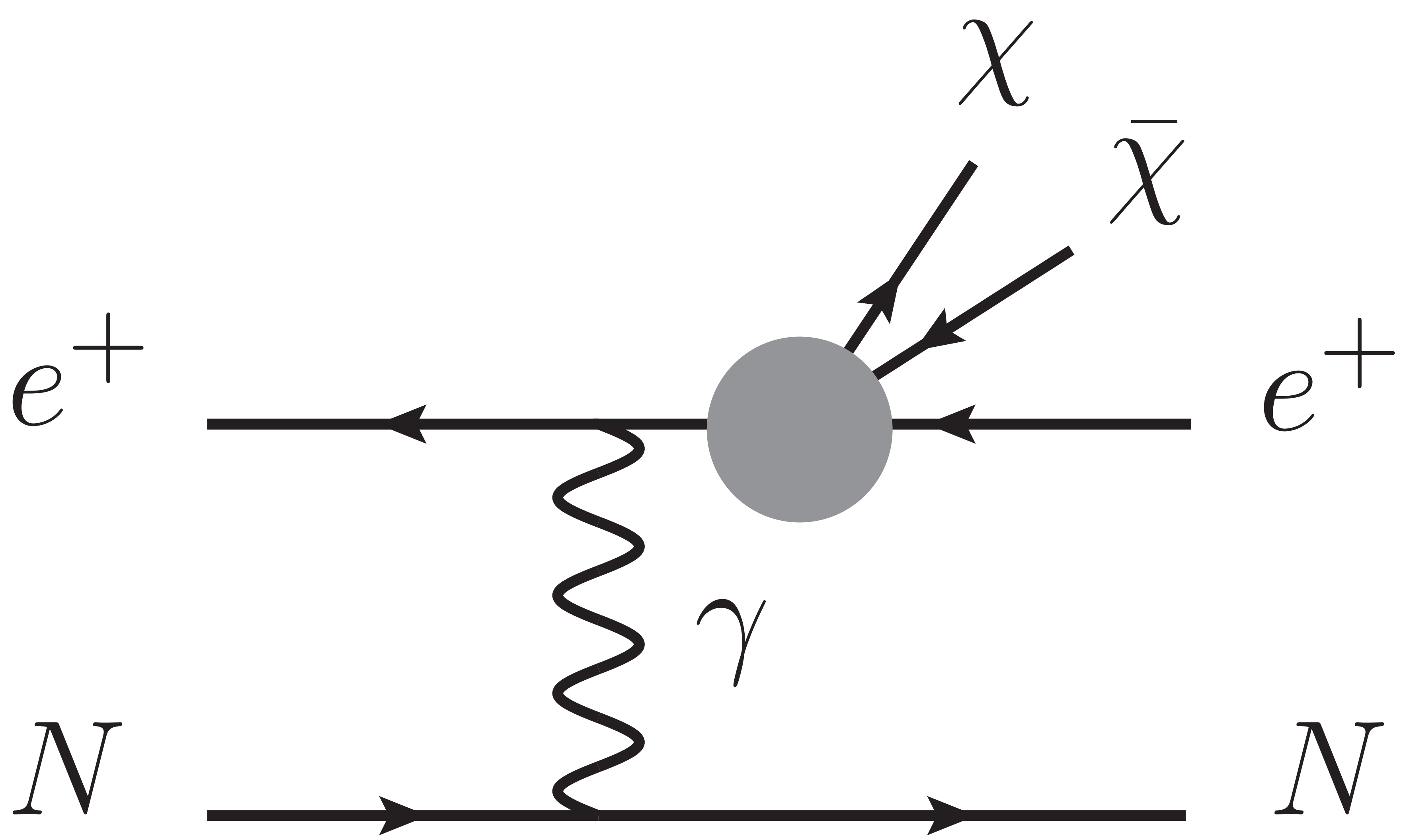
- ECL: e^- & e^+

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



Positron interaction with ECL



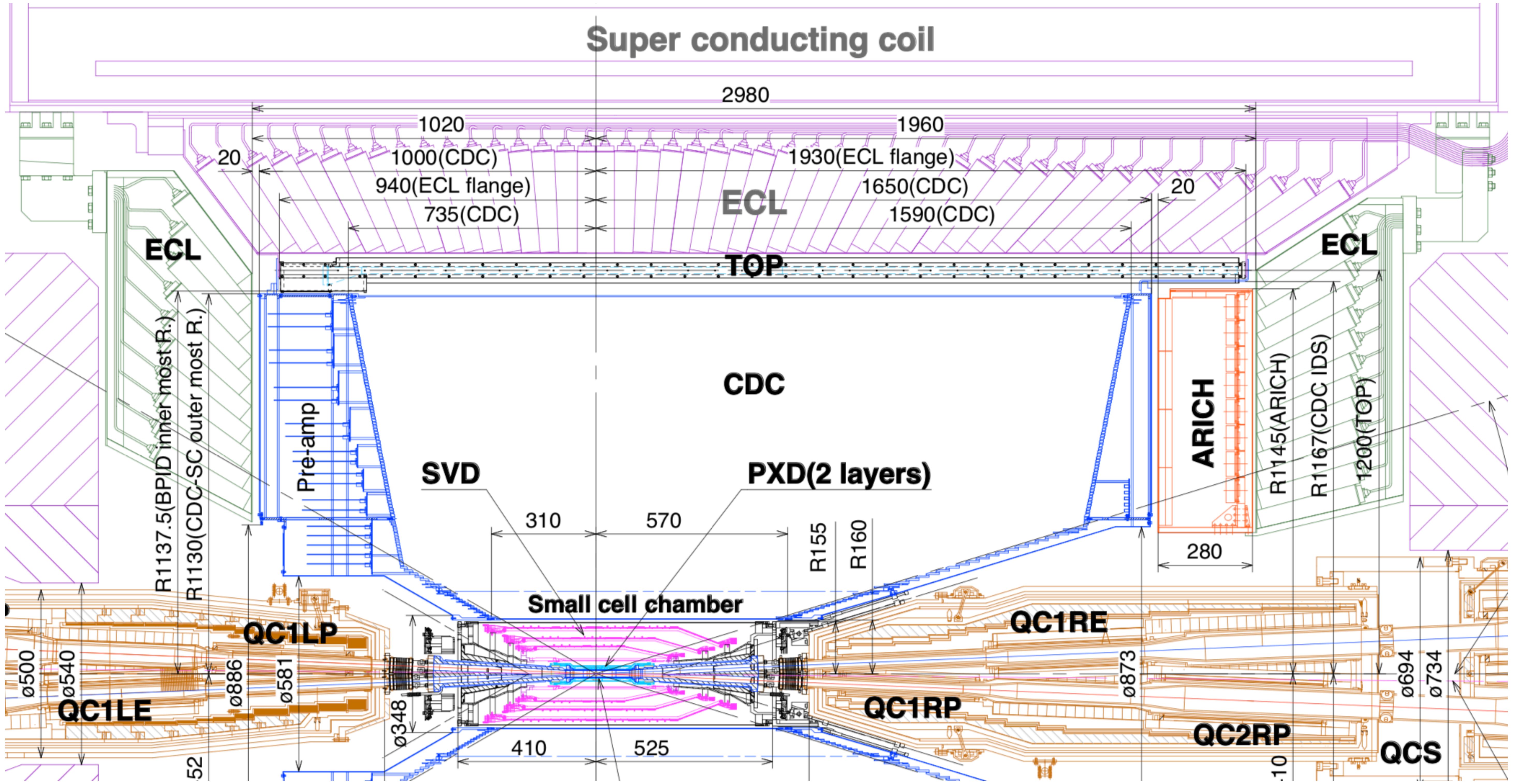


annihilation w/
atomic electrons

bremsstrahlung w/
target nucleus

Use the ECL barrel region as the fixed target

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

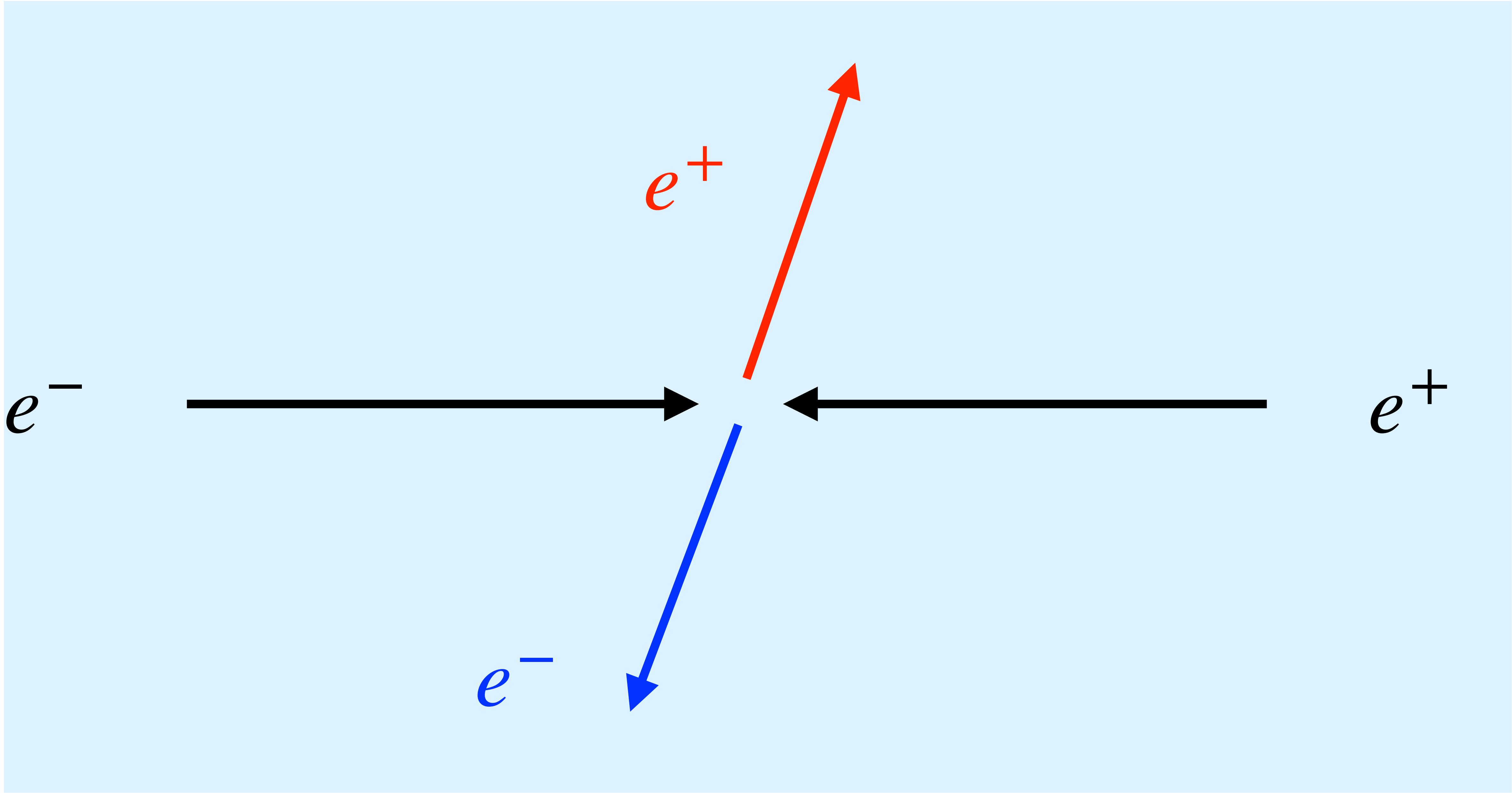


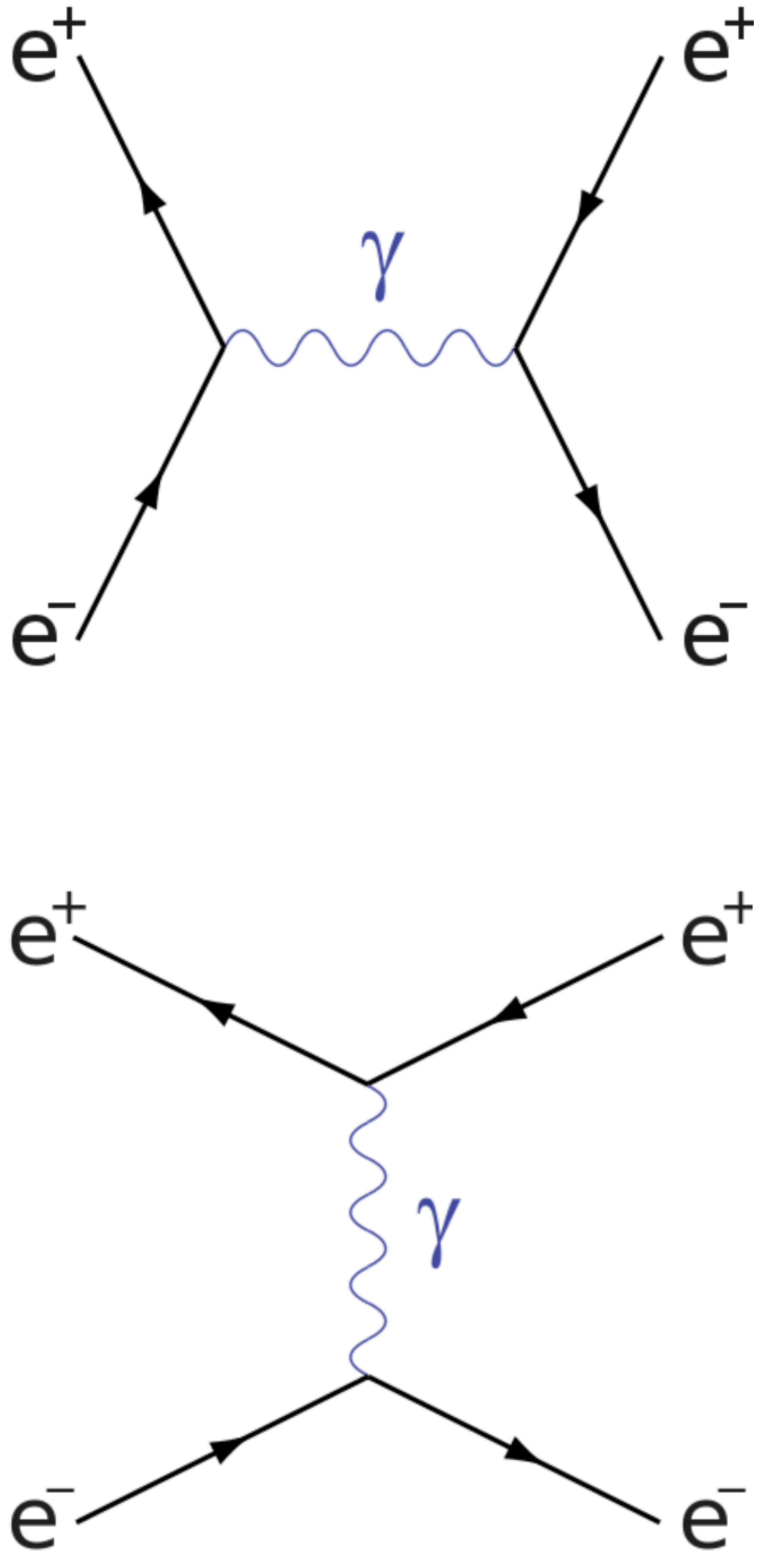
Better hermiticity (non-projective gaps between ECL crystals)

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

More beam BG in Endcaps

Positrons in Bhabha scattering



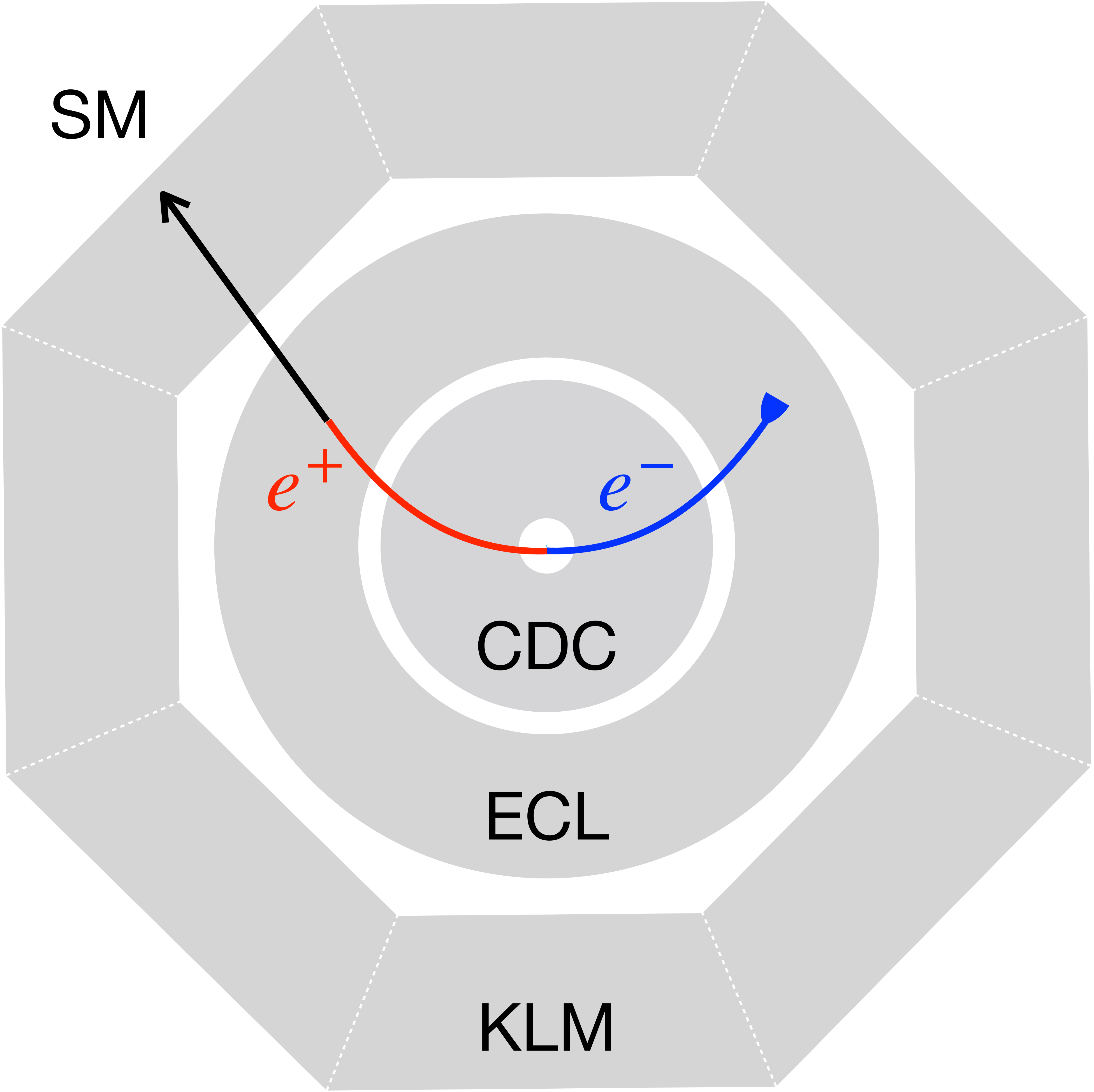


$6 \times 10^{11}\, e^+e^-$ in the barrel region with 50/ab

2 Standard model backgrounds

Standard model backgrounds

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

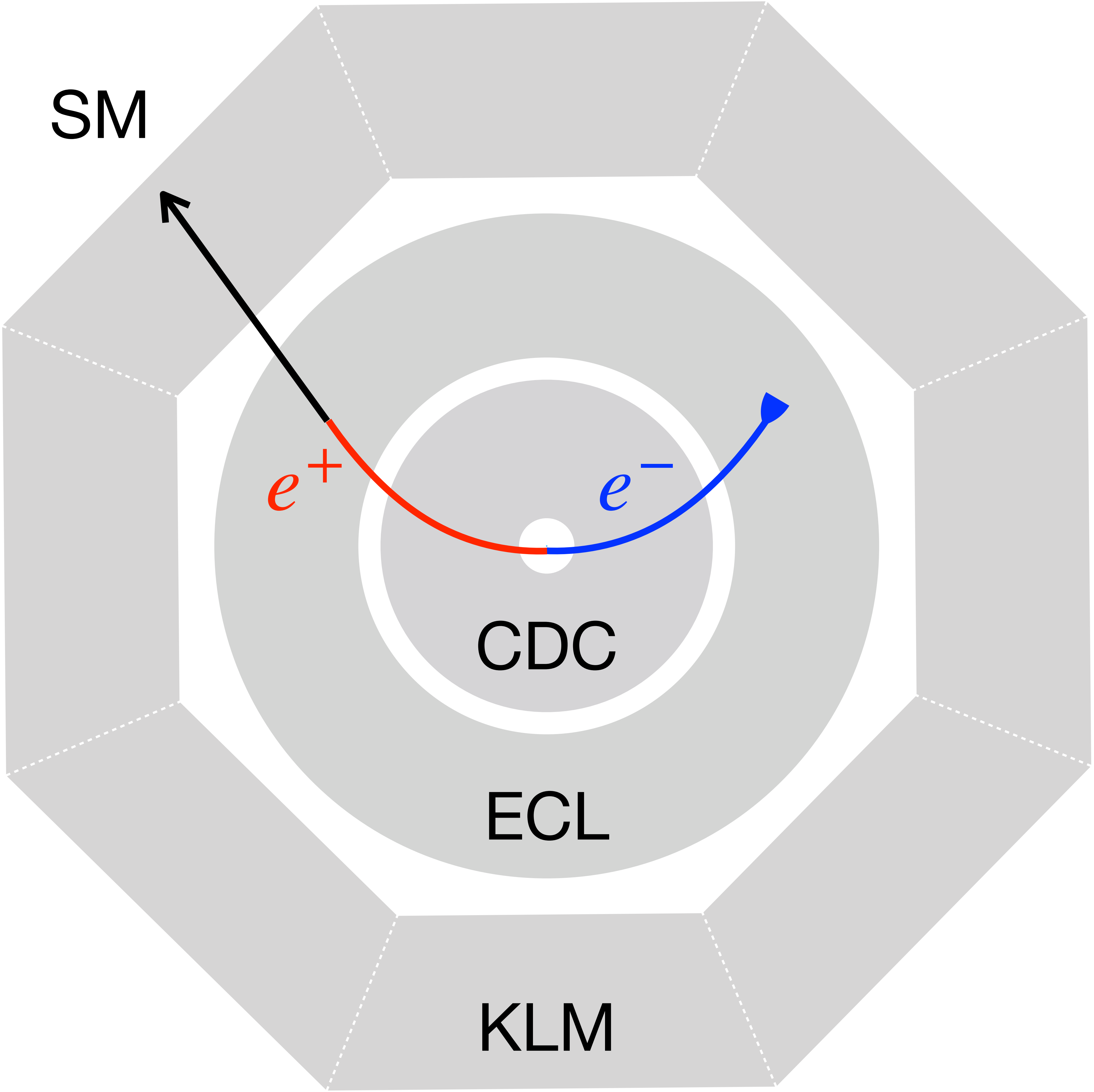


Standard model backgrounds

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

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

- Neutral particles (n, γ, ν): more difficult to detect



Standard model backgrounds

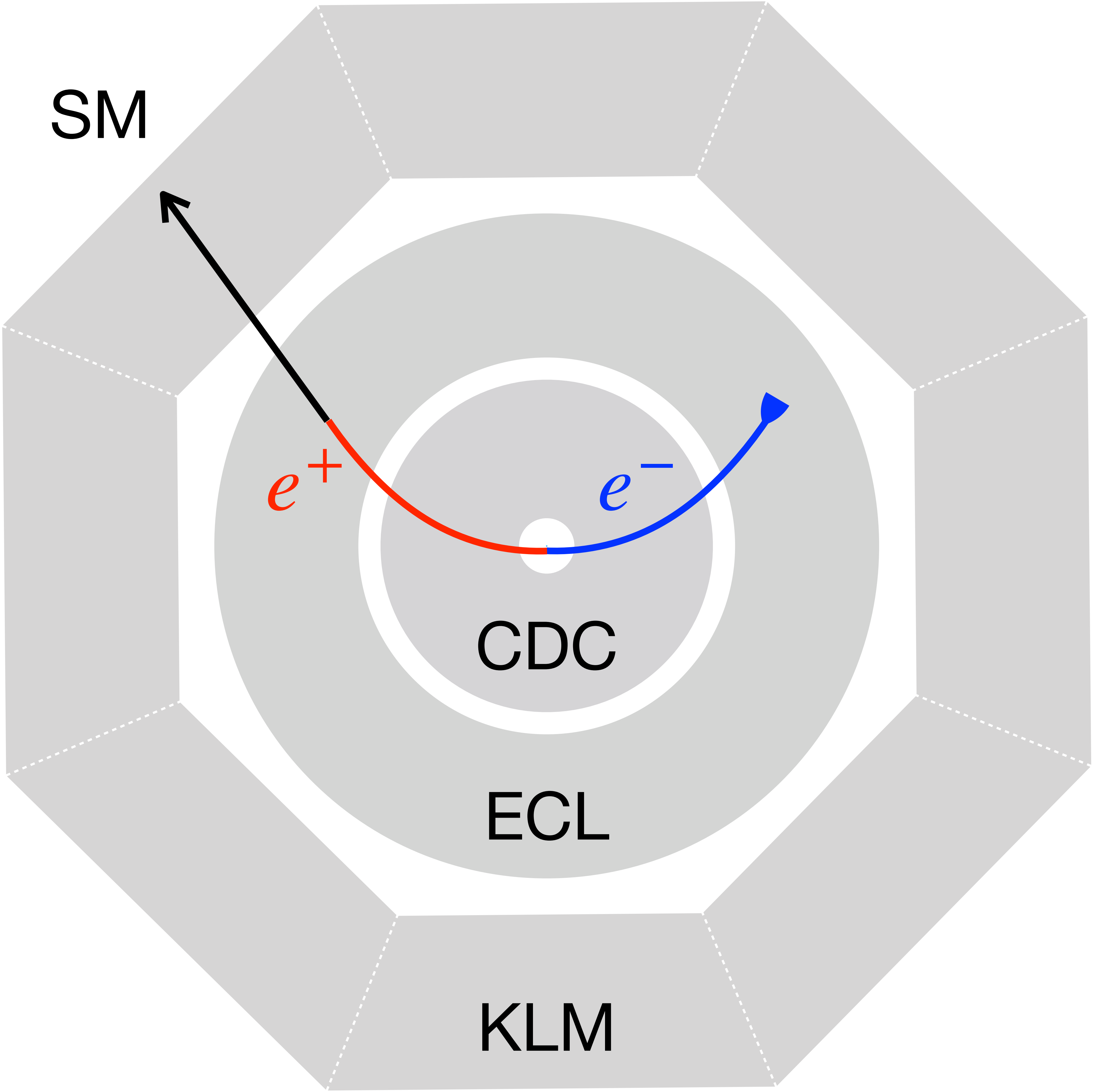
BG: e^+ + ECL $\rightarrow \mathrm{SM}$
which then escape detection

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

- Neutral particles (n, γ, ν): more difficult to detect

Neutrino BG is negligible (xsec is small)

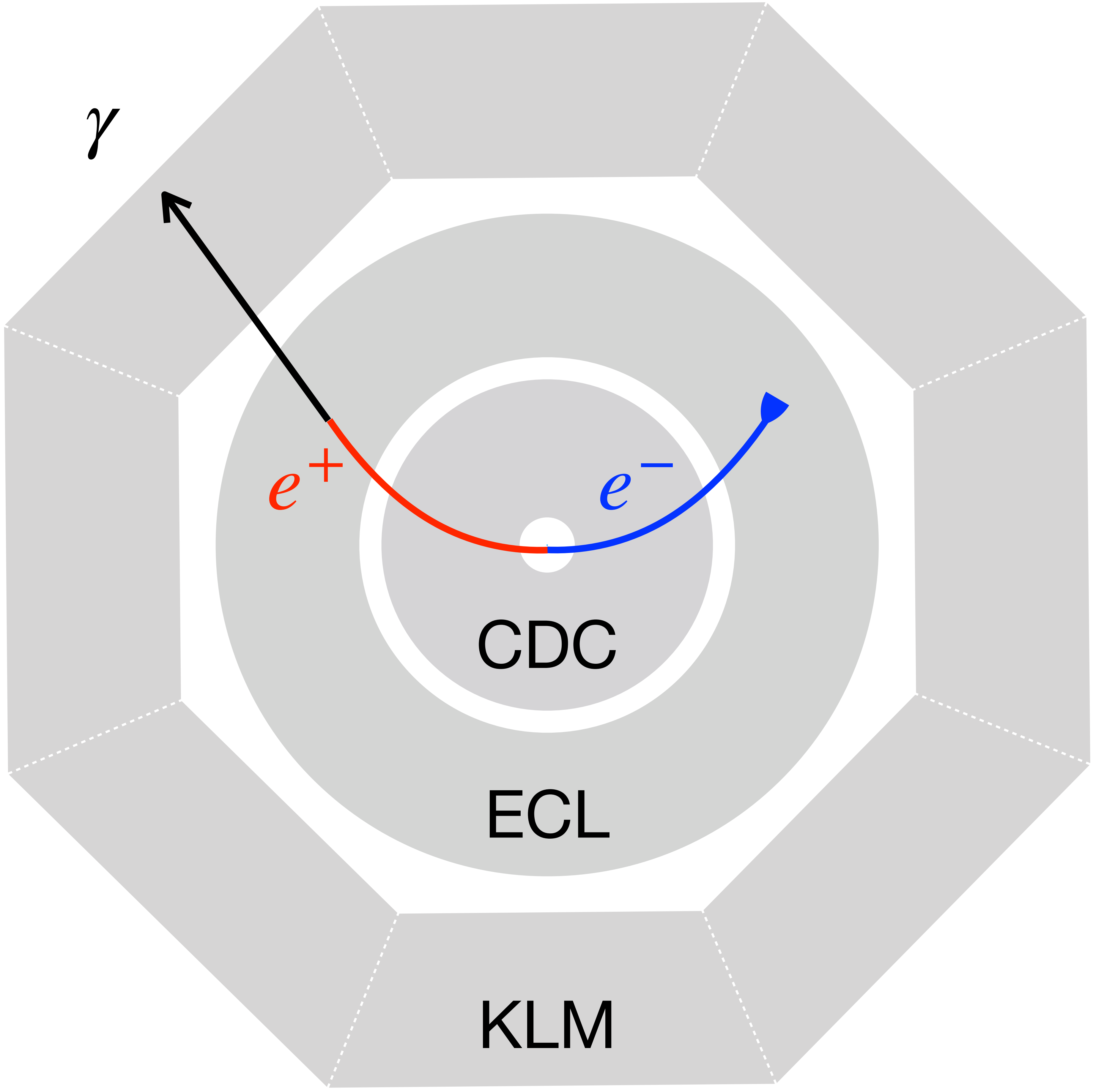
Main BG is due to n/γ



Photon-induced background

Photon energy measured in ECL

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



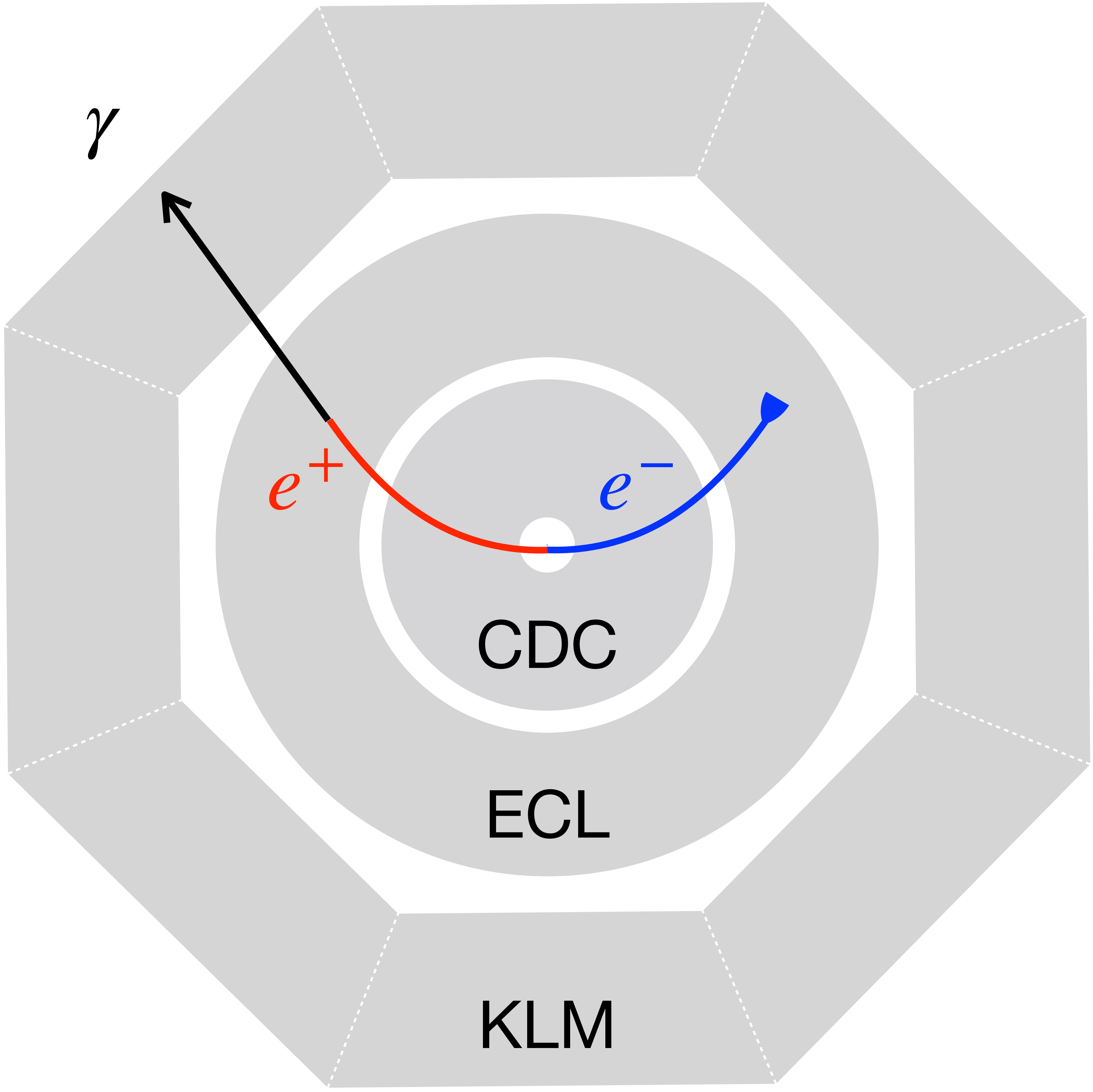
Photon-induced background

Photon energy measured in ECL

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

Photon can also be detected by KLM

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



Photon escapes ECL

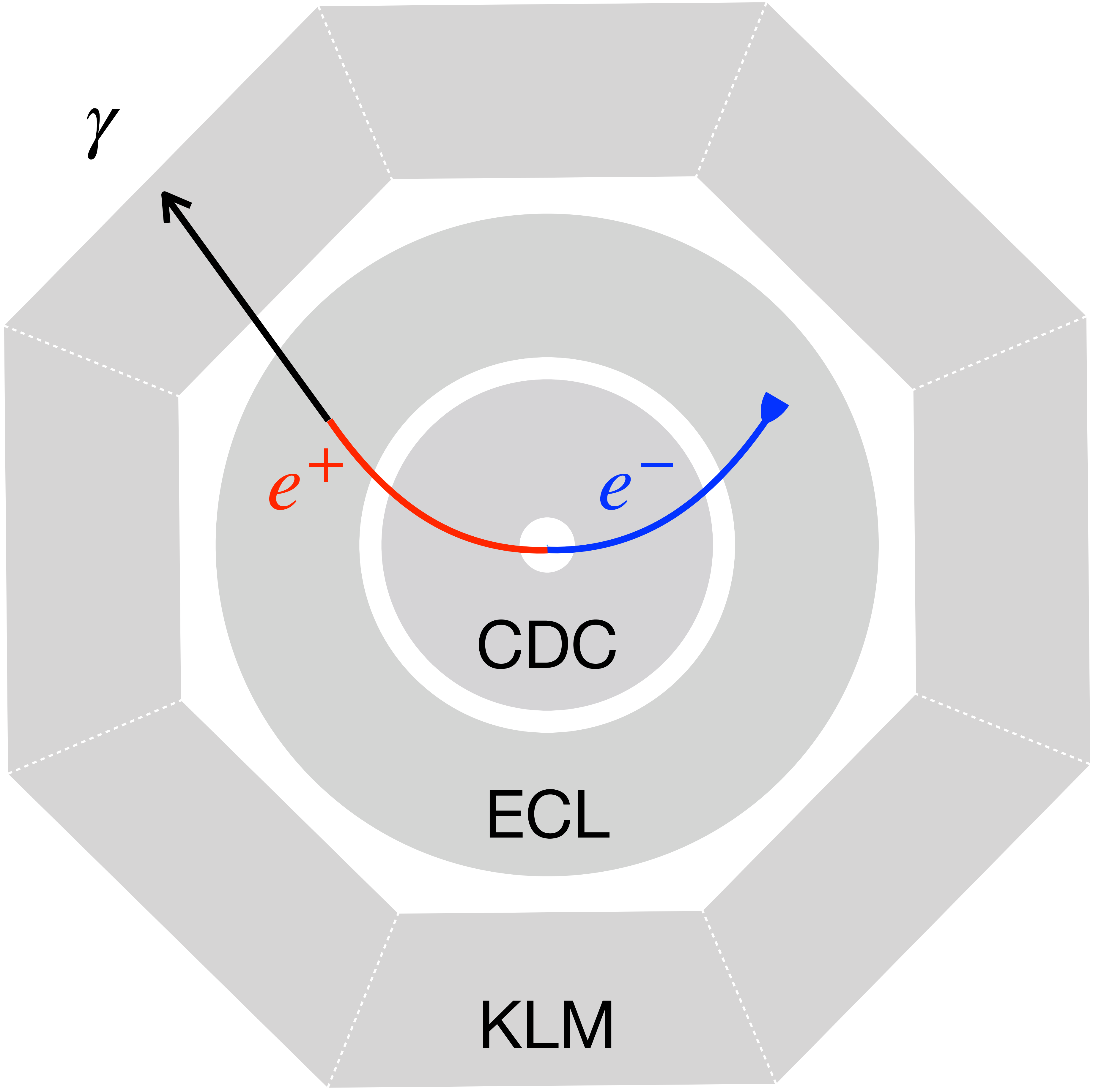
Photon energy spectrum due to e^+ collision with ECL

[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



Photon escapes ECL

Photon energy spectrum due to e^+ collision with ECL

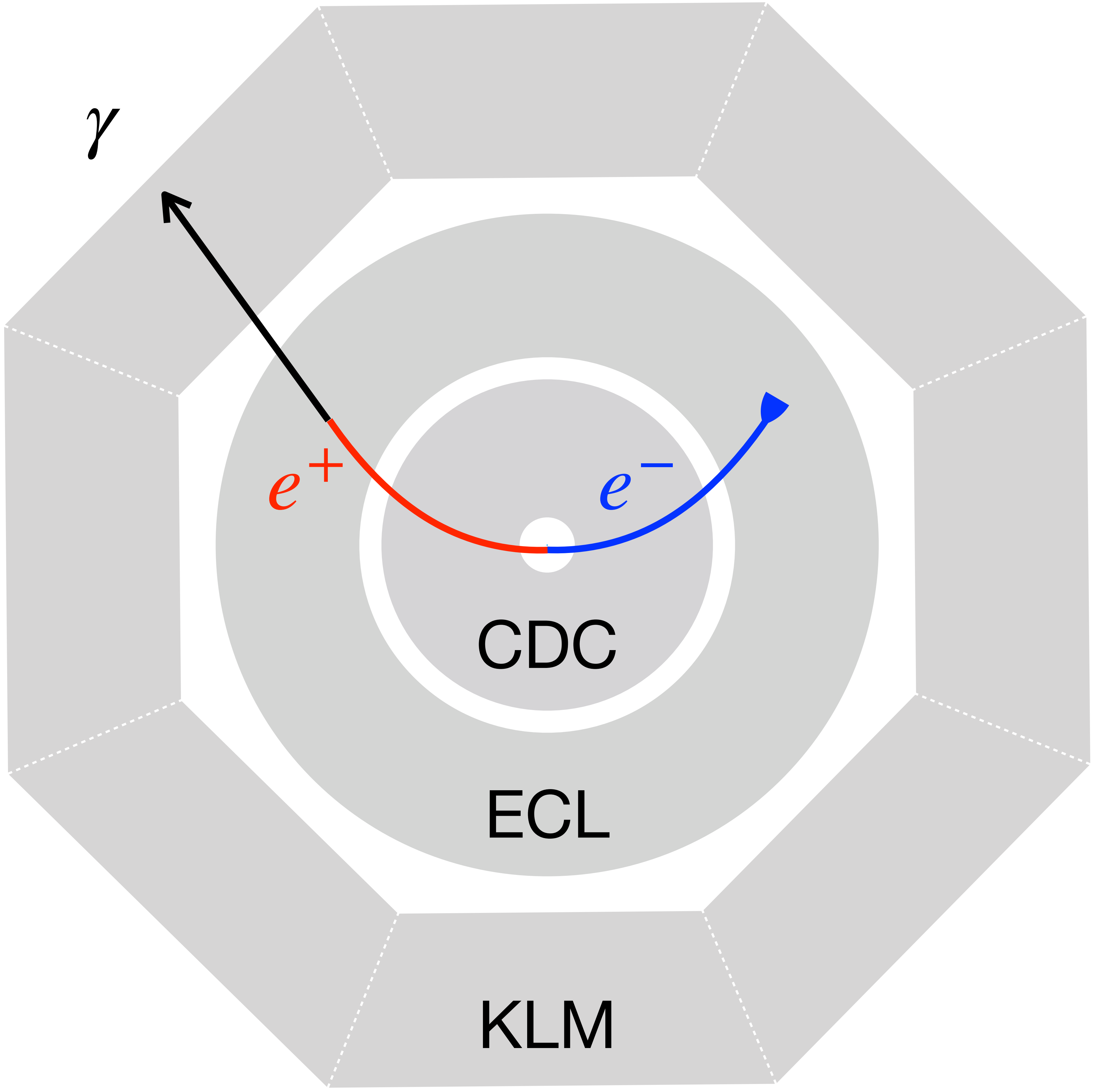
[Tsai & Whitis 1966]

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

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

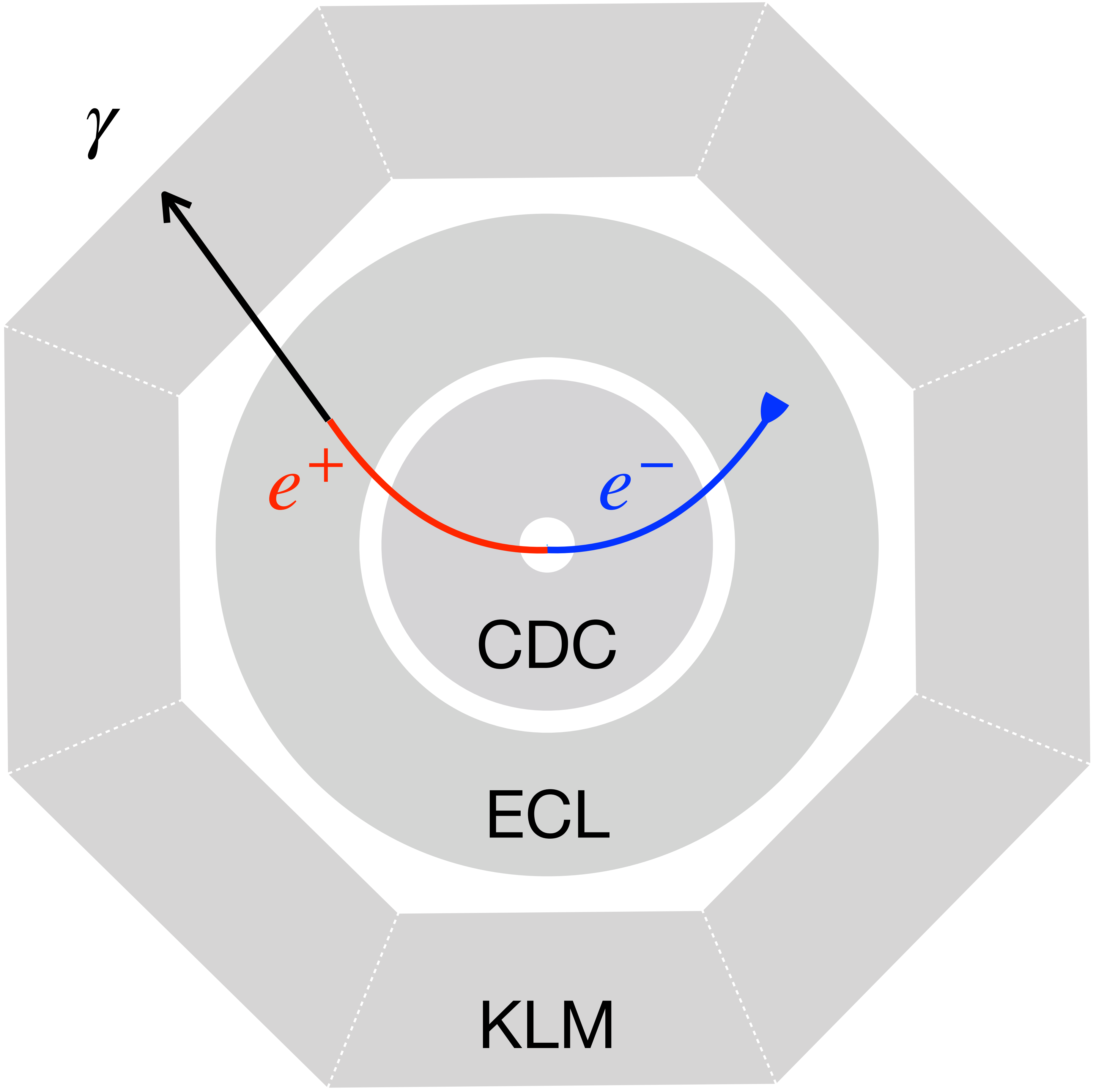
$$\int_{0.95}^{1} dx_\gamma \frac{dN_\gamma}{dx_\gamma}(t = 16, x_\gamma) \simeq 4.7 \times 10^{-8}$$

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



KLM veto capability on photon

GeV γ is unlikely to penetrate the KLM

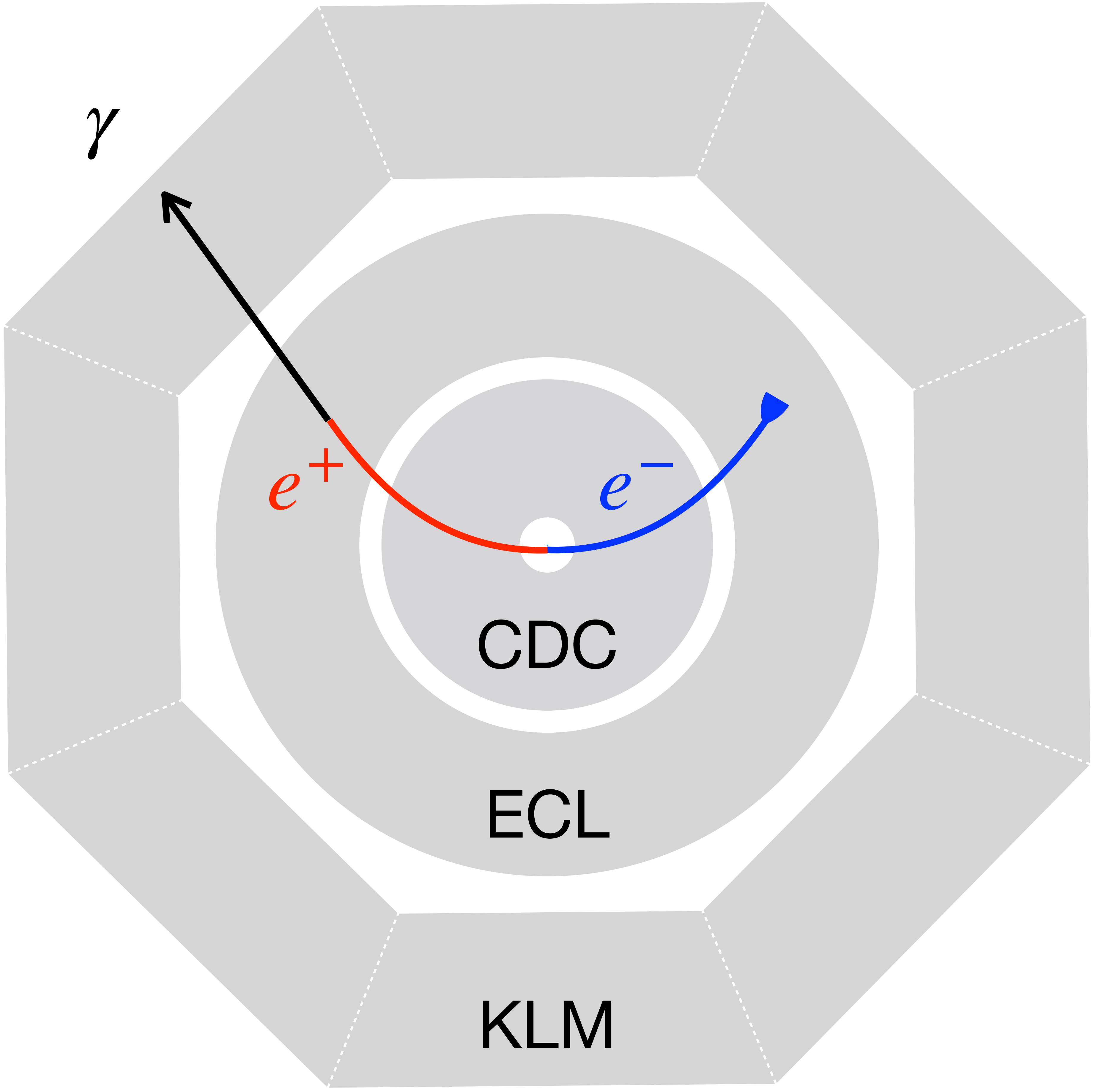


KLM veto capability on photon

GeV γ is unlikely to penetrate the KLM

However, γ can be absorbed by non-instrumented setups (e.g., magnet coil)

KLM veto power is limited



KLM veto capability on photon

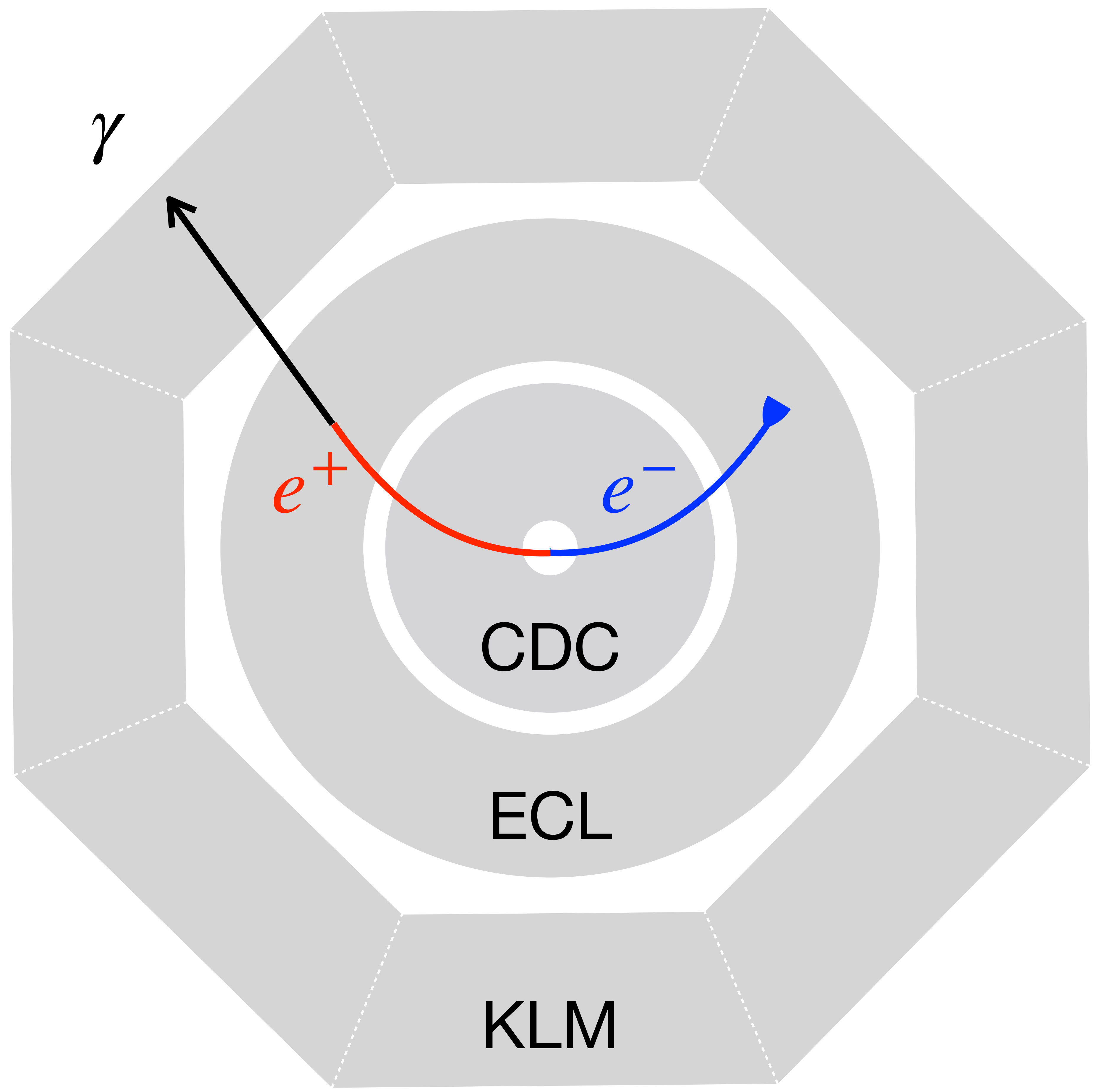
GeV γ is unlikely to penetrate the KLM

However, γ can be absorbed by non-instrumented setups (e.g., magnet coil)

KLM veto power is limited

IFR @ BaBar, veto eff = 4.5×10^{-4}

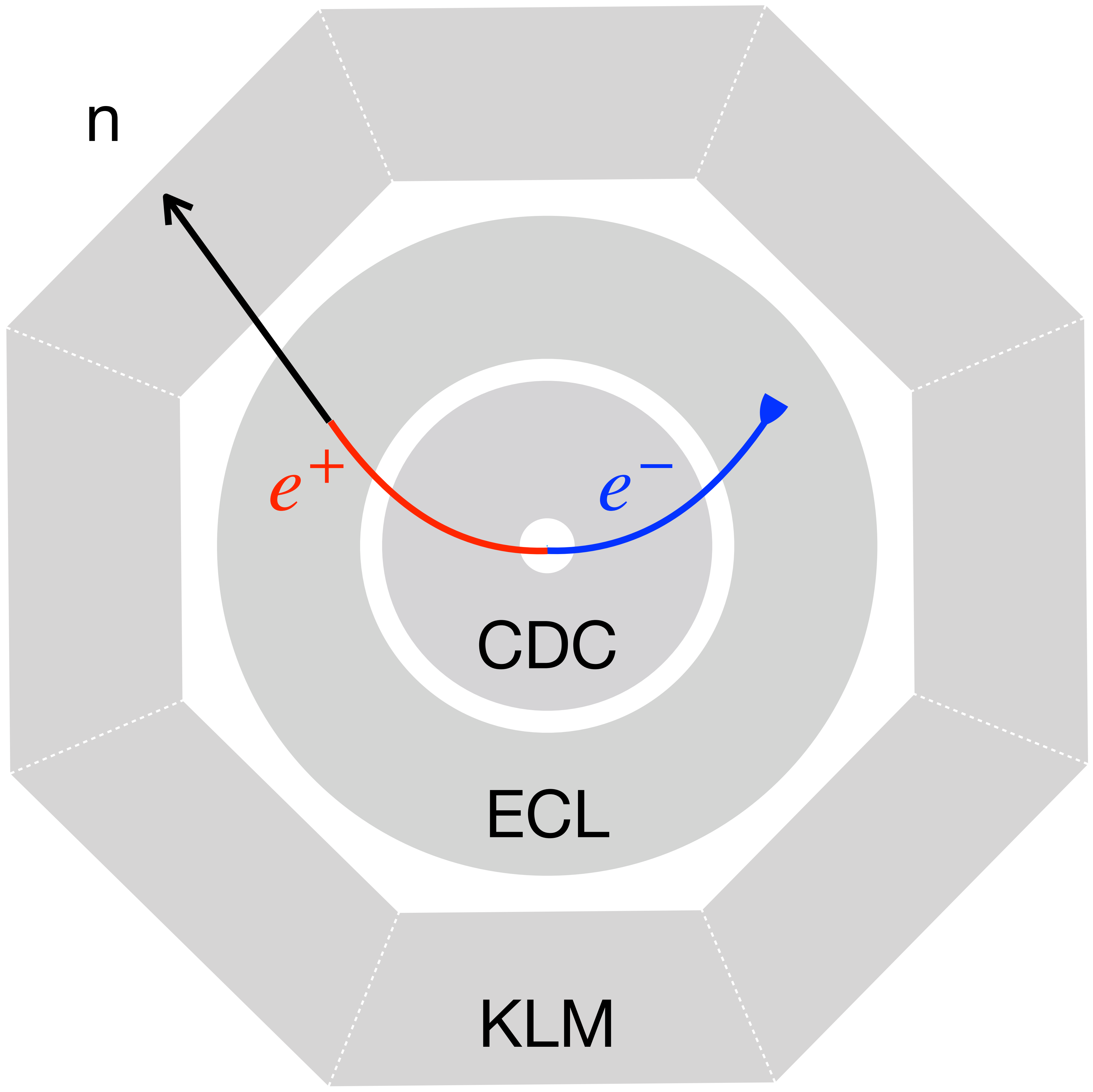
13 photon BG (conservative)



Neutron-induced backgrounds: GEANT4 simulations

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)



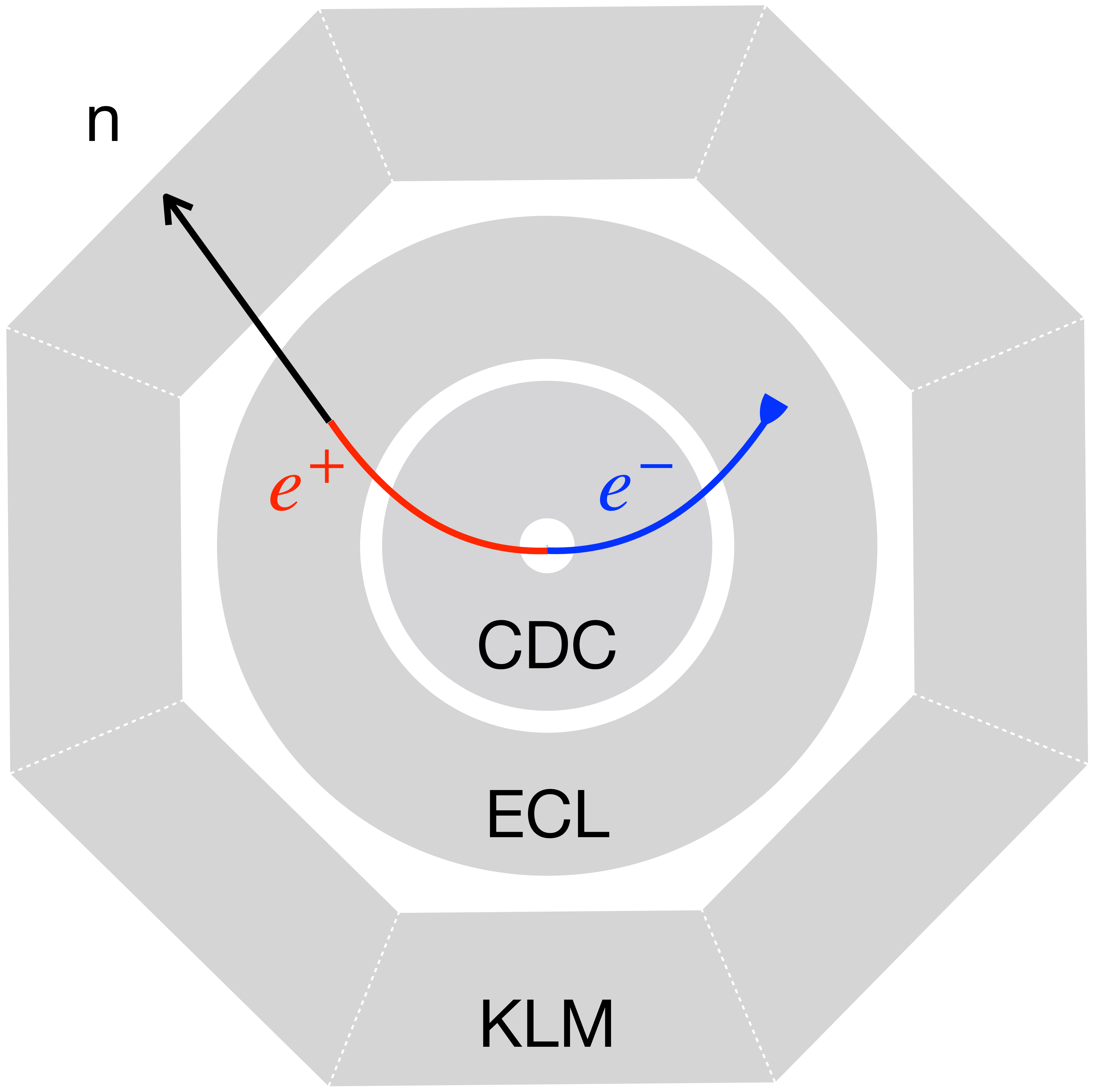
Selection in GEANT4 simulations

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

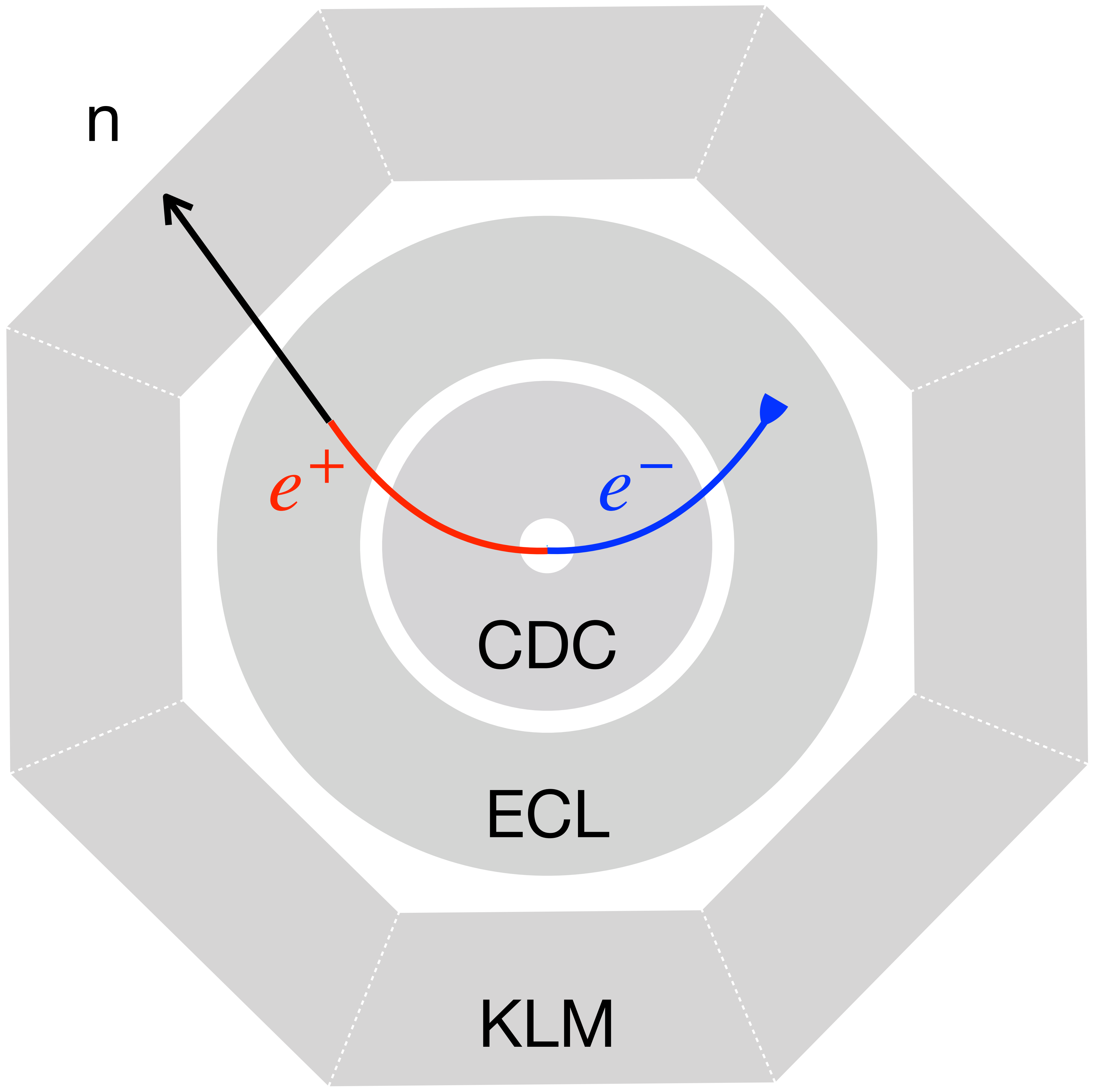
Prob to penetrate a target with length L

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

λ_0 = hadronic interaction length

KLM has $\sim 3.9\,\lambda_0$

ECL has $\sim 0.8\,\lambda_0$



Probability for a neutron to penetrate ECL & KLM

Prob to penetrate a target with length L

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

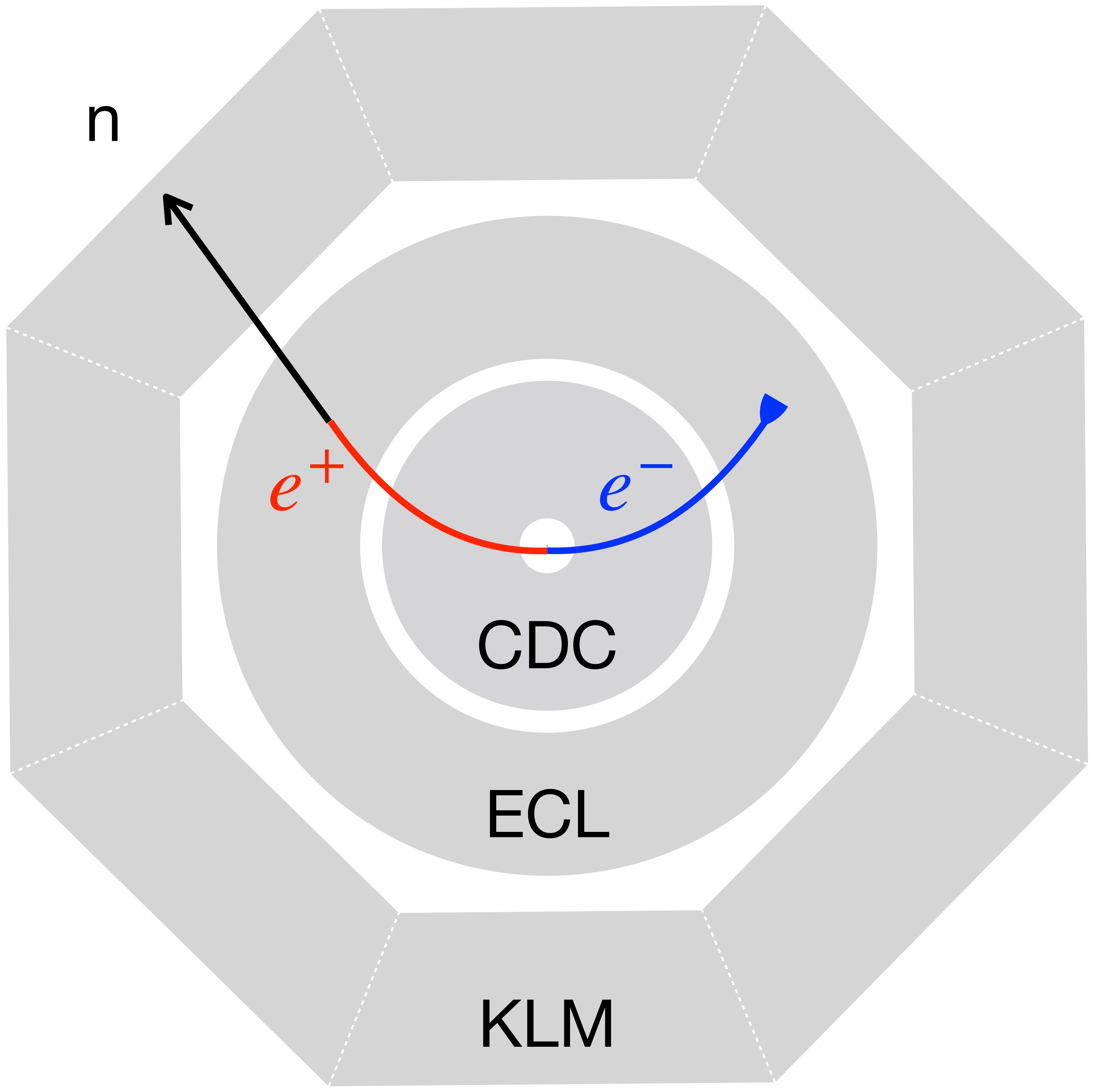
λ_0 = hadronic interaction length

KLM has $\sim 3.9\,\lambda_0$

ECL has $\sim 0.8\,\lambda_0$

Prob to penetrate ECL & KLM is about 1%

about 81 neutron background in total



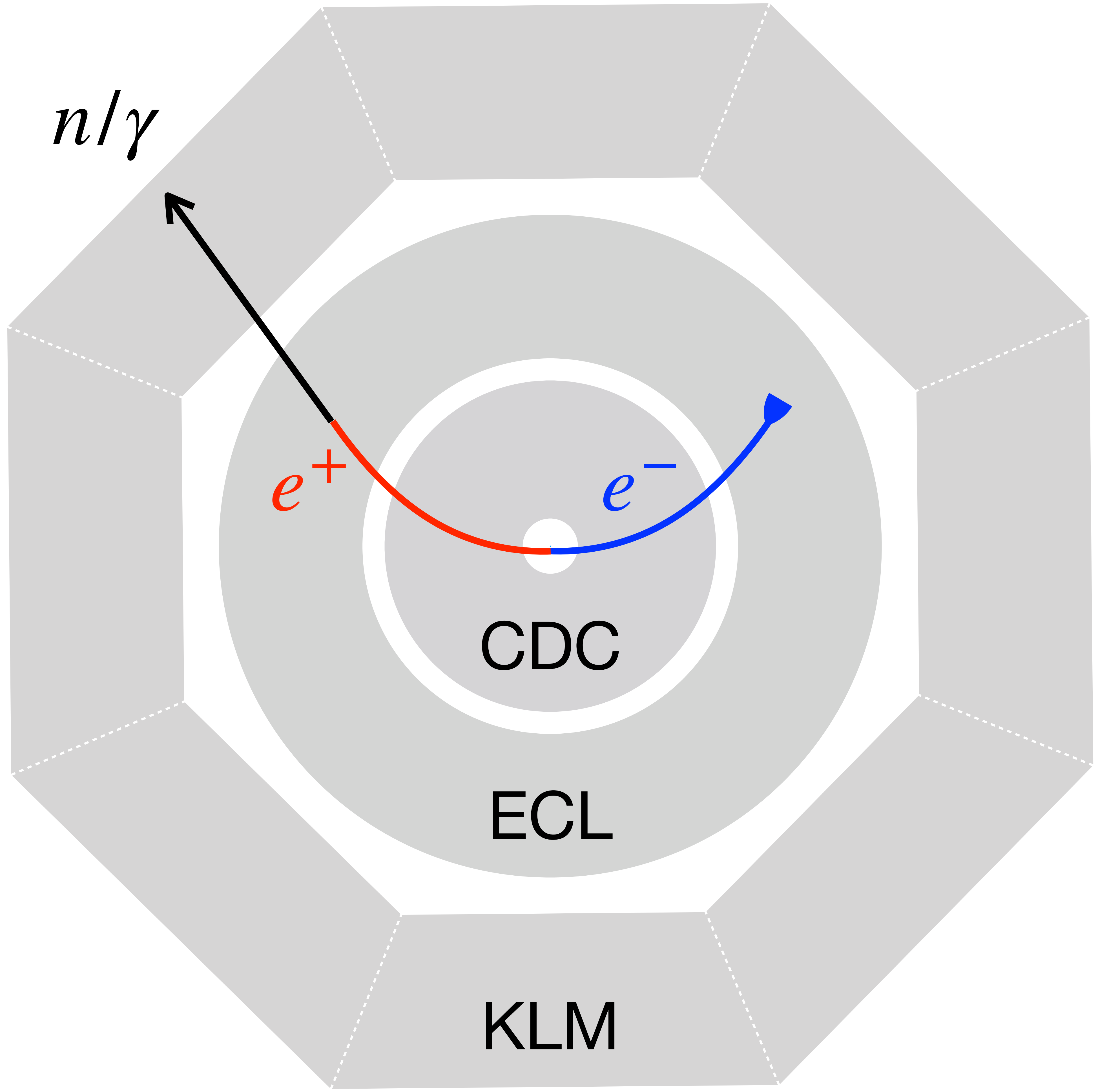
Summary on background estimation

BG: e^+ + ECL $\to \gamma/n$ 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

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

[Holdom 1986]

[Foot & He 1991]

[Kors & Nath 2004]

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

dark photon A'_μ

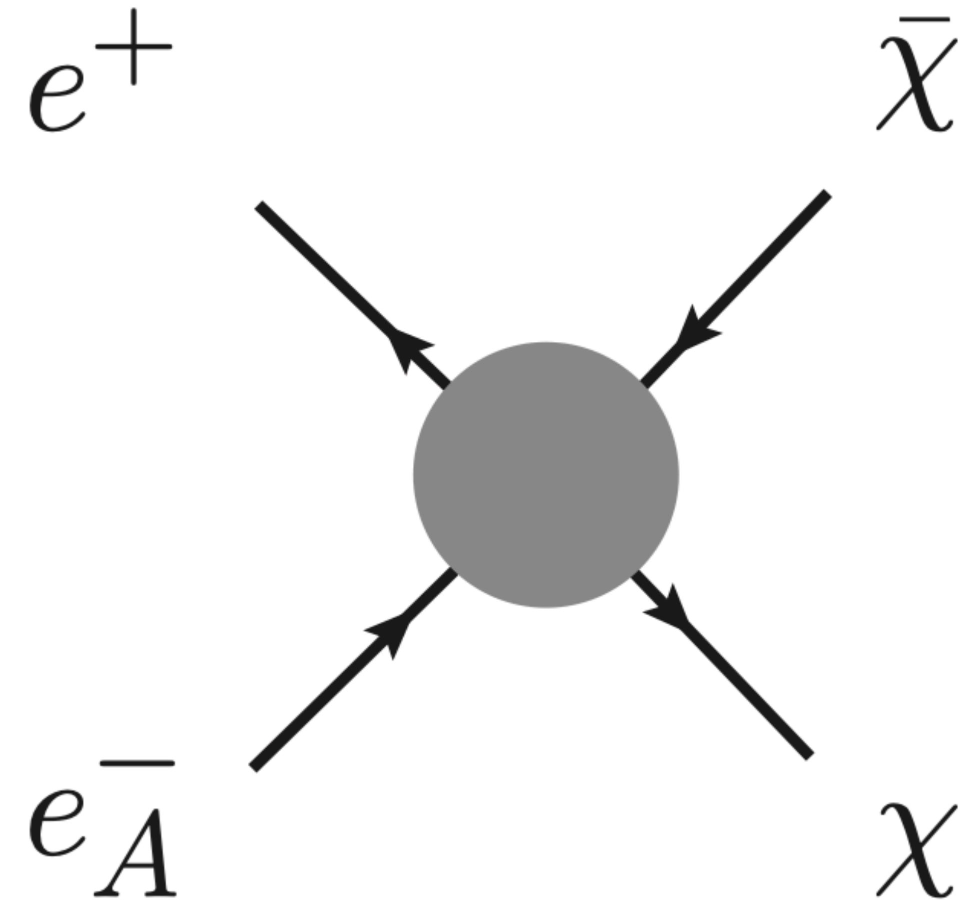
suppressed coupling ϵ to SM fermion

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

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

Annihilation with atomic electrons

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



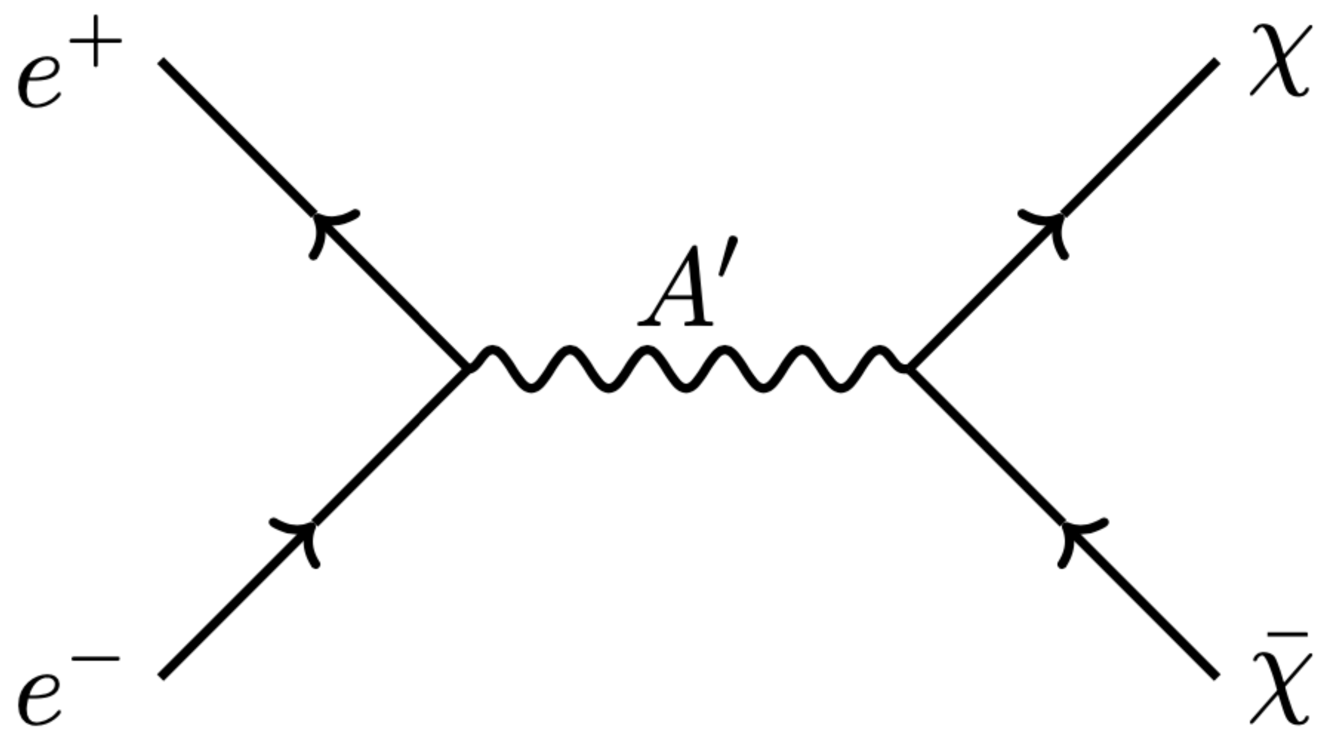
$$\sigma_{\mathrm{ann}}(\sqrt{s}) = \frac{e^2\epsilon^2\alpha_D}{3}\frac{s+2m_\chi^2}{(s-m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2}\sqrt{1-\frac{4m_\chi^2}{s}}$$

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

Annihilation with atomic electrons (continued)

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

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



n_e is the electron # density

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

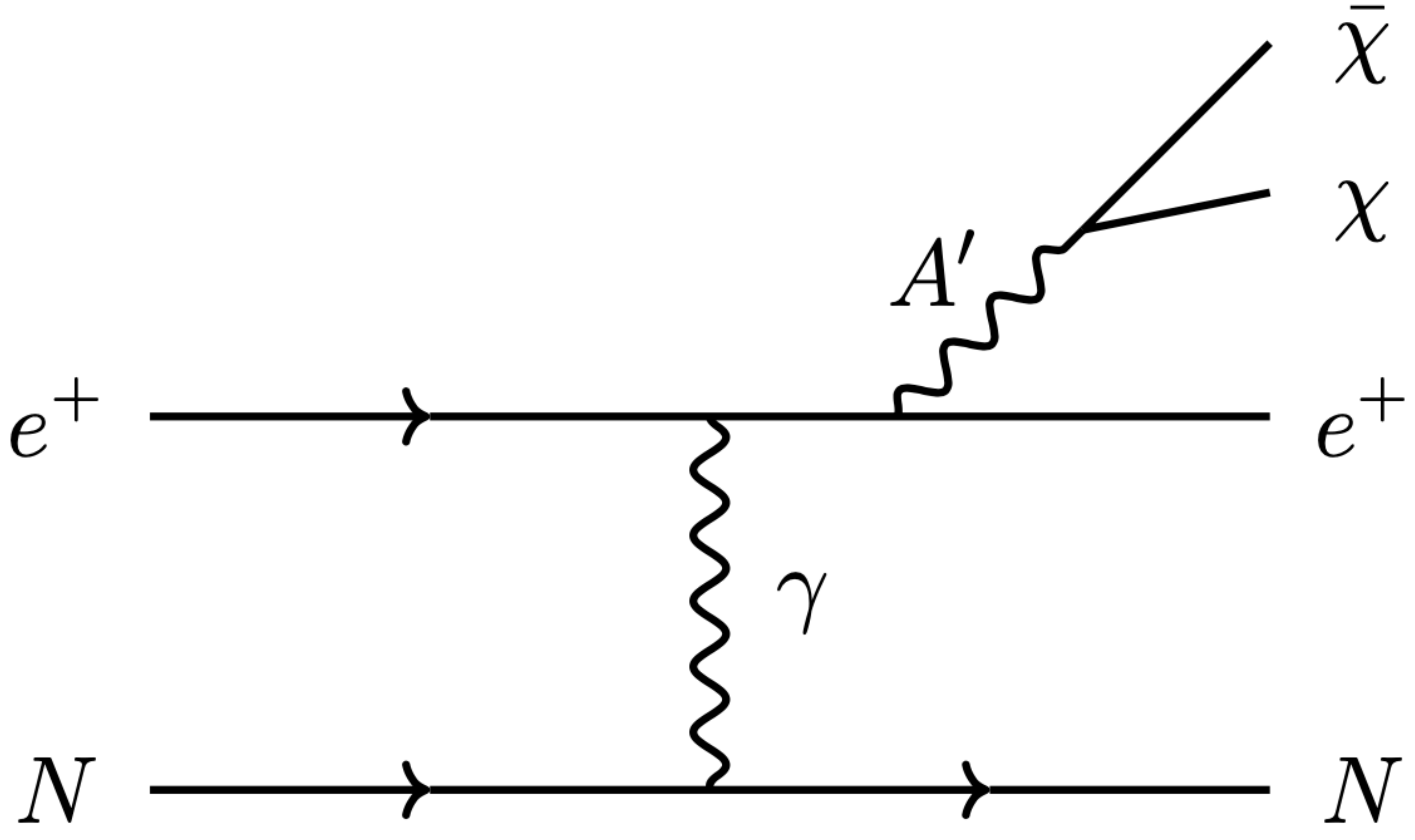
[Tsai & Whitis 1966] [Bjorken et al, 1988]

Bremsstrahlung with target nucleus

dominated by on-shell A' production

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

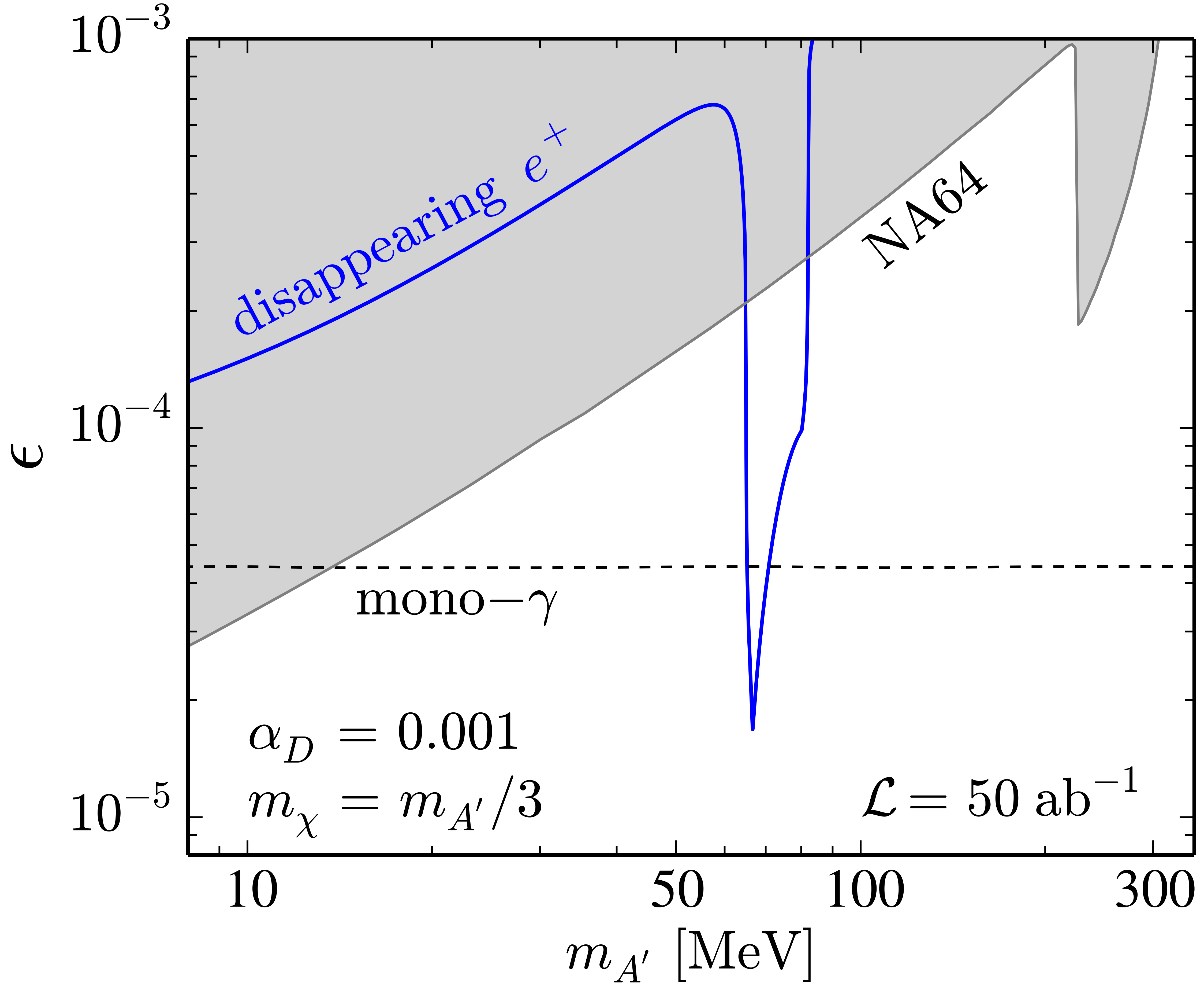
$\dfrac{d\sigma_{\text{bre}}}{dE_{A'}}$ = xsec of on-shell produced A'



[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 detection

We find that this new DM channel at Belle II can probe new parameter space of invisible dark photon, surpassing both the mono-photon channel at Belle II and the missing momentum search at 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]

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

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]

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

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

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]:

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

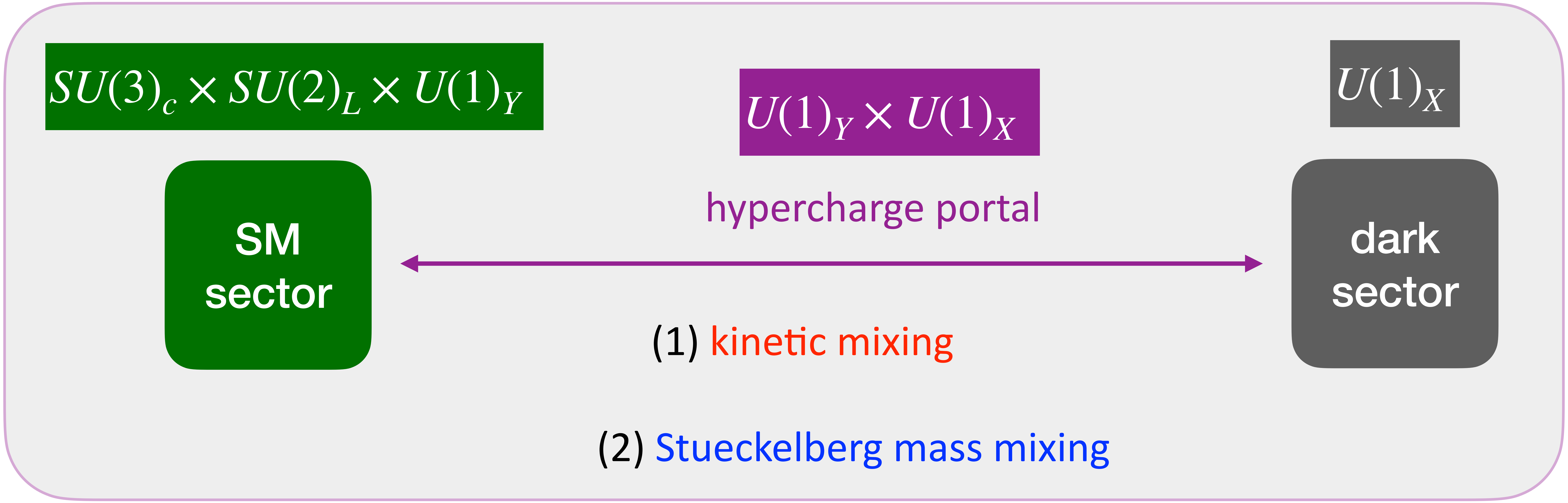
with $t_{\rm min} = (m_{A'}^2/2E')^2$, $t_{\rm max} = m_{A'}^2 + m_e^2$, $a = 111m_e^{-1}Z^{-1/3}$, and $d = 0.164A^{-2/3}$ GeV^2. We use $Z = 53\,(55)$ and $A = 127\,(133)$ for I (Cs). Here we only consider the dominant elastic form factor.

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

Hypercharge portal models $\Longrightarrow$ dark photon

[Holdom 1986] [Foot & He 1991] [Kors & Nath 2004] [Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

Hypercharge portal models $\Longrightarrow$ dark photon



[Holdom 1986] [Foot & He 1991] [Kors & Nath 2004] [Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon}\, B_\mu)^2$$

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

kinetic mixing

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

kinetic mixing

mass mixing

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

kinetic mixing

mass mixing

kinetic mixing $\tilde{\delta}$ & mass mixing $\tilde{\epsilon}$ are degenerate (w/o χ): only $\epsilon \sim (\tilde{\epsilon} - \tilde{\delta})$ is physical

dark photon & millicharged particles

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

dark photon & millicharged particles

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

- $X_\mu \Longrightarrow A'_\mu$ (dark photon), if $M_1 \ll M_Z$

  $\epsilon e Q_f A'_\mu \bar{f}\gamma^\mu f$ (SM sector) and $g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ (dark sector)

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

dark photon & millicharged particles

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

- $X_\mu \Longrightarrow A'_\mu$ (dark photon), if $M_1 \ll M_Z$

  $\epsilon e Q_f A'_\mu \bar{f}\gamma^\mu f$ (SM sector) and $g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ (dark sector)

- $X_\mu \Longrightarrow Z'_\mu$ (hypercharge-like), if $M_1 \gg M_Z$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

dark photon & millicharged particles

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

- $X_\mu \Longrightarrow A'_\mu$ (dark photon), if $M_1 \ll M_Z$

  $\epsilon e Q_f A'_\mu \bar{f}\gamma^\mu f$ (SM sector) and $g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ (dark sector)

- $X_\mu \Longrightarrow Z'_\mu$ (hypercharge-like), if $M_1 \gg M_Z$

If A'_μ or Z'_μ is massive, χ is millicharged ($\epsilon e A_\mu \bar{\chi}\gamma^\mu \chi$) only when $\tilde{\epsilon} \neq 0$

[Feldman, ZL, Nath, hep-ph/0702123, 373 cites]

[see also Fabbrichesi+, 2005.01515, Dark Photon Review]