Millicharged particles at electron colliders

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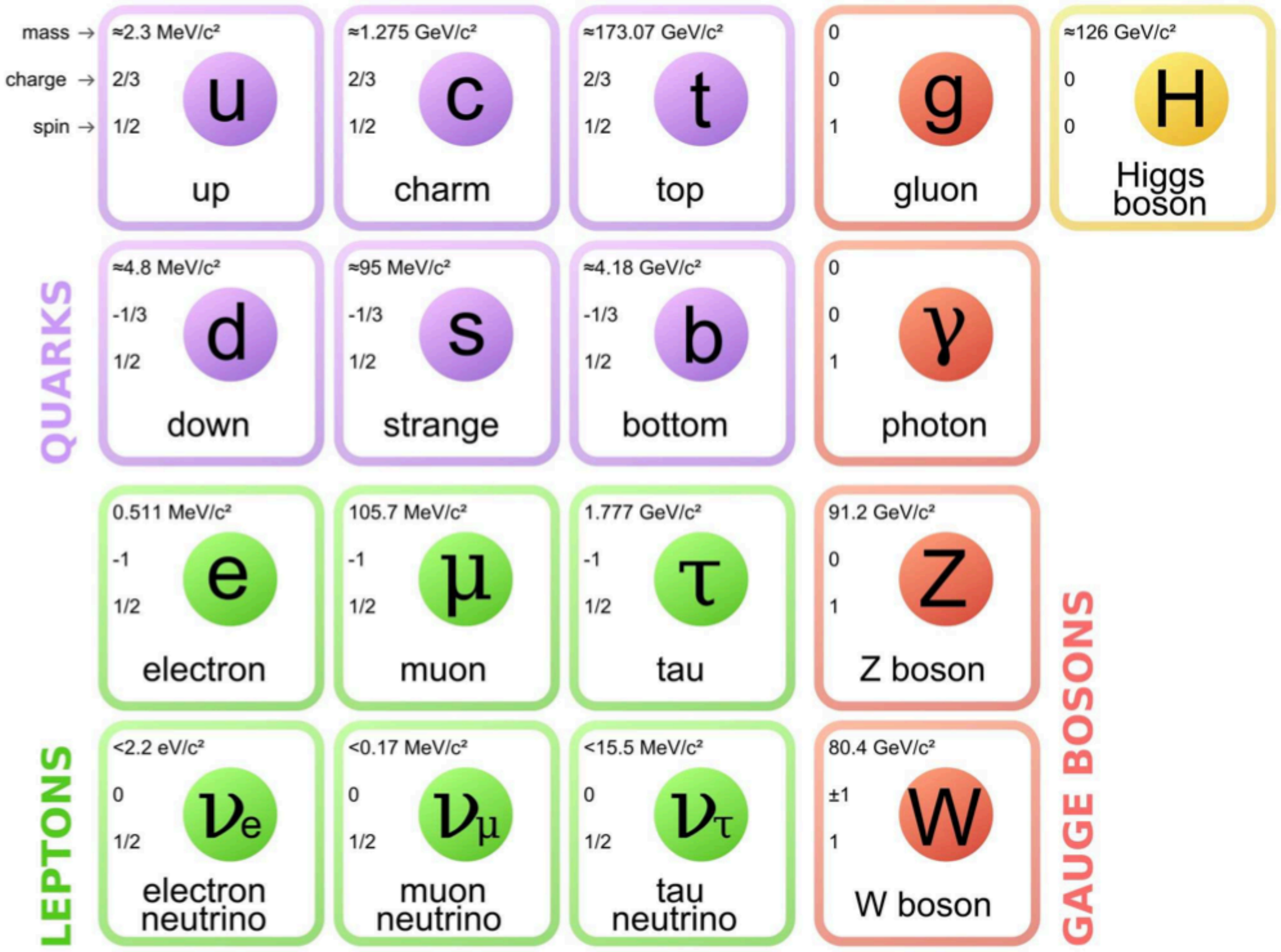
SUSY2021

Outline

- Introduction and motivation
- Current constraint
- Mono photon signal
- Irreducible background and reducible background
- Result and summary

SM particles



New particles:

- heavy
- weak coupling

Millicharged particles

$$L_{int} = \epsilon e A_\mu \bar{\chi} \gamma^\mu \chi$$

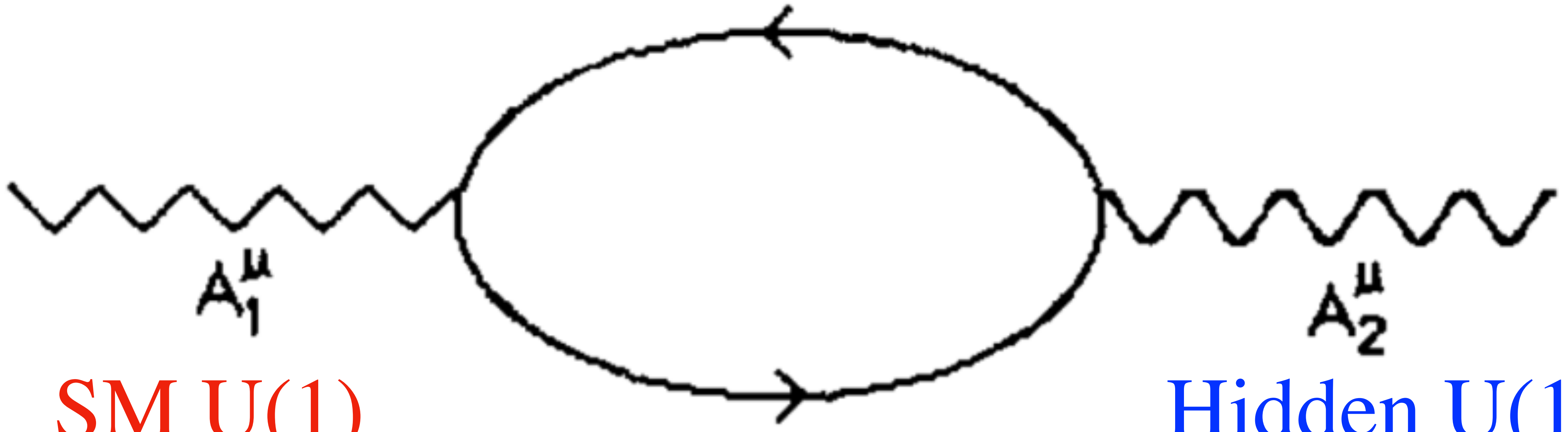
A_μ: SM photon

χ: millicharged particle

ϵ: the charge of millicharged particle in unit of electron charge

Millicharge: $\epsilon \ll 1$

Millicharge generated by kinetic mixing



SM U(1)

Hidden U(1)

Very heavy fermions couple to both U(1)s

→ Kinetic mixing between two U(1)s

→ A fermion with hidden U(1) charge will be millicharged particle

Holdom, 1986

Millicharge generated by mass mixing

Stueckelberg mass mixing for hypercharge $U(1)_Y$ & hidden $U(1)_X$

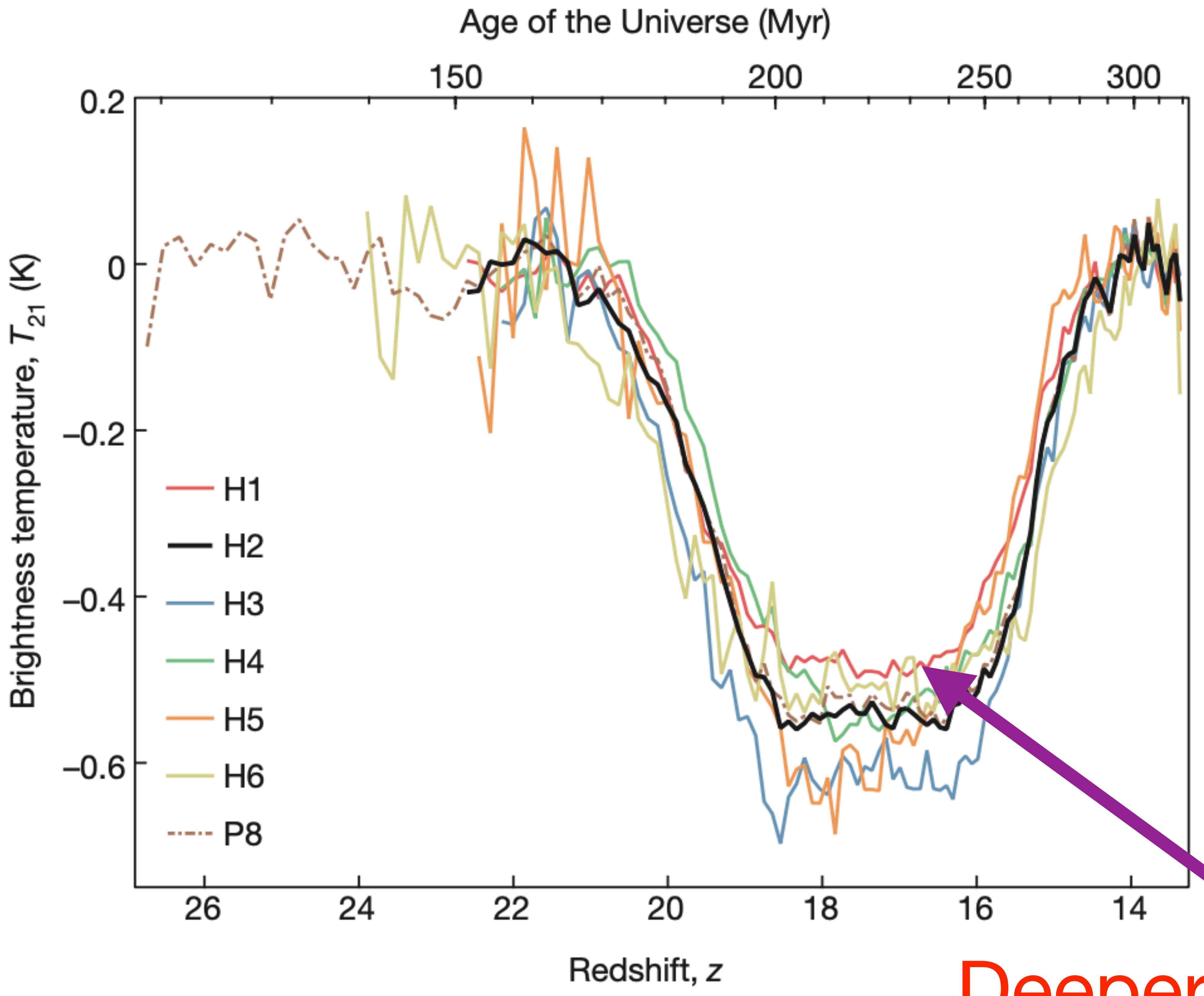
$$\mathscr{L} \sim -\frac{1}{2}\left(\partial_\mu \sigma + m_1 X_\mu + m_2 B_\mu^Y\right)^2$$

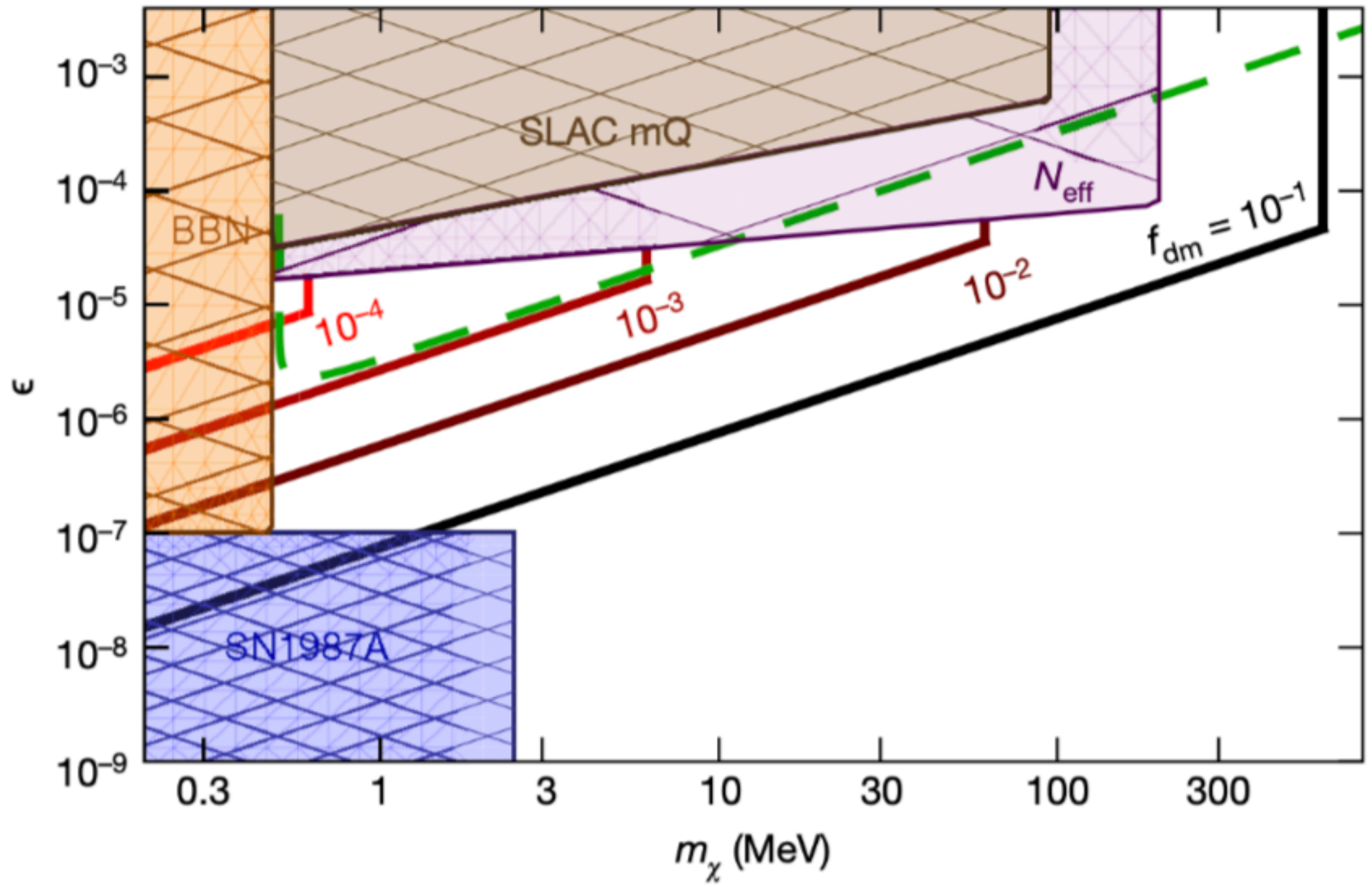
→ Mass mixing between $U(1)_Y$ and $U(1)_X$

→ A fermion with only hidden $U(1)_X$ charge will be millicharged particle with $\epsilon \sim m_2/m_1$

Feldman, Liu, Nath, 2007

Millicharge and 21 cm anomaly





Deeper than expected

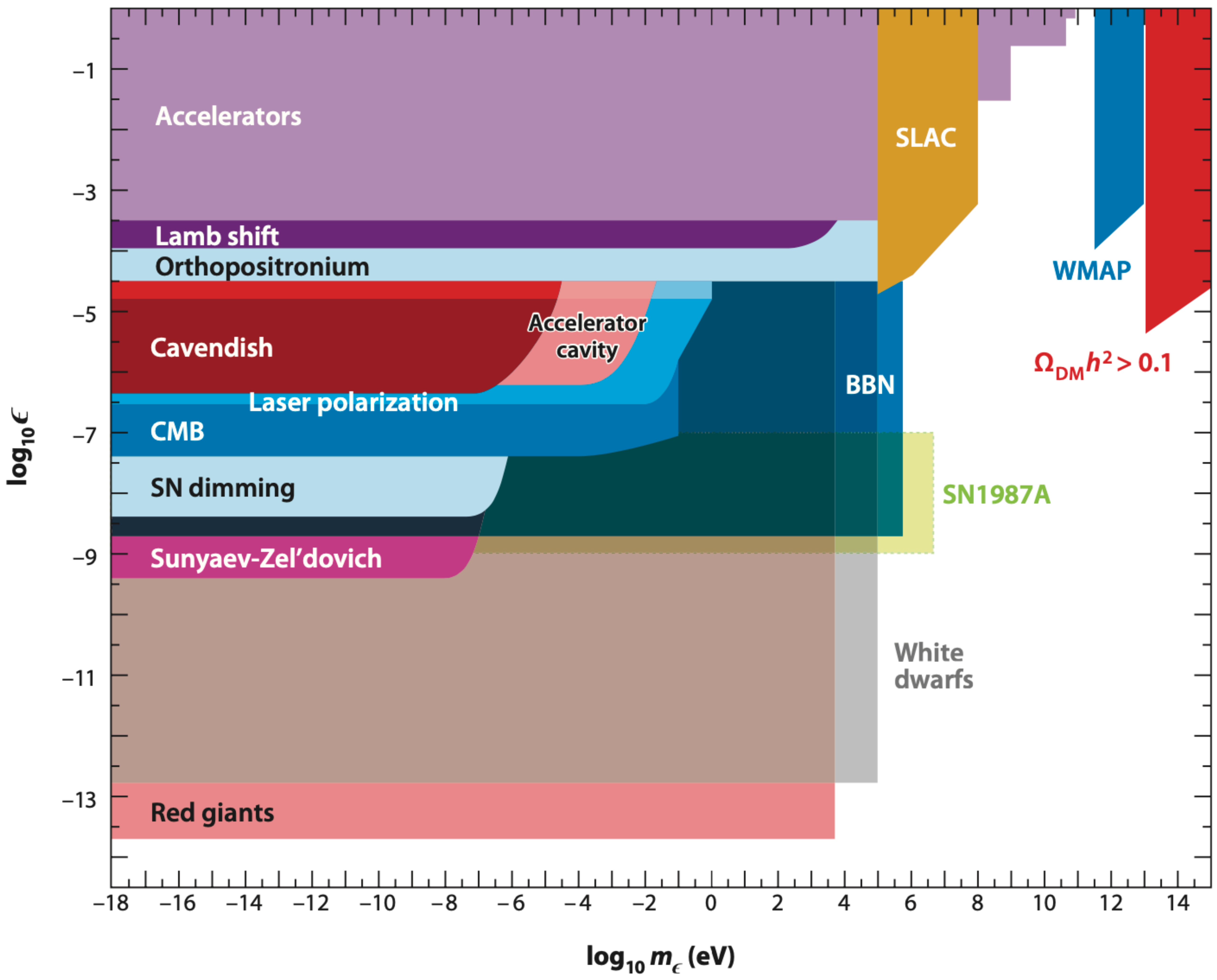
Cool down baryon

Cross section between millicharge DM and baryon

$$\bar{\sigma}_t = \frac{2\pi c^2 \hbar^2 \alpha^2 \epsilon^2 \xi}{\mu_{\chi,t}^2 v^4}$$

Bowman+ 2018; Muñoz, Loeb 2018

Constraints



Jaeckel, Ringwald,1002.0329

Astrophysical constraints:

SN1987A, Red giants, CMB, BBN…

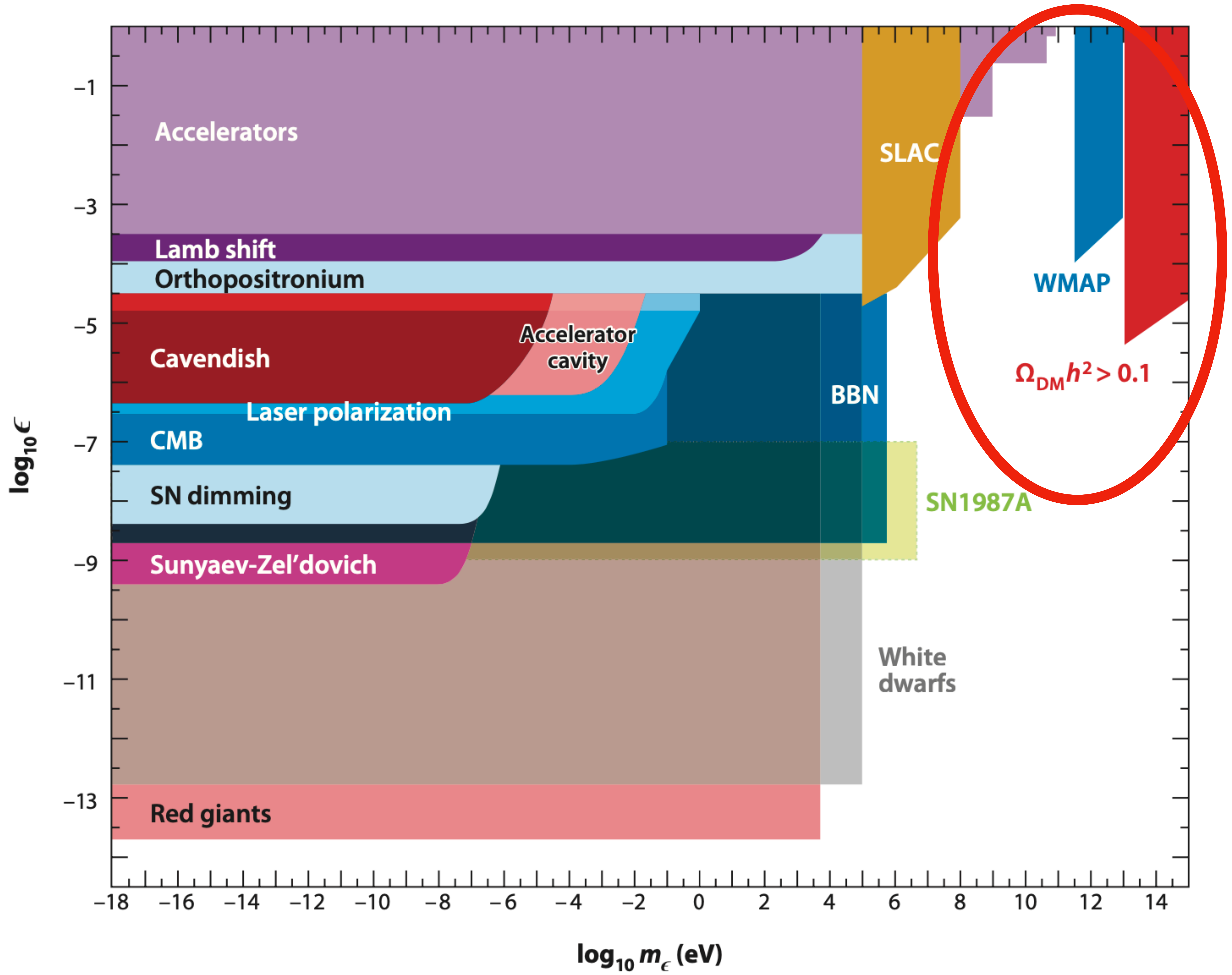
Electromagnetic experiment constraints:

Lamb shift, Cavendish…

Accelerators constraints:

SLAC…

Probing millicharge with GeV electron colliders

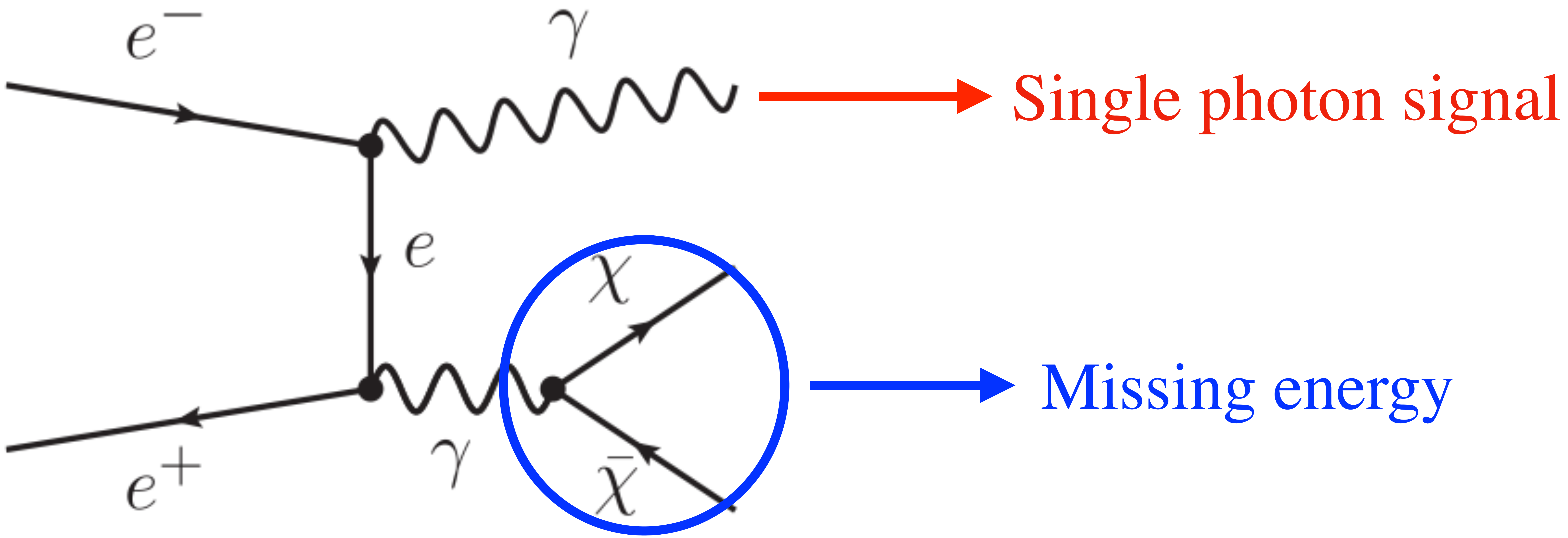


Poorly constrained at GeV mass

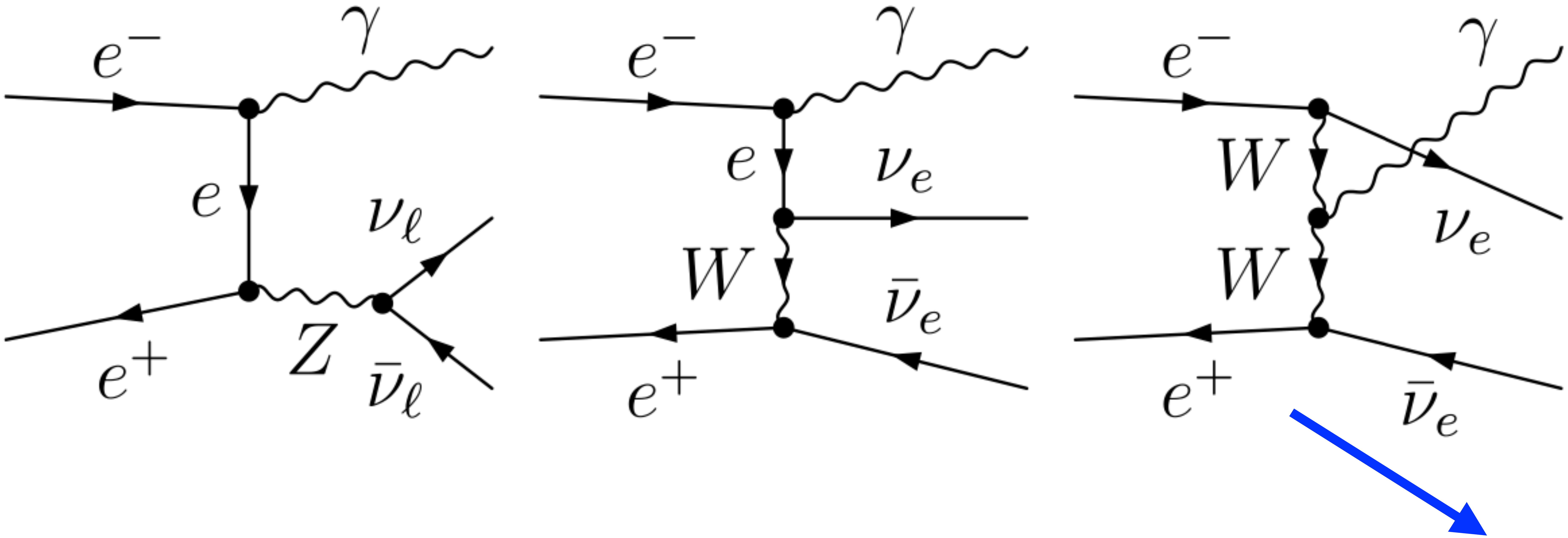
- BESIII ($\sqrt{s} \simeq 3\text{GeV}$)
- BABAR ($\sqrt{s} \simeq 10\text{GeV}$)
- Belle II ($\sqrt{s} \simeq 10\text{GeV}$)
- STCF ($\sqrt{s} \simeq 4\text{GeV}$)

Jaeckel, Ringwald,1002.0329

Single photon signal



Irreducible Background



Can be neglected when $\sqrt{s} \ll m_W$

Neutrino is undetectable in collider detectors

Splitting function for initial state radiation

$$\frac{d\sigma_{e^+e^-\to f\bar{f}\gamma}}{dz_\gamma dx_\gamma} = \sigma_{e^+e^-\to f\bar{f}}(s_{f\bar{f}})R(x_\gamma, z_\gamma, s)$$

$$R(x_\gamma, \theta_\gamma, s) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left[\frac{1+\left(1-x_\gamma\right)^2}{1-z_\gamma^2} - \frac{x_\gamma^2}{2}\right]$$

$$s_{f\bar{f}} = m_{f\bar{f}}^2 = s - 2\sqrt{s}E_\gamma$$

$$x_\gamma = E_\gamma/(\sqrt{s}/2)$$

Photon only couples to initial state particles

Nicrosini, Trentadue 1989; Montagna+ 1995; Chu+, 2018

Differential cross section

Signal: $e^+e^- \to \chi\bar{\chi}\gamma$ [Liu, Zhang 2018]

$$\frac{d\sigma}{dE_\gamma dz_\gamma} = \frac{8\alpha^3\varepsilon^2\left(1+2m_\chi^2/s_\gamma\right)\beta_\chi}{3sE_\gamma\left(1-z_\gamma^2\right)}\left[1+\frac{E_\gamma^2}{s_\gamma}\left(1+z_\gamma^2\right)\right]$$

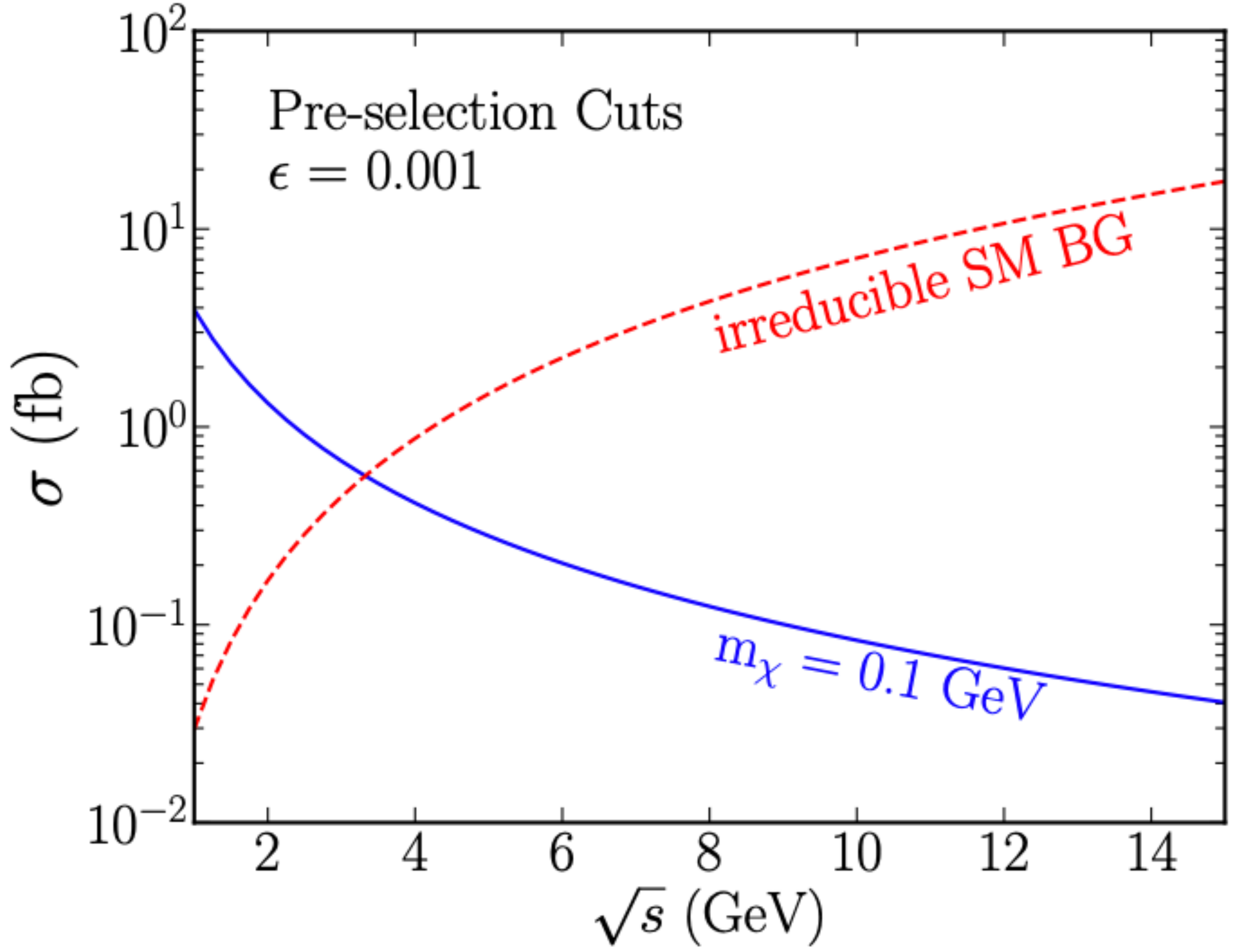
$$s_\gamma = s - 2\sqrt{s}E_\gamma \qquad \beta_\chi = \left(1-4m_\chi^2/s_\gamma\right)^{1/2}$$

Irreducible BG: $e^+e^- \to \nu\bar{\nu}\gamma$ [Ma, Okada1978; Gaemers+ 1979]

$$\frac{d\sigma}{dE_\gamma dz_\gamma} = \frac{\alpha G_F^2 s_\gamma^2}{4\pi^2 sE_\gamma\left(1-z_\gamma^2\right)} f\left(s_W\right)\left[1+\frac{E_\gamma^2}{s_\gamma}\left(1+z_\gamma^2\right)\right]$$

$$f\left(s_W\right) = 8s_W^4 - 4s_W^2/3 + 1$$

Signal and Irreducible background



Pre-selection Cuts [BESIII, 1707.05178]:

$E_\gamma > 25\text{MeV}$ with $|\cos\theta| < 0.8$

or

$E_\gamma > 50\text{MeV}$ with $0.86 < |\cos\theta| < 0.92$

$\frac{S}{\sqrt{B}}$ increase with lower collider energy

Reducible background

Leptons and photons are undetected due to the lack of acceptance or inefficiency in the detectors

beam BG: all undetected particle escape from the beam direction.

gap BG: there is at least one particle escape from the gap of detector

$$e^+e^- \to \not\gamma\gamma$$

$$e^+e^- \to \not\gamma\not\gamma\gamma$$

$$e^+e^- \to \not\ell^+\not\ell^-\gamma$$

Belle II detectors

CDC:

(17,150)

ECL:

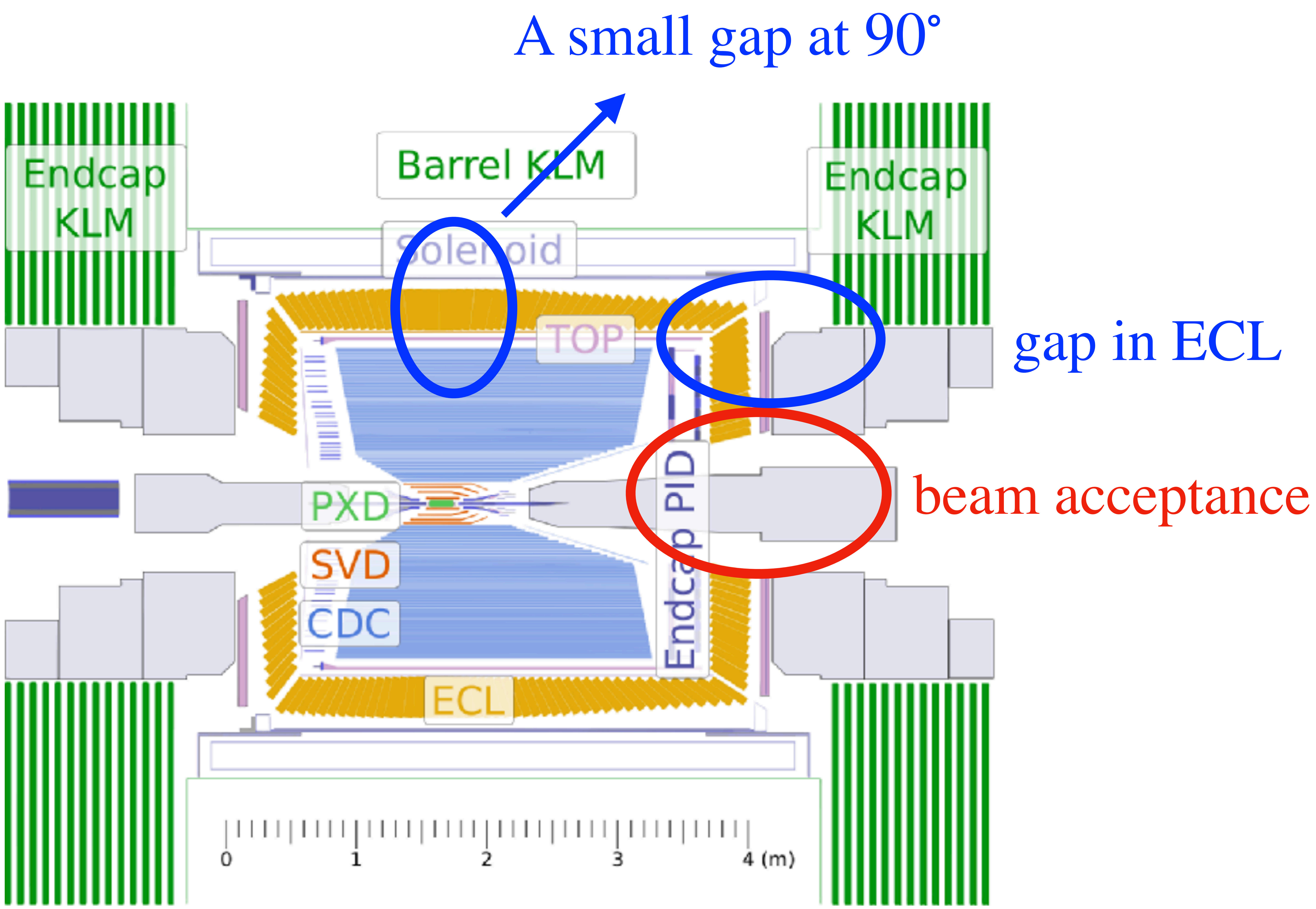
(12.4, 31.4) (32.2, 128.7) (130.7, 155.1)

KLM:

(25, 40) (40, 129) (129, 155)

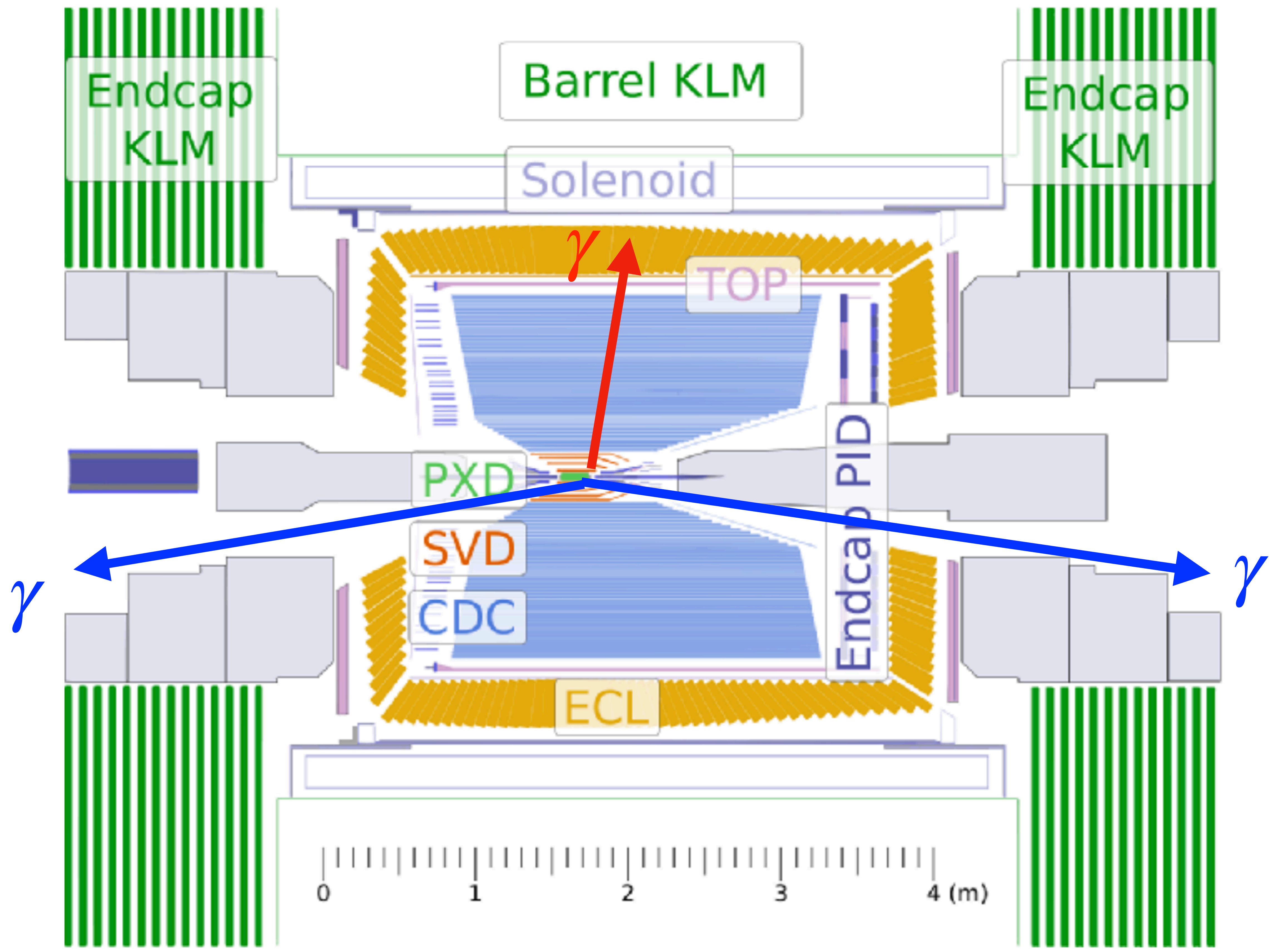
Photon: ECL, KLM

Charged particles: CDC, ECL, KLM

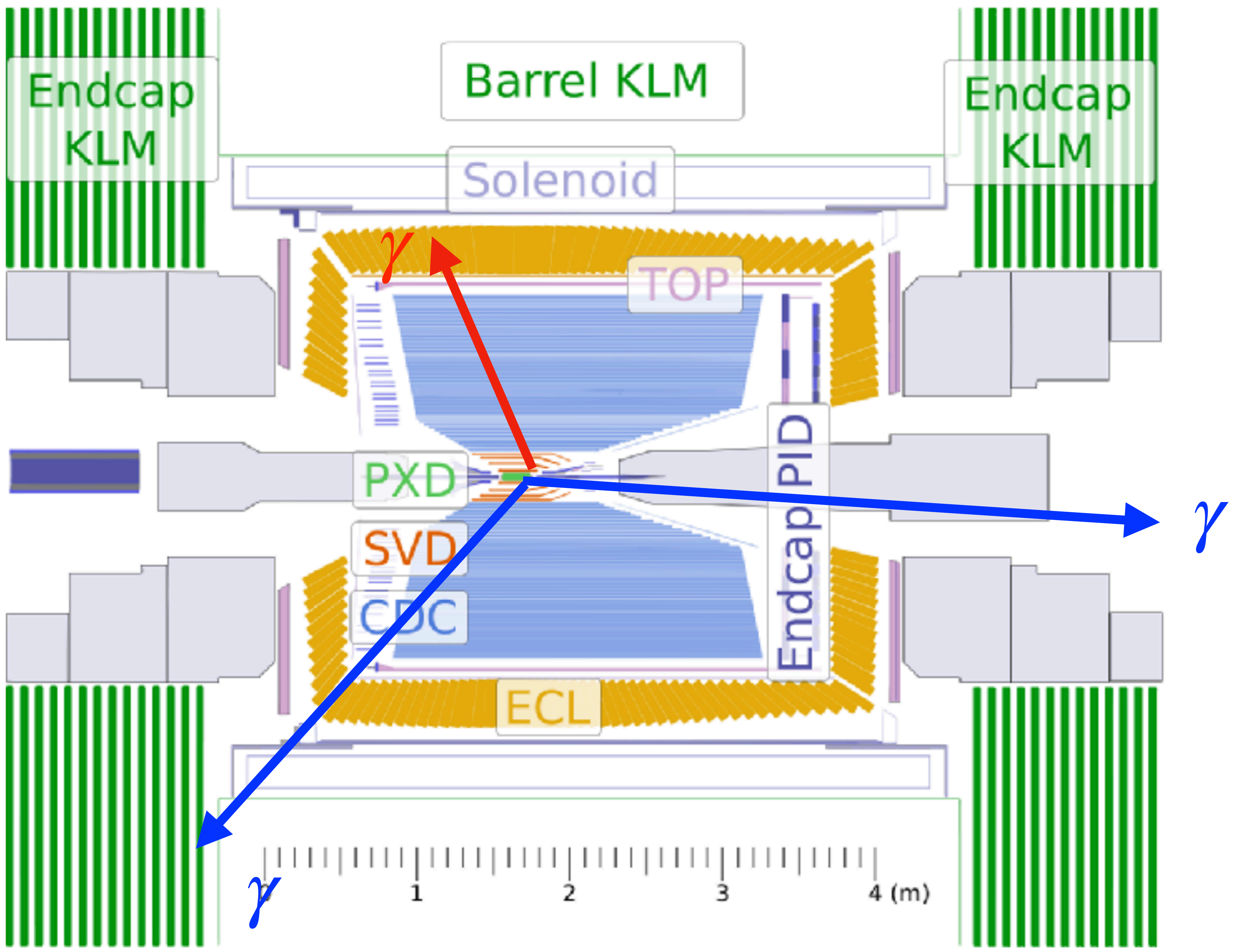


Svidras's talk, 2020

beam BG and gap BG

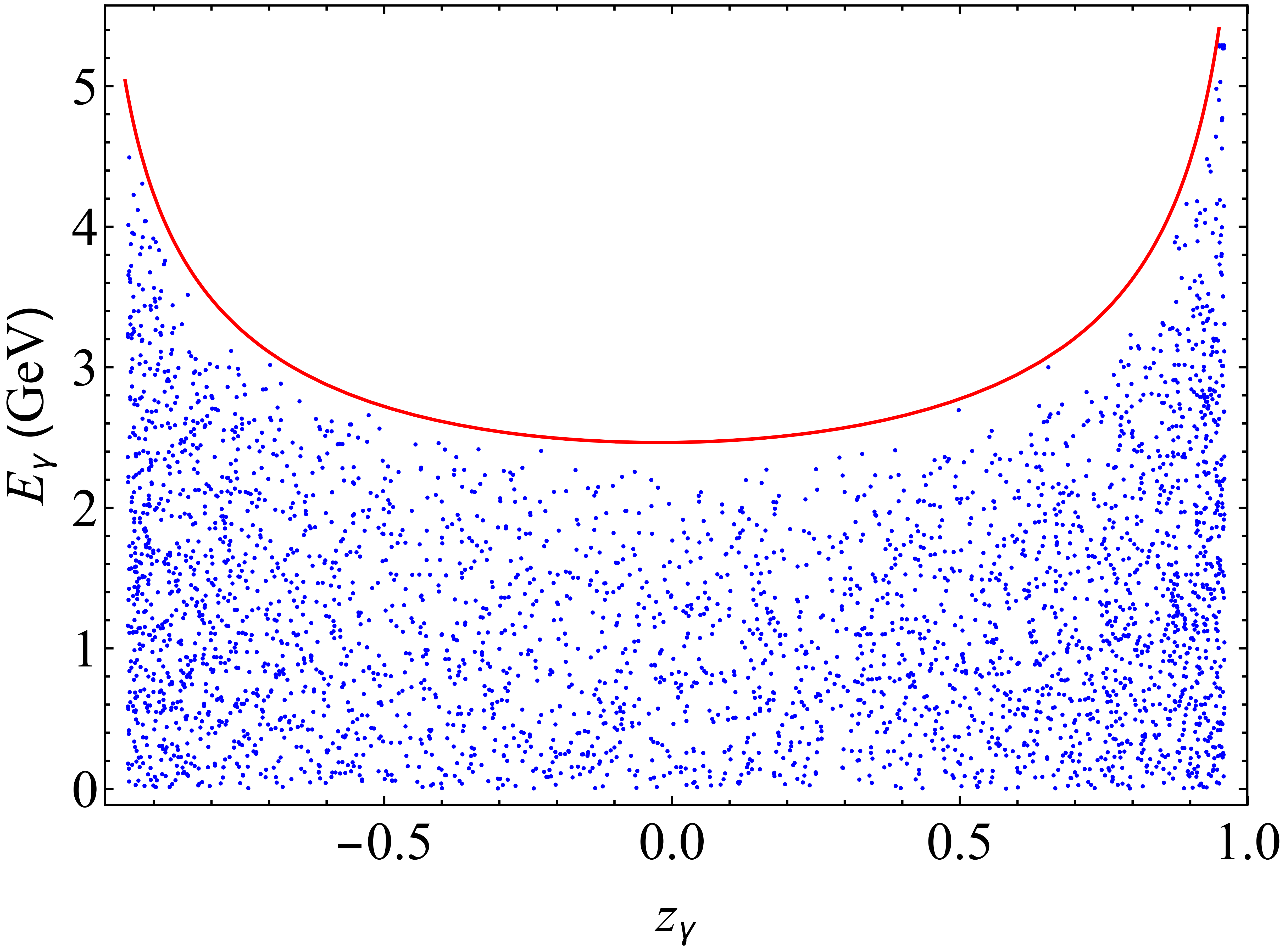


beam BG



gap BG

Beam background



bBG cut

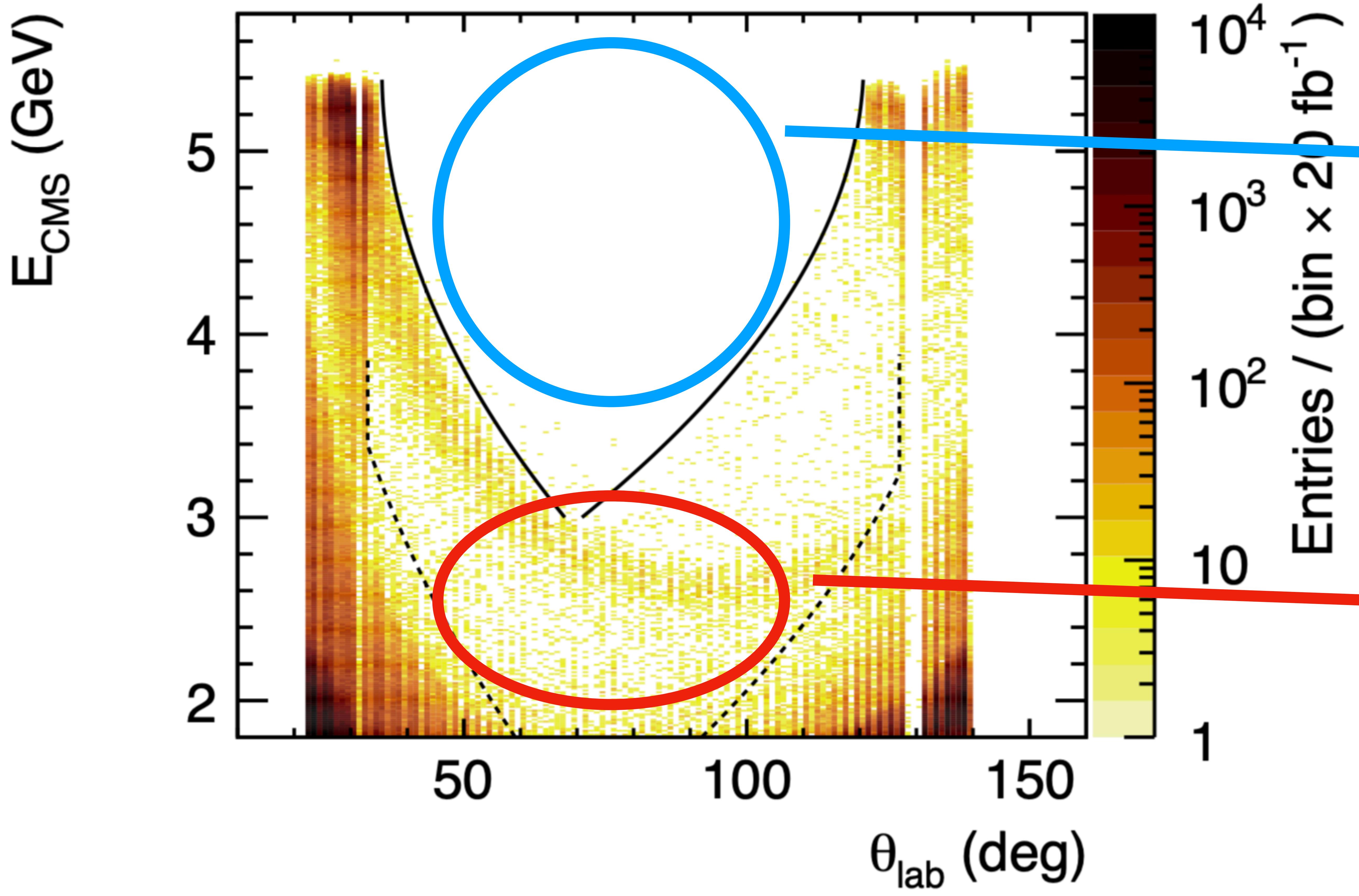
$$E^m_\gamma(\theta_\gamma) = \frac{\sqrt{s}\,(A\cos\theta_1 - \sin\theta_1)}{A(\cos\theta_1 - \cos\theta_\gamma) - (\sin\theta_\gamma + \sin\theta_1)}$$

$$A = (\sin\theta_1 - \sin\theta_2)\,/\,(\cos\theta_1 - \cos\theta_2)$$

θ_1, θ_2 : the edge of detector

Eliminate all beam backgrounds!

Gap background

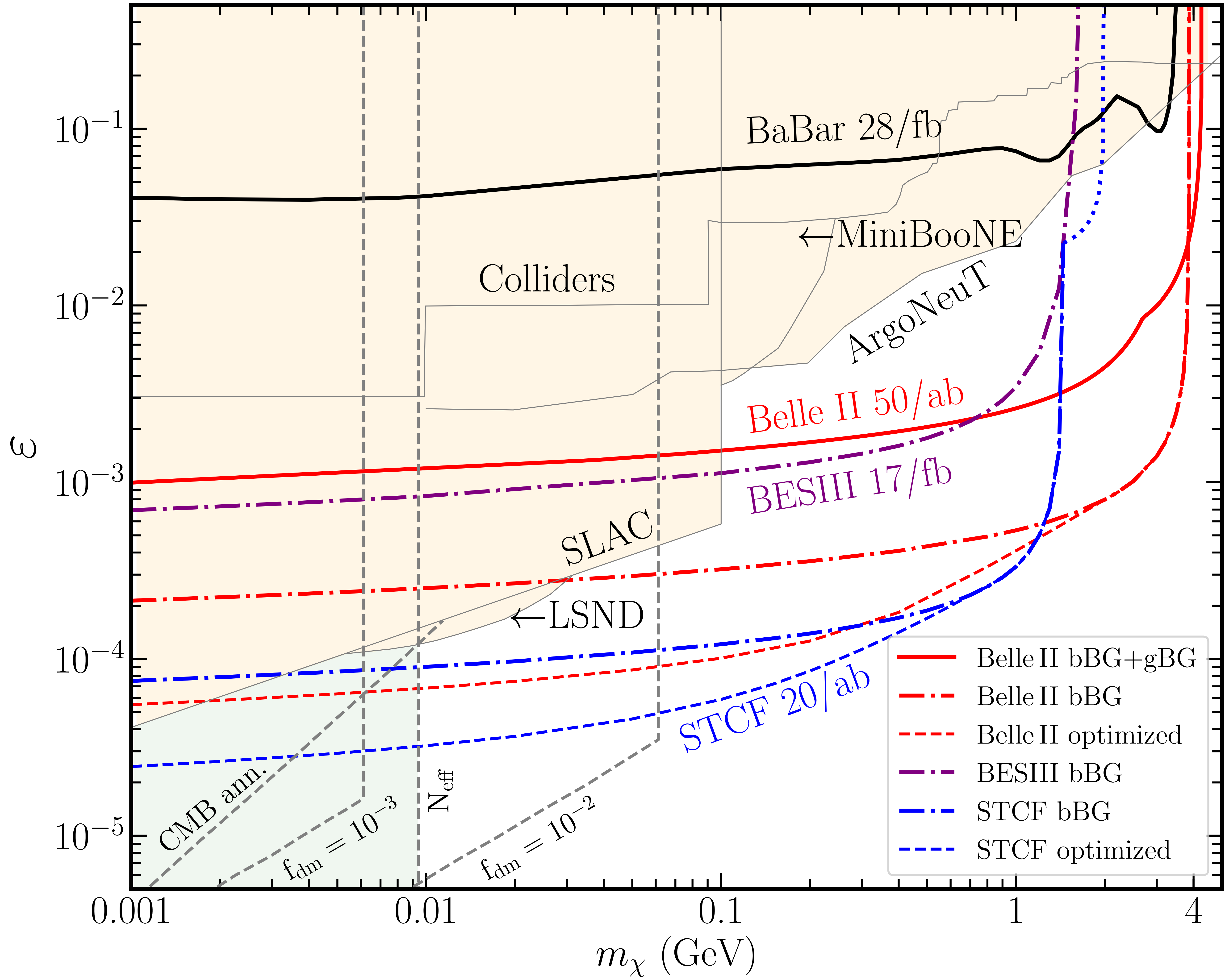


300 events (20/fb),
only gap backgrounds due to
ECL 90˚ gap

25000 events (20/fb),
gap backgrounds due to ECL
barrel-endcap gap dominate

Ferber+, 1808.10567

Constraints



Belle II can probe new parameter space at the GeV mass region.

Gap backgrounds are neglected in BESIII and STCF for the lack of detailed simulation. Constraints will be weaker in some mass region if gap backgrounds are considered.

Summary

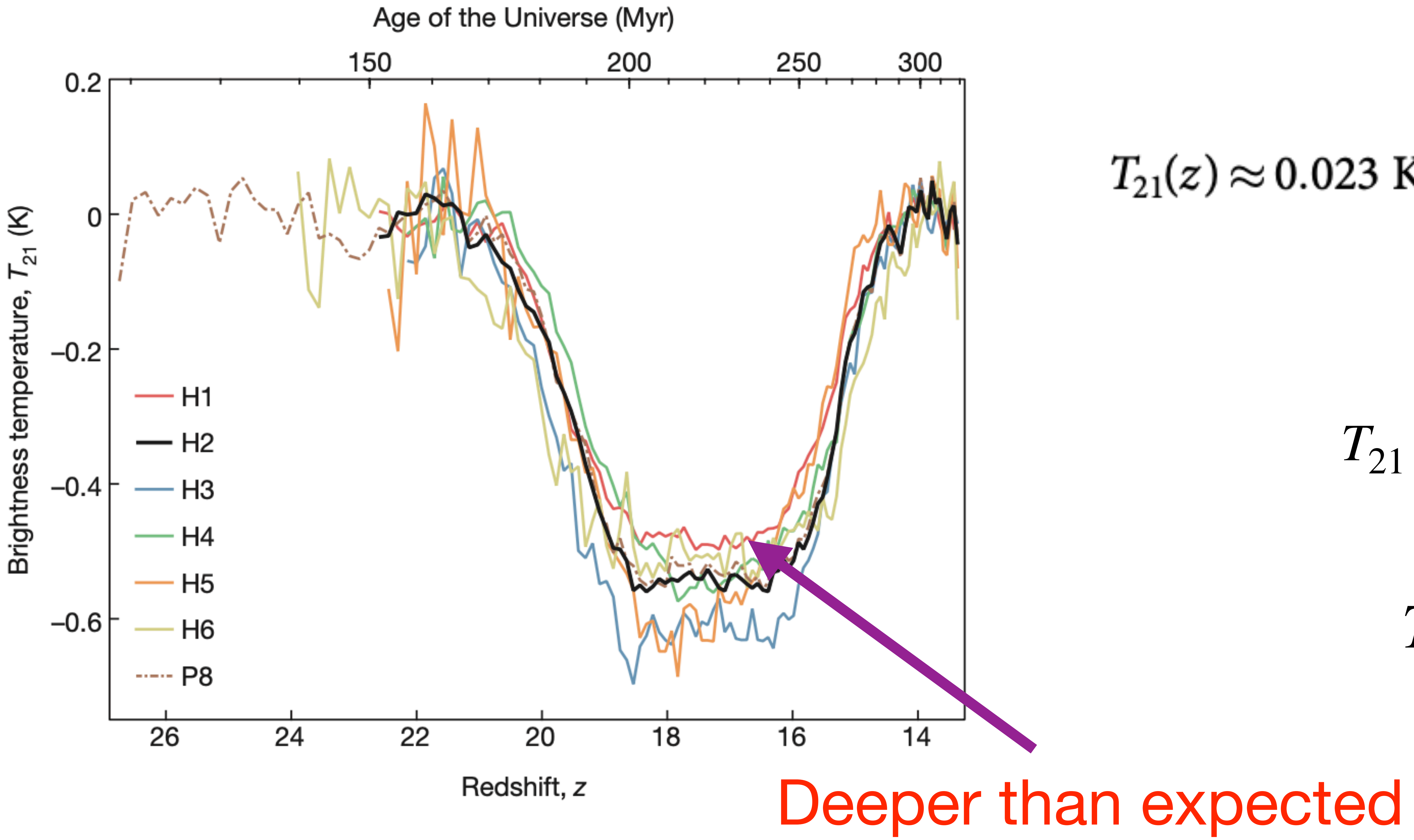
- Millicharged particles have been probed by many experiments including astrophysical observation, precise electromagnetic measurement and accelerator experiment.

- GeV electron colliders can probe new parameter space of millicharged particles at GeV mass.

Thank You !

Backup

Millicharge and 21 cm anomaly



$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

$$T_{21} \propto 1 - \frac{T_{CMB}}{T_S} \simeq 1 - \frac{T_{CMB}}{T_b}$$

$$T_{CMB} > T_b > T_{DM}$$

Bowman+ 2018; Muñoz, Loeb 2018

Millicharge generated by mass mixing

Stueckelberg mass mixing for hypercharge & $U(1)_X$

$$\mathcal{L} \sim -\frac{1}{2}\left(\partial_\mu \sigma + m_1 X_\mu + m_2 B_\mu\right)^2$$

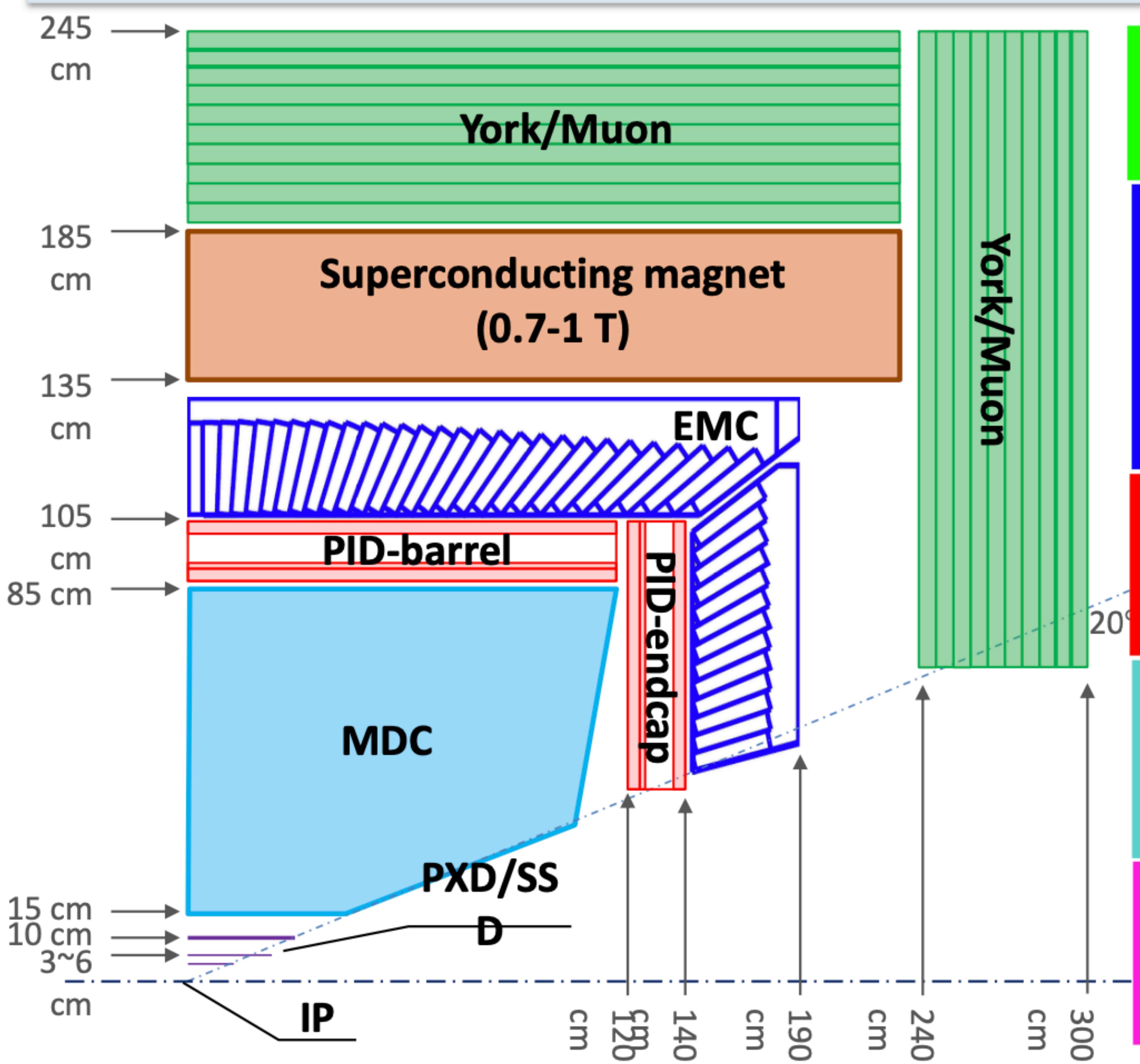
$$\delta B_\mu = \partial_\mu \lambda_X, \qquad \delta C_\mu = 0, \qquad \delta\sigma = -M_2 \lambda_X,$$
$$\delta B_\mu = 0, \qquad \delta C_\mu = \partial_\mu \lambda_Y, \qquad \delta\sigma = -M_1 \lambda_Y.$$

$$\mathcal{L} \sim -\frac{1}{2}\left(m_1^2 X_\mu X^\mu + m_2^2 B_\mu B^\mu + 2 m_1 m_2 X_\mu B^\mu\right)$$

Feldman, Liu, Nath, 2007

SCTF detectors

10 years data taking，total 20/ab conservatively



MUD
- μ/π suppression power >10/30

EMC
- Energy range: 0.02-2.5 GeV
- At 1 GeV σ_E(%)
  - Barrel(Cs(I): 2
  - Endcap (Cs): 4

PID
- π/K (and K/p) 3-4σ separation up to 2GeV/c

MDC (Low mass)
- σ_{xy}=130 mm
- dE/dx<7%, σ_p/p =0.5% at 1 GeV

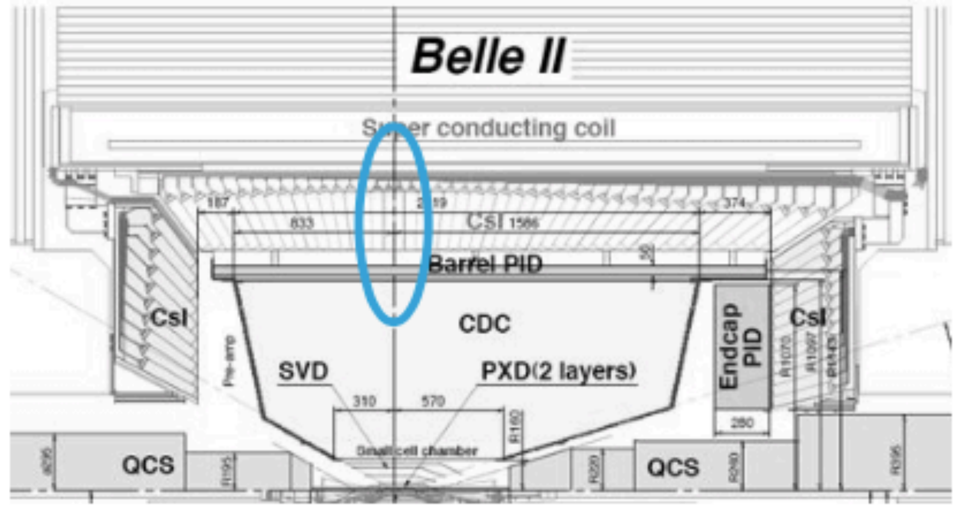
PXD
- Material budget ~0.15%X_0/layer
- σ_{xy}=50 mm

$\sqrt{s} \sim 2 - 7\text{GeV}$

Peng's talk, 2019

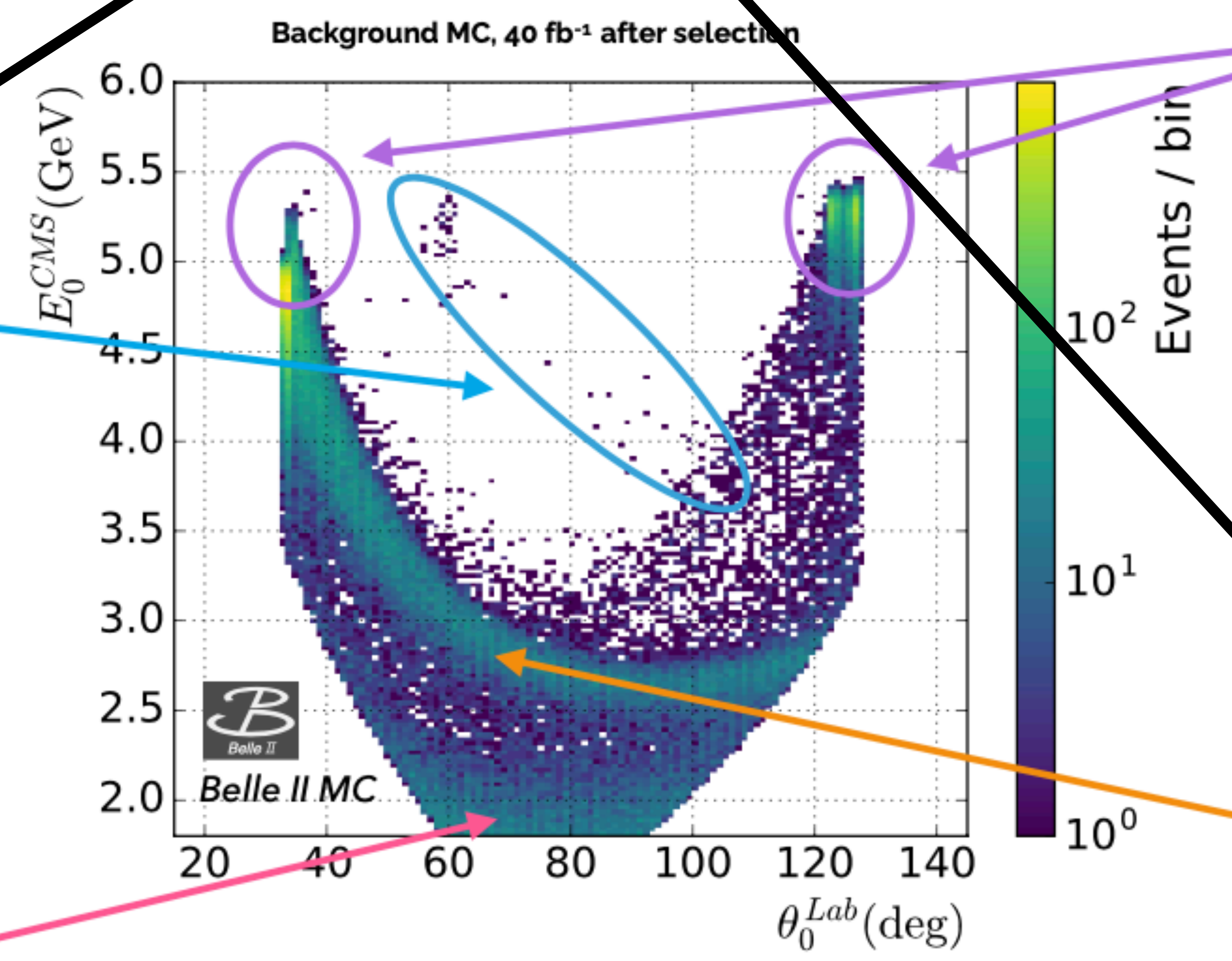
Reducible Background at BelleII

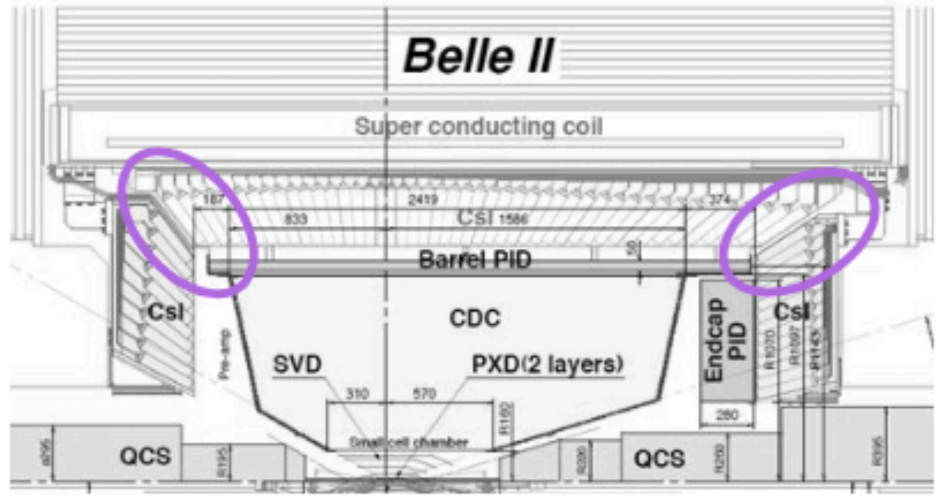
gBG



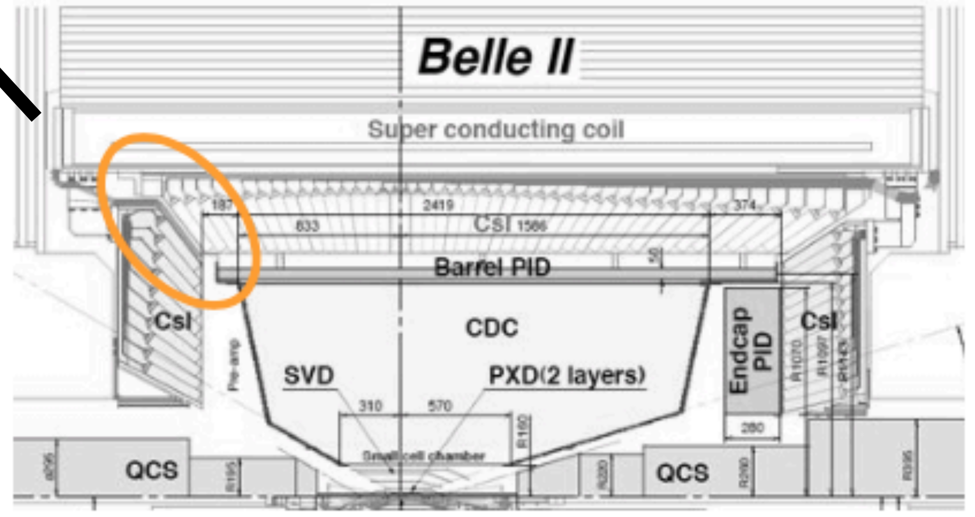
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$





ee→2γ
1γ in ECL BWD or FWD gap

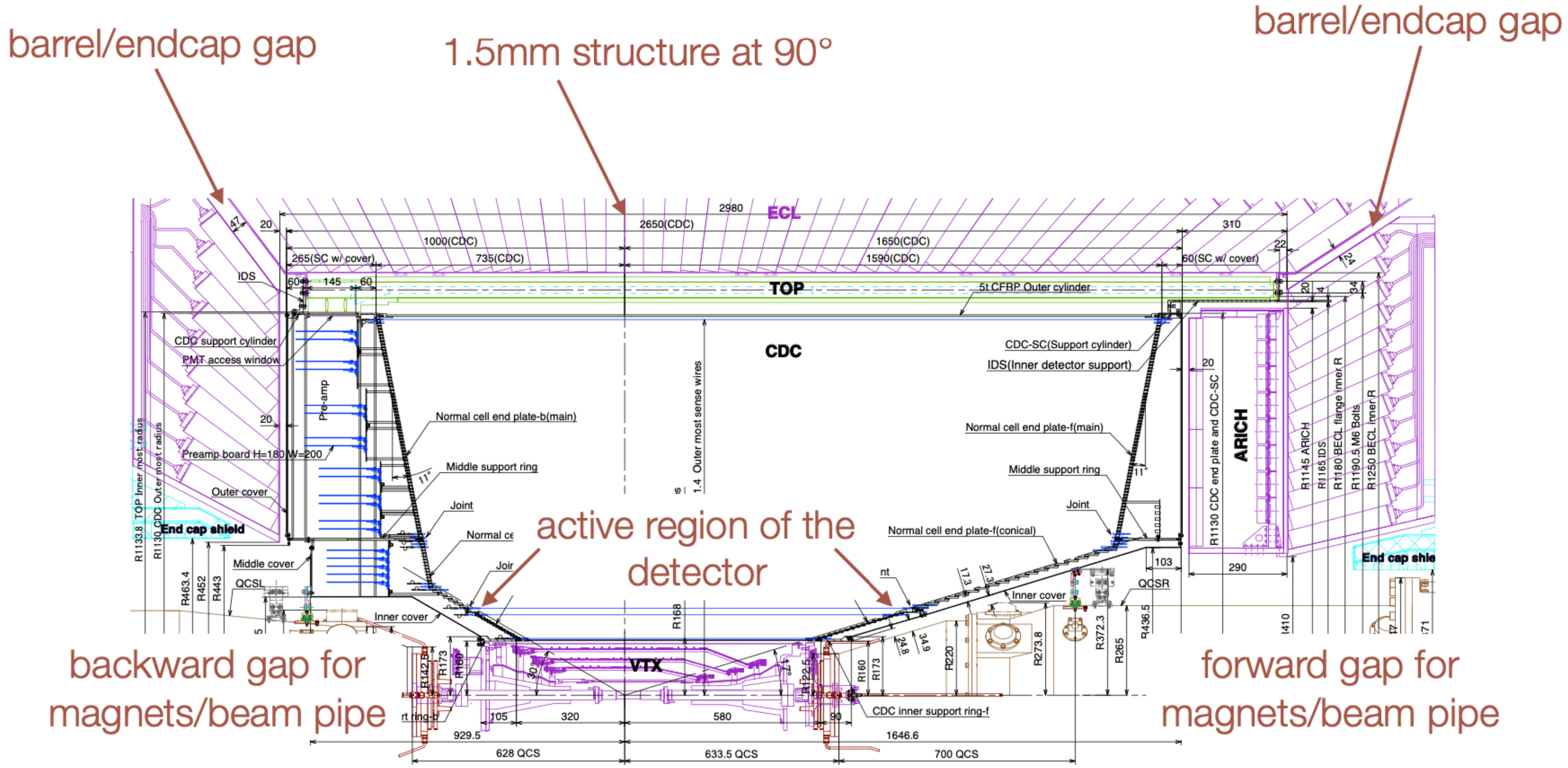


ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

bBG

BelleII detector



1808.10567