Probing millicharge @ electron colliders

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Millicharge is a very small electric charge

photon

↓

$$e\, Q_f\, A_\mu^\gamma\, \bar{f} \gamma^\mu f$$

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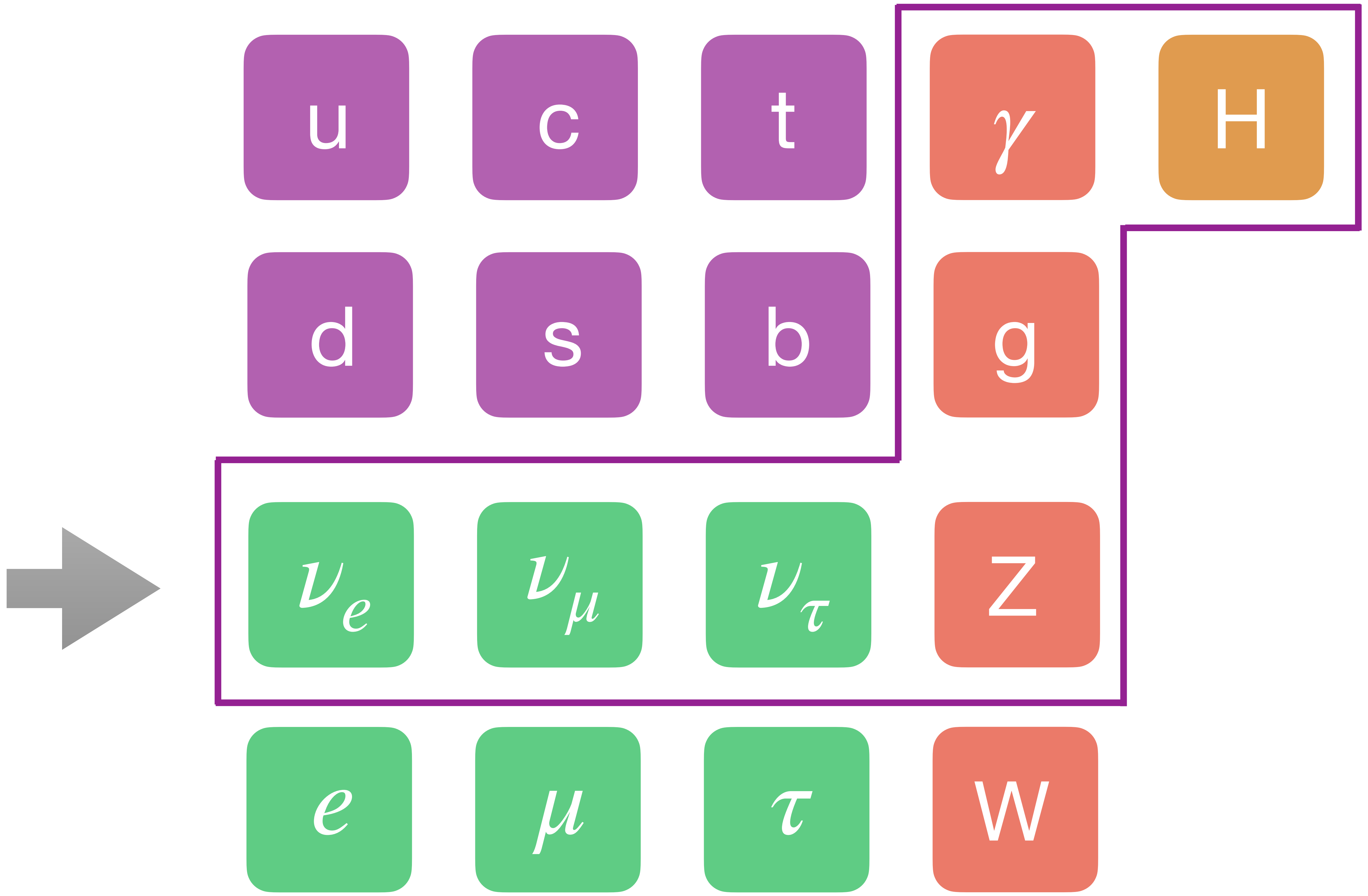
$$e\, Q_f\, A^{\gamma}_{\mu}\, \bar{f} \gamma^{\mu} f$$

Millicharge is a very small electric charge

$Q = 0$



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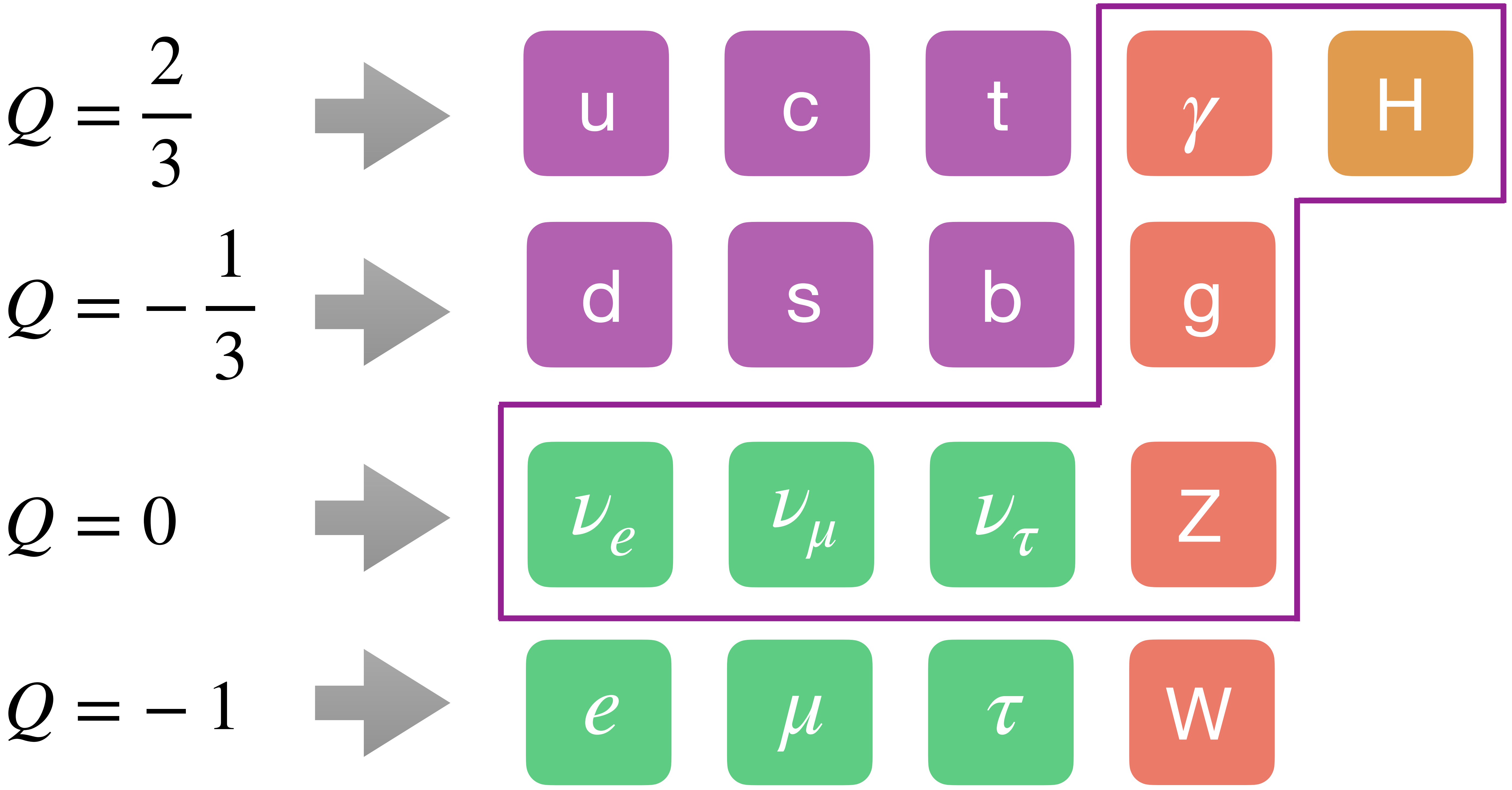

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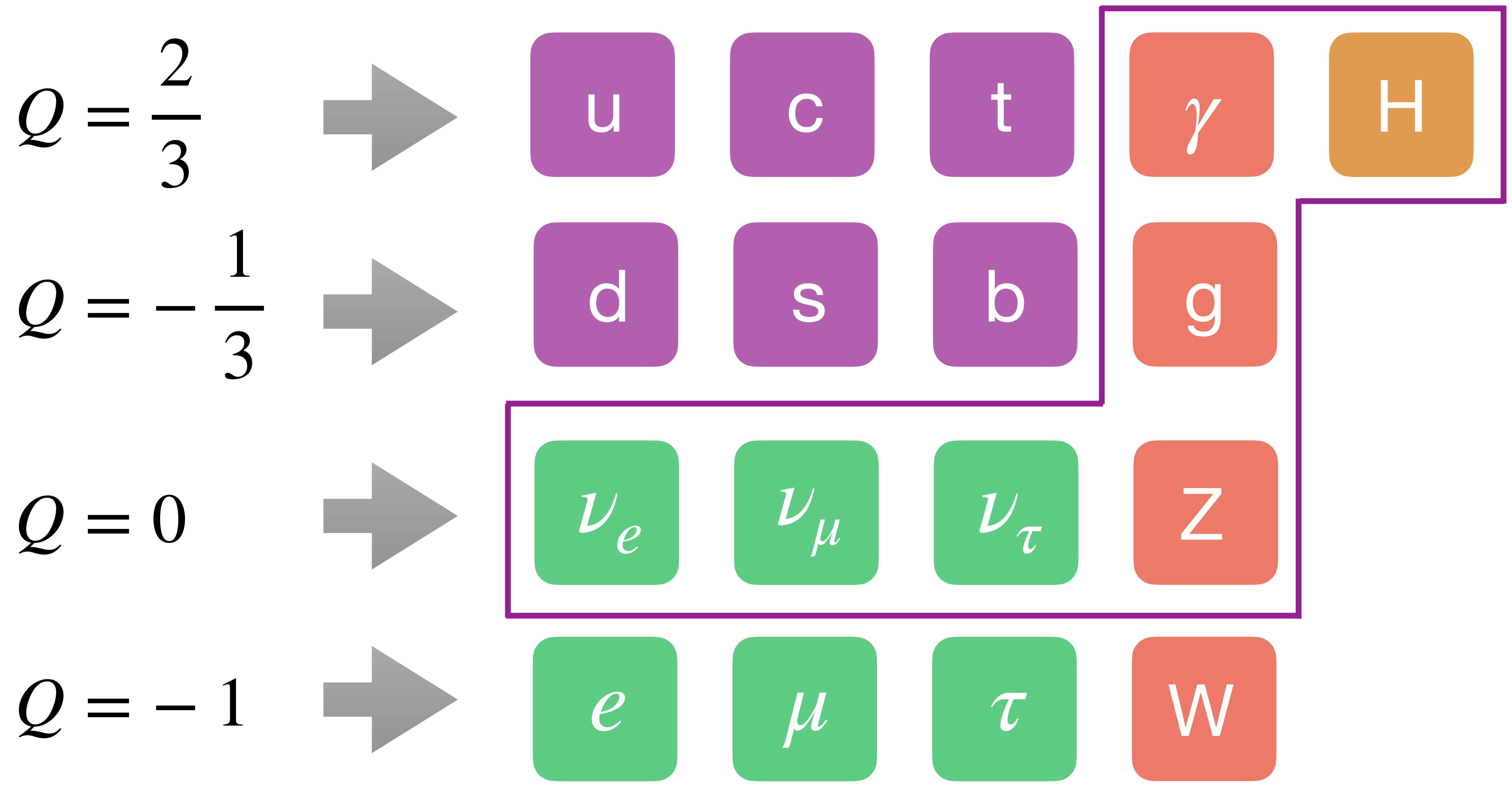

photon

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$Q_f = \frac{n}{3}$ is quantized in SM

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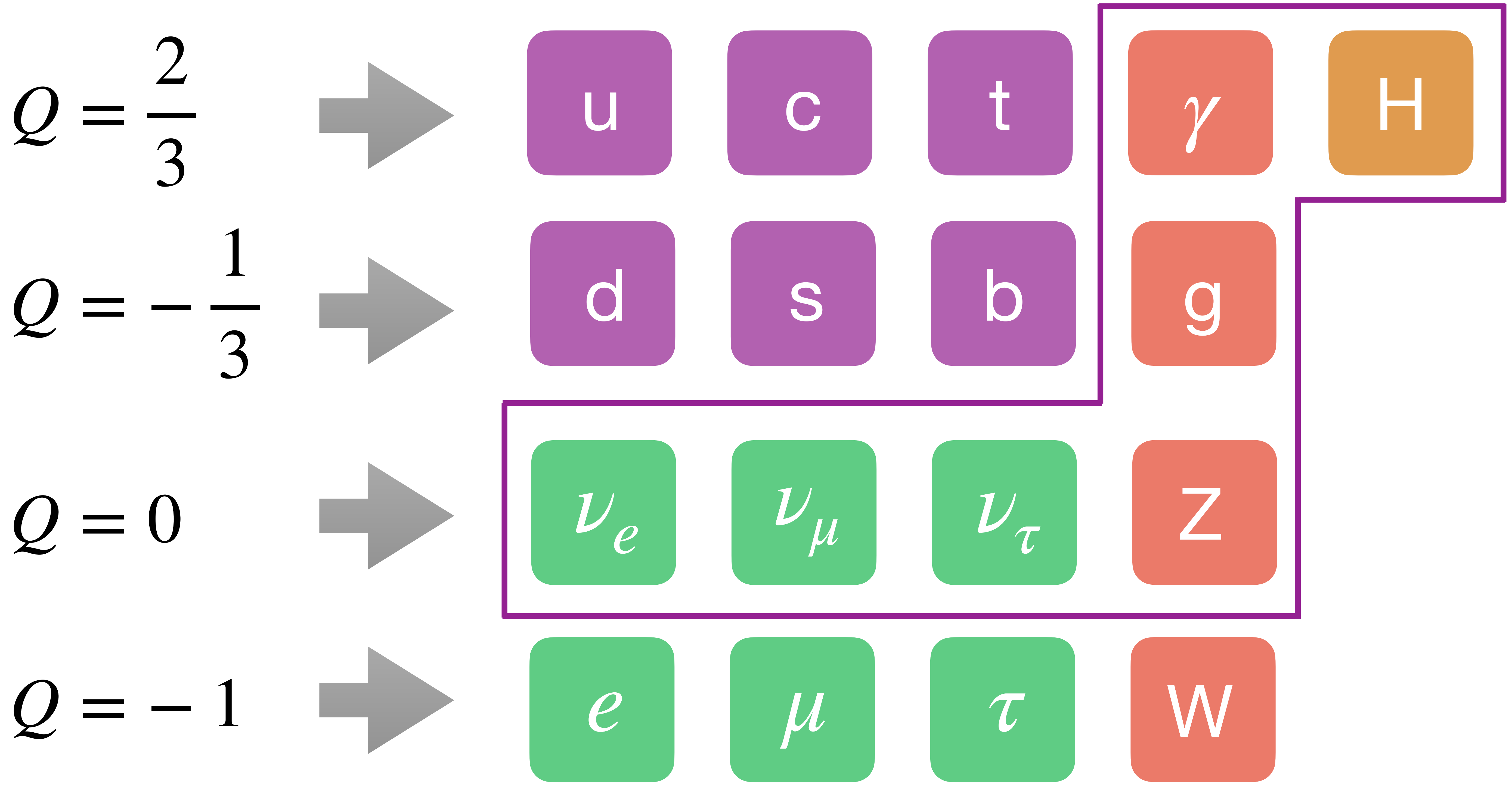

photon

↓

$$e\, Q_f\, A_\mu^\gamma\, \bar{f} \gamma^\mu f$$

$Q_f = \frac{n}{3}$ is quantized in SM

non-quantized $Q_f \equiv \epsilon \ll 1$ → millicharge

Magnetic monopole leads to charge quantization

Dirac's paper on magnetic monopole & charge quantization in 1931

Quantised singularities in the electromagnetic field,

[from https://inspirehep.net/]

Paul Adrien Maurice Dirac (St John's Coll., Cambridge) (Sep 1, 1931)

Published in: *Proc.Roy.Soc.Lond.A* 133 (1931) 821, 60-72

DOI cite 2,263 citations

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magnetic monopole

↓

charge quantization

$$e = \frac{2\pi\hbar n}{\mu}$$

n is integer

μ is magnetic strength

e is electric strength

Standard model & grand unified theories

"charge quantization" is not resolved completely in SM

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

Standard model & grand unified theories

"charge quantization" is not resolved completely in SM

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

Embedded into a bigger gauge group, e.g. SU(5) **[Georgi & Glashow, PRL.32.438, 1974]**

→ charge quantization

Stringent constraints on millicharge in SM

$$Q_p - Q_e < (0.8 \pm 0.8) \times 10^{-21} e$$

[Marinelli et al. 1984]

$$Q_n < (-0.1 \pm 1.1) \times 10^{-21} e$$

[Bressi et al. 2011]

$$Q_n < (-0.4 \pm 1.1) \times 10^{-21} e$$

[Baumann et al. 1988]

$$Q_\nu < 10^{-17} e$$

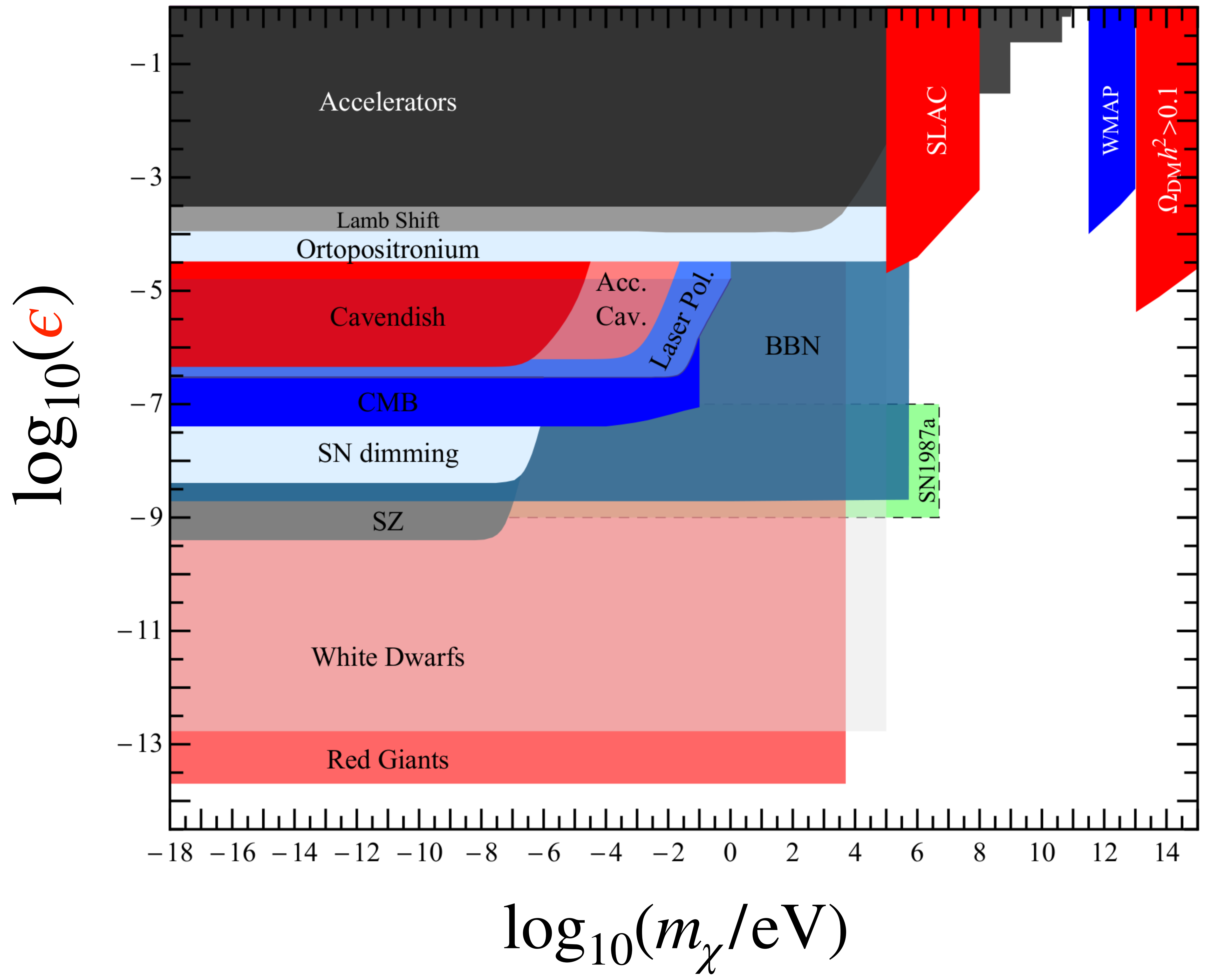
[Barbiellini et al. 1987]

[Siemensen et al., PRD 97, 052004 (2018)]

Millicharge in BSM can be quite "large"

[Jaeckel & Ringwald, 1002.0329]

$$e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$$



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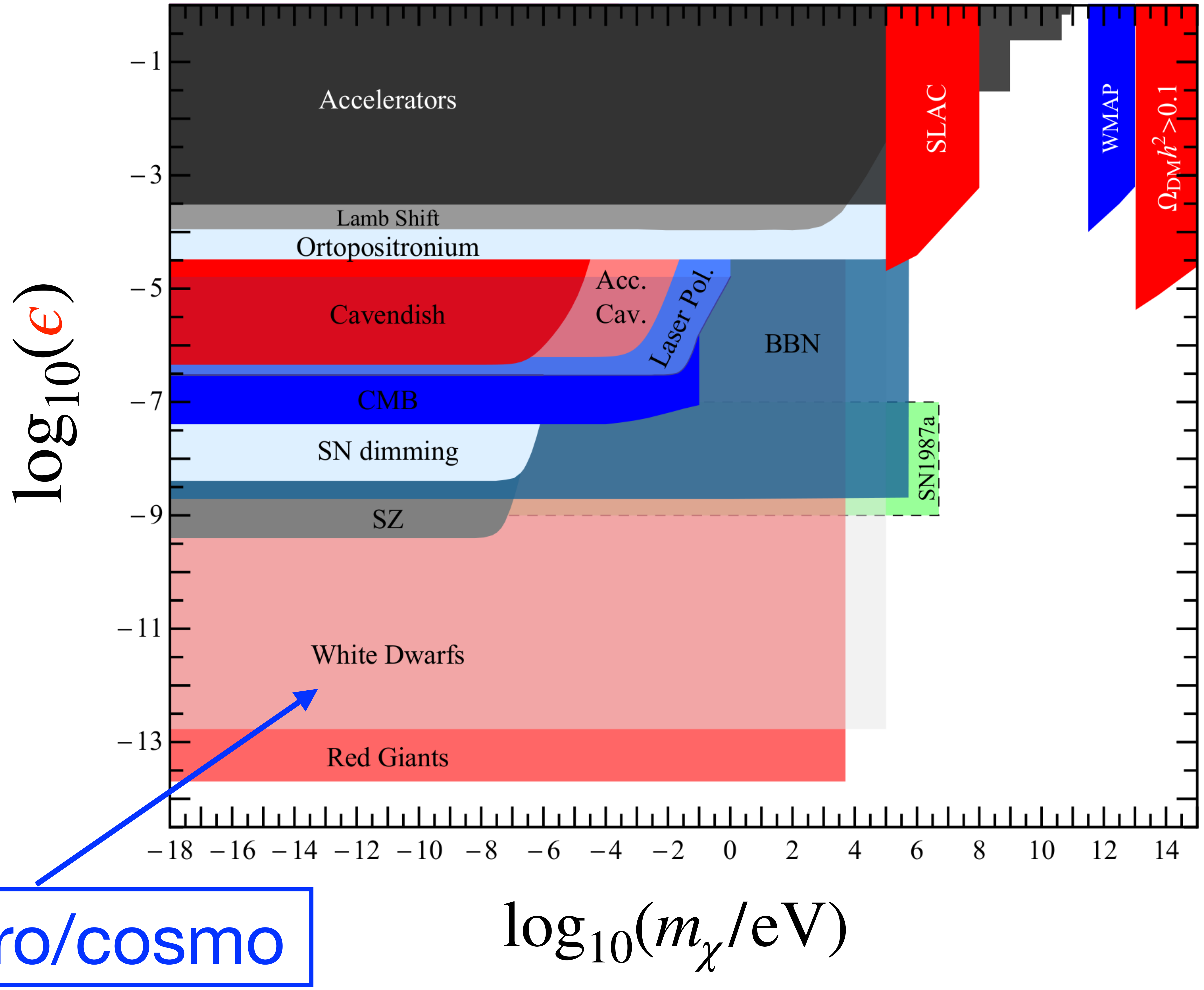

astro/cosmo

Millicharge in BSM can be quite "large"

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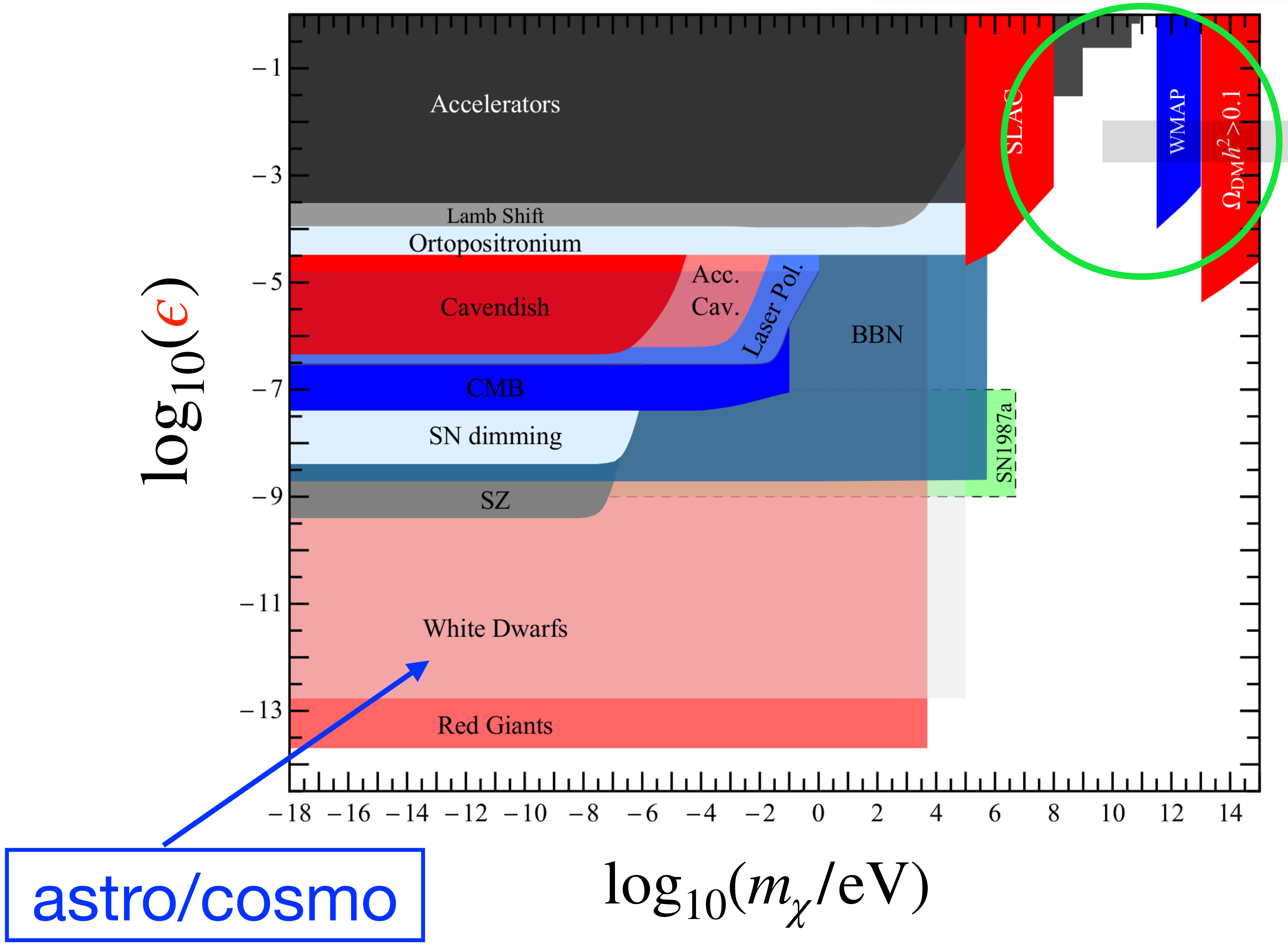
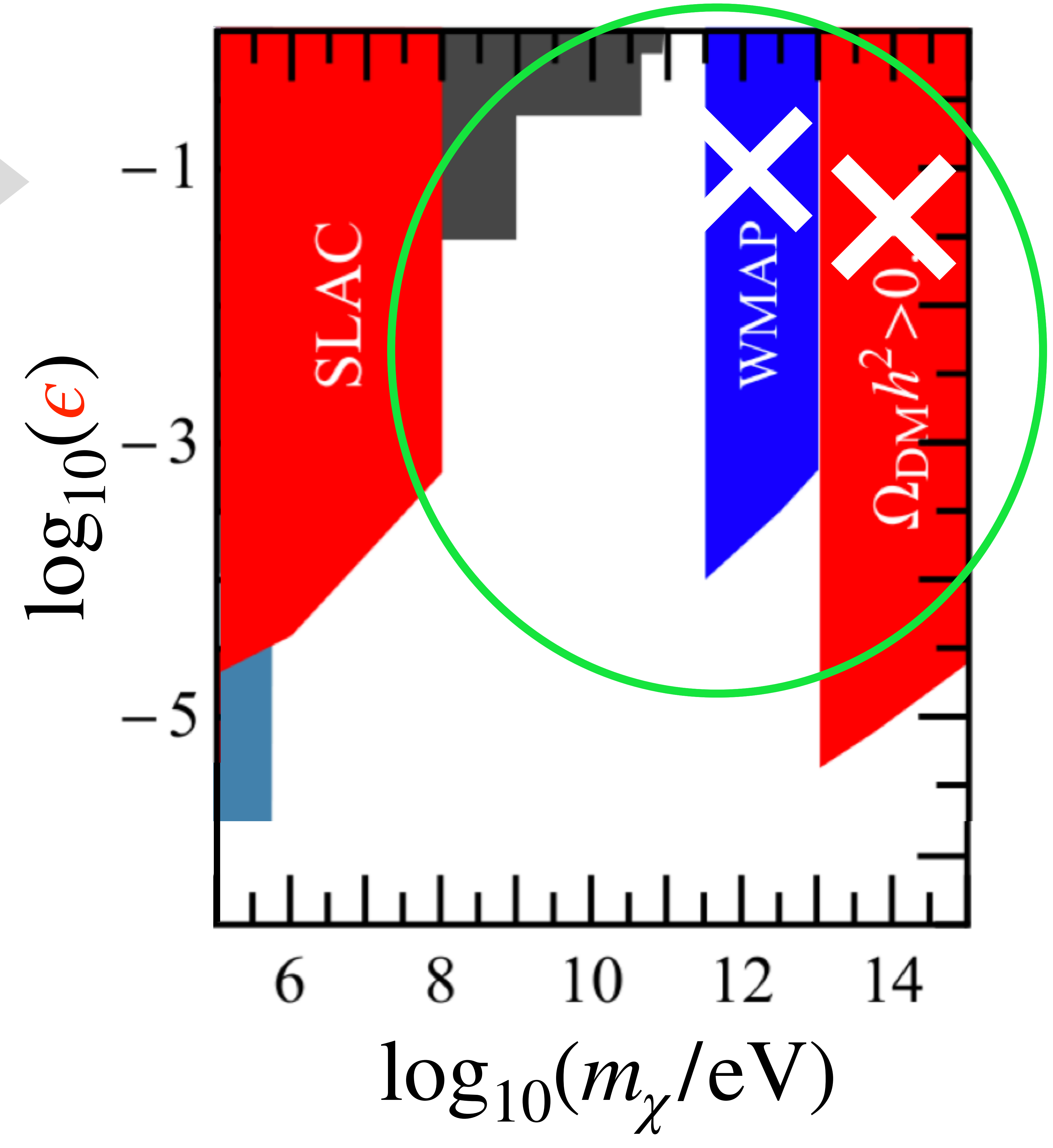
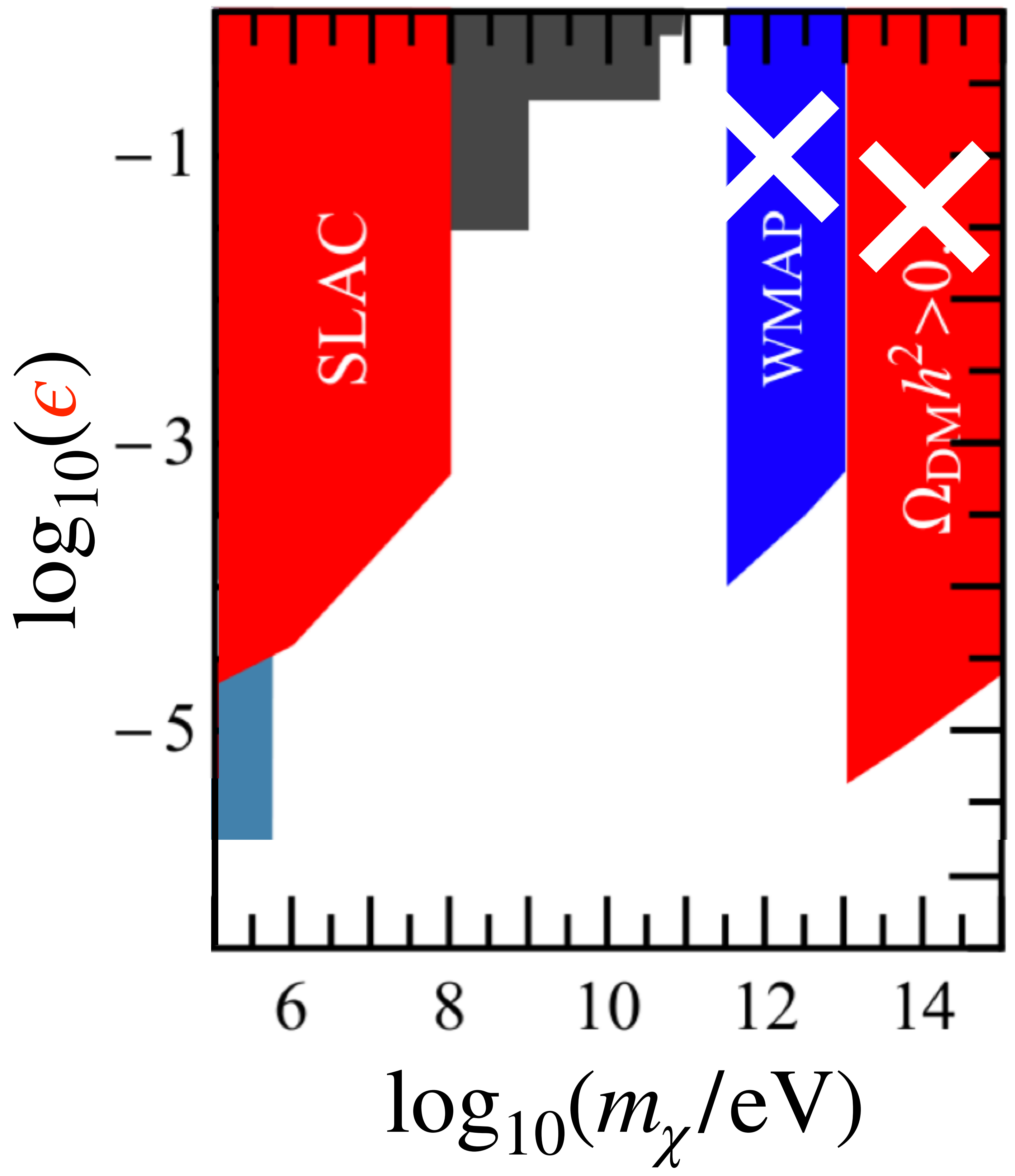
significant ϵ allowed





Probing millicharge at electron colliders

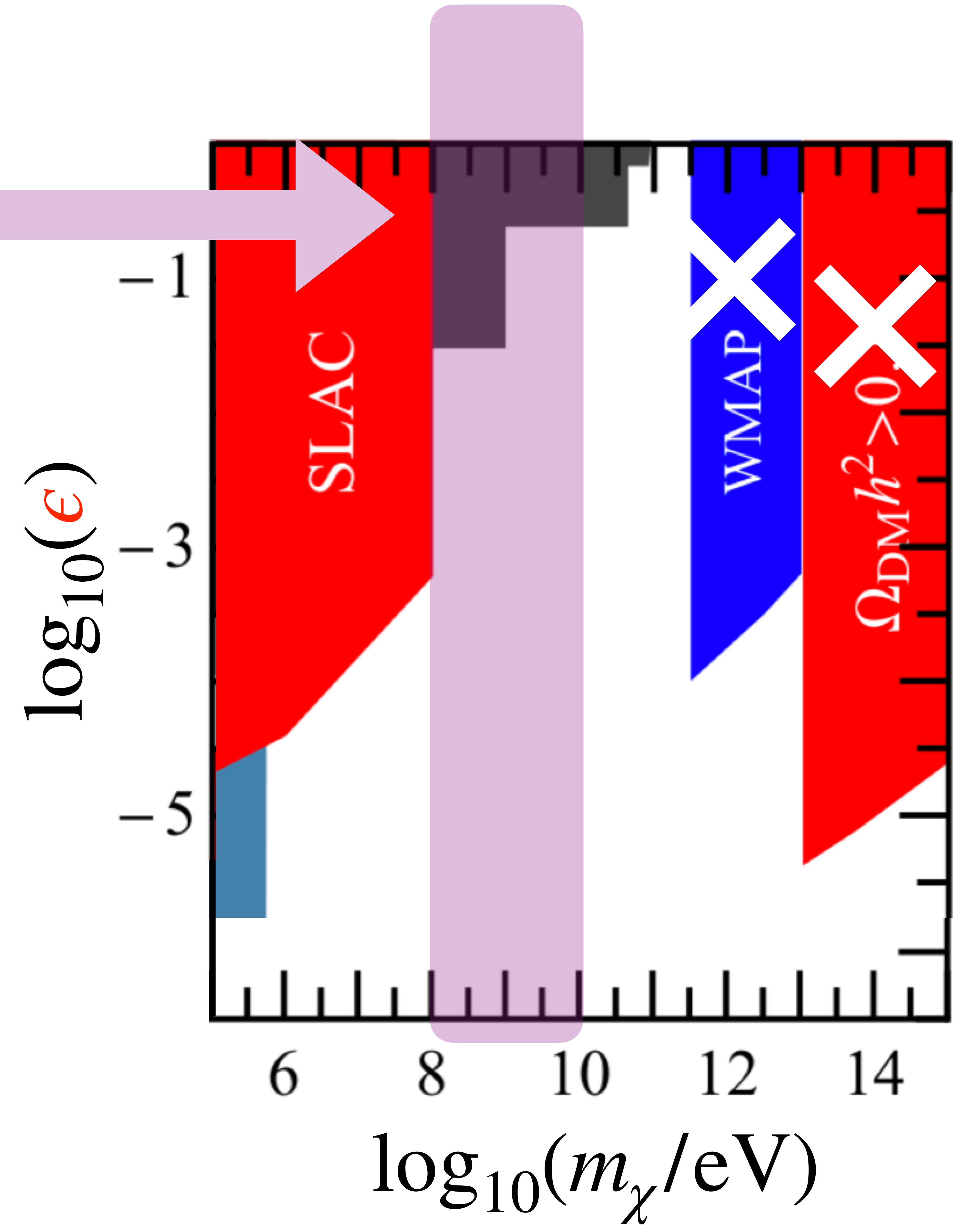


Probing millicharge at electron colliders

0.1-10 GeV

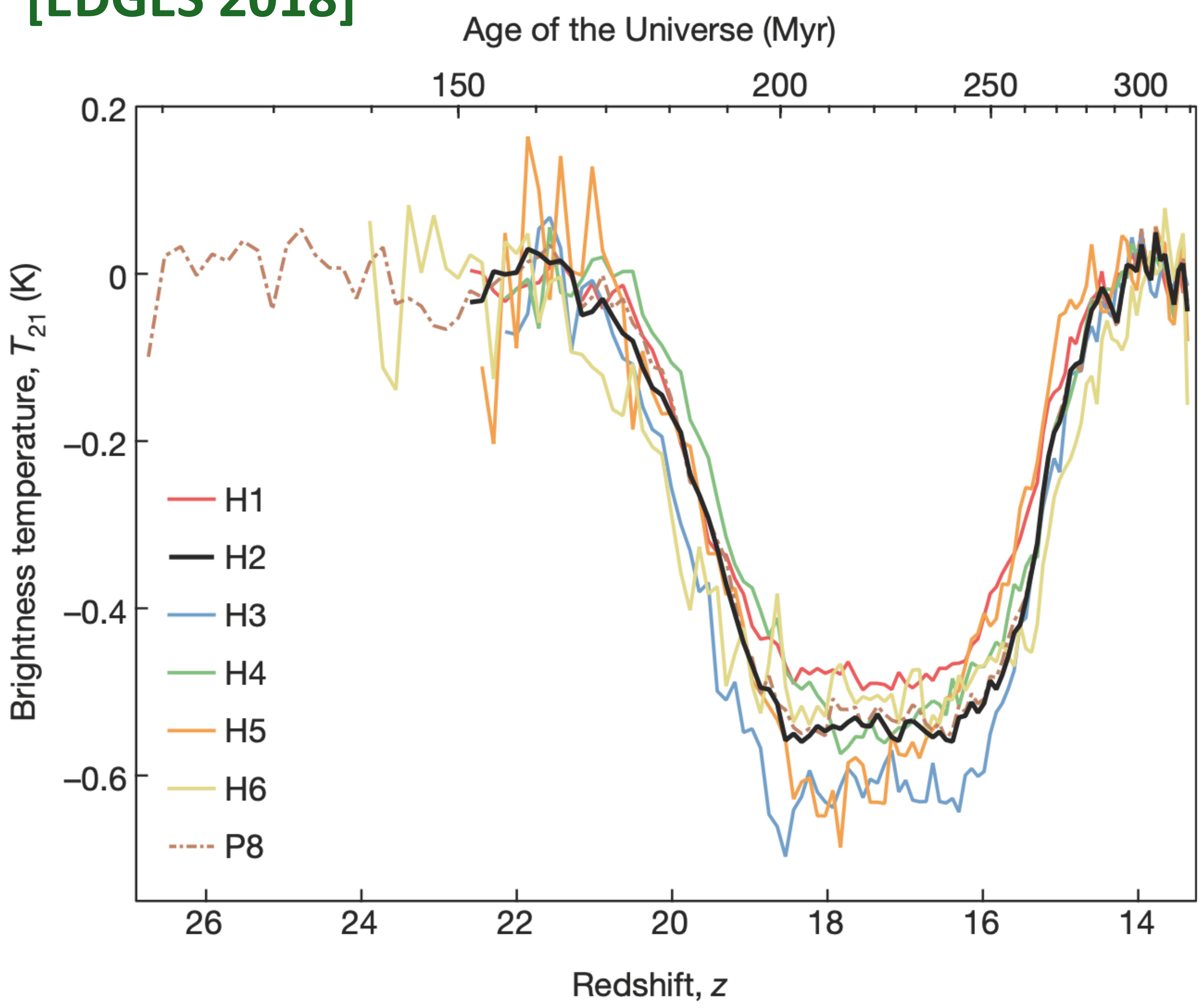
accessible at electron colliders

BaBar
BESIII
Belle II
STCF



Millicharged DM explains EDGES 21 cm anomaly

[EDGES 2018]



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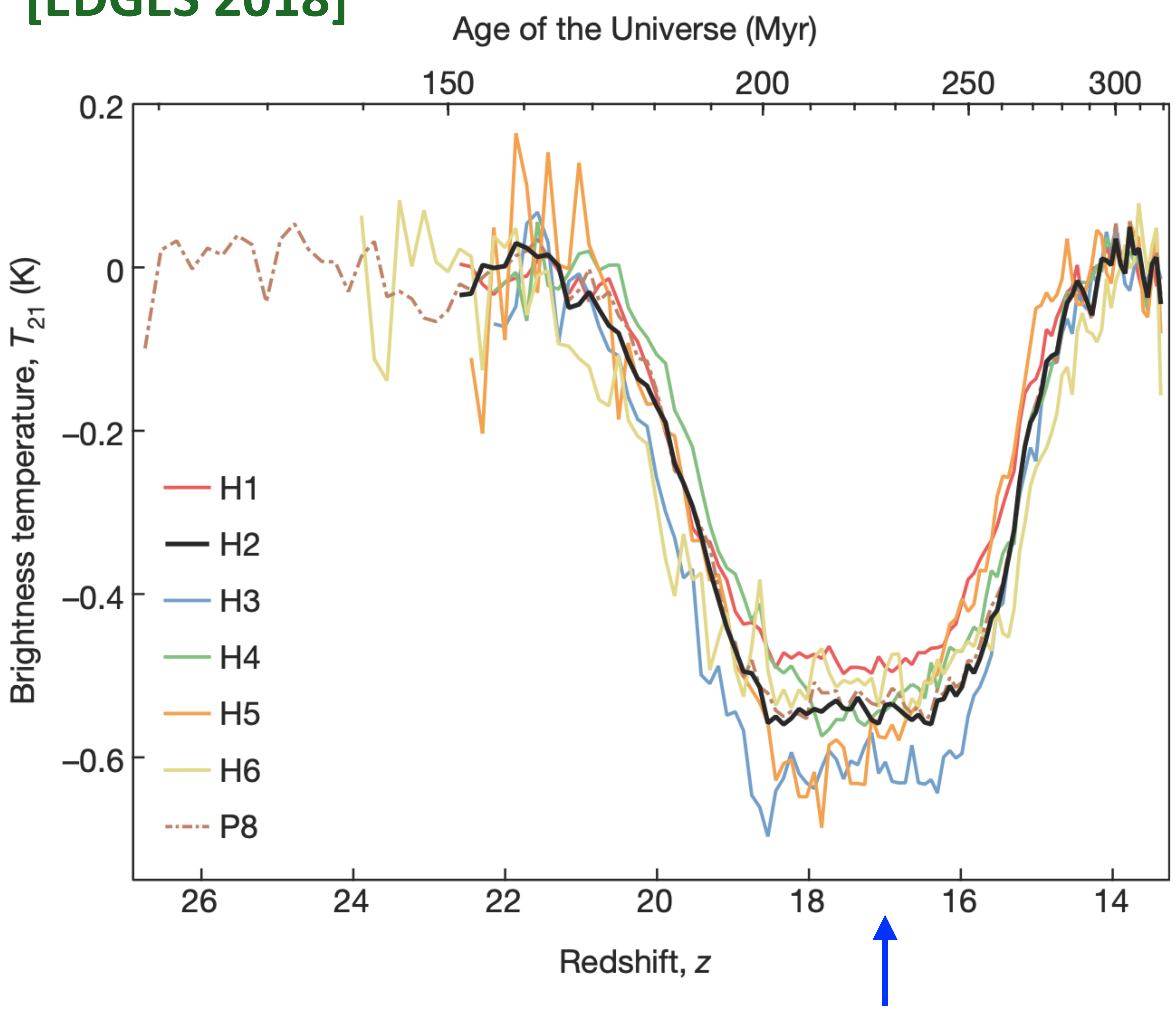

colder gas or hotter CMB than expected

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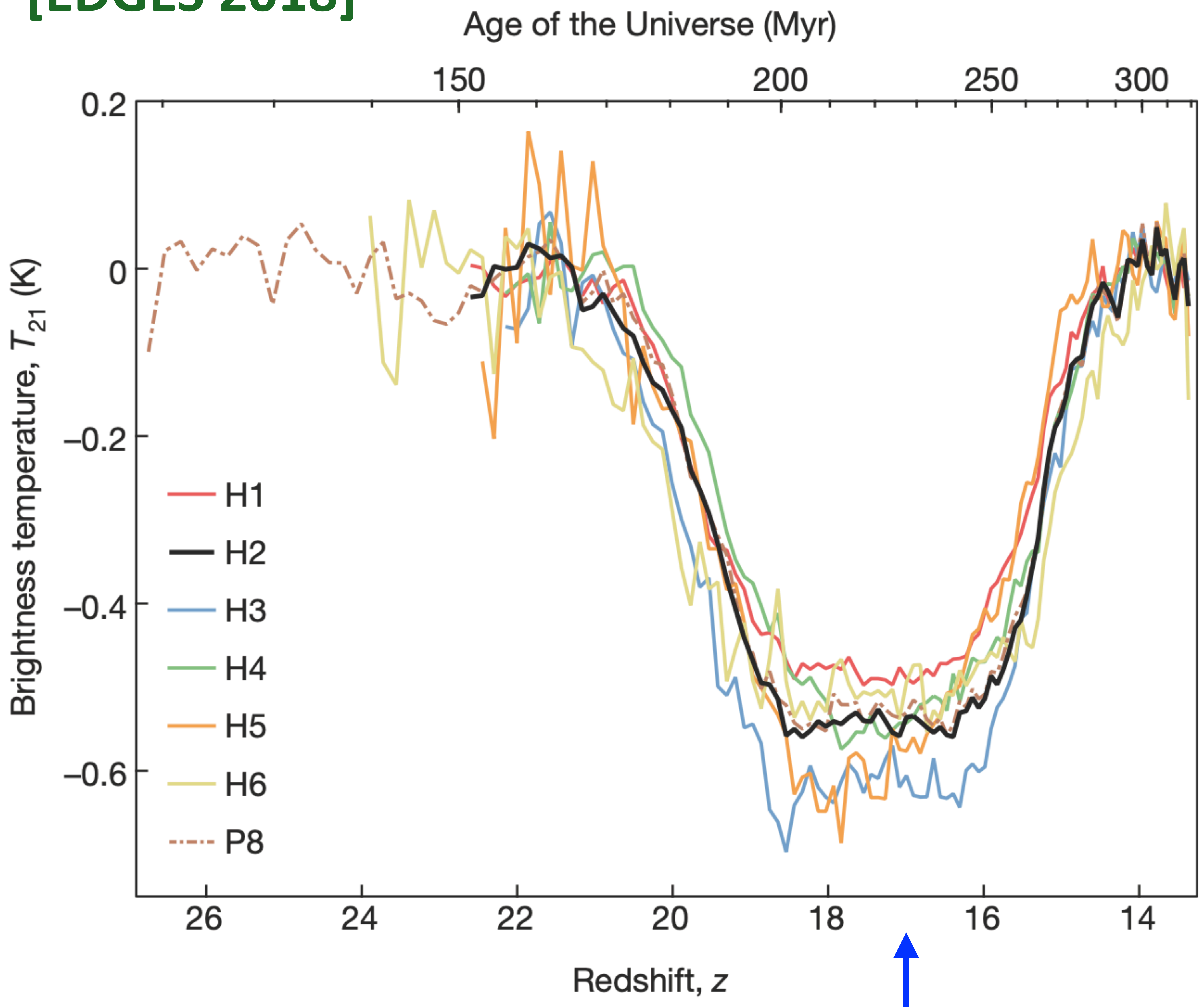

colder gas or hotter CMB than expected

DM can cool gas

Millicharged DM xsec

$$\sigma \propto v^{-4}$$

easier to evade early universe constraints

Outline: discussions on millicharge

1. theoretical models

[Feldman, ZL, Nath, hep-ph/0702123, 299 cites]

2. terrestrial searches

3. electron colliders' sensitivity

[ZL, Zhang, 1808.00983]

[Liang, ZL, Ma, Zhang, 1909.06847]

1 theoretical models

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Models to generate millicharged particles (MCPs)

$$e\,\epsilon\,A^{\gamma}_{\mu}\,\bar{\chi}\,\gamma^{\mu}\,\chi \quad \rightarrow \quad \chi \text{ is MCP}$$

Kinetic mixing

Mass mixing

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Kinetic mixing between two U(1) fields

Kinetic mixing between two U(1) fields: A_1 & A_2

$$\mathscr{L} = -\frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{\delta}{2}F_{2\mu\nu}F_1^{\mu\nu} - \frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu}$$

[Holdom, Phys.Lett. 166B, 196 (1986)]

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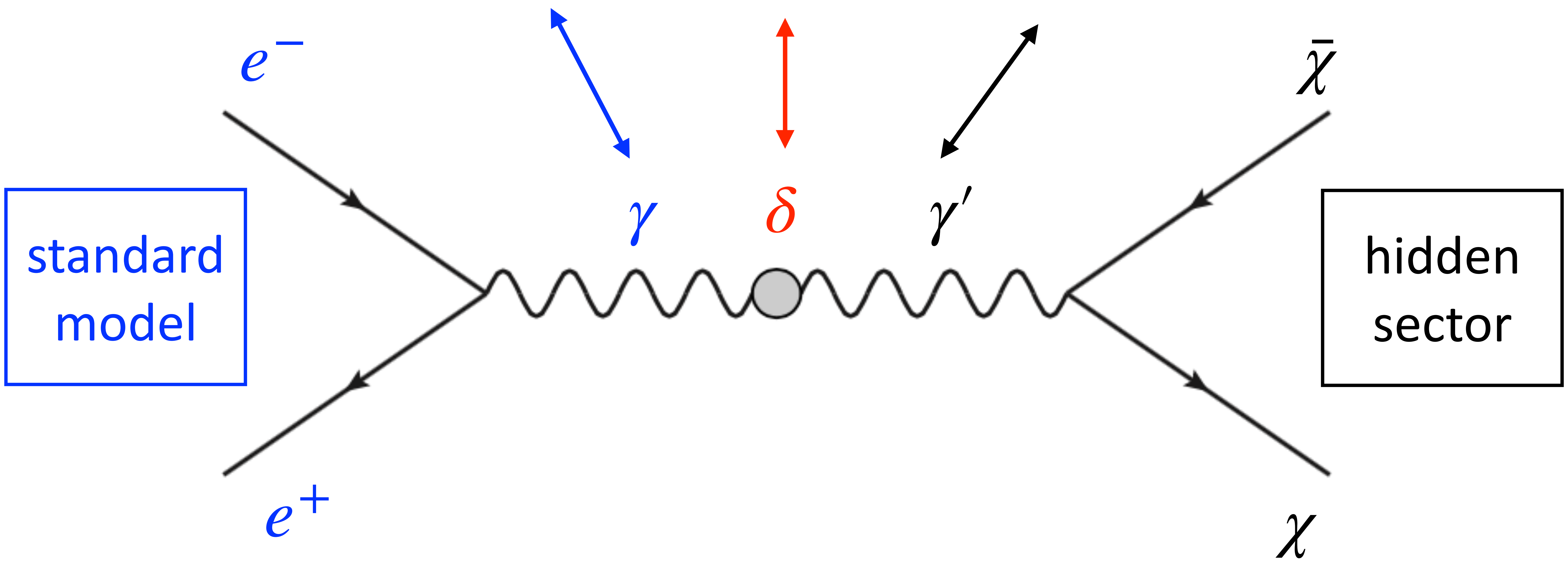

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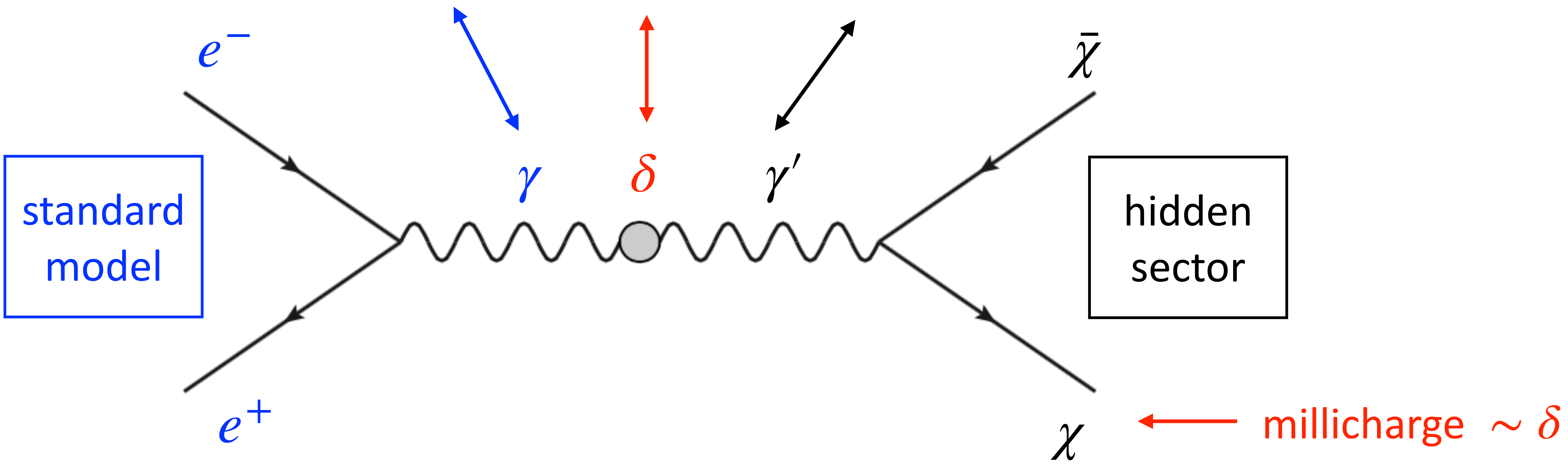
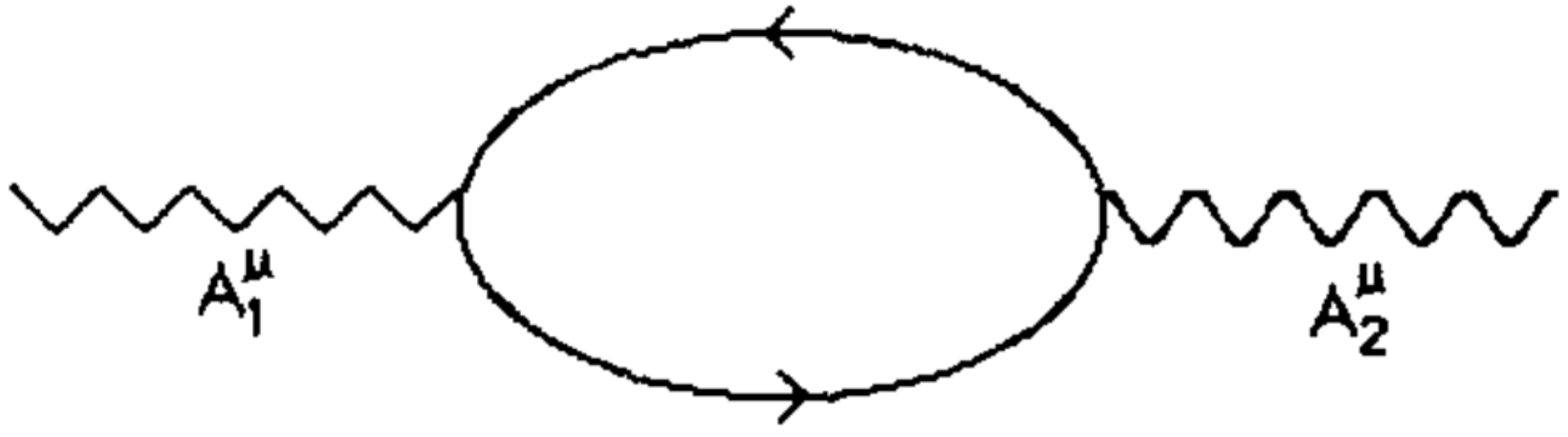


One example to generate kinetic mixing

[Holdom, Phys.Lett. 166B (1986) 196-198]

2 high scale fermions charged under two U(1)s



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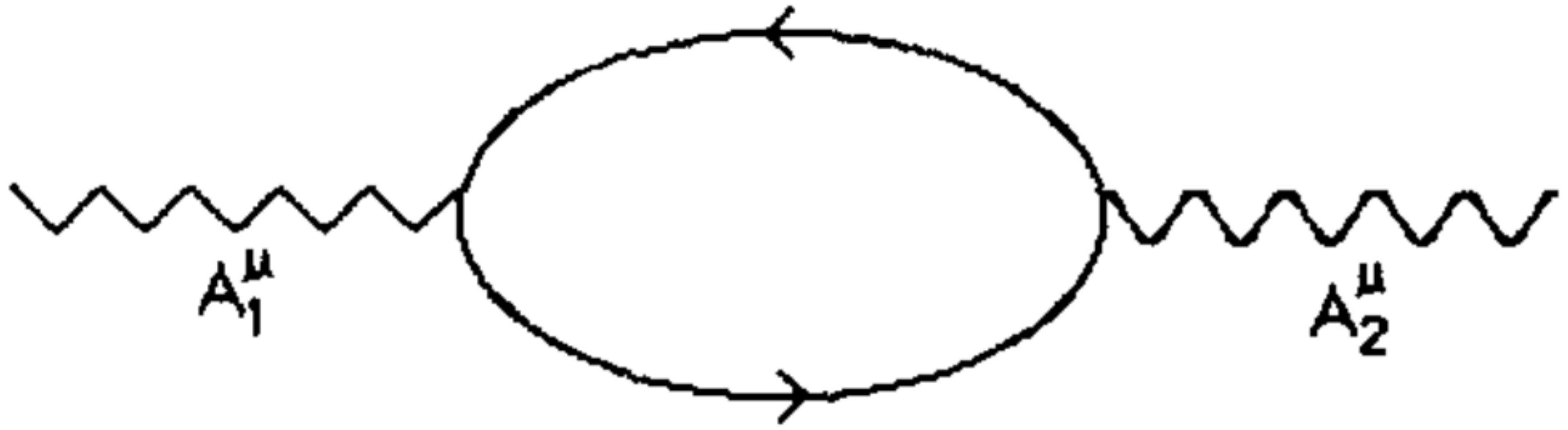

$$\mathscr{L} = -\frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu} - \frac{\delta}{2}F_{2\mu\nu}F_1^{\mu\nu}$$

$$\delta = \frac{e_1 e_2}{6\pi^2}\ln\frac{m'_{12}}{m_{12}}$$

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Kinetic mixing

Mass mixing

Stueckelberg mass mixing between two U(1) fields

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[Kors & Nath hep-ph/0402047]

[Feldman, ZL, Nath, hep-ph/0603039]

[Cheung & Yuan hep-ph/0701107]

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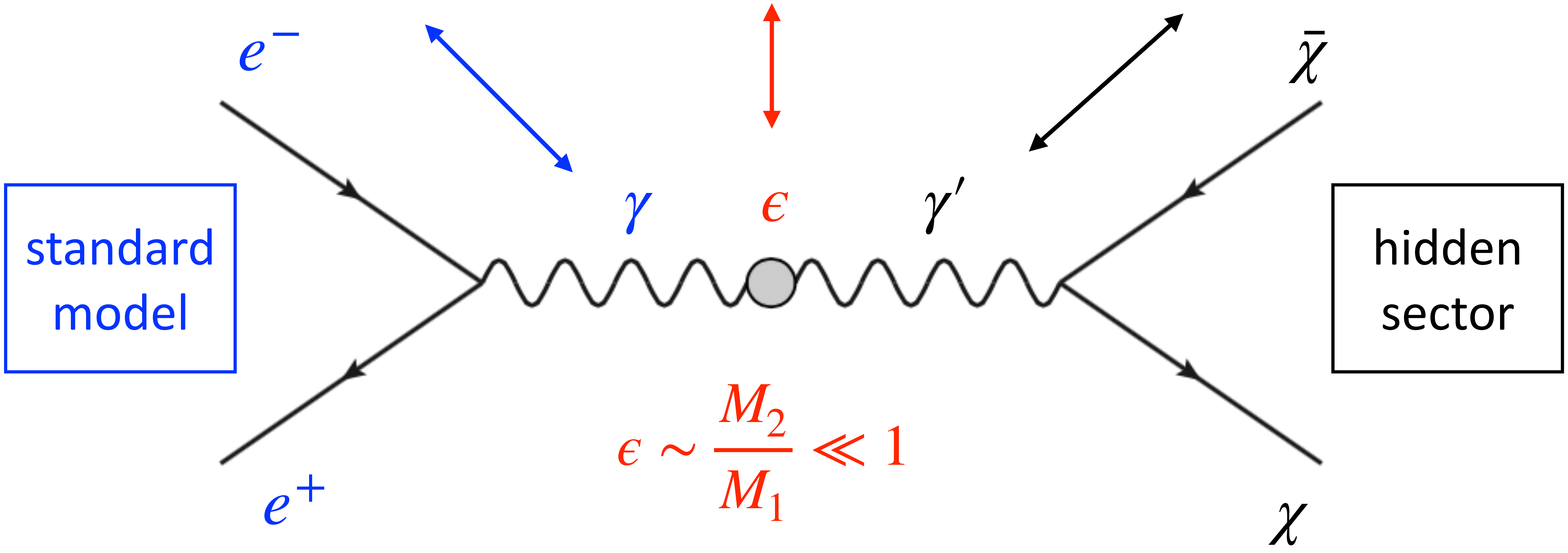

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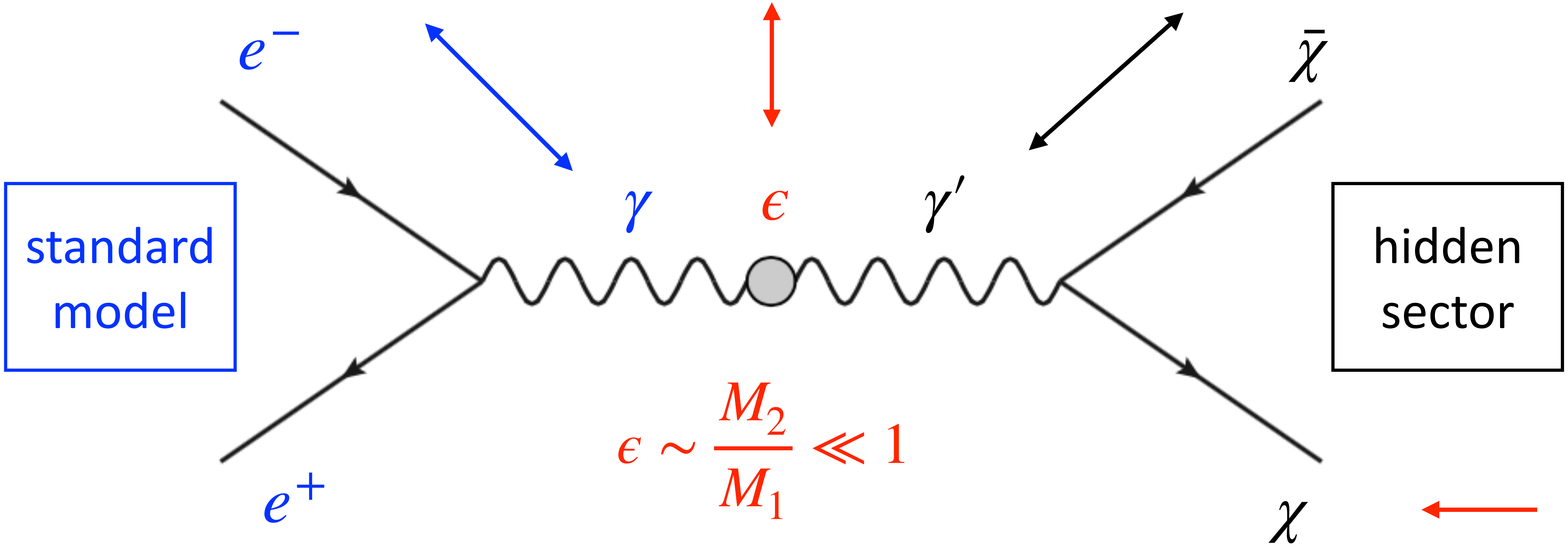

$$\epsilon \sim \frac{M_2}{M_1} \ll 1$$

millicharge $\sim \epsilon$

“Toy” model w/ both kinetic & mass mixings

$$-\frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu} - \frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{\delta}{2}F_{1\mu\nu}F_2^{\mu\nu} + J'_\mu A_1^\mu + J_\mu A_2^\mu - \frac{1}{2}M_1^2 A_{1\mu}A_1^\mu - \frac{1}{2}M_1^2\epsilon^2 A_{2\mu}A_2^\mu - M_1^2\epsilon A_{1\mu}A_2^\mu$$

[Feldman, ZL, Nath, hep-ph/0702123, 299 cites]

[Fabbrichesi et al., 2005.01515, The Dark Photon, p 7-9]

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after field redefinition & rotation $\longrightarrow$ canonical $(-F^2/4)$ & diagonal mass matrix

$$\frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(\frac{\epsilon-\delta}{\sqrt{1-\delta^2}}J_\mu + \frac{1-\delta\epsilon}{\sqrt{1-\delta^2}}J'_\mu\right)A_M^\mu + \frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(J_\mu - \epsilon J'_\mu\right)A_\gamma^\mu$$

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SM photon

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dark photon

SM photon

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degeneracy ↓ dark photon ↓ SM photon ↓

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mass mixing $\rightarrow$ millicharge

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"Realistic" model w/ both kinetic & mass mixings

common features

hidden boson mix w/ hypercharge (instead of photon) $\Longrightarrow$ 3 by 3 mass matrix

hidden boson →
- photon-like (dark photon) $m_{A'} \ll m_Z$
- hypercharge-like $m_{A'} \gg m_Z$

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difference

mass mixing $\Longrightarrow$ millicharge & massive dark photon

kinetic mixing $\Longrightarrow$ millicharge & massless dark photon

[Feldman, ZL, Nath, hep-ph/0702123, 299 cites]

2 terrestrial searches

Two ways to "detect" millicharged particles

$$e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi \quad \Rightarrow \quad \chi \text{ is MCP}$$

scintillation/ionization/scattering

missing energy

[ZL, Zhang, 1808.00983]

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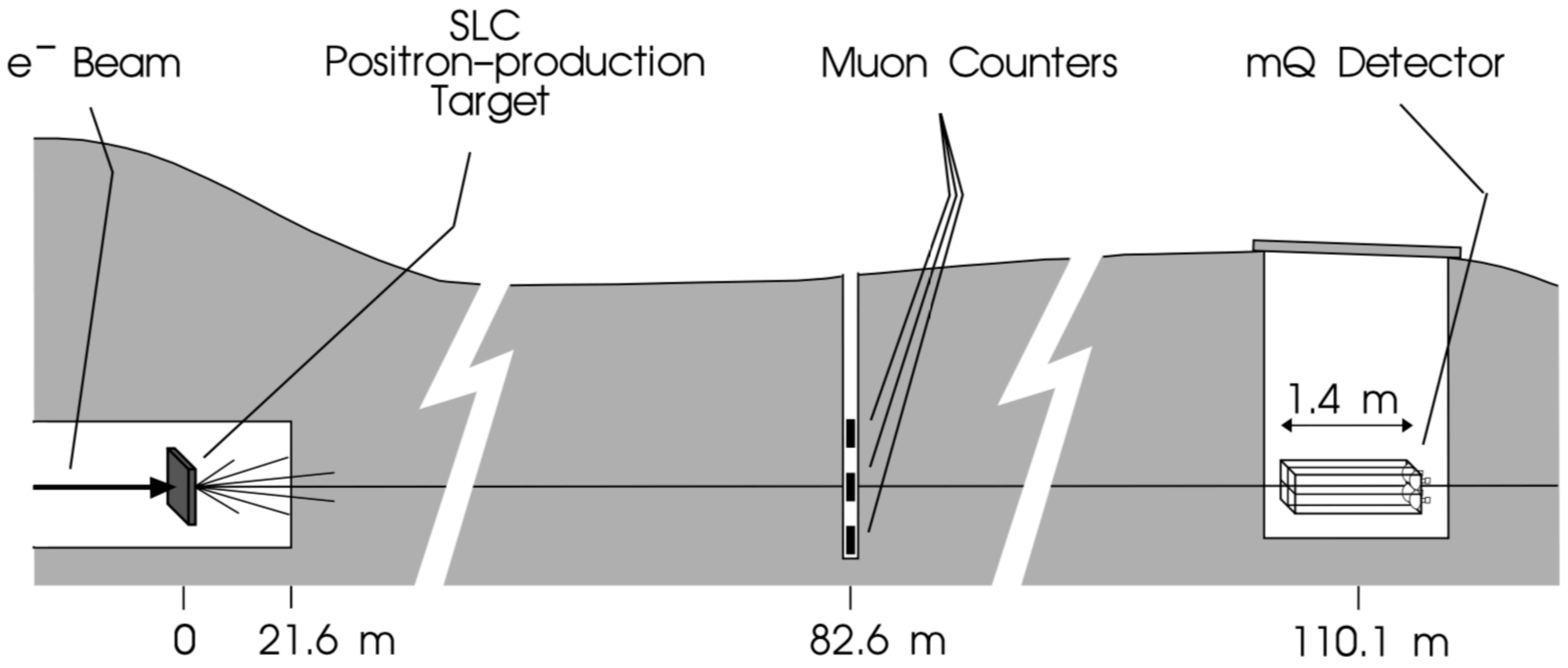
SLAC mQ: electron beam dump experiment

[Prinz et al, PRL 81.1175, 1998]



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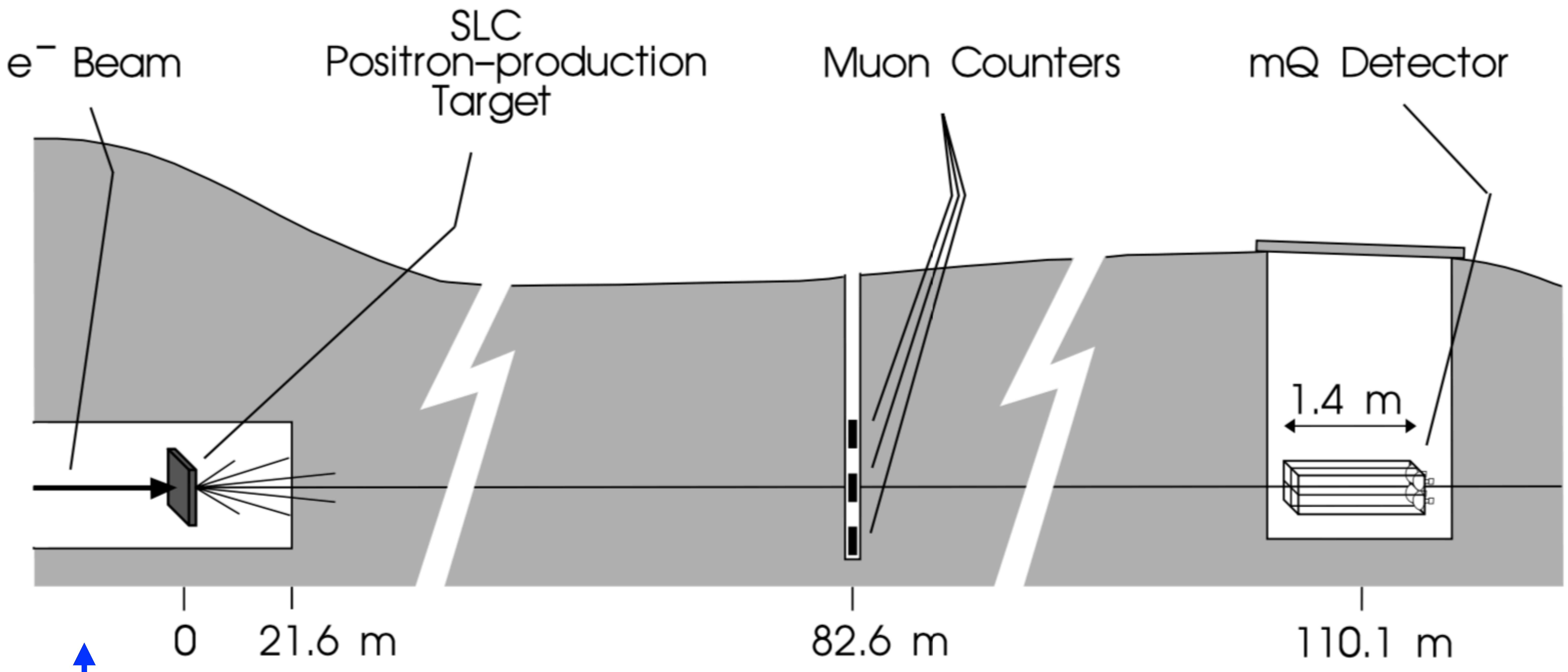

electron beam

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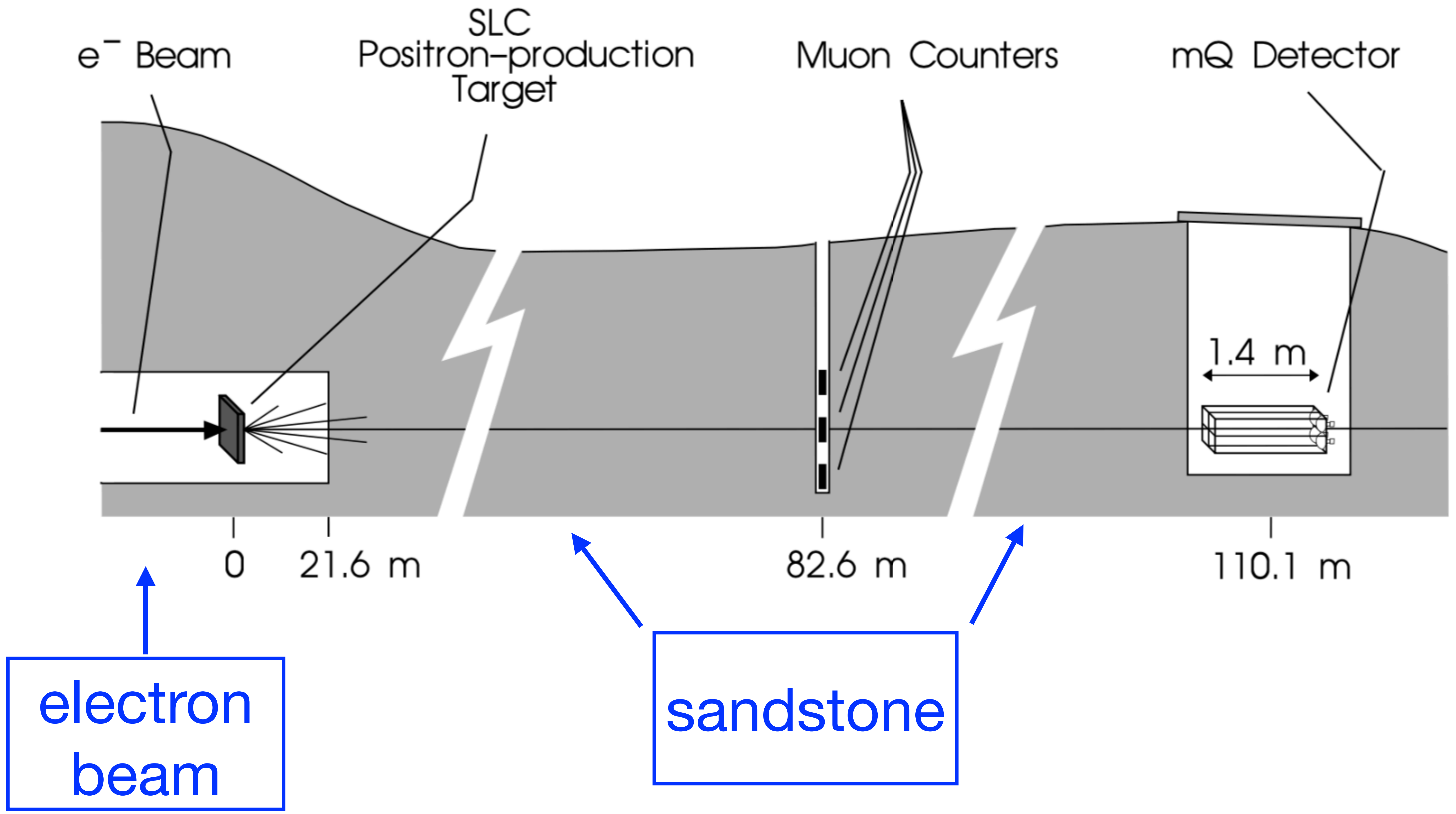

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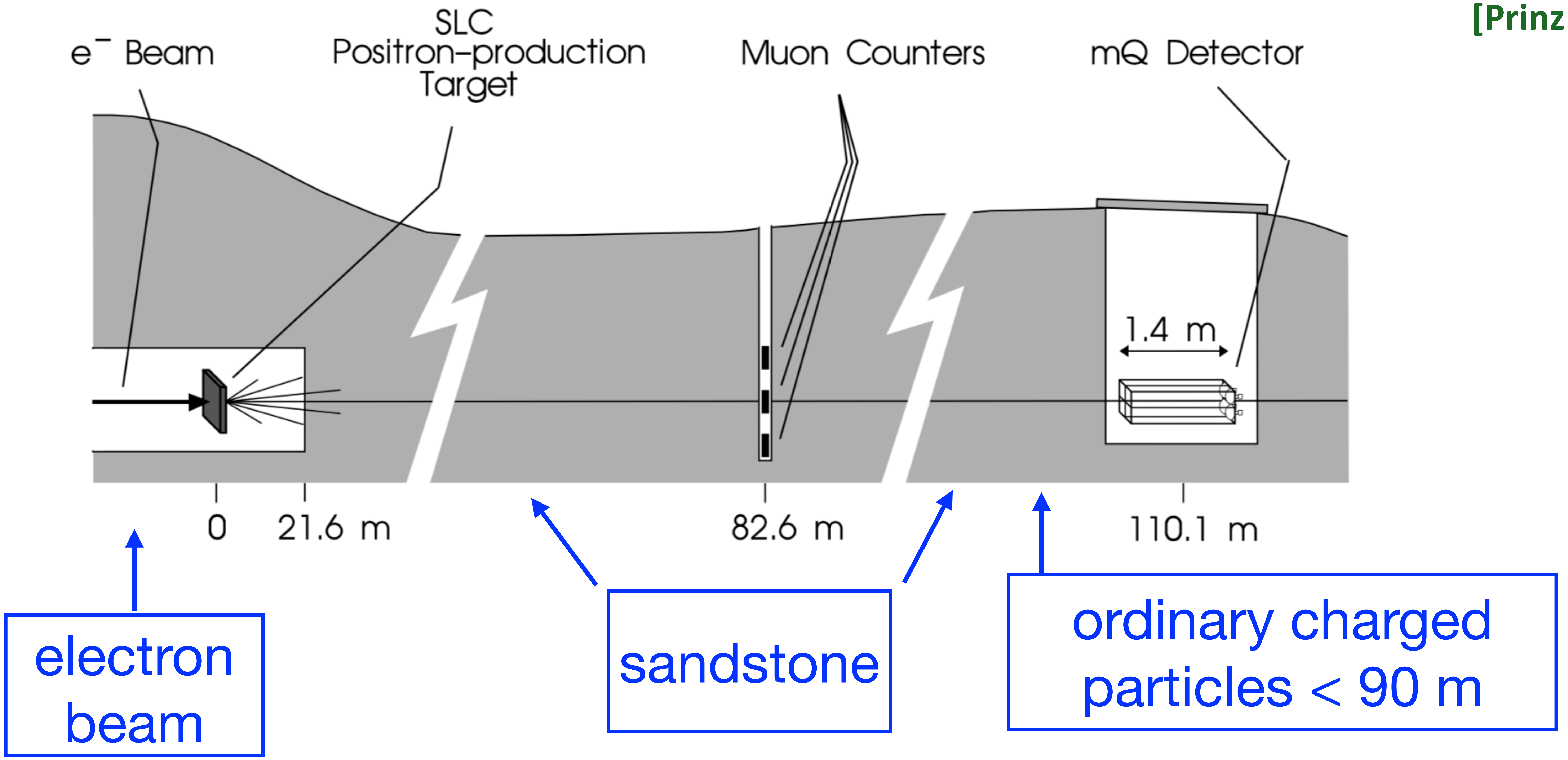

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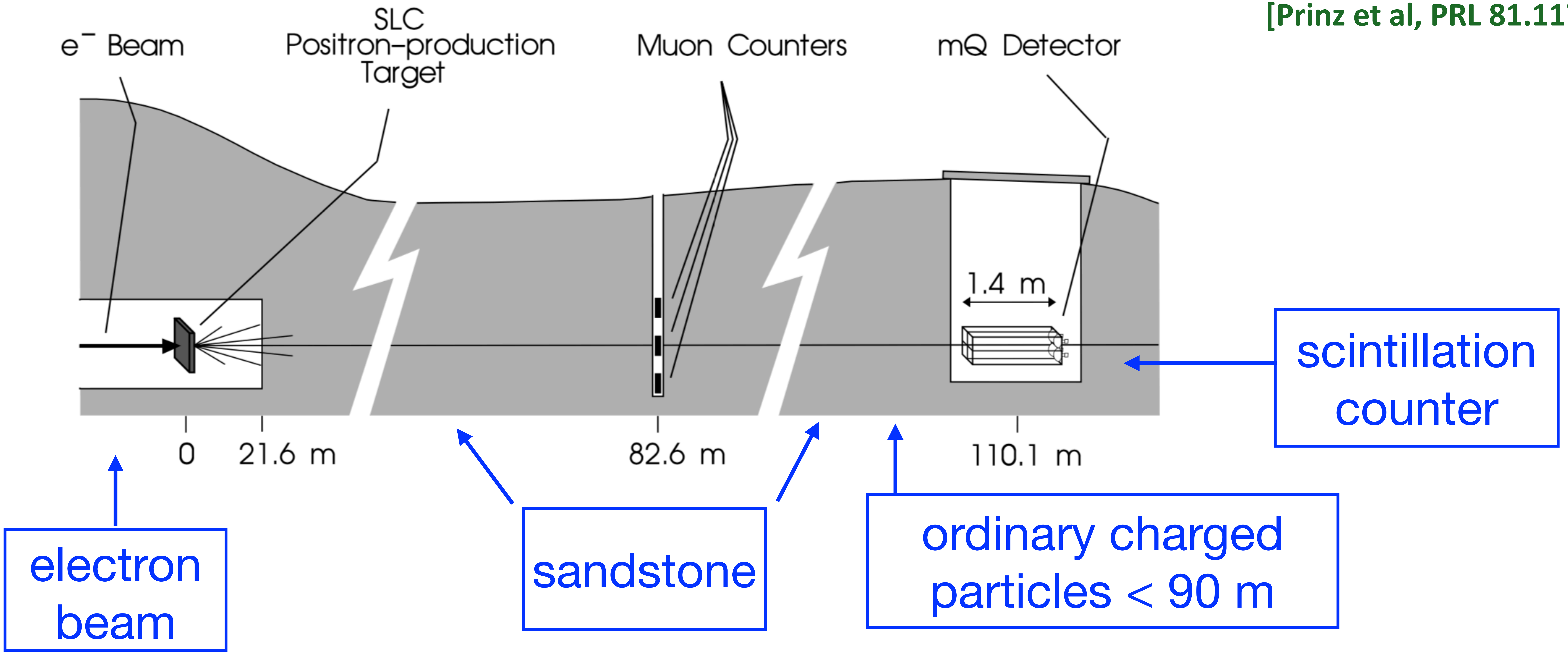
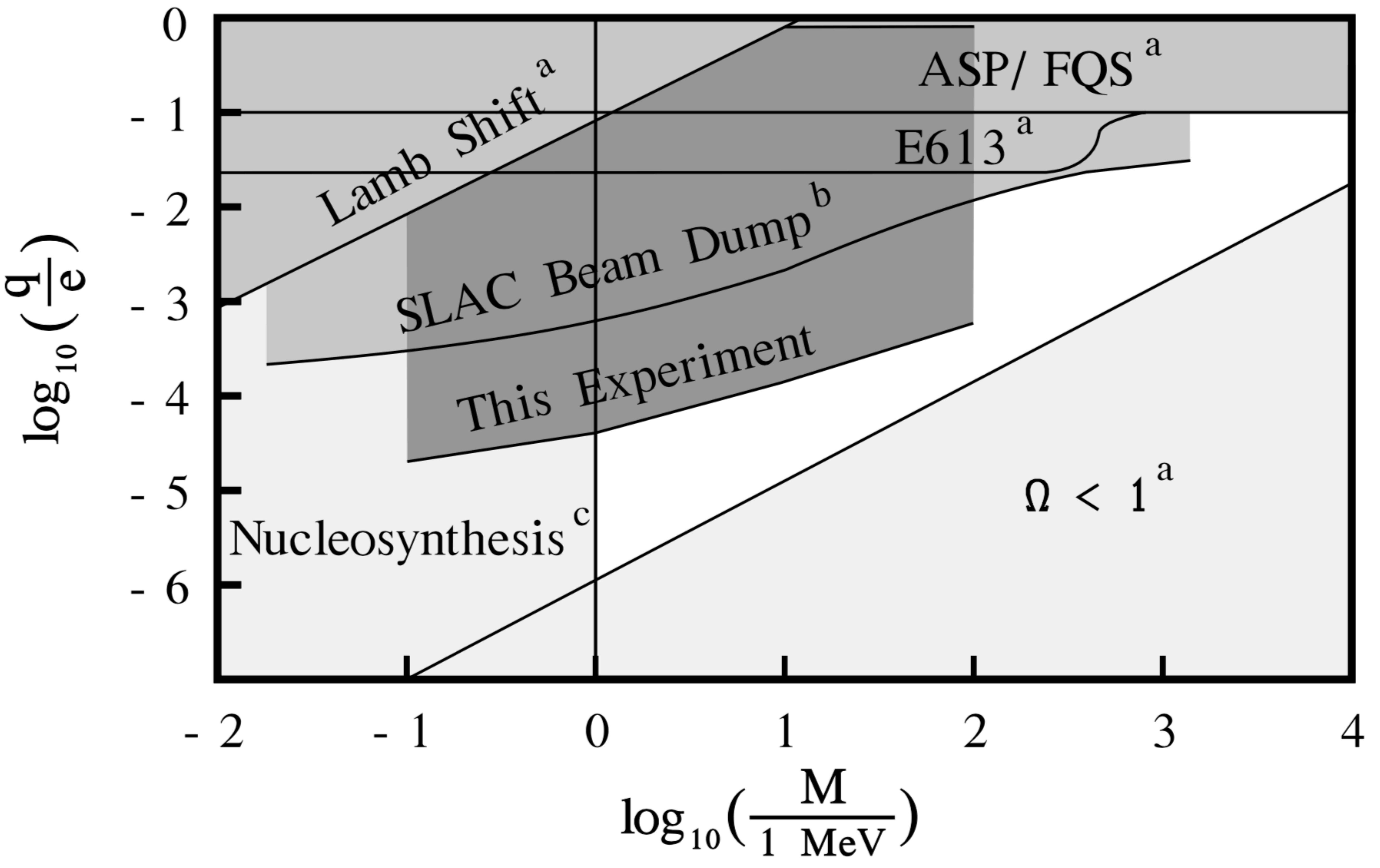


SLAC mQ constraints on millicharge



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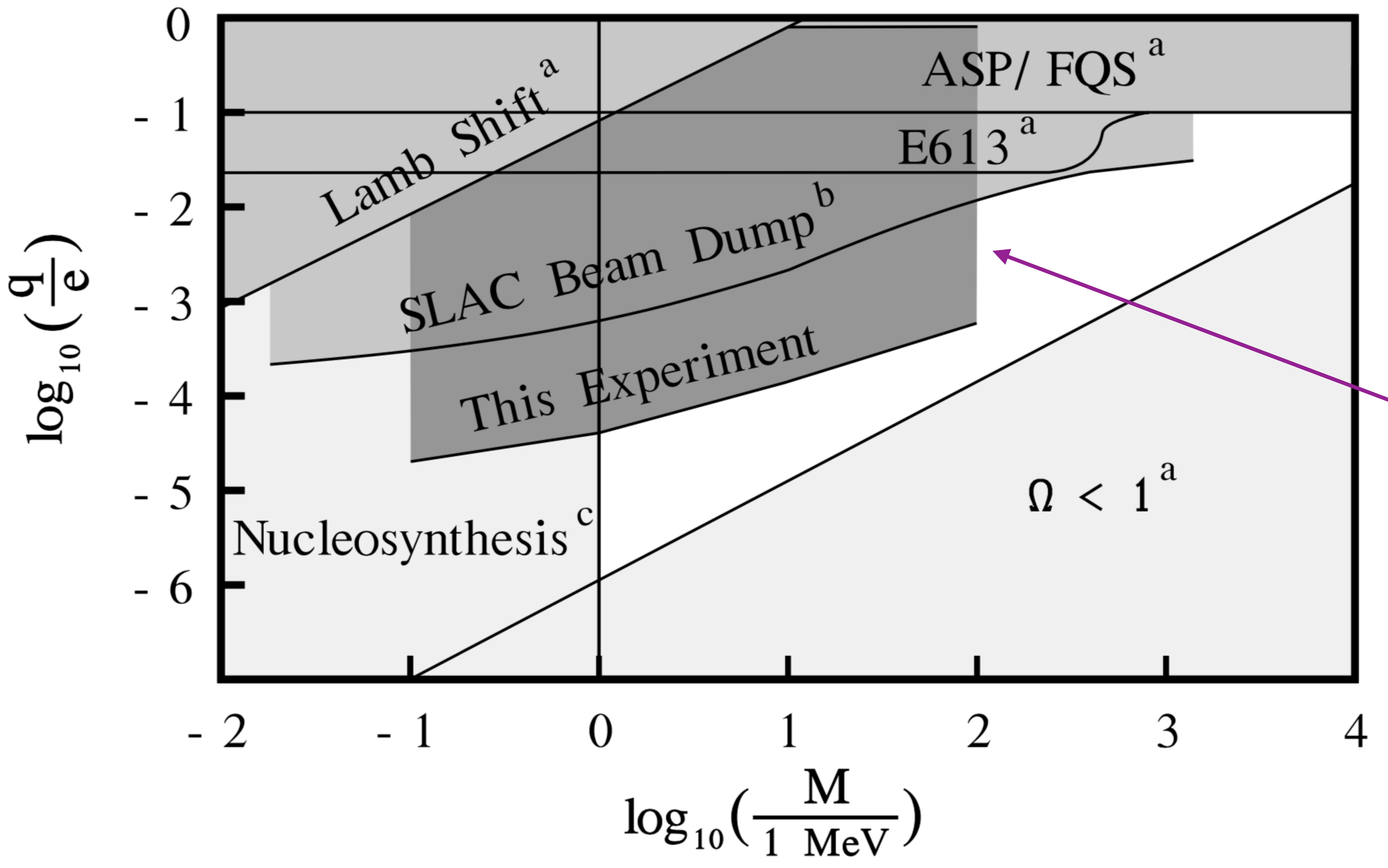
SLAC mQ constraints on millicharge

[Prinz et al, PRL 81.1175, 1998]

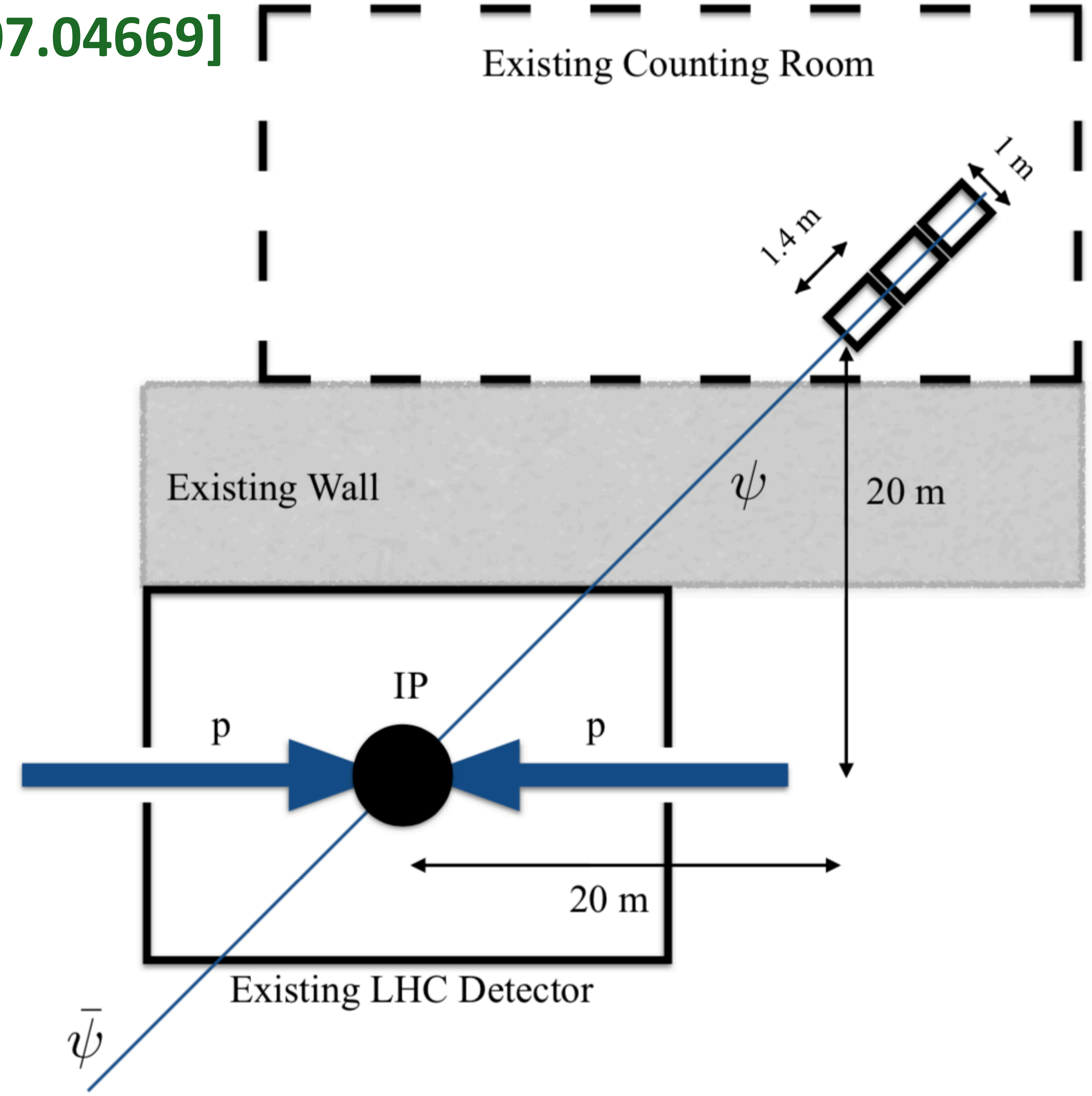


m > 100 MeV
MCP yield die off

MilliQan: proposed scintillation detector @ LHC

[Haas et al., 1410.6816]

[Ball et al., 1607.04669]



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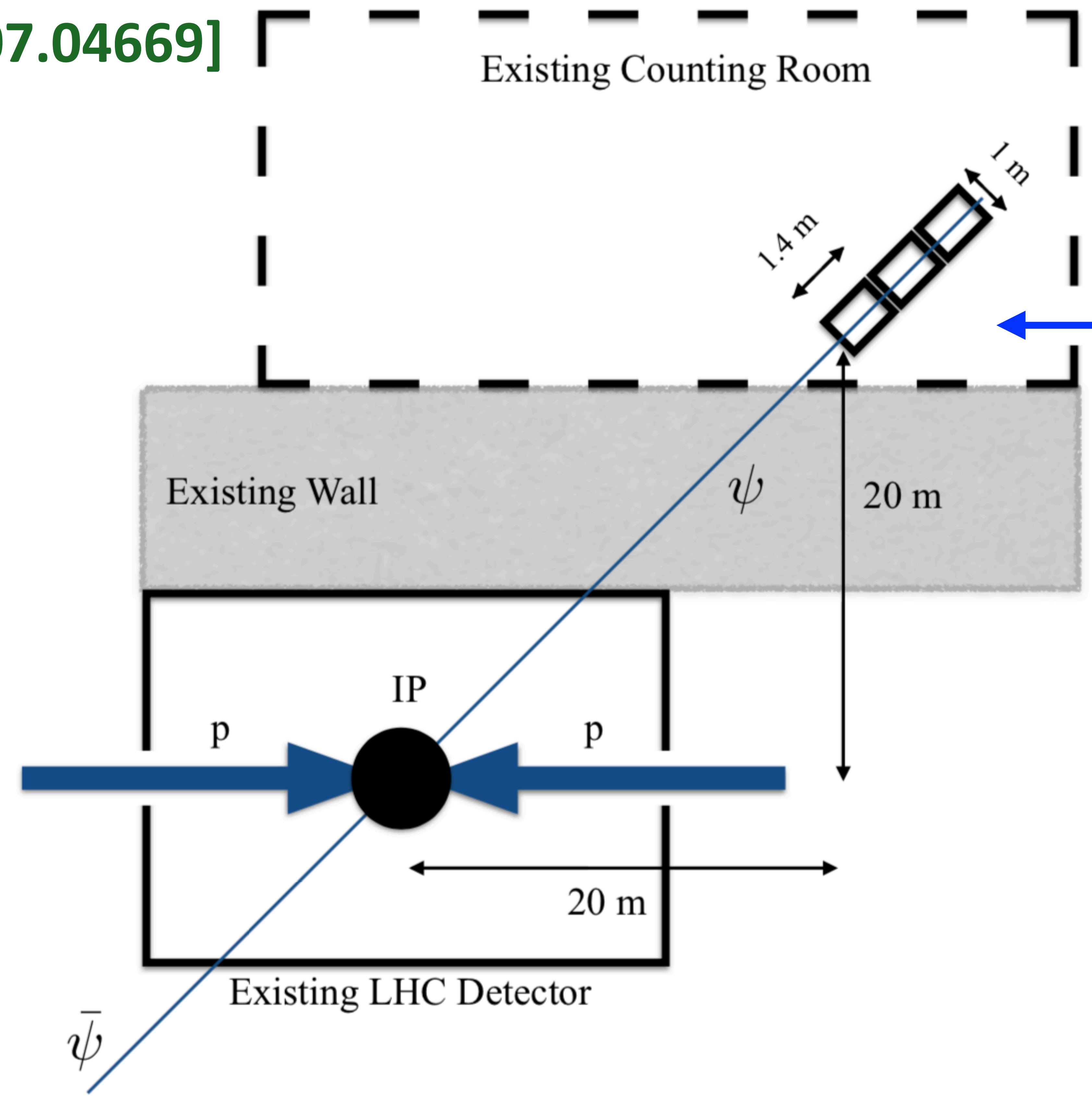
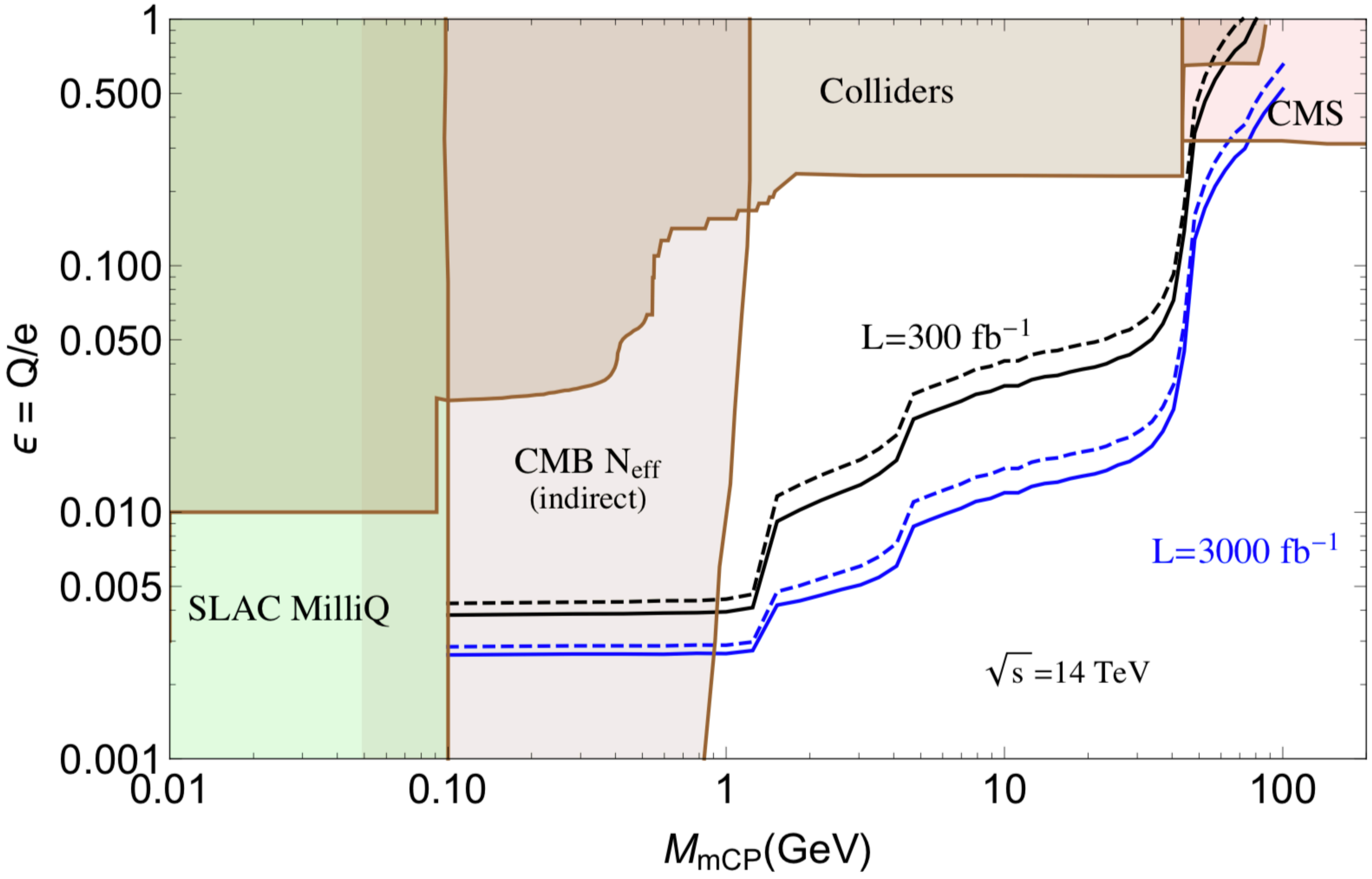


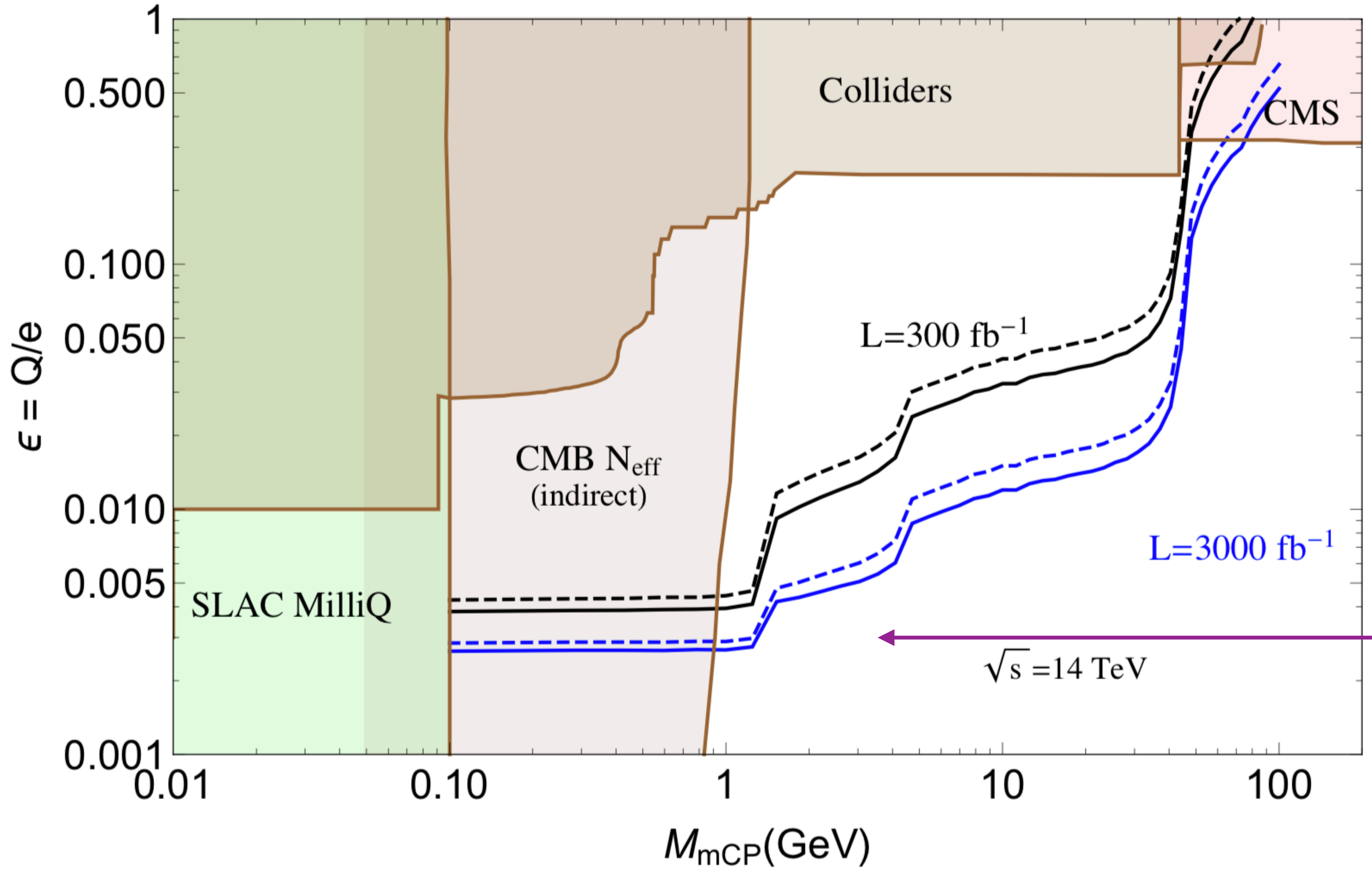
$1\ \text{m} \times 1\ \text{m} \times 3\ \text{m}$ plastic scintillators array with 3 sections (pointing to CMS IP), each containing 400 $5\ \text{cm} \times 5\ \text{cm} \times 80\ \text{cm}$ scintillator bars coupled to PMT. 33 m away from CMS IP.

MilliQan sensitivity on millicharged particles



[Ball et al., 1607.04669]

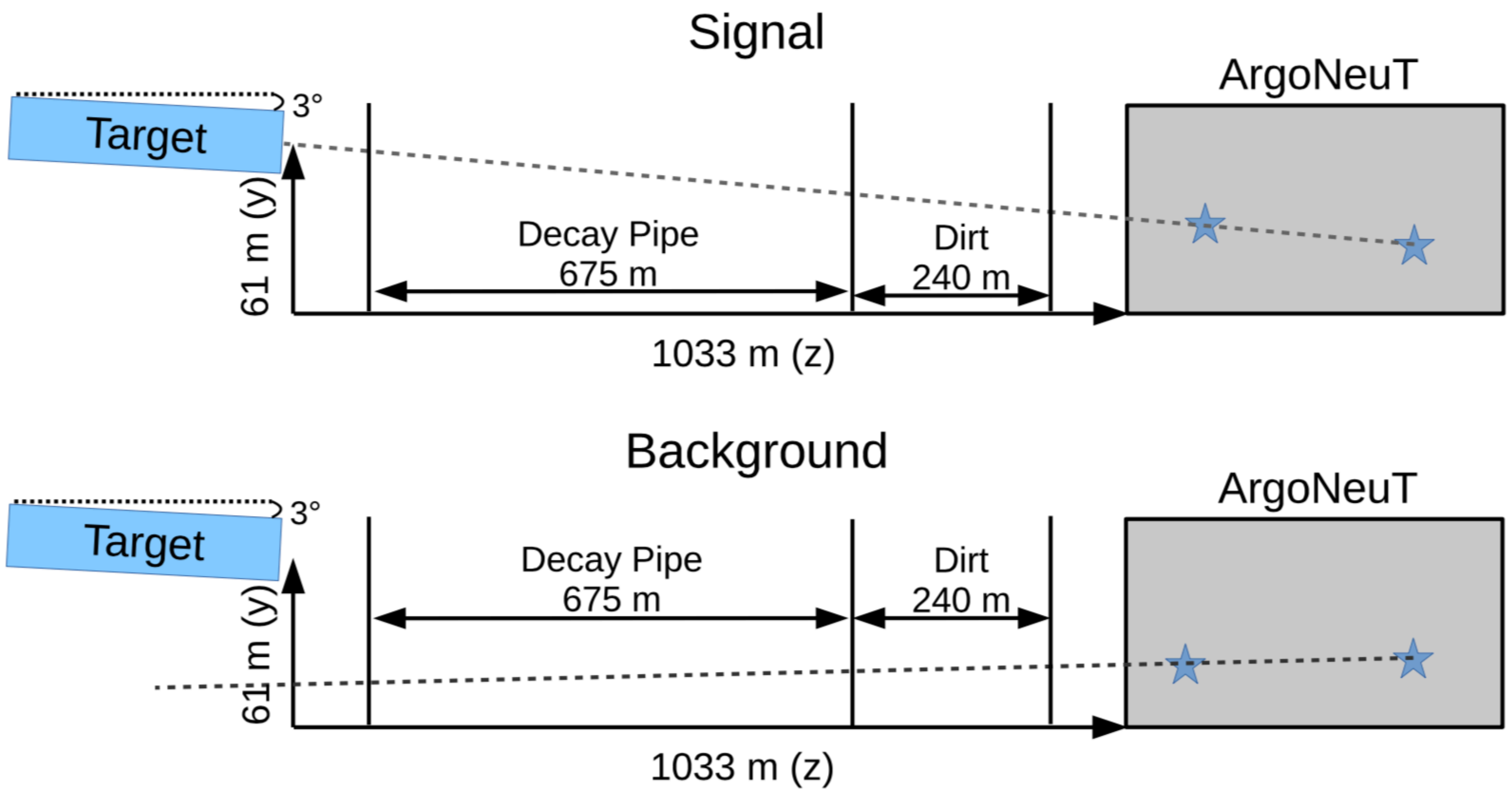
MilliQan sensitivity on millicharged particles



[Ball et al., 1607.04669]

photoelectron drops below one when $\epsilon \lesssim O(10^{-3})$

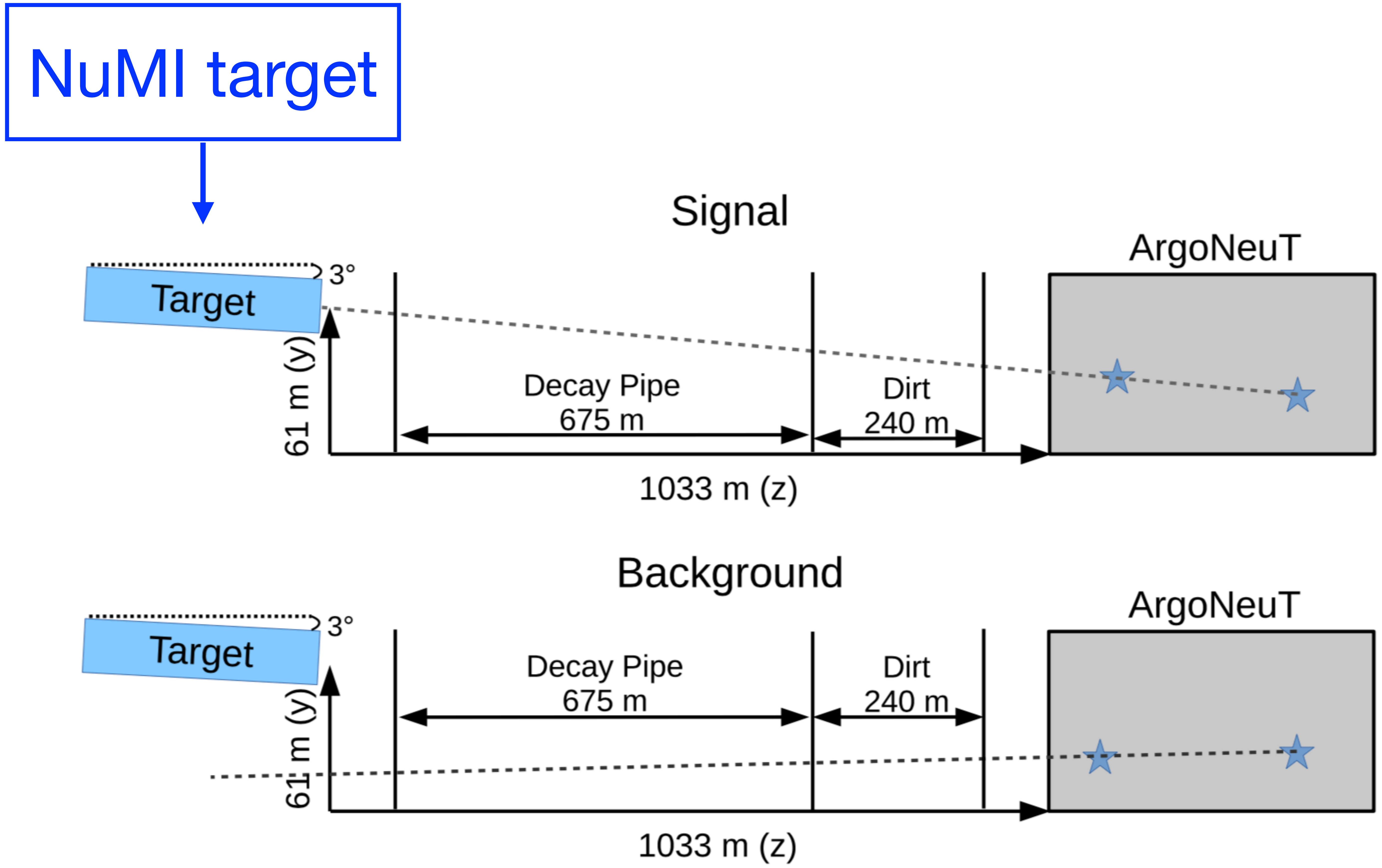
ArgoNeuT @ FermiLab: liquid argo neutrino detector



[Harnik et al., 1902.03246]

[ArgoNeuT, 1911.07996]

ArgoNeuT @ FermiLab: liquid argo neutrino detector



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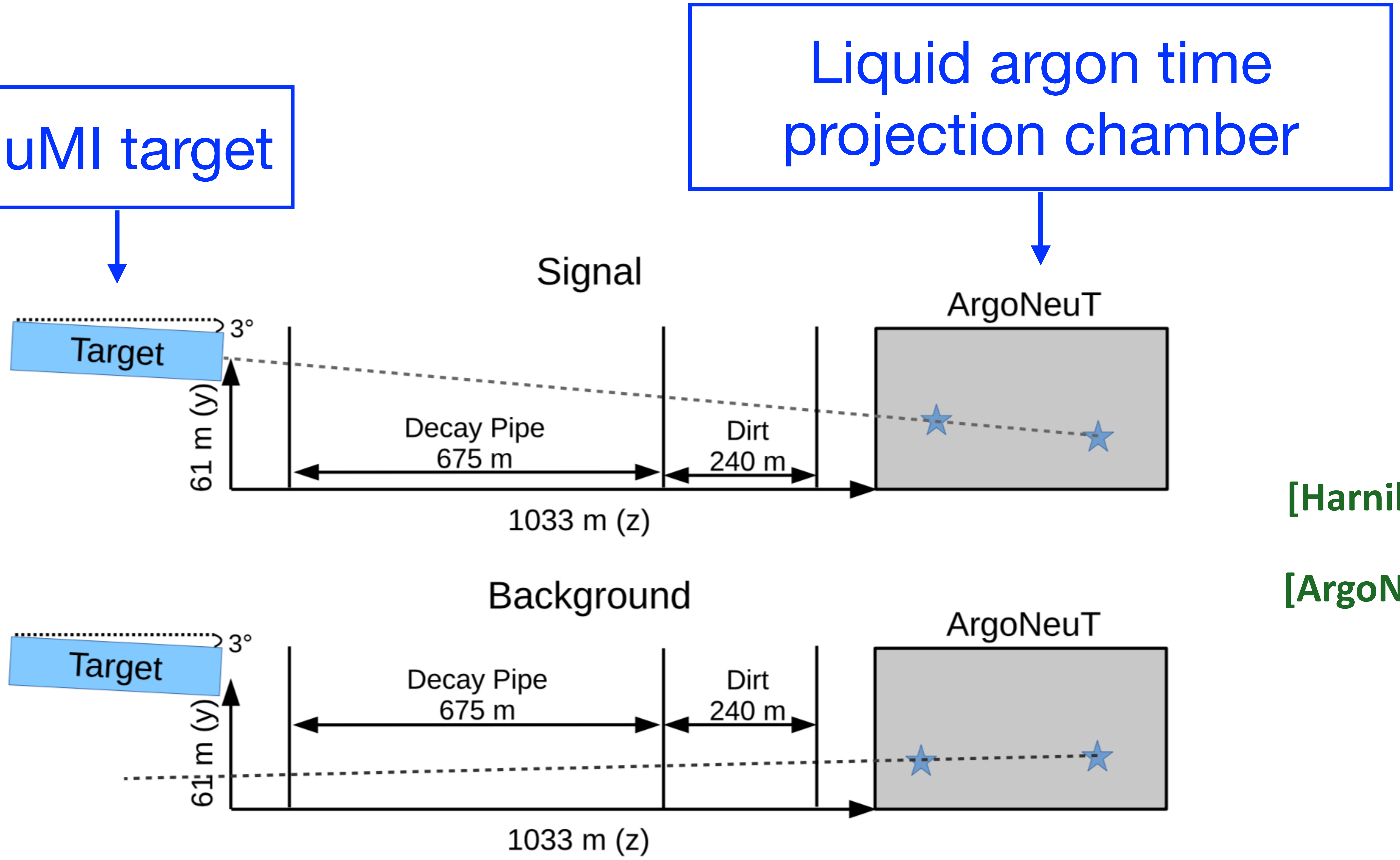
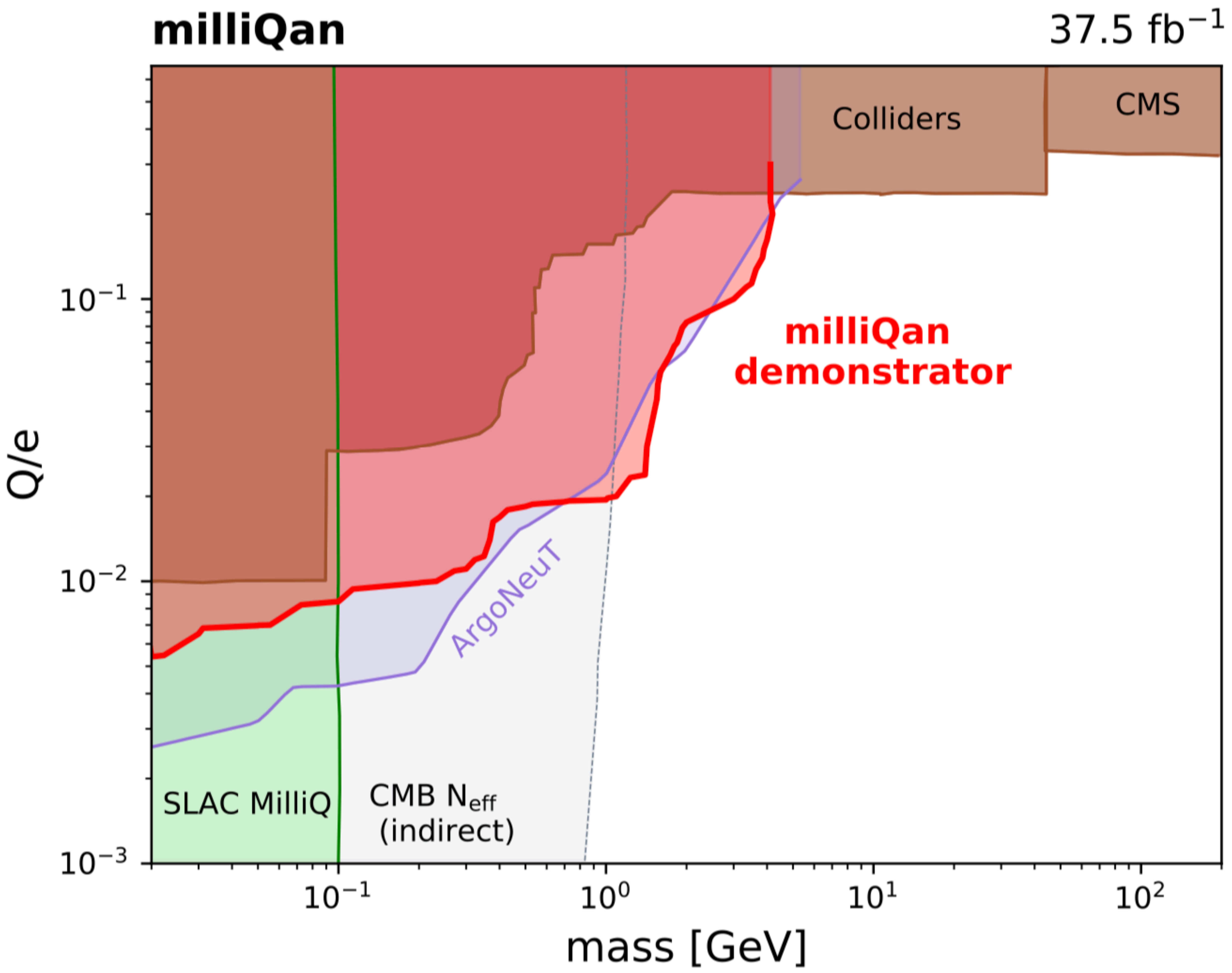


[Harnik et al., 1902.03246]

[ArgoNeuT, 1911.07996]

Limits from ArgoNeuT & MilliQan demonstrator (1%)



[ArgoNeuT, 1911.07996]

ArgoNeuT 10^{20} POT

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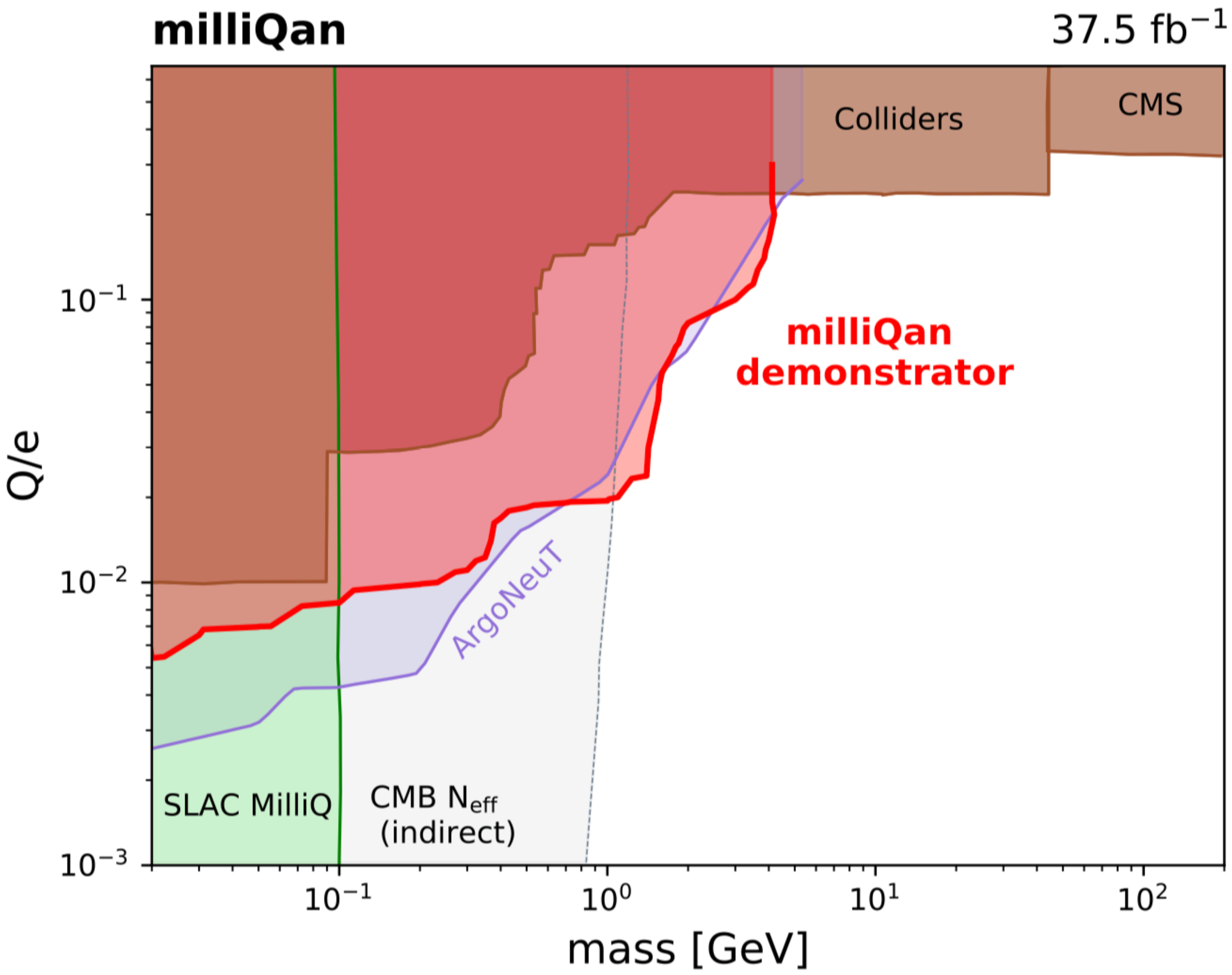


[ArgoNeuT, 1911.07996]

ArgoNeuT 10^{20} POT

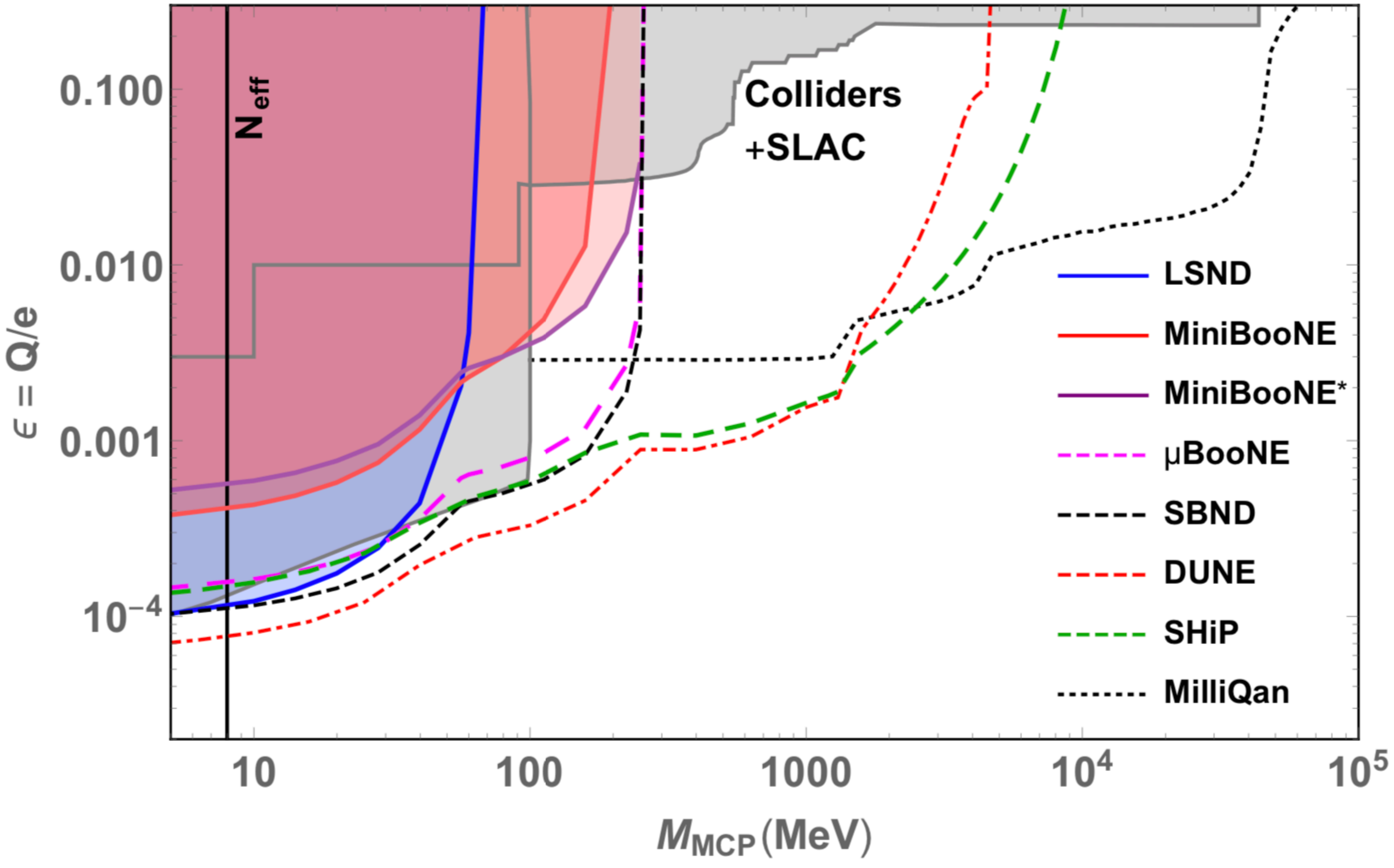
[milliQan demonstrator, 2005.06518]

1% of total detector

37/fb in 2018

MCP scatters w/ neutrino experiment target

MCP produced in proton fixed-target experiments → MCP scatters w/ target (electron) in the neutrino detector



[Magill et al., 1806.03310]

solid: data
dashed: projection

Some future experiments on millicharge (incomplete)

LDMX: electron fixed target

NA64: muon fixed target

FerMINI: scintillators @ proton fixed target

SUBMET: scintillators @ JPARC

neutrino experiments

DM experiments

3 electron colliders' sensitivity

[ZL, Zhang, 1808.00983]

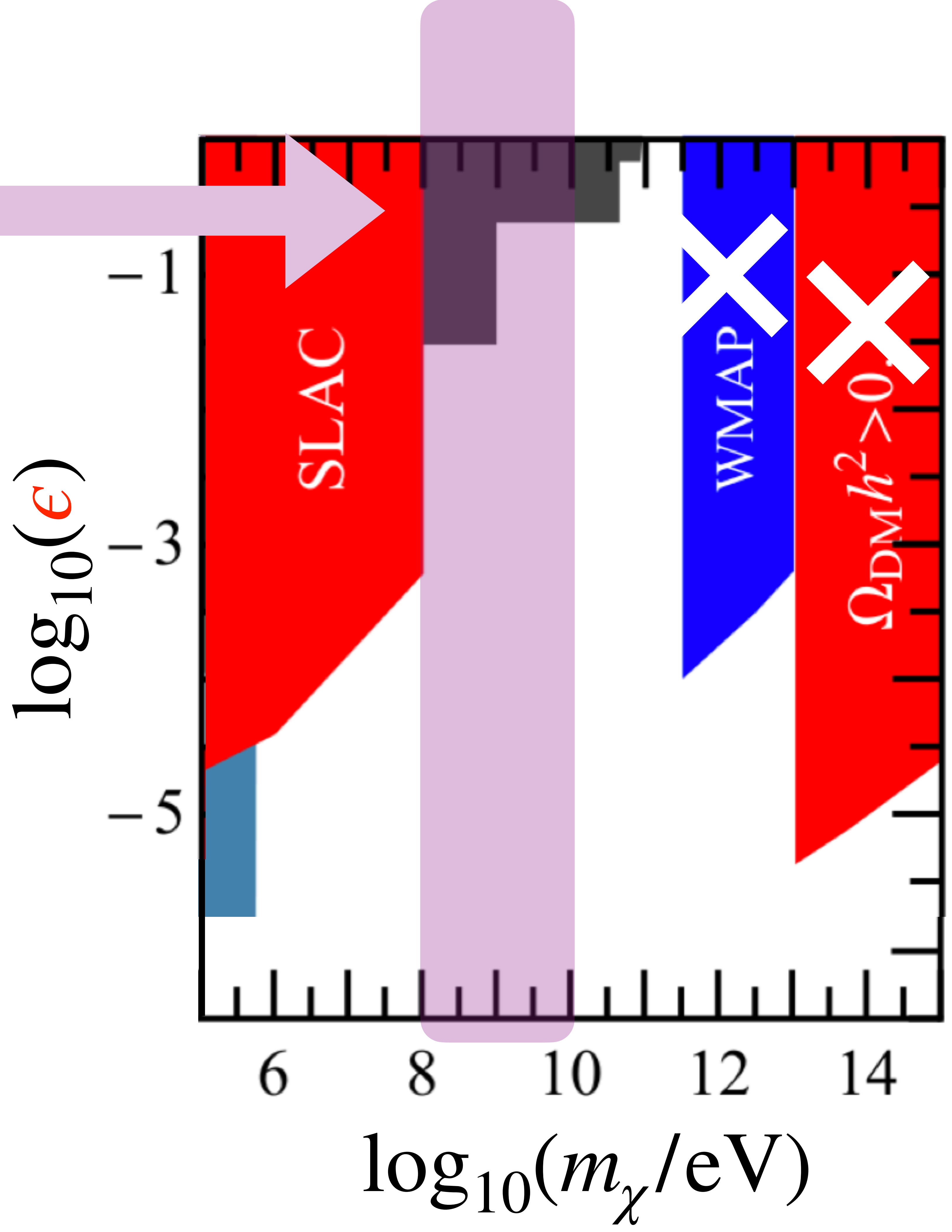
[Liang, ZL, Ma, Zhang, 1909.06847]

Probing millicharge at electron colliders

0.1-10 GeV

accessible at electron colliders

BaBar
BESIII
Belle II
STCF



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Probing millicharge at electron colliders

0.1-10 GeV

accessible at electron colliders

BaBar
BESIII
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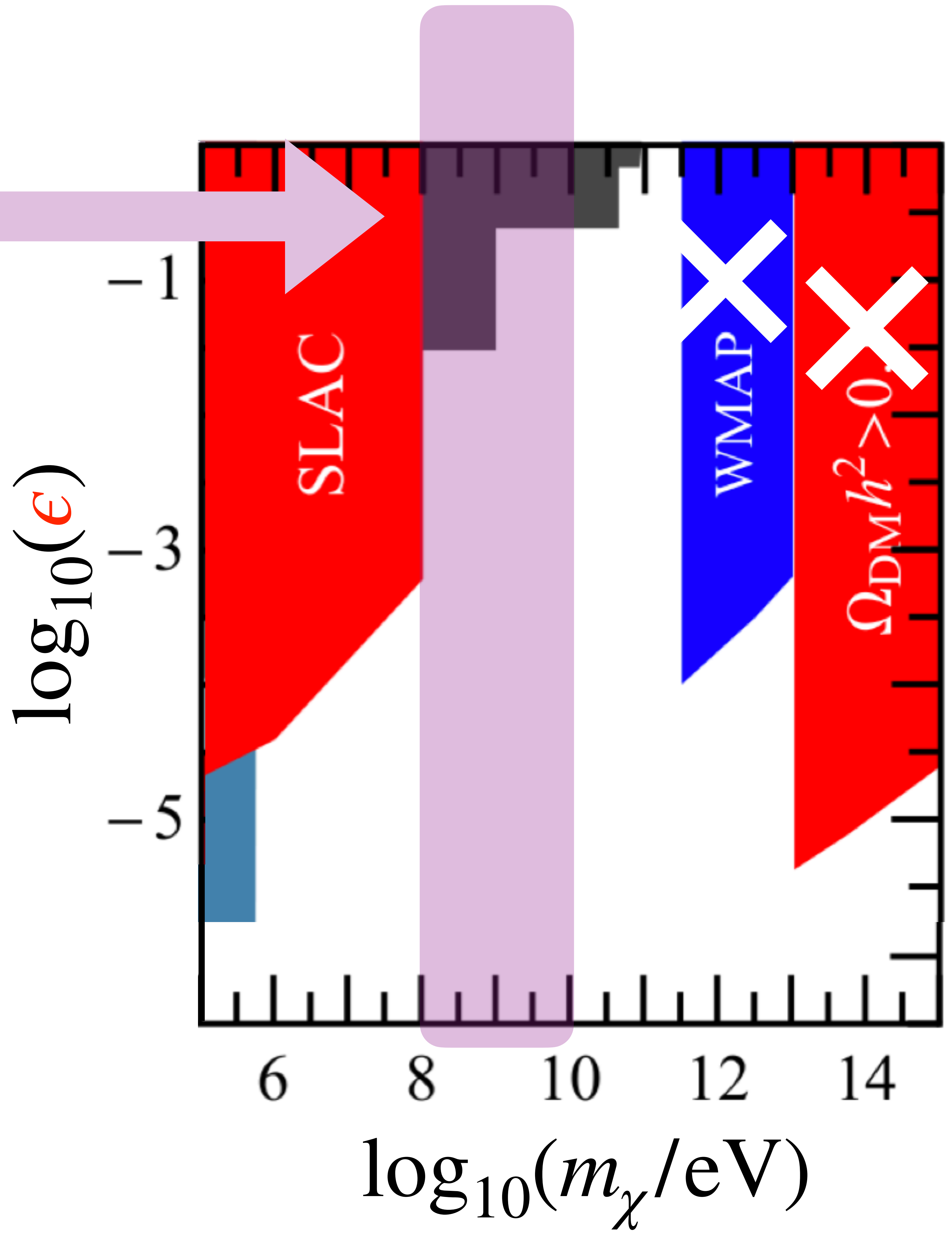
STCF

inability of the detectors

missing energy

[ZL, Zhang, 1808.00983]

[Liang, ZL, Ma, Zhang, 1909.06847]



Process to search for millicharged particles

very small ionization signal from millicharge → mono-photon @ electron colliders

[ZL, Zhang, 1808.00983]

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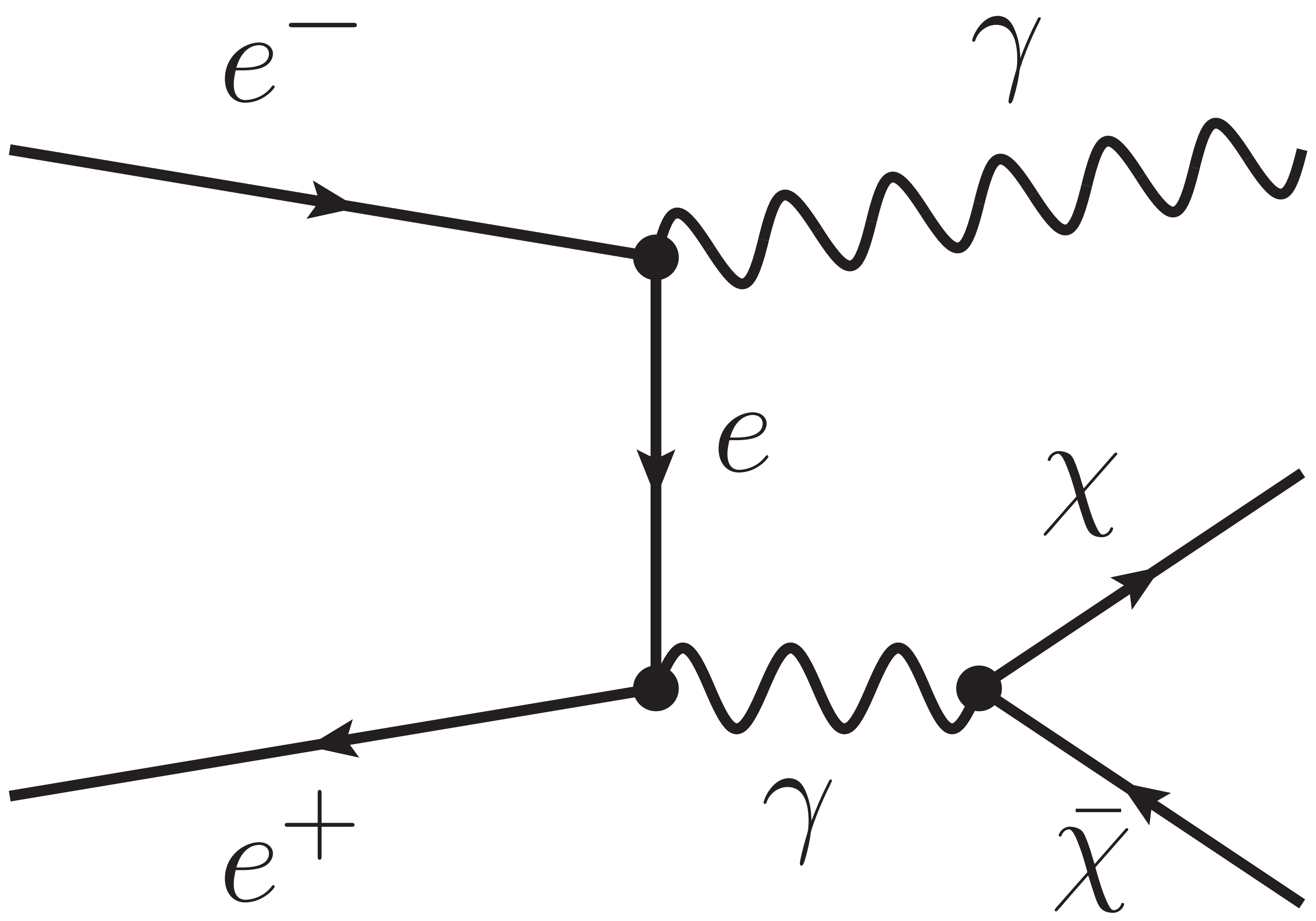

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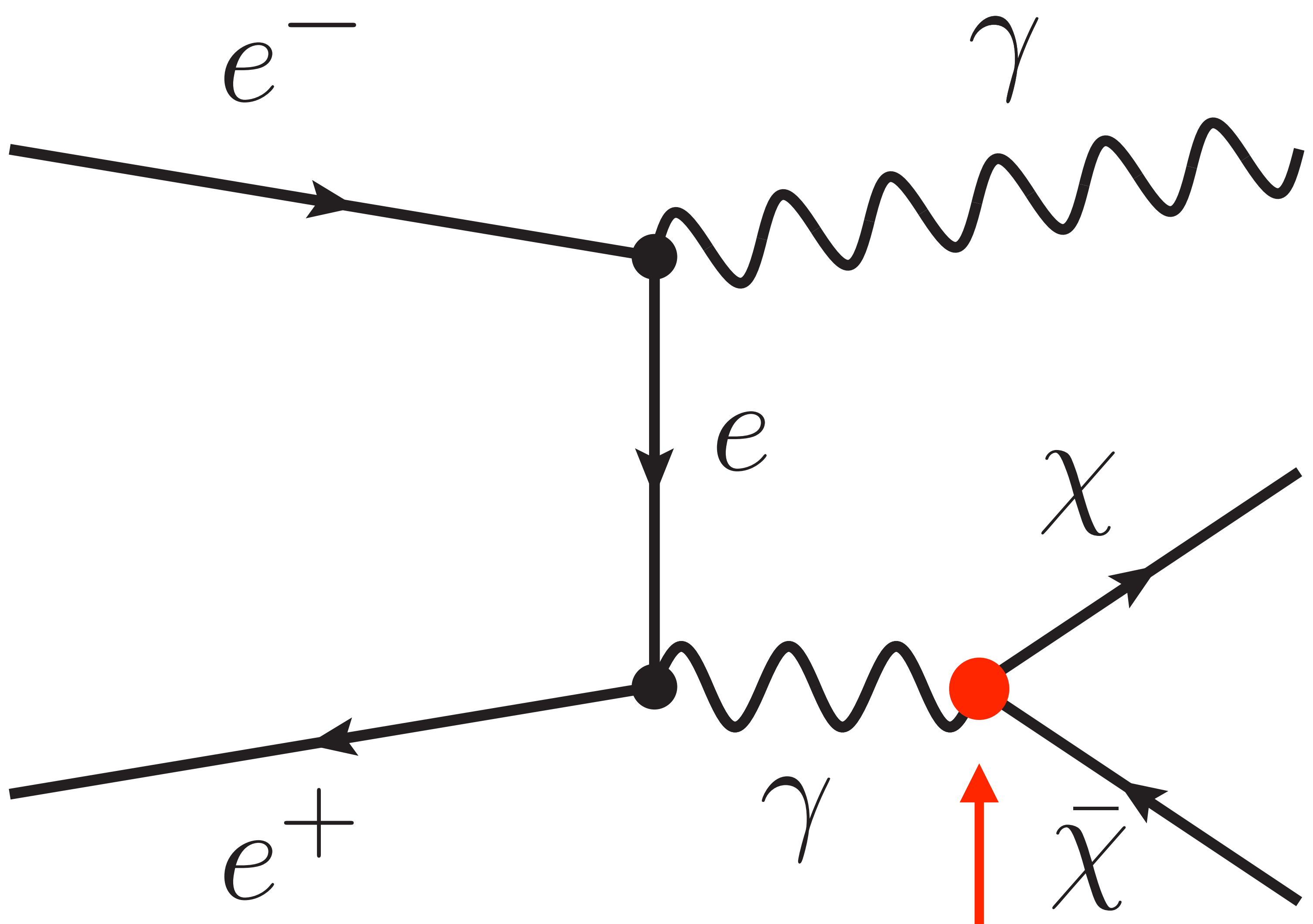

millicharge vertex: $e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$

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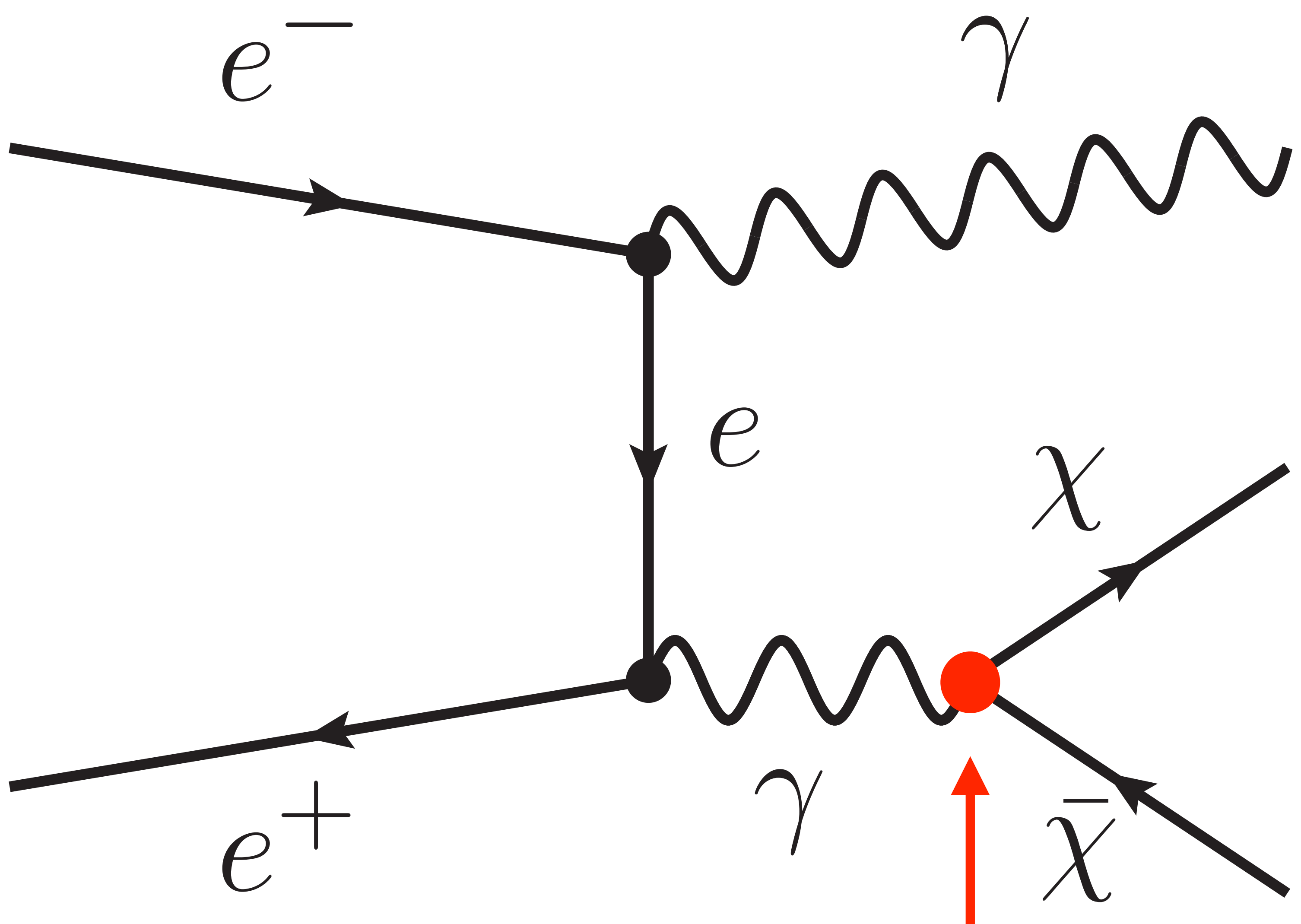

"invisible" at electron colliders

millicharge vertex: $e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$

Process to search for millicharged particles

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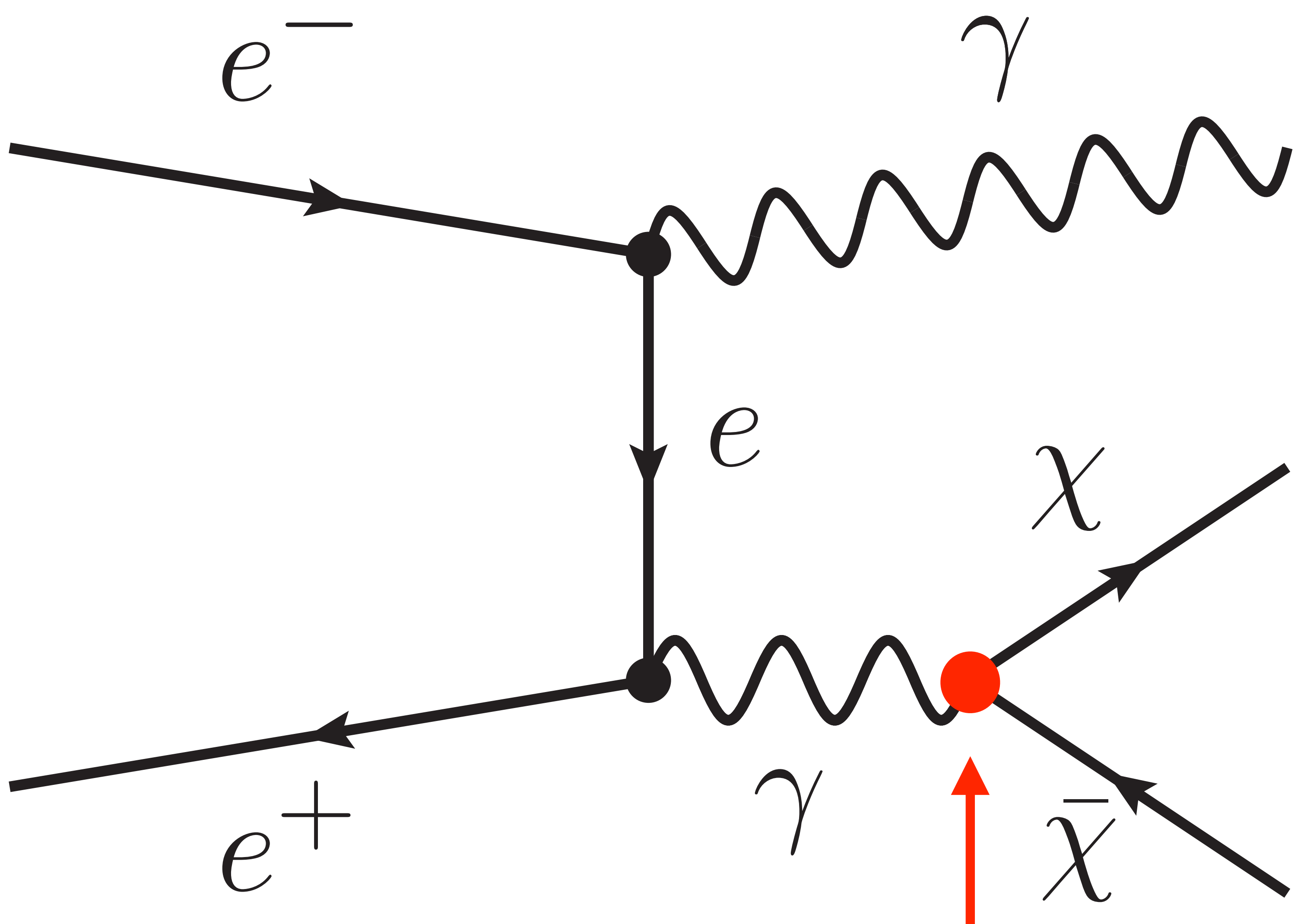

monophoton

"invisible" at electron colliders

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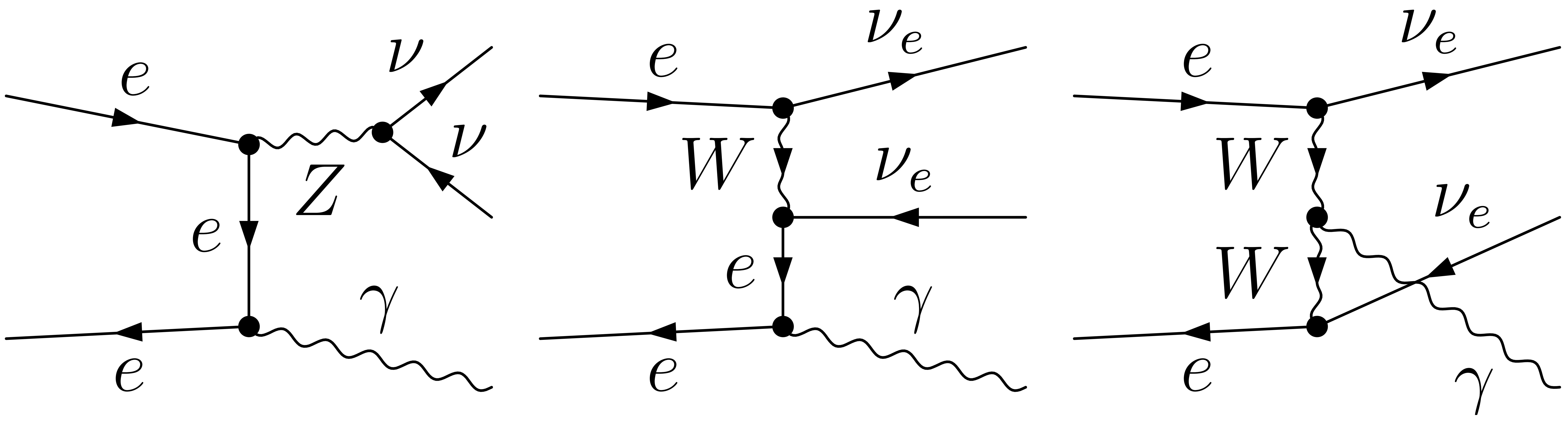
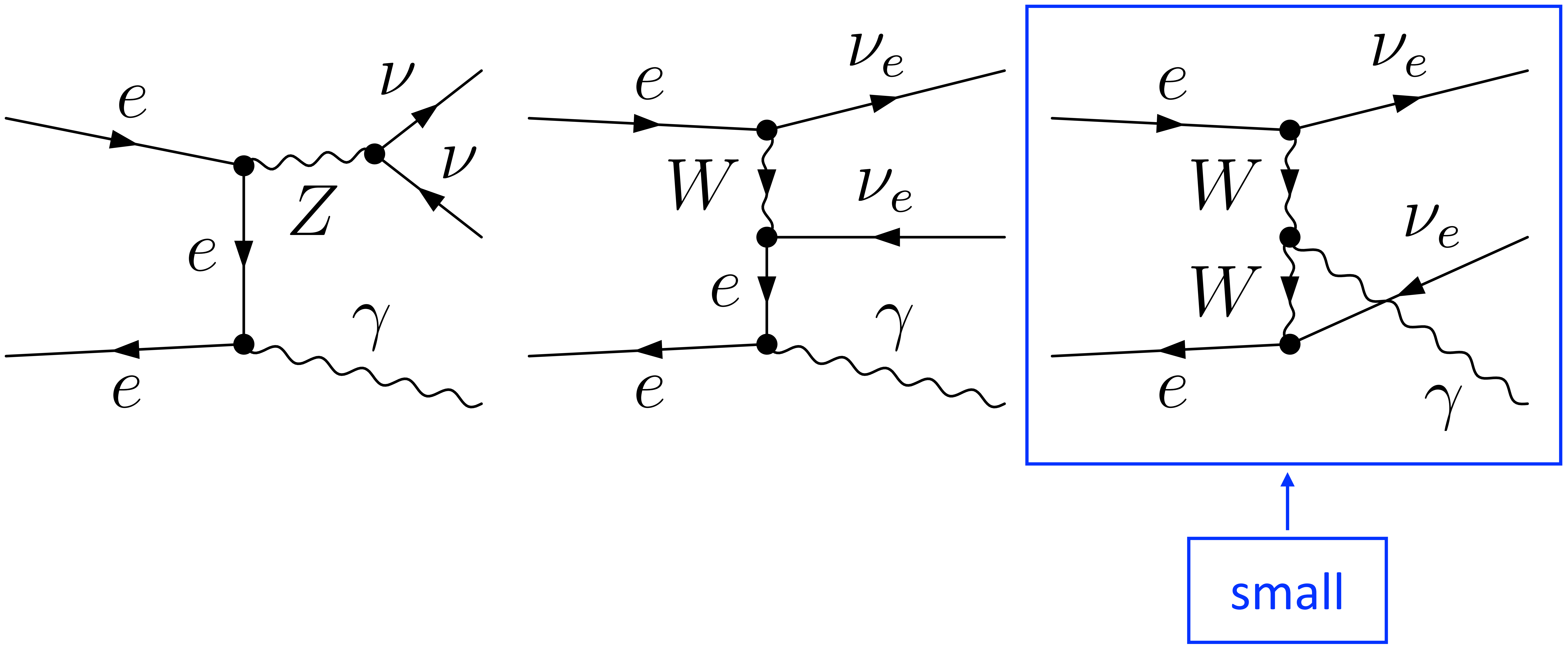
Irreducible BG (monophoton plus 2 neutrinos)

Irreducible BG: $e^+e^- \to \gamma\nu\nu$



Irreducible BG (monophoton plus 2 neutrinos)

Irreducible BG: $e^+e^- \to \gamma\nu\nu$



monophoton cross section @ electron colliders

millicharge process: $e^+ e^- \rightarrow \chi \chi \gamma$

[ZL, Zhang, 1808.00983]

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

$$z_\gamma \equiv \cos\theta_\gamma \qquad s_\gamma = s - 2\sqrt{s}E_\gamma \qquad \beta_\chi = (1 - 4m_\chi^2/s_\gamma)^{1/2}$$

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irreducible BG: $e^+ e^- \to \gamma\nu\nu$

[Ma, Okada 1978]

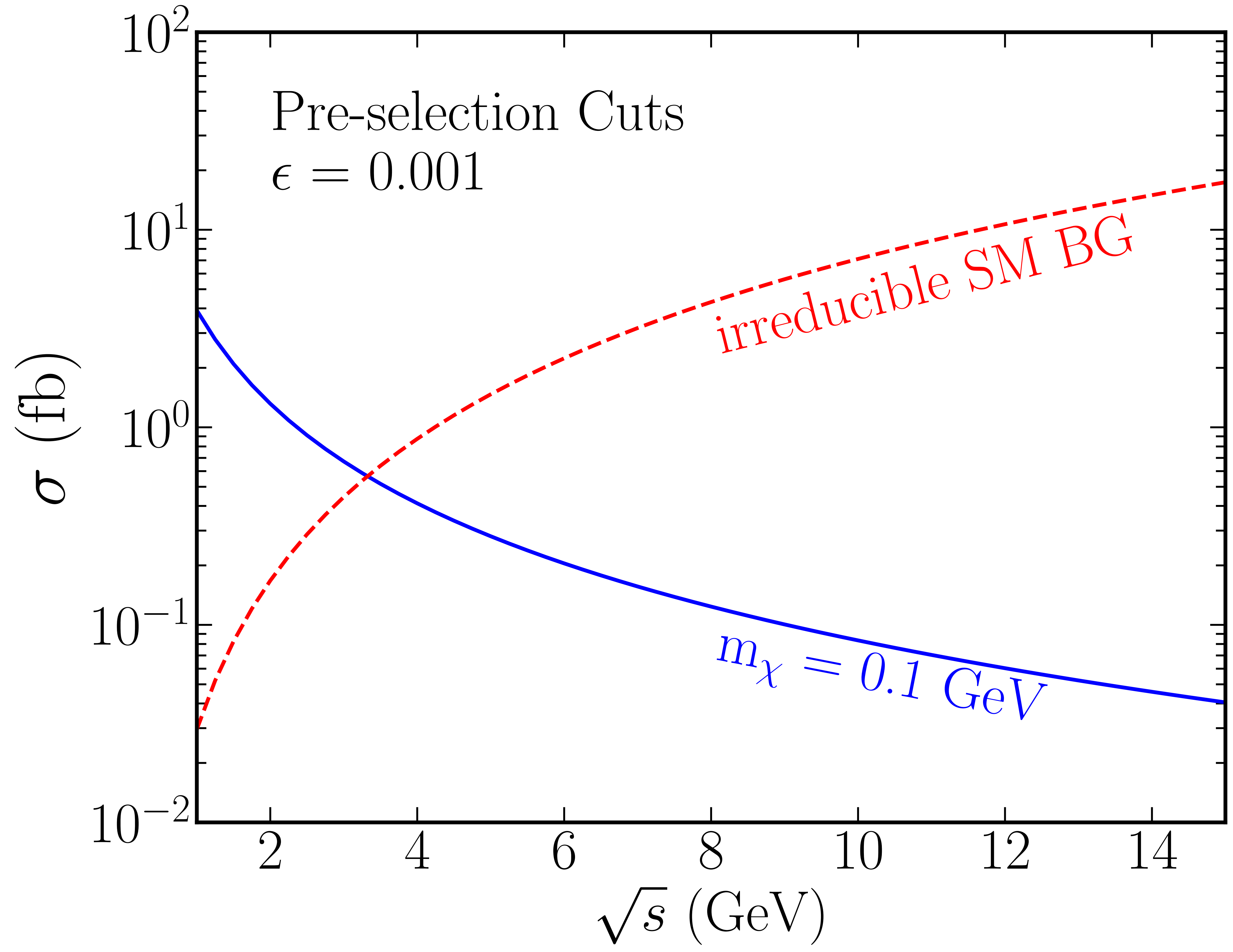
[Gaemers + 1979]

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

$$s_W \equiv \sin\theta_W \qquad f(s_W) = 8s_W^4 - 4s_W^2/3 + 1$$

“Low” colliding energy is better to probe MCPs

if irreducible BG is the only important BG



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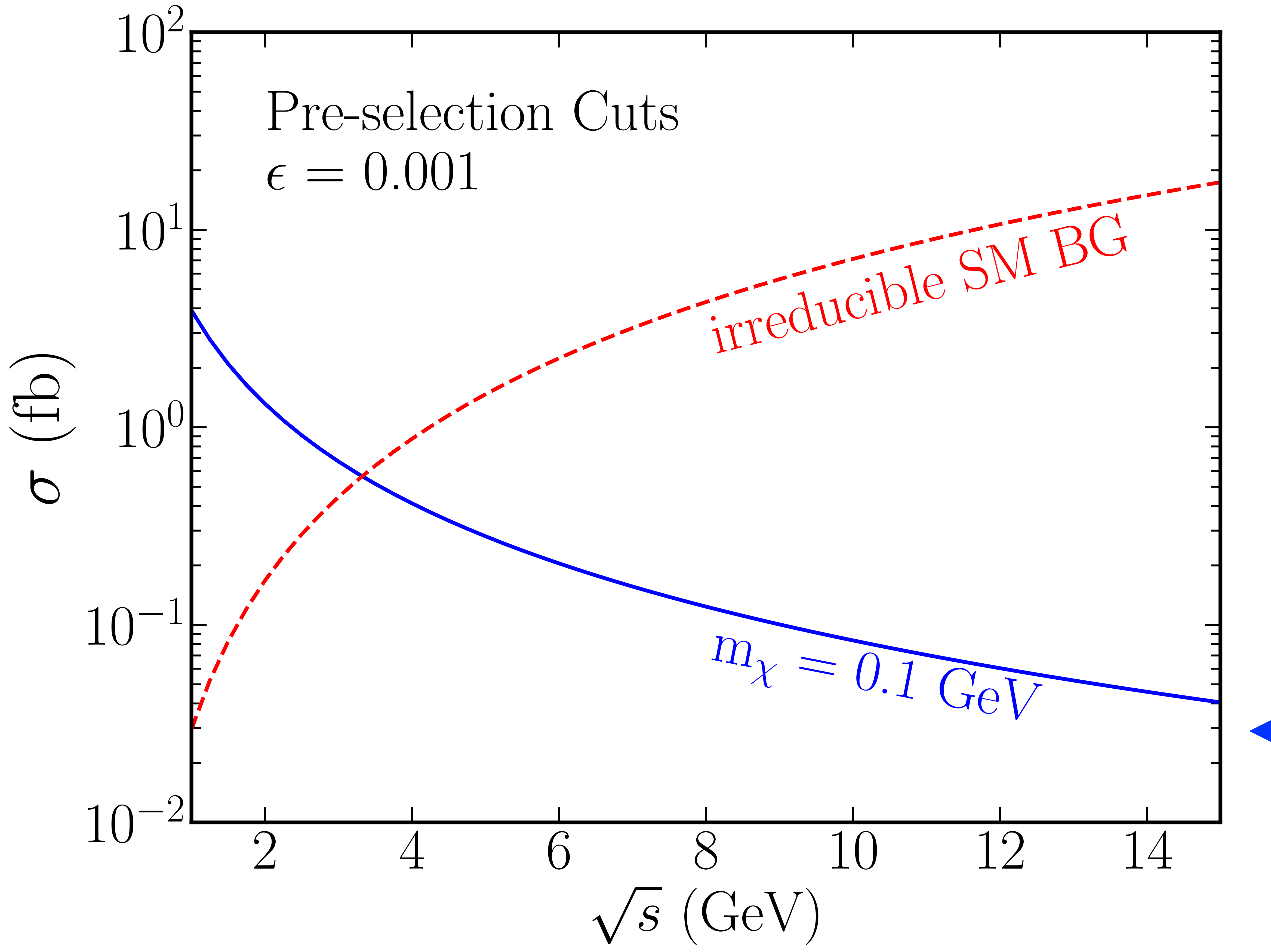

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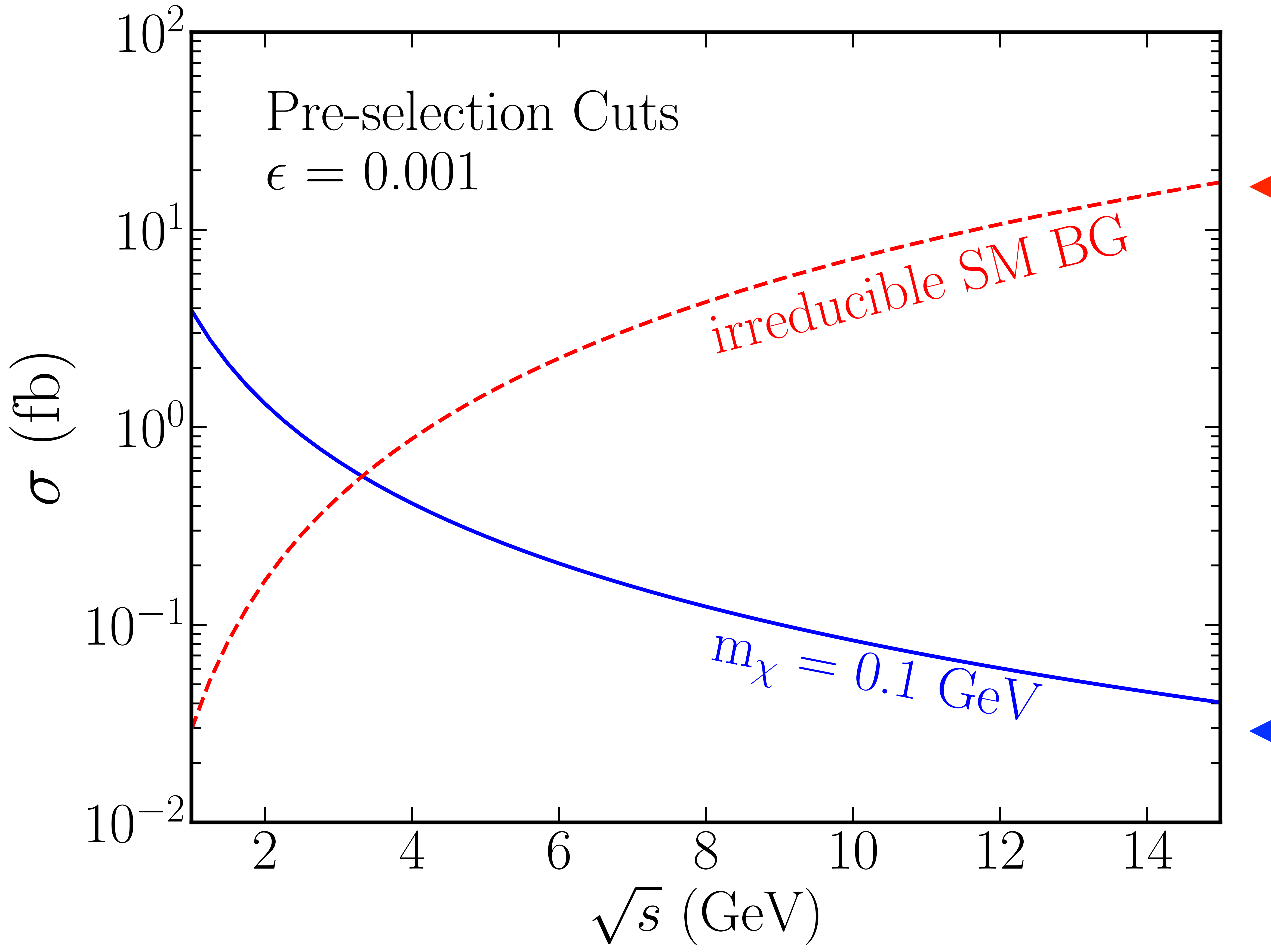
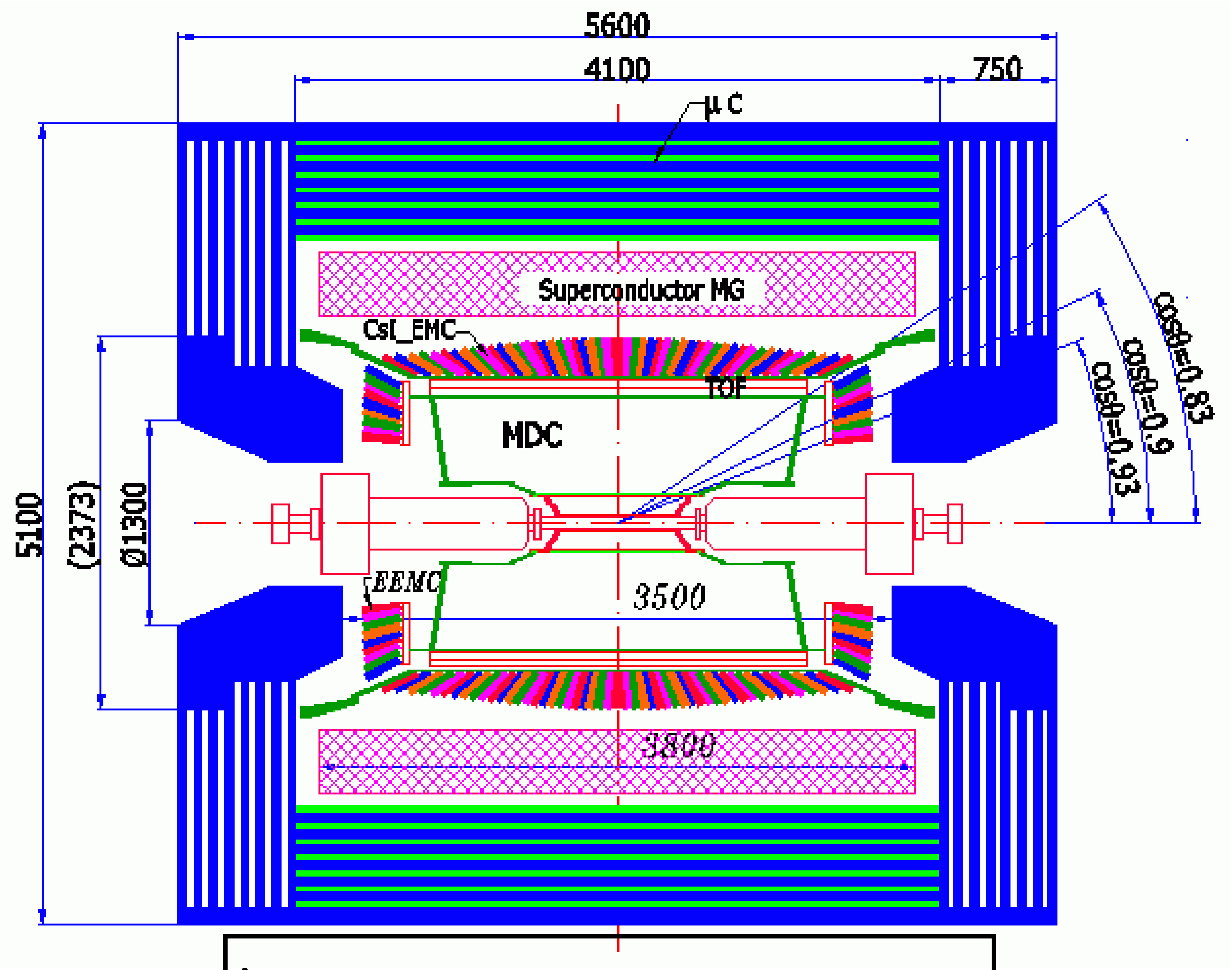


$e^+e^- \to \gamma\bar{\nu}\nu$

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

BESIII detectors & reducible BG

[Chao, Wang et al. 0809.1869]



beam energy: 1.0-2.3 GeV

Main drift chamber (MDC)

$|\cos(\Theta_\gamma)|<0.93$

Time-of-Flight (TOF)

$|\cos(\Theta_\gamma)|<0.83$

$0.85<|\cos(\Theta_\gamma)|<0.95$

Electromagnegtic calorimeter (EMC)

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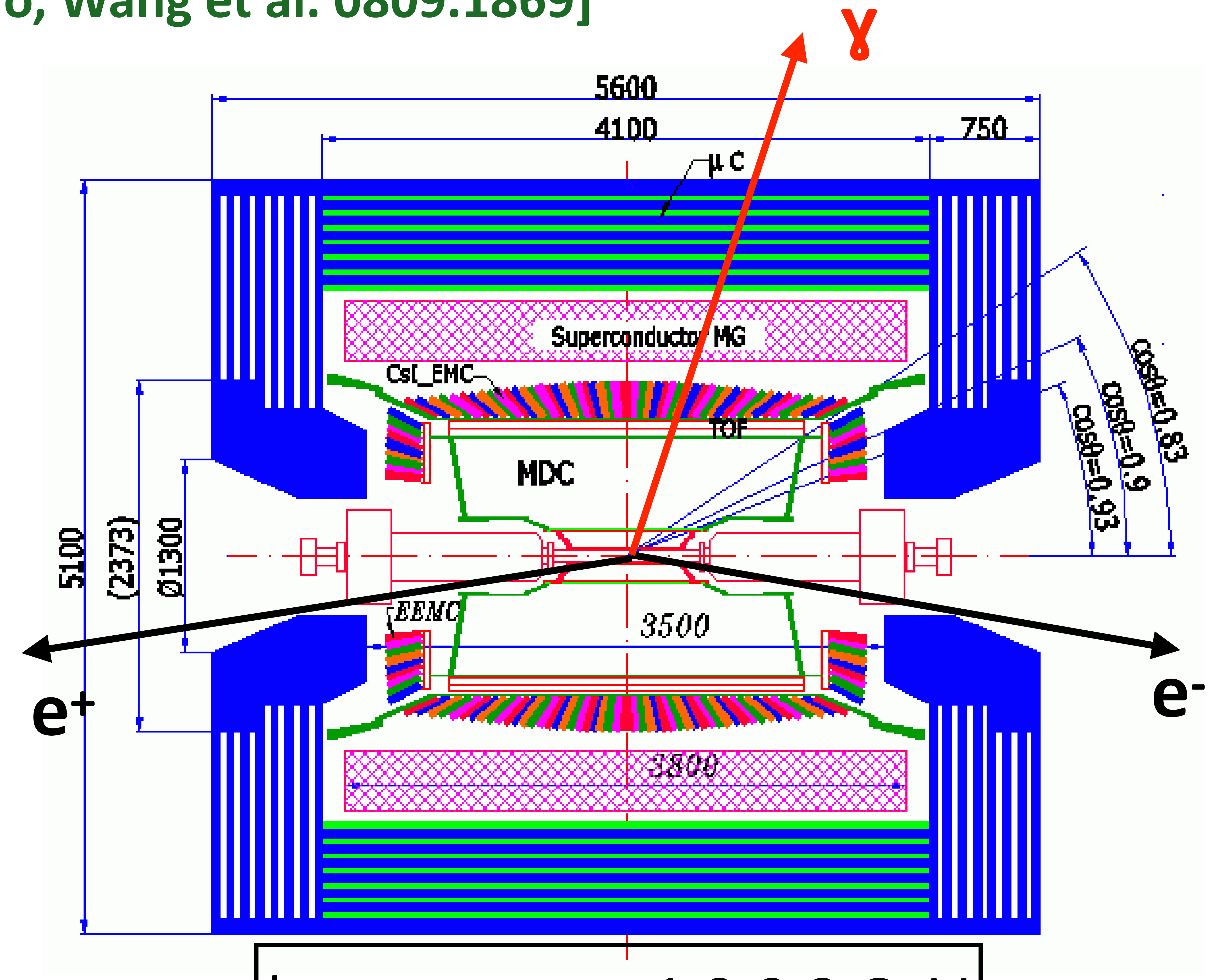

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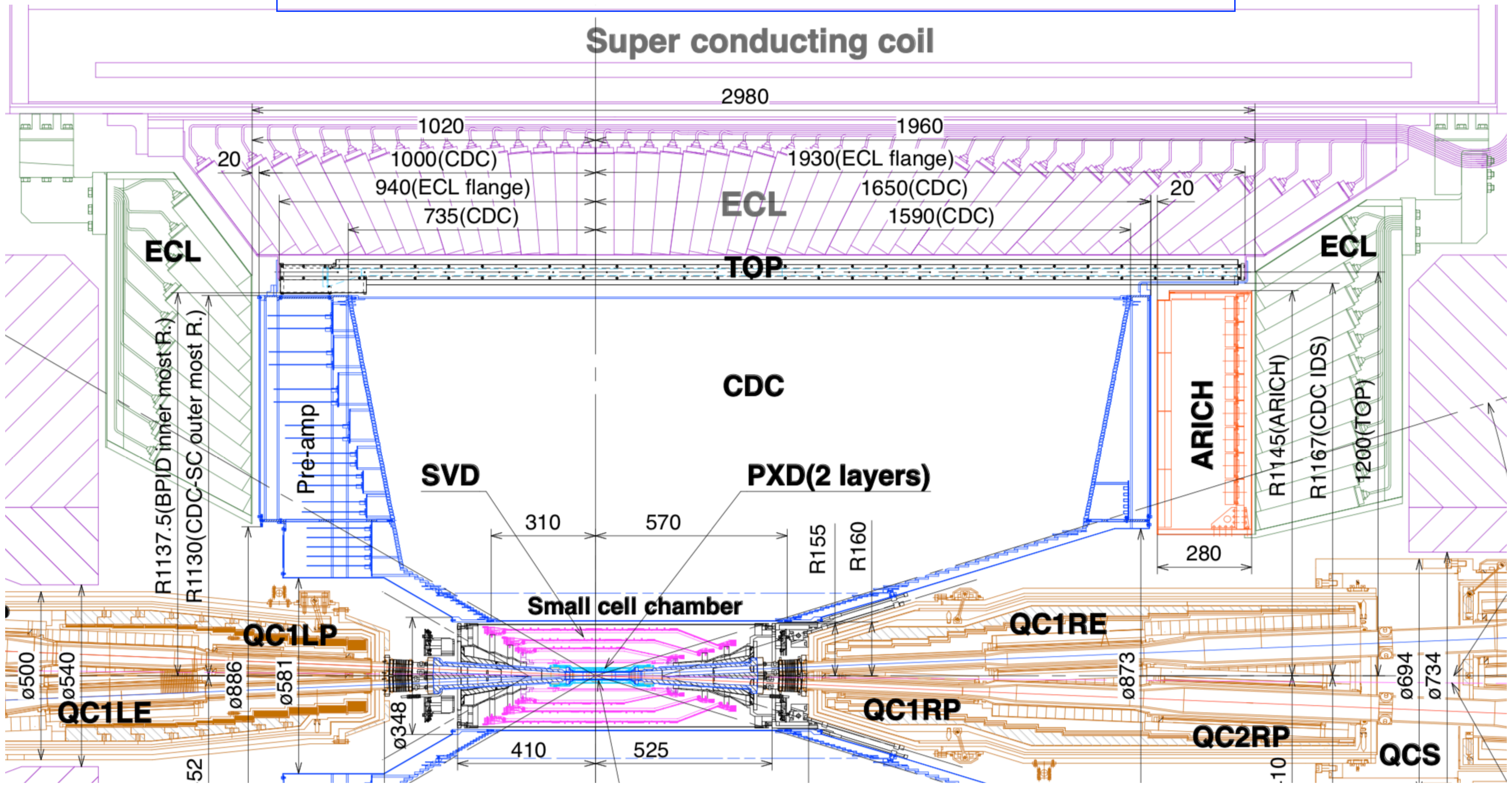
Belle II has several uncovered angular regions

7 GeV electron collides w/ 4 GeV positron



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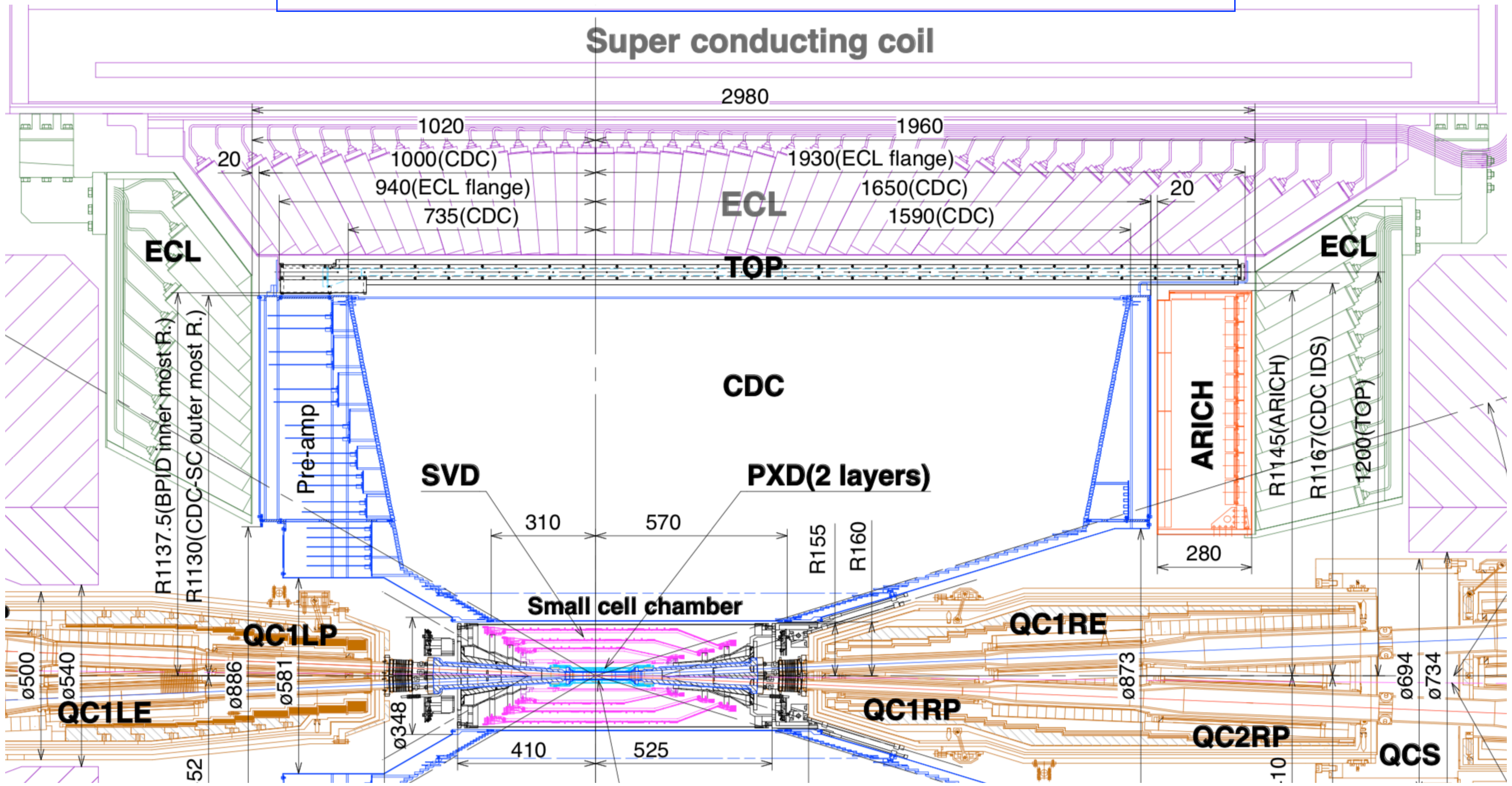


ECL angles

(lab frame)

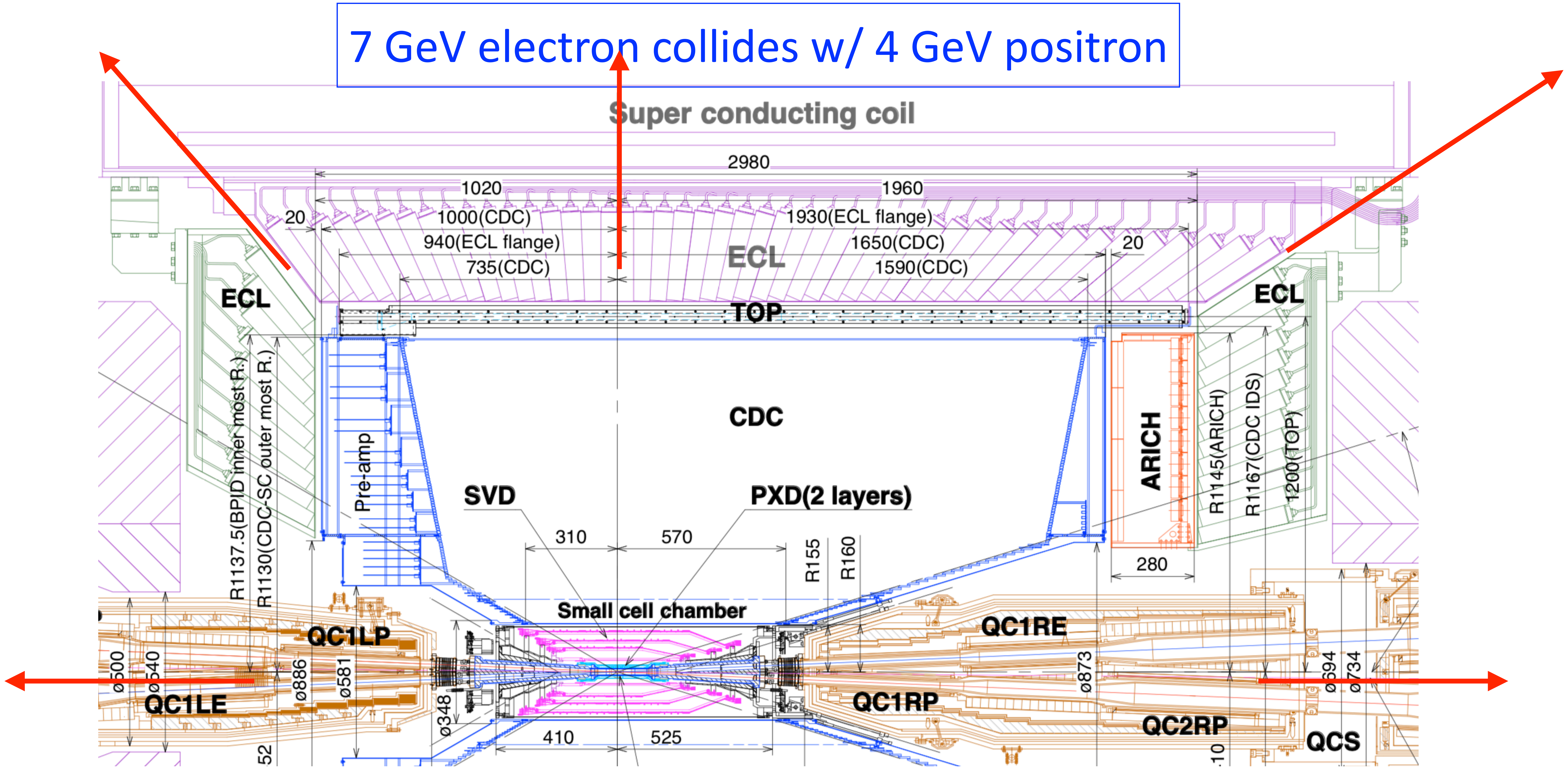
$$12.4^\circ < \theta < 31.4^\circ$$

$$32.2^\circ < \theta < 128.7^\circ$$

$$130.7^\circ < \theta < 155.1^\circ$$

[Belle II 1808.10567]

Belle II has several uncovered angular regions



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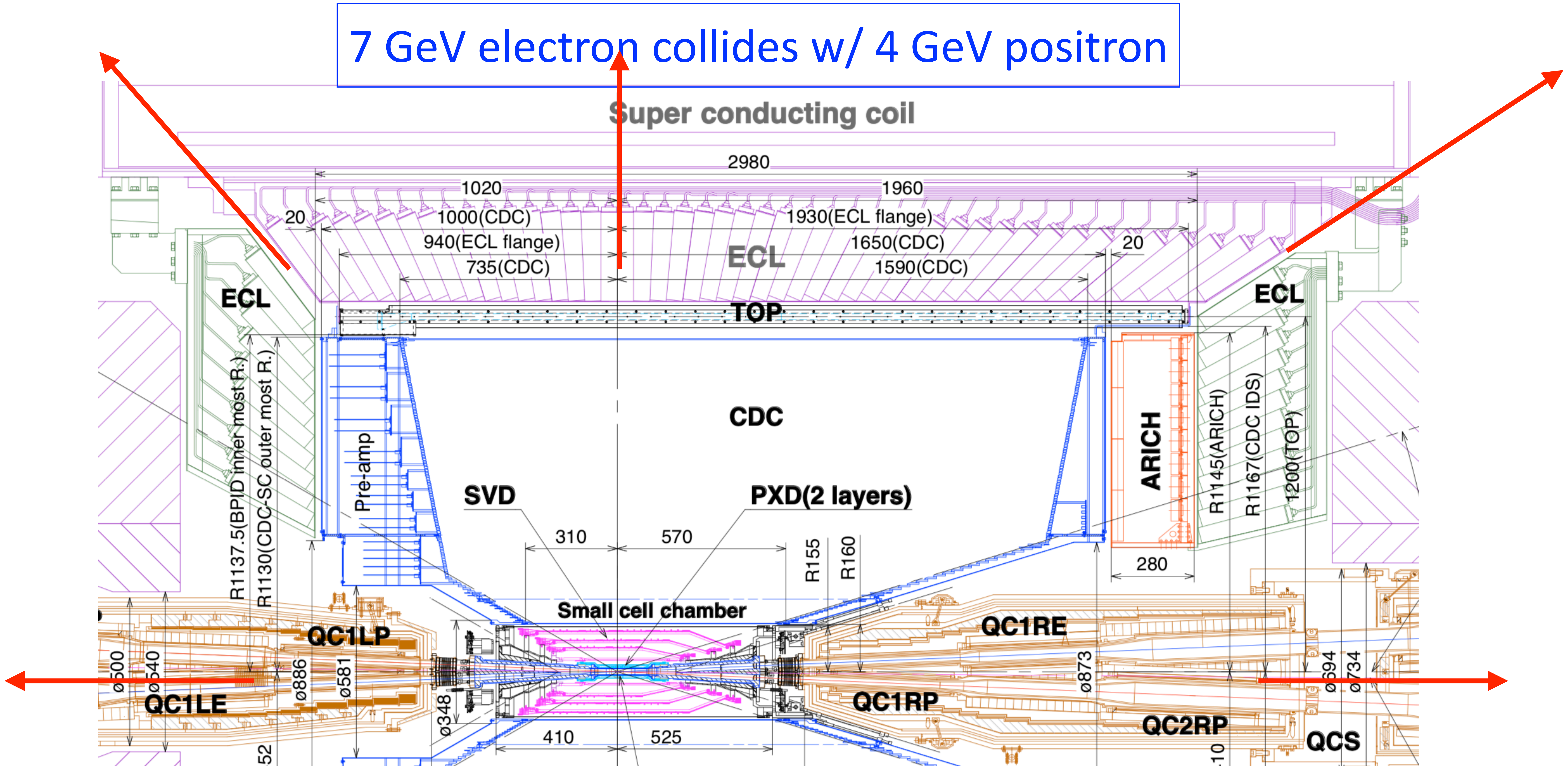

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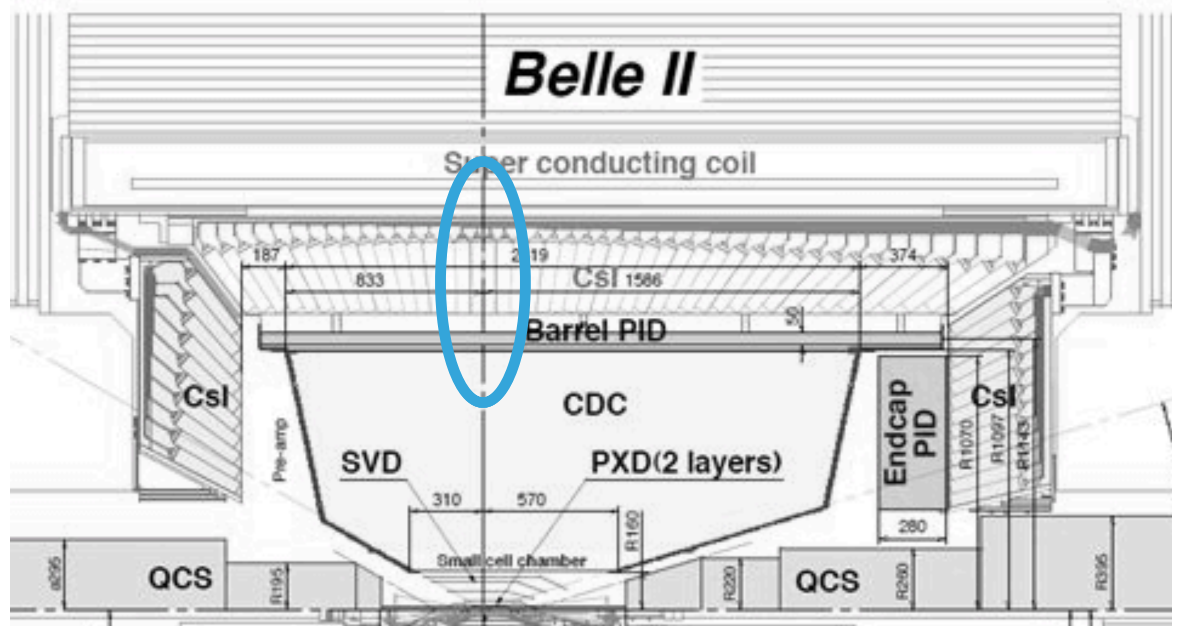
[Belle II 1808.10567]

reducible BG
- BG due to ECL gaps (gBG)
- BG due to beam (bBG)

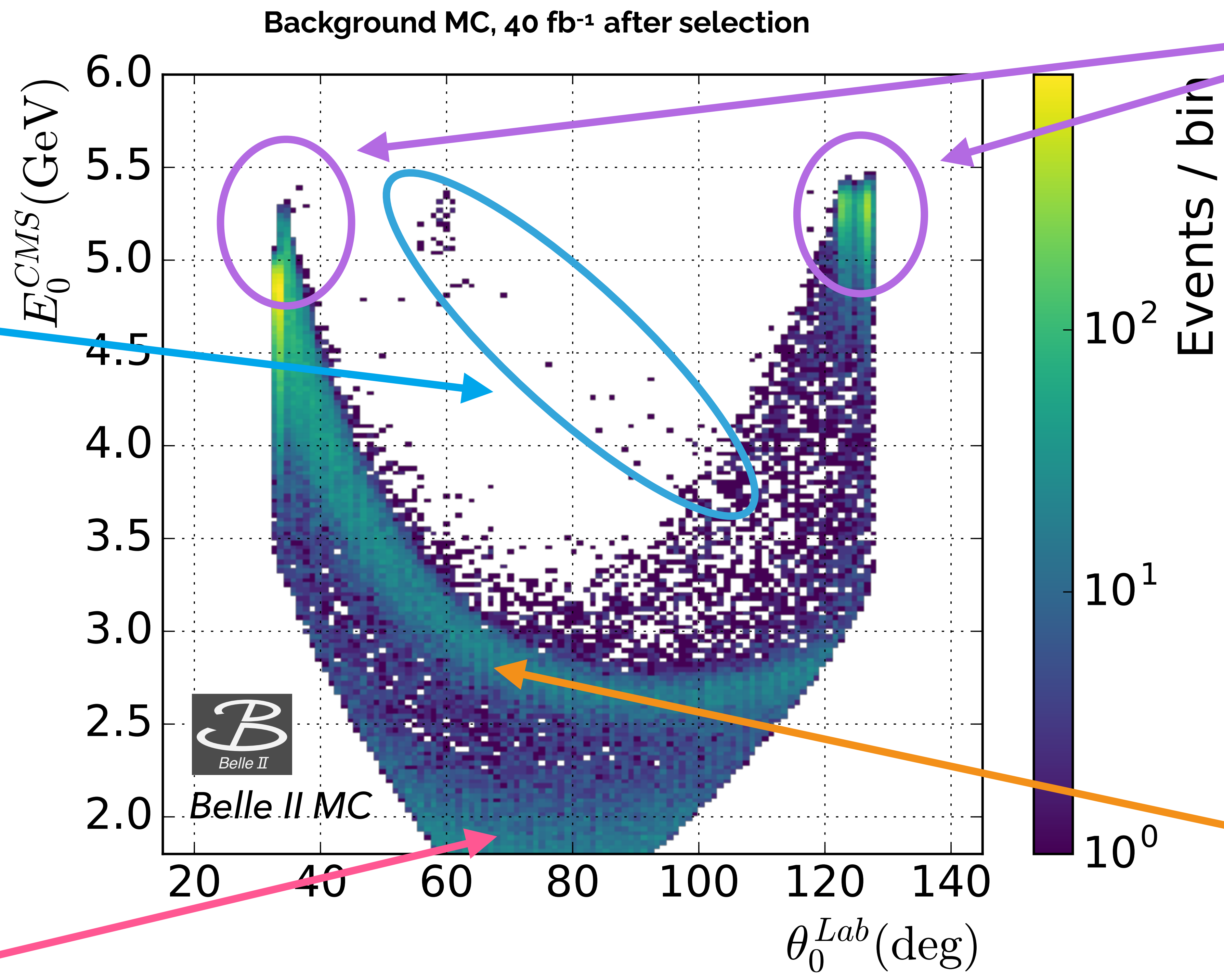
[taken from Torben Ferber's talk]

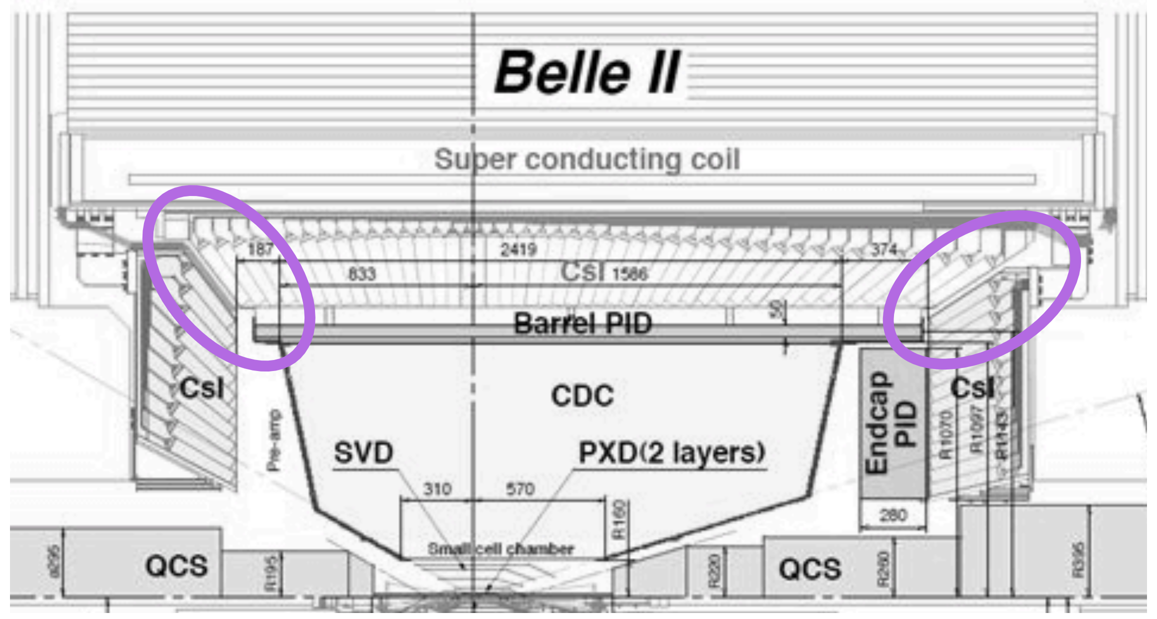
B: Invisible Dark Photon searches



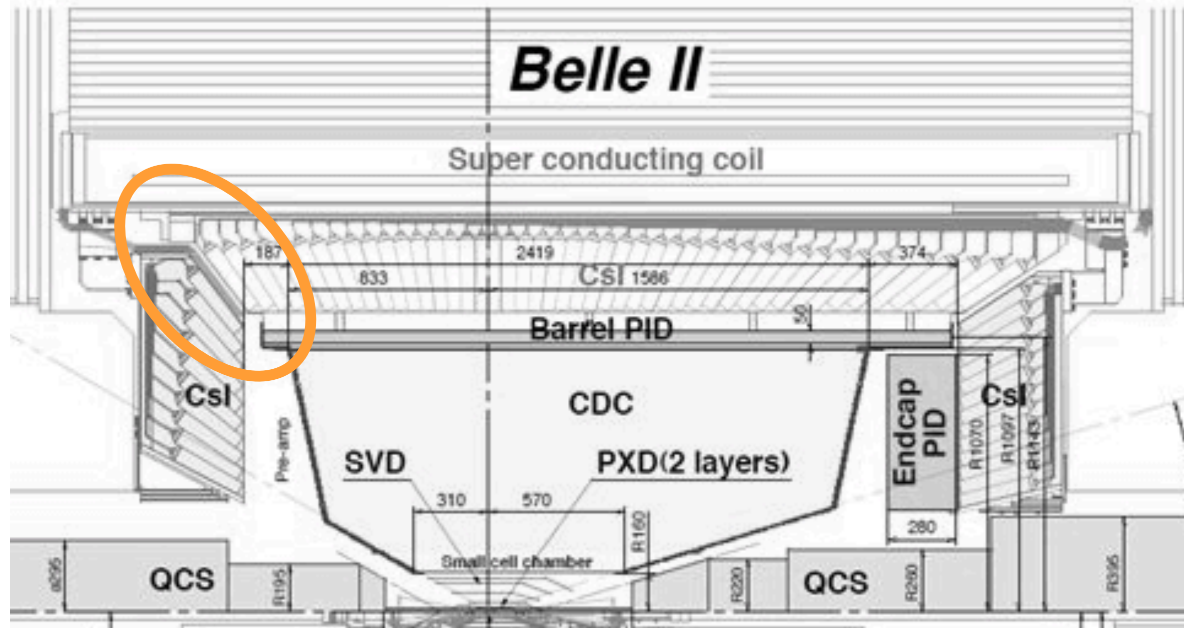
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

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





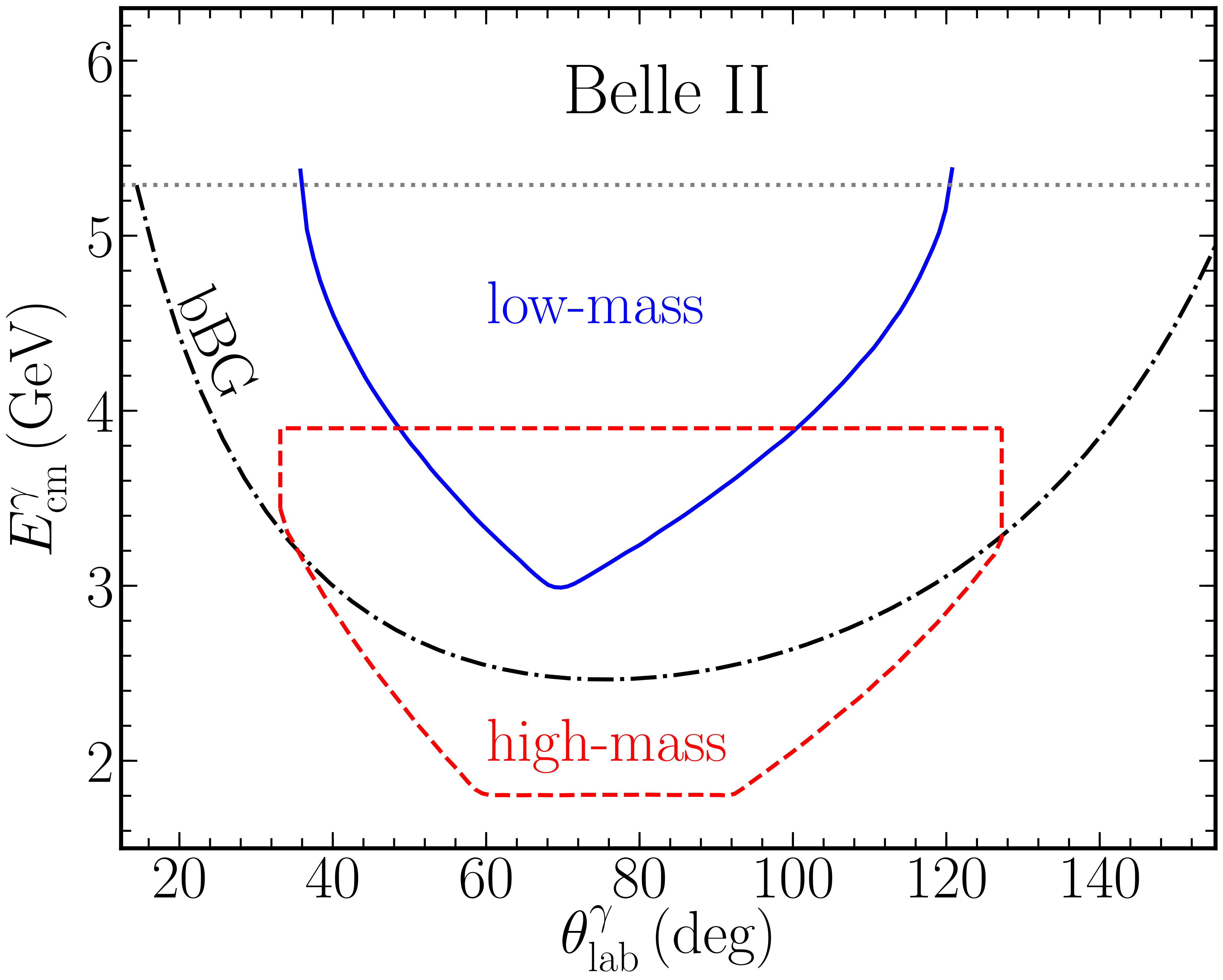
ee→2γ
1γ in ECL BWD or FWD gap



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

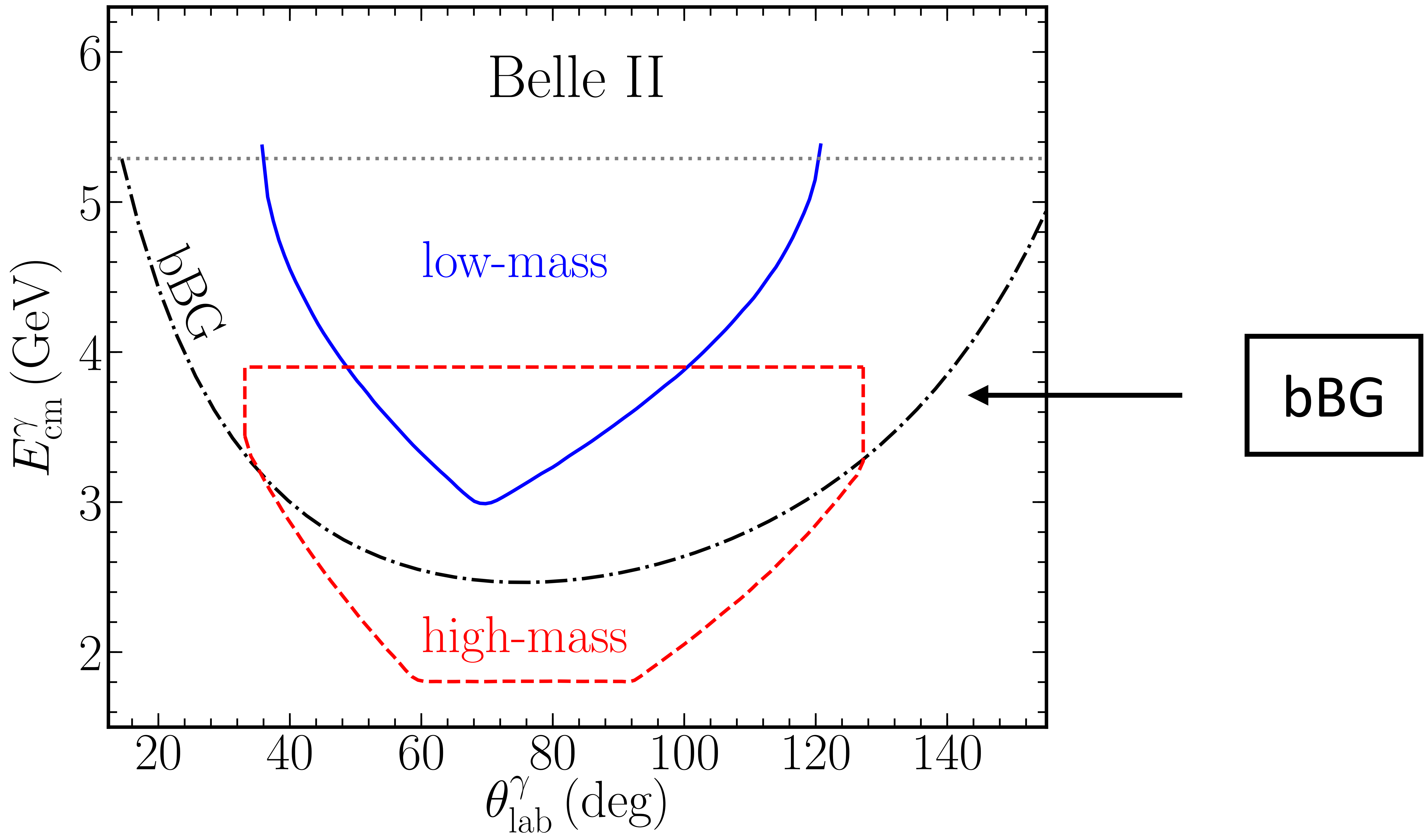
ee→eeγ
both electrons
out of tracking acceptance

Photon energy and angular cuts @ Belle II



[Liang, Liu, Ma, Zhang, 1909.06847]

Photon energy and angular cuts @ Belle II



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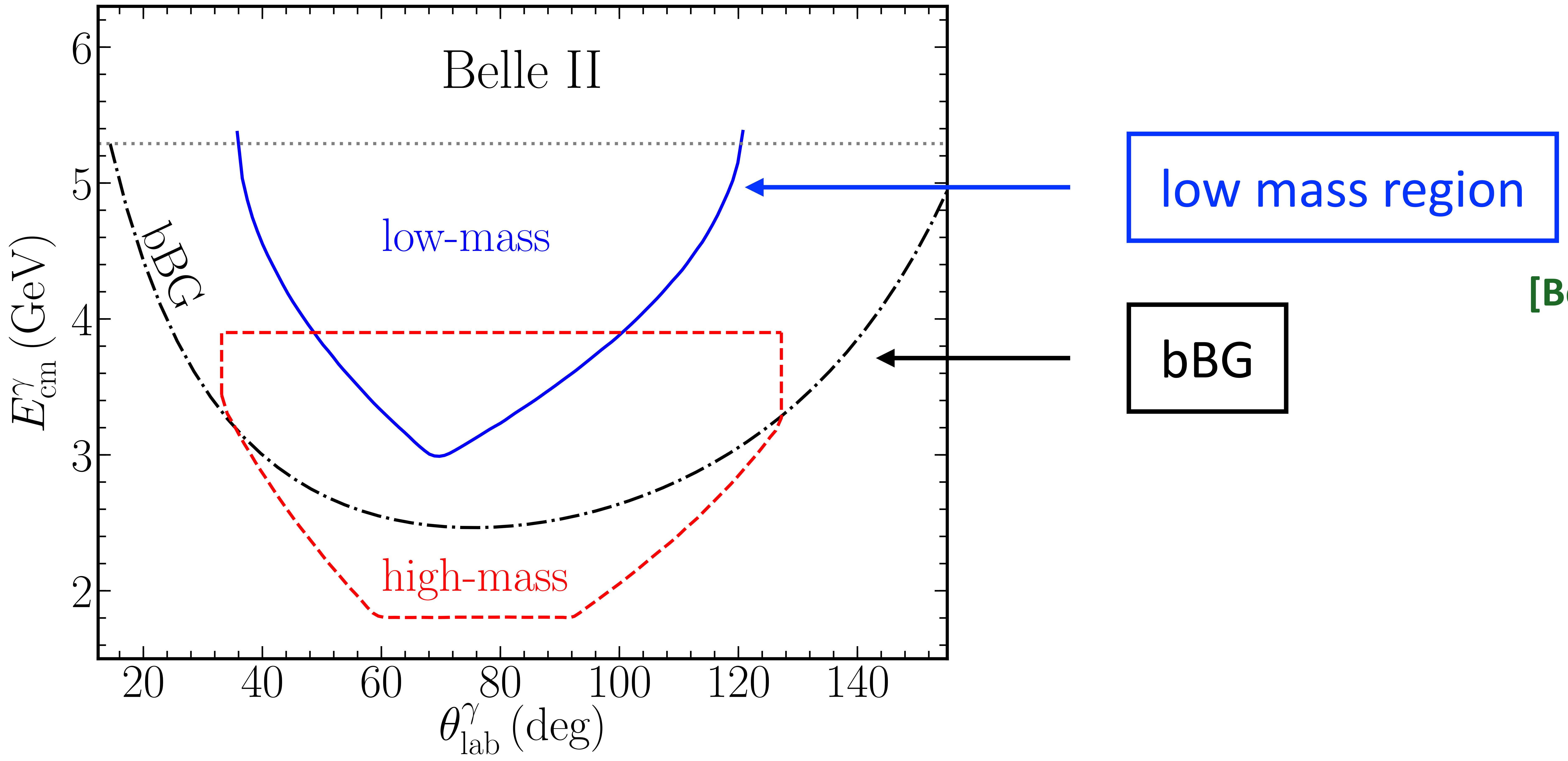

[Belle II 1808.10567]

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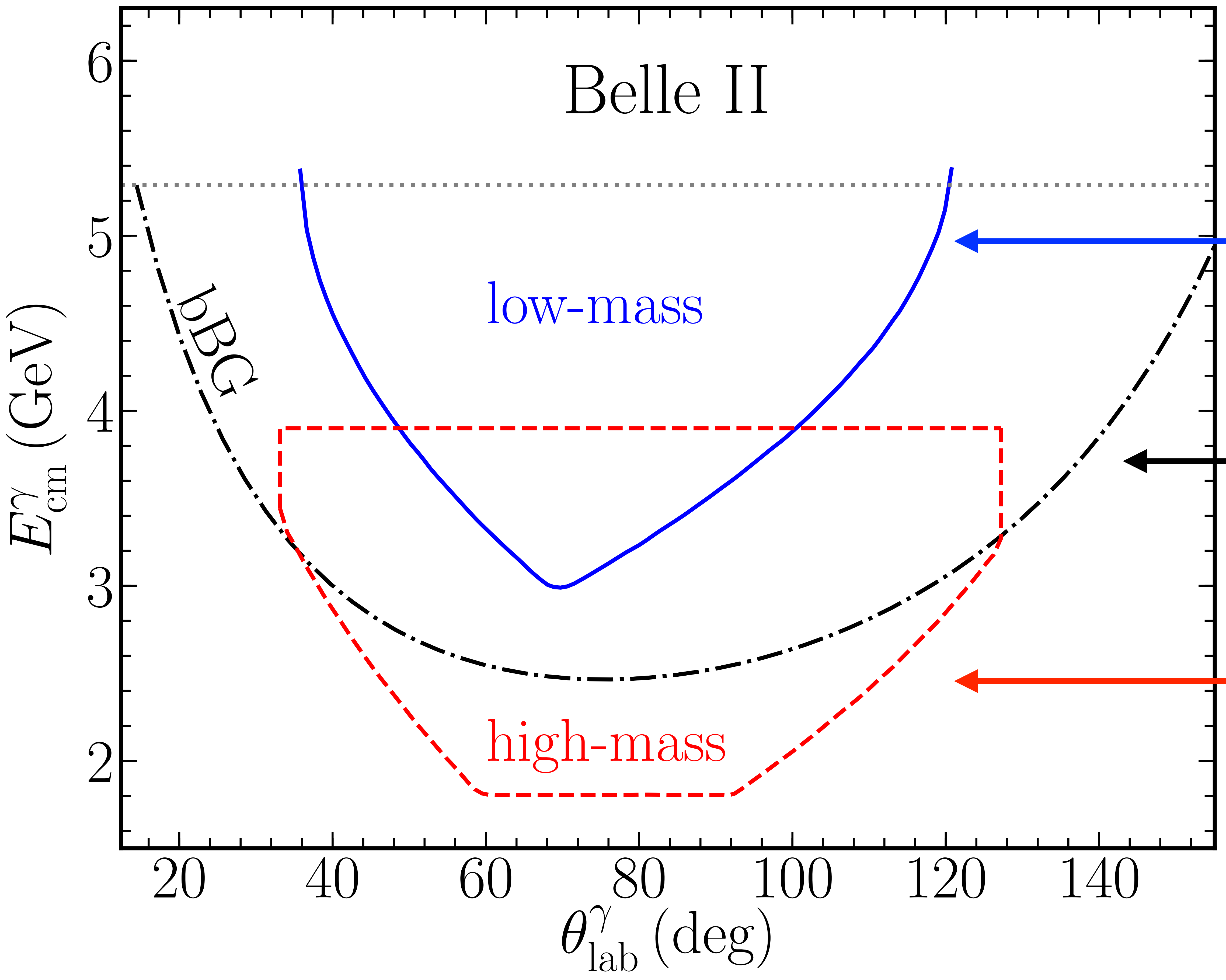
Photon energy and angular cuts @ Belle II



low mass region

[Belle II 1808.10567]

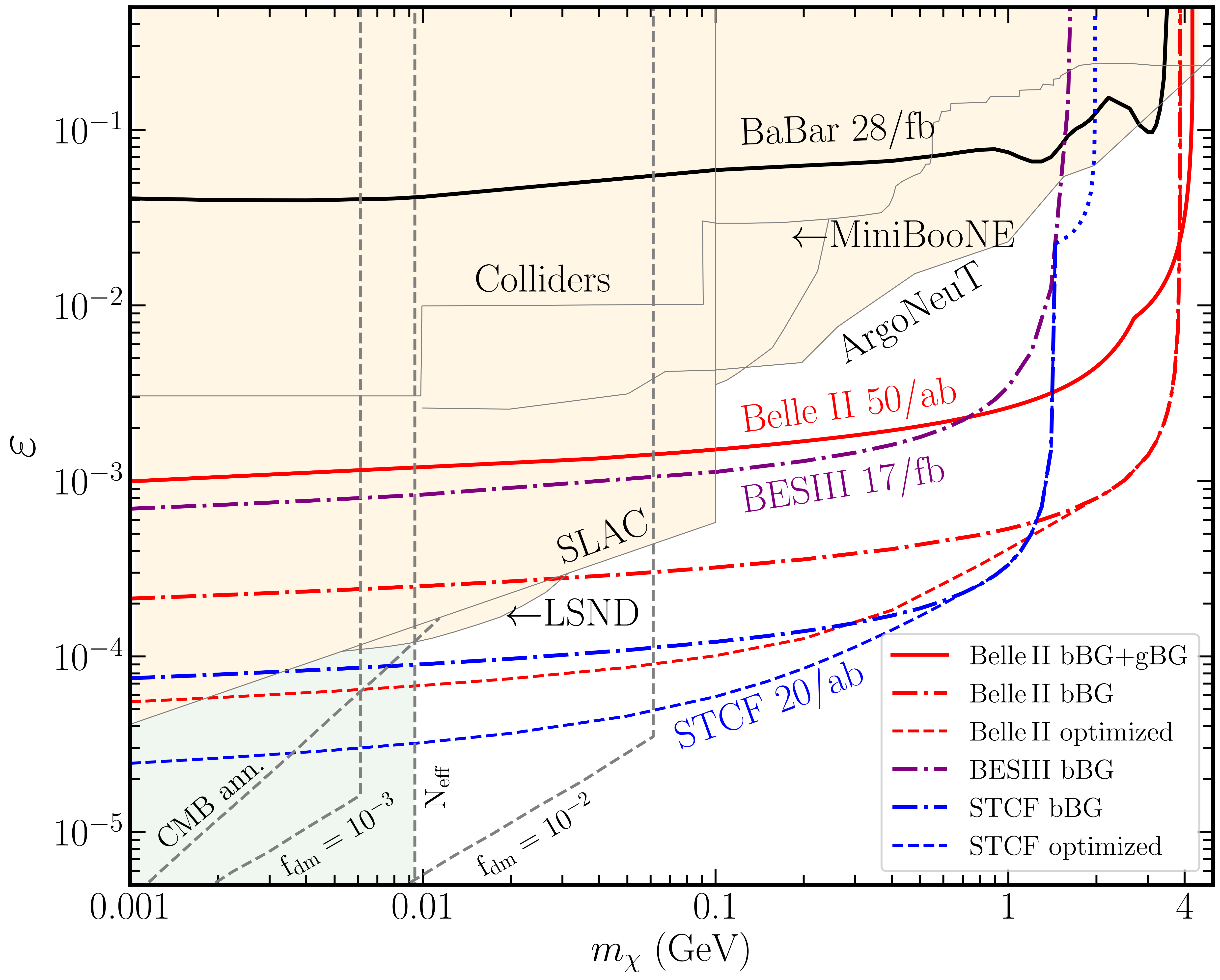
bBG

high mass region

[Belle II 1808.10567]

[Liang, Liu, Ma, Zhang, 1909.06847]

electron colliders probe new parameter region (95% CL)



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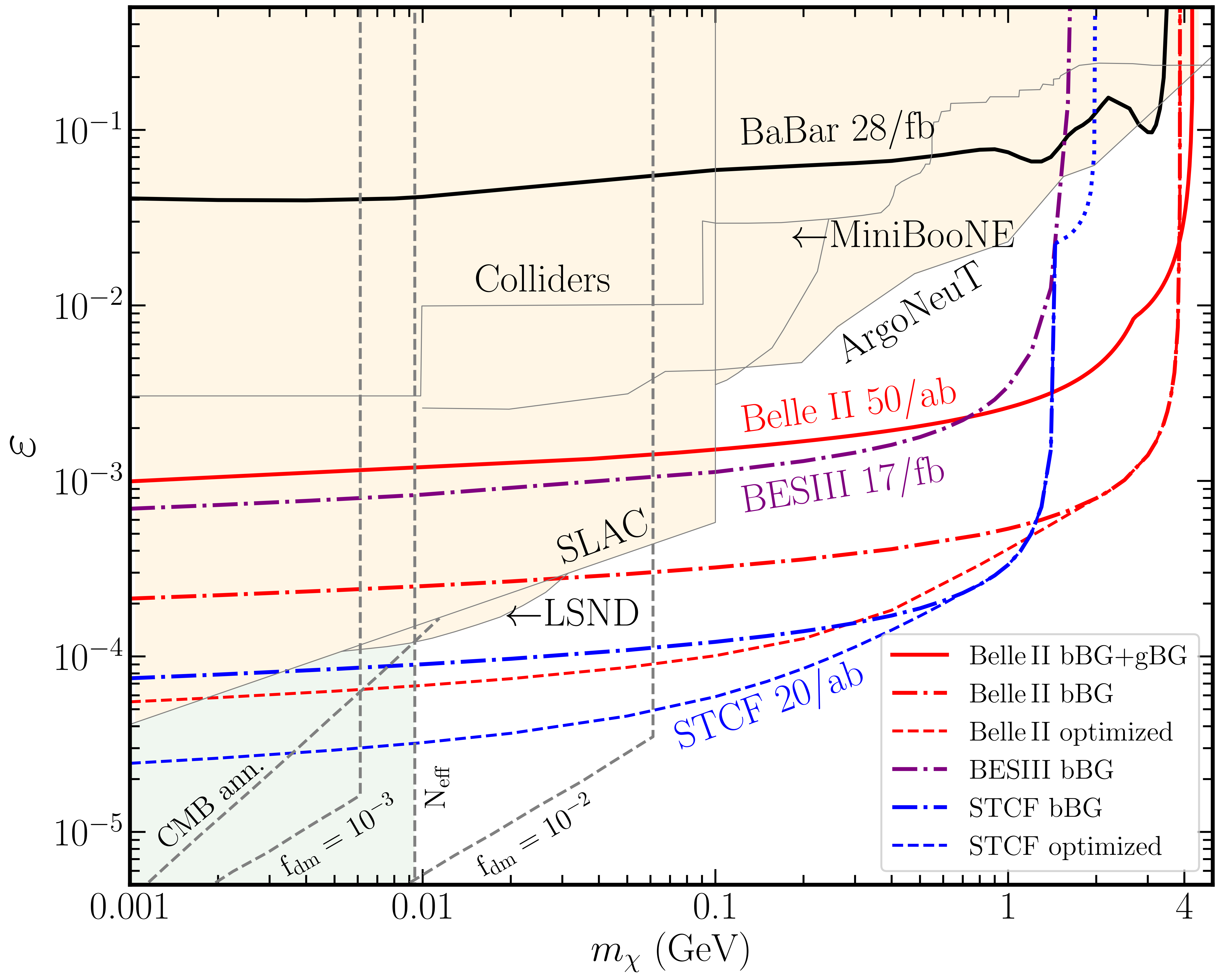

BaBar

[Liang, Liu, Ma, Zhang, 1909.06847]

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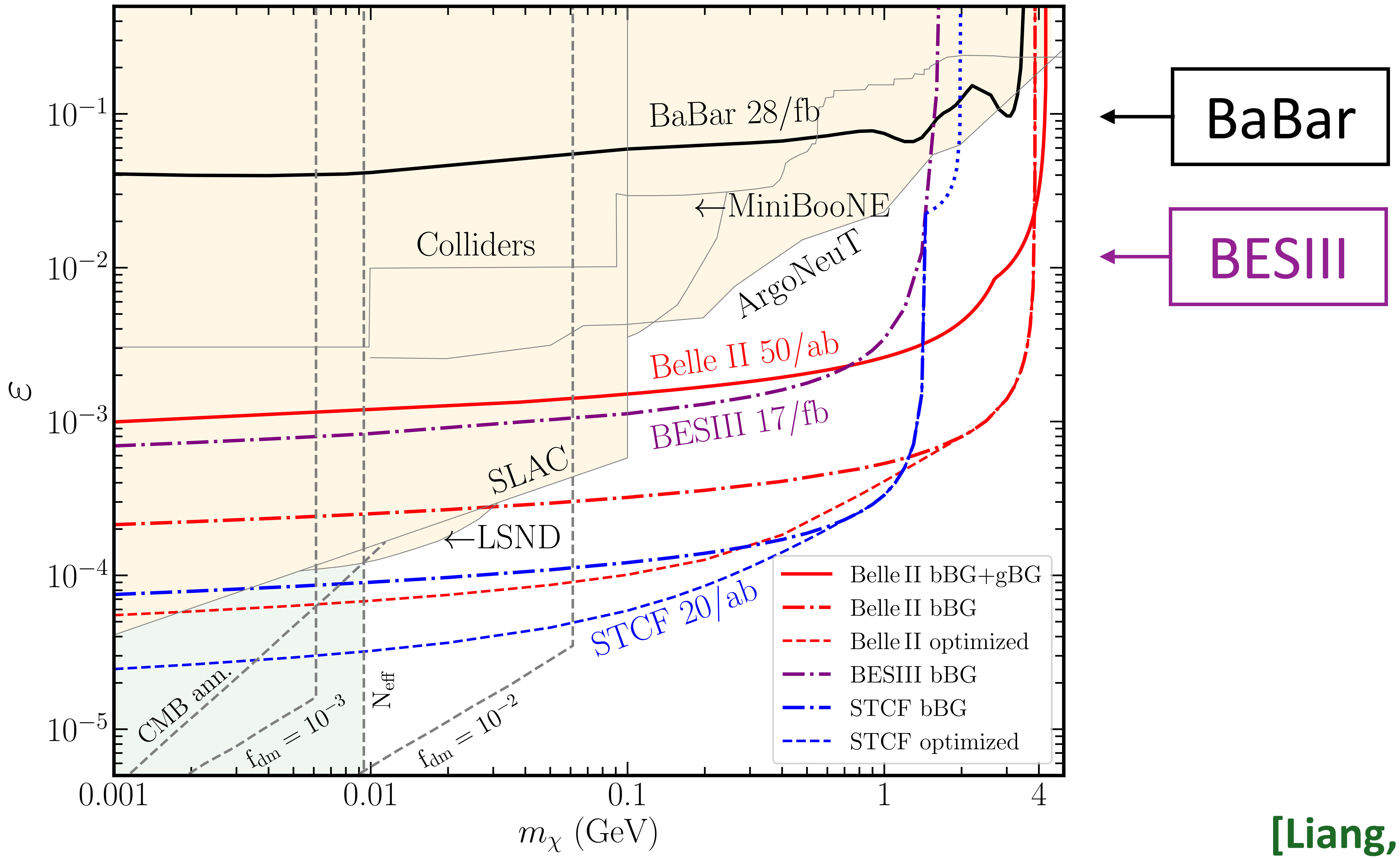

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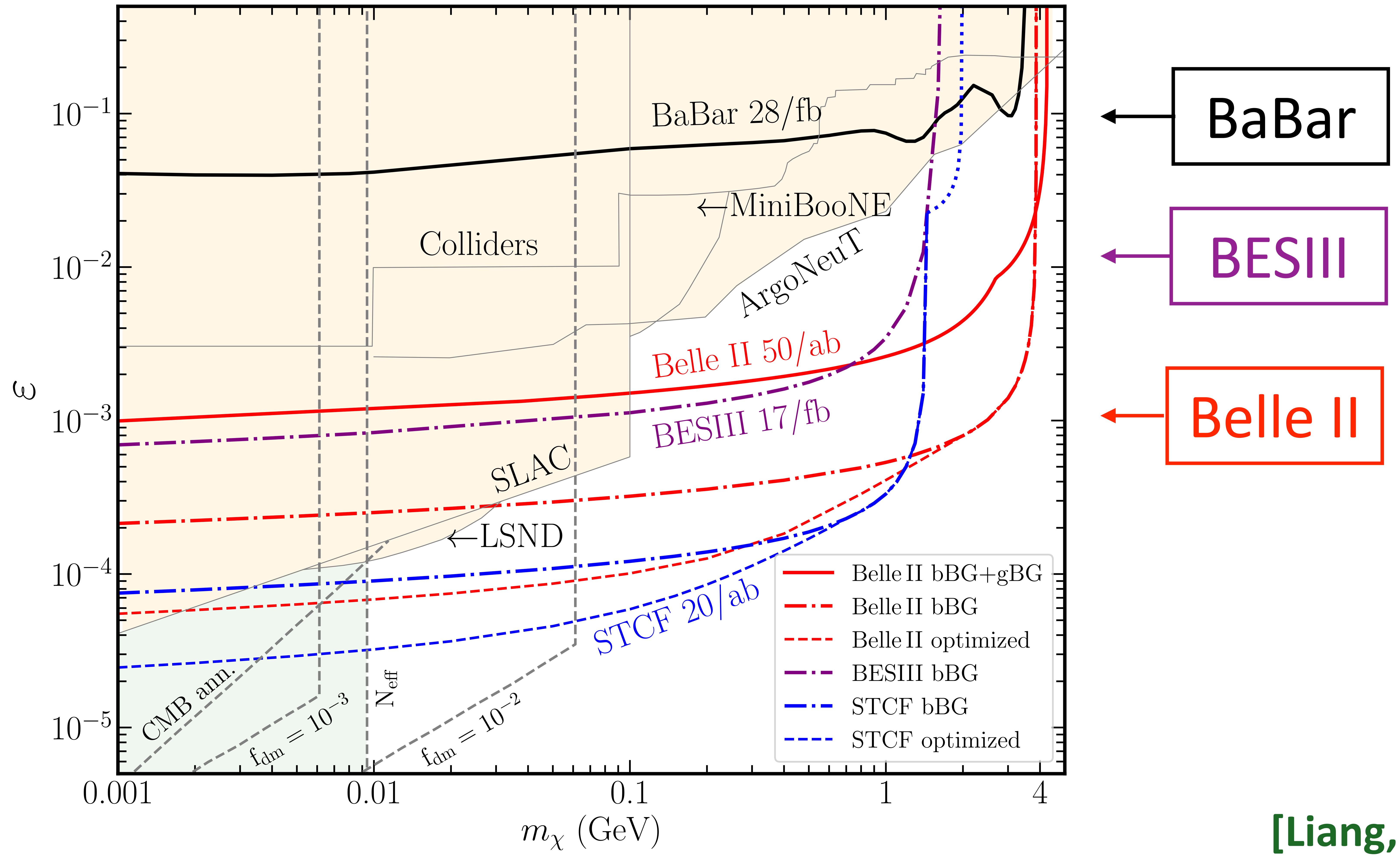

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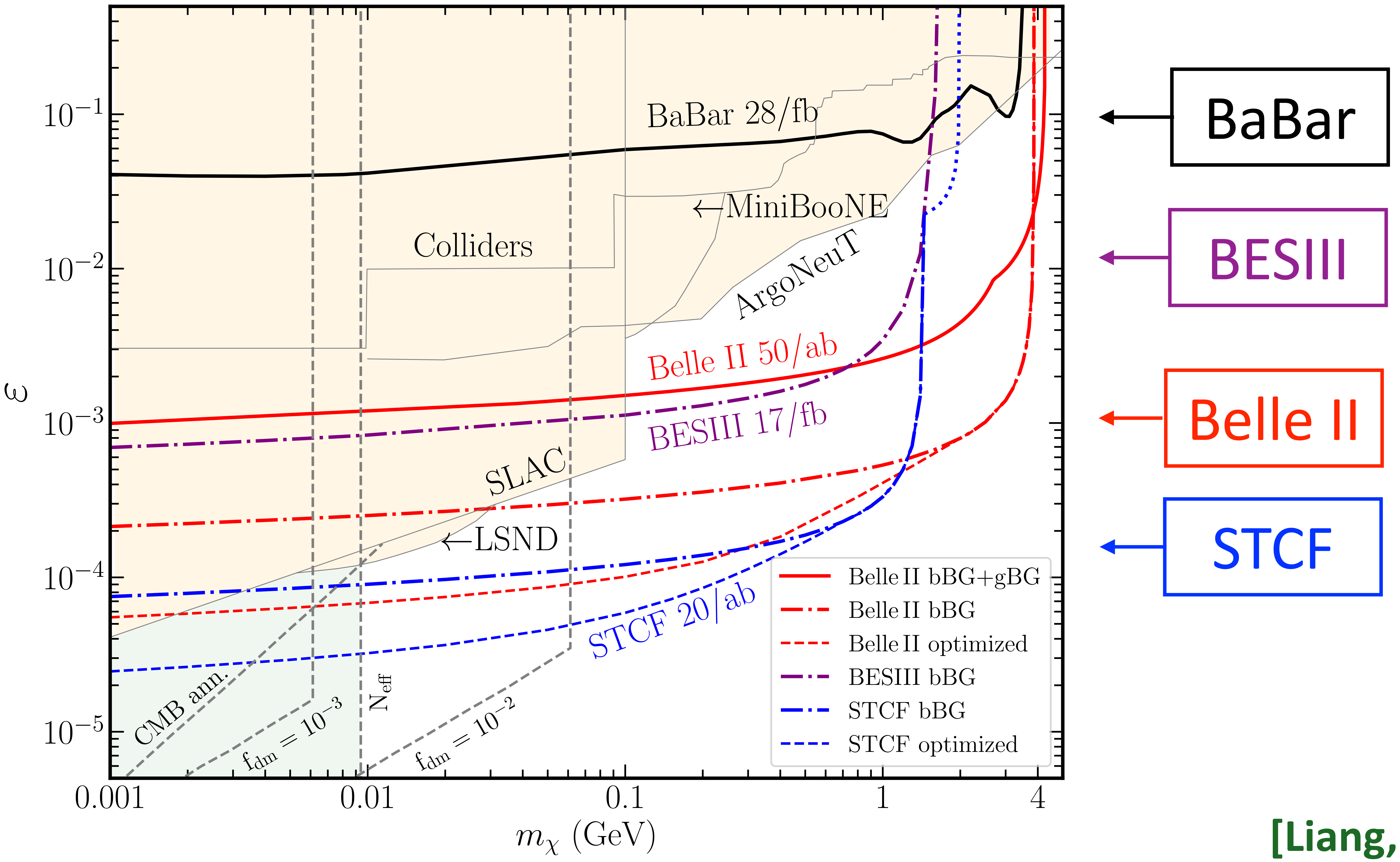

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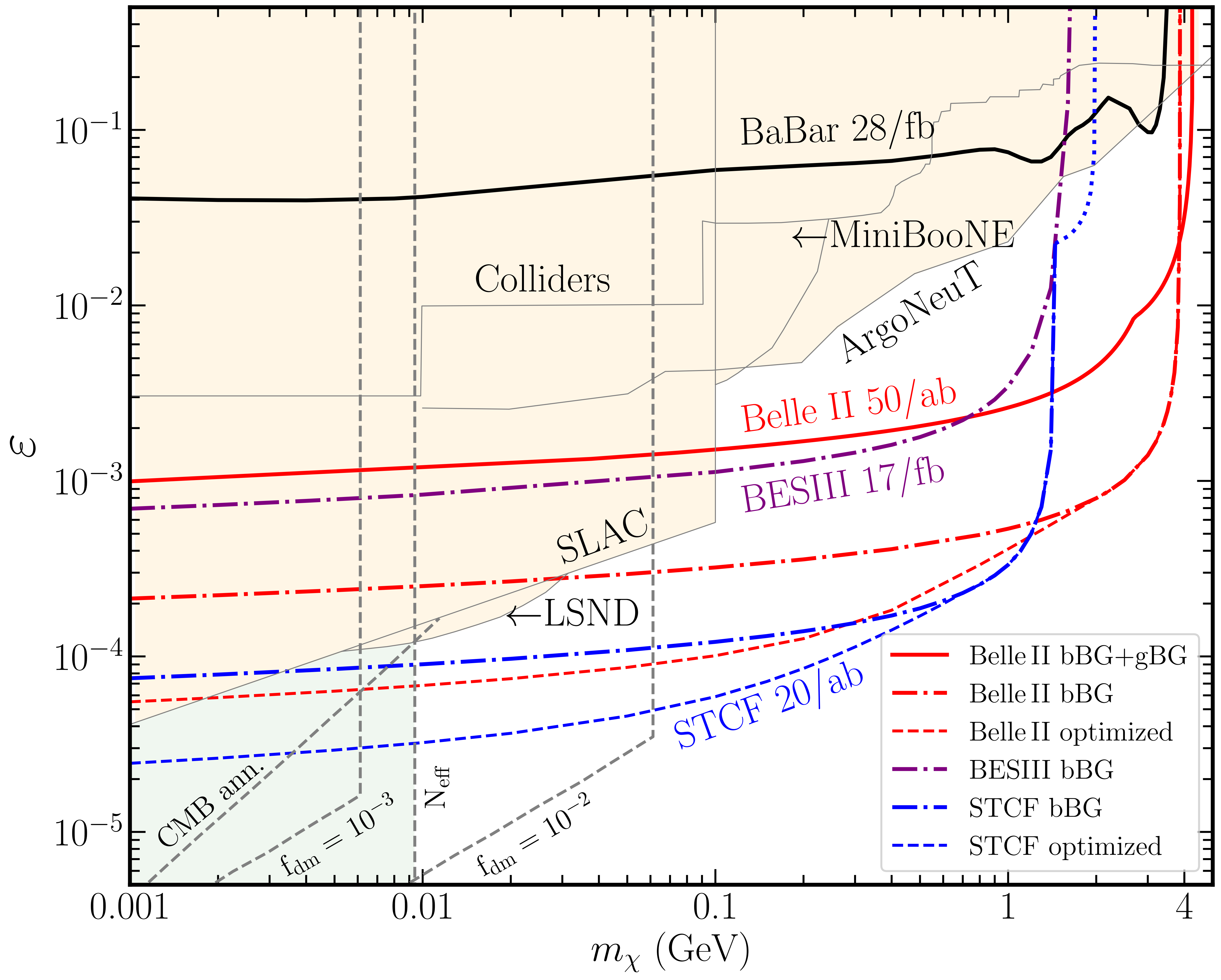


diff BG considerations

BaBar

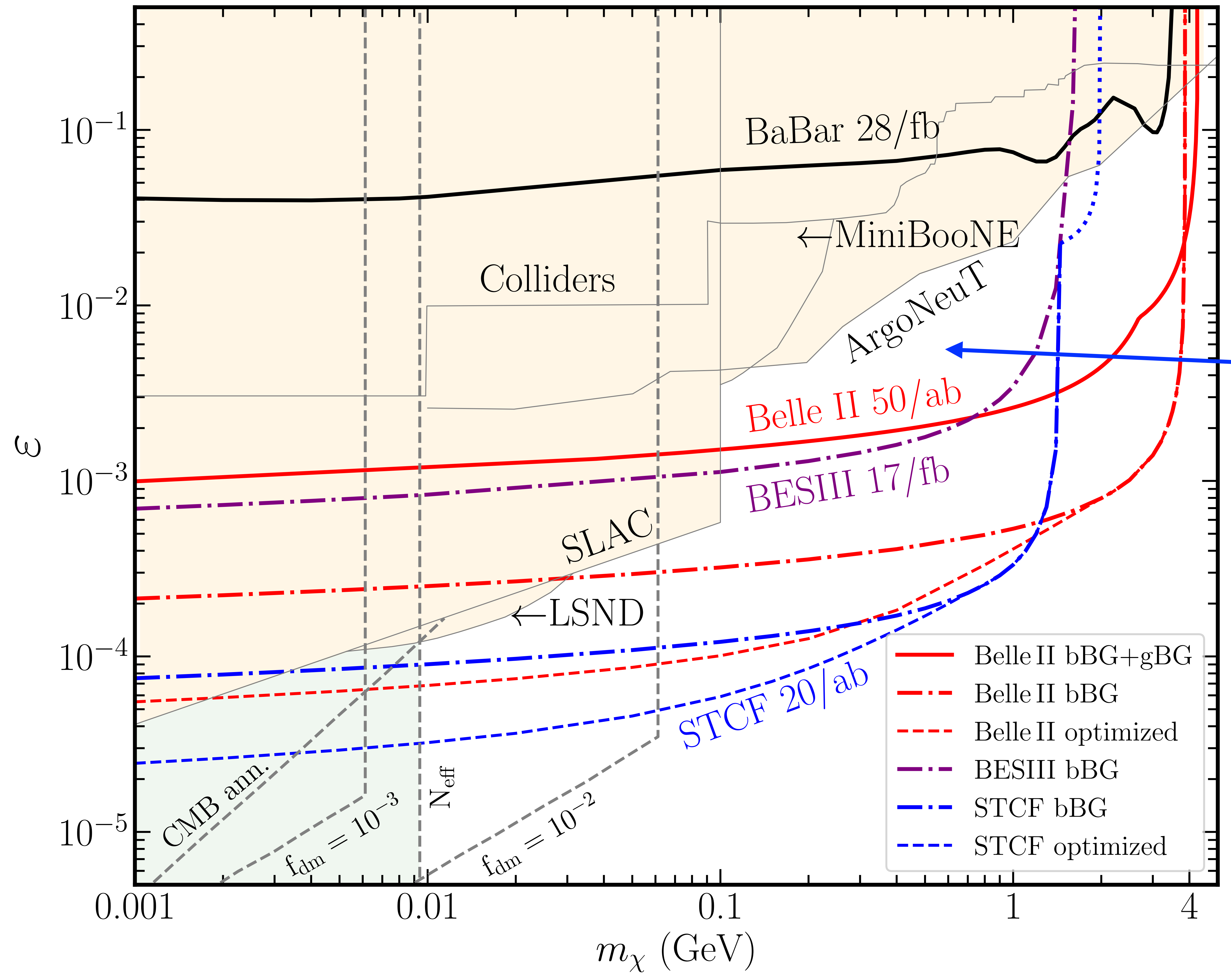
BESIII

Belle II

STCF

[Liang, Liu, Ma, Zhang, 1909.06847]

electron colliders probe new parameter region (95% CL)



diff BG considerations

BaBar

BESIII

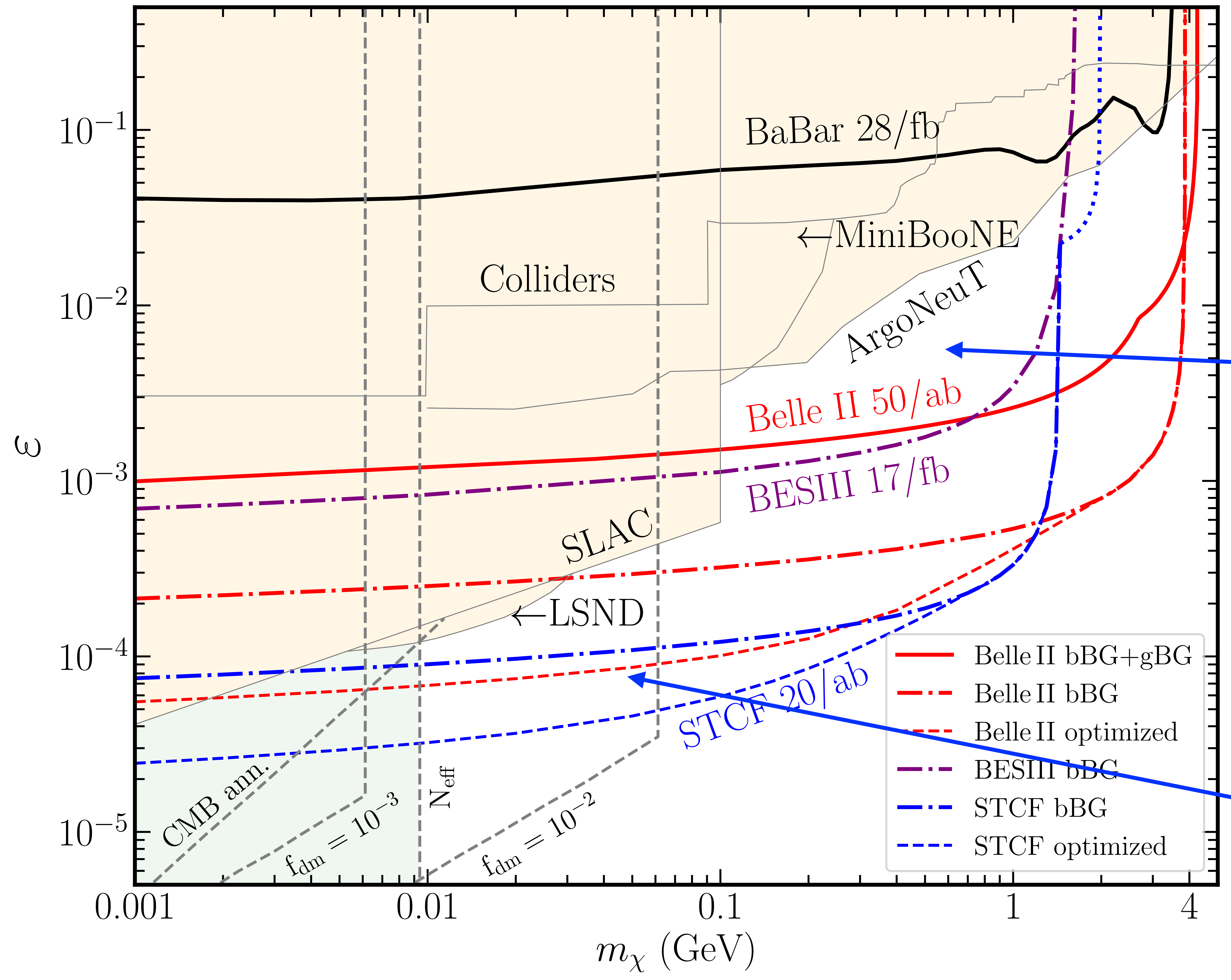
new regions: 0.1-4 GeV

Belle II

STCF

[Liang, Liu, Ma, Zhang, 1909.06847]

electron colliders probe new parameter region (95% CL)



diff BG considerations

BaBar

BESIII

new regions: 0.1-4 GeV

Belle II

STCF

$\epsilon \lesssim O(10^{-4})$?

[Liang, Liu, Ma, Zhang, 1909.06847]

Summary

Millicharged particles can appear in kinetic mixing or Stueckelberg mass mixing models

[Feldman, ZL, Nath, hep-ph/0702123, 299 cites]

A number of terrestrial experiments have been carried out or proposed to search for millicharged particles

We propose to search for millicharged particles at electron colliders, including BESIII, Belle-II and STCF, which can probe currently unexplored parameter regions: $\epsilon \lesssim O(10^{-3})$ for 100 MeV $\lesssim m \lesssim$ several GeV

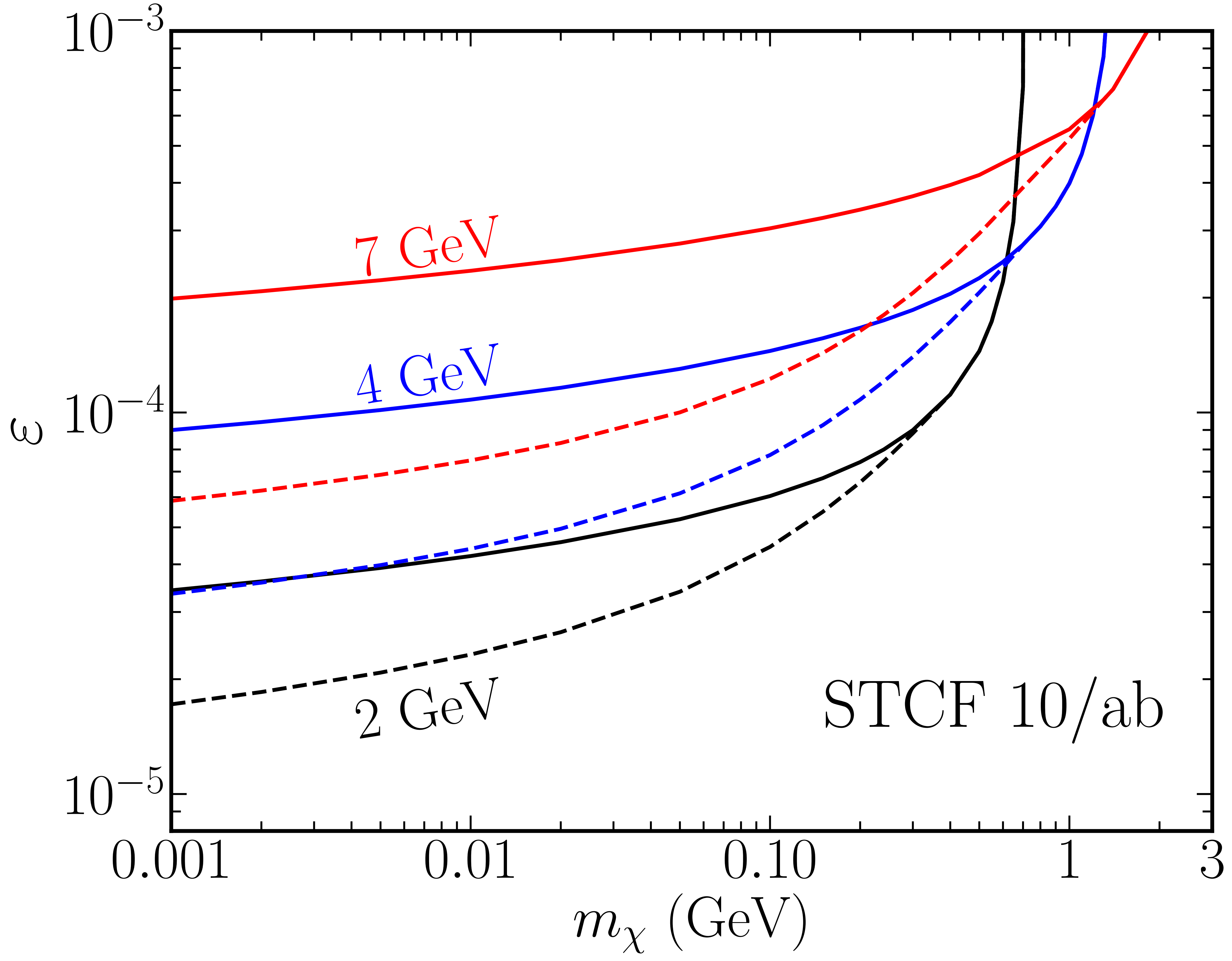
[ZL, Zhang, 1808.00983]

[Liang, ZL, Ma, Zhang, 1909.06847]

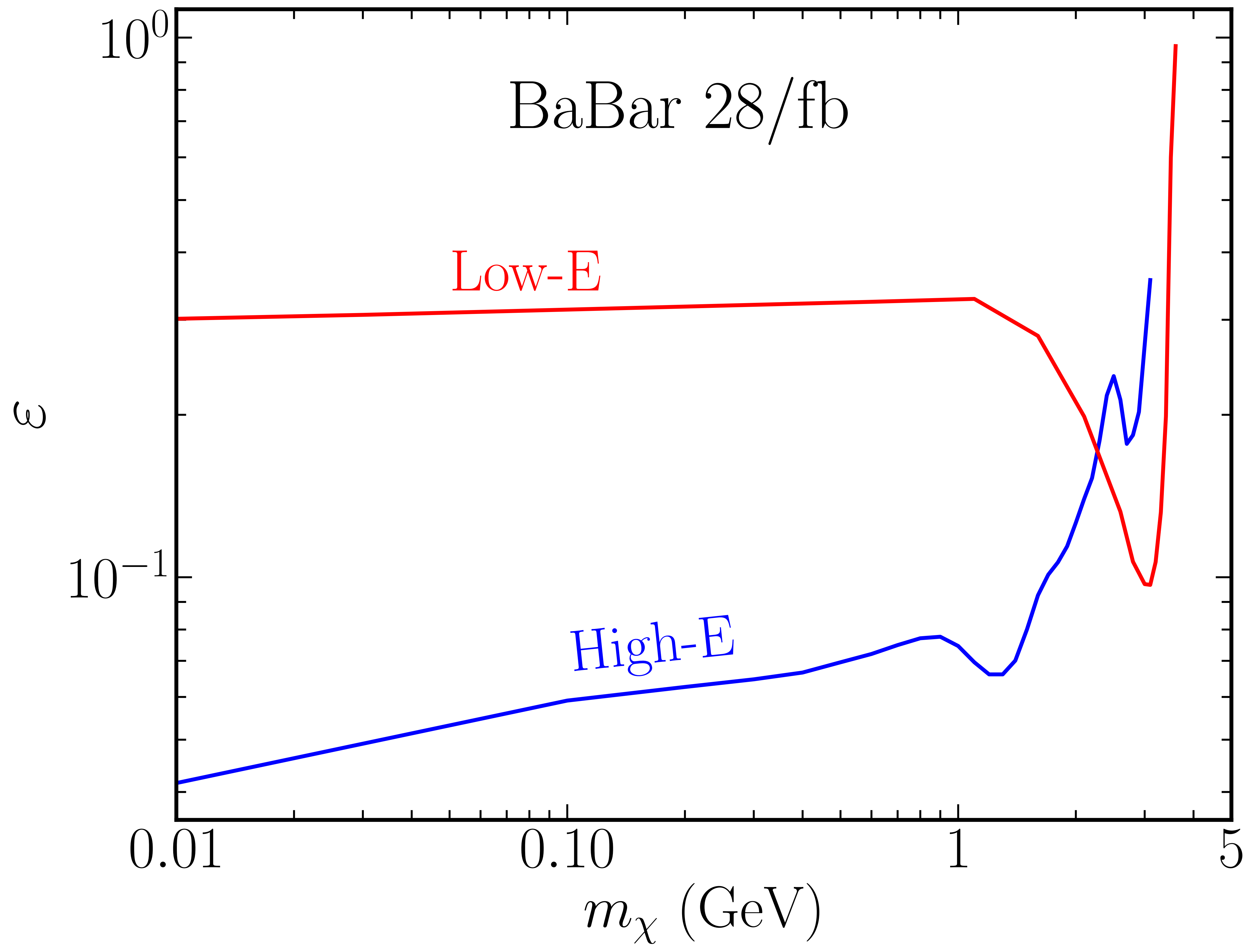
additional slides

Different STCF colliding energies

STCF low-E mode: better for low mass



BaBar sensitivity on millicharge



High-E

$3.2 < E^*_\gamma < 5.5$ GeV

$-0.31 < \cos\theta^*_\gamma < 0.6$

Low-E

$2.2 < E^*_\gamma < 3.7$ GeV

$-0.46 < \cos\theta^*_\gamma < 0.46$

[BaBar, 0808.0017]

high-E data has better sensitivity to light mass

Mass growth via Stueckelberg

Make massive QED gauge invariant by adding axion **σ**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}A_\mu^2$$

$$\Longrightarrow \quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mA_\mu + \partial_\mu\sigma)^2$$

invariant under gauge transformation

$$\delta A_\mu = \partial_\mu\lambda, \quad \delta\sigma = -m\lambda$$

σ : longitudinal mode of the vector boson

[E.C.G. Stueckelberg, Helv. Phys. Acta 11, 225 (1938)]

Stueckelberg in extra dimensions

compactification of a 5D theory on half-circle S^1/Z_2

$$\mathcal{L}_5 = -\frac{1}{4}F_{ab}(z)F^{ab}(z), a, b = 0, 1, 2, 3, 5$$

$$z^a = (x^\mu, y), \mu = 0, 1, 2, 3 \qquad A_a = (A_\mu(z), \phi(z))$$

infinite number of massive KK modes in 4D

$$\mathcal{L}_4 = -\frac{1}{4}\sum_n F^{(n)}_{\mu\nu}(x)F^{\mu\nu(n)}(x)$$
$$-\frac{1}{2}\sum_n M_n^2 \left(A^{(n)}_\mu(x) + \frac{1}{M_n}\partial_\mu\phi^{(n)}(x)\right)^2$$

Stueckelberg mass in 4D due to compactification

[Nath 0812.0958]

Stueckelberg vs Higgs

U(1) boson w/ a Higgs potential

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left[(\partial_\mu + igA_\mu)\phi\right]^2 - \left[\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2\right]$$

Decompose the Higgs field in polar coordinates

$$\phi = \left(\frac{v + h}{\sqrt{2}}\right) e^{i\frac{\sigma}{v}} \qquad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

Unitary gauge $\phi^U = \frac{v+h}{\sqrt{2}}$ & $A^U_\mu = A_\mu - \frac{1}{gv}\partial_\mu\sigma$

$$\mathcal{L} = -\frac{F_U^2}{4} + \frac{(\partial_\mu h)^2}{2} + \frac{g^2}{2}(h+v)^2 A^U_\mu A^{U\mu} - \frac{\lambda}{4}(h^2 + 2hv)^2 + \frac{\lambda}{4}v^4$$

$M_A = gv$ $\qquad$ $M_h = \sqrt{2\lambda}v$ $\qquad$ **σ** disappears

decouple the Higgs particle

Take the limits $-\mu^2 \to \infty$, $\lambda \to \infty$ with $v = \sqrt{-\mu^2/\lambda}$ fixed. In this case, the Higgs field $M_h = \sqrt{2\lambda} v$ becomes infinitely heavy and decouples, whereas the gauge boson mass $M_A = gv$ remains unchanged.

Low energy effective theory $\mathcal{L} = -\frac{F_U^2}{4} + \frac{M_A^2}{2} A_\mu^U A^{U\mu}$

$$A_\mu^U = A_\mu - \frac{1}{M_A} \partial_\mu \sigma$$

$$\mathcal{L} = -\frac{F_{\mu\nu}^2}{4} + \frac{1}{2} \left(M_A A_\mu - \partial_\mu \sigma \right)^2$$

The Higgs mechanism leads to the Stueckelberg mechanism.

[Allen, Bowick, Lahiri, Mod. Phys. Lett. A 6, 559, (1991)]

[Nath, arXiv:0812.0958] [Nelson, Scholtz, arXiv:1105.2812]