Probing dark matter particles at CEPC

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Outline

CEPC sensitivities on different dark matter (DM) models

1. Millicharged DM
2. Vector portal DM
3. DM with EFT interactions

Interaction Lagrangian for different Dirac DM models

millicharged DM $\mathcal{L} = e\varepsilon A_\mu \bar{\chi}\gamma^\mu \chi$

[Feldman, ZL, Nath, hep-ph/0702123, 366 cites]

vector-portal DM $\mathcal{L} = Z'_\mu \bar{\chi}\gamma^\mu (g_V^\chi - g_A^\chi \gamma_5)\chi + Z'_\mu \bar{f}\gamma^\mu (g_V^f - g_A^f \gamma_5) f$

DM models with EFT interaction

scalar (s) $\frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell$

vector $\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell$

scalar (t) $\frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$

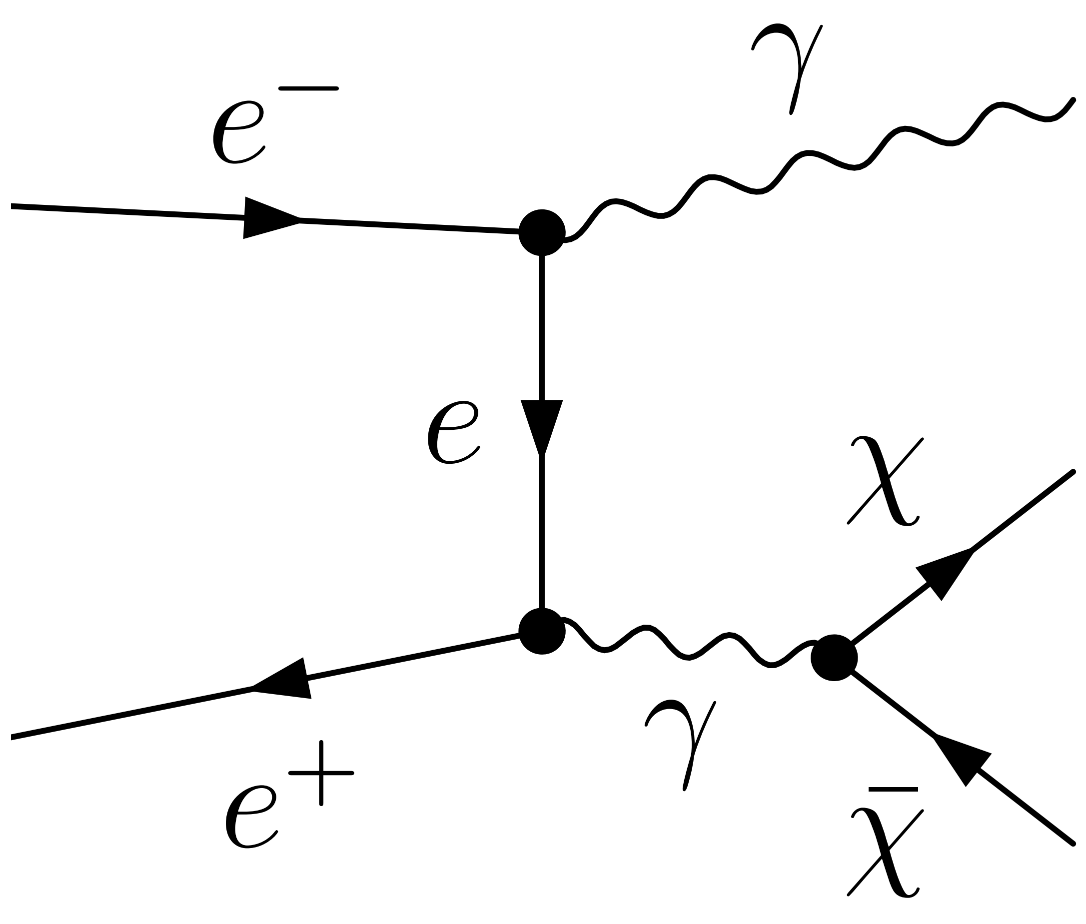
axial-vector $\frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell$

[Fox, Harnik, Kopp, Tsai, 1103.0240; Chae, Perelstein, 1211.4008]

Signal process: mono-photon final state at CEPC

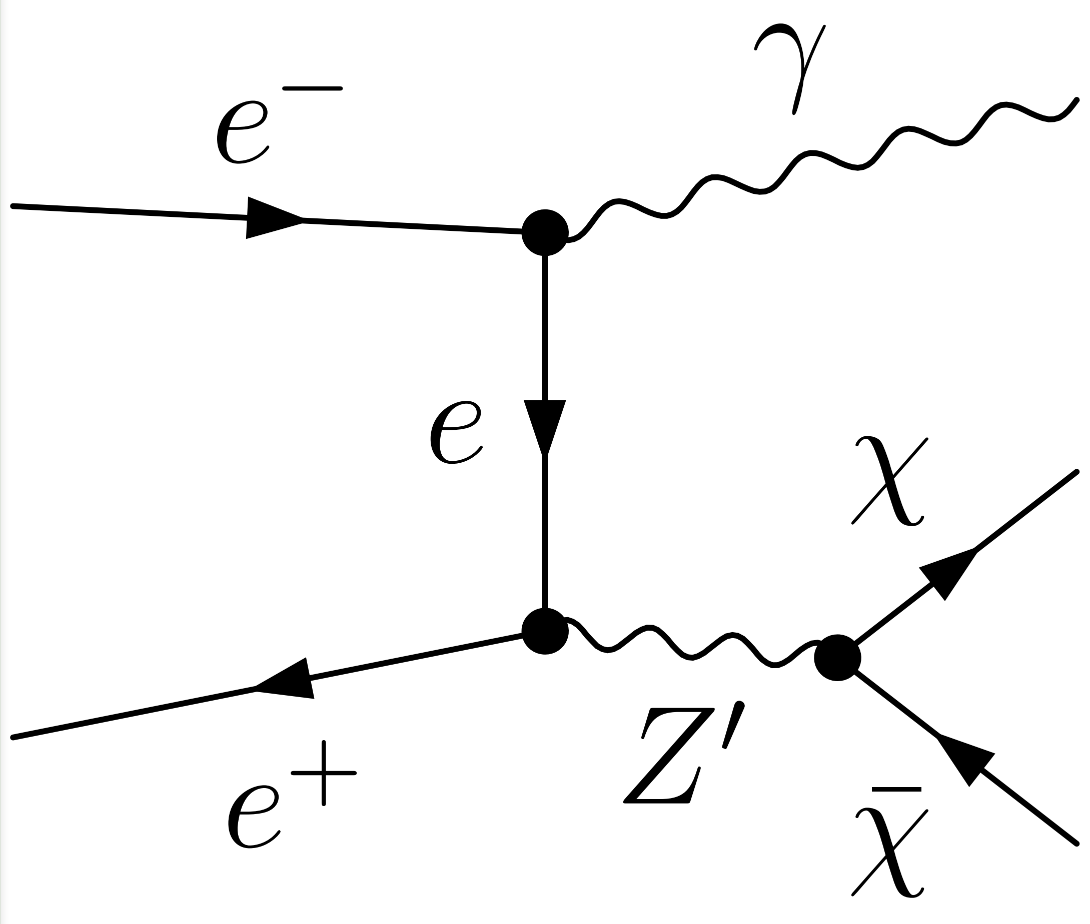
new physics process: $e^+e^- \to \bar{\chi}\chi\gamma$

millicharged DM



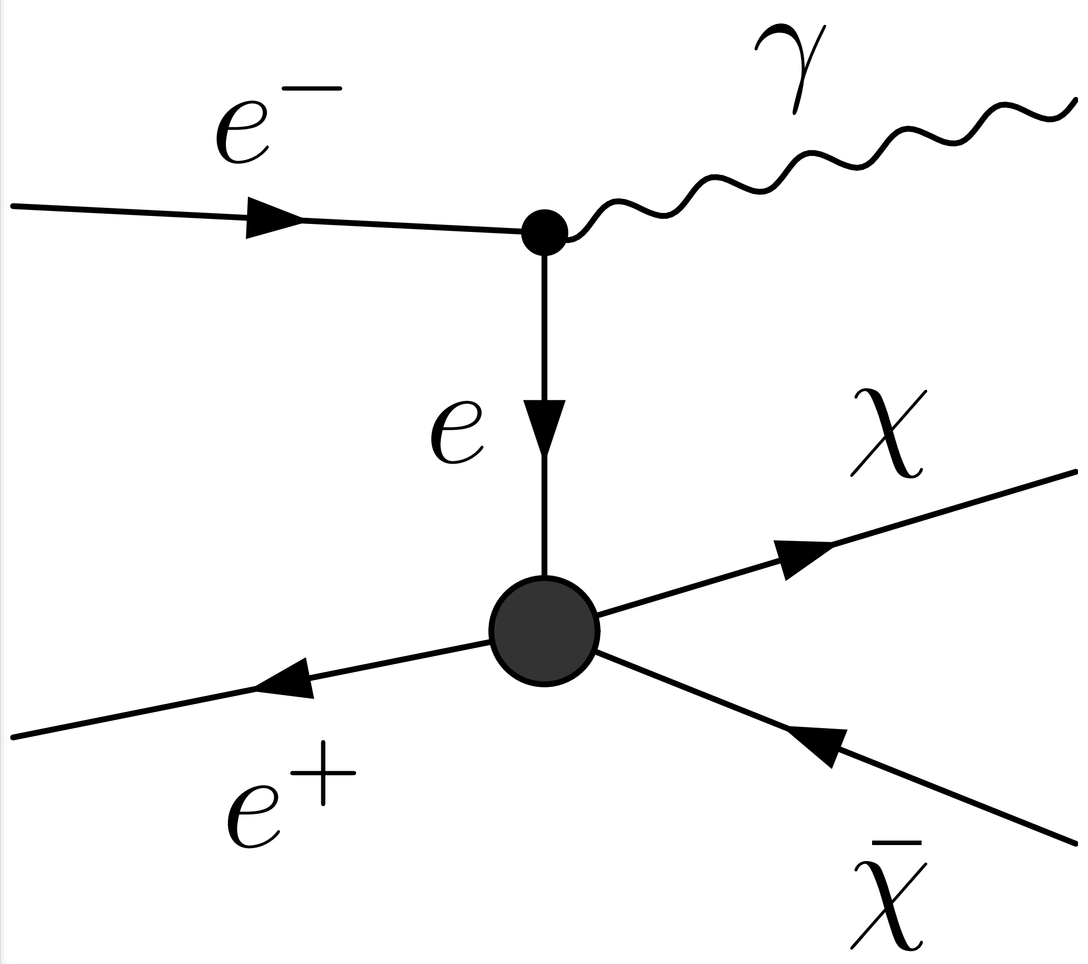
photon mediator

vector-portal DM



Z' mediator

EFT DM



4-F interaction

maximum photon energy $E_\gamma < \frac{s - 4m_\chi^2}{2\sqrt{s}} \equiv E_\chi^m$

3 CEPC running modes

H-mode: 240 GeV & 5.6/ab
Z-mode: 91.2 GeV & 16 /ab
WW-mode: 160 GeV & 2.6/ab

[CEPC Conceptual Design Report: Volume 2 - Physics & Detector, 1811.10545]

Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

NP mono-photon xsec @ CEPC

millicharged DM

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

[Liu, Zhang, 1808.00983]

vector-portal DM

$$\frac{d\sigma}{dE_\gamma dz_\gamma} = \frac{\alpha\left[(g_V^f)^2+(g_A^f)^2\right]\left[(g_V^\chi)^2(1+2y)+(g_A^\chi)^2(1-4y)\right]s_\gamma^2\beta_\chi}{6\pi^2 sE_\gamma\left[(s_\gamma-M_{Z'}^2)^2+M_{Z'}^2\Gamma_{Z'}^2\right]}\left[\frac{1+x(1+z_\gamma^2)}{1-z_\gamma^2}\right]$$

E_γ is the energy of the final state photon

θ_γ is the polar angle of the final state photon

s is the center-of-mass energy square

m_χ is the DM mass

$z_\gamma \equiv \cos\theta_\gamma$ $\quad s_\gamma = s - 2\sqrt{s}E_\gamma$

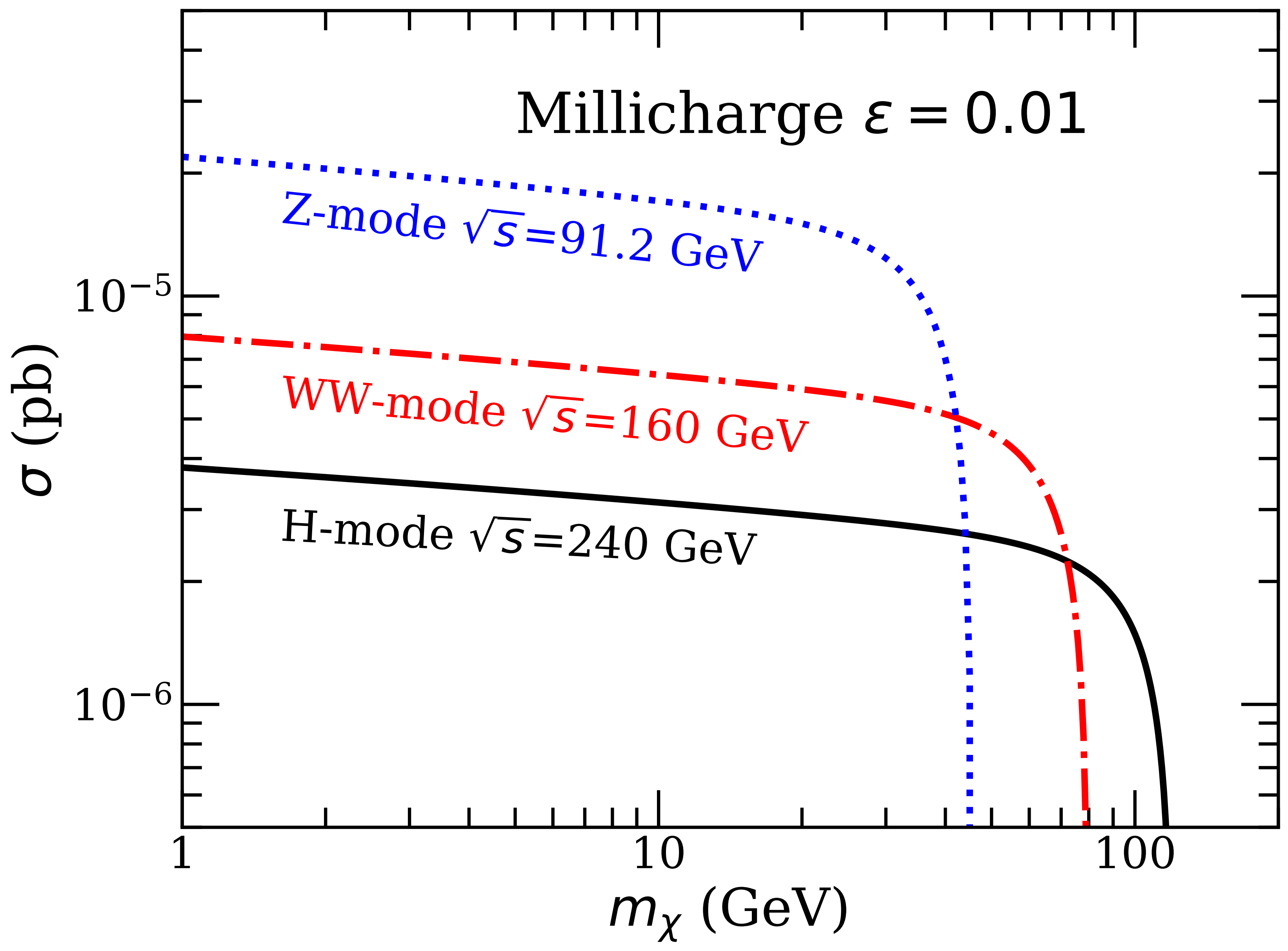
$x \equiv E_\gamma^2/s_\gamma$

$y \equiv m_\chi^2/s_\gamma$ $\quad \beta_\chi = (1-4y)^{1/2}$

mono-photon signal (mediators)

detector cuts $E_\gamma > 0.1\ \text{GeV}\ \&\ |z_\gamma| < 0.99$

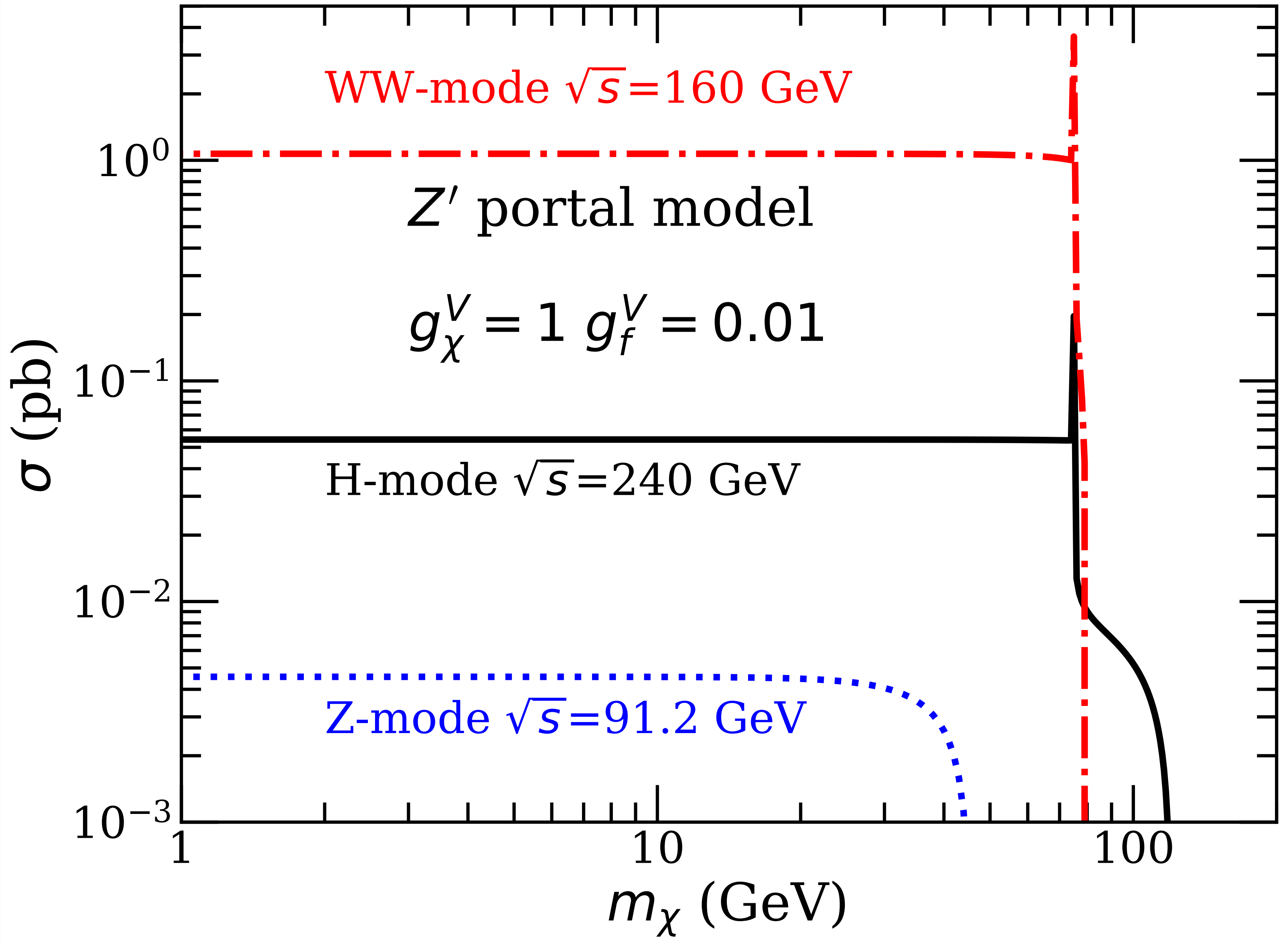
Millicharged DM $\epsilon = 0.01$



Z>WW>H

vector-coupling

Z'-portal DM $m_{Z'} = 150$ GeV

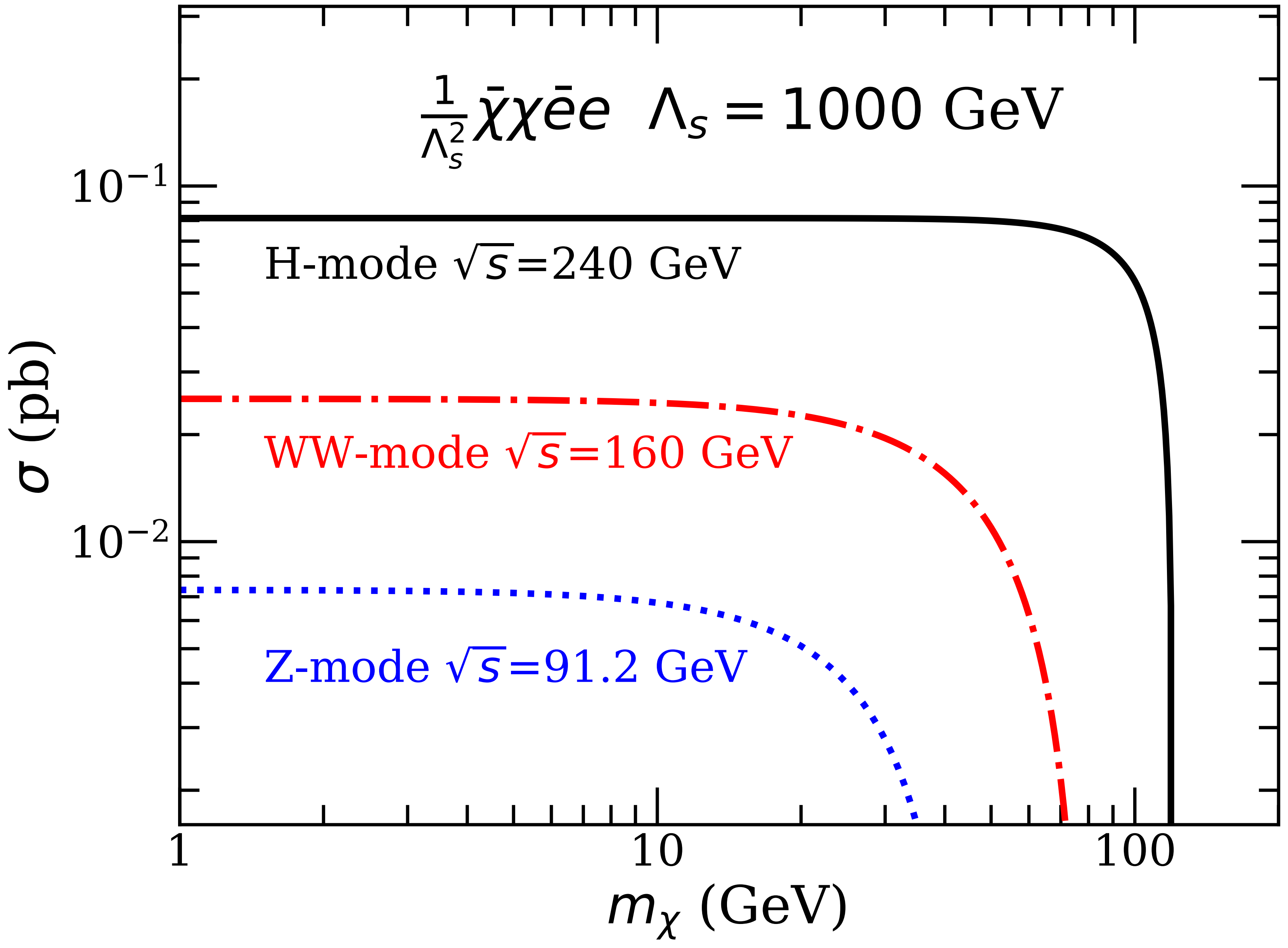


WW>H>Z

mono-photon signal (EFT)

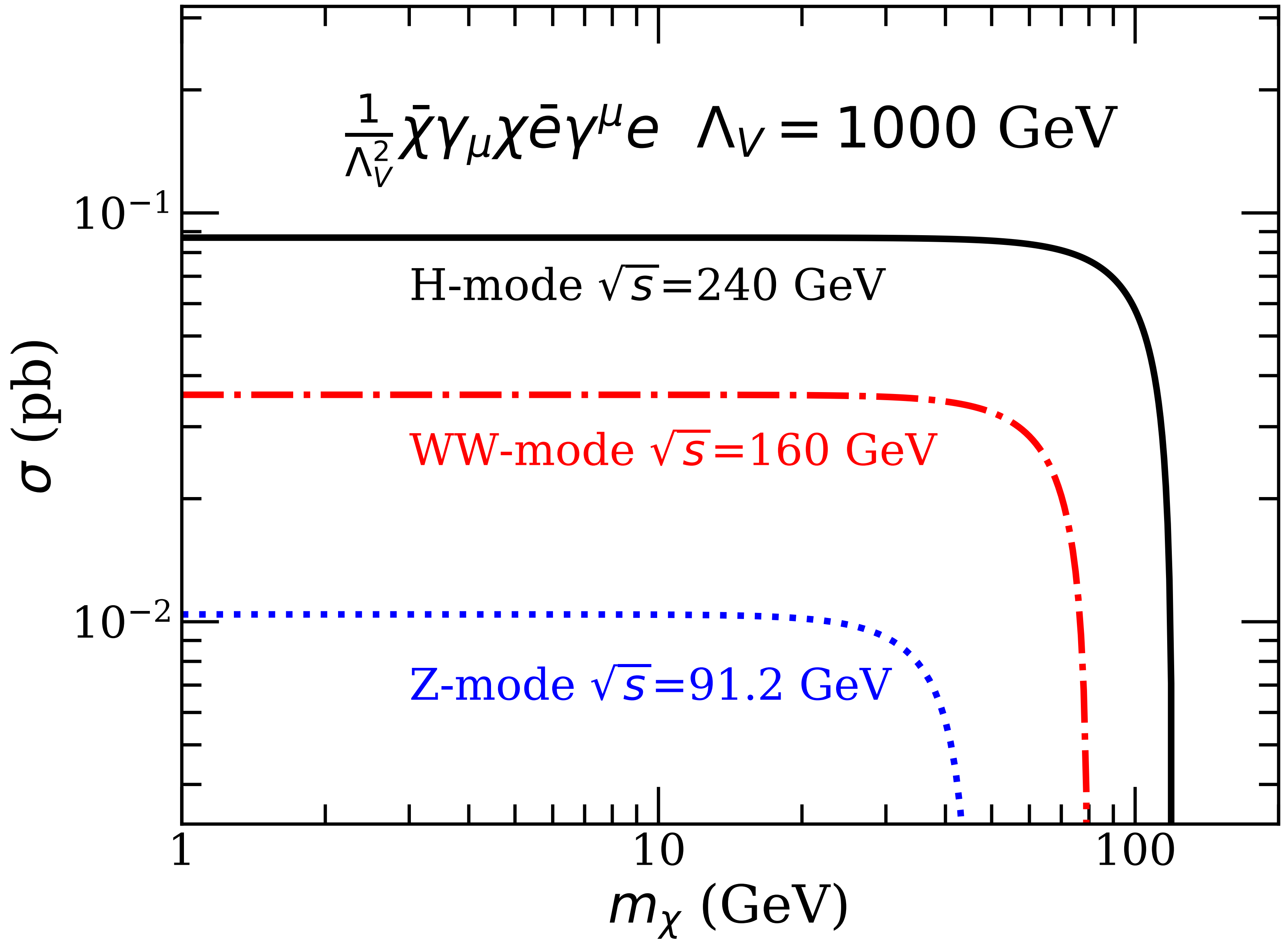
detector cuts $E_\gamma > 0.1\ \mathrm{GeV}\ \&\ |z_\gamma| < 0.99$

scalar-EFT DM $\Lambda = \mathrm{TeV}$



H>WW>Z

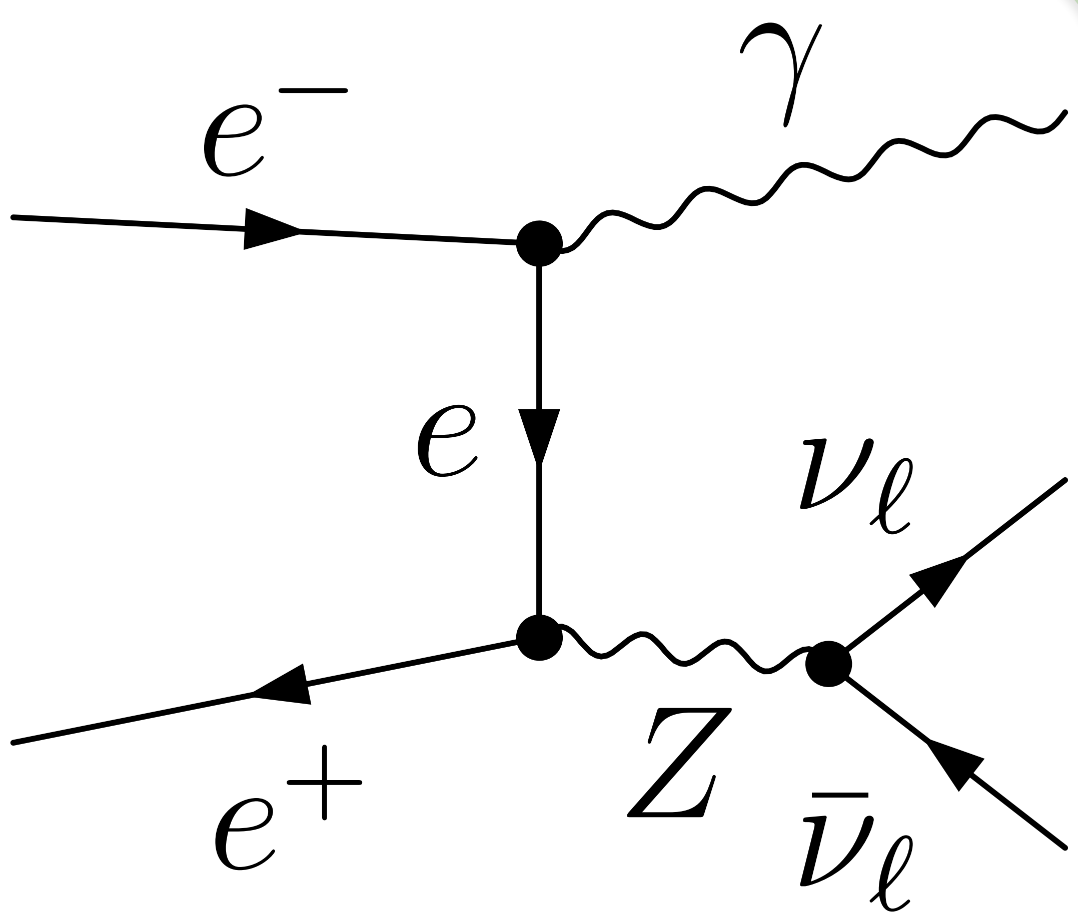
vector-EFT DM $\Lambda = \mathrm{TeV}$



H>WW>Z

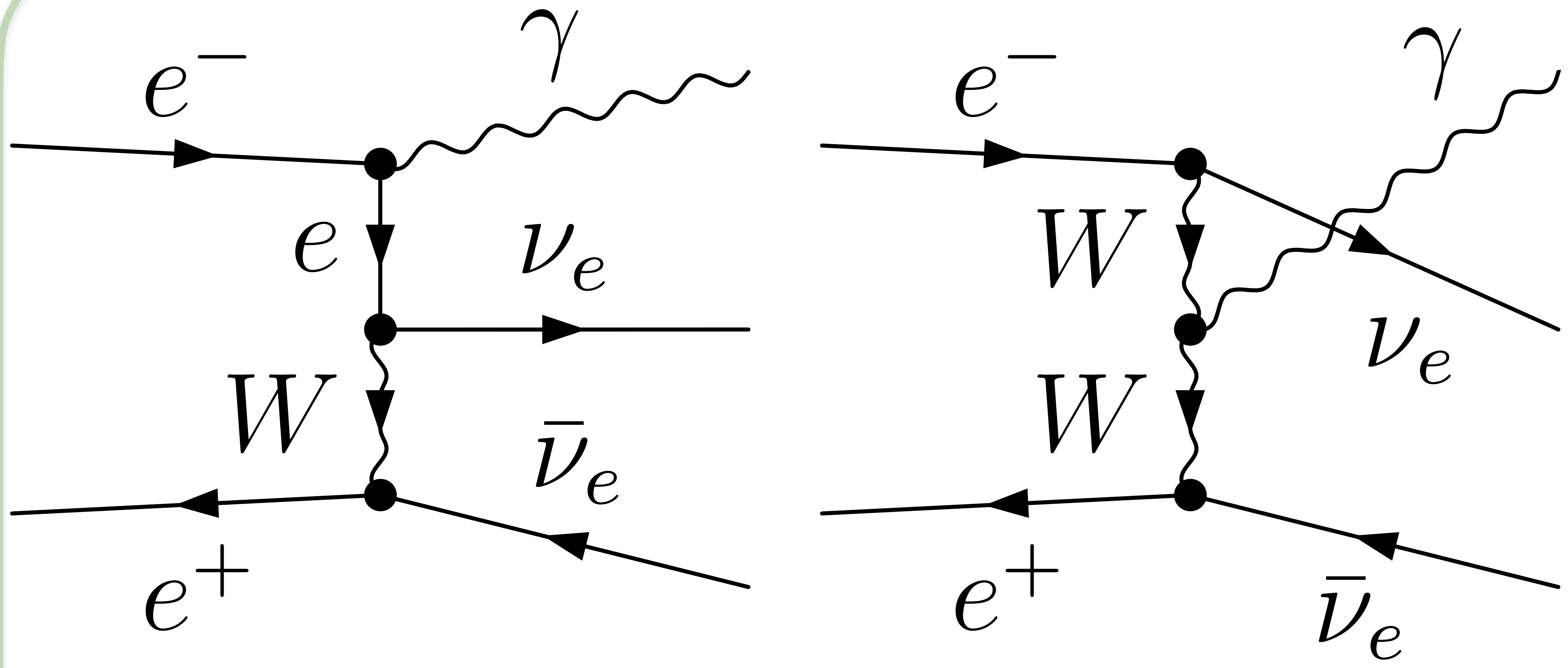
Irreducible SM background

irreducible BG: $e^+e^- \to \bar{\nu}\,\nu\,\gamma$



Z-diagram

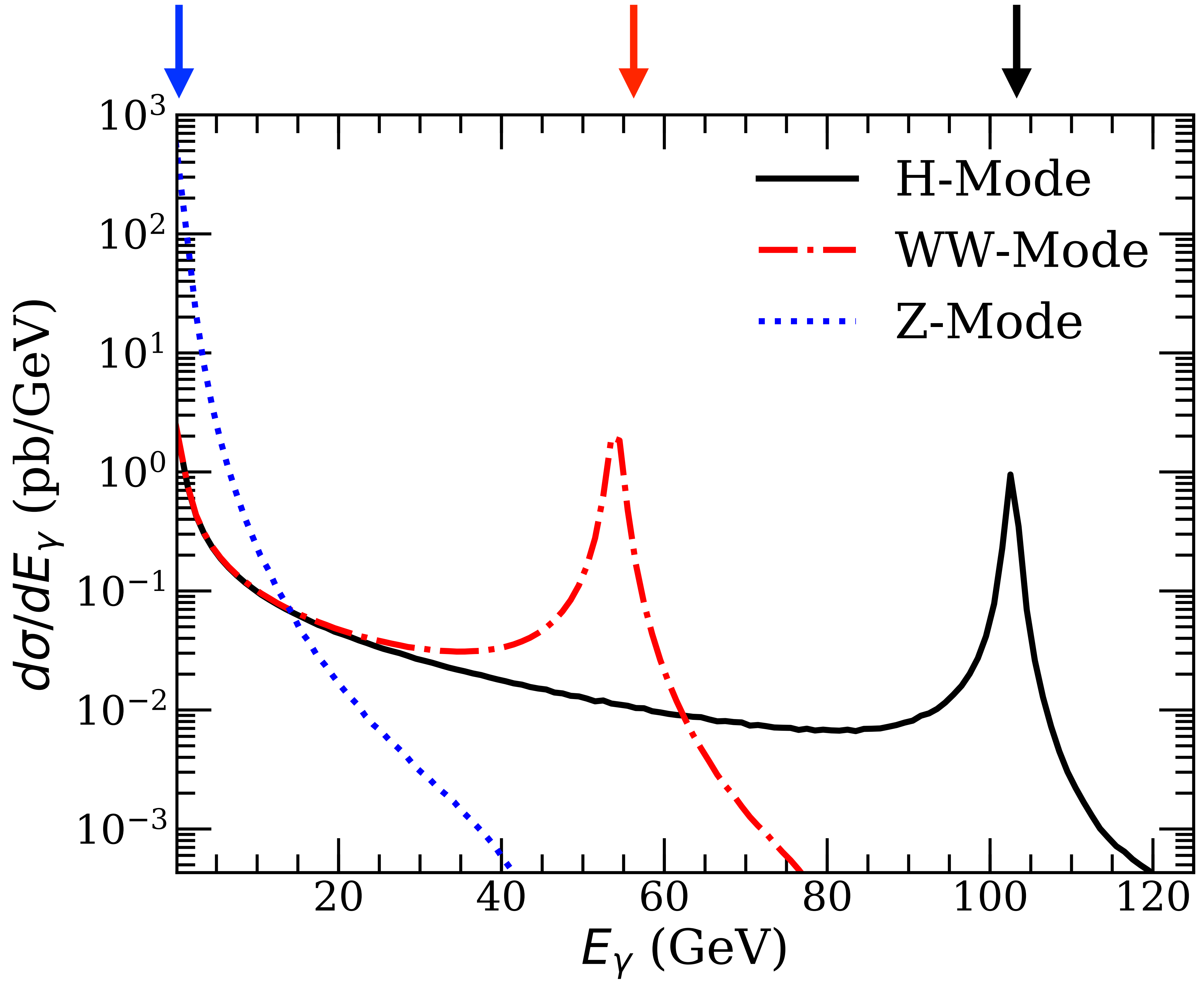
$\nu_\ell = \nu_e,\ \nu_\mu,\ \nu_\tau$



W-diagrams

electron neutrino

Photon energy in irreducible BG



``Z resonance'' $E_\gamma^Z = \dfrac{s - m_Z^2}{2\sqrt{s}}$

FWHM $\Gamma_\gamma^Z = \dfrac{m_Z \Gamma_Z}{\sqrt{s}}$

veto $E_\gamma \in (E_\gamma^Z \pm 5\Gamma_\gamma^Z)$

Reducible SM background

Reducible BG: $e^+e^- \to \gamma + \not{X}$ w/ $X = f\bar{f}, \gamma, \gamma\gamma$

X becomes invisible due to limited detection capability

[1811.10545] EMC coverage: $|\cos\theta| < 0.99$ & $E > 0.1$ GeV

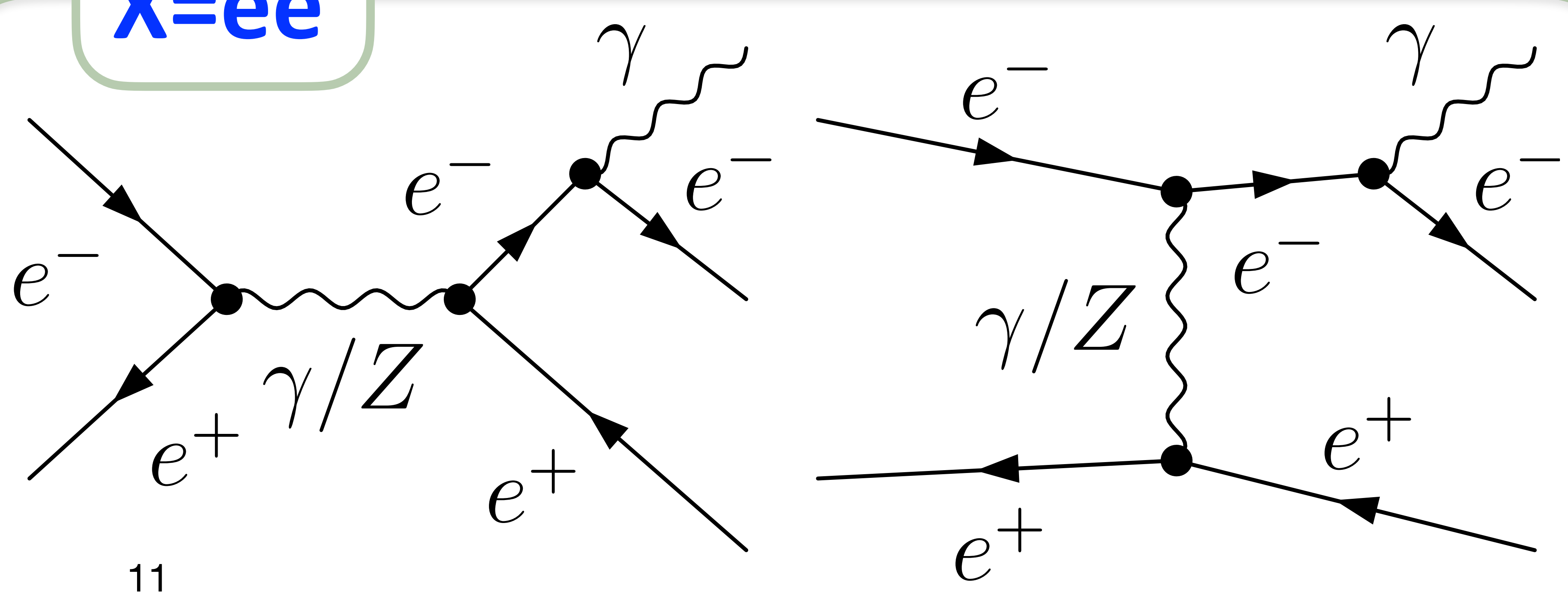
EMC energy resolution: $\dfrac{\sigma(E)}{E} = \dfrac{10.1\%}{\sqrt{E/\mathrm{GeV}}} \bigoplus 0.4\%$

EMC position resolution: ~ 0.1 mm [S. Wang, thesis, 2017]

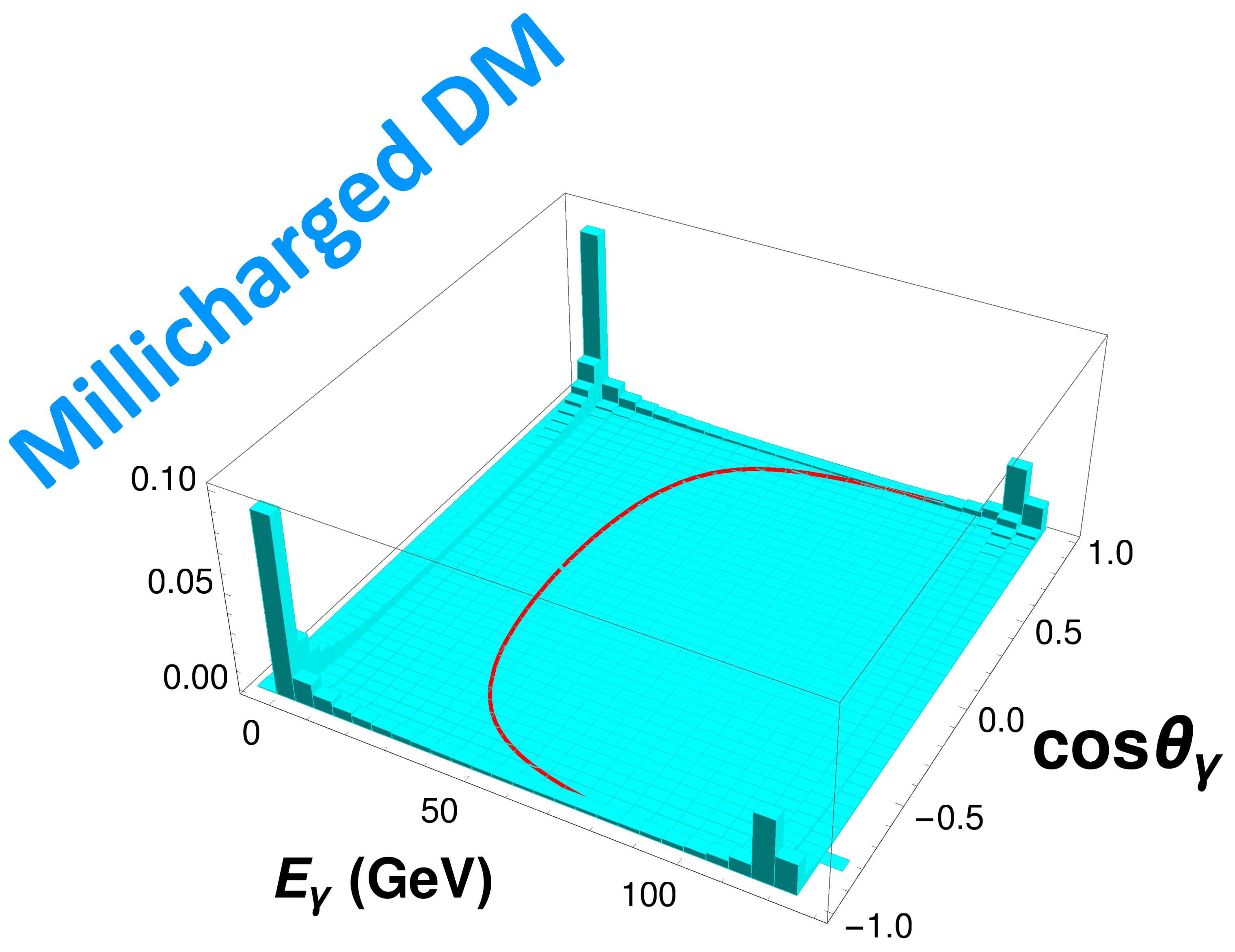
$X = \gamma$ is small

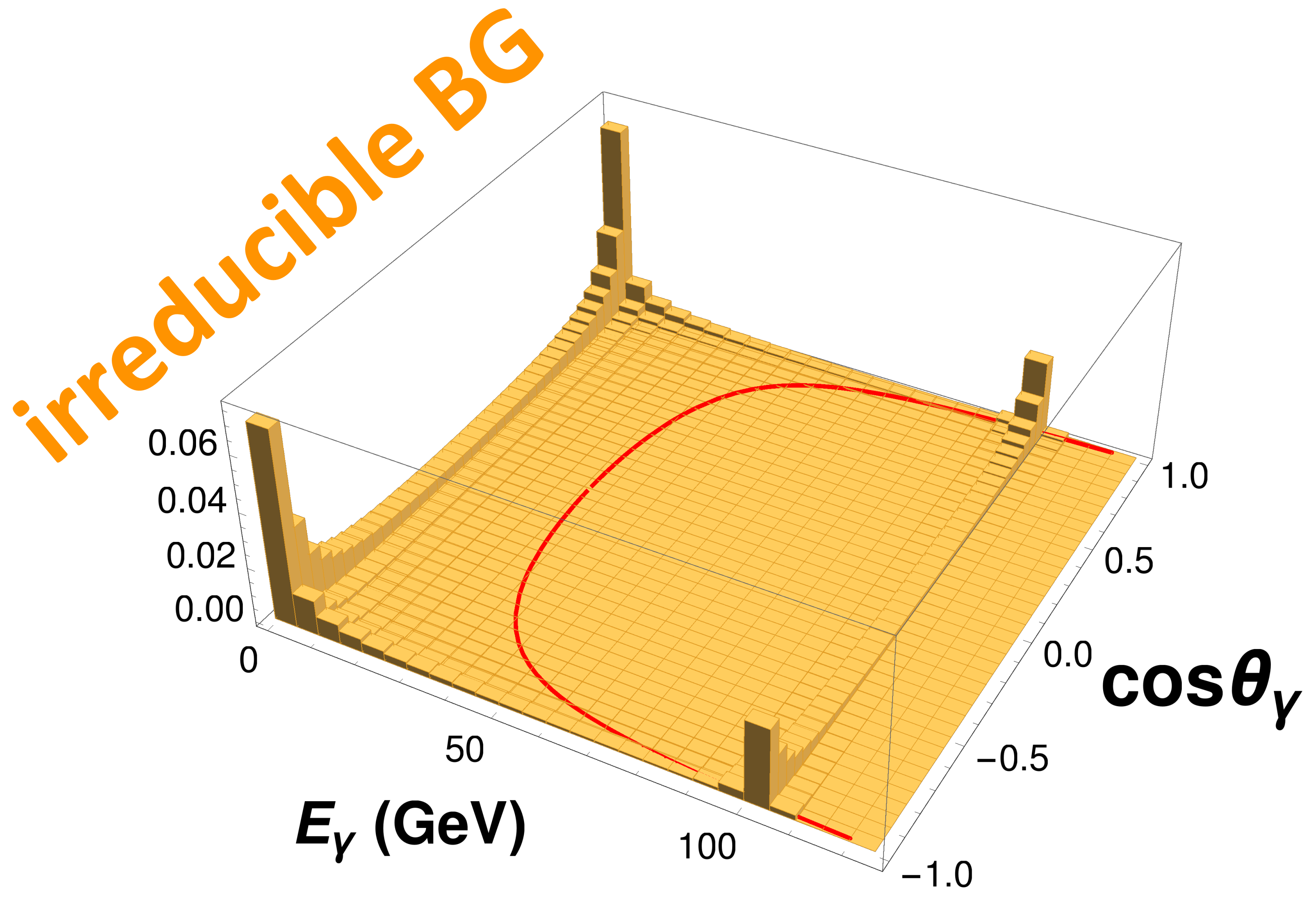
$X = \gamma\gamma, f\bar{f}$ are large

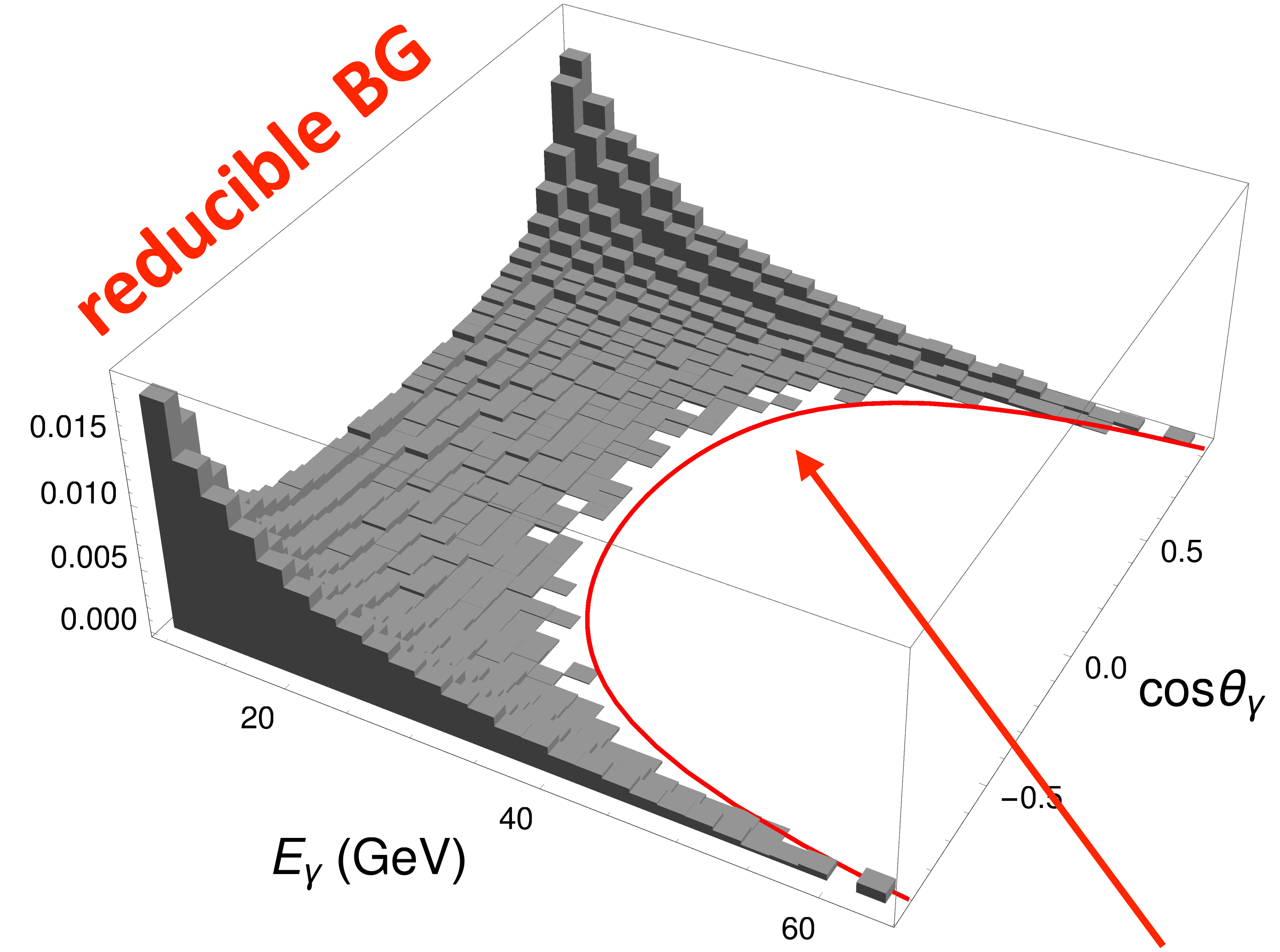
X=ee



Remove reducible BG







maximum photon energy

$$E_\gamma^m = \sqrt{s}\left[1 + \frac{\sin\theta_\gamma}{\sin\theta_b}\right]^{-1} \equiv E_B^m(\theta_\gamma)$$

$$\theta_{e^\pm} = \theta_b \qquad |\cos\theta_b| = 0.99$$

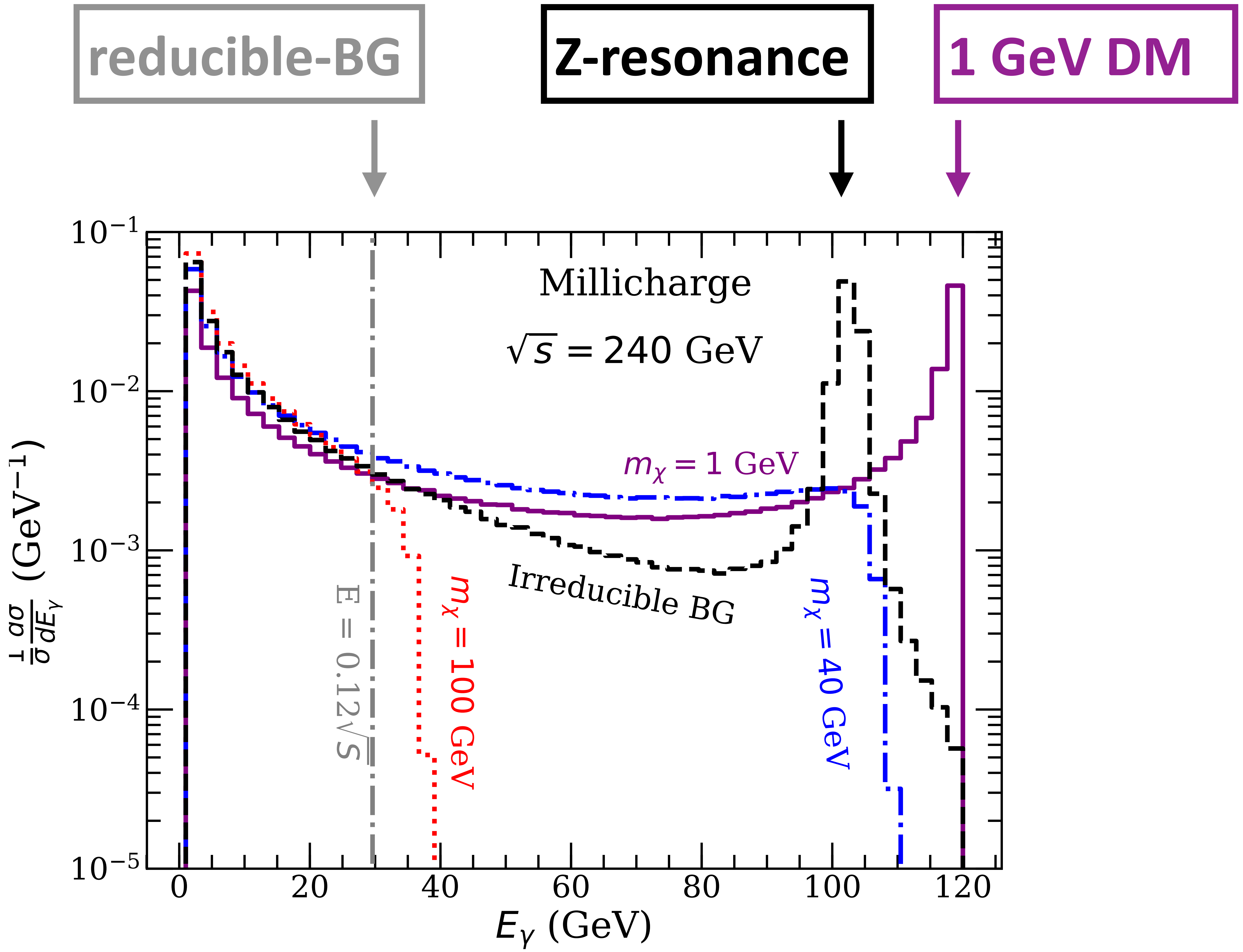
Detector cuts

- $E_\gamma > 0.1\ \mathrm{GeV}$ ⟵ EMC
- $|\cos\theta_\gamma| < |\cos\theta_b| = 0.99$ ⟵ EMC
- $E_\gamma < E^m_\chi = (s - 4m_\chi^2)/(2\sqrt{s})$ ⟵ DM
- veto $E_\gamma \in (E^Z_\gamma(s) \pm 5\Gamma^Z_\gamma(s))$ ⟵ Z resonance
- $E_\gamma(\theta_\gamma) > E^m_B(\theta_\gamma) = \sqrt{s}\Big/\left[1 + \frac{\sin\theta_\gamma}{\sin\theta_b}\right]$ ⟵ reducible BG

$(E^m_B)_{\min} \simeq 0.12\sqrt{s}$ when $\theta_\gamma = \pi/2$

1 millicharged DM

Energy distribution (H-mode)



Millicharged DM with mass = 1, 40, 100 GeV & ε = 0.01

detector cuts

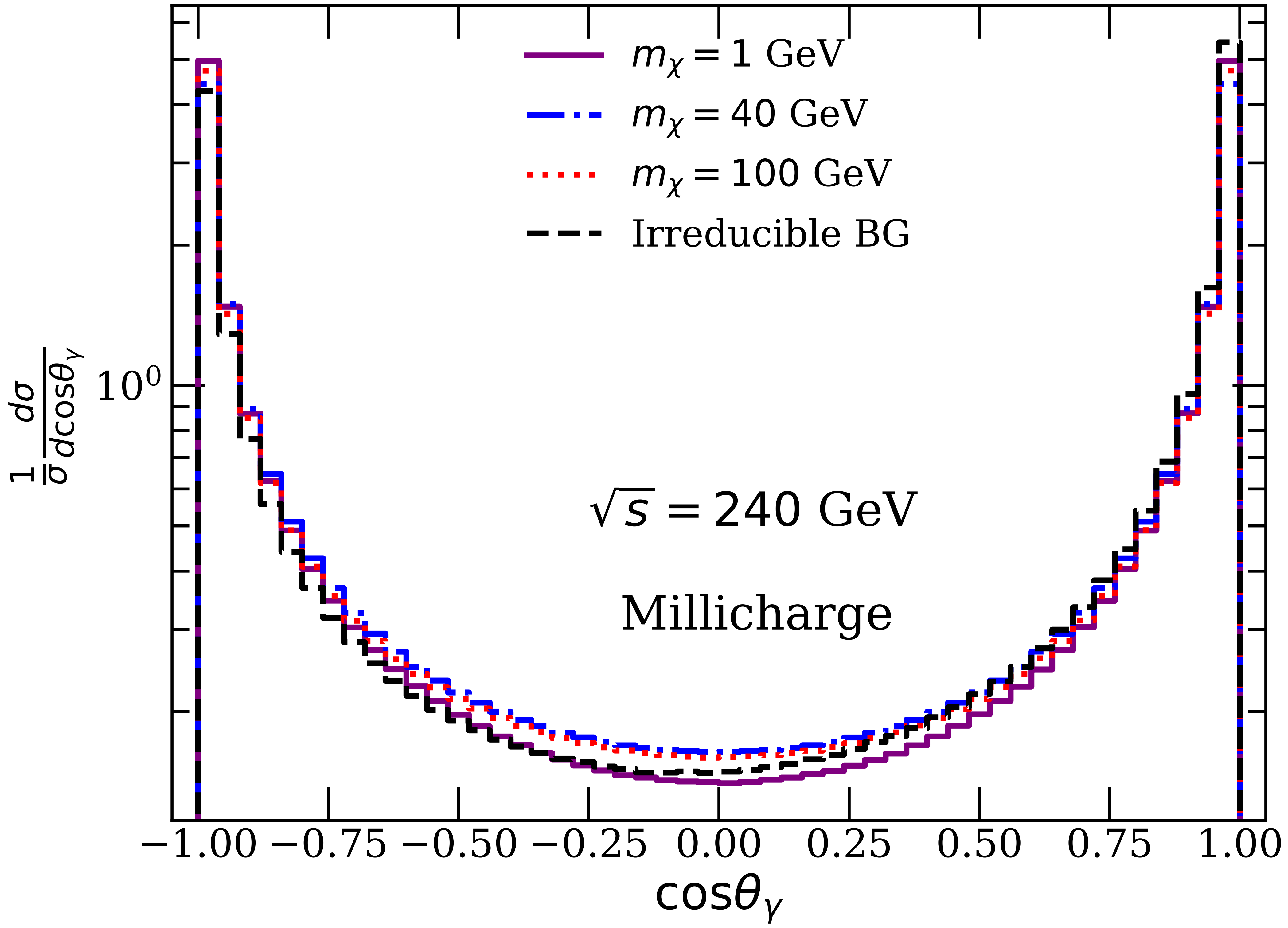
$$E_\gamma > 0.1 \text{ GeV} \ \& \ |z_\gamma| < 0.99$$

to enhance sensitivity

$$E_\gamma > E_\gamma^Z(s) + 5\Gamma_\gamma^Z(s)$$

for $m_\chi < 25$ GeV

Angular distribution (H-mode)



Millicharged DM with mass = 1, 40, 100 GeV & ε = 0.01

detector cuts

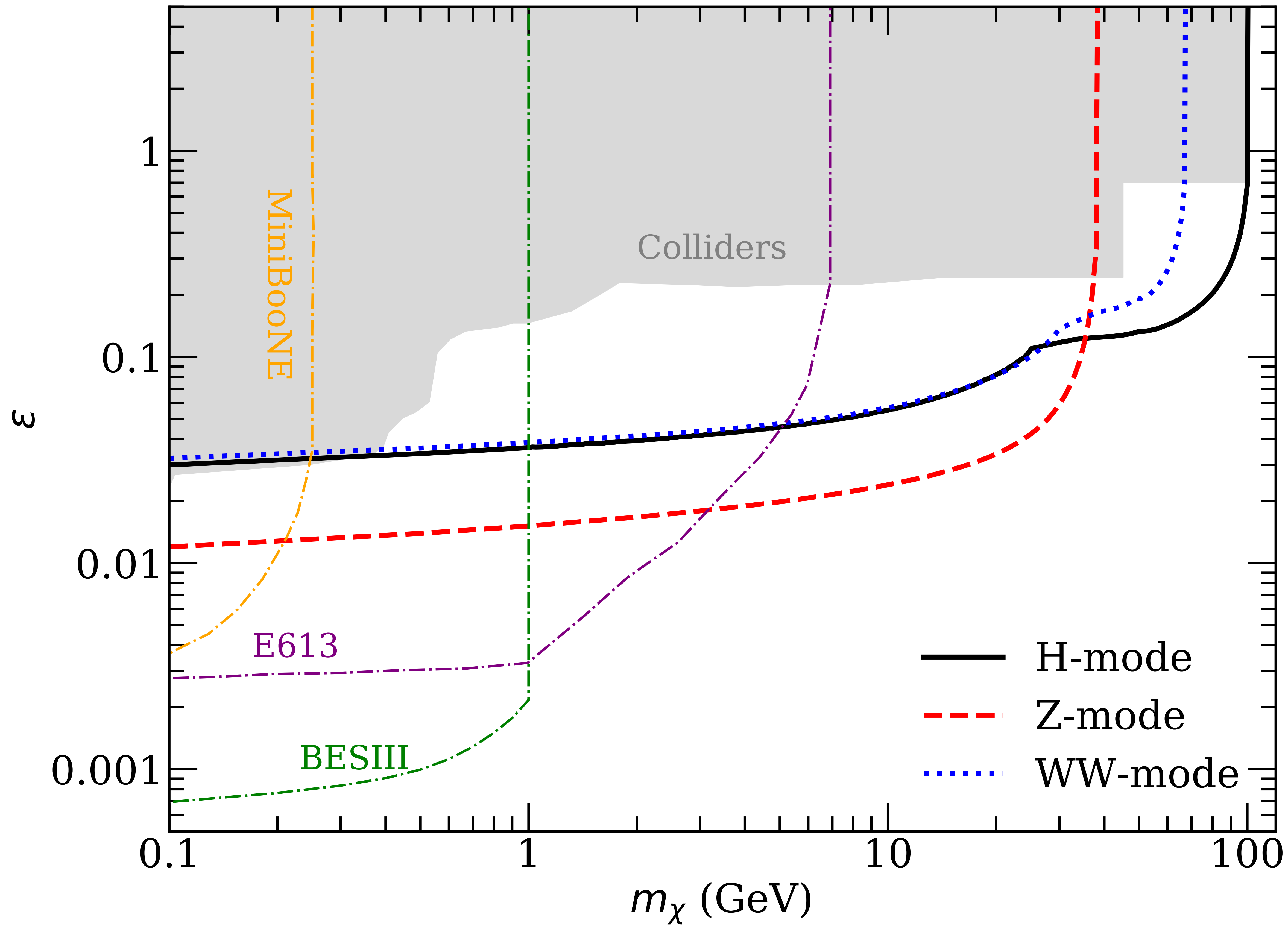
$$E_\gamma > 0.1 \text{ GeV} \ \& \ |z_\gamma| < 0.99$$

similar distributions $\Longrightarrow$

no further angular cut

CEPC sensitivity on millicharged DM

[ZL, Y.-H. Xu, and Y. Zhang,1903.12114]



95% CL bound

$S/\sqrt{B} = 2$

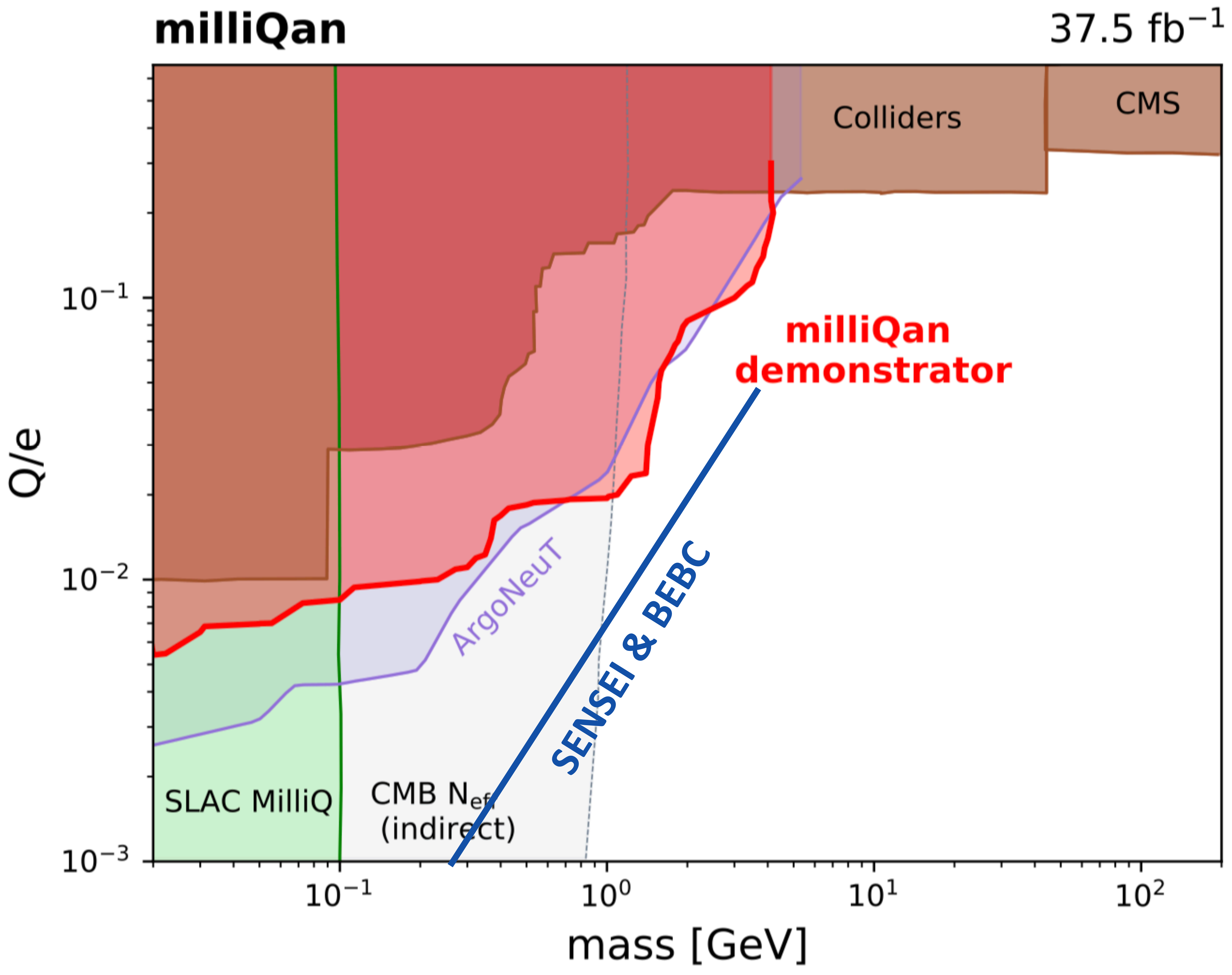
millicharged particle χ

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

Z-mode can probe
$\epsilon \sim 0.02$ for $m = 5$ GeV

CEPC can probe unexplored millicharge values

Recent limits on millicharged particles



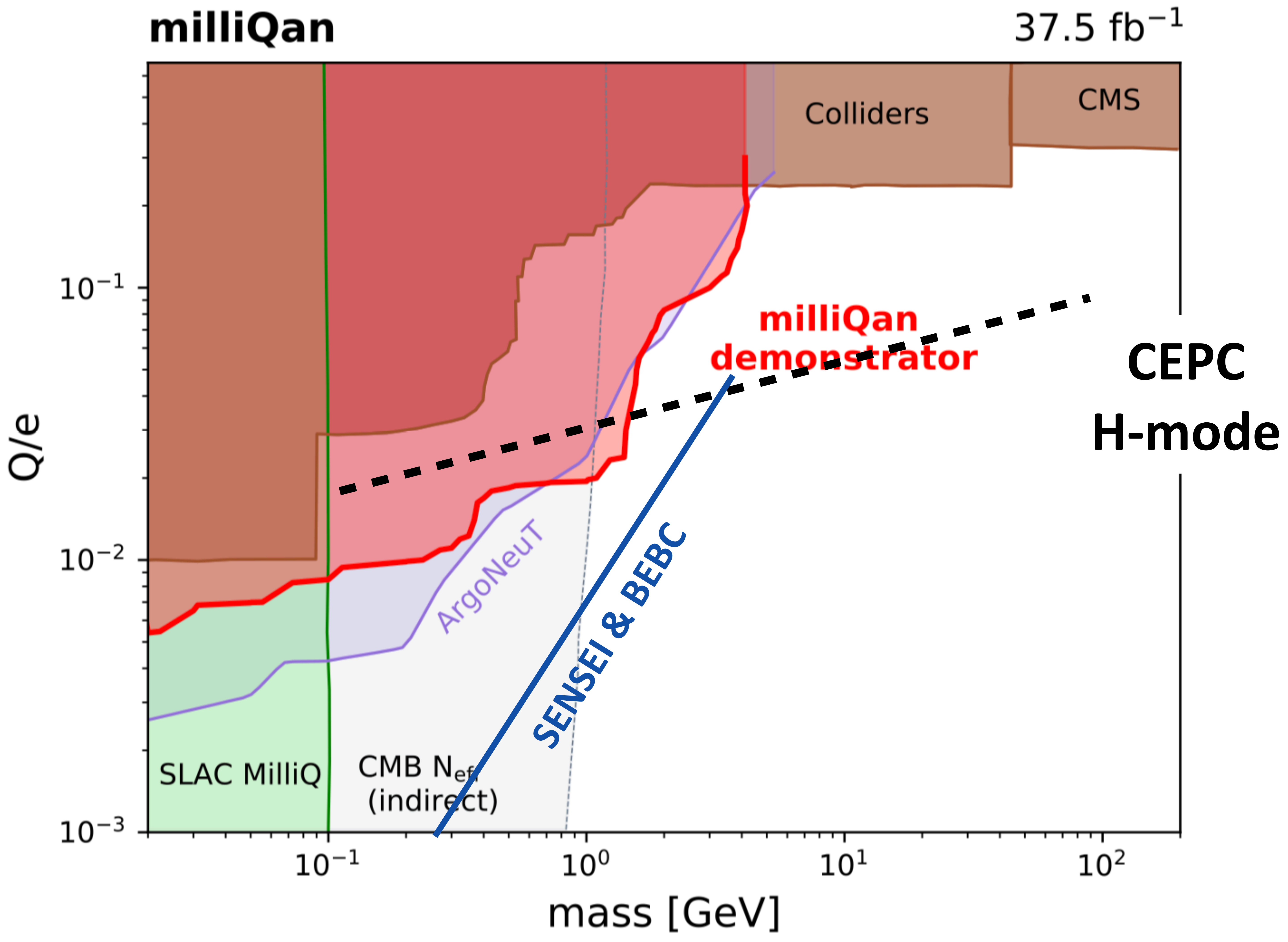
ArgoNeuT 10^{20} POT **[1911.07996]**

[milliQan, 2005.06518] 37/fb in 2018

SK & HK, 2002.11732, 2104.13924, 2211.11469

SENSEI & BEBC

Recent limits on millicharged particles



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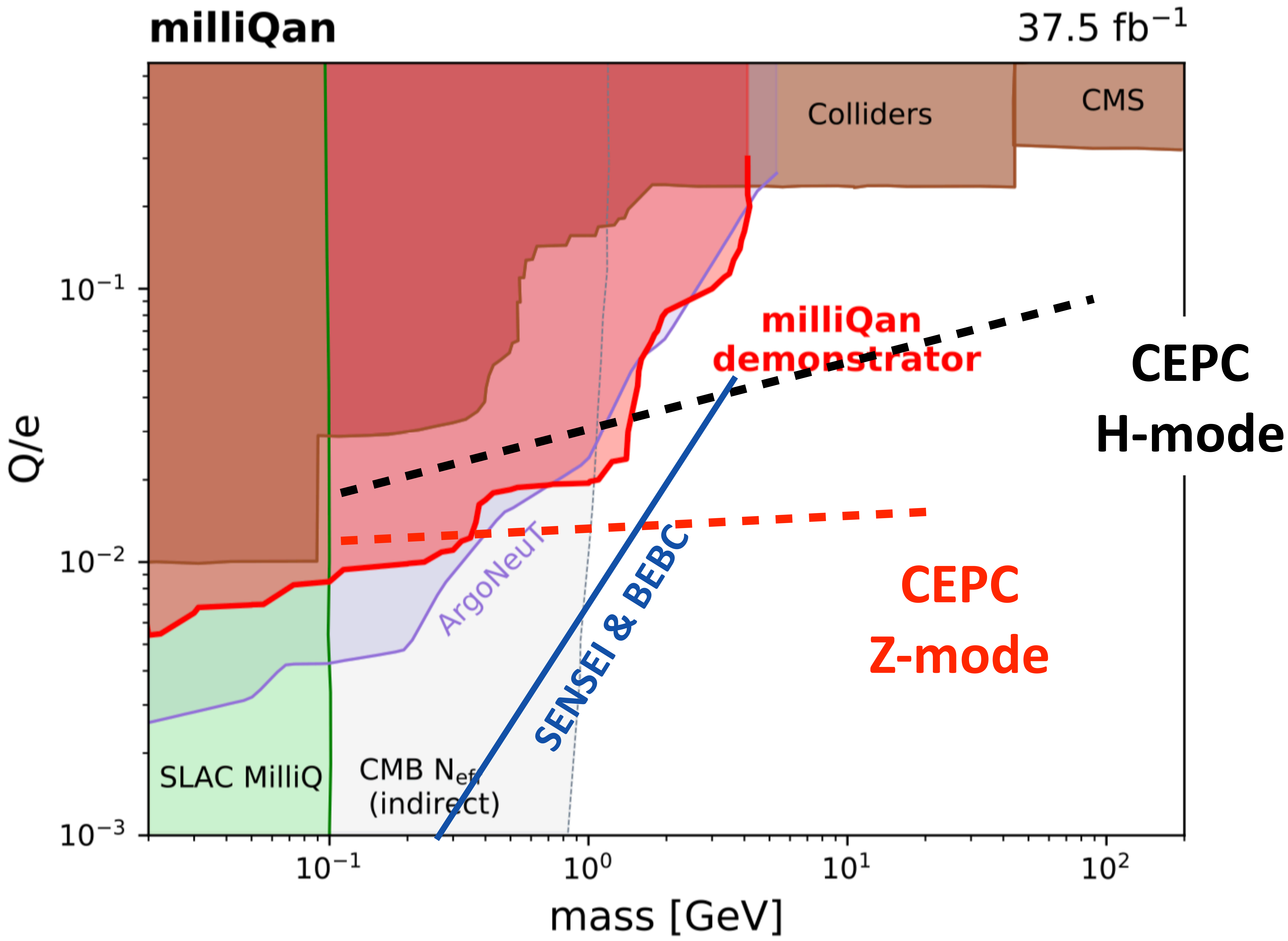

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[milliQan, 2005.06518] 37/fb in 2018

SK & HK, 2002.11732, 2104.13924, 2211.11469

SENSEI & BEBC

2 Vector portal DM

Vector-portal DM

$$\mathcal{L} = Z'_\mu \bar{\chi} \gamma^\mu (g_V^\chi - g_A^\chi \gamma_5) \chi + Z'_\mu \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma_5) f$$

Z’ mass = 150 GeV

2 scenarios

(1) vector coupling only

(2) axial-vector coupling only

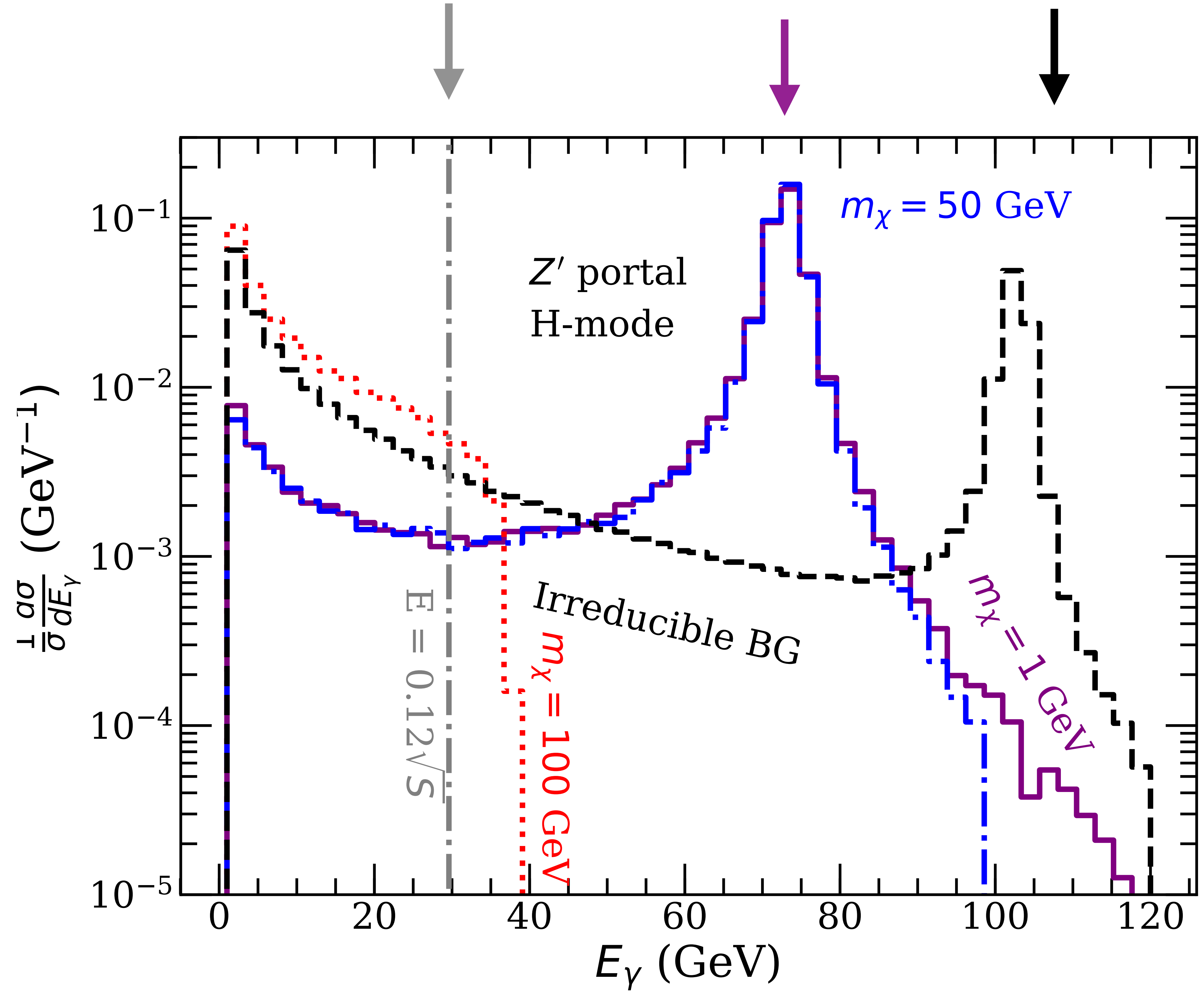
2 channels

(1) monophoton (invisible)

(2) di-muon (visible)

Energy distribution (Z' portal DM)

reducible-BG | 1 & 50 GeV DM | Z-resonance



$$E_\gamma > 0.1 \text{ GeV} \;\&\; |z_\gamma| < 0.99$$

$$m_{Z'} = 150 \text{ GeV}$$

"Z' resonance"

$$E_\gamma = \frac{s - m_{Z'}^2}{2\sqrt{s}}$$

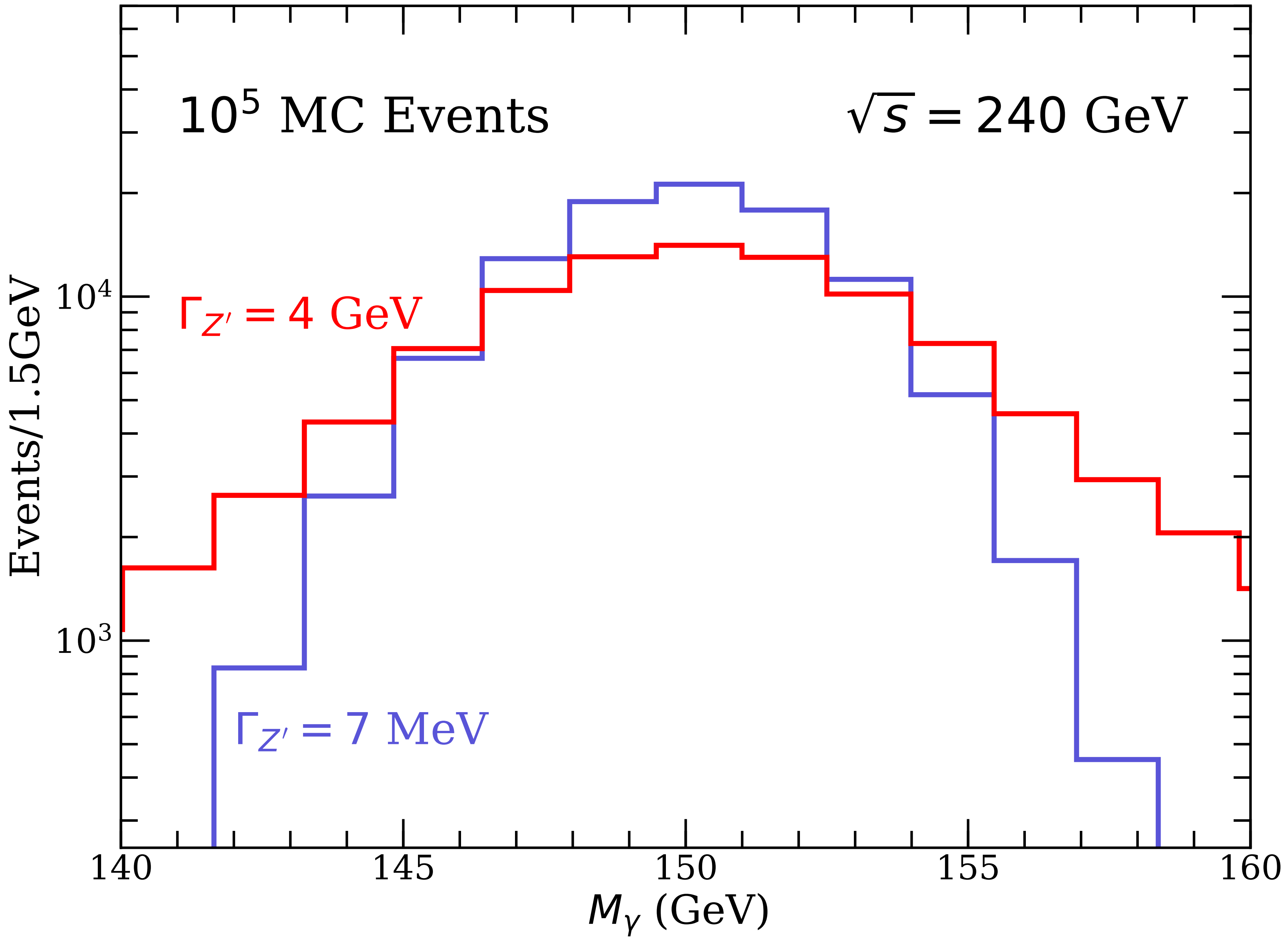
reconstruct Z'

$$M_\gamma = \sqrt{s - 2\sqrt{s}E_\gamma}$$

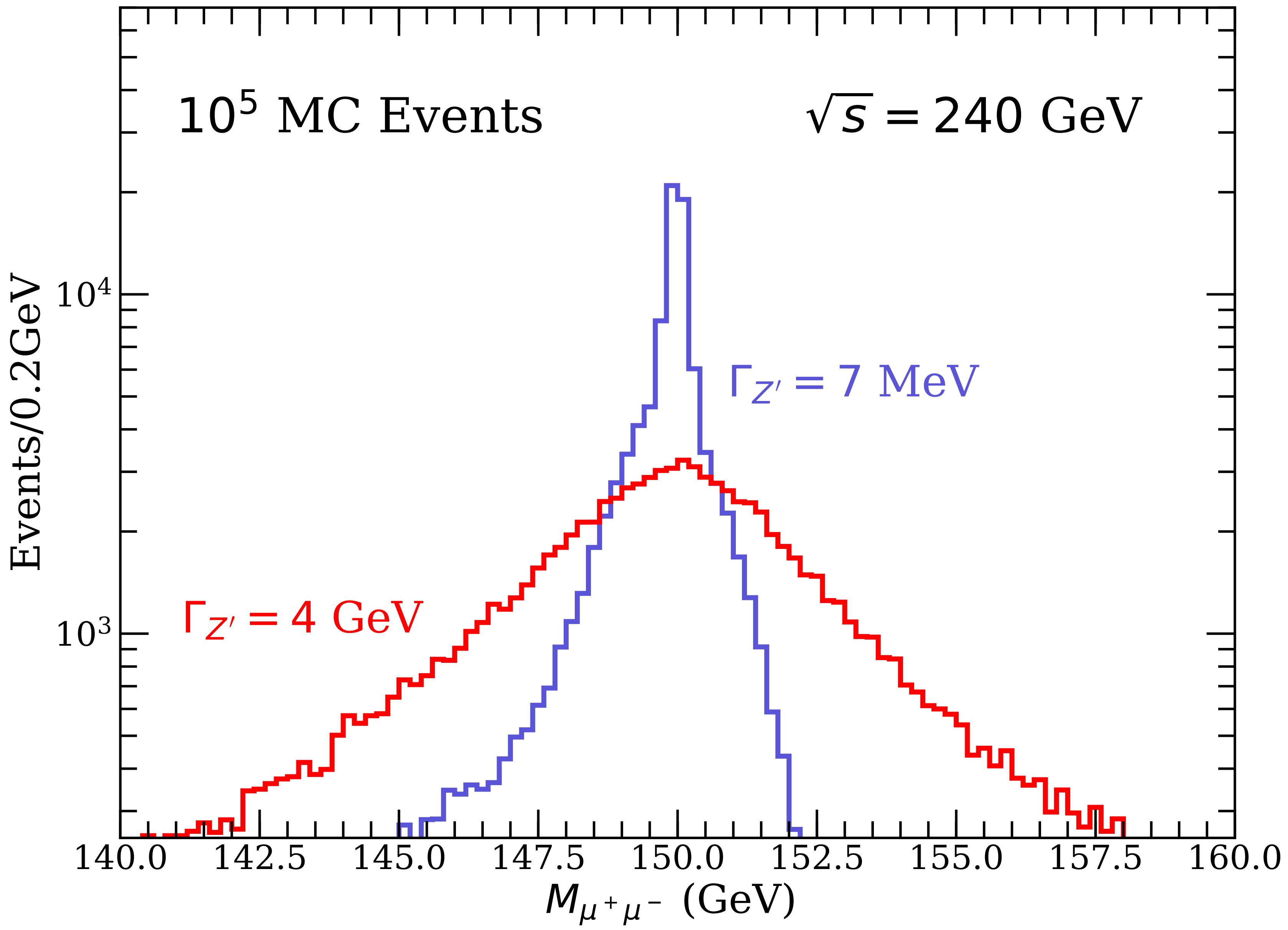
$$147 < M_\gamma/\text{GeV} < 153$$

Invisible versus visible

invisible: monophoton



visible: dimuon



dimuon

$$\frac{\delta p_T}{p_T} = \frac{p_T}{10^5\ \text{GeV}} \bigoplus 0.1\% \text{ for } |\eta| < 1.0$$

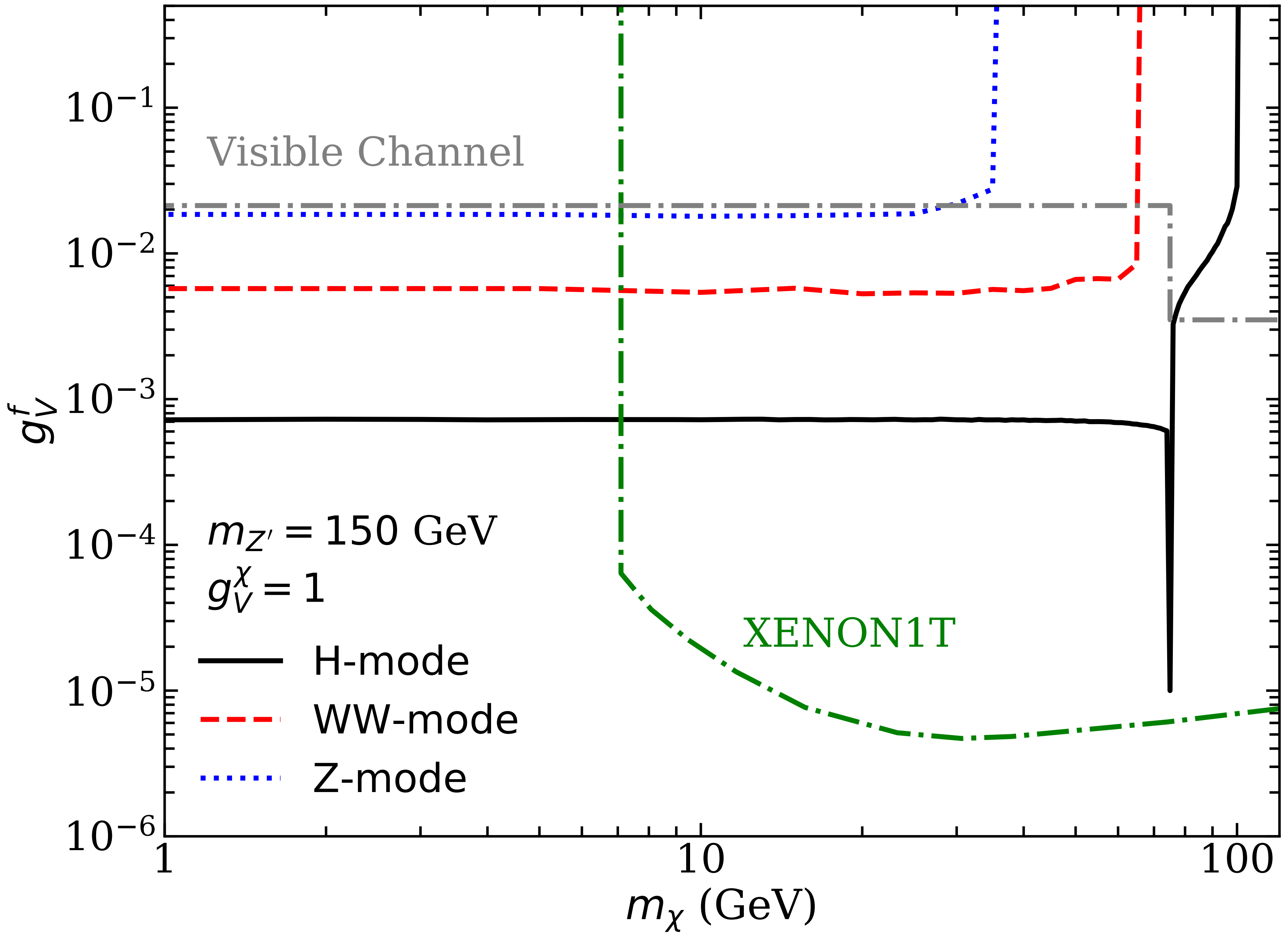
$$\& \text{ 10 times larger for } 1.0 < |\eta| < 3.0$$

[see also, e.g. Karliner, Low, Rosner, Wang, 1503.07209]

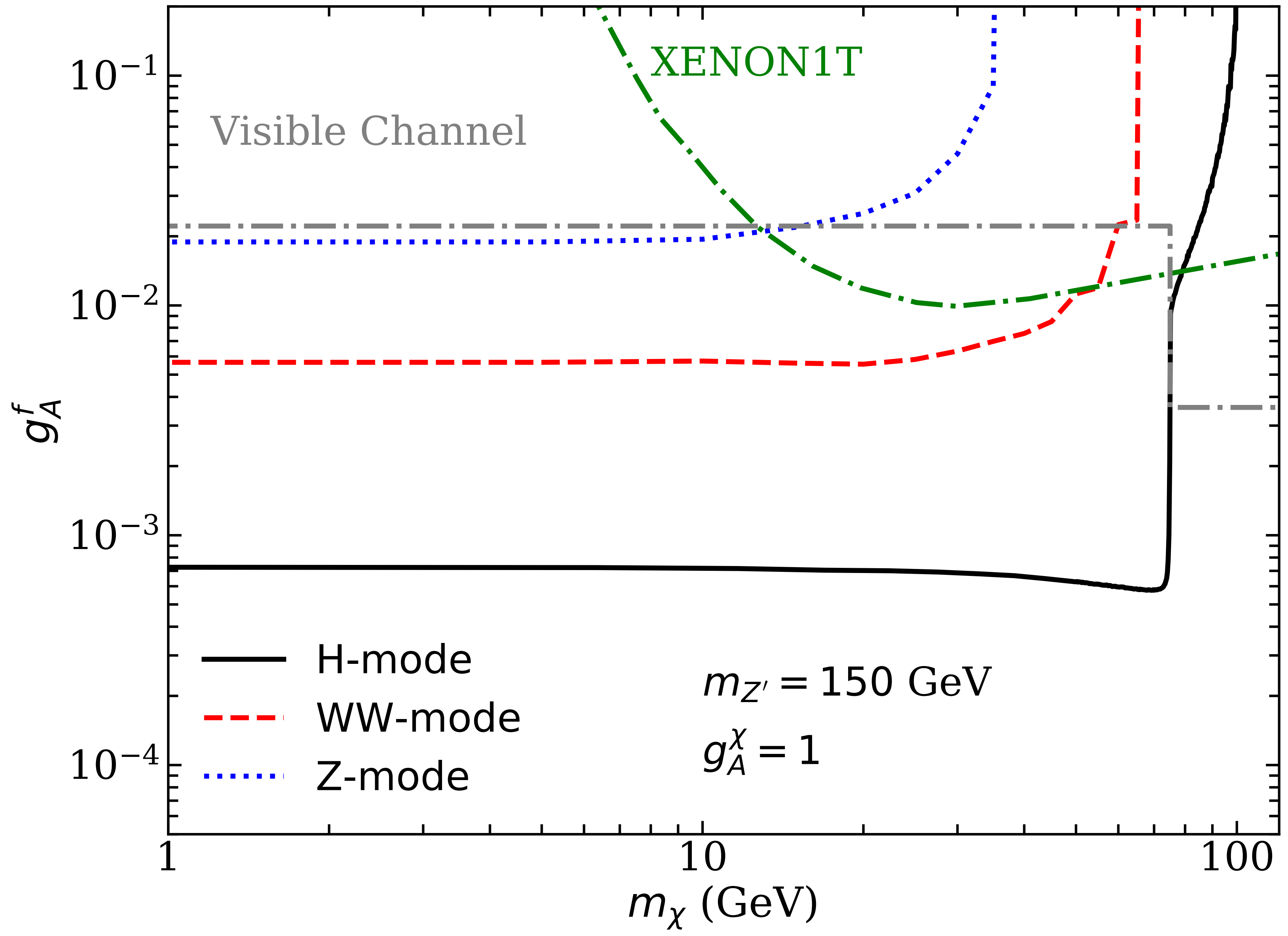
CEPC sensitivity to Z'-portal DM

[ZL, Y.-H. Xu, and Y. Zhang,1903.12114]

vector only



axial-vector only



strong coupling to χ: g ~ 1

DMDD: assume universal coupling to SM fermions

3 DM with EFT interactions

DM models with EFT interactions

[Fox, Harnik, Kopp, Tsai, 1103.0240]

[Chae, Perelstein, 1211.4008]

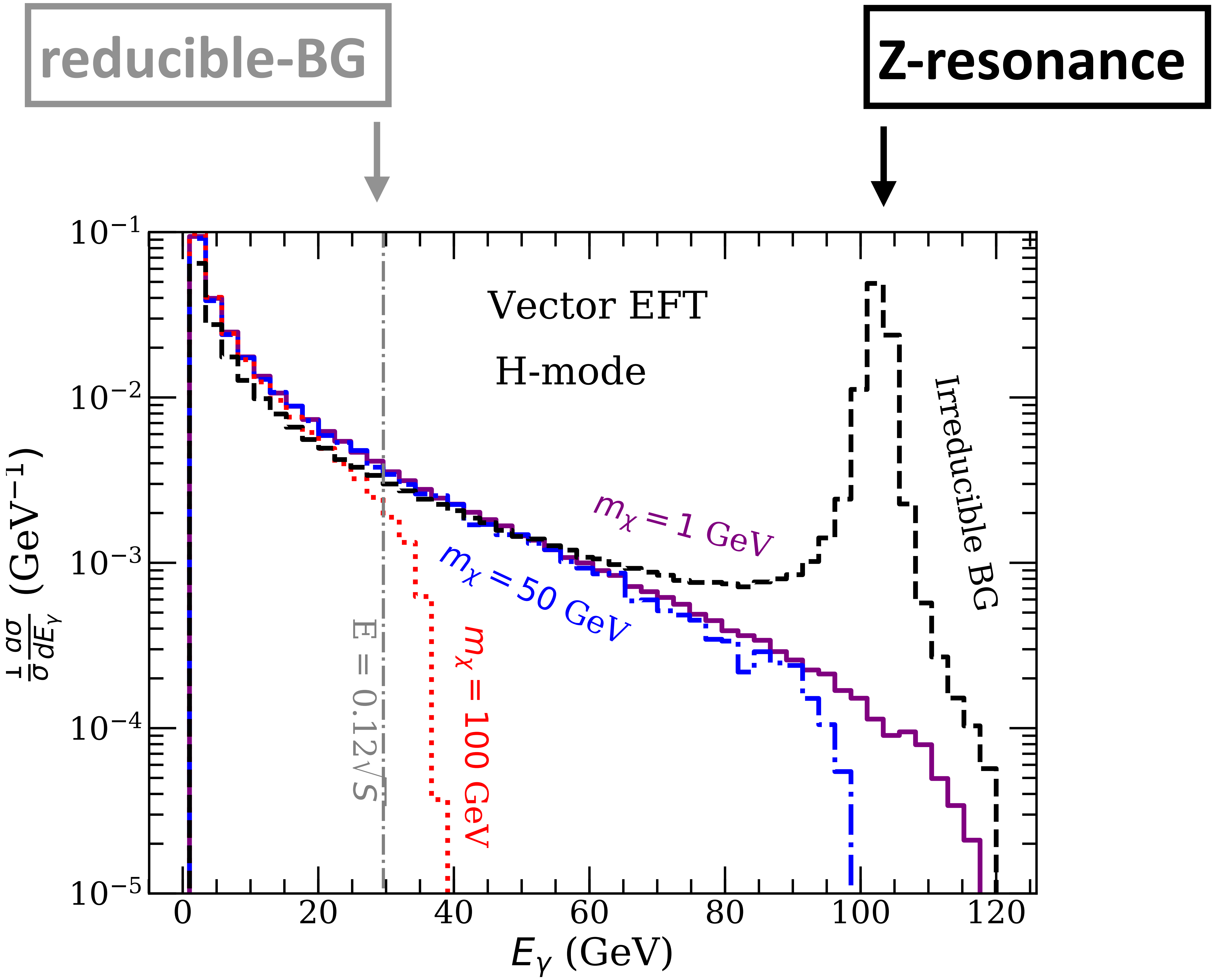
vector $$\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell$$

axial-vector $$\frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell$$

scalar (s-channel) $$\frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell$$

scalar (t-channel) $$\frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$$

Energy distribution (EFT DM)



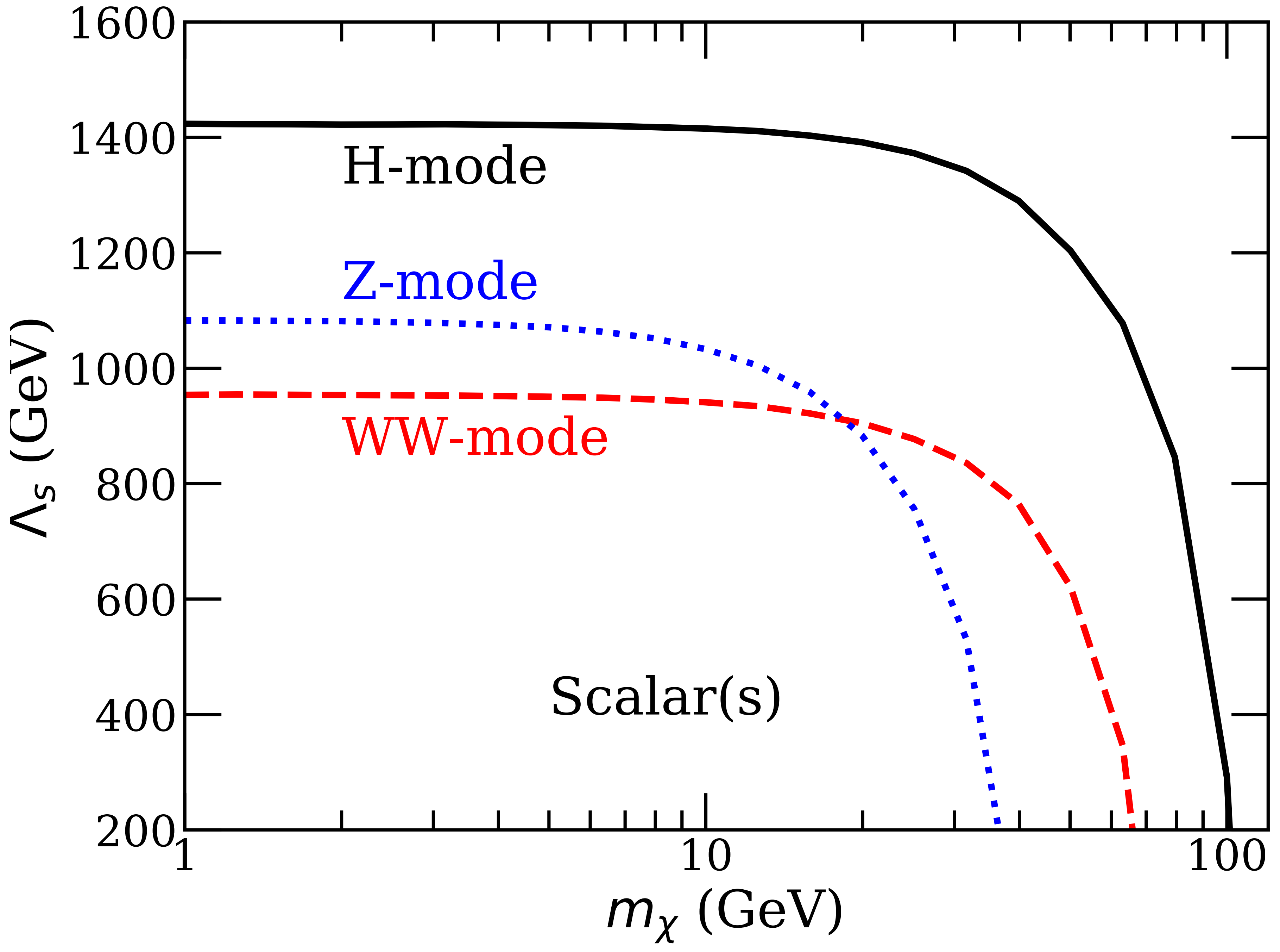
Vector EFT

detector cuts

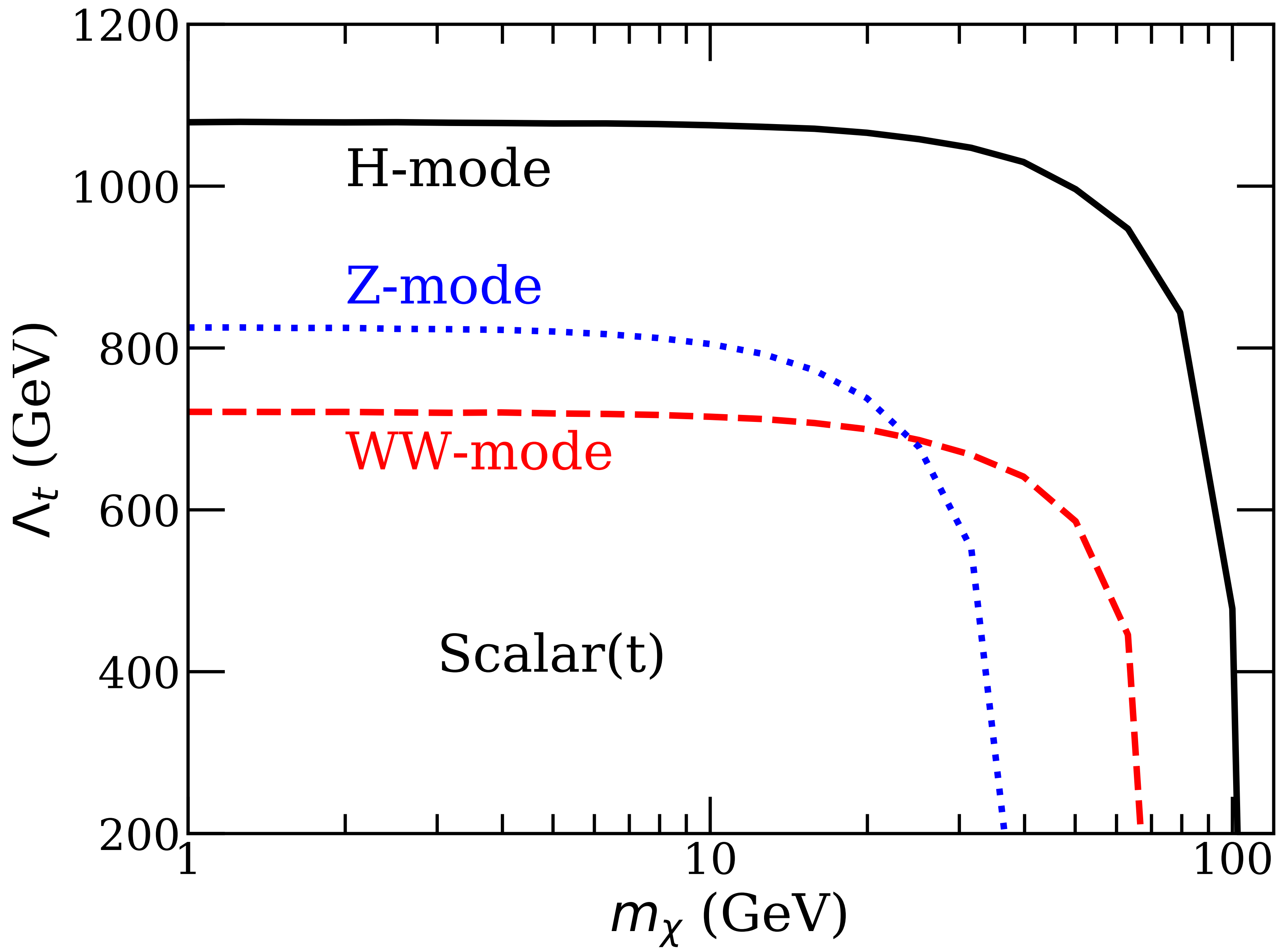
$$E_\gamma > 0.1\ \text{GeV}\ \&\ |z_\gamma| < 0.99$$

CEPC sensitivity to EFT DM (scalar cases)

Scalar (s) EFT



Scalar (t) EFT

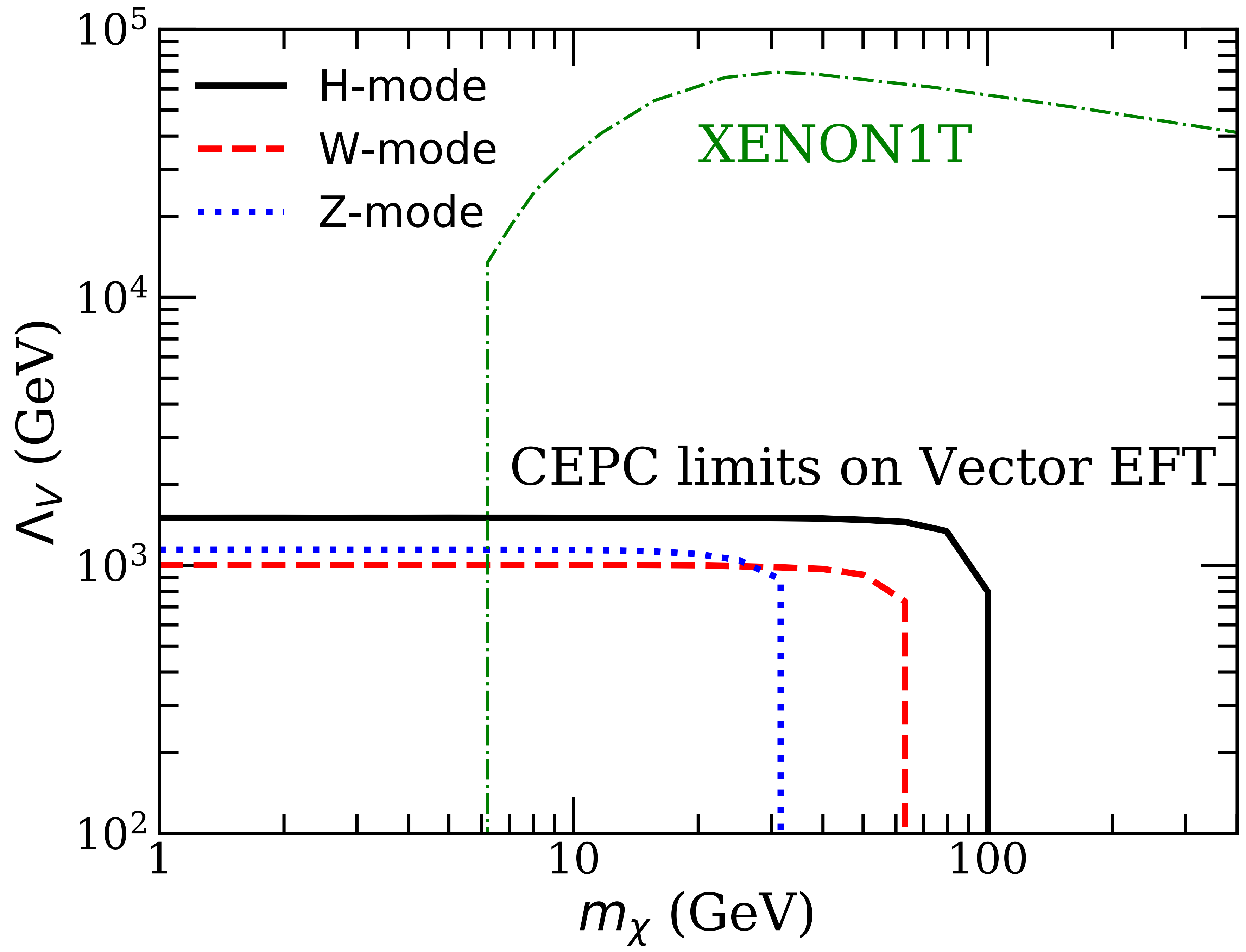


[ZL, Y.-H. Xu, and Y. Zhang,1903.12114]

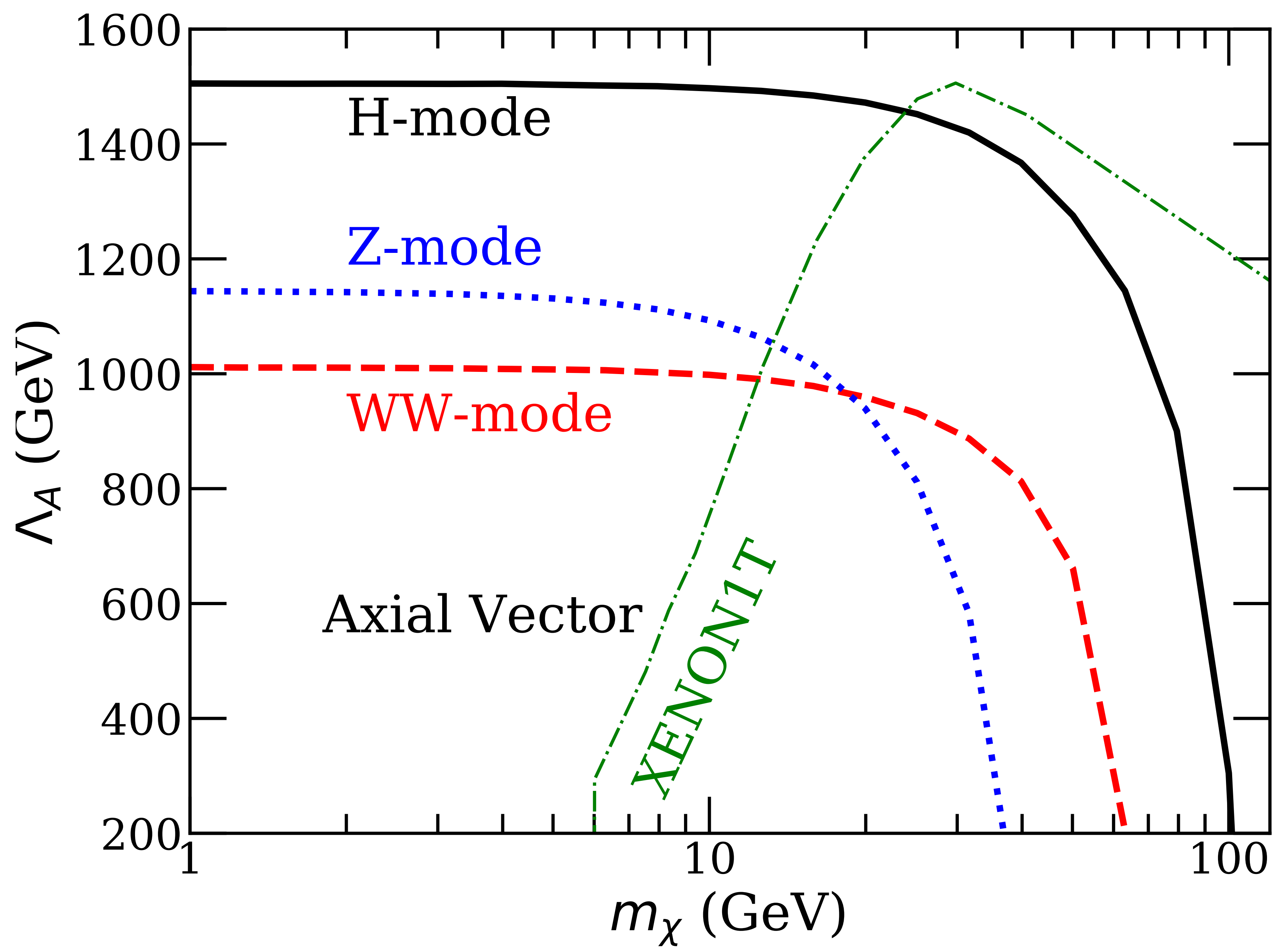
CEPC sensitivity to EFT DM (V & A cases)

[ZL, Y.-H. Xu, and Y. Zhang,1903.12114]

Vector EFT



Axial-vector EFT



DMDD: assume universal coupling to SM fermions

Summary

To optimize the CEPC sensitivity to different dark matter models, we propose a list of detector cuts to suppress the background

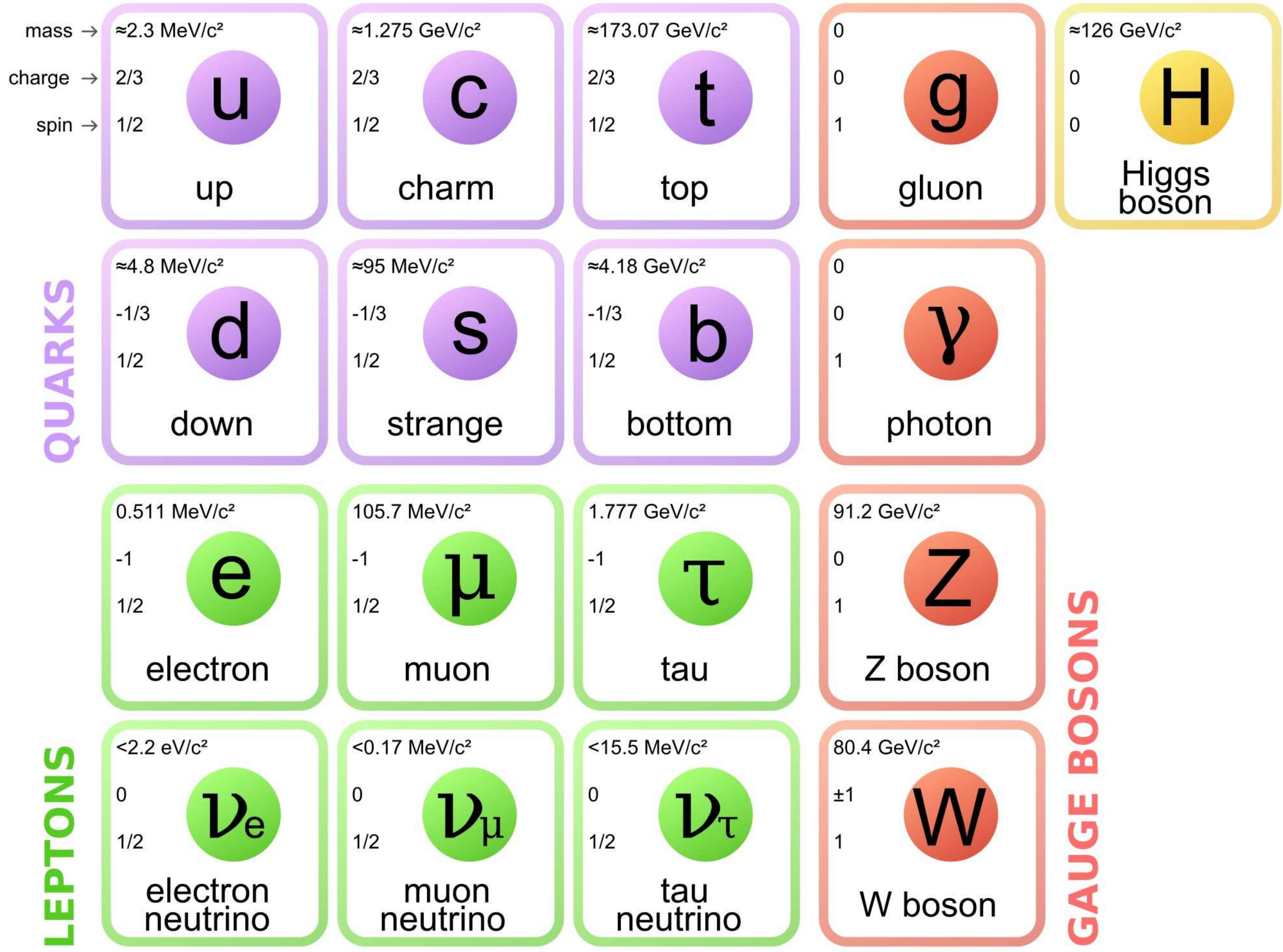
CEPC can probe millicharge DM that is currently unexplored

CEPC can probe the parameter space of vector-portal DM models and EFT DM models that are unconstrained by DMDD

[JHEP 06 (2019) 009, ZL, Yong-Heng Xu, Yu Zhang]

slides for Millicharged DM

Electric charge is quantized in SM



integer multiple of that of d-quark

Stringent experimental limits, e.g.

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

[Marinelli et al. 1984]

BSM particles with a millicharge

Kinetic mixing

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

[Foot & He, Phys. Lett. 267B, 509 (1991)]

$$\mathscr{L} = -\frac{\delta}{2} B_{\mu\nu} X^{\mu\nu} + X_\mu J_X^\mu$$

Stueckelberg mass mixing

[Kors & Nath hep-ph/0402047]

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

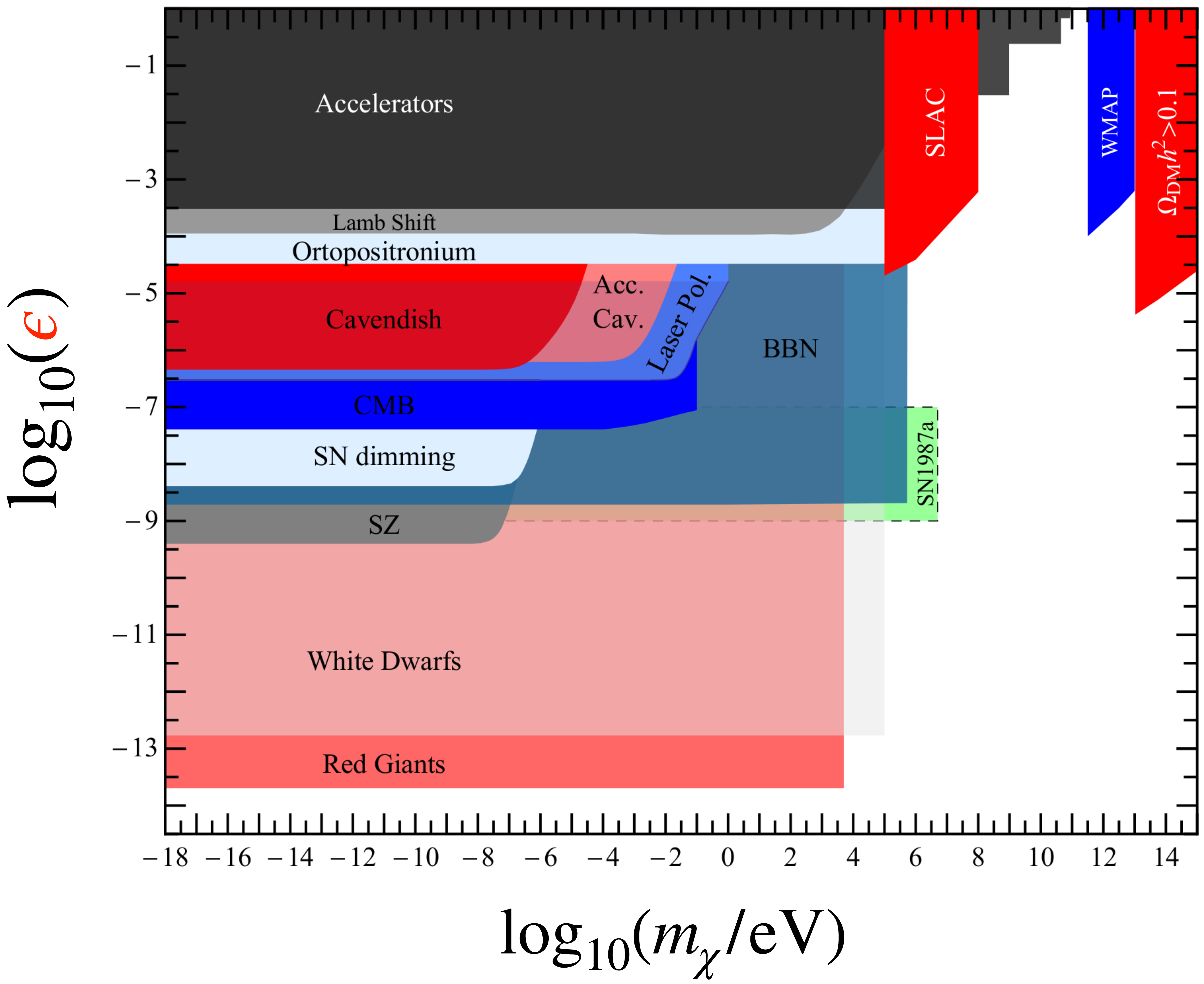
$$\mathscr{L} = -\frac{1}{2}(\partial_\mu \sigma + M_1 X_\mu + M_2 B_\mu)^2 + X_\mu J_X^\mu$$

Both kinetic mixing & Stueckelberg mass mixing

[Feldman, ZL, Nath, hep-ph/0702123, 366 cites]

Constraints on millicharged particles in BSM

[Jaeckel & Ringwald, 1002.0329]

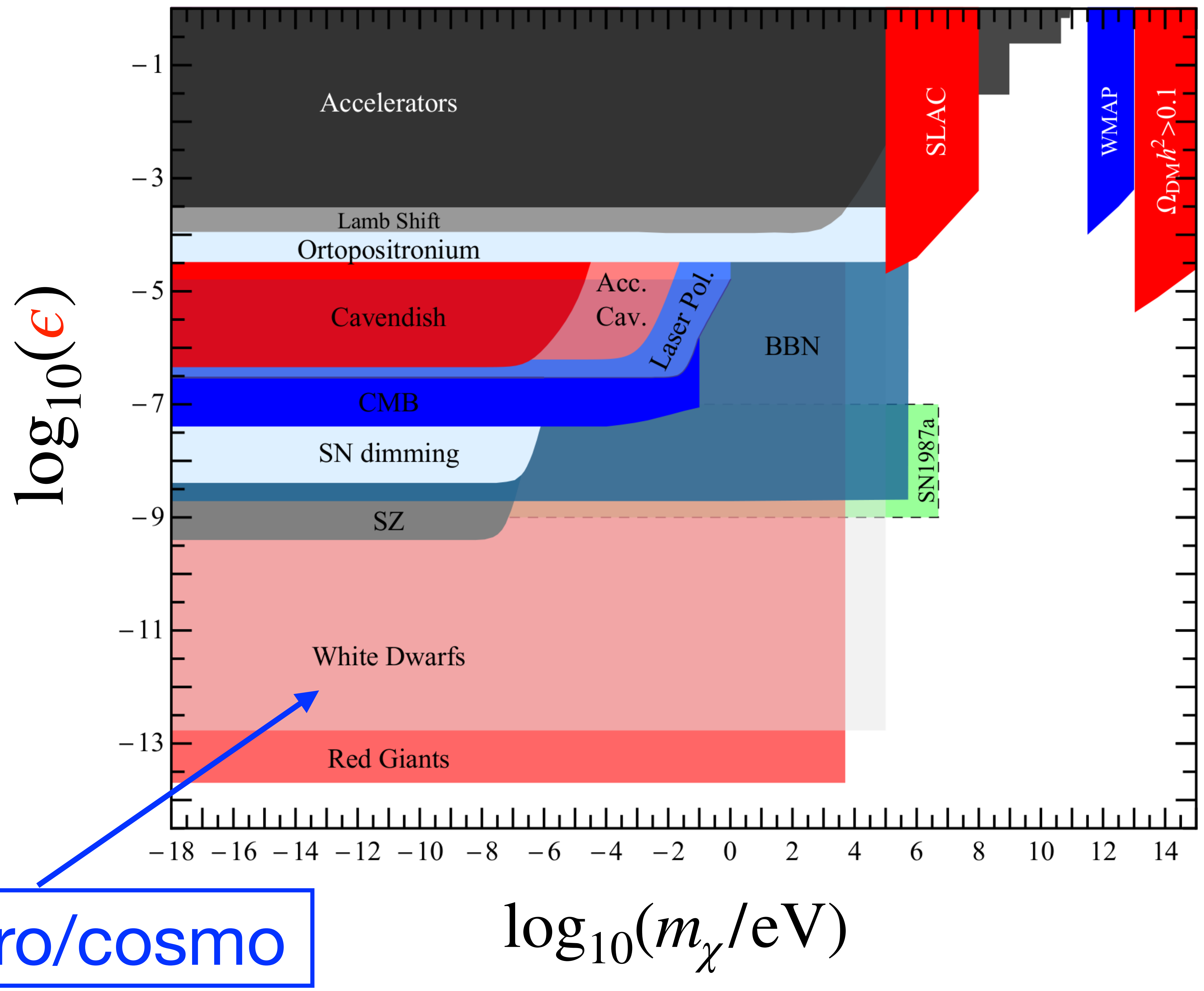


millicharged particle χ

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

Constraints on millicharged particles in BSM

[Jaeckel & Ringwald, 1002.0329]



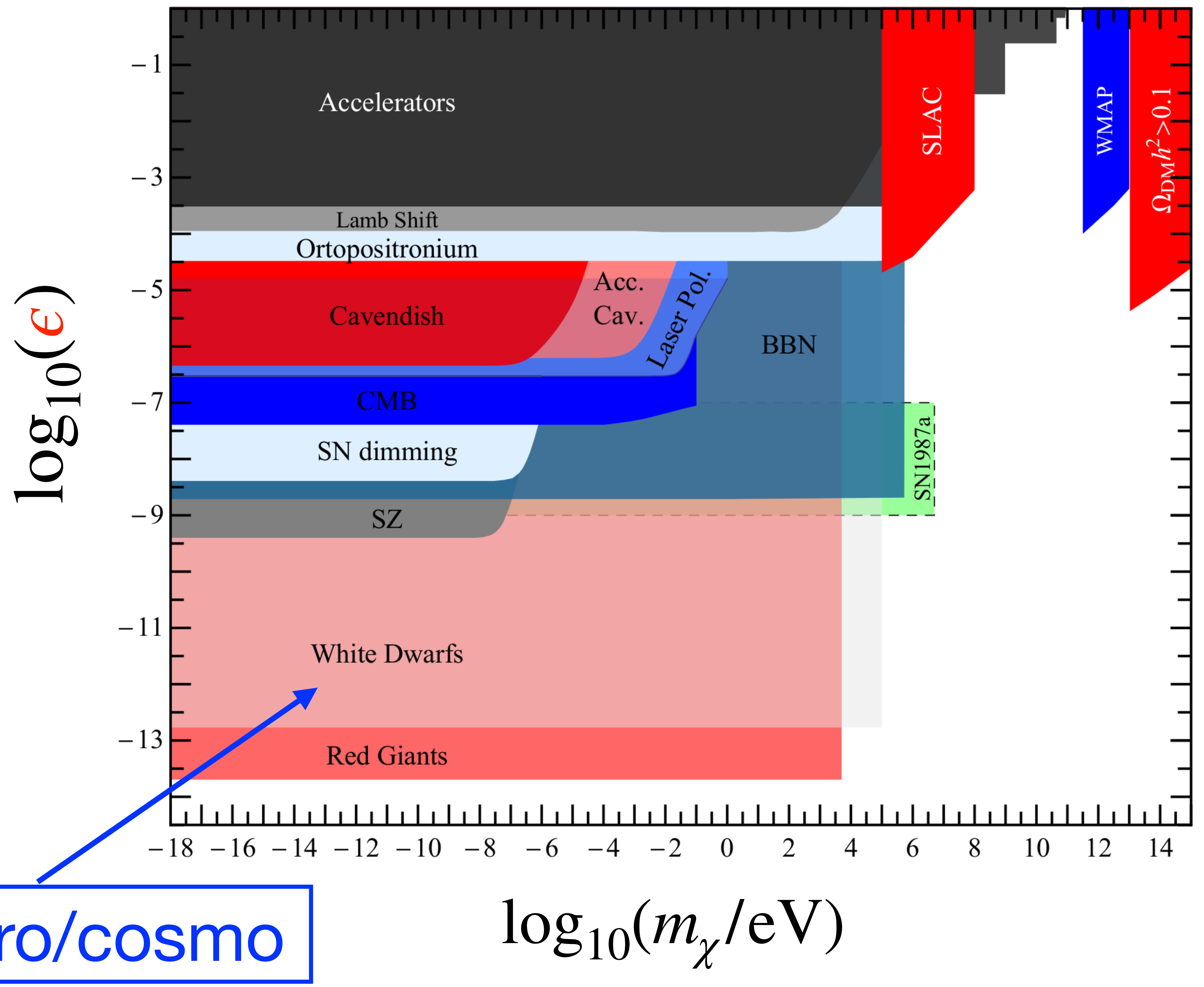
astro/cosmo

millicharged particle χ

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

Constraints on millicharged particles in BSM

[Jaeckel & Ringwald, 1002.0329]



terrestrial

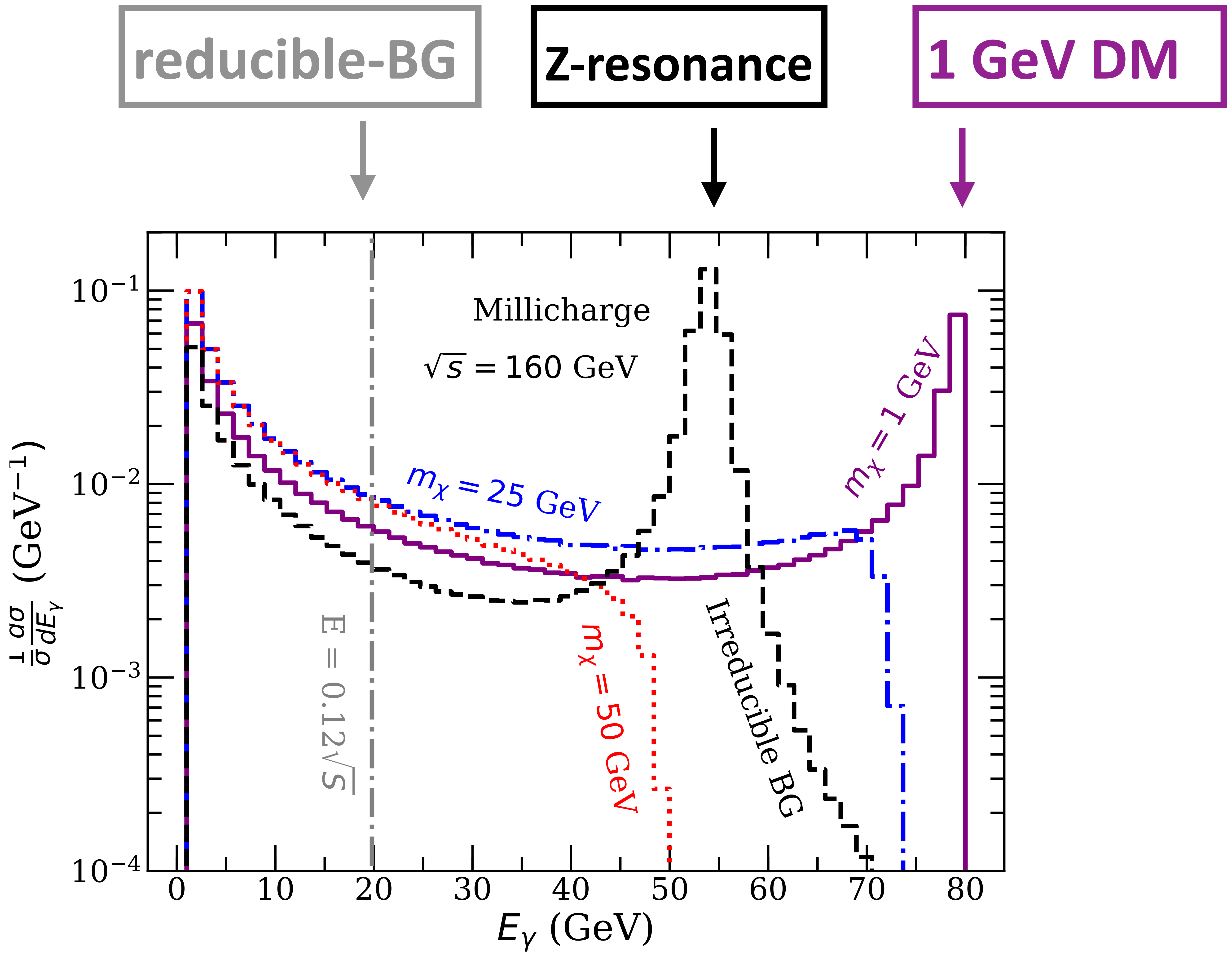
astro/cosmo

millicharged particle χ

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

Energy distributions for Millicharged DM

Energy distribution (WW-mode)



Millicharged DM w/ m = 1, 25, 50 GeV & ε = 0.01

detector cuts

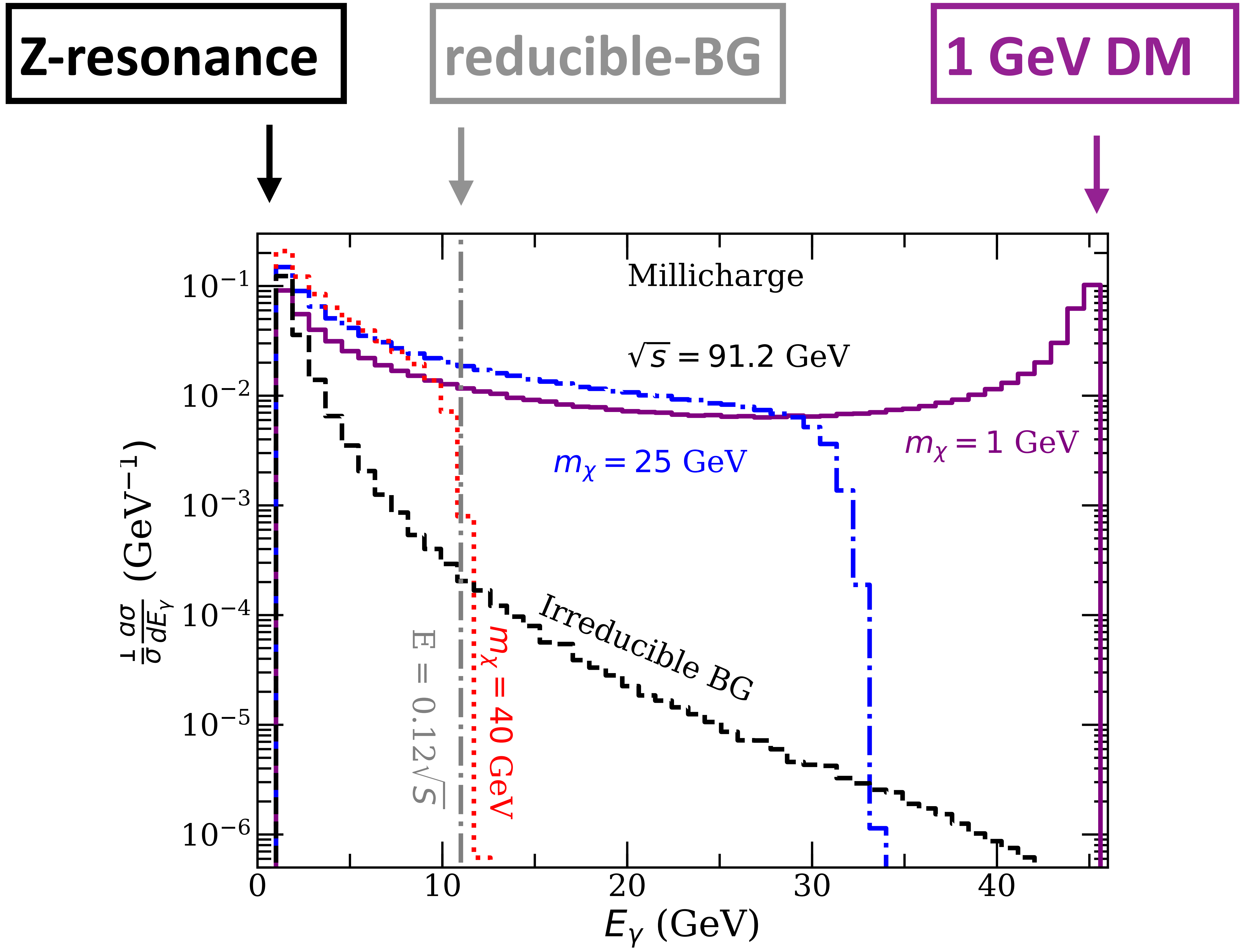
$$E_\gamma > 0.1 \text{ GeV} \;\&\; |z_\gamma| < 0.99$$

to enhance sensitivity

$$E_\gamma > E_\gamma^Z(s) + 5\Gamma_\gamma^Z(s)$$

for $m_\chi < 30$ GeV

Energy distribution (Z-mode)



Millicharged DM w/
m = 1, 25, 40 GeV &
ε = 0.01

detector cuts

$$E_\gamma > 0.1 \text{ GeV} \ \& \ |z_\gamma| < 0.99$$