Probing dark matter at e^+e^- colliders

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Zuowei Liu, **Yu Zhang**, 1808.00983, PRD
Zuowei Liu, Yong-Heng Xu, **Yu Zhang**, 1903.12114, JHEP
Jinhan Liang, Zuowei Liu, Yue Ma,**Yu Zhang**, 1909.06847
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第三届北京师范大学暗物质研讨会

珠海　　2019年12月8日

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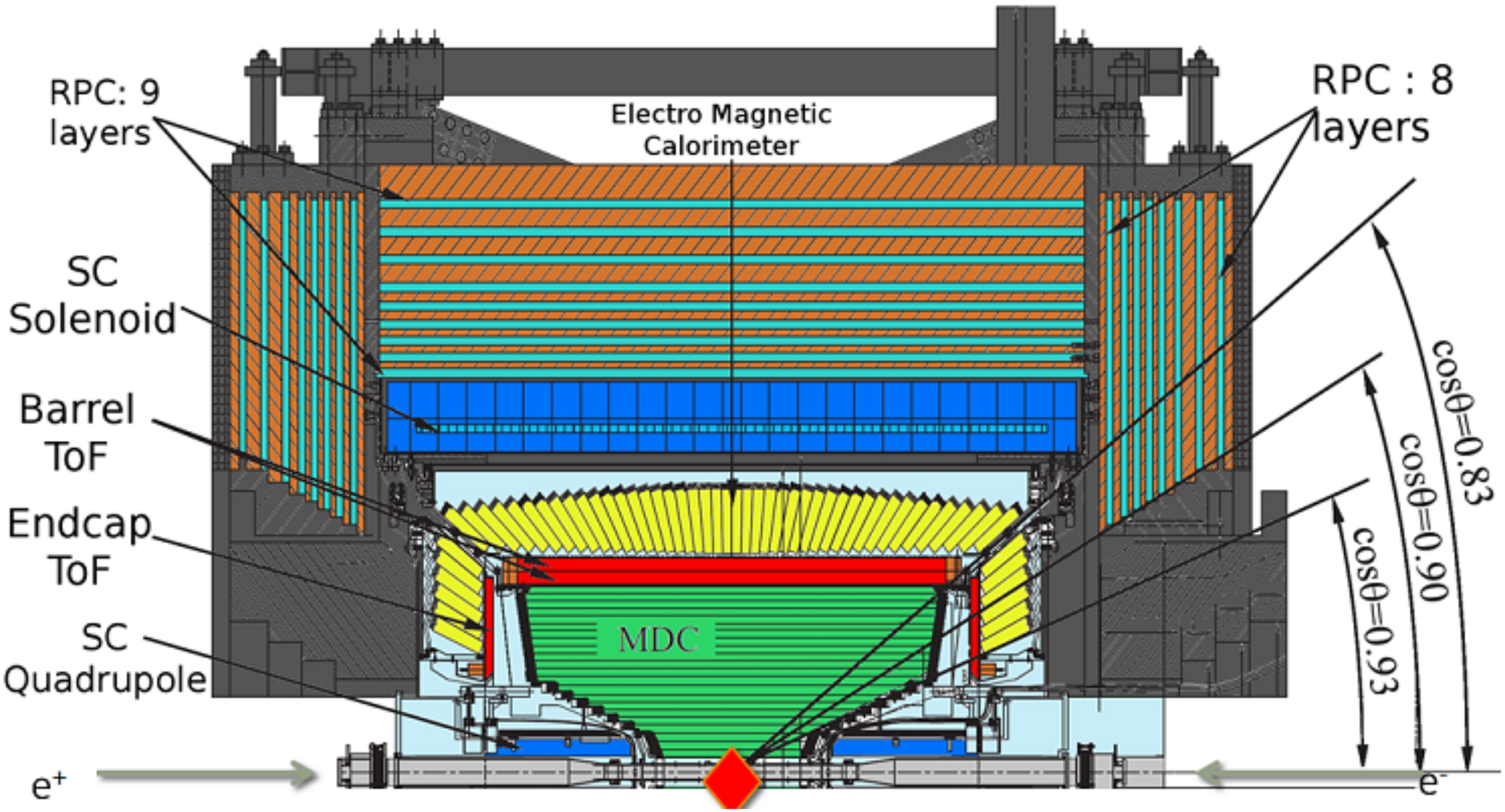
Outline

- e^+e^- colliders
- Millicharge DM models at BESIII/STCF/Belle2/ Babar/CEPC
- Z' DM models at CEPC
- DM effective operators at CEPC
- Dark photon invisible decay at BESIII/STCF
- Summary

e^+e^- colliders

BEPCII/BESIII

BESIII



主漂移室（MDC）：$|\cos\theta| < 0.93$

飞行时间计数器（TOF）：$|\cos\theta| < 0.83$　　$0.85 < |\cos\theta| < 0.95$

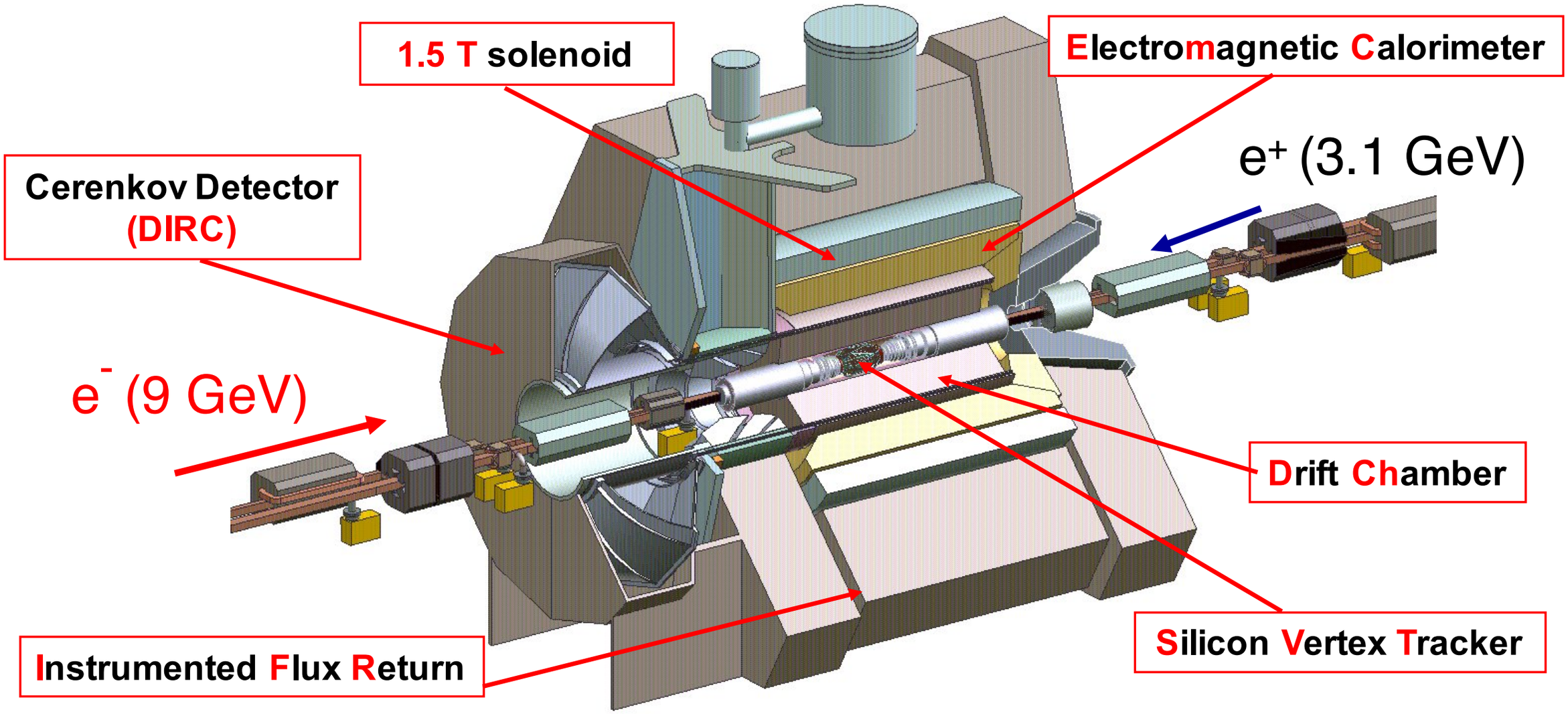
电磁量能器（EMC）：　$|\cos\theta| < 0.83$　　$0.85 < |\cos\theta| < 0.93$

Super Tau-Charm Facility (STCF)

- Peak luminosity 0.5-1×10^{35} $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2–7GeV
- Polarization available on electron beam (Phase II)
- Basic Features of machine :
  - Symmetric machine with dual-ring
  - Large Piwinski angle collision + crabbed waist solution for the IR
  - Siberia snake for polarization
  - Total cost 4B RMB

From H. Peng @CHARM18

PEP-II/BaBar



The BaBar detector was built at SLAC to study the millions of B mesons produced by the PEP-II storage ring.

PEP-II/BaBar

PEP-II Records

Last update:
April 8, 2008

Peak Luminosity

12.069×10^{33} $cm^{-2}sec^{-1}$ **August 16, 2006**

1722 bunches 2900 mA LER 1875 mA HER

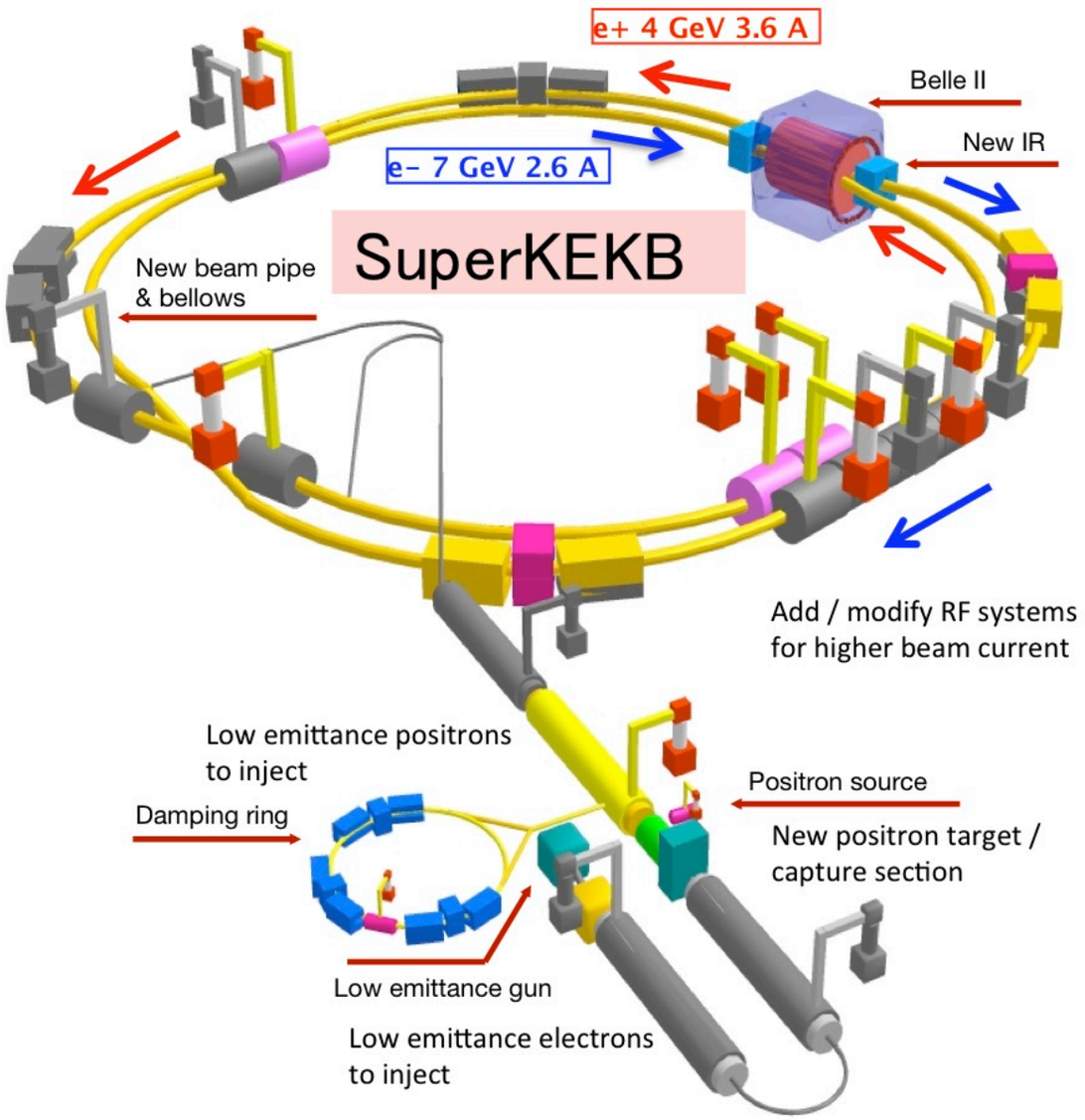
Integration records of delivered luminosity

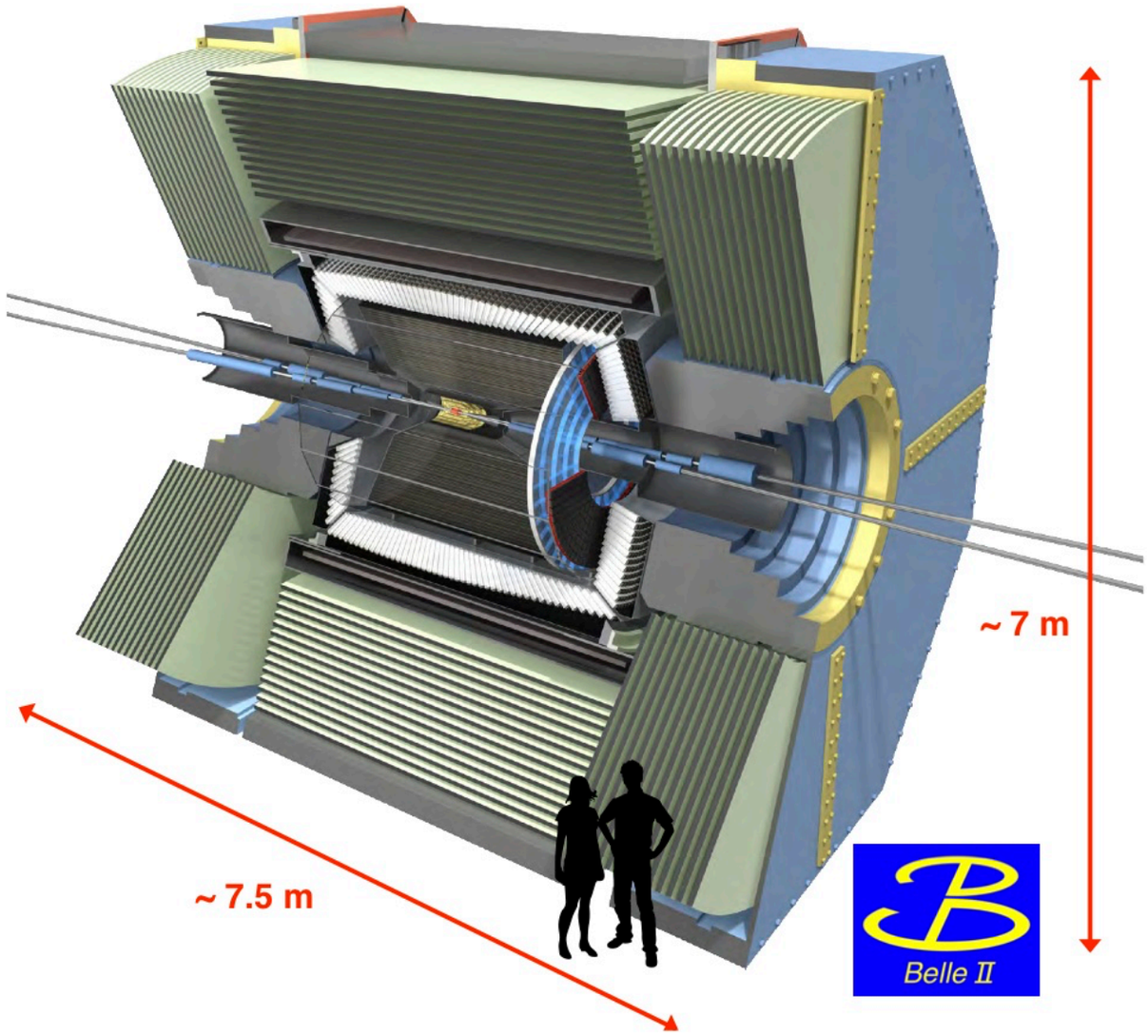
Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 pb^{-1}	Aug 16, 2006
Best 3 shifts in a row	910.7 pb^{-1}	Jul 2-3, 2006
Best day	858.4 pb^{-1}	Aug 19, 2007
Best 7 days (0:00 to 24:00)	5.411 fb^{-1}	Aug 14-Aug 20, 2007
Best week (Sun 0:00 to Sat 24:00)	5.137 fb^{-1}	Aug 12-Aug 18, 2007
Peak HER current	2069 mA	Feb 29, 2008
Peak LER current	3213 mA	Apr 7, 2008
Best 30 days	19.776 fb^{-1}	Aug 5 – Sep 3, 2007
Best month	19.732 fb^{-1}	August 2007

Total delivered 557 fb^{-1}

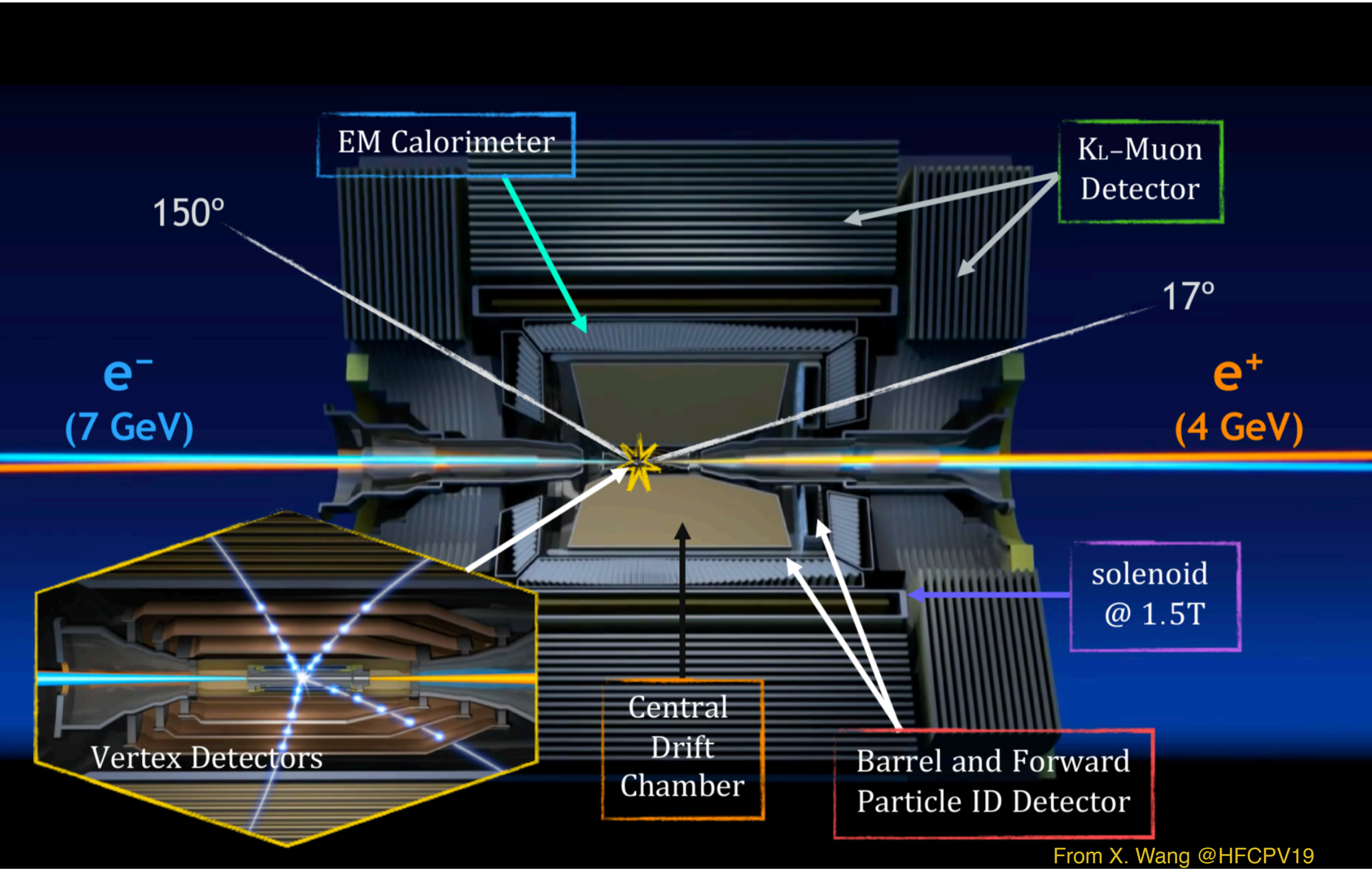
PEP-II turned off April 7, 2008

SuperKEKB/Belle-II



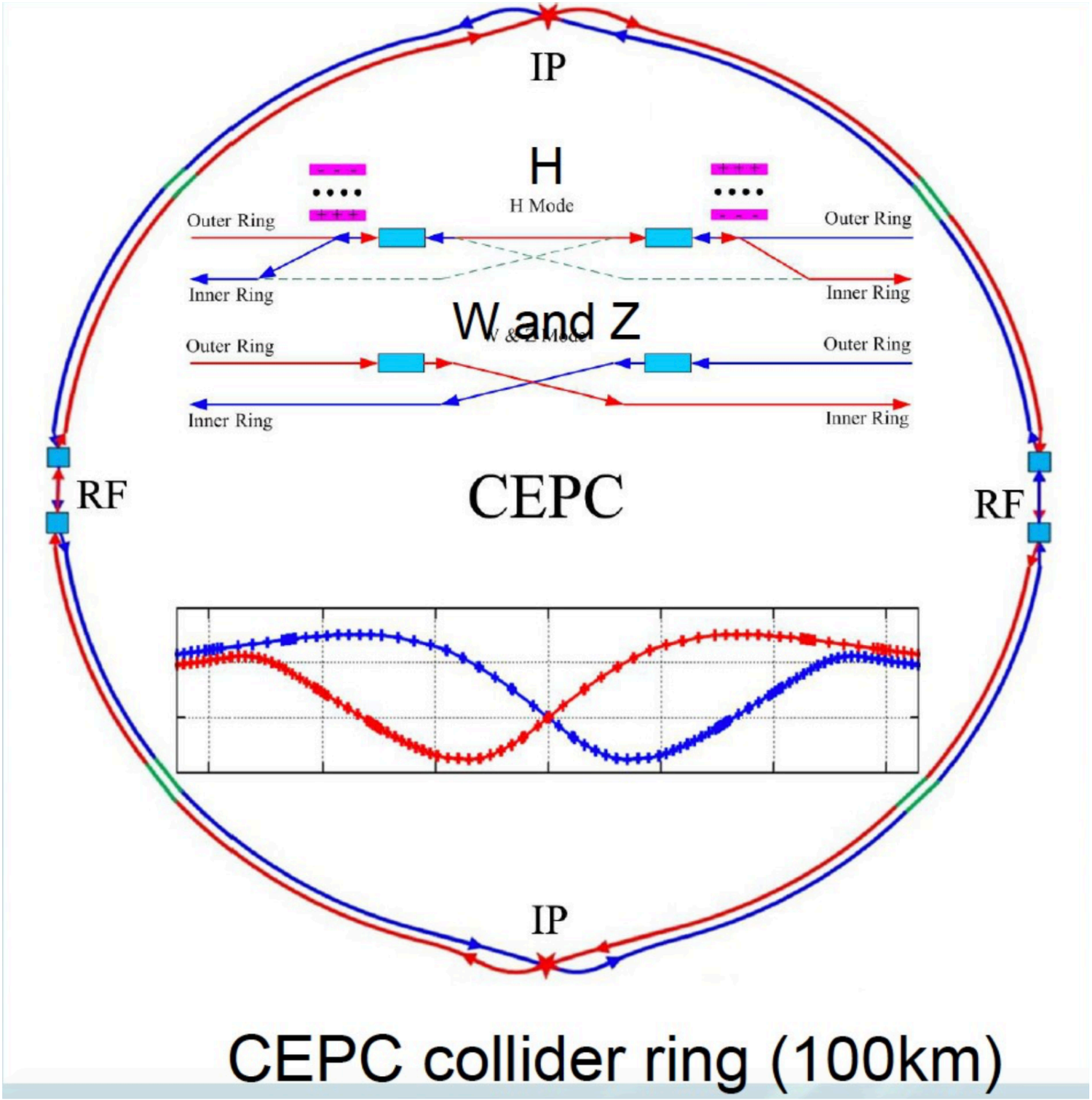


SuperKEKB/Belle-II



From X. Wang @HFCPV19

CEPC



H Mode: $e^+e^- \to ZH$

$\sqrt{s} = 240$ GeV

$L = 5.6\ ab^{-1}$

Z Mode: $e^+e^- \to Z$

$\sqrt{s} = 91.2$ GeV

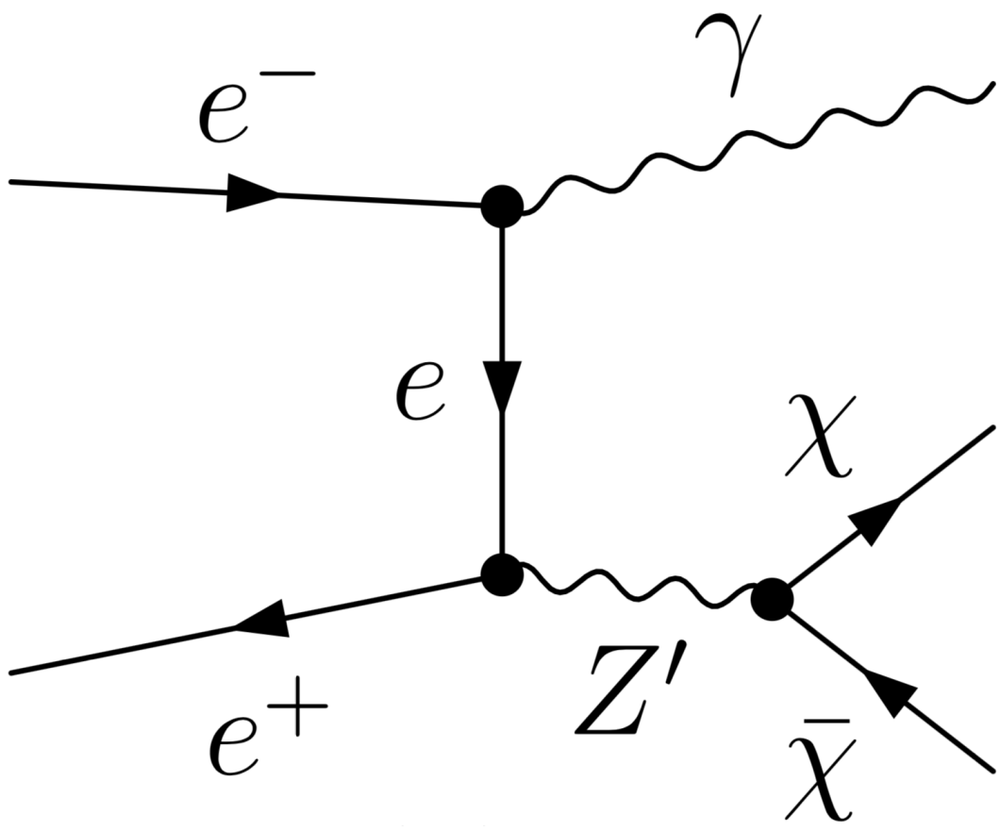
$L = 16\ ab^{-1}$

W Mode: $e^+e^- \to W^+W^-$

$\sqrt{s} = 158 \sim 172$ GeV

$L = 2.6\ ab^{-1}$

DM @ e^+e^- colliders



Monophoton

Undetected

Millicharge DM models

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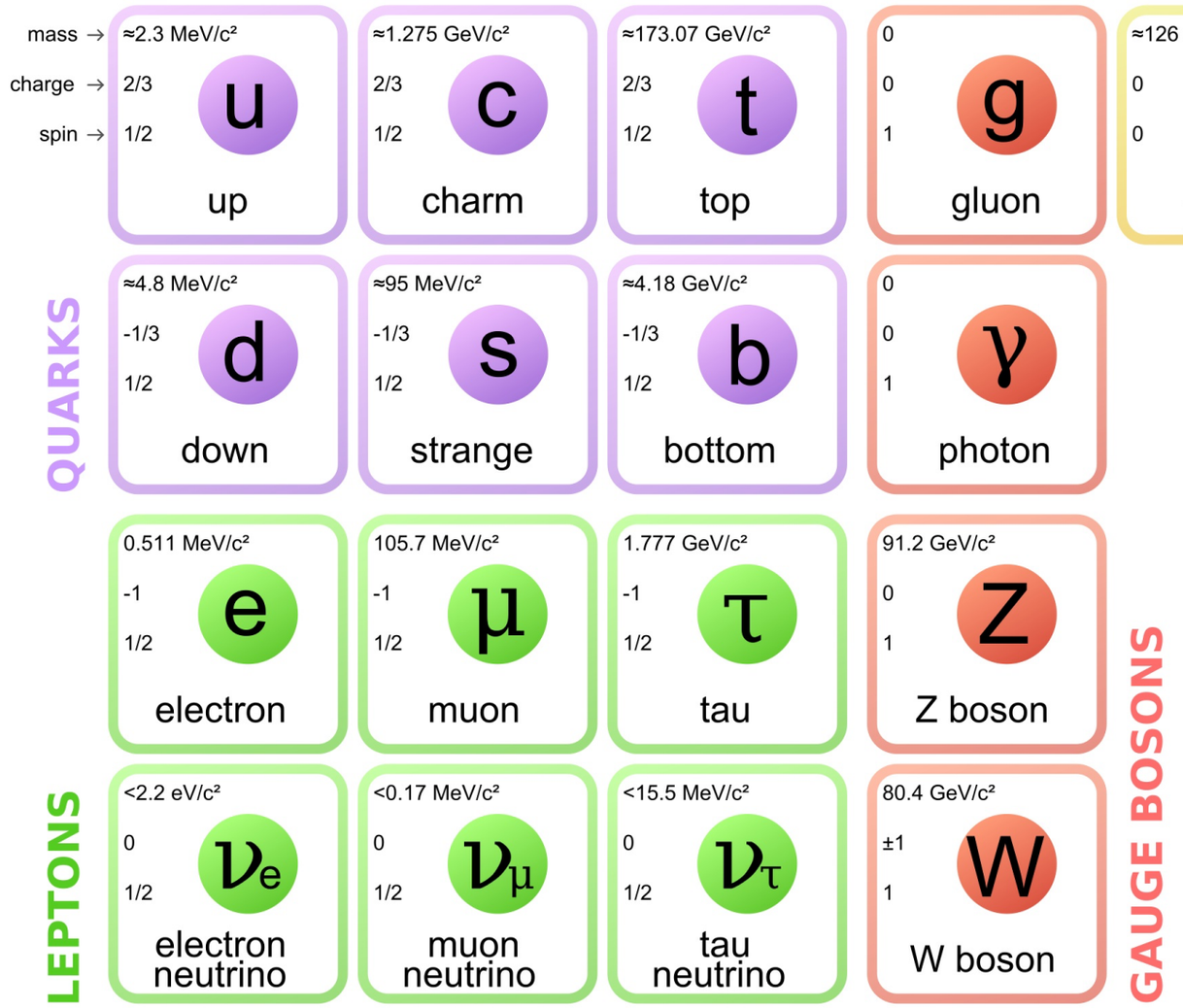
Charge quantization



$$Q_e = -1$$

$$Q_u = 2/3$$

$$Q_d = -1/3$$

$$Q_W = \pm 1$$

Millicharge

- In general, electric charge can be of any value
- $\mathscr{L}_{int} = \varepsilon e A_\mu \bar{\chi} \gamma^\mu \chi$
- $\varepsilon \ll 1, \quad \chi$ is millicharged
- Stringent constraints on millicharge of SM particles

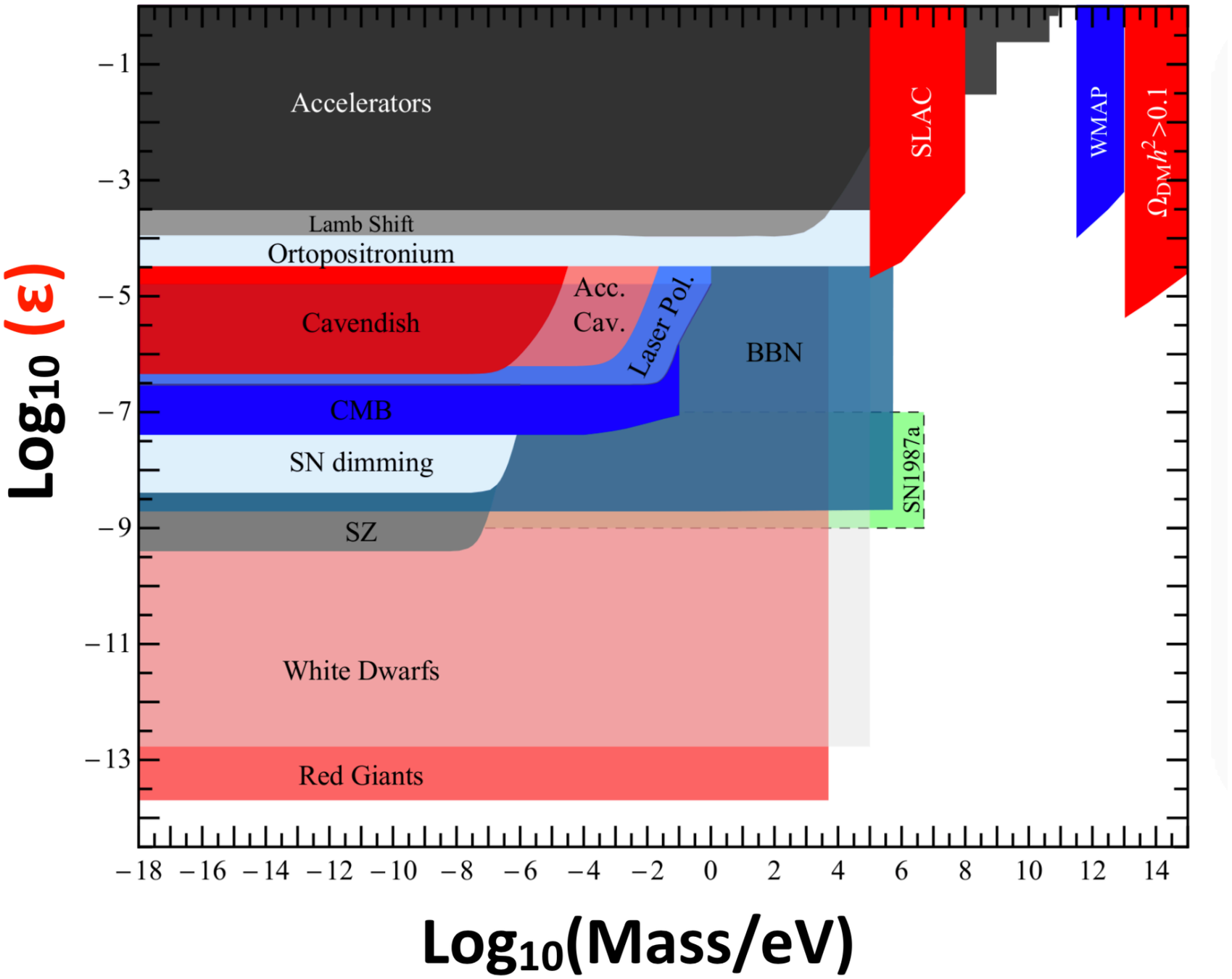
$$Q_p - Q_e < (0.8 \pm 0.8) \times 10^{-21} e \quad \textbf{Marinelli et al. 1984}$$

$$Q_n < (-0.1 \pm 1.1) \times 10^{-21} e \quad \textbf{Bressi et al. 2011}$$

$$Q_n < (-0.4 \pm 1.1) \times 10^{-21} e \quad \textbf{Baumann et al. 1988}$$

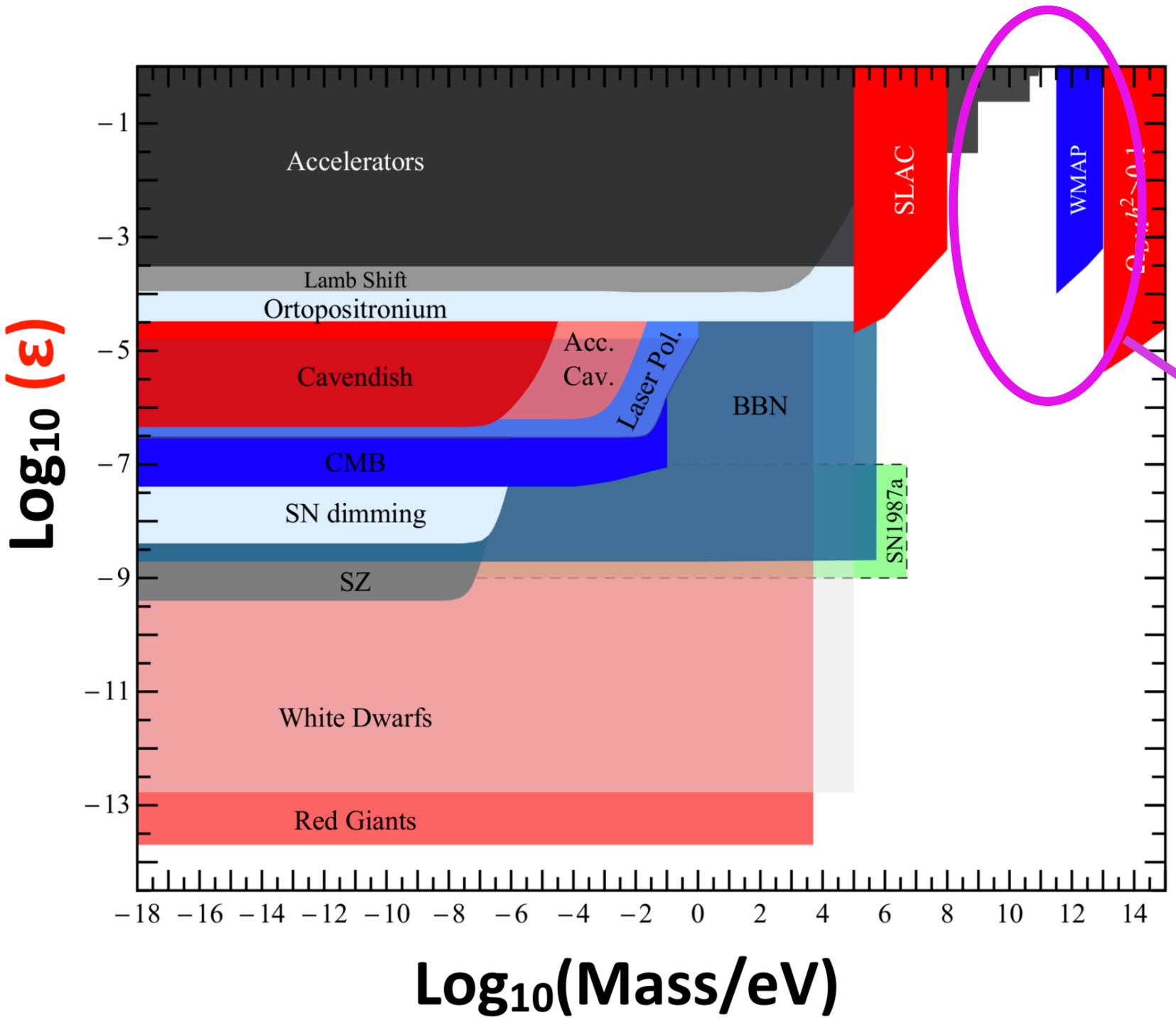
$$Q_\nu < 10^{-17} e \quad \textbf{Barbiellini et al. 1987}$$

Constraints on millicharge



Jaeckel, Ringwald, 1002.0329

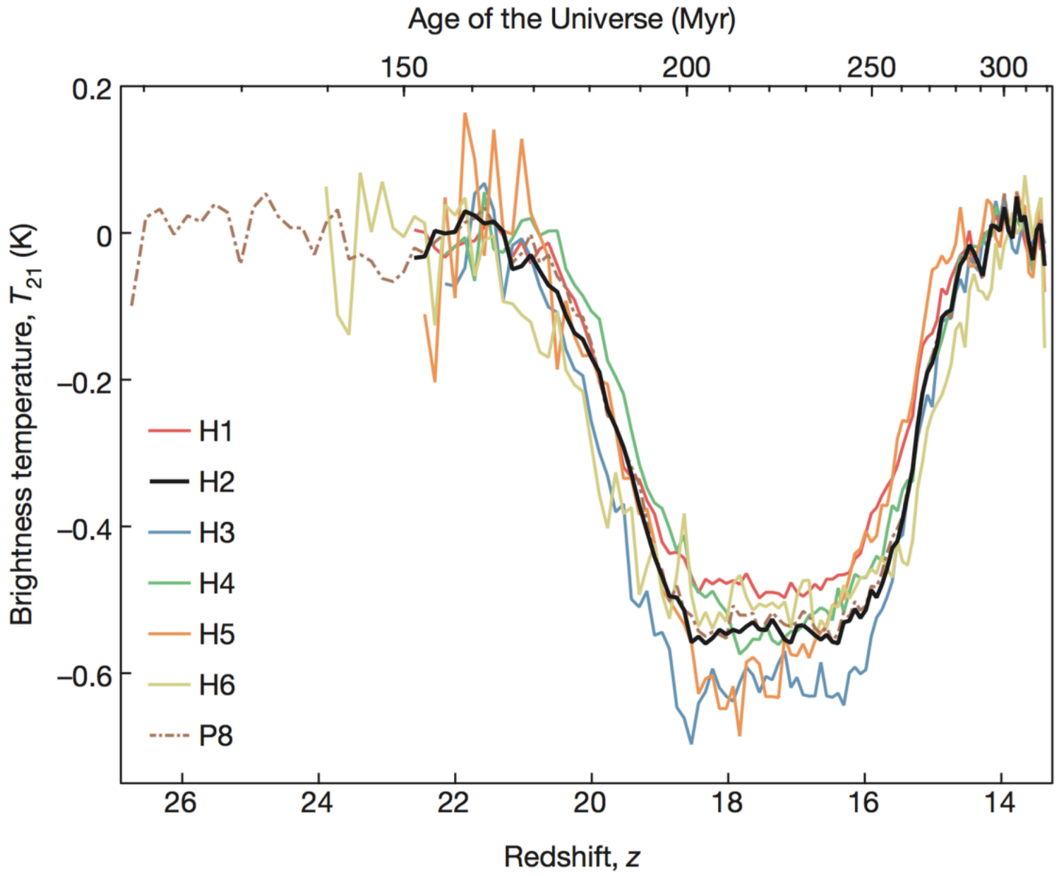
Constraints on millicharge

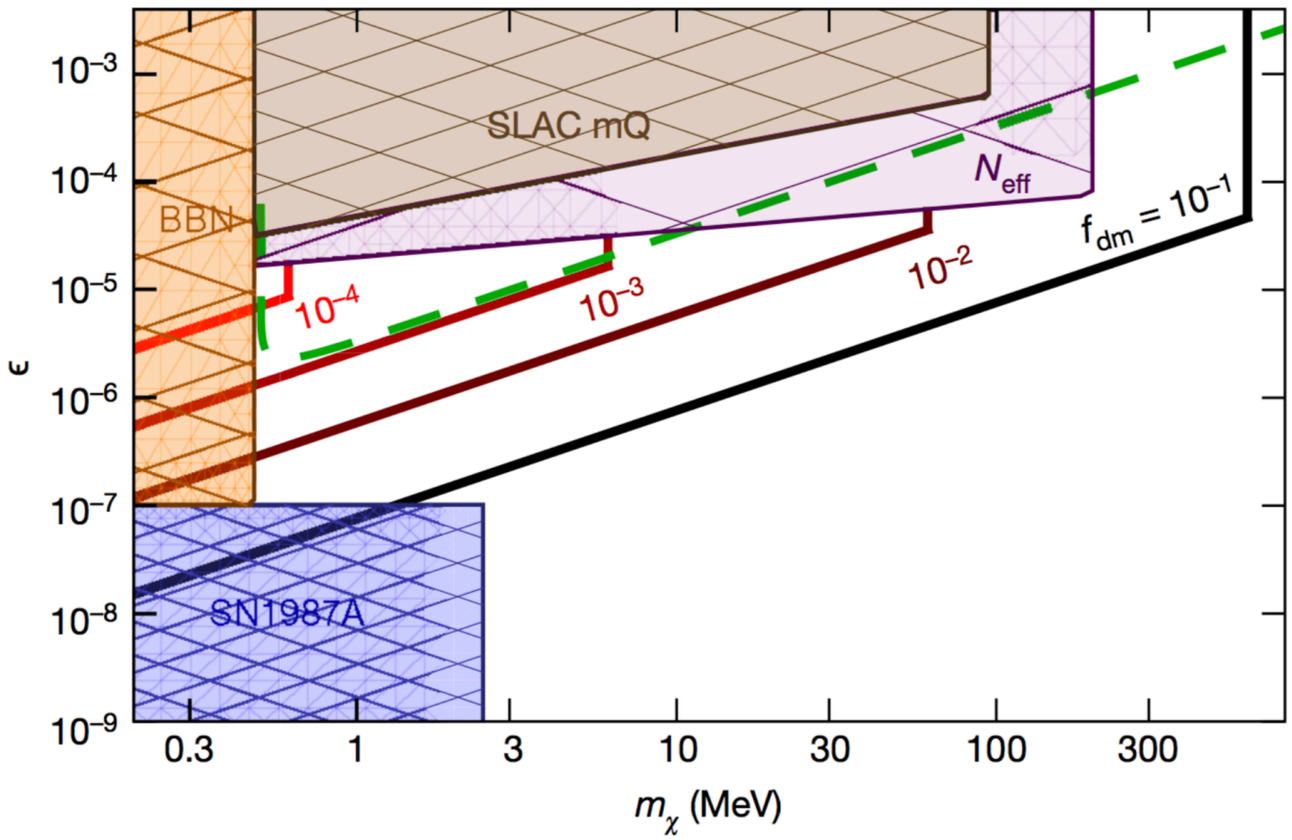


该区域限制很弱

Jaeckel, Ringwald, 1002.0329

Millicharge & 21 cm anomaly



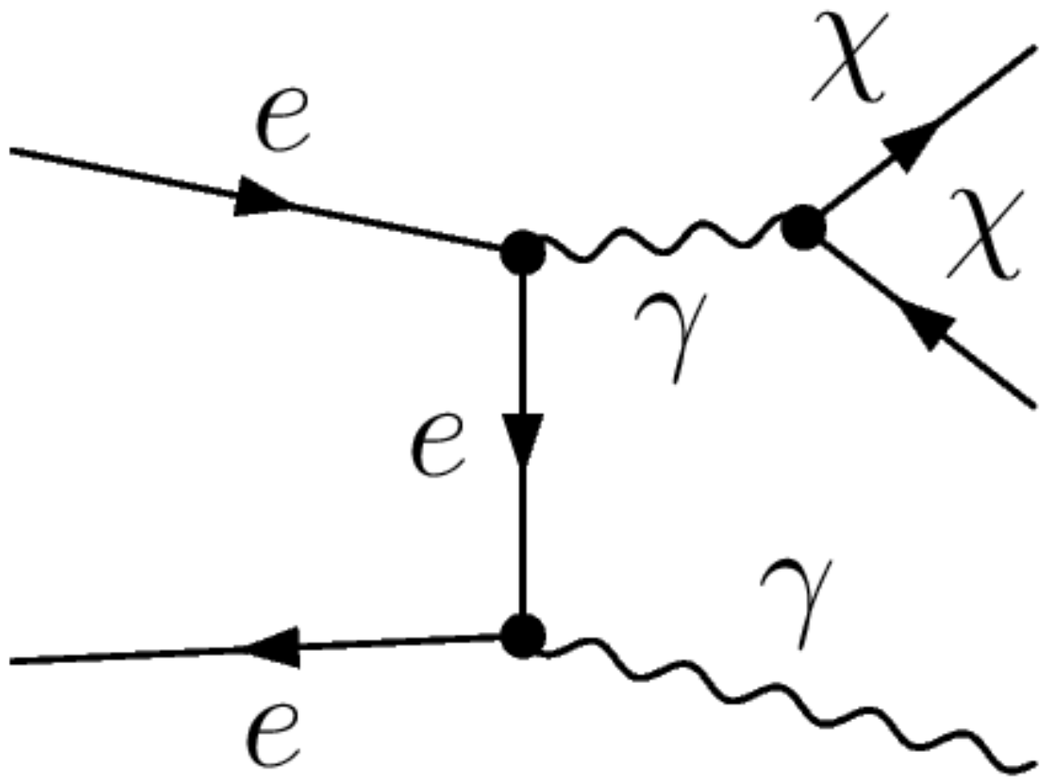


Bowman et al., Nature25792 (2018); Barkana, Nature25791 (2018); Munoz, Loeb, Nature 557 (2018) no.7707, 684; + others

Millicharge @ e^+e^- colliders

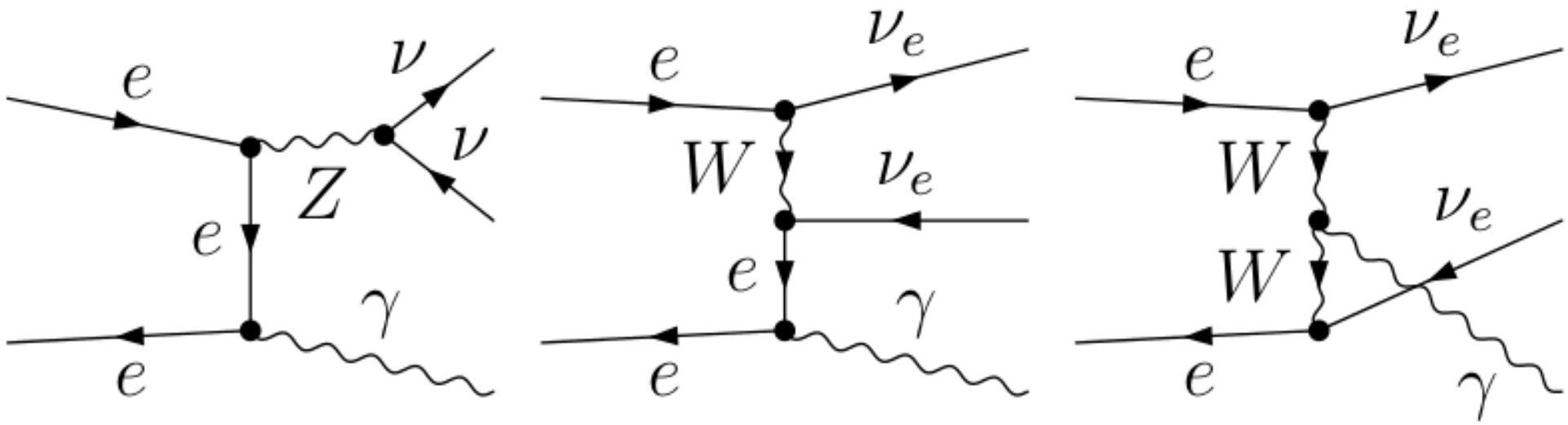
$$e^+e^- \to \chi\bar{\chi}\gamma$$

$$\mathscr{L}_{int} = \varepsilon e A_\mu \bar{\chi}\gamma^\mu \chi$$



Irreducible backgrounds

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



Basic detector cuts

BESIII & STCF: **BESIII, 1707.05178**

- EMC桶部(barrel)：

  $E_\gamma > 25\,\text{MeV}\ \&\ |\cos\theta_\gamma| < 0.8$

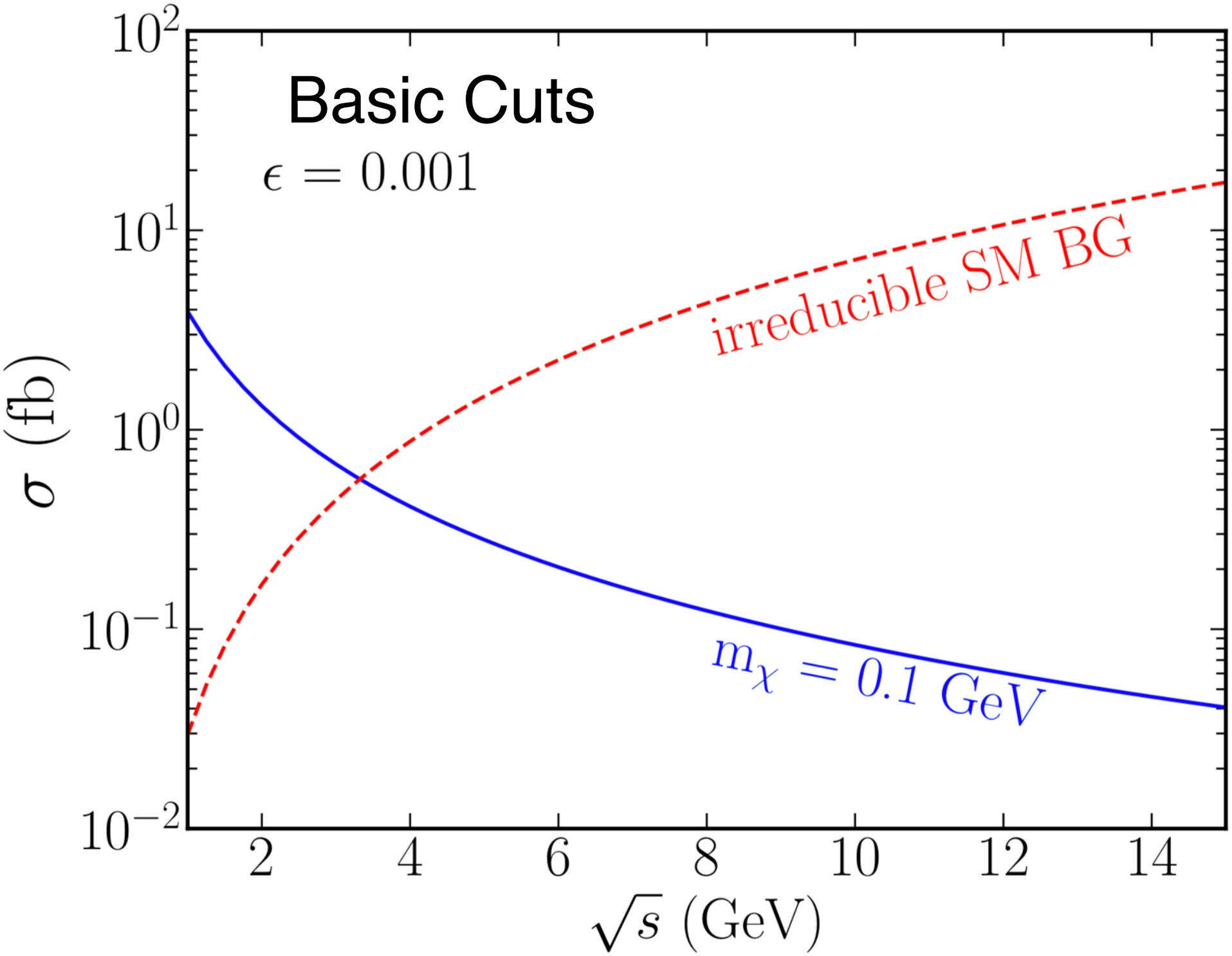
- EMC端盖(end-caps)：

  $E_\gamma > 50\,\text{MeV}\ \&\ 0.86 < |\cos\theta_\gamma| < 0.92$

CEPC: **CEPC, 1811.10545**

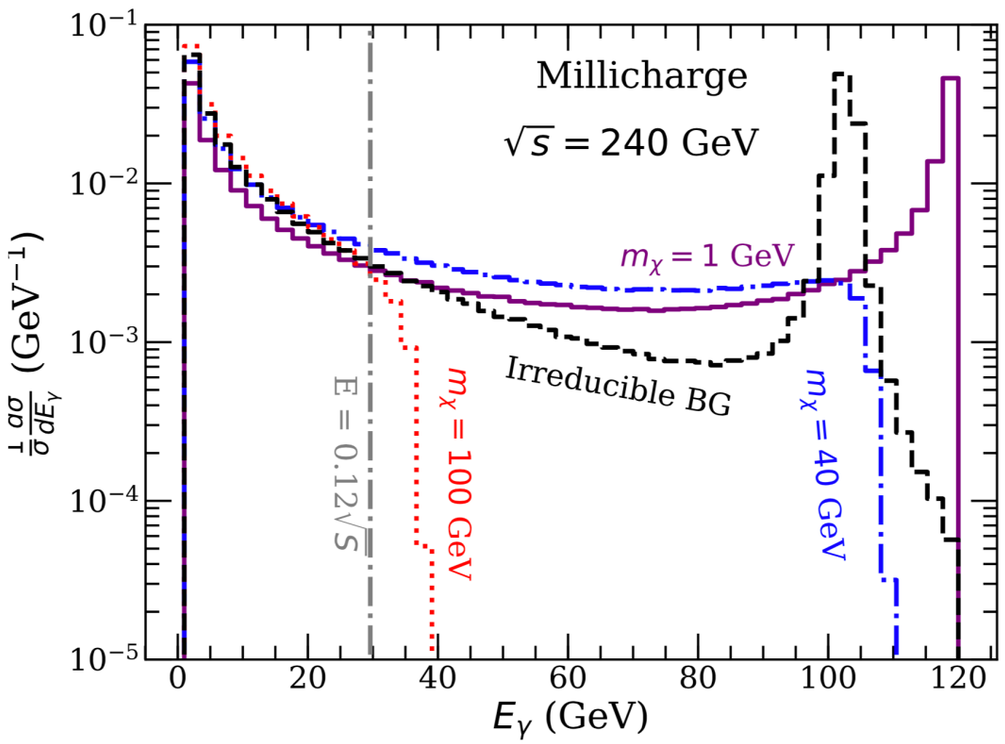
- $E_\gamma > 0.1\,\text{GeV}\ \&\ |\cos\theta_\gamma| < 0.99$

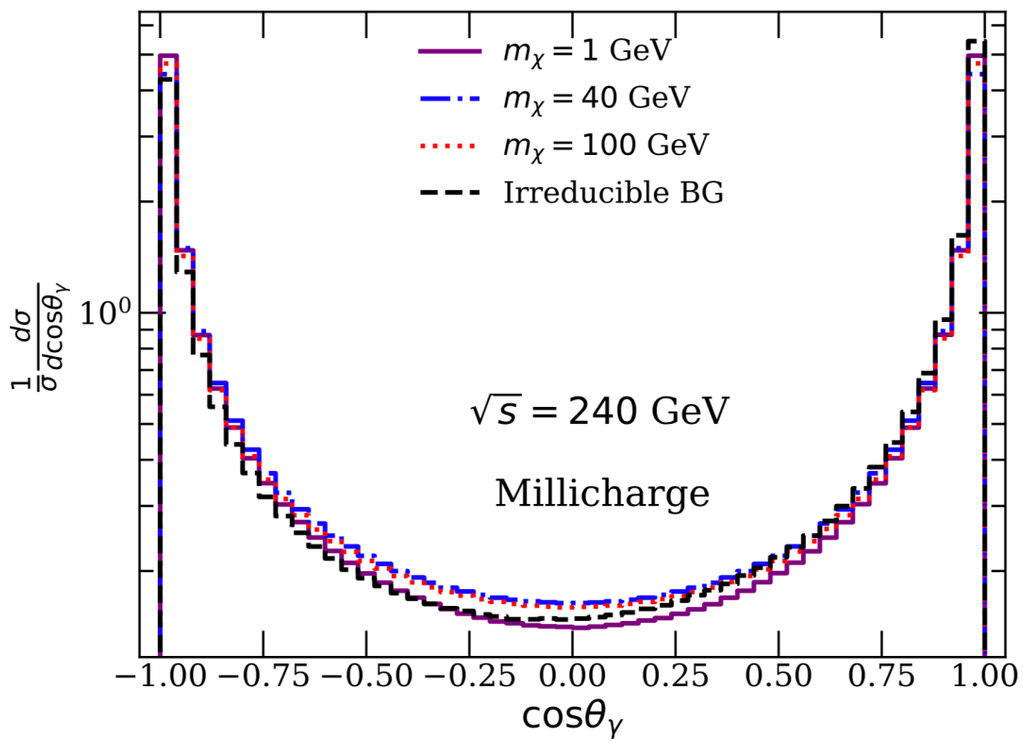
Xsec versus colliding energy

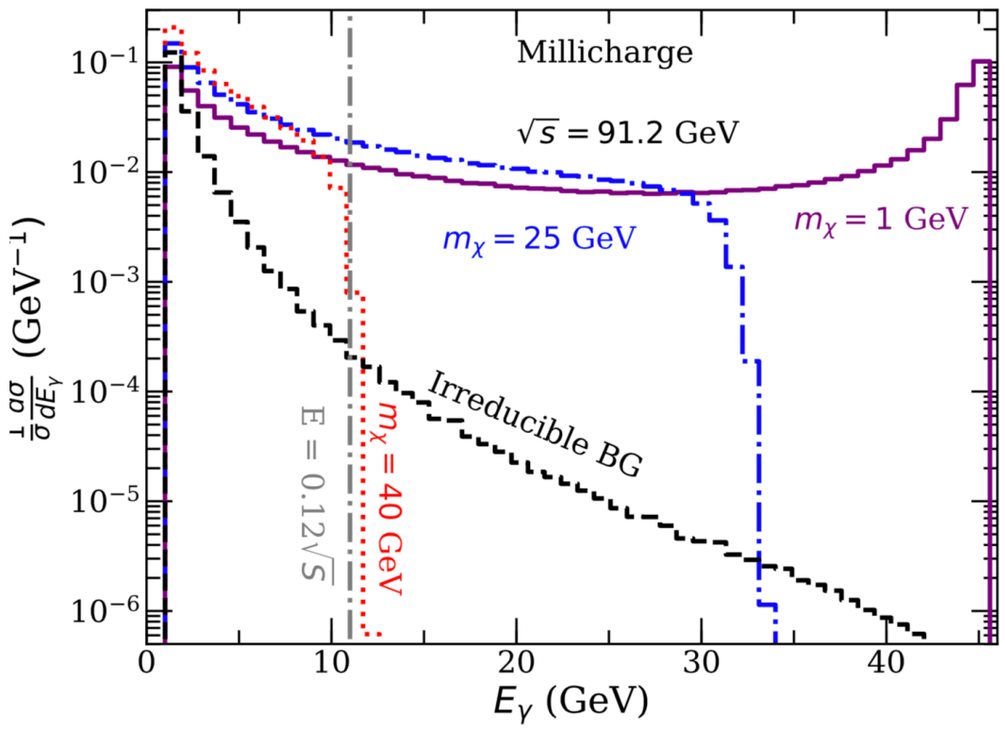


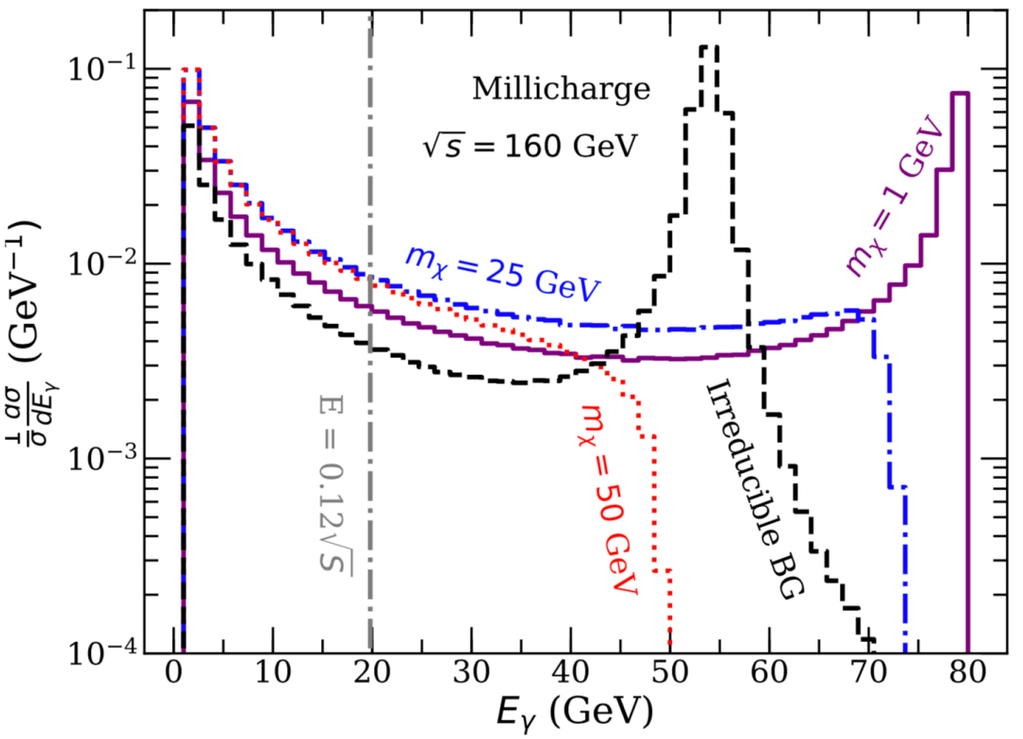
Smaller colliding energy has better sensitivity !

Distributions at CEPC



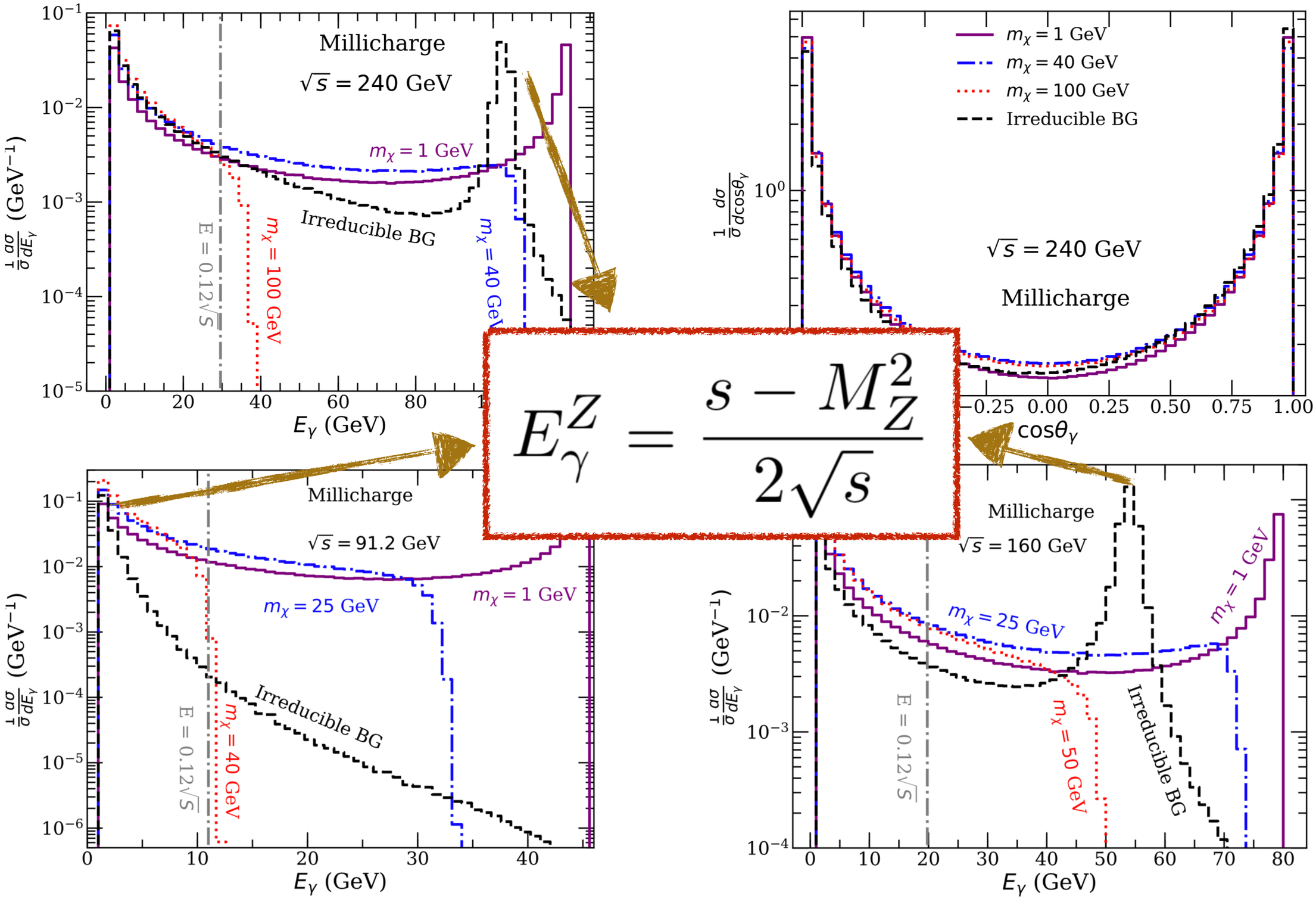






After Basic Cuts

Distributions at CEPC



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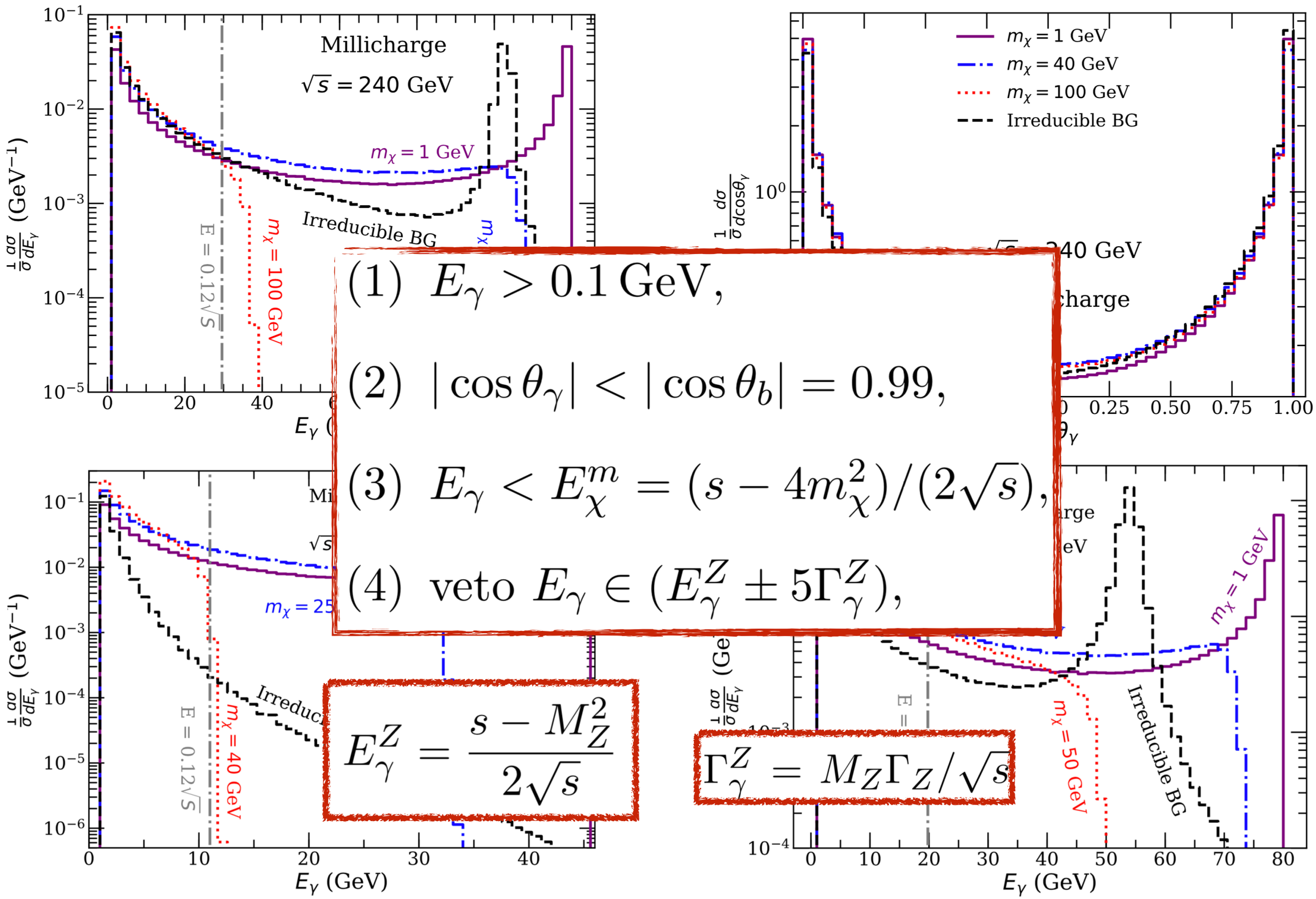


(1) $E_\gamma > 0.1\,\mathrm{GeV}$,

(2) $|\cos\theta_\gamma| < |\cos\theta_b| = 0.99$,

(3) $E_\gamma < E_\chi^m = (s - 4m_\chi^2)/(2\sqrt{s})$,

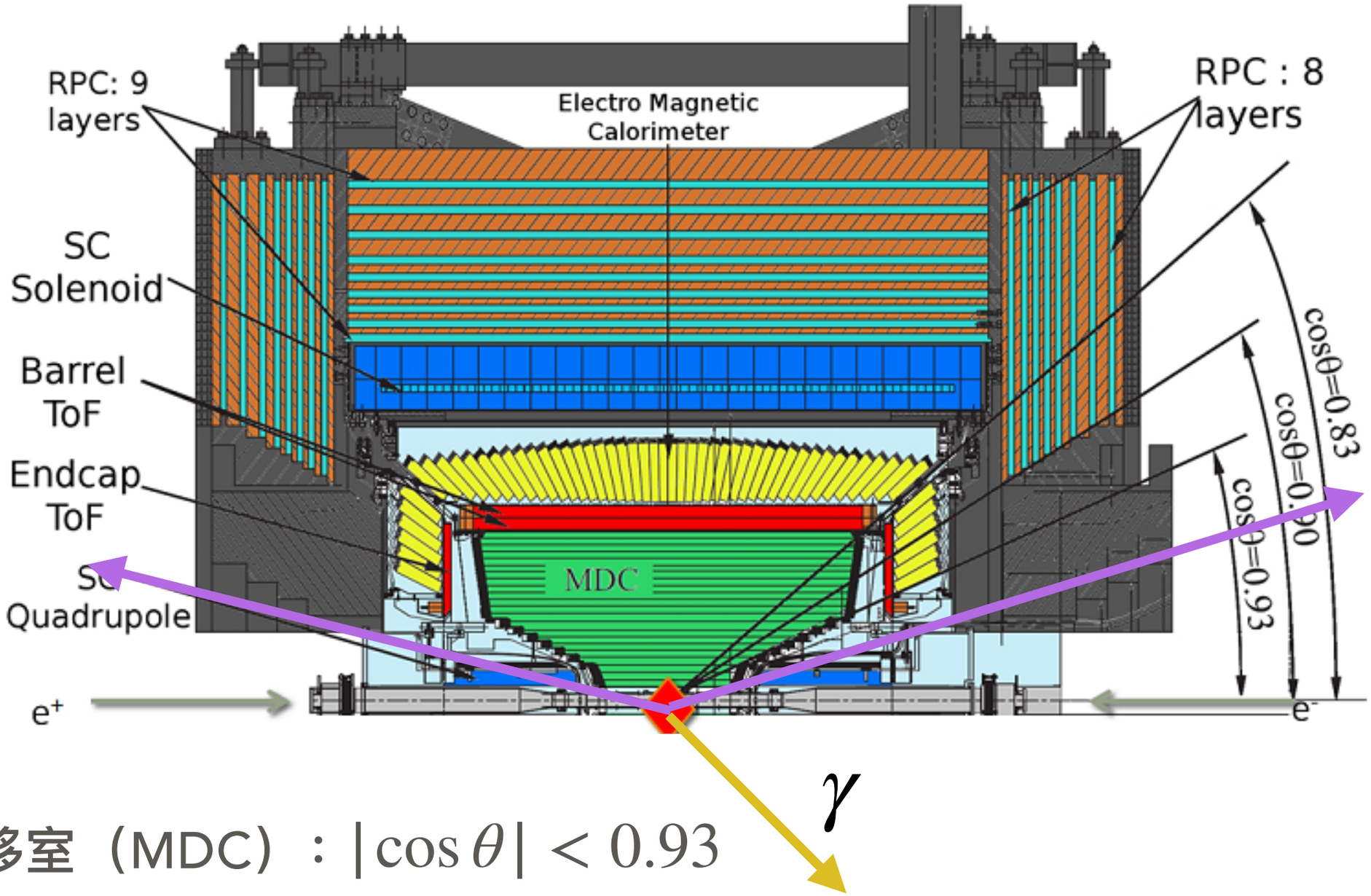
(4) veto $E_\gamma \in (E_\gamma^Z \pm 5\Gamma_\gamma^Z)$,

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

$$\Gamma_\gamma^Z = M_Z\Gamma_Z/\sqrt{s}$$

After Basic Cuts

Reducible backgrounds



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单光子产生的标准模型可约背景

1. 共振态衰变（比如 $J/\psi \to \gamma X$）

   ①$J/\psi \to \gamma \nu \nu$　可忽略的不可约背景，

   $Br=0.7\times 10^{-10}$ Gao 1408.4552

   ②$J/\psi \to \gamma X$　末态X探测不到

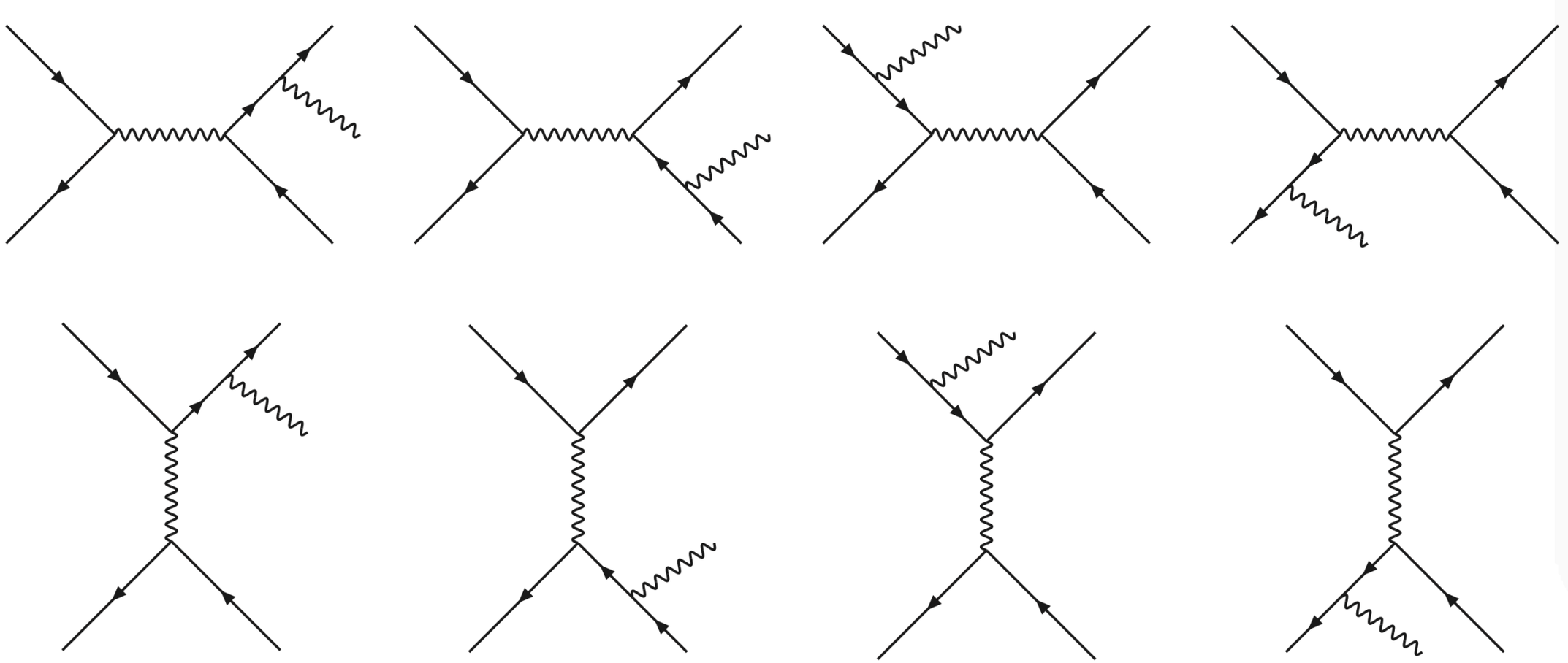
2. 过程$e^+ e^- \to e^+ e^- \gamma$ 末态电子探测不到

3. 过程$e^+ e^- \to f f \gamma$ 末态ff探测不到

4. 过程$e^+ e^- \to \gamma \gamma \gamma$ 末态只能探测到一个光子

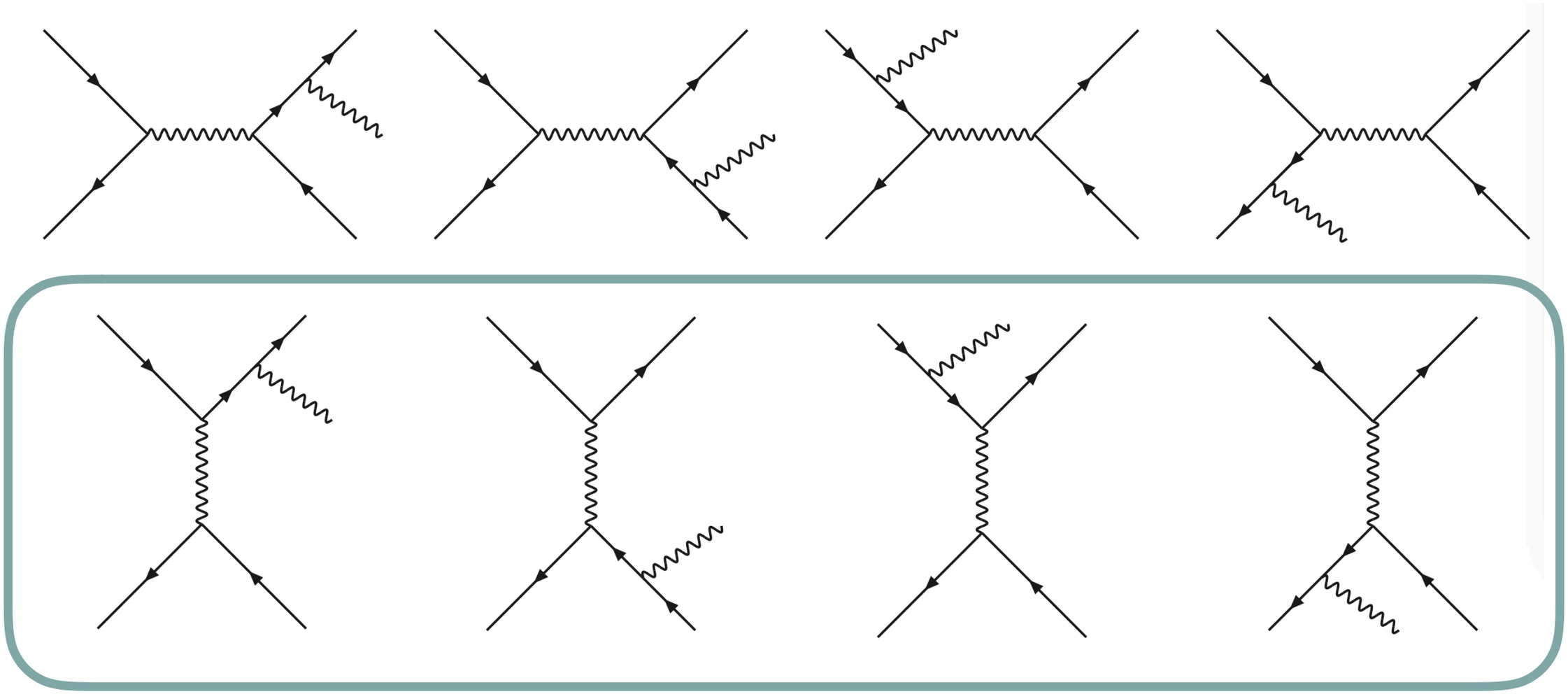
标准模型$e^+ e^- \to e^+ e^- \gamma$过程

AcMs, Mastrolia, Ossla, 0909.1750



标准模型$e^+ e^- \to e^+ e^- \gamma$过程

AcMs, Mastrolia, Ossla, 0909.1750

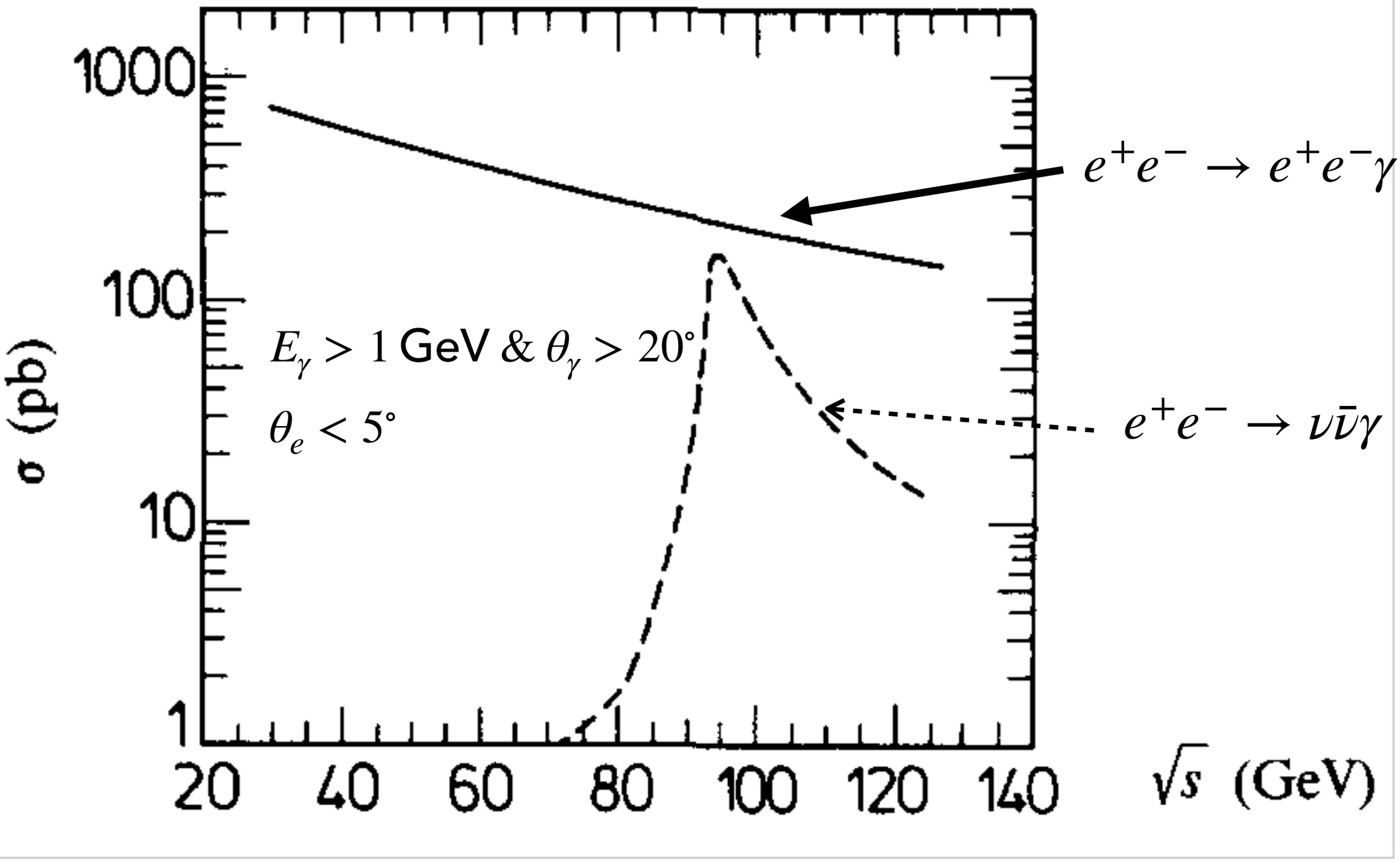


collinear singularity in the t-channel

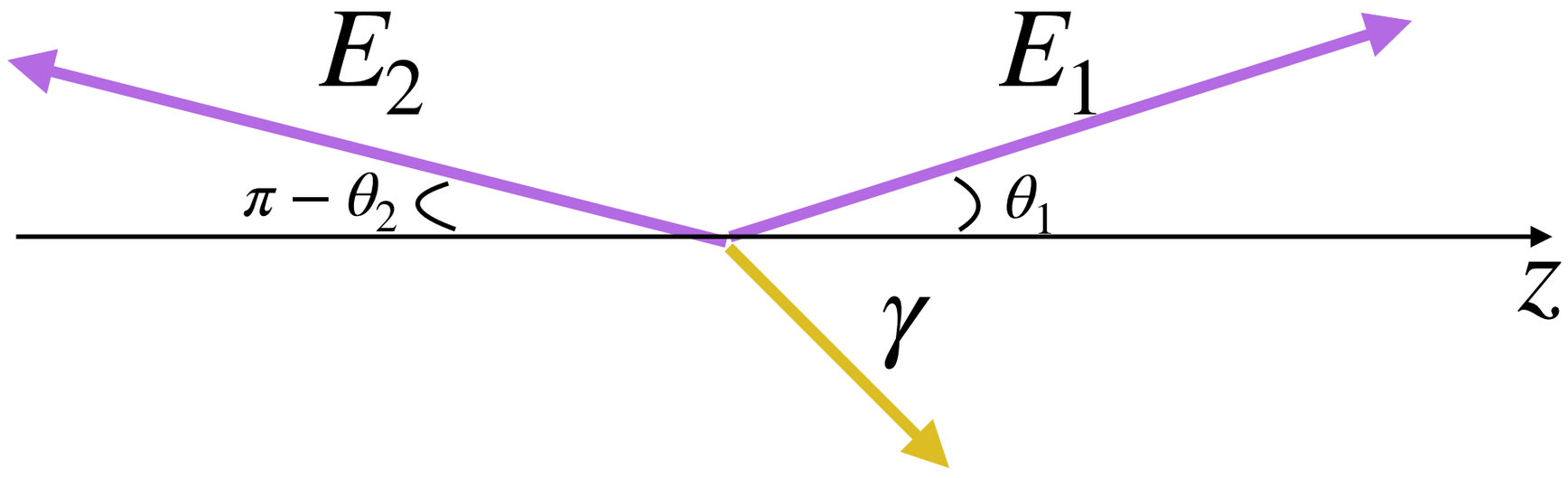
$$\overline{|\mathcal{M}|^2} \propto \frac{1}{t_{13}t_{24}} \sim \frac{1}{\theta_{13}^2 t_{24}} \text{ for } \theta_{13} \ll 1 \ \& \ m_e \to 0$$

标准模型中单光子产生截面

Mana, MarMnez, NPB 1987



Advanced cuts



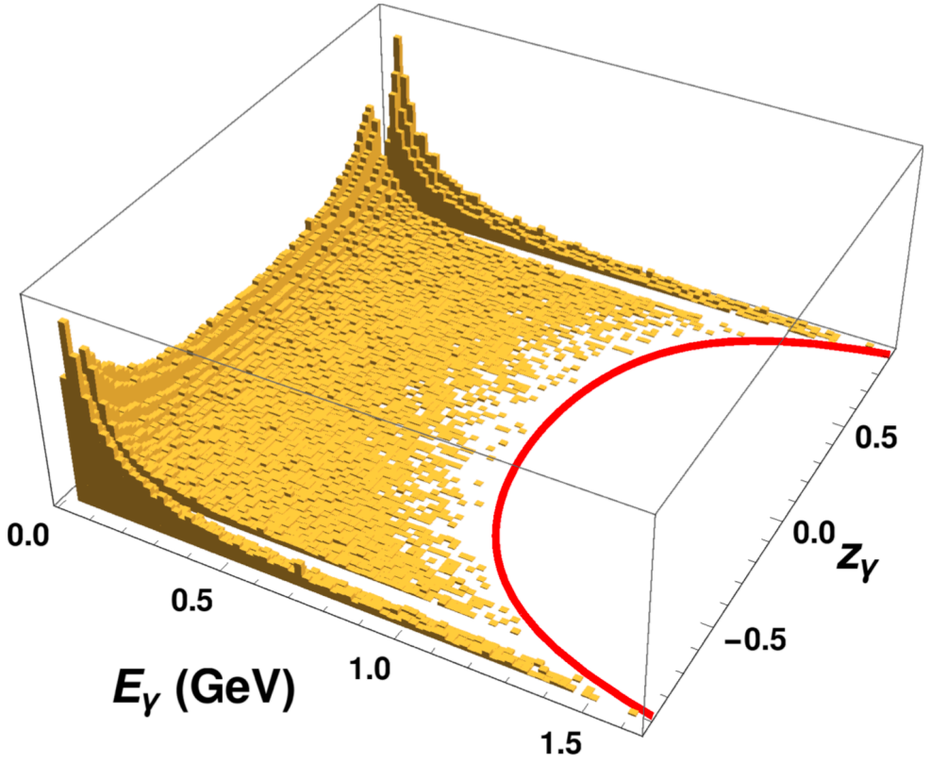
$$\begin{cases} E_\gamma^m \sin\theta_\gamma - E_1 \sin\theta_1 - E_2 \sin\theta_2 = 0 \\ E_\gamma^m \cos\theta_\gamma + E_1 \cos\theta_1 + E_2 \cos\theta_2 = 0 \\ E_\gamma^m + E_1 + E_2 = \sqrt{s}, \end{cases}$$

$$E_\gamma^m(\theta_\gamma) = \frac{\sqrt{s}(A\cos\theta_1 - \sin\theta_1)}{A(\cos\theta_1 - \cos\theta_\gamma) - (\sin\theta_\gamma + \sin\theta_1)}$$

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

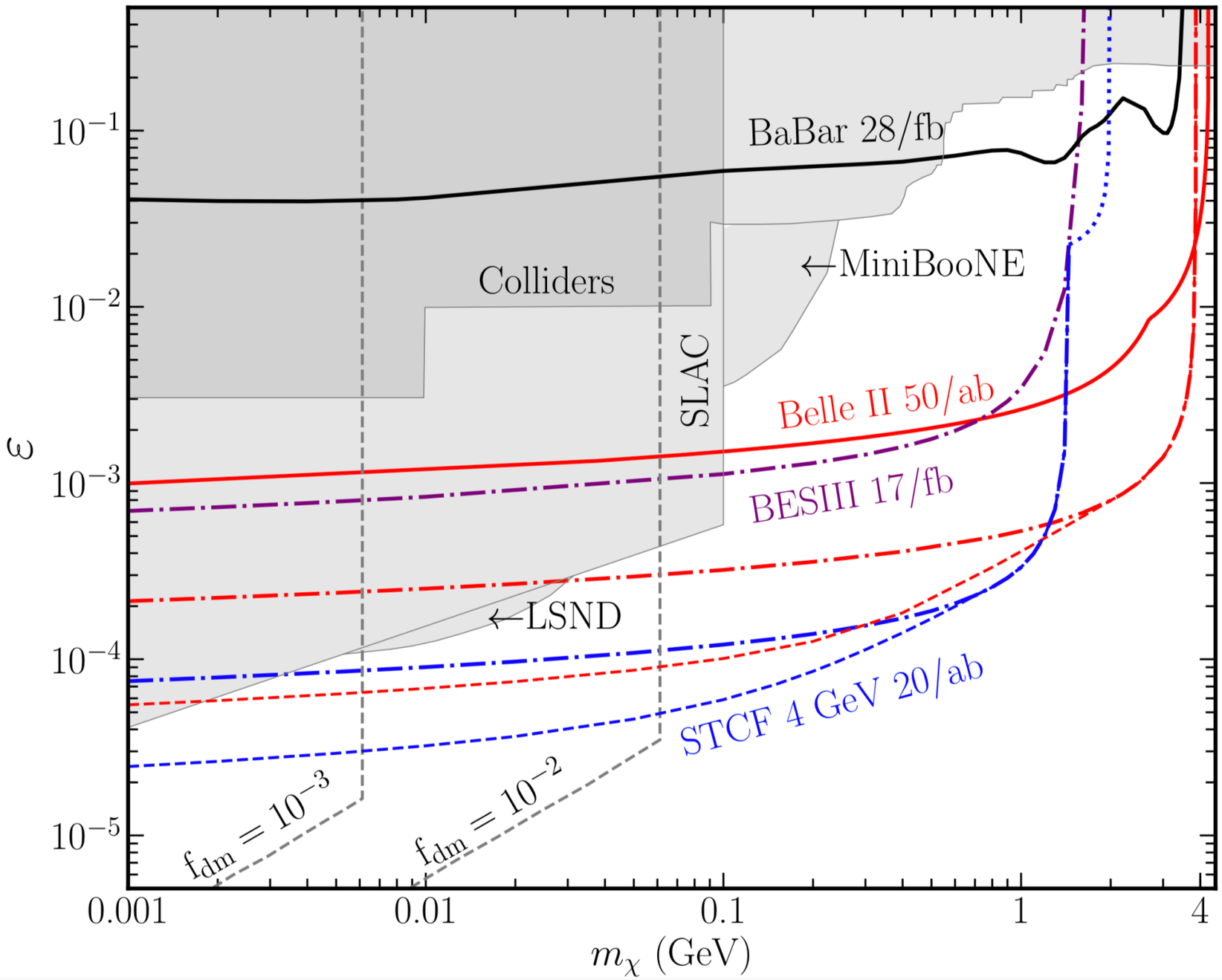
$$\sin\theta_1 = \sin\theta_2 = \sin\theta_b$$

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



$e^+e^- \to e^+e^-\gamma, |\cos\theta_{e^\pm}| > 0.95$

BESIII & STCF sensitivity on millicharge

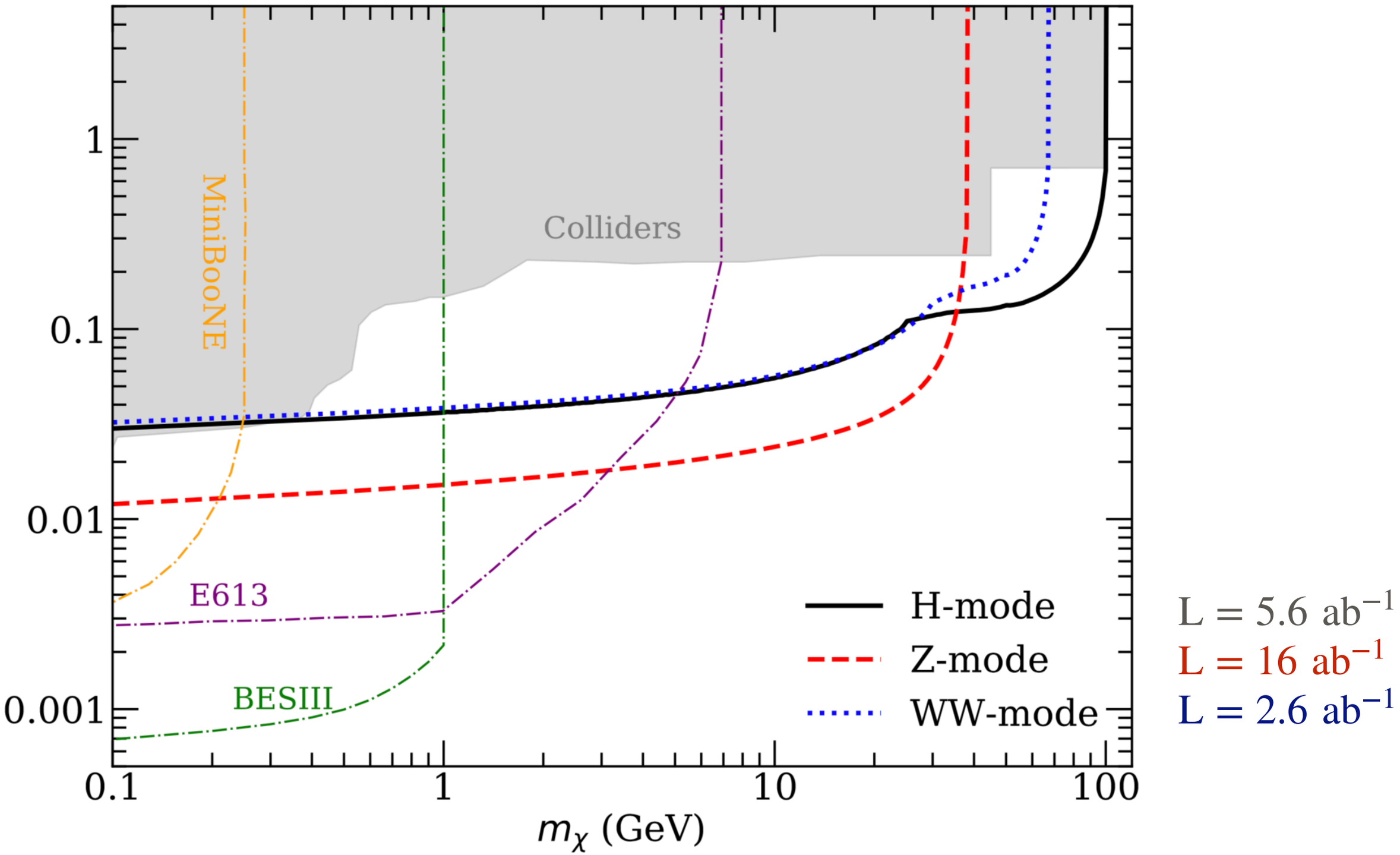


$$\chi_i^2(\varepsilon) \equiv \frac{S_i^2}{S_i + B_i}$$

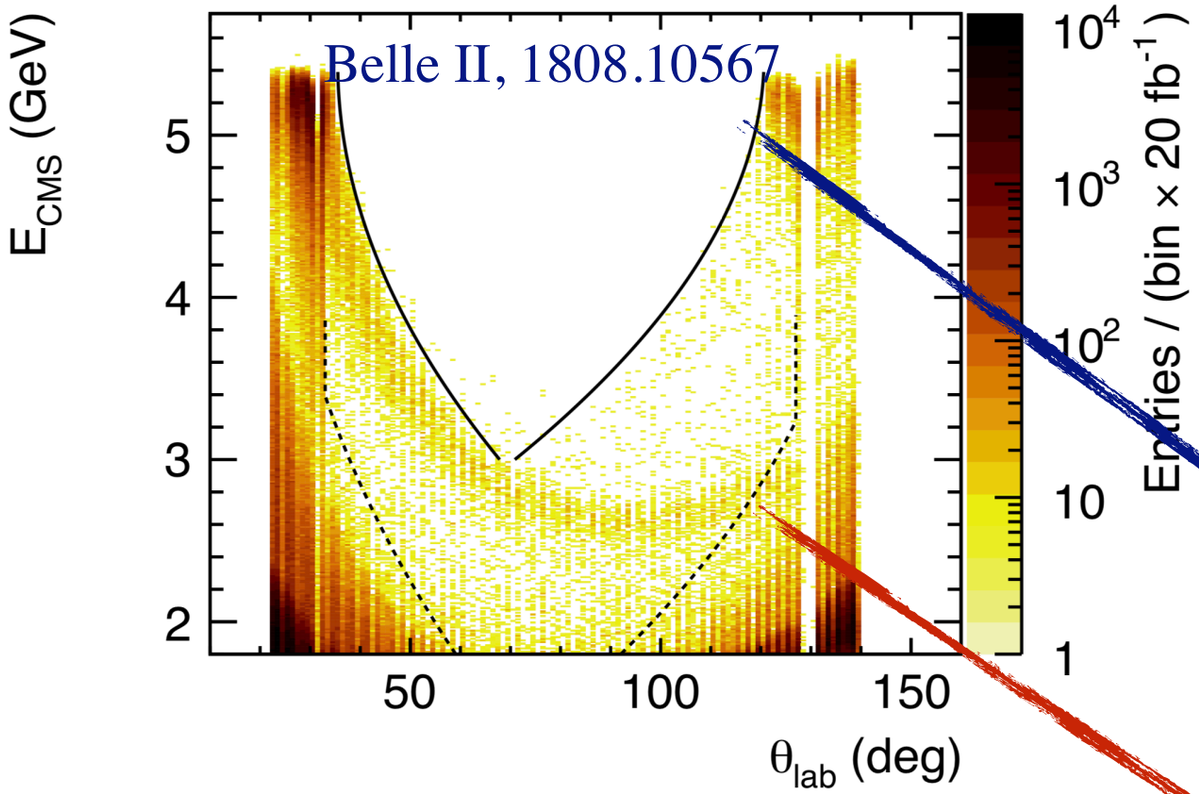
$$\chi_{\rm tot}^2(\varepsilon) = \sum_i \chi_i^2(\varepsilon)$$

$$\chi_{\rm tot}^2(\varepsilon_{95}) = \chi^2(0) + 2.71$$

CEPC sensitivity on millicharge

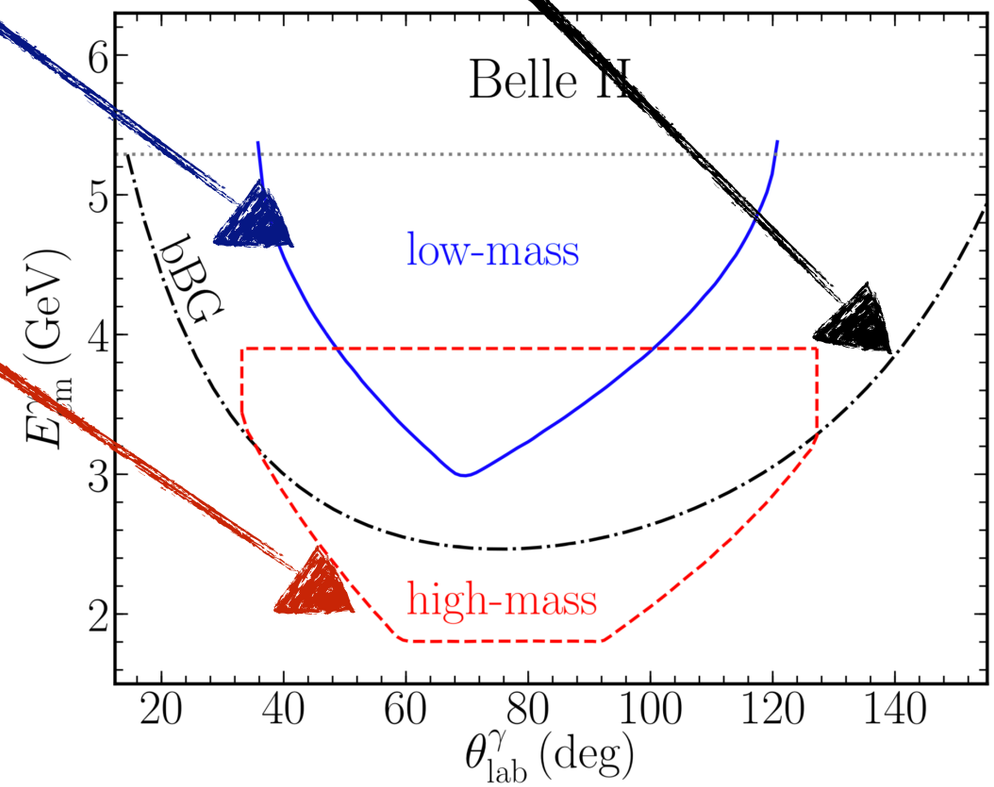


Cuts at Belle II

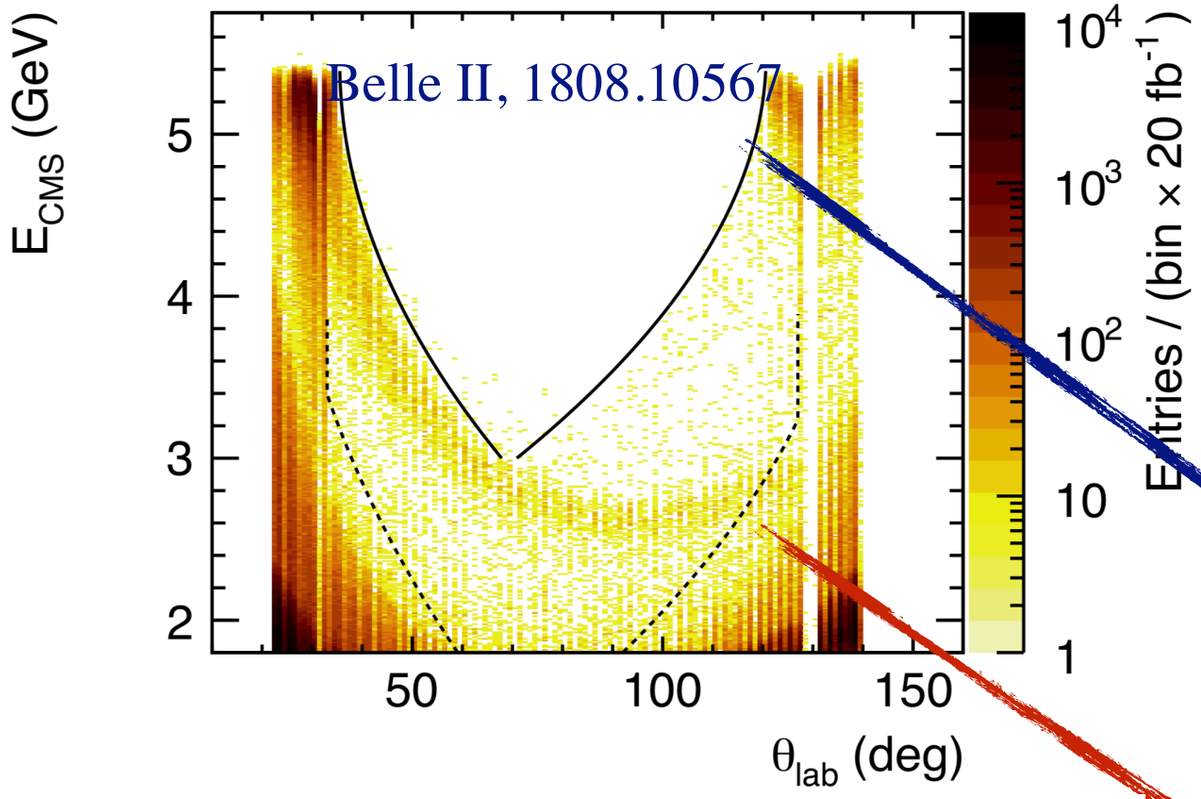


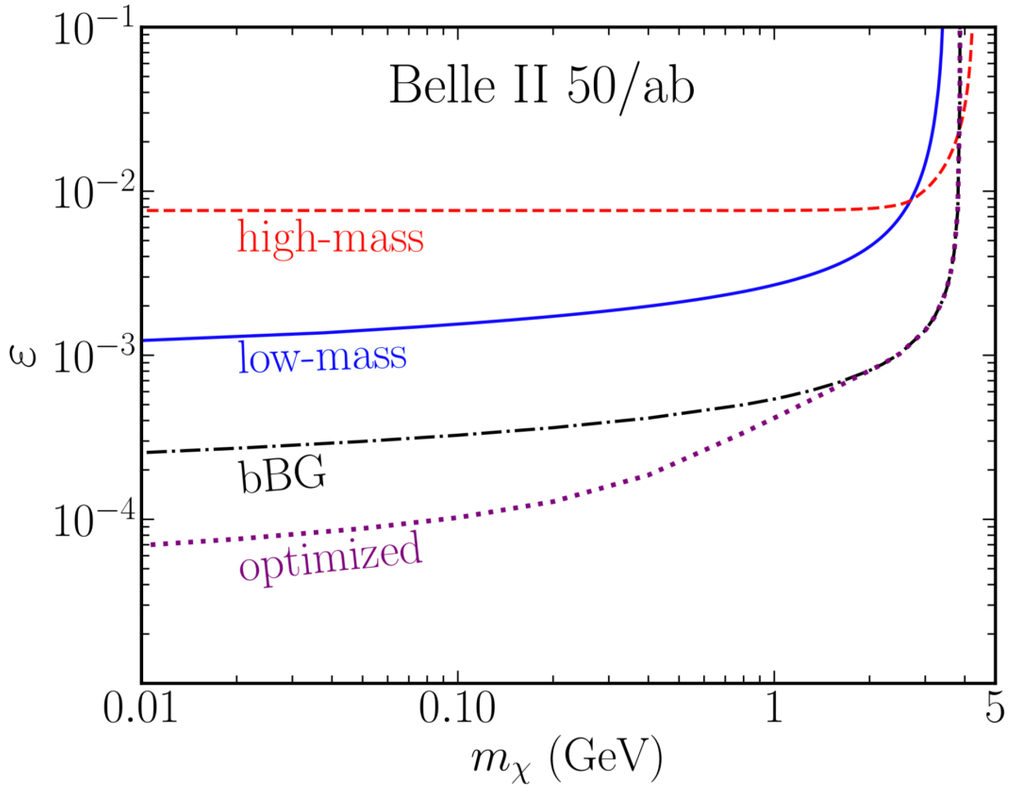
$$E_\gamma^m(\theta_\gamma) = \frac{\sqrt{s}(A\cos\theta_1 - \sin\theta_1)}{A(\cos\theta_1 - \cos\theta_\gamma) - (\sin\theta_\gamma + \sin\theta_1)}$$

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



Sensitivity at Belle II





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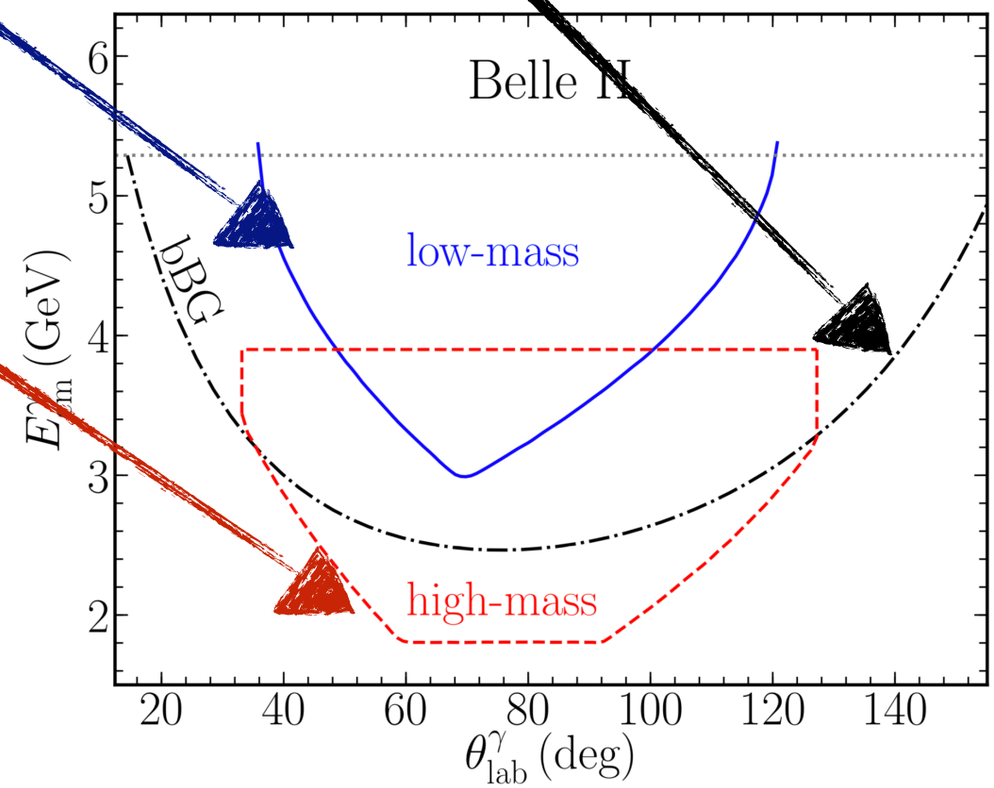
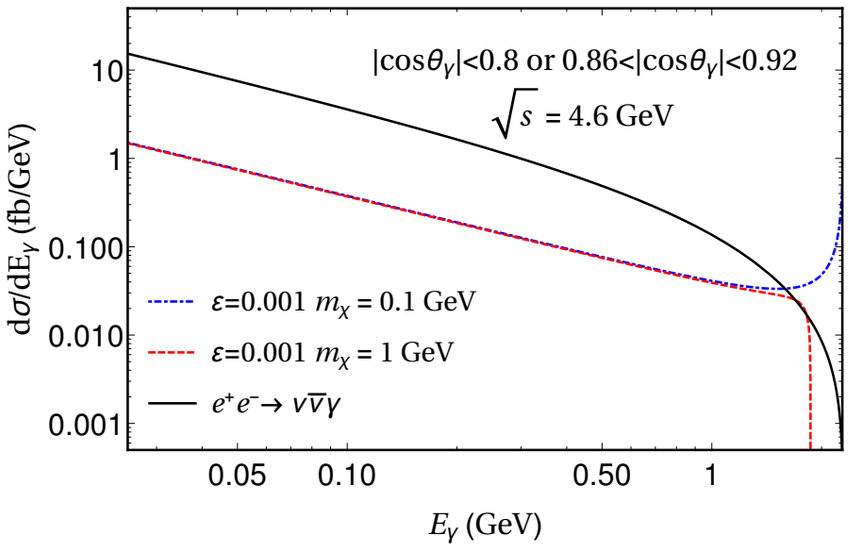
$$A = (\sin\theta_1 - \sin\theta_2)/(\cos\theta_1 - \cos\theta_2)$$

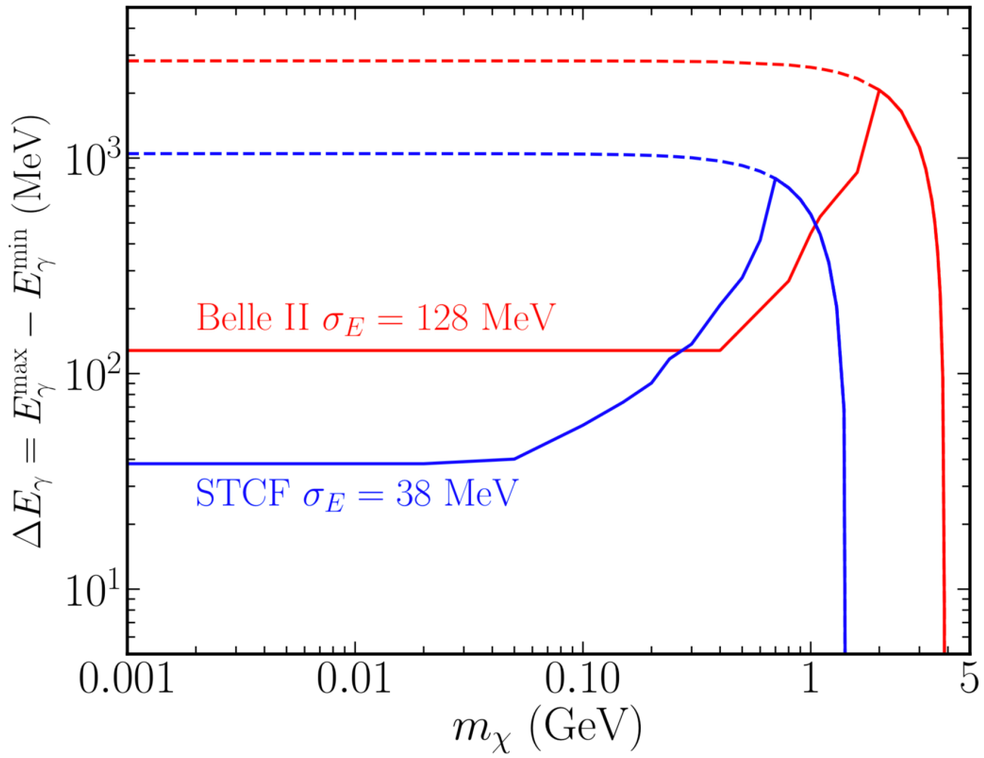


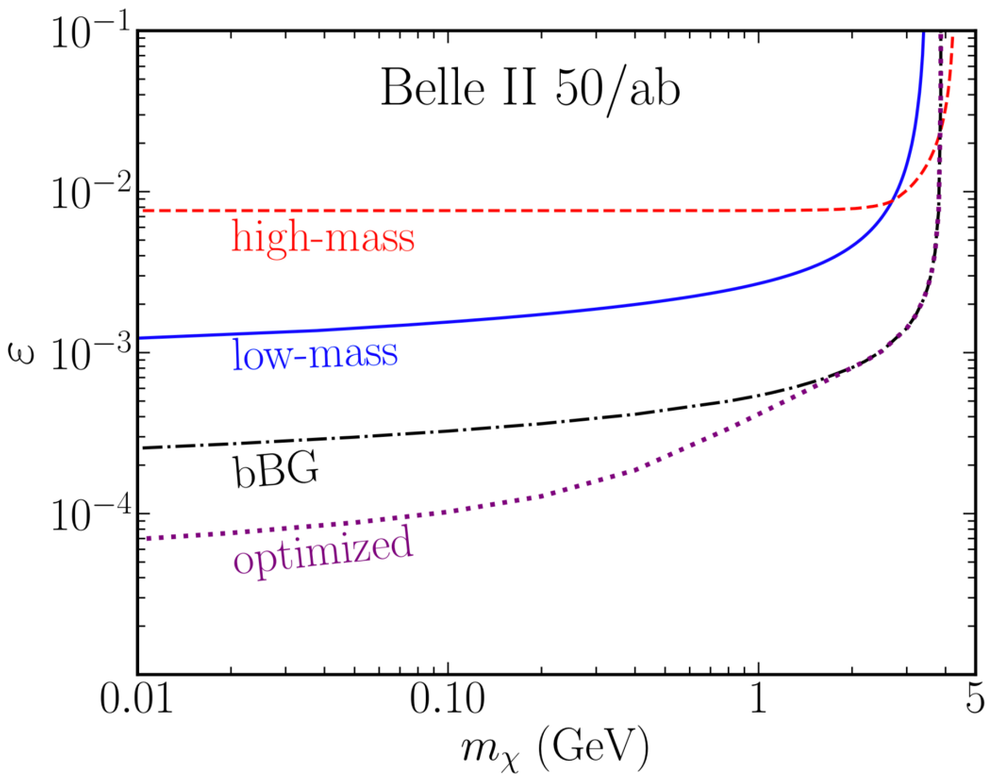
Optimized cut

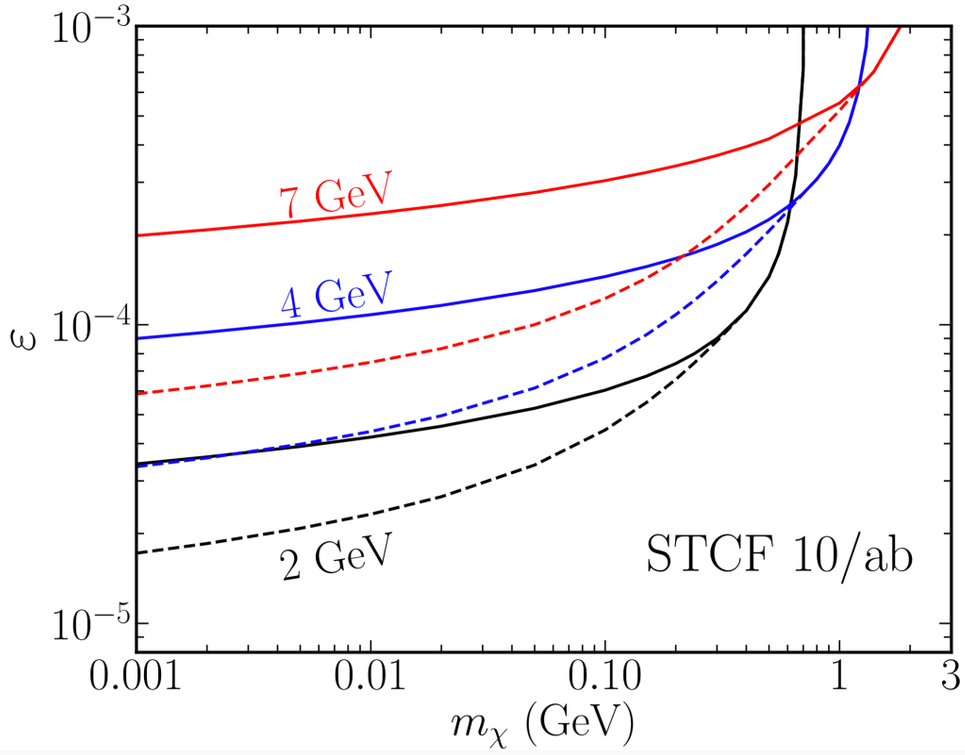


$$E_\gamma^{\min} < E_\gamma < E_\gamma^{\max} \qquad E_\gamma^{\max} = (s - 4m_\chi^2)/(2\sqrt{s})$$

$$\Delta E_\gamma \equiv E_\gamma^{\max} - E_\gamma^{\min}$$





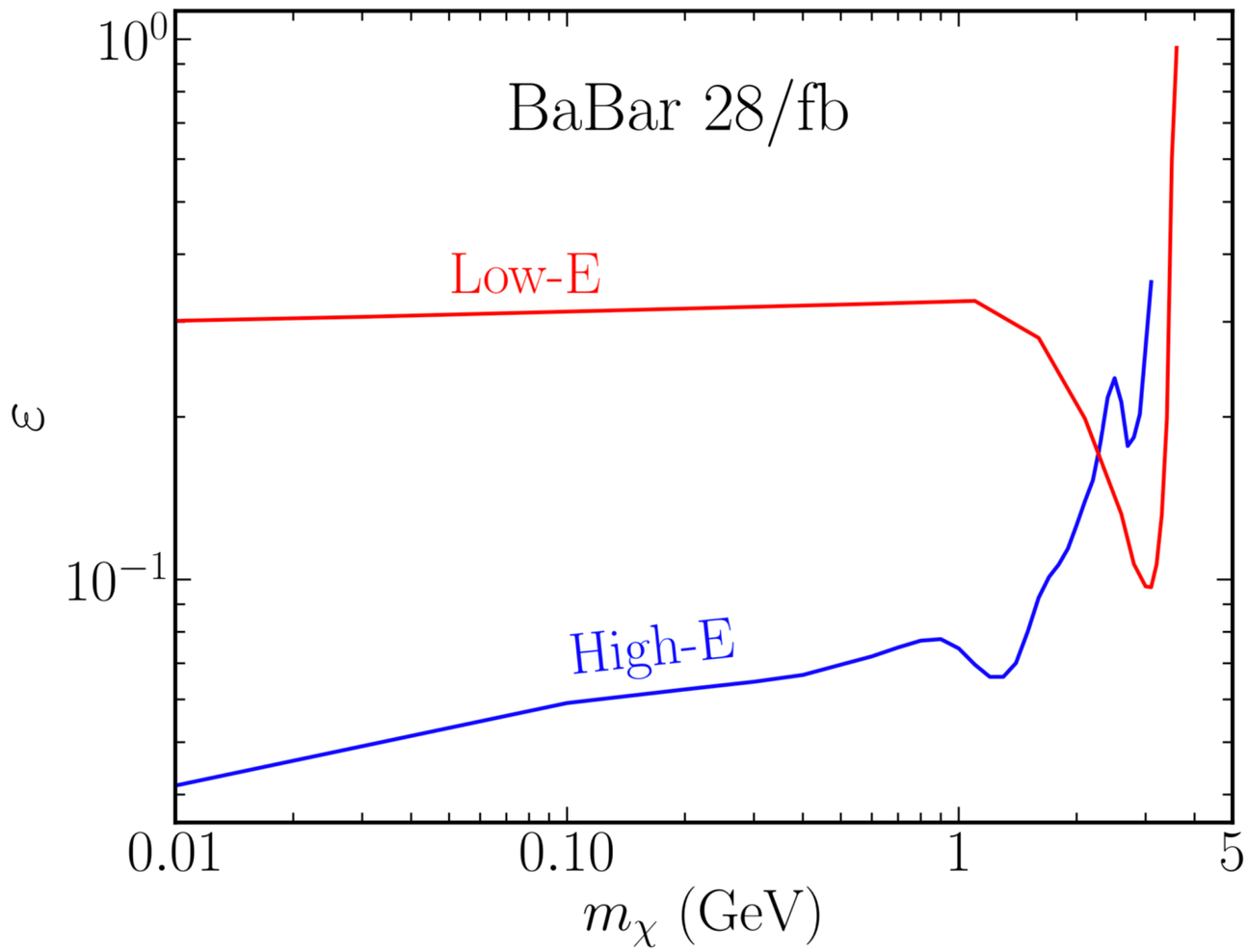


Limits from BaBar data

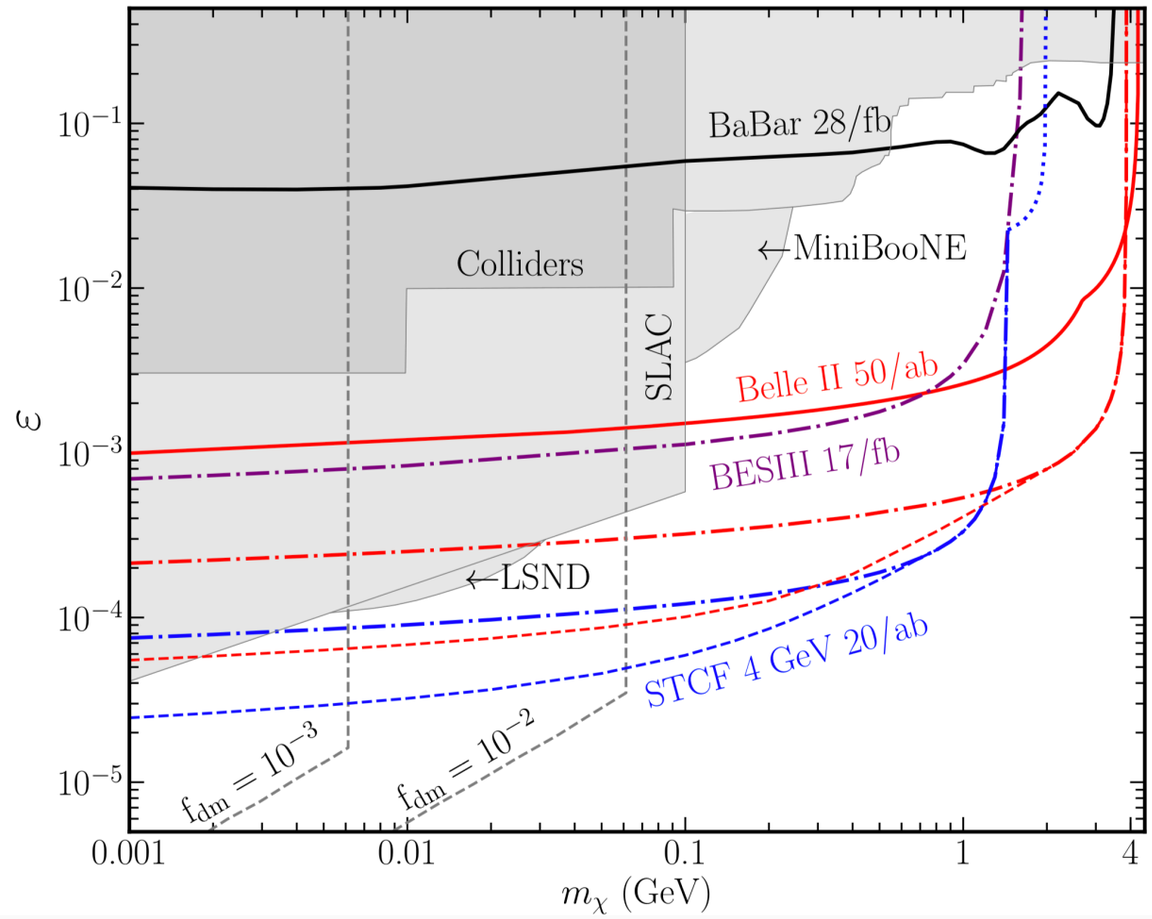
$$e^+e^- \to \Upsilon(3S) \to \gamma A^0$$ BaBar, 0808.0017

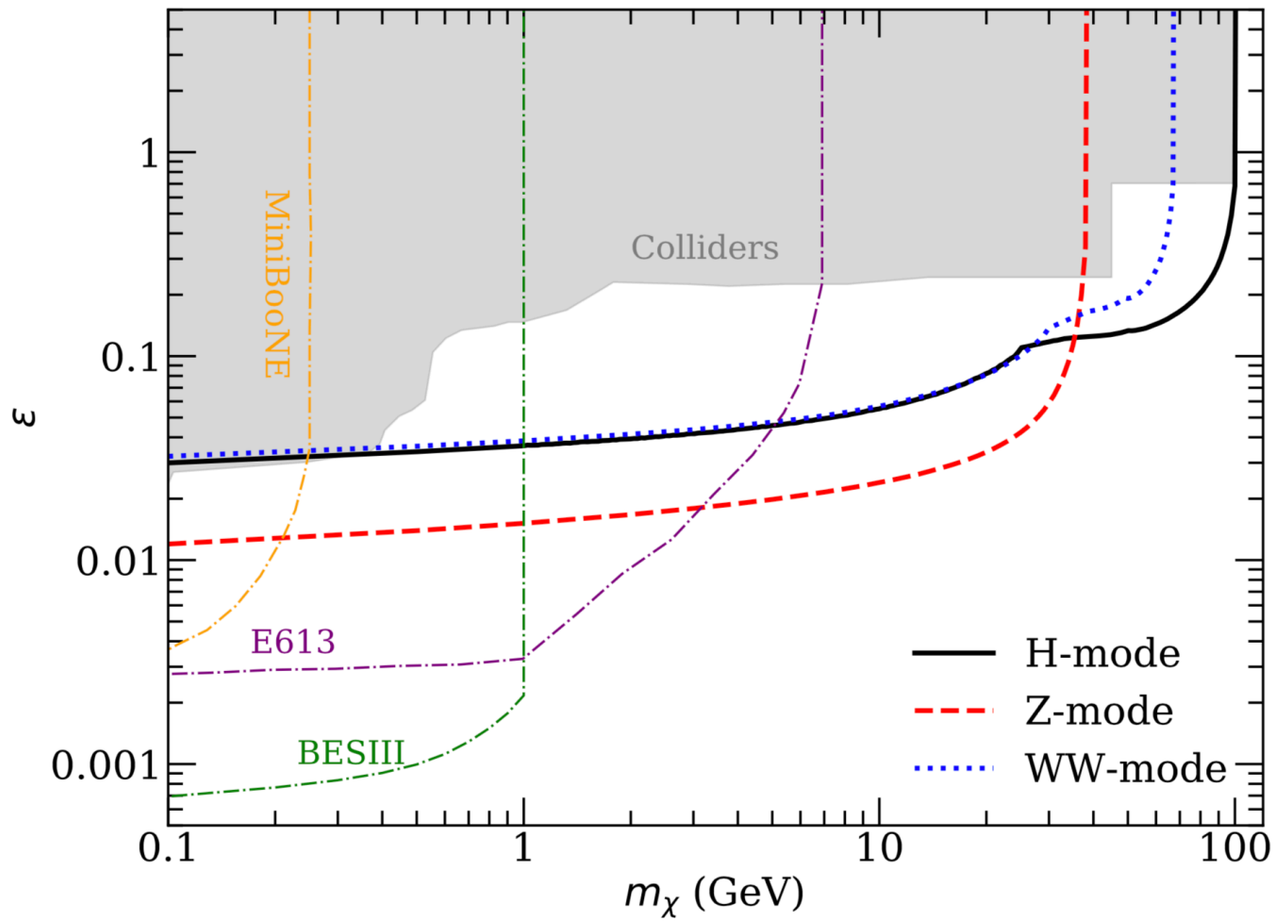
High-E (28/fb): $3.2\ \text{GeV} < E^{\gamma}_{\text{cm}} < 5.5\ \text{GeV},\ -0.31 < \cos(\theta^{\gamma}_{\text{cm}}) < 0.6$

Low-E (19/fb): $2.2\ \text{GeV} < E^{\gamma}_{\text{cm}} < 3.7\ \text{GeV},\ -0.46 < \cos(\theta^{\gamma}_{\text{cm}}) < 0.46$



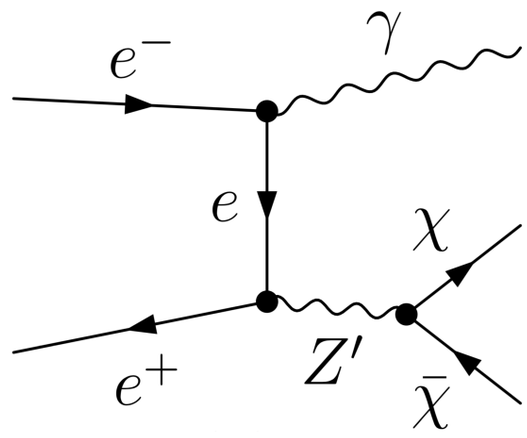
小结


BaBar 28/fb
Colliders
←MiniBooNE
SLAC
Belle II 50/ab
BESIII 17/fb
←LSND
STCF 4 GeV 20/ab
$f_{dm} = 10^{-3}$
$f_{dm} = 10^{-2}$
ϵ
m_χ (GeV)


MiniBooNE
Colliders
E613
BESIII
H-mode
Z-mode
WW-mode
ϵ
m_χ (GeV)

Z' DM models

Zuowei Liu, Yong-Heng Xu, **Yu Zhang**, 1903.12114, JHEP



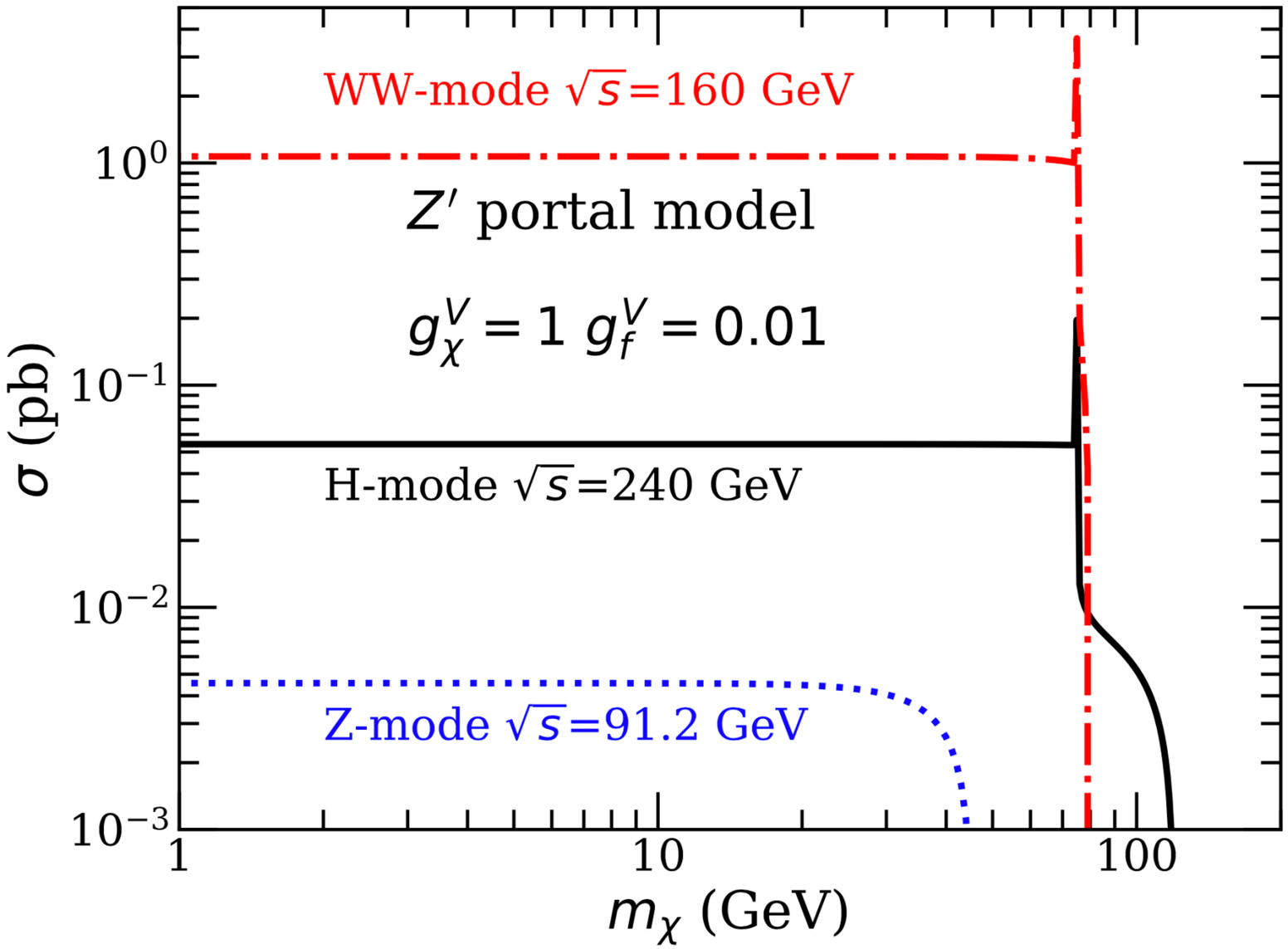
$$\mathcal{L} = Z'_\mu \bar{\chi} \gamma^\mu (g_V^\chi - g_A^\chi \gamma_5) \chi + Z'_\mu \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma_5) f$$

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

$$\Gamma_{Z'} = \Gamma(Z' \to \chi\bar{\chi}) + \sum_f \Gamma(Z' \to f\bar{f})$$

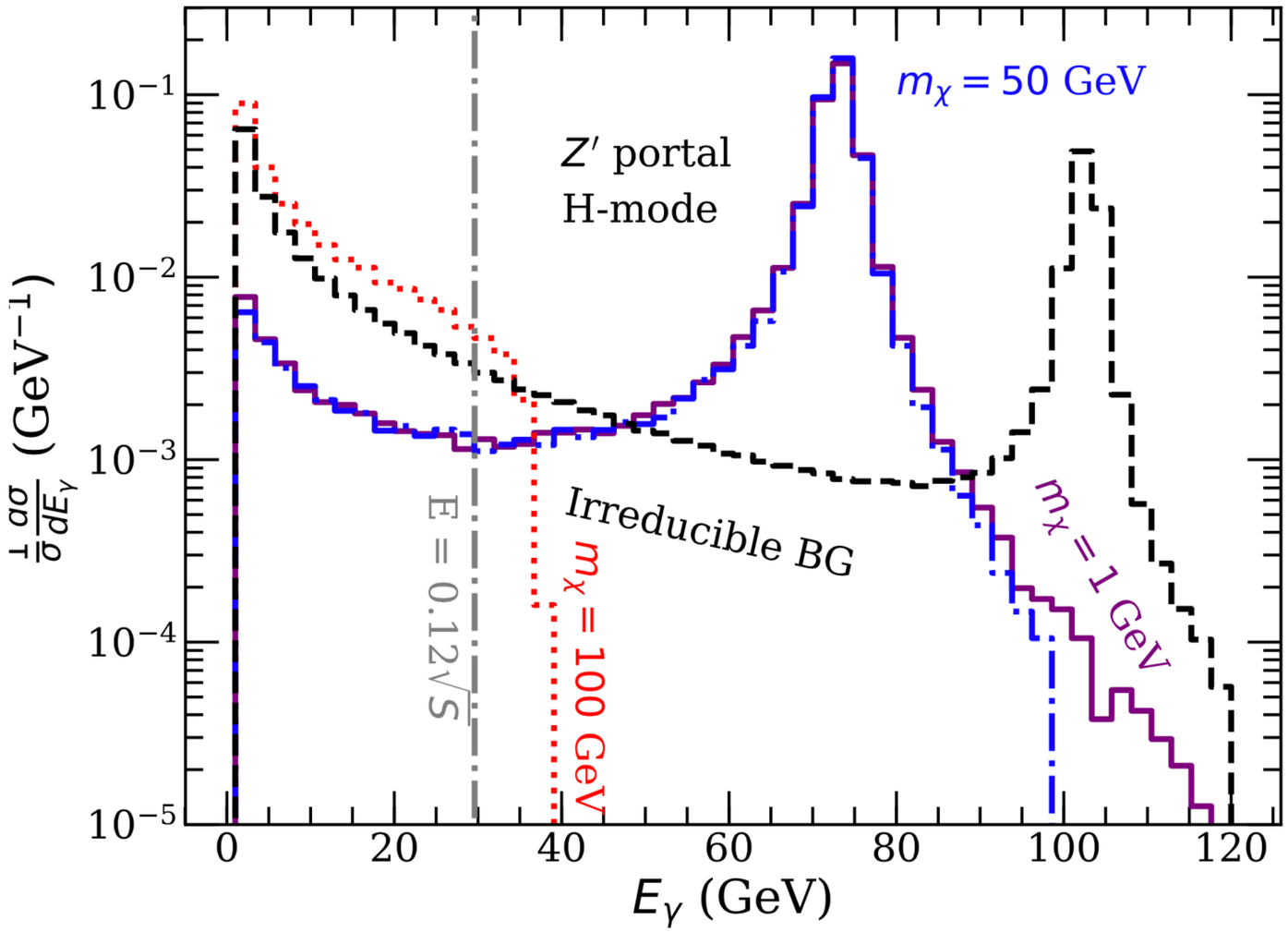
$$\Gamma(Z' \to \chi\bar{\chi}) = \frac{M_{Z'}}{12\pi} \sqrt{1 - 4\frac{m_\chi^2}{M_{Z'}^2}} \left[(g_V^\chi)^2 \left(1 + 2\frac{m_\chi^2}{M_{Z'}^2} \right) + (g_A^\chi)^2 \left(1 - 4\frac{m_\chi^2}{M_{Z'}^2} \right) \right]$$

Xsec versus mass



$$M_Z' = 150 \text{ GeV}$$

Distributions and cuts



(1) $E_\gamma > 0.1\,\mathrm{GeV}$,

(2) $|\cos\theta_\gamma| < |\cos\theta_b| = 0.99$,

(3) $E_\gamma < E_\chi^m = (s - 4m_\chi^2)/(2\sqrt{s})$,

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

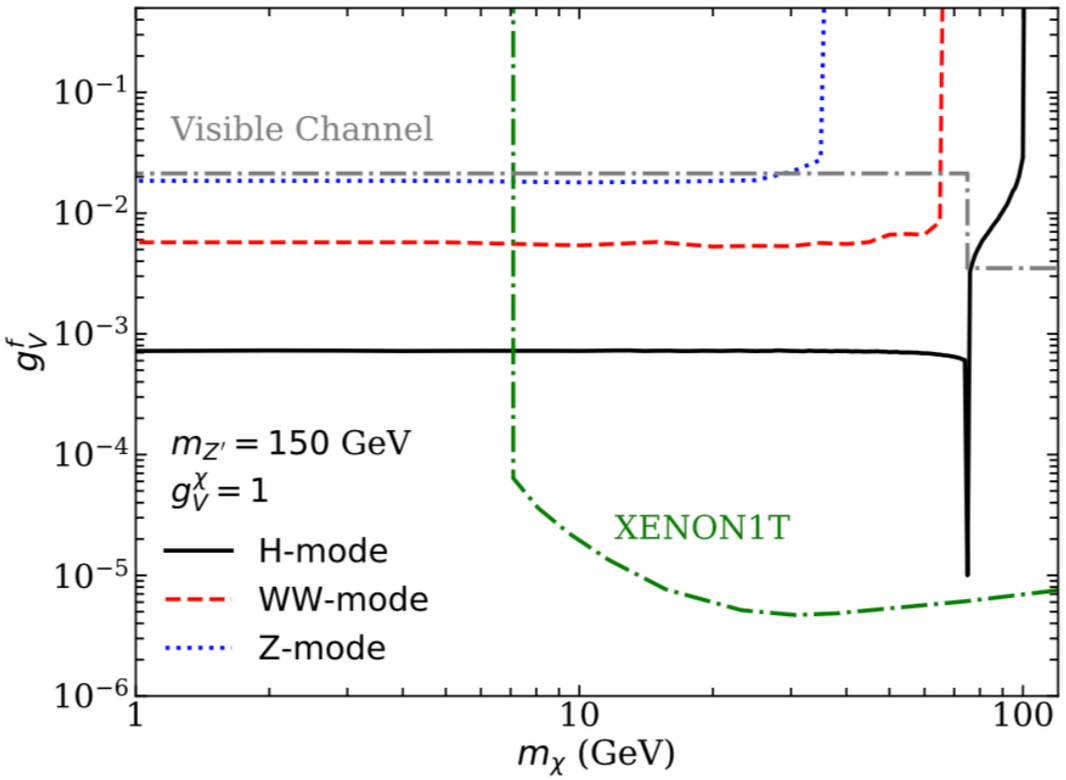
(5) $E_\gamma(\theta_\gamma) > E_B^m(\theta_\gamma) = \sqrt{s}(1 + \sin\theta_\gamma/\sin\theta_b)^{-1}$

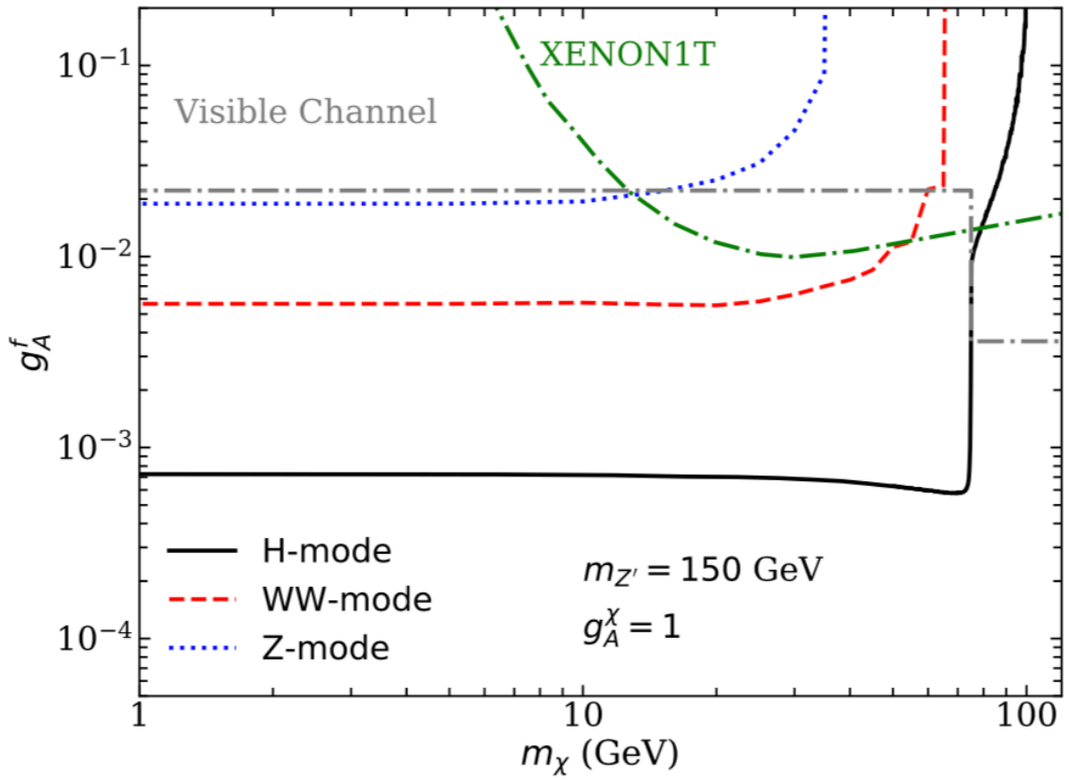
In the H mode: (for m < 75 GeV)

$147\ \mathrm{GeV} < M_\gamma < 153\ \mathrm{GeV}$

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

Sensitivity at CEPC





DM effective operators

Zuowei Liu, Yong-Heng Xu, **Yu Zhang**, 1903.12114, JHEP

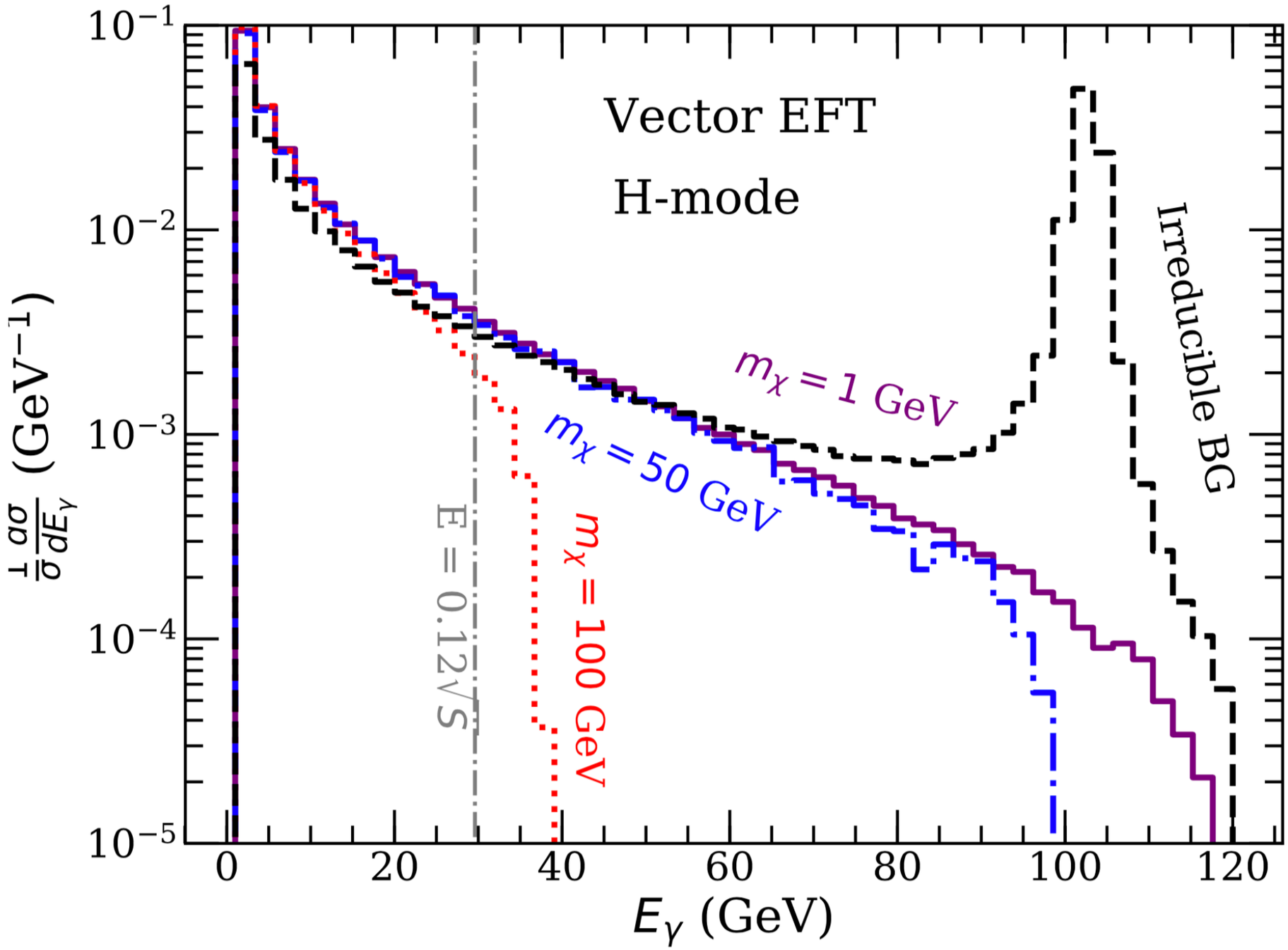
Vector: $$\mathcal{L} = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell,$$

Scalar(s): $$\mathcal{L} = \frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell,$$

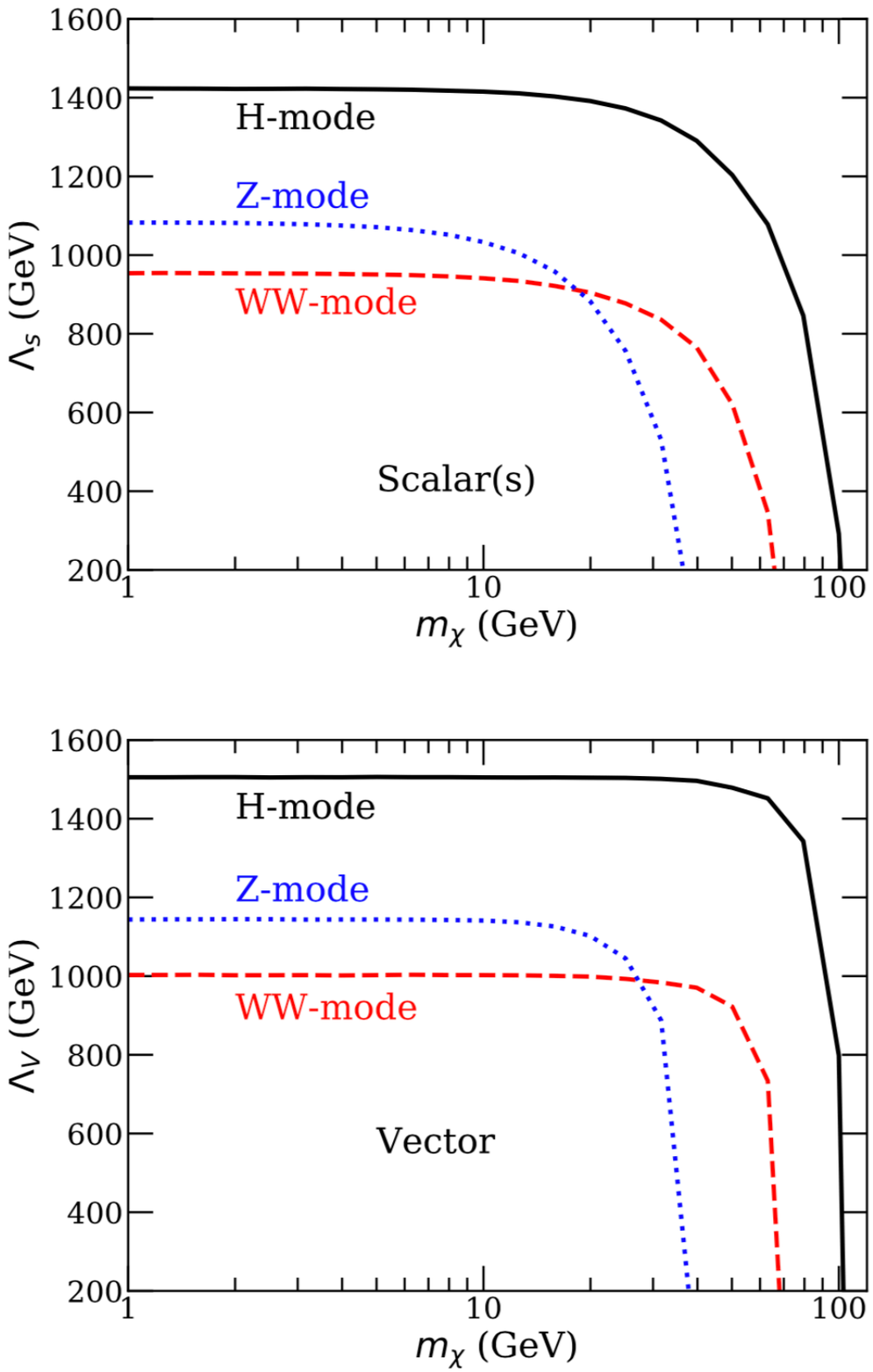
Axial vector: $$\mathcal{L} = \frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell,$$

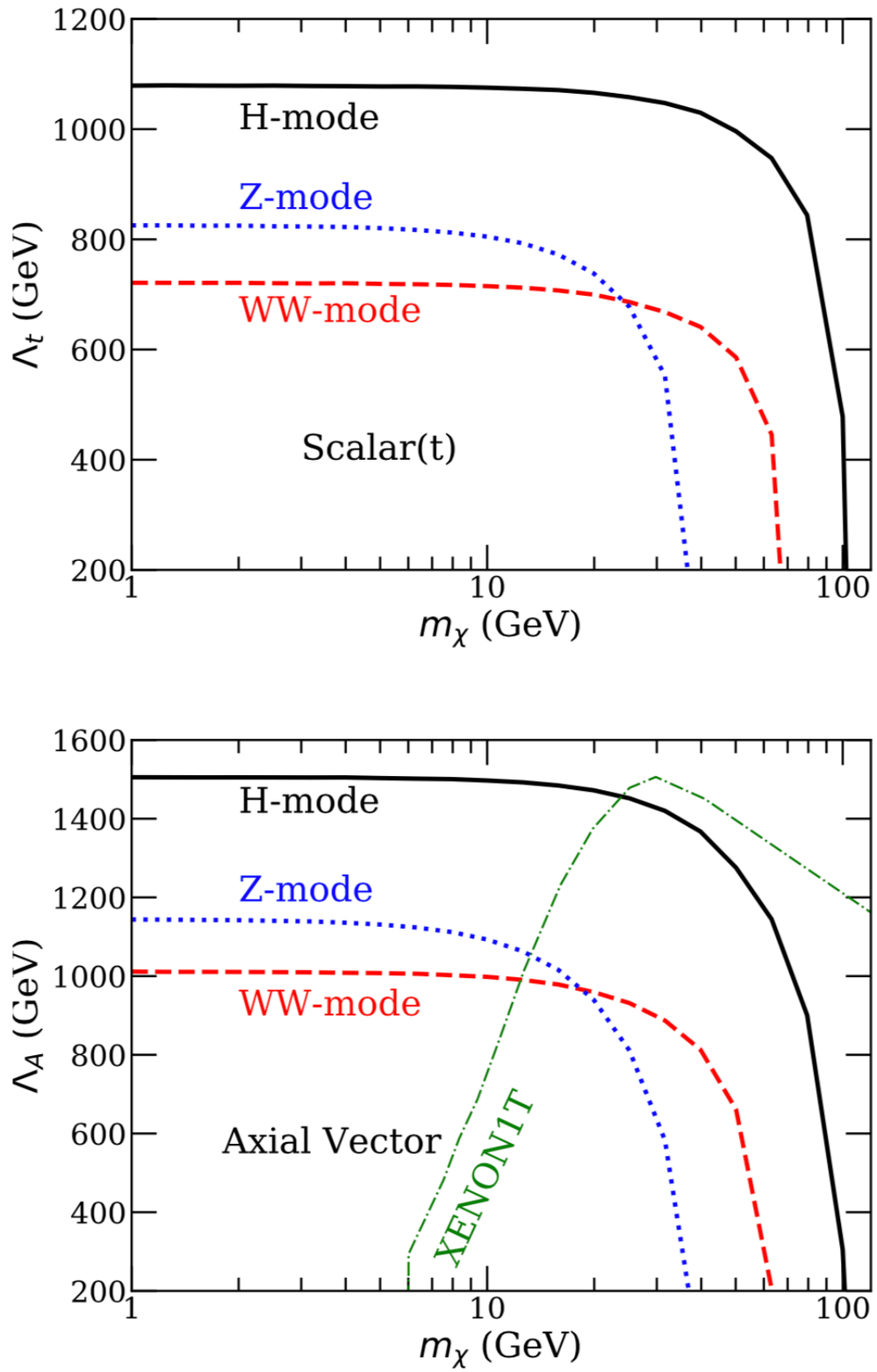
Scalar(t): $$\mathcal{L} = \frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$$

Distributions



Sensitivity at CEPC

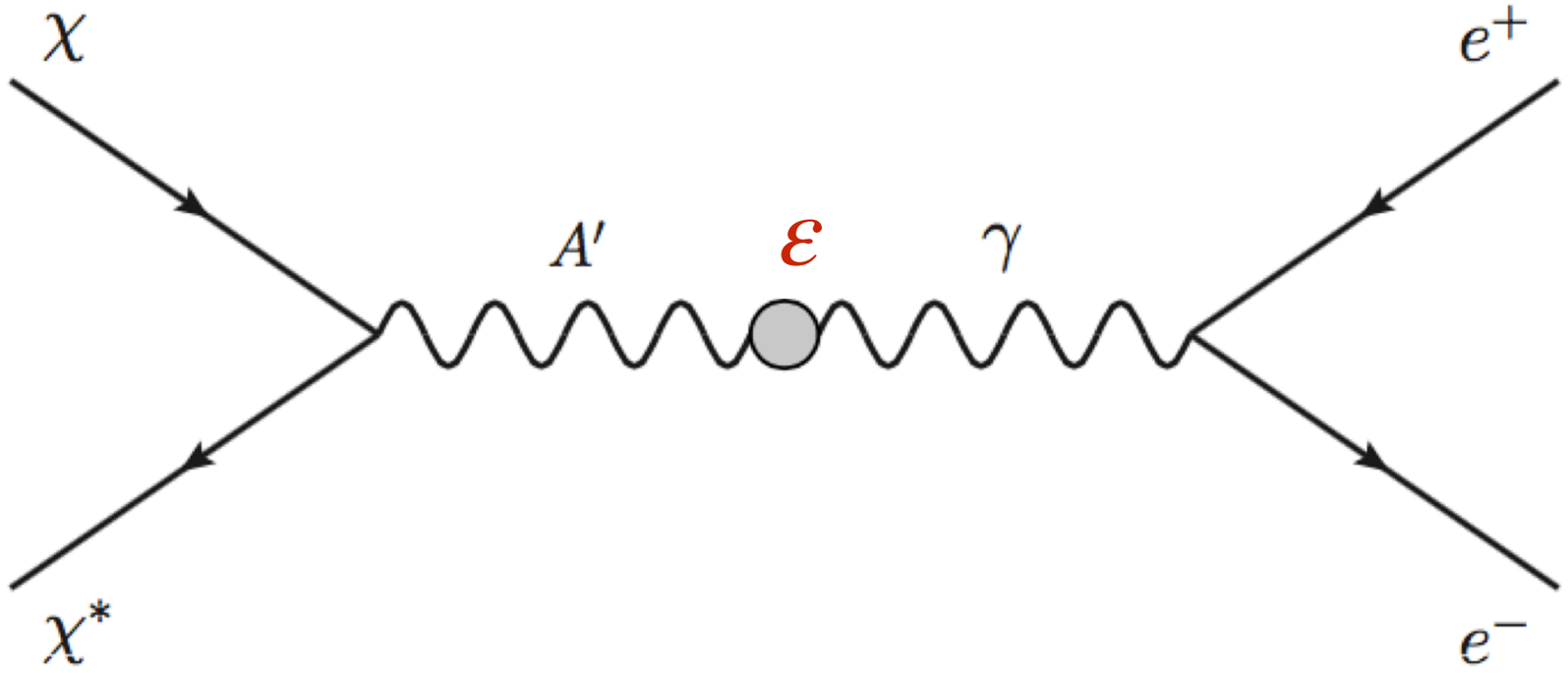




Dark photon invisible decay at BESIII/STCF

Yu Zhang, et. al., 1907.07046, PRD

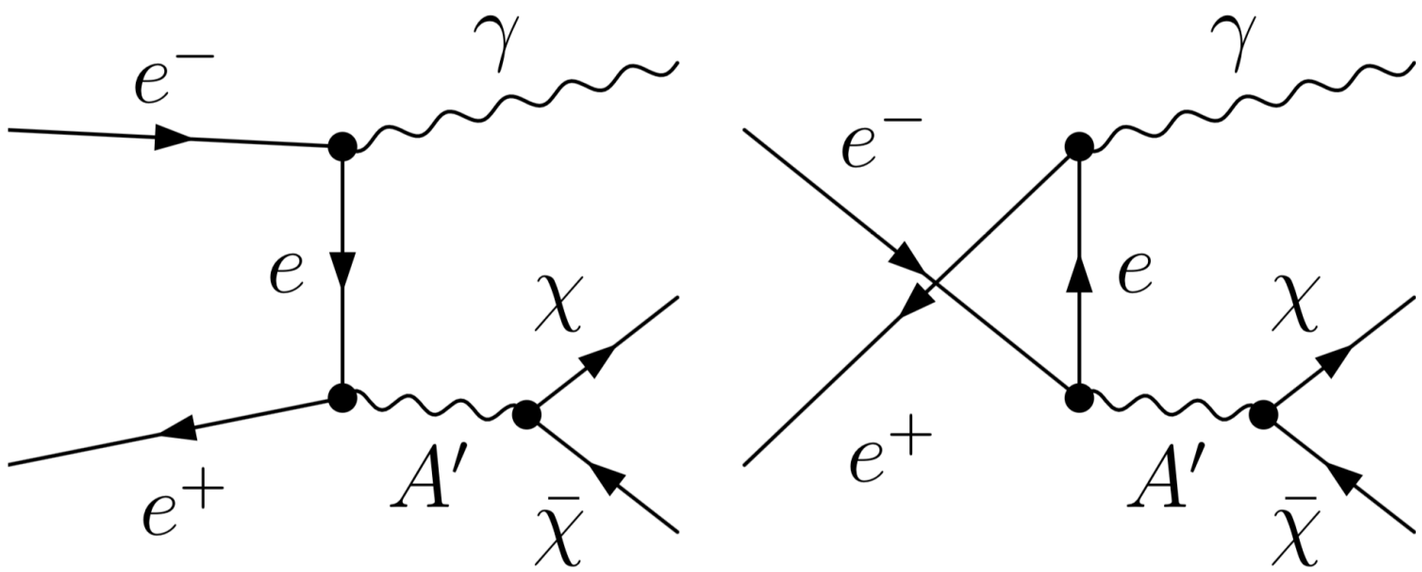
Dark photon



$$\mathscr{L}_{\text{kinetic mixing}} = -\frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

$$\varepsilon Q_f A' \bar{f} \gamma^\mu f$$

Dark photon production at e^+e^-colliders



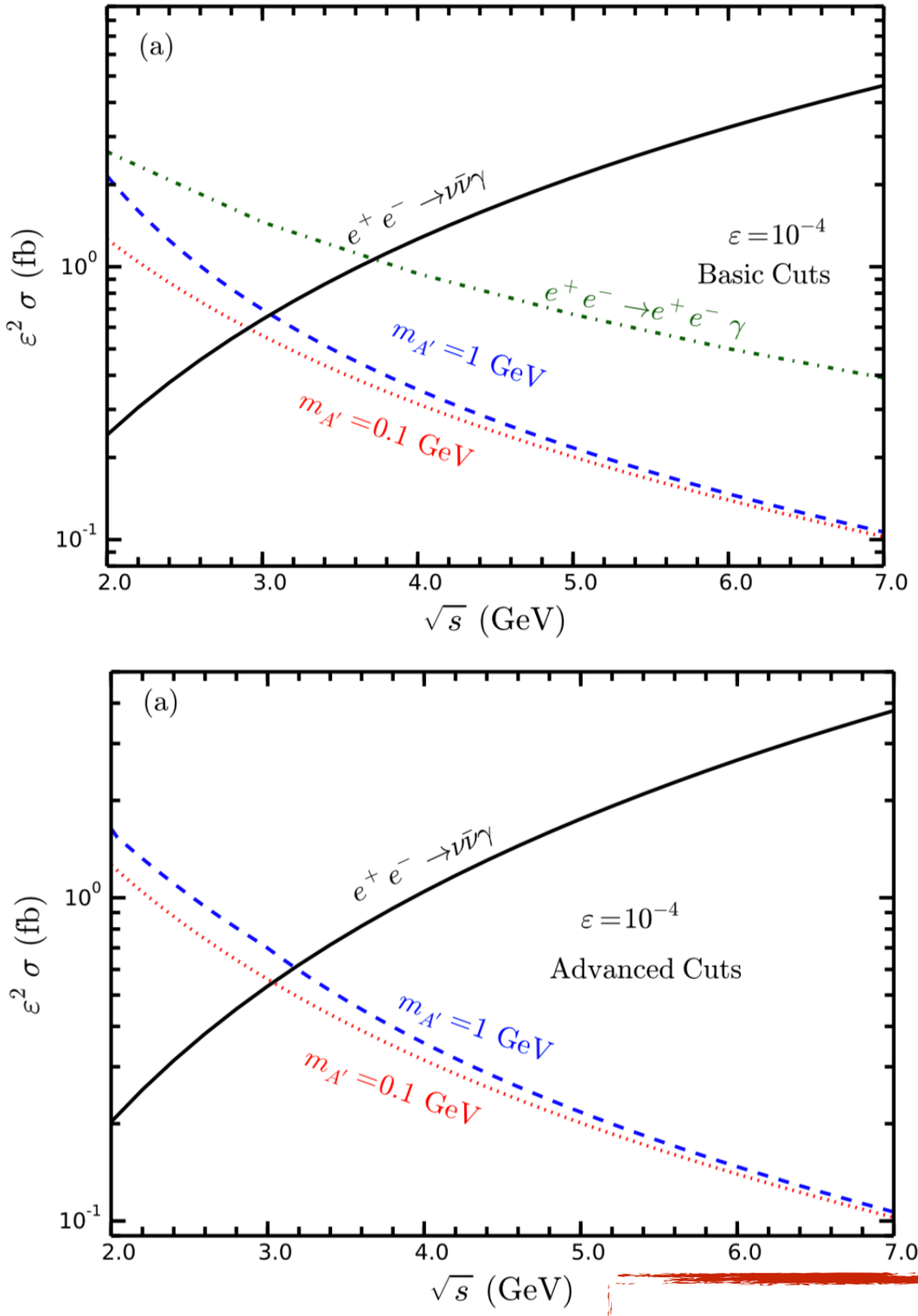
$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

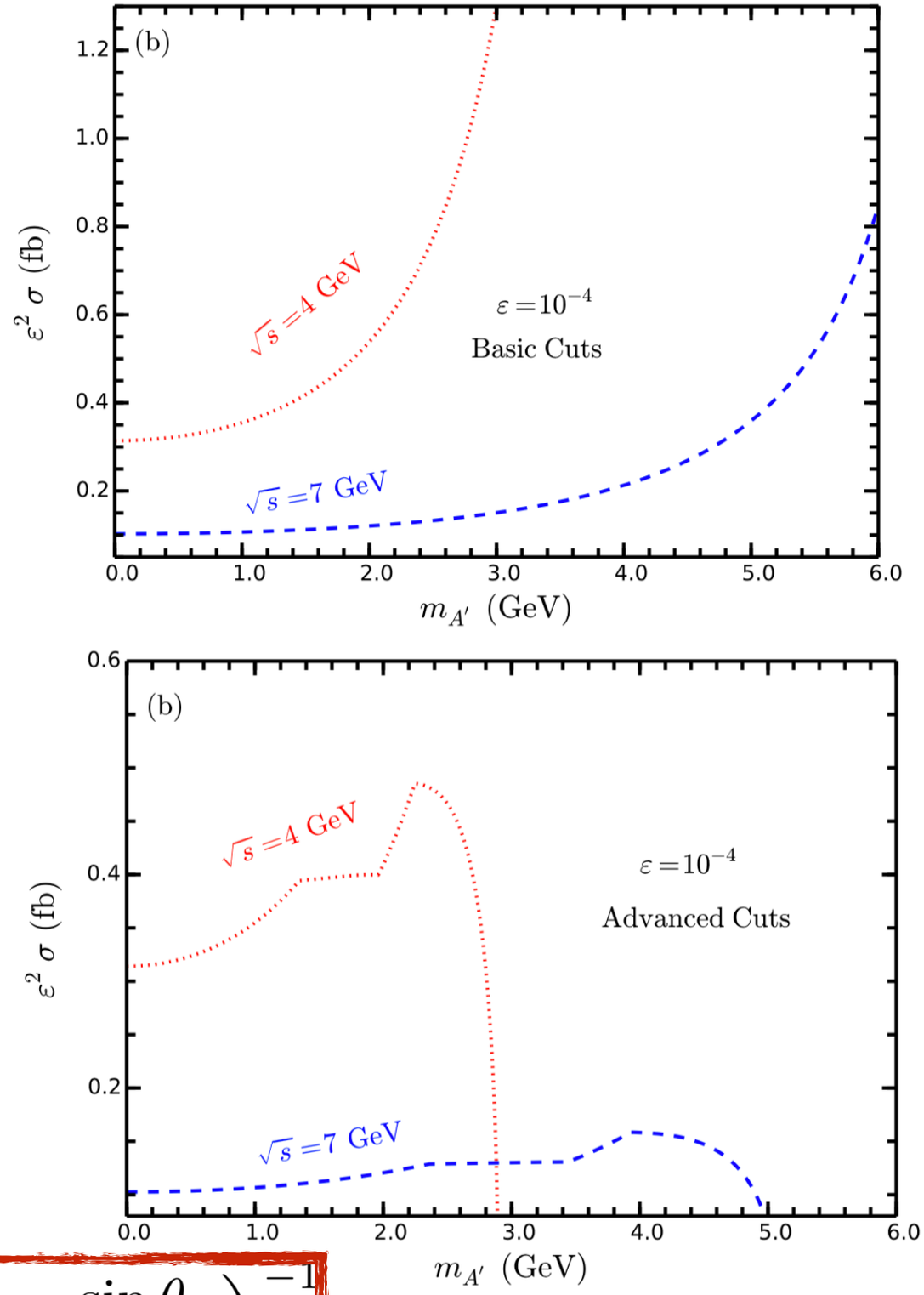
$$\frac{d\sigma_{\gamma A'}}{dz_\gamma} = \frac{2\pi\varepsilon^2\alpha^2}{s}\left(1 - \frac{m_{A'}^2}{s}\right)\frac{1 + z_\gamma^2 + \frac{4sm_{A'}^2}{(s-m_{A'}^2)^2}}{(1+z_\gamma)(1-z_\gamma)}$$

$$\sigma_{\gamma A'} = \frac{2\pi\varepsilon^2\alpha^2}{s}\left(1 - \frac{m_{A'}^2}{s}\right)\left[\left(1 + \frac{2sm_{A'}^2}{(s-m_{A'}^2)^2}\right)\mathcal{Z} - z_\gamma^{\max} + z_\gamma^{\min}\right]$$

$$\mathcal{Z} = \ln\frac{(1+z_\gamma^{\max})(1-z_\gamma^{\min})}{(1-z_\gamma^{\max})(1+z_\gamma^{\min})}$$

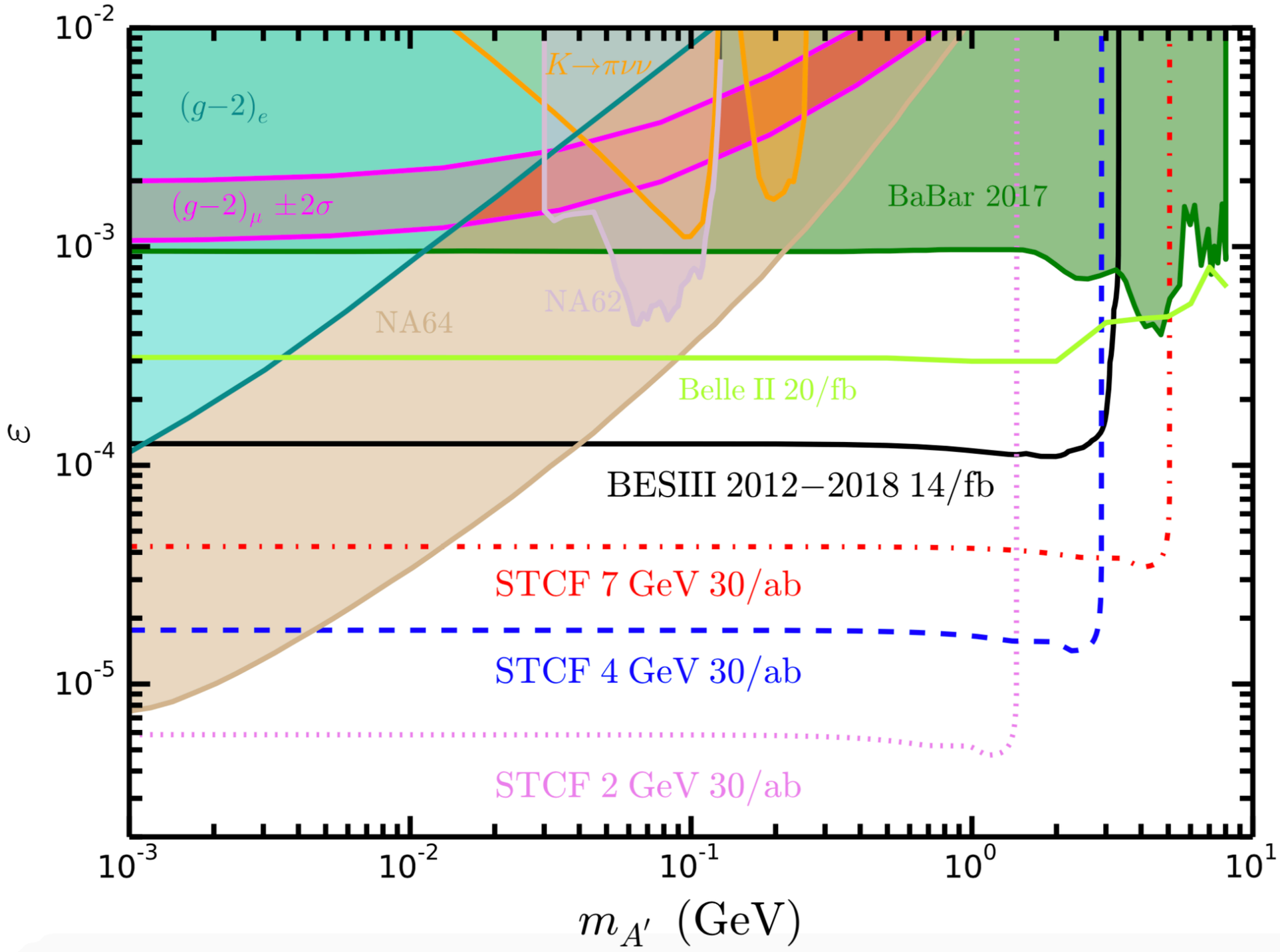
Xsec versus energy and mass





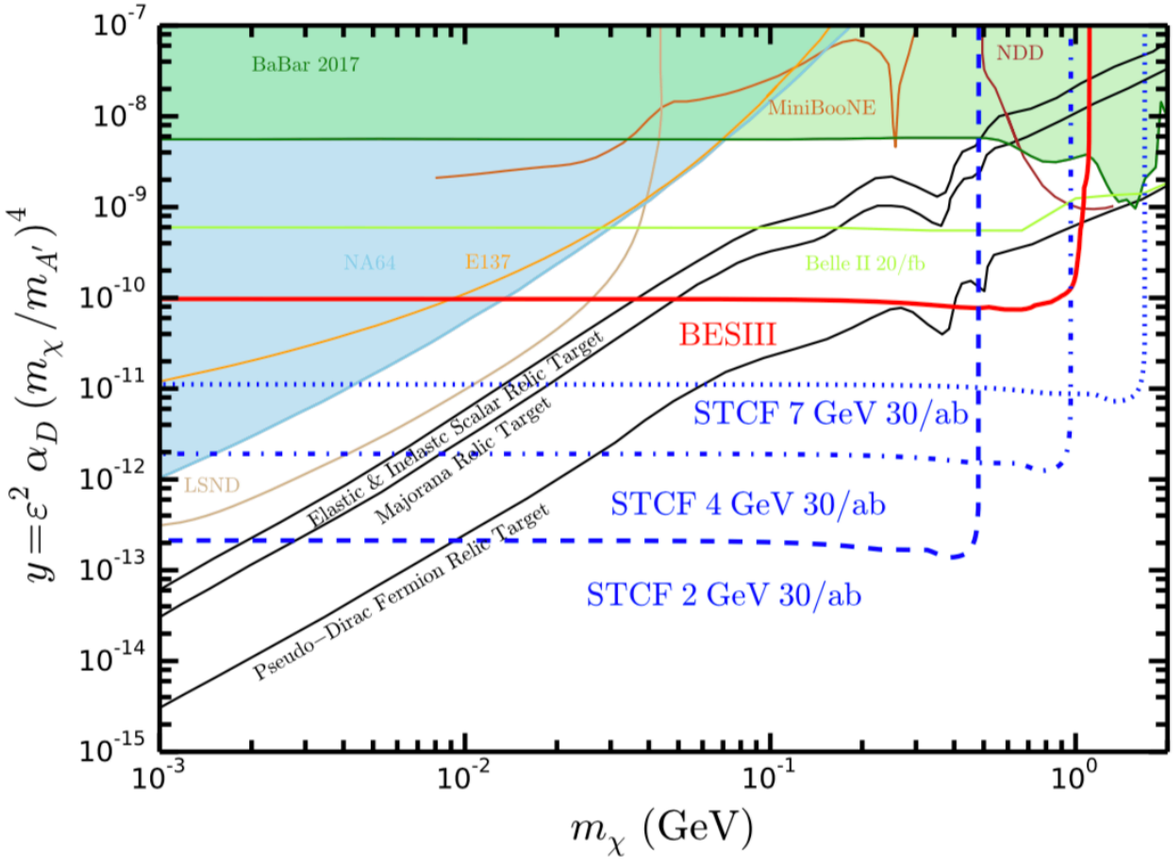
$$E_\gamma^m(\theta_\gamma) = \sqrt{s}\left(1+\frac{\sin\theta_\gamma}{\sin\theta_b}\right)^{-1}$$

Limits

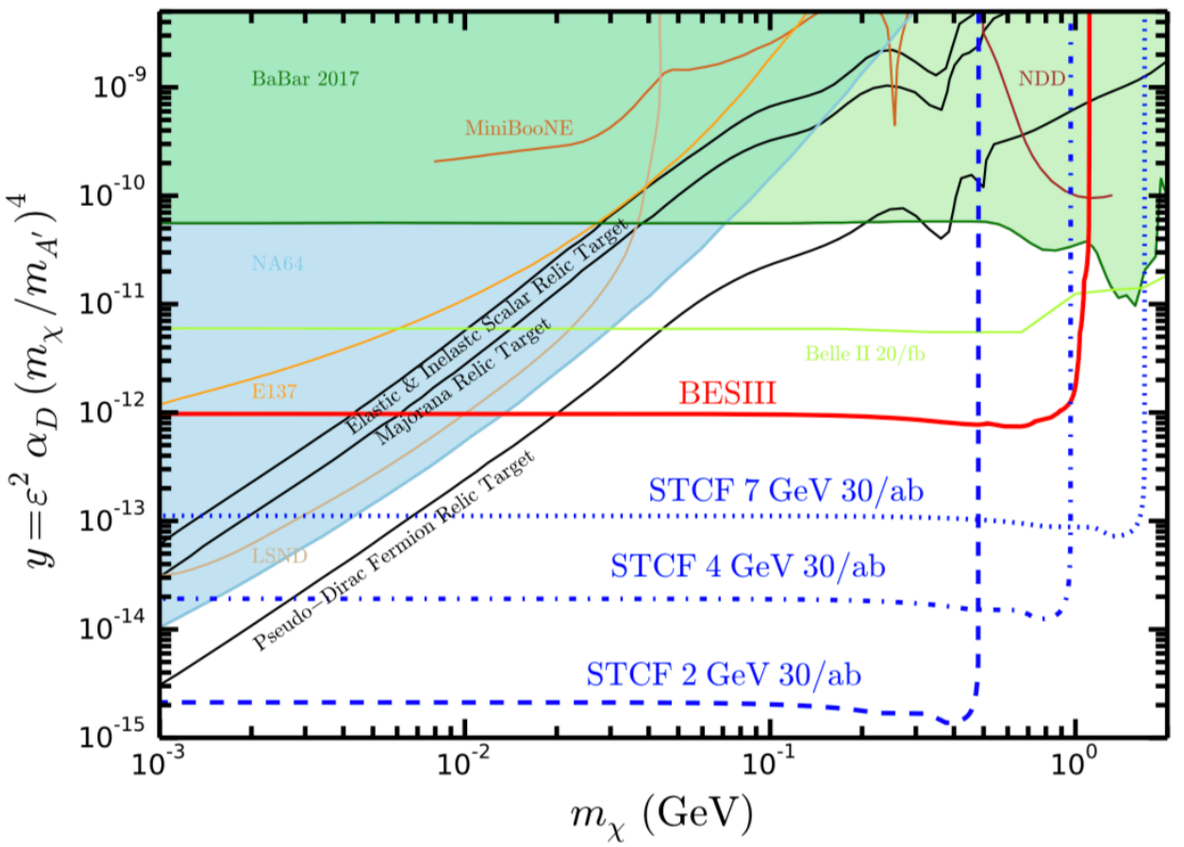

10^{-2}
10^{-3}
10^{-4}
10^{-5}
ω
$(g-2)_e$
$(g-2)_\mu \pm 2\sigma$
$K \to \pi\nu\nu$
BaBar 2017
NA62
NA64
Belle II 20/fb
BESIII 2012−2018 14/fb
STCF 7 GeV 30/ab
STCF 4 GeV 30/ab
STCF 2 GeV 30/ab
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$m_{A'}$ (GeV)

Constraints on light thermal DM

$$y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$$



$m_{A'} = 3m_\chi, \quad \alpha_D = 0.5$



$m_{A'} = 3m_\chi, \quad \alpha_D = 0.005$

安徽大学

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Anhui University

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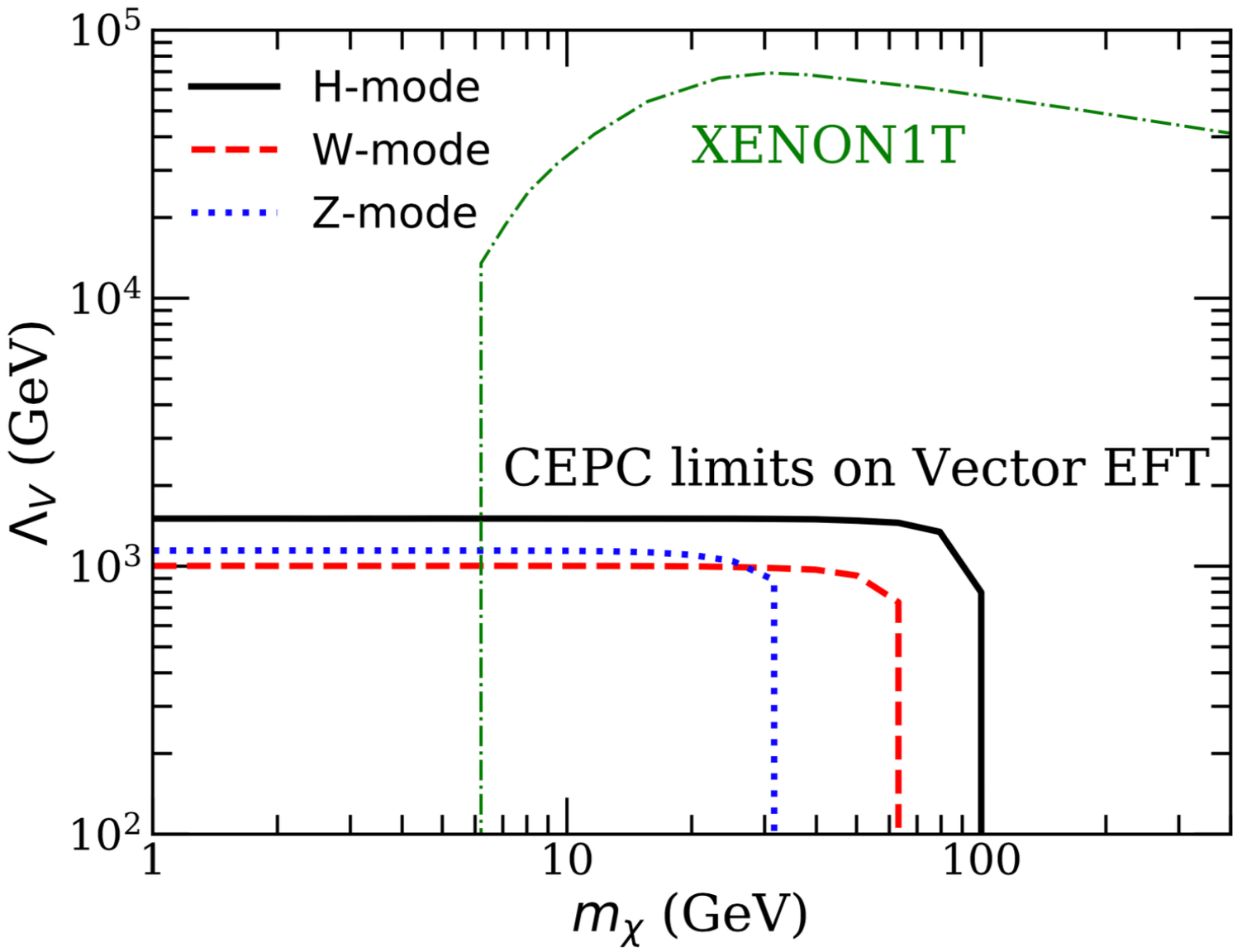
H-mode
W-mode
Z-mode
XENON1T
CEPC limits on Vector EFT
Λ_V (GeV)
m_χ (GeV)
10^5
10^4
10^3
10^2
1
10
100