Probing millicharge at the BESIII detector

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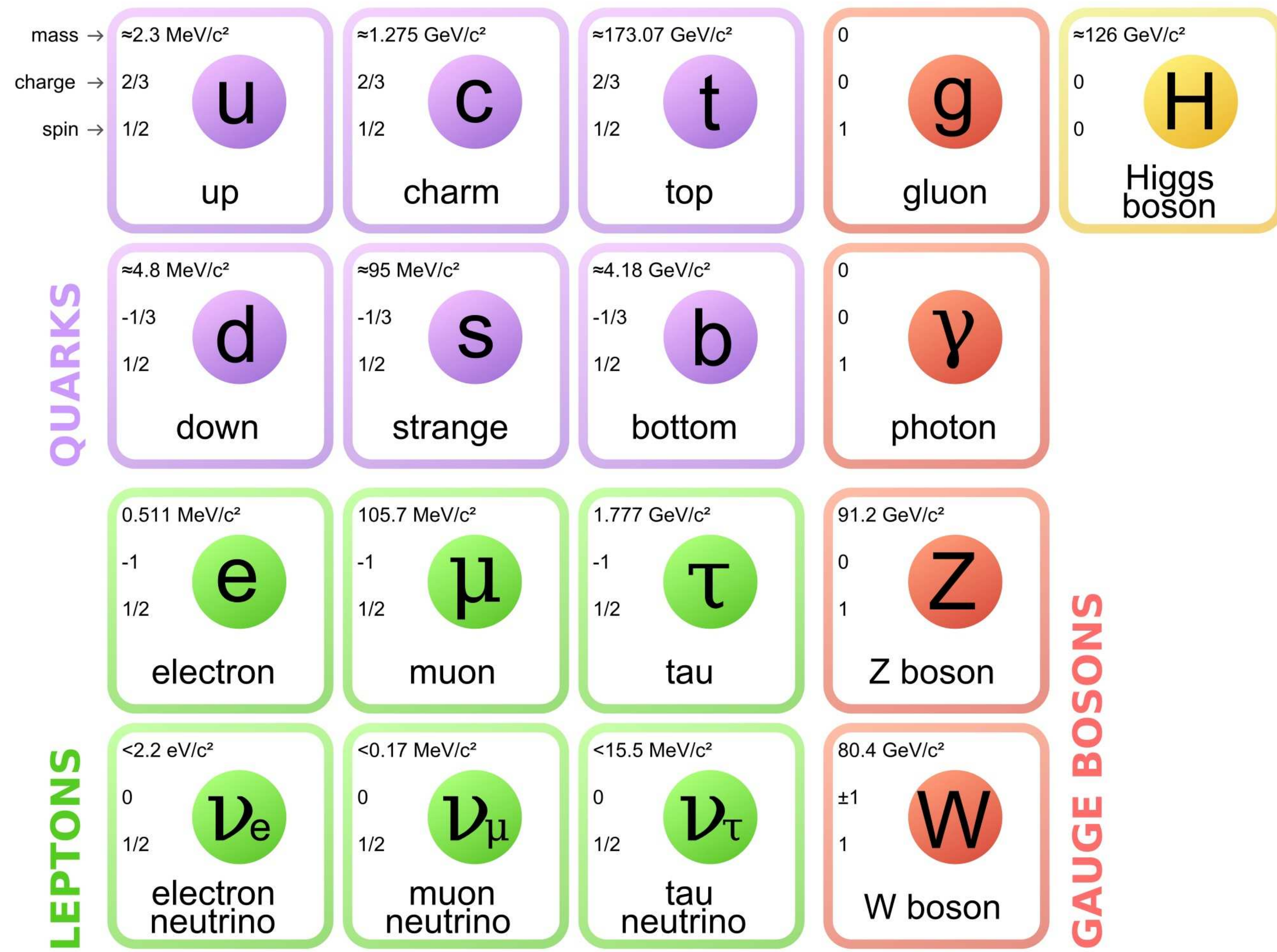
Charge quantization

Charge quantization is an empirical fact.



$Q_u = 2/3$

$Q_d = -1/3$

$Q_e = -1$

$Q_W = \pm 1$

What mechanism quantizes charge?

Magnetic monopole?

Millicharge

In general, electric charge can be of any value

millicharge ε → $\epsilon e A_\mu \bar{\psi}\gamma^\mu \psi$

ε≪1 ⇒ ψ is millicharged

Stringent constraints on millicharge of SM particles

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

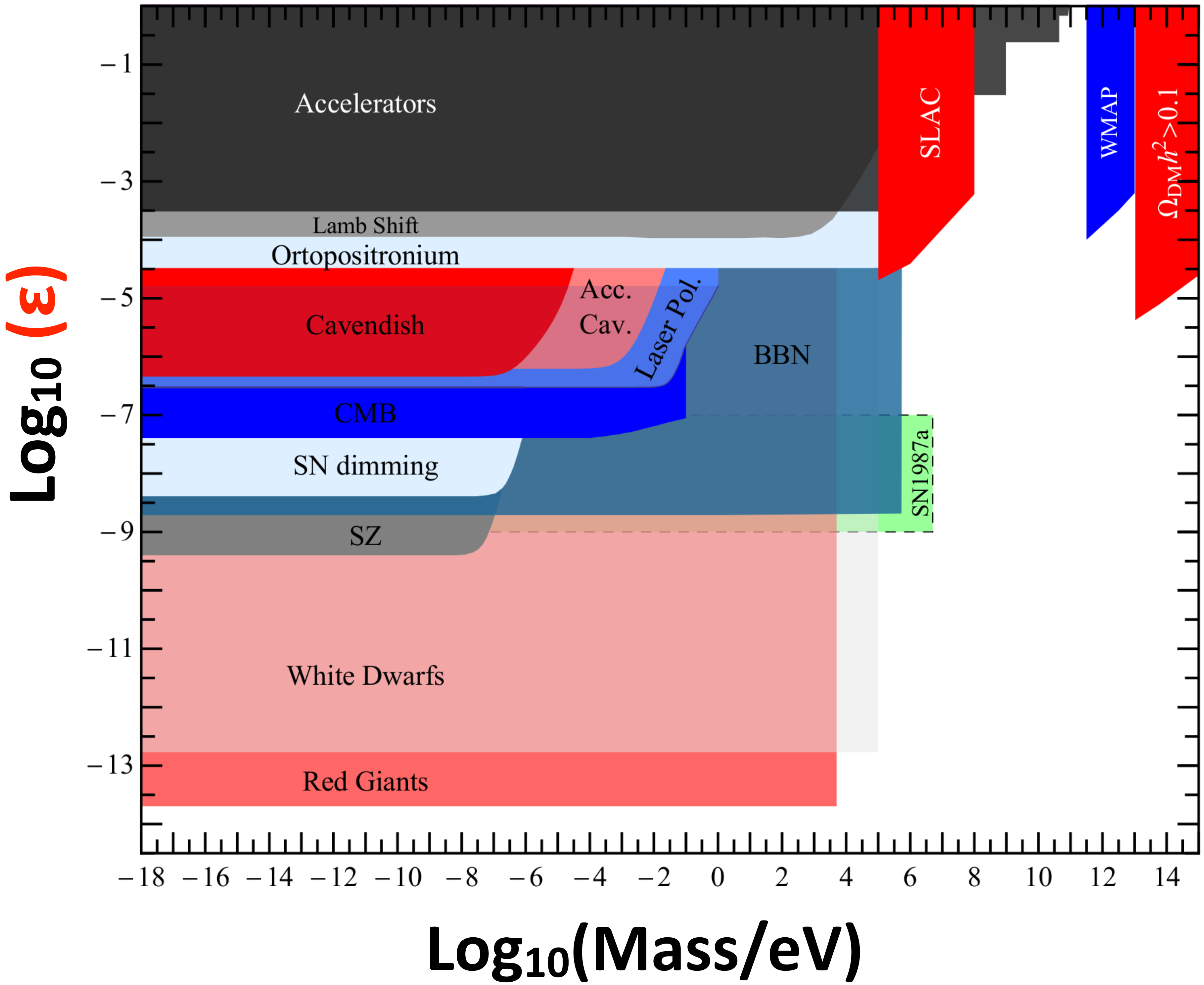
$Q_n < (-0.1 \pm 1.1) \times 10^{-21} e$ **Bressi et al. 2011**

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

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

Constraints on millicharge

millicharged particles beyond standard model



Jaeckel, Ringwald, 1002.0329

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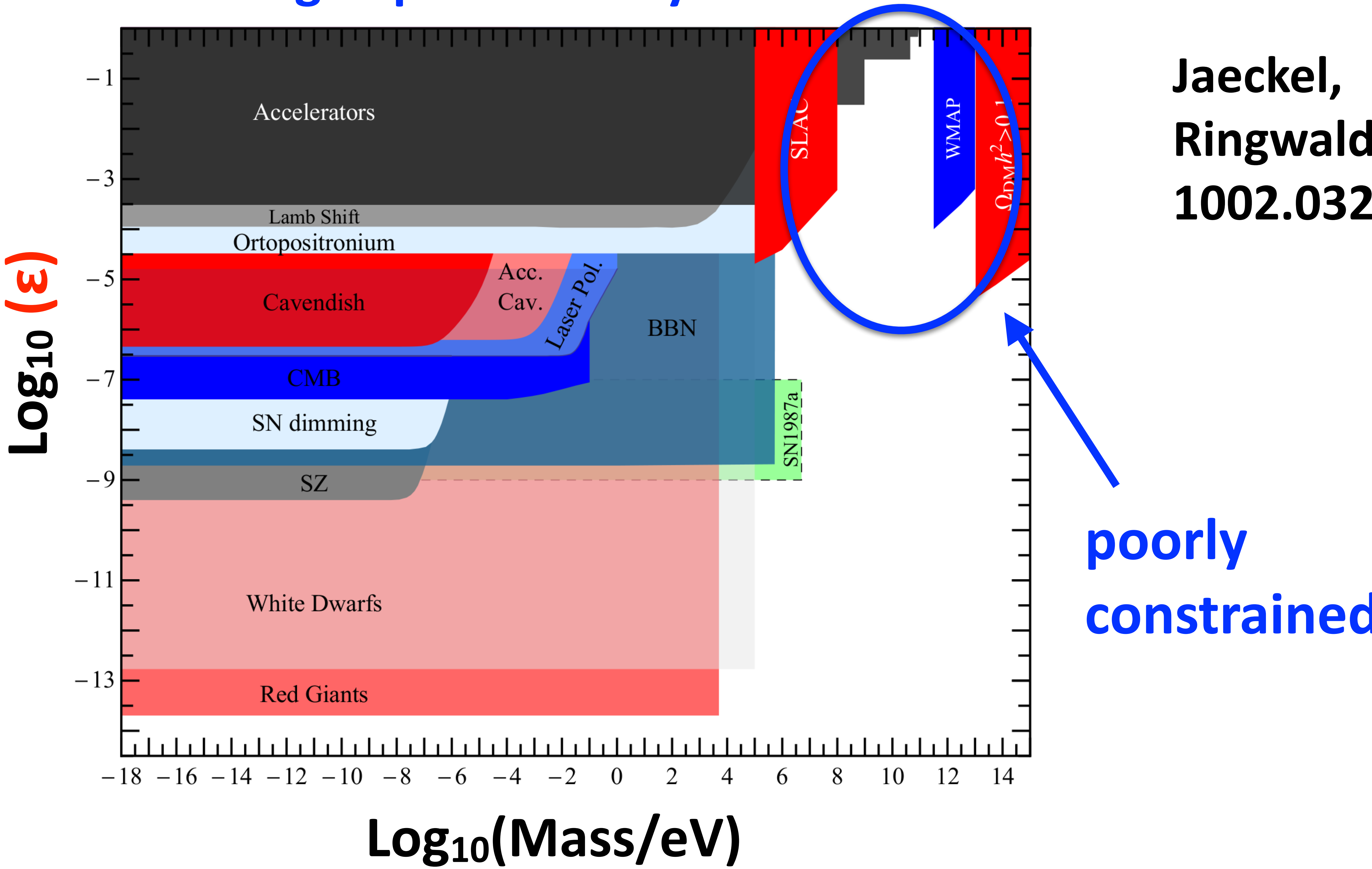

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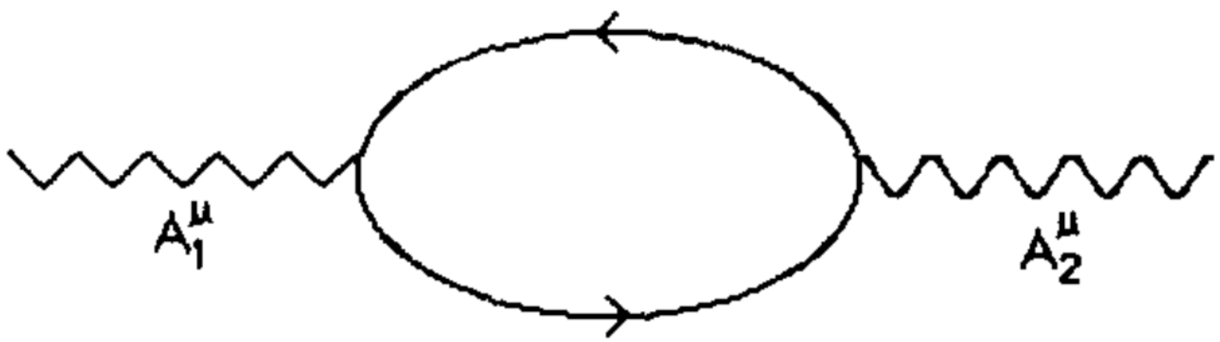
Apparent millicharge generation

Millicharge in low energy EFT



high scale fermions charged under both U(1)s

➡ **kinetic mixing between A_1 and A_2**

➡ **millicharged particles**

Holdom 1986

Millicharge in Stueckelberg models

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

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

➡ **mixing mass terms between $U(1)_Y$ & $U(1)_X$**

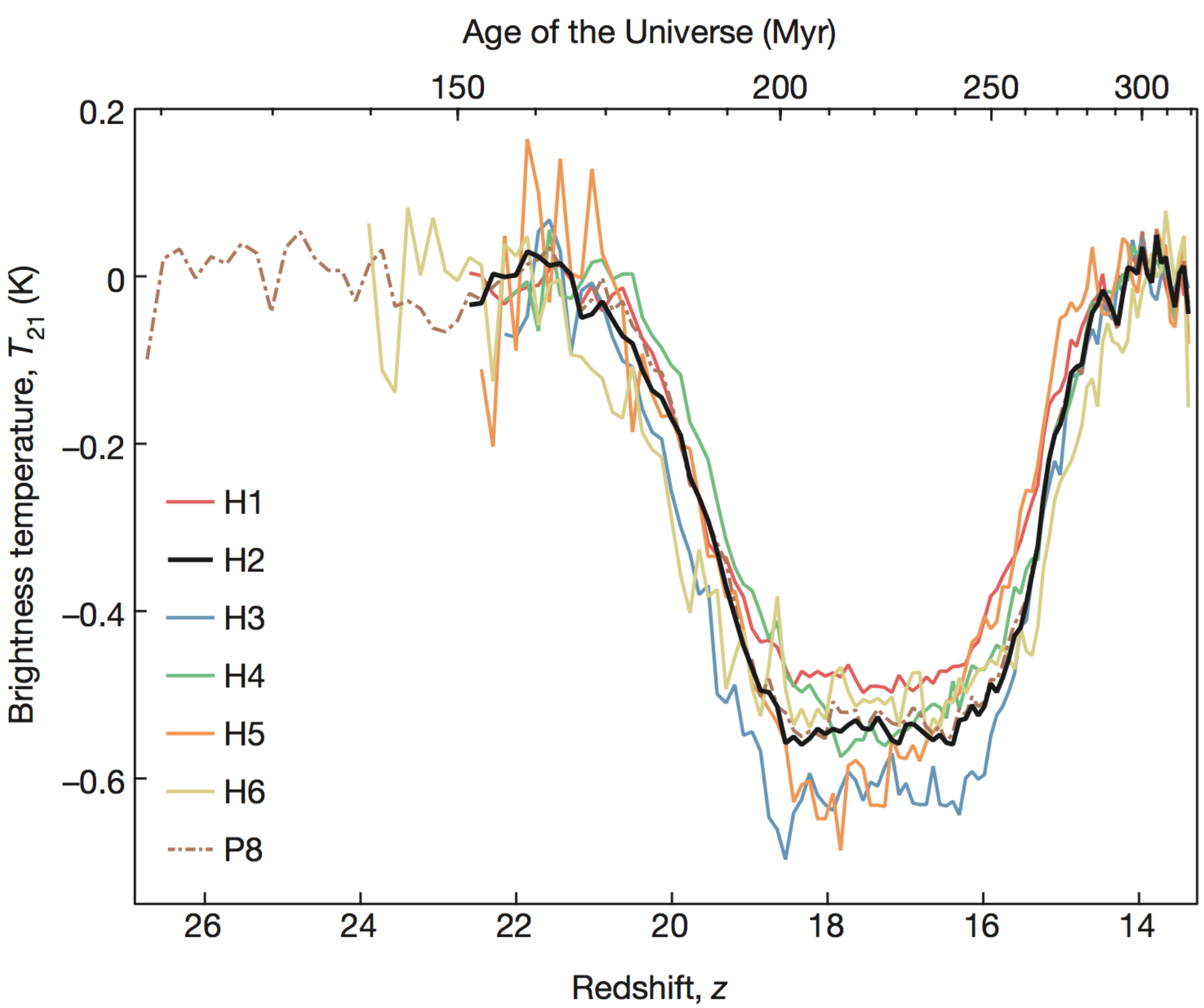
➡ **millicharged hidden sector particles**

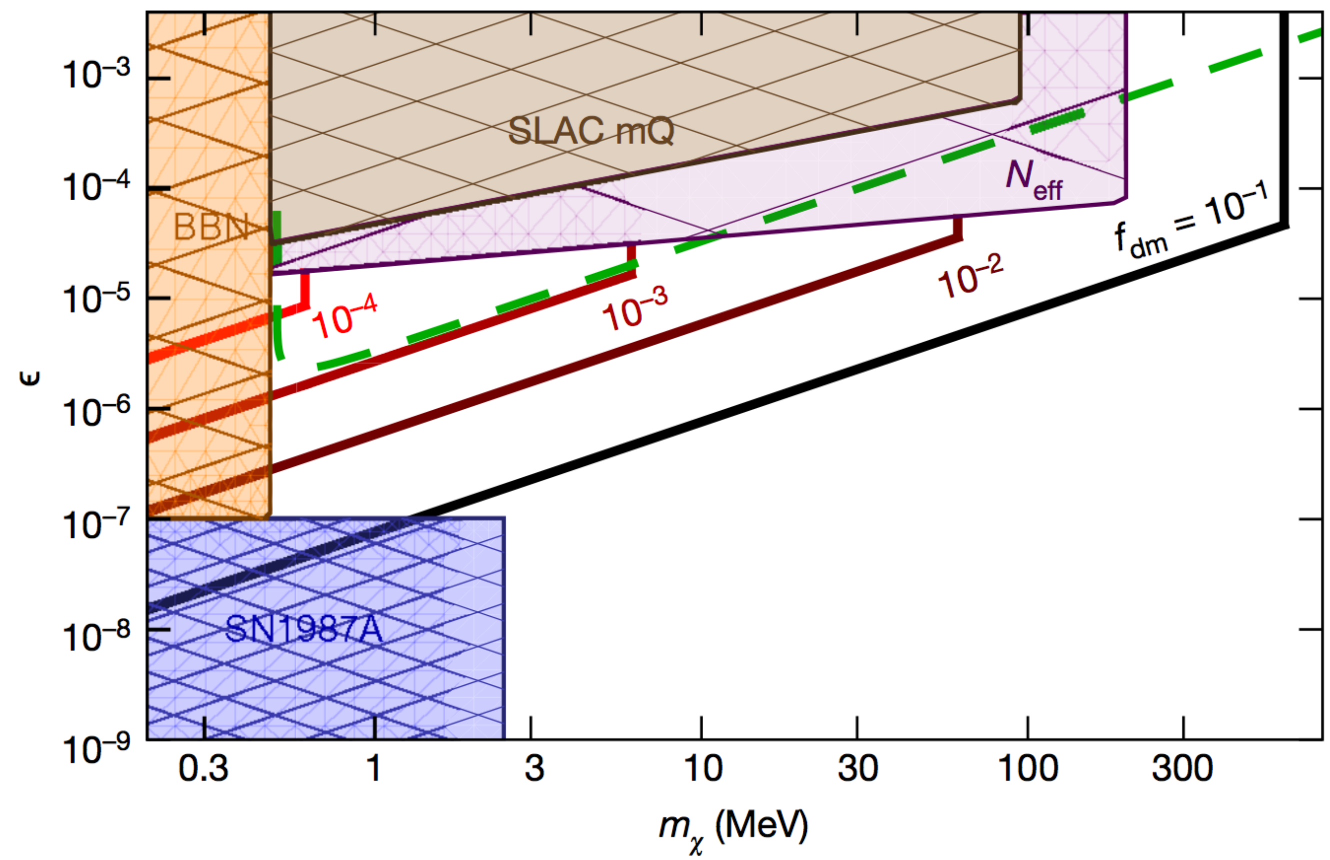
$$\epsilon \sim \frac{m_2}{m_1}$$

Feldman, ZL, Nath, PRD 2007 (235 cites)

Millicharge & 21 cm anomaly

21 cm @ EDGES





momentum transfer xsec

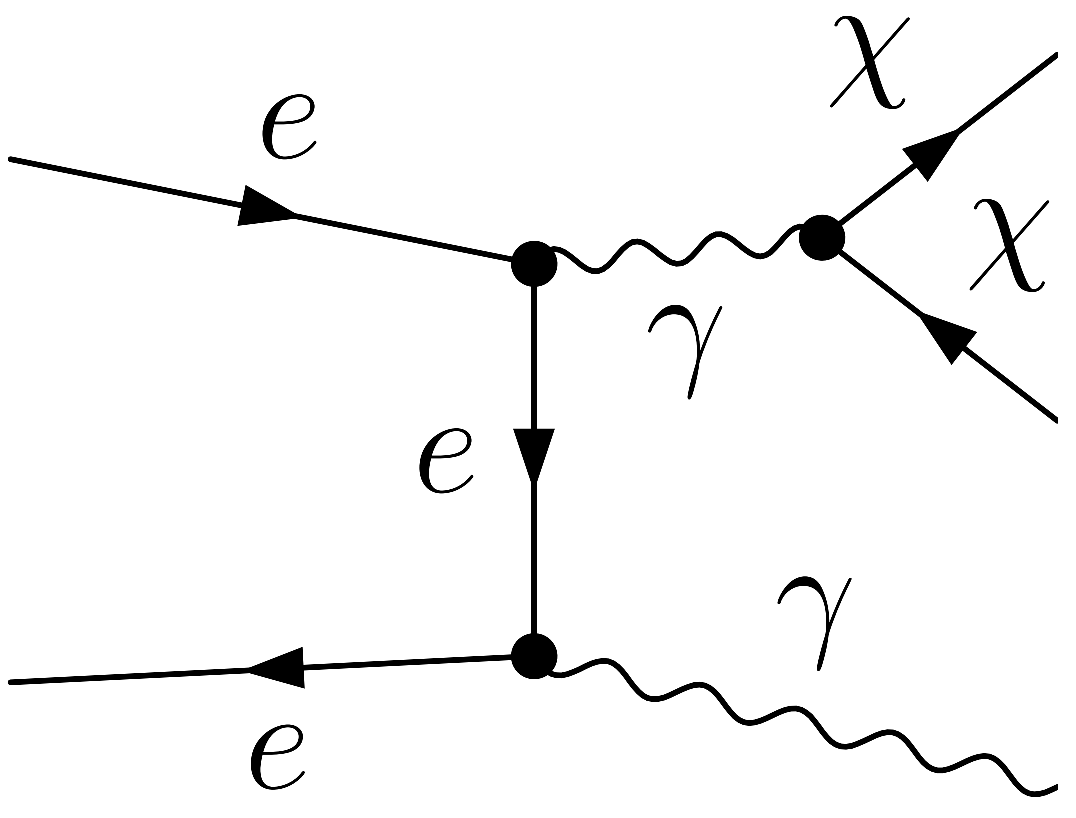
millicharge DM & baryon

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

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

Probing millicharge @ BESIII

new physics process: $e^+ e^- \rightarrow \chi\chi\gamma$



in collaboration with Zhang, Yu (张宇)

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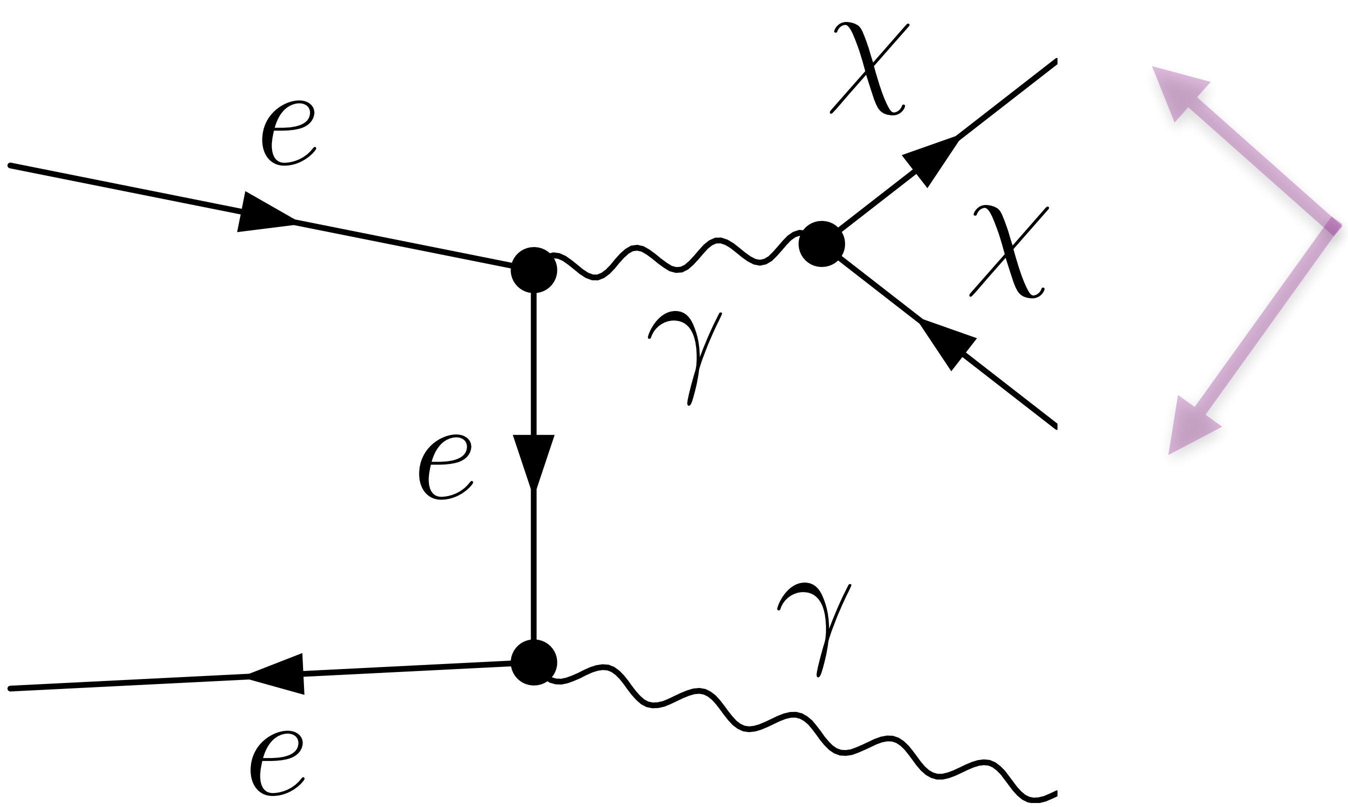

millicharged particles escape detectors

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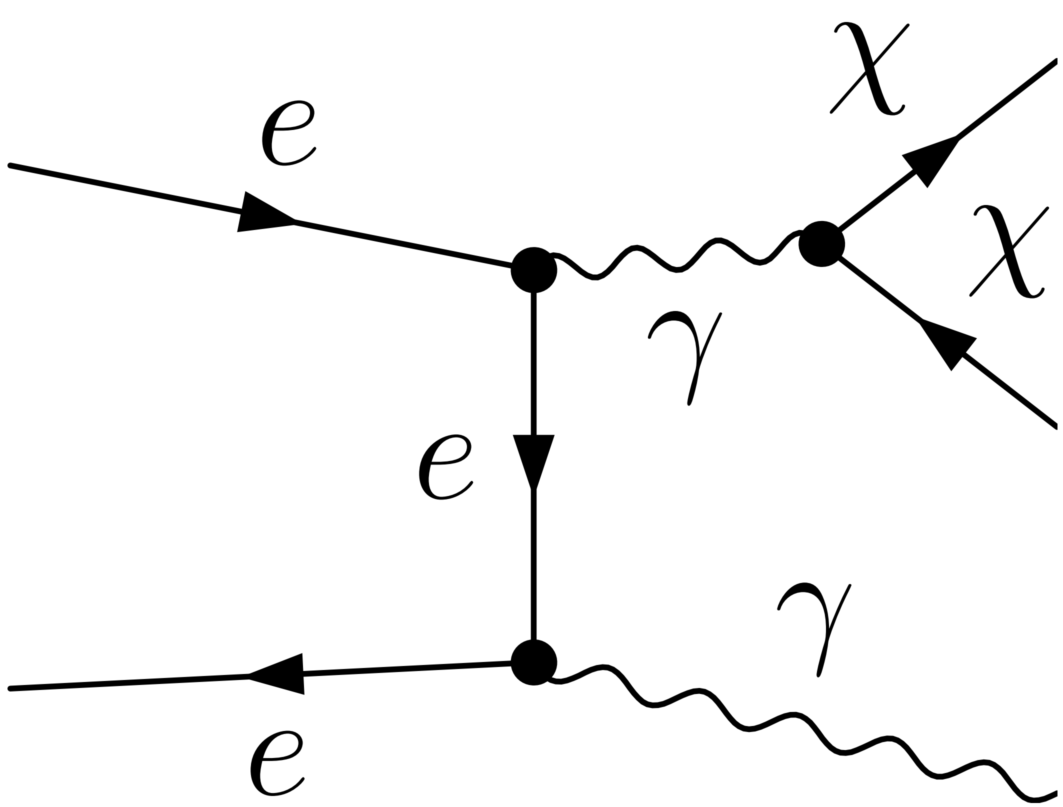


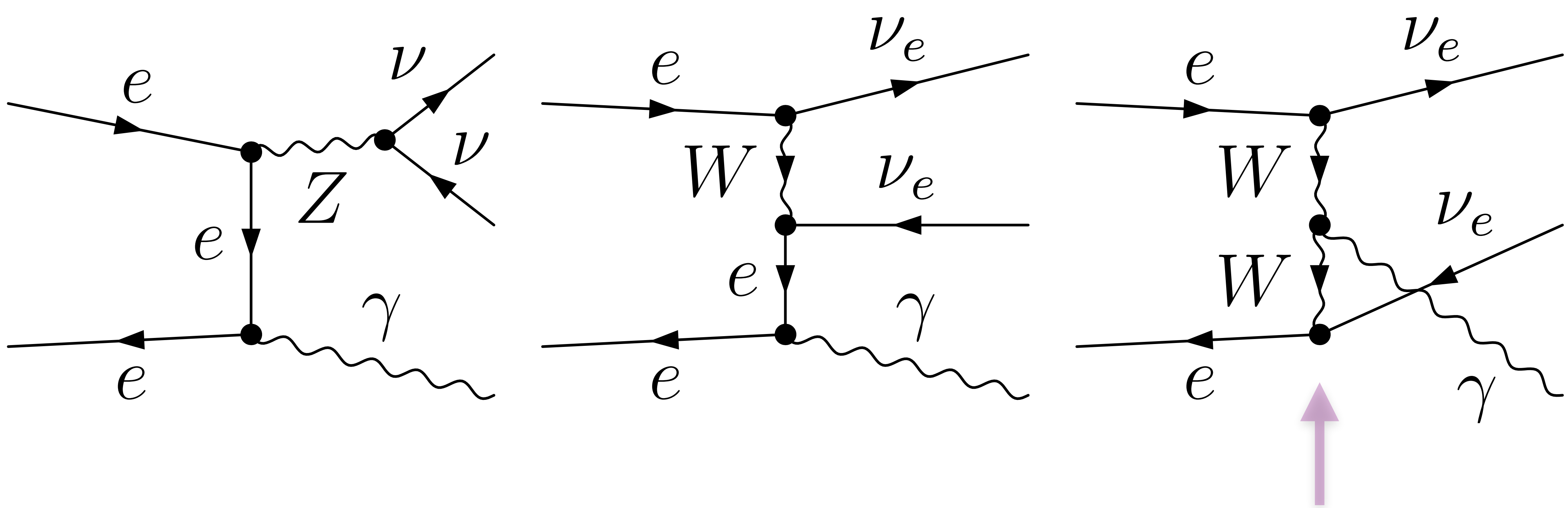
millicharged particles escape detectors

monophoton

in collaboration with Zhang, Yu (张宇)

Irreducible background in SM

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



2W-diagram can be neglected in low energy

Monophoton production xsec

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

$$z_\gamma \equiv \cos\theta_\gamma$$

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

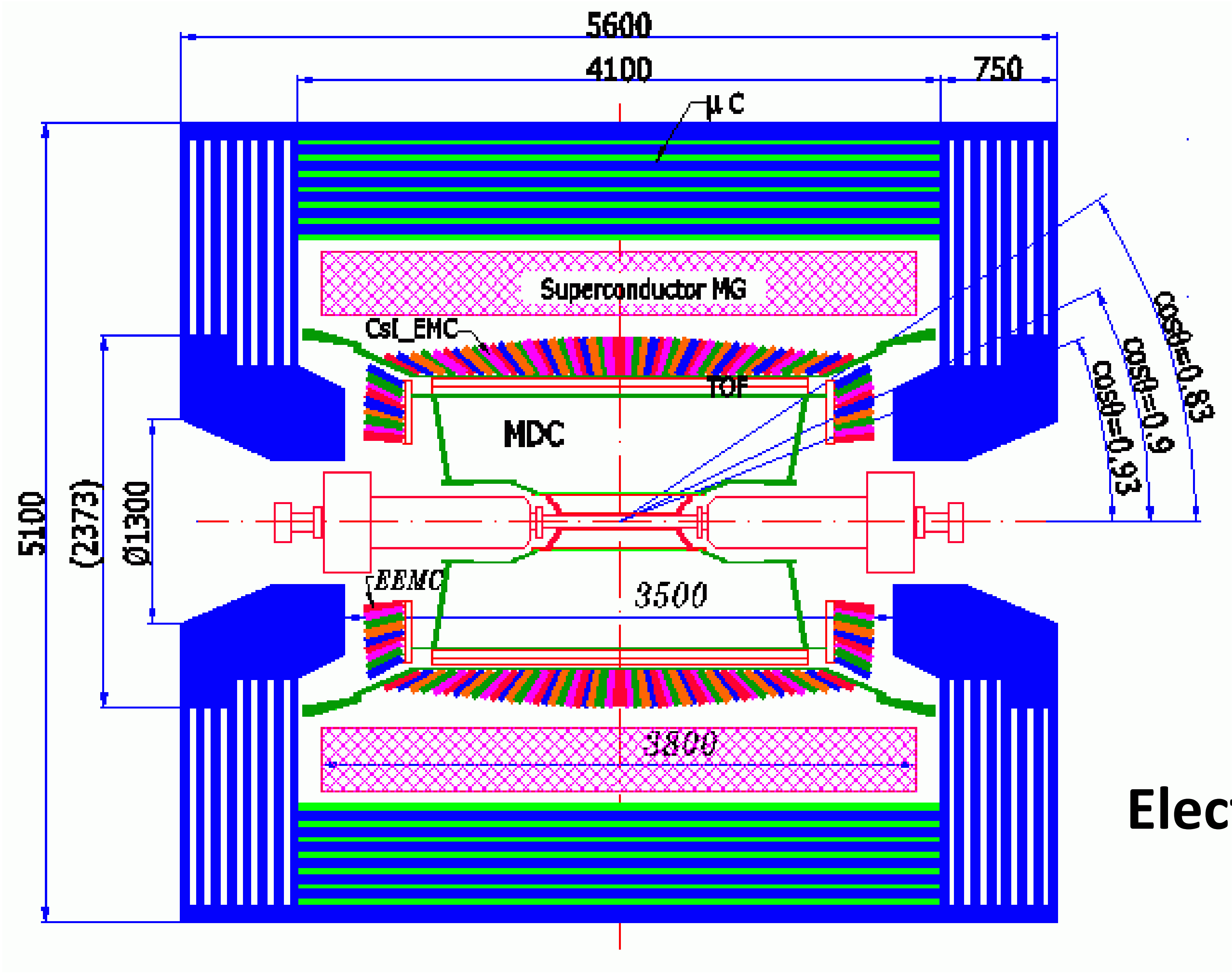
$$s_\gamma = s - 2\sqrt{s}E_\gamma \qquad \beta_\chi = (1 - 4m_\chi^2/s_\gamma)^{1/2}$$

irreducible BG: $e^+ e^- \to \gamma \nu \nu$ [Ma, Okada 1978; Gaemers + 1979]

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

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

The BESIII & its subdetectors



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)

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

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

Electromagnetic calorimeter (EMC)

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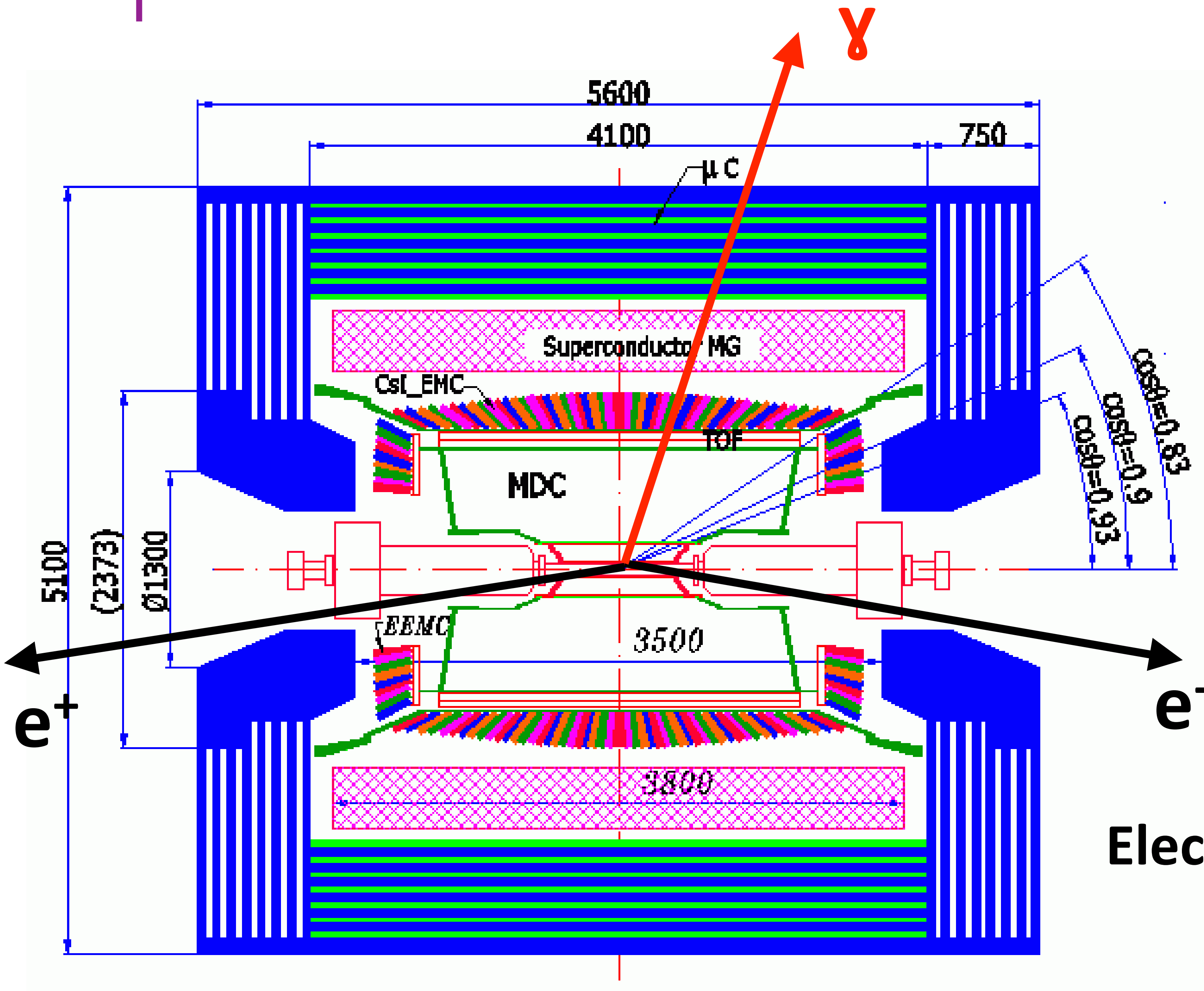

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Basic detector cuts

basic detector cuts

EMC energy range: 20 MeV - 2 GeV

EMC barrel $E_\gamma > 25$ MeV in $|\cos(\theta_\gamma)| < 0.8$

EMC end-caps $E_\gamma > 50$ MeV in $0.86 < |\cos(\theta_\gamma)| < 0.92$

BESIII, 1707.05178

Reducible SM backgrounds

(1) photon from resonance decay (e.g. $J/\psi \to \gamma X$)

(1a) $J/\psi \to \gamma \nu \nu$ negligible irreducible BG

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

(1b) $J/\psi \to \gamma f f$ w/ f being undetected

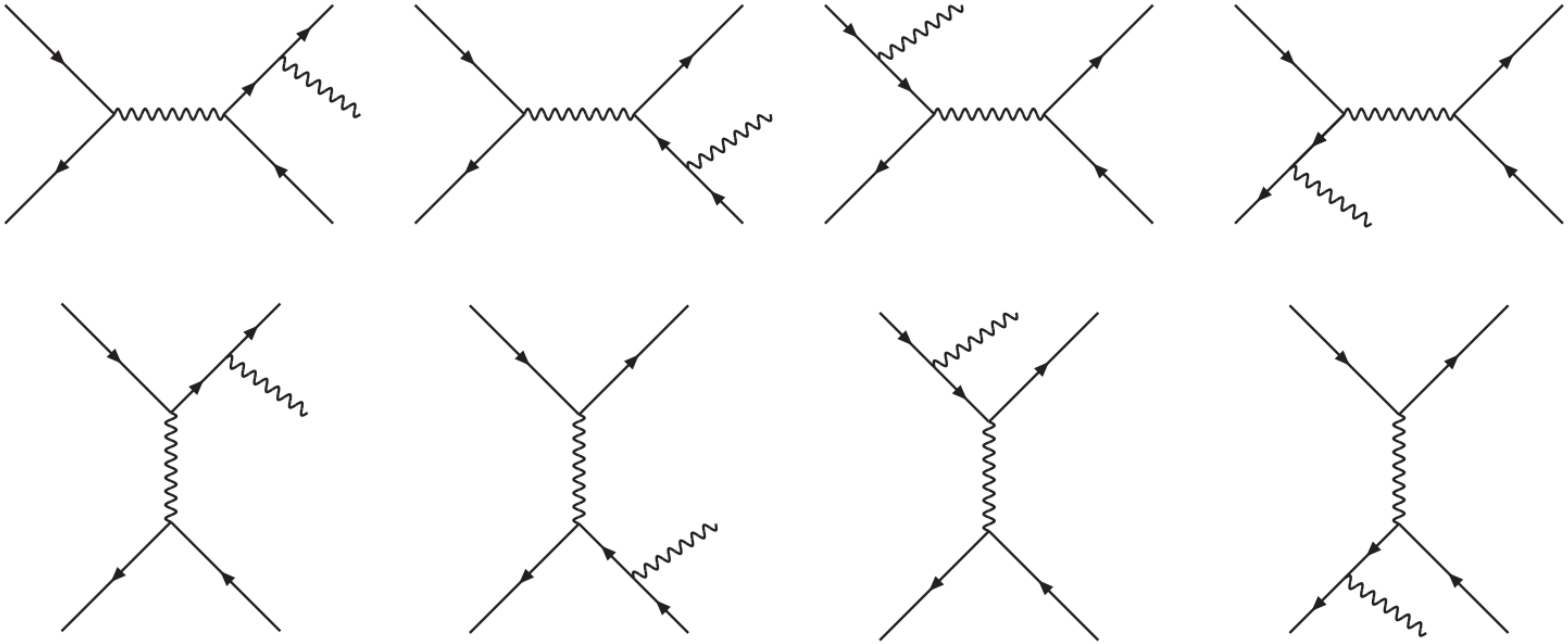
(2) photon in $e^+ e^- \to e^+ e^- \gamma$ w/ $e^+ e^-$ being undetected

(3) photon in $e^+ e^- \to f f \gamma$ w/ f f being undetected

(4) photon in $e^+ e^- \to \gamma \gamma \gamma$ w/ only 1 photon detected

$e^+ e^- \rightarrow e^+ e^- \gamma$ in SM

Actis, Mastrolia, Ossla, 0909.1750



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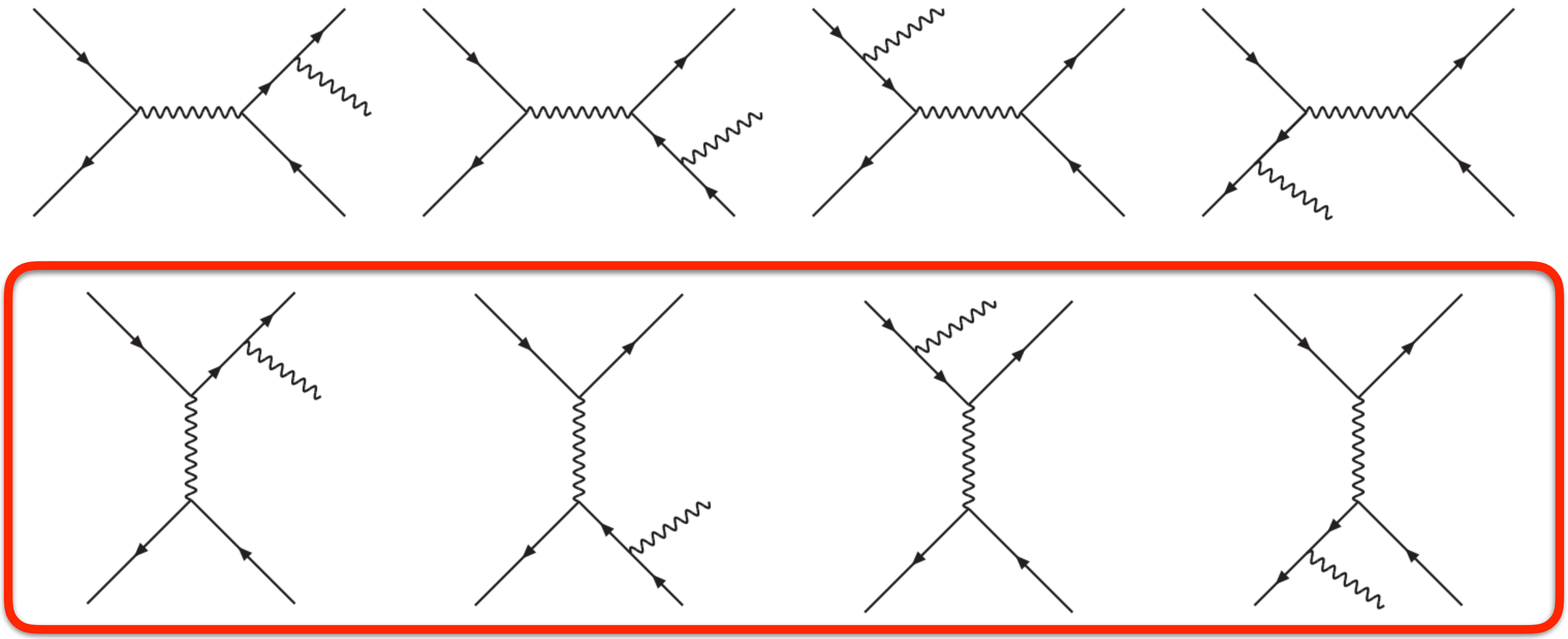


collinear singularity in the t-channel

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

Collider signal calculation

(1) Signal & irreducible BG — Analytic differential xsec

(2) Reducible BGs — FeynArts & FormCalc

$E_\gamma > 1$ MeV to remove the IR divergence in $e^+ e^- \to \gamma \gamma \gamma$

(3) Meson decays — EvtGen

BESIII detector simulation

Energy resolution in EMC **Chao, Wang et al. 0809.1869**

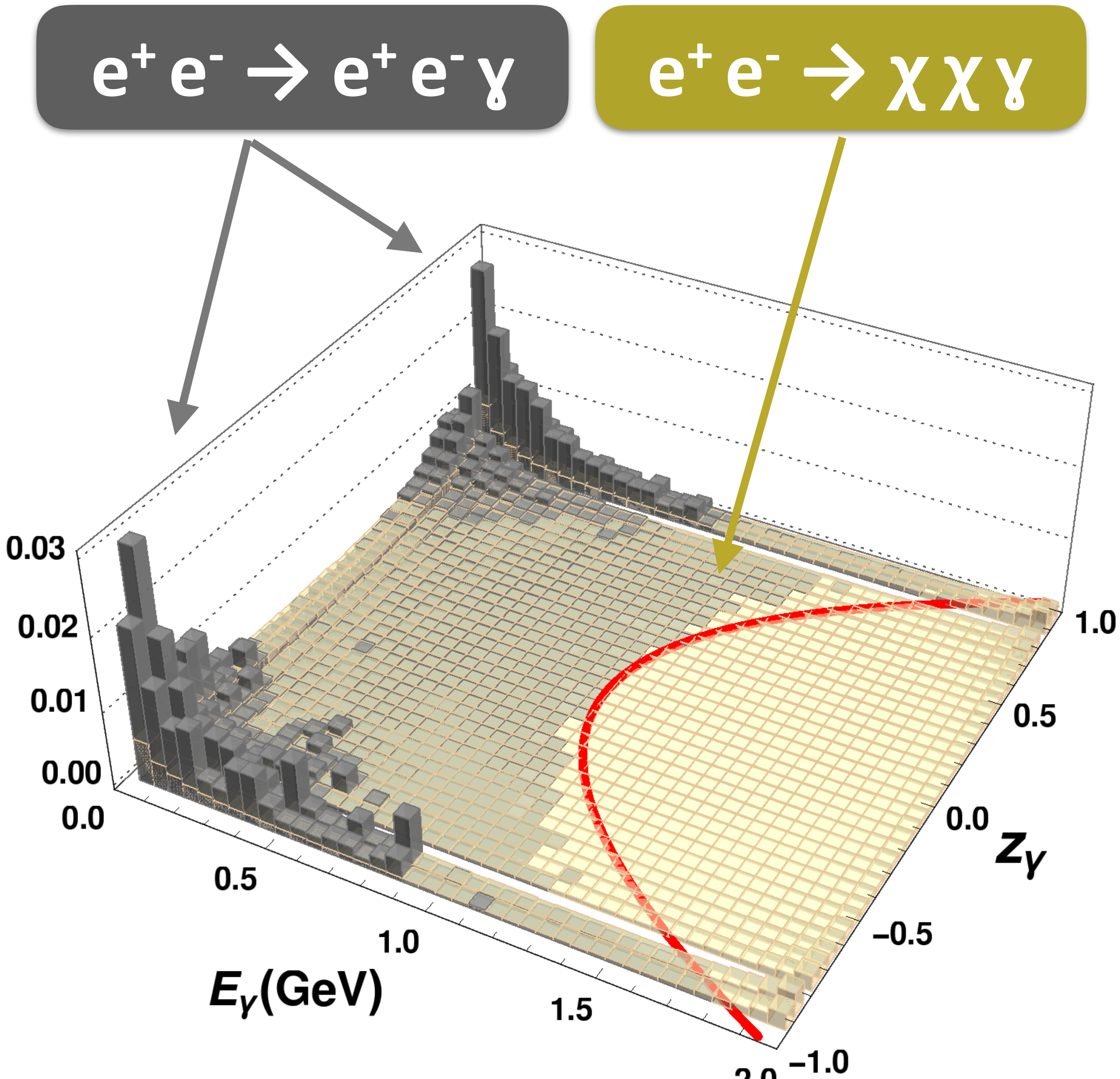
$$\frac{\sigma(E)}{E} = \frac{2.3\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$$

Angular resolution in EMC **Prasad et al. 1504.07870**

$$\sigma(\theta) = \left(\frac{0.024}{\sqrt{E/\mathrm{GeV}}} - 0.002\right)(\mathrm{rad})$$

Gaussian smearing for both energy and polar angle

E_γ & $\cos(\theta_\gamma)$ distribution



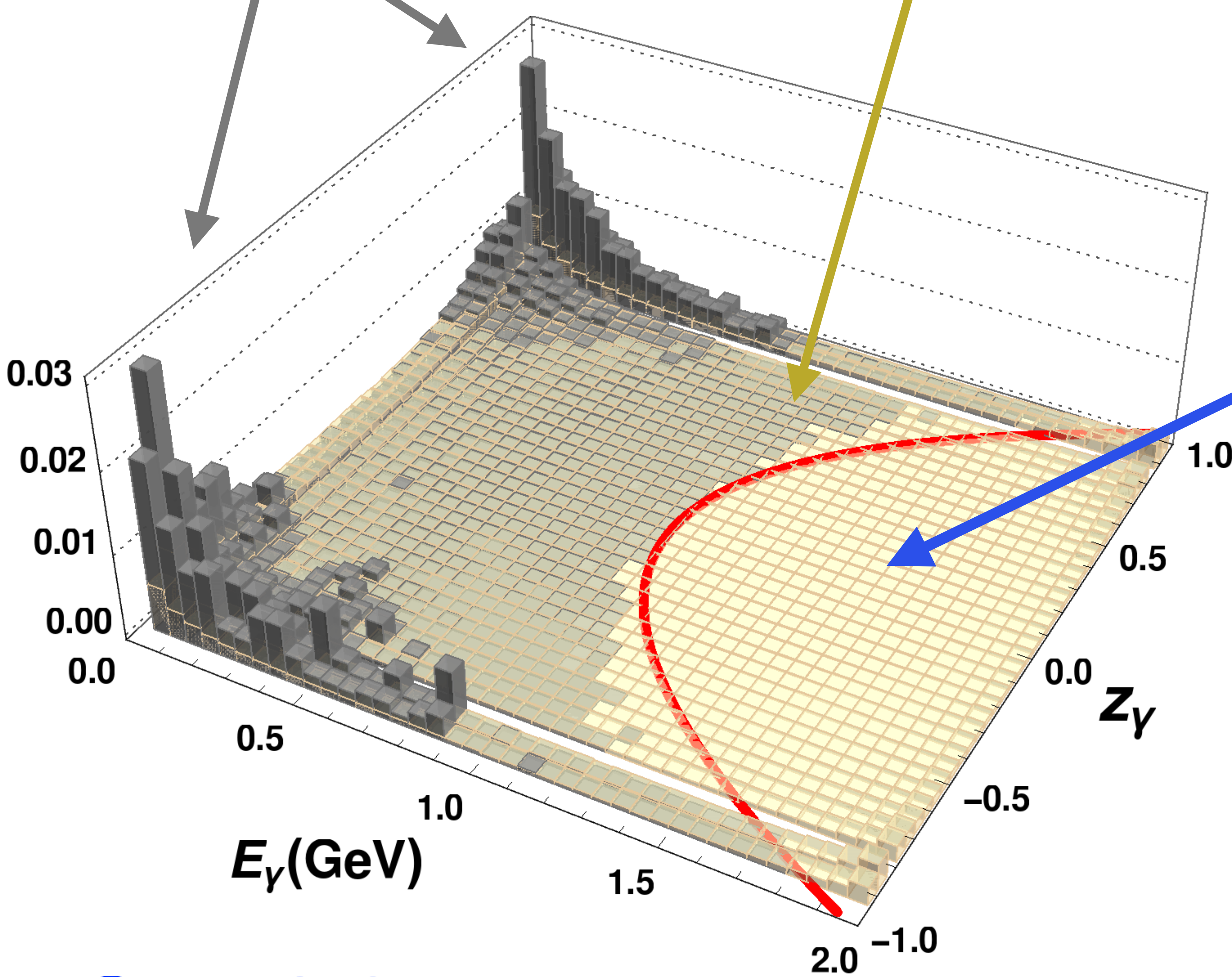
@ 4.18 GeV

E_γ & $\cos(\theta_\gamma)$ distribution

$e^+e^- \to e^+e^-\gamma$

$e^+e^- \to \chi\chi\gamma$

energy conservation violation in $e^+e^-\gamma$



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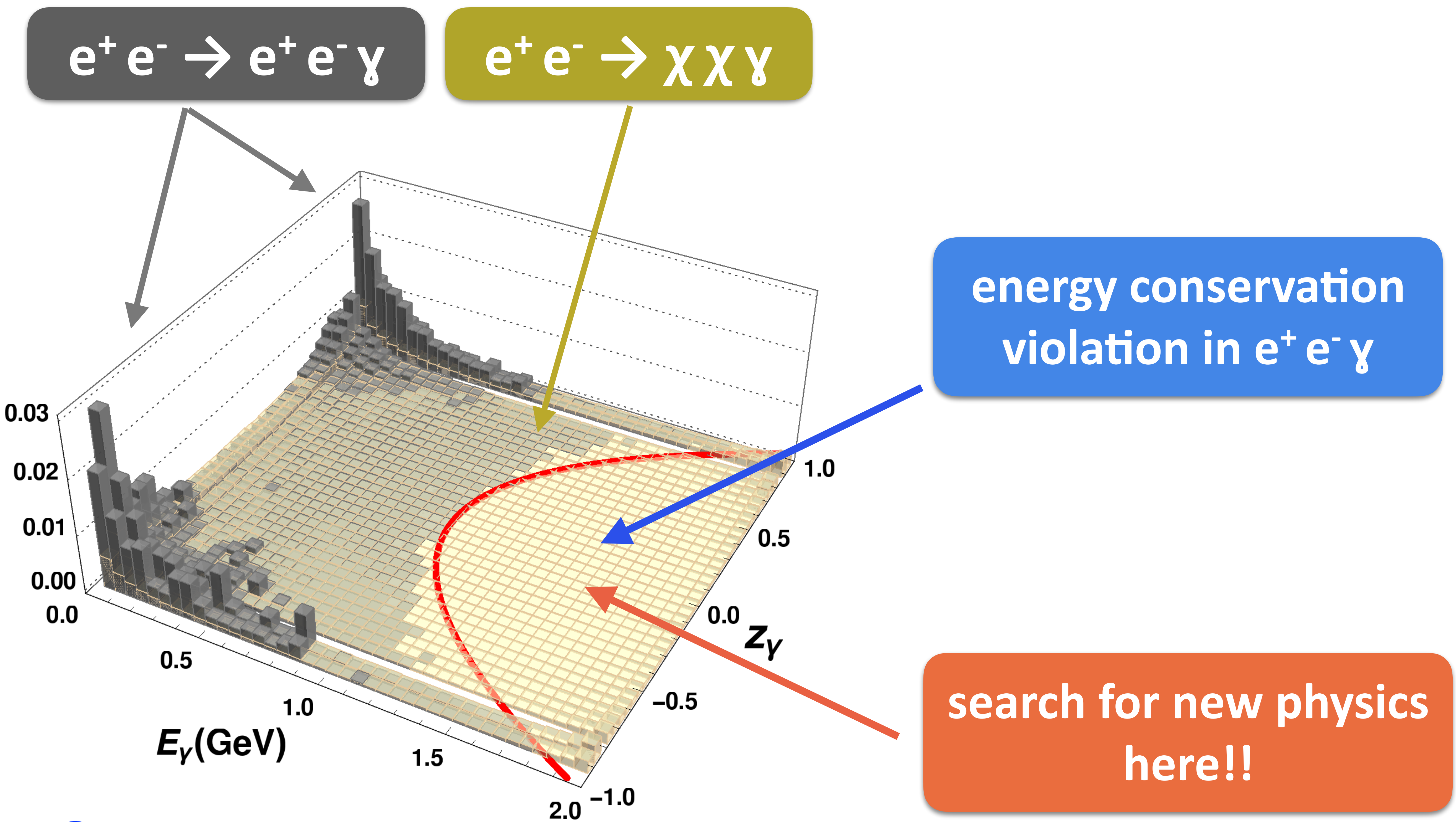
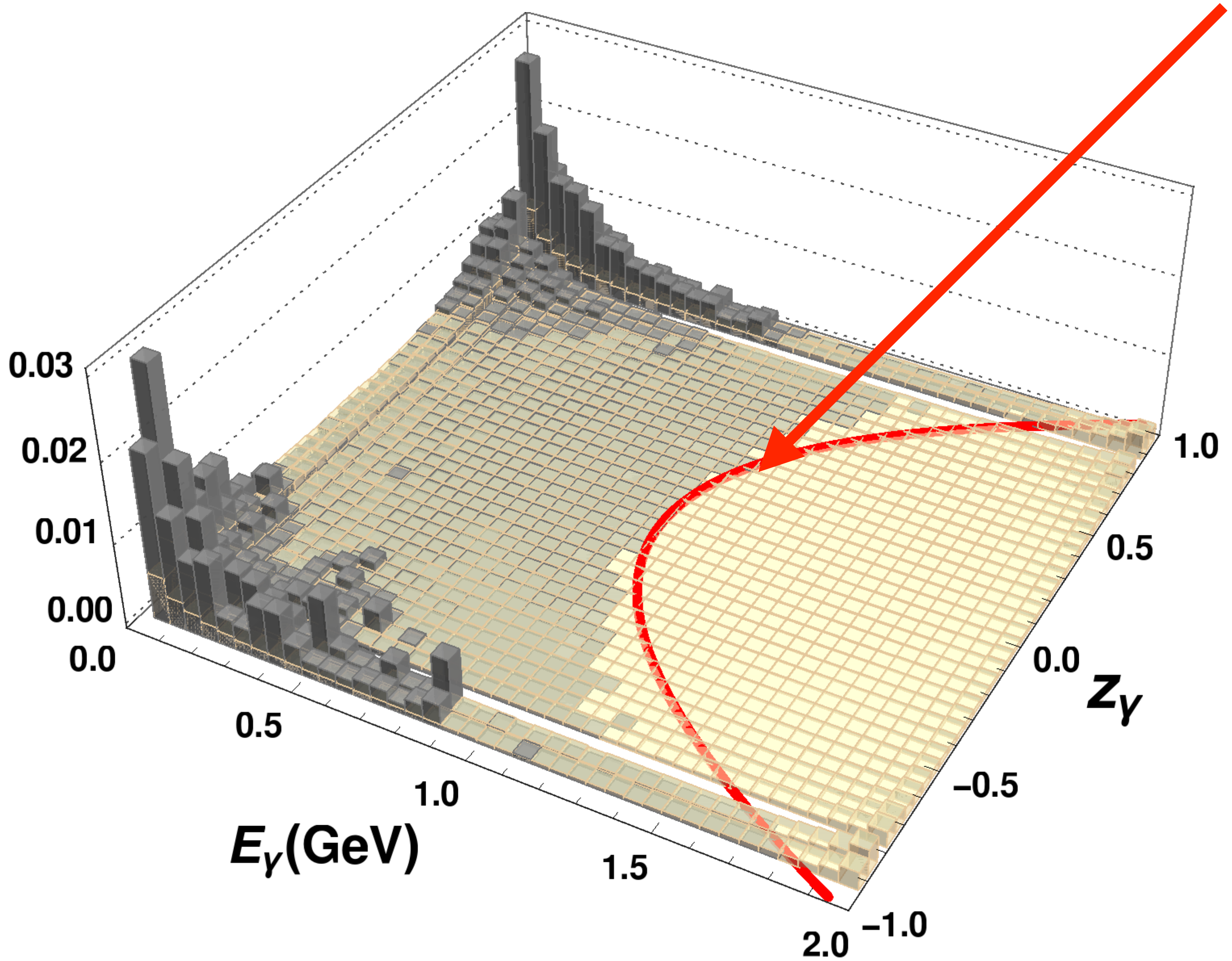


@ 4.18 GeV

Advanced cuts

@ 4.18 GeV



Advanced cuts

E_γ/GeV>a $\cos^2(\theta_\gamma)$ + b

@ 4.18 GeV

a = 0.99

b = 0.99

optimized for

$e^+e^-\gamma$ & $\gamma\gamma\gamma$

Advanced cuts remove the reducible BGs

NP versus SMBGs

@ 4.18 GeV

xsec in fb

$m_\chi = 0.1\,\mathrm{GeV}$ $\varepsilon = 0.01$

$\mathcal{L} = 1\ \mathrm{fb}^{-1}$

Cuts	$\chi\bar{\chi}\gamma$	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$\gamma\gamma\gamma$	$\mathcal{S}$
Basic	32.3	1.39	6.9×10^7	2.6×10^4	4.5×10^5	0.0038

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high efficiency for millicharge!

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high efficiency for millicharge!

Eliminating the reducible BGs!

$$\mathcal{S} = \frac{S}{\sqrt{S+B}}$$

BESIII data, cuts & limits

Year	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	a	b	ε_{95}
2015	2.125	0.1	0.52	0.53	0.015
2012	3.097	0.32	0.68	1.12	0.015
2017	3.515	0.5	0.79	0.86	0.0095
2011	3.554	0.024	0.84	0.86	0.044
2012	3.686	0.51	0.95	1.21	0.013
2011	3.773	1.99	0.89	0.94	0.0051
2017	3.872	0.2	0.90	0.96	0.016
2011	4.009	0.5	0.92	0.98	0.011
2016	4.18	3.1	0.99	0.99	0.0060
2013	4.23	1.05	1.00	1.01	0.011
2013	4.26	0.83	1.01	1.02	0.013
2017	4.28	3.9	1.04	1.04	0.0063
2012	4.36	0.5	1.06	1.05	0.019
2014	4.42	1	1.02	1.08	0.014
2014	4.6	0.5	1.04	1.14	0.024
11-17	-	15.024	-	-	8.6×10^{-4}

2011-2017 data

monophoton trigger since 2011

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optimized for each energy

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$E_\gamma/\mathrm{GeV} > a\cos^2(\theta_\gamma) + b$

optimized for each energy

m = 0.1 GeV

2011-2017 data

monophoton trigger since 2011

Methodology of combining data

combine data @ different collision energies

chi-square $$\chi_i^2 \equiv \frac{S_i}{\sqrt{S_i + B_i}}$$ **@ each running energy**

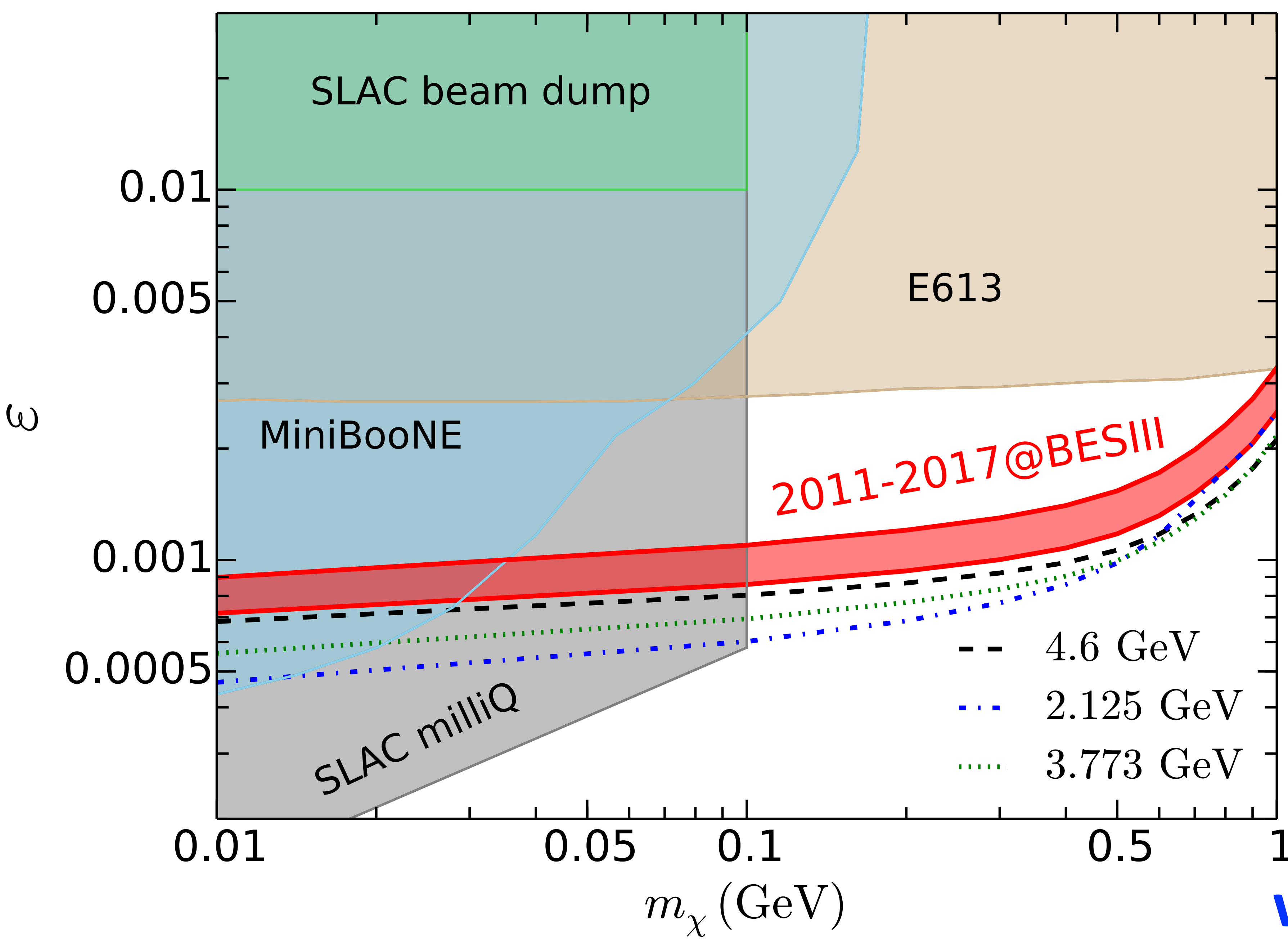
likelihood $$\mathcal{L}_i = \mathrm{Exp}\left(-\frac{1}{2}\chi_i^2\right)$$

total likelihood $$\mathcal{L} = \Pi_i \mathcal{L}_i$$

test-statistic $$\mathrm{TS}(\epsilon) = -2\ln\mathcal{L}(\epsilon)$$

95% C.L. limit $$\mathrm{TS}(\epsilon_{95}) - \mathrm{TS}(0) = 2.71$$

New leading limits



95% CL limit

data 2011-2017

5 more BG events (instrumental?)

projections w/ 10/fb @ 2.125 GeV

w/ 10/fb @ 4.6 GeV

w/ 15/fb @ 3.773 GeV

ZL, Zhang, 1808.00983

Summary

- **Millicharged particles are interesting beyond standard model new particles.**
- **Current (and future) data in the BESIII detector provide new leading limits on millicharged particles in the 100 MeV to GeV mass range.**
- **Millicharge $\varepsilon \sim 10^{-3}$ can be probed at BESIII for a 100 MeV mass.**
- **Our limits do not assume that millicharged particle is dark matter.**

Thank you!