Probing millicharge at colliders

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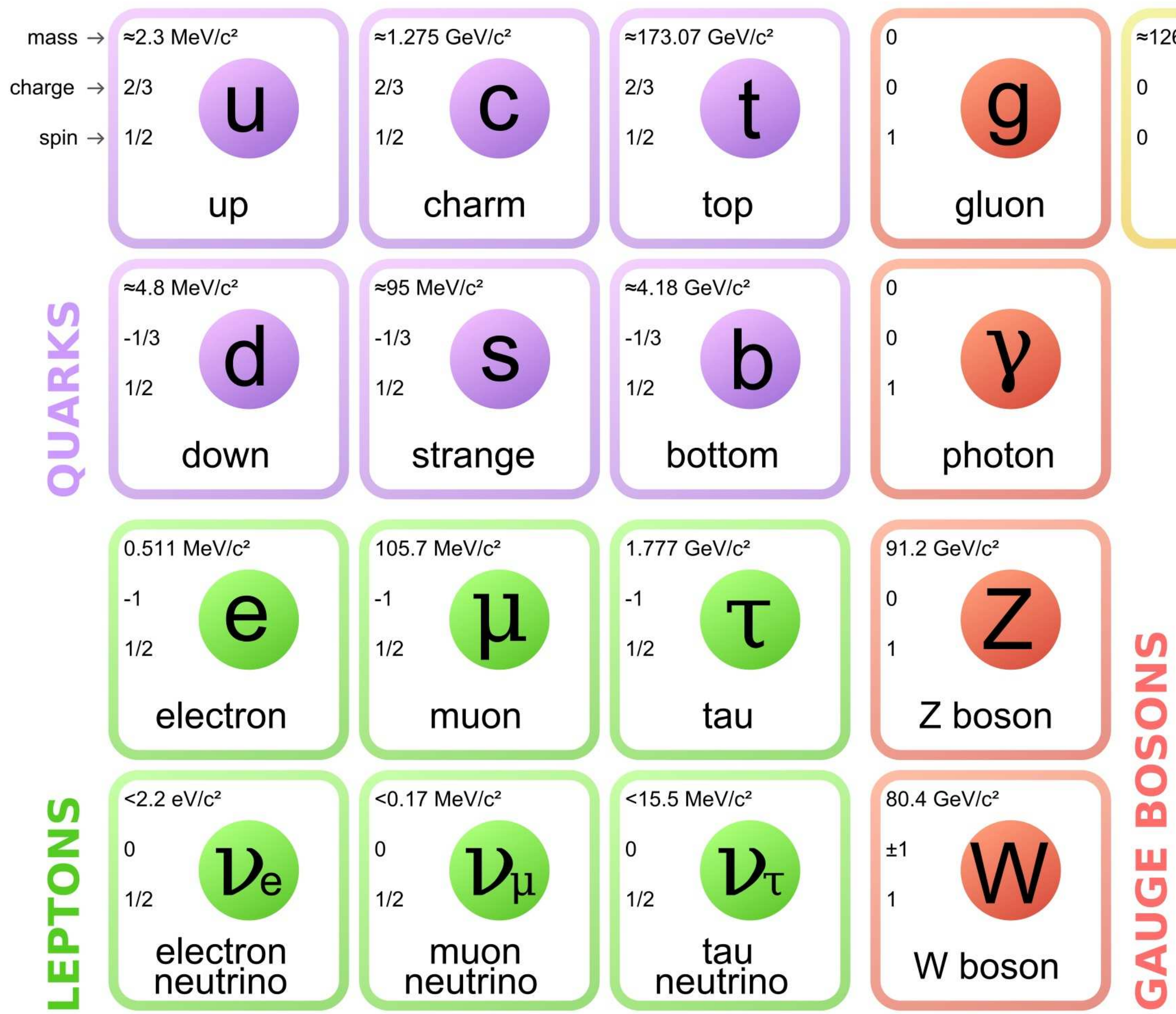
Outline

- Motivation
- Constraints on millicharge
- Collider searches
- Summary

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

particle ψ is called millicharged (w.r.t. SM photon A_μ), if ε is very small, i.e. ε≪1.

Stringent constraints on millicharge of SM particles

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

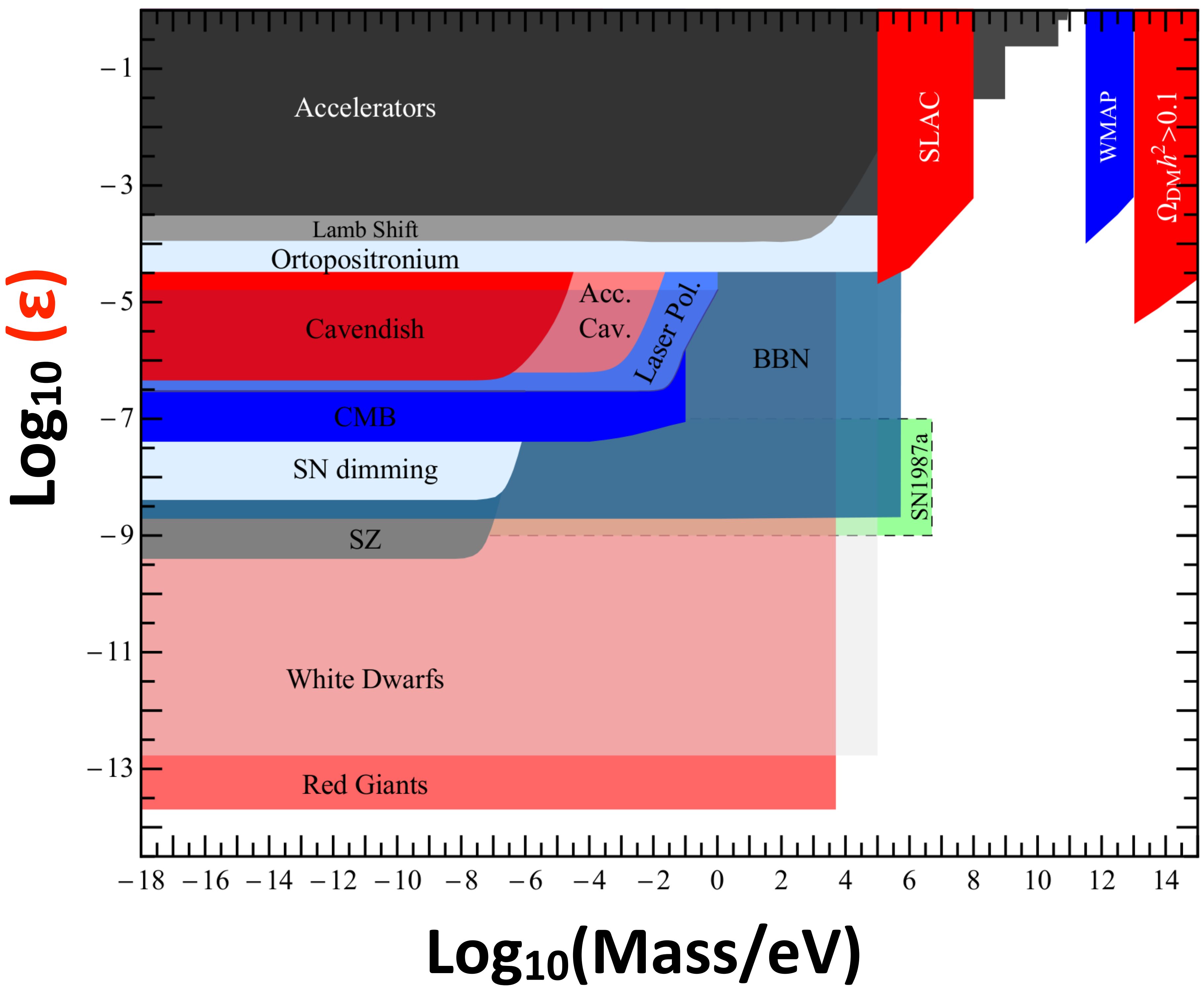
$Q_n < (-0.1 \pm 1.1) \times 10^{-21} e$ **Bressi et al. 2011**

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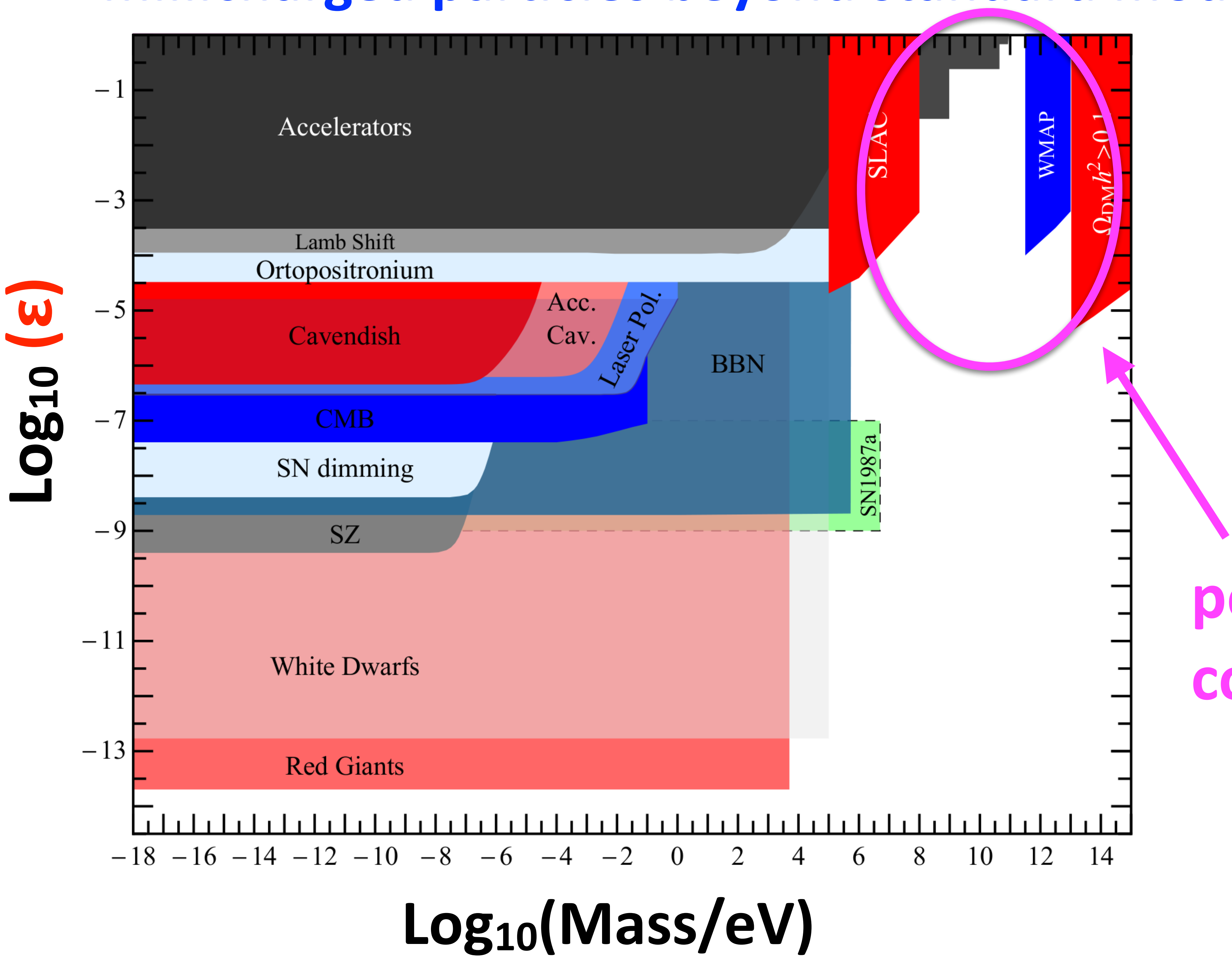

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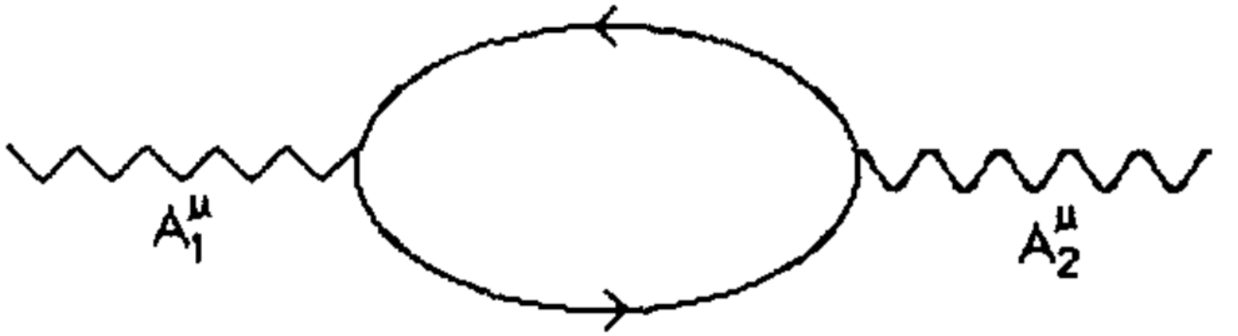
Apparent millicharge generation

Millicharge in low energy EFT



high scale fermions charged under 2 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)$_X$

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

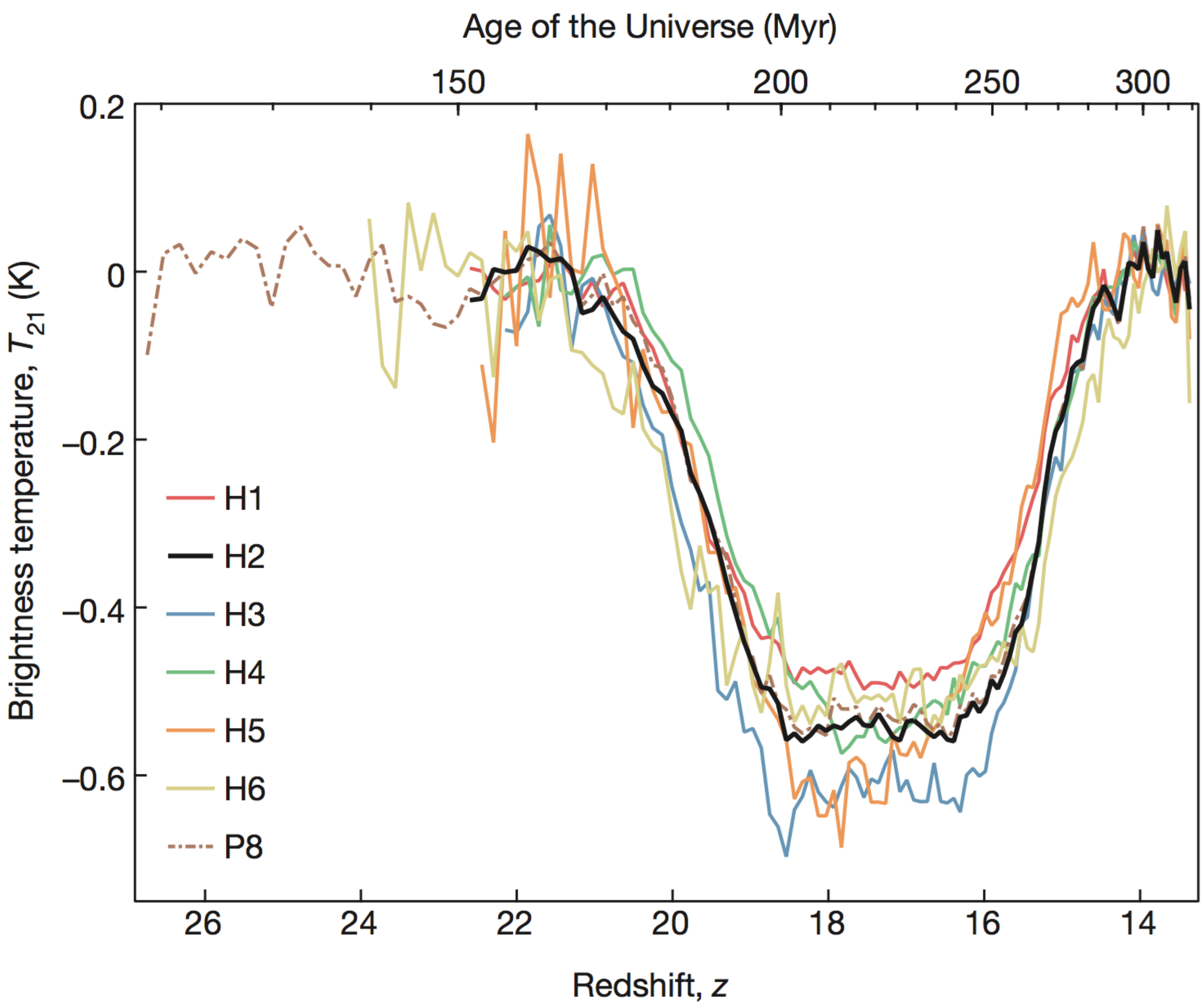
→ **mixing mass terms between U(1)$_Y$ & U(1)$_X$**

→ **millicharged hidden sector particles**

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

Feldman, ZL, Nath, PRD 2007 (230 cites)

Millicharge & 21 cm anomaly



momentum transfer xsec

millicharge DM & baryon

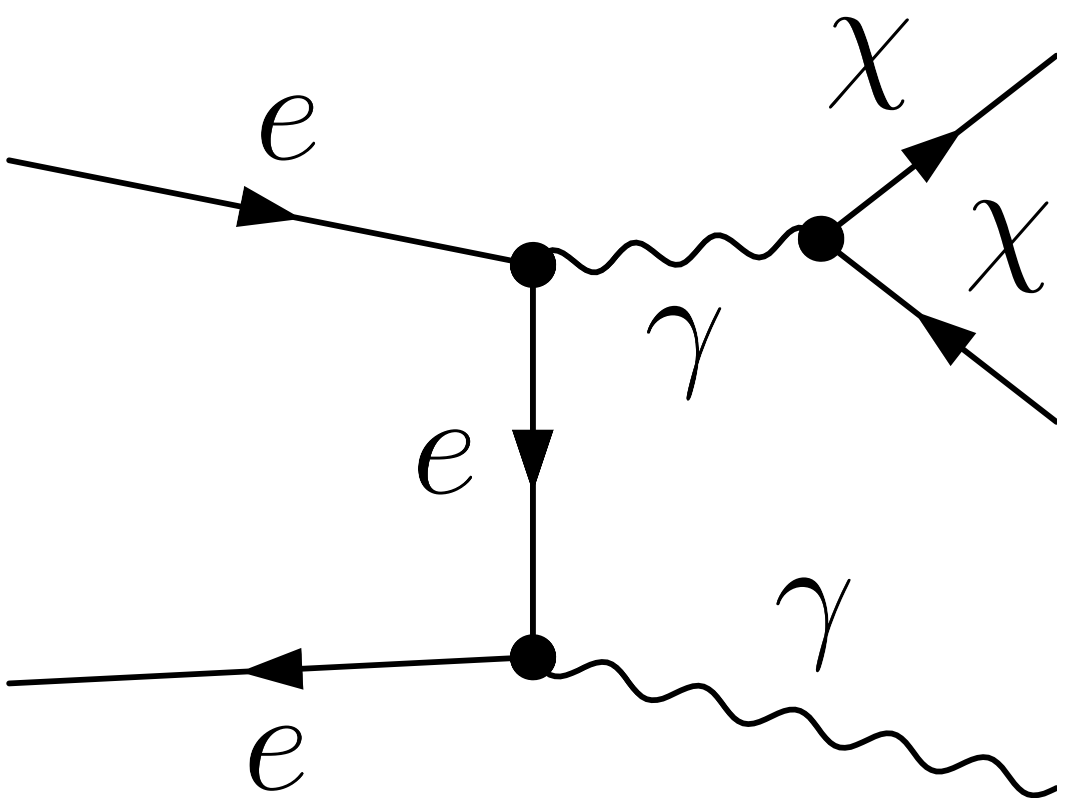
$$\bar{\sigma}_t = \frac{2\pi c^2 \hbar^2 \alpha^2 \epsilon^2 \xi}{\mu_{\chi,t}^2 v^4}$$

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

Probing millicharge @ colliders

electron-positron annihilation

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



in collaboration with Zhang, Yu (张宇)

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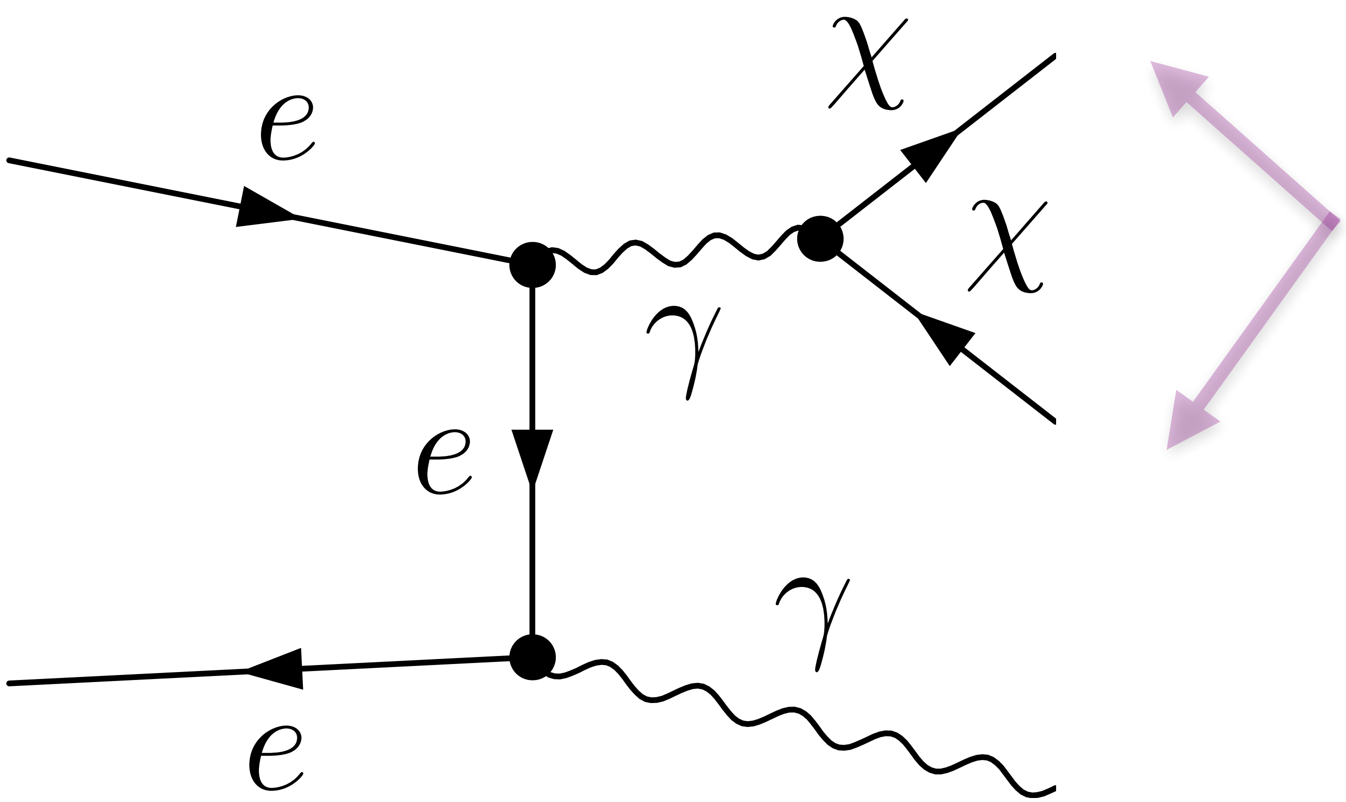

millicharged particles escape detectors

in collaboration with Zhang, Yu (张宇)

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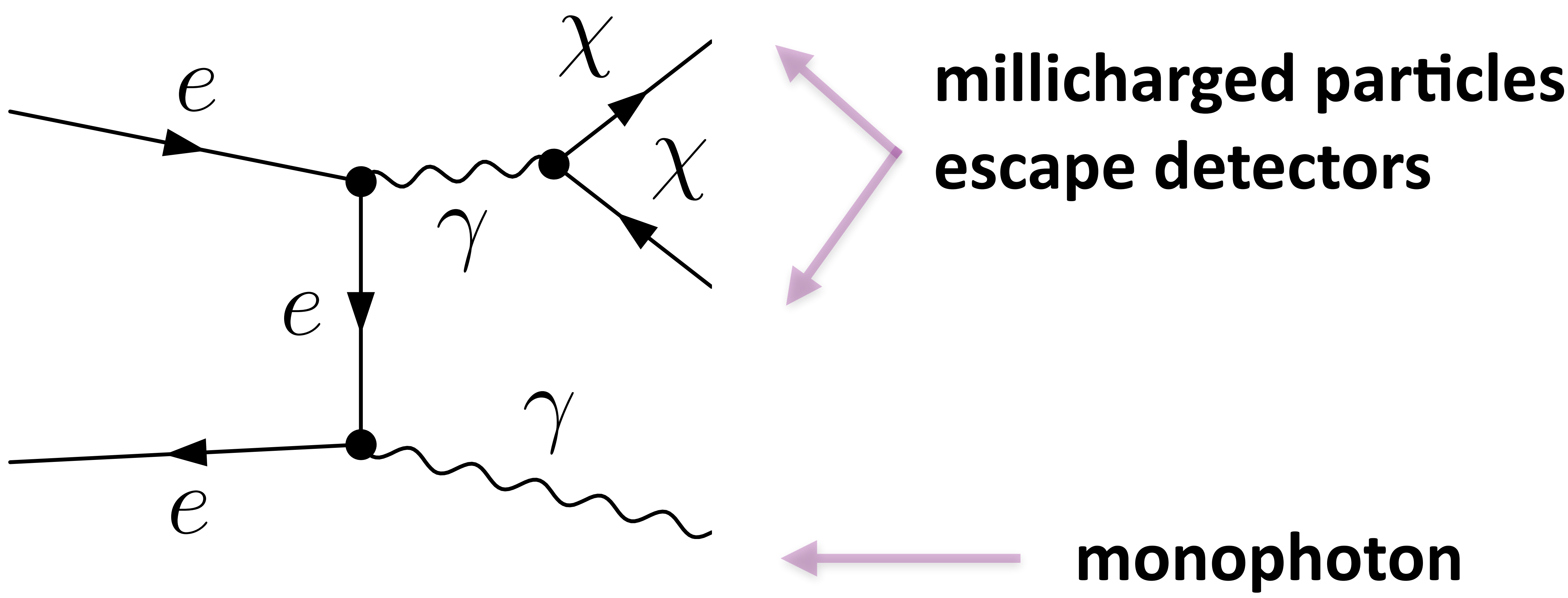
new physics process: $e^+ e^- \rightarrow \chi \chi \gamma$



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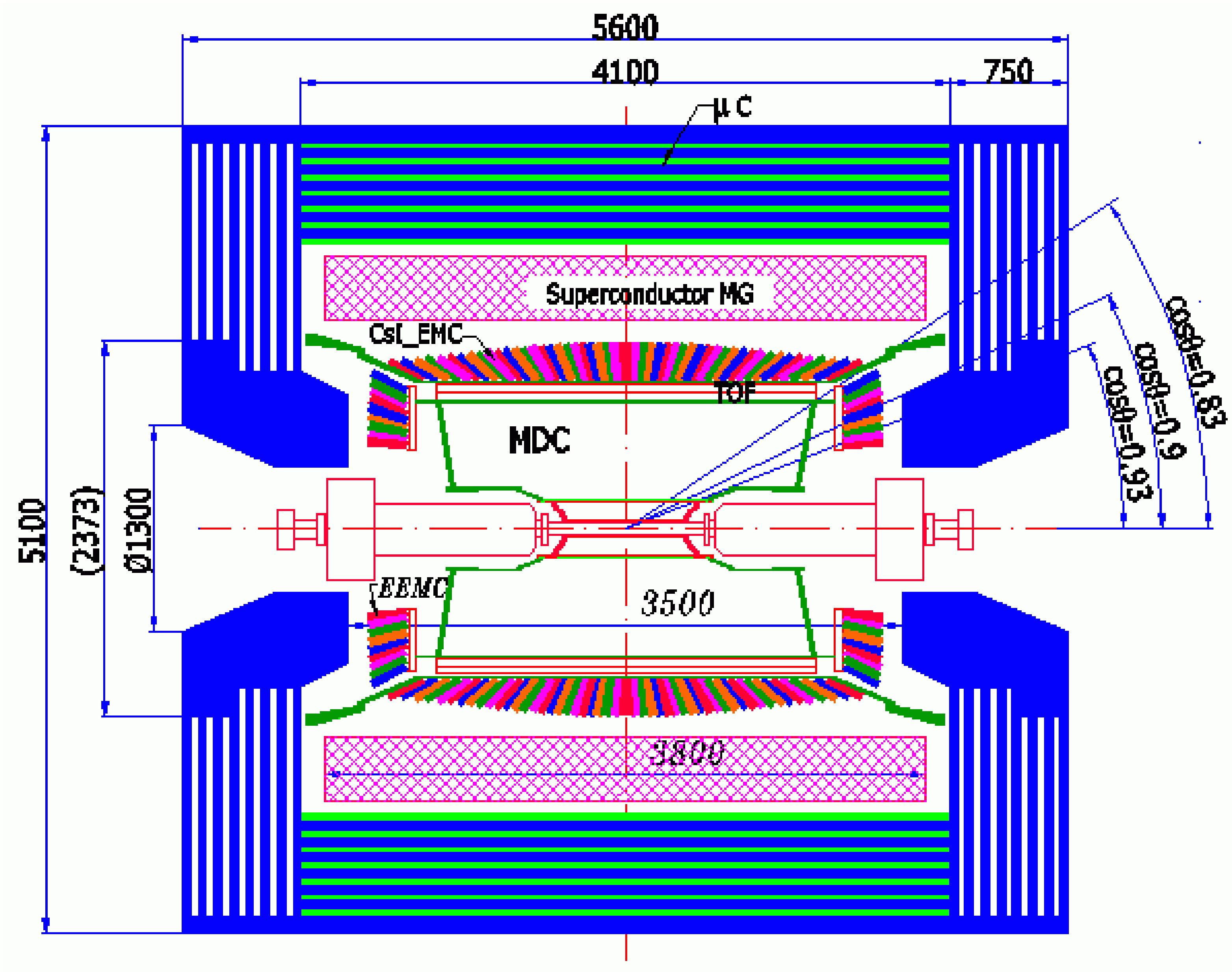
BESIII & basic detector cuts



Chao, Wang et al. 0809.1869

basic detector cuts

EMC barrel

$E_\gamma > 25$ MeV & $|\cos(\theta_\gamma)| < 0.8$

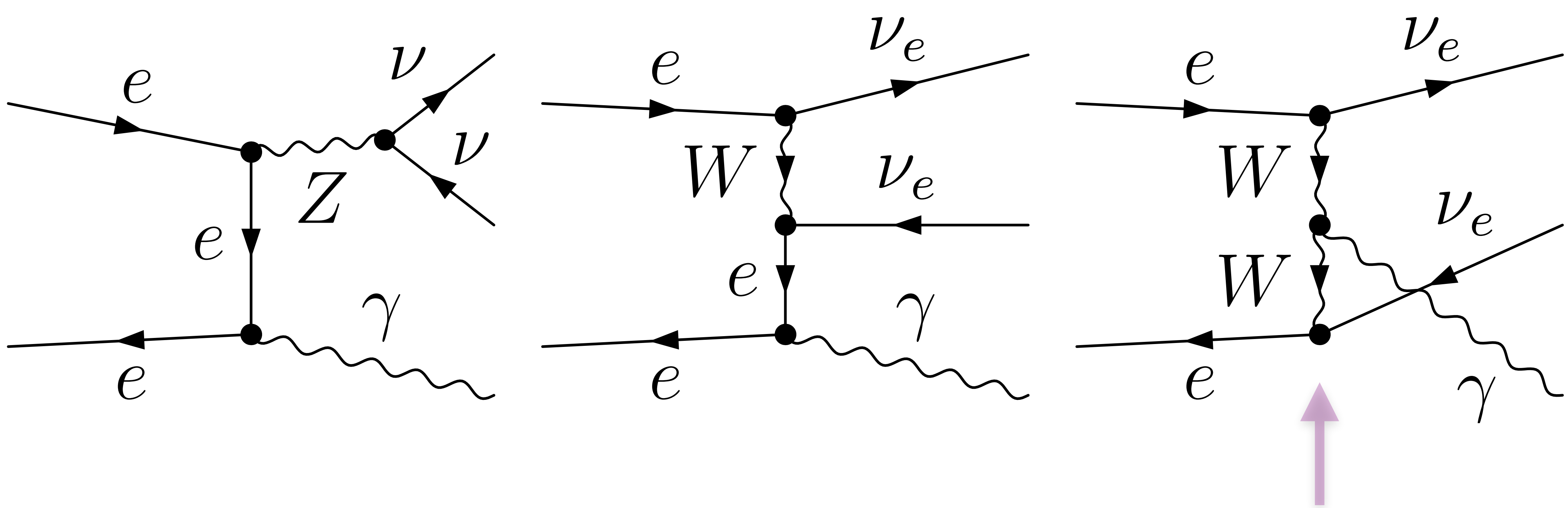
EMC end-caps

$E_\gamma > 50$ MeV & $0.86 < |\cos(\theta_\gamma)| < 0.92$

BESIII, 1707.05178

Irreducible background in SM

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



2W-diagram can be neglected in low energy

Other SM backgrounds

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

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

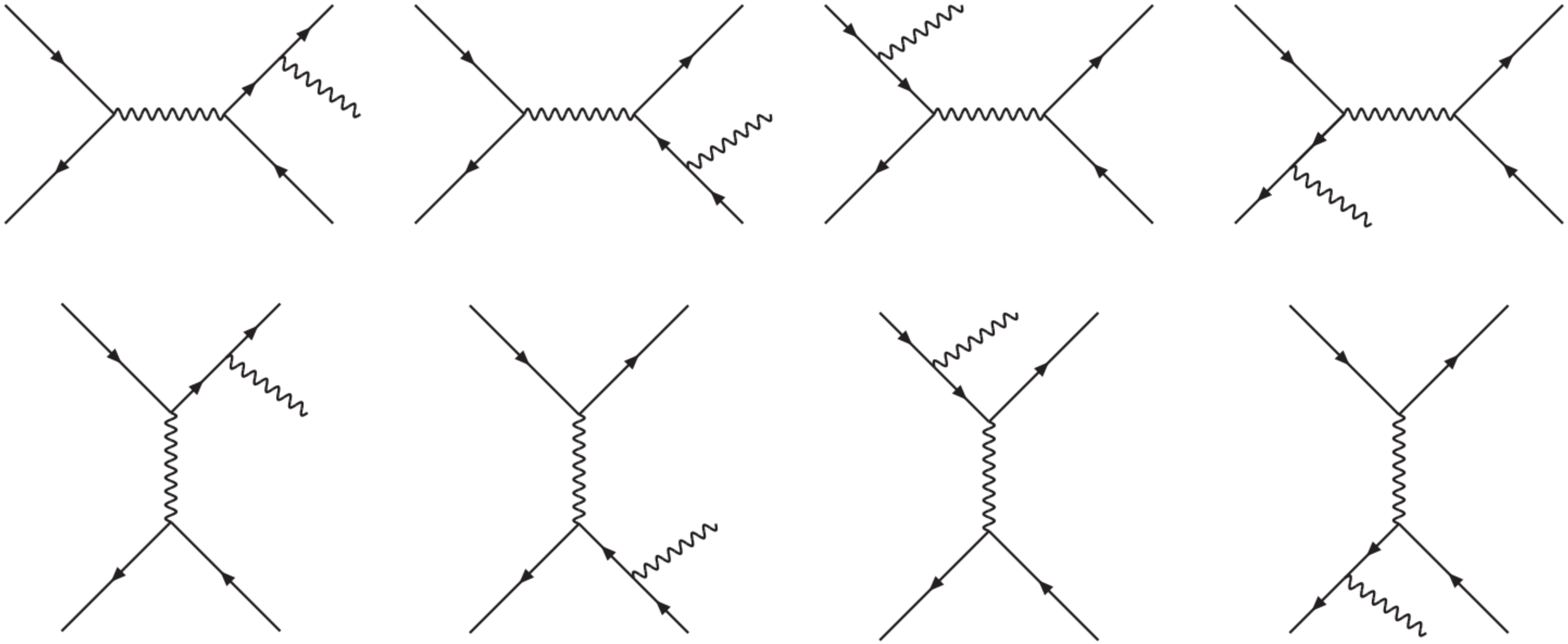
$BR = 0.7 \times 10^{-10}$ Gao 1408.4552

(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

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

Actis, Mastrolia, Ossla, 0909.1750

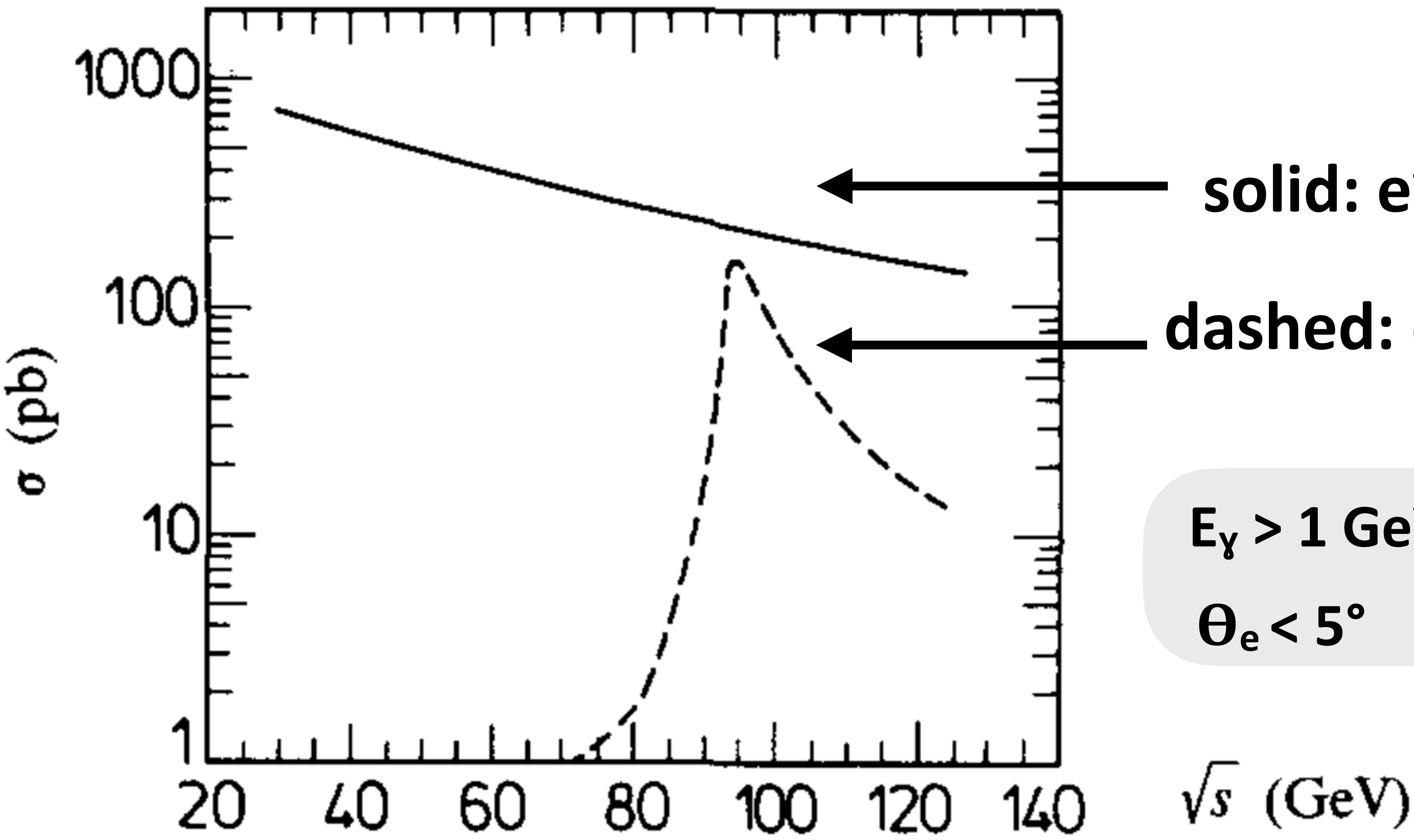


collinear singularity in the t-channel

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

$\nu\nu\gamma$ versus $e^+e^-\gamma$

Mana, Martinez, NPB 1987



solid: $e^+ e^- \rightarrow e^+ e^- \gamma$

dashed: $e^+ e^- \rightarrow \nu \nu \gamma$

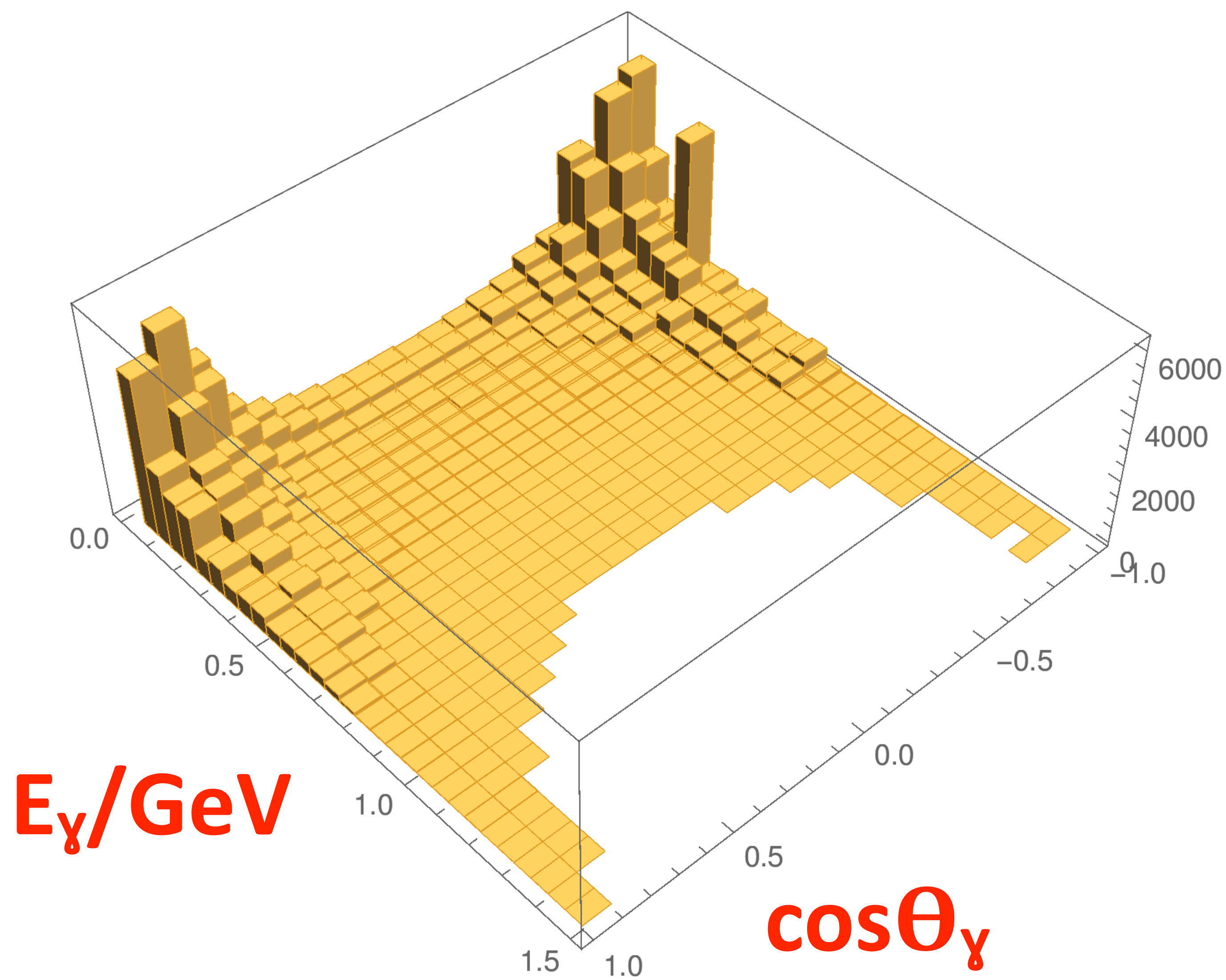
$E_\gamma > 1$ GeV & $\theta_\gamma > 20°$

$\theta_e < 5°$

E_γ & $\cos(\theta_\gamma)$ distribution ($e^+e^-\gamma$)

monophoton events from $e^+ e^- \to e^+ e^- \gamma$ (w/ basic cuts) @ J/ψ energy

$|\cos\theta|>0.93$ for any lepton or hadron



further cuts needed to remove this BG

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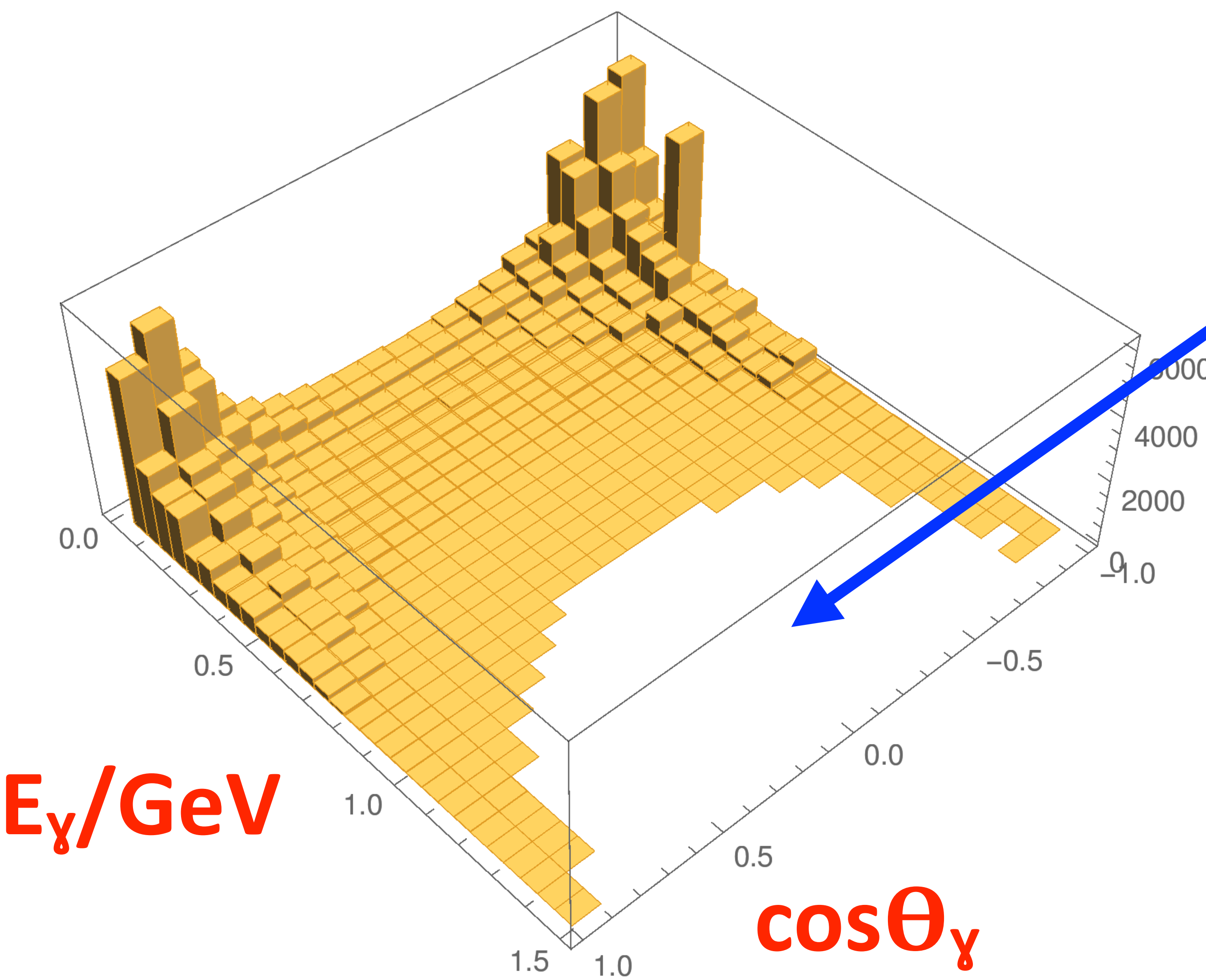

impossible to produce a sufficiently energetic photon in the central region

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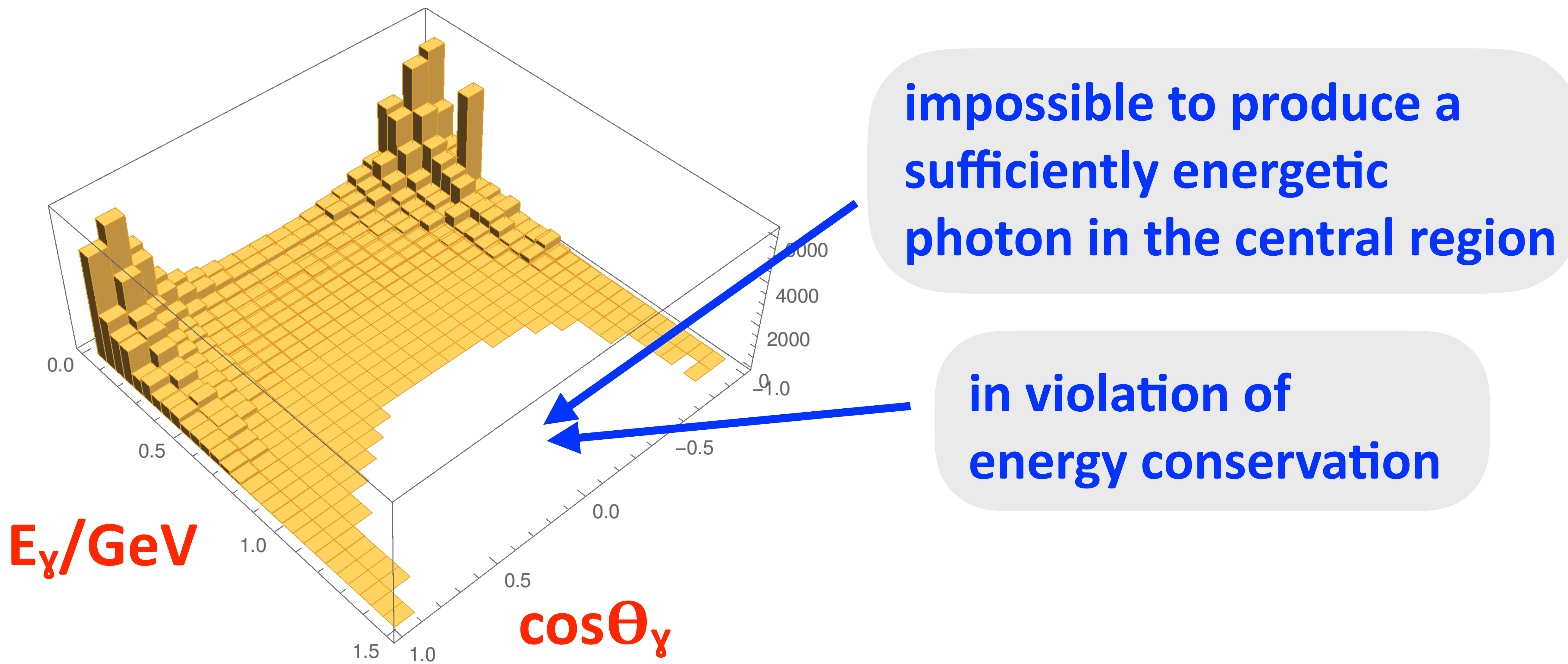

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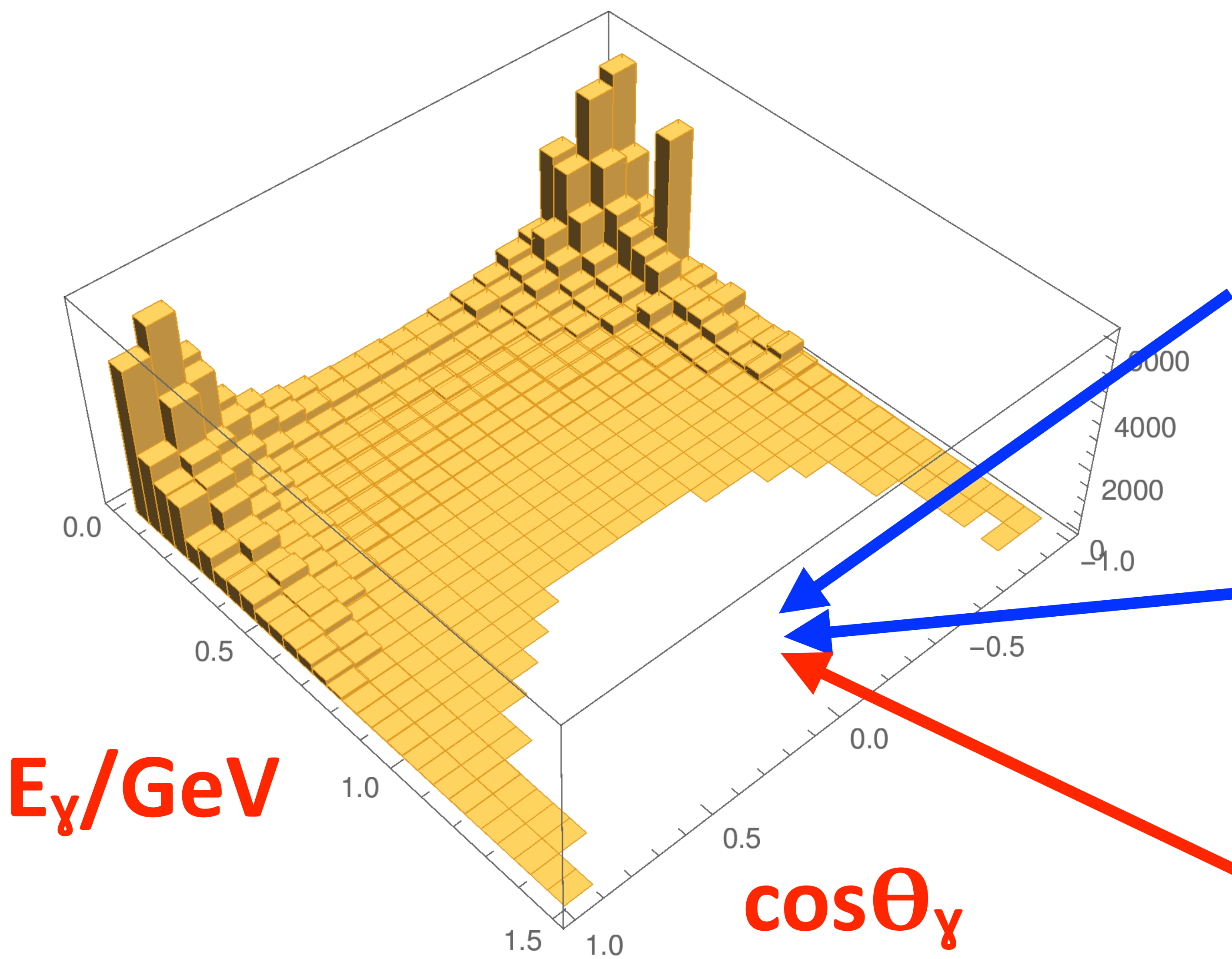


impossible to produce a sufficiently energetic photon in the central region

in violation of energy conservation

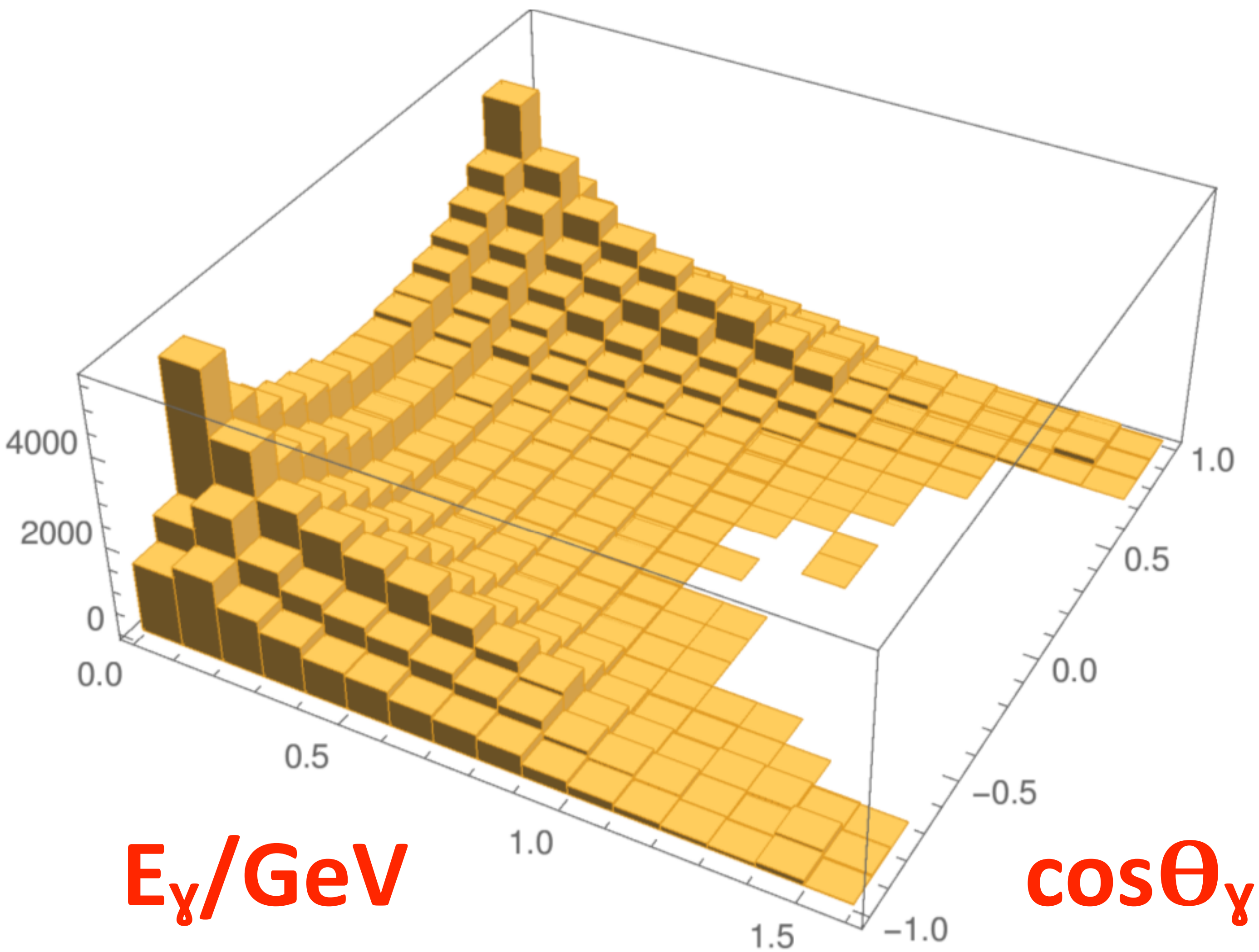
search for new physics here!!

further cuts needed to remove this BG

E_γ & $\cos(\theta_\gamma)$ distribution (J/ψ decay)

monophoton events from 2 x 10^8 J/ψ decays (w/ basic cuts)

$|\cos\theta|>0.93$ for any lepton or hadron



very similar to the $e^+ e^- \gamma$ case

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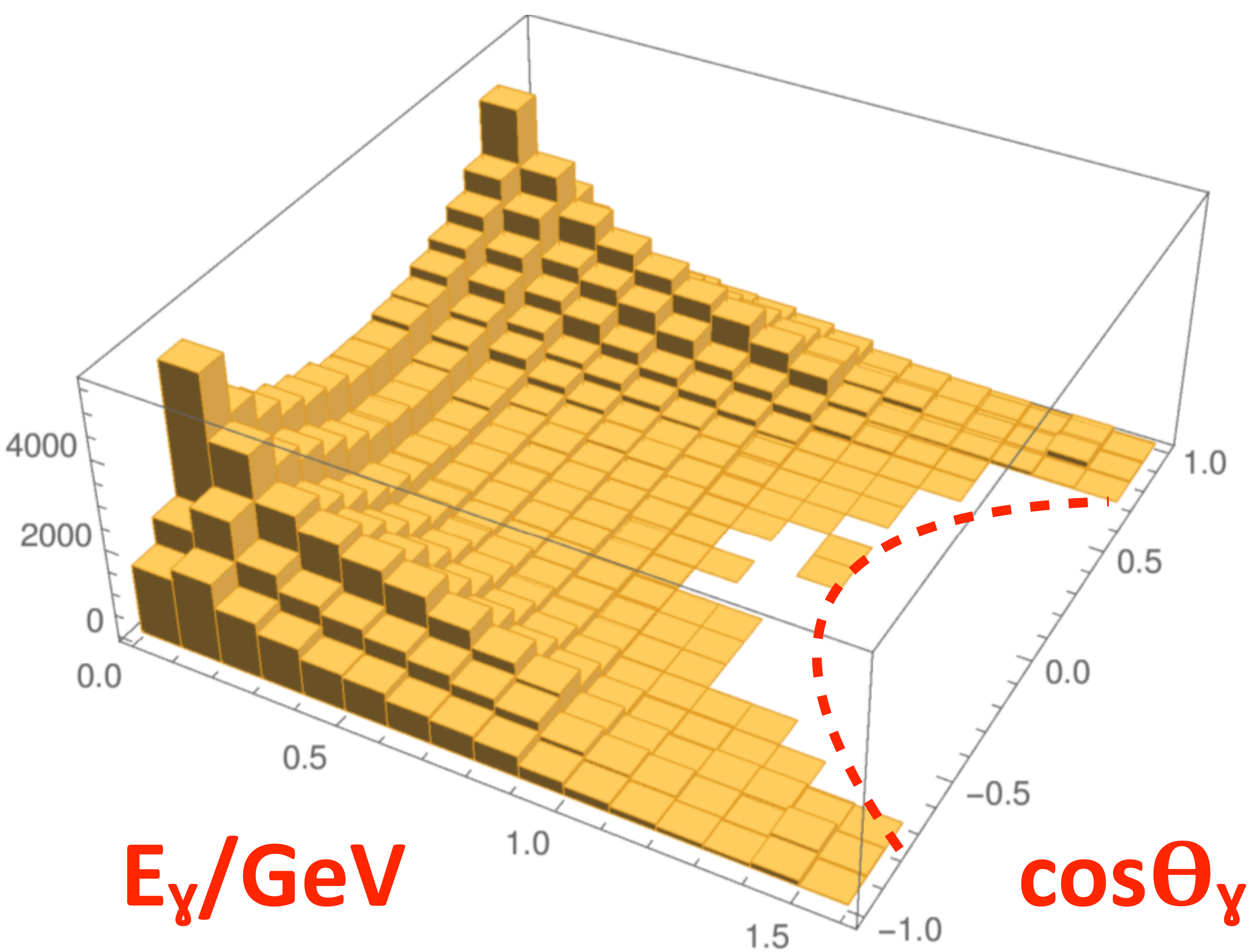

very similar to the $e^+ e^- \gamma$ case

parameterized cuts

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

for J/ψ energy

a = 0.68

b = 1.12

optimized for both J/ψ decay & $e^+e^-\gamma$

NP versus 3 major SMBGs

E_γ/GeV>0.68 $\cos^2(\Theta_\gamma)$ + 1.12

@ J/ψ energy

m_χ = 0.1 GeV

process	σ/pb w/ basic cuts	σ/pb w/ advanced cuts
$\chi\,\chi\,\gamma$	$7.7 \times 10^2\,\varepsilon^2$	$1.2 \times 10^2\,\varepsilon^2$
$\nu\,\nu\,\gamma$	7.5×10^{-4}	1.6×10^{-6}
J/ψ	4×10^3	0
$e^+\,e^-\,\gamma$	1.5×10^5	0

NP efficiency is only mildly affected by the advanced cuts!!

Data collected @ BESIII

Year	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	(a, b)
2015	2.125	0.1	(0.54,0.57)
2009+2012	3.097	0.08+0.32	(0.68,1.12)
2011	3.554	0.024	(0.88,0.95)
2009+2012	3.686	0.16+0.51	(0.95,1.21)
2010+2011	3.773	0.93+1.99	(0.86,1.1)
2011	4.009	0.5	(0.98,1.09)
2016	4.18	3.1	(1.08,1.08)
2013	4.23	1.9	(1.04,1.13)
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monophoton trigger since 2011

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

optimized for each energy

~17/fb since 2011

monophoton trigger since 2011

Methodology

combine data @ different collision energies

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

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

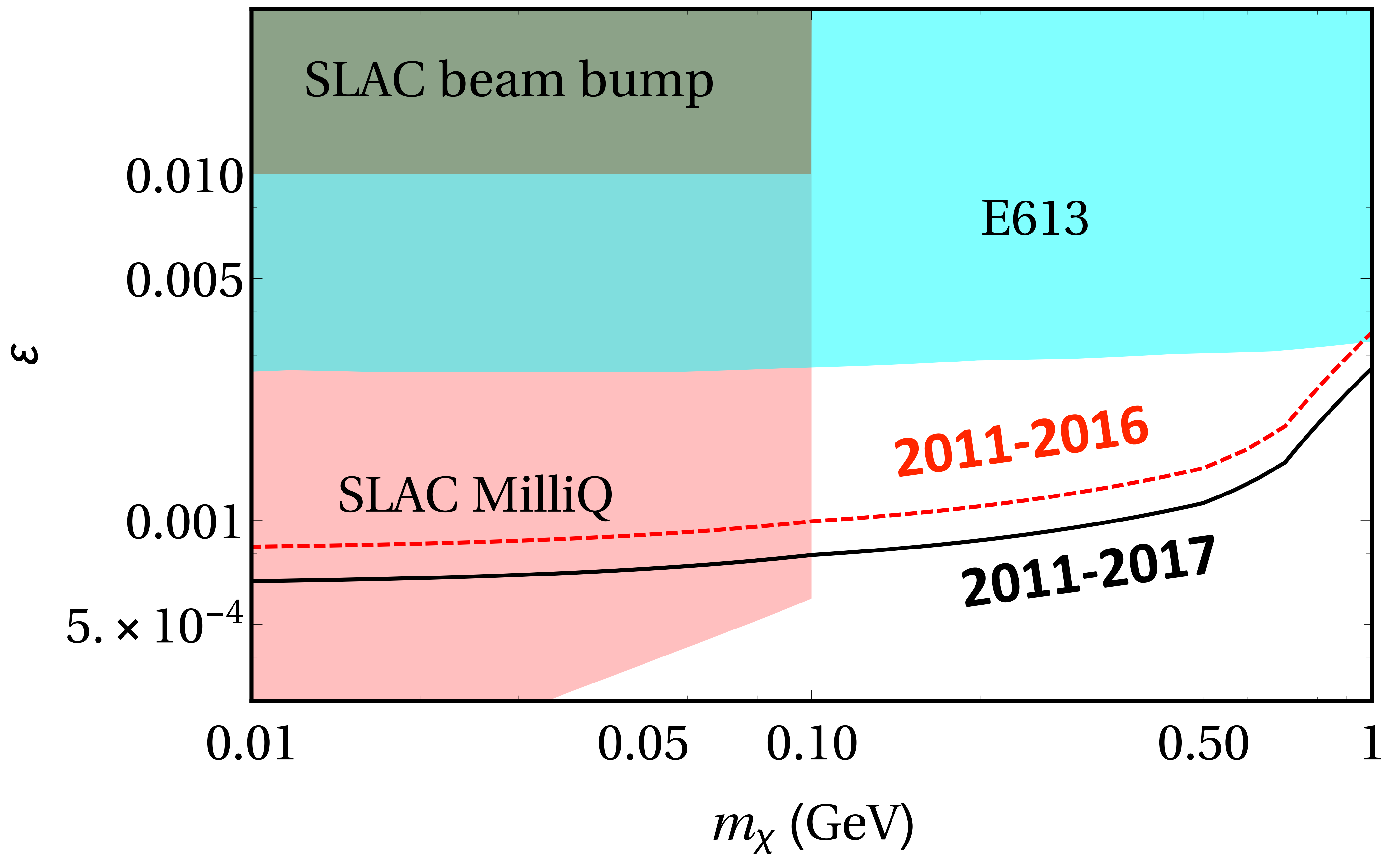
total likelihood $\mathcal{L} = \Pi_i \mathcal{L}_i$

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

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

Limits w/ existing luminosity

monophoton trigger since 2011

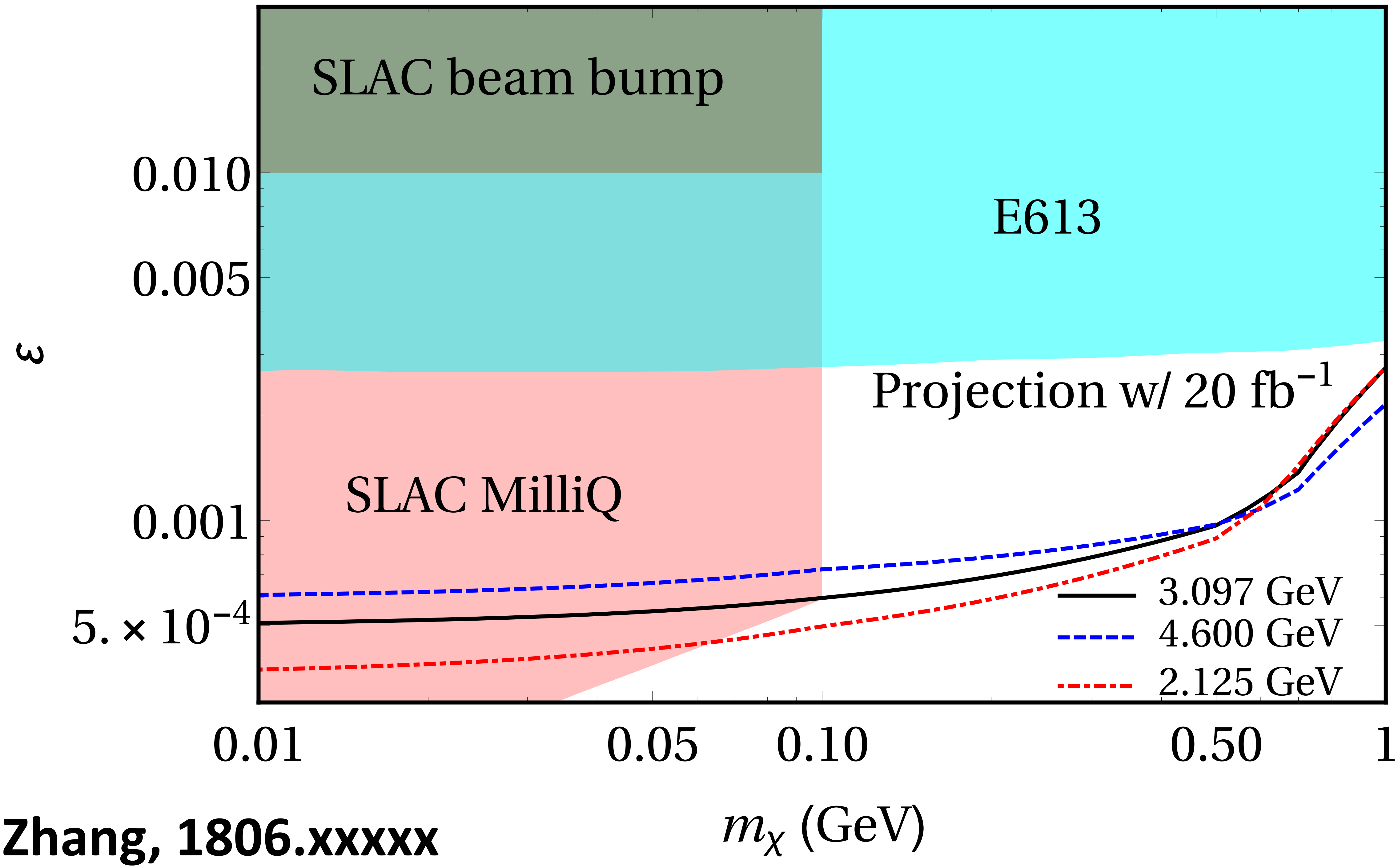


ZL, Zhang, 1806.xxxxx

95% CL limit

Projected limits

Suppose BES will accumulate the same amount data as before



ZL, Zhang, 1806.xxxxx

Summary

- Millicharged particles are interesting beyond stand model new particles.
- Current (and future) data in the BESIII detector provide very good limits on millicharged particles in the MeV to GeV mass range.
- Millicharge $\varepsilon \sim 10^{-3}$ can be probed at BESIII for a 100 MeV mass.

Thank you!