Search for L_μ-L_τ gauge boson at Belle-II and Neutrino beam experiments

Takashi Shimomura
(Miyazaki U.)

in collaboration with

Yuya Kaneta (Niigata U.)

"On the possibility of search for L_μ–L_τ gauge boson at Belle-II and neutrino beam experiments"

arXiv:1701.00156, PTEP

and

T. Araki, S. Hoshino, J. Sato, T. Ota (Saitama U.)

"Detecting the L_μ–L_τ gauge boson at Belle-II"

arXiv:1702.01497, PRD

May 31th, 2017 @ Kyoto Univ.

Introduction

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The standard model has been completed by the discovery of the Higgs particle.

However,

- Neutrino mass and mixing
- Dark matter / Dark energy
- muon (g-2)
- etc…

Need new physics beyond the SM

No good news from LHC so far. No SUSY, No extra dim. …

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Where is new physics?

- Further high energy scale?
- Low scale but unexpectedly hidden?

Motivation

Some “hints” have been reported in low energy & mass region.

- Deviation in cosmic neutrino flux at IceCube
- Anomalies in e^+-e^- distributions at Atomki
- Anomalous magnetic moment of muon
- Deviation of atomic radius of muonic hydrogen

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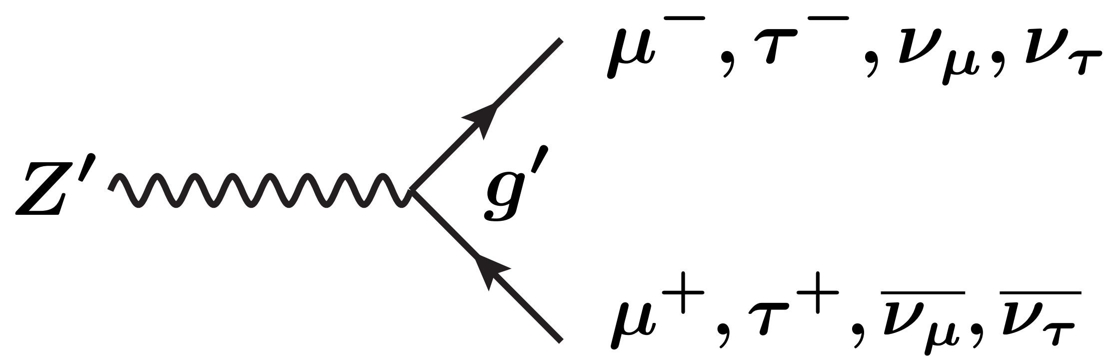
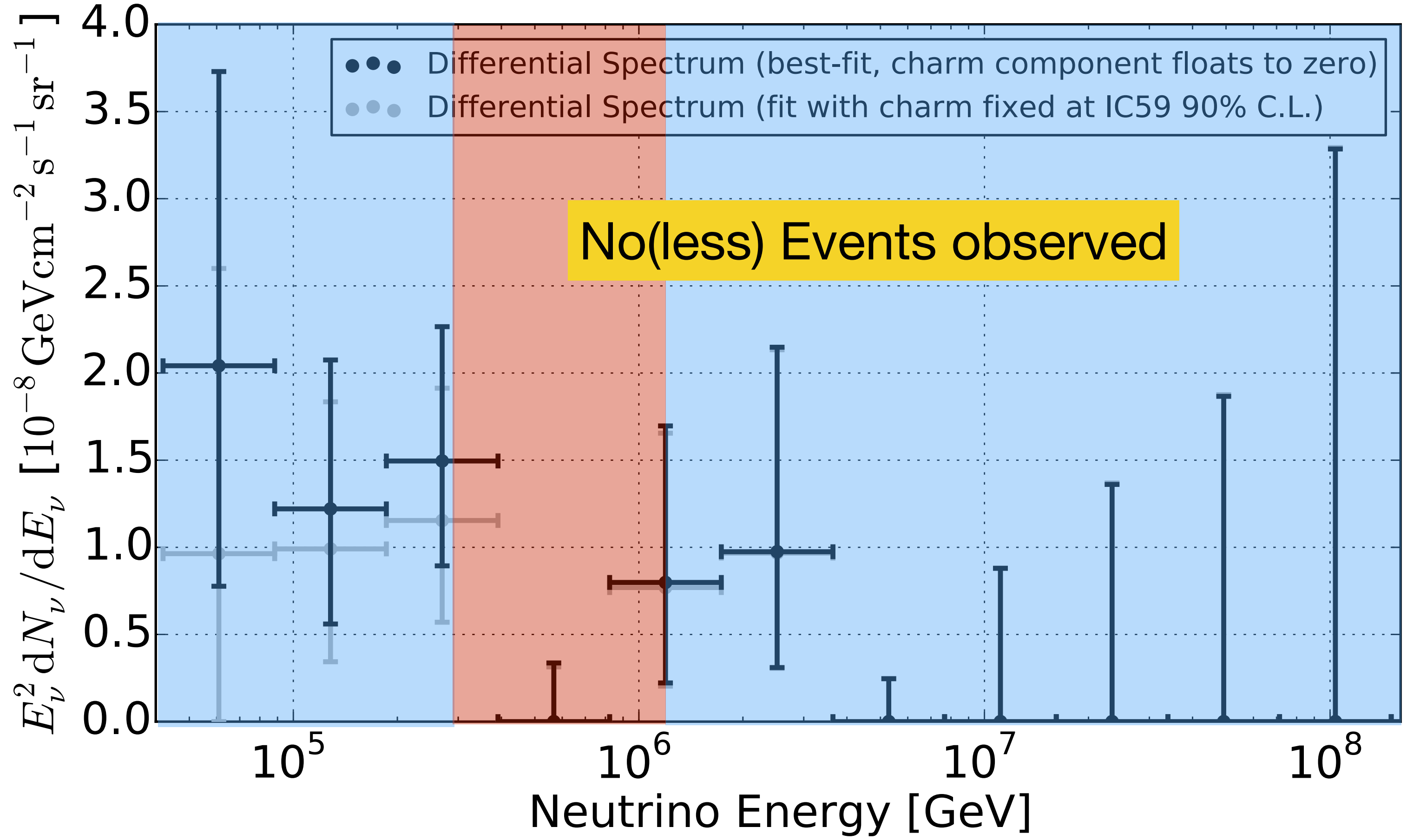


IceCube Gap

IceCube has observed high Energy Neutrinos



IceCube, PRL. 113 (2014)

A gap in the flux between 400TeV(700TeV)-1PeV

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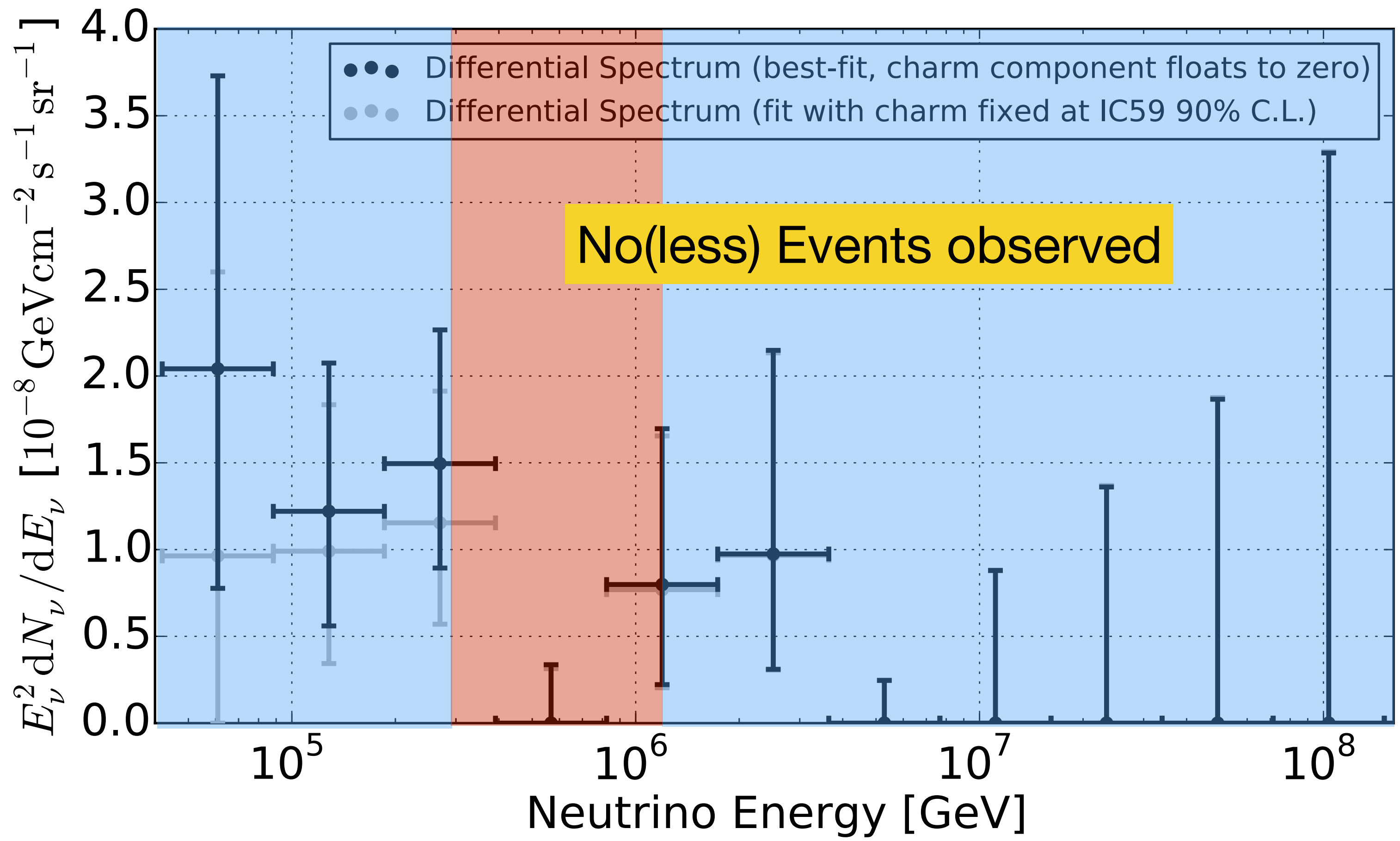

IceCube, PRL. 113 (2014)

A gap in the flux between 400TeV(700TeV)-1PeV

- Astrophysical origin
  e.g. two different sources
- Particle physics origin
  Attenuation of the cosmic ν

IceCube Gap

Ioka and Murase, PTEP 2014, Ng and Beacom, PRD90 (2014),
Ibe and Kaneta, PRD90 (2014)
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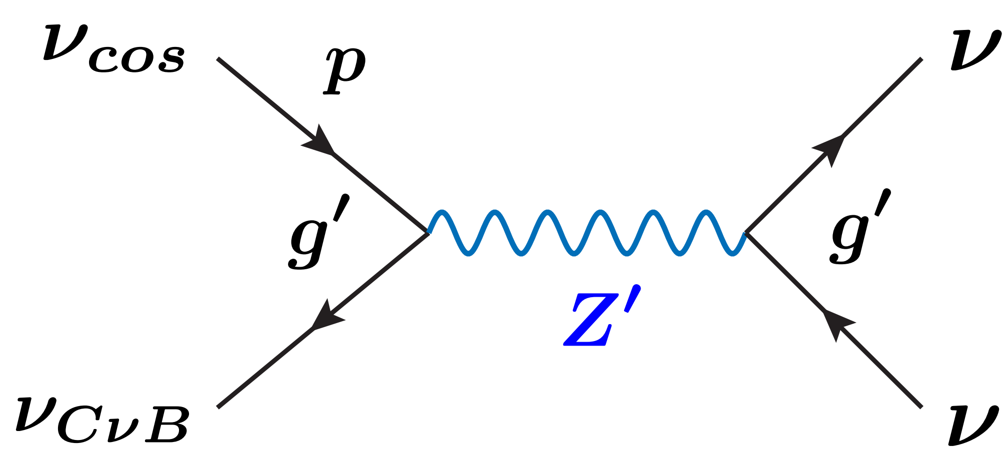
Attenuation of the cosmic ν

Introduce a new gauge/scalar boson which interacts with neutrinos.



Z' : L_μ-L_τ gauge boson
g' : gauge coupling

At the resonant, the scattering cross section is enhanced.

➡ The cosmic ν is attenuated by the cosmic ν BG.

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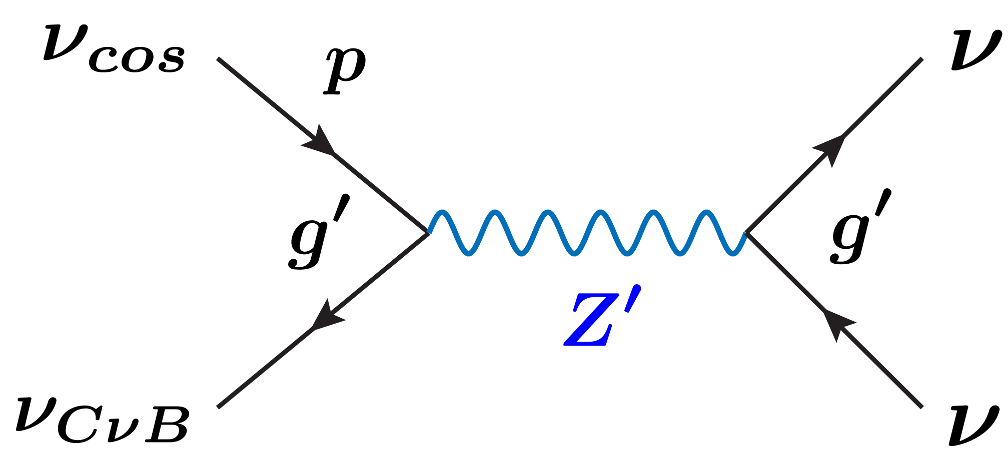

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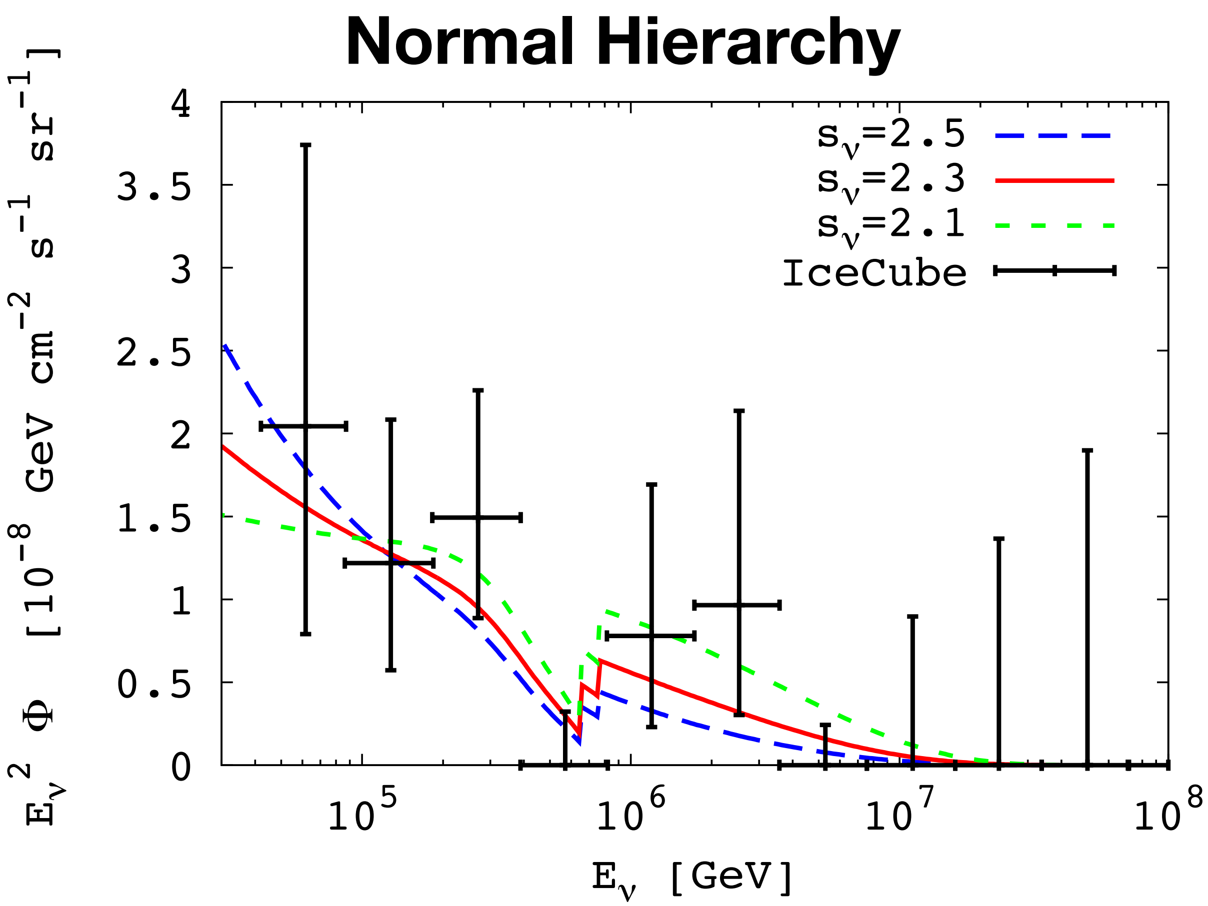
For the IceCube gap energy (1 PeV),

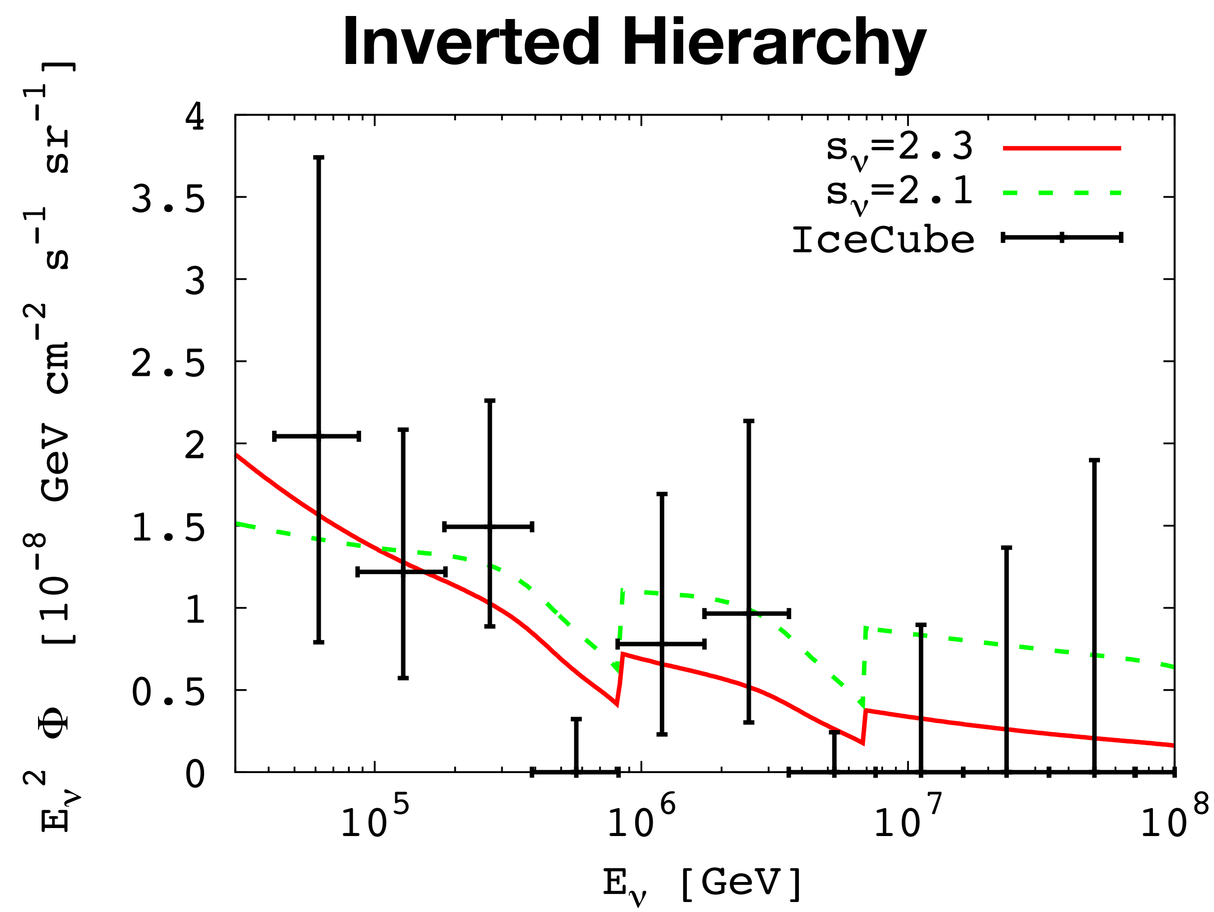
$$m_{Z'} = \sqrt{p^2} \simeq \sqrt{2m_\nu E_\nu} \simeq 10\ \mathrm{MeV}$$

Very light gauge boson

IceCube Gap

Araki, Kaneko, Konishi, Ota, Sato, T.S., PRD91 (2015)
Araki, Kaneko, Ota, Sato, T.S., PRD93 (2016)





$m_{Z'} = 11$ MeV & $g' = 5\times10^{-4}$

$m_{Z'} = 9$ MeV & $g' = 4\times10^{-4}$

IceCube Gap

Araki, Kaneko, Konishi, Ota, Sato, T.S., PRD91 (2015)
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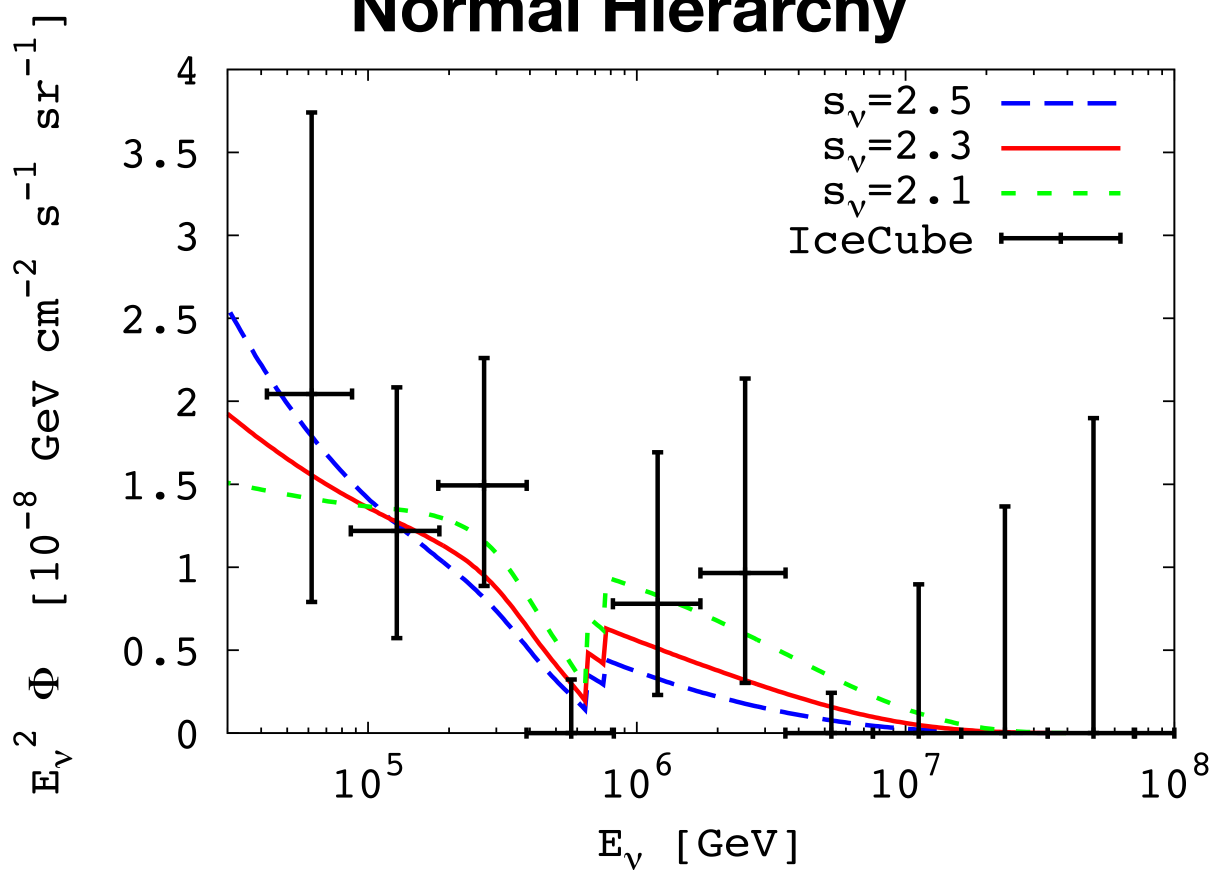
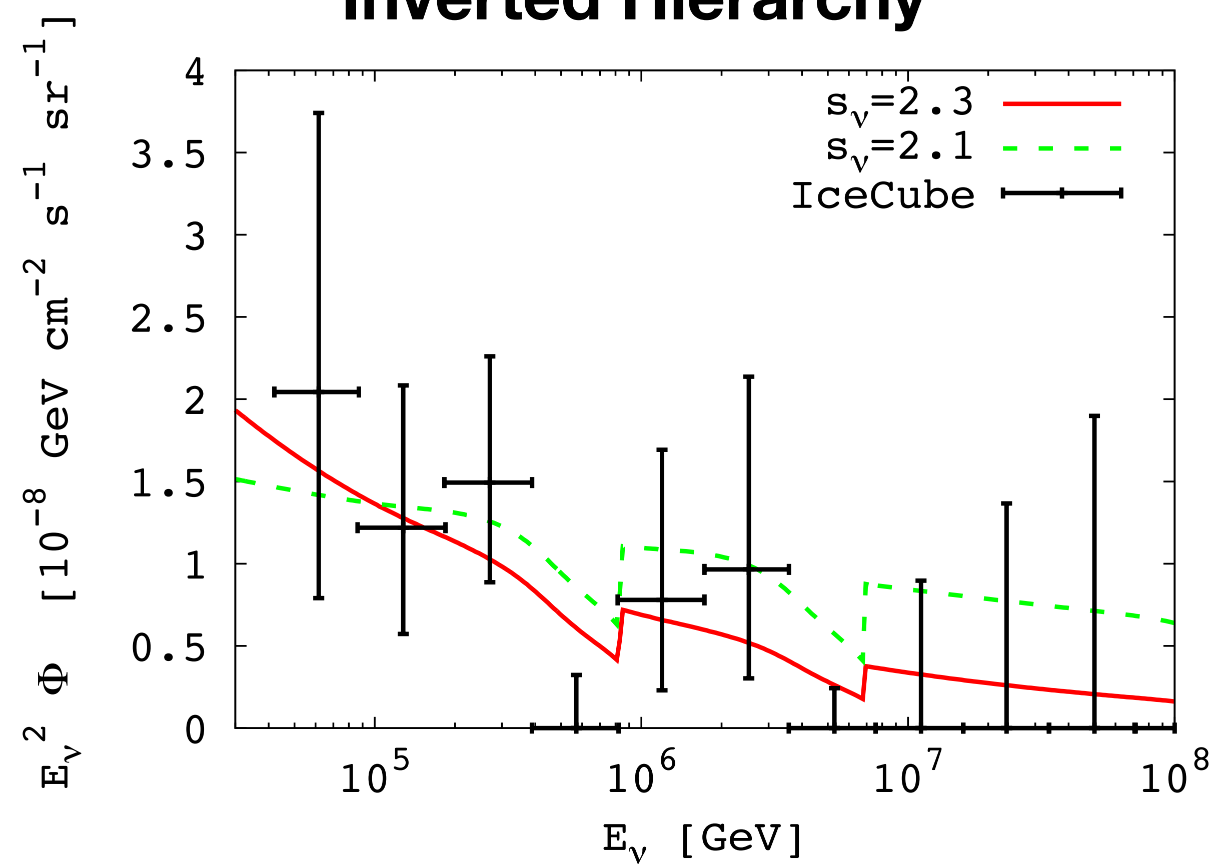
Normal Hierarchy



$m_{Z'}$ = 11 MeV & g' = 5×10^{-4}

Inverted Hierarchy



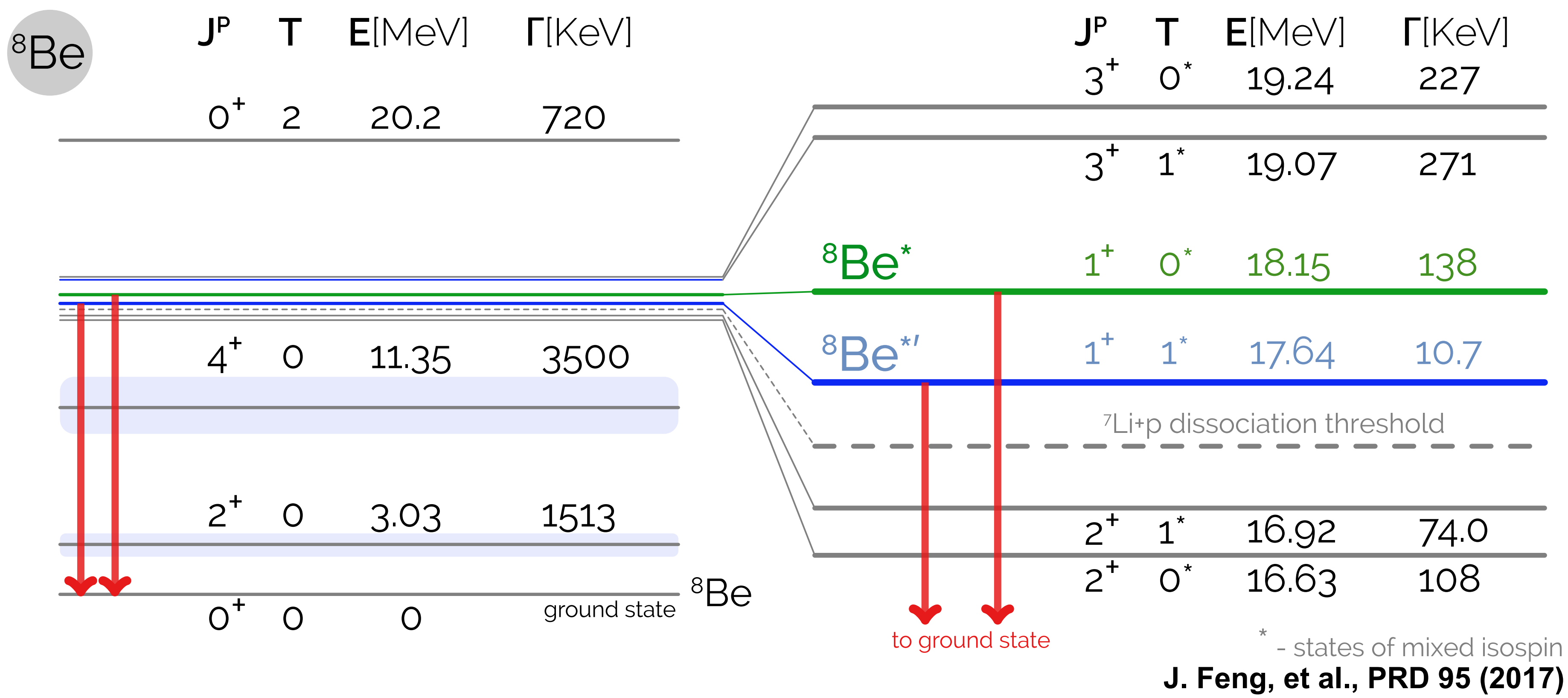
$m_{Z'}$ = 9 MeV & g' = 4×10^{-4}

The IceCube gap suggests

Very light and Weakly interacting Gauge Boson

Atomki anomaly

Excess of e^+-e^- pair from an excited state of ^{8}Be

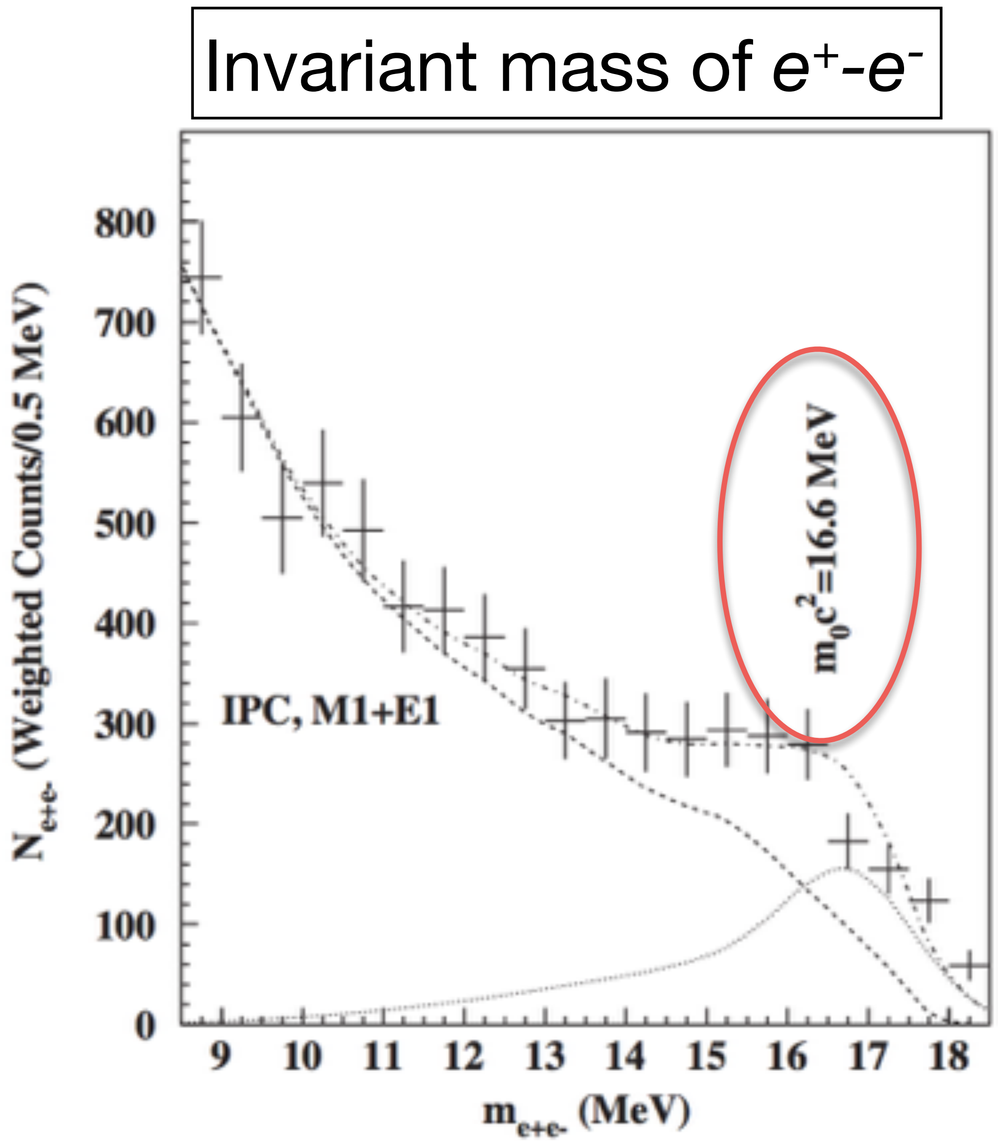


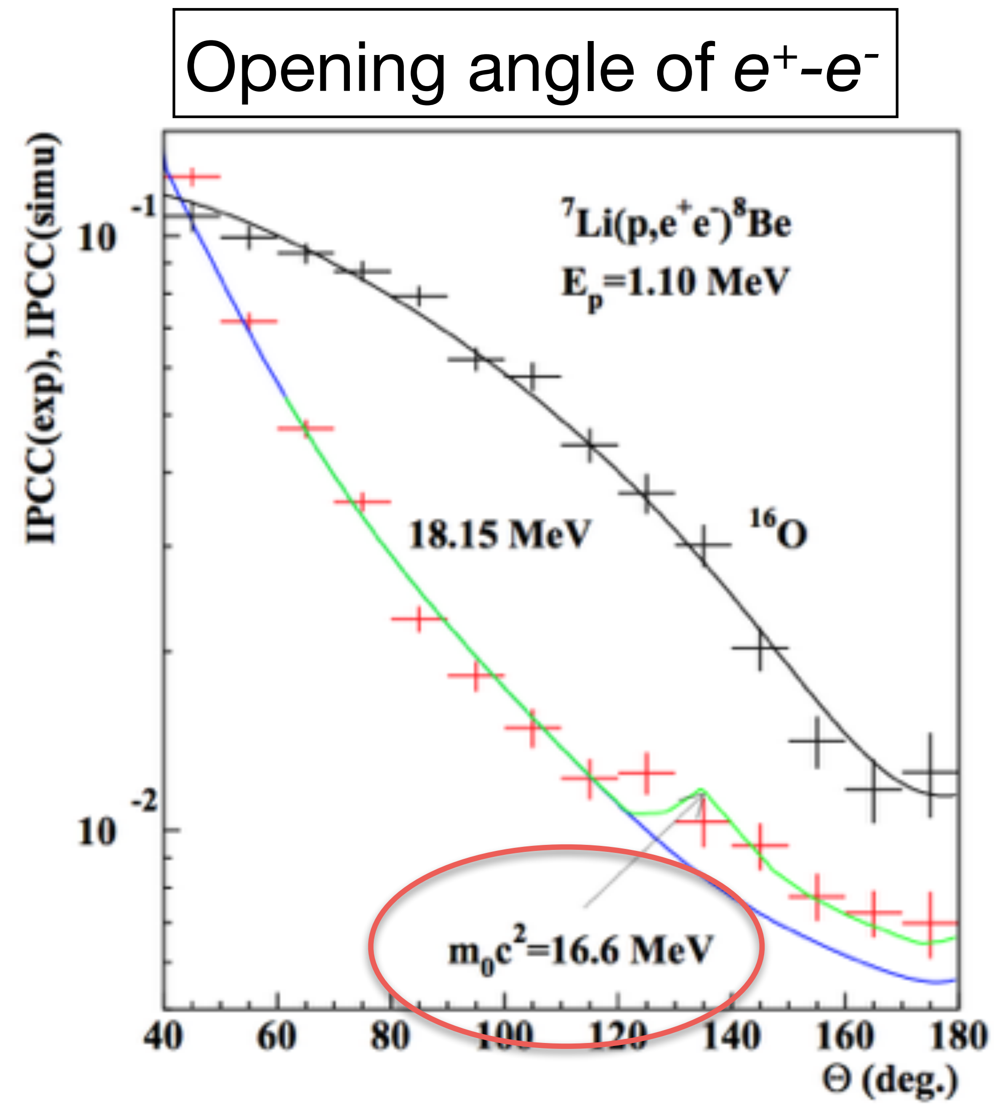
$$^8\mathrm{Be}^* \rightarrow ^8\mathrm{Be} + e^+ + e^-$$

- Parity conserving $1^+ \rightarrow 0^+ + 1^+$ transition
- M1 transition emitting a photon

Atomki anomaly

Krasznahorkay, etal., PRL. 116 (2016), EPJ Web Conf. 137 (2017)





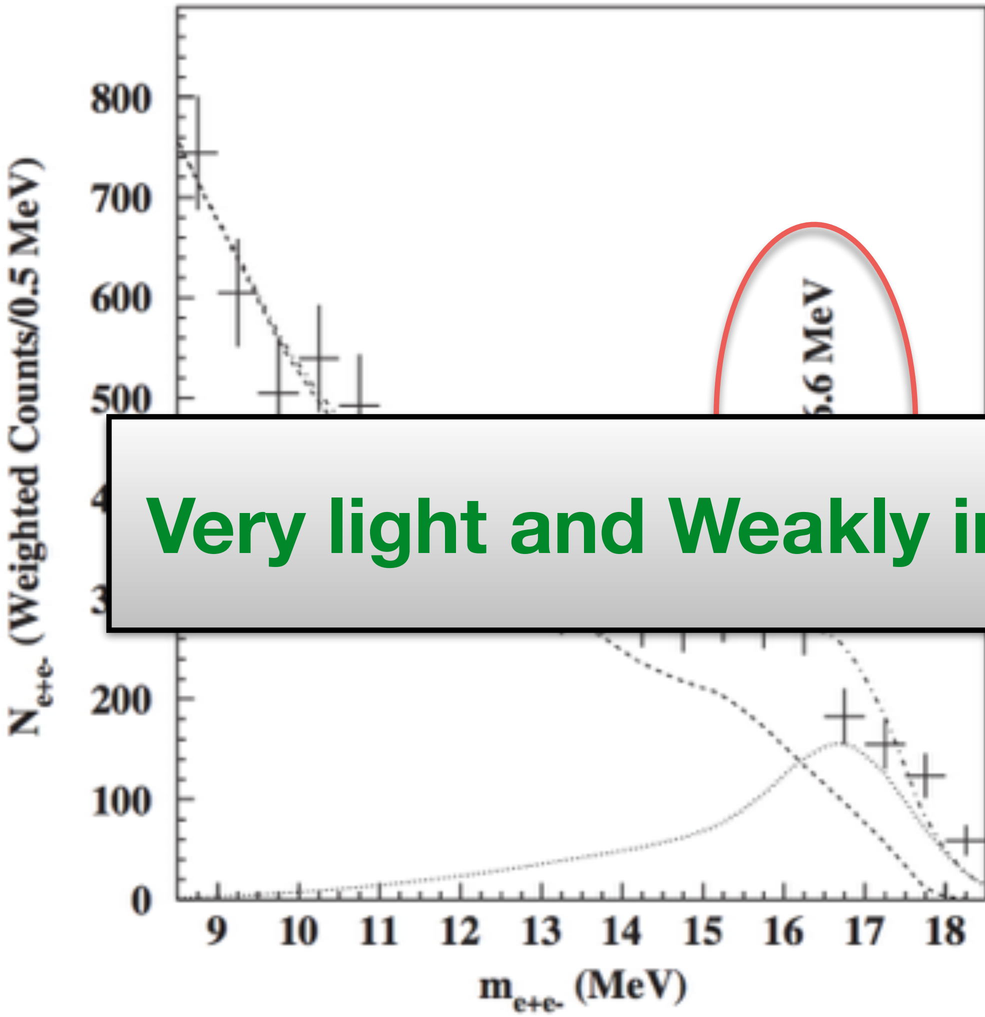
- 6.8σ deviation from the standard nuclear interpretation
- The best fit is 17.0±0.5(stat)±0.5(sys) MeV
- The coupling const. should be $O(10^{-4})$

J. Feng, et al. PRD 95 (2016), **O. Seto and T.S, PRD (2017)**

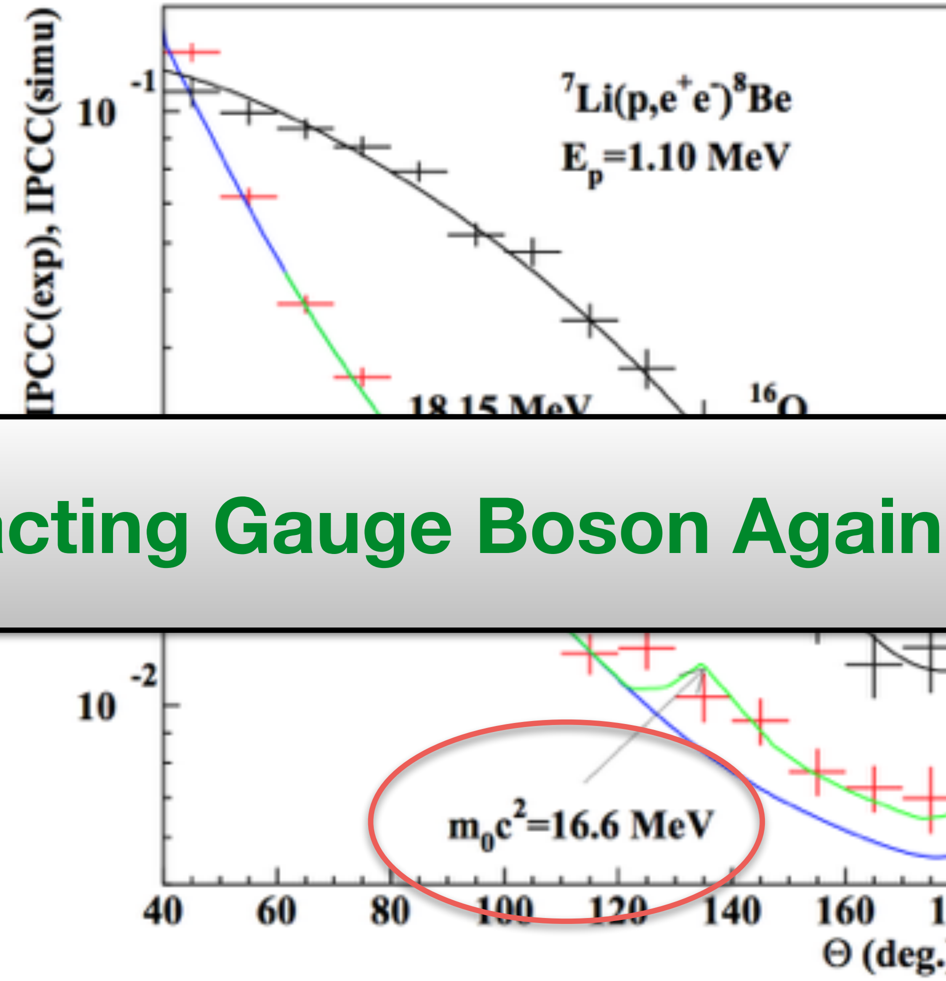
Atomki anomaly

Krasznahorkayetal., PRL. 116 (2016), EPJ Web Conf. 137 (2017)

Invariant mass of e^+-e^-



Opening angle of e^+-e^-



Very light and Weakly interacting Gauge Boson Again!

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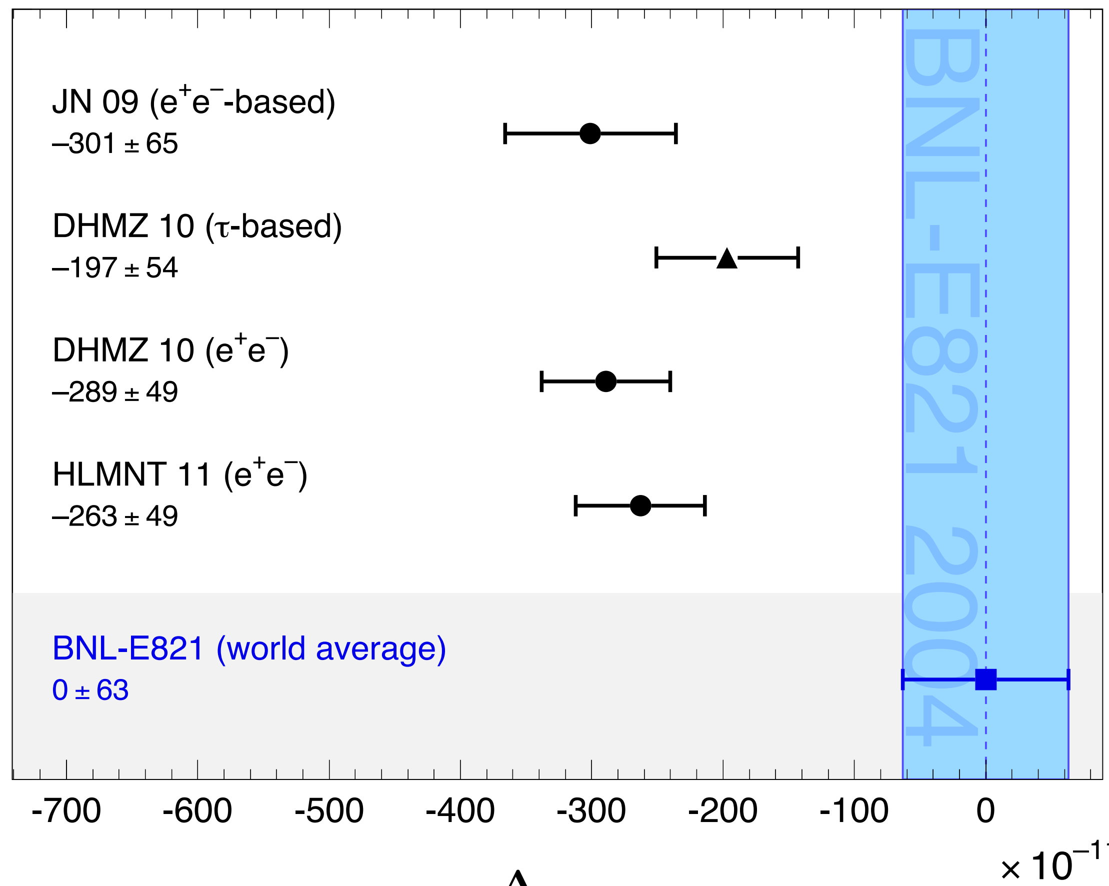
Muon (g-2)

PDG (2014)



Δa_μ

world average

$$a_\mu^{\mathrm{exp}} = (11\ 659\ 201.1(5.4)(3.3)) \times 10^{-10}$$

theory prediction

$$a_\mu^{\mathrm{SM}} = (11\ 659\ 182.8 \pm 4.9) \times 10^{-10}$$

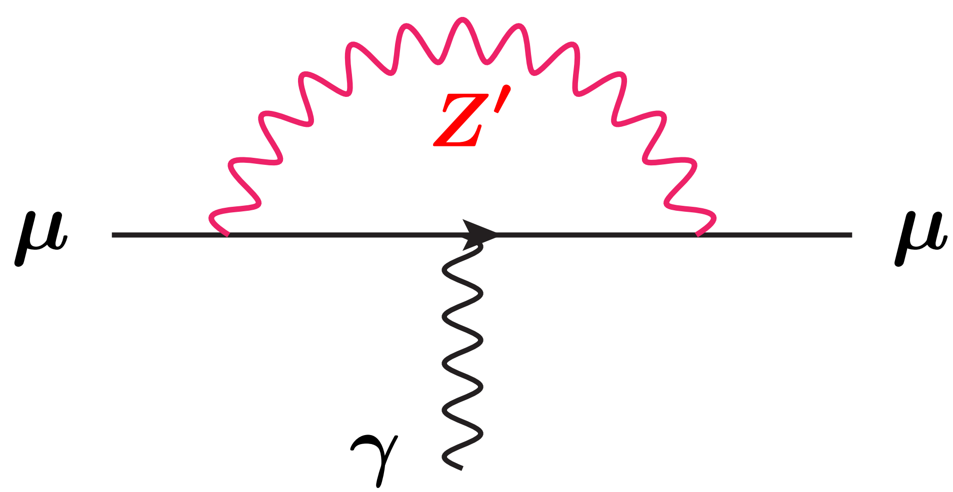
K. Hagiwara et al, J.Phys. G38 (2011)

$$\Delta a_\mu = 288(63)(49) \times 10^{-11}$$

3.3σ discrepancy

Muon (g-2)

Z' contribution to (g-2)$_\mu$



$$\Delta a_\mu = \frac{g'^2}{8\pi}\int_0^1 dx \frac{2m_\mu^2 x(1-x)^2}{x m_{Z'}^2 + (1-x)^2 m_\mu^2}$$

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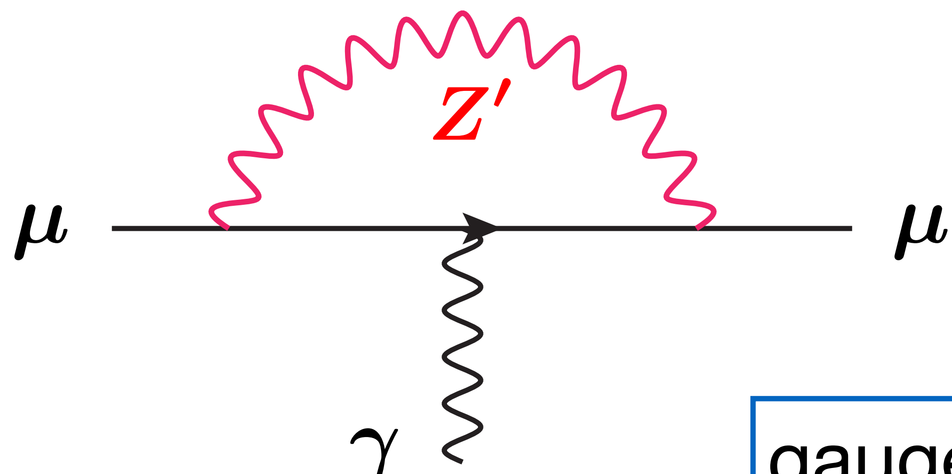

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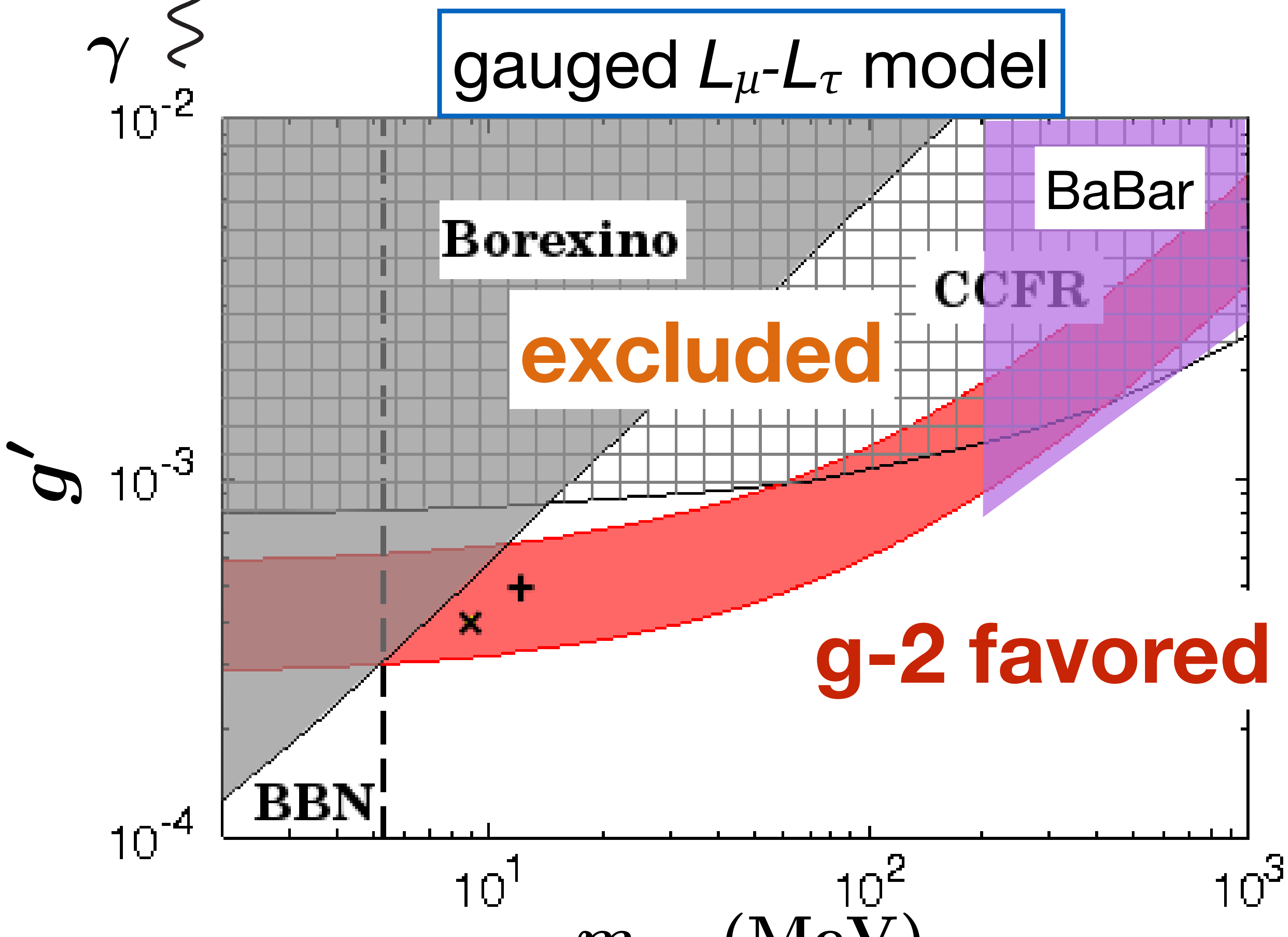

Araki, Kaneko, Ota, Sato, T.S, PRD93 (2016)

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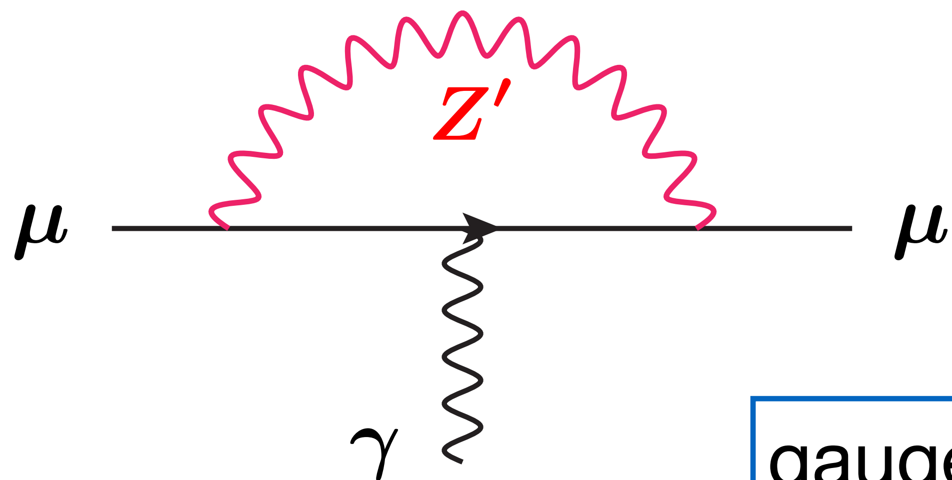

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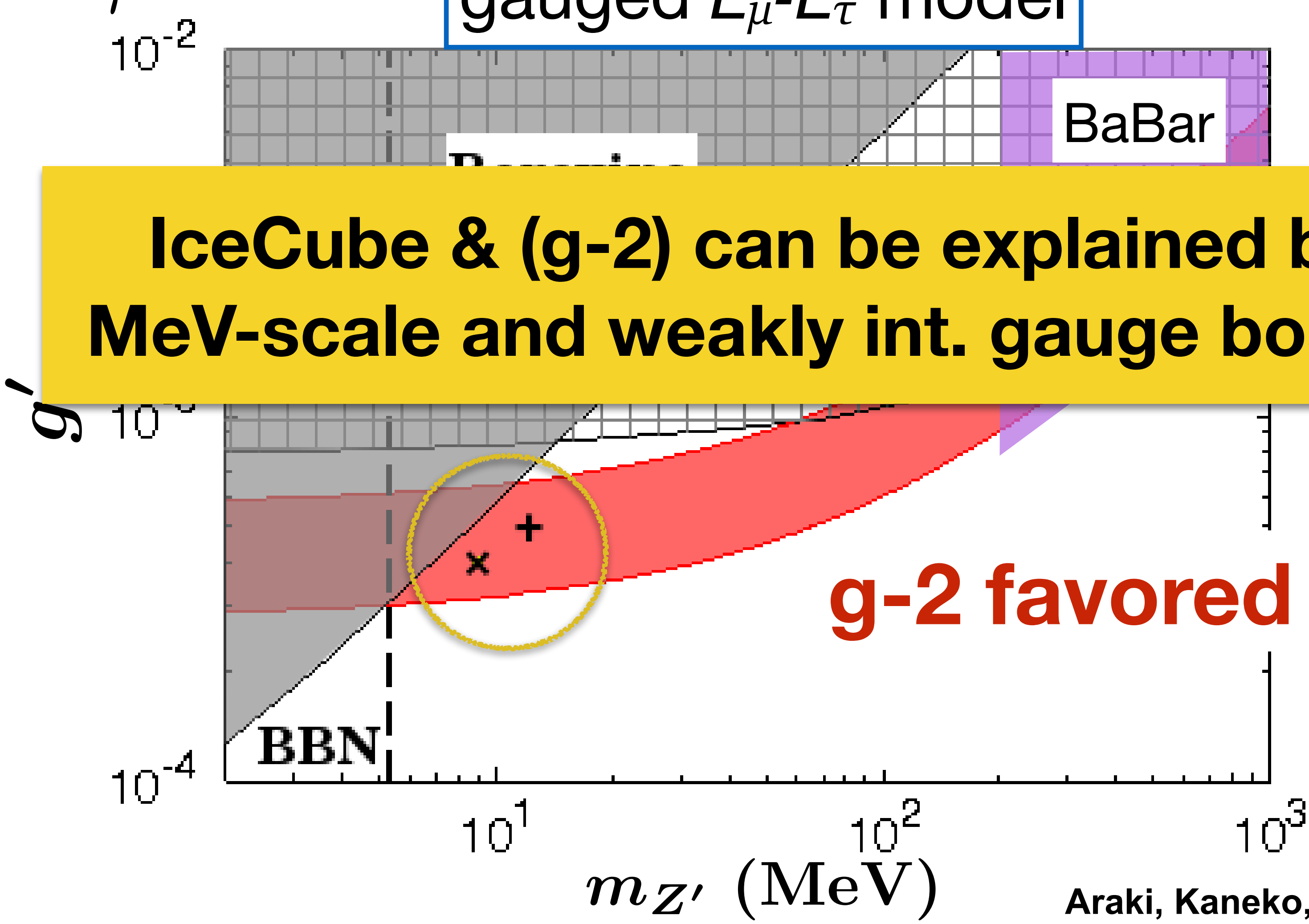
gauged L_μ-L_τ model



IceCube & (g-2) can be explained by MeV-scale and weakly int. gauge boson

Araki, Kaneko, Ota, Sato, T.S, PRD93 (2016)

Motivation

These anomalies/tensions can be explained by

$$m_{Z'} \simeq \mathcal{O}(10 - 100)\ \mathrm{MeV} \qquad g' \sim 10^{-5} - 10^{-4}$$

The origin of the mass = The spontaneous breaking of a symmetry

$$v = \frac{m_{Z'}}{g'} \sim \mathcal{O}(100 - 1000)\mathrm{GeV}$$

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New Physics above the EW scale

Purpose

How can we test such a light and weakly int. gauge boson?

- Need high statistics due to the weak int.
- Low energy beam enough to produce.
- Clear signal to discriminate from the SM BG.

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Belle-II experiment

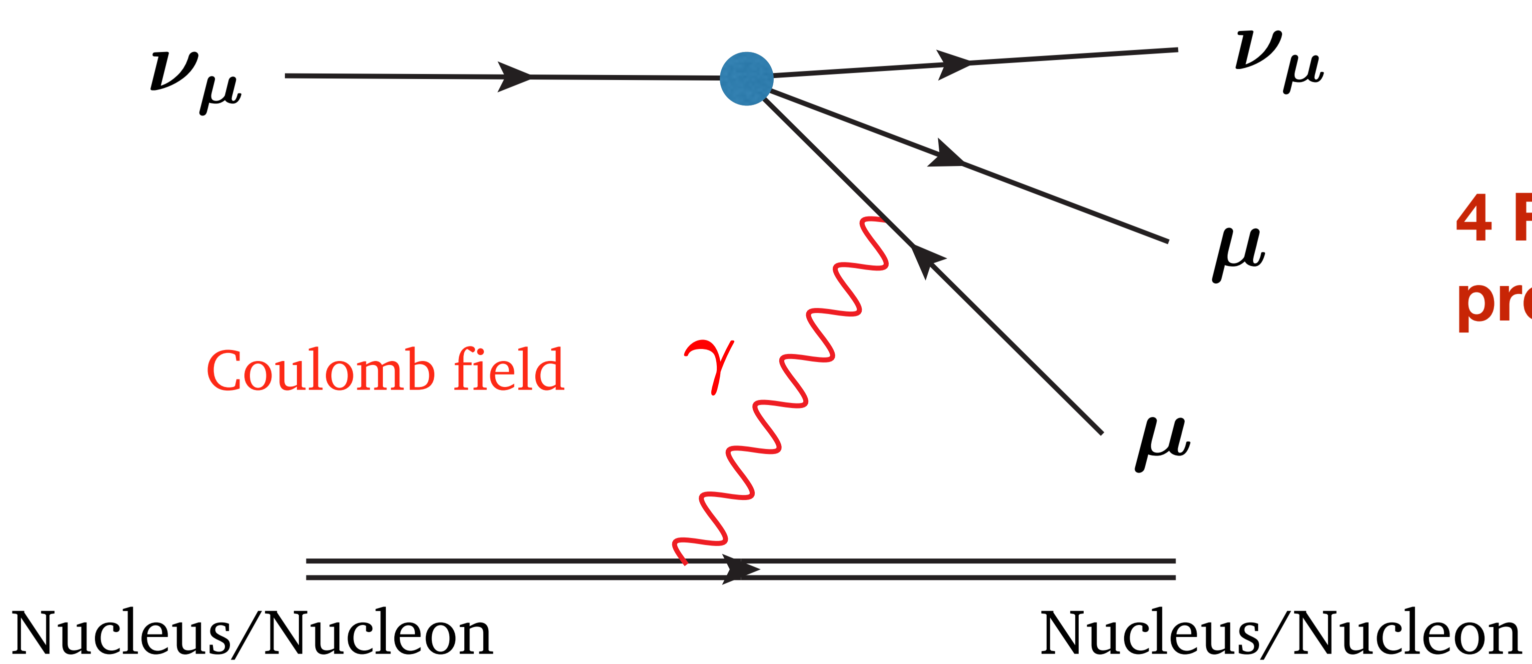
- e^+-e^- collider with the total luminosity = 50 ab^{-1}.
- the c.m. energy = 10.58 GeV.
- "One photon + Missing" event search.

Purpose

Neutrino beam experiment

- Various on-going/future plan with high statistics.
- Neutrino beam energy of O(1-10) GeV.
- “Neutrino Trident Production” Search

Altomannshofer, et al, PRL.113 (2014)



4 Fermi suppressed processes

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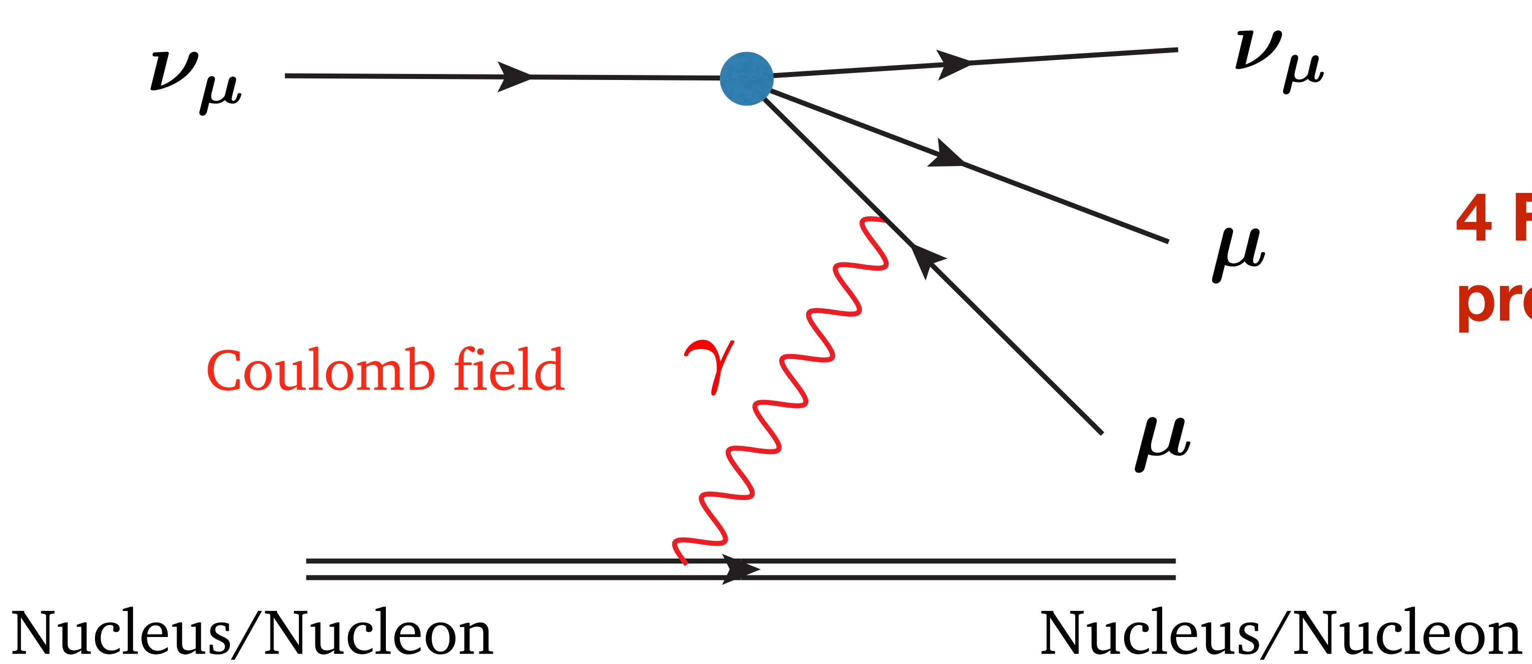

4 Fermi suppressed processes

Study the possibility of detecting the L_μ-L_τ gauge boson at Belle-II and Neutrino beam exp.

Outline

1. Introduction
2. Gauged L_μ-L_τ Model
3. Allowed region of parameters
4. Results
   Belle-II, Neutrino beam exp.
5. Summary

Gauged L_μ-L_τ Model

Gauged U(1)$_{L\mu\text{-}L\tau}$ model

He, Joshi, Lew, Volkas, PRD (1991) ,
R. Foot, Mod.Phys.Lett. (1991)

- A minimal extension of the SM
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- Large neutrino mixing (approx.)

Choubey, Rodejohann, Eur.Phys.J, (2005)
Ota, Rodejohann, Phys.Lett. (2006)

	l_e	e_R	l_μ	μ_R	l_τ	τ_R
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The Lagrangian

Kinetic mixing with SM gauge boson

$$\mathcal{L}_{\mathrm{new}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu + \frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu}$$

$$+ g' Z'_\mu (\bar{\mu}\gamma^\mu \mu + \bar{\nu}_\mu \gamma^\mu \nu_\mu - \bar{\tau}\gamma^\mu \tau - \bar{\nu}_\tau \gamma^\mu \nu_\tau)$$

new interactions for μ, τ and ν

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new interactions for *μ*, *τ* and *ν*

Simple model

- Only one new particle, *Z'*, is introduced.
- Three extra parameters ($m_{Z'}$, g' and ε) are added.

* The scalar sector is not specified.

Gauge interactions

In mass basis, the gauge int. is given as

$$\mathcal{L}_{\rm int} = Z'_\mu \left(e\epsilon \cos\theta_W J^\mu_{\rm EM} + g' J^\mu_{Z'}\right) + \mathcal{O}(\epsilon^2)$$

where

$$J^\mu_{\rm EM} = \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d - \bar{e}\gamma^\mu e + \cdots,$$

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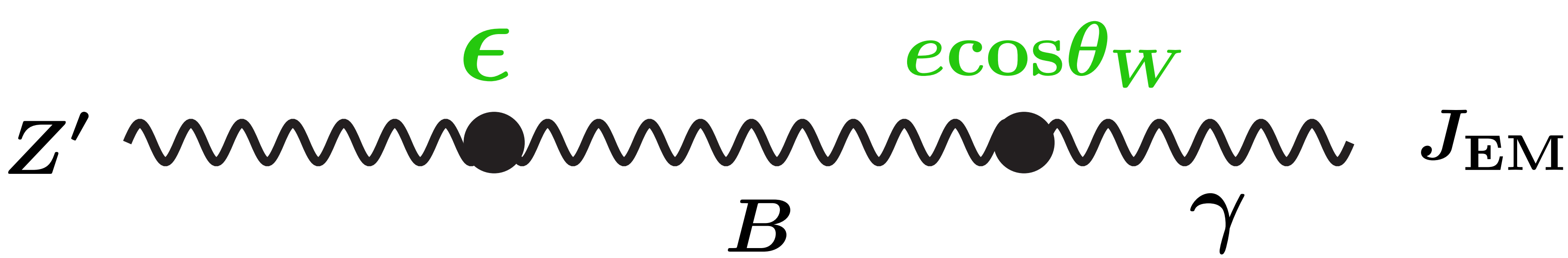

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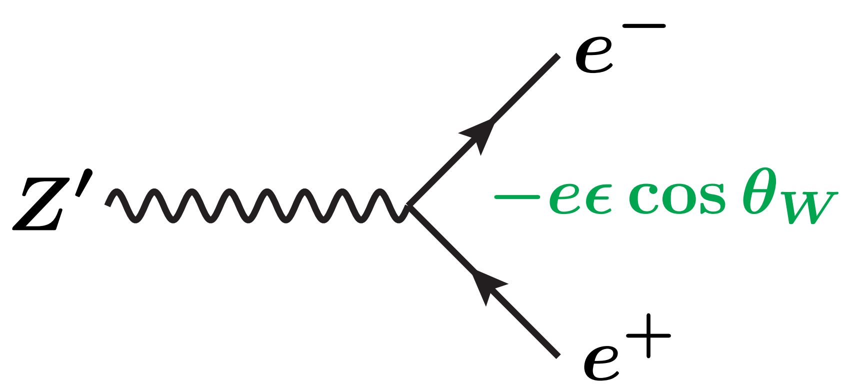

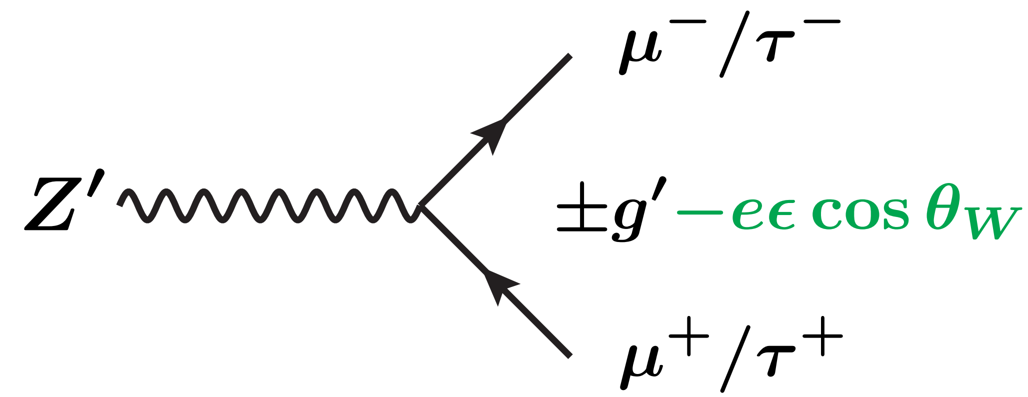

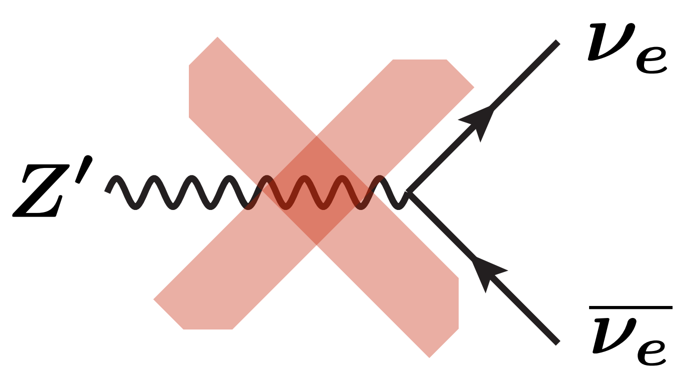

The coupling can be enhanced or suppressed

No constraints from reactor exp.

Kinetic Mixing

The kinetic mixing is allowed by the symmetries, however it must be small due to experimental constraints.

$$|\varepsilon| < 10^{-4}$$

Sometimes it is set to be zero…

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Two possible choices

(1) Tree-level kinetic mixing as a free parameter.

(2) Loop-induced kinetic mixing as func. of g' and $m_{Z'}$

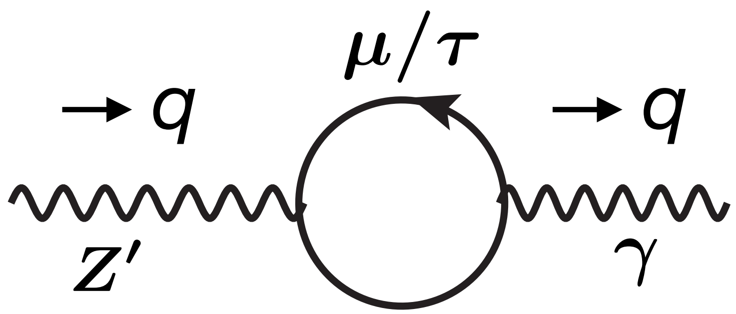
Tree-level kinetic mixing can be forbidden by a discrete symmetry at the QED level,

Ibe, Nakano, Suzuki, PRD95 (2017)

$$\mu \leftrightarrow \tau, \; Z'_\mu \to -Z'_\mu$$

Loop-induced Kinetic Mixing

Even if the tree-level kinetic mixing is zero, it is generated at a loop level,



$$= \frac{8eg'}{(4\pi)^2} \int_0^1 x(1-x) \ln \frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2} \, dx$$

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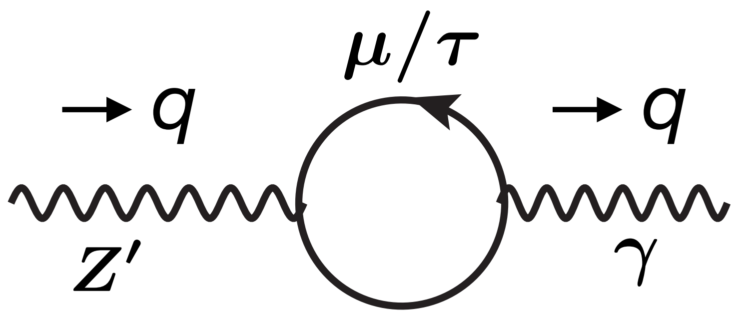

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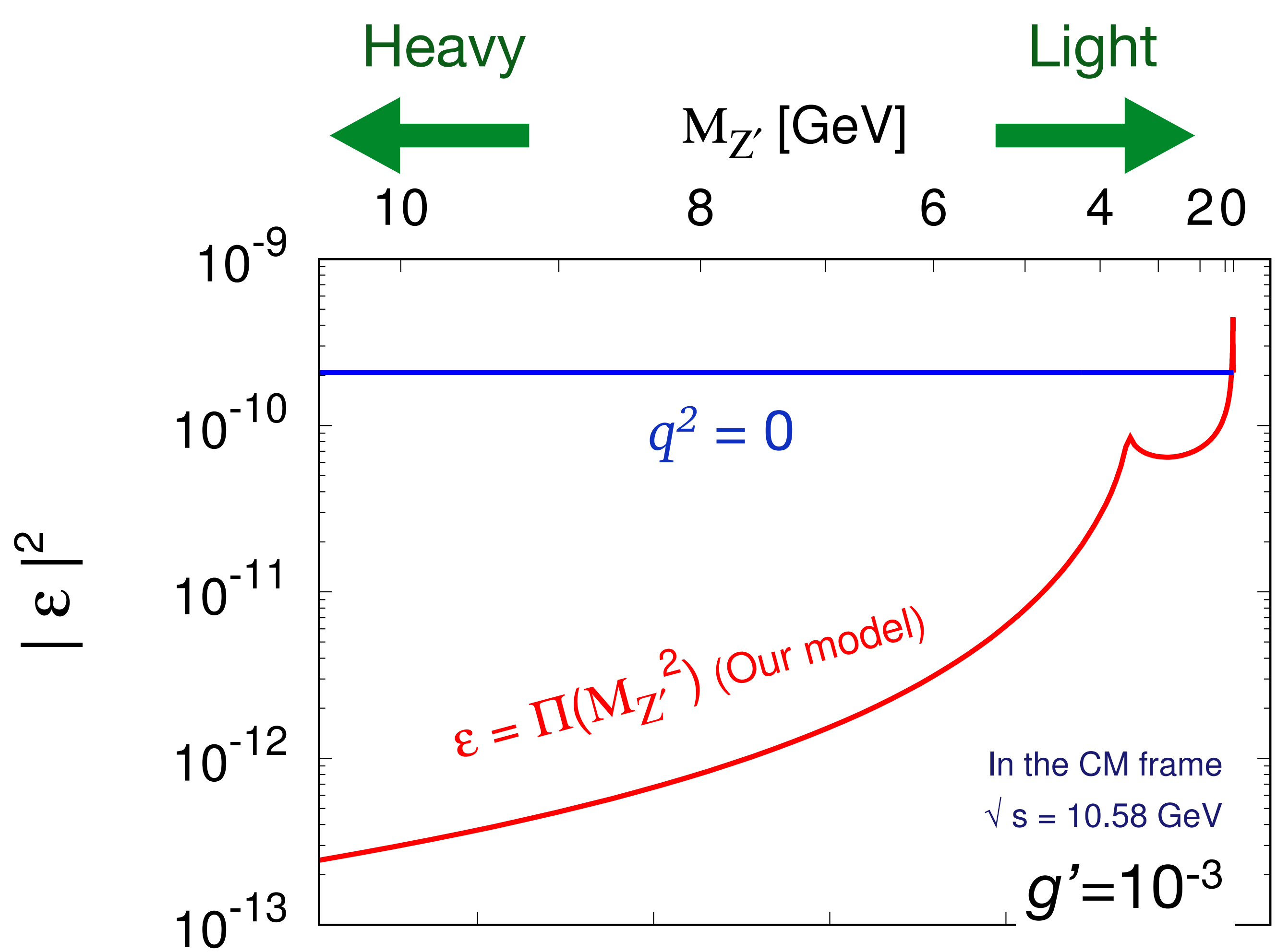
momentum dependence

$q^2 = M_{Z'}^2$

mass dependence



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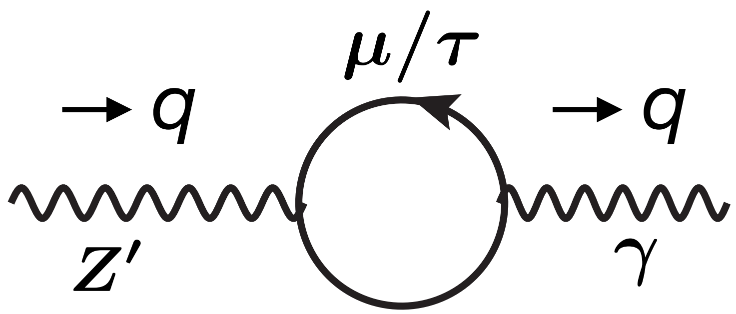

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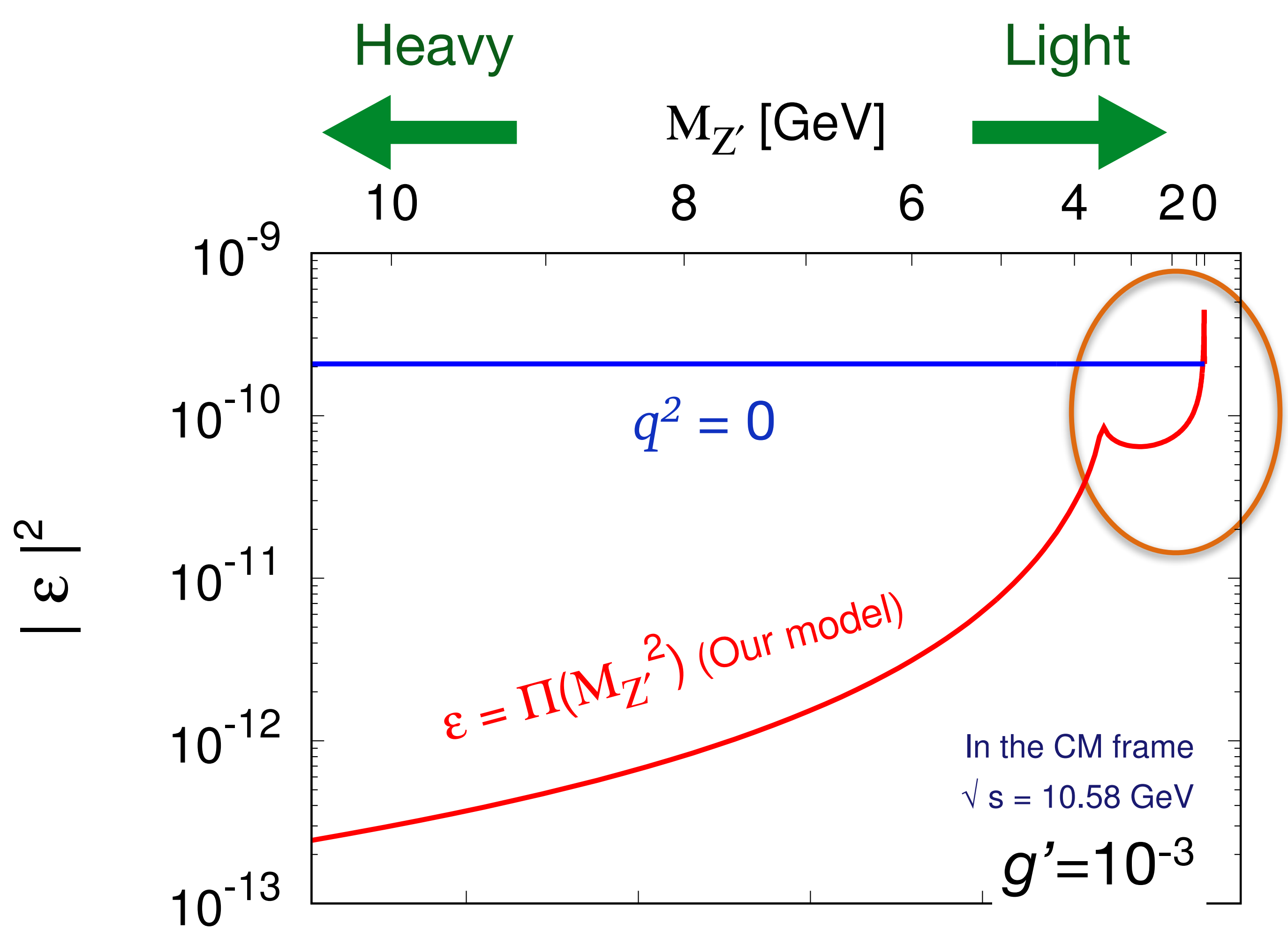


Larger for smaller $m_{Z'}$

Not negligible

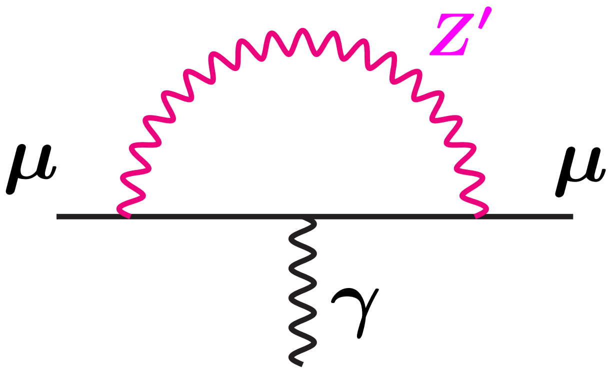
Allowed Region

Constraints

- A few constraints directly on the L_μ-L_τ model.
- Many constraints on dark photon and B-L model.
- Comparison of the corresponding coupling/kinetic mixing.

Constraints

1. Muon anomalous magnetic moment

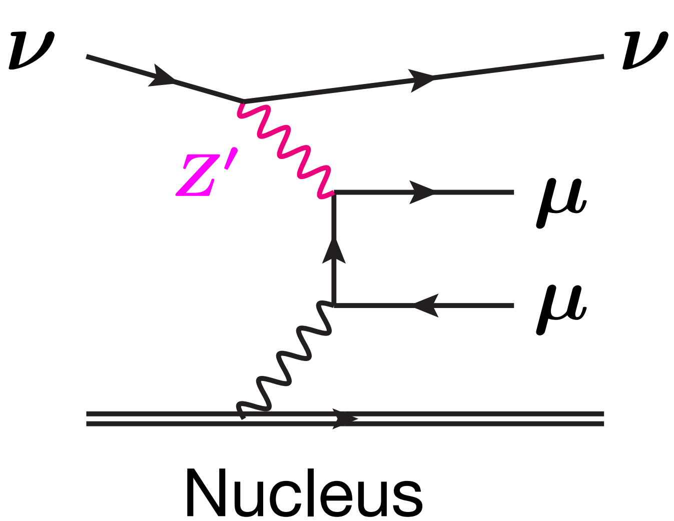


$$\Delta a_\mu^{Z'} = \frac{(g' - \epsilon e \cos\theta_W)^2}{8\pi^2} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{Z'}^2},$$

$$12.8\ (4.8) \leq \Delta a_\mu^{Z'} \times 10^{10} \leq 44.8\ (52.8)$$ @2σ (3σ)

2. Neutrino trident production processes

The scattering of a neutrino off a nuclei, producing muons

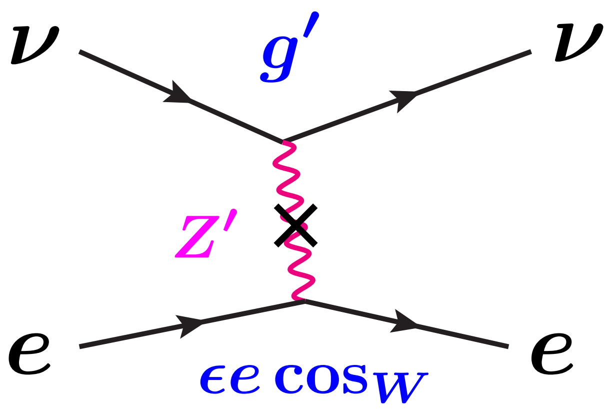


$$R_{\mathrm{CCFR}} \equiv \frac{\sigma_{\mathrm{CCFR}}}{\sigma_{\mathrm{SM}}} = 0.82 \pm 0.28$$

$$R_{\mathrm{CHARM-II}} \equiv \frac{\sigma_{\mathrm{CHARM-II}}}{\sigma_{\mathrm{SM}}} = 1.58 \pm 0.75$$

Constraints

3. Neutrino-Electron scattering



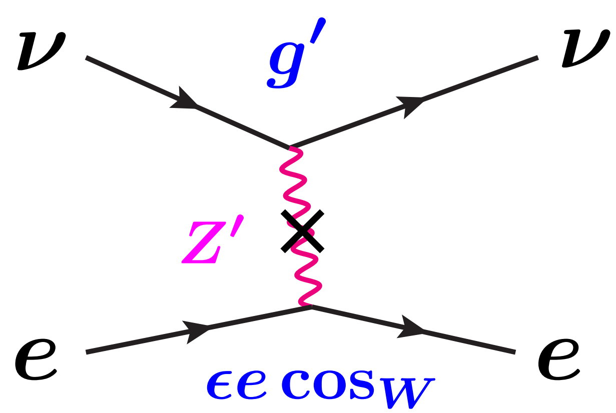
$$\left[(\epsilon e \cos\theta_W)^2 \sum_{j=1}^{3} f_i |g_{ij}|^2\right]^{1/4} < g_{B-L}$$

$$|g_{ij}| \equiv |g'(V^\dagger Q V)_{ij}|$$

f_i : mass eigenstates ratio at the Earth

Constraints

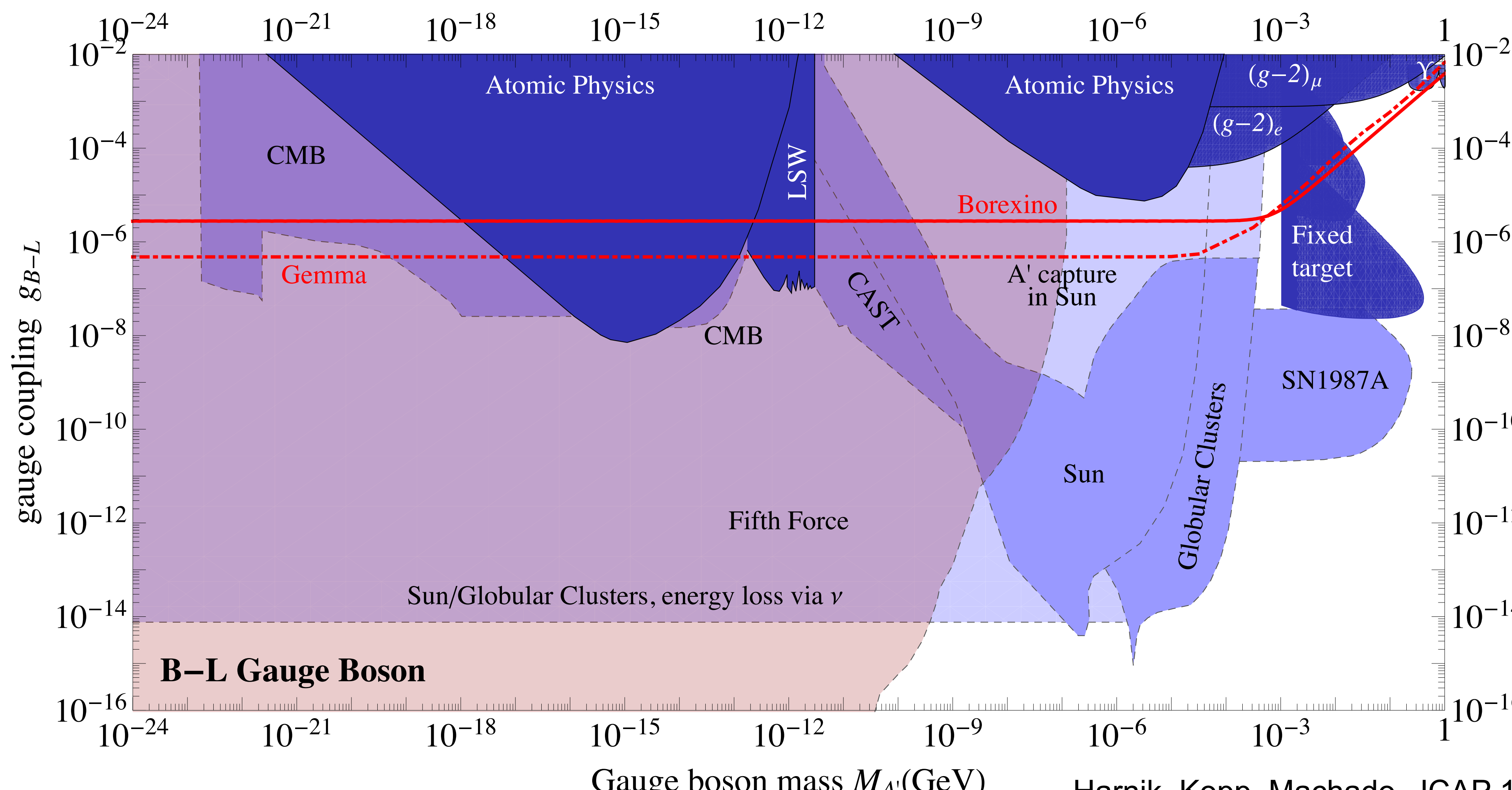
3. Neutrino-Electron scattering



$$\left[(\epsilon e \cos\theta_W)^2 \sum_{j=1}^{3} f_i |g_{ij}|^2 \right]^{1/4} < g_{B-L}$$

$$|g_{ij}| \equiv |g'(V^\dagger Q V)_{ij}|$$

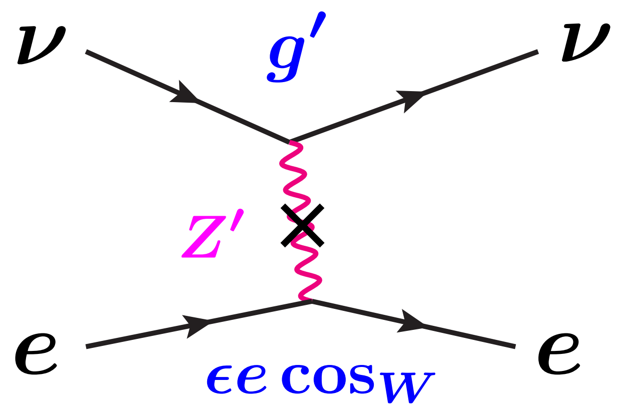
f_i : mass eigenstates ratio at the Earth



Harnik, Kopp, Machado, JCAP 1207 (2012)

Constraints

3. Neutrino-Electron scattering



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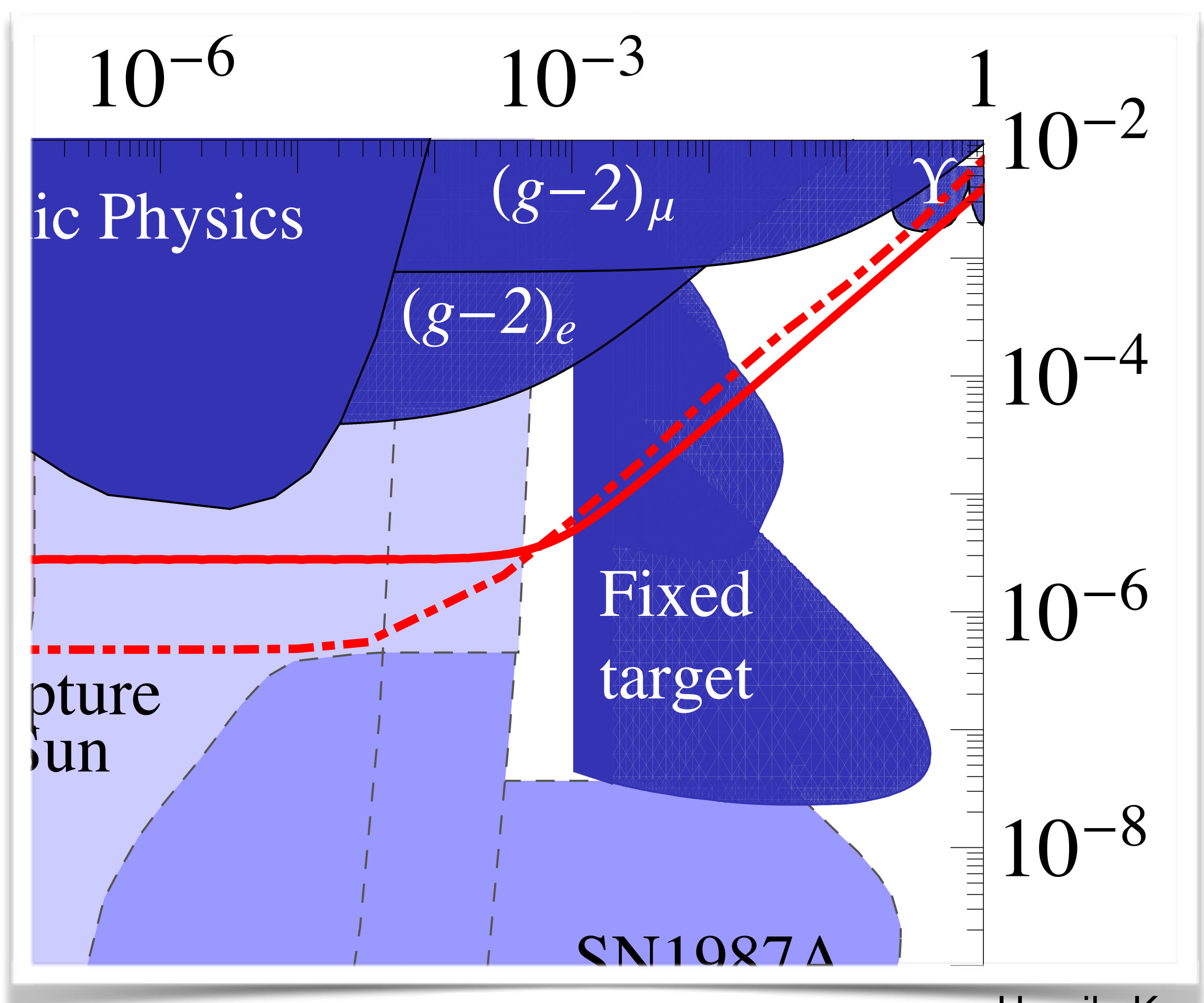
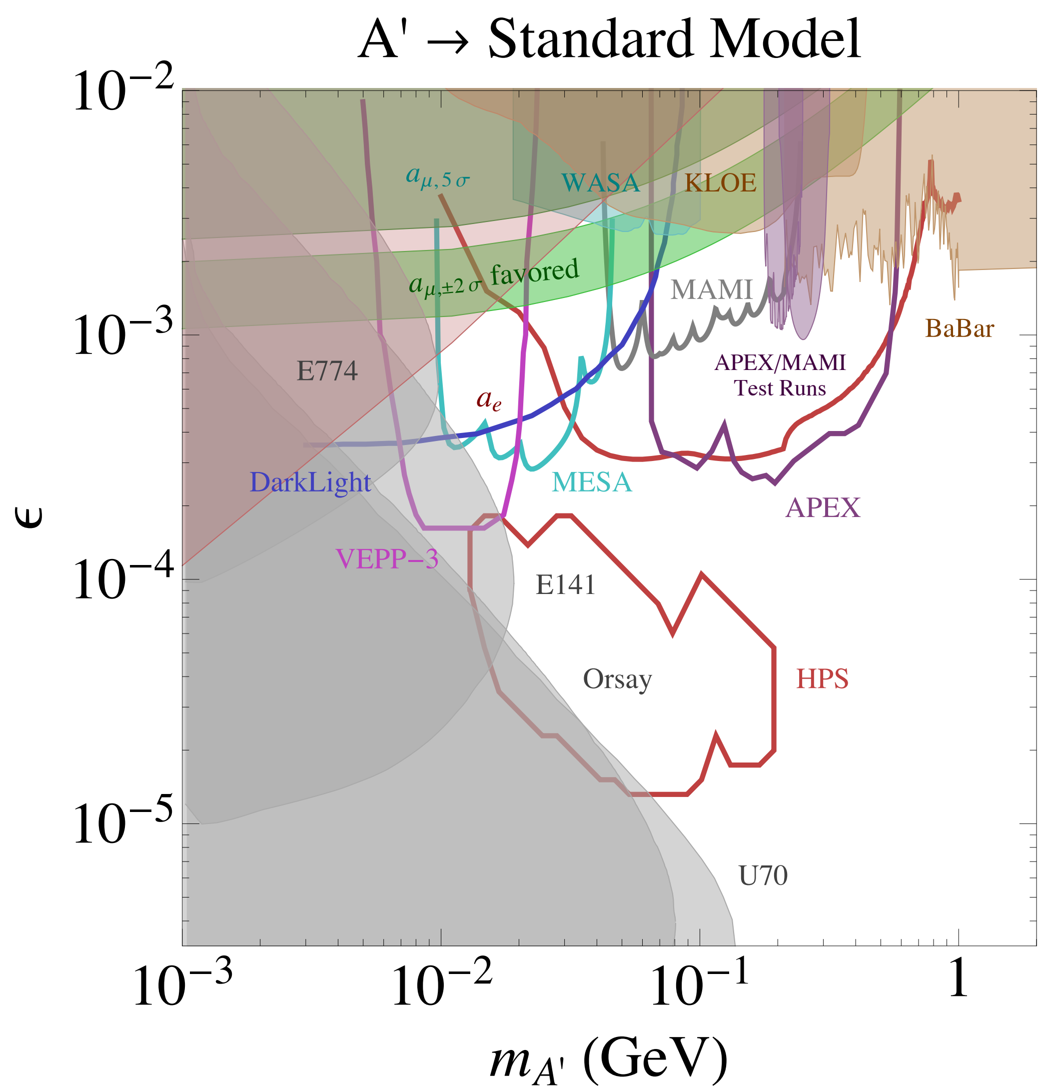


Harnik, Kopp, Machado, JCAP 1207 (2012)

Constraints

4. Beam dump experiment

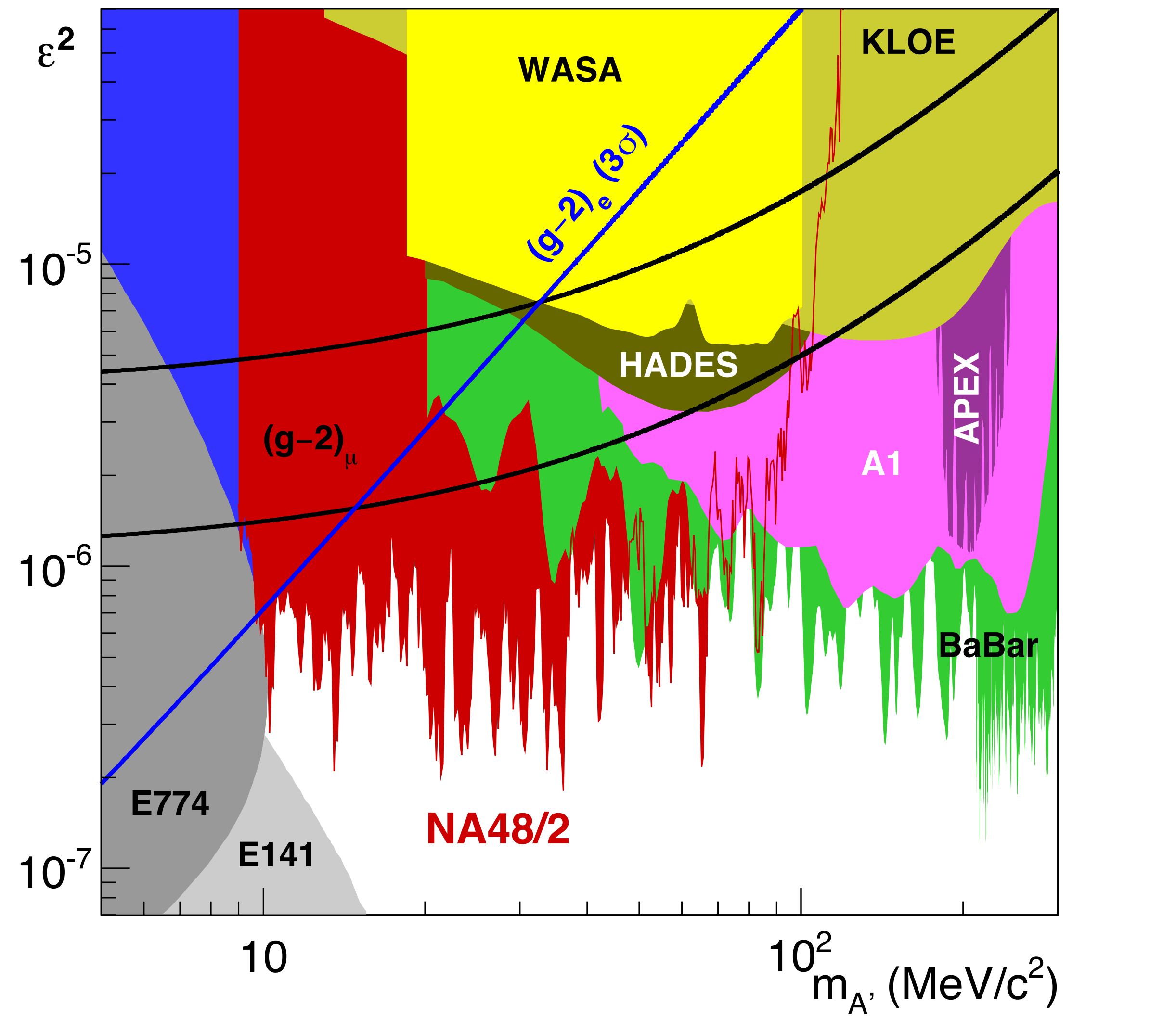
Essig, et al. arXiv:1311.0029



$$\frac{|\epsilon \cos\theta_W|}{\sqrt{\mathrm{Br}(Z' \to e^+e^-)}} > \epsilon_{\mathrm{BD}}$$

5. Meson decay

NA/48, PLB746 (2015) 178-185

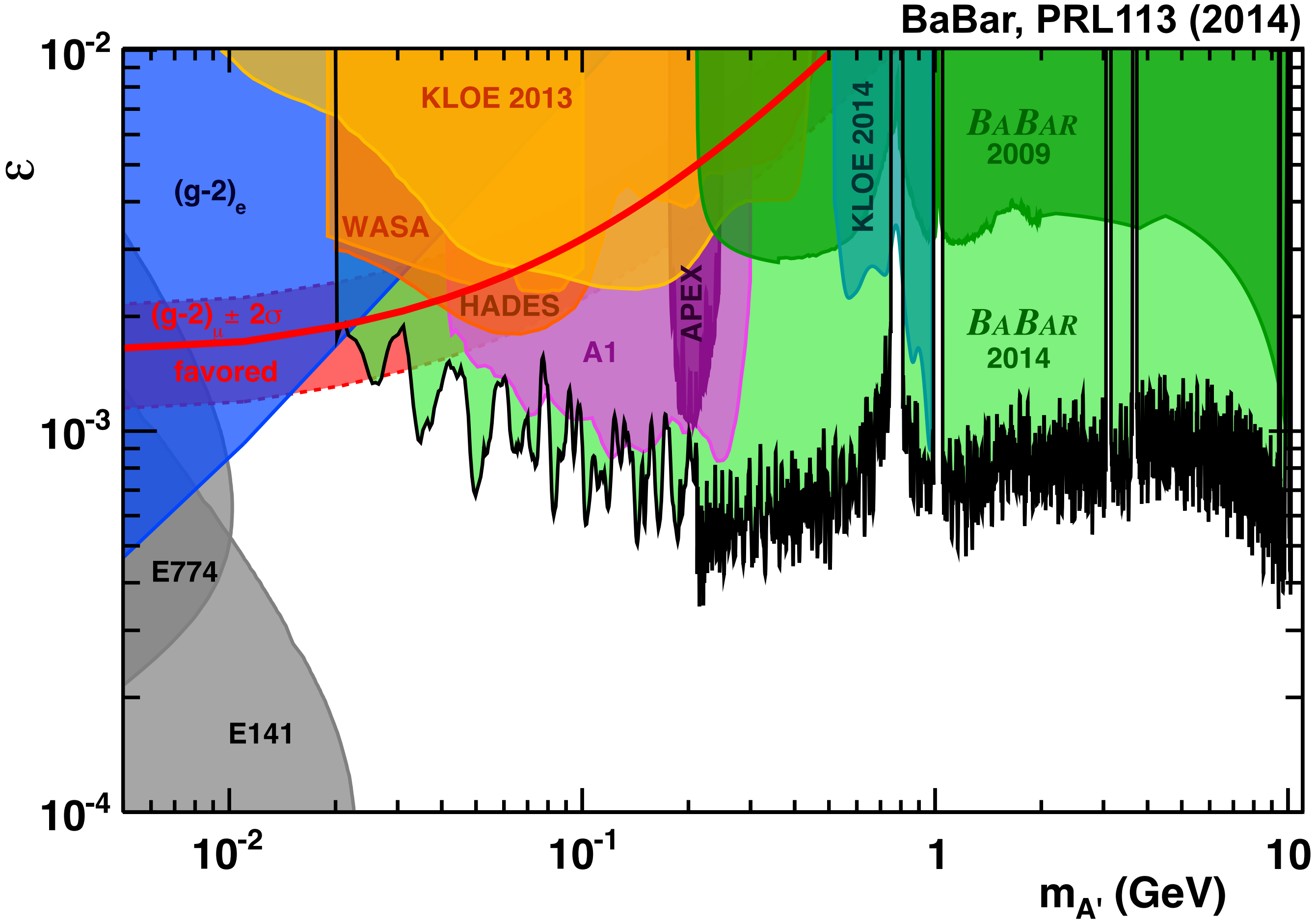


$$|\epsilon \cos\theta_W| \sqrt{\mathrm{Br}(Z' \to e^+e^-)} < \epsilon_{\mathrm{MD}}$$

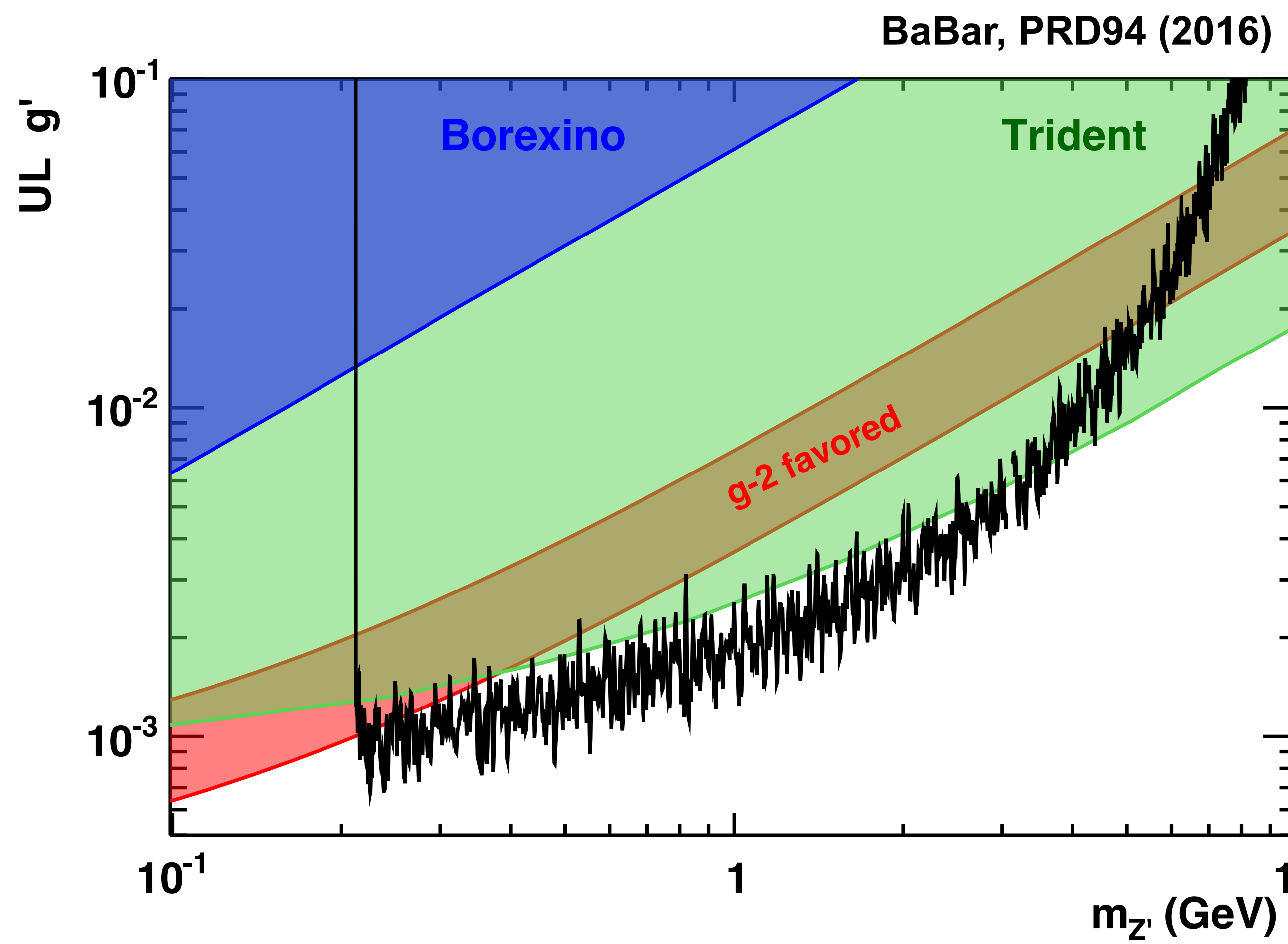
Constraints

6. e⁺-e⁻ collider at BaBar

Dark Photon Search

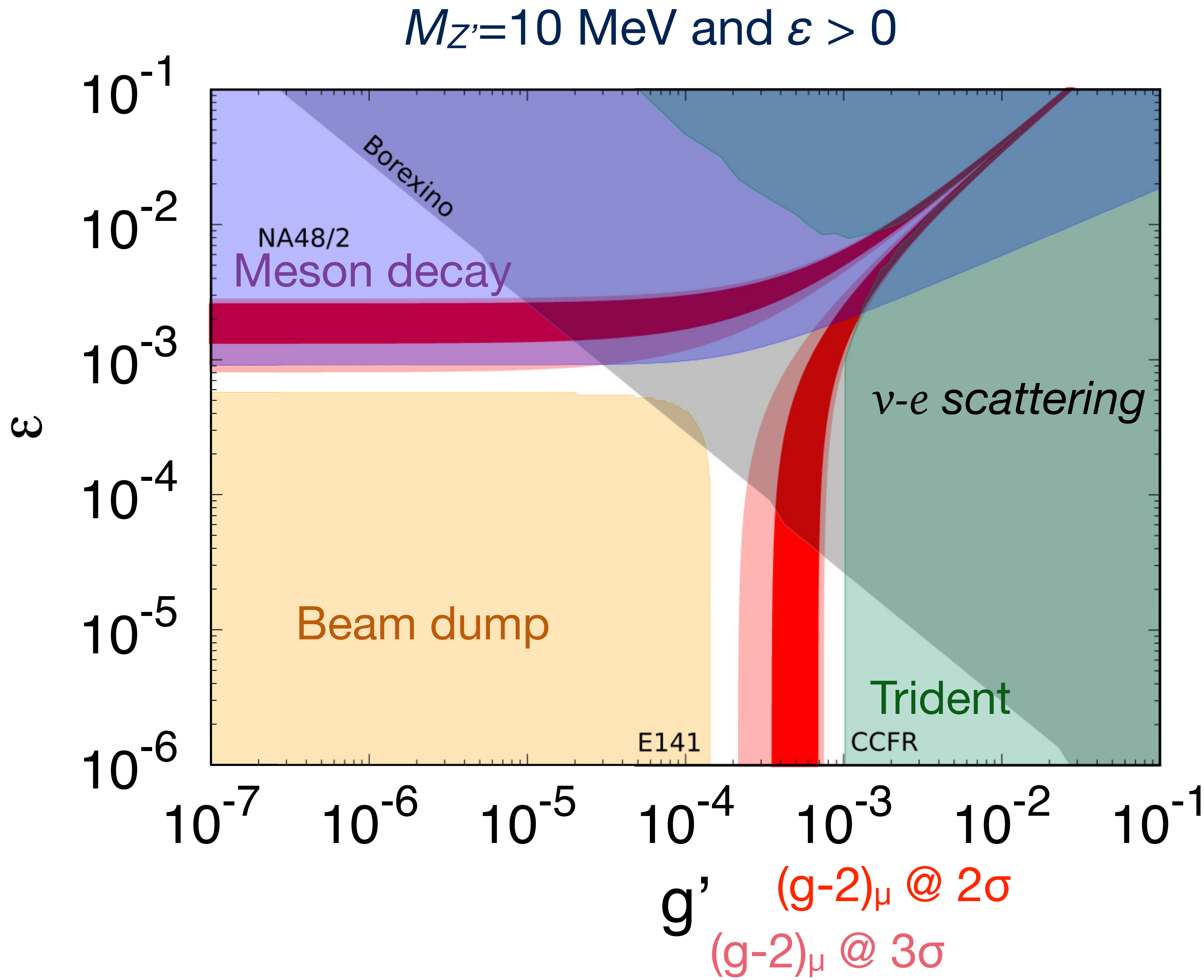


L_μ-L_τ Z' Search



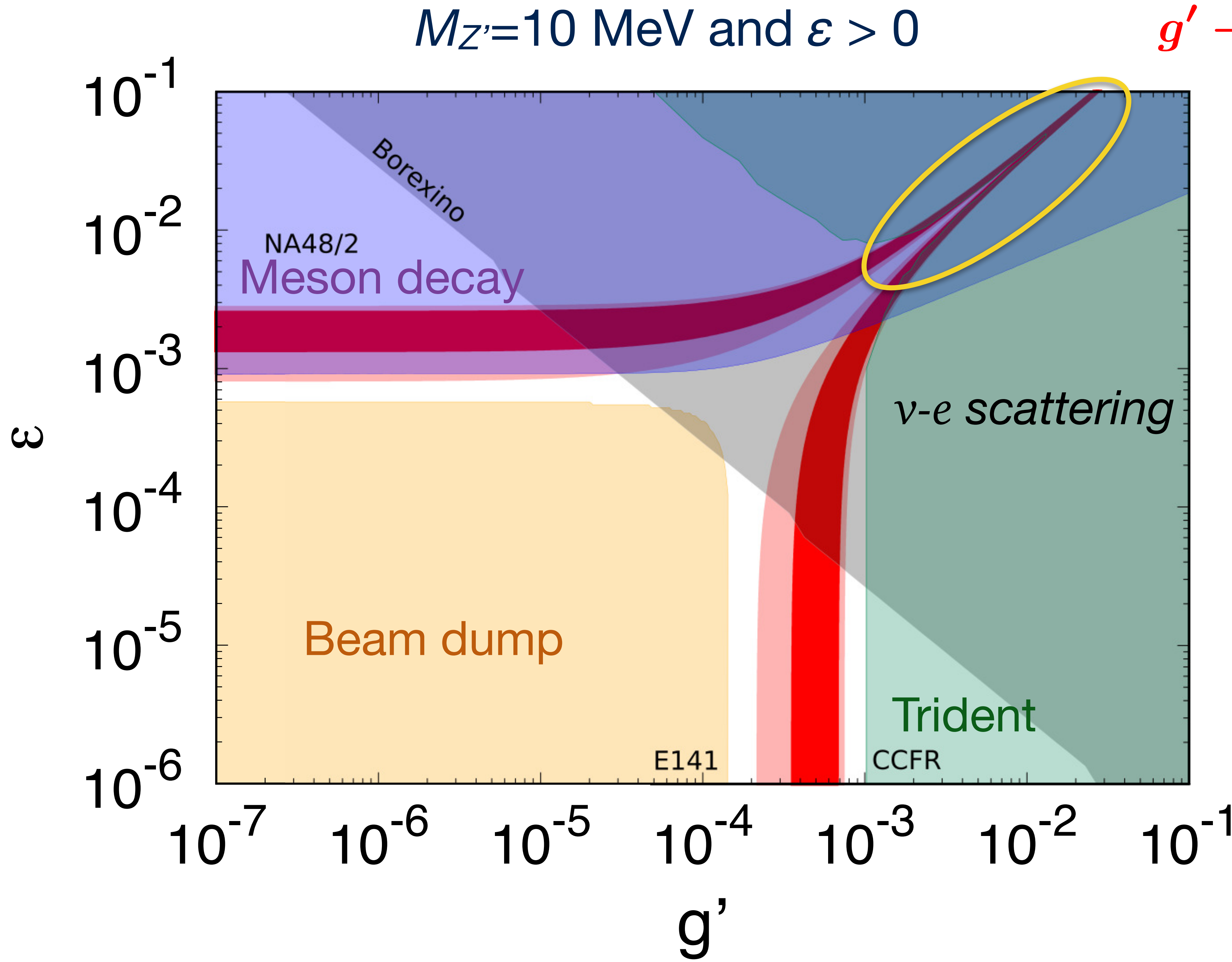
$$|\epsilon \cos_W| \sqrt{\mathrm{Br}(Z' \to l^+ l^-)} < \epsilon_{\mathrm{BaBar}}$$

Allowed Parameter Space

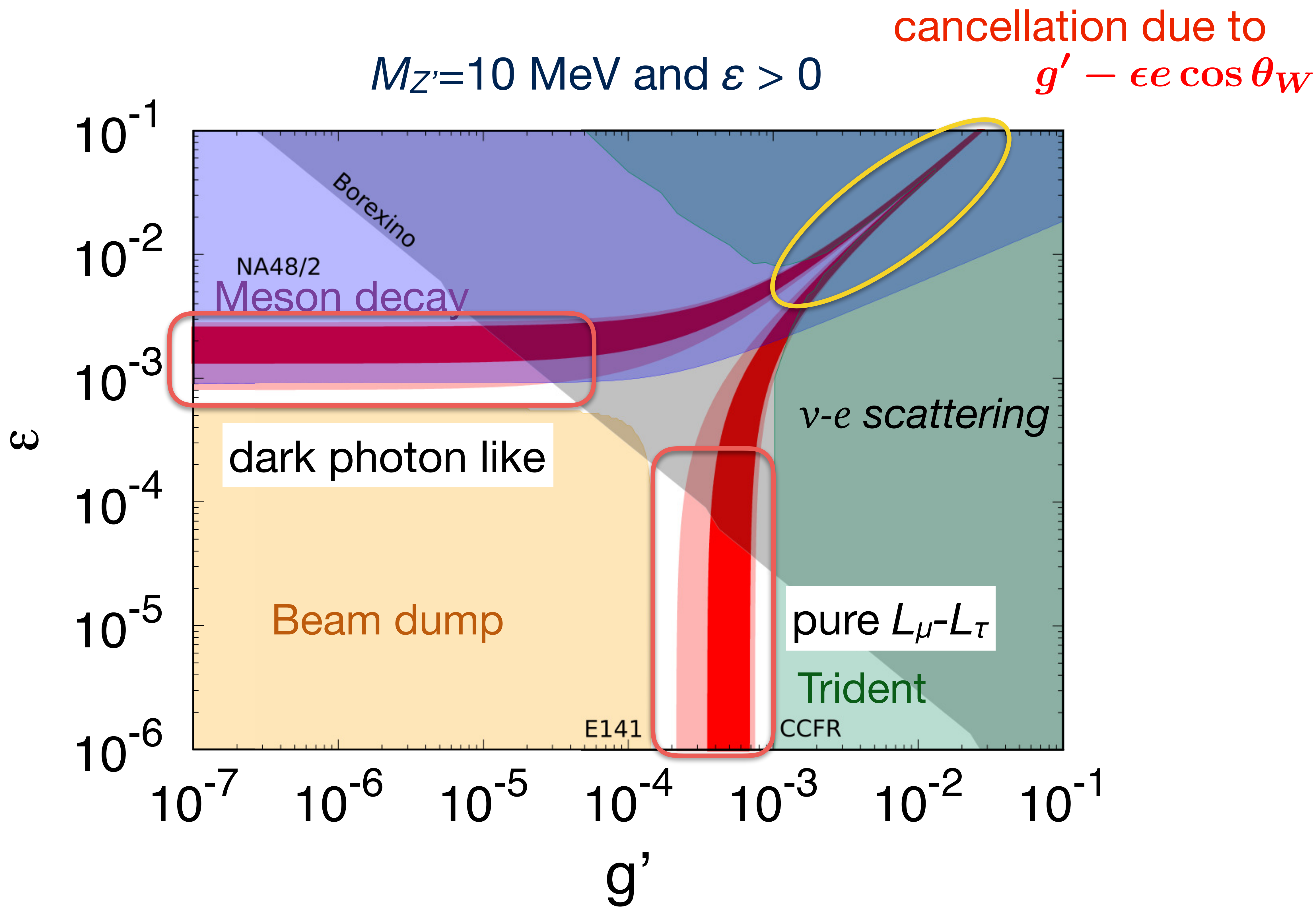


Allowed Parameter Space

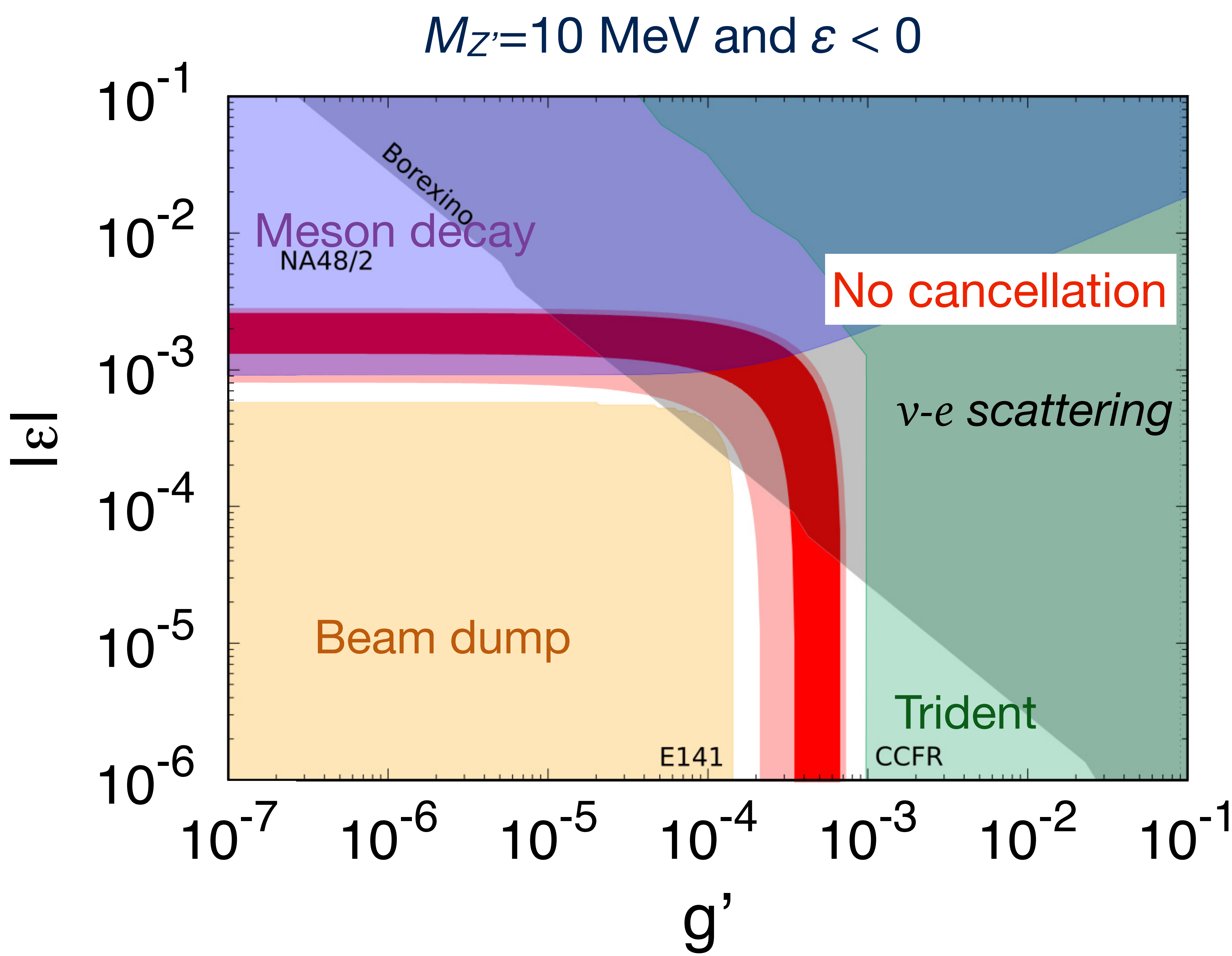
cancellation due to
$g' - \epsilon e \cos\theta_W$



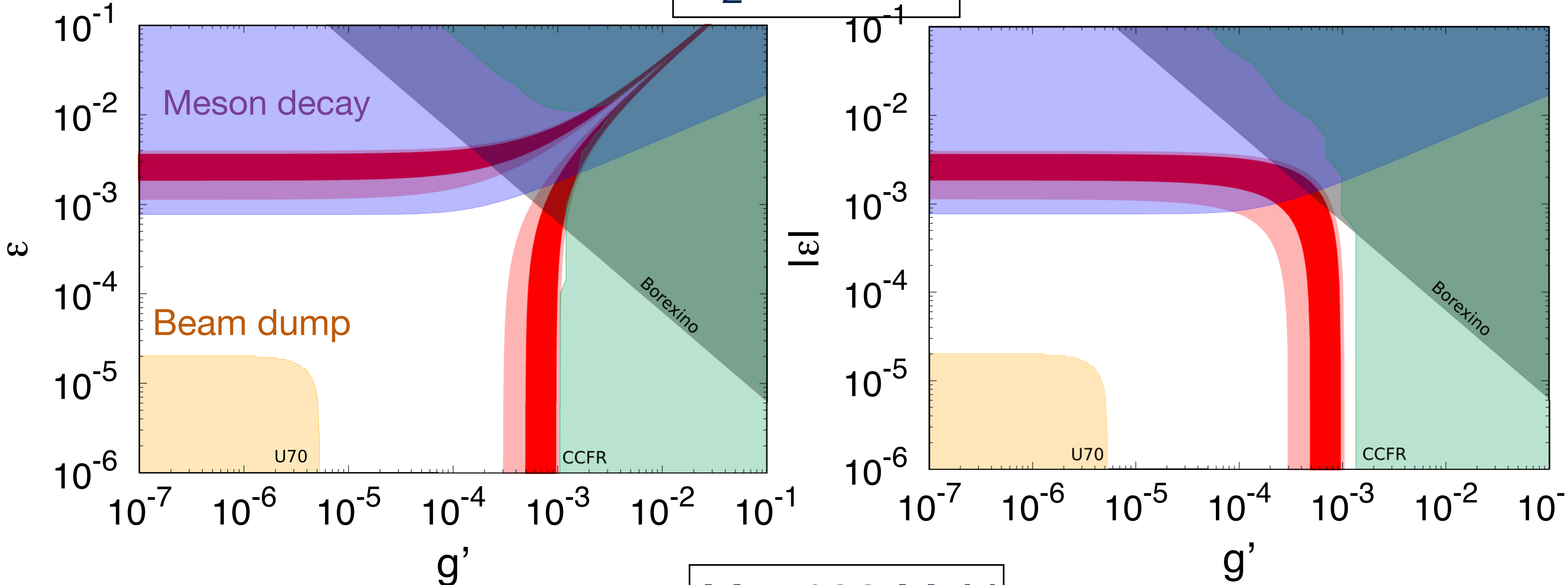
Allowed Parameter Space



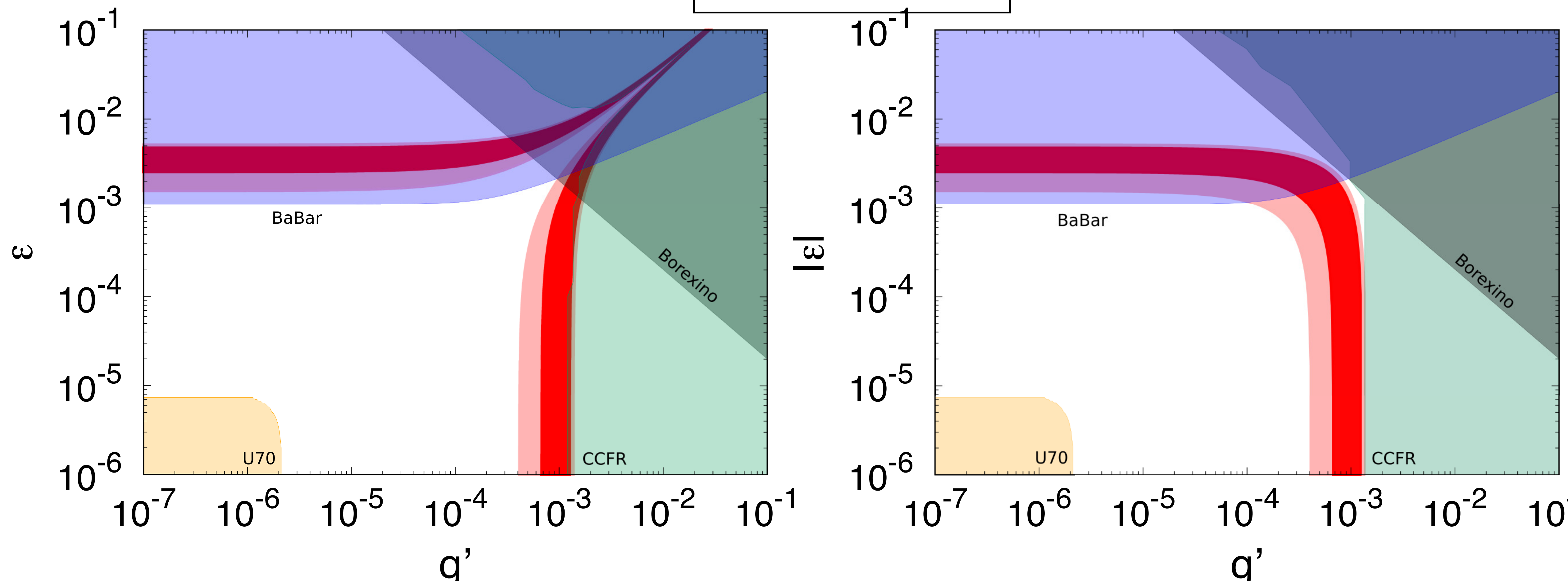
Allowed Parameter Space



$M_{Z'}$=50 MeV

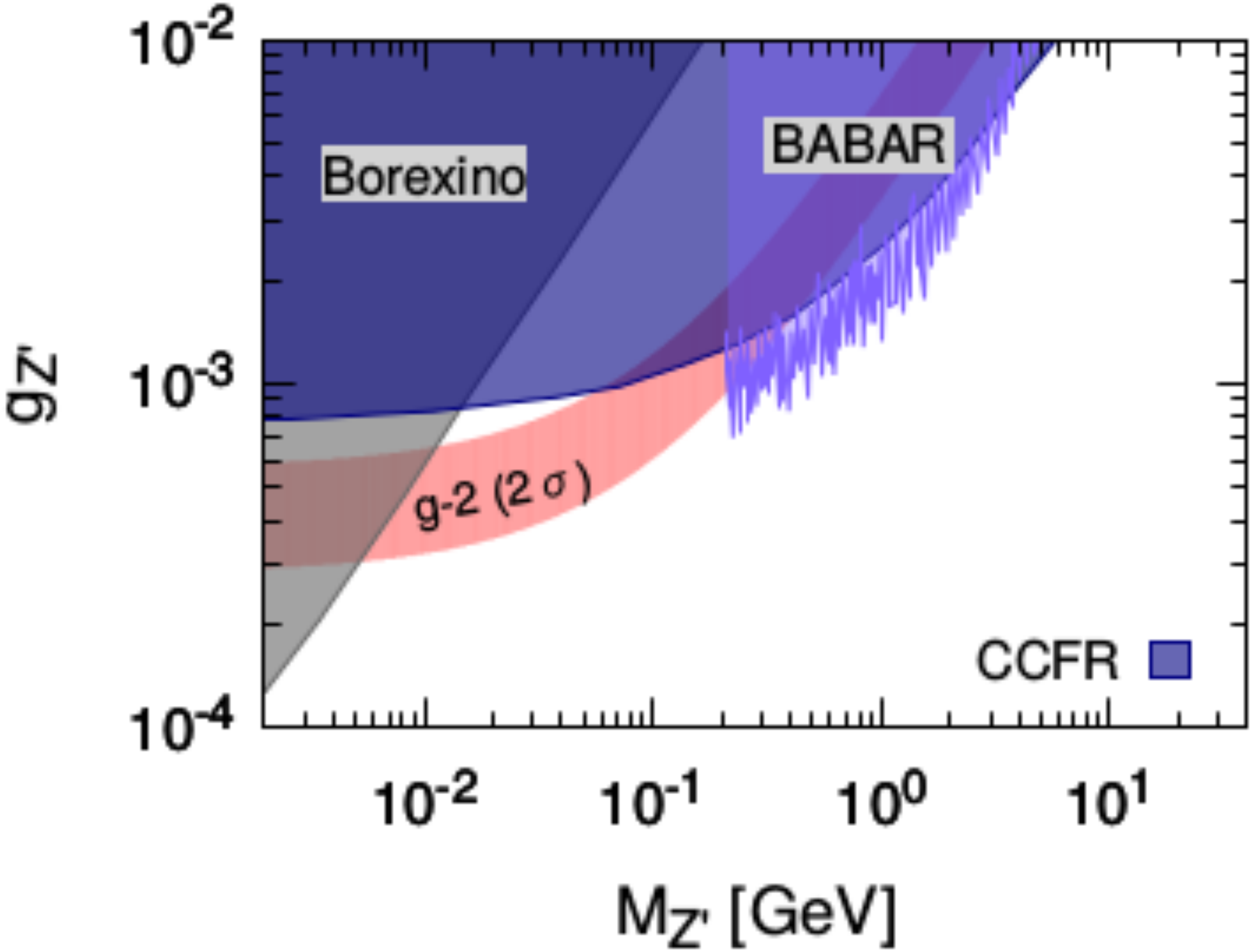


$M_{Z'}$=100 MeV



Allowed Parameter Space

Loop-induced kinetic mixing case



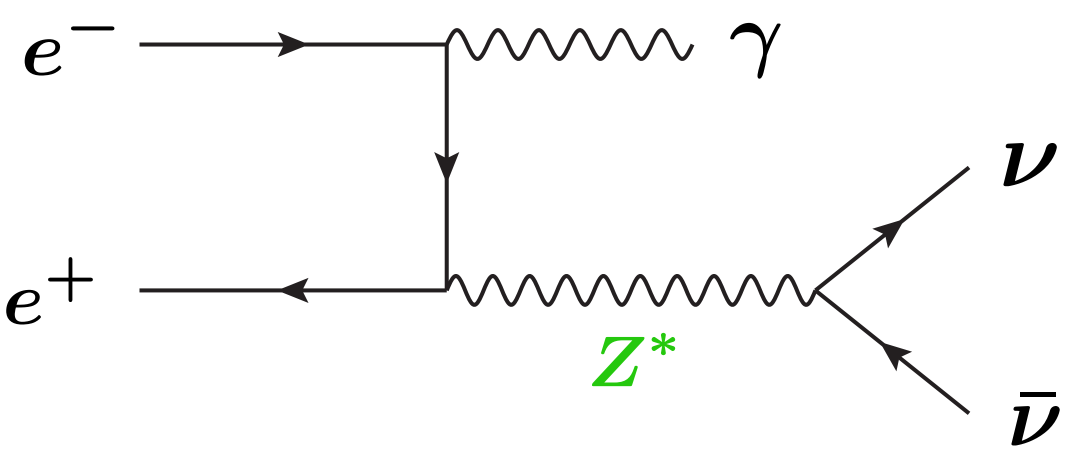
Search at Belle-II

One-Photon + Missing

The SM process

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

suppressed due to heavy *Z*/*W* mass



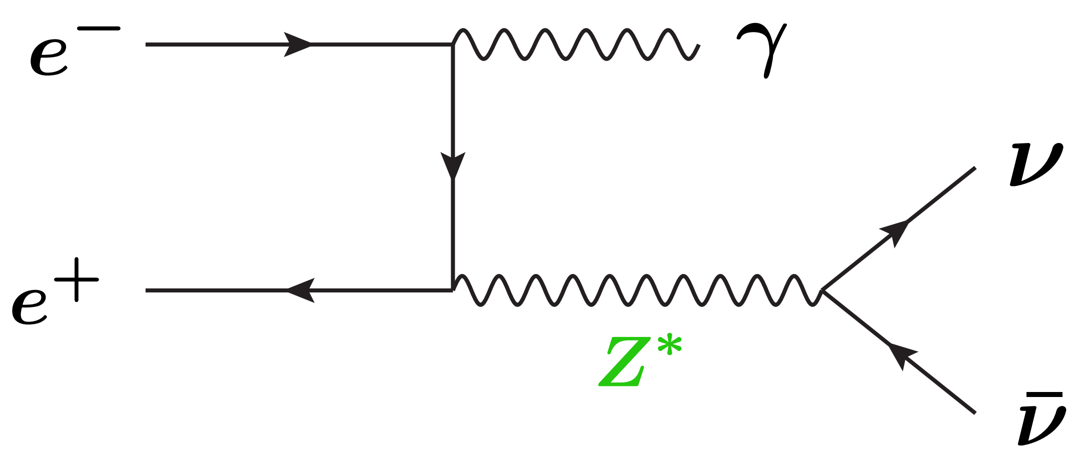
3-body final state

One-Photon + Missing

The SM process

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

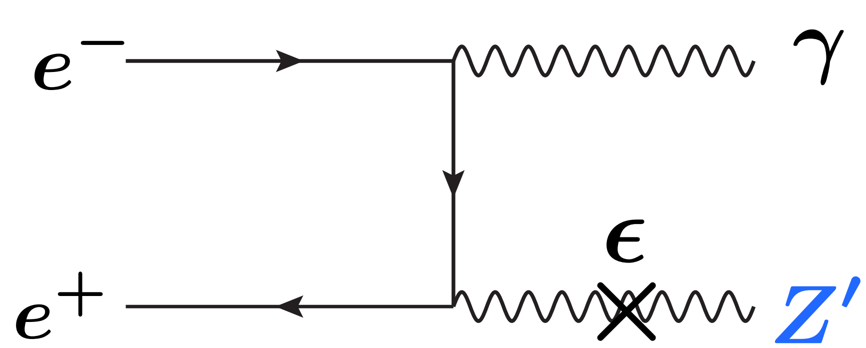
suppressed due to heavy *Z*/*W* mass

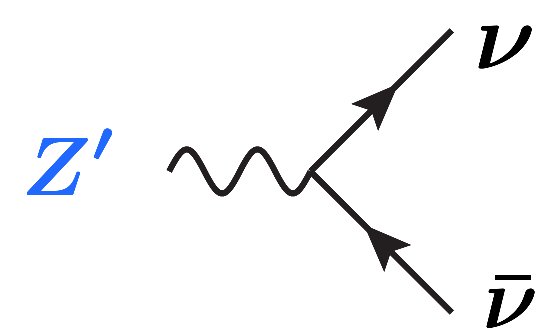


3-body final state

New process

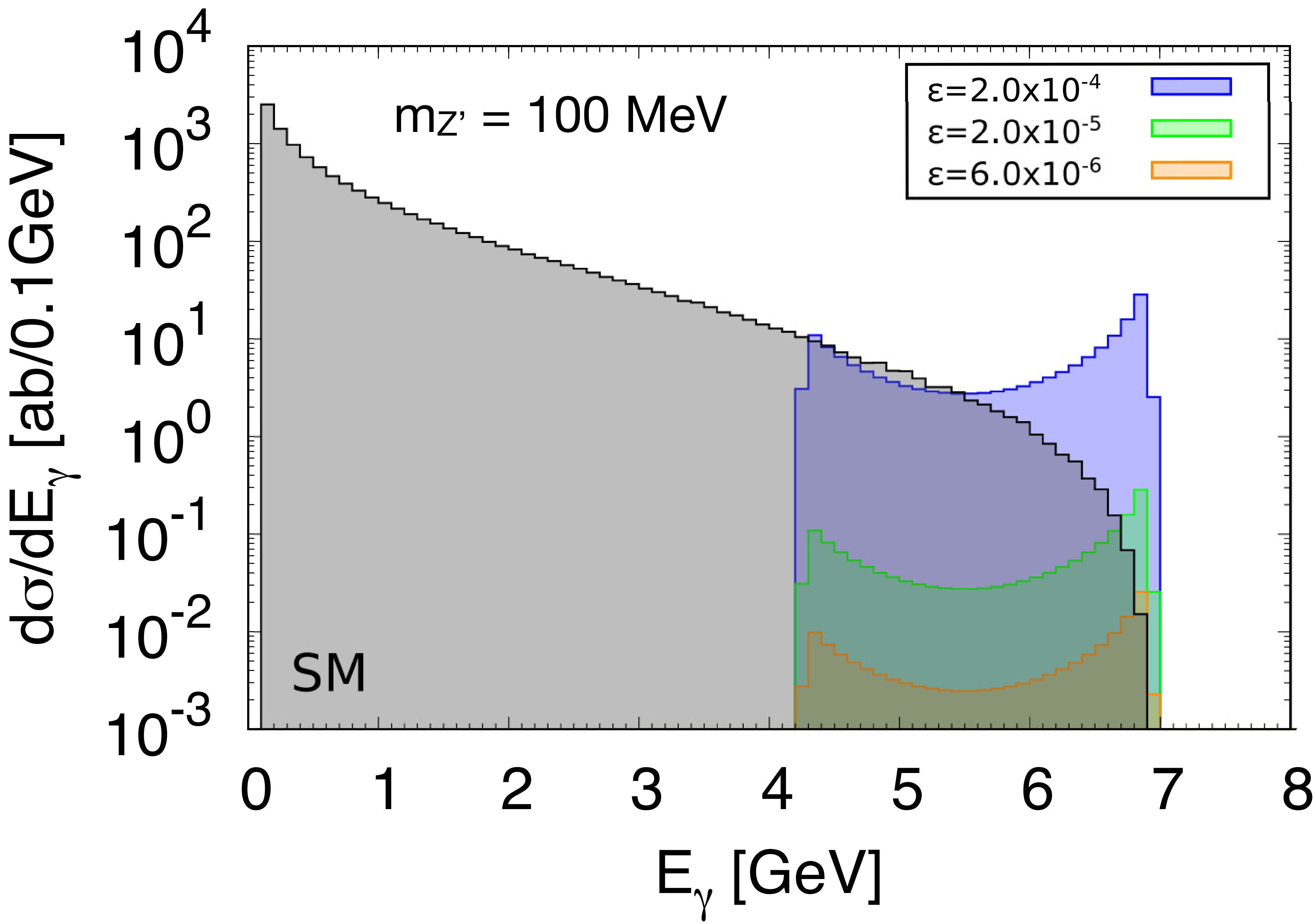
$$e^+e^- \to \gamma \underline{Z'} \quad \Rightarrow \quad \underline{Z' \to \nu\bar{\nu}}$$



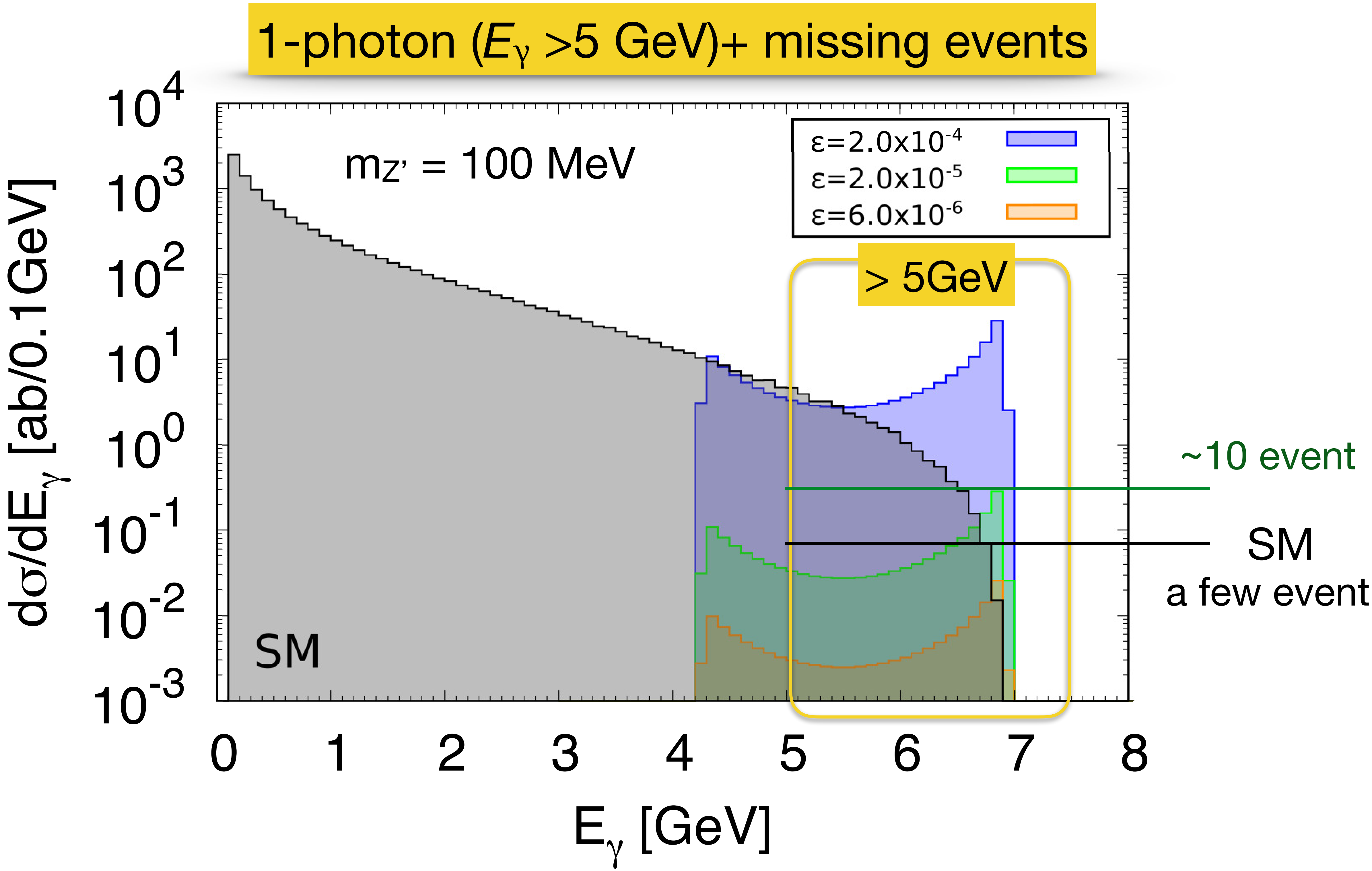


2-body final state

diff. Cross Section at Belle-II

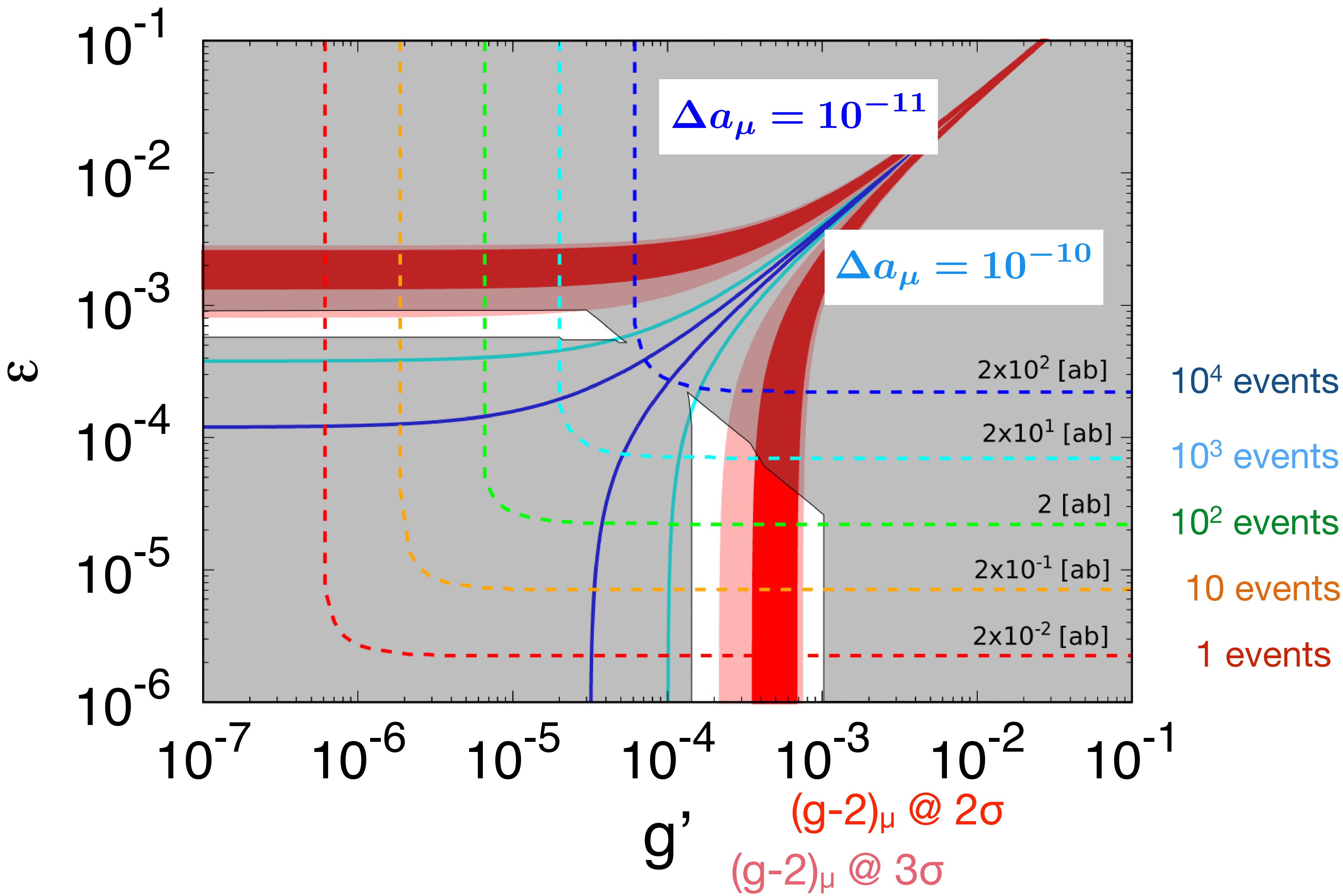


diff. Cross Section at Belle-II



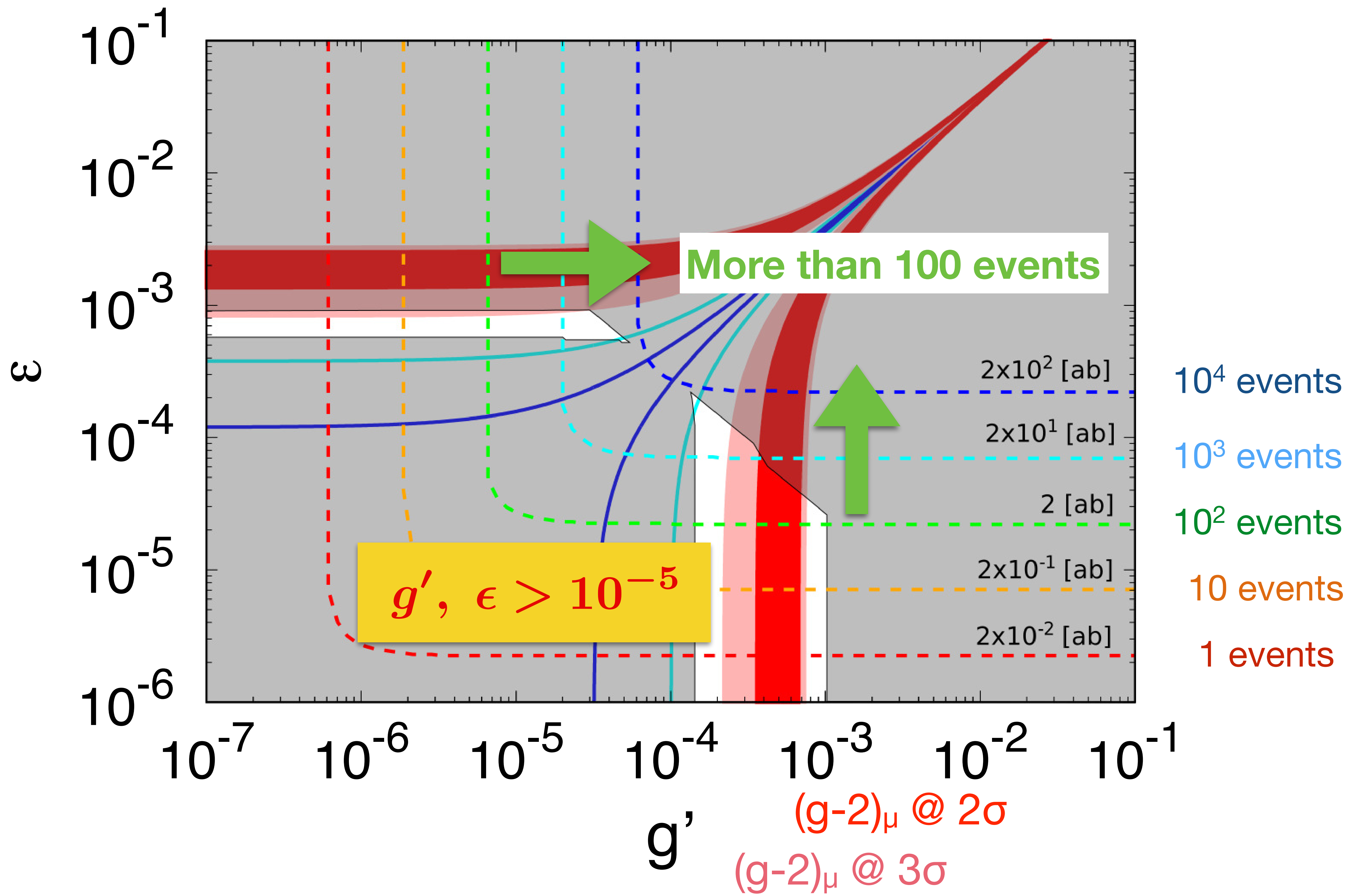
Belle-II

$M_{Z'}$=10 MeV and $\varepsilon > 0$

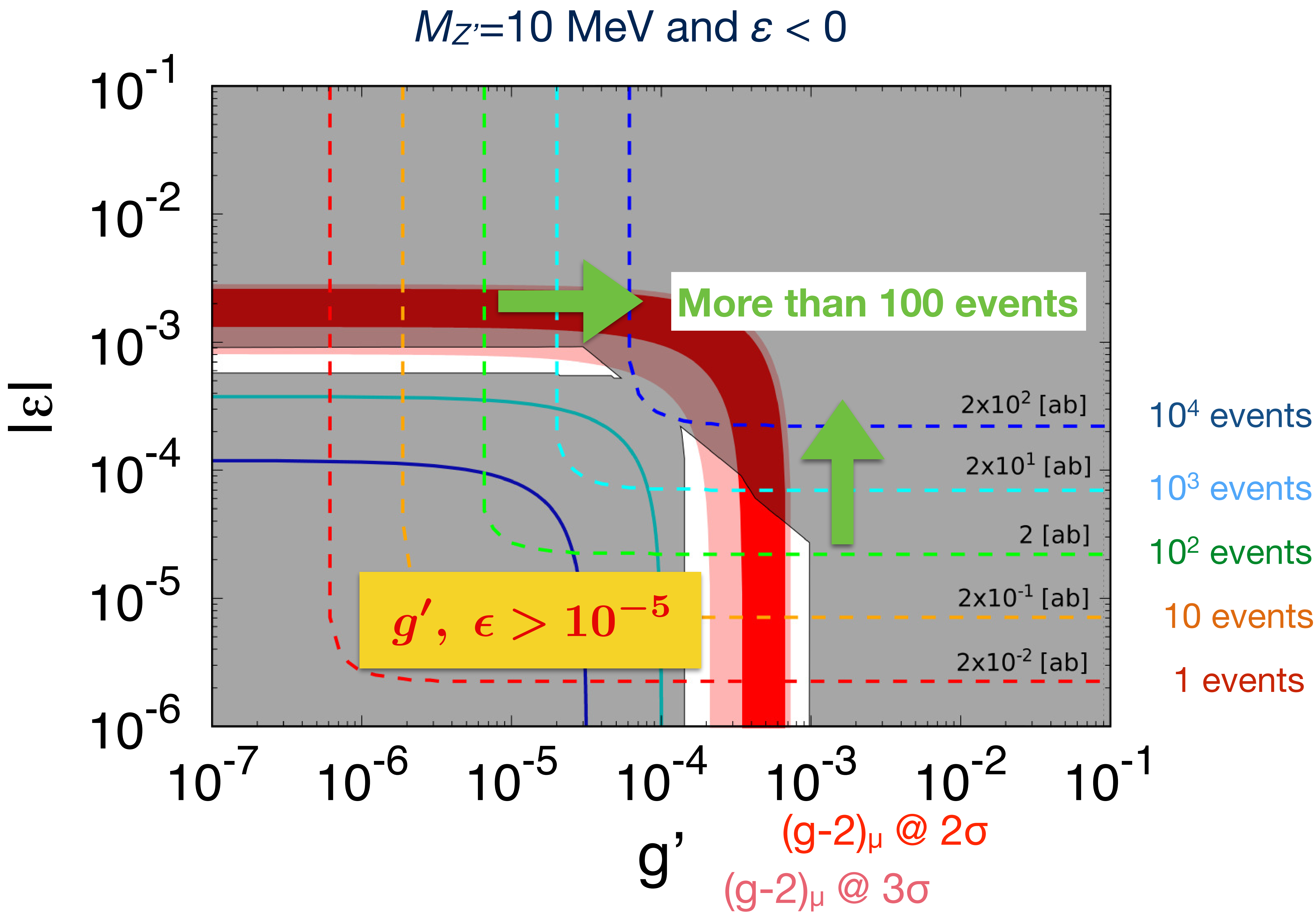


Belle-II

$M_{Z'}$=10 MeV and $\varepsilon > 0$

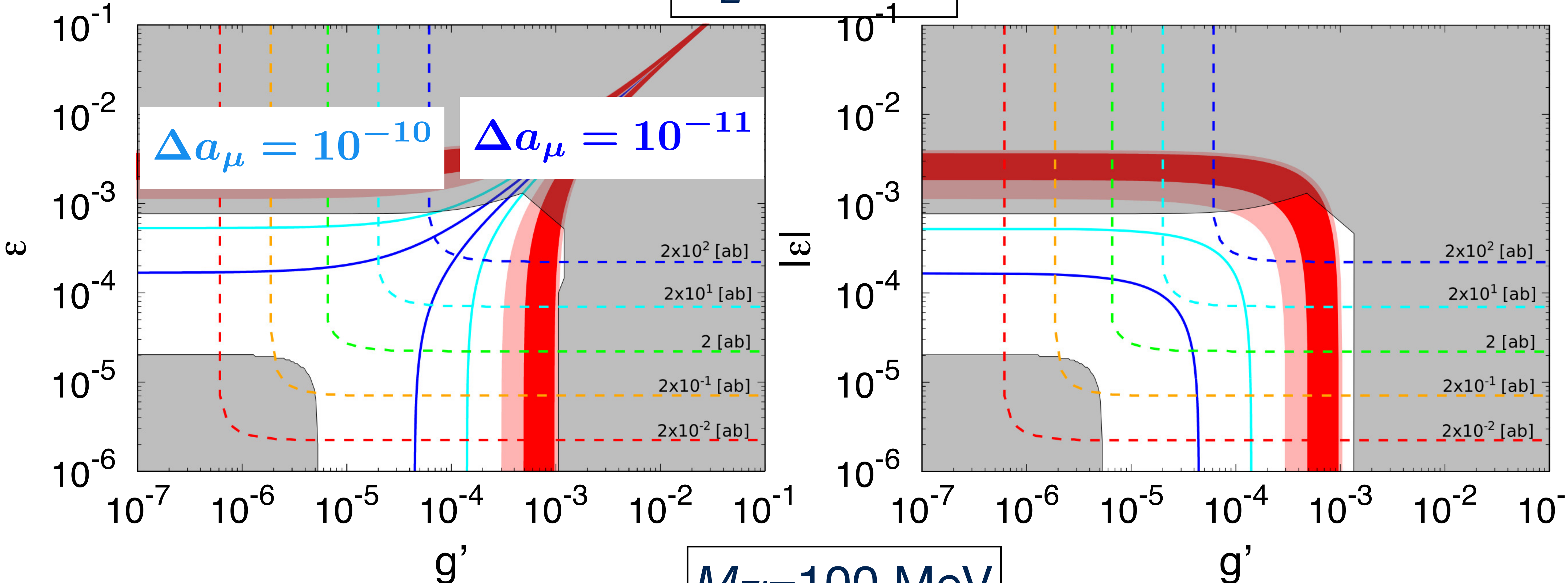


Belle-II

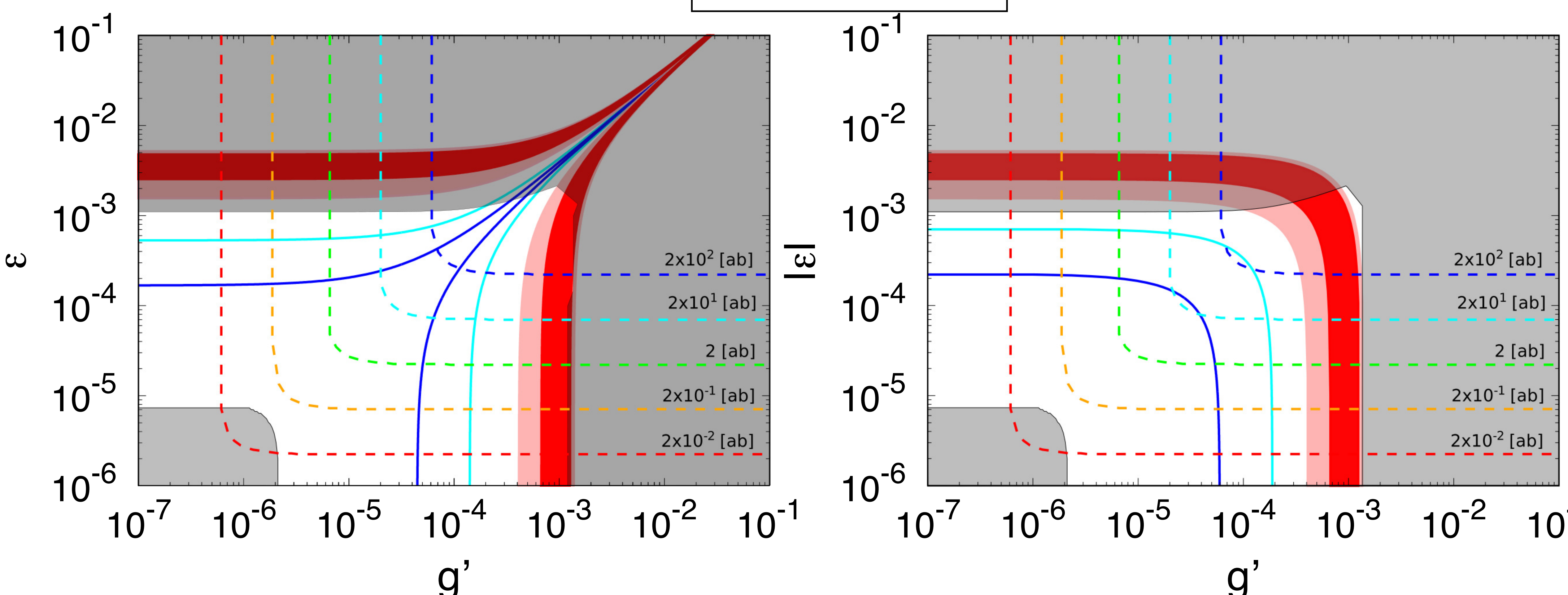


$M_{Z'}$=10 MeV and $\varepsilon < 0$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\varepsilon|$
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
g'
More than 100 events
$g', \epsilon > 10^{-5}$
2×10^{2} [ab]
2×10^{1} [ab]
2 [ab]
2×10^{-1} [ab]
2×10^{-2} [ab]
10^4 events
10^3 events
10^2 events
10 events
1 events
$(g-2)_\mu$ @ 2σ
$(g-2)_\mu$ @ 3σ

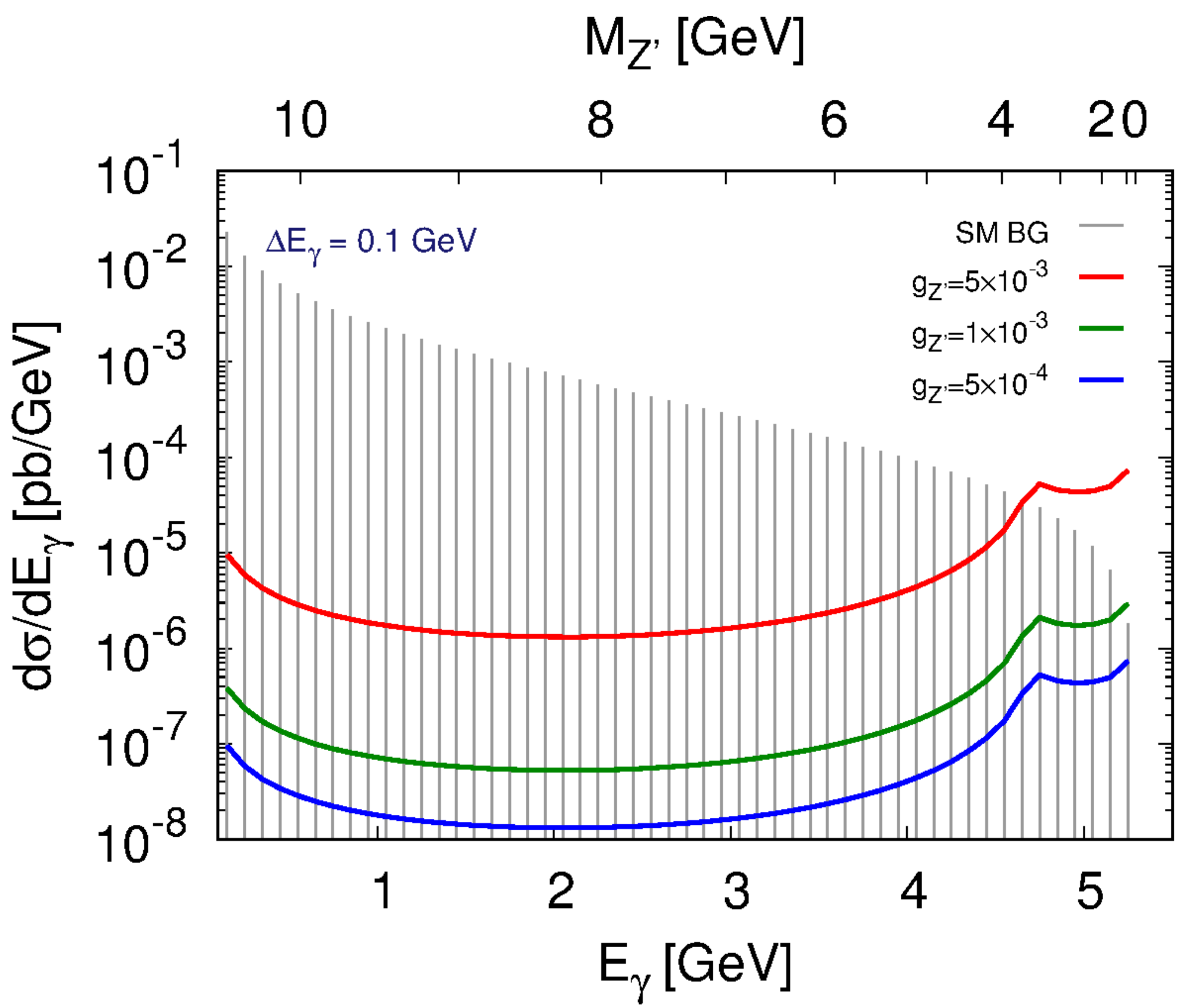
$M_{Z'}$=50 MeV



$M_{Z'}$=100 MeV



Loop-induced kinetic mixing



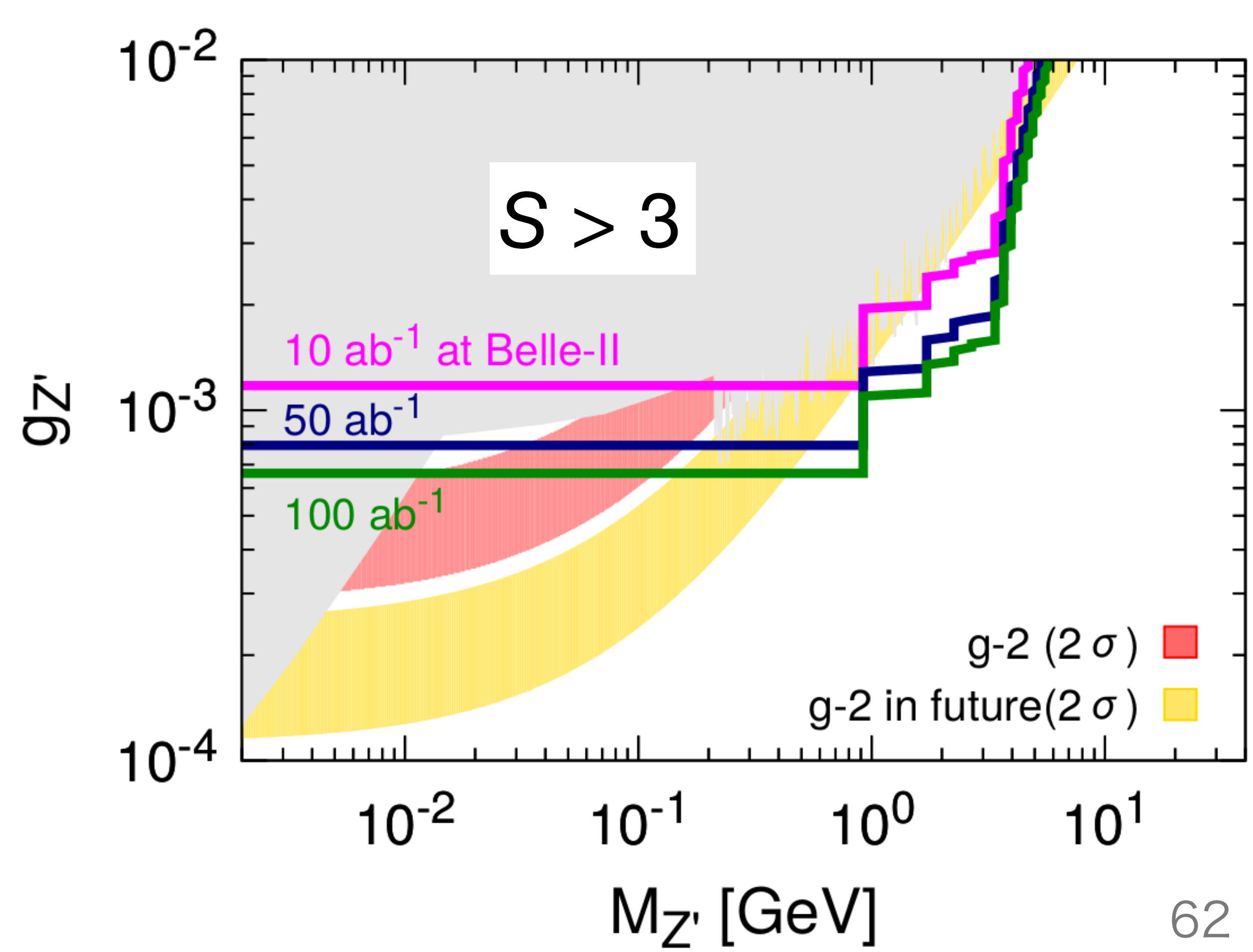
For the light gauge boson,

$$\epsilon \sim 10^{-2} g'$$

$g' > 6\times10^{-4}$

signal significance

$$\mathcal{S} \equiv \frac{N_{\rm sig}(g_{Z'}, M_{Z'})}{\sqrt{N_{\rm BG}}}$$



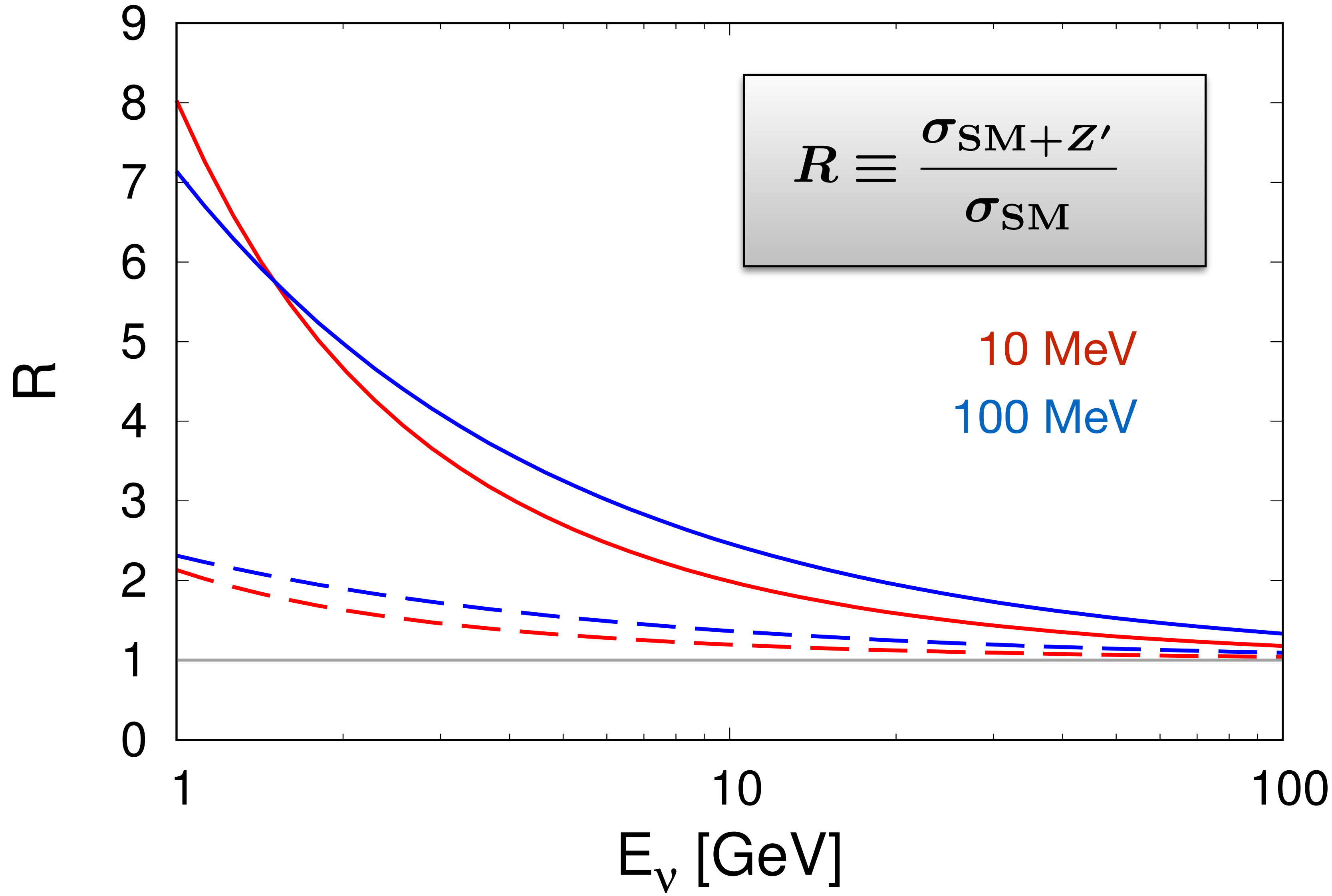
Search at ν beam exp.

Neutrino beam exp.

Neutrino Trident Production

$$\nu_\mu + N \to \nu_\mu + \mu + \mu + N$$

ν beam energy dependence

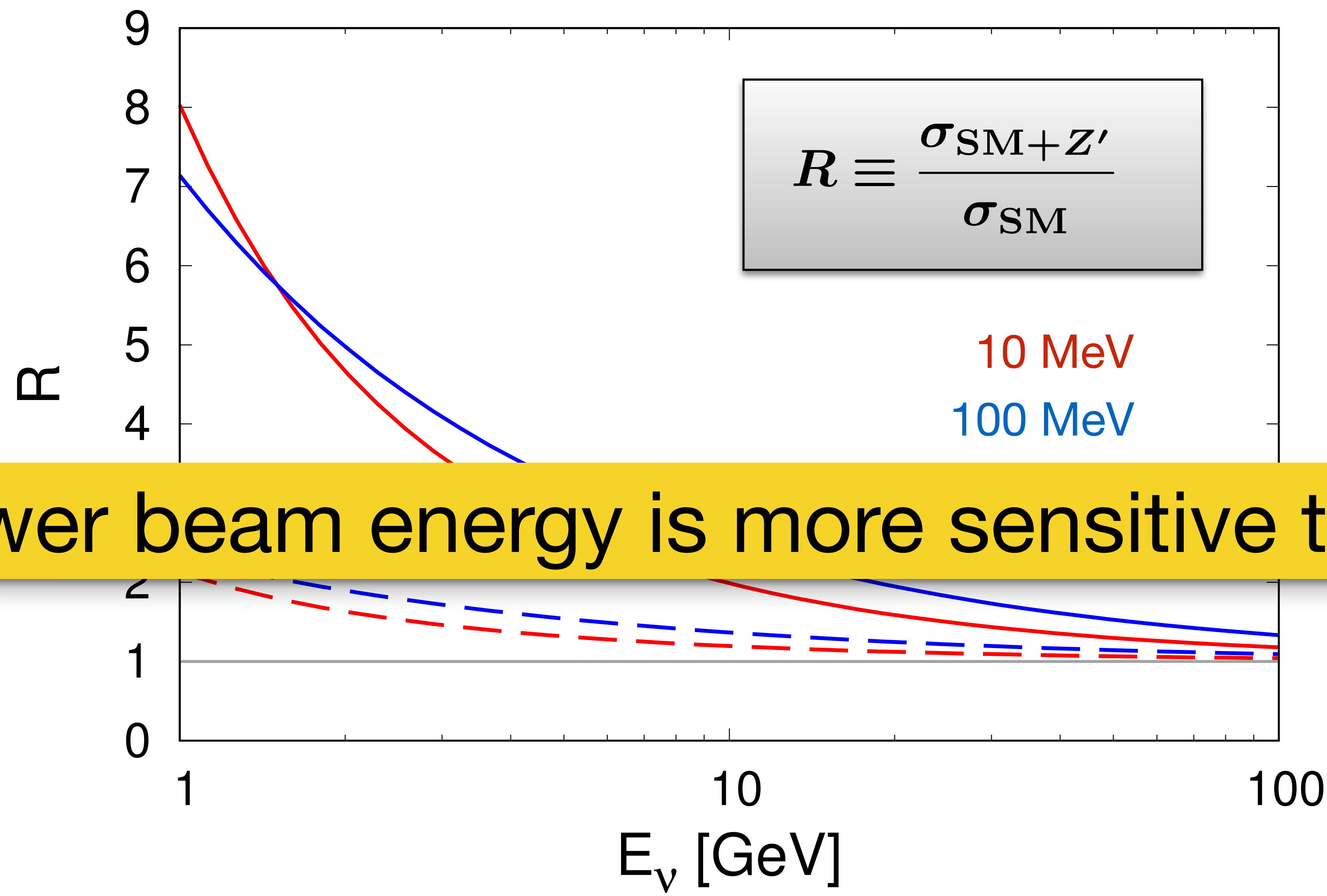


Neutrino beam exp.

Neutrino Trident Production

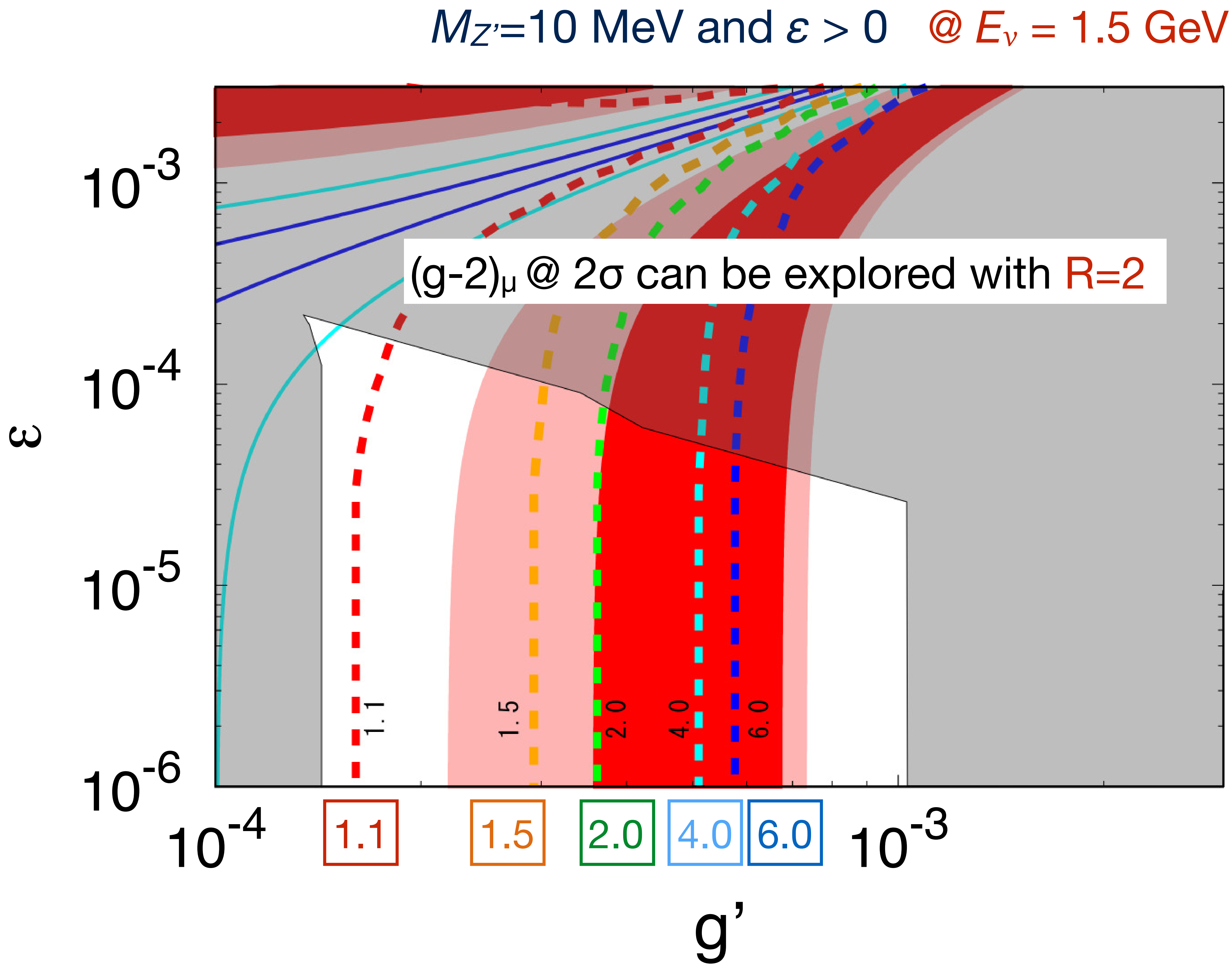
$$\nu_\mu + N \to \nu_\mu + \mu + \mu + N$$

ν beam energy dependence

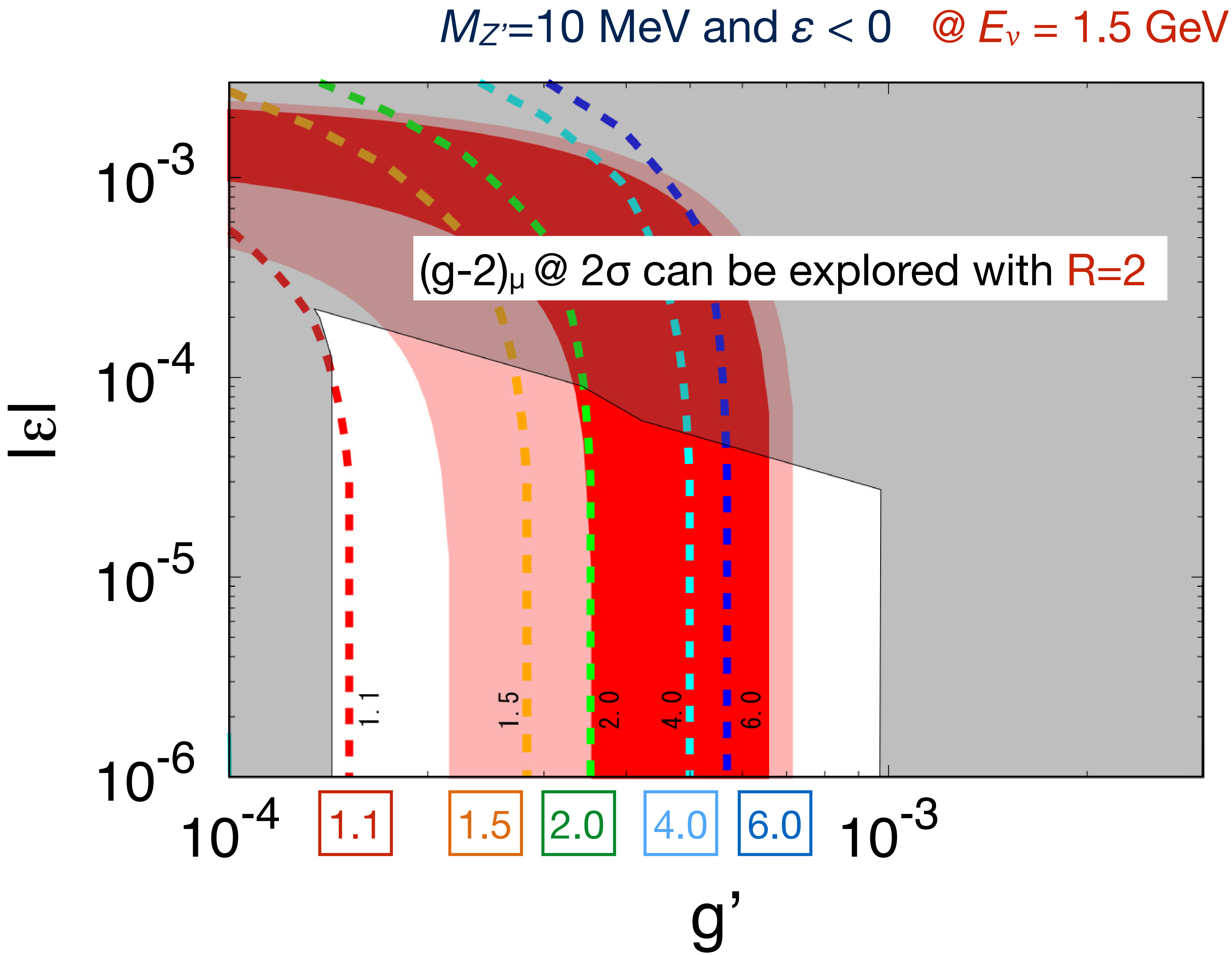


Lower beam energy is more sensitive to NP

Neutrino beam exp.



Neutrino beam exp.



Summary

Summary

- Motivated by IceCub and $(g\text{-}2)_\mu$, weakly int. gauge boson with MeV-scale mass was studied in the gauged L_μ-L_τ model.
- Allowed region of the parameter space was shown for different masses.
- One-photon + missing search at Belle-II will explore the region with g' & $\varepsilon > 10^{-5}$.
- Neutrino Trident Production search with E_ν=1.5 GeV covers the present 2σ region of $(g\text{-}2)_\mu$.