Signature of SUSY and $L_\mu - L_\tau$ gauge boson at Belle-II

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Based on: Heerak Banerjee and SR, arXiv:1811.00407

Introduction

- The presence of an extra $U(1)$ gauge boson Z' coupling exclusively to 2nd and 3rd generation leptons would leave its signatures in several processes

- An essential consequence of an extra $U(1)$ gauge symmetry is the presence of kinetic mixing

- We consider the effect of kinetic mixing at one loop to the $\gamma + \not{E}$ signal at Belle-II experiment

Introduction

- Most interesting feature: signal is independent of the absolute mass scale of the particles in the loop.

- Superheavy sparticles may leave their signatures.

- Belle-II can probe the narrow window of parameter still left to explain muon (g-2) anomaly in case of superheavy particles

- In the absence of SUSY the no. of events histogram may have an excess only in the highest photon energy bin. An excess in any other bin is a signature of SUSY

Why $U(1)_{L_\mu - L_\tau}$?

- The simplest choice for extending the gauge group an extra $U(1)$ - not anomalous

  $L_\mu - L_\tau$ contributes to muon (g-2)

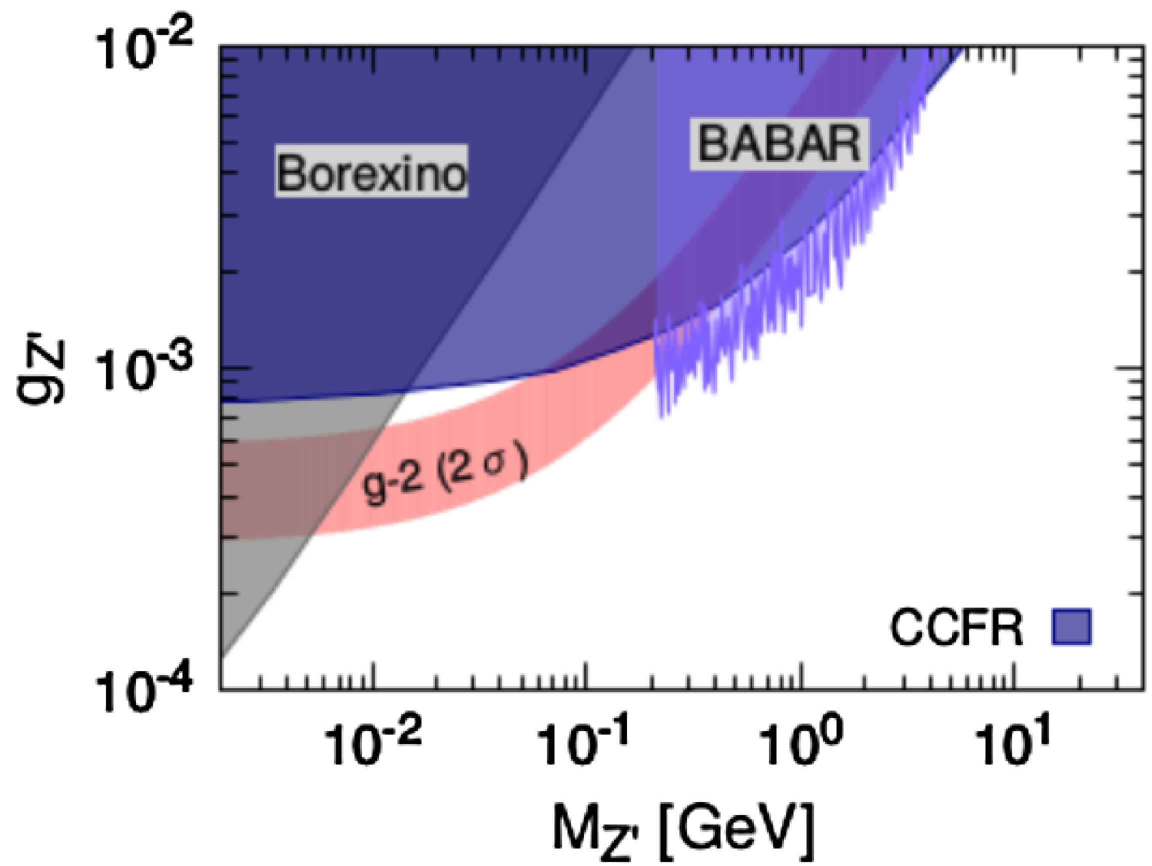
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.8 \pm 8.0) \times 10^{-10}$$

$$\Delta a_\mu^{Z'} = \frac{g_X^2 m_\mu^2}{4\pi^2} \int_0^1 dz \frac{z^2(1-z)}{m_\mu^2 z + M_{Z'}^2(1-z)}.$$

- It has been studied for neutrino masses and mixing dark matter, B-decay anomalies etc

However…

Constraints on $U(1)_{L_\mu - L_\tau}$ model come from processes like neutrino trident production, neutrino-electron scattering, neutrino-quark scattering etc



Araki et al, Phys. Rev. D95, 055006 (2017)

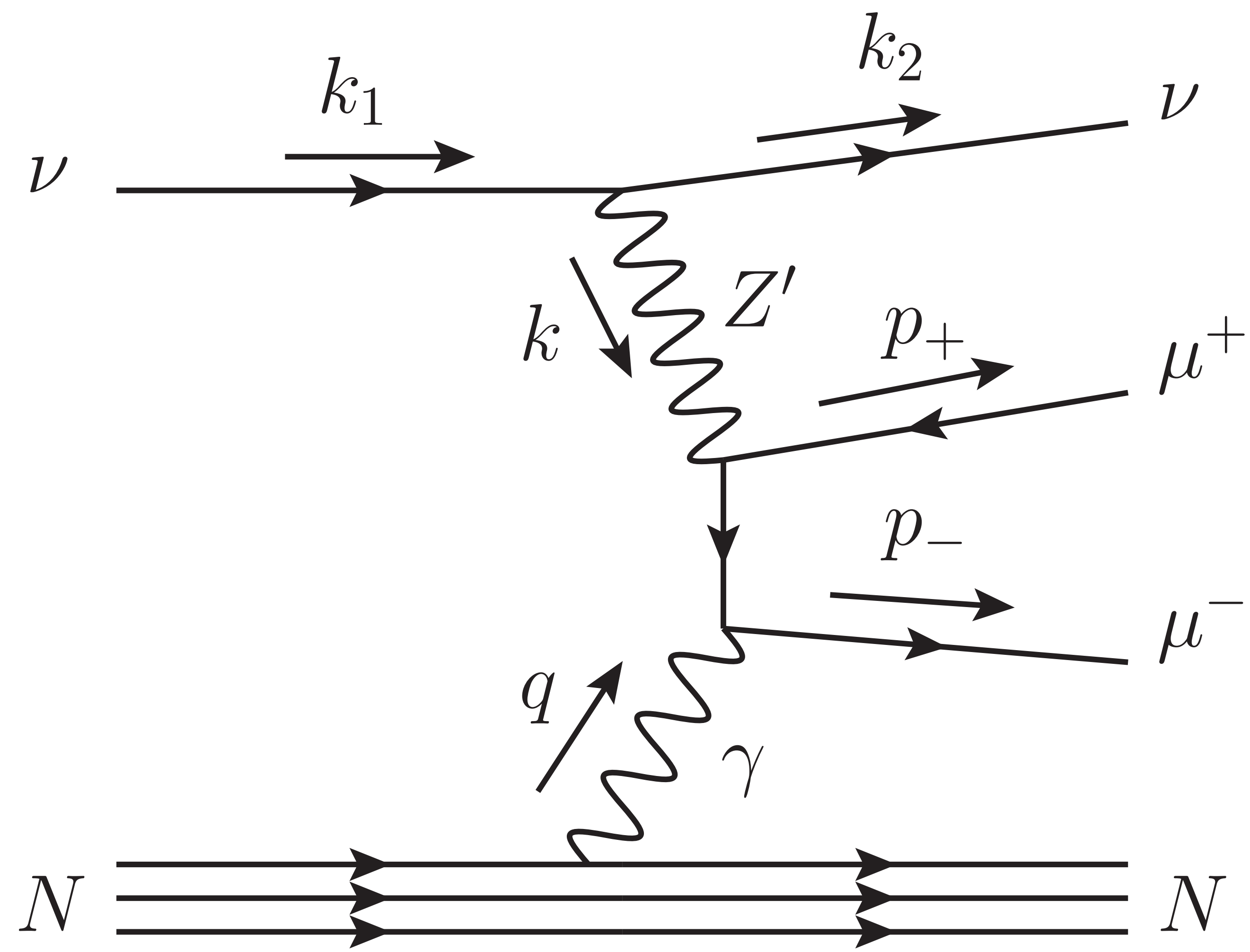
Constraints: Neutrino trident

Neutrino trident process

$$\nu N \to \nu N \mu\mu$$

is a good probe for the Z' boson

The agreement of observed cross section with SM places stringent bound on the Z' parameter space



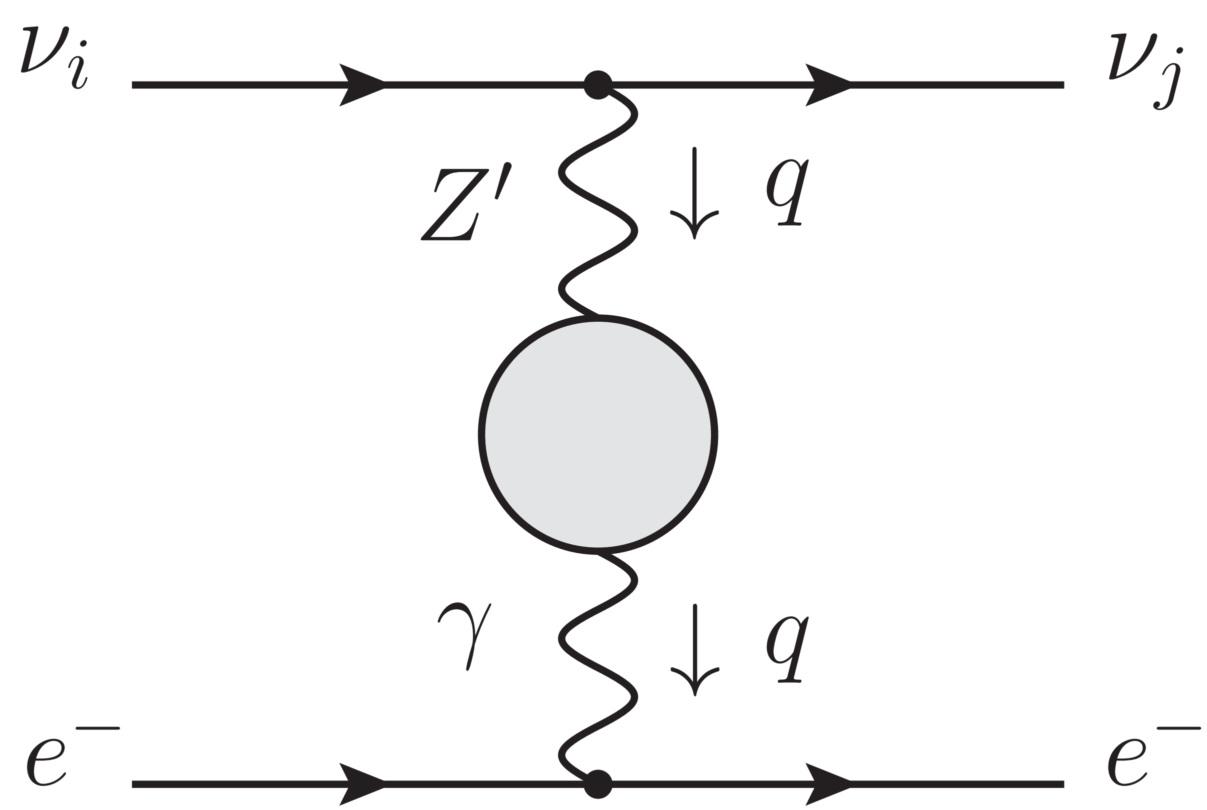
$$\frac{\sigma_{CCFR}}{\sigma_{SM}} = 0.82 \pm 0.28$$

CCFR Collaboration (Mishra, S.R. et al.)
Phys. Rev.Lett., 66 (1991)

Constraints: Borexino

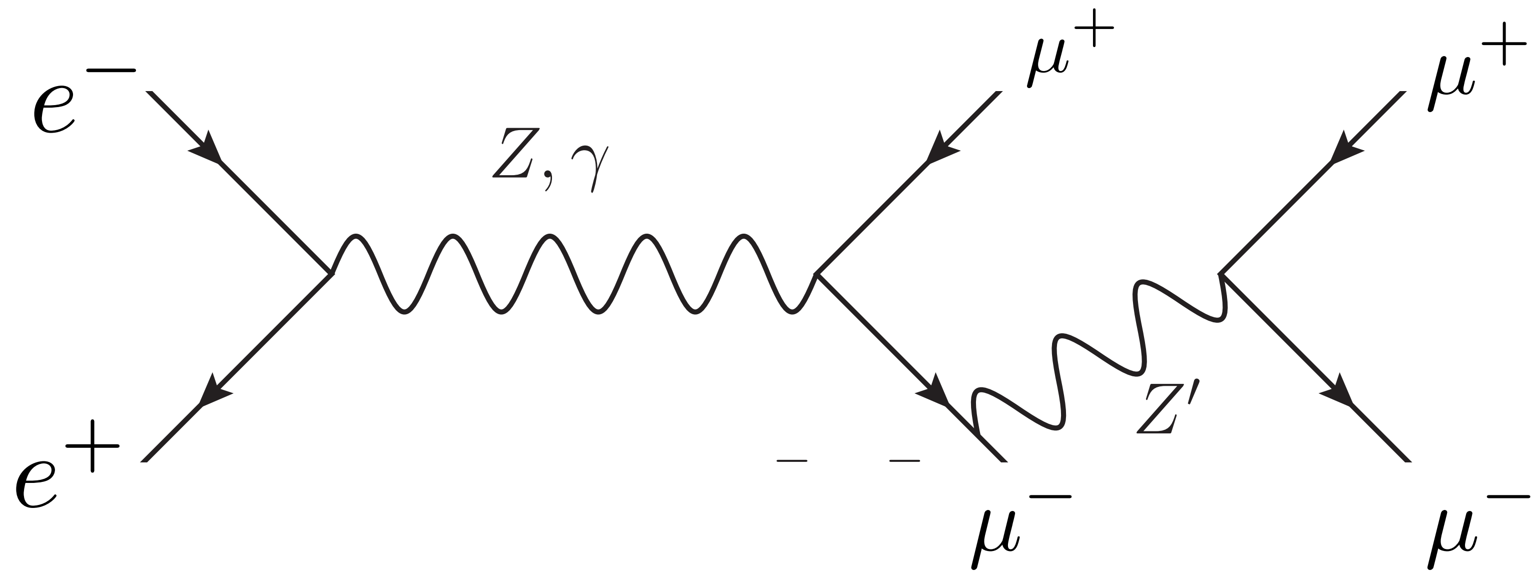
Borexino is quite sensitive to any changes to the neutrino-electron scattering rate.

Approximately, any BSM physics is constrained not to produce a scattering rate that is above the SM prediction by more than 8%.



R. Harnik, J. Kopp, P.A.N. Machado, JCAP 1207, 026 (2012)

Constraints: BaBar



The BaBar Collaboration looked for a four muon signal and did not find any significant excess. This also constraints the parameter space

J.P. Lees et al., BaBar Collaboration
Phys. Rev. D94, 011102 (2016)

Bottomline

- The parameter space is severely constrained by these observations

- Considering the only contribution to the muon (g-2) anomaly to be coming from the Z' loop, an additional gauge boson heavier than 210 MeV is ruled out from CCFR and BaBar data

- Borexino rules out a Z' boson lighter than 10 MeV to explain the muon anomalous magnetic moment in such a situation

$$10\ \mathrm{MeV} \lesssim M_{Z'} \lesssim 210\ \mathrm{MeV},\ 4\times 10^{-4} \lesssim g_X \lesssim 10^{-3}$$

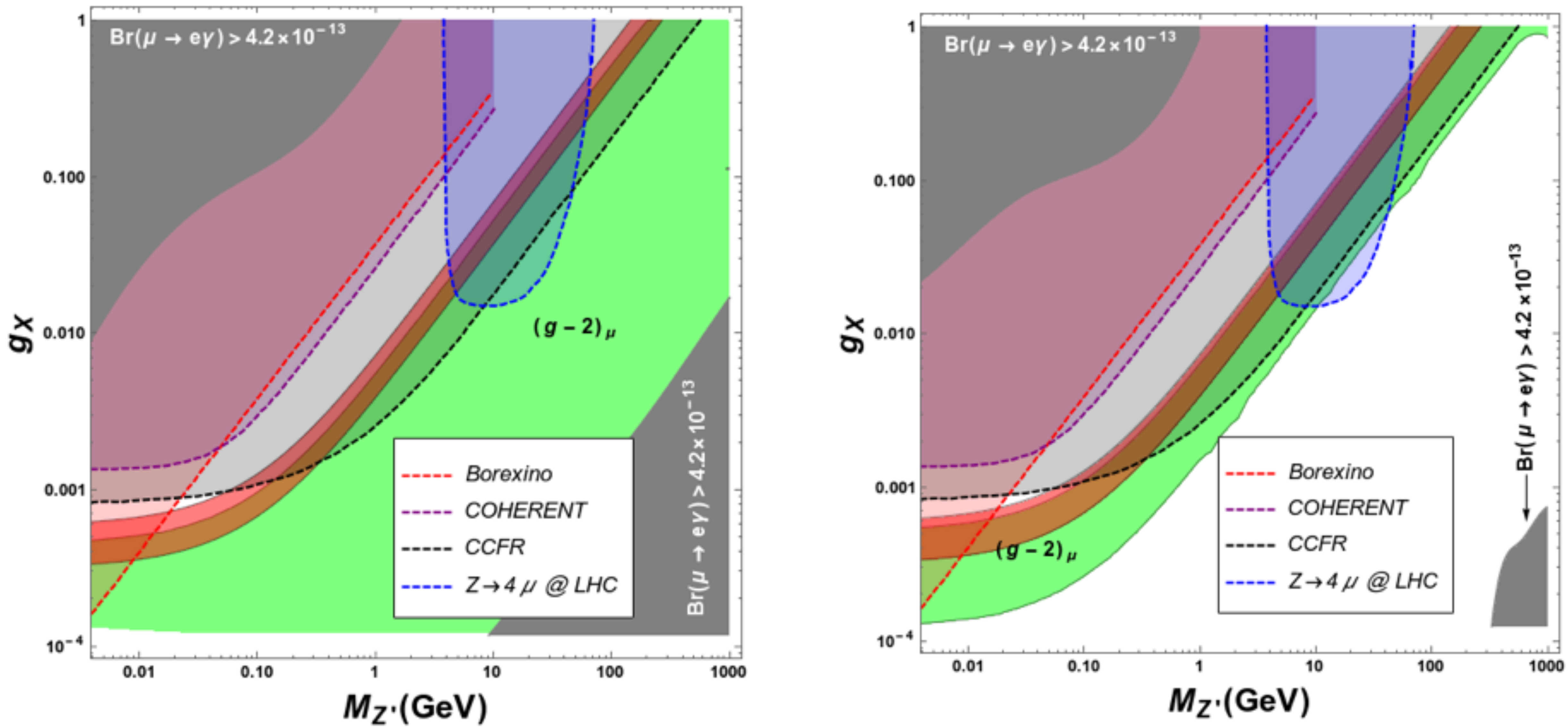
Why supersymmetry ?

- SUSY provides a natural framework for extra scalars that are charged under $U(1)_{L_\mu - L_\tau}$ that can acquire VEV

- It was shown that a SUSY gauged $U(1)_{L_\mu - L_\tau}$ model can alleviate the severe constraints on the model while simultaneously satisfying muon (g-2) and neutrino oscillation data

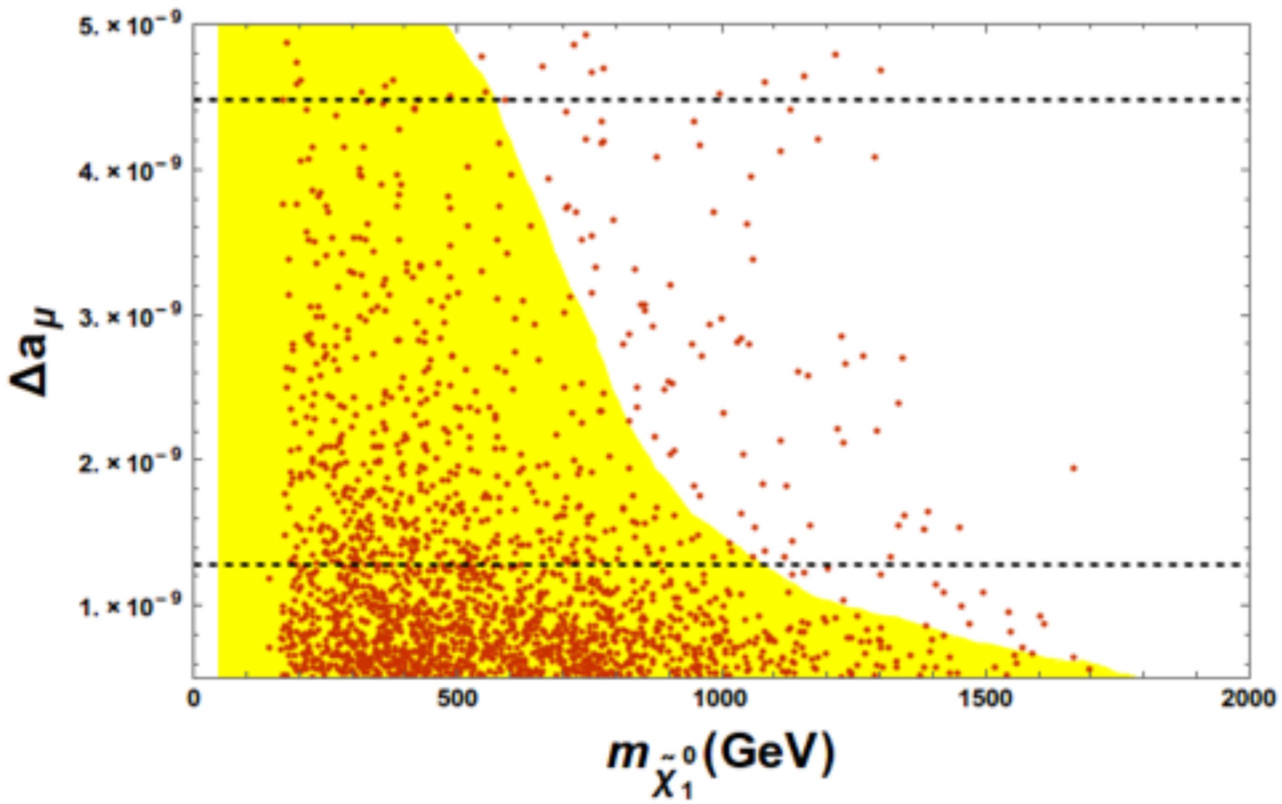
H. Banerjee, P. Bhakti, SR, Phys. ReV. D98, 075022 (2018)

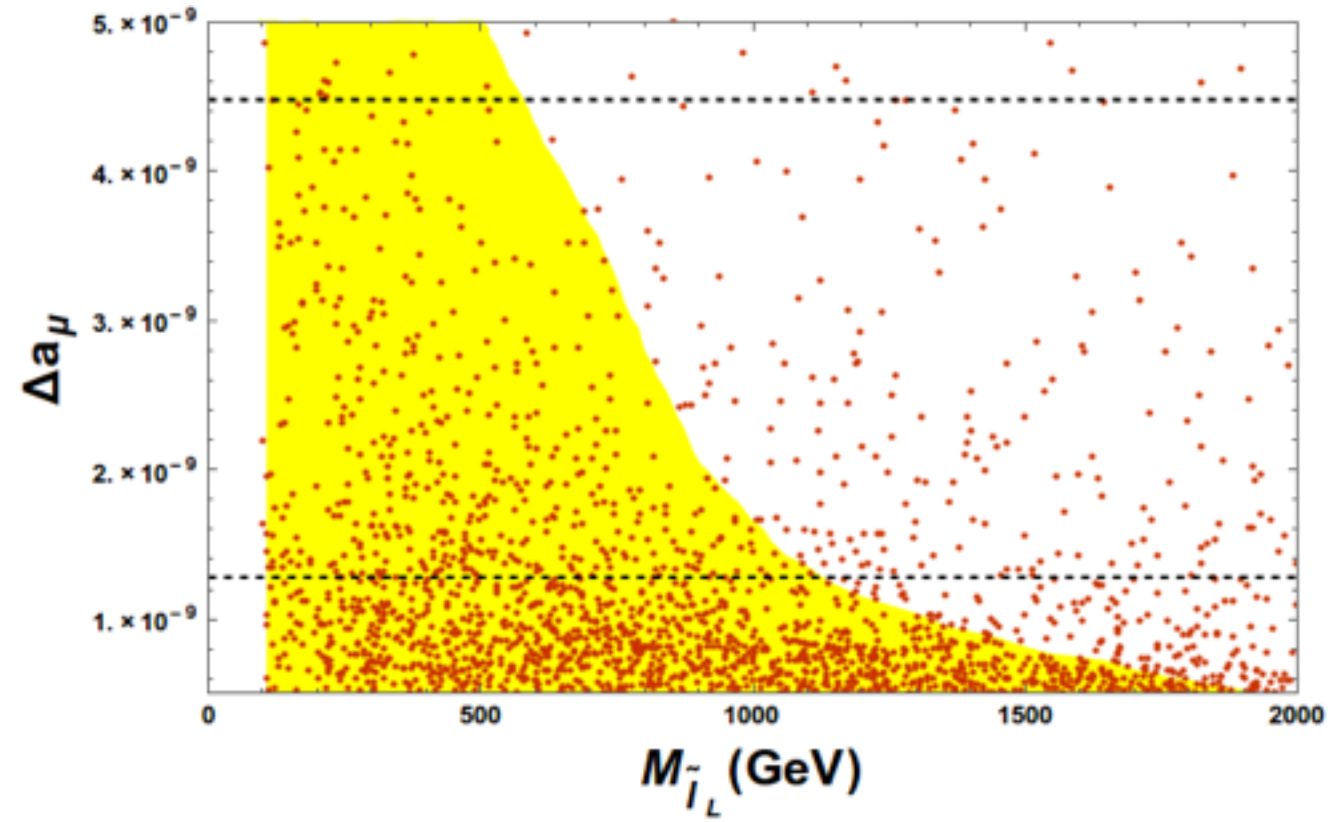
Supersymmetry salvages



Larger parameter space becomes accessible

Supersymmetry salvages

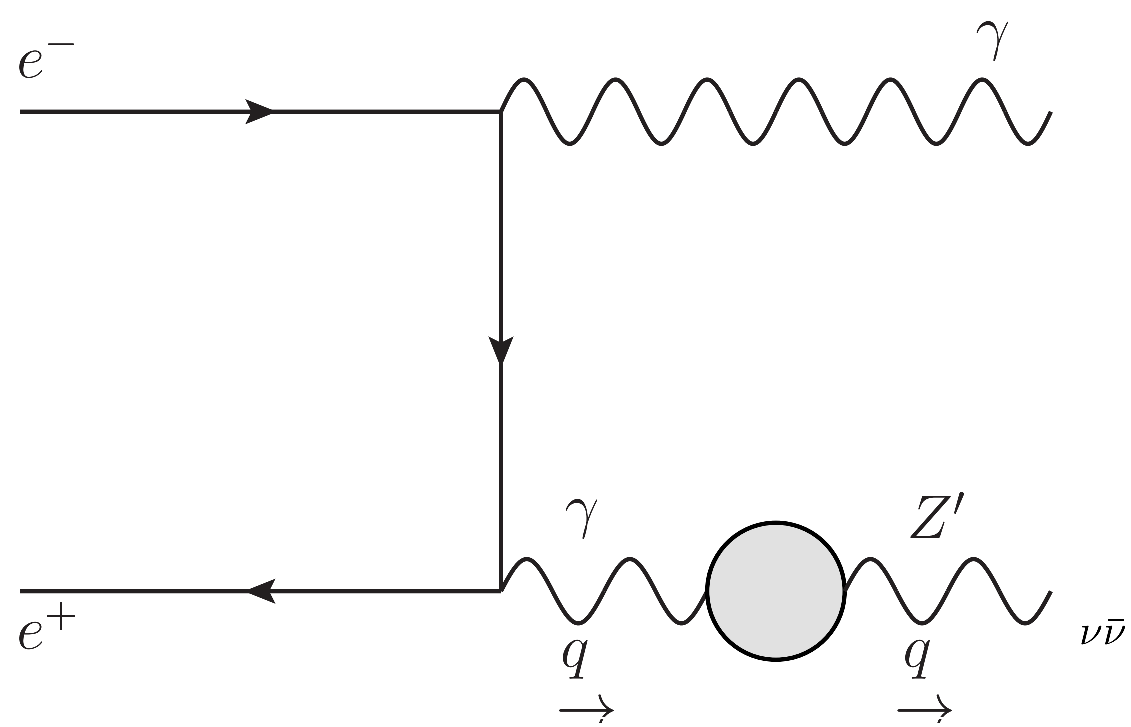




Heavier sparticle masses are also allowed from muon (g-2) compared to the MSSM

H. Banerjee, P. Bhakti, SR, Phys. Rev. D98, 075022 (2018)

Looking for the $L_\mu - L_\tau$ gauge boson at Belle-II



We look for the signal: $e^+e^- \to \gamma Z', \quad Z' \to \nu\bar{\nu}$

We focus on the $\nu\bar{\nu}$ mode because the process $e^+e^- \to \gamma + \not{E}$ does not suffer from EM background

Araki, Hoshino, Ota, Sato, Shimomura, Phys. Rev. D95, 055006(2017)

The calculation in brief

Kinetic mixing between $U(1)_{em}$ and $U(1)_{L_\mu - L_\tau}$

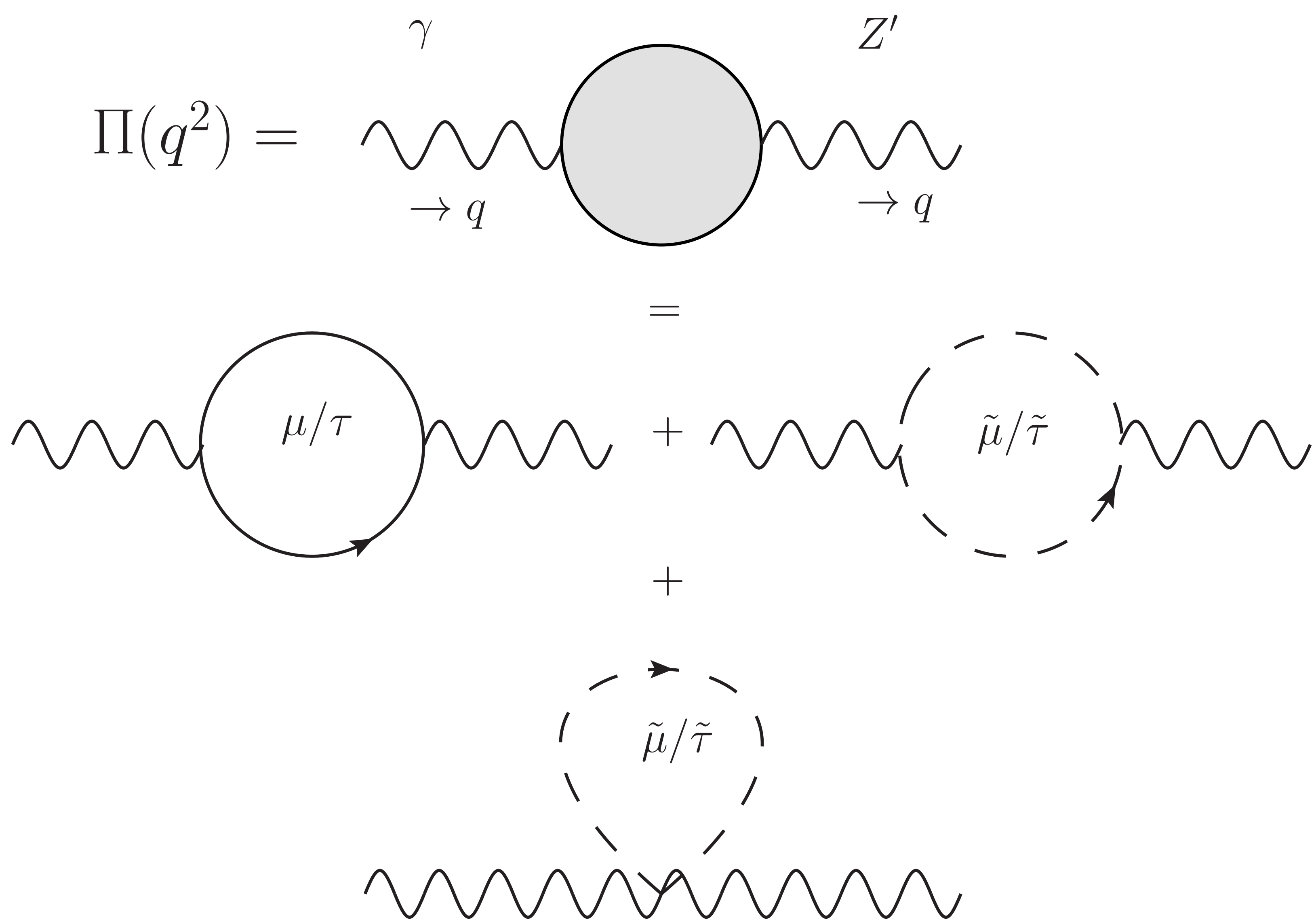
is given by

$$\mathcal{L}_{kin-mix} \;=\; \frac{\epsilon}{2}((\hat{W}^{(em)\alpha}\hat{W}_{\alpha}^{L_\mu - L_\tau})_F$$

We assume there is no kinetic mixing at the tree level

However, it is still generated radiatively

The kinetic mixing



The Kinetic mixing

$$\epsilon \equiv \Pi(q^2) \;=\; \frac{8eg_X}{(4\pi)^2}\int_0^1 x(1-x)\ln\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}dx$$
$$+ \frac{2eg_X}{(4\pi)^2}\int_0^1 (1-2x)^2\ln\frac{m_{\tilde{\tau}}^2 - x(1-x)q^2}{m_{\tilde{\mu}}^2 - x(1-x)q^2}dx \quad (2)$$

The kinetic mixing is a function of q^2

as it is generated radiatively.

For an on-shell Z' $\quad q^2 = M_{Z'}^2$

The dependence on slepton mass ratio $\quad r \equiv \dfrac{m_{\tilde{\tau}}}{m_{\tilde{\mu}}}$

makes the results different from those in non-SUSY gauged $L_\mu - L_\tau$ models

The cross section

The cross section is given by

$$\sigma(e^+e^- \to \gamma + Z') = \frac{2\pi\alpha^2|\Pi(M_{Z'}^2)|^2}{s}\left[1 - \frac{M_{Z'}^2}{s}\right]$$

$$\times \left[\left\{1 + \frac{2sM_{Z'}^2}{(s - M_{z'}^2)^2}\right\}\ln\frac{(1+\cos\theta_{\rm max})(1-\cos\theta_{\rm min})}{(1-\cos\theta_{\rm max})(1+\cos\theta_{\rm min})}\right.$$

$$\left. - \cos\theta_{\rm max} + \cos\theta_{\rm min}\right]. \qquad (6)$$

Here we have $\cos\theta_{\rm min} < \cos\theta < \cos\theta_{\rm max}$ with

$\cos\theta_{\rm min} = -0.821$ and $\cos\theta_{\rm max} = 0.941$

corresponds to the range of coverage of EM calorimeter

R. Essig, P. Schuster, N. Toro, Phys. Rev. D80, 015003 (2009)

Branching ratio

The rate for the signal process is calculated by multiplying this cross section by the branching ratio for $Z' \to \nu\bar{\nu}$

$$\mathrm{Br}(Z' \to \nu\bar{\nu}) = \begin{cases} 1, & (M_{Z'} < 2m_\mu), \\ \frac{\Gamma(Z'\to\nu\bar{\nu})}{\sum_{f=\nu,\mu}\Gamma(Z'\to f\bar{f})}, & (2m_\mu < M_{Z'} < 2m_\tau), \\ \frac{\Gamma(Z'\to\nu\bar{\nu})}{\sum_{f=\nu,\mu,\tau}\Gamma(Z'\to f\bar{f})}, & (2m_\tau < M_{Z'}). \end{cases}$$

The decay rates are given by

$$\Gamma(Z' \to \nu\bar{\nu}) = \frac{g_{Z'}^2}{12\pi} M_{Z'},$$

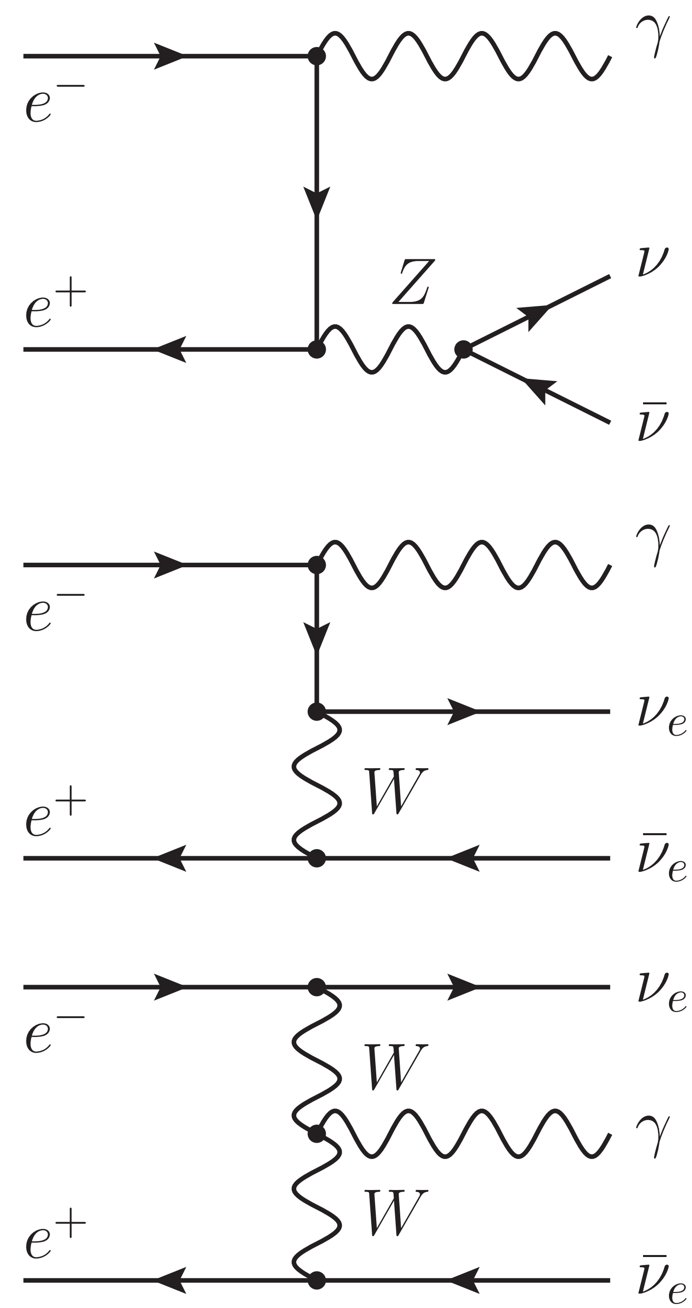
$$\Gamma(Z' \to \ell^+\ell^-) = \frac{g_{Z'}^2}{12\pi} M_{Z'} \left[1 + \frac{2m_\ell^2}{M_{Z'}^2}\right] \sqrt{1 - \frac{4m_\ell^2}{M_{Z'}^2}},$$

where $\ell = \{\mu, \tau\}$.

The Standard Model background

$$\frac{d\sigma_{\rm SM}}{dE_\gamma} = \frac{\alpha G_F^2}{3\pi^2}(g_L^2+g_R^2)E_\gamma\left[1-\frac{2E_\gamma}{\sqrt{s}}\right]$$
$$\times\left[\left[1-\frac{\sqrt{s}}{E_\gamma}+\frac{s}{2E_\gamma^2}\right]\ln\frac{(1+\cos\theta_{\max})(1-\cos\theta_{\min})}{(1-\cos\theta_{\max})(1+\cos\theta_{\min})}\right.$$
$$\left.-\cos\theta_{\max}+\cos\theta_{\min}\right] \qquad (17)$$

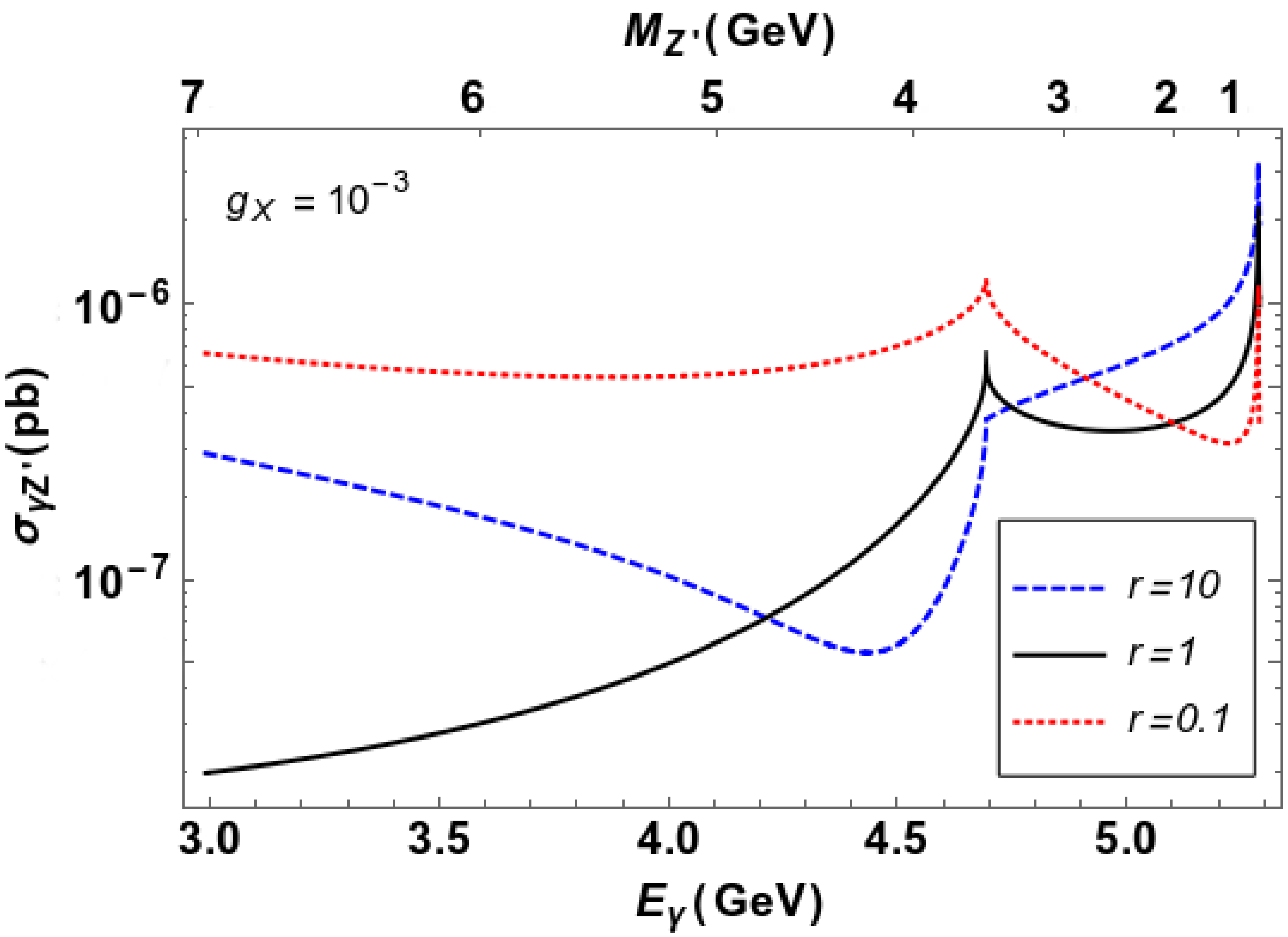
$$g_L = \begin{cases} -\frac{1}{2}+\sin^2\theta_W & (\text{for } \nu_\mu,\nu_\tau) \\ -\frac{1}{2}+\sin^2\theta_W+1 & (\text{for } \nu_e) \end{cases}$$
$$g_R = \sin^2\theta_W,$$



Belle-II

- An asymmetric e^+e^- collider
- Centre-of-mass energy $\sqrt{s}$ is 10.58 GeV
- Expected to reach an integrated luminosity of 50 ab^{-1}
- EM calorimeter has a sensitivity of 0.1 GeV which we take to be the photon energy bin width
- $-0.821 < \cos\theta < 0.941$ is the coverage of the calorimeter

Variation of the cross section



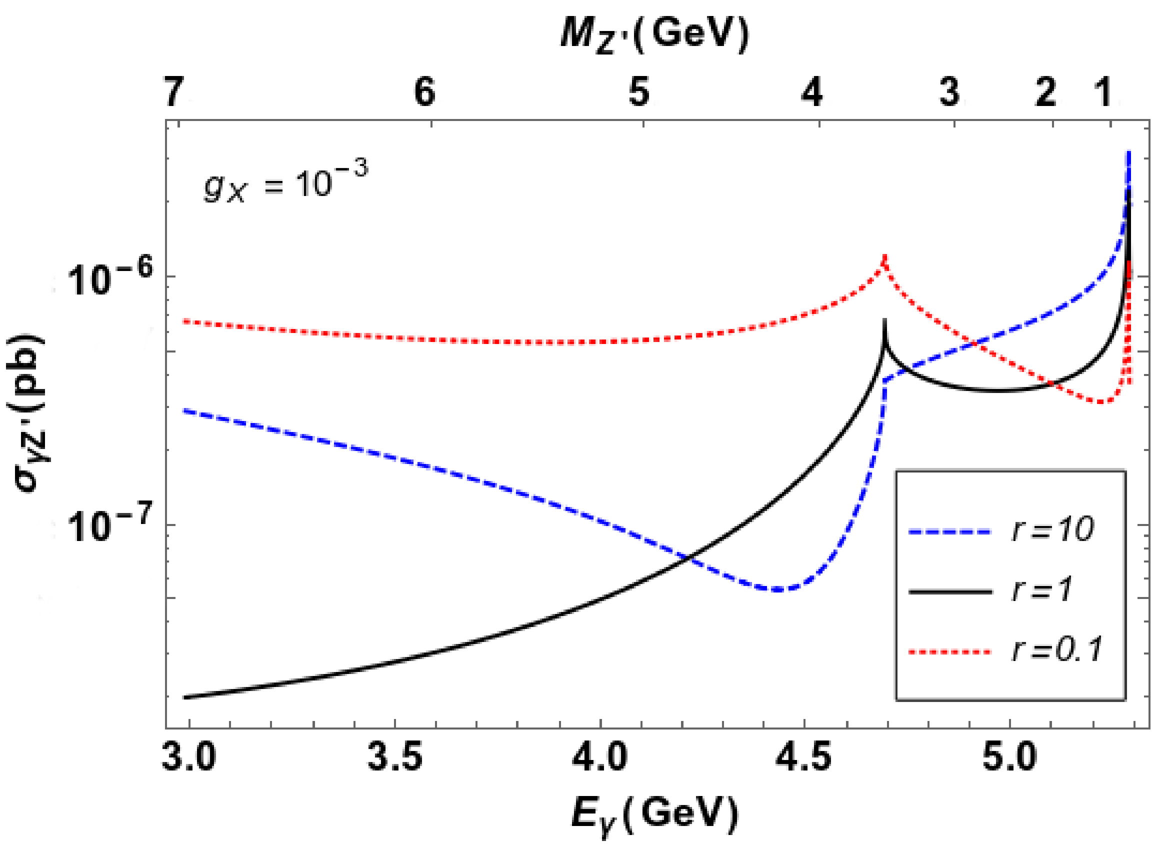
E_γ is the energy of the detected photon

$$E_\gamma = \frac{s-q^2}{2\sqrt{s}}.$$

$$r = \frac{m_{\tilde{\tau}}}{m_{\tilde{\mu}}}$$

r=1 corresponds to the case where the sleptons do not contribute to kinetic mixing

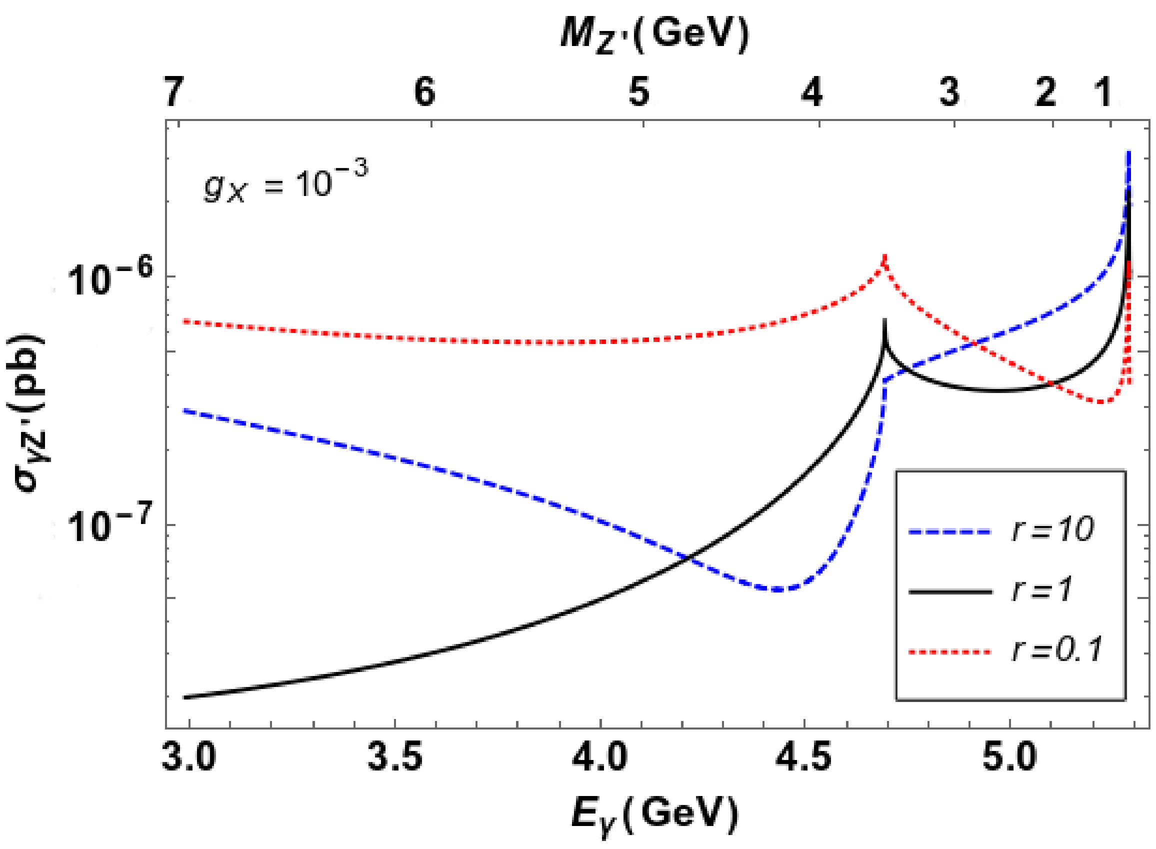
Variation of the cross section



The maximum value of E_γ is $\sqrt{s}/2$ (5.29 GeV at Belle-II) that corresponds to $m_{Z'}^2 = 0$ for an on-shell Z'

At Belle-II this process can probe the Z' gauge boson of mass $\lesssim$ 6 GeV, which corresponds to a maximum g_X of 4×10^{-3}

Variation of the cross section



The cross section is larger for larger values of r for higher photon energies

whereas a lighter stau $(r < 1)$ results in a larger cross section for most of the E_γ range

What do we look for ?

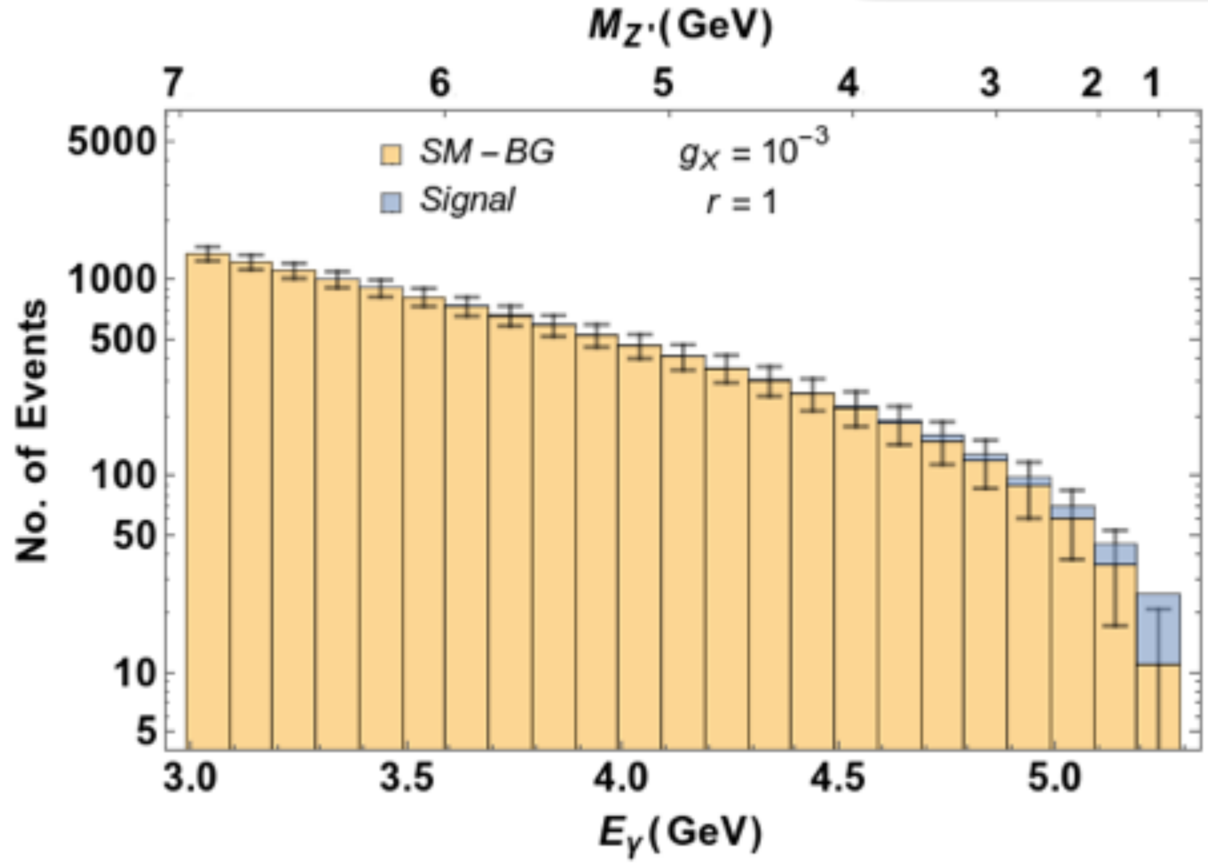
- The number of single photon + missing energy events observed at Belle-II in each photon energy bin

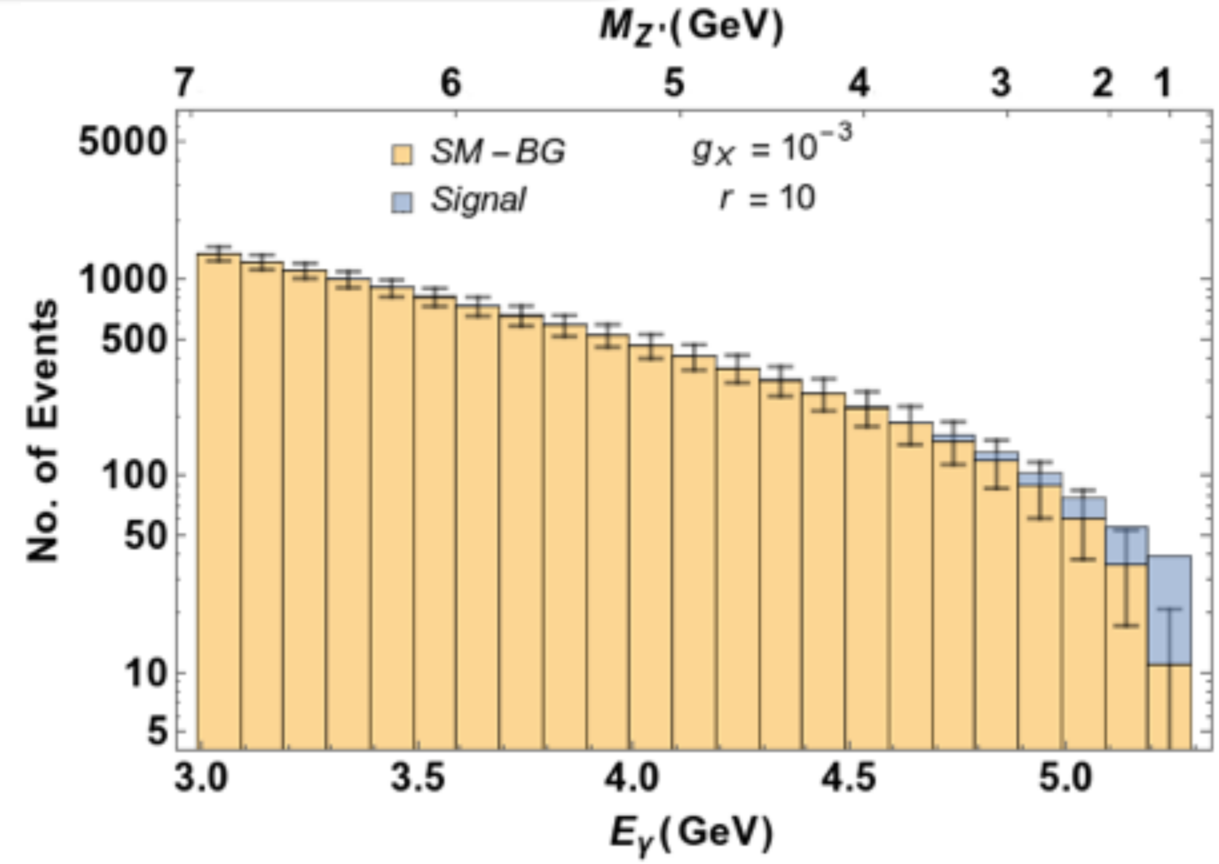
- The signal involves a monochromatic photon and hence an excess from it would appear in any one of bins

- The background processes produce events in all the energy bins in the photon energy range studied.

- We have compared the number of events corresponding to signal and background processes for $3.0 \text{ GeV} < E_\gamma < 5.29 \text{ GeV}$ for Belle-II for an integrated luminosity of $50\ ab^{-1}$

The event histograms

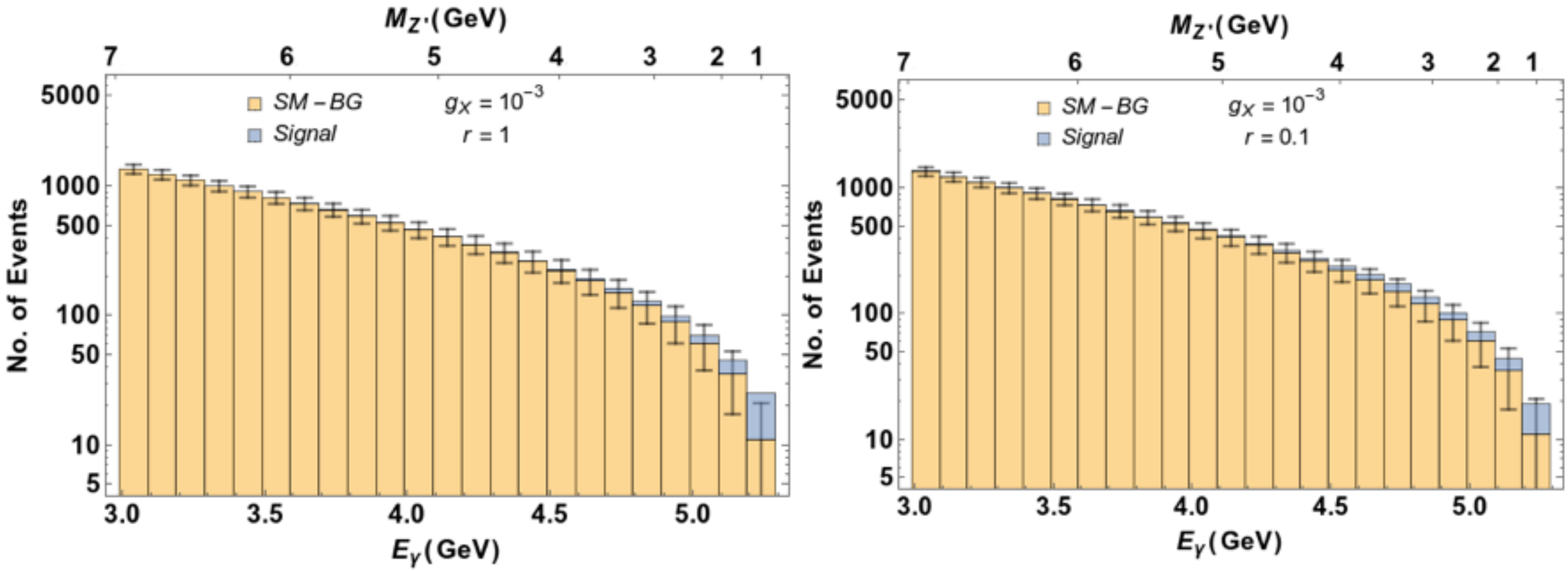




$$M_{Z'} < 1.38 \text{ GeV} \rightarrow E_\gamma > 5.20 \text{ GeV}$$

Hence correlating with the allowed range of $M_{Z'}$ where we can explain the muon (g - 2) anomaly, it is impossible to have an excess in any of the bins apart from the highest one in a non-SUSY scenario.

The event histograms



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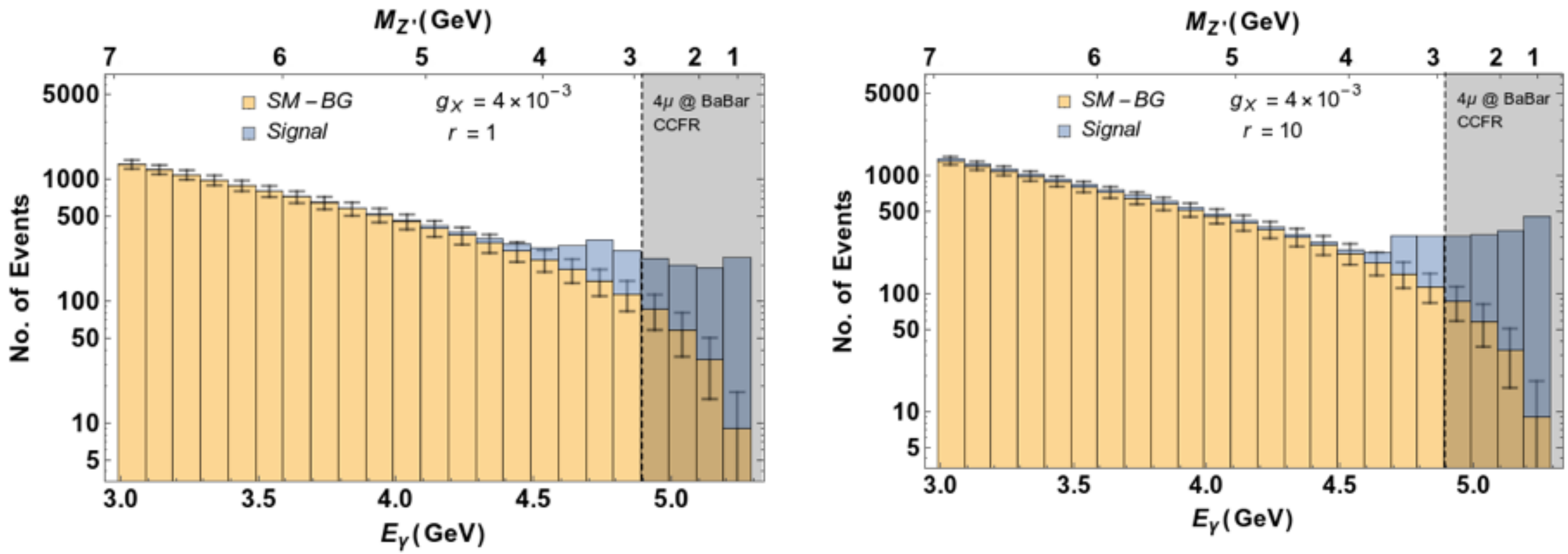

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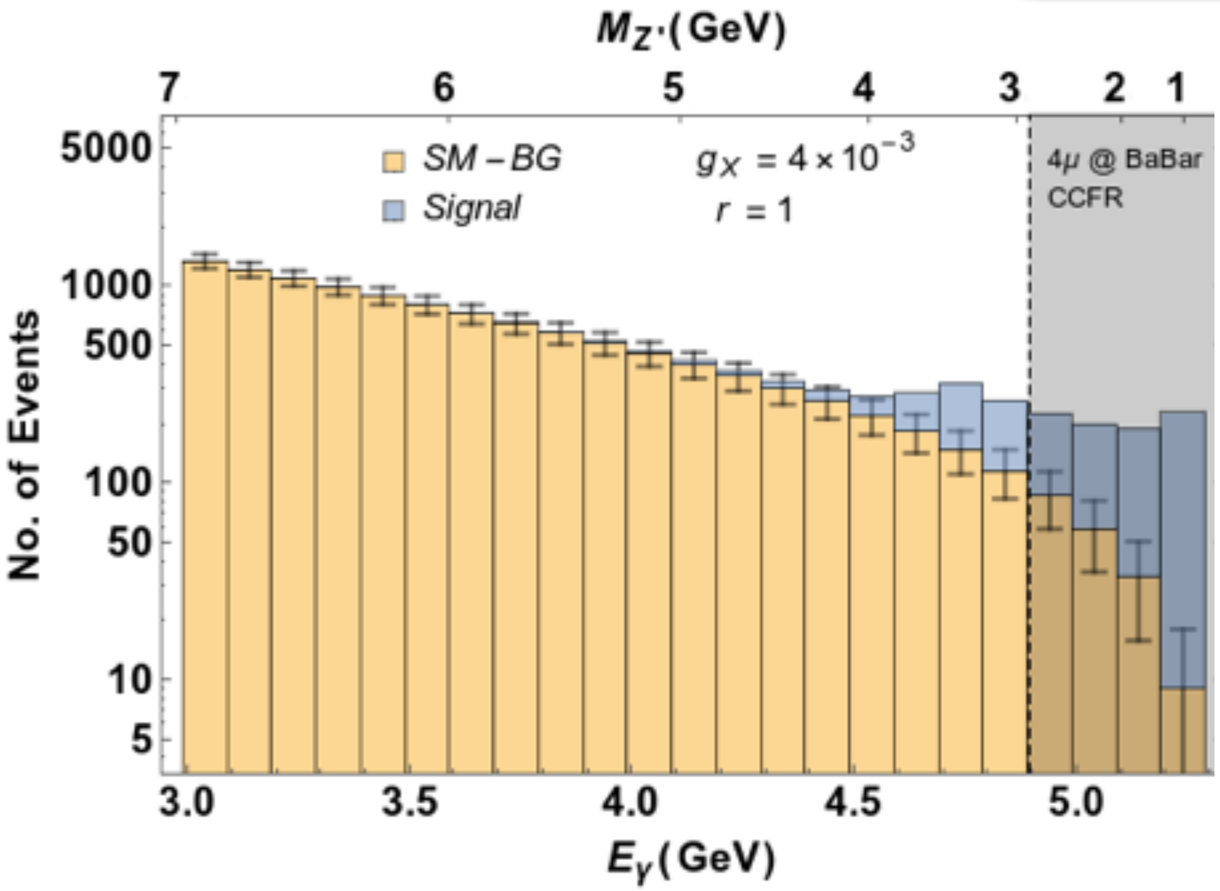

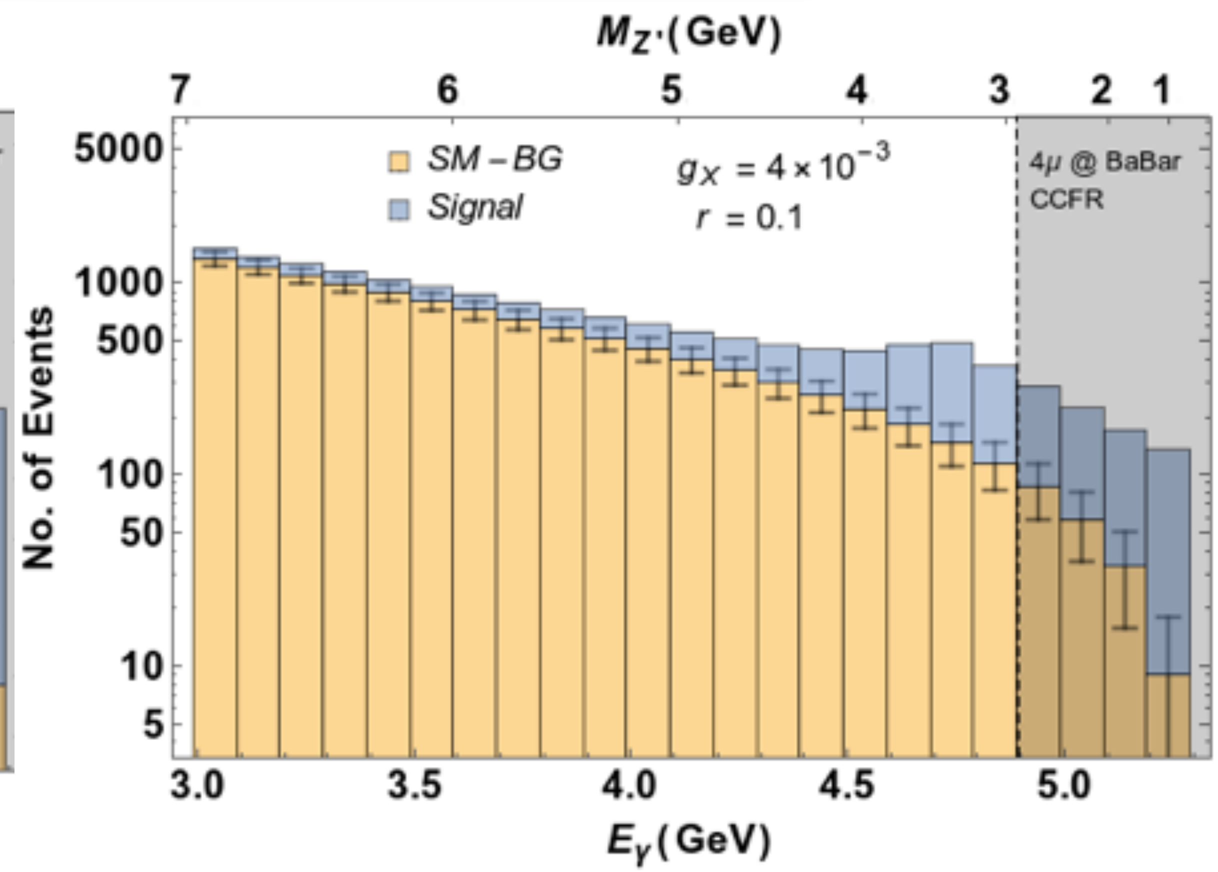

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Hence correlating with the allowed range of $M_{Z'}$ where we can explain the muon (g - 2) anomaly, it is impossible to have an excess in any of the bins apart from the highest one in a non-SUSY scenario.

Some features of the signal

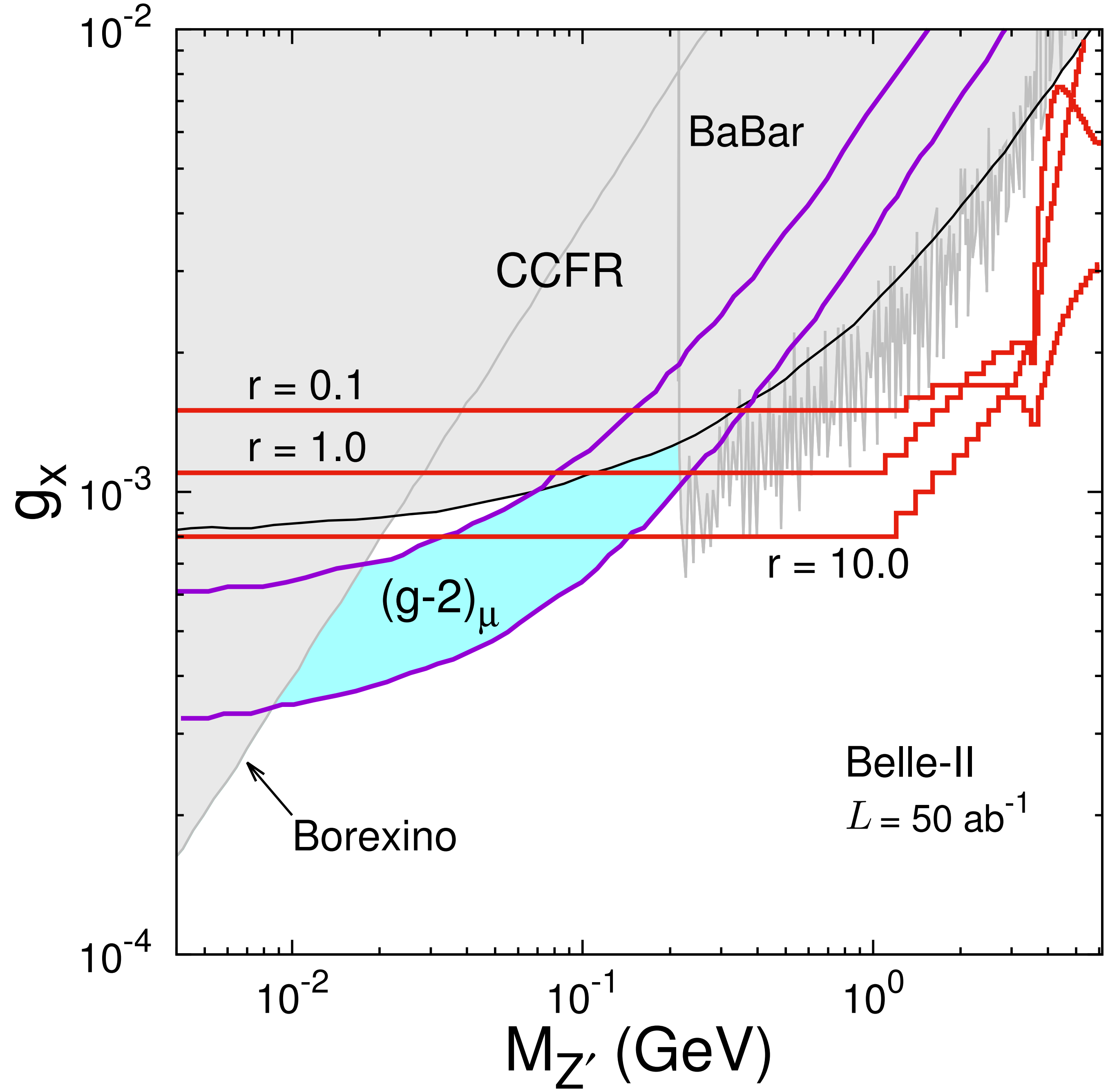
If Belle-II observes any significant excess in any of the energy bins apart from the last one, it would be an unmistakeable signature of sleptons contributing to the kinetic mixing, and an additional source for muon (g - 2) anomaly apart from the Z' contribution

Some features of the signal

The signal significance is independent of the individual masses of the sleptons

Even if the sleptons are massive enough to have evaded detection at the LHC, they could leave their traces in this process

Exclusion in the absence of any significant excess



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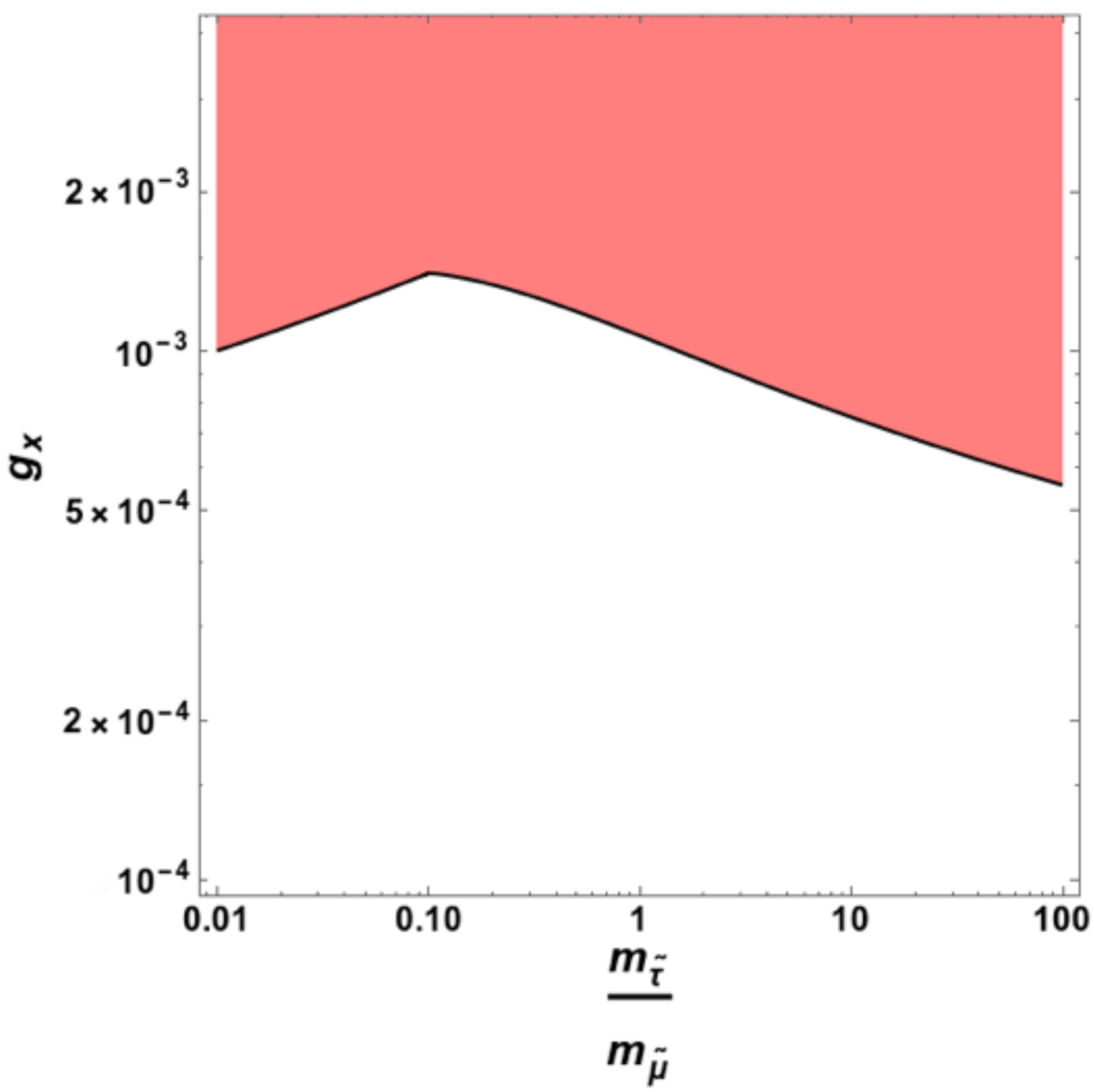

Conclusion

- This is an extremely important channel to look for the $L_\mu - L_\tau$ gauge boson at Belle-II given current bounds from muon (g - 2)

- While non-SUSY BSM physics would show up only at the highest energy bin, SUSY would show up at lower energy bins too

- The signal is independent of the masses of individual sparticles

- Exclusion plots from this channel would significantly affect any implementations of gauged $L_\mu - L_\tau$ model