An Updated Analysis on Lepton Flavor Violating Radiative Decays in Non-sterile Electroweak-scale Right-handed Neutrino Model

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Outline

- 1. Motivation
- 2. The Model
- 3. The calculation
  - Process $l_i \rightarrow l_j + \gamma$
  - Magnetic Dipole Moment and Electric Dipole Moment
- 4. Analysis and discussion
- 5. Summary

Motivation

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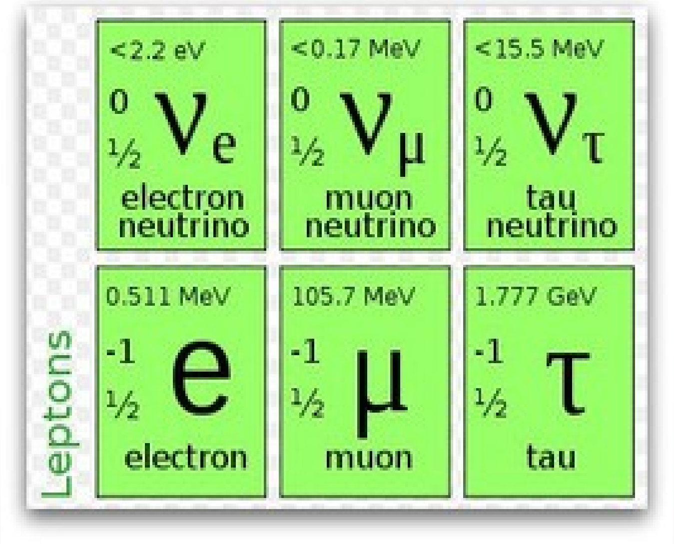

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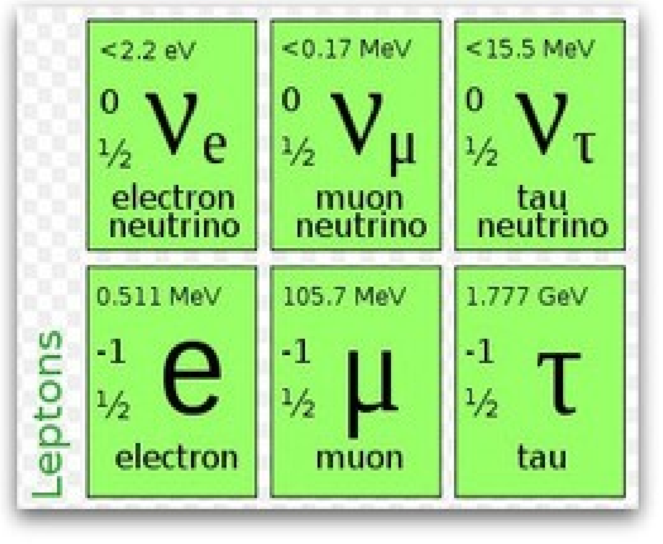
→ Why not have charged lepton flavour violation (cLFV) ?



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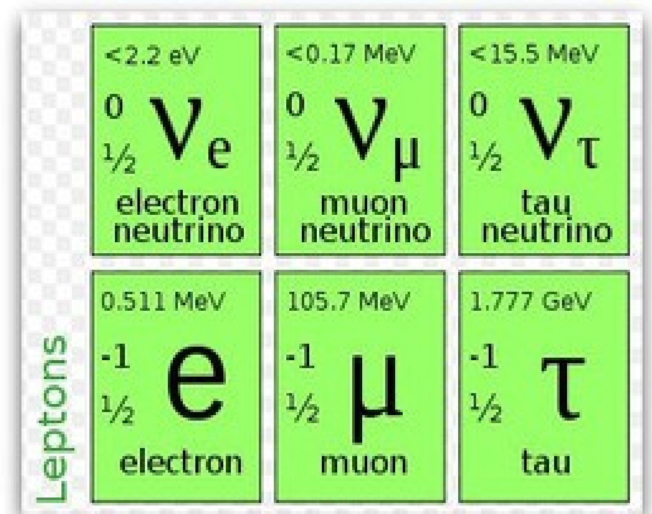

- If observed:
  - Probe the origin of lepton mixing
  - Probe the origin of new physics

Motivation

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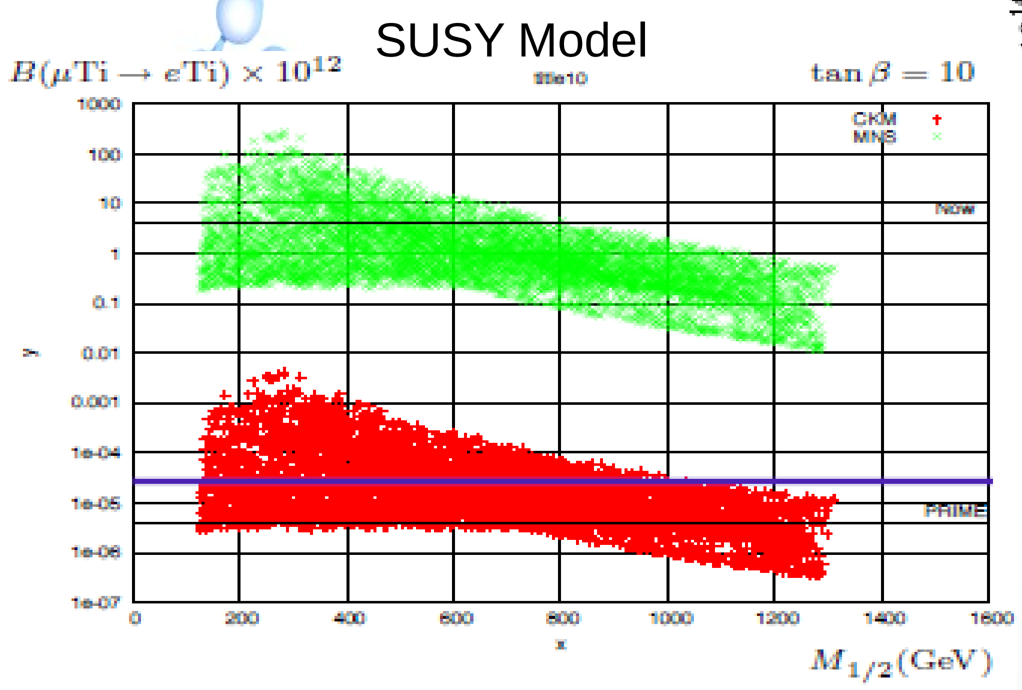
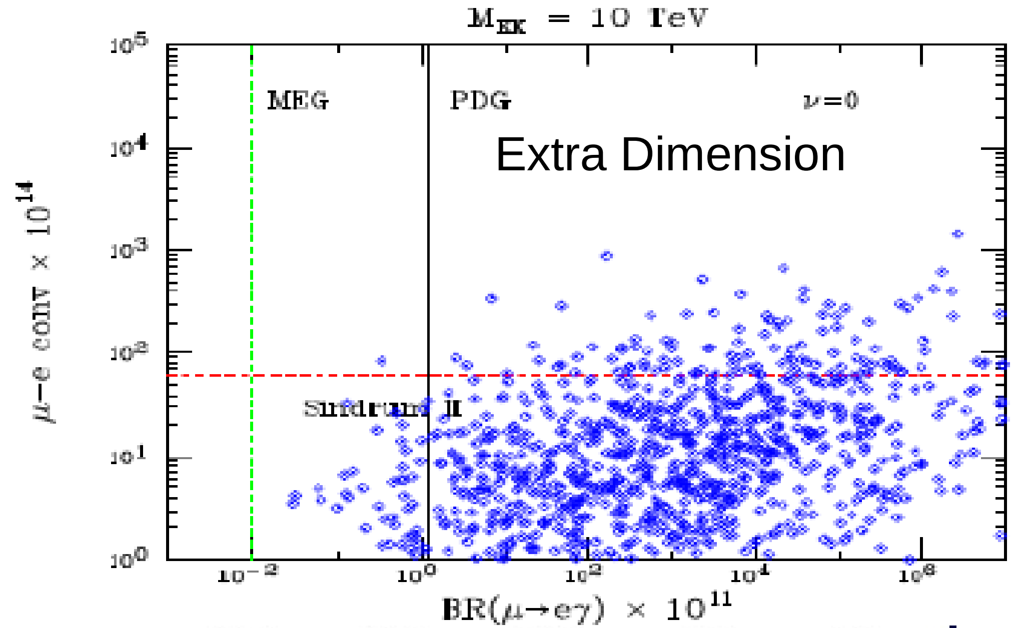
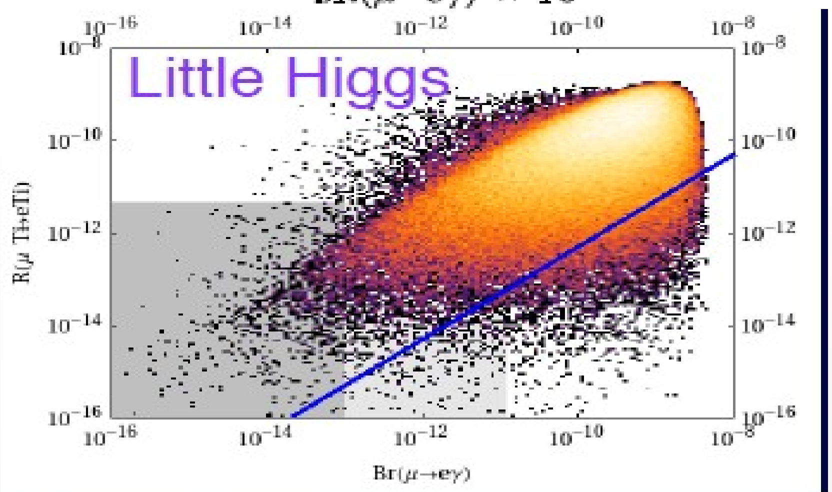
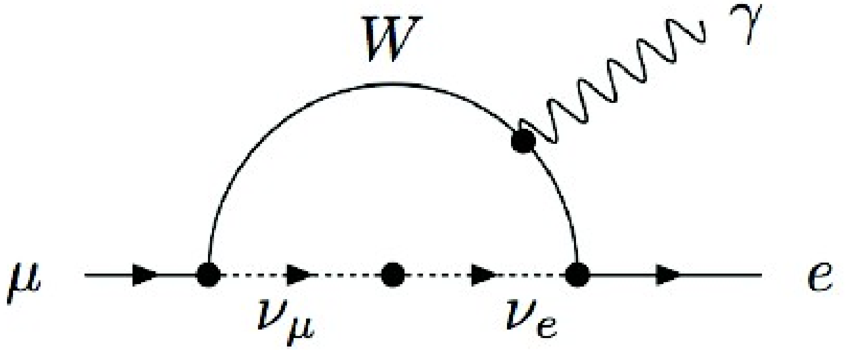






Motivation

Neutrino-mediated LFV is un-observably small



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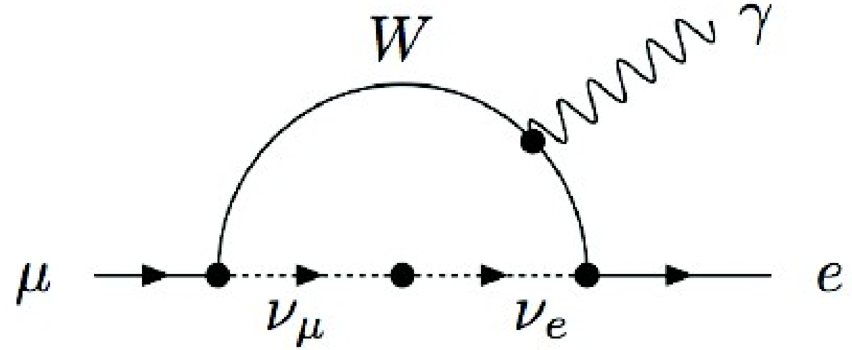

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

$\sim O(10^{-54})$

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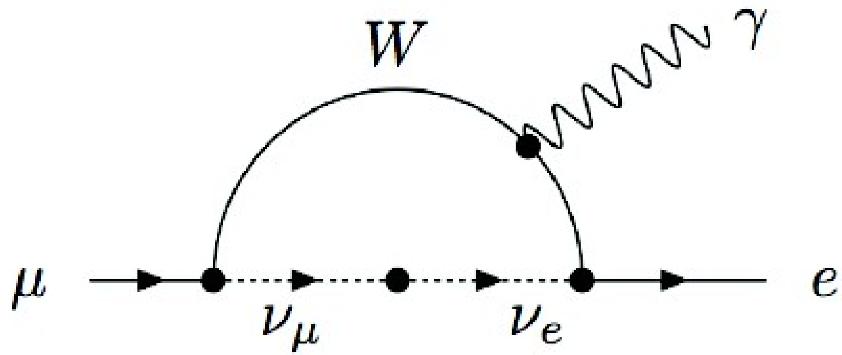

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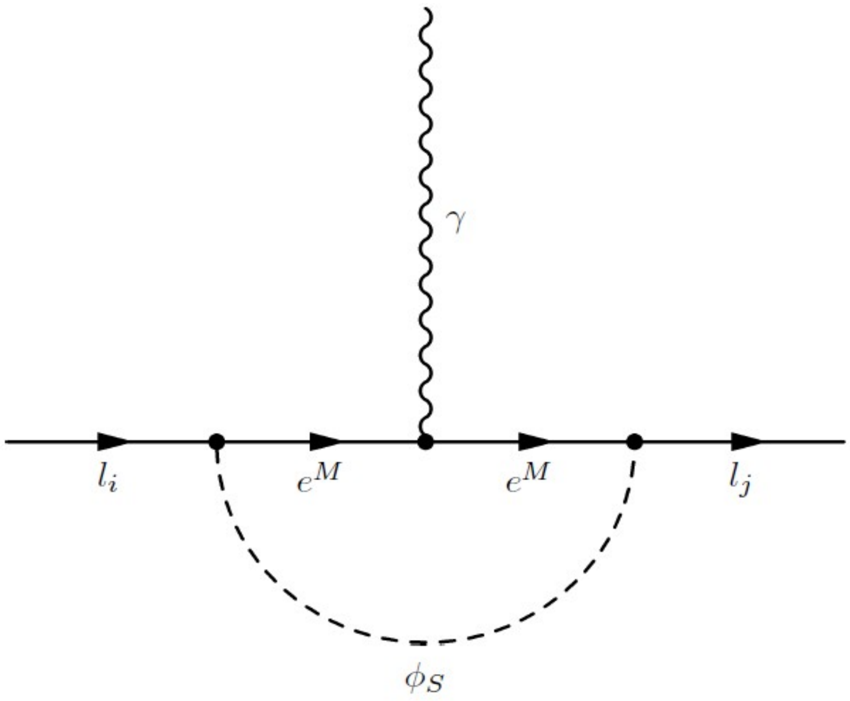
Could there be other mechanisms for LFV?

Motivation



Dominant diagram for $l_i \to l_j + \gamma$

Such processes have been discussed in a generic fashion in **EW νR Model** *(arXiv:0711.0733 [hep-ph], P. L. B. 659, 585 (2008))*

Motivation

In this article, we will present an update of the process $\mu \to e\,\gamma$ taking into account recent developments of the model, including experimental inputs from the recently-discovered 125 GeV SM-like scalar.

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The Model

Non-sterile Electroweak-scale Right-handed Neutrino Model (The EW νR Model) ***[P.Q Hung 2007]***

The Model

The EW νR Model [PQ Hung 2007]

What is it?

The Model

The EW νR Model [PQ Hung 2007]

What is it?

Model in which right-handed neutrinos have Majorana masses of the order of Λ_{EW} **naturally.**

The EW νR Model

Gauge group

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$SU(3)_C \times SU(2) \times U(1)_Y$

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Model Content

The EW νR Model

Gauge group

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Model Content

Leptons

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$e_R$$

The EW νR Model

Gauge group

$SU(3)_C \times SU(2) \times U(1)_Y$

Model Content

Leptons

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \longleftrightarrow l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix},$$

$$e_R \longleftrightarrow e_L^M$$

The EW νR Model

Quarks

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$u_R,\ d_R$$

The EW νR Model

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The EW ν_R Model

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Mirror particles are totally different from the SM particles!

The EW νR Model

Higgs Sector:

The EW νR Model

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- **Doublet** → give masses to all charged fermions

The EW νR Model

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$$L_{Y_l} = g_l \, \bar{l}_L \, \Phi \, e_R + h.c.$$

$$L_{Y_q} = g_q \, \bar{q}_L \, \Phi \, u_R + h.c.$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \langle \phi^0 \rangle = \frac{v_2}{\sqrt{2}}$$

The EW νR Model

Higgs Sector: **Triplets**

The EW νR Model

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- $Y/2 = 1$ triplet → gives an electroweak-scale Majorana mass to the right-handed neutrino

The EW νR Model

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$$
\begin{aligned}
\tilde{\chi} &= (3,\ Y/2 = 1) \\
\tilde{\chi} &= \frac{1}{\sqrt{2}}\,\vec{\tau}.\vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^{+} & \chi^{++} \\ \chi^{0} & -\frac{1}{\sqrt{2}}\chi^{+} \end{pmatrix}
\end{aligned}
$$

The EW νR Model

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$$\begin{aligned} L_M &= g_M \left(l_R^{M,T}\,\sigma_2\right)\,(i\,\tau_2\,\tilde{\chi})\,l_R^M \\ &= g_M\,\nu_R^T\,\sigma_2\,\nu_R\,\chi^0 - \frac{1}{\sqrt{2}}\,\nu_R^T\,\sigma_2\,e_R^M\,\chi^+ + \ldots \end{aligned}$$

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If $\langle\chi^0\rangle = v_M \sim \Lambda_{EW}$ → Majorana mass $M_R = g_M . v_M$

The EW νR Model

Higgs Sector: **Triplets**

- Y/2 = 0 triplet

$$\xi\ (Y/2 = 0) = (\xi^{+}, \xi^{0}, \xi^{-})$$

The EW νR Model

Higgs Sector: **Triplets**

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$$\xi\ (Y/2 = 0) = (\xi^+, \xi^0, \xi^-)$$

- In order to restore the Custodial Symmetry (ρ = 1) *(Chanowitz, Golden and Georgi, Machacek)*

$$\langle \chi^0 \rangle = \langle \xi^0 \rangle = v_M$$

The EW vR Model

Higgs Sector: One Singlet (in original Model)

$$\phi_S\,(1,\ Y/2 = 0)$$

The EW νR Model

Higgs Sector: One Singlet (in original Model)

$$\phi_S \, (1, \; Y/2 = 0)$$

$$L_S = g_{Sl} \, \bar{l}_L \; \phi_S \; l_R^M + h.c.$$

$$= g_{Sl}(\bar{\nu}_L \; \nu_R \; + \bar{e}_L \; e_R^M) \; \phi_S + h.c. \, .$$

The EW νR Model

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With $\langle \Phi_S \rangle = v_{S,}$ → gives the Dirac mass $m^D = g_{Sl}\, v_S$

The EW ν_R Model

Higgs Sector: Singlets (in extended model) *P. Q. Hung and T. Le, arXiv:1501.02538 [hep-ph].*

The EW νR Model

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The Yukawa interactions

$$L_S = \bar{l}_L^0 \left(g_{0S}\phi_{0S} + g_{1S}\tilde{\phi}_S + g_{2S}\tilde{\phi}_S \right) l_R^{M,0} + H.c. \, ,$$

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Obtain the neutrino mass matrix

$$M_\nu^D = \begin{pmatrix} g_{0S}v_0 & g_{1S}v_3 & g_{2S}v_2 \\ g_{2S}v_3 & g_{0S}v_0 & g_{1S}v_1 \\ g_{1S}v_2 & g_{2S}v_1 & g_{0S}v_0 \end{pmatrix}$$

The EW νR Model

Some works done on this Model:

- **EW precision**

V. Hoang, P. Q. Hung and A. S. Kamat, *Nucl. Phys. B 877, 190 (2013) [arXiv:1303.0428 [hep-ph]].*

- **Implications of the 125-GeV SM-like scalar**: Dr Jekyll (SM-like) and Mr Hyde (very different from SM) V. Hoang, P. Q. Hung and A. S. Kamat, *arXiv:1412.0343 [hep-ph] (To appear in Nuclear Physics B).*

- **Signals of mirror fermions** (Paper in preparation)

P.Q. Hung, Trinh Le (UVA); Nandi, Chakdar, Gosh (Oklahoma State University).

- **On neutrino and charged lepton masses and mixings: A view from the electroweak-scale right-handed neutrino model** *P. Q. Hung and T. Le, arXiv:1501.02538 [hep-ph].*

The calculation

$$l_i \to l_j + \gamma$$

The Yukawa interaction can be cast into the following form:

$$\mathcal{L}^{A_4}_{\text{Charged},S} = -\sum_{k=0}^{3}\sum_{i,m=1}^{3}\left(\overline{l_{Li}}\,\mathcal{U}^{L\,k}_{im}\,l^M_{Rm} + \overline{l_{Ri}}\,\mathcal{U}^{R\,k}_{im}\,l^M_{Lm}\right)\phi_{Sk} + \text{H.c.}$$

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Where

$$\mathcal{U}^{L\,k}_{im} = \left(U^{\dagger}_{\mathrm{PMNS}} \cdot M^{k} \cdot U^{l^M}_{\mathrm{PMNS}}\right)_{im}$$

$$\mathcal{U}^{R\,k}_{im} = \left(U'^{\dagger}_{\mathrm{PMNS}} \cdot M'^{k} \cdot U'^{l^M}_{\mathrm{PMNS}}\right)_{im}$$

$l_i \rightarrow l_j + \gamma$

The Lorentz-invariant amplitude for the process $l_i(p) \rightarrow l_j(p') + \gamma(q)$ is

$$\mathcal{M}\left(l_i^- \rightarrow l_j^- \gamma\right) = \epsilon_\mu^*(q)\bar{u}_j(p')\left\{i\sigma^{\mu\nu}q_\nu\left[C_L^{ij}P_L + C_R^{ij}P_R\right]\right\}u_i(p)$$

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Where $P_{R,L} = 1/2\,(1 \pm \gamma^5)$ and

$$C_L^{ij} = +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\left\{\frac{1}{m_{l_m^M}^2}\left[m_i\mathcal{U}_{jm}^{R\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^* + m_j\mathcal{U}_{jm}^{L\,k}\left(\mathcal{U}_{im}^{L\,k}\right)^*\right]\mathcal{I}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)\right.$$
$$\left. + \frac{1}{m_{l_m^M}}\mathcal{U}_{jm}^{R\,k}\left(\mathcal{U}_{im}^{L\,k}\right)^*\mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)\right\}$$

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$l_i \to l_j + \gamma$

The partial width

$$\Gamma\left(l_i \to l_j\gamma\right) = \frac{1}{16\pi} m_{l_i}^3 \left(1 - \frac{m_{l_j}^2}{m_{l_i}^2}\right)^3 \left(|C_L^{ij}|^2 + |C_R^{ij}|^2\right)$$

The magnetic dipole moment anomaly for lepton l_i

$$\Delta a_{l_i} = \frac{2m_{l_i}}{e}\left(\frac{C_L^{ii}+C_R^{ii}}{2}\right)$$

$$= +\frac{1}{16\pi^2}\left\{\sum_{k=0}^{3}\sum_{m=1}^{3} 2\left(|\mathcal{U}_{im}^{L\,k}|^2+|\mathcal{U}_{im}^{R\,k}|^2\right)\frac{m_{l_i}^2}{m_{l_m^M}^2}\mathcal{I}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)\right.$$

$$\left.+\sum_{k=0}^{3}\sum_{m=1}^{3}\mathrm{Re}\left(\mathcal{U}_{im}^{L\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\right)\frac{m_{l_i}}{m_{l_m^M}}\mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)\right\}$$

The electric dipole moment for lepton l_i

$$d_{l_i} = \frac{i}{2}\left(C_L^{ii} - C_R^{ii}\right) \quad ,$$
$$= +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\frac{1}{m_{l_m^M}}\mathrm{Im}\left(\mathcal{U}_{im}^{L\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\right)\mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)$$

Analysis and Discussion

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- For the masses of the Higgs singlets, we take

$$m_{\phi_{S0}} : m_{\phi_{S1}} : m_{\phi_{S2}} : m_{\phi_{S3}} = M_S : 2M_S : 3M_S : 4M_S$$

with a fixed common mass M_S = 10 MeV.

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$$m_{l_m^M} = M_{\mathrm{mirror}} + \delta_m$$

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- We assume all the Yukawa couplings g_{0S}, g_{1S}, g_{2S}, g'_{S0}, g'_{S1}, and g'_{S2} to be all real and we also take $g_{0S} = g'_{S0}$, $g_{1S} = g'_{S1}$, $g_{S2} = (g_{1S})^*$ *and* $g'_{S2} = (g'_{S1})^*$

Analysis and Discussion

For the three unknown mixing matrices, we consider 2 scenarios

– Scenario 1

$$U^{l^M}_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^{l^M}_{\mathrm{PMNS}} = U^{\dagger}_{CW}$$

– Scenario 2

$$U^{l^M}_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^{l^M}_{\mathrm{PMNS}} = U_{\mathrm{PMNS}}$$

Where the Cabibbo-Wolfenstein matrix

$$U_{CW} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

And PMNS matrix:

For Normal Hierarchy (NH)

$$U_{\rm PMNS}^{\rm NH} = \begin{pmatrix} 0.8221 & 0.5484 & -0.0518 + 0.1439i \\ -0.3879 + 0.07915i & 0.6432 + 0.0528i & 0.6533 \\ 0.3992 + 0.08984i & -0.5283 + 0.05993i & 0.7415 \end{pmatrix}$$

For Inverted Hierarchy (IH)

$$U_{\rm PMNS}^{\rm IH} = \begin{pmatrix} 0.8218 & 0.5483 & -0.08708 + 0.1281i \\ -0.3608 + 0.0719i & 0.6467 + 0.04796i & 0.6664 \\ 0.4278 + 0.07869i & -0.5254 + 0.0525i & 0.7293 \end{pmatrix}$$

- Limit on B(μ → eγ) from MEG experiment:

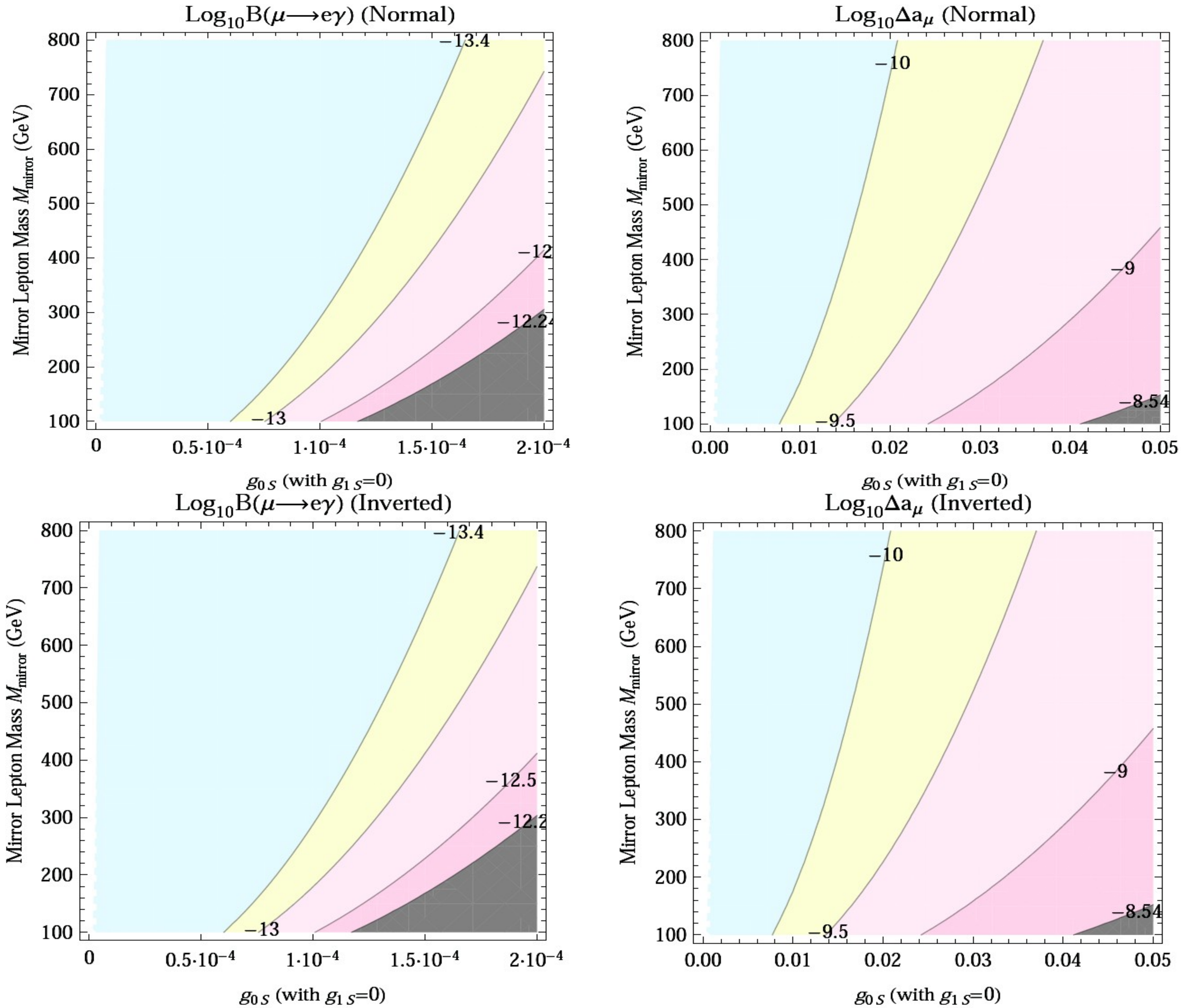
B(μ → eγ) ≤ 5.7×10^{-13} (90 C.L.)[MEG, 2013]

B(μ → eγ) ~ 4×10^{-14} [Projected Sensitivity]

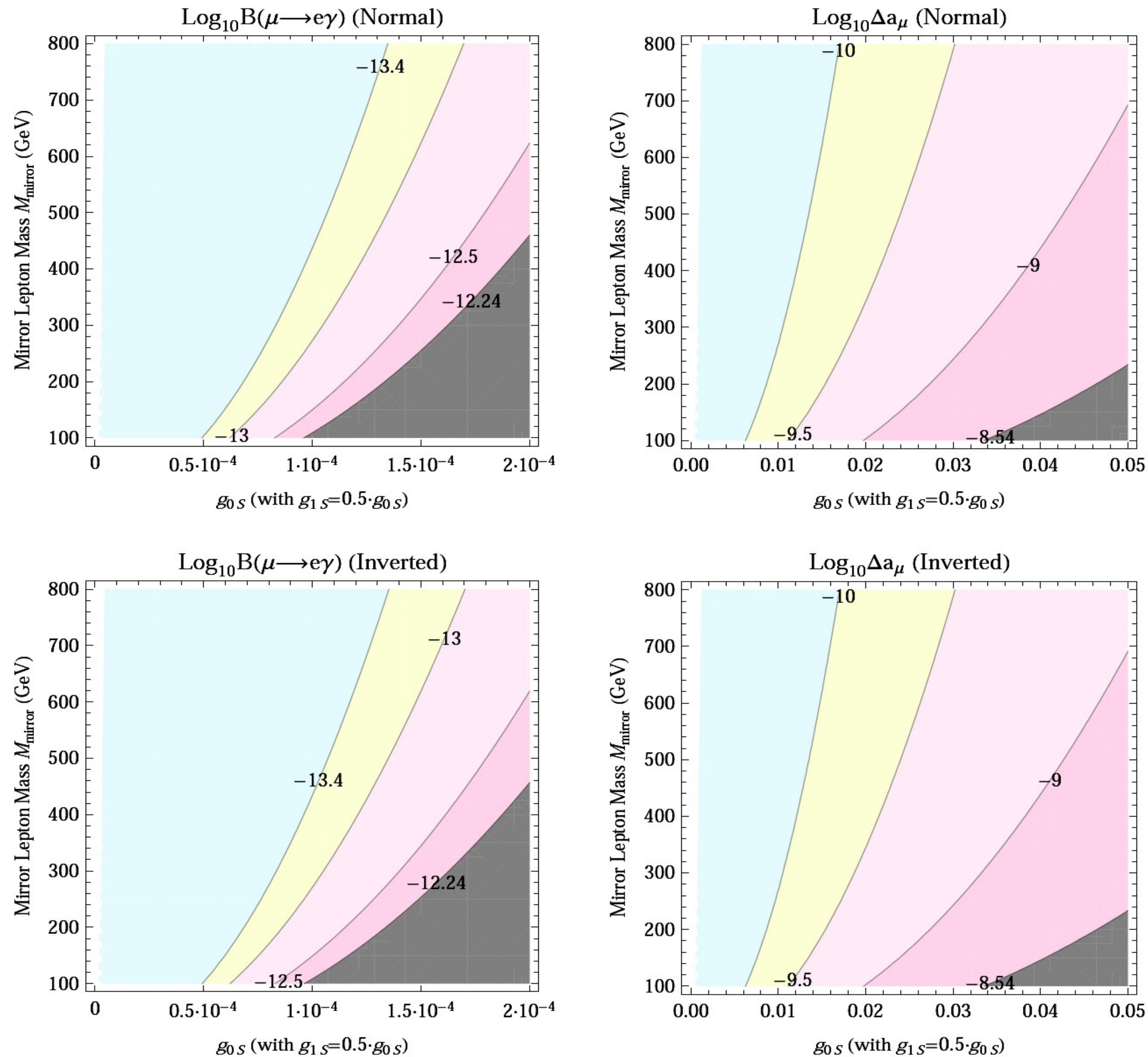
- Δa_{μ} from E821 experiment

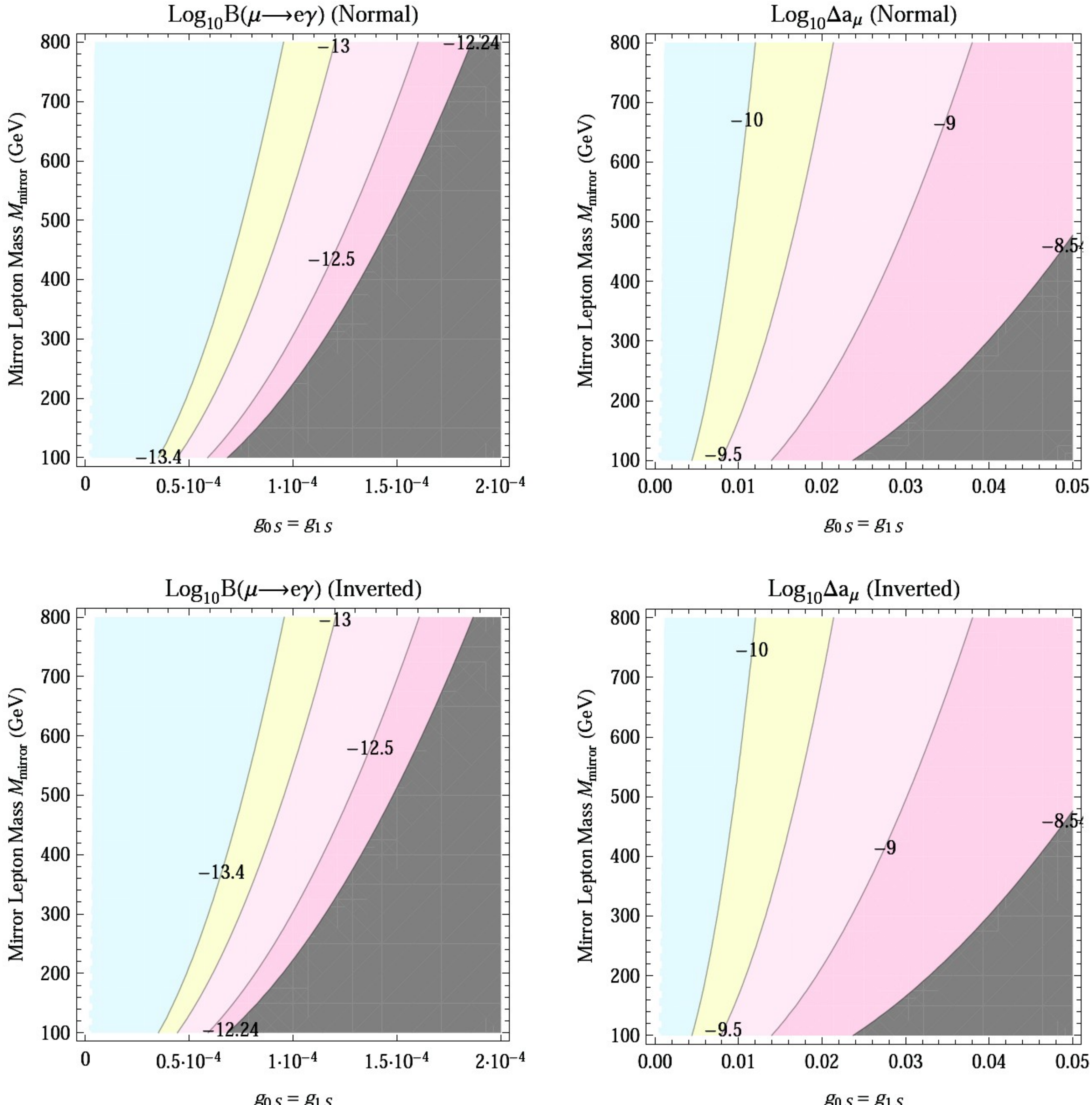
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11}$$

Scenario 1



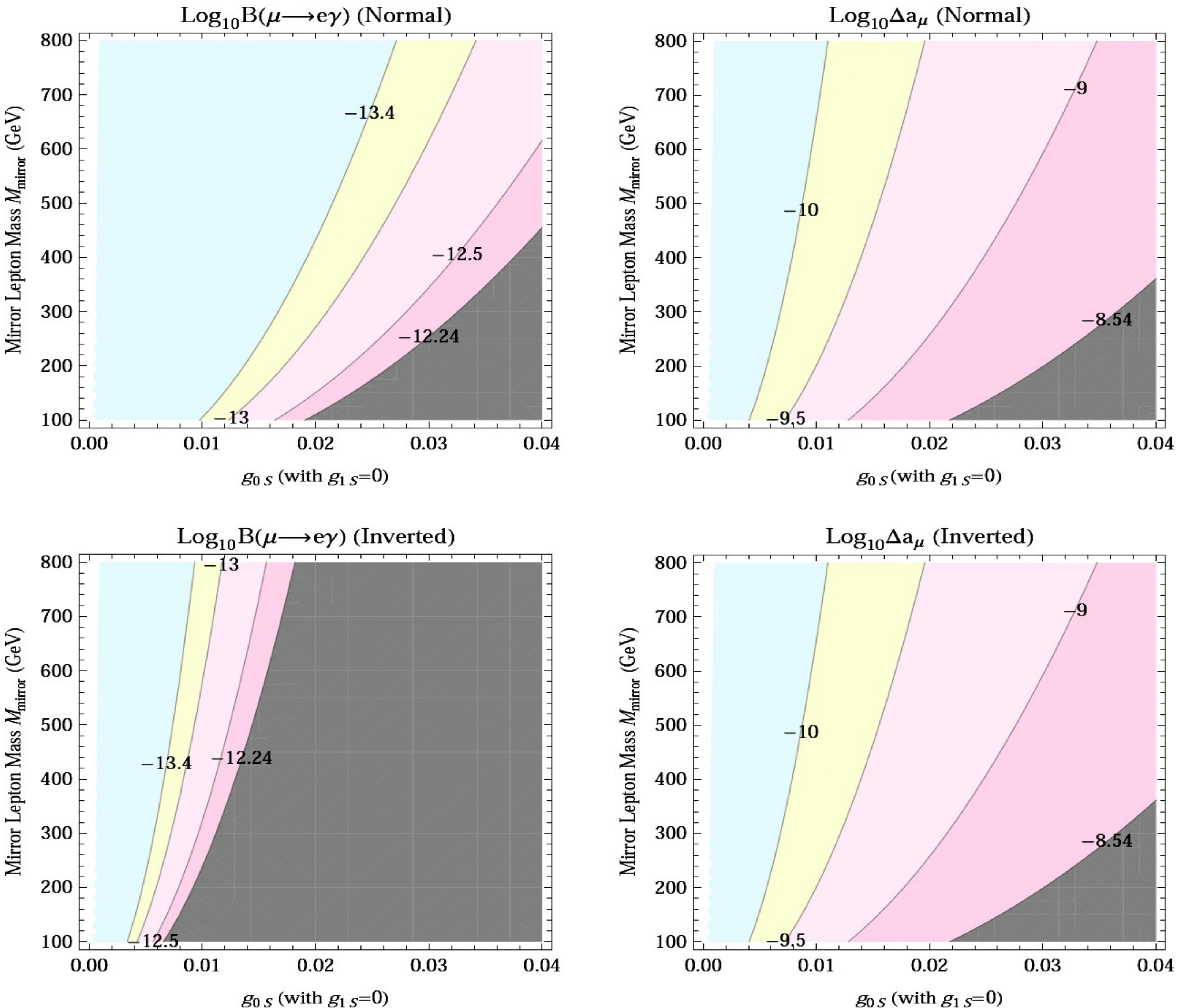
$\mathrm{Log}_{10}\mathrm{B}(\mu \longrightarrow e\gamma)$ (Normal)
$\mathrm{Log}_{10}\Delta a_\mu$ (Normal)
$\mathrm{Log}_{10}\mathrm{B}(\mu \longrightarrow e\gamma)$ (Inverted)
$\mathrm{Log}_{10}\Delta a_\mu$ (Inverted)
Mirror Lepton Mass M_{mirror} (GeV)
g_{0S} (with g_{1S}=0)
−13.4
−13
−12.5
−12.2
−10
−9.5
−9
−8.54
800
700
600
500
400
300
200
100
0
$0.5\cdot10^{-4}$
$1\cdot10^{-4}$
$1.5\cdot10^{-4}$
$2\cdot10^{-4}$
0.00
0.01
0.02
0.03
0.04
0.05


Log10B(μ⟶eγ) (Normal)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0.5·g0 S)
−13.4
−13
−12.5
−12.24
0
0.5·10−4
1·10−4
1.5·10−4
2·10−4
100
200
300
400
500
600
700
800
Log10Δaμ (Normal)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0.5·g0 S)
−10
−9.5
−9
−8.54
0.00
0.01
0.02
0.03
0.04
0.05
Log10B(μ⟶eγ) (Inverted)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0.5·g0 S)
−13
−13.4
−12.24
−12.5
Log10Δaμ (Inverted)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0.5·g0 S)
−10
−9
−9.5
−8.54

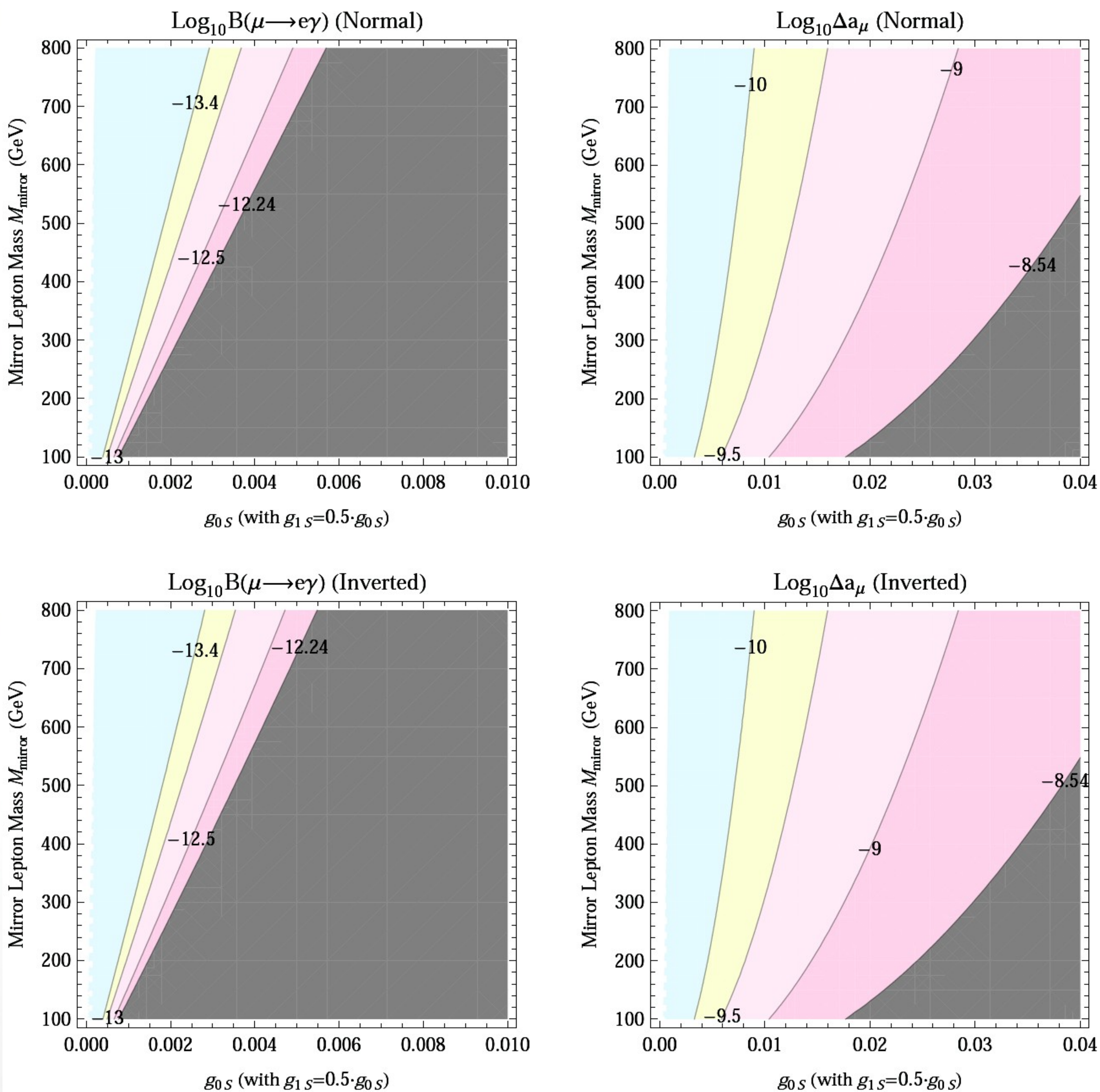


Log10B(μ⟶eγ) (Normal)
Mirror Lepton Mass M_mirror (GeV)
g0 s = g1 s
−13
−12.24
−12.5
−13.4
Log10Δaμ (Normal)
−10
−9
−8.5
−9.5
Log10B(μ⟶eγ) (Inverted)
−13
−12.5
−13.4
−12.24
Log10Δaμ (Inverted)
−10
−8.5
−9
−9.5

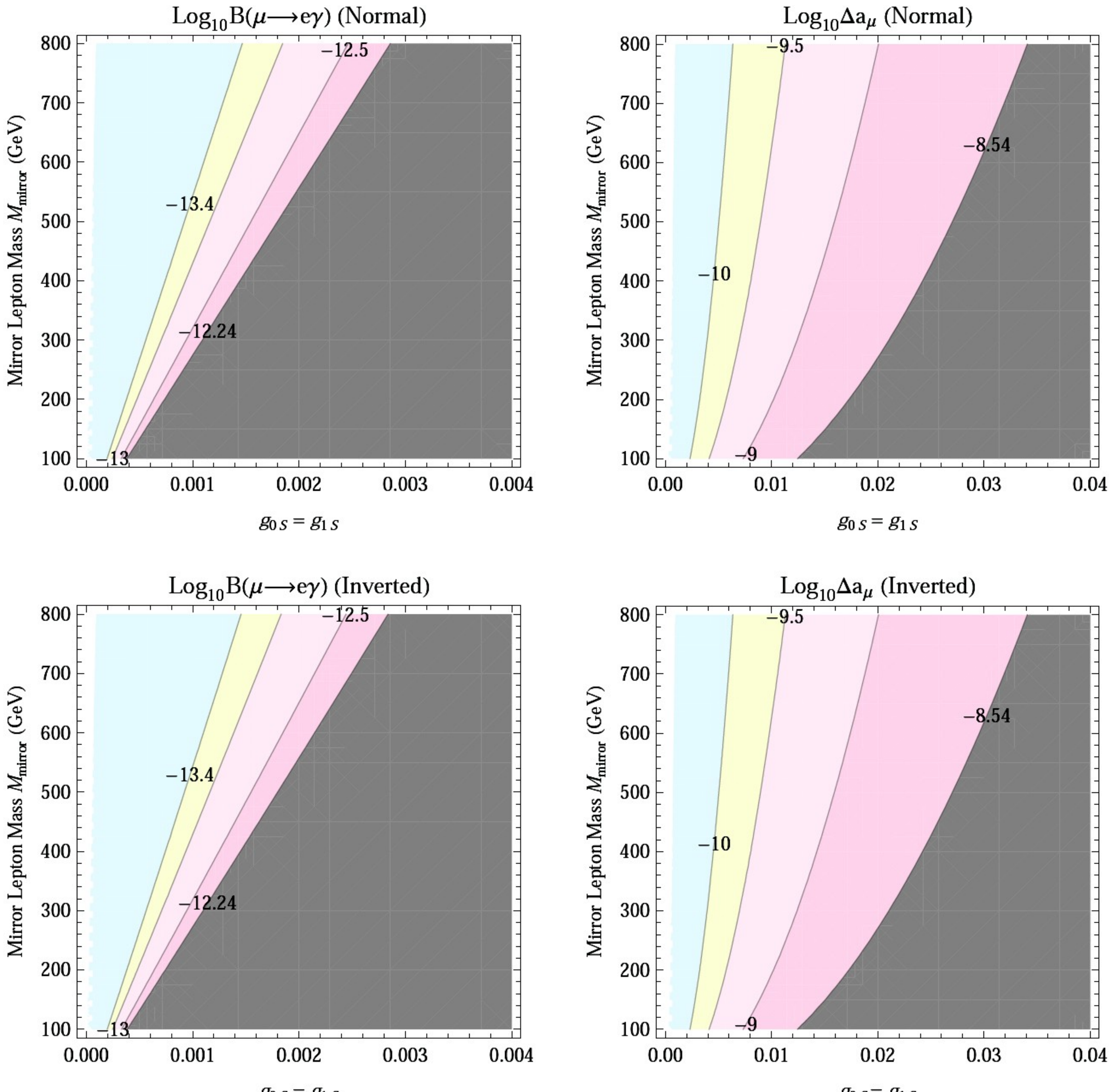
Scenario 2



Log10B(μ⟶eγ) (Normal)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0)
−13.4
−12.5
−12.24
−13
Log10Δaμ (Normal)
−9
−10
−8.54
−9.5
Log10B(μ⟶eγ) (Inverted)
−13
−13.4
−12.24
−12.5
Log10Δaμ (Inverted)
−9
−10
−8.54
−9.5



Log10B(μ⟶eγ) (Normal)
Mirror Lepton Mass M_mirror (GeV)
g0 S (with g1 S=0.5·g0 S)
−13.4
−12.24
−12.5
−13
Log10Δa_μ (Normal)
−10
−9
−8.54
−9.5
Log10B(μ⟶eγ) (Inverted)
−13.4
−12.24
−12.5
−13
Log10Δa_μ (Inverted)
−10
−8.54
−9
−9.5


Log10B(μ⟶eγ) (Normal)
Log10Δaμ (Normal)
Log10B(μ⟶eγ) (Inverted)
Log10Δaμ (Inverted)
Mirror Lepton Mass Mmirror (GeV)
g0 s = g1 s
−13.4
−12.5
−12.24
−13
−9.5
−8.54
−10
−9
100
200
300
400
500
600
700
800
0.000
0.001
0.002
0.003
0.004
0.00
0.01
0.02
0.03
0.04

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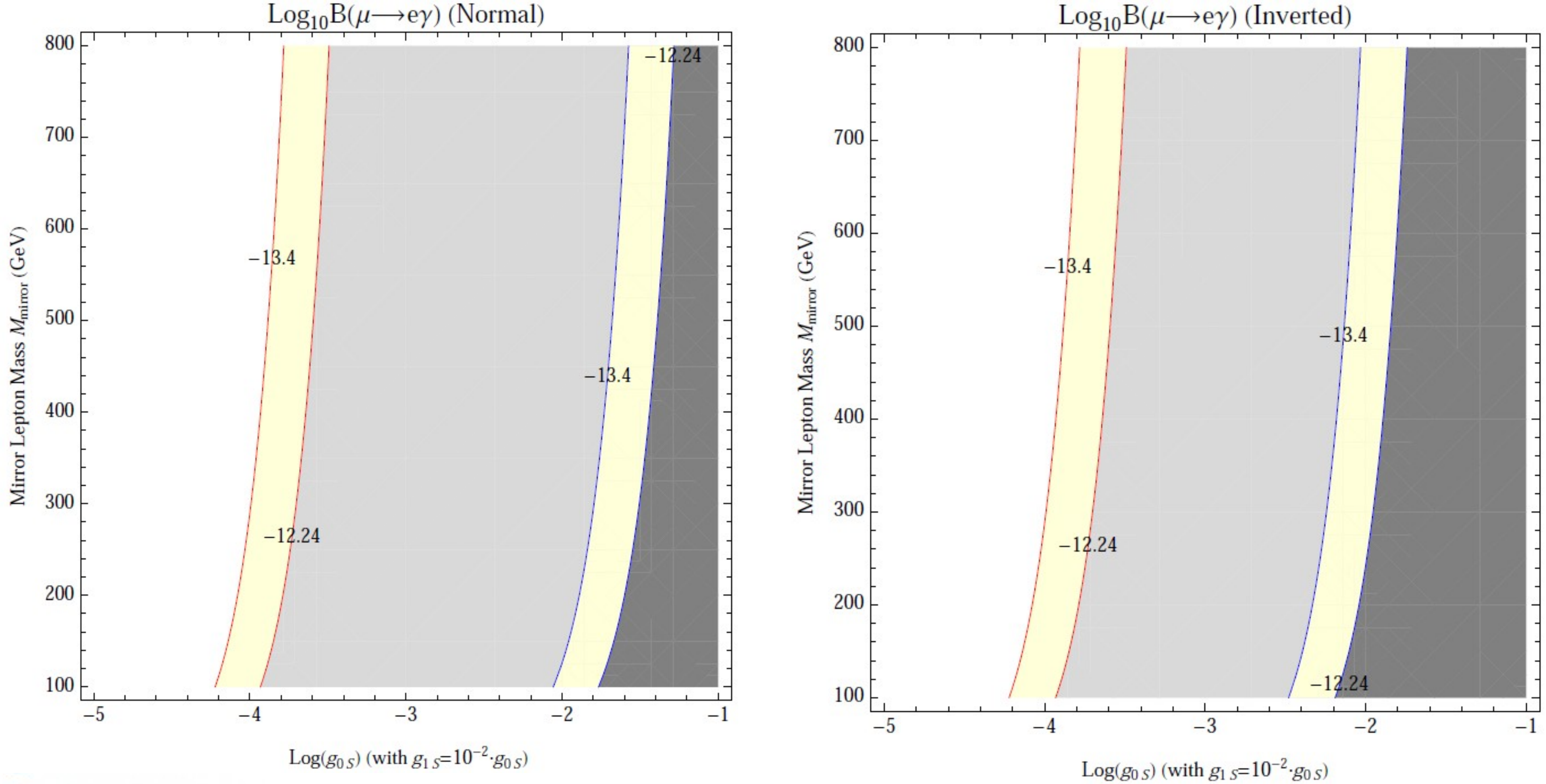
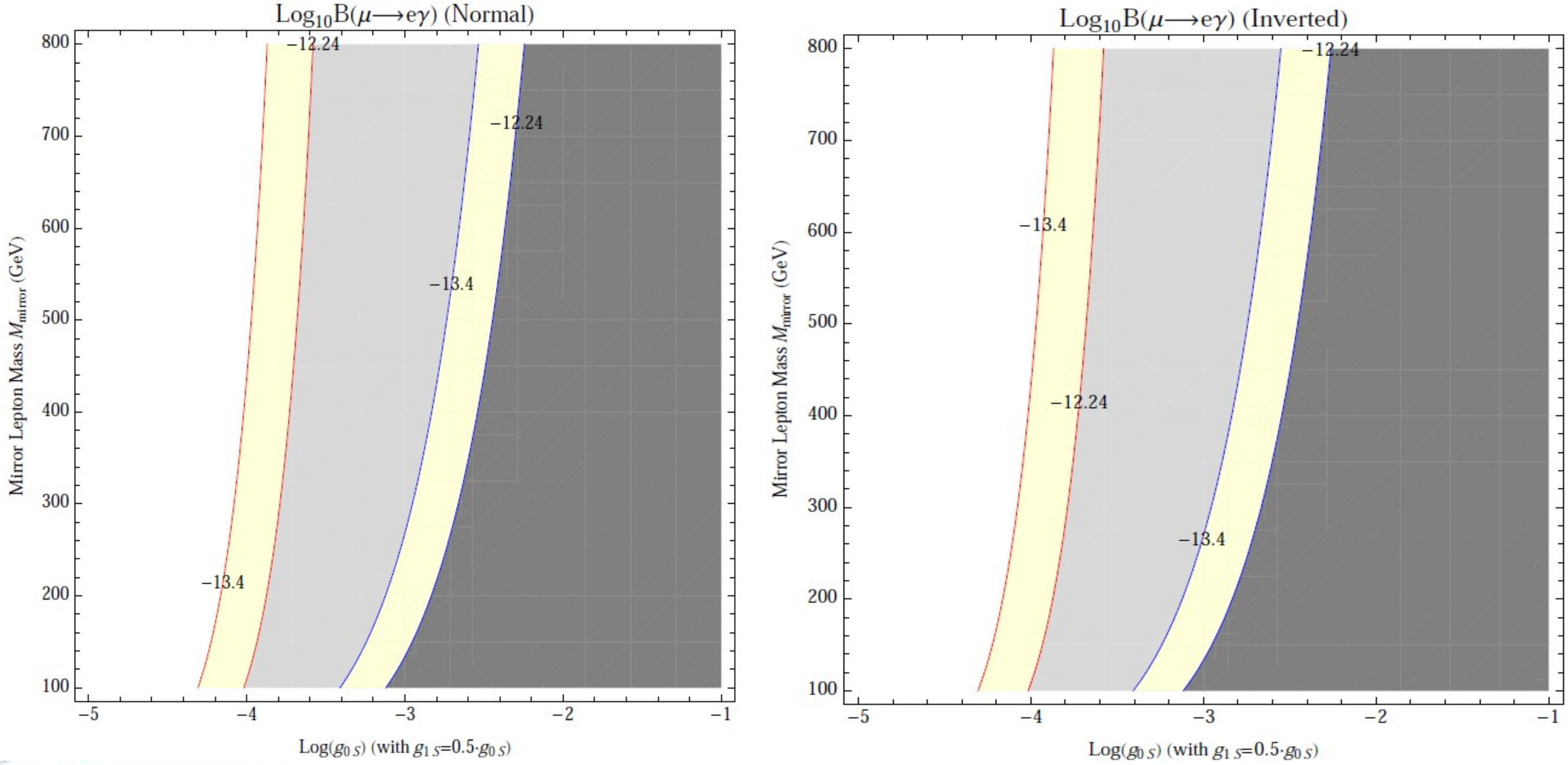
4. The sensitivity of the couplings in the B($\mu \to e + \gamma$) has been weakened by one to two order of magnitudes for scenario 2, while for the muon anomalous magnetic moment it stays more or less the same.



Contour plots of Log10B($\mu \rightarrow e + \gamma$) on the (Log10 g_{0S};M_{mirror}) plane for normal (left panel) and inverted (right panel) hierarchy in Scenario 1 (red) and 2 (blue) with $g_{0S} = g'_{0S}$ and $g_{1S} = g'_{1S} = 10^{-2}\ g_{0S}$.



Contour plots of Log10B($\mu \to e + \gamma$) on the (Log10 g_{0S};M_{mirror}) plane for normal (left panel) and inverted (right panel) hierarchy in Scenario 1 (red) and 2 (blue) with $g_{0S} = g'_{0S}$ and $g_{1S} = g'_{1S} = 0.5\ g_{0S}$.

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- By the recent and future expectation data at MEG we figured out some interesting constraints on the model


THANK YOU