SEESAW LEPTON MASSES AND MUON G-2 FROM HEAVY VECTOR-LIKE LEPTONS

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Table of contents

Table of contents

Muon g-2 and Anomaly

- Muon g-2

B. Abi *et al.* [Muon g-2],
Phys. Rev. Lett. **126**, no.14, 141801 (2021)

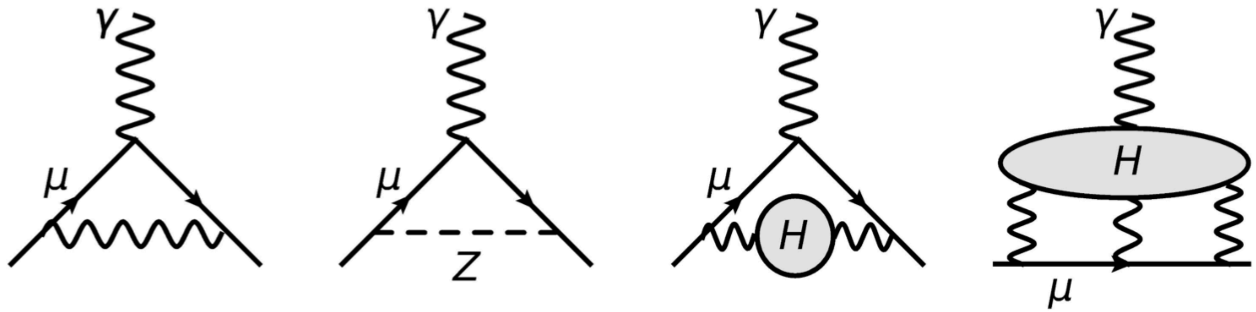
  - The magnetic moments of the electron and muon

$$\vec{\mu}_\ell = g_\ell \left(\frac{q}{2m_\ell} \right) \vec{s} \quad \text{where} \quad g_\ell = 2(1 + a_\ell) \, (\ell = e, \mu)$$

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B}$$

  - $g_e = g_\mu = 2$ at the tree-level
    muon behaves like a heavy electron in a magnetic field
    →Generational structure of the SM
  - Muon magnetic moment in the SM:

$$a_\mu(\text{SM}) \quad = \quad 116\,591\,810(43) \times 10^{-11} \; (0.37\,\text{ppm})$$



Muon g-2 and Anomaly

B. Abi *et al.* [Muon g-2],
Phys. Rev. Lett. **126**, no.14, 141801 (2021)

- Muon g-2
  - Sensitive for New Physics for many cases

e.g. for the W & Z bosons of the SM
many hypothetical new particles

$$a_l \sim \left(\frac{m_l}{m_{NP}}\right)^2 \rightarrow \left(\frac{m_\mu}{m_e}\right)^2 \sim 43000$$ more sensitive than a_e

(experimental precision → factor 19)

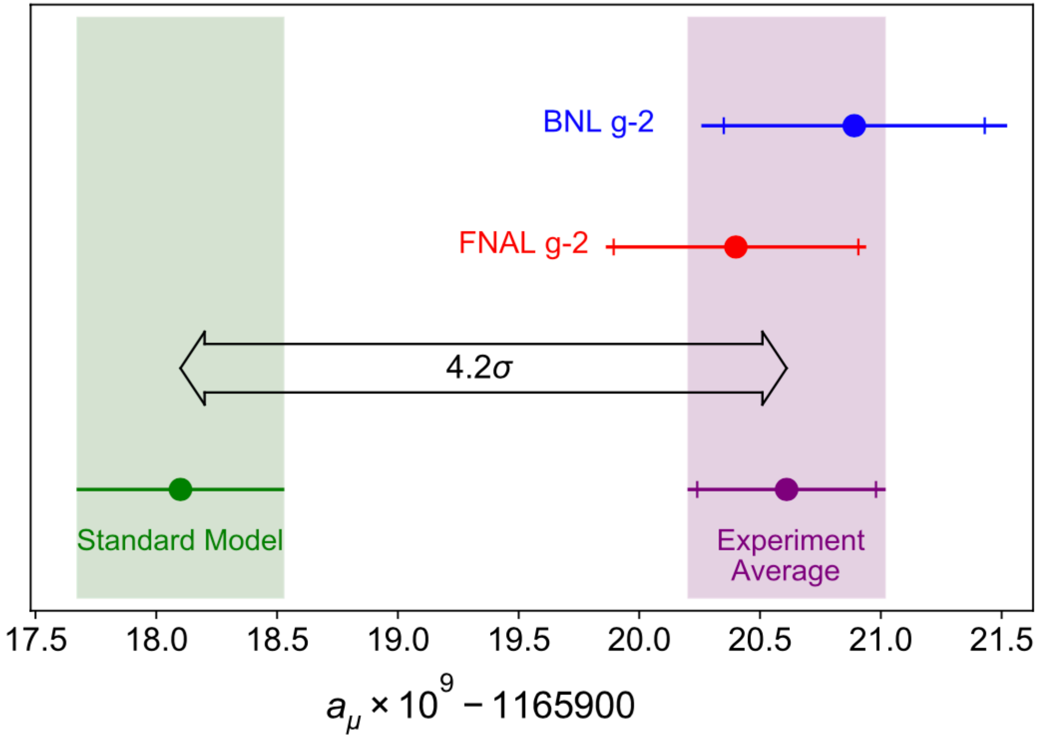
talk slide by Andreas Nyffeler,
https://www2.kek.jp/physics-seminar/files2016_2/20161201_g-2.pdf

The muon anomaly has an advantage
when searching for effects of new heavy physics

Muon g-2 and Anomaly

- Muon g-2 anomaly

B. Abi *et al.* [Muon g−2], Phys. Rev. Lett. **126**, no.14, 141801 (2021)



Brookhaven E821 experiment

Fermilab E989 experiment

Combined average

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11}$$

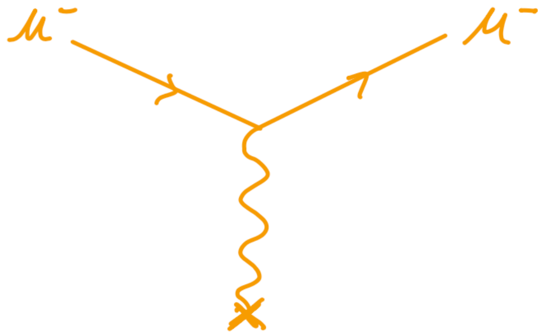
cf. Electron g-2:

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = -88(36) \times 10^{-14}, \quad ({\rm Cs})$$
$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = 48(30) \times 10^{-14}, \quad ({\rm Rb}),$$

tension between Cs data and Rb data at 5.4 sigma
→need to confirm on these measurements

New Physics Contributions

- Scattering in the external (magnetic) field A_e



$$ie\overline{u}(\vec{p'})\gamma_\mu u(\vec{p})A^\mu_e(\vec{q}=\vec{p'}-\vec{p})$$

$$\supset \frac{ie}{2m}\overline{u}(\vec{p'})(i\sigma^{\mu\nu}q_\nu)u(\vec{p})A_{e\mu}(\vec{q})$$

Chirality is flipped

Relevant part for $\vec{\mu}_\ell = g_\ell\left(\frac{e}{2m_\ell}\right)\vec{s}$ where $g_\ell = 2(1+a_\ell)$

- New Physics Contributions which make a chirality flip can be large
- Because for considering radiative corrections (loop), a light particle is also appreciated

New Physics Contributions

One field extension

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\rm BNL}$, Δa_μ^{2021}
1	0	$(\mathbf{1},\mathbf{1},1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1},\mathbf{3},-1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}},\mathbf{1},1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}},\mathbf{1},4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}},\mathbf{3},1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3},\mathbf{2},1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1},\mathbf{2},-1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1},\mathbf{2},-3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	UV completion problems
18	1	$(\mathbf{1},\mathbf{3},0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}},\mathbf{1},-2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}},\mathbf{1},-5/3)$	Excluded: LHC searches
21	1	$(\overline{\mathbf{3}},\mathbf{2},-5/6)$	UV completion problems
22	1	$(\overline{\mathbf{3}},\mathbf{2},1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}},\mathbf{3},-2/3)$	Excluded: proton decay

Two fields extension

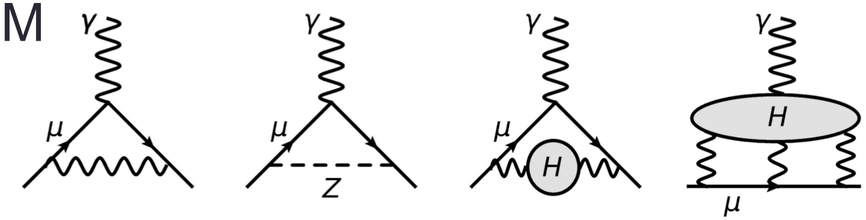
$(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\rm spin}$	$+\mathbb{Z}_2$	Result for $\Delta a_\mu^{\rm BNL}$, Δa_μ^{2021}
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{3},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},-1)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{1},0)_{1/2} - (\mathbf{1},\mathbf{1},1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{3},-1)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: $\Delta a_\mu < 0$

P. Athron, C. Balazs, D. H. Jacob, W. Kotlarski,
D. Stockinger and H. Stockinger-Kim, JHEP **09**, 080 (2021)

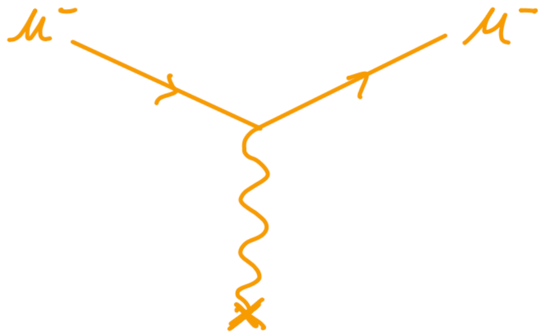
Many directions, but hard to explain for many cases

New Physics Contributions

recall SM



- Scattering in the external (magnetic) field A_e



$$ie\overline{u}(\vec{p'})\gamma_\mu u(\vec{p})A^\mu_{\rm e}(\vec{q} = \vec{p'} - \vec{p})$$

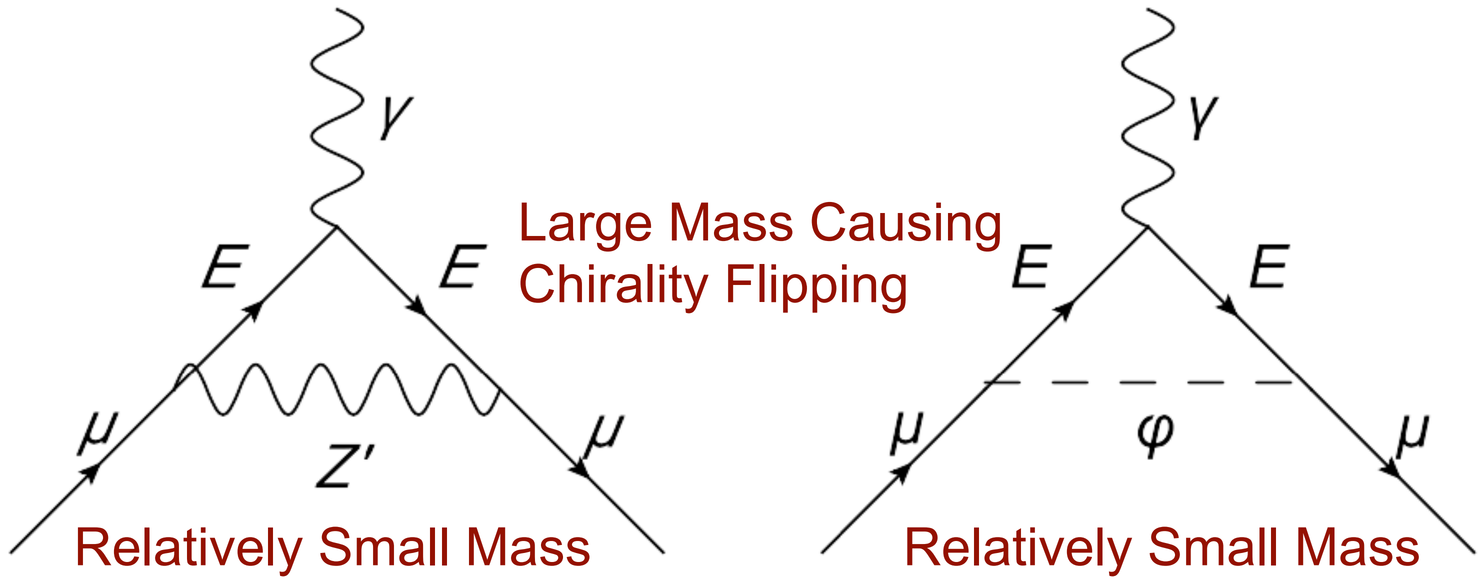
$$\supset \frac{ie}{2m}\overline{u}(\vec{p'})(i\sigma^{\mu\nu}q_\nu)u(\vec{p})A_{{\rm e}\mu}(\vec{q})$$

Chirality is flipped

Relevant part for $\vec{\mu}_\ell = g_\ell\left(\frac{\rm e}{2m_\ell}\right)\vec{s}$ where $g_\ell = 2(1 + a_\ell)$

- New Physics Contributions which make a chirality flip can be large→Heavy charged fermion?
- Because for considering radiative corrections (loop), a light particle is appreciated→Light neutral particle also?

New Physics Contributions



- New Physics Contributions which make a chirality flip can be large→Heavy charged fermion?→E in our model
- Because for considering radiative corrections (loop), a light particle is appreciated→Light neutral particle also?

  →Z' and φ in our model

Table of contents

Field Contents, Symmetry, Lagrangian

- U(1)’ and Z_2 symmetries

New

	q_L	u_R	d_R	l_L	l_R	H	H'	E_L	E_R	ϕ
$U(1)'$	0	0	0	0	0	0	$+2$	-2	-2	-2
Z_2	$+$	$-$	$-$	$+$	$+$	$-$	$+$	$+$	$+$	$+$

Z’ boson
as
U(1)’ gauge boson

- U(1)’ is spontaneously broken
- Z_2 parity is softly broken (before spontaneously broken) for avoiding for creating a domain wall

Field Contents, Symmetry, Lagrangian

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\sin\xi F'_{\mu\nu}B^{\mu\nu} + |D_\mu\phi|^2 + |D_\mu H'|^2 - V(\phi, H, H') + \mathcal{L}_{VLSM}$$

$$\begin{aligned} V(\phi, H, H') &= \mu_1^2 H^\dagger H + \mu_2^2 H'^\dagger H' + (\mu_3 \phi H^\dagger H' + \text{h.c.}) \\ &+\lambda_1 (H^\dagger H)^2 + \lambda_2 (H'^\dagger H')^2 + \lambda_3 (H^\dagger H)(H'^\dagger H') \\ &+\mu_\phi^2 \phi^*\phi + \lambda_\phi(\phi^*\phi)^2 + \lambda_{H\phi} H^\dagger H \phi^*\phi + \lambda_{H'\phi} H'^\dagger H' \phi^*\phi \end{aligned}$$

$$\mathcal{L}_{VLSM} = -y_d \bar{q}_L d_R H - y_u \bar{q}_L u_R \tilde{H} - M_E \bar{E}E - \lambda_E \phi \bar{E}_L l_R - y_E \bar{l}_L E_R H' + \text{h.c.}.$$

No SM lepton mass term

	q_L	u_R	d_R	l_L	l_R	H	H'	E_L	E_R	ϕ
$U(1)'$	0	0	0	0	0	0	+2	−2	−2	−2
Z_2	+	−	−	+	+	−	+	+	+	+

Seesaw Mechanism

$$\mathcal{L}_{L,\mathrm{mass}} = -M_E \bar{E} E - (m_R \bar{E}_L l_R + m_L \bar{l}_L E_R + \mathrm{h.c.})$$

- After diagonalizing the mass matrix

$$m^2_{l_1,l_2} = \frac{1}{2}\left(M_E^2 + m_L^2 + m_R^2 \mp \sqrt{(M_E^2 + m_L^2 - m_R^2)^2 + 4m_R^2 M_E^2}\right)$$

$$\begin{pmatrix} l_L \\ E_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & \sin\theta_L \\ -\sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} l_{1L} \\ l_{2L} \end{pmatrix} \qquad \sin(2\theta_R) = \frac{2M_E m_R}{m^2_{l_2} - m^2_{l_1}},$$

$$\begin{pmatrix} l_R \\ E_R \end{pmatrix} = \begin{pmatrix} \cos\theta_R & \sin\theta_R \\ -\sin\theta_R & \cos\theta_R \end{pmatrix} \begin{pmatrix} l_{1R} \\ l_{2R} \end{pmatrix} \qquad \sin(2\theta_L) = \frac{m_L^2}{m_{l_1} m_{l_2}} \cdot \sin(2\theta_R)$$

$$m_R, m_L \ll M_E \quad m^2_{l_1} \approx \frac{m_R^2 m_L^2}{M_E^2} \quad m^2_{l_2} \approx M_E^2 + m_L^2 + m_R^2$$

Small mass can be generated as $m_\mu \sim m^2/M_E$

Seesaw Mechanism

- From perturbativity condition $\lambda_E < 1$ and $y_E < 1$,

$$\mathcal{L}_{L,\text{mass}} = -M_E \bar{E} E - (m_R \bar{E}_L l_R + m_L \bar{l}_L E_R + \text{h.c.})$$

$$m_R = \lambda_E v_\phi \text{ and } m_L = \frac{1}{\sqrt{2}} y_E v_2$$

$m_{l_1} \approx \frac{\lambda_E y_E v_\phi v_2}{\sqrt{2} M_E}$ Choosing $m_{l_1} = m_\mu$

$$M_E \simeq \frac{\lambda_E y_E v_\phi v_2}{\sqrt{2} m_\mu} < 6700\,\text{GeV}\left(\frac{v_\phi v_2}{10^3\,\text{GeV}^2}\right)$$

Muon mass can be generated
with a very heavy vector-like lepton

Seesaw Mechanism

- for $m_R, m_L \ll M_E$,

$$\sin(2\theta_R) \simeq \frac{2m_{l_1}}{m_L}, \quad \sin(2\theta_L) \simeq \frac{2m_L}{m_{l_2}}. \rightarrow \theta_R\theta_L \sim \frac{m_l}{M_E}$$

- Family structures

$$(\theta_L^e\theta_R^e)/(\theta_L^\mu\theta_R^\mu) \simeq \frac{m_e}{m_\mu} \simeq 0.0048 \text{ for the same } M_E$$

$$(\theta_L^\mu\theta_R^\mu)/(\theta_L^\tau\theta_R^\tau) \simeq \frac{m_\mu}{m_\tau} \simeq 0.059$$

- If E exists for each generation, different M_E can make more suppressions/enhancements

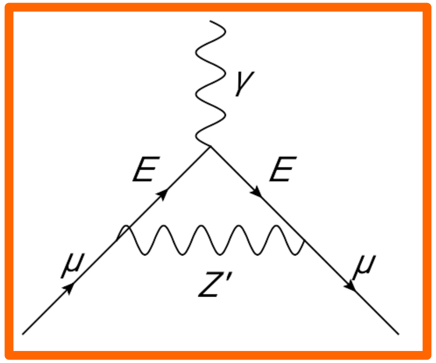
Table of contents

Z' boson & Dark Higgs Contributions

Small

$$\mathcal{L}_{L,\text{eff}} \supset g_{Z'} Z'_\mu \bar{l}\gamma^\mu (v'_l + a'_l\gamma^5) l + \left(g_{Z'} Z'_\mu \bar{l}\gamma^\mu (c_V + c_A\gamma^5) E + \text{h.c.}\right)$$
$$+ \frac{g}{2c_W}(a_l s_L c_L)\,\bar{l}\gamma^\mu(1-\gamma^5) E Z_\mu + \text{h.c.}$$

Dominant Contribution



Small

$$v'_l = e\varepsilon/g_{Z'} - \sin^2\theta_R - \sin^2\theta_L,$$
$$a'_l = \sin^2\theta_L - \sin^2\theta_R,$$
$$c_V = \frac{1}{2}(\sin 2\theta_R + \sin 2\theta_L),$$
$$c_A = \frac{1}{2}(\sin 2\theta_R - \sin 2\theta_L), \qquad a_l = -\frac{1}{2}.$$

Dominant Contribution

$$\Delta a_\mu^{Z',E} \simeq \begin{cases} \dfrac{g_{Z'}^2 M_E m_\mu}{16\pi^2 m_{Z'}^2}(c_V^2 - c_A^2), & M_E \gg m_{Z'}, \\ \dfrac{g_{Z'}^2 M_E m_\mu}{4\pi^2 m_{Z'}^2}(c_V^2 - c_A^2), & m_\mu \ll M_E \ll m_{Z'}. \end{cases}$$

$M_E \gg m_Z,$

No enhancement (Note that $|c_V|=|c_A|$)

$$\Delta a_\mu^{Z,E} \simeq -\frac{5g^2 c_V^2 m_\mu^2}{96\pi^2 c_W^2 m_Z^2}\left(1 + \frac{6m_Z^2}{5M_E^2}\right),$$

Also, negative contribution

Z' boson & Dark Higgs Contributions

Large

$$\Delta a_\mu^{Z',E} \simeq \frac{g_{Z'}^2 M_E m_\mu}{16\pi^2 m_{Z'}^2}(c_V^2 - c_A^2), \qquad M_E \gg m_{Z'}$$

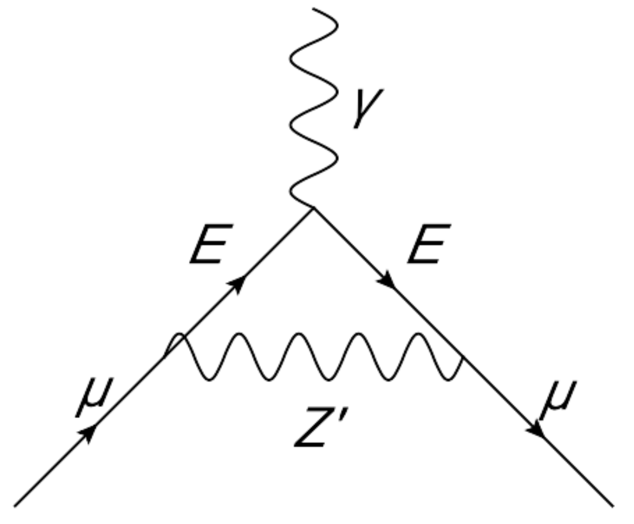
Small

$\gg m_\mu$

Enhancement

$$c_V^2 - c_A^2 \sim 4\theta_L\theta_R \sim 4\frac{m_\mu}{M_E}$$

$$\Delta a_\mu^{Z',E} \propto g_{Z'}^2 m_\mu^2 / m_Z^2$$



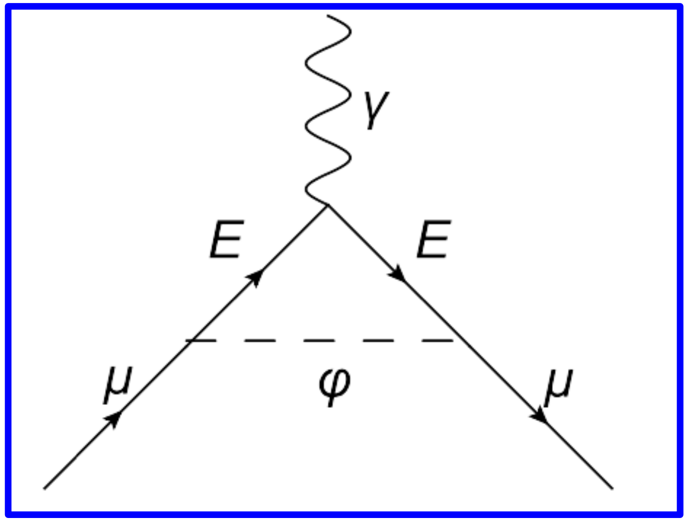
Chiral enhancement & the coupling by seesaw mechanism make Δa independent from M_E for $M_E \gg m_\mu$

Z' boson & Dark Higgs Contributions

$$\mathcal{L}_l \supset -\left(\bar{\mu}(v_i^E - i a_i^E \gamma^5) E h_i + \text{h.c.}\right)$$

$$v_3^E = \frac{m_R}{2\sqrt{2} v_\phi}(c_L c_R - s_L s_R),$$

$$-i a_3^E = -\frac{m_R}{2\sqrt{2} v_\phi}(c_L c_R + s_L s_R)$$



$h_3 = \varphi$ Assumed that others are decoupled (heavy)

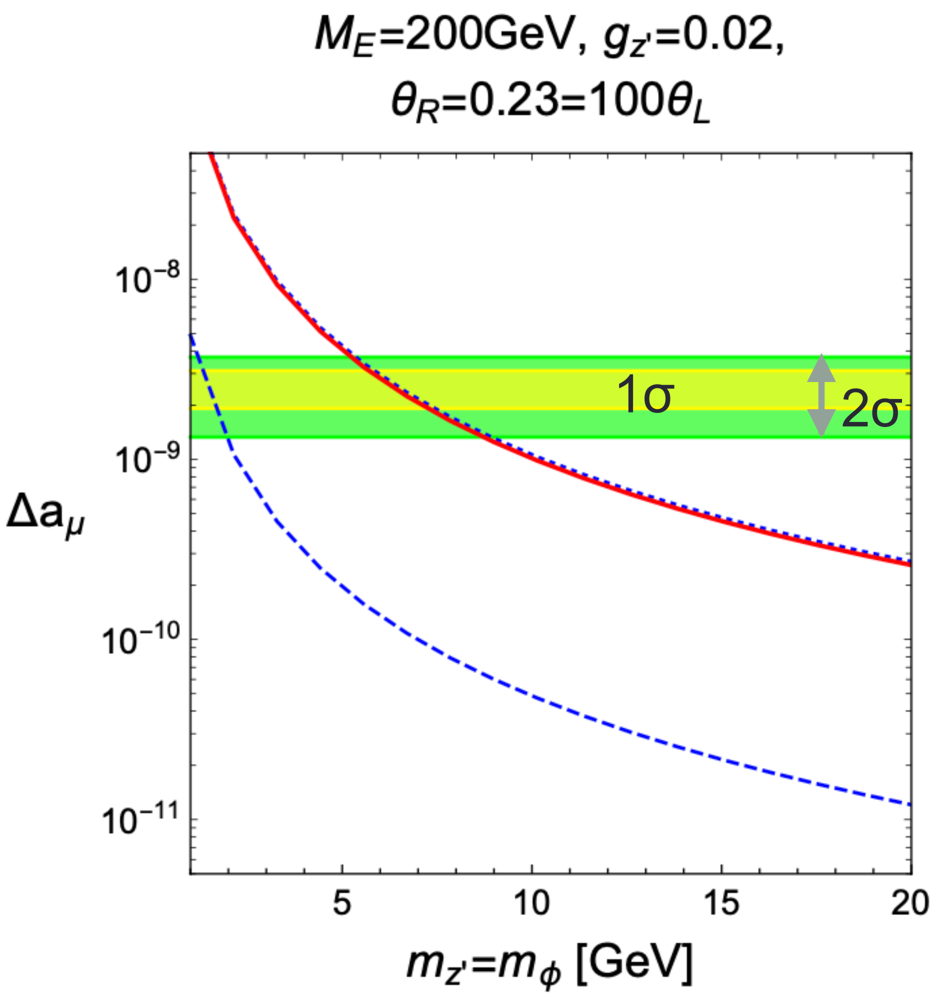
$$\Delta a_\mu^{h,E} \simeq \frac{m_\mu^2}{48\pi^2 M_E^2}\left[|v_i^E|^2 + |a_i^E|^2 + \frac{3M_E}{m_\mu}(|v_i^E|^2 - |a_i^E|^2)\right], \; M_E \gg m_{h_i}$$

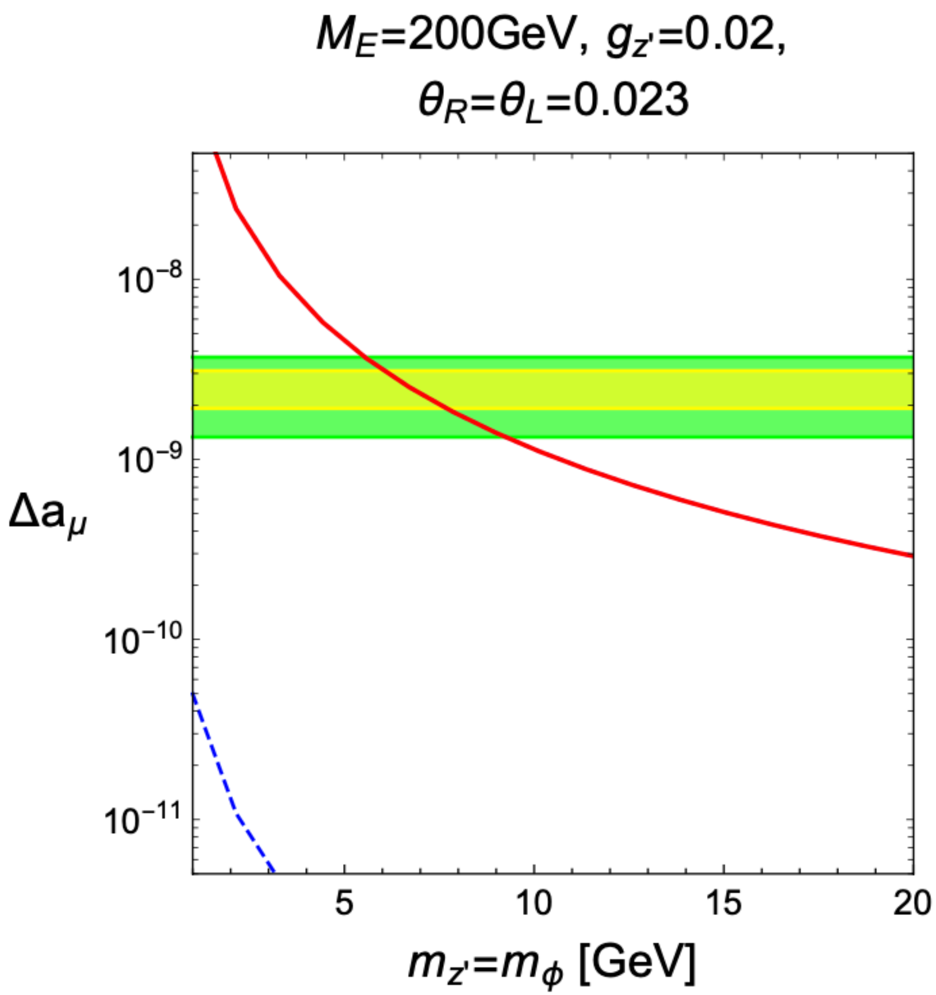
$$|v_3^E|^2 + |a_3^E|^2 \sim \tfrac{1}{4}(m_R/v_\phi)^2$$

$$|v_3^E|^2 - |a_3^E|^2 \sim -\tfrac{1}{2}(m_R/v_\phi)^2 s_L s_R \sim -\tfrac{1}{2}(m_R/v_\phi)^2 \frac{m_\mu}{M_E}$$

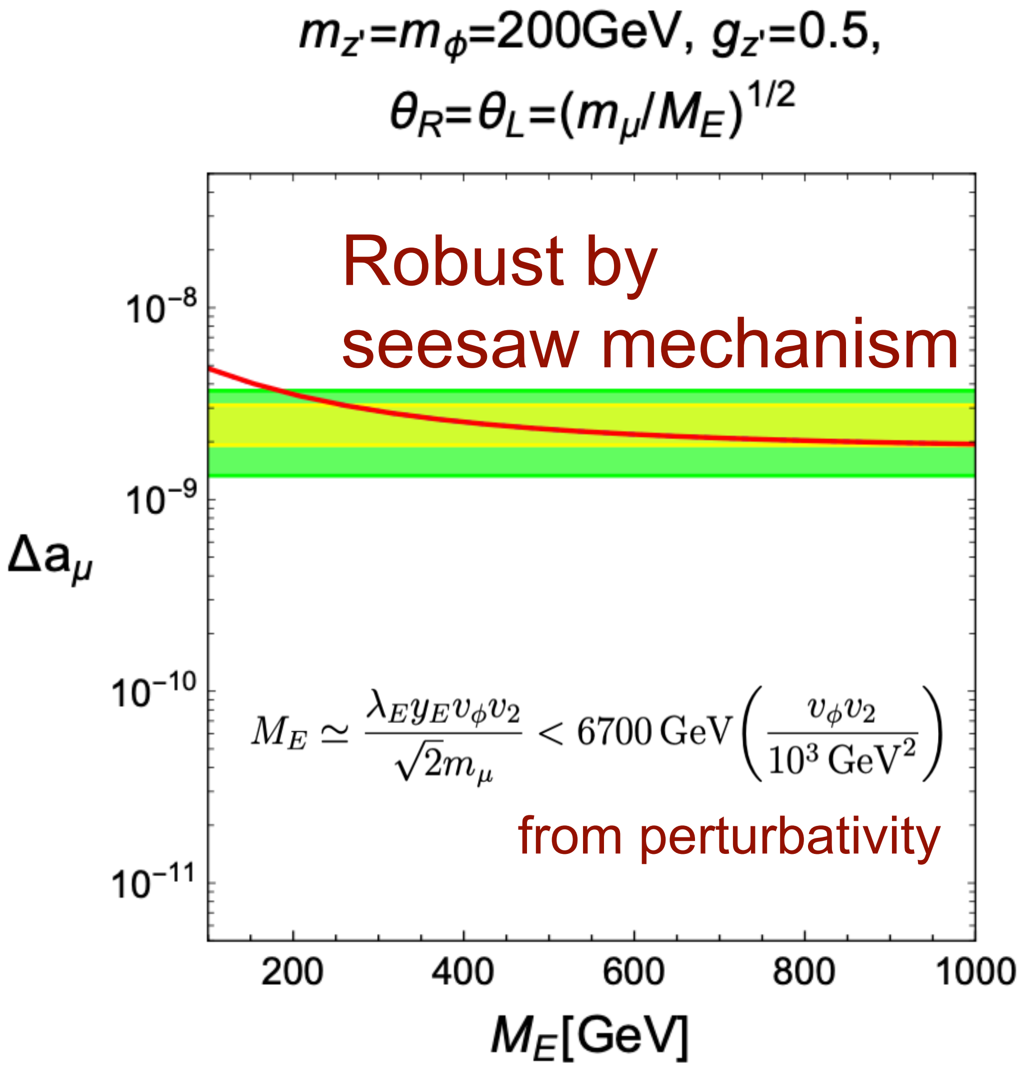
→Δa is independent from M_E for large M_E

Z' boson & Dark Higgs Contributions





Z' boson & Dark Higgs Contributions



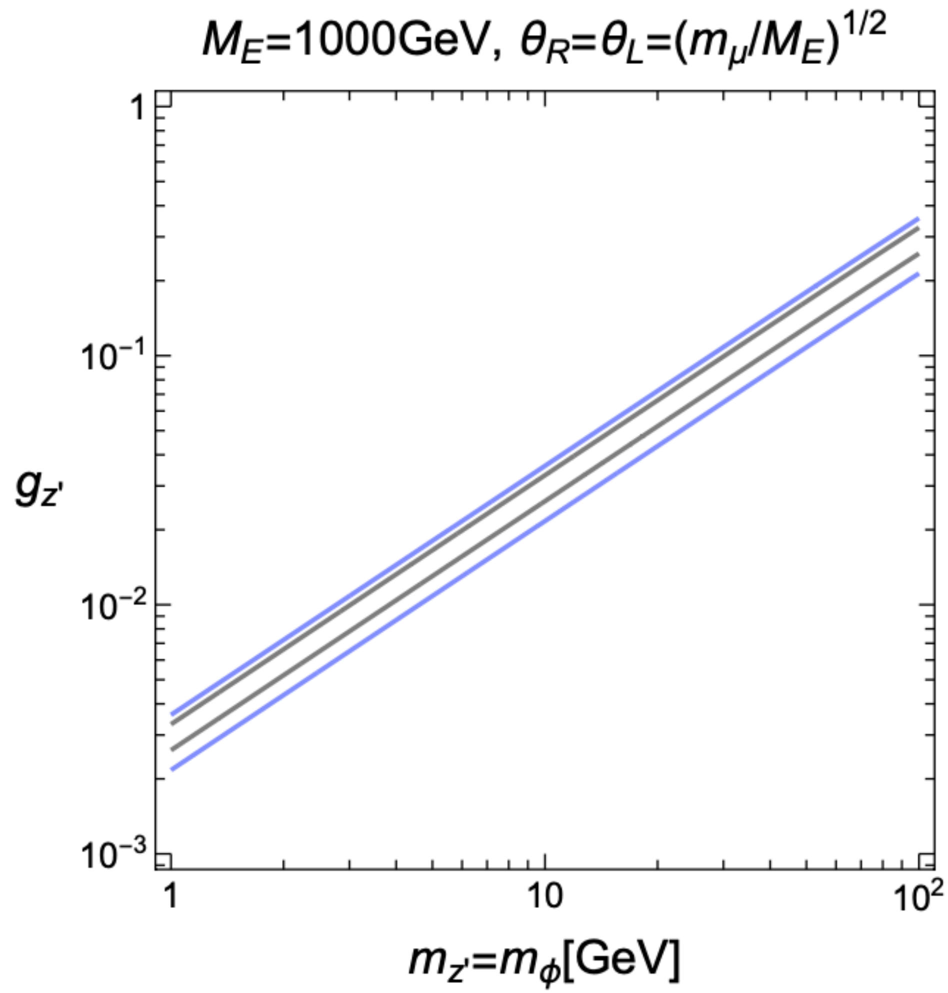
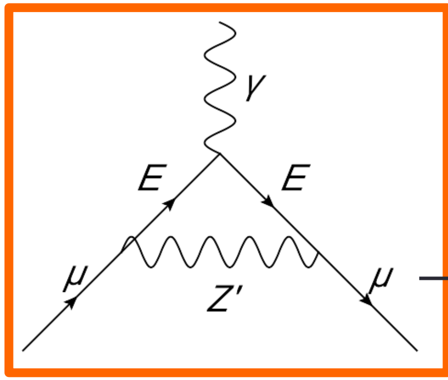


Table of contents

Lepton Flavor Violation



→e/τ

For $M_E \gg m_{Z'}$,

$$\mathrm{BR}(\mu \to e\gamma) \simeq \tau_\mu \cdot \frac{\alpha m_\mu^3}{256\pi^4}\left(\frac{g_{Z'}^4 M_E^2}{m_{Z'}^4}\right)[(\theta_R^\mu \theta_L^e)^2 + (\theta_L^\mu \theta_R^e)^2],$$

$$\mathrm{BR}(\tau \to \mu\gamma) \simeq \tau_\tau \cdot \frac{\alpha m_\tau^3}{256\pi^4}\left(\frac{g_{Z'}^4 M_E^2}{m_{Z'}^4}\right)[(\theta_R^\tau \theta_L^\mu)^2 + (\theta_L^\mu \theta_R^\tau)^2],$$

$$\mathrm{BR}(\tau \to e\gamma) \simeq \tau_\tau \cdot \frac{\alpha m_\tau^3}{256\pi^4}\left(\frac{g_{Z'}^4 M_E^2}{m_{Z'}^4}\right)[(\theta_R^\tau \theta_L^e)^2 + (\theta_L^e \theta_R^\tau)^2]$$

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13},$$
$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8},$$
$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}.$$

$$\theta_R^e = \theta_L^e \lesssim 2(3) \times 10^{-4}\sqrt{m_e/M_E}$$

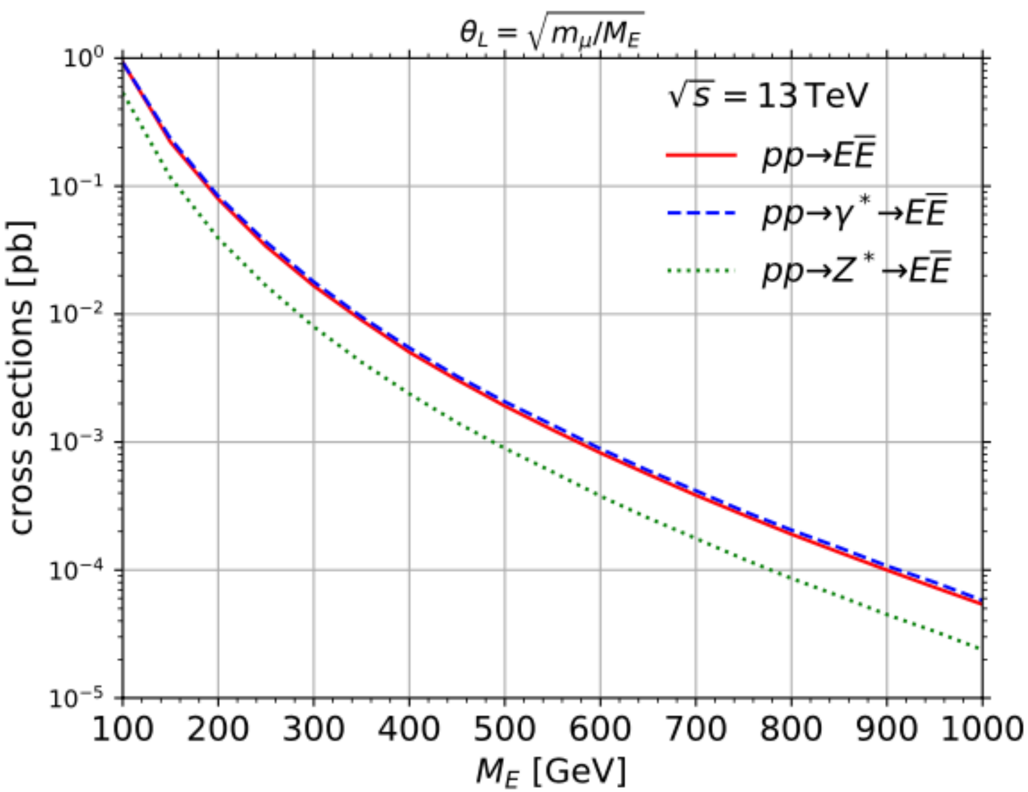
$$\theta_R^\tau = \theta_L^\tau \lesssim 0.04(0.08)\sqrt{m_\tau/M_E}$$

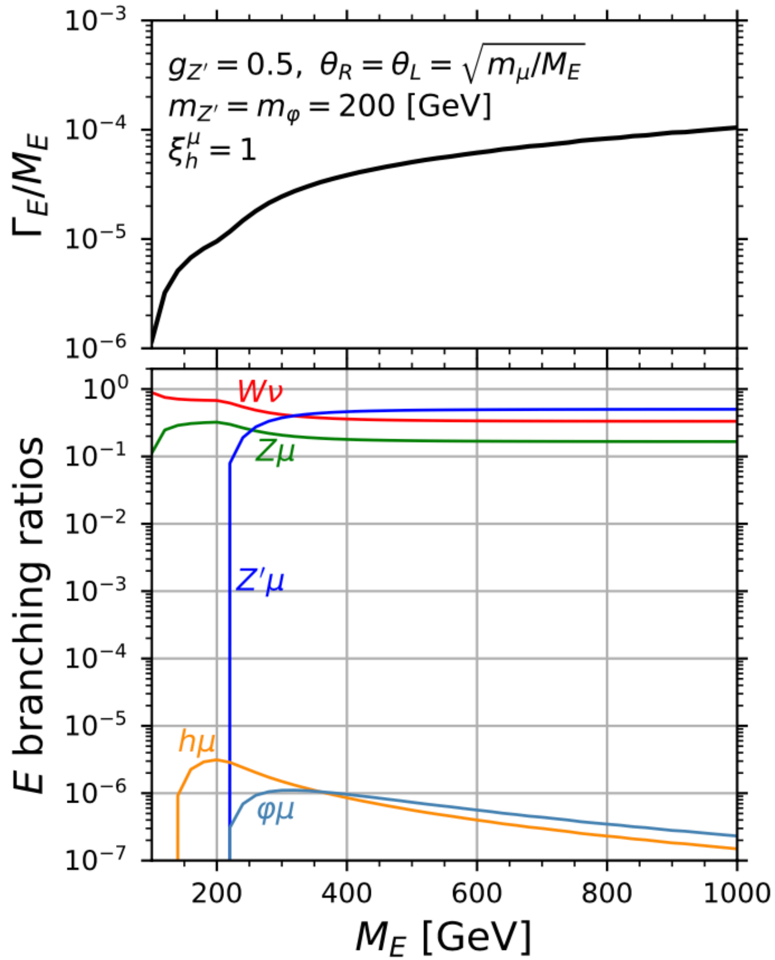
Suppose that this seesaw mechanism is applied

Note that if there are different E's for different generations, we can avoid constraints

Electroweak Precision, Higgs Data, Colliders

- Safe from a rho parameter measurement and Di-photon rate from Higgs via vector-like lepton E
- Production at the LHC and decay ratio of E

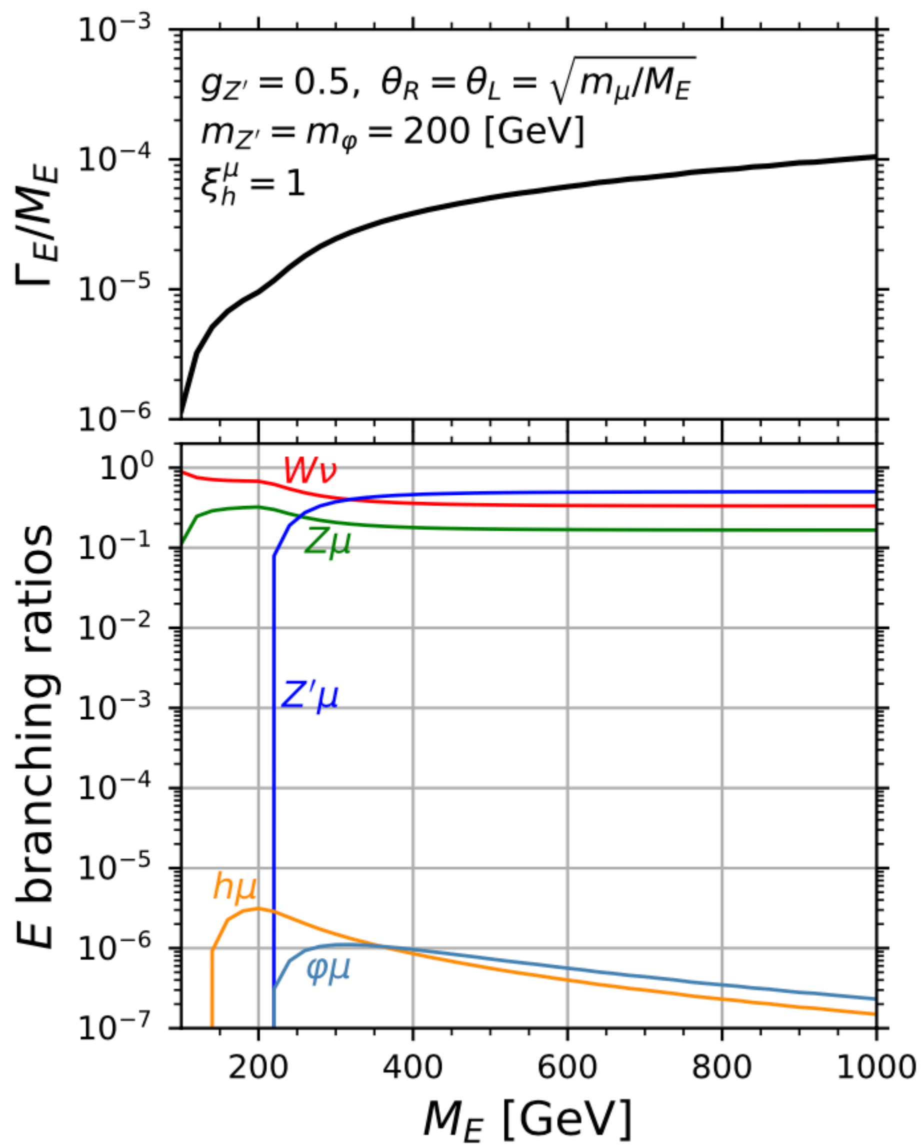




Electroweak Precision, Higgs Data, Colliders

- Light Z'
  pp→ EE, E—> Z'μ, Z'—>μμ
  →6 leptons
- Heavy Z': $m_{Z'} > M_E/2$
  pp→ EE, E—> Wν, Zν,
  Z —>*ll* case,
  → Also, multi-leptons
- Light Z' case is more severe, but we can still explain muon g-2 even for M_E > 1 TeV constraint from multi-lepton searches

J. Kawamura and S. Raby,
Phys. Rev. D **104**, no.3, 035007 (2021)



Summary

- Muon g-2 Anomaly gives us a hint for potential existence of heavy charged lepton and neutral light particles
- We concentrate on a muon sector and generate a small muon mass via the seesaw mechanism
- In this mechanism, heavy charged lepton contributes on muon g-2 with robust in high mass parameter region
- Then, we can still explain muon g-2 even for $M_E > 1$ TeV from multi-lepton searches

Couplings predicted by seesaw mechanism