Dark sector as origin of tiny lepton masses and new sources of $(g\text{-}2)_\mu$

Kei Yagyu（Osaka U.）

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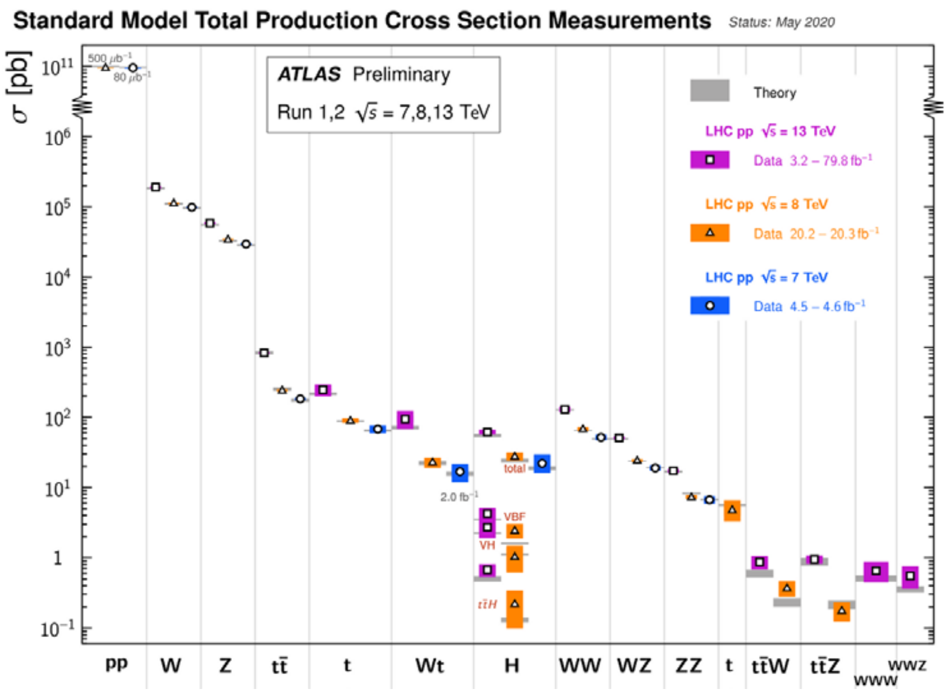
Kai-Feng Chen, Cheng-Wei Chiang, KY, 2006.07929 [hep-ph] (JHEP)

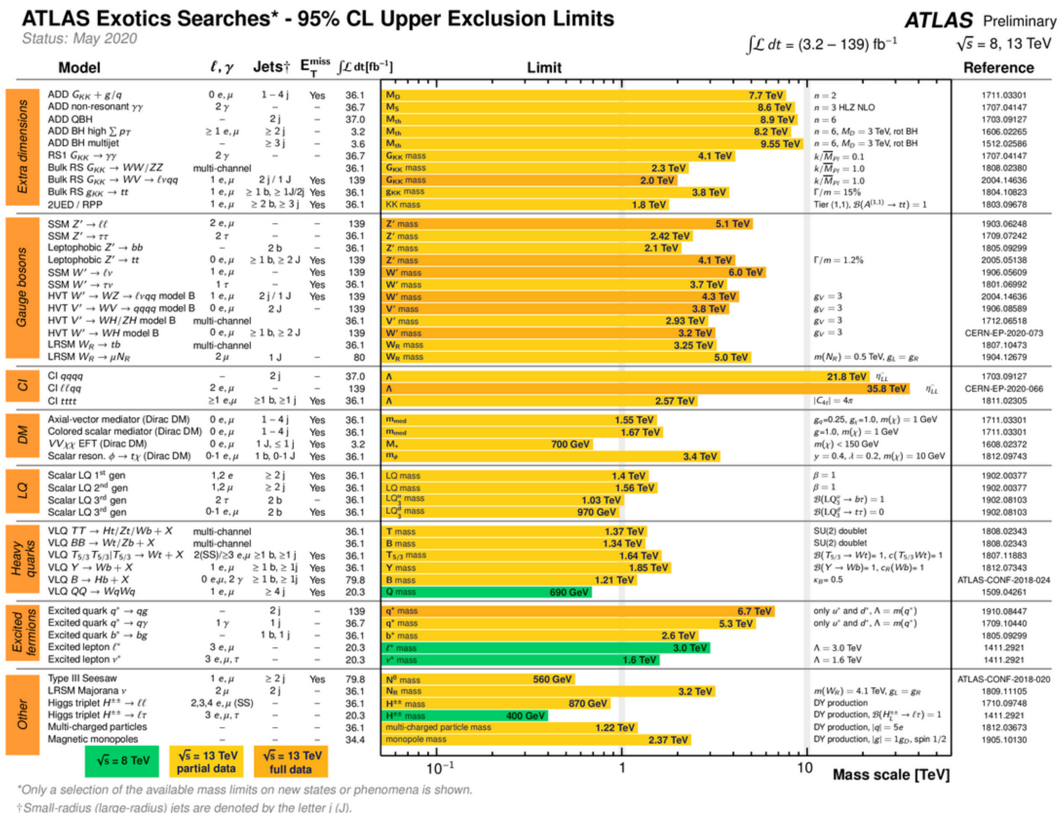
Cheng-Wei Chiang, KY, 2104.00890 [hep-ph] (PRD)

12th October, Nagoya U. (Online)

SM well describes high energy phenomena



SM predictions are good agreement.



New particles have not been observed.

Q. Does the SM enough?

A. Of course, No!

New physics must exist

Established BSM Phenomena

- Neutrino oscillations
- Dark matter, dark energy
- Baryon asymmetry of the Universe
- Cosmic inflation

Theoretical Issues

- Origin of EWSB
- Flavor hierarchies
- Strong QCD
- Unification of the forces
- Quantization of gravity, ⋯

Some of these problems suggest the existence of TeV scale NP, but why are they not found so far??

Where is New Physics?

1. New particles are heavy.

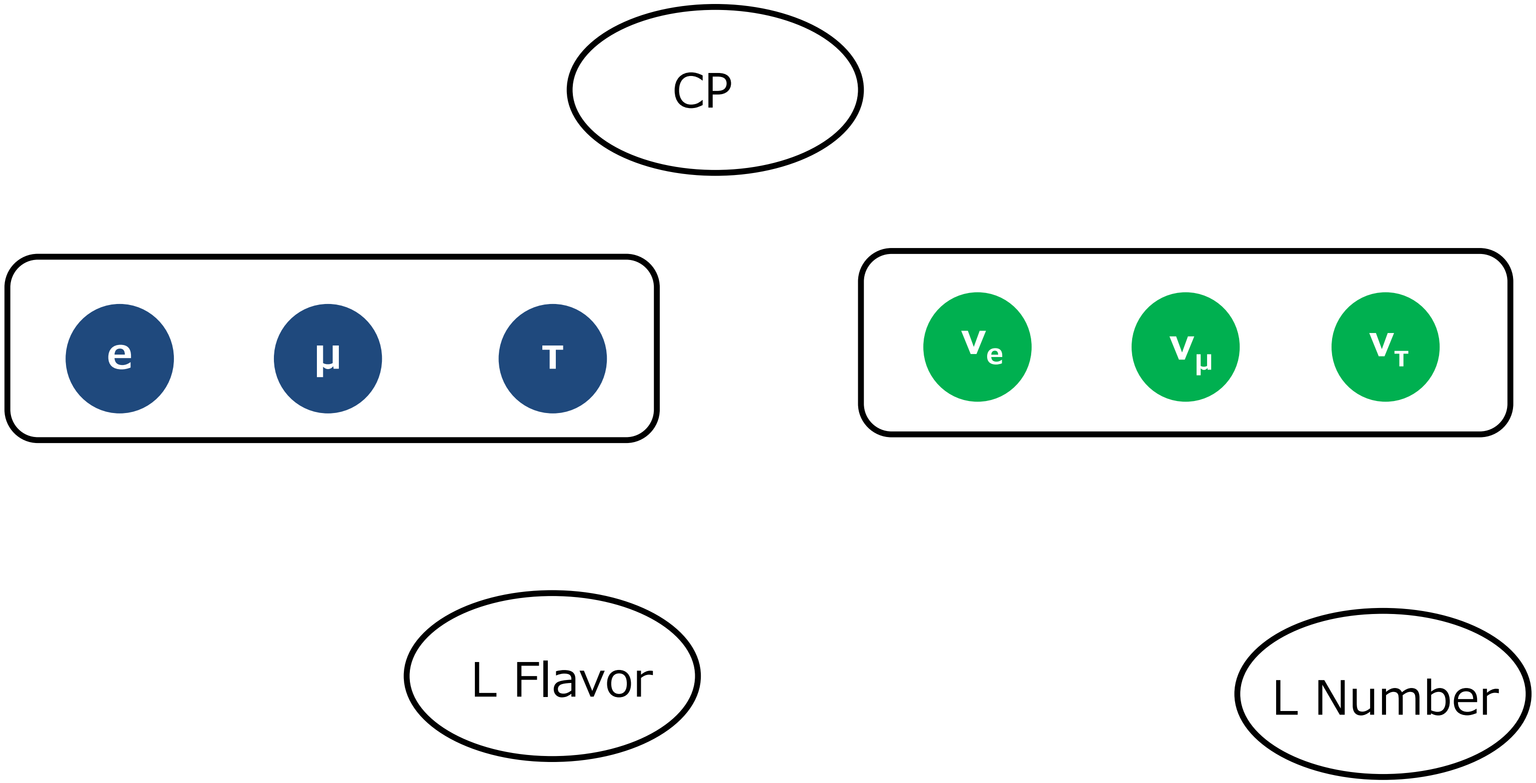
2. New particles are light, but ⋯
   - they feebly couple to SM particles.
   - their decay is hidden by backgrounds.

Q. Are there any “traces” of NP effects in low energy observables?

A. Yes.

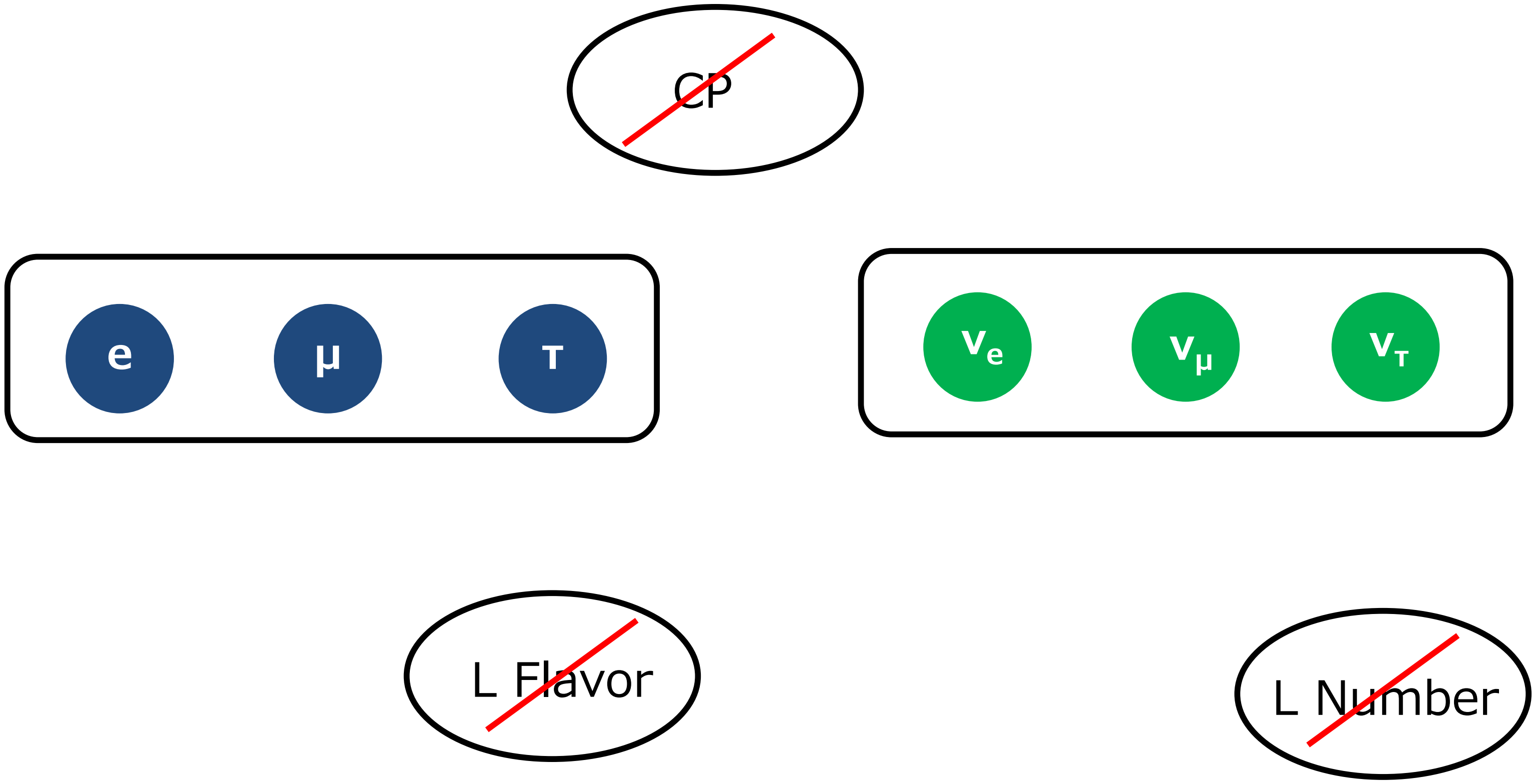
Lepton sector is a good example to provide such observables.

Lepton Sector Physics



Lepton Sector Physics

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c}{\Lambda} L_L L_L H H + \frac{c'}{\Lambda^2} (\bar{L}_L \sigma^{\mu\nu} i \gamma_5 e_R) F_{\mu\nu} H + \cdots$$



Lepton Sector Physics

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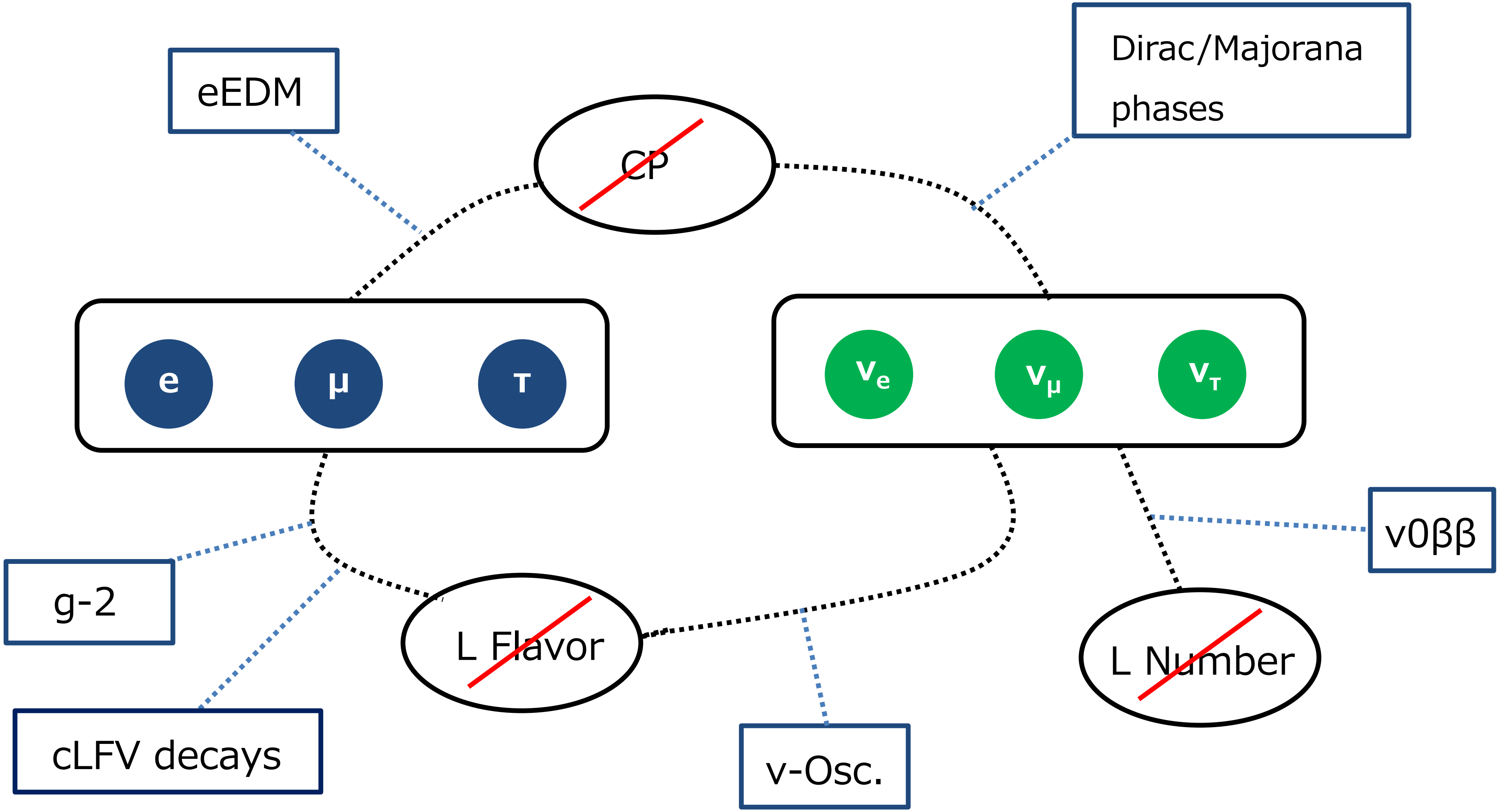
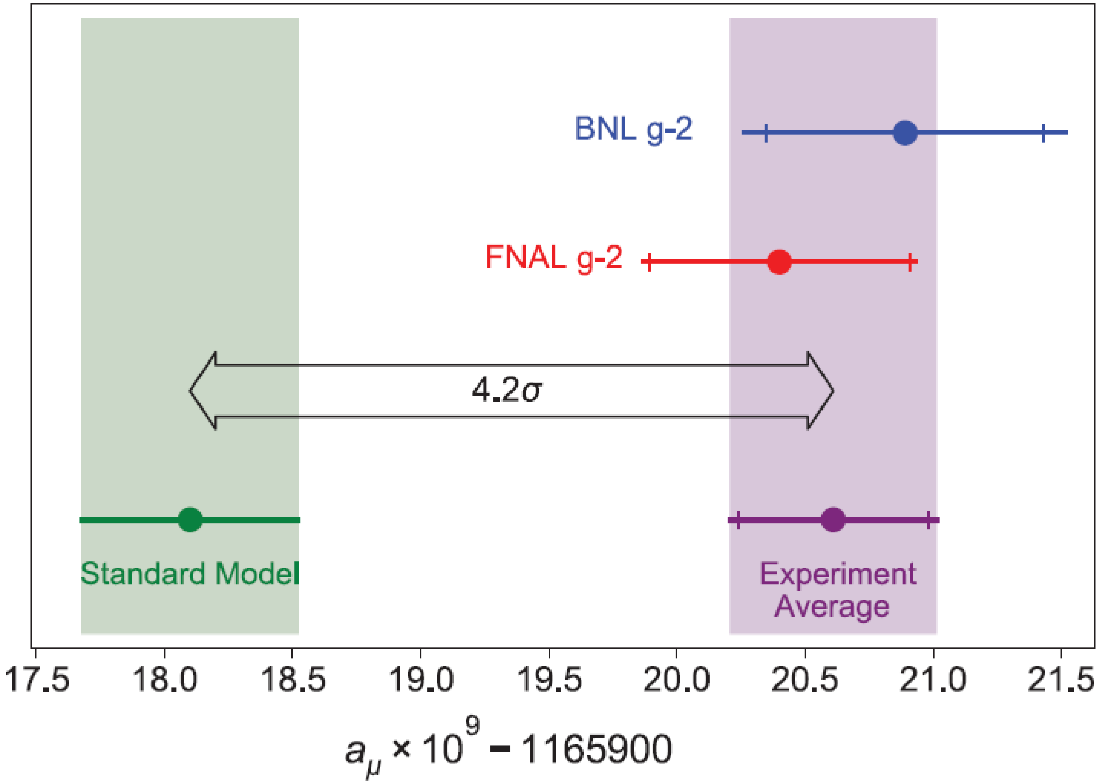


Muon g-2 anomaly

FNAL, 2104.03281 [hep-ex]



$$\Delta a_\mu \equiv a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}}$$

Before: $\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9}$ (3.7σ)

After: $\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$ **(4.2σ!!)**

Festival on arXiv

[16] arXiv:2104.03217 [pdf, other]
Supersymmetric Interpretation of the Muon $g-2$ Anomaly
Motoi Endo, Koichi Hamaguchi, Sho Iwamoto, Teppei Kitahara

[17] arXiv:2104.03223 [pdf, other]
Wino-Higgsino dark matter in the MSSM from the $g-2$ anomaly
Sho Iwamoto, Tsutomu T. Yanagida, Norimi Yokozaki

[18] arXiv:2104.03227 [pdf, other]
Lepton-specific inert two-Higgs-doublet model confronted with the new results for muon and electron g-2 anomaly and multi-lepton searches at the LHC
Xiao-Fang Han, Tianjun Li, Hong-Xin Wang, Lei Wang, Yang Zhang

[19] arXiv:2104.03228 [pdf, other]
Muon $g-2$ and B-anomalies from Dark Matter
Giorgio Arcadi, Lorenzo Calibbi, Marco Fedele, Federico Mescia

[20] arXiv:2104.03231 [pdf, other]
Confronting spin-3/2 and other new fermions with the muon g-2 measurement
Juan C. Criado, Abdelhak Djouadi, Niko Koivunen, Kristjan Müürsepp, Martti Raidal, Hardi Veermäe

[21] arXiv:2104.03238 [pdf, other]
Probing light dark matter with scalar mediator: muon $(g-2)$ deviation, the proton radius puzzle
Bin Zhu, Xuewen Liu

[22] arXiv:2104.03239 [pdf, other]
Heavy Bino and Slepton for Muon g-2 Anomaly
Yuchao Gu, Ning Liu, Liangliang Su, Daohan Wang

[23] arXiv:2104.03242 [pdf, other]
Revisiting the μ-τ-philic Higgs doublet in light of the muon $g-2$ anomaly, τ decays, and multi-lepton searches at the
Hong-Xin Wang, Lei Wang, Yang Zhang

• • •

[46] arXiv:2104.03302 [pdf, other]
The Tiny (g-2) Muon Wobble from Small-μ Supersymmetry
Sebastian Baum, Marcela Carena, Nausheen R. Shah, Carlos E. M. Wagner

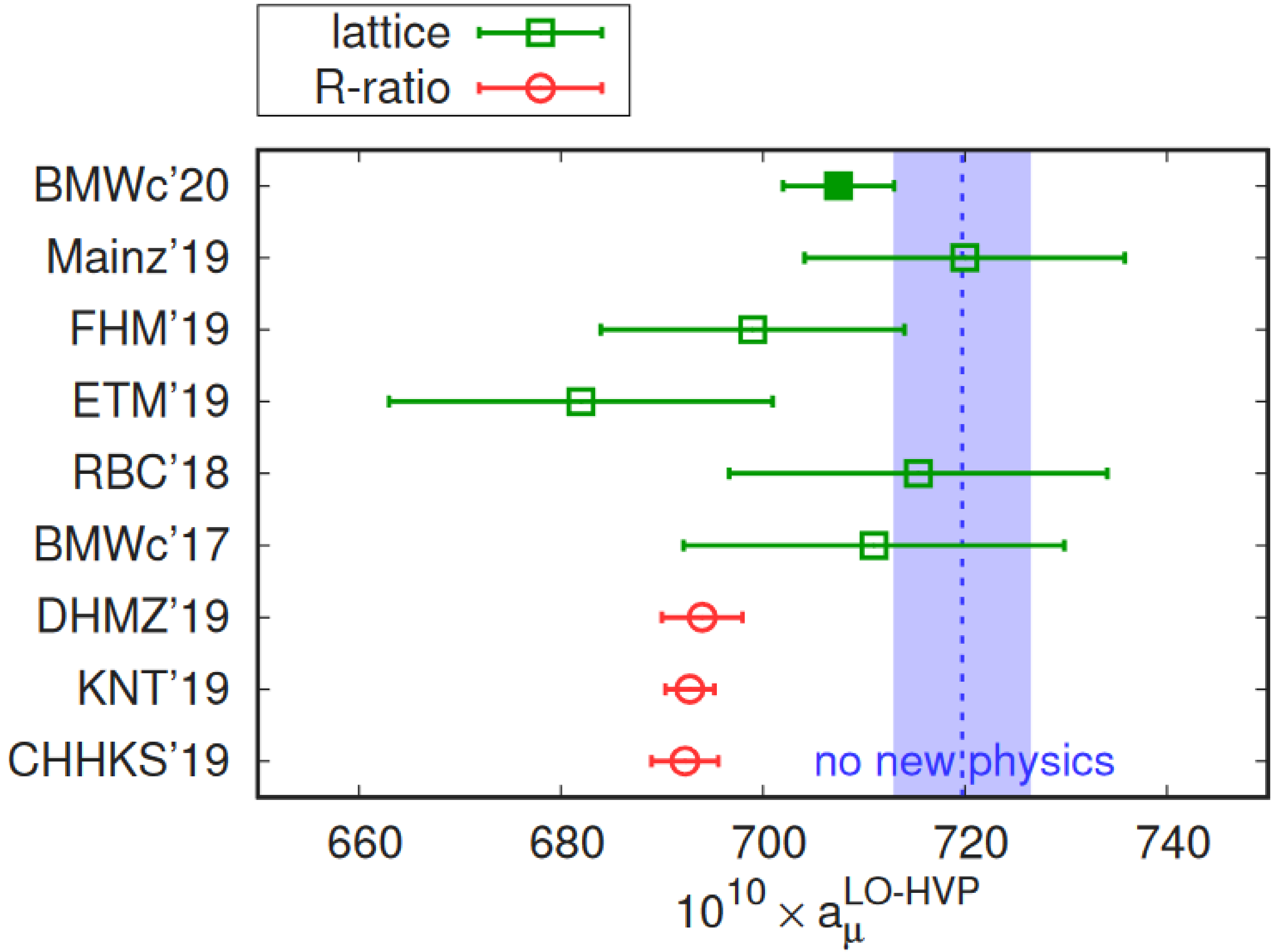
31 papers (8th April)

- SUSY
- Extended Higgs
- WIMP DM
- Axion-like particles
- Extended gauge sym.

…

Muon g-2 anomaly

BMW Collaboration, 2002.12347 [hep-lat]



Electron g-2 anomaly

Measurement of the fine-structure constant as a test of the Standard Model

Richard H. Parker,[1*] Chenghui Yu,[1*] Weicheng Zhong,[1] Brian Estey,[1] Holger Müller[1,2†]

Measurements of the fine-structure constant α require methods from across subfields and are thus powerful tests of the consistency of theory and experiment in physics. Using the recoil frequency of cesium-133 atoms in a matter-wave interferometer, we recorded the most accurate measurement of the fine-structure constant to date: $\alpha = 1/137.035999046(27)$ at 2.0×10^{-10} accuracy. Using multiphoton interactions (Bragg diffraction and Bloch oscillations), we demonstrate the largest phase (12 million radians) of any Ramsey-Bordé interferometer and control systematic effects at a level of 0.12 part per billion. Comparison with Penning trap measurements of the electron gyromagnetic anomaly $g_e - 2$ via the Standard Model of particle physics is now limited by the uncertainty in $g_e - 2$; a 2.5σ tension rejects dark photons as the reason for the unexplained part of the muon's magnetic moment at a 99% confidence level. Implications for dark-sector candidates and electron substructure may be a sign of physics beyond the Standard Model that warrants further investigation.

Science

Science 13 Apr 2018:
Vol. 360, Issue 6385, pp. 191-195
DOI: 10.1126/science.aap7706

$$\frac{c}{\Lambda}\bar{\ell}_L \sigma^{\mu\nu} \ell_R F_{\mu\nu}, \quad c \sim \frac{m_\ell}{v}$$

$$\left|\frac{\Delta a_e}{\Delta a_\mu}\right| \sim \frac{1}{3000} \gg \frac{m_e^2}{m_\mu^2} \left(\sim \frac{1}{40000}\right)$$

$$\Delta a_e \equiv a_e^{\rm exp} - a_e^{\rm SM} = (-8.8 \pm 3.6) \times 10^{-13}$$ (-2.5 σ)

Nature, 588 (2020)

$$\Delta a_e = (4.8 \pm 3.0) \times 10^{-13}$$ (1.6σ)

CPV in neutrino oscillations

2108.08219 [hep-ex]

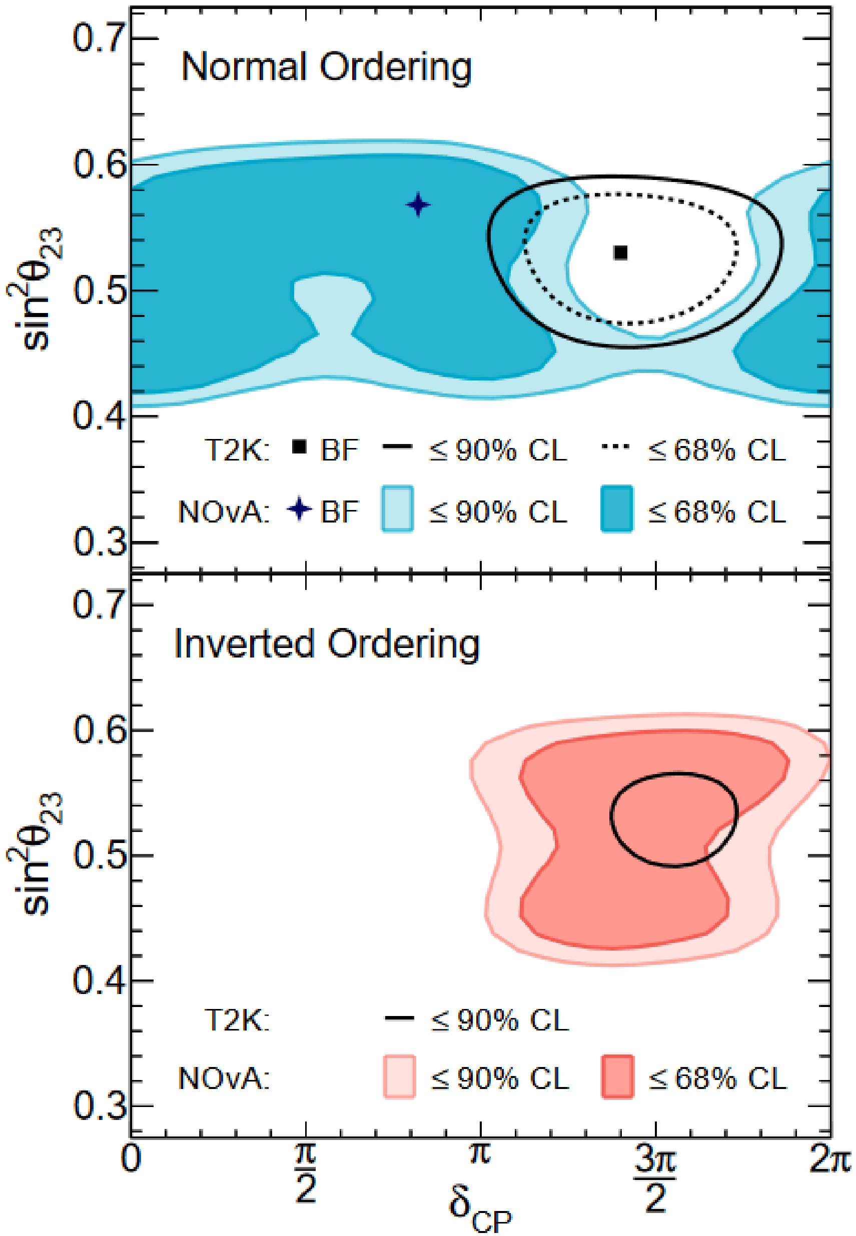
CPV in the neutrino sector can be sizable.

C. Jarlskog (1985)

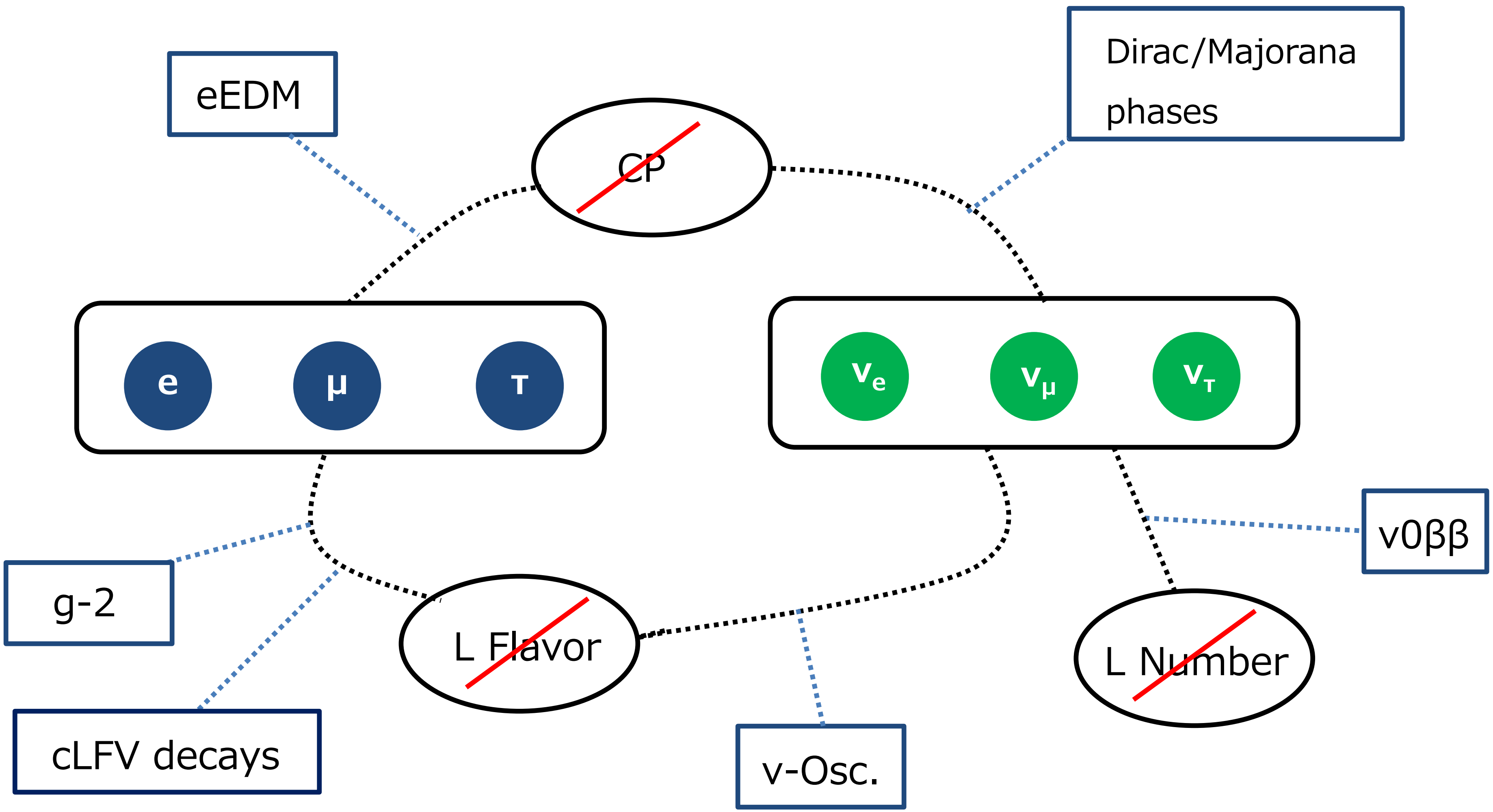
$$J_{\rm CP}^{\rm CKM} \equiv {\rm Im}(V_{us}V_{ub}^{*}V_{cs}^{*}V_{cb}) \sim 3 \times 10^{-5}$$

$$J_{CP}^{\rm PMNS} \equiv {\rm Im}(U_{e2}U_{e3}^{*}U_{\mu 2}^{*}U_{\mu 3}) \sim 3.3 \times 10^{-2} \times \sin\delta_{CP}$$

Such a sizable CPV can be related to the baryon asymmetry of the Universe.



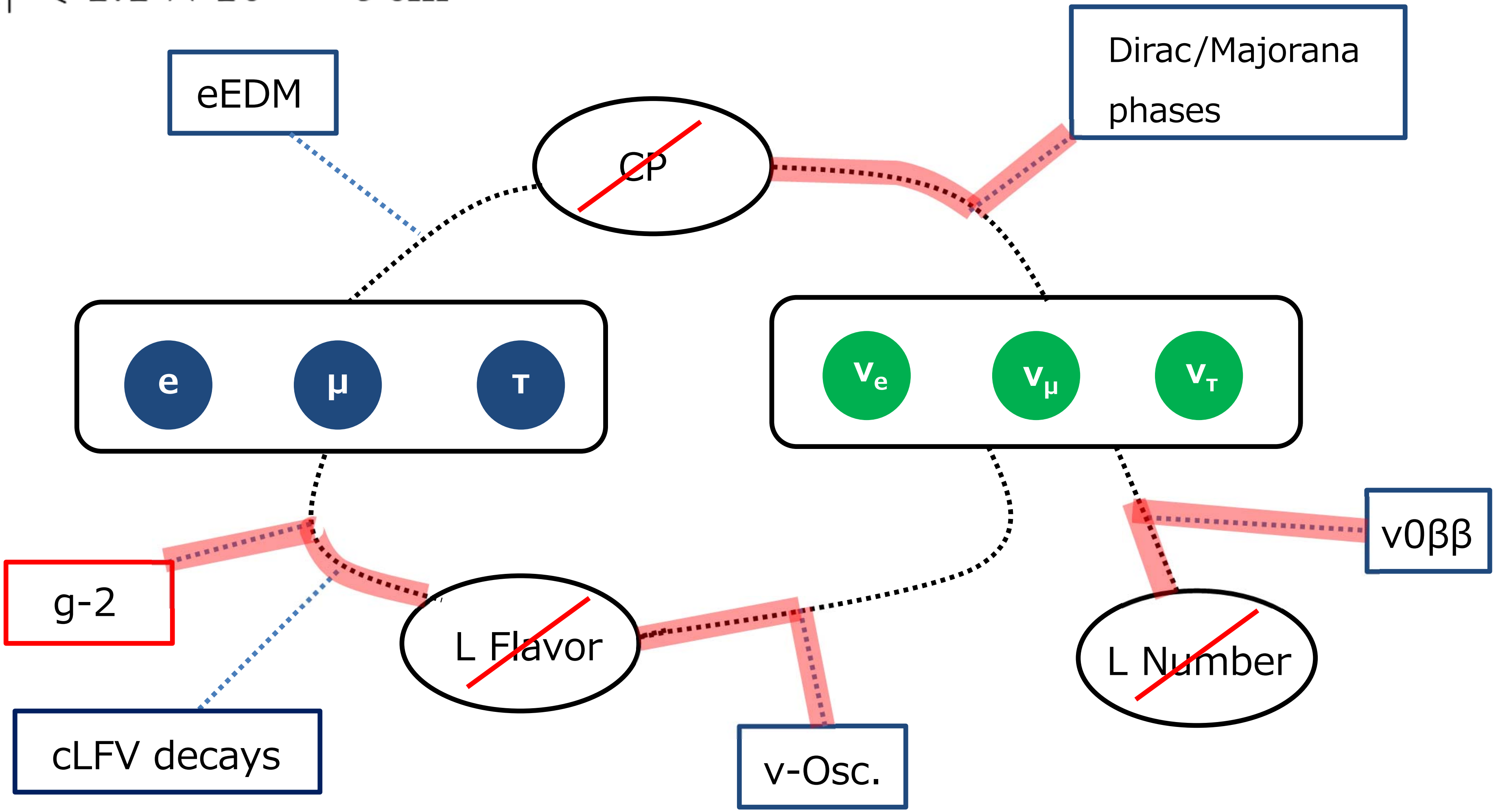
Lepton Sector Physics



Lepton Sector Physics

$|d_e| < 1.1 \times 10^{-29}\ e\,\mathrm{cm}$

ACME Collaboration (2018)



$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

MEG Collaboration (2016)

Contents

New physics contribution at 1-loop

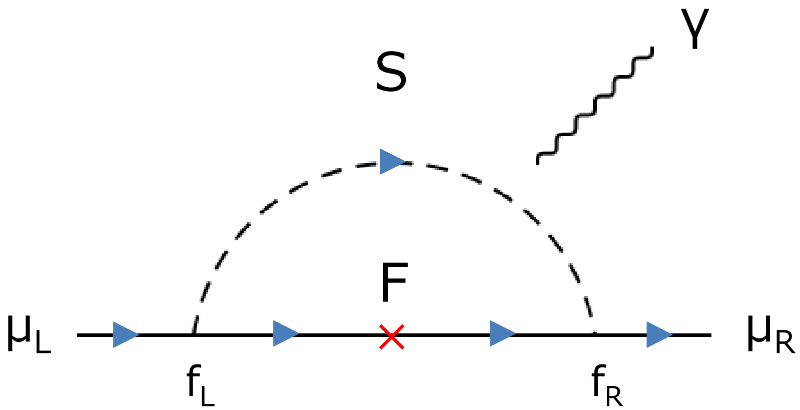
- Effective dim. 5 dipole operator

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\left(\frac{e}{2m}a_f\right)\bar{\mu}_L\sigma^{\mu\nu}\mu_R\,F_{\mu\nu} + \mathrm{h.c.}$$

New physics contribution at 1-loop

- Effective dim. 5 dipole operator

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\left(\frac{e}{2m}a_f\right)\bar{\mu}_L\sigma^{\mu\nu}\mu_R\,F_{\mu\nu} + {\rm h.c.}$$



- New interactions:

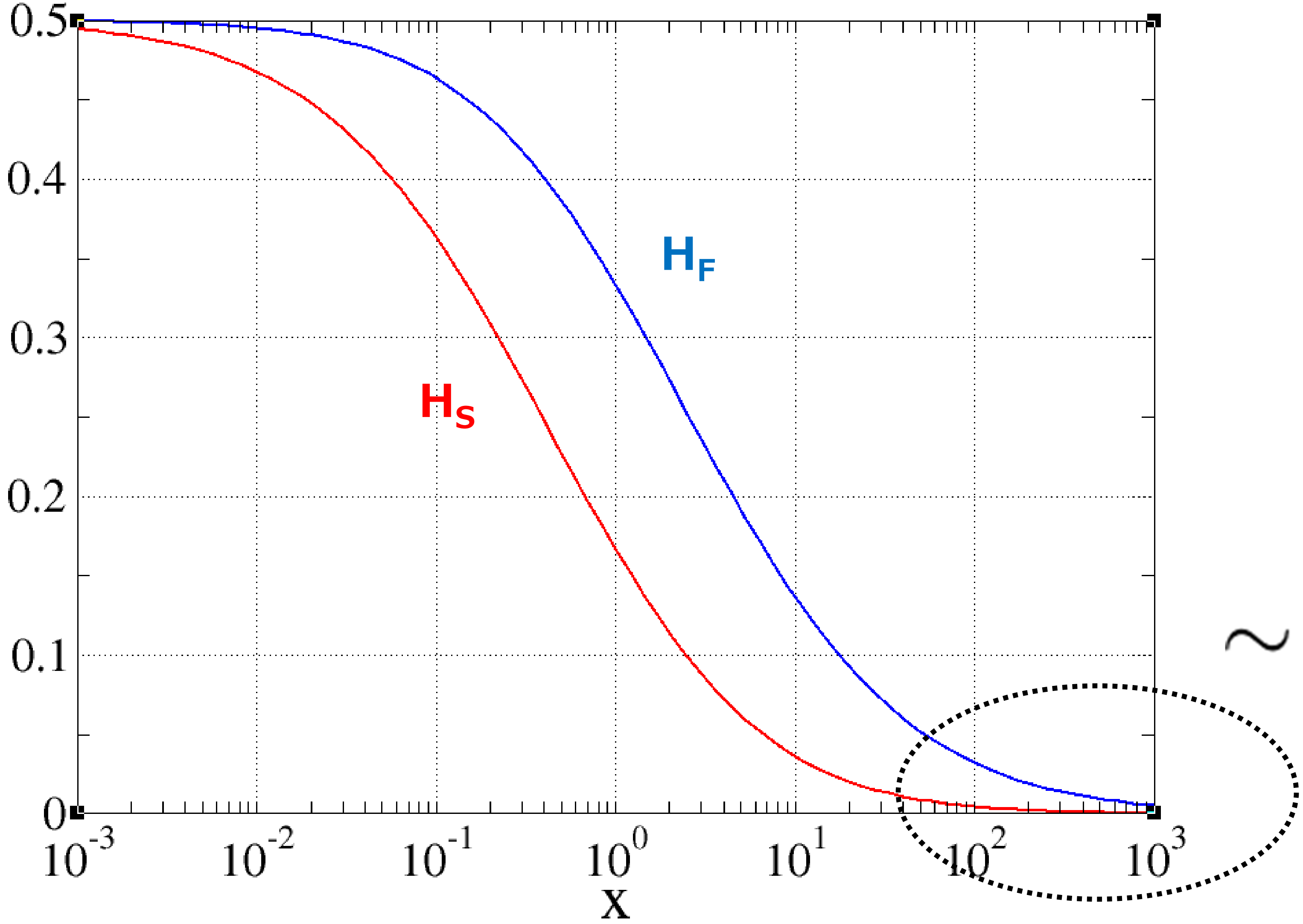
$$\mathcal{L}_{\rm new} = \bar{F}(f_L P_L + f_R P_R)\mu\,S + {\rm h.c.}$$

$$a_\mu \simeq \frac{1}{8\pi^2}\frac{m_\mu}{M_F}f_L f_R\left[-Q_F\,H_F\left(\frac{M_S^2}{M_F^2}\right) + Q_S\,H_S\left(\frac{M_S^2}{M_F^2}\right)\right]$$

$$\sim \frac{f_L f_R}{8\pi^2}\left(\frac{m_\mu}{M_F}\right)\left(\frac{M_F}{M_S}\right)^2$$

for $M_F \ll M_S$

$$H_F(x) = \frac{1 - 4x + 3x^2 - 2x^2 \ln x}{2(1-x)^3} \qquad H_S(x) = \frac{1 - x^2 + 2x \ln x}{2(1-x)^3}$$



$\sim 1/x$

New physics contribution at 1-loop

- Effective dim. 5 dipole operator

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\left(\frac{e}{2m}a_f\right)\bar{\mu}_L\sigma^{\mu\nu}\mu_R F_{\mu\nu} + {\rm h.c.}$$

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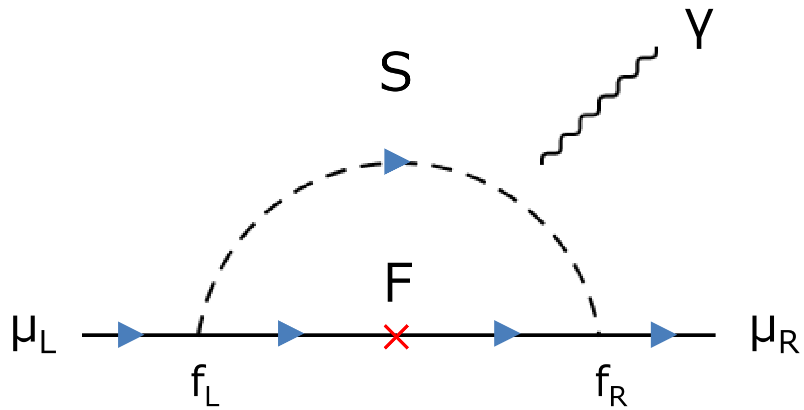


$$\Rightarrow \quad a_\mu \simeq \frac{1}{8\pi^2}\frac{m_\mu}{M_F} f_L f_R\left[-Q_F\, H_F\left(\frac{M_S^2}{M_F^2}\right) + Q_S\, H_S\left(\frac{M_S^2}{M_F^2}\right)\right]$$

$$\sim \frac{f_L f_R}{8\pi^2}\left(\frac{m_\mu}{M_F}\right)\left(\frac{M_F}{M_S}\right)^2 \qquad \text{for } M_F \ll M_S$$

There are 2 enhancement sources, i.e., 1) coupling enhancement, 2) chiral enhancement.

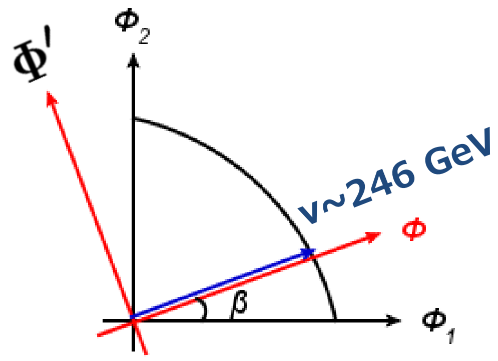
Ex. in the charged radiative seesaw model (Sec. 3)

$$a_\mu^{\rm NP} \sim 3\times 10^{-9} \times \frac{3\,{\rm TeV}}{M} \times \frac{f_L}{0.1} \times \frac{f_R}{0.1}$$

Quick review of 2 Higgs doublet models

- **Higgs basis** *Davidson, Haber (2005)*

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix} \qquad \tan\beta = v_2/v_1$$



NG boson

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix} \qquad \Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

CP-even Higgs

CP-odd Higgs

125 GeV Higgs

- **Higgs boson masses**

$$m_h^2 \sim \lambda v^2, \quad m_\Phi^2 \sim M^2 + \lambda' v^2 \qquad (\Phi = H^\pm, A, H)$$

- **Decoupling limit:** $M^2 \to \infty$

- **Alignment limit:** $\sin(\beta - \alpha) \to 1$

2HDM with NFC

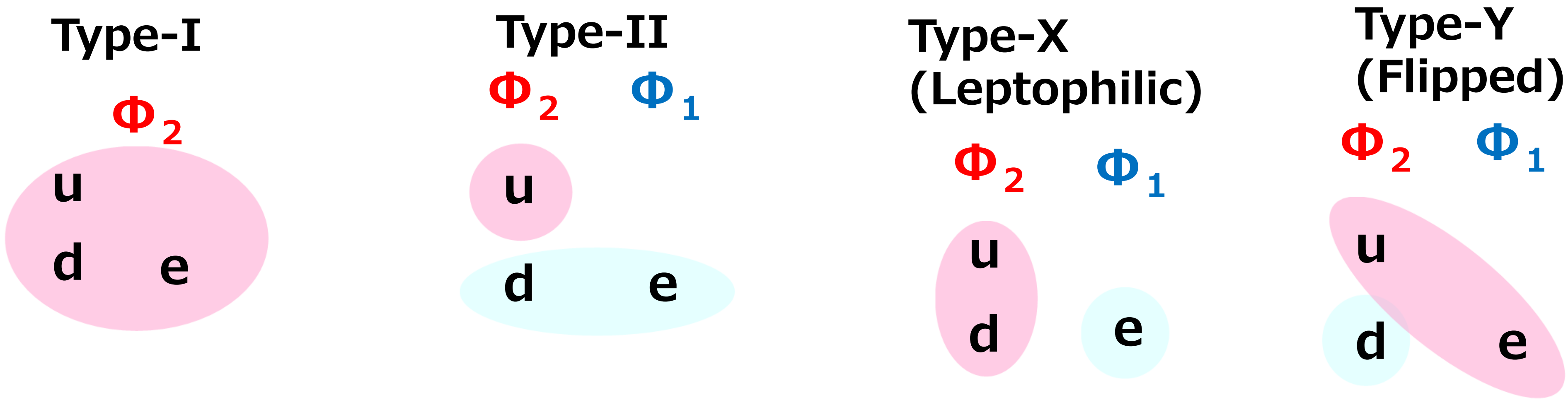
- Natural Flavor Conservation (NFC) Scenario

$\Phi_{u,d,e}$: Either Φ_1 or Φ_2

$$\boxed{-\mathcal{L}_Y = Y_u \bar{Q}_L (i\sigma_2)\Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \mathrm{h.c.}}$$

- This can be realized by imposing a (softly-broken) Z_2 symmetry.

Barger, Hewett, Phillips, PRD41 (1990);Grossman, NPB426 (1994)



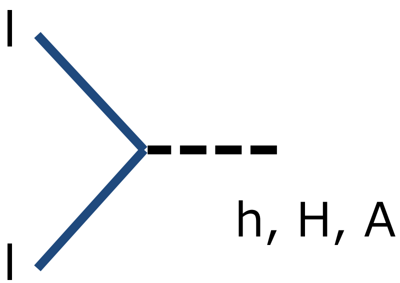
Yukawa couplings

- Lepton Yukawa interactions

$$\mathcal{L}_{\text{lep}} = -Y_\ell \bar{L}_L \Phi_\ell \ell_R = -Y_\ell \bar{L}_L (\Phi + \xi_\ell \Phi') \ell_R$$

$$\frac{\sqrt{2}}{v}\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

cotβ (Type-I, Y) -tanβ (Type-II, X)



$$\frac{m_\ell}{v}(s_{\beta-\alpha} + c_{\beta-\alpha}\xi_\ell)$$ (for h)

$$\frac{m_\ell}{v}(c_{\beta-\alpha} - s_{\beta-\alpha}\xi_\ell)$$ (for H)

$$i\frac{m_\ell}{v}\xi_\ell$$ (for A)

2HDMs with Z_2

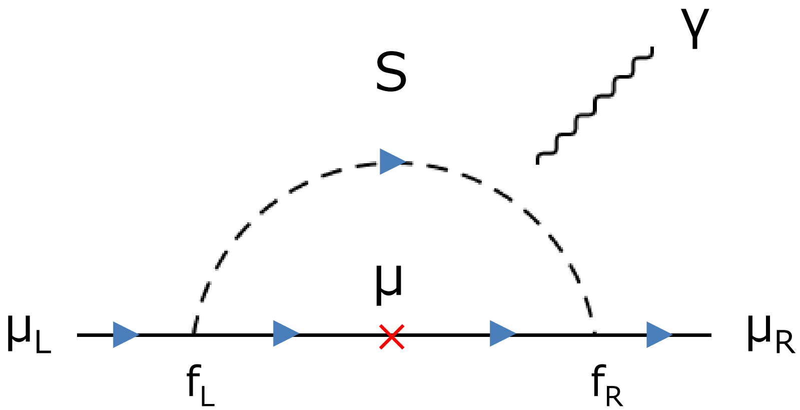
- New interactions:

$$\frac{m_\mu}{v}\xi_\ell$$

$$\mathcal{L}_{\rm new} = \bar{F}(f_L P_L + f_R P_R)\mu\, S + \text{h.c.}$$

Muon

h, H, A and $H^\pm$



This corresponds to the chirality suppressed case:

$$\sim \frac{1}{8\pi^2}\left(\frac{m_\mu}{v}\xi_\ell\right)^2 \times \left(\frac{m_\mu}{m_H}\right)^2 \sim 2\times 10^{-9} \times \left(\frac{100\ \text{GeV}}{m_H}\right) \times \left(\frac{\xi_\ell}{1000}\right)^2$$

Type-II and Type-X 2HDMs: $\xi_\ell \to \tan\beta$

However, such a super large tanβ is not allowed in these 2HDMs (e.g., LHC, Flavor exp.).

2HDMs with Z_2

- New interactions:

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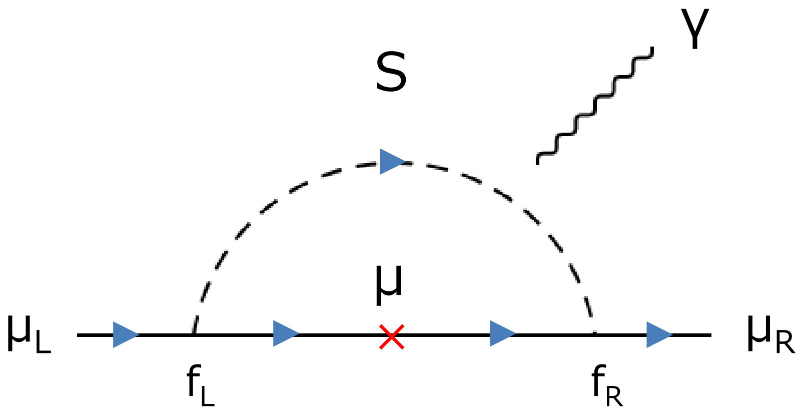

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Type-II and Type-X 2HDMs: $\xi_\ell \to \tan\beta$

However, such a super large tanβ is not allowed in these 2HDMs (e.g., LHC, Flavor exp.).

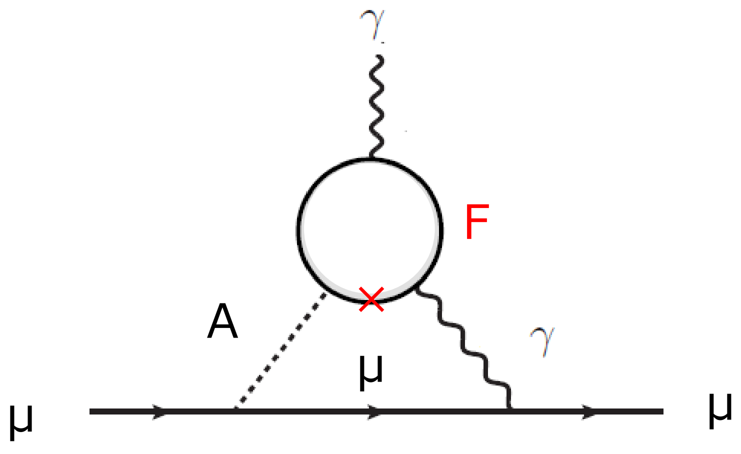
"Muon Specific 2HDM" Abe, Sato, KY, 1705.01469 (JHEP)

- Way out 1: Extending Z_2 and having tanβ enhancement only in the muon Yukawa coupling.
- Way out 2: 2-loop Barr-Zee contribution in the Type-X 2HDM.
- Way out 3: Forget about the Z_2 symmetry.

2HDMs with Z_2

- 2-loop Barr-Zee contribution

$$a_\mu \sim \left(\frac{1}{16\pi^2}\right)^2 16e^2 \frac{m_\mu^2}{v^2}\frac{m_F^2}{m_A^2}\xi_\ell \xi_F$$



- In the Type-X case, tau-loop (F = τ) can be important.

Chun et.al., 1409.3199

Abe, Sato, KY, 1504.07059

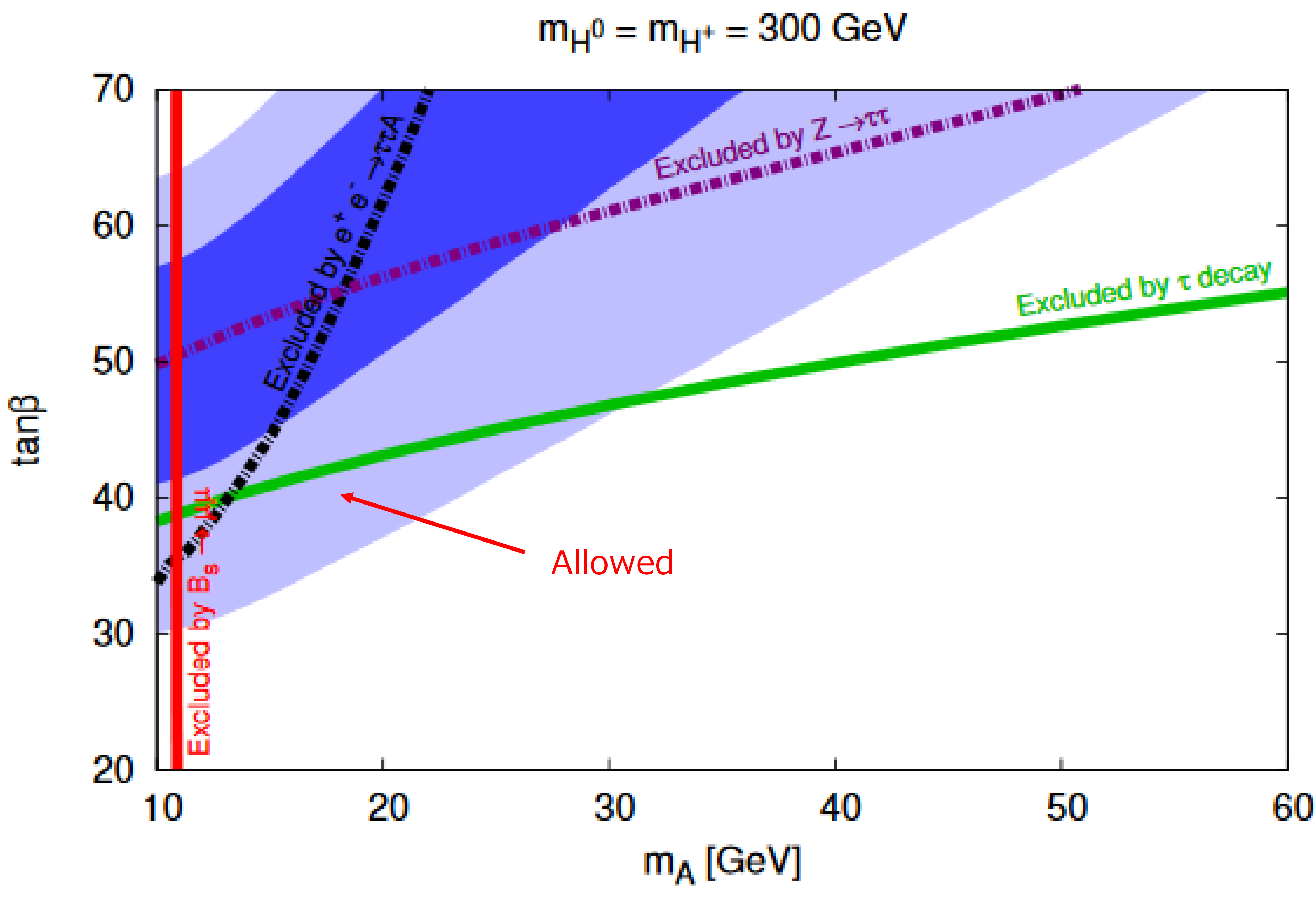
c.f. 1-loop contribution $\sim \frac{1}{16\pi^2}\times\frac{m_\mu^2}{v^2}\times\frac{m_\mu^2}{m_H^2}\times(\tan\beta)^2$

$$a_\mu \sim \left(\frac{1}{16\pi^2}\right)^2 16e^2 \frac{m_\mu^2}{v^2}\frac{m_\tau^2}{m_A^2}(\tan\beta)^2 \sim 10^{-9}\times\left(\frac{\tan\beta}{50}\right)^2\times\left(\frac{20\text{ GeV}}{m_A}\right)^2$$

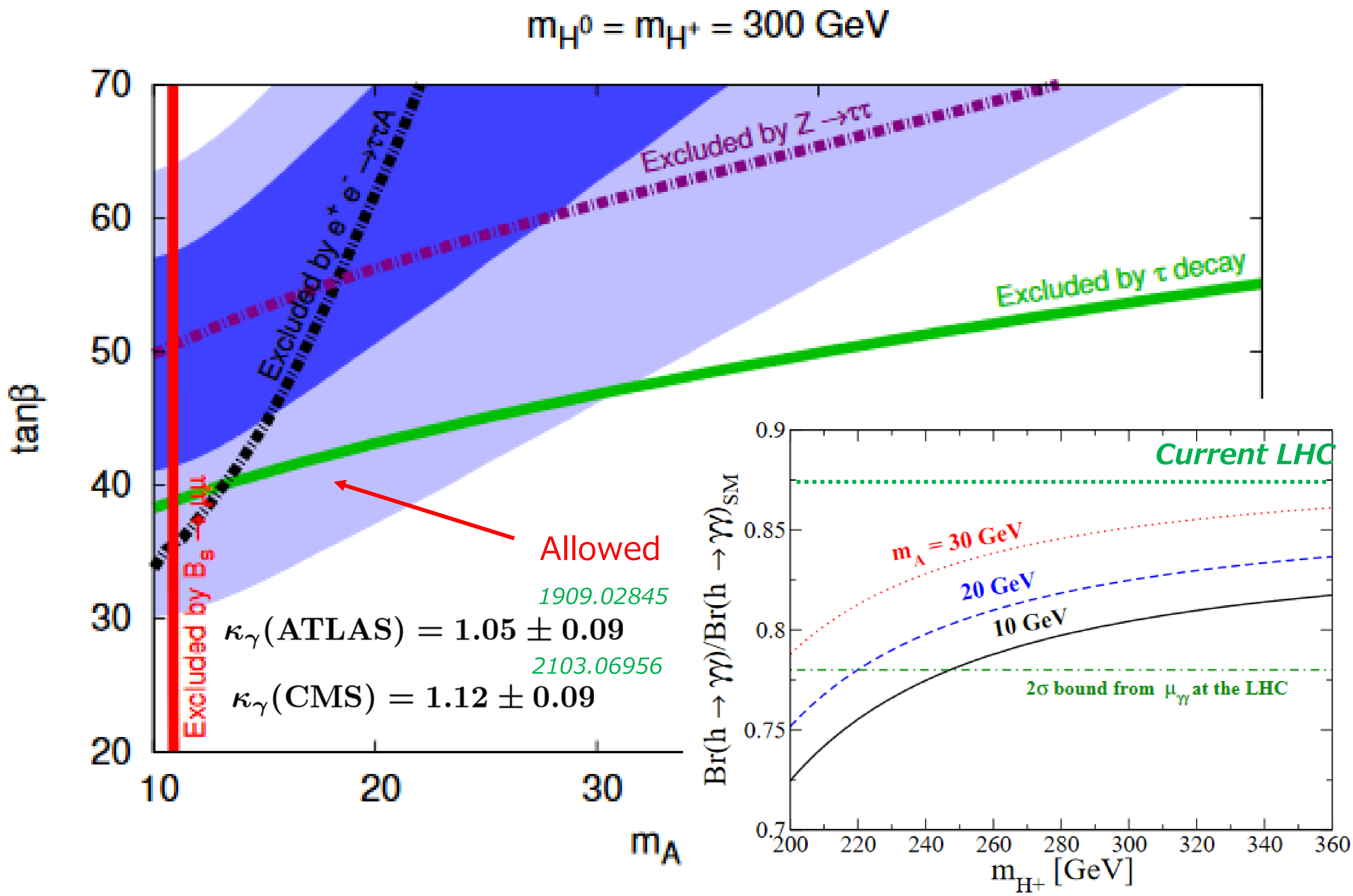
Chun, Kang, Takeuchi, Tsai, 1507.08067

Light CP-odd Higgs boson is required, which mainly decays into a tau pair.

Abe, Sato, KY, 1504.07059



Abe, Sato, KY, 1504.07059



2HDMs without Z_2

Omura, Senaha, Tobe, 1502.07824

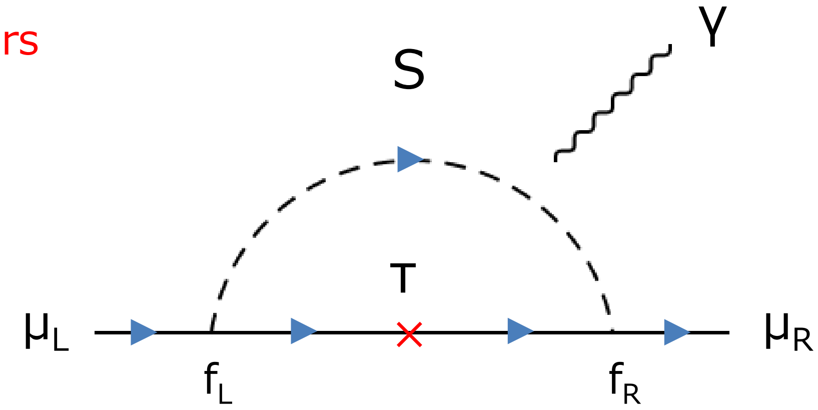
- New interactions:

Free parameters

$$\mathcal{L}_{\rm new} = \bar{F}(f_L P_L + f_R P_R)\mu\, S + \text{h.c.}$$

τ

h, H, A and $H^{\pm}$



$$a_\mu^{\rm NP} \sim \frac{f_L f_R}{8\pi^2}\left(\frac{m_\mu}{M_F}\right)\left(\frac{M_F}{M_S}\right)^2$$

$$\sim \frac{1}{16\pi^2}\times\frac{m_\mu}{m_\tau}\times\frac{m_\tau^2}{m_H^2}\times(f_L f_R) \sim 10^{-9}\times\left(\frac{v}{m_H}\right)\times\left(\frac{f_L f_R}{0.3^2}\right)$$

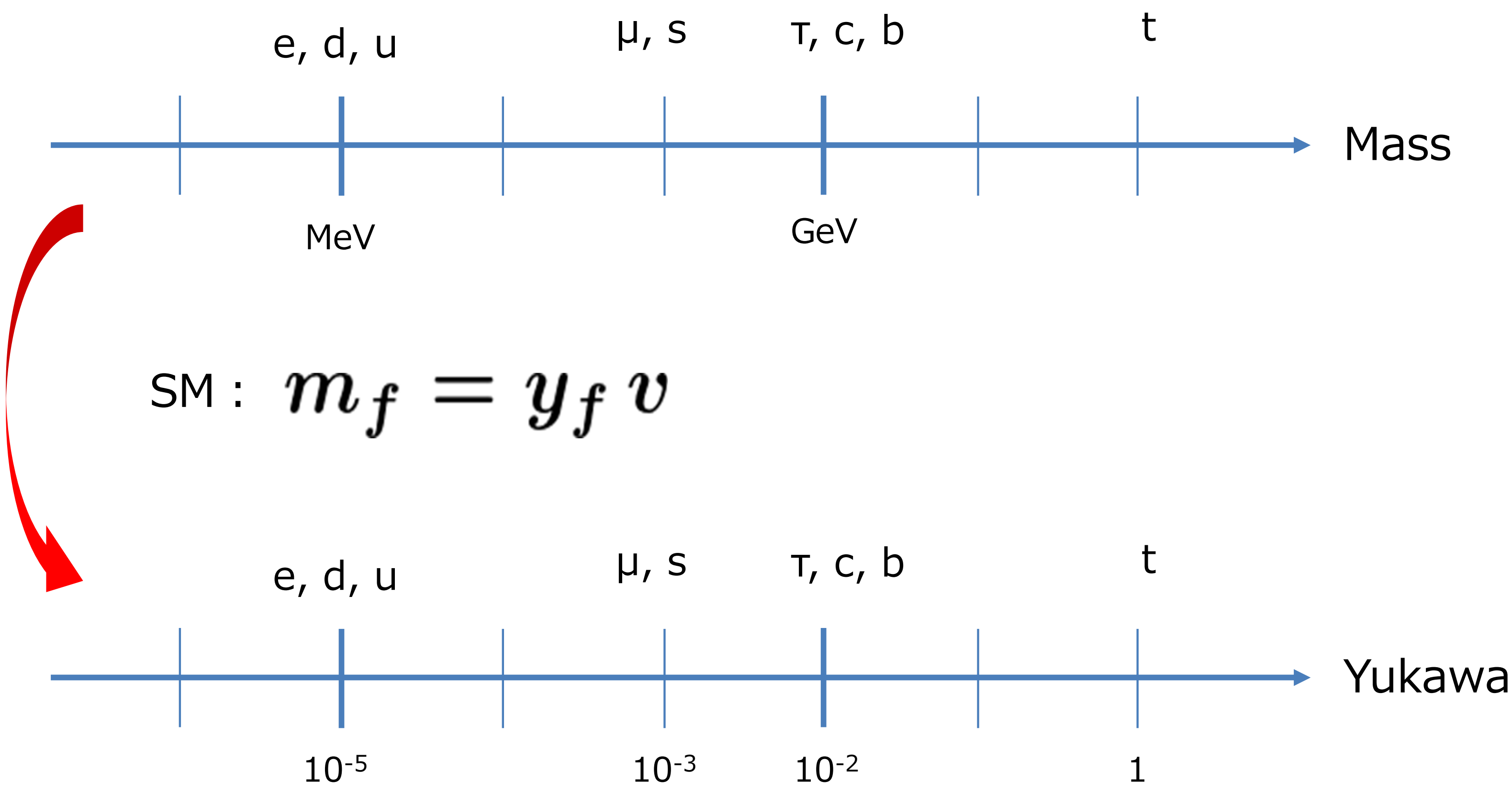
- We can explain $(g\text{-}2)_\mu$, but the flavor problem may happen ⋯.

- Can we explain $(g\text{-}2)_\mu$ and DM at the same time?

  Yes!

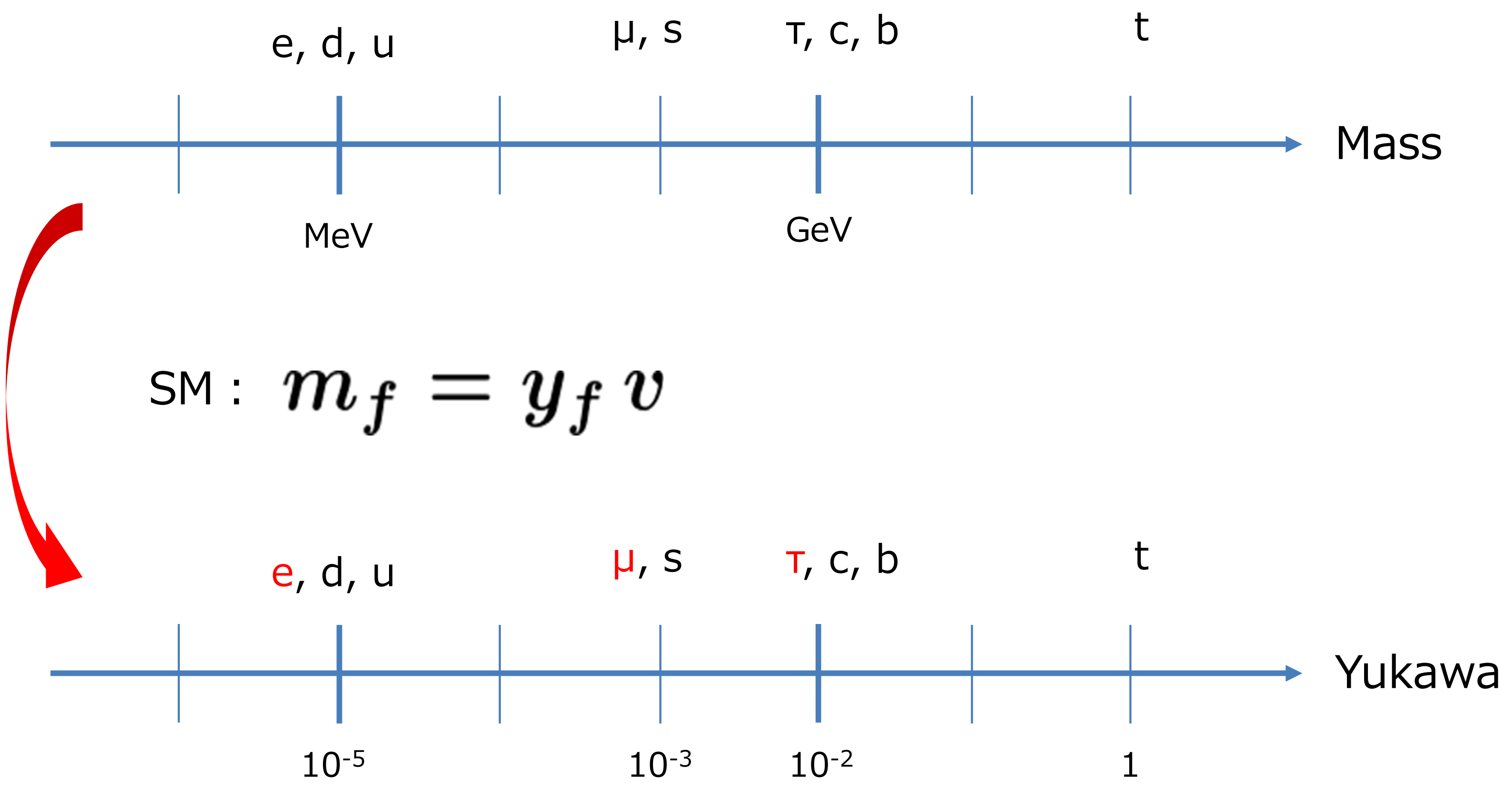
Contents

Fermion Mass Hierarchy



Can we explain the mass hierarchy with O(1) couplings?

Fermion Mass Hierarchy

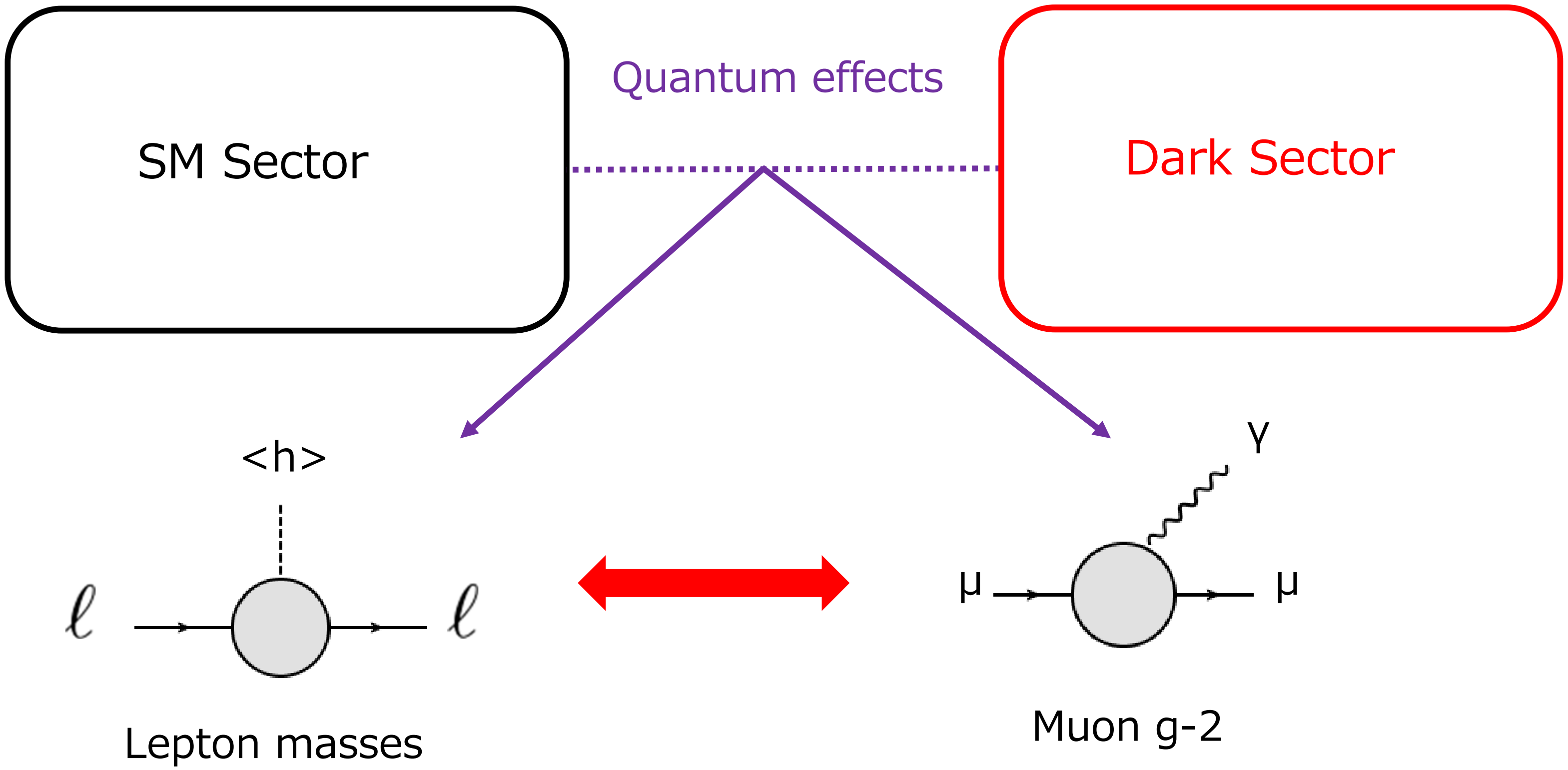


Can we explain the mass hierarchy with O(1) couplings?

In particular, we focus on the charged lepton mass hierarchy.

Dark sector as origin of lepton masses

- Introduction of "dark sector" to the SM



$$\sim \left(\frac{1}{16\pi^2}\right)^N \times \left(\frac{v}{M}\right) \times Y_{\mathrm{New}}$$

"Radiative Charged Seesaw"

Dark sector simultaneously explains tiny lepton masses and $(g\text{-}2)_\mu$ anomaly.

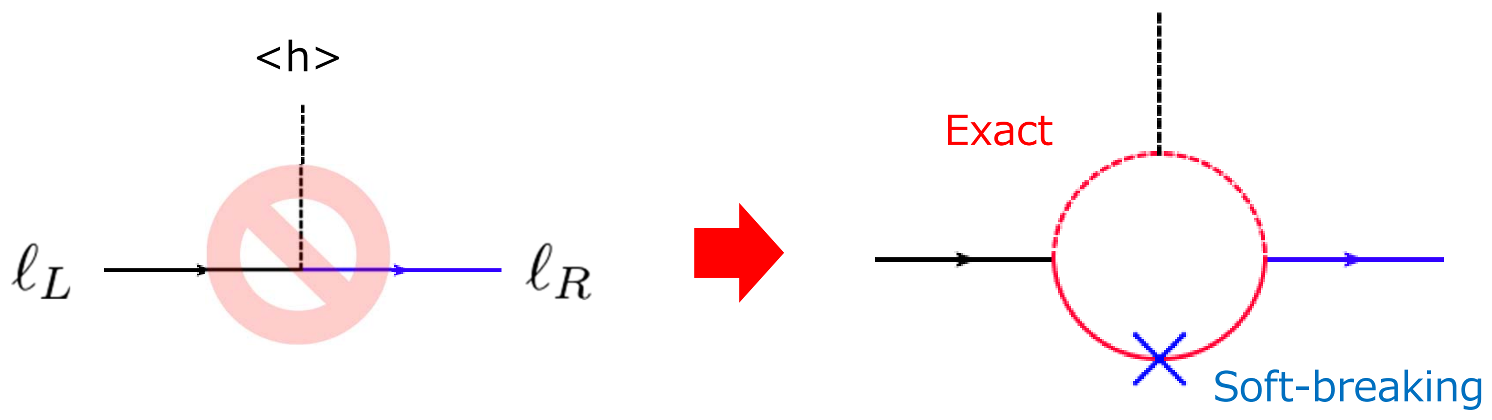
How to realize the mechanism?

1. Dark sector can be defined by introducing a Z_2 symmetry.

$$\Psi_{\rm SM} \to +\Psi_{\rm SM}, \quad \Psi_{\rm Dark} \to -\Psi_{\rm Dark}$$

2. Tree level Yukawa should be forbidden by another Z_2' symmetry which has to be softly-broken to generate a finite mass.

3. Chirality flip should be introduced in the loop.
   - Vector-like mass
   - Higgs mechanism



Model

- We consider the case with the tree level tau mass and 1-loop induced μ/e masses.

	Fermions				Scalars		
Fields	$(L_L^e, L_L^\mu, L_L^\tau)$	(e_R, μ_R, τ_R)	(F_L^e, F_L^μ)	(F_R^e, F_R^μ)	H	Φ_L	Φ_R
$U(1)_\ell$ (exact)	$(q_e, q_\mu, 0)$	$(q_e, q_\mu, 0)$	(q_e, q_μ)	(q_e, q_μ)	0	0	0
Z_2 (exact)	$(+,+,+)$	$(+,+,+)$	$(-,-)$	$(-,-)$	$+$	$-$	$-$
Z_2' (soft-breaking)	$(+,+,+)$	$(-,-,+)$	$(+,+)$	$(-,-)$	$+$	$-$	$-$

New particles (Dark sector)

Forbid LFVs

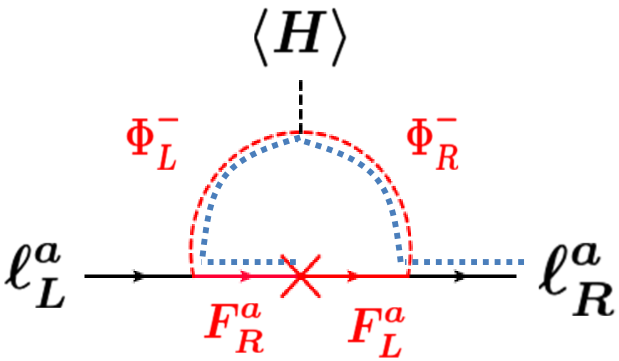
Forbid tree level mixing

Forbid tree level Yukawa

Stabilize the DM candidate

- Lagrangian for the lepton sector

$$\mathcal{L} = -y_\tau \bar{L}_L^\tau H \tau_R - \sum_{a=e,\mu} \left(M^a \overline{F_L^a} F_R^a + f_L^a \overline{L_L^a} \Phi_L F_R^a + f_R^a \overline{\ell_R^a} \Phi_R F_L^a \right)$$
$$- \mu H \Phi_L \Phi_R$$



Charge assignment under SU(2)$_I$×U(1)$_Y$

- We list the possible sets of the SU(2)$_I$ × U(1)$_Y$ charge.

$$F \sim (I_F, Y_F) \qquad \Phi_{L,R} \sim (I_{L,R}, Y_{L,R}) \qquad \bar{L}_L \Phi_L F_R$$

with $Y_L = -1/2 - Y_F, \quad Y_R = -1 - Y_F$ $\qquad \bar{\ell}_R \Phi_R F_L$

(I_F, Y_F)	(I_L, Y_L)	(I_R, Y_R)	Sign of Δa_ℓ
$(\mathbf{1}, 0)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, -1)$	$+$
$(\mathbf{1}, -1)$	$(\mathbf{2}, 1/2)$	$(\mathbf{1}, 0)$	$-$
$(\mathbf{2}, 1/2)$	$(\mathbf{1}\ \text{or}\ \mathbf{3}, -1)$	$(\mathbf{2}, -3/2)$	$+$
$(\mathbf{2}, -1/2)$	$(\mathbf{1}\ \text{or}\ \mathbf{3}, 0)$	$(\mathbf{2}, -1/2)$	$-$ or $\pm$
$(\mathbf{2}, -3/2)$	$(\mathbf{1}\ \text{or}\ \mathbf{3}, 1)$	$(\mathbf{2}, 1/2)$	$-$
$(\mathbf{3}, 1)$	$(\mathbf{2}, -3/2)$	$(\mathbf{3}, -2)$	$+$
$(\mathbf{3}, 0)$	$(\mathbf{2}, -1/2)$	$(\mathbf{3}, -1)$	$\pm$
$(\mathbf{3}, -1)$	$(\mathbf{2}, 1/2)$	$(\mathbf{3}, 0)$	$-$
$(\mathbf{3}, -2)$	$(\mathbf{2}, 3/2)$	$(\mathbf{3}, 1)$	$-$

E. Ma, 1311.3213

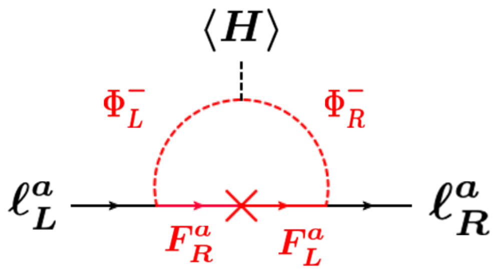
Common dark sector contributes to mass and (g-2)$_\mu$ → Sign of (g-2)$_\mu$ is fixed.

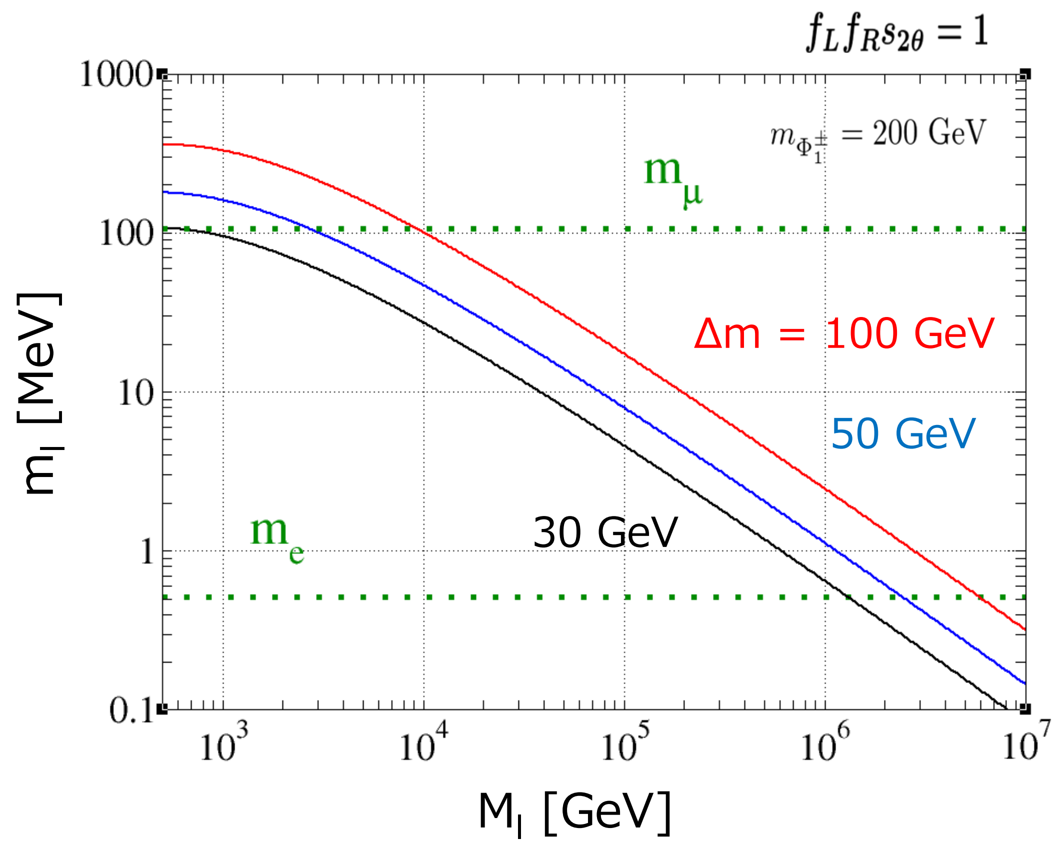
Let us focus on the simplest case with F ~ (**1**, 0).

Charged lepton masses

- Mass eigenstates of the charged scalars $\begin{pmatrix}\Phi_L^\pm\\ \Phi_R^\pm\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\Phi_1^\pm\\ \Phi_2^\pm\end{pmatrix}$

$$m_\ell \simeq -\frac{f_L^\ell f_R^\ell s_{2\theta}}{16\pi^2} M_\ell \left[\left(\frac{m_{\Phi_1^\pm}}{M_\ell}\right)^2 \ln\left(\frac{m_{\Phi_1^\pm}}{M_\ell}\right)^2 - \left(\frac{m_{\Phi_2^\pm}}{M_\ell}\right)^2 \ln\left(\frac{m_{\Phi_2^\pm}}{M_\ell}\right)^2\right]$$ for $M_l \gg m_\Phi{}^\pm$





- Case with an O(1) coupling :

Muon mass → M ~ O(1) TeV

Electron mass → M ~ O(1) PeV

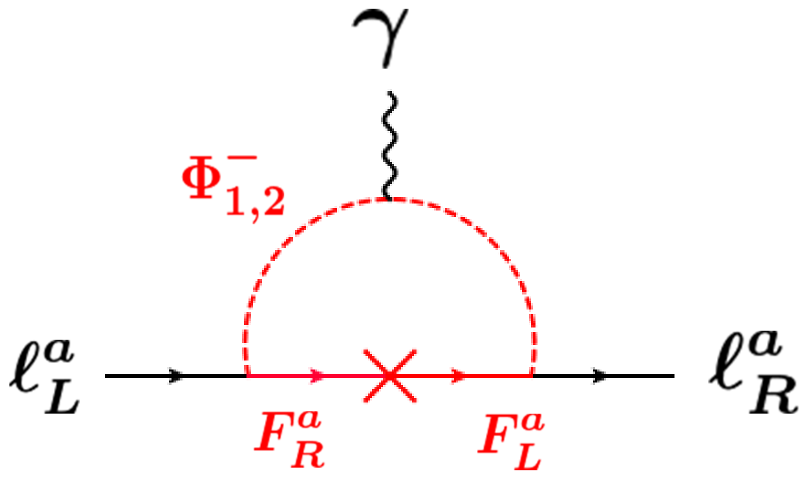
Anomalous magnetic moments

$$\Delta a_\ell \equiv a_\ell^{\rm exp} - a_\ell^{\rm SM}$$

$$\Delta a_\mu = -\frac{f_L f_R s_{2\theta}}{16\pi^2}\frac{m_\ell}{M_\ell}\left[H_S\left(\frac{m^2_{\Phi_1^\pm}}{M_\ell^2}\right) - H_S\left(\frac{m^2_{\Phi_2^\pm}}{M_\ell^2}\right)\right]$$

$$\simeq \boxed{\left(\frac{m_\ell}{M_\ell}\right)^2\left[1+\frac{3}{2}\frac{1}{1+\ln(m_\Phi^2/M_\ell^2)}\right]}$$

for $M_l \gg m_{\Phi 1} = m_{\Phi 2}\,(=m_\Phi)$



・It gives a positive contribution to $(g\text{-}2)_l$.

・The dependence of the new Yukawa couplings does not explicitly appear.

Anomalous magnetic moments

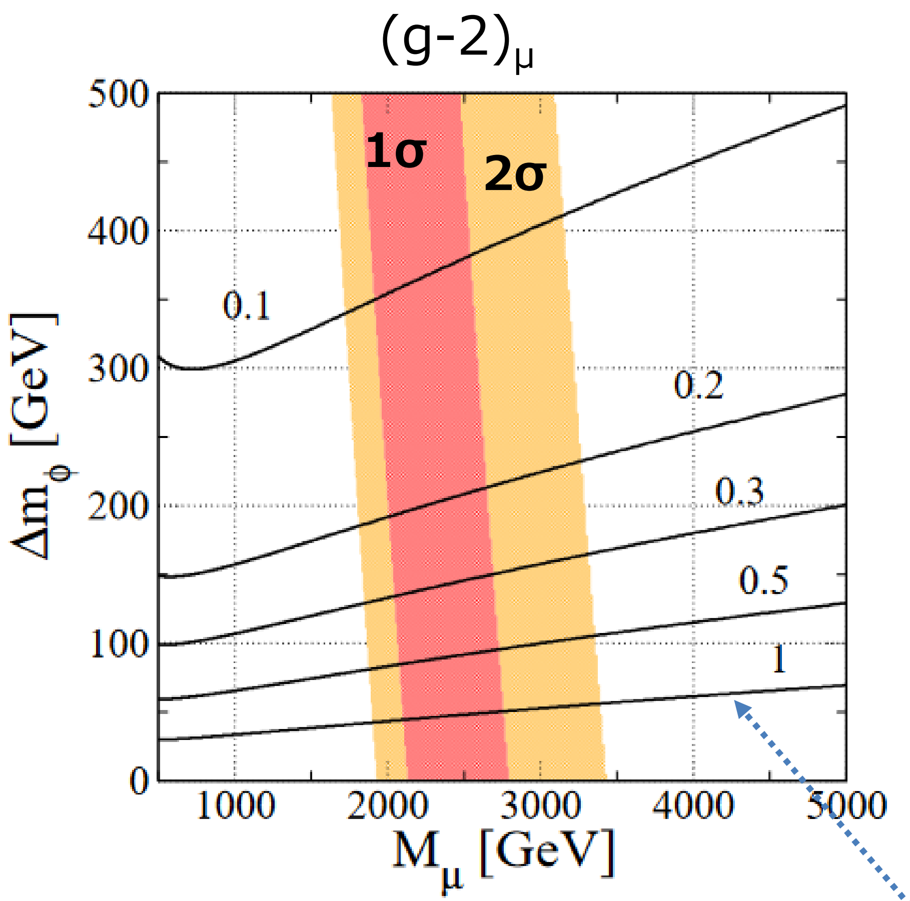
Cheng-Wei Chiang, KY, 2104.00890 [hep-ph]

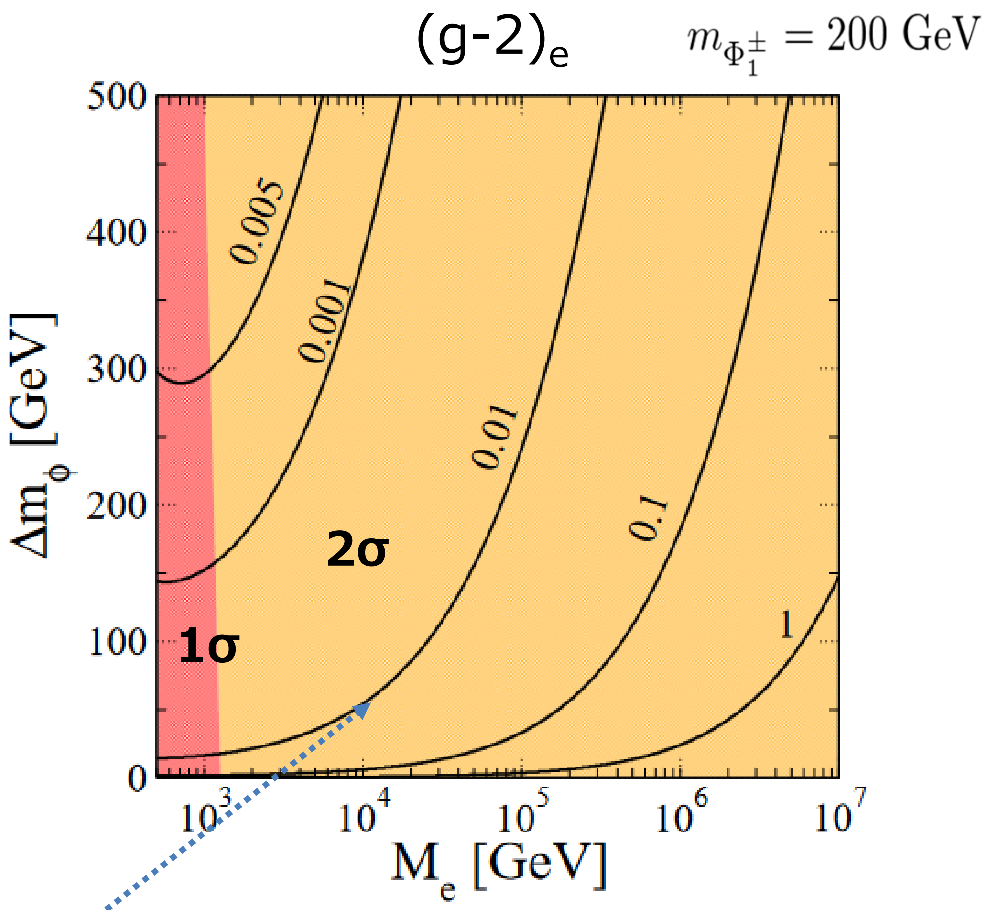
FNAL (2021)

$$\Delta a_\mu = (251 \pm 59) \times 10^{-11} \quad (4.2\sigma)$$

Nature, 588 (2020)

$$\Delta a_e = (4.8 \pm 3.0) \times 10^{-13} \quad (1.6\sigma)$$

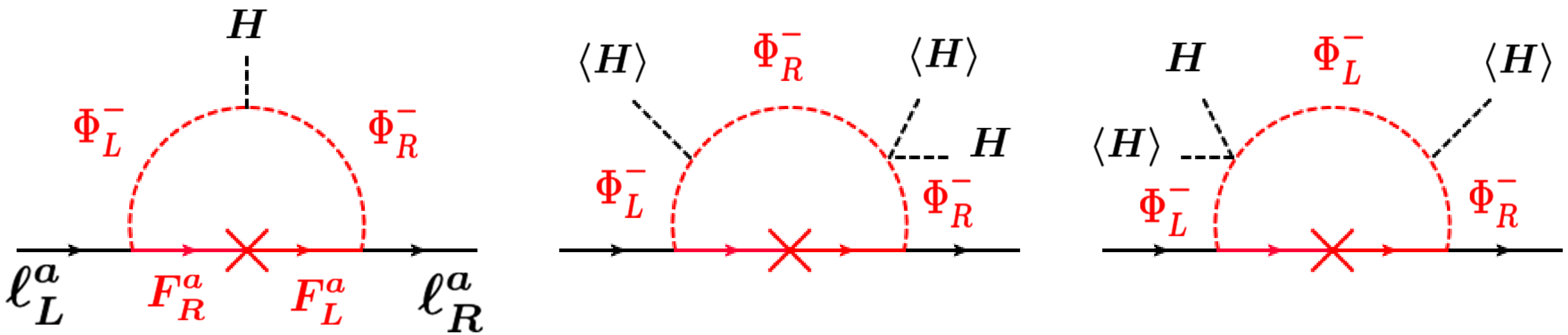




$f_L f_R s_{2\theta}$

Yukawa coupling

- Yukawa coupling does not simply obey $y_f = m_f / v$.



$$y_\ell \simeq \frac{m_\ell}{v} \underbrace{\frac{1}{|1+\ln(m_{\Phi_1}^2/M_\ell^2)|}\left[\left|2+\ln\left(\frac{m_{\Phi_1}^2}{M_\ell^2}\right)\right| + \frac{v^2\lambda_0}{m_{\Phi_1^\pm}^2}\right]}_{\equiv \kappa_\ell}$$ for $M_l \gg m_{\Phi 1} = m_{\Phi 2}$ $(= m_\Phi)$

$$\lambda_0 = \frac{m_{\rm DM}^2}{v^2} + \lambda_{\rm DM} - \frac{\lambda_{HR}}{2}$$

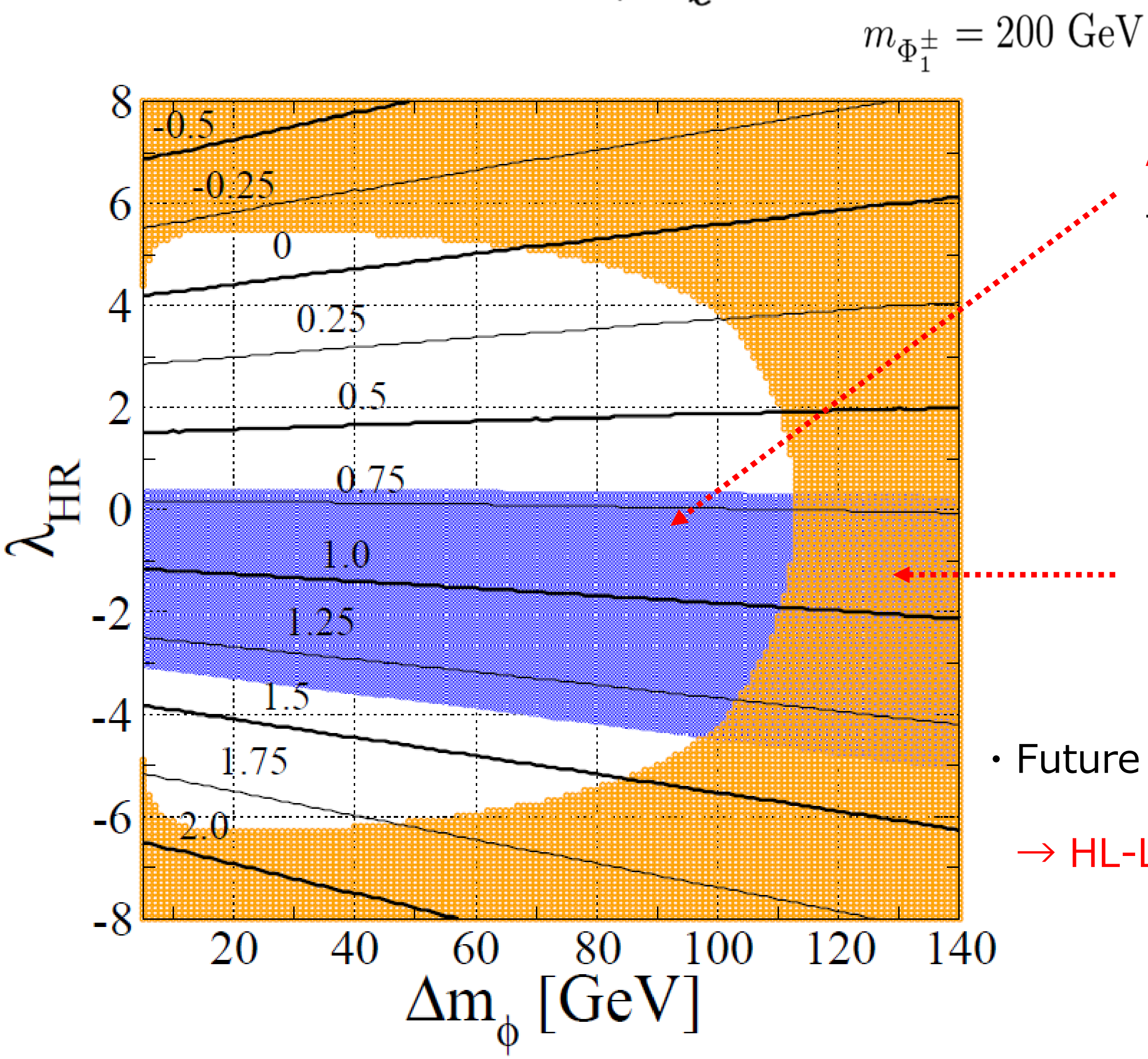
$$V = \lambda_{HR}(H^\dagger H)(\Phi_R^* \Phi_R) + \cdots$$

・The deviation is not suppressed by the loop factor, and it can be sizable.

Yukawa coupling

Cheng-Wei Chiang, KY, 2104.00890 [hep-ph]

- Contours for $\kappa_\ell = y_\ell / y_\ell^{\rm SM}$



Allowed (95%CL) by the signal strength for pp → h → μμ.

ATLAS, 2007.07830 [hep-ex]

CMS-PAS-HIG-19-006

Excluded by perturbativity bound by using 1-loop RGEs.

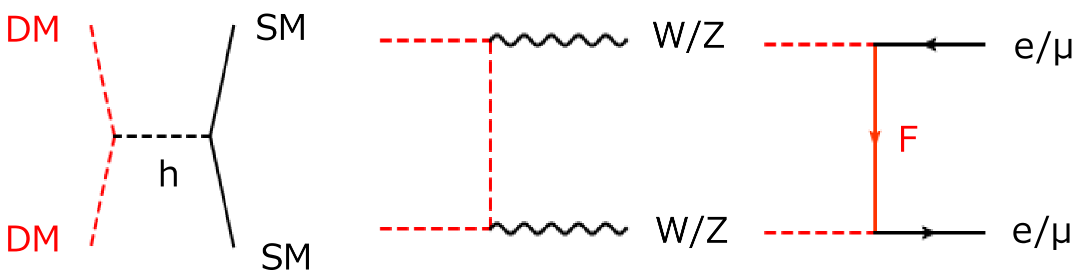
- Future measurements of the μ-Yukawa:

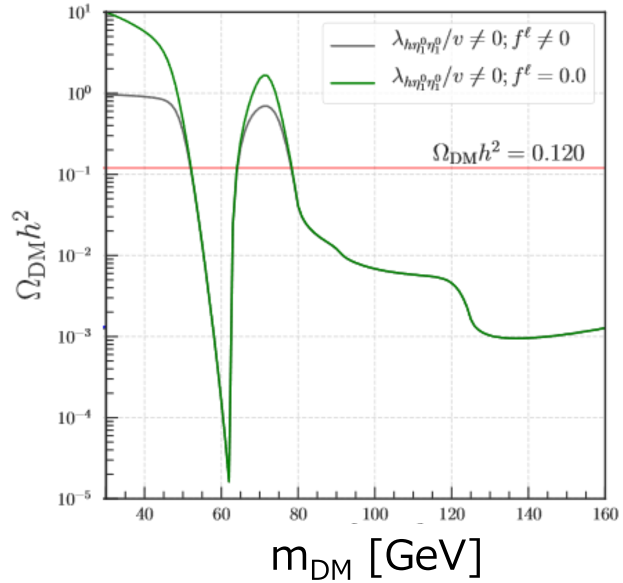
→ HL-LHC ~ 7%, ILC(250) ~5%

Dark matter

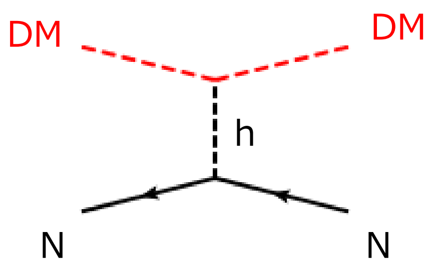
Kai-Feng Chen, Cheng-Wei Chiang, KY, 2006.07929 (JHEP)

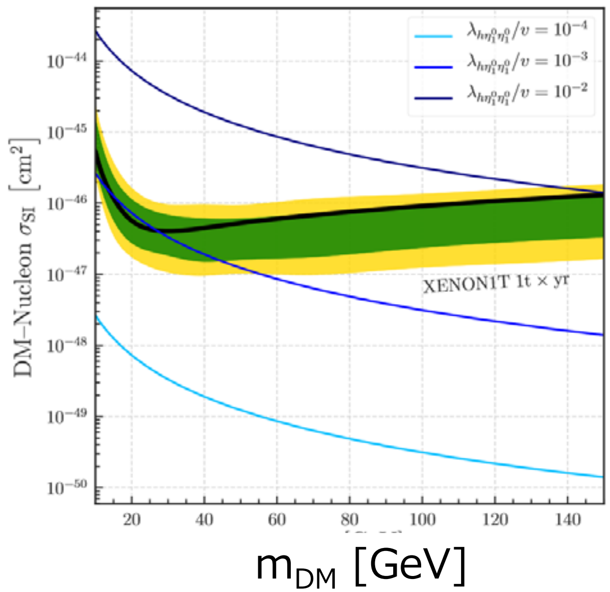
- DM = Re ($\Phi_L{}^0$)
- Annihilation processes





- Direct searches





- There are solutions at m_{DM} ~ 63 GeV and 80 GeV.
- We need $|\lambda_{DM}| < 10^{-3}$ to avoid direct search constraint.

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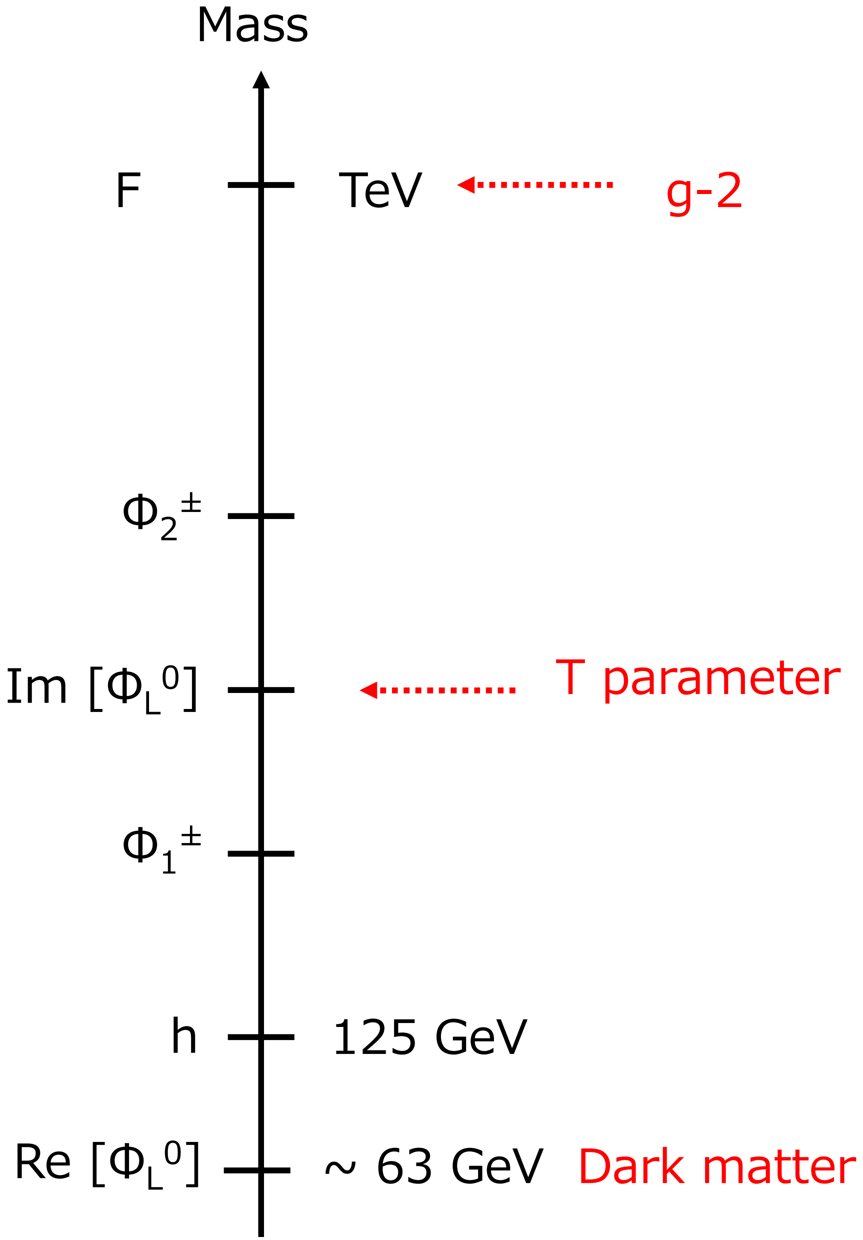
III. Radiative Charged Seesaw Mechanism

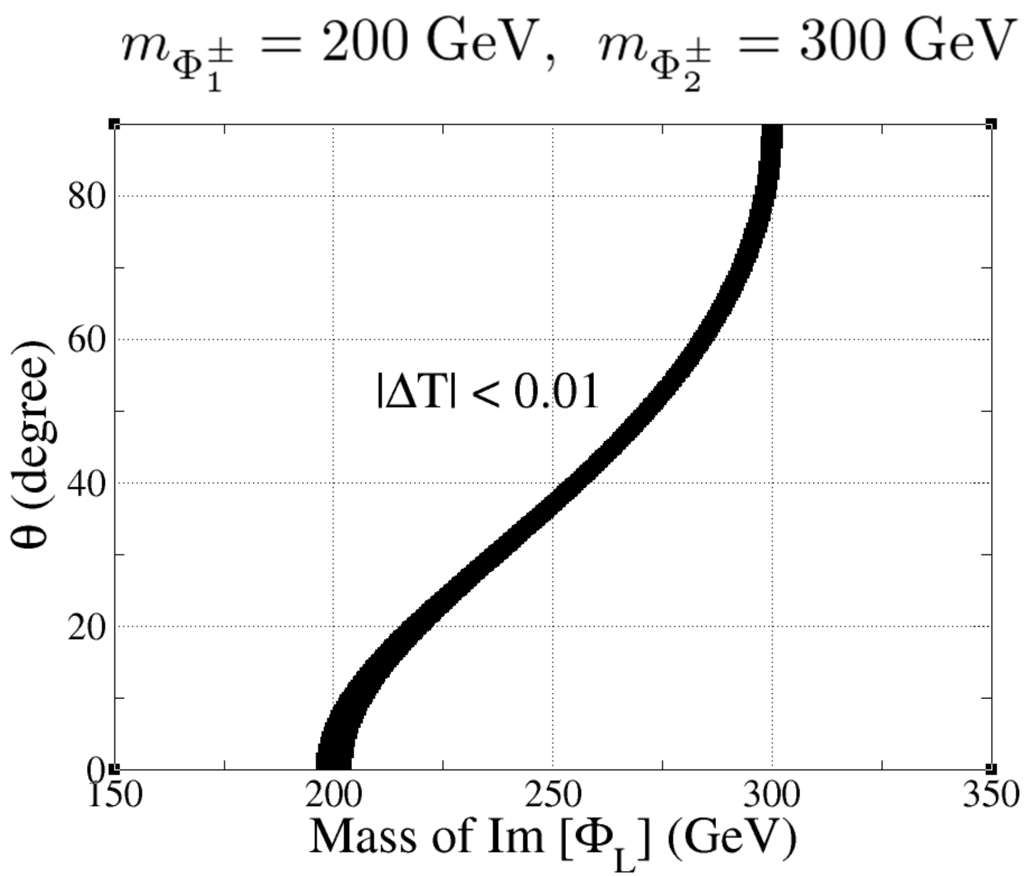
IV. Collider phenomenology (on going)

Cheng-Wei Chiang, Ryomei Obuchi, KY, work in progress

V. Summary

Mass Spectrum



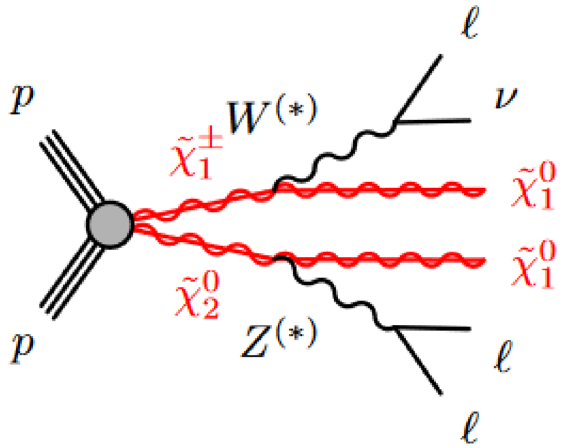


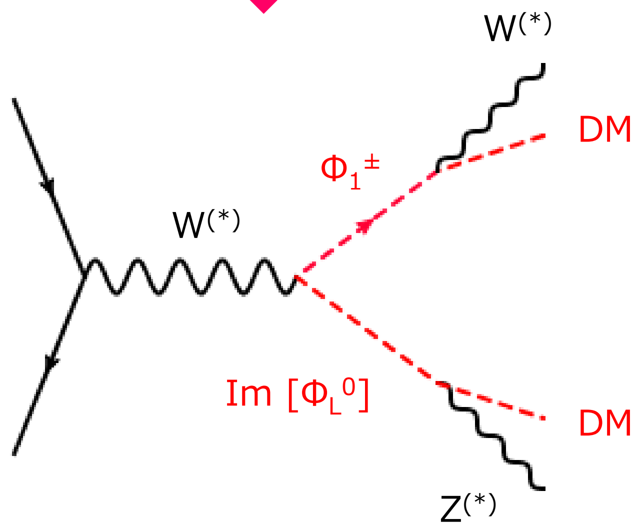
- Dark scalars typically decay into DM + W/Z/h.

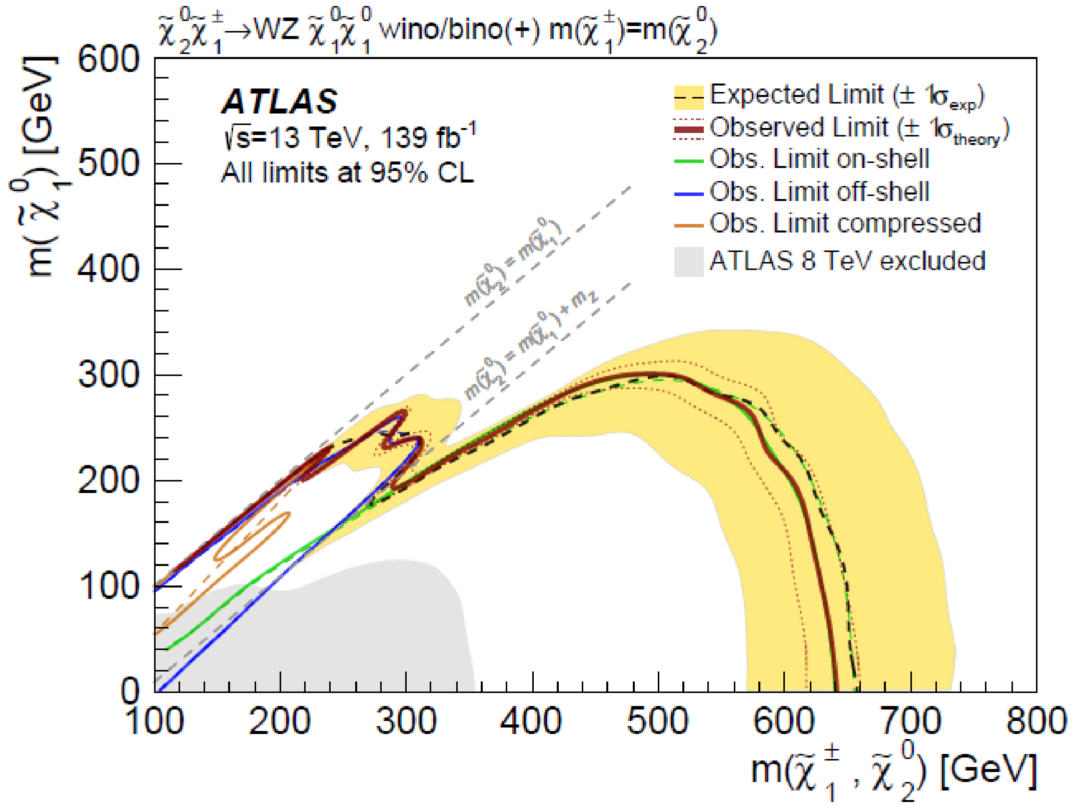
LHC Search

2106.01676 (ATLAS)

- SUSY search







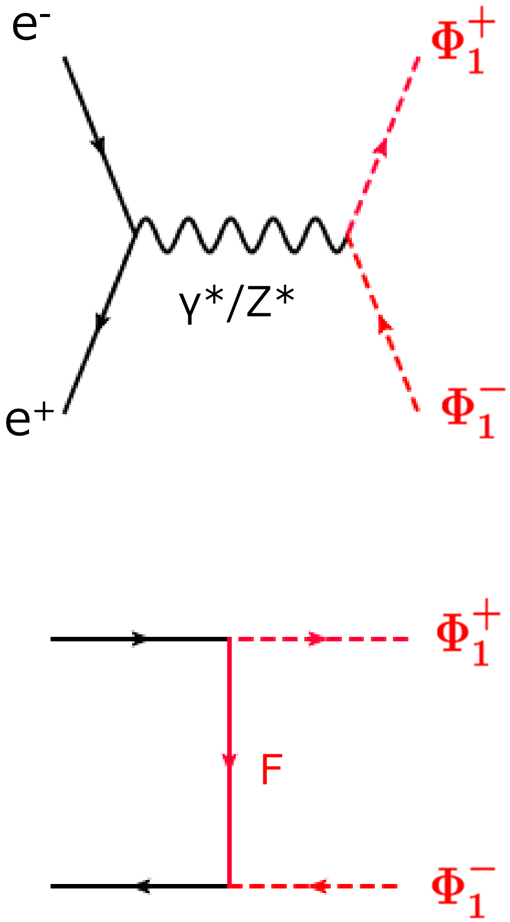
・Large region has already been excluded, but a careful study is needed to apply the limit to our model.

・If $\Phi_1^\pm$ are singlet-like, we may be able to avoid the bound even for small mass region.

ILC Search

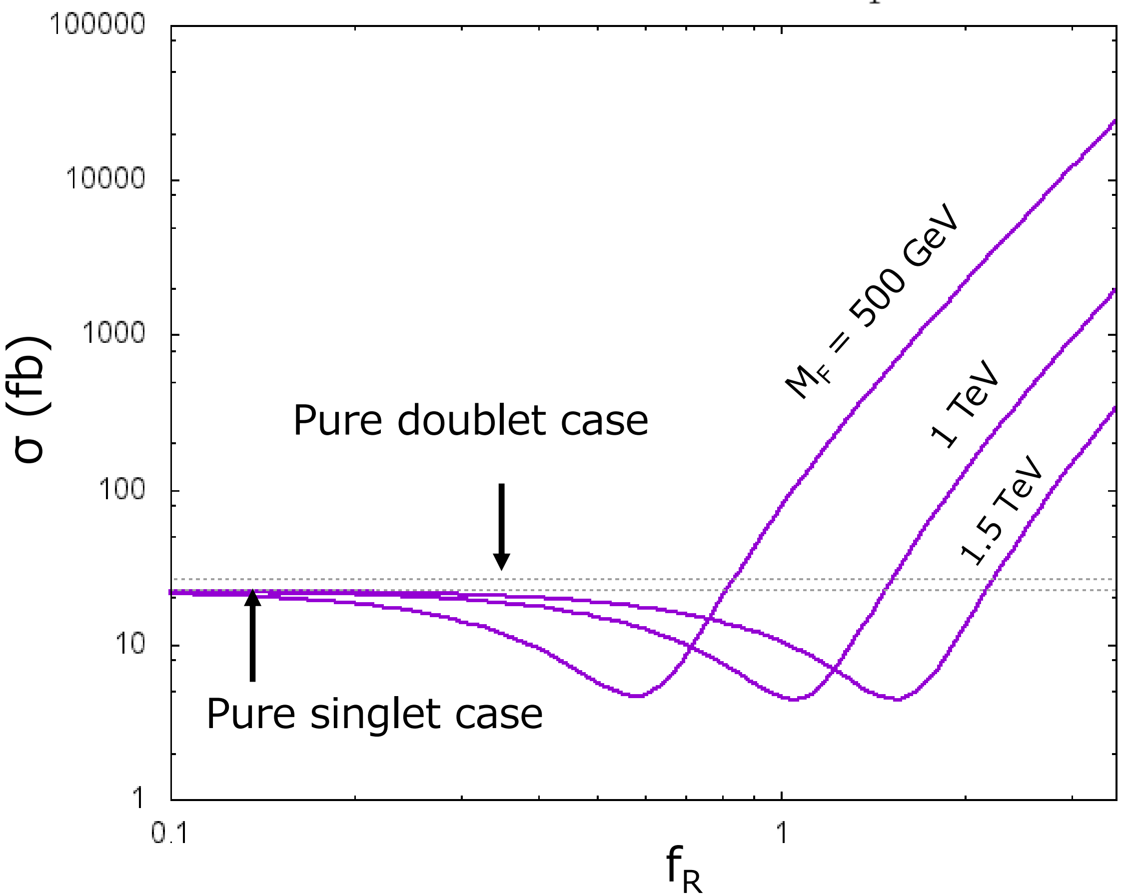
Cheng-Wei Chiang, Ryomei Obuchi, KY, work in progress

- Lighter charged scalars can be produced in pair.



$|\mathcal{M}_t|^2 \propto f_R^4$ (for θ ~ π/2)

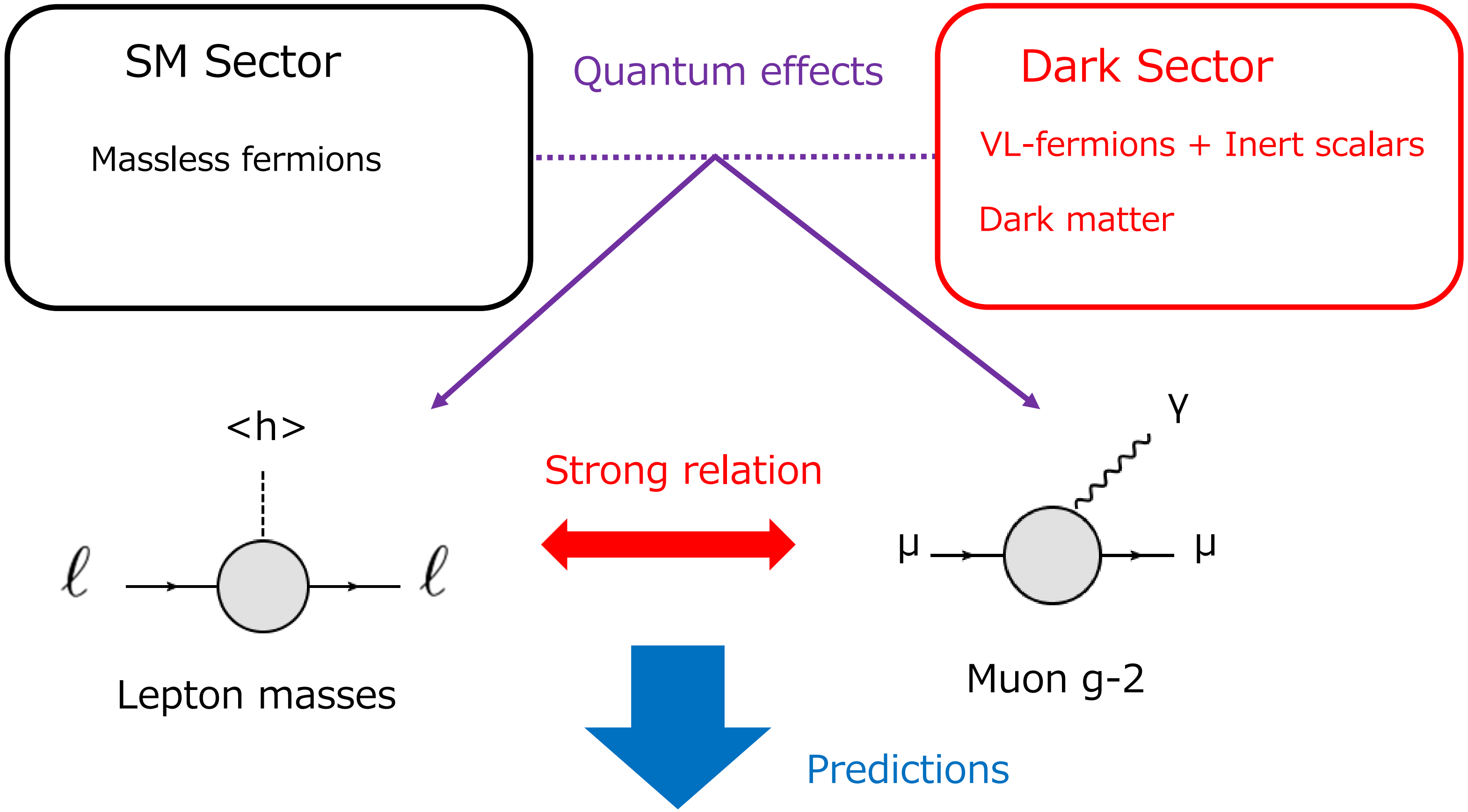
$\sqrt{s} = 500\ \mathrm{GeV},\ \cos\theta = 0.1,\ m_{\Phi_1^\pm} = 200\ \mathrm{GeV}$



- New fermion can sizably change the cross section.
- Polarized beam would be useful to extract the signal.

Summary

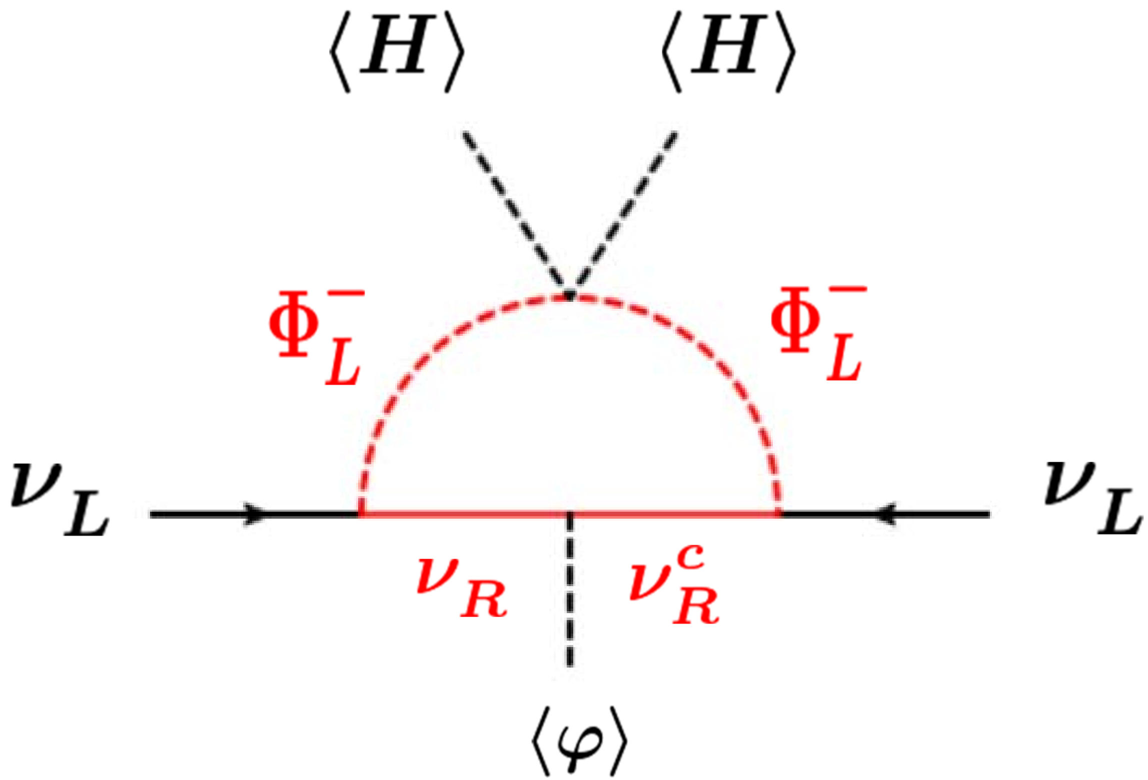
Radiative charged seesaw scenarios can naturally solve DM and $(g\text{-}2)_\mu$.



(1) Large deviations in the muon Yukawa coupling

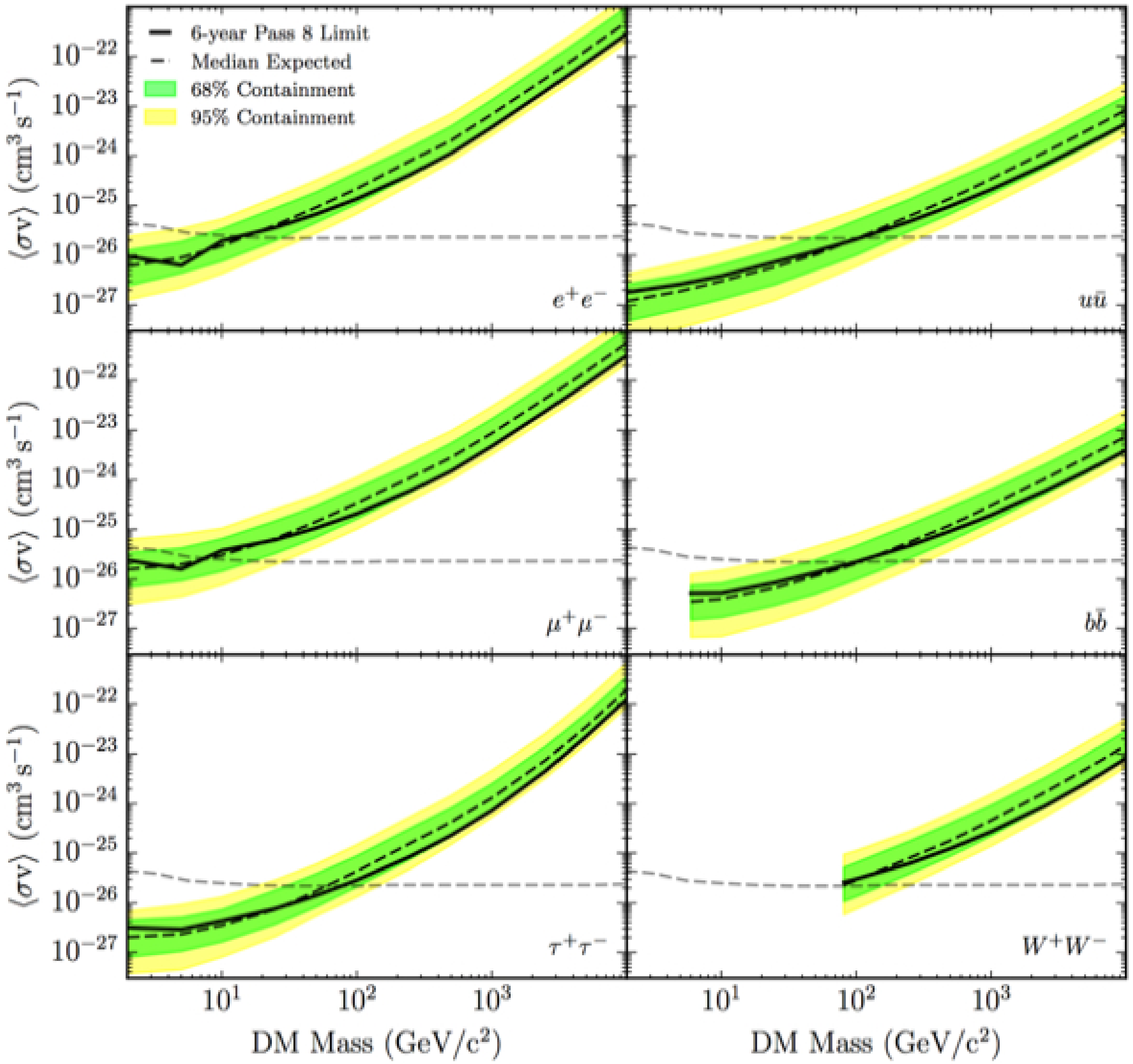
(2) Light dark scalars can directly be detected at collider experiments.

Neutrino masses

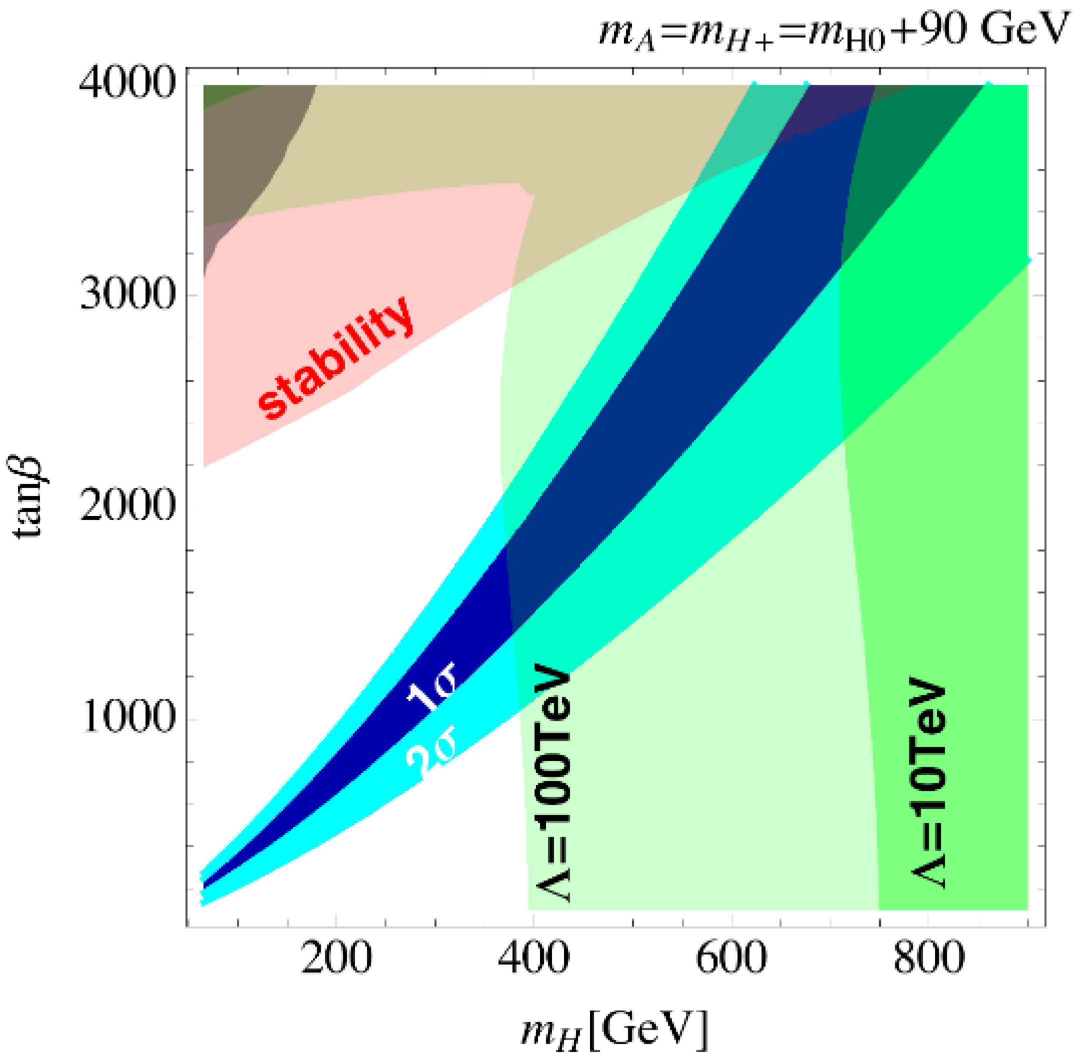


Dark matter indirect searches

1503.02641 (Fermi-LAT)



The limits on the thermally averaged annihilation cross section of dark matter as a function of energy. The different graphs represent various annihilation channels. (Credit: Fermi-LAT collab)

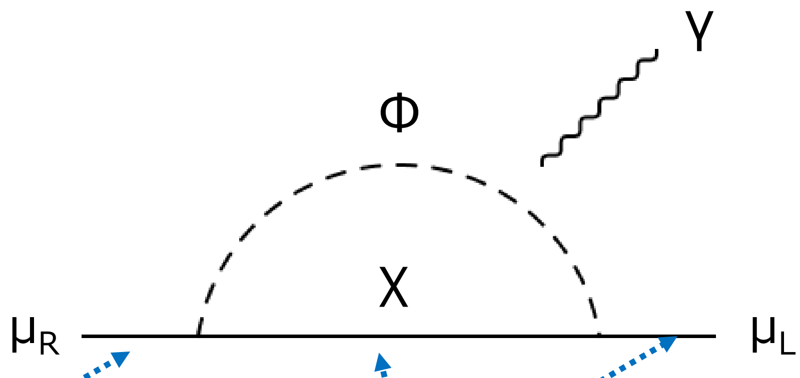


m_{H^0} [GeV]	$m_{A^0}(= m_{H^\pm})$ [GeV]	$\tan\beta$	$\sigma_{13\text{TeV}}$ [fb]	$N_{\mu\text{-THDM}}$	$\mathcal{L}_{3\sigma}$ [fb^{-1}]
600	700	3000	0.41	6.6	-
620	710	3000	0.369	5.9	-
640	730	3100	0.316	5.2	44
660	750	3300	0.2707	4.5	58
680	770	3400	0.2334	3.9	75
700	790	3700	0.20	3.4	97

New physics contribution at 1-loop

- Effective dim. 5 dipole operator

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}\left(\frac{e}{2m}a_f\right)\bar{\mu}_L\sigma^{\mu\nu}\mu_R F_{\mu\nu} + \text{h.c.}$$



- New interactions:

$$\mathcal{L}_{\text{new}} = \bar{\chi}\left(f_L P_L + f_R P_R\right)\mu\phi + \text{h.c.}$$

$$a_\mu = -\frac{Q_\chi}{16\pi^2}\frac{m_\mu}{M_\chi}\left[f_L^2\frac{m_\mu}{2M_\chi}G_2\left(\frac{m_\phi^2}{M_\chi^2}\right) + f_R^2\frac{m_\mu}{2M_\chi}G_2\left(\frac{m_\phi^2}{M_\chi^2}\right) + f_L f_R G_1\left(\frac{m_\phi^2}{M_\chi^2}\right)\right]$$

For $M_\chi \gg m_\mu$, the last term can be dominant. In this case, we can estimate

$$\boxed{a_\mu^{\text{NP}} \simeq 3\times 10^{-9}\times\left(\frac{2\ \text{TeV}}{M_\chi}\right)\times\left(\frac{f_L}{0.1}\right)\times\left(\frac{f_R}{0.1}\right)}$$