Scalar doublets charged under μ-τ-philic Z_n flavor symmetry

Koji Tsumura (Kyoto U.)

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Based JHEP 06 (2019) 142 with Y. Abe (Kyoto U.), T. Toma (McGill U.)
"A μ-τ-philic scalar doublet under Z_n flavor symmetry"

Contents

- Muon g-2
- Flavor Symmetry
  - $U(1)_{\mu\text{-}\tau}$
  - Z_n
- Minimal Model
  - g-2
  - LHC, EW precision data, Lepton Universality, …
  - Signature
- Summary

Magnetic Moment of Muon

- g-factor : Int. btw Spin-B (Magnetic field)
  - ✓ Classical (Dirac Eq.) → g=2
  - ✓ Quantum → g=2(1+a_μ) [a_μ=(g-2)/2]

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} \quad \left(\vec{\mu} = g\frac{e}{2m}\vec{S}\right)$$

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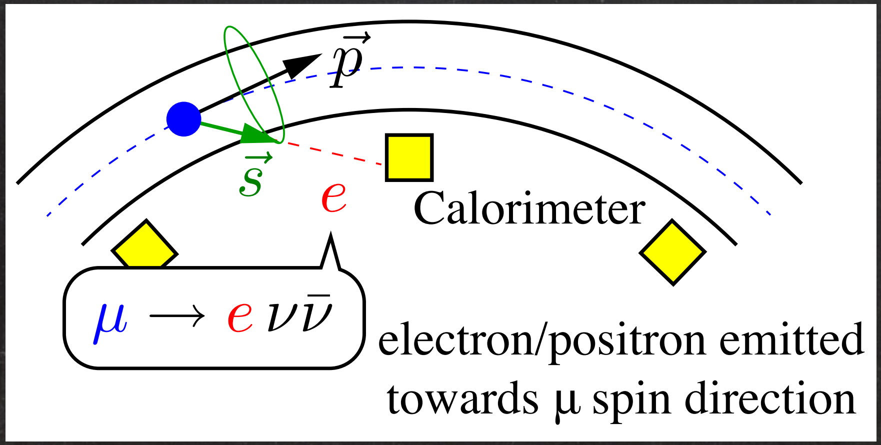
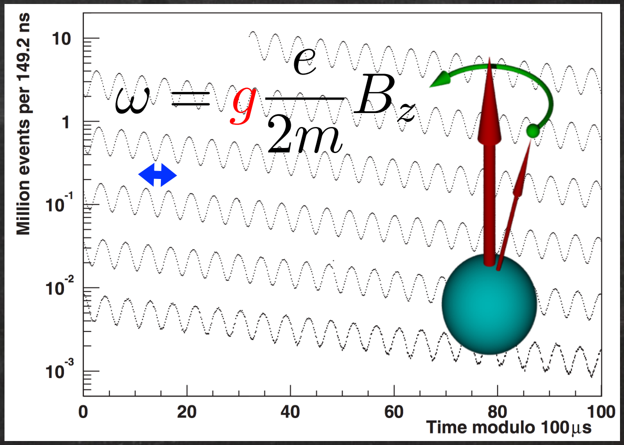
- Experiment : BNL E821

Larmor Precession





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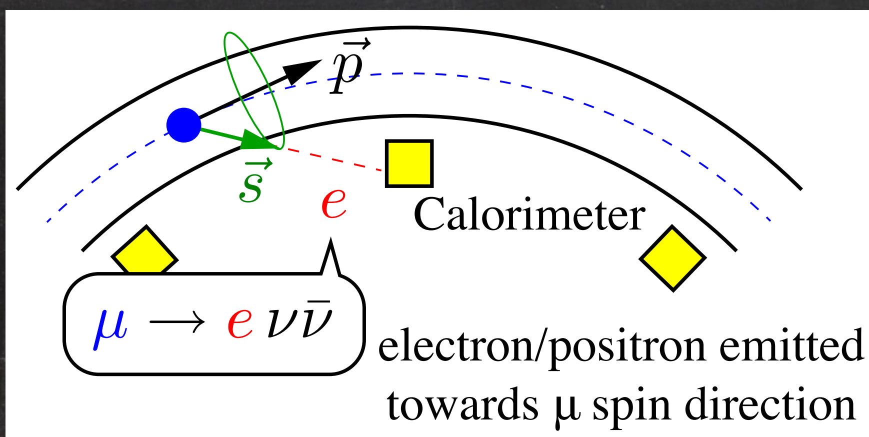

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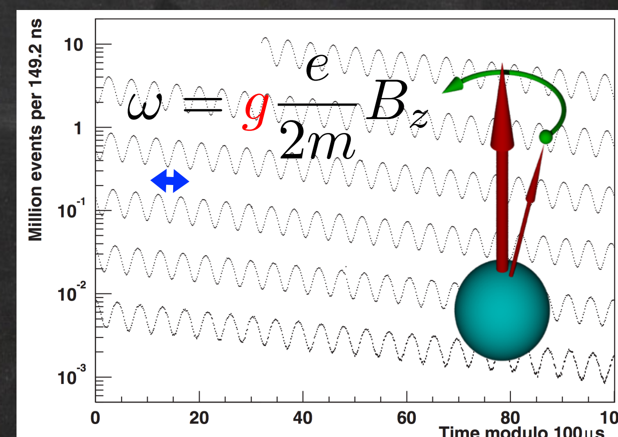
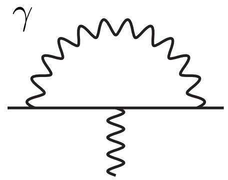


$$a_\mu^{\rm exp} = 116\,592\,091(54)_{\rm stat}(33)_{\rm sys} \times 10^{-11}$$

KNT18 a_μ^{SM} update [KNT18: arXiv:1802.02995, PRD (in press)]



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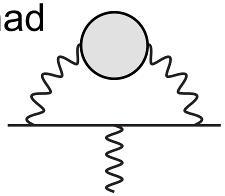
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 **(2.46)**	this work
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	this work
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	this work
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	this work



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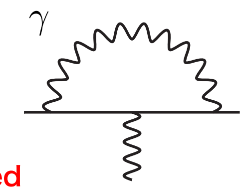

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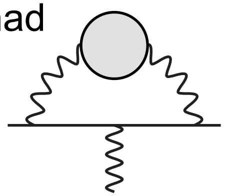

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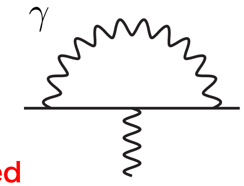

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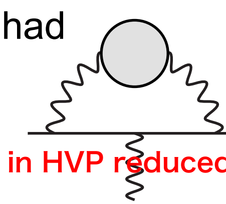

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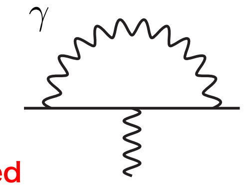

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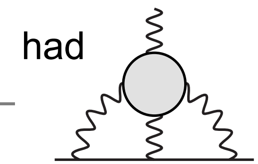

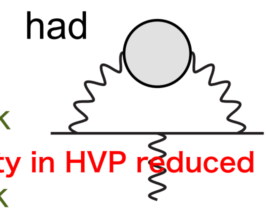

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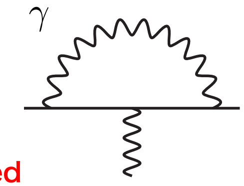

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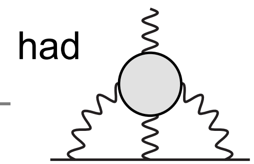

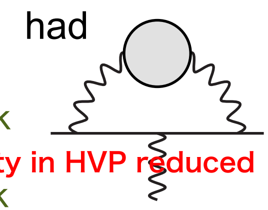

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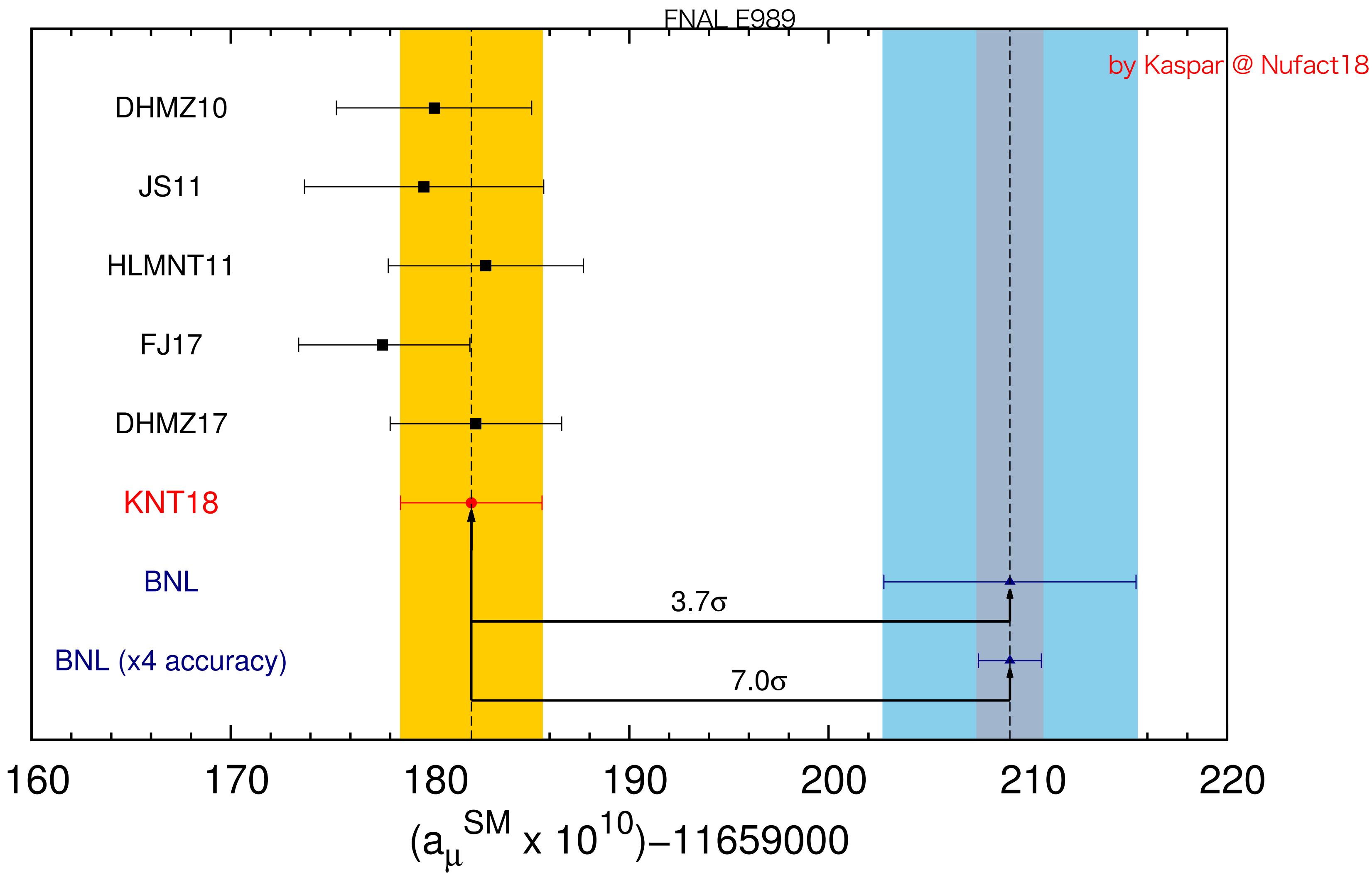

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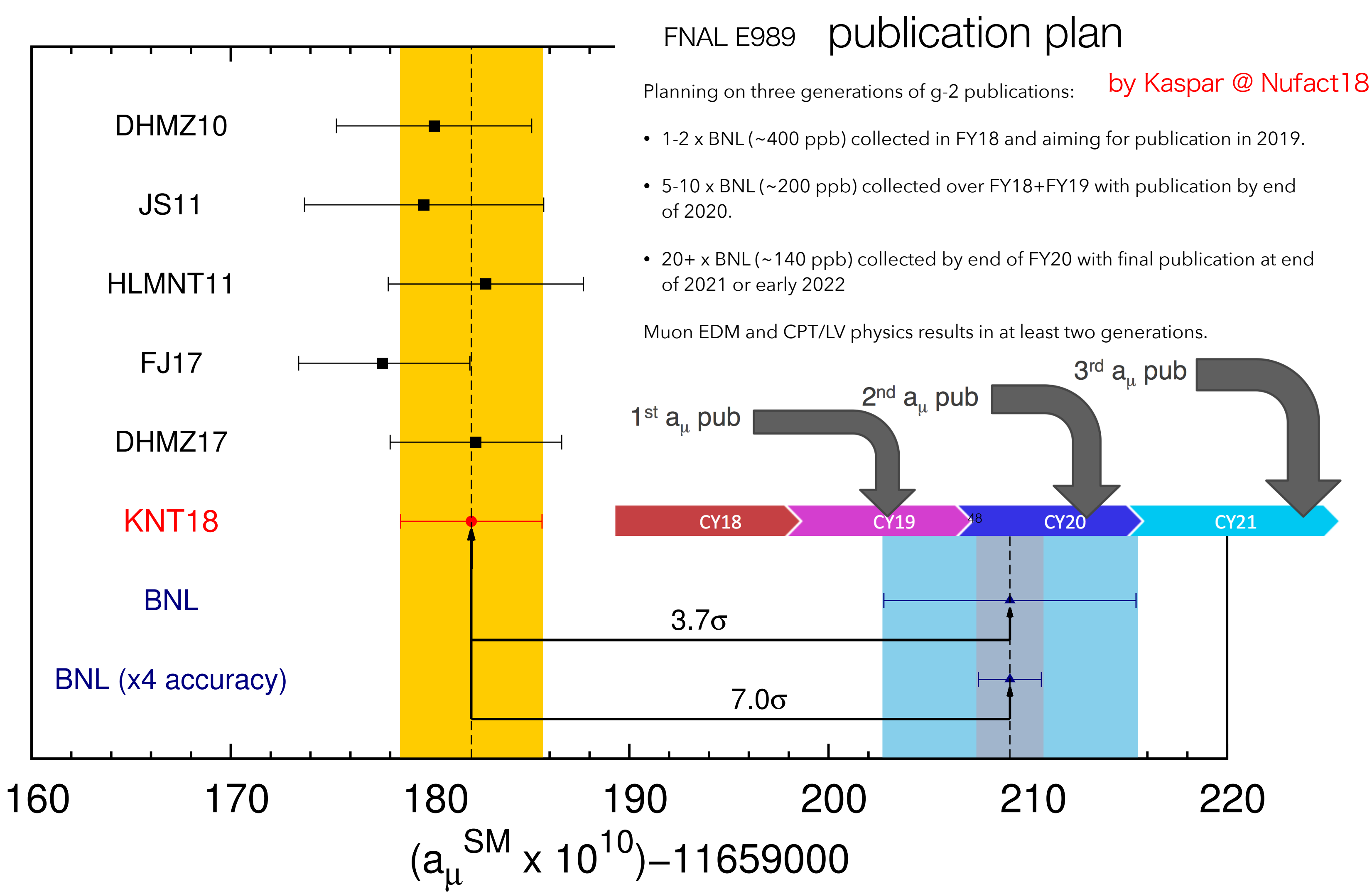
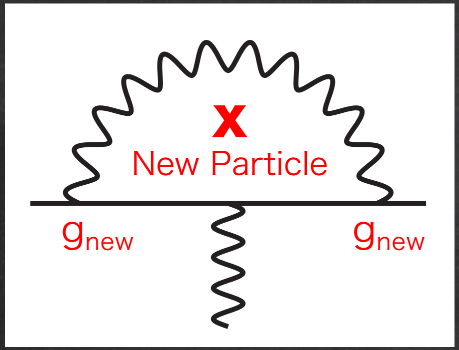


New Physics



$$\Delta a_\mu^{\text{new}} \sim \frac{g_{\text{new}}^2}{(4\pi)^2}\frac{M_\mu^2}{M_X^2}$$

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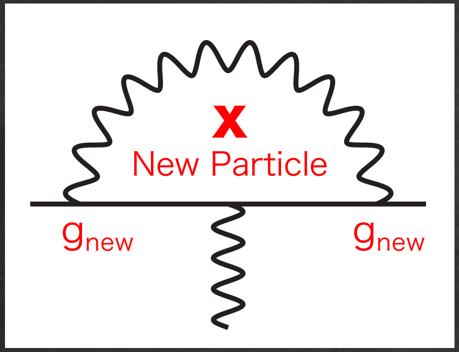

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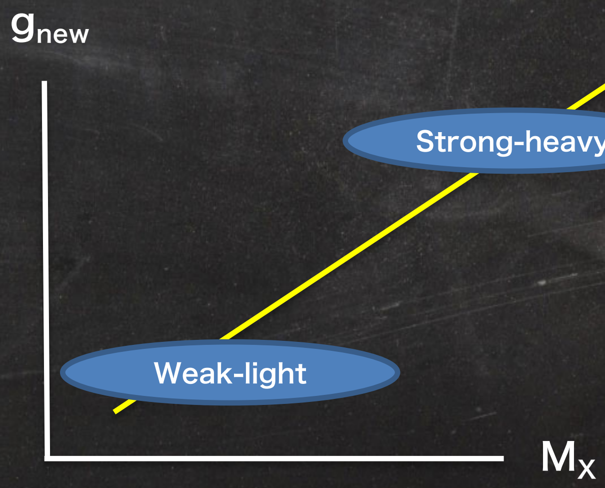

To fit the observed discrepancy

$g_{new} \approx g_{weak}$ and $M_X \approx M_W$

($g_{new} \approx 10^{-3}$ and $M_X \approx M_\mu$)

Flavor symmetry ang a_μ

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

He, Joshi, Lew, Volkas (91)
Foot (91)

- A minimal ext. of SM
- Anomaly free

	ℓ_e	e_R	ℓ_μ	μ_R	ℓ_τ	τ_R
L_μ	0	0	$+1$	$+1$	0	0
L_τ	0	0	0	0	$+1$	$+1$
$U(1)_{L_\mu - L_\tau}$	0	0	$+1$	$+1$	-1	-1

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Lagrangian

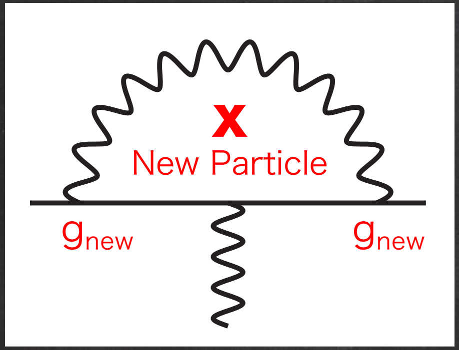
Kinetic mixing w/ SM gauge boson

$$\mathcal{L}_{\rm new} = -\frac{1}{4}Z'_{\alpha\beta}Z'^{\alpha\beta} + \frac{M_{Z'}^2}{2}Z'_\alpha Z'^\alpha + \frac{\epsilon}{2}B_{\alpha\beta}Z'^{\alpha\beta}$$
$$+ g' Z'_\alpha(+\bar{\mu}\gamma^\alpha\mu + \overline{\nu_\mu}\gamma^\alpha\nu_\mu - \bar{\tau}\gamma^\alpha\tau - \overline{\nu_\tau}\gamma^\alpha\nu_\tau)$$

New gauge int. for μ and τ

Gauged U(1)$_{\mu-\tau}$ and a$_\mu$

- Z' can give a sufficient amount of $\Delta a_\mu^{\rm new}$



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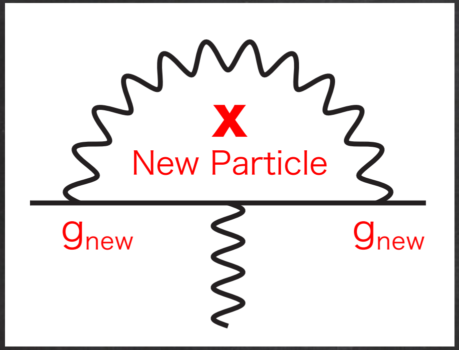

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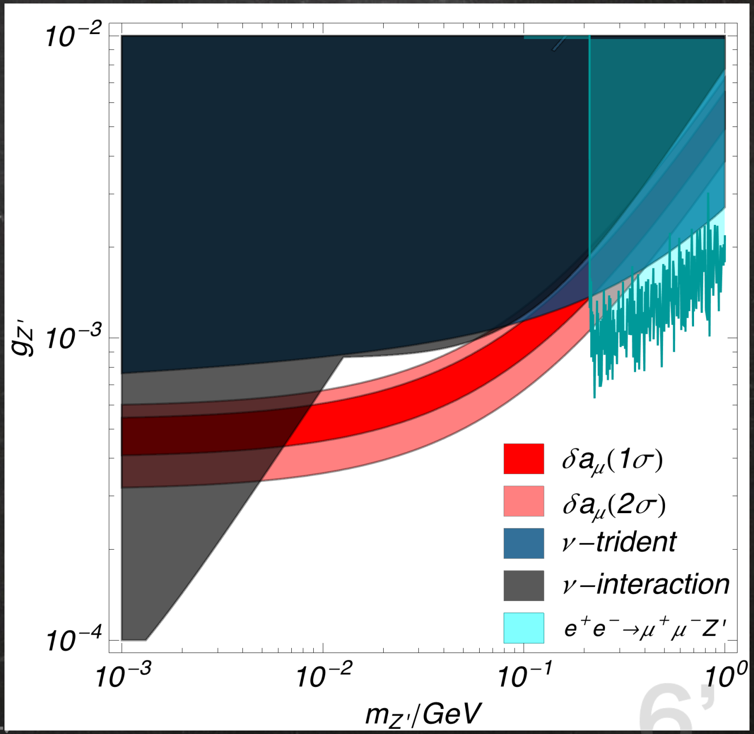
"weakly" interacting low mass Z'

Ibe, Nakano, Suzuki (16)



Global U(1)$_{\mu\text{-}\tau}$?

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- No Z' boson
- Flavor charged scalars?

	$U(1)_{\mu-\tau}$
$[L_e, L_\mu, L_\tau]$	$[0, +1, -1]$
$[e_R, \mu_R, \tau_R]$	$[0, +1, -1]$
H	0
Φ	$+2$
$\underline{\Phi}$	-2

$$-\mathcal{L}_{\text{yukawa}} = \begin{pmatrix} \overline{e_R} & \overline{\mu_R} & \overline{\tau_R} \end{pmatrix} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau} \underline{\Phi}^\dagger \\ & y_{\tau\mu} \Phi^\dagger & y_\tau H^\dagger \end{pmatrix} \begin{pmatrix} \ell_e \\ \ell_\mu \\ \ell_\tau \end{pmatrix} + \text{H.c.}$$

A pair of scalar doublets can have Yukawa int.

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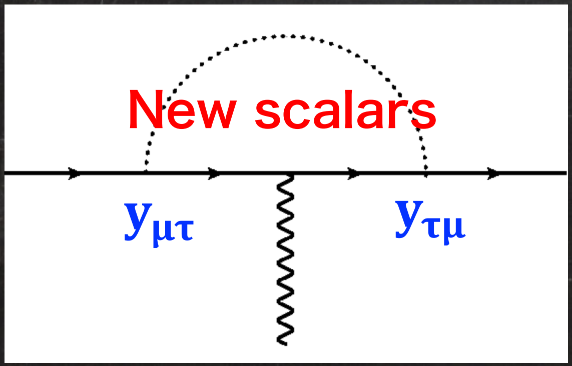

$$\Delta a_\mu^{\text{new}} \simeq \frac{y_{\mu\tau} y_{\tau\mu}}{(4\pi)^2} \frac{M_\mu^2}{M_\Phi^2} \left(\frac{M_\tau}{M_\mu} \right)$$

Chirality enhancement!!

Global U(1)$_{\mu-\tau}$ and a$_\mu$

- No Z' boson
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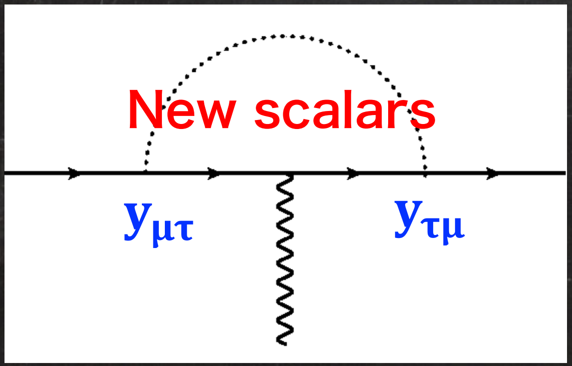

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Chirality enhancement!!

U(1) breaking is NOT necessary!!

Global U(1)$_{\mu\text{-}\tau}$ and M$_\nu$

- Large neutrino mixing

Choubey, Rodejohann (05)
Ota, Rodejohann (06)

$$M_\nu \propto \begin{pmatrix} m_{11} & & \\ & & m_{23} \\ & m_{23} & \end{pmatrix}$$

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- Symmetry breaking by S

$$M_\nu \propto \begin{pmatrix} m_{11} & \epsilon_{12}\langle S^* \rangle & \epsilon_{13}\langle S \rangle \\ \epsilon_{12}\langle S^* \rangle & & m_{23} \\ \epsilon_{13}\langle S \rangle & m_{23} & \end{pmatrix}$$

✓ Fit with ν oscillation data
✓ Massless NGB

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$$M_\nu \propto \begin{pmatrix} m_{11} & \epsilon_{12}\langle S^* \rangle & \epsilon_{13}\langle S \rangle \\ \epsilon_{12}\langle S^* \rangle & & m_{23} \\ \epsilon_{13}\langle S \rangle & m_{23} & \end{pmatrix}$$

✓ Fit with ν oscillation data

✓ Massless NGB

⇨ Explicit U(1)$_{\mu\text{-}\tau}$ breaking : Z$_n$

Z_n flavor symmetries

Z_n subgroup of $U(1)_{\mu\text{-}\tau}$

	$U(1)_{\mu-\tau}$	Z_2	Z_3	Z_4	Z_n
$[L_e, L_\mu, L_\tau]$	$[0, +1, -1]$	$[+, -, -]$	$[1, \omega, \omega^2]$	$[1, +i, -i]$	$[1, \omega, \underline{\omega}]$
$[e_R, \mu_R, \tau_R]$	$[0, +1, -1]$	$[+, -, -]$	$[1, \omega, \omega^2]$	$[1, +i, -i]$	$[1, \omega, \underline{\omega}]$
H	0	$+$	1	1	1
Φ	$+2$	$+$	ω^2	-1	ω^2
$\underline{\Phi}$	-2	$+$	ω	-1	$\underline{\omega}^2$

For n≧5, global $U(1)_{\mu\text{-}\tau}$ is recovered

$$V \sim +\lambda_5 (H^\dagger \Phi)(H^\dagger \underline{\Phi})$$

Z_n flavor symmetries

Z_n subgroup of $U(1)_{\mu\text{-}\tau}$

	$U(1)_{\mu-\tau}$	Z_2	Z_3	Z_4	Z_n
$[L_e, L_\mu, L_\tau]$	$[0, +1, -1]$	$[+, -, -]$	$[1, \omega, \omega^2]$	$[1, +i, -i]$	$[1, \omega, \underline{\omega}]$
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H	0	$+$	1	1	1
Φ	$+2$	$+$	ω^2	-1	ω^2
$\underline{\Phi}$	-2	$+$	ω	-1	$\underline{\omega^2}$

Φ and $\underline{\Phi}$ are identical

$$V \sim +\lambda_5 (H^\dagger \Phi)^2$$

Candidates for the Minimal Model

Z_n conserving Yukawa int.

Structure of Yukawa int.

$$-\mathcal{L}^{\rm yukawa}_{Z_2} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger + y_{ee}\Phi^\dagger & & \\ & y_\mu H^\dagger + y_{\mu\mu}\Phi^\dagger & g_{\mu\tau}H^\dagger + y_{\mu\tau}\Phi^\dagger \\ & g_{\tau\mu}H^\dagger + y_{\tau\mu}\Phi^\dagger & y_\tau H + y_{\tau\tau}\Phi^\dagger \end{pmatrix} L + \text{H.c.}$$

$$-\mathcal{L}^{\rm yukawa}_{Z_3} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger & \underline{y_{e\mu}\Phi^\dagger} & y_{e\tau}\Phi^\dagger \\ y_{\mu e}\Phi^\dagger & y_\mu H^\dagger & \underline{y_{\mu\tau}\Phi^\dagger} \\ \underline{y_{\tau e}\Phi^\dagger} & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

$$-\mathcal{L}^{\rm yukawa}_{Z_4} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau}\Phi^\dagger \\ & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

$$-\mathcal{L}^{\rm yukawa}_{Z_{n\geq 5}} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & \underline{y_{\mu\tau}\Phi^\dagger} \\ & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

Z_n conserving Yukawa int.

Structure of Yukawa int.

No distinction btw H and Φ
(Φ tends to have VEV)

$$-\mathcal{L}^{\text{yukawa}}_{Z_2} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger + y_{ee}\Phi^\dagger & & \\ & y_\mu H^\dagger + y_{\mu\mu}\Phi^\dagger & g_{\mu\tau} H^\dagger + y_{\mu\tau}\Phi^\dagger \\ & g_{\tau\mu} H^\dagger + y_{\tau\mu}\Phi^\dagger & y_\tau H + y_{\tau\tau}\Phi^\dagger \end{pmatrix} L + \text{H.c.}$$

$$-\mathcal{L}^{\text{yukawa}}_{Z_3} = \overline{\ell_R}\begin{pmatrix} y_e H^\dagger & y_{e\mu}\Phi^\dagger & y_{e\tau}\Phi^\dagger \\ y_{\mu e}\Phi^\dagger & y_\mu H^\dagger & y_{\mu\tau}\Phi^\dagger \\ y_{\tau e}\Phi^\dagger & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

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Source of LFV

$$-\mathcal{L}^{\rm yukawa}_{Z_4} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau}\Phi^\dagger \\ & y_{\tau\mu}\Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

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Z_n conserving Yukawa int.

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$$-\mathcal{L}^{\rm yukawa}_{Z_2} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger + y_{ee}\Phi^\dagger & & \\ & y_\mu H^\dagger + y_{\mu\mu}\Phi^\dagger & g_{\mu\tau} H^\dagger + y_{\mu\tau}\Phi^\dagger \\ & g_{\tau\mu} H^\dagger + y_{\tau\mu}\Phi^\dagger & y_\tau H + y_{\tau\tau}\Phi^\dagger \end{pmatrix} L + {\rm H.c.}$$

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Candidates
for the Minimal Model

Minimal Model

Z_4 model

- Z_2 symmetric 2HDM

$$
\begin{aligned}
V(H,\Phi) =& -\mu_H^2 H^\dagger H + m_\Phi^2 \Phi^\dagger \Phi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\Phi^\dagger \Phi)^2 \\
&+ \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \Phi)(\Phi^\dagger H) + \left[+ \frac{\lambda_5}{2} (H^\dagger \Phi)^2 + \text{H.c.} \right]
\end{aligned}
$$

Z_4 model

- Z_2 symmetric 2HDM

$$V(H,\Phi) = -\mu_H^2 H^\dagger H + m_\Phi^2 \Phi^\dagger\Phi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\Phi^\dagger\Phi)^2 + \lambda_3 (H^\dagger H)(\Phi^\dagger\Phi) + \lambda_4 (H^\dagger\Phi)(\Phi^\dagger H) + \left[+ \frac{\lambda_5}{2}(H^\dagger\Phi)^2 + \mathrm{H.c.}\right]$$

- **Positive mass square for Φ**

$$H = \begin{pmatrix} 0 \\ (v + h_{125})/\sqrt{2} \end{pmatrix} \qquad \Phi = \begin{pmatrix} \phi^+ \\ (\rho + i\,\eta)/\sqrt{2} \end{pmatrix}$$

Z_4 model

$$M_\rho^2 - M_\eta^2 = \lambda_5 v^2$$

- Z_2 symmetric 2HDM

$$V(H,\Phi) = -\mu_H^2 H^\dagger H + m_\Phi^2 \Phi^\dagger \Phi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\Phi^\dagger \Phi)^2 + \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \Phi)(\Phi^\dagger H) + \left[+ \frac{\lambda_5}{2} (H^\dagger \Phi)^2 + \text{H.c.} \right]$$

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- Positive mass square for Φ

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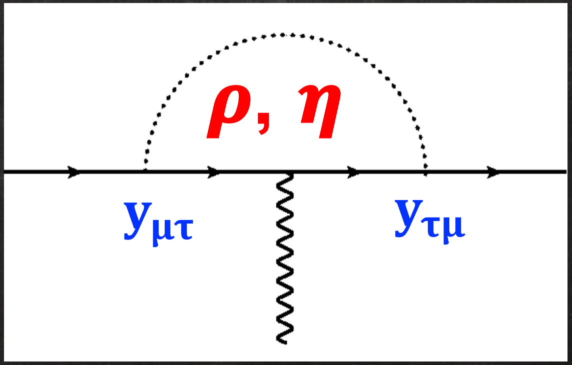
$$-\mathcal{L}_{Z_4}^{\text{yukawa}} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau} \Phi^\dagger \\ & y_{\tau\mu} \Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

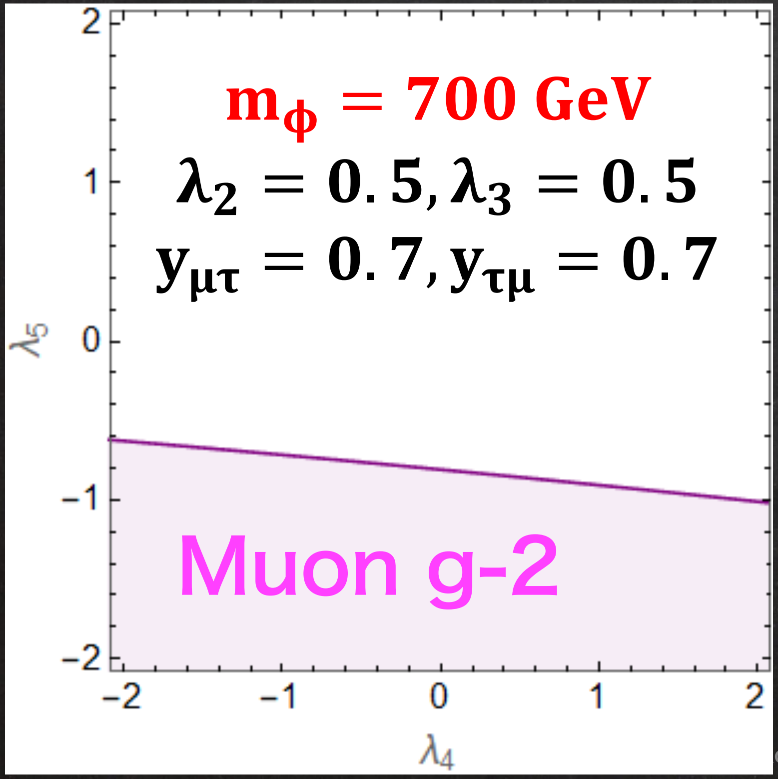


Z_4 model and a_μ

- Muon g-2

$$M_\rho^2 - M_\eta^2 = \lambda_5 v^2$$

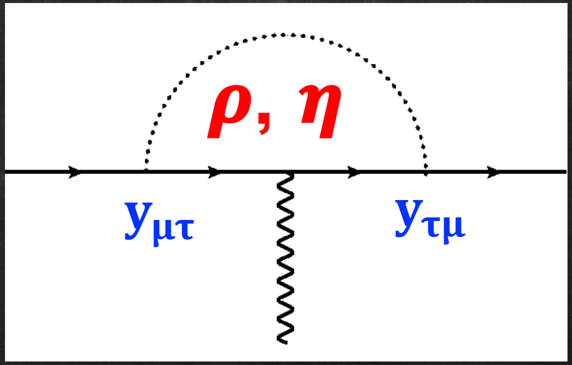
$$\Delta a_\mu^{\rm new} \simeq \frac{{\rm Re}(y_{\mu\tau} y_{\tau\mu})}{(4\pi)^2} \frac{M_\mu^2}{M_\phi^2} \left(\frac{M_\tau}{M_\mu}\right) \left(\frac{\lambda_5 v^2}{M_\phi^2}\right) \left(\frac{5}{2} + \ln\frac{M_\tau^2}{M_\phi^2}\right)$$



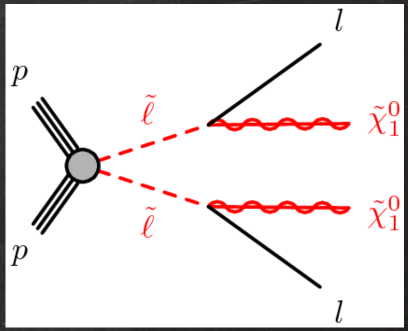
✓ Chirality Enhancement

✓ Mass splitting btw ρ and η

✓ Large Yukawa (w/ heavy scalar)

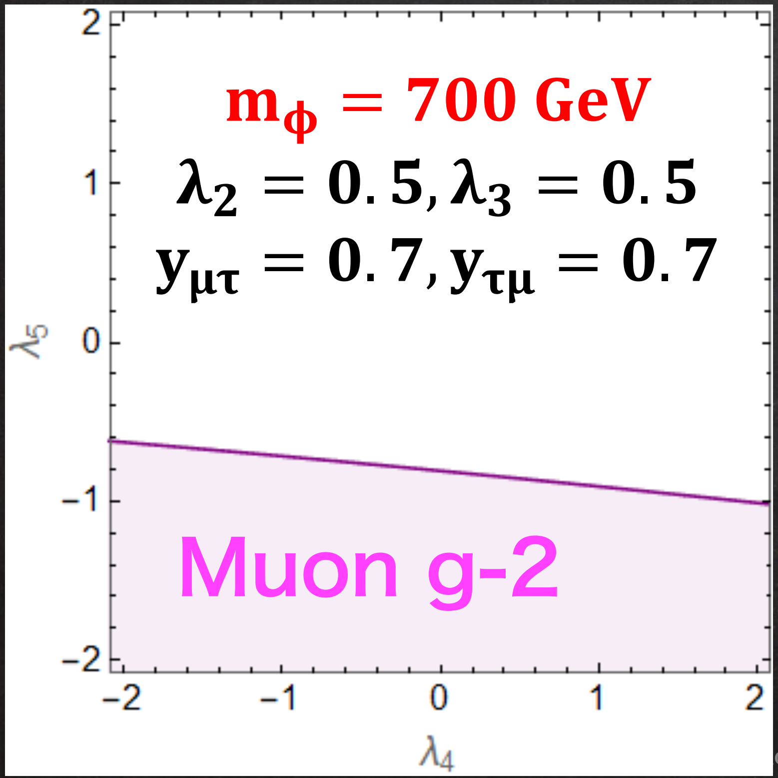


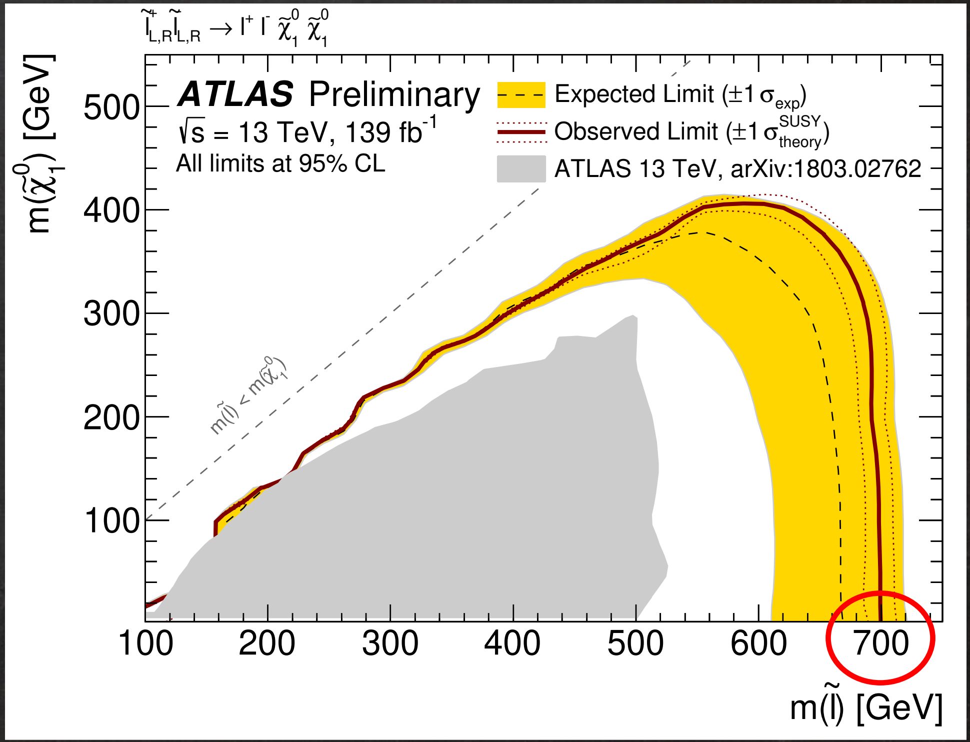
Z_4 model @ LHC



- EW pair production and $\phi^\pm \to \ell^\pm \nu$
  (Slepton mass bound w/ massless neutralino)

$M_\phi \gtrsim 700$ GeV

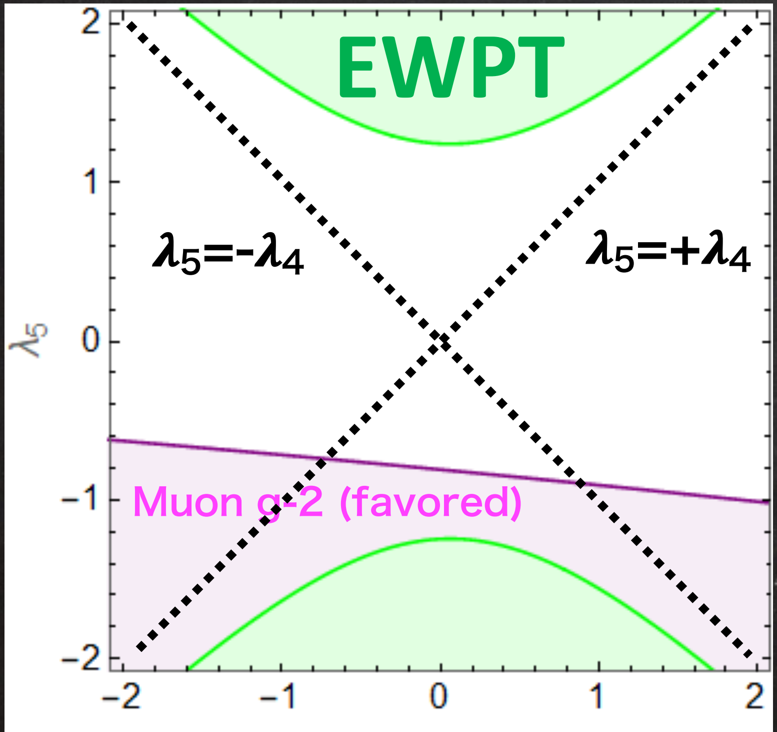




Z_4 model and EW precision Test

- Peskin-Takeuchi's T parameter

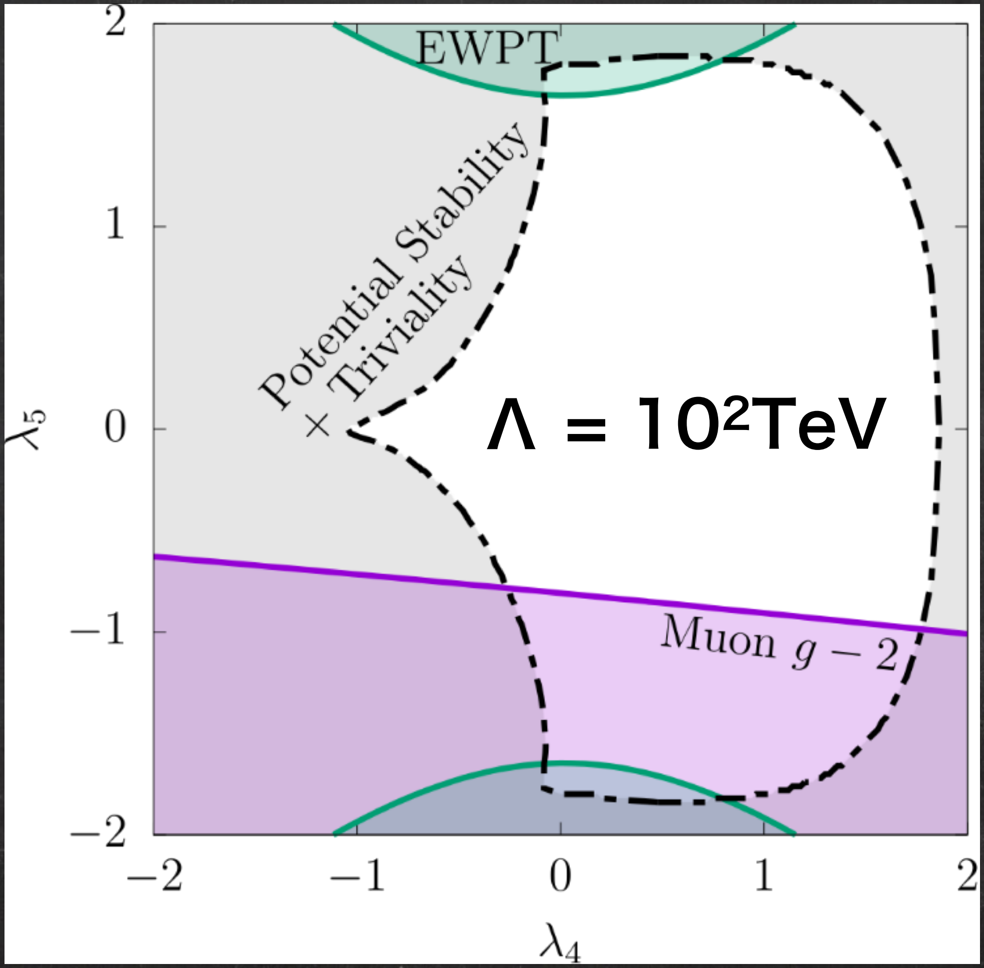
$$\alpha_{\rm EM} T \simeq \frac{\lambda_4^2-\lambda_5^2}{12(4\pi)^2}\frac{v^2}{M_\phi^2} \qquad (T = 0.09 \pm 0.13)$$



✓ EWPT favors mass degeneracy

$$\begin{cases} M_\rho^2 &= M_\phi^2 + (\lambda_4+\lambda_5)\frac{v^2}{2} \\ M_\eta^2 &= M_\phi^2 + (\lambda_4-\lambda_5)\frac{v^2}{2} \end{cases}$$

Z_4 model and Theory constraints



Triviality

$$|\lambda_i(\Lambda)| < 4\pi$$

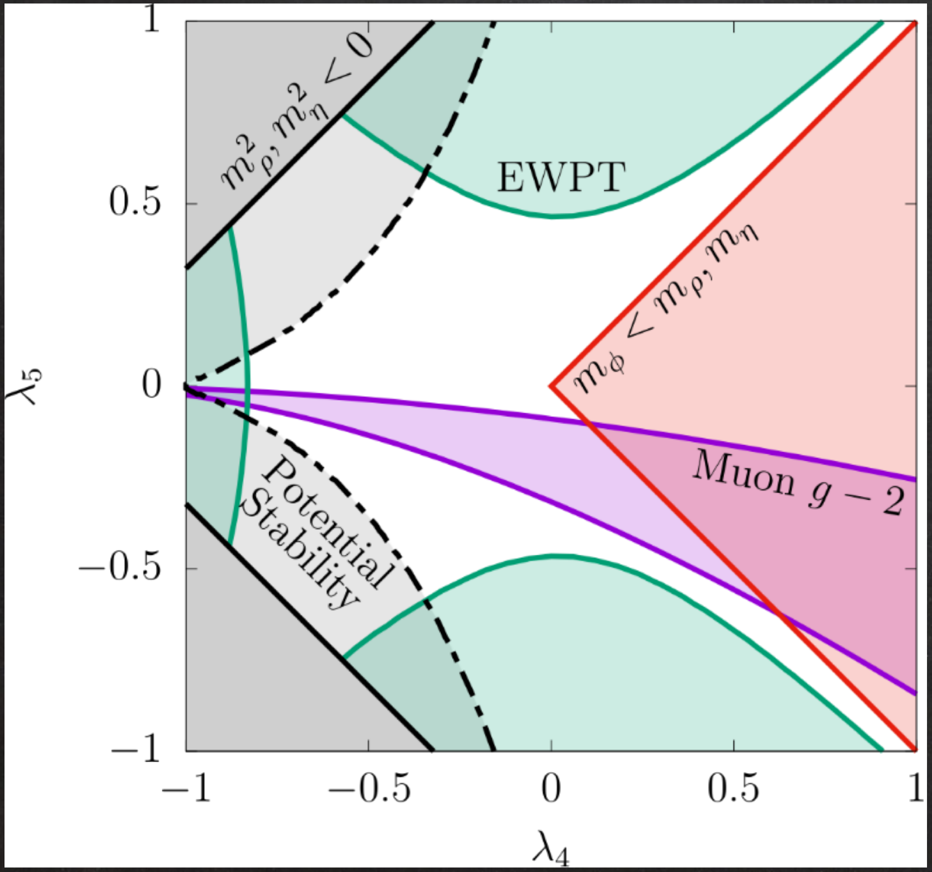
Stability

$$2\sqrt{\lambda_1(\Lambda)\lambda_2(\Lambda)} + \lambda_3(\Lambda) + \lambda_4(\Lambda) \pm |\lambda_5(\Lambda)| > 0$$

LHC bound revisited

- Cascade decay $\phi^+ \to W^+\rho, W^+\eta$

Slepton mass bound cannot be applied



Low mass solution possible

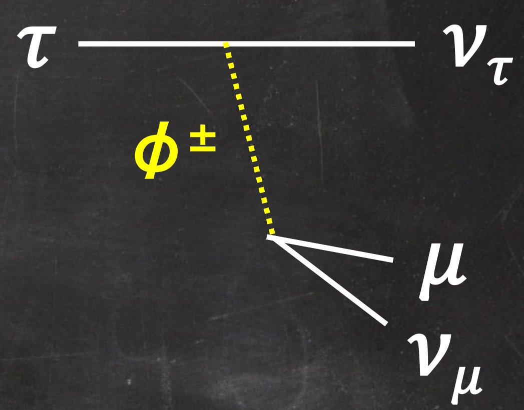
$$\mathbf{m_\phi = 200\ GeV}$$

$$\lambda_2 = 0.5, \lambda_3 = 0.5$$

$$y_{\mu\tau} = 0.2, y_{\tau\mu} = 0.2$$

Lepton Universality Violation

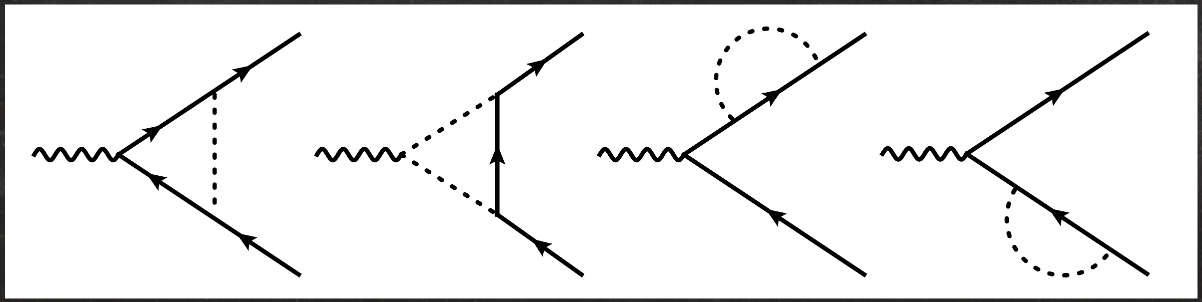
- τ Michel decay @ Tree



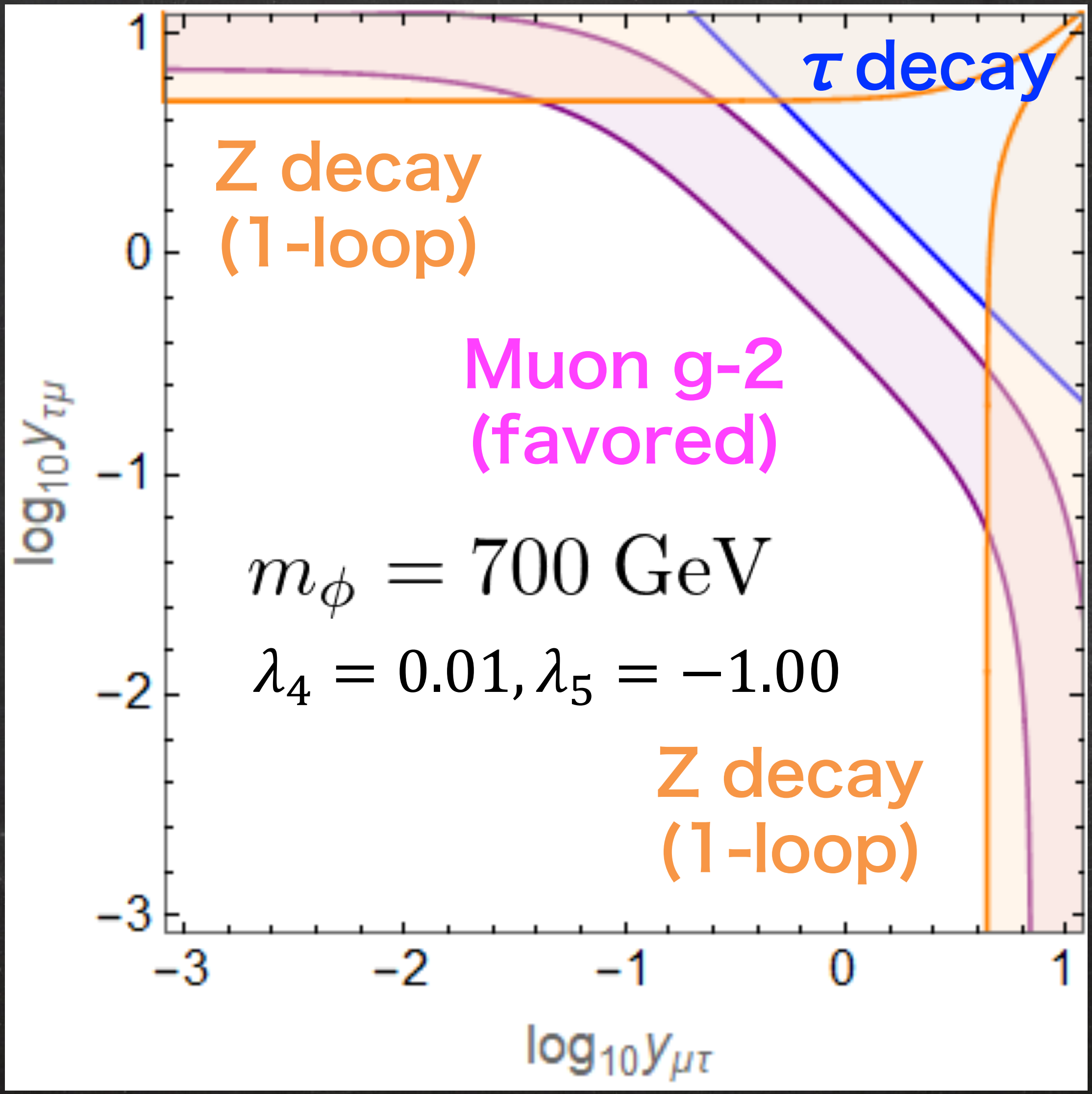
$$\Gamma \simeq \Gamma^{\rm SM}\left(1 + \frac{|y_{\mu\tau}|^2 |y_{\tau\mu}|^2}{32 G_F^2 M_\phi^2}\right)$$

- Z decay @ 1-loop

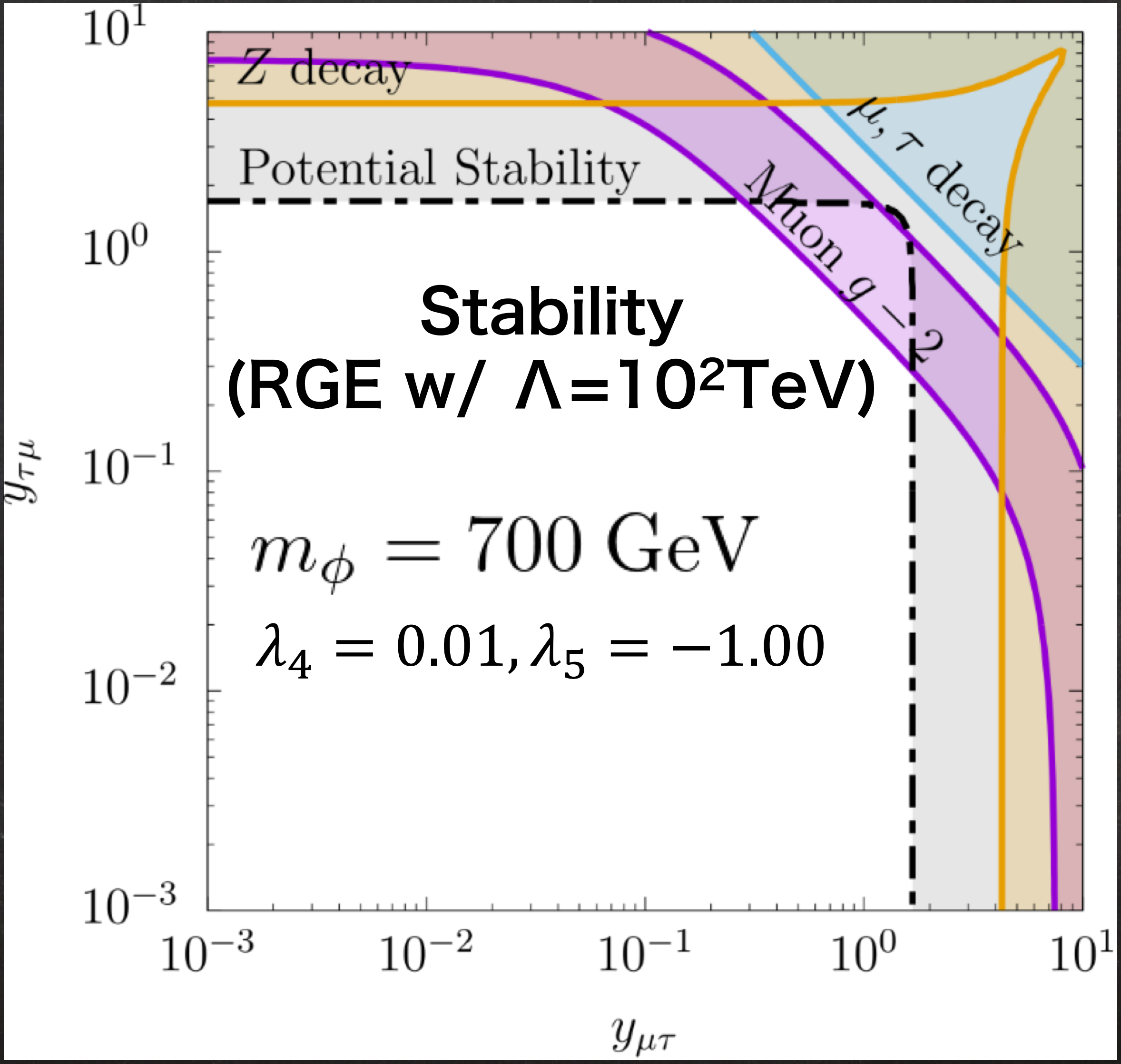
$$\delta g^L_{Z\mu\bar{\mu}}, \delta g^R_{Z\tau\bar{\tau}} \propto |y_{\tau\mu}|^2, \quad \delta g^R_{Z\mu\bar{\mu}}, \delta g^L_{Z\tau\bar{\tau}} \propto |y_{\mu\tau}|^2$$



Constraints on Yukawa plane



Constraints on Yukawa plane



Signals ?

Collider signature

- μ-τ specific scalar from EW pair production

$$\mathcal{B}(\rho, \eta \to \mu\tau) \simeq 100\%$$

⇨ Clear $M_{\tau\mu}$ signal with small LFV BG

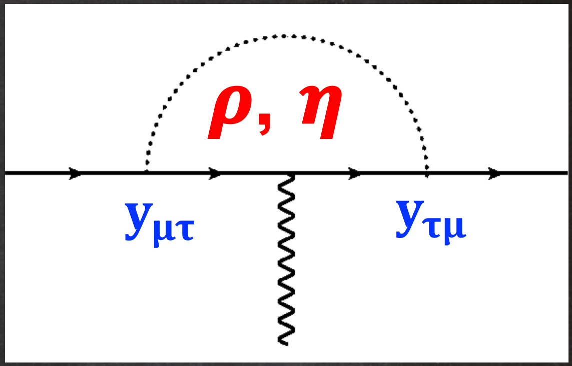
Summary

Contents

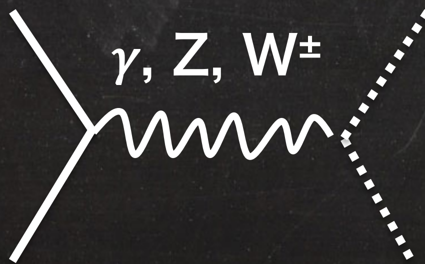
- Muon g-2
- Flavor Symmetry
  - $U(1)_{\mu-\tau}$
  - Z_n
- Minimal Model
  - g-2
  - LHC, EW precision data, Lepton Universality, …
  - Signature
- Summary

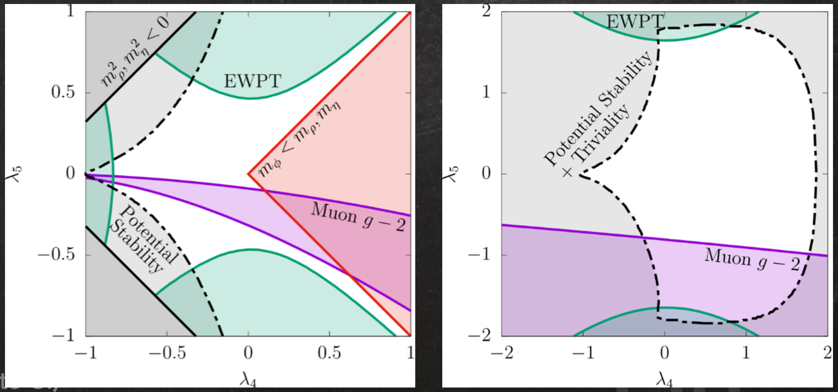
Summary

- Muon g-2 → 3.7σ anomaly
- Flavor Symmetry
  - $U(1)_{\mu-\tau}$
  - Z_n



- Minimal Model → Z_4 symmetry w/ 1 more scalar doublet
  - g-2 (Chirality enhancement)
  - LHC, EW precision data, Lepton Universality, …
  - Signature





Acknowledgment

Thank you

- The work of KT is supported by the MEXT Grant-in-Aid for Scientific Research on Innovation Areas (Grant No. 16H00868)
- This visit is supported by The Kyoto University Foundation

Backup

Z_4 model and M_ν

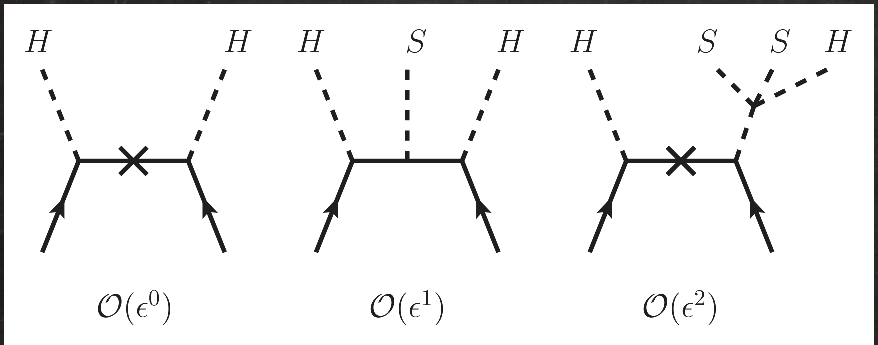
- Large neutrino mixing

Choubey, Rodejohann (05)
Ota, Rodejohann (06)

$$M_\nu \propto \begin{pmatrix} m_{11} & & \\ & & m_{23} \\ & m_{23} & \end{pmatrix}$$

- Symmetry breaking by S

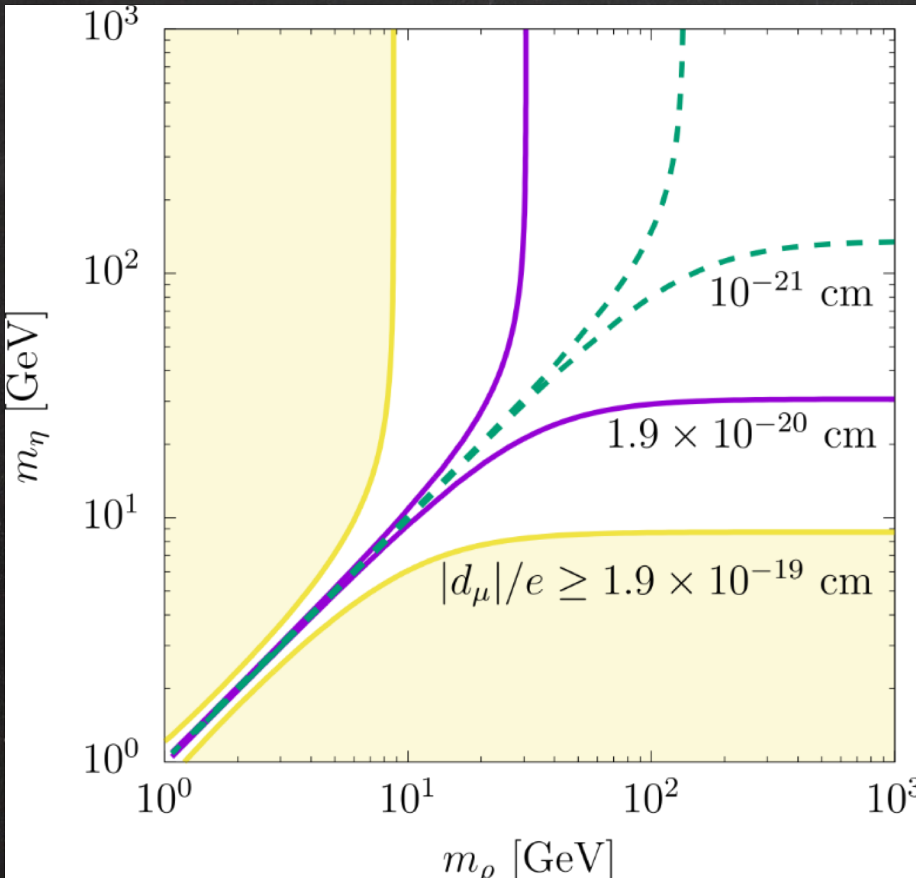
$$M_\nu \propto \begin{pmatrix} m_{11} & \epsilon_{12}\langle S^* \rangle & \epsilon_{13}\langle S \rangle \\ \epsilon_{12}\langle S^* \rangle & \mathcal{O}(\kappa\epsilon^2) & m_{23} \\ \epsilon_{13}\langle S \rangle & m_{23} & \mathcal{O}(\kappa\epsilon^2) \end{pmatrix}$$



Induced VEV for Φ

$$+\kappa\, S^2 H^\dagger \Phi$$

Muon EDM



$$\frac{d_\mu}{e} \simeq \frac{\mathrm{Im}(y_{\mu\tau} y_{\tau\mu})}{2(4\pi)^2}\left[-\frac{M_\tau \lambda_5 v^2}{6M_\phi^4}\right]$$

$$\mathrm{Im}(y_{\mu\tau} y_{\tau\mu}) = 1.00$$

(Depend of Imaginary Part, Not guaranteed)