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A Large Muon EDM from Dark Matter

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with

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Based on JHEP02(2023)234

Introduction

- Anomalous magnetic moment of the muon is one of the well-studied observable — both theoretically and experimentally

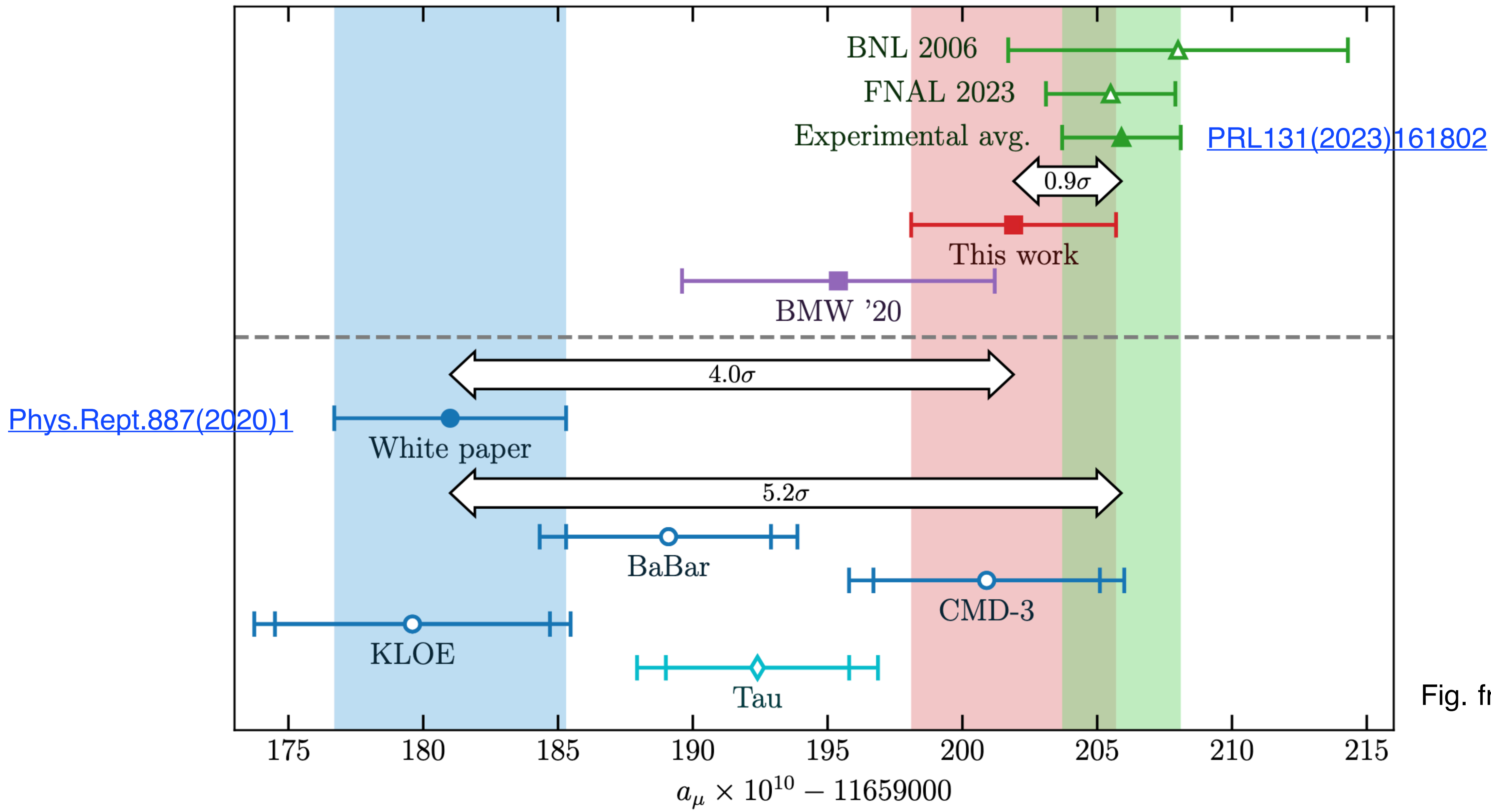

Fig. from 2407.10913

- Large room for new physics (until yesterday…?) WP25, 2505.21476

Introduction

- Lots of NP models for explanation of muon g-2:

  Two Higgs doublet model, L_μ-L_τ model, leptoquarks, SUSY, …

- But, how about muon electric dipole moment (μEDM)???

  NP models generally have additional (and physical) CP phases

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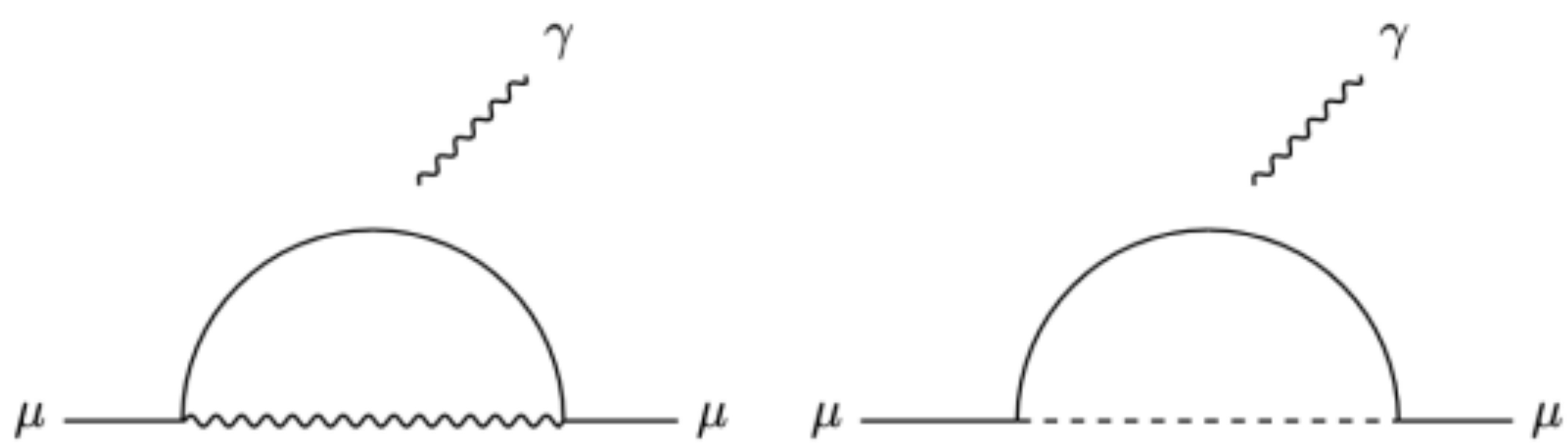
- g-2 and EDM are originated from same diagrams:



- If similar contributions to g-2 and EDM, we have

$$|d_\mu| \sim \frac{e}{2m_\mu}\Delta a_\mu \simeq 2.33\times 10^{-22}\left(\frac{\Delta a_\mu}{2.49\times 10^{-9}}\right) e\,\mathrm{cm}$$

Giudice, Paradisi, Passera
JHEP11(2012)113

Introduction

- Current bounds and future prospects:

[1] EPJ Web Conf. 118(2016)01005
[2] PTEP2019(2019)053C02
[3] 2102.08838 [hep-ex]
[4] JPS Conf.Proc. 37(2022)020604
[5] PoS NuFact2021(2022)136
[6] PRL93(2004)052001

$$|d_\mu| < \begin{cases} 1.8\times10^{-19}\,e\,\mathrm{cm} & (95\%\,\mathrm{C.L.,\ direct\ bound}) \\ 6.3\times10^{-21}\,e\,\mathrm{cm} & (90\%\,\mathrm{C.L.,\ indirect\ bound}) \\ 8.4\times10^{-28}\,e\,\mathrm{cm} & (90\%\,\mathrm{C.L.,\ MFV\ bound}) \end{cases}$$

Muon (g-2) collab. PRD80(2009)052008
Ema, Gao, Pospelov, PRL128(2022)131803, PLB835(2022)137496
MFV bound: $|d_\mu| = |m_\mu/m_e| \times |d_e|$

	$|d_\mu|$[e cm]	Ref.
Fermilab $(g-2)$ exp.	10^{-21}	[1]
J-PARC	$\mathcal{O}(10^{-21})$	[2]
PSI	6×10^{-23}	[3-5]
J-PARC (dedicated)	10^{-24}	[6]

- Large μEDM is interesting, but naive extension is severely constrained by electron EDM… ($|d_e| < 4.1\times10^{-30}$ e cm!) JILA exp.

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Different structure for e and μ is required!

e.g., μ-specific 2HDM, μ-LQ model, radiative muon mass model, …

Introduction

- Radiative muon mass model (m_μ-rad. model) JHEP05(2021)174 for g-2

  Exotic particles only couple to the muon (and Higgs)

- Essence: $d_\mu \propto \frac{y_\phi y_\eta}{16\pi^2} \frac{1}{M_{\rm exo.}} = \frac{|m_\mu^{\rm rad}|}{M_{\rm exo.}^2} \times (\text{loop func.})$

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  loop factor disappears!

- Comparison with other models

$$d_\mu \sim \delta_{\text{CPV}} \times \begin{cases} \left(\frac{\lambda^2}{16\pi^2}\right)^k \frac{m_\mu}{M_{\text{NP}}^2} & (\text{Spurion}) \\ \frac{y_{\mu f}^2}{\lambda^2}\left(\frac{\lambda^2}{16\pi^2}\right)^k \frac{m_f}{M_{\text{NP}}^2} & (\text{Flavor changing}) \\ \frac{|m_\mu^{\text{rad}}|}{M_{\text{NP}}^2}\left(= \frac{m_\mu}{M_{\text{NP}}^2}\right) & (\text{Radiative stability}) \end{cases}$$

Model examples:
→ 2HDM, SUSY
→ L_μ-L_τ, LQ model
→ This model

Even when M_{NP} = O(TeV), our model can predict large μEDM!

m_μ-rad. model

- Model details

Exotic particles (ψ_L, ψ_R, ϕ, η)

	L_L^μ	μ_R	H	ψ_L	ψ_R	ϕ	η	
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	
Y	$-\frac{1}{2}$	-1	$\frac{1}{2}$	0	0	$\frac{1}{2}$	1	
L_μ	$-$	$-$	$+$	$+$	$+$	$-$	$-$	→ avoid LFV constraints
X	$+$	$+$	$+$	$-$	$-$	$-$	$-$	→ DM stability
S_a	$+$	$-$	$+$	$+$	$+$	$+$	$-$	→ no tree y_μ coupling

JHEP05(2021)174 for g-2

Class 1 w/ $Y_\psi = 0$

$$\mathcal{L} \supset \left(-y_\phi \overline{L_L^\mu}\phi^\dagger \psi_R - y_\eta \overline{\psi}_L \eta \mu_R - m_D \overline{\psi}_L \psi_R - \frac{m_{LL}}{2}\overline{\psi}_L \psi_L^c - \frac{m_{RR}}{2}\overline{\psi_R^c}\psi_R + \mathrm{h.c.}\right) - V_{\rm scl}\,,$$

⇨

$$V_{\rm scl} = \sum_{s=H,\phi,\eta}\left[m_s^2 s^\dagger s + \frac{\lambda_s}{2}(s^\dagger s)^2\right] + \lambda_{H\phi}(H^\dagger H)(\phi^\dagger\phi) + \lambda_{H\eta}(H^\dagger H)(\eta^\dagger\eta) + \lambda_{\phi\eta}(\phi^\dagger\phi)(\eta^\dagger\eta)$$

$$+\lambda'_{H\phi}(H^\dagger\phi)(\phi^\dagger H) + \left(aH\eta^\dagger\phi + \frac{\lambda''_{H\phi}}{2}(H^\dagger\phi)^2 + \mathrm{h.c.}\right)\,.$$

m$_\mu$-rad. model

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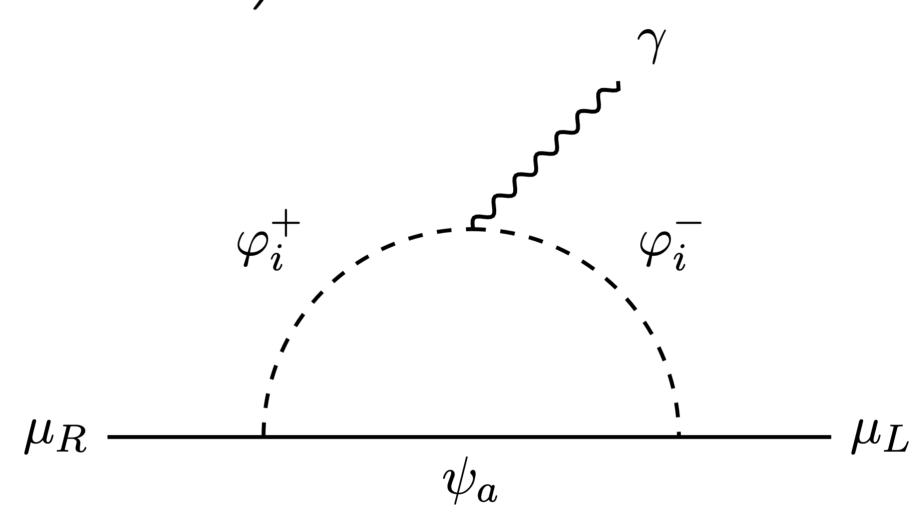
physical CP phase: $\theta_{\text{phys}} = \frac{1}{2} \arg \left(\frac{m_{LL} m_{RR}}{m_D^2} \right)$

$$V_{\text{scl}} = \sum_{s=H,\phi,\eta} \left[m_s^2 s^\dagger s + \frac{\lambda_s}{2} (s^\dagger s)^2 \right] + \lambda_{H\phi} (H^\dagger H)(\phi^\dagger \phi) + \lambda_{H\eta} (H^\dagger H)(\eta^\dagger \eta) + \lambda_{\phi\eta} (\phi^\dagger \phi)(\eta^\dagger \eta)$$
$$+ \lambda'_{H\phi} (H^\dagger \phi)(\phi^\dagger H) + \left(a H \eta^\dagger \phi + \frac{\lambda''_{H\phi}}{2} (H^\dagger \phi)^2 + \text{h.c.} \right) .$$

- g-2 and μEDM are predicted by

  also, rad. muon mass w/o photon



m_μ-rad. model

- Dark matter candidate: ψ_a … totally singlet under G_{SM}

  we check the DM relic density via [micrOMEGAs]

- Other constraints on the model

  ✓ h → $\mu^+\mu^-$ decay $\kappa_\mu = \sqrt{\frac{\Gamma(h \to \mu^+\mu^-)|_{\text{SM+NP}}}{\Gamma(h \to \mu^+\mu^-)|_{\text{SM}}}} \simeq 1$

  ✓ Z → $\mu^+\mu^-$ decay $\frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} = 1.0009 \pm 0.0028$

  ⇒ Small NP effects

  PLB812(2021)135980, JHEP01(2021)148
  Phys.Rept.427(2006)257

  ✓ Perturbative unitarity of scalar couplings

  ✓ Collider searches … exotic particles should be enough heavy

- We explore a viable parameter space for large μEDM, together with prediction of the muon g-2

m_μ-rad. model

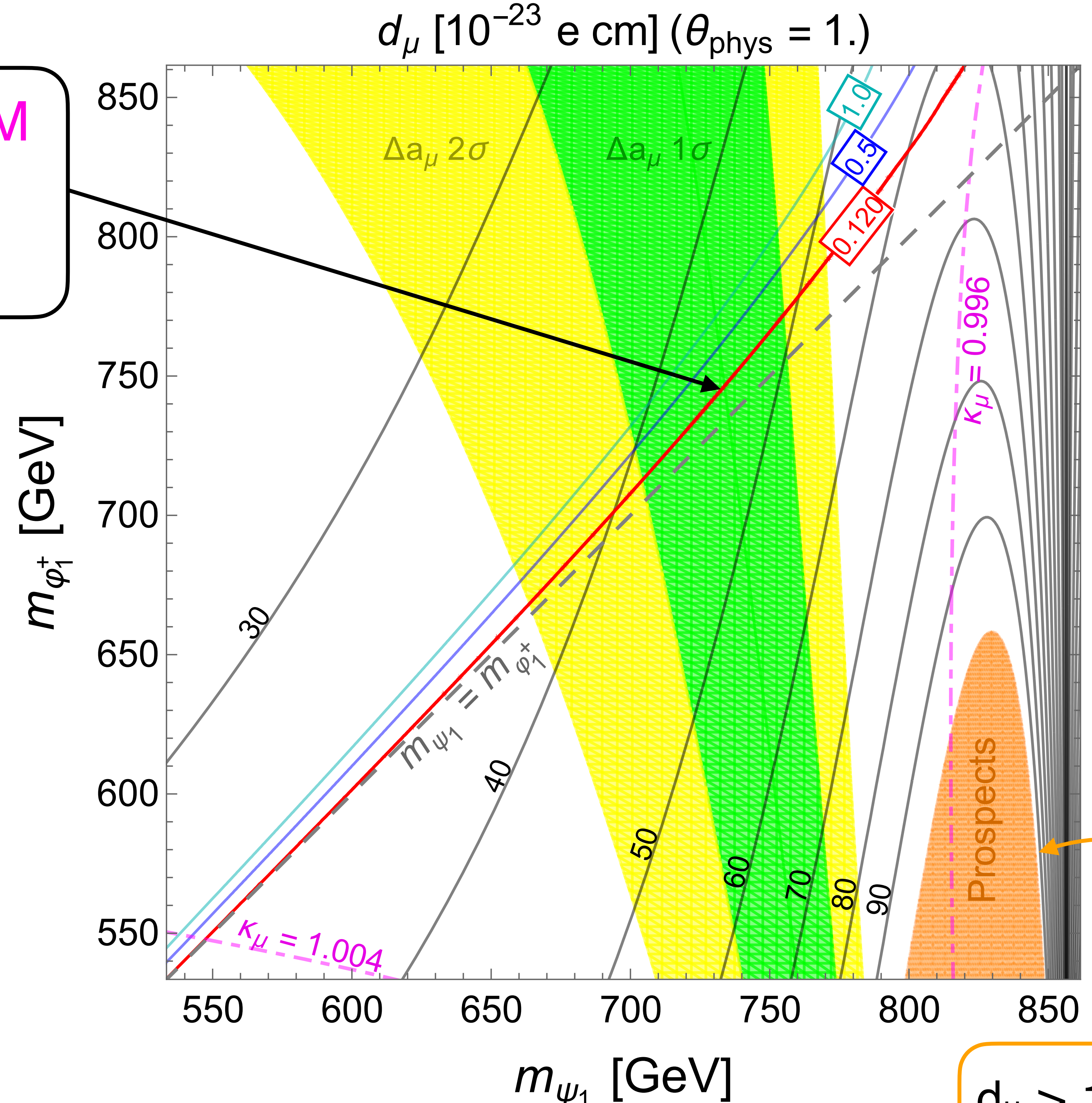
- Result

Relevant parameters:

$$(540\,\mathrm{GeV})^2 \le M_\eta^2 \le (1000\,\mathrm{GeV})^2,\ 320\,\mathrm{GeV} \le m_{LL} \le 1200\,\mathrm{GeV}$$

$$\text{with} \begin{cases} y_\phi = 1.2,\ M_\phi^2 = (1000\,\mathrm{GeV})^2,\ a = 900\,\mathrm{GeV}, \\ m_D = 700\,\mathrm{GeV},\ m_{RR} = 1000\,\mathrm{GeV},\ \theta_{\mathrm{phys}} = 1.0 \end{cases}$$

✓ Large μEDM
✓ Proper g-2
✓ DM relic



$d_\mu > 10^{-21}$ is also predicted

m_μ-rad. model

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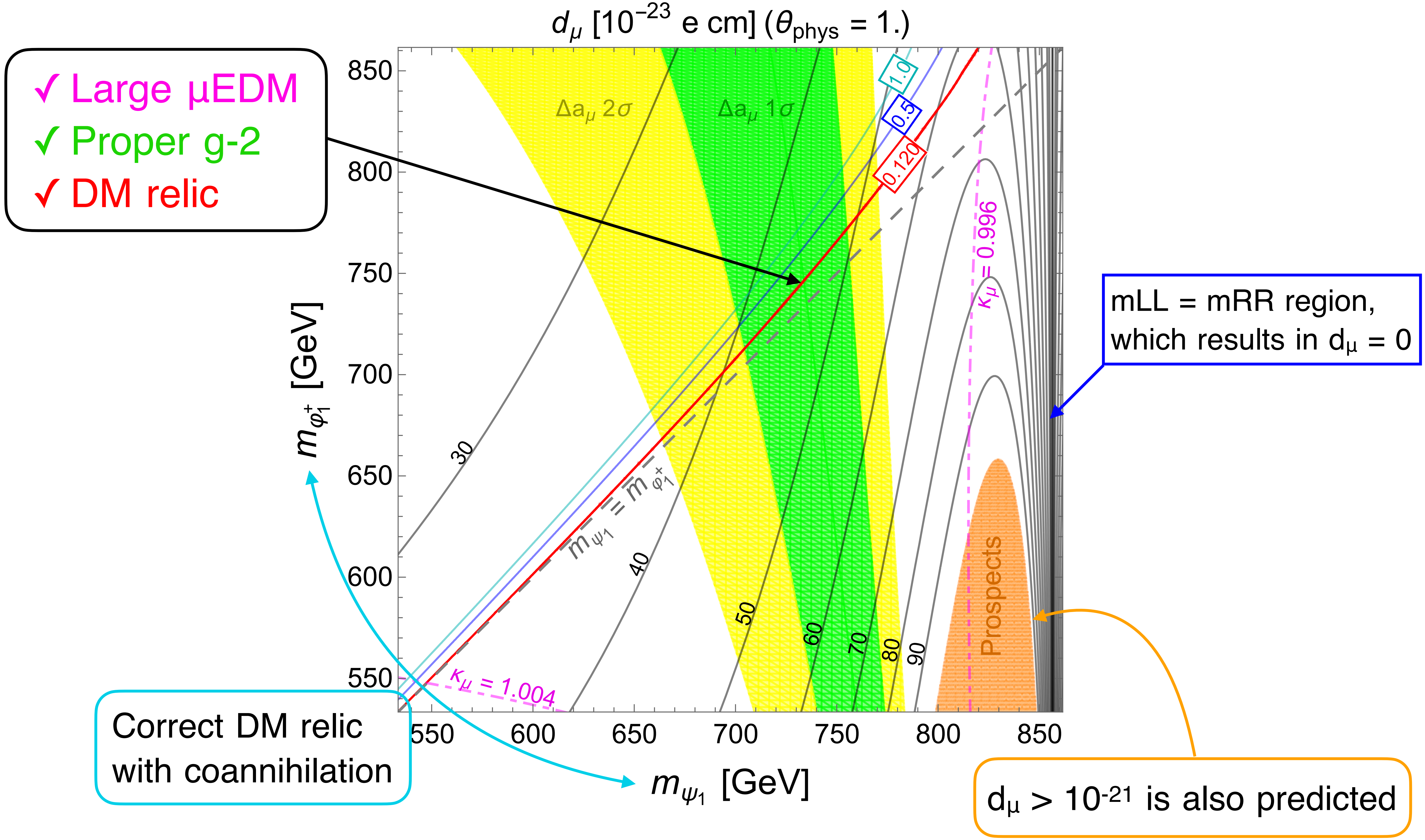

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- Result, w/ WP25 2505.21476

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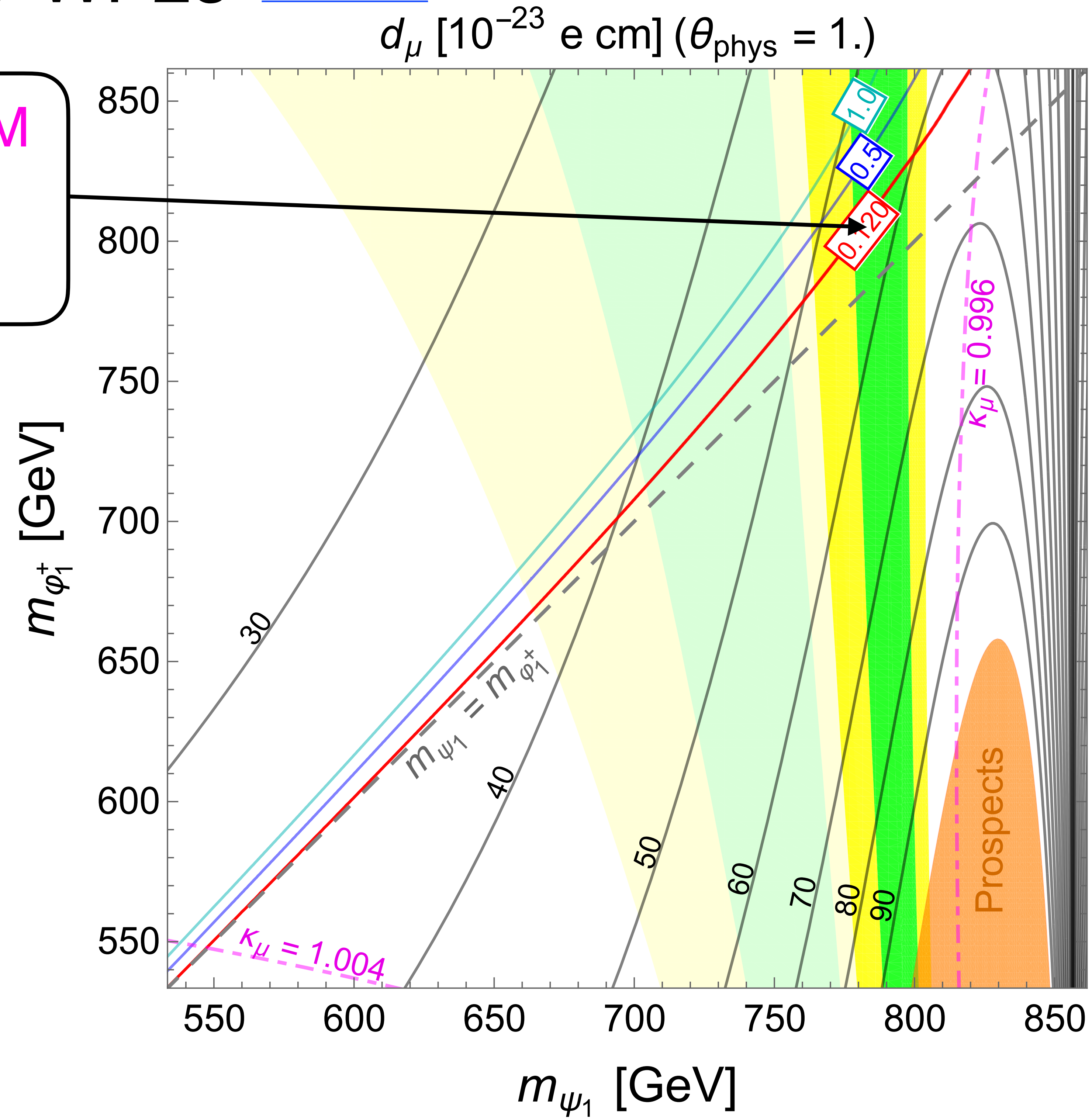


Summary

- We explore prediction of μEDM in m_μ-rad. model
- Exotic particles play roles of:
  - ✓ muon mass generation
  - ✓ muon g-2 and EDM contribution
  - ✓ DM candidate (Majorana fermion DM)
- We found large μEDM (~ $O(10^{-22})$ e.cm!) with
  - ★ consistent with g-2 deviation
  - ★ explain current DM relic density
- Our model can be tested at future experiments!

  PSI, Fermilab, J-PARC, …

Thank you!

Back up

m_μ-rad. model

- Radiative muon mass

$$m_\mu^{\rm rad} = \frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4}\mathcal{F}(x_{1,1},x_{1,2},x_{2,1},x_{2,2}) \;\Rightarrow\; \frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4} = \frac{m_\mu^{\rm exp}}{|\mathcal{F}(x_{1,1},x_{1,2},x_{2,1},x_{2,2})|}$$

$$\mathcal{F}(x_{1,1},x_{1,2},x_{2,1},x_{2,2}) = m_{\psi_1}e^{-i\tau}\left(\frac{x_{1,1}\ln x_{1,1}}{x_{1,1}-1} - \frac{x_{2,1}\ln x_{2,1}}{x_{2,1}-1}\right) - m_{\psi_2}e^{i\tau}\left(\frac{x_{1,2}\ln x_{1,2}}{x_{1,2}-1} - \frac{x_{2,2}\ln x_{2,2}}{x_{2,2}-1}\right)$$

$$\text{w/ } x_{j,a} = \frac{m^2_{\varphi_j^+}}{m^2_{\psi_a}}$$

need chiral rotation for μ field, $\mu \to e^{-i\theta_\mu\gamma_5/2}\mu$, for real mass

- Dipole operators change as

$$\mathcal{L}_{\rm dipole} = \frac{e}{2}C_T(q^2)\left(\bar\mu\sigma^{\alpha\beta}\mu\right)F_{\alpha\beta} + \frac{e}{2}C_{T'}(q^2)\left(\bar\mu i\sigma^{\alpha\beta}\gamma_5\mu\right)F_{\alpha\beta}$$

$$\to -\frac{e}{4m_\mu}a_\mu\left(\bar\mu\sigma^{\alpha\beta}\mu\right)F_{\alpha\beta} - \frac{i}{2}d_\mu\left(\bar\mu i\sigma^{\alpha\beta}\gamma_5\mu\right)F_{\alpha\beta}$$

$$a_\mu = 2m_\mu\left(C_T(0)\cos\theta_\mu + C_{T'}(0)\sin\theta_\mu\right)$$

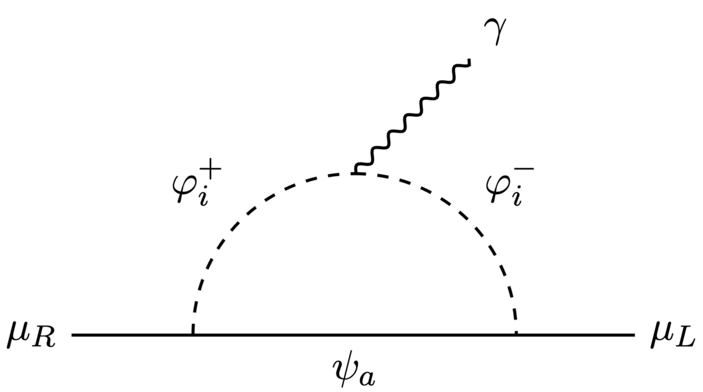
$$d_\mu = e\left(C_{T'}(0)\cos\theta_\mu + C_T(0)\sin\theta_\mu\right)$$

$$m_\mu^{\rm rad} = |m_\mu^{\rm rad}|e^{i\theta_\mu}\,,\;\; |m_\mu^{\rm rad}| = m_\mu^{\rm exp}$$

m_μ-rad. model

- Radiative muon mass

$$m_\mu^{\rm rad} = \frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4}\mathcal{F}(x_{1,1},x_{1,2},x_{2,1},x_{2,2}) \Rightarrow \boxed{\frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4}} = \frac{m_\mu^{\rm exp}}{|\mathcal{F}(x_{1,1},x_{1,2},x_{2,1},x_{2,2})|}$$



$$C_T(q^2), C_{T'}(q^2)$$

- Coefficients of dipole operators (with $q^2 = 0$)

$$C_T(0) = \boxed{\frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4}}\cos\tau\sum_{j,a=1}^{2}(-1)^{j+a}\frac{x_{j,a}^2-1-2x_{j,a}\ln x_{j,a}}{2m_{\psi_a}(1-x_{j,a})^3}$$

$$C_{T'}(0) = \boxed{\frac{y_\phi y_\eta}{16\pi^2}\frac{s_{2\theta}s_{2\alpha}}{4}}\sin\tau\sum_{j,a=1}^{2}(-1)^{j}\frac{x_{j,a}^2-1-2x_{j,a}\ln x_{j,a}}{2m_{\psi_a}(1-x_{j,a})^3}$$

⇨ a_μ and d_μ are $\sim \dfrac{m_\mu^2}{M_{\rm NP}^2}$ and $\sim \dfrac{m_\mu}{M_{\rm NP}^2}$, without loop factor!

m_μ-rad. model

- Mass eigenstates for exotic particles
  - Charged scalars (all elements are real and positive)

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\sigma_\phi + i a_\phi) \end{pmatrix}, \quad \eta = \eta^+$$

$$\mathcal{M}_\pm^2 = \begin{pmatrix} m_\phi^2 + \frac{\lambda_{H\phi}}{2} v_H^2 & \frac{a v_H}{\sqrt{2}} \\ \frac{a v_H}{\sqrt{2}} & m_\eta^2 + \frac{\lambda_{H\eta}}{2} v_H^2 \end{pmatrix} \Rightarrow \begin{cases} \phi^\pm = +\varphi_1^\pm c_\theta + \varphi_2^\pm s_\theta \\ \eta^\pm = -\varphi_1^\pm s_\theta + \varphi_2^\pm c_\theta \end{cases}$$

  - Majorana fermions (mLL, mRR and mD are real and positive parameters)

$$\mathcal{M}_\psi = \begin{pmatrix} m_{LL} & m_D e^{-i\theta_{\rm phys}} \\ m_D e^{-i\theta_{\rm phys}} & m_{RR} \end{pmatrix} \Rightarrow \begin{cases} \psi_L = +\psi_1^c c_\alpha + \psi_2^c s_\alpha e^{-i\tau} \\ \psi_R = -\psi_1 s_\alpha e^{-i\tau} + \psi_2 c_\alpha \end{cases}$$

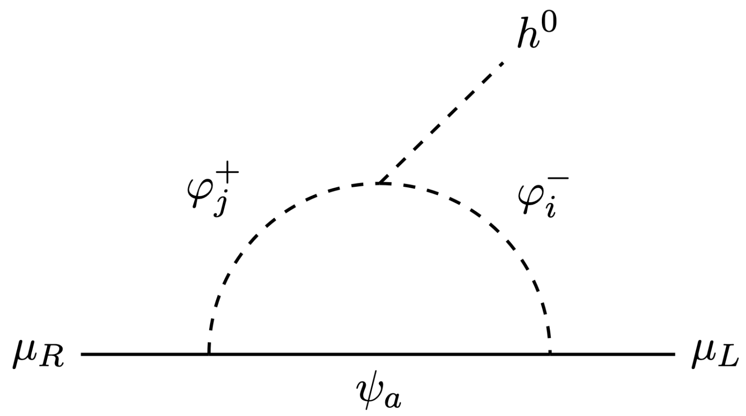
- More detailed calculation for Majorana fermion sector

off-diagonal element gives $\left(m_{\psi_2}^2 - m_{\psi_1}^2\right) s_\alpha c_\alpha e^{i\tau} = m_D \left(m_{LL} e^{-i\theta_{\rm phys}} + m_{RR} e^{i\theta_{\rm phys}}\right)$

$$\Rightarrow \quad \tan\tau = -\frac{m_{LL} - m_{RR}}{m_{LL} + m_{RR}} \tan\theta_{\rm phys}$$

m_μ-rad. model — constraints

- Effective muon Yukawa coupling: $\mathcal{L}_{\rm eff} \supset -\frac{y_\mu^{\rm eff}}{\sqrt{2}} \bar{\mu}_L \mu_R h^0 + {\rm h.c.}$



… Due to complex couplings, $y_\mu^{\rm eff}$ is complex

- Partial decay width, $h \to \mu^+\mu^-$

$$\Gamma_{h\to\mu^+\mu^-} = \frac{m_h}{16\pi^2}\sqrt{1-\frac{4m_\mu^2}{m_h^2}}\left[\left(1-\frac{4m_\mu^2}{m_h^2}\right)\left({\rm Re}\, y_\mu^{\rm eff}\right)^2 + \left({\rm Im}\, y_\mu^{\rm eff}\right)^2\right]$$

- Experiments constrain the size of ratio of Γ:

$$|\kappa_\mu| \equiv \sqrt{\frac{\Gamma_{h\to\mu^+\mu^-}}{\Gamma^{\rm SM}_{h\to\mu^+\mu^-}}} = \frac{1}{\sqrt{2}}\frac{v_H}{m_\mu}\sqrt{\left({\rm Re}\, y_\mu^{\rm eff}\right)^2 + \left(1-\frac{4m_\mu^2}{m_h^2}\right)^{-1}\left({\rm Im}\, y_\mu^{\rm eff}\right)^2}$$

exp. constraints: $\text{ATLAS: } |\kappa_\mu| < 1.47, \quad \text{CMS: } 0.61 < |\kappa_\mu| < 1.44$

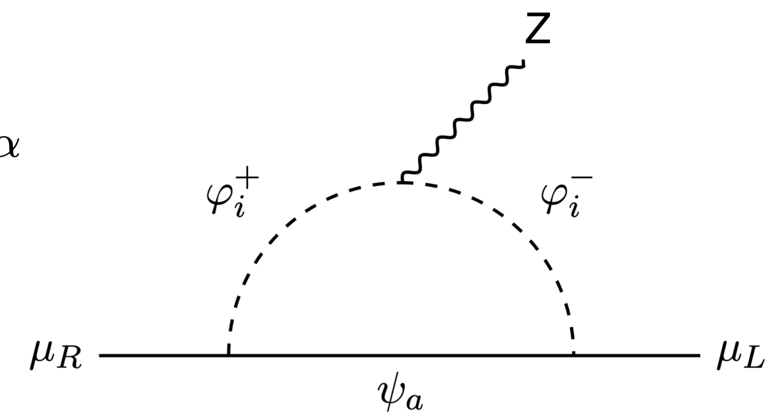
PLB812(2021)135980 JHEP01(2021)148

m_μ-rad. model — constraints

- $Z \to \mu^+\mu^-$ decay:

$$\mathcal{L}_Z \supset \frac{g}{c_W}\bar{\mu}\gamma^\alpha\left[\left(-\frac{1}{2}+s_W^2+\delta g_L^\mu\right)P_L+\left(s_W^2+\delta g_R^\mu\right)P_R\right]\mu Z_\alpha$$

NP contributions to Z-μ coupling:



- Ratio of partial decay width

$$\frac{\Gamma(Z\to\mu^+\mu^-)}{\Gamma(Z\to e^+e^-)} \simeq 1+\frac{2g_L^e\mathrm{Re}\left(\delta g_L^\mu\right)+2g_R^e\mathrm{Re}\left(\delta g_R^\mu\right)}{(g_L^e)^2+(g_R^e)^2}$$

$$g_L^e=-\frac{1}{2}+s_W^2,\quad g_R^e=s_W^2$$

- LO contributions from m_μ-rad. model JHEP04(2021)151

$$\delta g_L^\mu \simeq \frac{y_\phi^2}{128\pi^2}\sin^2(2\theta)\left(g_\eta-g_\phi\right)F_Z^{(1)}(x_1,x_2)$$

$$\delta g_R^\mu \simeq -\frac{y_\eta^2}{128\pi^2}\sin^2(2\theta)\left(g_\eta-g_\phi\right)F_Z^{(1)}(x_1,x_2)$$

$$\text{w/ } g_\phi=\frac{1}{2}-s_W^2\,,\ g_\eta=-s_W^2\,,\ x_j=\frac{m_{\varphi_j^+}^2}{m_\psi^2}$$

Loop function: $F_Z^{(1)}=\frac{1}{x_1-x_2}\left(\frac{x_2^2+x_1x_2-2x_1}{(x_2-1)^2}x_2\ln x_2-\frac{x_1^2+x_1x_2-2x_2}{(x_1-1)^2}x_1\ln x_1\right)+2+\frac{1}{x_1-1}+\frac{1}{x_2-1}$