Extended Ma model and dark matter

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based on
SB, Hiroshi Okada, Kei Yagyu, JHEP 1504 (2015) 049 [arXiv:1501.01530];
SB, Work in progress

Outline

- The Model: extension of Ma model with gauged L_μ-L_τ symmetry
- Predictions on the neutrino sector
- $(g-2)_{\mu}$, constraints on the model
- Conclusions

The Model

- Ma model + $U(1)_{\mu-\tau}$ gauge symmetry with scalar S

	Lepton Fields			Scalar Fields		
	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N_R^i	Φ	η	S
$SU(2)_L$	**2**	**1**	**1**	**2**	**2**	**1**
$U(1)_Y$	$-1/2$	-1	0	$+1/2$	$+1/2$	0
Z_2	$+$	$+$	$-$	$+$	$-$	$+$

- Allowed Yukawa interactions:

	(L_L^e, e_R, N_R^e)	$(L_L^\mu, \mu_R, N_R^\mu)$	$(L_L^\tau, \tau_R, N_R^\tau)$	S
$U(1)_{\mu-\tau}$	0	$+1$	-1	$+1$

$$
\begin{aligned}
-\mathcal{L}_Y = &\frac{1}{2} M_{ee} \overline{N_R^{ec}} N_R^e + \frac{1}{2} M_{\mu\tau} (\overline{N_R^{\mu c}} N_R^\tau + \overline{N_R^{\tau c}} N_R^\mu) + \text{h.c.} \\
&+ y_e \overline{L_L^e} \Phi e_R + y_\mu \overline{L_L^\mu} \Phi \mu_R + y_\tau \overline{L_L^\tau} \Phi \tau_R + \text{h.c.} \\
&+ h_{e\mu} (\overline{N_R^{ec}} N_R^\mu + \overline{N_R^{\mu c}} N_R^e) S^* + h_{e\tau} (\overline{N_R^{ec}} N_R^\tau + \overline{N_R^{\tau c}} N_R^e) S + \text{h.c.} \\
&+ f_e \overline{L_L^e} (i\sigma_2) \eta^* N_R^e + f_\mu \overline{L_L^\mu} (i\sigma_2) \eta^* N_R^\mu + f_\tau \overline{L_L^\tau} (i\sigma_2) \eta^* N_R^\tau + \text{h.c.}
\end{aligned}
$$

Scalar masses

- Scalar potential:

$$\mathcal{V} = \mu_\Phi^2|\Phi|^2 + \mu_\eta^2|\eta|^2 + \mu_S^2|S|^2$$
$$+ \frac{1}{2}\lambda_1|\Phi|^4 + \frac{1}{2}\lambda_2|\eta|^4 + \lambda_3|\Phi|^2|\eta|^2 + \lambda_4|\Phi^\dagger\eta|^2 + \frac{1}{2}\lambda_5[(\Phi^\dagger\eta)^2 + \text{h.c.}]$$
$$+ \lambda_S|S|^4 + \lambda_{S\Phi}|S|^2|\Phi|^2 + \lambda_{S\eta}|S|^2|\eta|^2,$$

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \varphi_H + iG^0) \end{bmatrix}, \quad \eta = \begin{bmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta_H + i\eta_A) \end{bmatrix}, \quad S = \frac{1}{\sqrt{2}}(v_S + S_H + iG_S),$$

- Scalar masses:

$$m_{\eta^\pm}^2 = \mu_\eta^2 + \frac{v_S^2}{2}\lambda_{S\eta} + \frac{v^2}{2}\lambda_3,$$
$$m_{\eta_A}^2 = \mu_\eta^2 + \frac{v_S^2}{2}\lambda_{S\eta} + \frac{v^2}{2}(\lambda_3 + \lambda_4 - \lambda_5),$$
$$m_{\eta_H}^2 = \mu_\eta^2 + \frac{v_S^2}{2}\lambda_{S\eta} + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5).$$

$$\mathcal{M}_H^2 = \begin{pmatrix} v^2\lambda_1 & vv_S\lambda_{S\Phi} \\ vv_S\lambda_{S\Phi} & 2v_S^2\lambda_S \end{pmatrix}$$

$$\begin{pmatrix} \varphi_H \\ S_H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} \quad \tan 2\alpha = \frac{2(\mathcal{M}_H^2)_{12}}{(\mathcal{M}_H^2)_{11} - (\mathcal{M}_H^2)_{22}}$$

Fermion masses

- Charged leptons, right-handed neutrinos

$$\mathcal{M}_\ell = \frac{v}{\sqrt{2}}\text{diag}(|y_e|, |y_\mu|, |y_\tau|), \quad \mathcal{M}_N = \begin{pmatrix} |M_{ee}| & \frac{v_S}{\sqrt{2}}|h_{e\mu}| & \frac{v_S}{\sqrt{2}}|h_{e\tau}| \\ \frac{v_S}{\sqrt{2}}|h_{e\mu}| & 0 & |M_{\mu\tau}|e^{i\theta_R} \\ \frac{v_S}{\sqrt{2}}|h_{e\tau}| & |M_{\mu\tau}|e^{i\theta_R} & 0 \end{pmatrix}$$

- Diagonalization of right-handed neutrino mass matrix

$$V^T \mathcal{M}_N V = \mathcal{M}_N^{\text{diag}} \equiv \text{diag}(M_1, M_2, M_3)$$

- Neutrino masses from one-loop

$$-\mathcal{L}_Y = + f_e \overline{L_L^e}(i\sigma_2)\eta^* N_R^e + f_\mu \overline{L_L^\mu}(i\sigma_2)\eta^* N_R^\mu + f_\tau \overline{L_L^\tau}(i\sigma_2)\eta^* N_R^\tau + \text{h.c.}$$

$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2} \sum_{k=1\text{-}3} (f_i V_{ik}) M_{N_k} (f_j V_{jk}) \left(\frac{m_{\eta_H}^2}{M_k^2 - m_{\eta_H}^2} \ln \frac{m_{\eta_H}^2}{M_k^2} - \frac{m_{\eta_A}^2}{M_k^2 - m_{\eta_A}^2} \ln \frac{m_{\eta_A}^2}{M_k^2} \right)$$

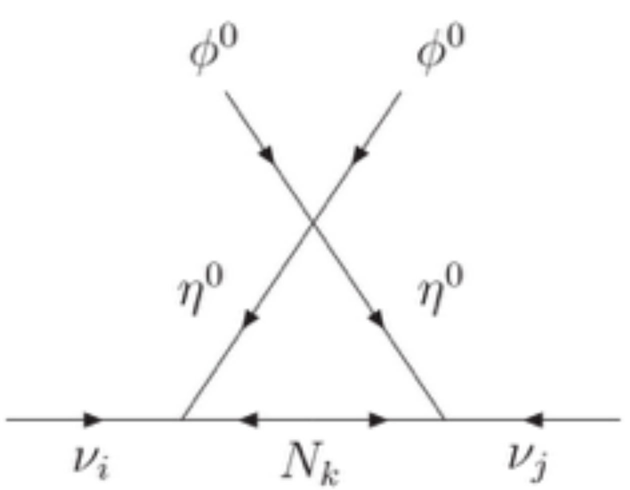


FIG. 1. One-loop generation of neutrino mass.

Neutrino masses and PMNS

- For $m_0^2 \equiv (m_{\eta_H}^2 + m_{\eta_A}^2)/2 \gg M_k^2$, two-zero texture form is obtained from $U(1)_{\mu-\tau}$!!

$$\mathcal{M}_\nu = \begin{pmatrix} f_e^2 M_{11} & f_e f_\mu M_{12} & f_e f_\tau M_{13} \\ f_e f_\mu M_{12} & 0 & f_\mu f_\tau M_{23} e^{i\theta_R} \\ f_e f_\tau M_{13} & f_\mu f_\tau M_{23} e^{i\theta_R} & 0 \end{pmatrix},$$

- 5-indep. parameters→ 9 observables (3 masses, 3 mixing angles, 3 CPV phases) are predicted.
- From 5 neutrino oscillation data,

$$s_{12}^2 = 0.323\ (0.278\text{-}0.375),\quad s_{23}^2 = 0.573\ (0.403\text{-}0.640),\quad s_{13}^2 = 0.0229\ (0.0193\text{-}0.0265),$$

$$\Delta m_{21}^2 = 7.60\ (7.11\text{-}8.18) \times 10^{-5}\ \mathrm{eV}^2,\quad |\Delta m_{31}^2| = 2.38\ (2.20\text{-}2.54) \times 10^{-3}\ \mathrm{eV}^2,$$

we predict, m_1, 3-CPV phases.

Neutrino masses and PMNS

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 0.0408 & -0.0186 & -0.0378 \\ -0.0186 & 0 & -0.0420 - 0.00631i \\ -0.0378 & -0.0420 - 0.00631i & 0 \end{pmatrix} \text{ eV} \quad \text{(BF)},$$

δ=-1.96

$$(m_1, m_2, m_3)\ [\text{eV}] = 0.0583,\ 0.0589,\ 0.0420,\ (\rho, \sigma) = (0.956, -1.34) \quad \text{(BF)},$$

Inverted hierarchy

$(g\text{-}2)_\mu$

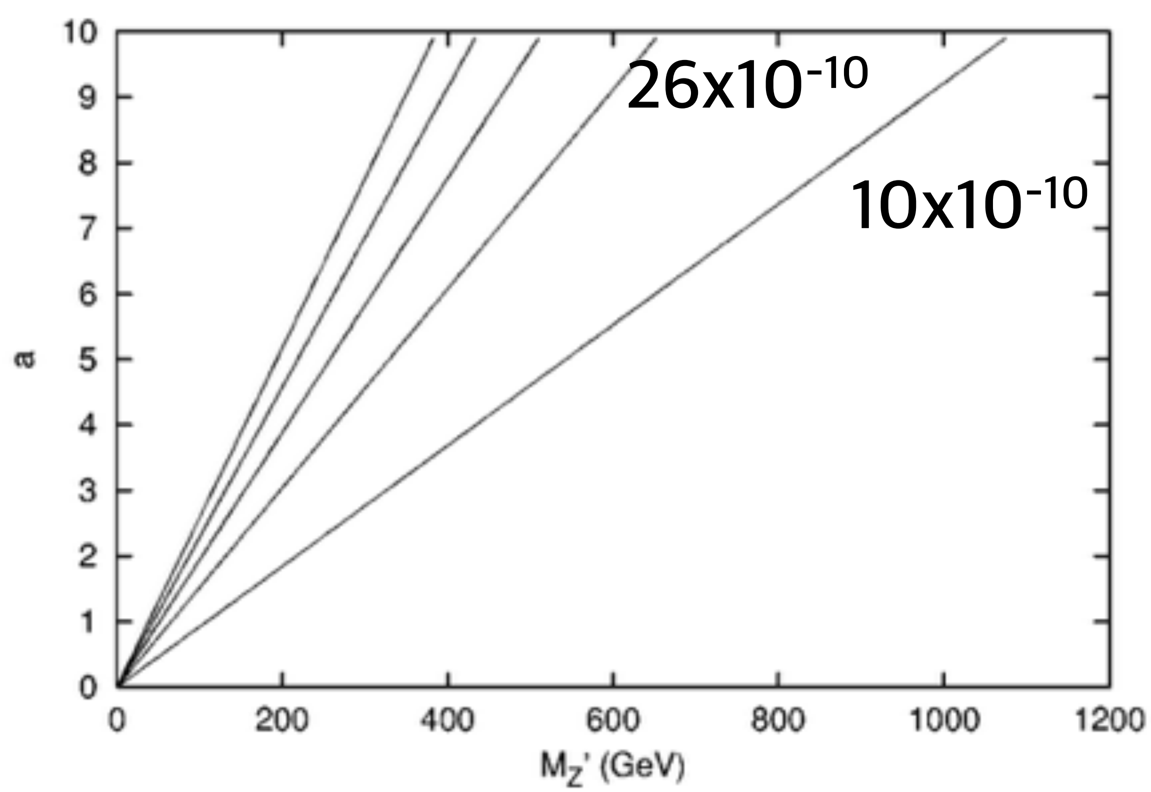
- ~3σ discrepancy

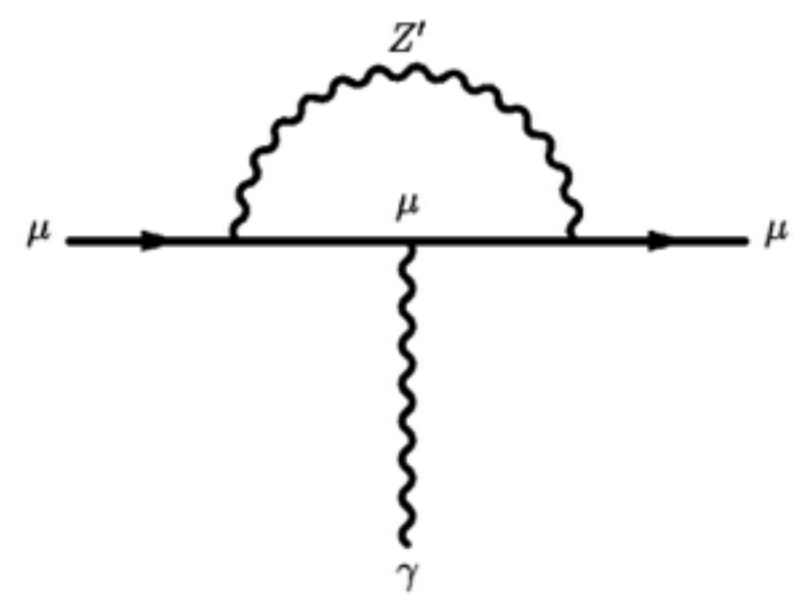
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (29.0 \pm 9.0 \text{ to } 33.5 \pm 8.2) \times 10^{-10}.$$

F. Jegerlehner, A. Nyffeler (2009);
M. Benayoun, et.al.(2012)

- Z' contribution in $U(1)_{\mu-\tau}$ model can accommodate $(g\text{-}2)_\mu$

SB, N. G. Deshpande, X. G. He, P. Ko (2001)



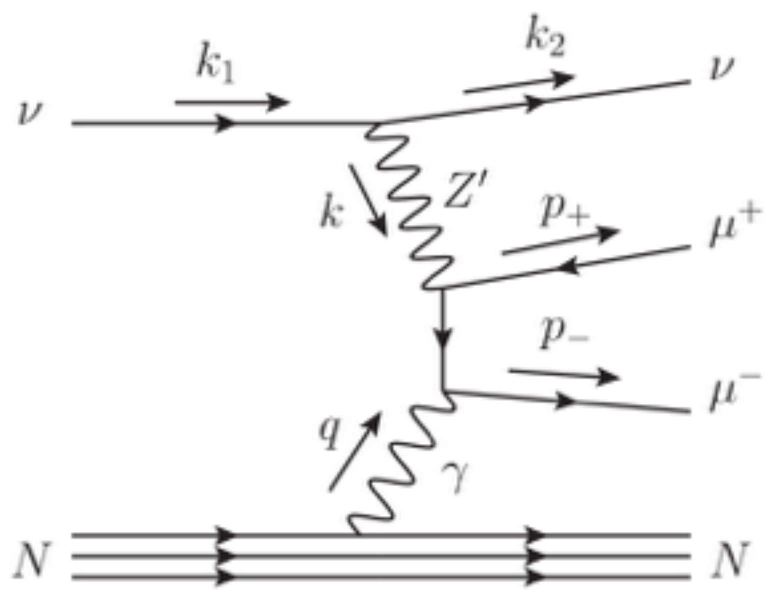


$$L = \frac{ea}{c_W}(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau)Z'_\mu$$

Constraint on $U(1)_{\mu-\tau}$

- Neutrino trident production

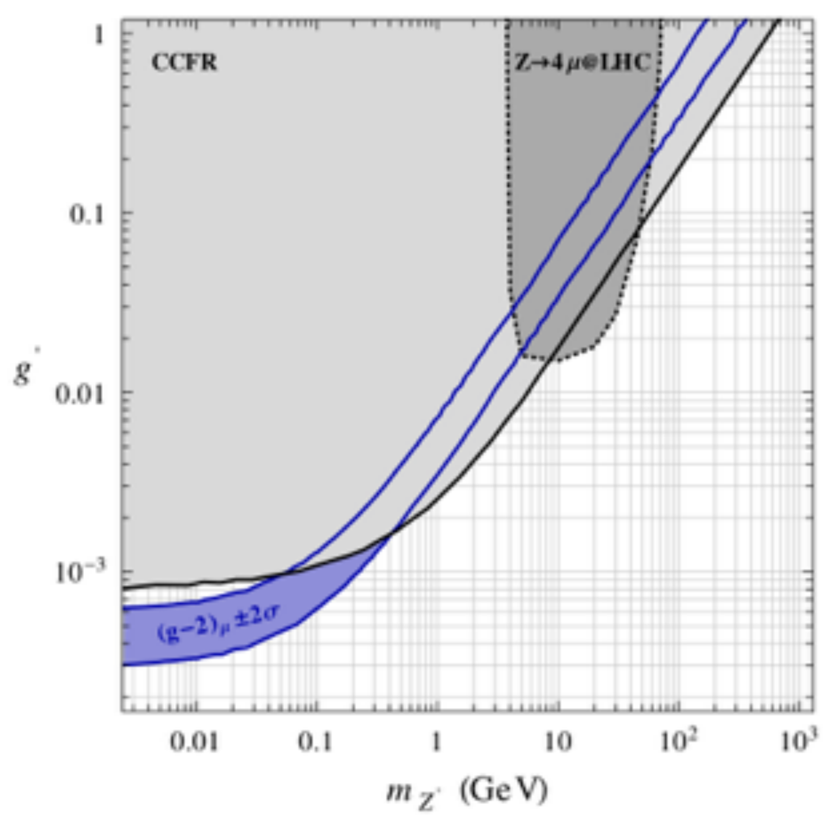
W. Altmannshofer, et.al. (2014)

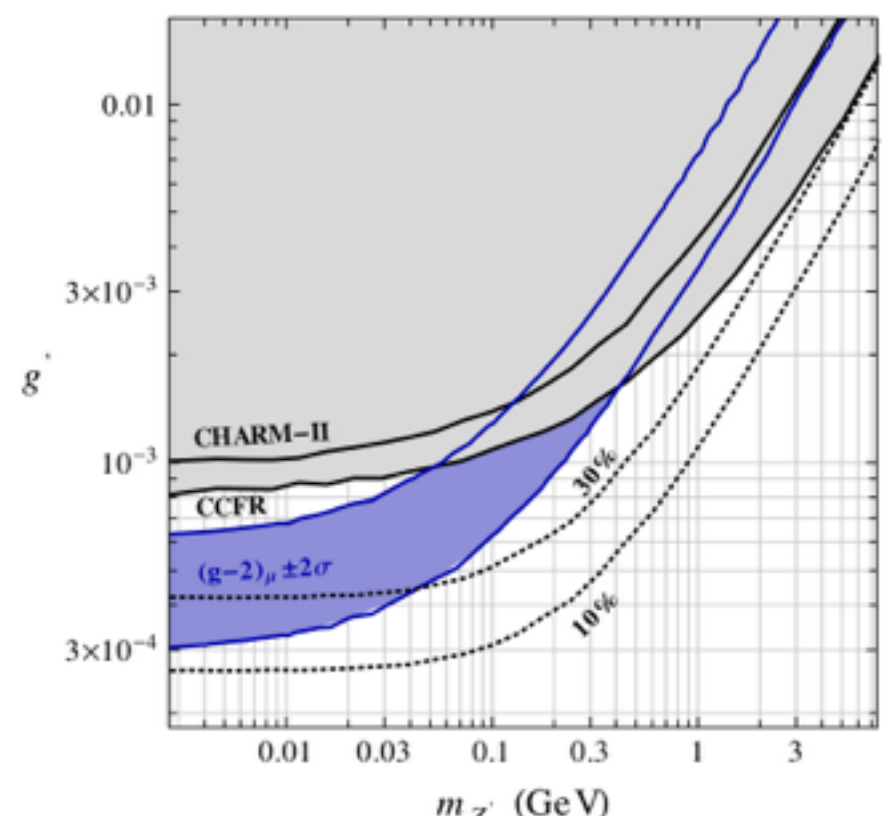


The Z’ contribution is constructive with the SM

$$\sigma_{\text{CHARM-II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57, \quad (1990)$$

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28. \quad (1991)$$

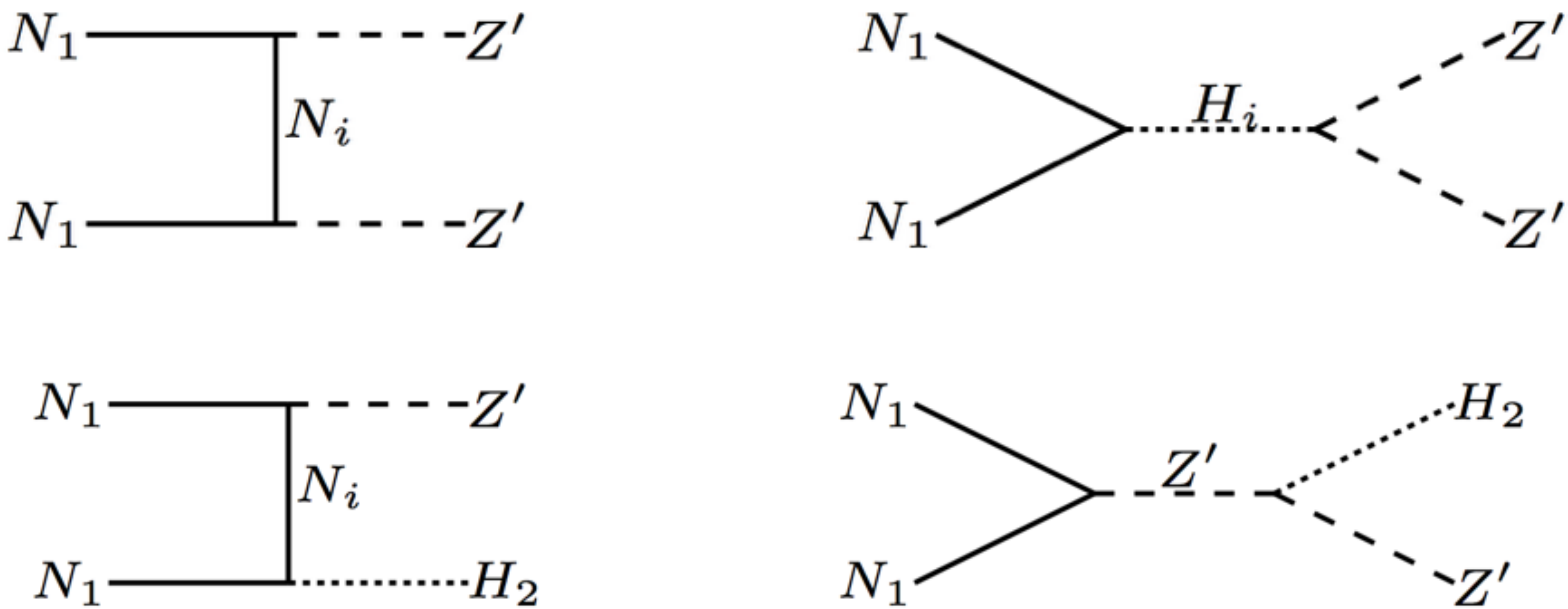




$M_{Z'}$<400MeV can account for the discrepancy in $(g-2)_\mu$

Relic density of DM

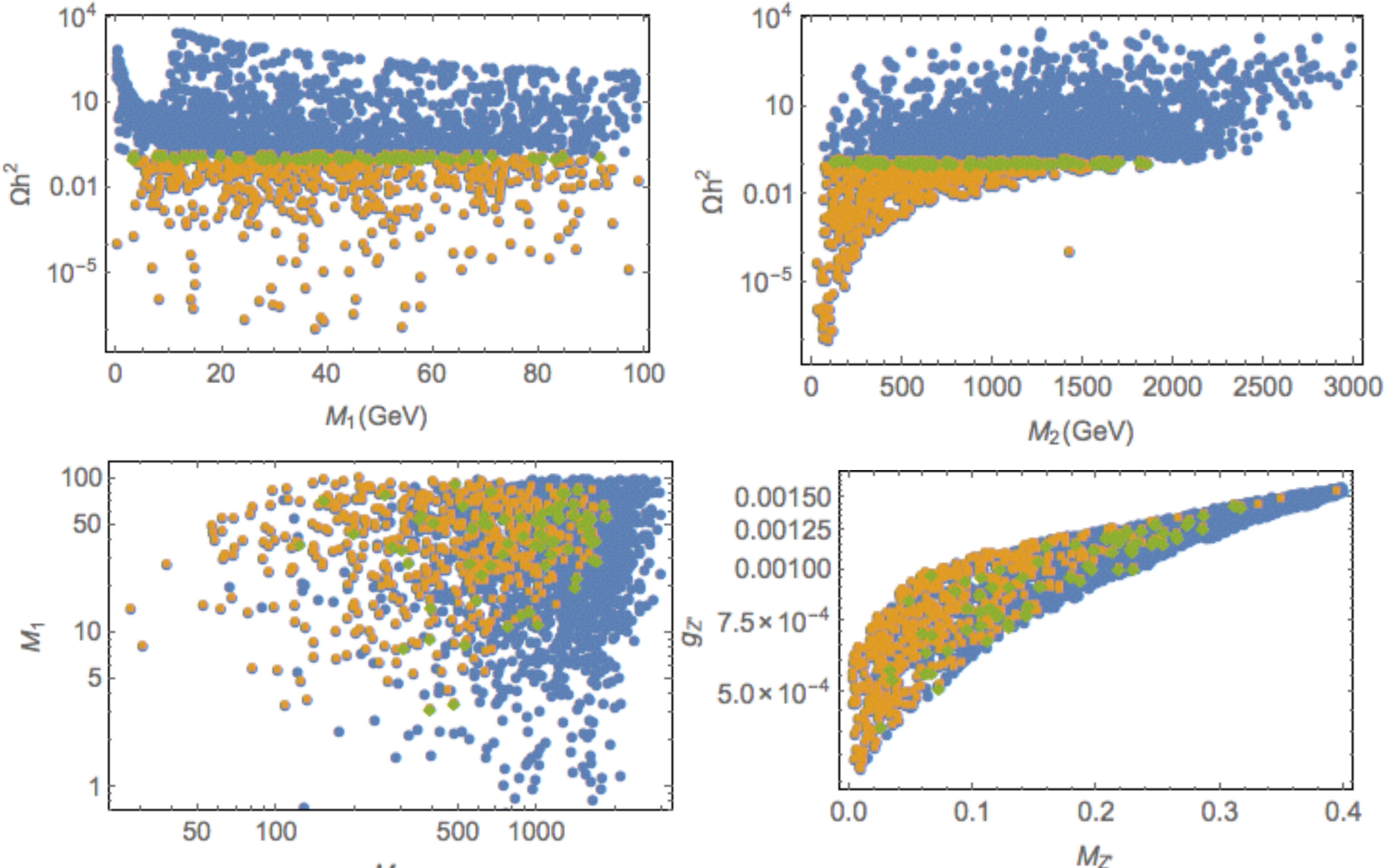
In the $(g\text{-}2)_\mu$ compatible region, relic abundance is achieved by



Annihilation cross section enhanced by $\frac{M_1^4}{m_{Z'}^4}$

$N_{2,3}$ provides s-wave annihilation

Relic density of DM



Constraint on $U(1)_{\mu\text{-}\tau}$

- MEG exp: $\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ MEG (2013)

$$\mathcal{B}(\mu \to e\gamma) \simeq (900\ \mathrm{GeV}^2)^2 \times \left| \sum_{i=1\text{-}3} \frac{f_e f_\mu}{2m_{\eta^\pm}^2} V_{1i} V_{2i}^* G\left(\frac{M_i^2}{m_{\eta^\pm}^2}\right) \right|^2$$

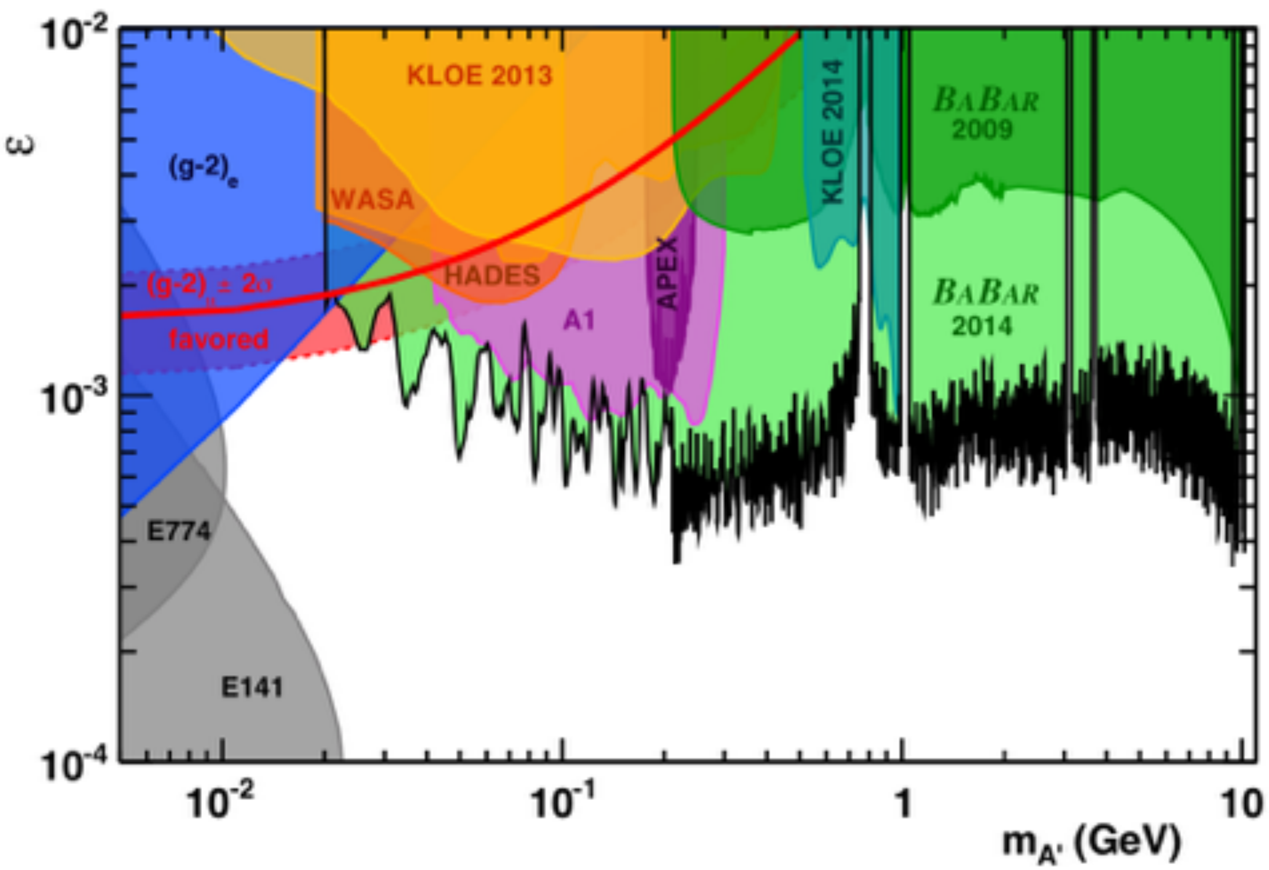
- With $\sum_{i=1\text{-}3} f_e f_\mu V_{1i} V_{2i}^* \lesssim \mathcal{O}(10^{-3})$ and $m_{\eta^\pm} = \mathcal{O}(1)\ \mathrm{TeV},$

 we can avoid the MEG constraint.

Dark photon search does not constrain $U(1)_{\mu-\tau}$

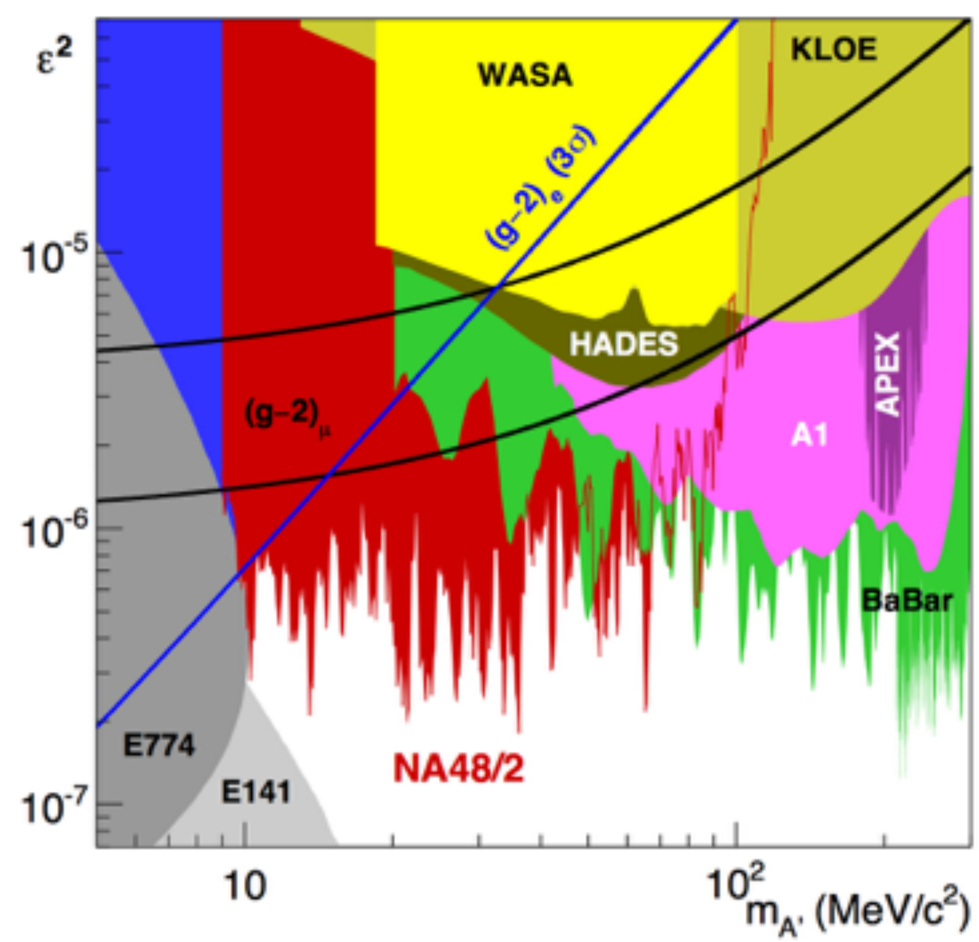
BaBar (2014)

$$e^+e^- \to \gamma A', A' \to e^+e^-, \mu^+\mu^-$$



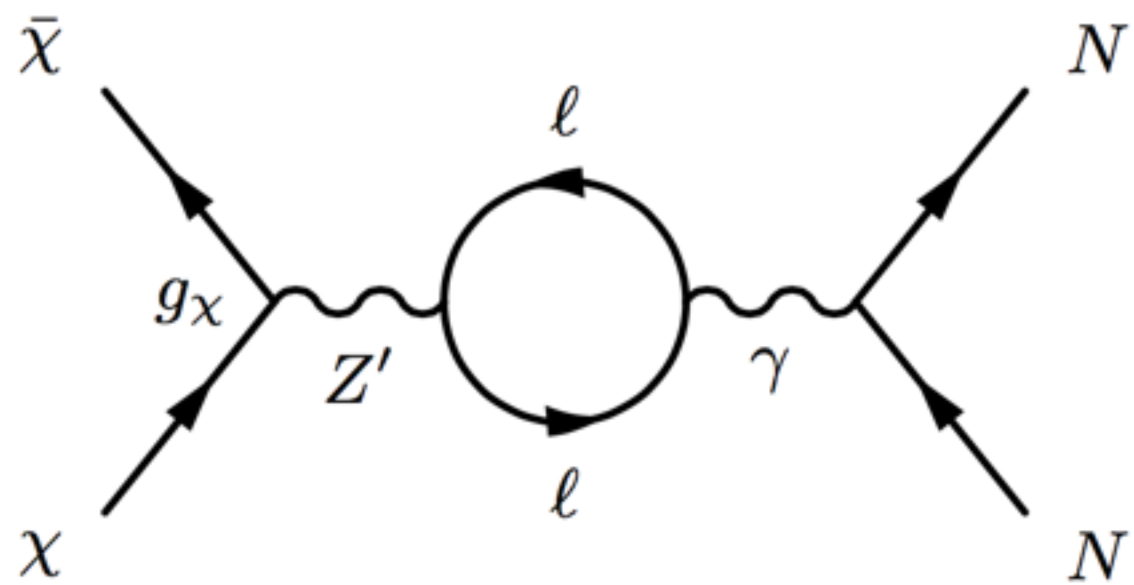
NA48/2 (2015)

$$K^\pm \to \pi^\pm\pi^0, \pi^0 \to \gamma A', \quad A' \to e^+e^-.$$



- Dark photon searches are NOT applicable to $U(1)_{\mu-\tau}$

Constraint from direct detection experiments

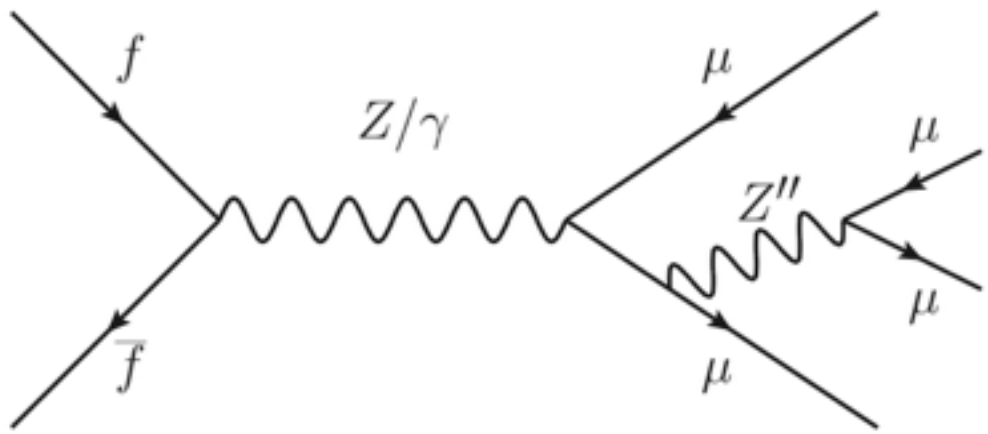


- Direct detection exps. gives bound on Z-Z' mixing parameter

$$\epsilon = \frac{g_Y g_\ell}{16\pi^2}\log\left(\frac{\mu^2}{m_\ell^2}\right) \lesssim \mathcal{O}(10^{-3}) - \mathcal{O}(10^{-4})$$

- Easily satisfied by small gauge coupling in the muon (g-2) consistent region.

Constraint from LHC search



$f\bar{f} \to \mu\mu\mu\mu, \mu\mu\tau\tau$

SB, P. Ko (2009); K. Harigaya, et.al., 1311.0870

- 14 TeV LHC w/ 300 fb^{-1} can observe Z' in 4μ channel

for $M_{Z'}$=80-100 GeV and g'=0.3

- In our model, the cross section is much less than 1 fb

Conclusions

- Considered $U(1)_{\mu-\tau}$ extension of Ma model
- The model predicts Inverted mass hierarchy, δ~250°, m_3=0.04 eV.
- $(g-2)_\mu$ can be explained with light Z', $m_{Z'}$~O(100) MeV
- Right-handed neutrino DM can explain the current relic abundance
- The model can avoid constraints from CLFV, dark photon search, DM direct detection and LHC searches

Thank you!