Dark matter and muon (g-2) in an extended Ma model

Seungwon Baek (KIAS)

Dark Side of the Universe 2015
14-18 Dec 2015, Kyoto, Japan

based on
SB, Hiroshi Okada, Kei Yagyu, JHEP 1504 (2015) 049 [arXiv:1501.01530]
SB, arXiv:1510.02168

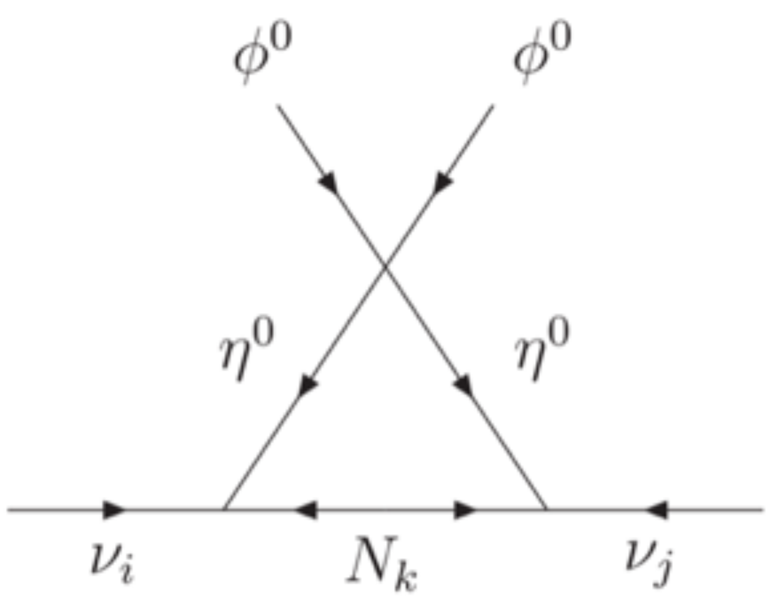
Outline

- The Model: extension of Ma's scotogenic model with gauged L_μ-L_τ symmetry
- Predictions on the neutrino sector
- $(g-2)_\mu$, relic abundance of dark matter, constraints on the model
- Conclusions

Ma's scotogenic Model

- 3 generation of right-handed neutrino $N_R^i (i=1,2,3)$, and $SU(2)_L$ doublet scalar η
- Odd under Z2→DM candidates, no tree-level neutrino masses
- Neutrino masses are generated radiatively at one-loop mediated by DM

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



$$\mathcal{L}_Y = f_{ij}(\phi^- \nu_i + \bar{\phi}^0 l_i) l_j^c + h_{ij}(\nu_i \eta^0 - l_j \eta^+) N_j + \text{H.c.}$$

$$\frac{1}{2} M_i N_i N_i + \text{H.c.}$$

E. Ma, PRD73 (2006)

$$\frac{1}{2} \lambda_5 (\Phi^\dagger \eta)^2 + \text{H.c.}$$

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right]$$

Ma's scotogenic Model

- DM and neutrino masses are related
- New particle masses can be TeV scale. Can be tested at colliders.
- λ_5~0.01, h_{ij}~0.01, M~10 GeV, m_0~10 TeV

$$m_R^2 - m_I^2 = 2\lambda_5 v^2$$

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2 m_0^2} \sum_k h_{ik} h_{jk} M_k \sim 0.1 \text{ eV}$$

- Does not predict neutrino mixing angles
- Cannot accommodate muon (g-2)

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	$+1$

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

Fermion masses

- Charged leptons, right-handed neutrinos

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

- Diagonalization of right-handed neutrino mass matrix

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

- Neutrino masses from one-loop

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

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{f_i V_{ik} f_j V_{jk} M_k}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right]$$
$$\simeq \frac{\lambda_5 v^2}{8\pi^2 m_0^2} f_i (\mathcal{M}_N)^*_{ij} f_j$$

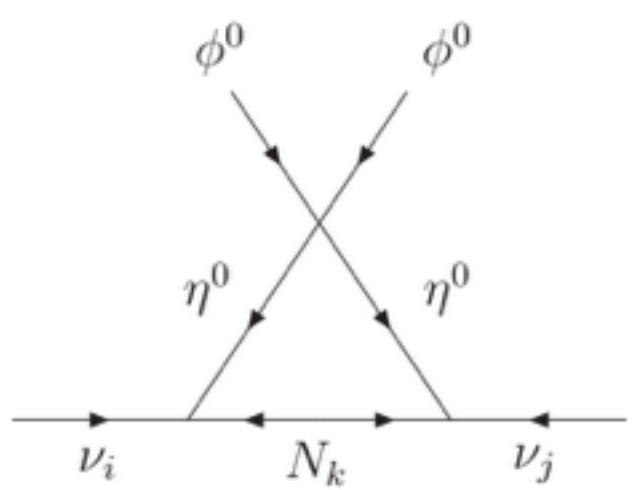


FIG. 1. One-loop generation of neutrino mass.

Neutrino masses and PMNS

- 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): predictive
- From 5 neutrino oscillation data,

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

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

we predict, m_1, 3-CPV phases.

Neutrino masses and PMNS

- Best fit value for δ: $\delta = \pm 1.96 \text{ (BF)}$
- Negative δ is preferred for IH.

δ=-1.96

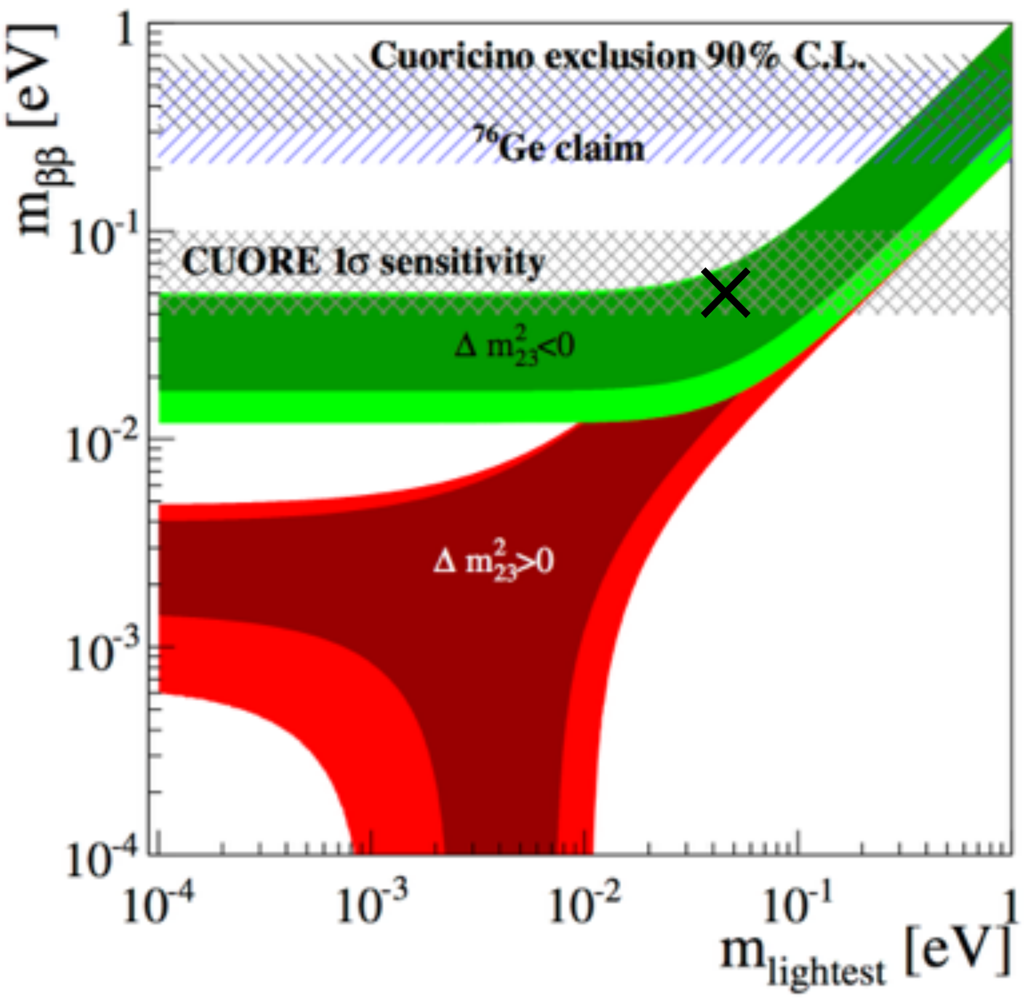
D. V. Forero, M. Tortola, J. W. F. Valle, 1405.7540

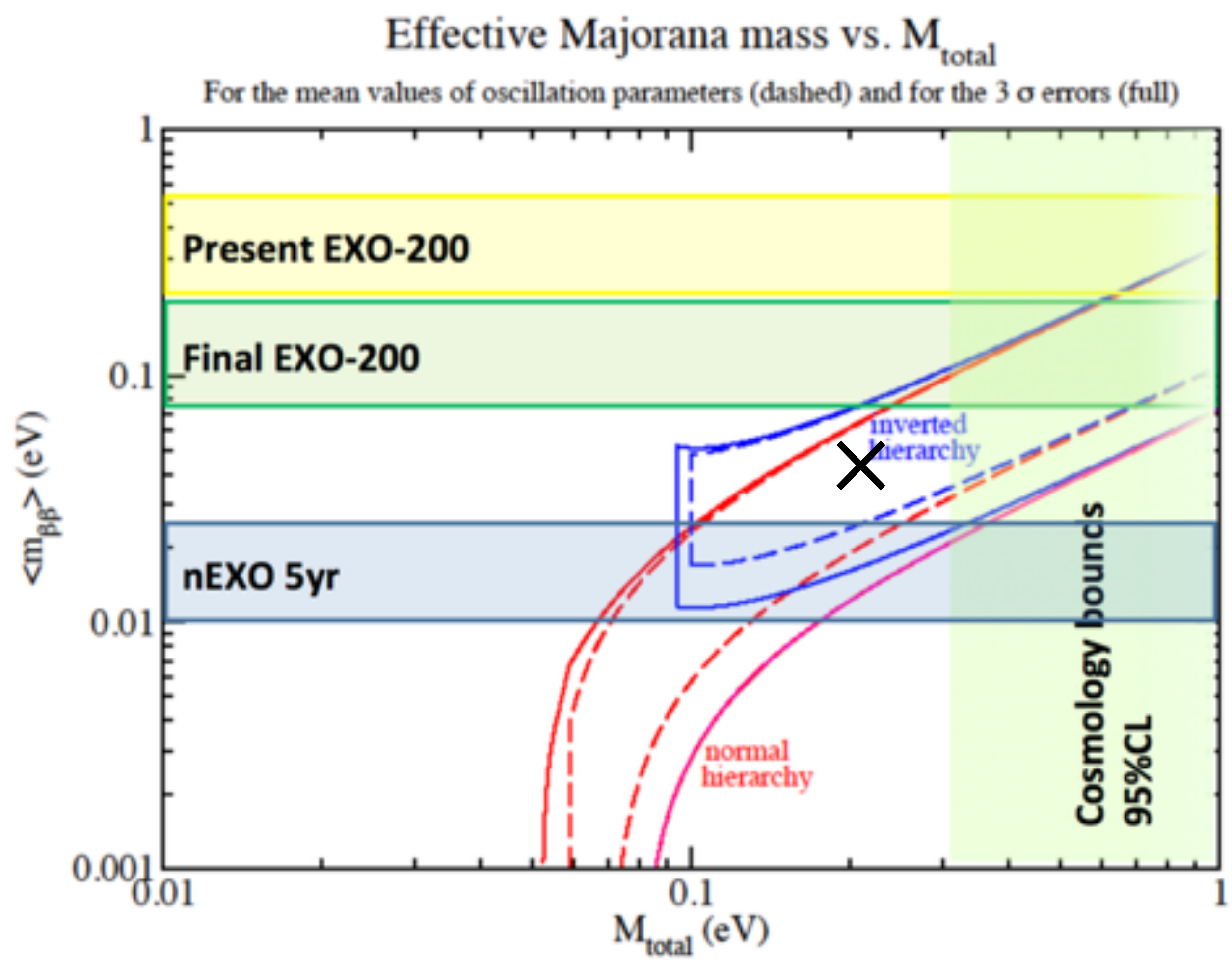
T2K, 1502.01550

$$(m_1, m_2, m_3)[\text{eV}] = (0.0702, 0.0708, 0.0506), \quad (\rho, \sigma) = (-0.958, +1.34)$$

0νββ Experiments

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} m_i U_{ei}^2| \simeq 0.051 \text{ (eV)}$$





SSI 2015

Lisa Kaufman

CUORE, 1402.6072

$(g-2)_\mu$

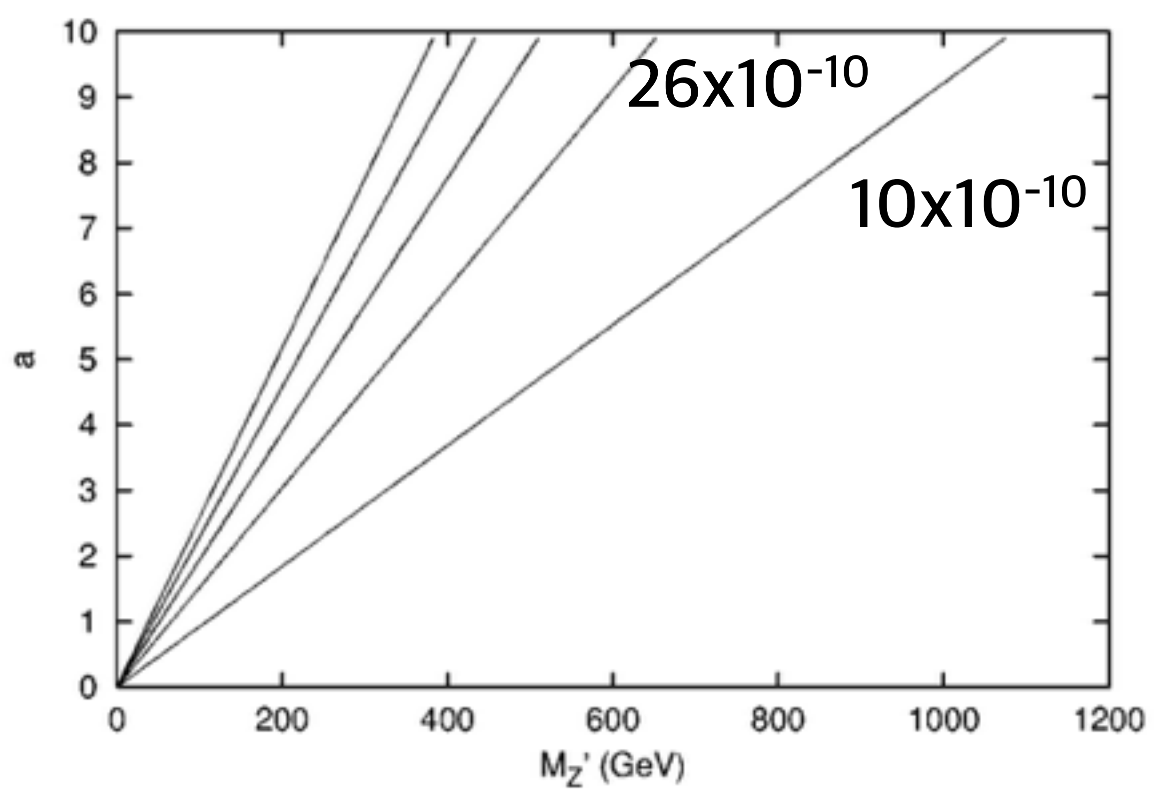
- ~3σ discrepancy

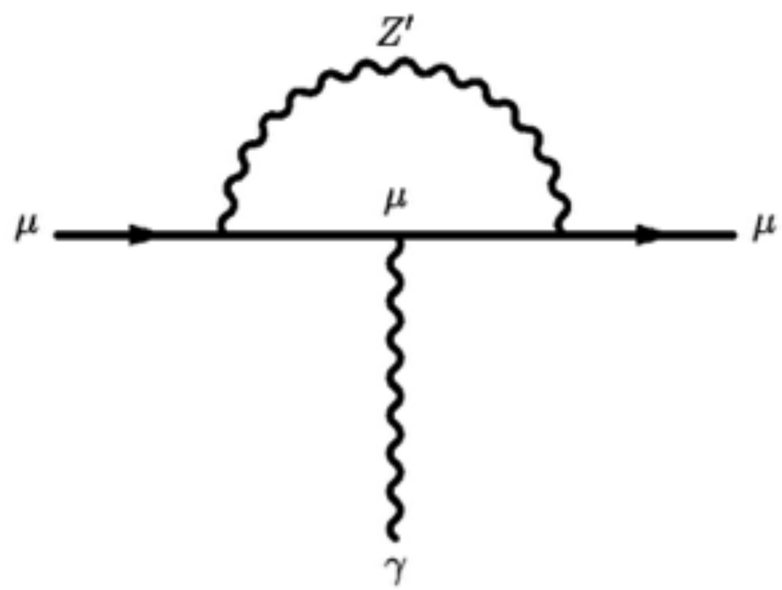
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.0 \pm 9.0 \text{ to } 33.5 \pm 8.2) \times 10^{-10}.$$

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

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

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

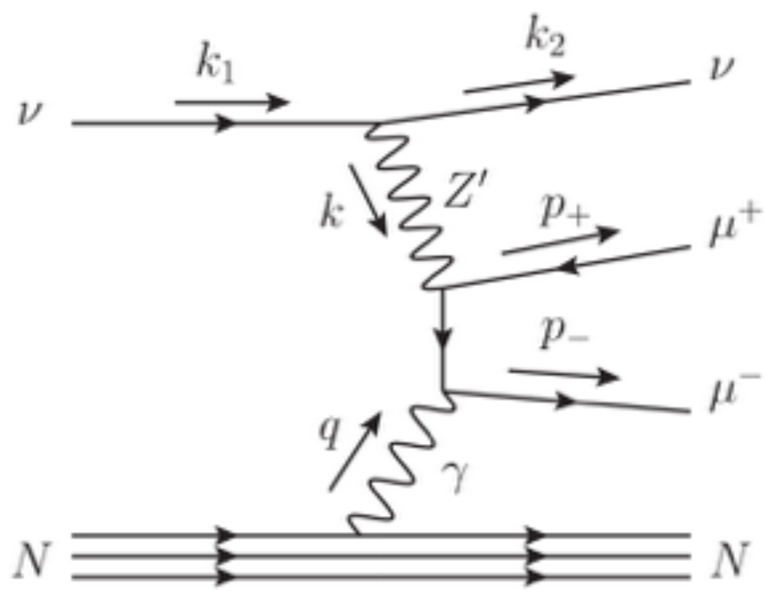




$$L = \frac{ea}{c_W}(\bar{\mu}\gamma^\mu \mu - \bar{\tau}\gamma^\mu \tau) Z'_\mu$$

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

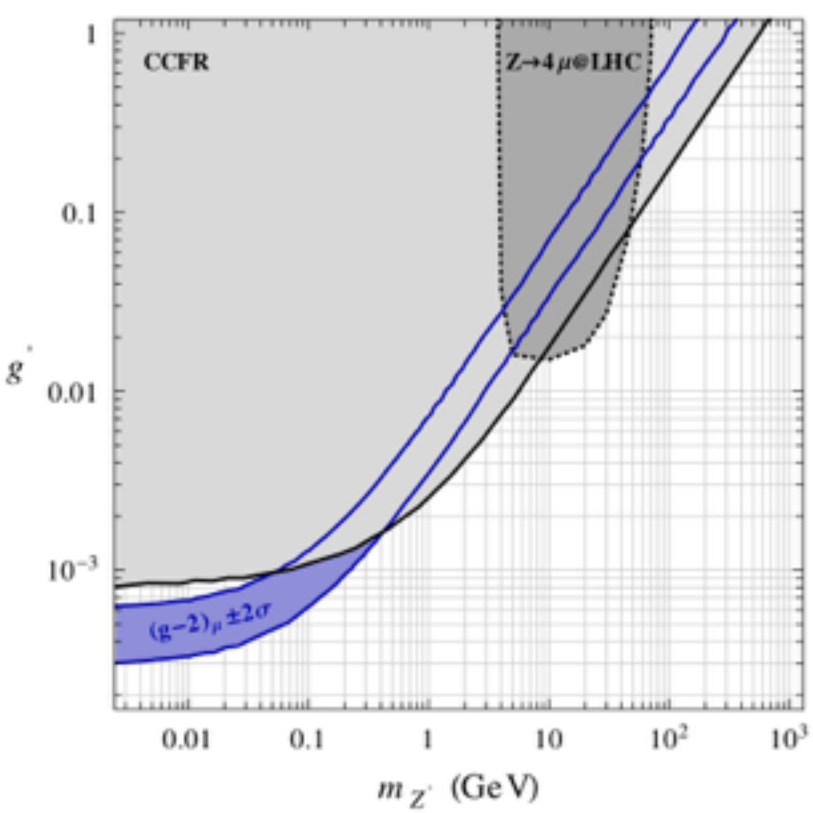
- Neutrino trident production   W. Altmannshofer, et.al. (2014)

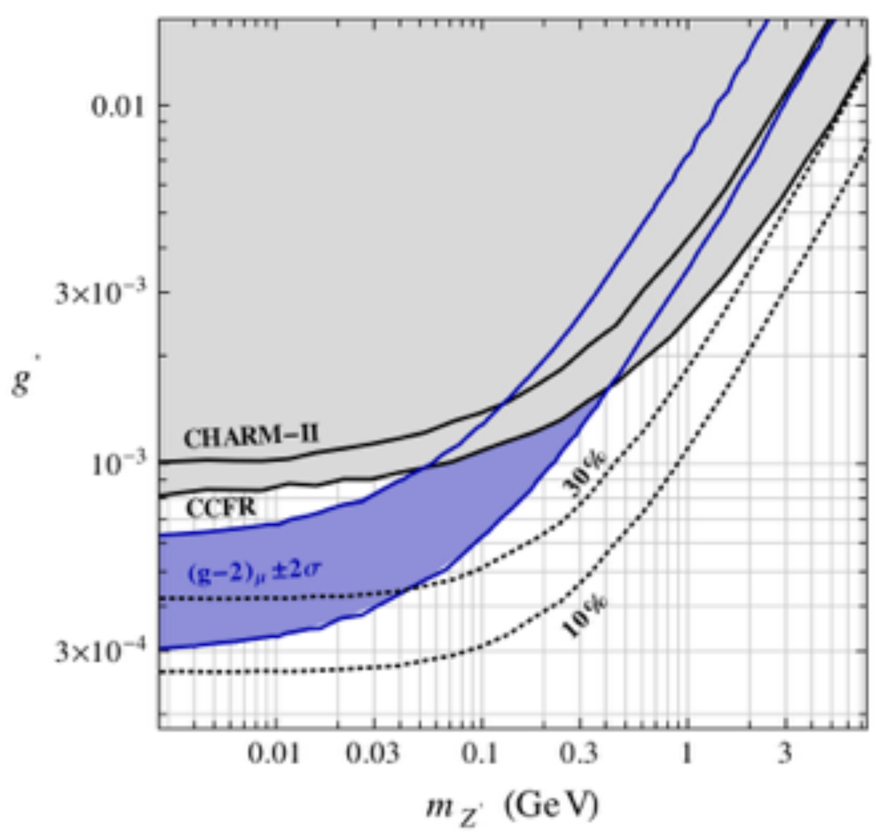


The Z’ contribution is constructive with the SM

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

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

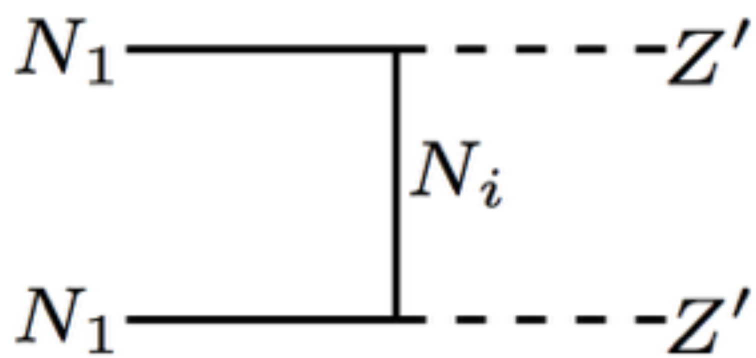


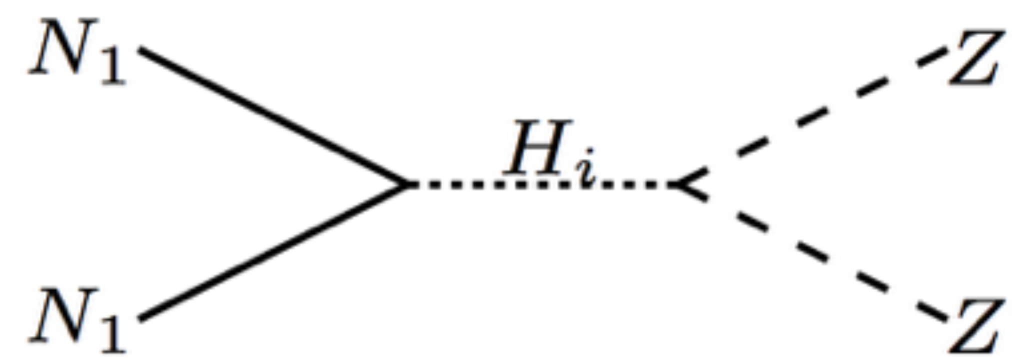


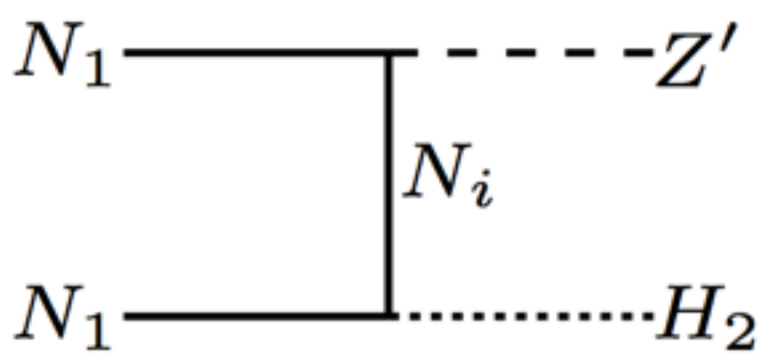
$10\text{MeV} < M_{Z'} < 400\text{MeV}$,
$10^{-4} < g_{Z'} < 10^{-3}$
can account for the discrepancy in $(g-2)_\mu$

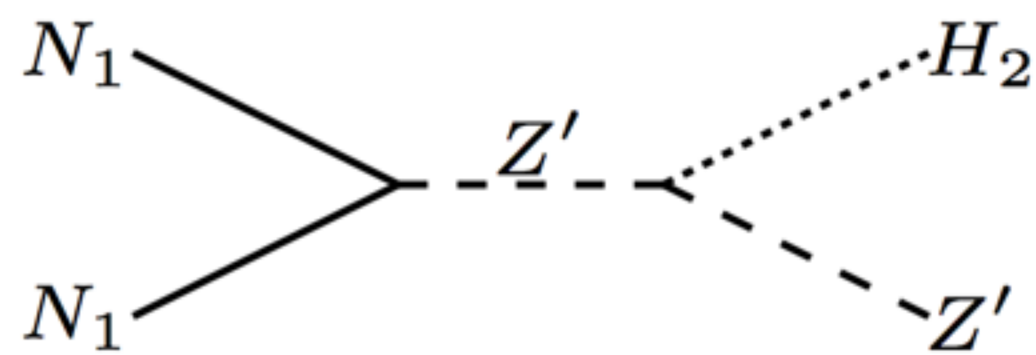
Relic density of DM

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









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

$$\epsilon^{*\mu}(p) \sim p^\mu / m_{Z'}$$

Relic density of DM

Scanned parameters

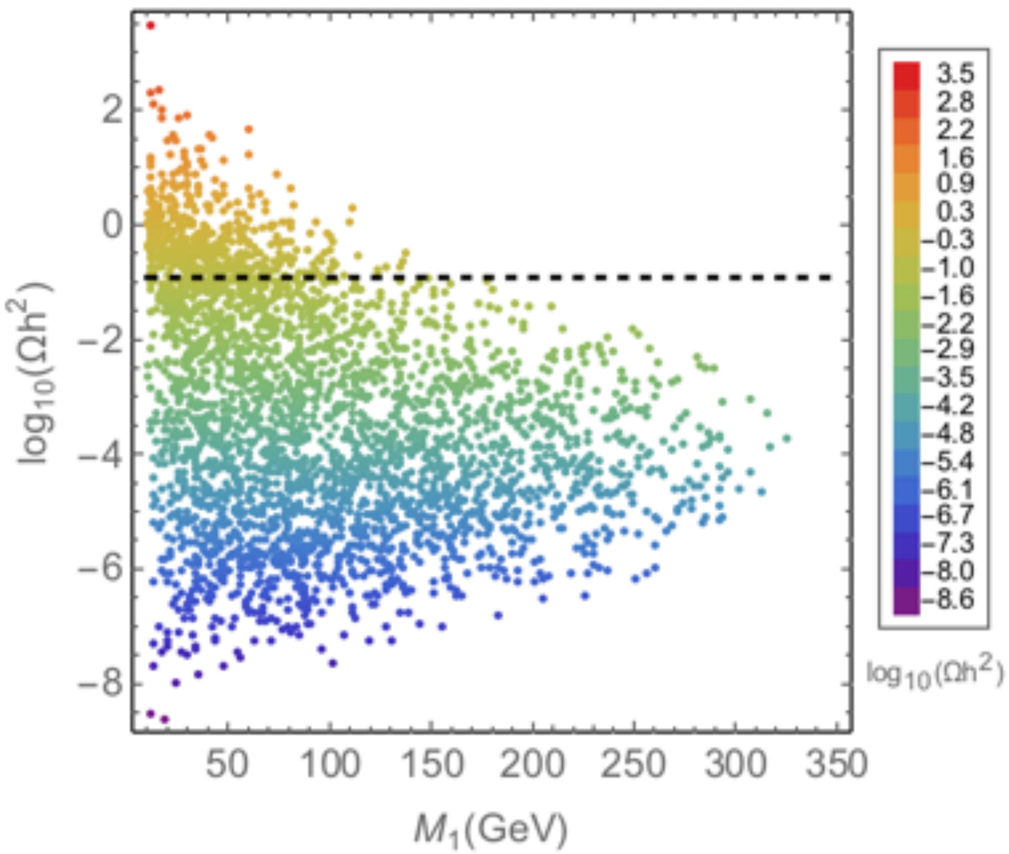
$$
\begin{aligned}
0 < & \quad m_{H_2} & < \sqrt{4\pi} m_{Z'}/g_{Z'}, \\
10\ \text{GeV} < & \quad M_{ee}\ (M_{\mu\tau}) & < 150\ (1000)\ \text{GeV}, \\
0 < & \quad h_{e\mu}, h_{e\tau} & < 4\pi,
\end{aligned}
$$

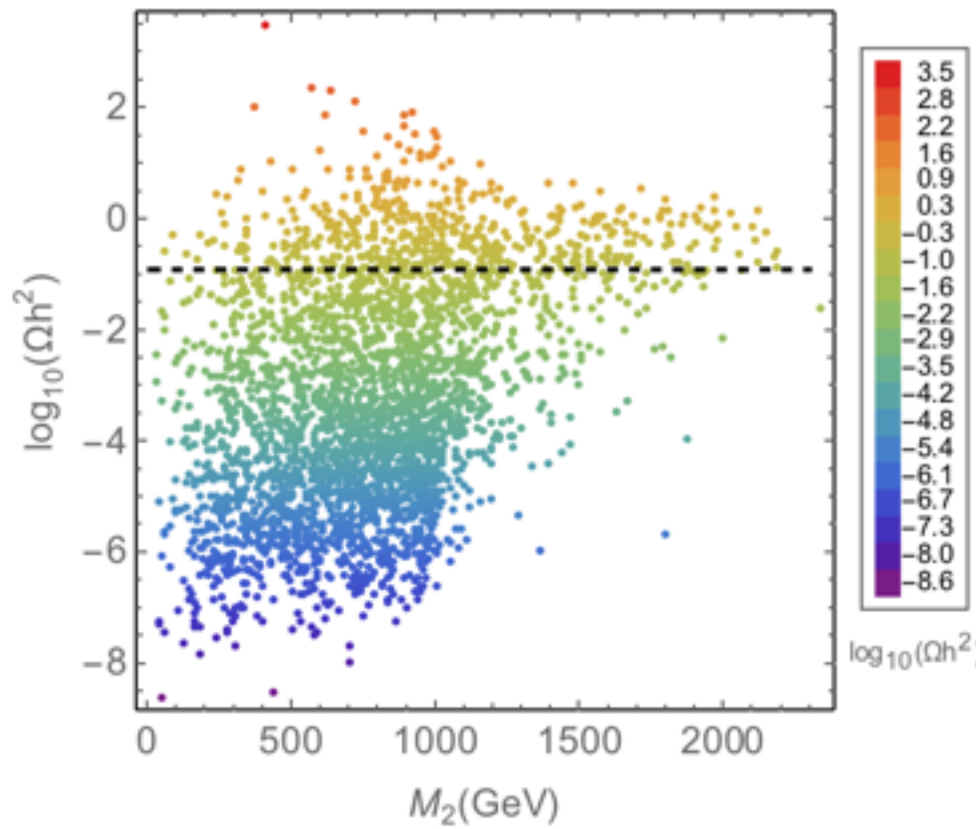
neutrino →

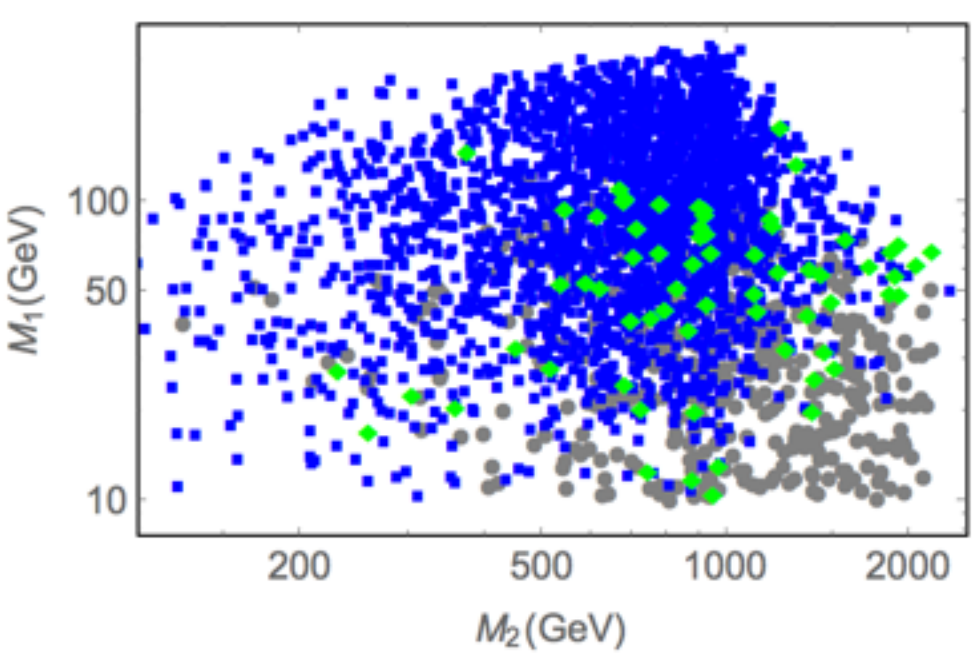
$$
\boxed{
\begin{aligned}
\pi/2 < & \quad \theta_R & < 3\pi/2, \\
0.3 < & \quad |h_{e\mu} h_{e\tau}| v_S^2 / 4 M_{ee} M_{\mu\tau} & < 0.5,
\end{aligned}
}
$$

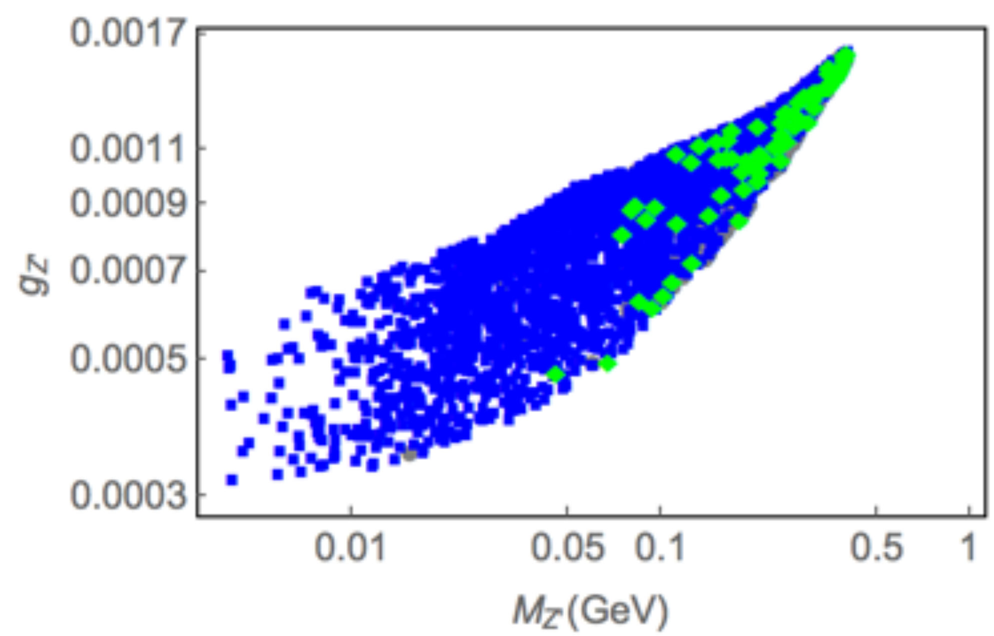
$$
\mathcal{M}_N = \begin{pmatrix} |M_{ee}| & \frac{v_S}{\sqrt{2}}|h_{e\mu}| & \frac{v_S}{\sqrt{2}}|h_{e\tau}| \\ \frac{v_S}{\sqrt{2}}|h_{e\mu}| & 0 & |M_{\mu\tau}|e^{i\theta_R} \\ \frac{v_S}{\sqrt{2}}|h_{e\tau}| & |M_{\mu\tau}|e^{i\theta_R} & 0 \end{pmatrix}
\qquad
\mathcal{M}_\nu = \begin{pmatrix} f_e^2 M_{11} & f_e f_\mu M_{12} & f_e f_\tau M_{13} \\ f_e f_\mu M_{12} & 0 & f_\mu f_\tau M_{23} e^{-i\theta_R} \\ f_e f_\tau M_{13} & f_\mu f_\tau M_{23} e^{-i\theta_R} & 0 \end{pmatrix}
$$

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)

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

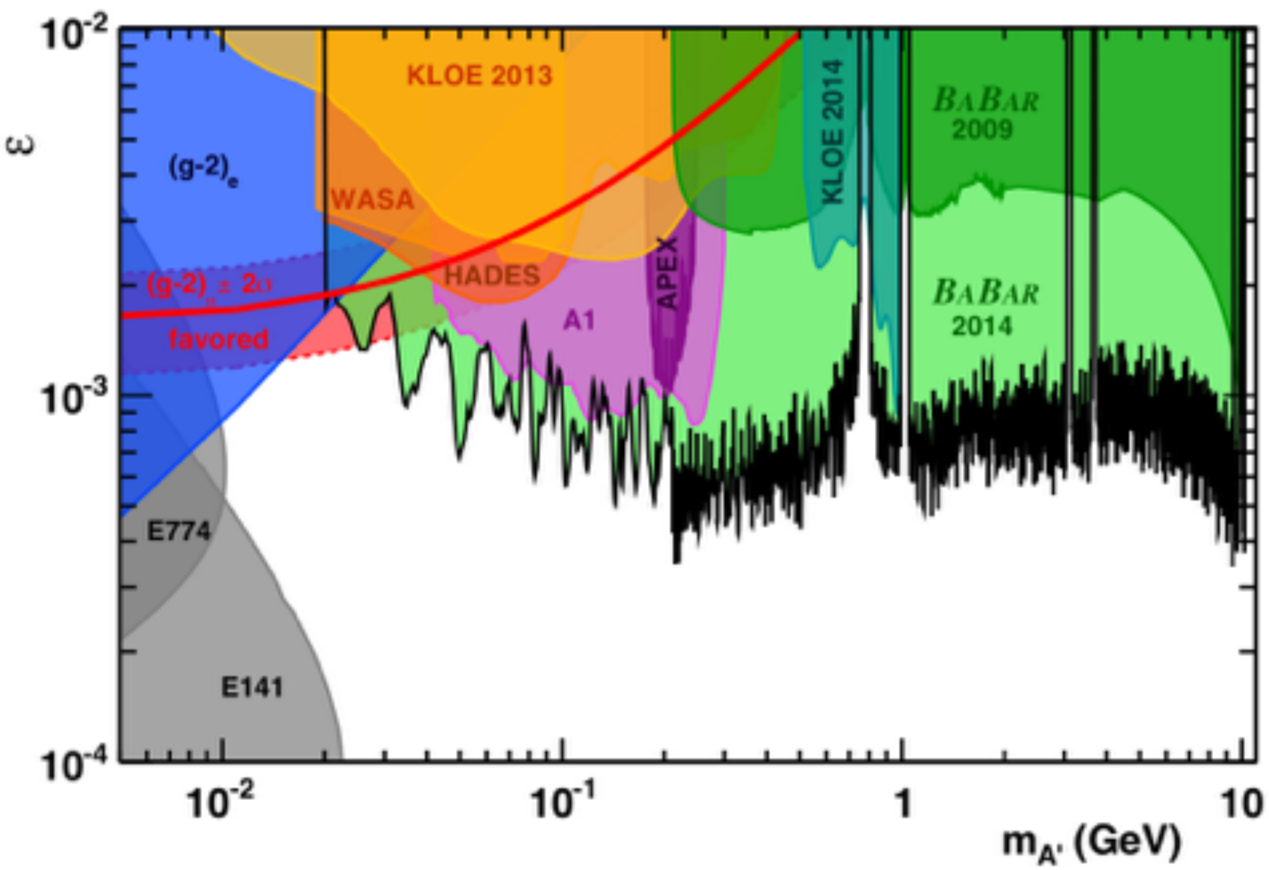
- With $\sum_{i=1\text{-}3} f_e f_\mu V_{1i} V_{2i}^* \lesssim \mathcal{O}(10^{-3})$ and $m_{\eta^\pm} = \mathcal{O}(1)\ \mathrm{TeV}$,

  we can avoid the MEG constraint.

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

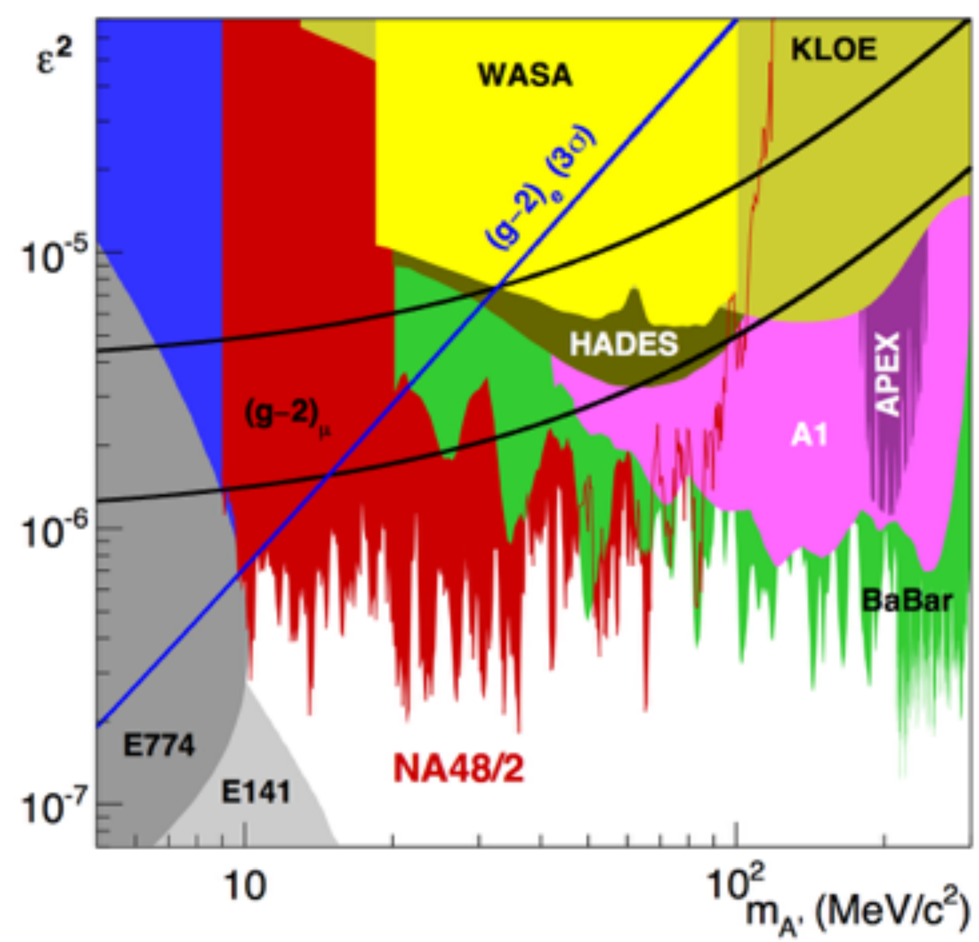
BaBar (2014)

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



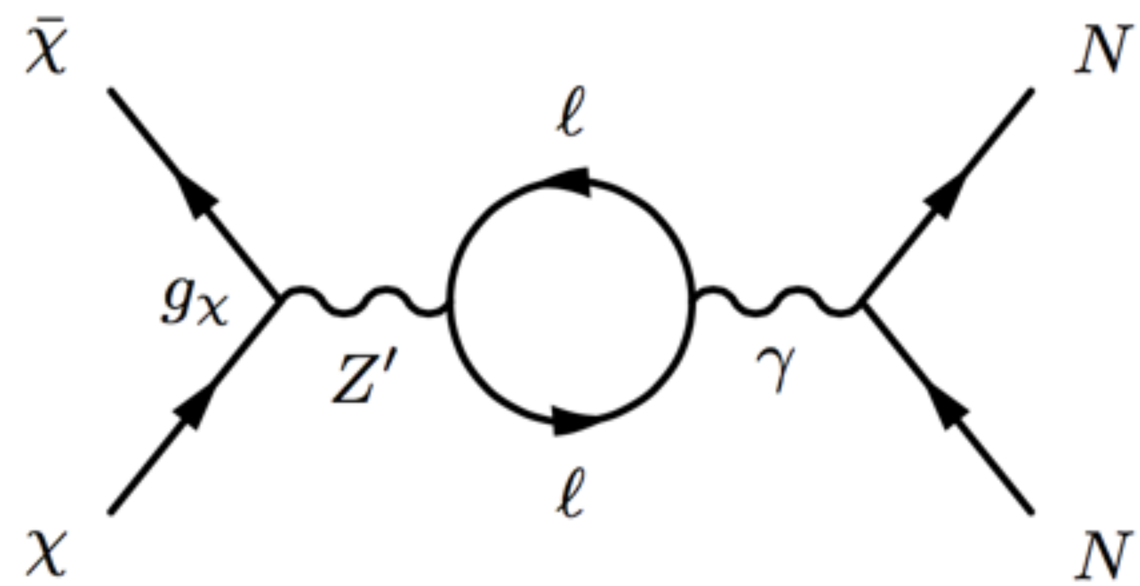
NA48/2 (2015)

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



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

Constraint from direct detection experiments

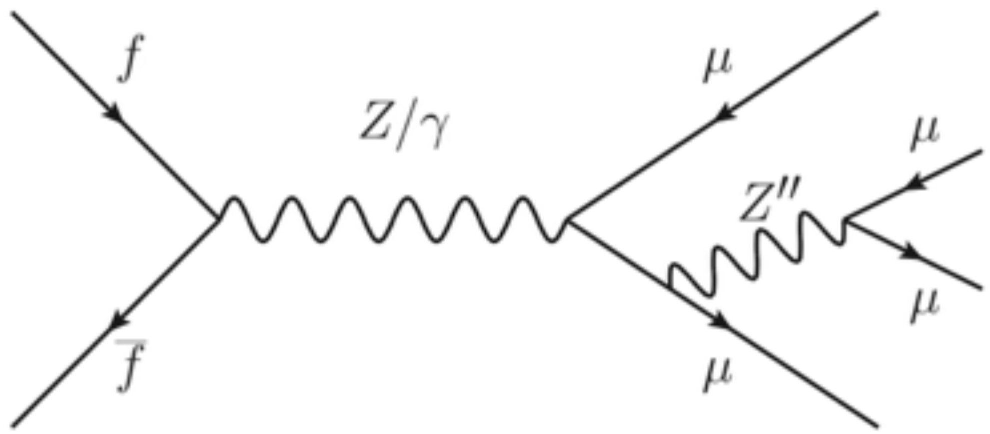


- Direct detection exps. give bound on Z-Z' mixing parameter

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

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

Constraint from colliders



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

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

- Dedicated search @LHC and/or Belle II may further constrain the low $M_{Z'}$ region

ATLAS Z decay into 4-leptons

$e^+e^-e^+e^-$ $(4e)$, $\mu^+\mu^-\mu^+\mu^-$ (4μ) and $e^+e^-\mu^+\mu^-$ $(2e2\mu)$

Selection cuts

1. four isolated leptons, which have two opposite sign and same-flavor di-lepton pairs, where $p_{T,\mu} > 4\,\text{GeV}$ and $|\eta_\mu| < 2.7$ ($p_{T,e} > 7\,\text{GeV}$ and $|\eta_e| < 2.47$).
2. the leading three leptons must have $p_{T,\ell} > 20,\ 15,$ and $8\,\text{GeV}$, and if the third (p_T-ordered) lepton is an electron it must have $p_{T,e_3} > 10\,\text{GeV}$.
3. the four leptons are required to be separated as $\Delta R_{\ell\ell} > 0.1$.
4. the invariant masses of the same-flavor and opposite-sign leptons are required to have $m_{l^+l^-} > 5\,\text{GeV}$.
5. $m_{12} > 20\,\text{GeV}$ and $m_{34} > 5\,\text{GeV}$, where m_{12} is the invariant mass of the same flavor and opposite sign di-lepton pair which is the closest to the Z boson mass among the possible combinations, while the other one is called m_{34}.
6. the invariant mass of the four leptons is in the m_Z window, $80\,\text{GeV} < m_{4l} < 100\,\text{GeV}$.

Future trident events

- Planned neutrino facility LBNE can be sensitive to (g-2) favored region W. Altmannshofer, et.al. (2014)

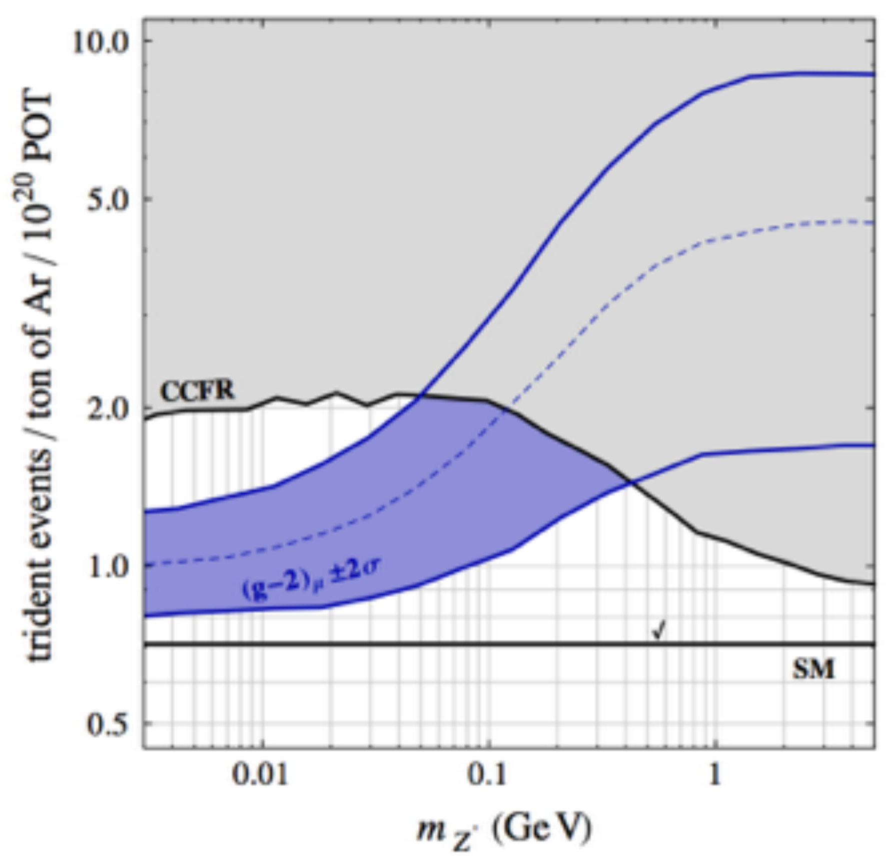


FIG. 4 (color online). Expected number of trident events per ton of argon and per 10^{20} POT at the LBNE near detector for a neutrino energy of $E_\nu = 5$ GeV as a function of the Z' mass. The horizontal line shows the SM prediction. The purple (dark grey) region corresponds to Z' masses and couplings that yield a contribution to the muon g-2 in the range $\Delta a_\mu = (2.9 \pm 1.8) \times 10^{-9}$. The light grey region is excluded by CCFR.

1 year of data corresponding to ~6×10^{20} and 18 tons of Ar gives ~100 trident events

Conclusions

- Considered $U(1)_{\mu-\tau}$ extension of Ma model
- The model predicts inverted mass hierarchy, δ~250°, m_1=0.07 eV, $m_{\beta\beta}$=0.051 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
- Constraints from CLFV, dark photon search, DM direct detection
- Searches at colliders, $0\nu\beta\beta$ decay experiments, neutrino facilities.

Thank you!