Muon g-2 & Thermal WIMP DM in U(1)$_{L_\mu - L_\tau}$ Models

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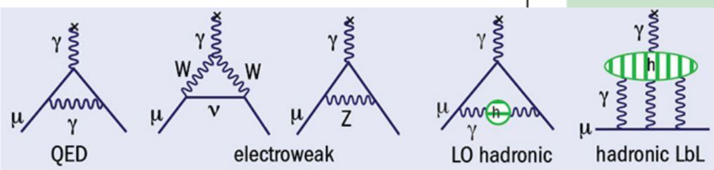
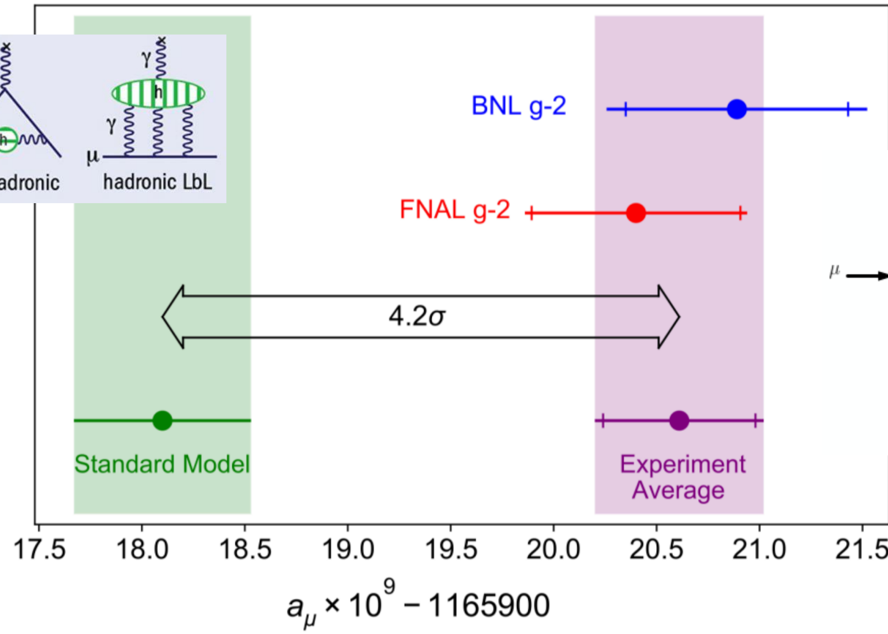
Based on arXiv: 2204.04889
In collaboration with Seungwon Baek (Korea U.), Pyungwon Ko (KIAS)

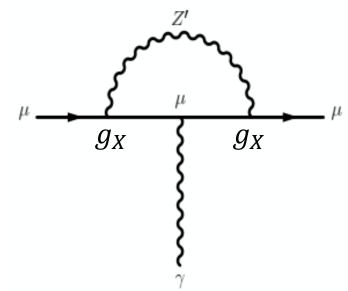
Evidences – Muon g-2 anomaly

- Anomalous muon magnetic moment

Muon g-2 collaboration, PRL 2021







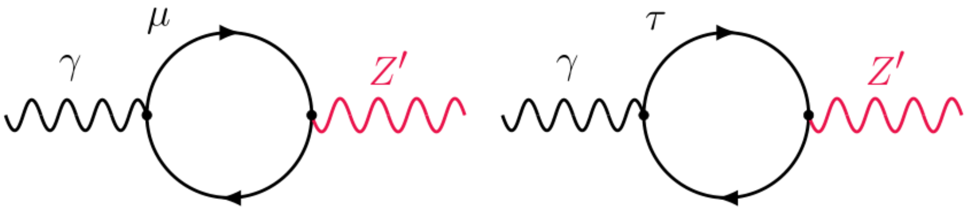
- $g_X \sim (4-8)\times 10^{-4}$ & $M_{Z'} \sim O(10)$MeV when $M_{Z'} < M_\mu$

$$\Delta a_\mu = \frac{g_X^2}{8\pi}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2}$$

S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
…

Leptophilic Z' model

- Possible to gauge one of the differences of two lepton-flavor numbers
  - $L_e - L_\mu, L_\mu - L_\tau,$: anomaly free without extension of fermion contents
  - Symmetry including L_e is strongly constrained
  - The simplest anomaly free U(1) extension that couple to the SM fermions directly

- No kinetic mixing between Z' and B @ high-energy
  - Kinetic mixing is generated through
  - 

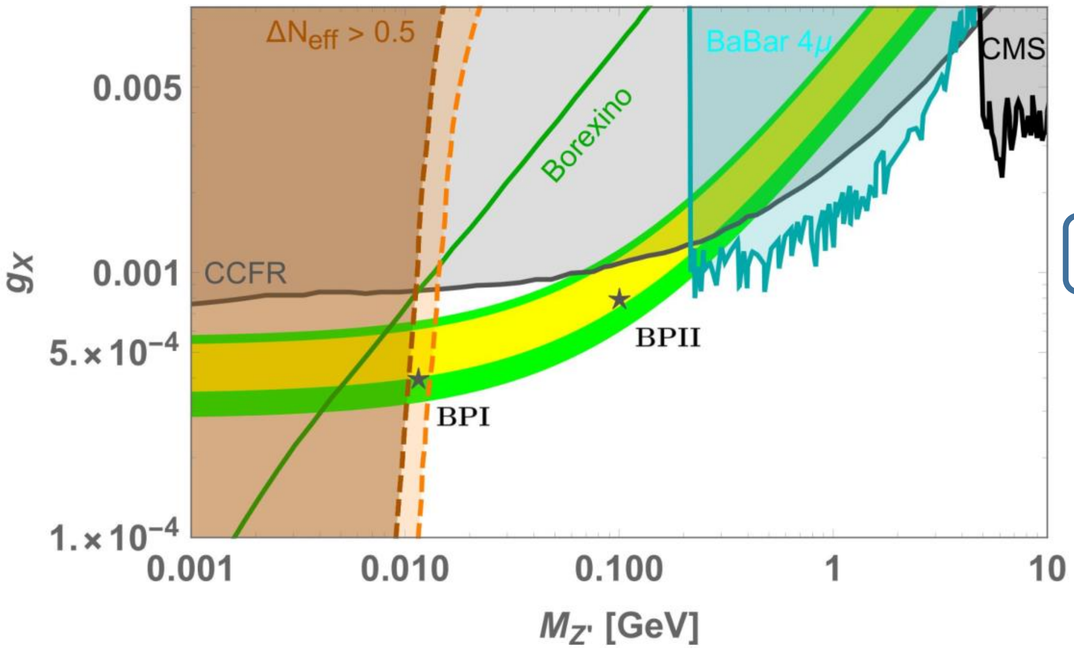
  - $\epsilon = -\frac{e g_{\mu-\tau}}{2\pi^2}\int_0^1 dx\, x(1-x)\log\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right] \xrightarrow[m_\mu \gg q]{} -\frac{e g_{\mu-\tau}}{12\pi^2}\log\frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70}.$

Leptophilic Z' model

- ***Hubble tension***

M. Escudero et al, JHEP 2019

  - Tension between early and late-time determinations of Hubble constant
  - $10 - 20\text{MeV}\ Z'$ reached thermal equilibrium in the early Universe and decays, heating the neutrino population
  - Delay the process of neutrino decoupling
  - $0.2 < \Delta N_{\text{eff}} < 0.5$: substantially relaxes the tension

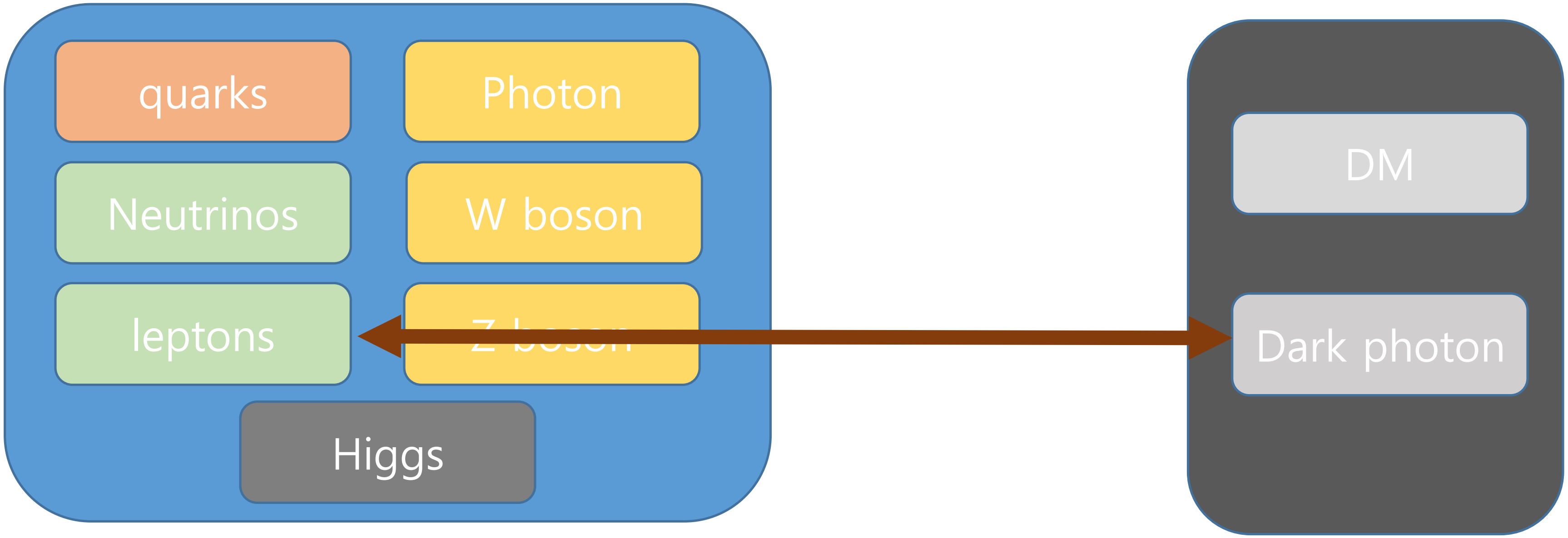


In this talk

- BPI : $M_{Z'} = 11.5\text{MeV},\ g_X = 4 \times 10^{-4}$
- BPII: $M_{Z'} = 100\text{MeV},\ g_X = 8 \times 10^{-4}$

$U(1)_{L_\mu - L_\tau}$-charged DM

- $U(1)_{dark} \equiv U(1)_{L_\mu - L_\tau}$

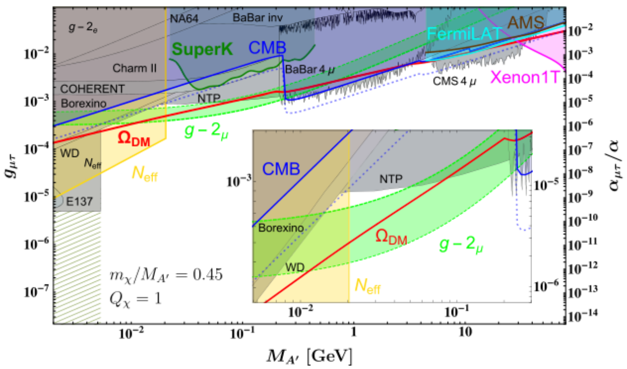


- Let's call Z', $U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

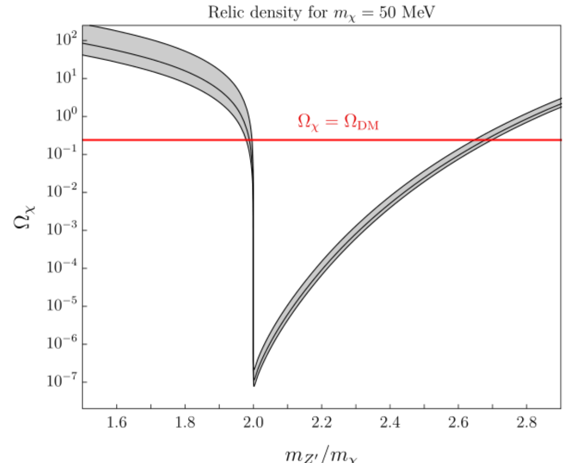
Leptophilic Z' model + DM

- $\chi\bar{\chi}(X\bar{X}) \to Z'^{*} \to \nu\bar{\nu}$: dominant annihilation channels
  - $M_{Z'} \sim 2M_{\chi}$ with the s-channel Z' resonance only gives the correct relic density

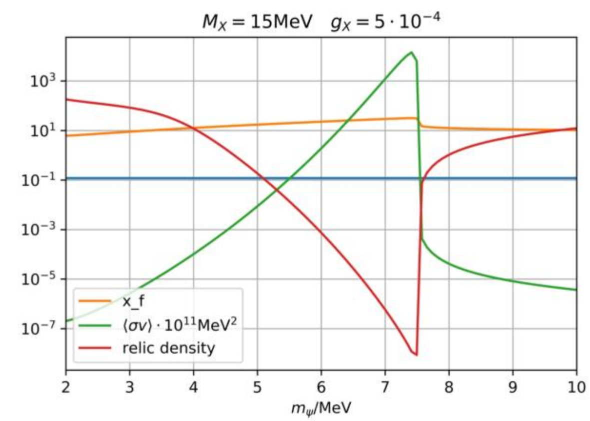
P. Foldenauer, PRD 2019



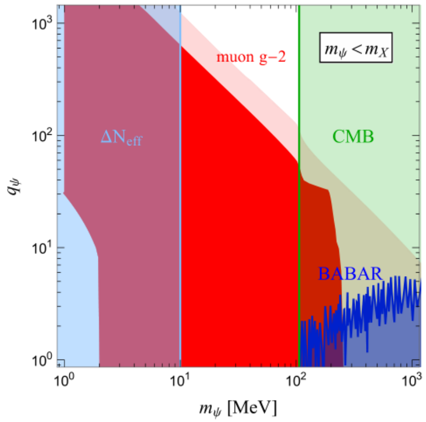
I. Holst. D. Hooper, G. Krnjaic, PRL 2022

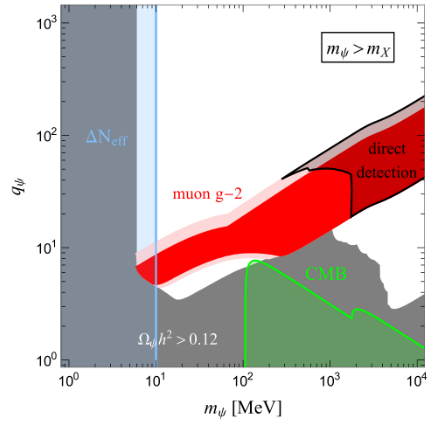


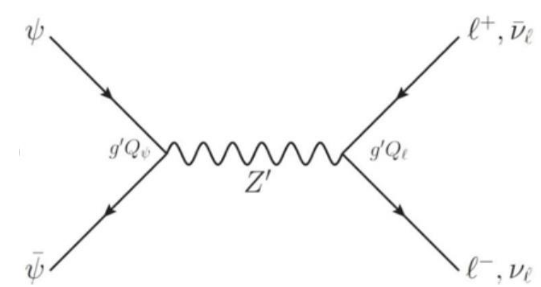
M. Drees, W. Zhao, PLB 2022



- Large DM charges **Asai, Okawa, Tsumura, JHEP 2021**

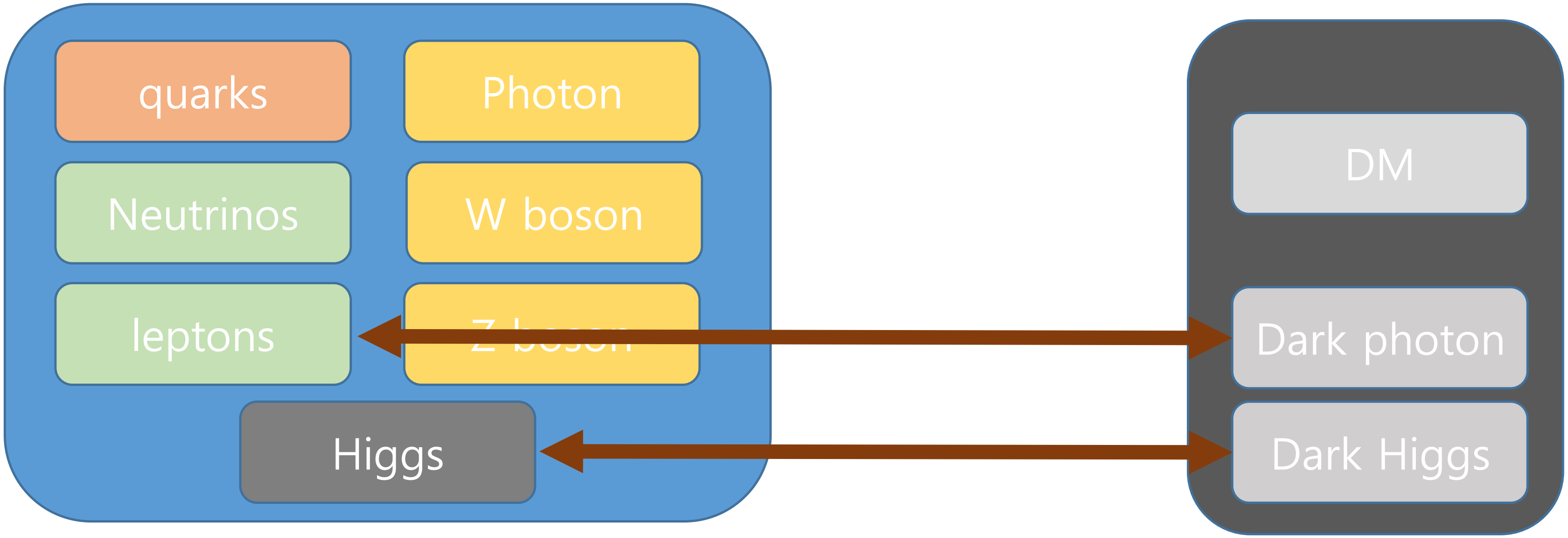






$U(1)_{L_\mu - L_\tau}$-charged DM

- $U(1)_{dark} \equiv U(1)_{L_\mu - L_\tau}$



- Let's call Z', $U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM

DM physics with dark Higgs

- If dark symmetry is spontaneously broken,

$$\Phi(x) = \frac{1}{\sqrt{2}}\left(v_\Phi + \phi(x)\right)$$

- Dark photon Z' gets massive: $M_{Z'} = g_X |Q_\Phi| v_\Phi$

- Two CP-even neutral scalar bosons
  - $\begin{pmatrix} \phi \\ h \end{pmatrix} = O \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$ $\qquad \tan 2\alpha = \frac{\lambda_{\Phi H} v_\Phi v_H}{\lambda_H v_H^2 - \lambda_\Phi v_\Phi^2}$
  - $\begin{pmatrix} 2\lambda_\Phi v_\Phi^2 & \lambda_{\Phi H} v_\Phi v_H \\ \lambda_{\Phi H} v_\Phi v_H & 2\lambda_H v_H^2 \end{pmatrix} = \begin{pmatrix} M_{H_1}^2 c_\alpha^2 + M_{H_2}^2 s_\alpha^2 & (M_{H_2}^2 - M_{H_1}^2) c_\alpha s_\alpha \\ (M_{H_2}^2 - M_{H_1}^2) c_\alpha s_\alpha & M_{H_1}^2 s_\alpha^2 + M_{H_2}^2 c_\alpha^2 \end{pmatrix}$
  - 3 independent parameters: $M_{H_1},\ M_{H_2},\ sin\alpha$

SM Higgs

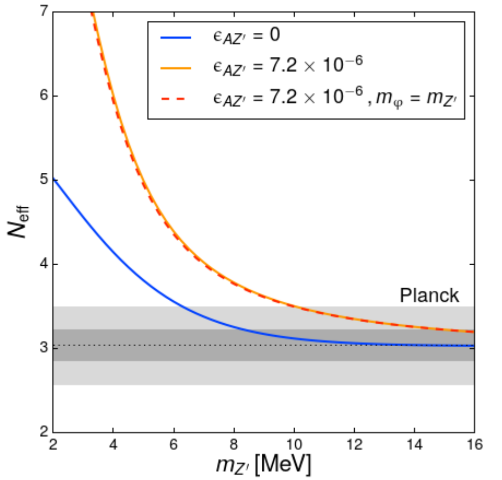
Dark Higgs constraints

- After spontaneous symmetry breakings
  - Additional interactions with the dark Higgs

$$\mathcal{L}_\phi \supset \frac{1}{2} g_X^2 Q_\Phi^2 Z'^\mu Z'_\mu \phi^2 + g_X^2 Q_\Phi^2 v_\Phi Z'^\mu Z'_\mu \phi - \lambda_\Phi v_\Phi \phi^3 - \lambda_H v_H h^3 - \frac{\lambda_{\Phi H}}{2} v_\Phi \phi h^2 - \frac{\lambda_{\Phi H}}{2} v_H \phi^2 h$$

- Constraint from N_{eff} @ T_{CMB}
  - If light dark Higgs masses are lighter than T_{dec}^{ν}~1MeV, the light dark Higgs mainly decays into $e^{\pm} \rightarrow \Delta N_{eff} \neq 0$
  - The dark Higgs decay before 1sec

- Higgs invisible decay
  - $\mathrm{Br}(H_2 \rightarrow \mathrm{inv.}) = \frac{\Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}}{\Gamma_{H_2}^{SM} + \Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}} < 11\%$ **PDG 2022**
  - $sin\alpha$ should be small
  - Take $sin\alpha \leq 10^{-4}$ → $\phi \cong H_1, h \cong H_2$



Local symmetry in Dark Sector

- The required longevity of DM can be guaranteed by a symmetry
  - If the symmetry is global, it can be broken by gravitational effects

S. Beak, P. Ko, W.I. Park, JHEP 2013

$$-\mathcal{L}_{\rm decay} = \begin{cases} \frac{\lambda_{X,\rm non}}{M_{\rm P}} X F_{\mu\nu} F^{\mu\nu} & \text{for bosonic DM } X \\ \frac{\lambda_{\psi,\rm non}}{M_{\rm P}} \overline{\psi} \left(\not{D} \ell_{Li} \right) H^\dagger & \text{for fermionic DM } \psi \end{cases}$$

M. Ackermann et al, PRD 86, 2012

- $\tau_{DM} \geq 10^{26-30}\text{sec} \rightarrow \begin{cases} m_{DM} \leq O(10)\text{keV} \quad (\text{Scalar}) \\ m_{DM} \leq O(1)\text{GeV} \ (\text{Fermion}) \end{cases}$

  - **WIMP DM is unlikely to be stable**
  - **Consider a gauge symmetry in dark sector, too**

Local Z_2 fermion DM + Muon g-2

- Taking $\mathbf{2Q_\chi = Q_\Phi = 2}$

$$\mathcal{L}_{\rm DM} = \overline{\chi}(i\not{D} - m_\chi)\chi - \left(y_\Phi \overline{\chi^C}\chi\Phi^\dagger + H.c.\right).$$

- After symmetry breaking $U(1)_X \to Z_2$
  - Nonzero y_Φ → Dirac fermion χ is decomposed into two Majorana fermion (χ_R, χ_I)
  - Mass gap: $\delta \equiv M_R - M_I = 2y_\Phi v_\Phi$
  - χ_I: DM & χ_R: XDM

- DM Lagrangian

inelastic / elastic scattering, DM annihilation

$$\mathcal{L}_{\rm DM} = \frac{1}{2}\sum_{i=R,I} \bar{\chi}_i \left(i\partial_\mu\gamma^\mu - M_i\right)\chi_i - i\frac{g_X}{2}Z'_\mu\left(\bar{\chi}_R\gamma^\mu\chi_I - \bar{\chi}_I\gamma^\mu\chi_R\right) - \frac{1}{2}y_\Phi\left(c_\alpha H_1 + s_\alpha H_2\right)\left(\bar{\chi}_R\chi_R - \bar{\chi}_I\chi_I\right).$$

- $\chi_I\chi_I \to Z'Z', H_1H_1$ annihilation & $\chi_I\chi_R \to H_1 Z'$

$m_{H_1}, m_{Z'} < m_{\chi_I}$

$m_{H_1} + m_{Z'} < m_{\chi_I} + m_{\chi_R}$

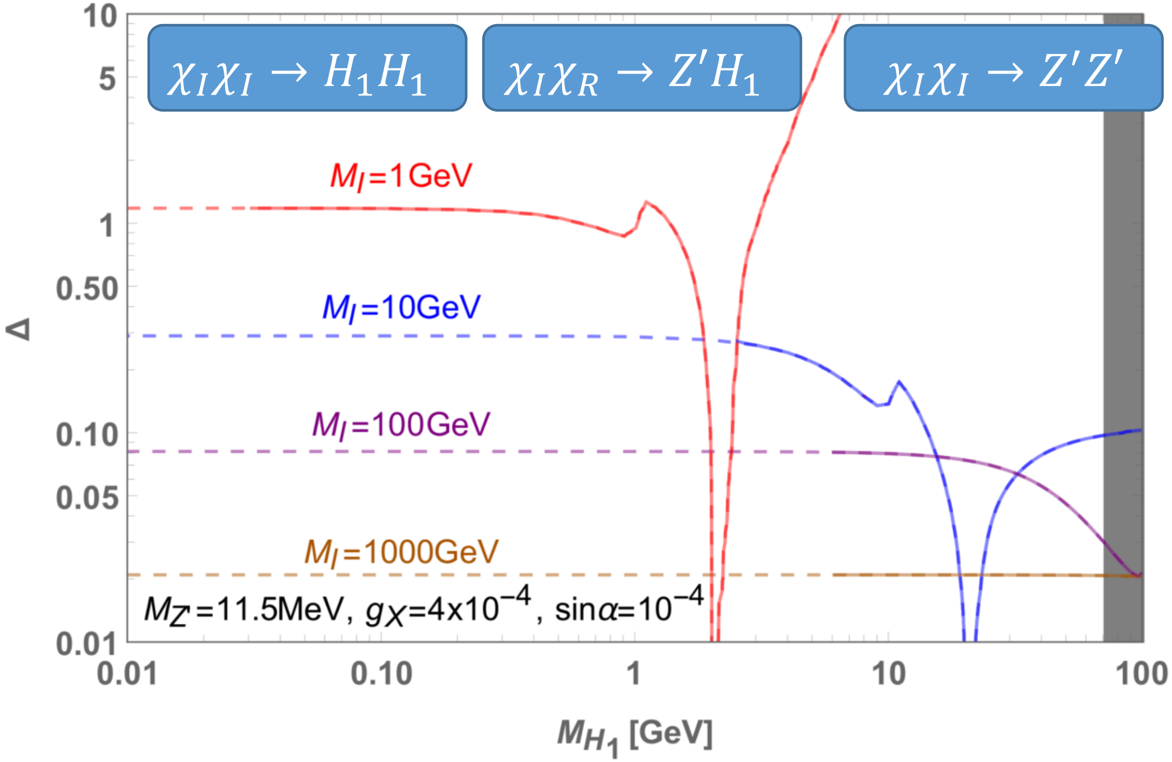
Local Z_2 fermion DM + Muon g-2

- DM-Nucleon elastic scattering

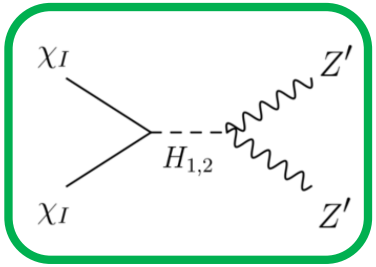
P. Ko et al, JHEP 2020
S. Baek, JKK, P.Ko, PLB 2020

- $\sigma_{\rm SI} = \frac{\mu_N^2}{\pi}\Delta^2\left(\frac{M_I M_N}{v_H v_\Phi}\right)^2 f_N^2 s_\alpha^2 c_\alpha^2\left(\frac{1}{M_{H_1}^2}-\frac{1}{M_{H_2}^2}\right)^2$

$$\Delta = \frac{M_R - M_I}{M_I}$$



Resonance



Local Z_2 scalar DM + Muon g-2

- Take $2Q_\chi = Q_\Phi = 2$
  - DM Lagrangian at renormalizable level

$$\mathcal{L}_{\rm DM} = \underline{|D_\mu X|^2} - m_X^2|X|^2 - \lambda_{HX}|X|^2\left(|H|^2 - \frac{v_H^2}{2}\right) - \lambda_{\Phi X}|X|^2\left(|\Phi|^2 - \frac{v_\Phi^2}{2}\right)$$

$$\underline{-\mu(X^2\Phi^\dagger + H.c.)}$$

$$\mu\left(X^2\phi^\dagger + H.c.\right) = \frac{1}{\sqrt{2}}\mu v_\Phi (X_R^2 - X_I^2)\left(1 + \frac{\phi}{v_\Phi}\right)$$

- $M_R^2 = M_X^2 + \sqrt{2}\mu v_\Phi, \quad M_I^2 = M_X^2 - \sqrt{2}\mu v_\Phi.$

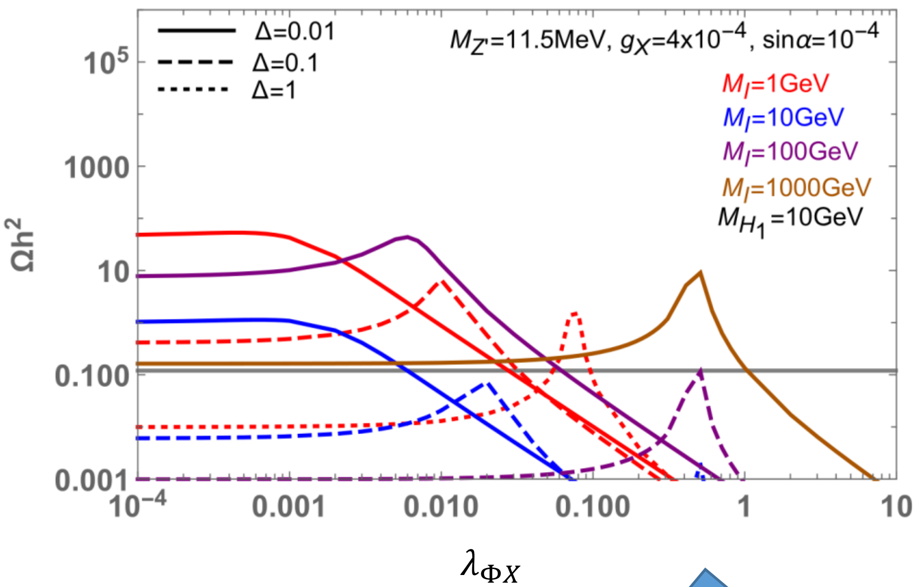
- Off-diagonal interaction $\mathcal{L} \supset g_X Z'^\mu \left(X_R\partial_\mu X_I - X_I\partial_\mu X_R\right)$

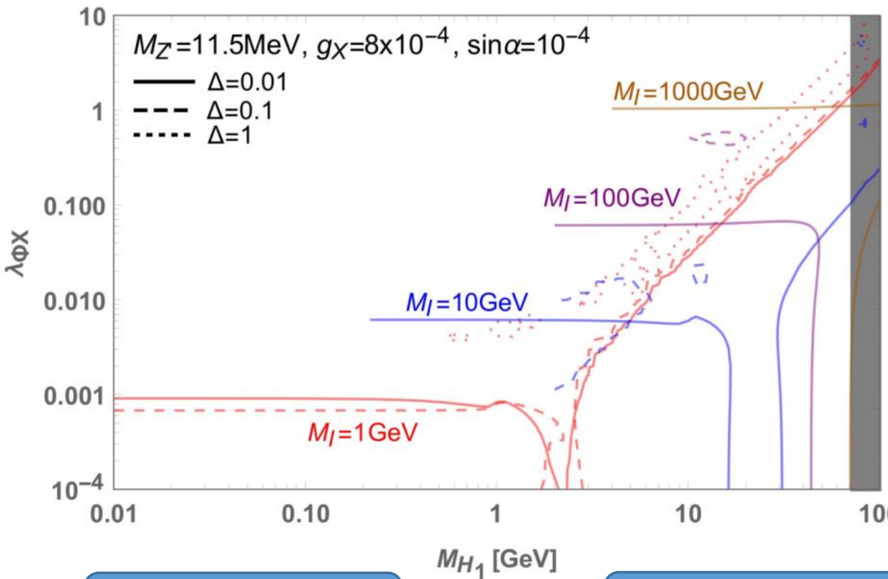
- $X_I X_I^\dagger \to H_1 H_1, Z'Z'$ annihilation
  - $X_R X_R^\dagger \to H_1 H_1, Z'Z'$

Local Z_2 scalar DM + Muon g-2

- DM-Nucleon scattering

$$\sigma_{\rm SI} = \frac{\mu_N^2}{4\pi}\left(\frac{M_N}{M_I}\right)^2 \frac{c_\alpha^4}{M_{H_1}^4} f_N^2 \left[\left(\lambda_{\Phi X} - \frac{\sqrt{2}\mu}{v_\Phi}\right)\frac{v_\Phi}{v_H} t_\alpha \left(1 - \frac{M_{H_1}^2}{M_{H_2}^2}\right) - \lambda_{HX}\left(t_\alpha^2 + \frac{M_{H_1}^2}{M_{H_2}^2}\right)\right]^2$$





$X_I X_I \to H_1 H_1$

$X_I X_I \to Z' Z'$

- $\Delta = \frac{M_R - M_I}{M_I}$

$$\lambda_1 = \left(\lambda_{\Phi X} v_\Phi - \sqrt{2}\mu\right) c_\alpha - \lambda_{HX} v_H s_\alpha \text{ and } \lambda_2 = \left(\lambda_{\Phi X} v_\Phi - \sqrt{2}\mu\right) s_\alpha + \lambda_{HX} v_H c_\alpha .$$

Conclusions

- New physics beyond the Standard Model shows up through 80% dark matter

- DM physics with massive dark photon cannot be complete without including dark gauge symmetry breaking mechanism which have been largely ignored by DM community

- Muon g-2 example shows the importance of the dark Higgs in DM phenomenology

Conclusions

- New physics beyond the Standard Model shows up through 80% dark matter
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Thank you very much
for listening to
my presentation

- Muon g-2 example shows the importance of the dark Higgs in DM phenomenology