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

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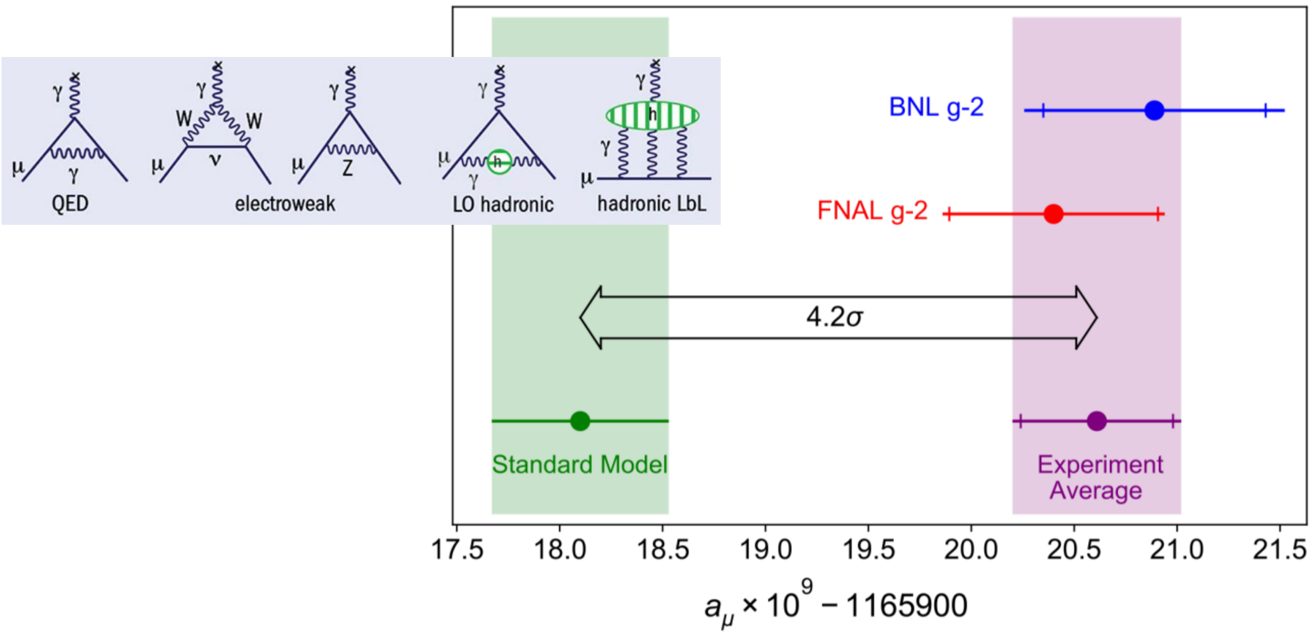
Contents

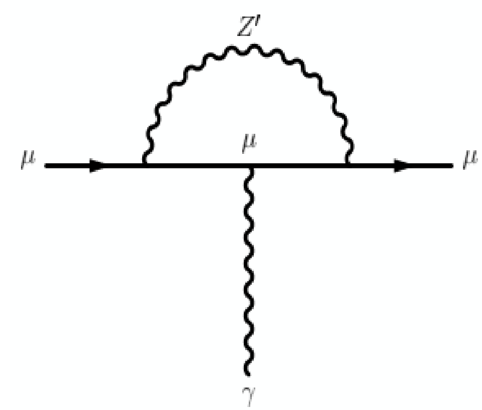
- Muon g-2 anomaly
- Leptophilic Z' boson constraints
- $\mathrm{U(1)}_{L_\mu - L_\tau}$ Dark matter Models
    - Local Z_2 scalar/ fermion DM model
- Conclusions

Muon g-2 Anomaly

- Anomalous muon magnetic moment

Muon g-2 collaboration, PRL 2021





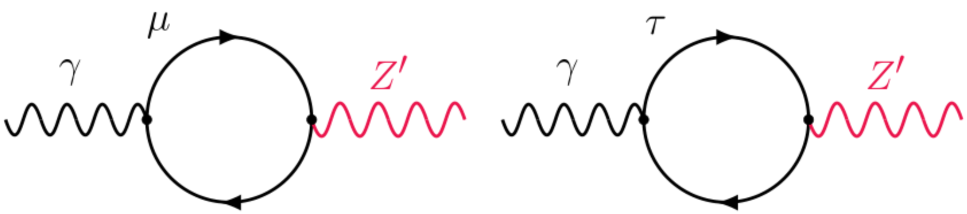
- $g_X \sim (4-8)\times 10^{-4}$ & $M \sim O(10)$MeV when $M_{Z'} < M_\mu$

$$\Delta a_\mu = \frac{\alpha'}{2\pi}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi}\frac{2m_\mu^2}{3M_{Z'}^2}$$

Leptophilic Z' model

- Possible to gauge one of the differences of two lepton-flavor numbers

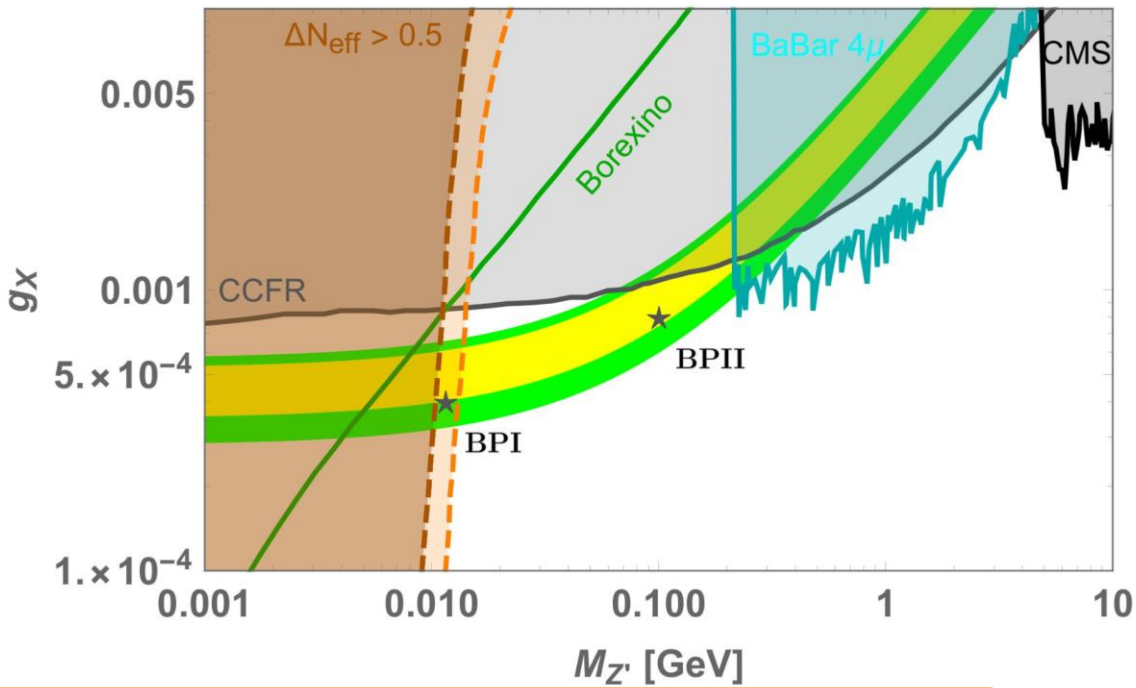
  Beak, Deshpande, He, Ko, PRD 2001 …

  - $L_e - L_\mu, L_\mu - L_\tau, L_\tau - L_e$: anomaly free
- Symmetries including L_e are strongly constrained
- No kinetic mixing between Z' and B @ high-energy
  - Kinetic mixing is generated through
  - 

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

$$\Gamma_{Z'\to e^+e^-} = \frac{(\epsilon e)^2 m_{Z'}}{12\pi}\left(1+\frac{2m_e^2}{m_{Z'}^2}\right)\sqrt{1-\frac{4m_e^2}{m_{Z'}^2}},$$

Leptophilic Z' model



- BPI : $M_{Z'} = 11.5\text{MeV},\ g_X = 4 \times 10^{-4}$
  - Muon g-2 anomaly, Hubble tension
- BPII: $M_{Z'} = 100\text{MeV},\ g_X = 8 \times 10^{-4}$
  - Muon g-2 anomaly

Leptophilic Z' DM model

- Minimum model set-up

Beak, Ko, JCAP 2008
…

$$\mathcal{L} \supset \mathcal{L}_{SM} - \frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + i\overline{\psi}\gamma_\alpha \partial^\alpha \psi + \frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha - m_\psi \overline{\psi}\psi$$
$$+ g' Q'_\psi Z'_\alpha \overline{\psi}\gamma^\alpha \psi + g' Z'_\alpha \sum_{f=\mu,\tau,\nu_\mu,\nu_\tau} Q'_f \overline{f}\gamma^\alpha f$$

  - New gauge boson Z' plays a role of messenger particle between DM and the SM leptons

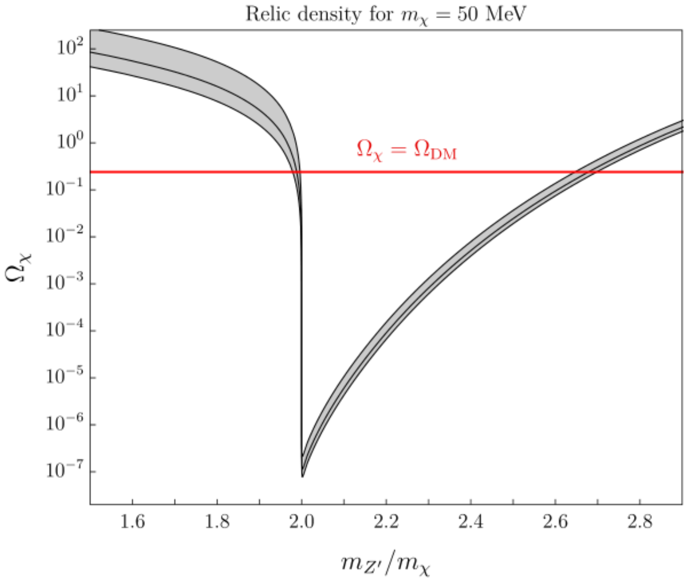
- New parameters: $g', m_{DM}, Q'_{DM}, m_{Z'}$
  - Consider Z' boson only & $g_X \sim (4-8) \times 10^{-4}$ for the muon g-2
  - $g_X \sim 10^{-4}$ is too small to get $\Omega_\chi h^2 = 0.12$

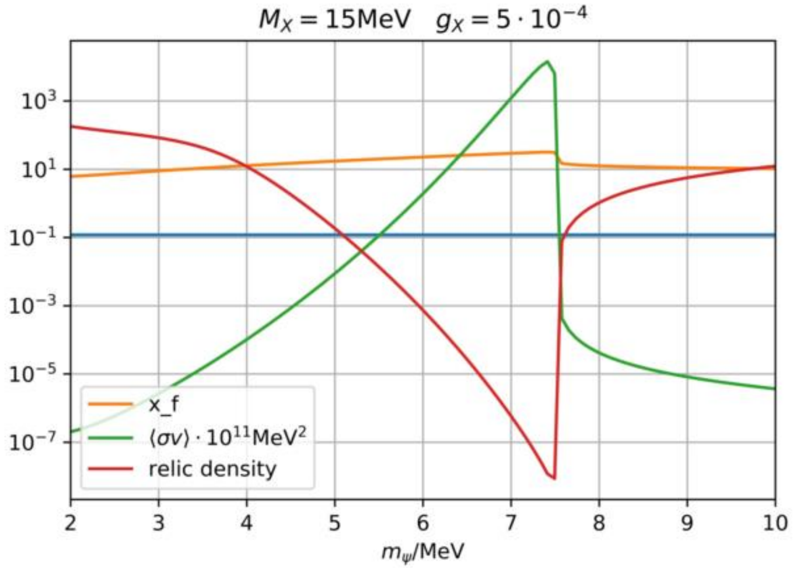
Leptophilic Z' DM model

- $\chi\bar{\chi}(X\bar{X}) \rightarrow f_{SM}\bar{f}_{SM}$: dominant annihilation channels
  - $M_{Z'} \sim 2M_\chi$ with the s-channel Z' resonance gives the correct relic density

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

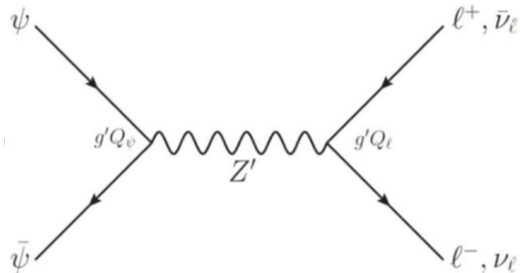
M. Drees, W. Zhao, PLB 2022





- Large DM charges

Asai, Okawa, Tsumura, JHEP



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**

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

Field	Z'_μ	$X(\chi)$	Φ	$L_\mu = (\nu_{L\mu}, \mu_L), \mu_R$	$L_\tau = (\nu_{L\tau}, \tau_L), \tau_R$
spin	1	0 (1/2)	0	1/2	1/2
$U(1)$ charge	0	$Q_X(Q_\chi)$	Q_Φ	+1	-1

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} - g_X Z'_\mu \left(\bar{\ell}_\mu \gamma^\mu \ell_\mu - \bar{\ell}_\tau \gamma^\mu \ell_\tau + \bar{\mu}_R \gamma^\mu \mu_R - \bar{\tau}_R \gamma^\mu \tau_R \right)$$

$$+ D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) \left(H^\dagger H - \frac{v^2}{2} \right) + \mathcal{L}_{\text{DM}},$$

- We consider both Complex Scalar (X) / Dirac fermion fermion (χ)
- Physics depends on Q_Φ, Q_X and Q_χ

- $Q_\Phi = 2Q_{X(\chi)}$ need special cares, since there are extra gauge invariant op's that break $U(1) \to Z_2$

Leptophilic Z' DM model

- If dark symmetry is spontaneously broken,

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

- Z' mass: $M_{Z'} = g_X |Q_\Phi| v_\Phi$

- 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: $M_{H_1},\ M_{H_2},\ sin\alpha$

Dark Higgs constraints

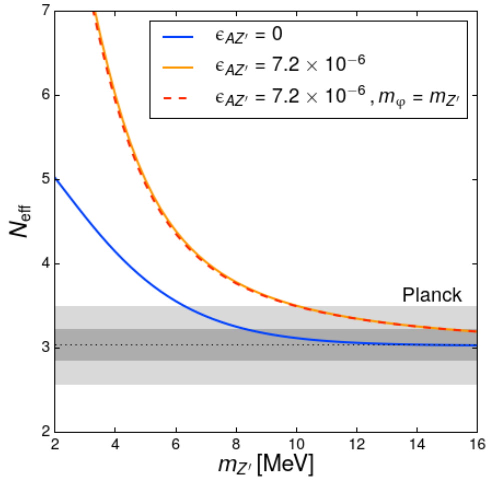
- After spontaneous symmetry breakings
  - Additional interactions with the dark Higgs

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

- The dark Higgs decay before 1sec
- 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 $e^{\pm} \to \Delta N_{eff} \neq 0$
- Higgs invisible decay

PDG 2021

  - $\mathrm{Br}(H_2 \to \mathrm{inv.}) = \frac{\Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}}{\Gamma_{H_2}^{SM} + \Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}} = 11\%$
  - Taking $sin\alpha = 10^{-4}$



Local Z_2 scalar DM

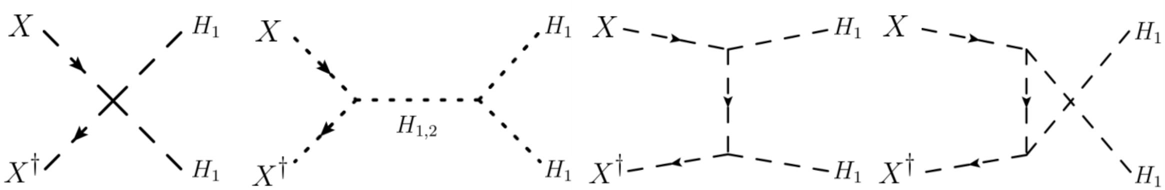
S. Baek, et al, PLB 2015
S. Baek, JKK, P.Ko, PLB 2020

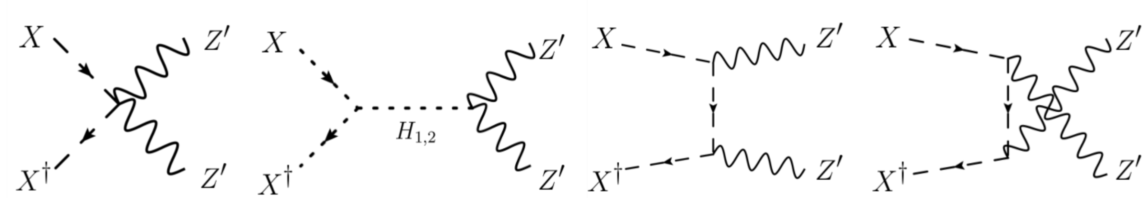
- Take $2Q_\chi = Q_\Phi = 2$
  - DM Lagrangian at renormalizable level

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

$$- \frac{1}{\sqrt{2}}\mu v_\Phi (X_R^2 - X_I^2)\left(1 + \frac{\phi}{v_\Phi}\right)$$

- $X_I X_I^\dagger \rightarrow H_1 H_1, Z'Z'$ annihilation

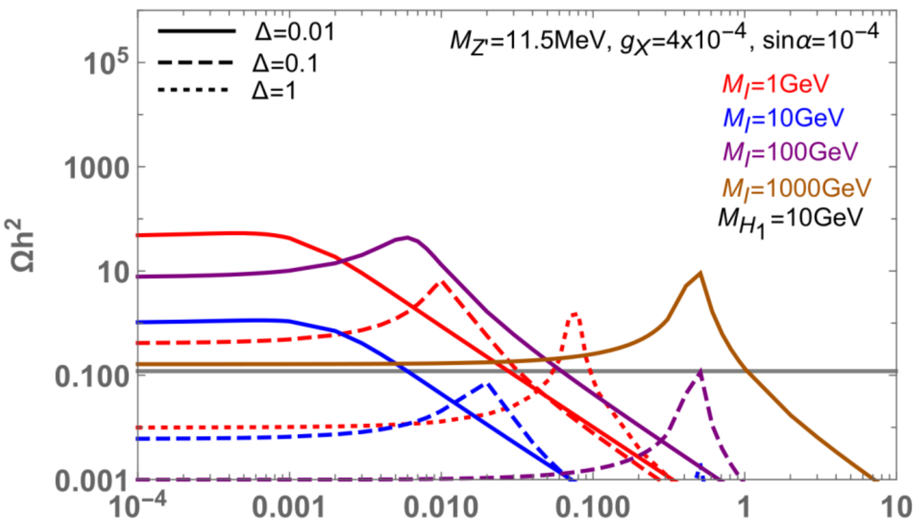


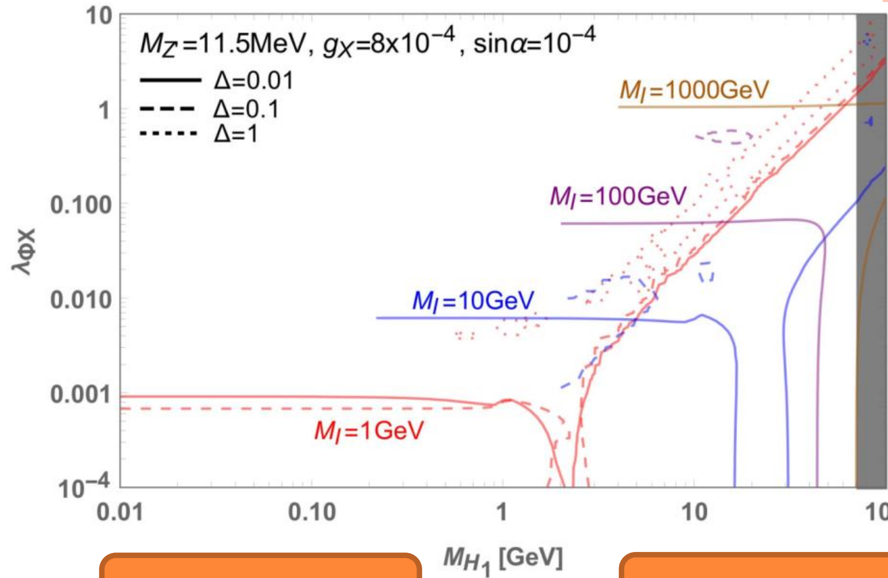


Local Z_2 scalar DM

- DM-Nucleon scattering

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





$X_I X_I \to H_1 H_1$

$X_I X_I \to Z' Z'$

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

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

Local Z_2 fermion DM

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

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

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

- 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)

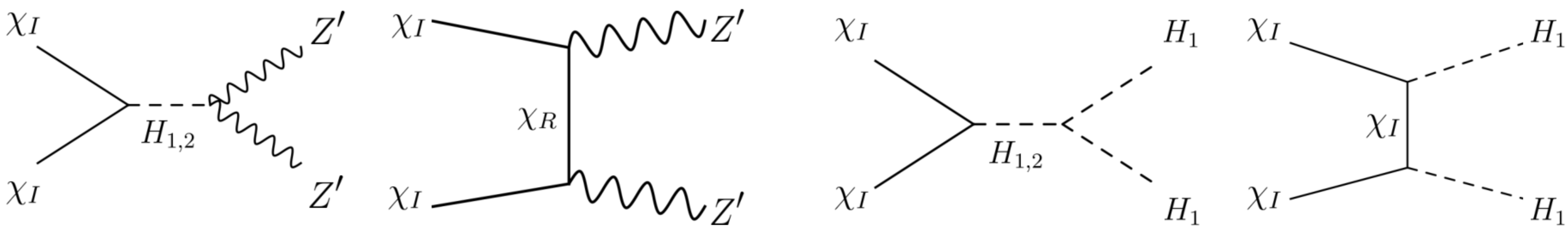
$$\delta \equiv M_R - M_I = 2y_\Phi v_\Phi.$$

- DM Largrangian

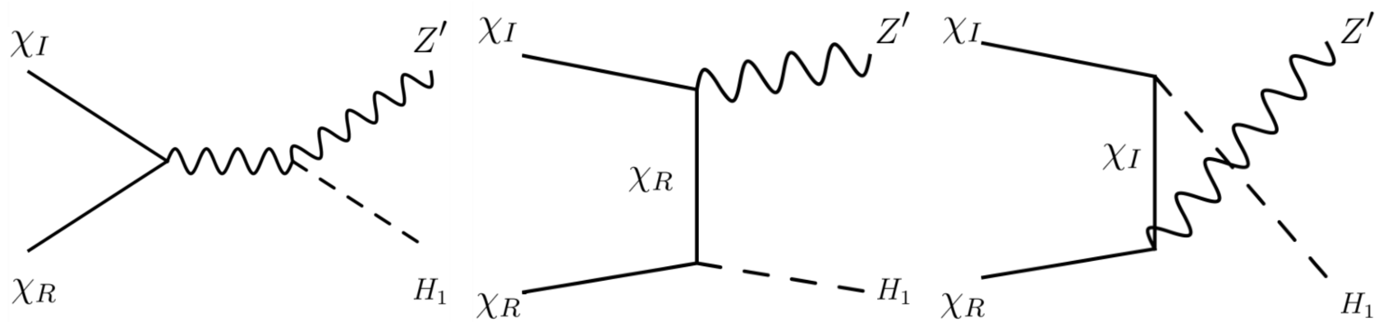
$$\mathcal{L}_{\rm DM} = \frac{1}{2}\sum_{i=R,I}\bar{\chi}_i\left(i\partial_\mu\gamma^\mu - M_i\right)\chi_i - i\frac{g_X}{2}Z'_\mu\left(\bar{\chi}_R\gamma^\mu\chi_I - \bar{\chi}_I\gamma^\mu\chi_R\right) - \frac{1}{2}y_\Phi\left(c_\alpha H_1 + s_\alpha H_2\right)\left(\bar{\chi}_R\chi_R - \bar{\chi}_I\chi_I\right).$$

Local Z_2 fermion DM

- $\chi_I \chi_I \to Z' Z', H_1 H_1$

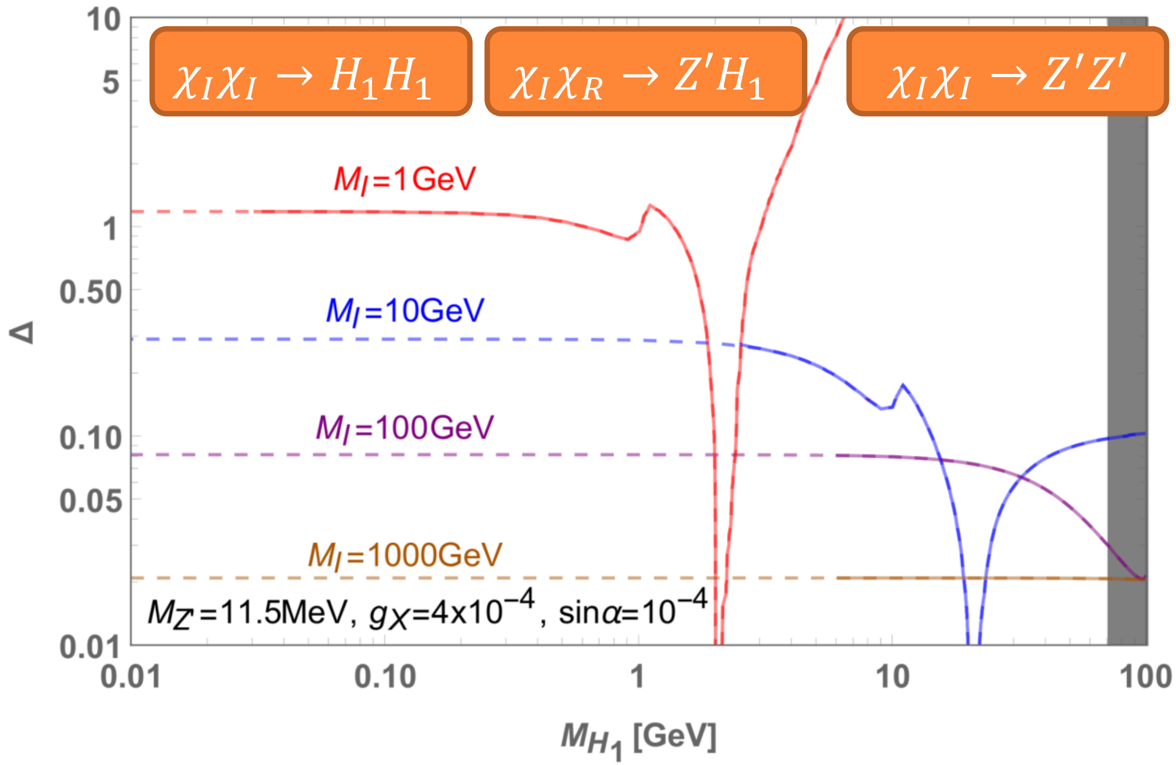


- $\chi_I \chi_R \to H_1 Z'$



Local Z_2 fermion DM

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



Conclusions

- We consider the Δa_μ and thermal WIMP DM
- Δa_μ can be accommodated for $M_{Z'} \sim O(10)$MeV & $g_X \sim 10^{-4}$
  - Thermal DM could be achieved near the Z' resonance
- We include the contributions of the dark Higgs boson
- Thanks to newly open channels, the DM mass range becomes much wider from GeV to O(a few) TeV

Conclusions

- We consider the Δa_μ and thermal WIMP DM
- Δa_μ can be accommodated for $M_{Z'} \sim O(10)$MeV &

Thank you very much for listening

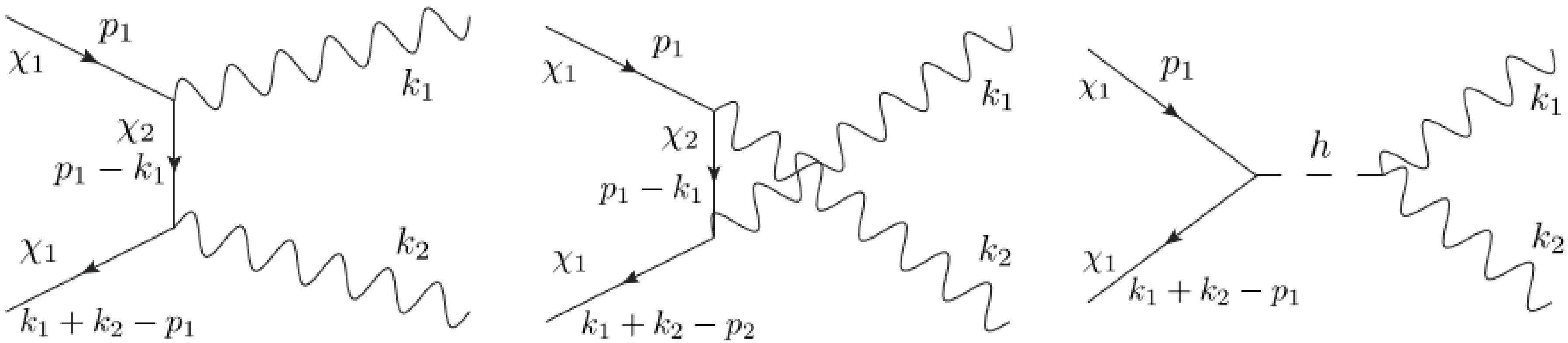
- Thanks to newly open channels, the DM mass range becomes much wider from GeV to O(a few) TeV

Back-up

Importance of dark Higgs

P. Ko et al, JHEP 2020

- DM DM → $Z'_L Z'_L$

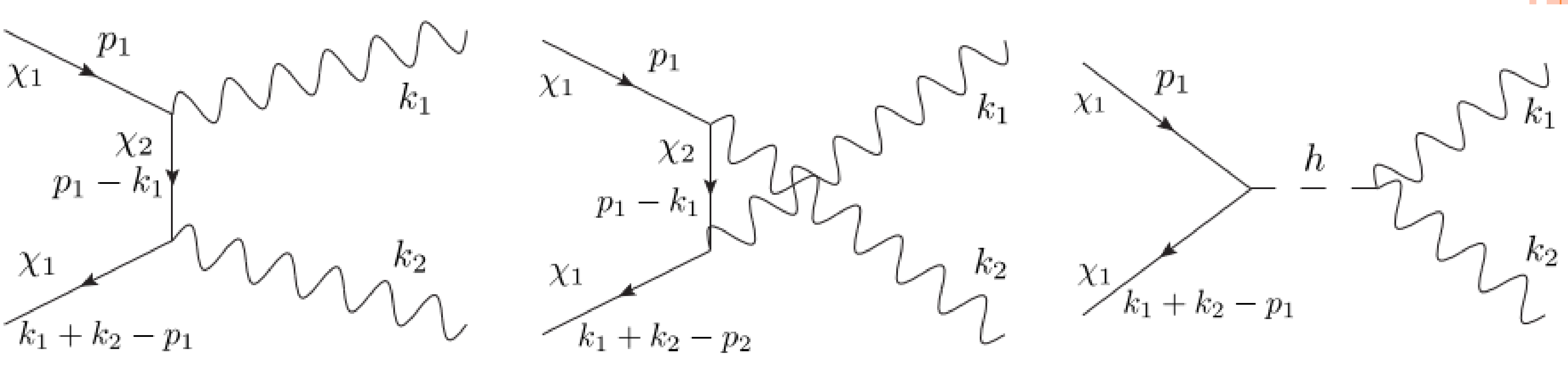


- Polarization of the longitudinal mode : $\epsilon_L(k) = \left(\frac{|\vec{k}|}{m_{\gamma'}}, \frac{E}{m_{\gamma'}}\frac{\vec{k}}{|\vec{k}|}\right) \xrightarrow{E \gg m'_\gamma} \frac{k}{m_{\gamma'}} + O\left(\frac{m_{\gamma'}}{E}\right)$
- The first is proportional to $\frac{(m_{\chi 1} - m_{\chi 2})^2}{m_{Z'}^2}$
- The second is proportional to $\frac{m_{\chi 1} - m_{\chi 2}}{m_{Z'}^2}$
- It would violate immediately the unitarity if $m_{Z'} \ll m_{\chi 1,2}$

Importance of dark Higgs

P. Ko et al, JHEP 2020

- DM DM → $Z'_L Z'_L$



- Without dark Higgs, the sum of the **first 2 Feynman diagrams** shows a bad high energy behavior like in the SM without Higgs
- Including the dark Higgs (the **last Feynman diagram**), this bad behavior is cured, and the theory becomes healthy