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Particles, Cosmology, and Strings

Contributions from the Dark Side of the Universe

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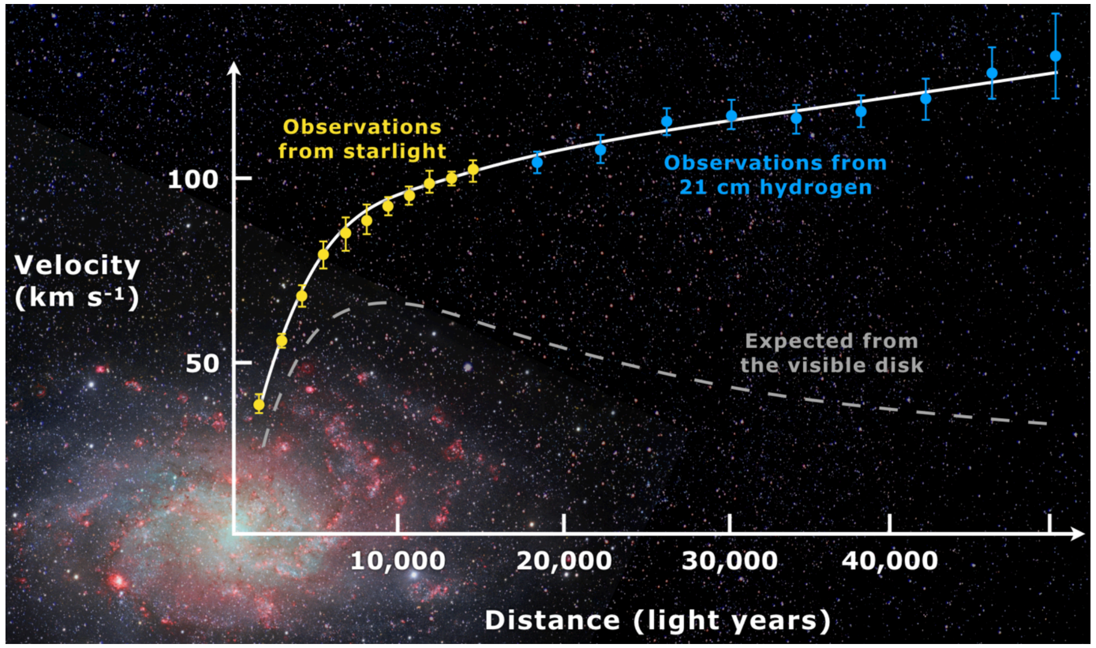
Outline

- Motivations
- Our model setup
- g–2 anomalies
- Dark matter phenomenology
- Collider phenomenology
- Summary

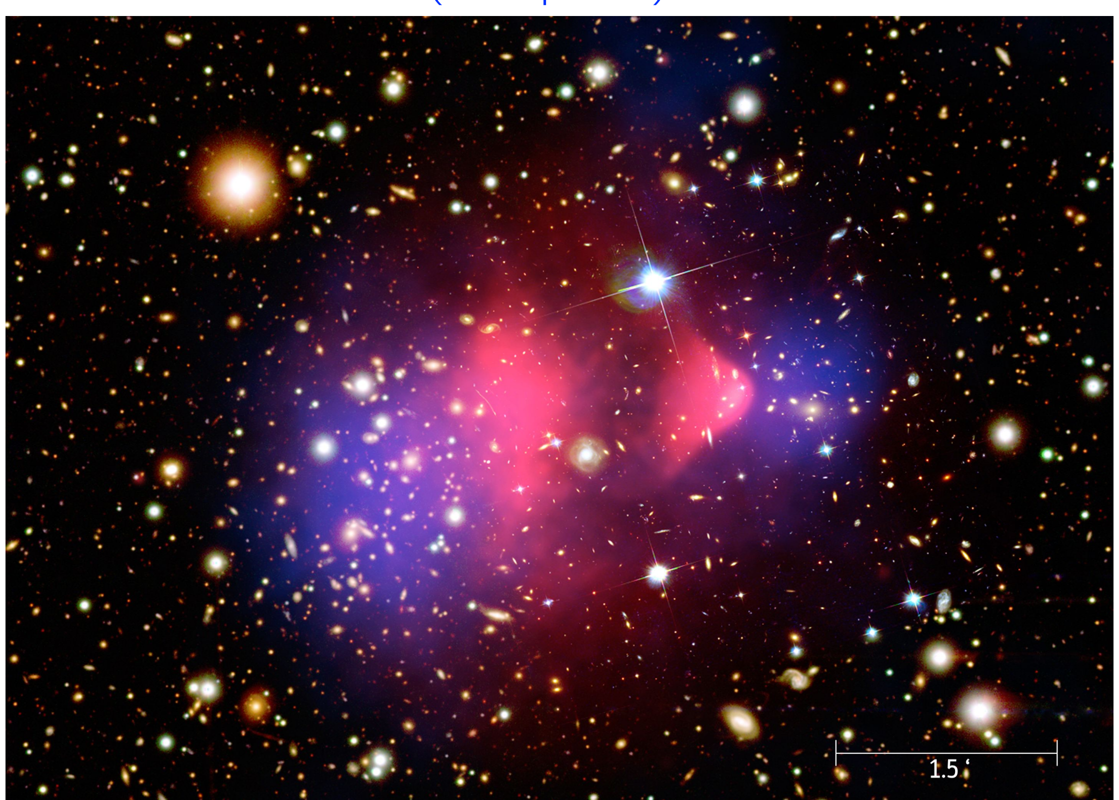
MOTIVATIONS

Mounting Evidence of DM

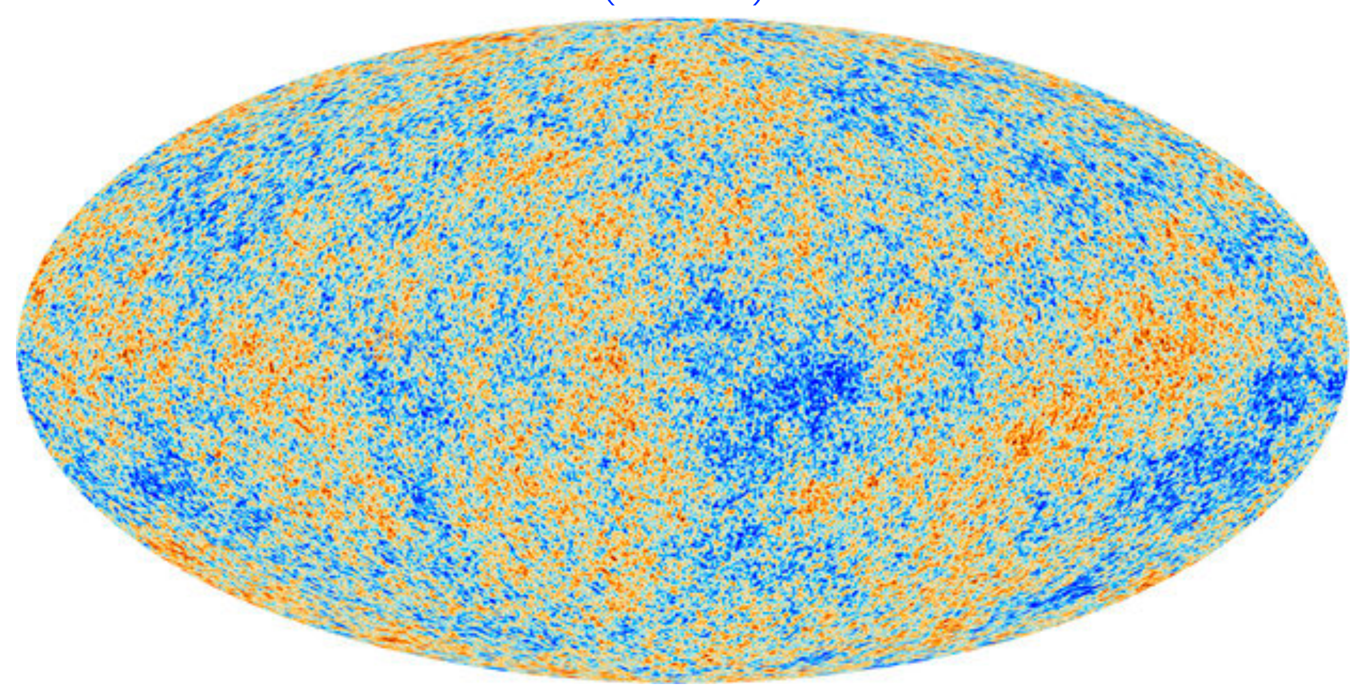


Rotation curve of spiral galaxy Messier 33 (Wikipedia)

Strong and weak gravitational lensing (NASA)



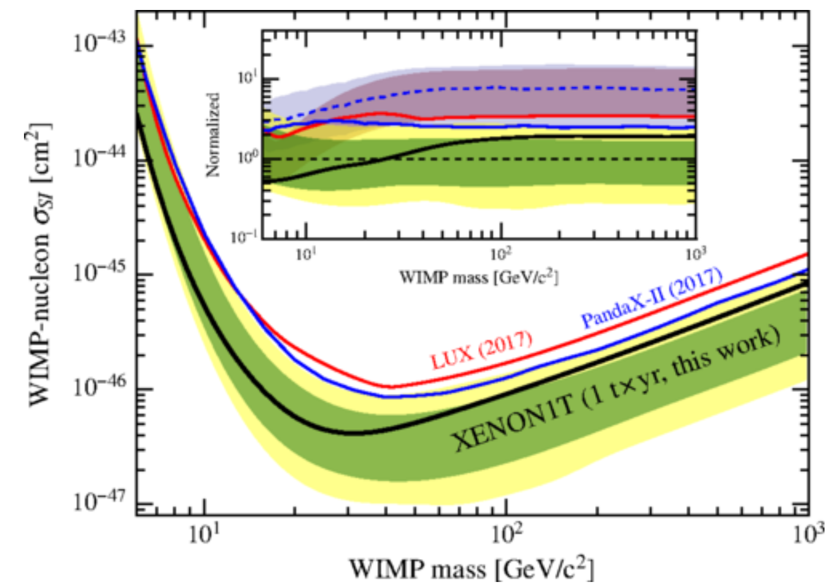
Bullet cluster (Wikipedia)



CMB (Planck Collaboration)

Dark Contributions

- We observe gravitational effects of dark matter at large scales, but not through other interactions in terrestrial experiments yet.*
  *We do see some direct/indirect hints from time to time.
  ➠ no coherent picture among different experiments



XENON1T 2018

- Do we need dark matter or dark sector in general in particle physics?
- Does it help us explaining any observed experimental anomalies?
  ➠ contributions from the dark side of the Universe to the subatomic world

Anomalous Dipole Moment

- For point-like spin-1/2 fermions, such as electrons or muons, that obey the Dirac equation, one can derive its interaction with an external magnetic field as

$$H = -\boldsymbol{\mu} \cdot \mathbf{B} \quad \text{with} \quad \boldsymbol{\mu} = g \frac{Q\mathbf{S}}{2mc}$$

where g is the gyromagnetic ratio (= 2 in the Dirac theory), Q is the electric charge (–e for electron), m is the mass, and **S** is the intrinsic spin.

- Because of radiative corrections, the gyromagnetic ratio g deviates from 2 and manifests in anomalous Larmor spin precession, with the deviation commonly expressed as the anomalous magnetic dipole moment

$$a = \frac{g-2}{2}$$

Muon g-2 Anomaly

- A long-lasting anomaly in particle physics is the muon anomalous magnetic dipole moment, $a_\mu \equiv (g-2)_\mu/2$.
- It has been thought as a harbinger for new physics (NP) for about two decades.

Czarnecki, Marciano 2001
Giudice, Paradisi, Passera 2012

- According to BNL measurement and SM expectation,

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = 261(79) \times 10^{-11}$$

➠ 3.3σ discrepancy

BNL Muon g-2 Collab. 2006
Aoyama, Hayakawa, Kinoshita, Nio 2012
Jegerlehner 2018
Keshavarzi, Nomura, Teubner 2018
RBC and UKQCD Collabs. 2018
Davier, Hoecker, Malaescu, Zhang 2020

*Aoyama et al (2006.04822) claims a larger discrepancy of 3.7σ, while Borsányi et al (2002.12347) claims no need for NP.

Electron g-2 Anomaly

- Recently, with a more precise determination of the fine-structure constant at LBNL, we now have

$$\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = -88(36) \times 10^{-14}$$

Aoyama, Hayakawa, Kinoshita, Nio 2012
Parker, Yu, Zhong, Estey, Müller 2018

➠ 2.4σ discrepancy

opposite sign from Δa_μ

New Physics Invitations

- These tantalizing opposite deviations have invited many studies that explore suitable NP models:
  - A. Crivellin, M. Hoferichter and P. Schmidt-Wellenburg, Combined explanations of $(g-2)_{\mu,e}$ and implications for a large muon EDM, PRD 98 (2018) 113002 [arXiv:1807.11484].
  - J. Liu, C.E.M. Wagner and X.-P. Wang, A light complex scalar for the electron and muon anomalous magnetic moments, JHEP 03 (2019) 008 [arXiv:1810.11028].
  - M. Endo and W. Yin, Explaining electron and muon $g-2$ anomaly in SUSY without lepton-flavor mixings, JHEP 08 (2019) 122 [arXiv:1906.08768].
  - M. Abdullah, B. Dutta, S. Ghosh and T. Li, $(g-2)_{\mu,e}$ and the ANITA anomalous events in a three-loop neutrino mass model, PRD 100 (2019) 115006 [arXiv:1907.08109].
  - M. Bauer, M. Neubert, S. Renner, M. Schnubel and A. Thamm, Axionlike Particles, Lepton-Flavor Violation, and a New Explanation of a_μ and a_e, PRL 124 (2020) 211803 [arXiv:1908.00008].
  - M. Badziak and K. Sakurai, Explanation of electron and muon $g-2$ anomalies in the MSSM, JHEP 10 (2019) 024 [arXiv:1908.03607].
  - G. Hiller, C. Hormigos-Feliu, D.F. Litim and T. Steudtner, Anomalous magnetic moments from asymptotic safety, arXiv:1910.14062.
  - C. Cornella, P. Paradisi and O. Sumensari, Hunting for ALPs with Lepton Flavor Violation, JHEP 01 (2020) 158 [arXiv:1911.06279].
  - N. Haba, Y. Shimizu and T. Yamada, Muon and Electron $g-2$ and the Origin of Fermion Mass Hierarchy, arXiv:2002.10230.

OUR MODEL

Overview

- We propose a model with a set of new particles whose interactions are constrained by a flavor-dependent global $U(1)_\ell$ symmetry and a $\mathbb{Z}_2$ symmetry.
  ➠ simultaneously accommodate both g–2 anomalies and offer a DM candidate.
- These new symmetries also forbid BSM contributions to lepton flavor-violating decays, e.g. $\mu \to e\gamma$, and guarantee the DM stability.

Particle Content

- Particle content and charge assignment under the symmetries $SU(2)_L \otimes U(1)_Y \otimes U(1)_\ell \otimes \mathbb{Z}_2$ are as follows.
- The $U(1)_\ell$ charges depend on the lepton flavor and $q_e \neq q_\mu$.
- Two scenarios: $Y_D = 0$ or 1 for $\mathbb{Z}_2$-odd particles.
  ➠ at least one neutral particle to be a DM candidate.

vector-like isospin singlets

	SM Fermion			Scalar		BSM
Fields	$(L_L^e, L_L^\mu, L_L^\tau)$	(e_R, μ_R, τ_R)	(χ_e, χ_μ)	Φ	η_D	η_S
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$\mathrm{U}(1)_Y$	$-1/2$	-1	$-Y_D$	$1/2$	$Y_D - 1/2$	$Y_D - 1$
$\mathrm{U}(1)_\ell$	$(q_e, q_\mu, 0)$	$(q_e, q_\mu, 0)$	(q_e, q_μ)	0	0	0
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$

global symmetries

all are SU(3) color-neutral

assumed to have zero VEV

Scalar Fields

- The scalar fields are parameterized as

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(h + v + iG^0\right) \end{pmatrix}$$

246 GeV

125-GeV Higgs boson,
no mixing from η's because of $\mathbb{Z}_2$

$$\eta_D = \begin{cases} \begin{pmatrix} \frac{1}{\sqrt{2}}\left(\eta_H^0 + i\eta_A^0\right) \\ \eta^- \end{pmatrix} & \text{for } Y_D = 0 \\ \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}\left(\eta_H^0 + i\eta_A^0\right) \end{pmatrix} & \text{for } Y_D = 1 \end{cases}$$

zero VEV to preserve $\mathbb{Z}_2$

$$\eta_S = \begin{cases} \eta_S^\pm & \text{for } Y_D = 0 \\ \eta_S^0 & \text{for } Y_D = 1 \end{cases}$$

zero VEV to preserve $\mathbb{Z}_2$

Yukawa Interactions

- The lepton Yukawa interactions and the mass term for χ_a (a = flavor index) are given by

$$\mathcal{L}_Y = \sum_{i=e,\mu,\tau} y^i_{\rm SM} \bar{L}^i_L \ell^i_R \Phi$$

— same as SM

generally complex, assumed real for simplicity

$$+ \sum_{a=e,\mu} \left[f^a_L \left(\bar{L}^a_L \chi_{R,a} \right) \eta_D + f^a_R \left(\bar{\ell}^a_R \chi_{L,a} \right) \eta_S \right.$$

not for τ

flavor-diagonal because of $U(1)_\ell$ ➠ no $\mu \to e\gamma$ at all orders

$$\left. + M_{\chi_a} \left(\bar{\chi}_{L,a} \chi_{R,a} \right) \right]$$

$$+ \text{h.c.}$$

both $\eta_{D,S}$ are required for giving the different Yukawa interactions

- $\eta_{D,S}$ act as bridges between visible and dark sectors.
- The Lagrangian for the quark and gauge sectors are the same as in the SM.

Scalar Potential

- The most general form of the scalar potential consistent with all the symmetries is given by

all parameters real ➠ CP-symmetric

$$V = -\mu_\Phi^2|\Phi|^2 + \mu_D^2\left|\eta_D\right|^2 + \mu_S^2\left|\eta_S\right|^2 + \frac{\lambda_1}{2}|\Phi|^4 + \frac{\lambda_2}{2}\left|\eta_D\right|^4$$
$$+ \lambda_3|\Phi|^2\left|\eta_D\right|^2 + \lambda_4\left|\Phi^\dagger\eta_D\right|^2 + \left[\frac{\lambda_5}{2}\left(\Phi\cdot\eta_D\right)^2 + \text{h.c.}\right]$$
$$+ \frac{\lambda_6}{2}\left|\eta_S\right|^4 + \lambda_7|\Phi|^2\left|\eta_S\right|^2 + \lambda_8\left|\eta_D\right|^2\left|\eta_S\right|^2 + \left[\kappa\left(\eta_D^\dagger\Phi\eta_S\right) + \text{h.c.}\right]$$

$\mu_\Phi^2, \mu_D^2, \mu_S^2 > 0$ to preserve SM vacuum stability

where the combination

$$\Phi\cdot\eta_D = \begin{cases} \Phi^\dagger\eta_D & \text{for } Y_D = 1 \\ \Phi^T\left(i\tau_2\right)\eta_D & \text{for } Y_D = 0 \end{cases}$$

*Phases of λ_5 and κ can be removed by a redefinition of the scalar fields in general.

The Two Scenarios

- When $Y_D = 0$, the singlet η_S is charged and mixes with the charged field of η_D:

$$\begin{pmatrix} \eta^\pm \\ \eta_S^\pm \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \eta_1^\pm \\ \eta_2^\pm \end{pmatrix}$$

- When $Y_D = 1$, the singlet η_S is neutral and mixes with the neutral field of η_D:

physical

$$\begin{pmatrix} \eta_H^0 \\ \eta_S^0 \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \eta_1^0 \\ \eta_2^0 \end{pmatrix}$$

Theory Bounds

- Parameters in the scalar potential are subject to:
  - Perturbativity: $\lambda_i^2 < 4\pi$;
  - Perturbative unitarity: $f(\lambda_i) < 8\pi$;

$$(c_1, c_2, c_3) = \begin{cases} (1, \sqrt{2}, 2) & \text{for } Y_D = 0 \\ (2, 2, 6) & \text{for } Y_D = 1 \end{cases}$$

$$f(\lambda_i) \in \left\{ \left| \frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right)\right| \ , \ \left| \frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right)\right| \ , \ |\lambda_3 + 2\lambda_4 \pm 3\lambda_5| \ , \right.$$
$$\left. |\lambda_3 \pm \lambda_5| \ , \ |\lambda_3 \pm \lambda_4| \ , \ c_1 |\lambda_{7,8}| \ , \ \text{and eigs} \begin{pmatrix} 3\lambda_1 & 2\lambda_3 + \lambda_4 & c_2\lambda_7 \\ 2\lambda_3 + \lambda_4 & 3\lambda_2 & c_2\lambda_8 \\ c_2\lambda_7 & c_2\lambda_8 & c_3\lambda_6 \end{pmatrix} \right\}$$

consistent with next-to-2HDM

Muhlleitner, Sampaio, Santos , Wittbrodt 2017

  - Vacuum stability (bounded from below): $\lambda_i \in \Omega_1 \cup \Omega_2$;

$$\Omega_1 = \left\{ \lambda_1, \lambda_2, \lambda_6 > 0; \sqrt{\lambda_1\lambda_6} + \lambda_7 > 0; \sqrt{\lambda_2\lambda_6} + \lambda_8 > 0 \right.$$
$$\left. \sqrt{\lambda_1\lambda_2} + \lambda_3 + D > 0; \lambda_7 + \sqrt{\frac{\lambda_1}{\lambda_2}}\lambda_8 \geq 0 \right\}$$

$$\Omega_2 = \left\{ \lambda_1, \lambda_2, \lambda_6 > 0; \sqrt{\lambda_2\lambda_6} \geq \lambda_8 > -\sqrt{\lambda_2\lambda_6}; \sqrt{\lambda_1\lambda_6} > -\lambda_7 \geq \sqrt{\frac{\lambda_1}{\lambda_2}}\lambda_8 \right.$$
$$\left. \sqrt{(\lambda_7^2 - \lambda_1\lambda_6)(\lambda_8^2 - \lambda_2\lambda_6)} > \lambda_7\lambda_8 - (D + \lambda_3)\lambda_6 \right\}$$

$$D = \max\{0, \lambda_4 - \lambda_5\}$$

g-2 ANOMALIES

New Contributions to a_ℓ

- One-loop contributions to muon/electron a_ℓ with $\mathbb{Z}_2$-odd particles running in the loop:

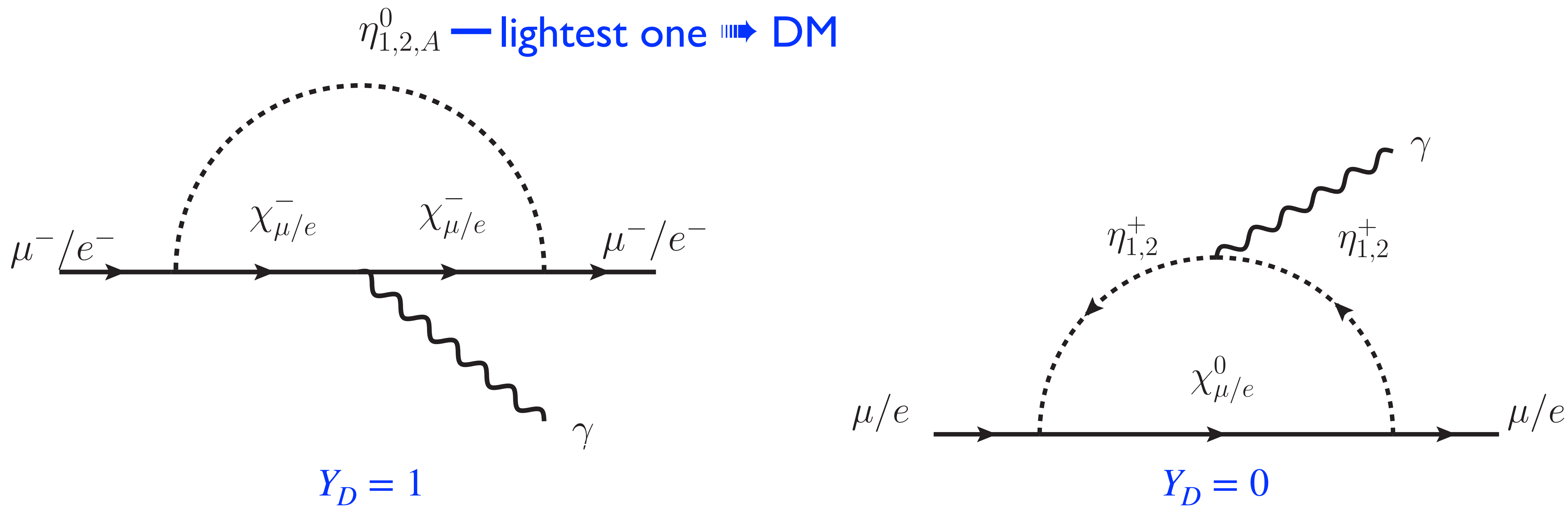


Figure 1. Feynman diagrams for the muon/electron $g-2$. The left (right) diagram contributes to $g-2$ in the model with $Y_D = 1$ ($Y_D = 0$).

New Contributions to a_ℓ

- New physics corrections:

$$\Delta a_\ell^{\rm NP} = \begin{cases} -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2}\left[\dfrac{m_\ell^2}{m_{\eta_k^\pm}^2}\left(\left|g_L^{\ell,k}\right|^2+\left|g_R^{\ell,k}\right|^2\right)F_2\left(\dfrac{M_{\chi_\ell}^2}{m_{\eta_k^\pm}^2}\right)\right. \\ \left. +\dfrac{2M_{\chi_\ell}m_\ell}{m_{\eta_k^\pm}^2}{\rm Re}\left(g_L^{\ell,k}g_R^{\ell,k*}\right)F_3\left(\dfrac{M_{\chi_\ell}^2}{m_{\eta_k^\pm}^2}\right)\right] & Y_D=0 \\ -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2}\left[\dfrac{m_\ell^2}{M_{\chi_\ell}^2}\left(\left|g_L^{\ell,k}\right|^2+\left|g_R^{\ell,k}\right|^2\right)F_2\left(\dfrac{m_{\eta_k}^2}{M_{\chi_\ell}^2}\right)\right. \\ \left. +\dfrac{2m_\ell}{M_{\chi_\ell}}{\rm Re}\left(g_L^{\ell,k}g_R^{\ell,k*}\right)F_1\left(\dfrac{m_{\eta_k}^2}{M_{\chi_\ell}^2}\right)\right] - \dfrac{\left|f_L^\ell\right|^2}{32\pi^2}\dfrac{m_\ell^2}{M_{\chi_\ell}^2}F_2\left(\dfrac{m_{\eta_A}^2}{M_{\chi_\ell}^2}\right) & Y_D=1 \end{cases}$$

where $g_{L,R}^{\ell,k}$ denote the Yukawa couplings for the $\bar\chi_\ell P_{L,R}\ell\eta_k^\pm$ ($\bar\chi_\ell P_{L,R}\ell\eta_k^0$) vertices in the $Y_D = 0\ (1)$ scenario.

More Explicitly

- The couplings

related to scalar rotation

$$g_L^{\ell,1} = f_L^\ell c_\theta, \quad g_L^{\ell,2} = -f_L^\ell s_\theta, \quad g_R^{\ell,1} = f_R^\ell s_\theta, \quad g_R^{\ell,2} = f_R^\ell c_\theta \quad (\text{for } Y_D = 0)$$

$$g_L^{\ell,1} = \frac{f_L^\ell}{\sqrt{2}} c_\theta, \quad g_L^{\ell,2} = -\frac{f_L^\ell}{\sqrt{2}} s_\theta, \quad g_R^{\ell,1} = f_R^\ell s_\theta, \quad g_R^{\ell,2} = f_R^\ell c_\theta \quad (\text{for } Y_D = 1)$$

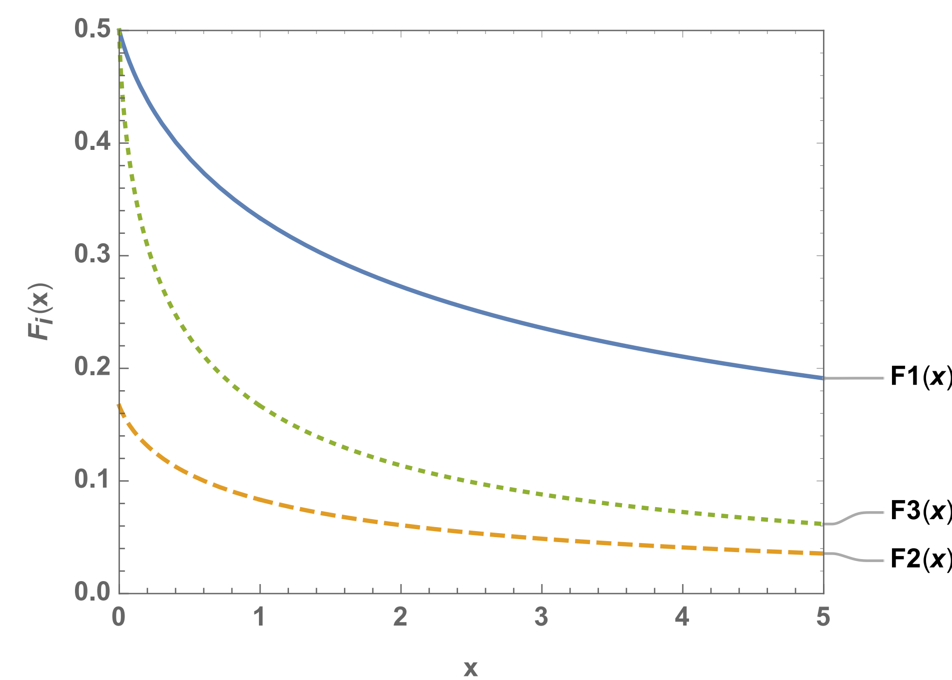
- The loop functions

$$F_1(x) = \frac{1 - 4x + 3x^2 - 2x^2 \ln x}{2(1-x)^3}$$

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1-x)^4}$$

$$F_3(x) = \frac{1 - x^2 + 2x \ln x}{2(1-x)^3}$$

$F_1(x) \geq F_3(x) > F_2(x)$, $\forall x$



New Contributions to a_ℓ

- New physics corrections:

loop functions $F_1(x) \geq F_3(x) > F_2(x) > 0$, $\forall x$

$$\Delta a_\ell^{\rm NP} = \begin{cases} -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2}\left[\dfrac{m_\ell^2}{m_{\eta_k^\pm}^2}\left(\left|g_L^{\ell,k}\right|^2+\left|g_R^{\ell,k}\right|^2\right)F_2\left(\dfrac{M_{\chi_\ell}^2}{m_{\eta_k^\pm}^2}\right)\right. \\ \left. +\dfrac{2M_{\chi_\ell}m_\ell}{m_{\eta_k^\pm}^2}\,\mathrm{Re}\left(g_L^{\ell,k}g_R^{\ell,k*}\right)F_3\left(\dfrac{M_{\chi_\ell}^2}{m_{\eta_k^\pm}^2}\right)\right] & Y_D = 0 \\ -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2}\left[\dfrac{m_\ell^2}{M_{\chi_\ell}^2}\left(\left|g_L^{\ell,k}\right|^2+\left|g_R^{\ell,k}\right|^2\right)F_2\left(\dfrac{m_{\eta_k}^2}{M_{\chi_\ell}^2}\right)\right. \\ \left. +\dfrac{2m_\ell}{M_{\chi_\ell}}\,\mathrm{Re}\left(g_L^{\ell,k}g_R^{\ell,k*}\right)F_1\left(\dfrac{m_{\eta_k}^2}{M_{\chi_\ell}^2}\right)\right] - \dfrac{\left|f_L^\ell\right|^2}{32\pi^2}\dfrac{m_\ell^2}{M_{\chi_\ell}^2}F_2\left(\dfrac{m_{\eta_A}^2}{M_{\chi_\ell}^2}\right) & Y_D = 1 \end{cases}$$

$g_{L,R}^{\ell,k} \propto f_{L,R}^\ell \sin\theta$ (or $\cos\theta$)

more dominant than the others by M_{χ_ℓ}/m_ℓ

where $g_{L,R}^{\ell,k}$ denote the Yukawa couplings for the $\bar{\chi}_\ell P_{L,R}\ell\eta_k^\pm$ ($\bar{\chi}_\ell P_{L,R}\ell\eta_k^0$) vertices in the $Y_D = 0$ (1) scenario.

New Physics Corrections

- Dominant NP corrections:

$$\Delta a_\ell^{\rm NP} \simeq \begin{cases} -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2} \dfrac{2M_{\chi_\ell} m_\ell}{m^2_{\eta_k^\pm}} \mathrm{Re}\left(g_L^{\ell,k} g_R^{\ell,k*}\right) F_3\left(\dfrac{M^2_{\chi_\ell}}{m^2_{\eta_k^\pm}}\right) & Y_D = 0 \\ -\dfrac{1}{16\pi^2}\displaystyle\sum_{k=1,2} \dfrac{2m_\ell}{M_{\chi_\ell}} \mathrm{Re}\left(g_L^{\ell,k} g_R^{\ell,k*}\right) F_1\left(\dfrac{m^2_{\eta_k}}{M^2_{\chi_\ell}}\right) & Y_D = 1 \end{cases}$$

- Contribution to the dominant terms from lighter scalars (η_1^0 or $\eta_1^\pm$) is opposite in sign to that from the heavier ones (η_2^0 or $\eta_2^\pm$) due to the scalar orthogonal rotation.
  - ➠ require mass splitting to avoid cancellation
  - ➠ sign of Δa_ℓ^{NP} is determined by $\mathrm{Re}(g_L^{\ell,1} g_R^{\ell,1*})$
  - ➠ choose $\mathrm{Re}(g_L^{\mu,1} g_R^{\mu,1*}) < 0$ and $\mathrm{Re}(g_L^{e,1} g_R^{e,1*}) > 0$
- This can be realized by taking $f_L^\mu > 0$, $f_R^\mu < 0$, $f_{L,R}^e > 0$, and the mixing angle θ in the first quadrant.

$Y_D = 1$ Scenario

- Take $|f_L^\ell| = |f_R^\ell|$ $(\equiv f^\ell)$ for simplicity in our analyses.
- For two sets of benchmark parameters differing in Δm_η:

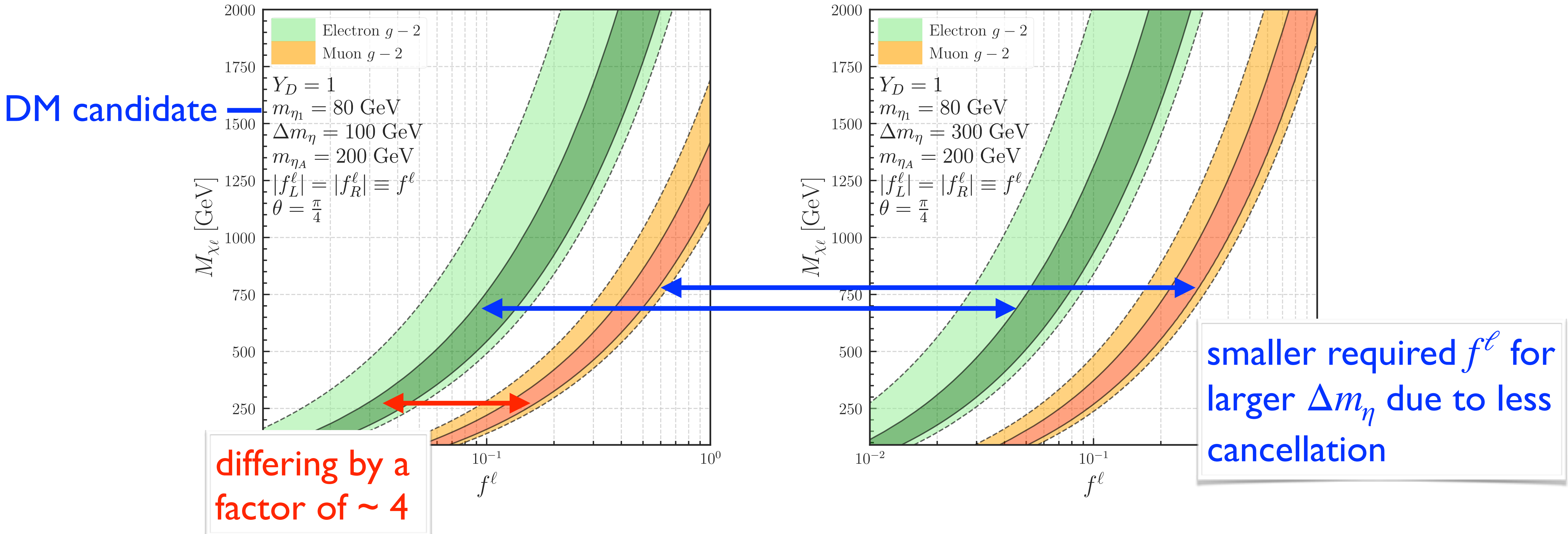


Figure 2. Regions in the plane of $f^\ell \equiv |f_L^\ell| = |f_R^\ell|$ and M_{χ_ℓ} that can explain the corresponding $(g-2)_\ell$ for the scenario of $Y_D = 1$ at the 1σ (darker color) and 2σ (lighter color) levels.

$$\left|\frac{\Delta a_\mu^{\rm NP}}{\Delta a_e^{\rm NP}}\right| \simeq \frac{m_\mu}{m_e}\left|\frac{f^\mu}{f^e}\right|^2 \simeq 3000 \ \text{ if } \ M_{\chi_\mu} = M_{\chi_e}$$

$Y_D = 0$ Scenario

- Take $|f_L^\ell| = |f_R^\ell|$ $(\equiv f^\ell)$ for simplicity in our analyses.
- For two sets of benchmark parameters differing in Δm_η:

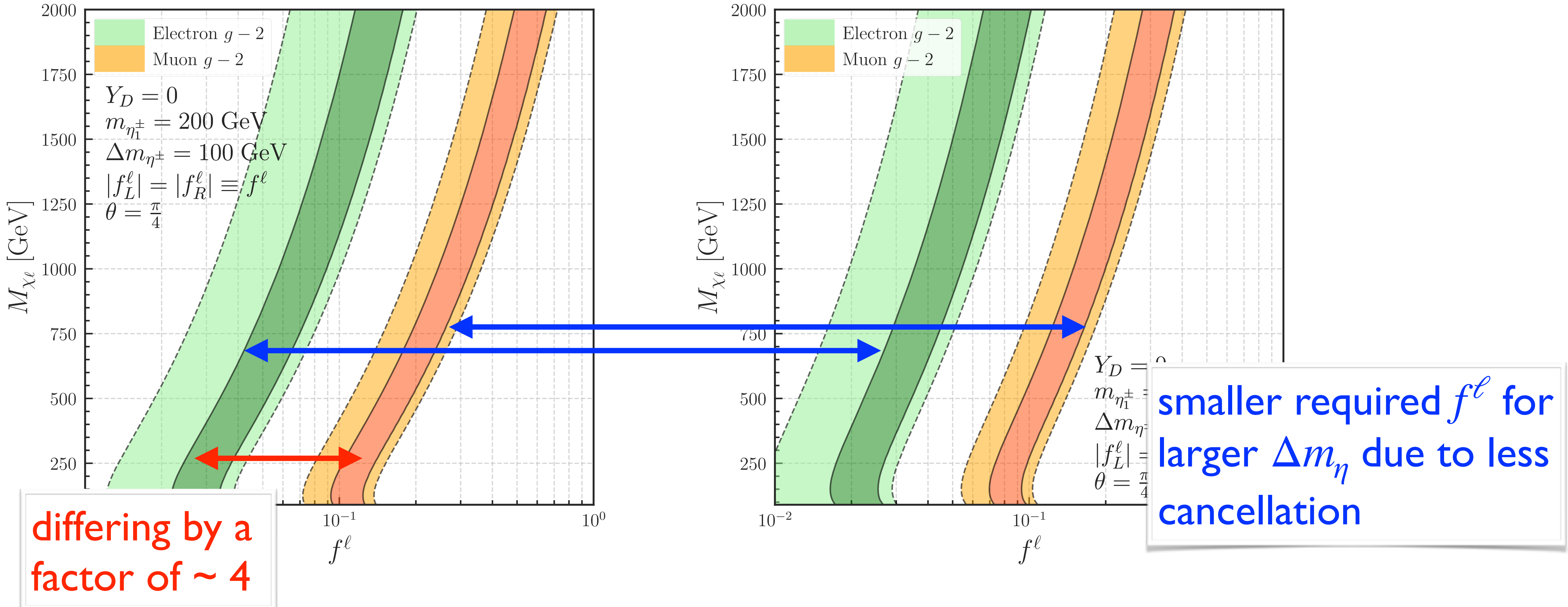


Figure 3. As in figure 2, but in the scenario of $Y_D = 0$. The mass of the lighter charged scalar $\eta_1^\pm$ is set to be 200 GeV.

$$\left|\frac{\Delta a_\mu^{\rm NP}}{\Delta a_e^{\rm NP}}\right| \simeq \frac{m_\mu}{m_e}\left|\frac{f^\mu}{f^e}\right|^2 \simeq 3000 \quad \text{if} \quad M_{\chi_\mu} = M_{\chi_e}$$

DARK MATTER PHENOMENOLOGY

DM Candidates

- The lightest neutral $\mathbb{Z}_2$-odd particles serve as DM candidates:
  - The $Y_D = 0$ scenario: η_H^0 or χ_ℓ^0.
  - The $Y_D = 1$ scenario: η_1^0 (mixture of η_H^0 and η_S^0)
- DM relic density:

$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

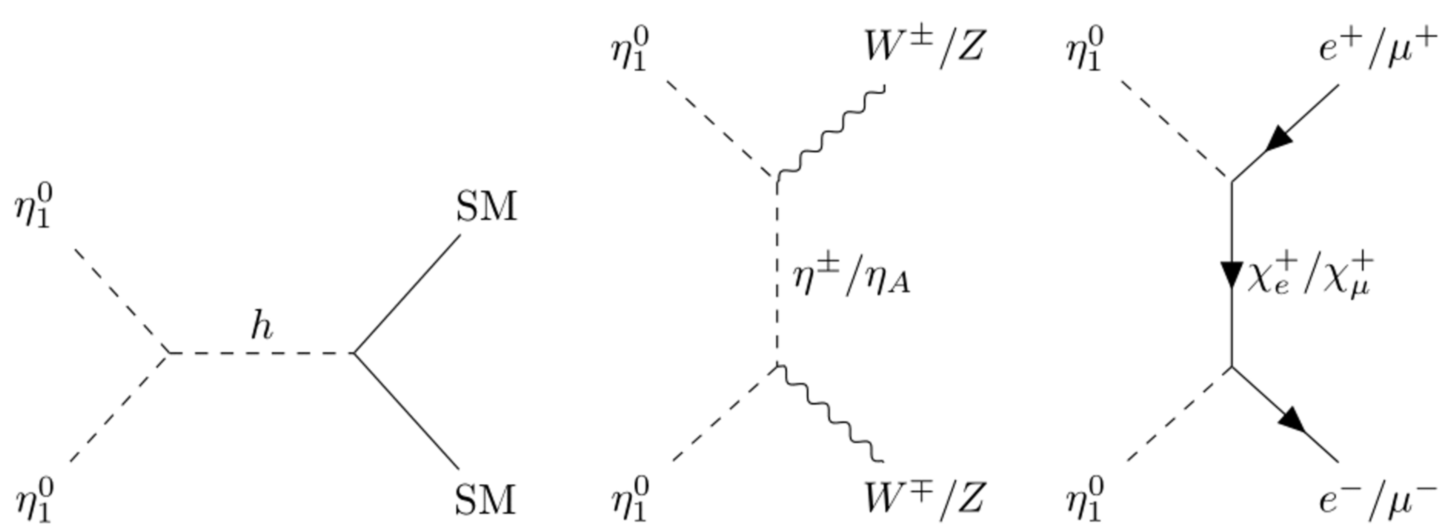
Planck 2018

- For numerical calculations, we have implemented our model using `FeynRules` and derived the relic density and direct search constraints using `MadDM`.

Alloul et al 2014
Degrande et al 2012
Backovic et al 2014
Backovic et al 2015
Ambrogi et al 2019

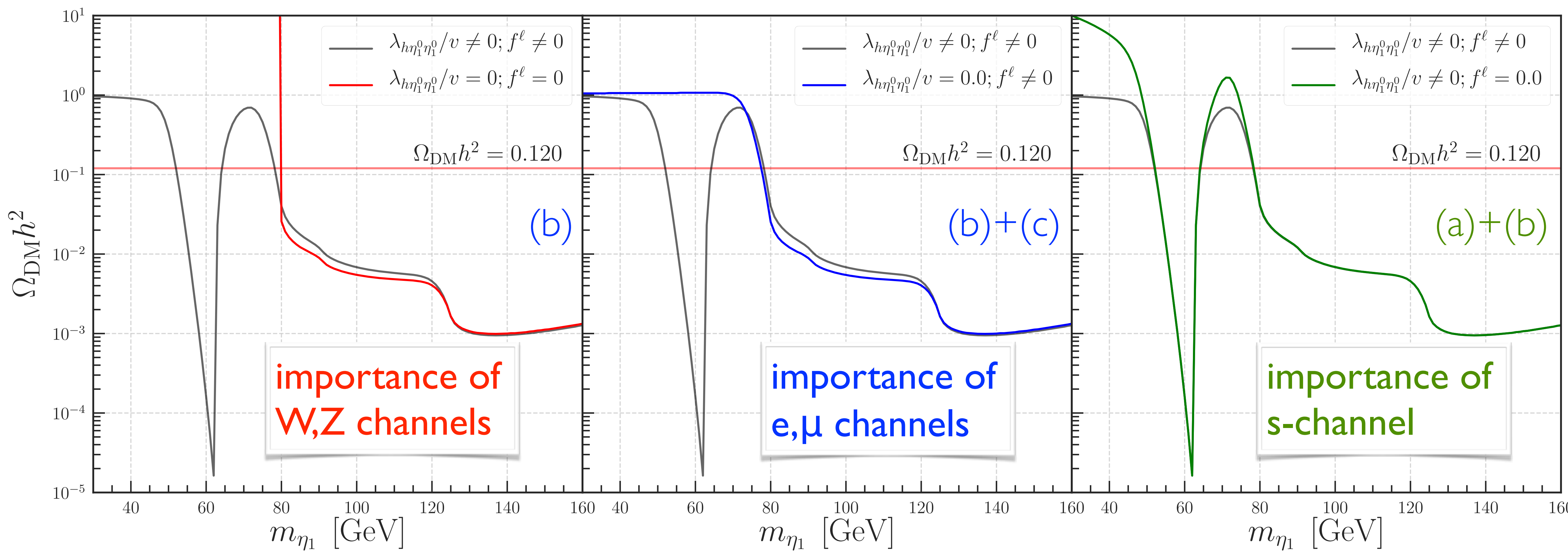
$Y_D = 1$ Scenario

- The s-channel amplitude is important when $m_{\rm DM}$ is close to $m_H/2$ due to the resonance effect.
- The t-channel amplitude mediated by heavier $\mathbb{Z}_2$-odd scalars becomes important when $m_{\rm DM} > 80$ GeV because of the threshold of W,Z channels.
- The t-channel process mediated by χ_ℓ is sensitive to the Yukawa couplings $f^\ell_{L,R}$, while weakly depending on the mass of the lighter vector-like lepton.



$Y_D = 1$ Scenario

- The black curves show a benchmark case with the parameter choice $(f^e, f^\mu, \lambda_{h\eta_1^0\eta_1^0}/v) = (0.1, 0.2, 0.01)$ and $(m_{\eta_2}, m_{\eta_A}, m_{\eta^\pm}, M_{\chi_e}, M_{\chi_\mu}) = (380, 200, 200, 1100, 600)$ GeV, where M_{χ_ℓ} are selected to satisfy $\Delta a_{e,\mu}$ within 1σ for $m_{\eta_1} = 80$ GeV.
- Three solutions at $m_{\eta_1} \sim 50, 65, 80$ GeV.



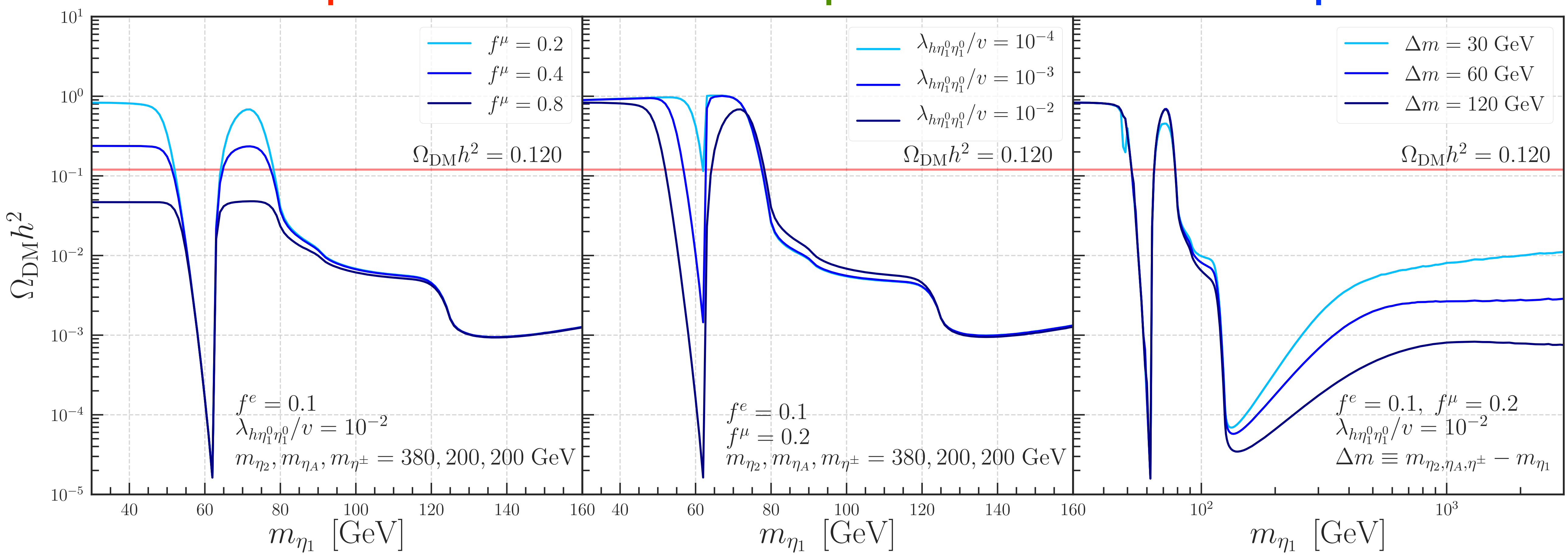
Impacts of Key Parameters

- We also study dependence on (a) the magnitude of f^μ, (b) the $\lambda_{h\eta_1^0\eta_1^0}$ coupling, and (c) the mass splitting Δm between the DM and all the other heavier $\mathbb{Z}_2$-odd scalars.

no solution for $f^\mu \gtrsim 0.54$

only one solution for $\lambda_{h\eta_1^0\eta_1^0}/v \lesssim 10^{-4}$

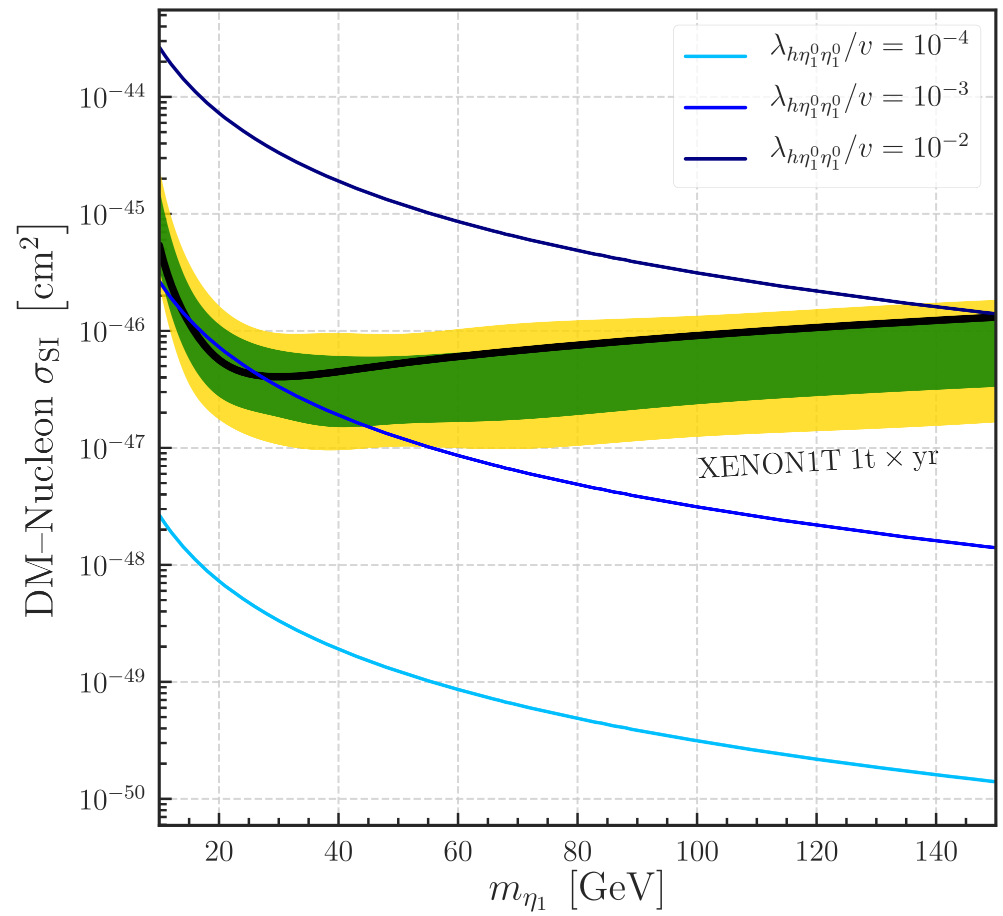
unlike IDM, no solution for m_{η_1} at O(TeV)



Direct Detection Constraint

- In addition to DM annihilation, the $\lambda_{h\eta_1^0\eta_1^0}$ coupling contributes to the scattering of DM with nuclei via the Higgs mediation, allowing our DM candidate to be probed by the direct search experiments.
- $\lambda_{h\eta_1^0\eta_1^0}/v$ has to be < 0.0026, 0.0034, and 0.0047 for m_{DM} to be around 50, 65 and 80 GeV, respectively.
- black curve: 90% CL upper limit from XENON1T
- green and yellow regions mark 1 and 2σ sensitivity bands

XENON1T 2018



$Y_D = 0$ Scenario

- Assume η_H^0 to be the DM candidate.
  ➠ results very similar to the $Y_D = 1$ scenario

- Assume χ_ℓ^0 to be the DM candidate.
  ➠ dominant annihilation channels are the t-channel processes $\chi_\ell \bar{\chi}_\ell \to \nu_\ell \bar{\nu}_\ell / \ell^+ \ell^-$ mediated by a neutral or charged $\mathbb{Z}_2$-odd scalar
  ➠ cross section too small to account for the observed relic density
  ➠ fermionic DM in our model ruled out

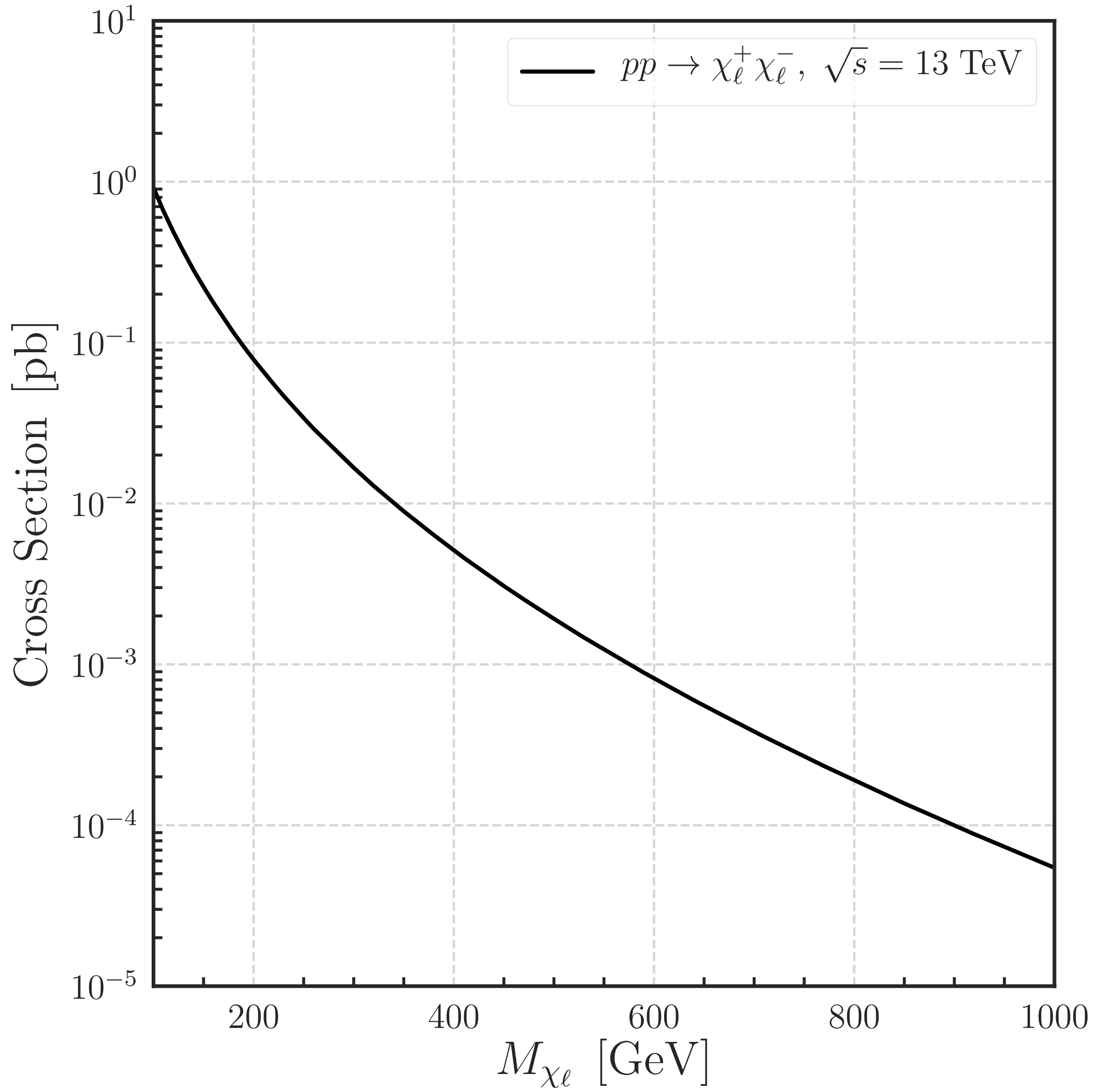
COLLIDER PHENOMENOLOGY

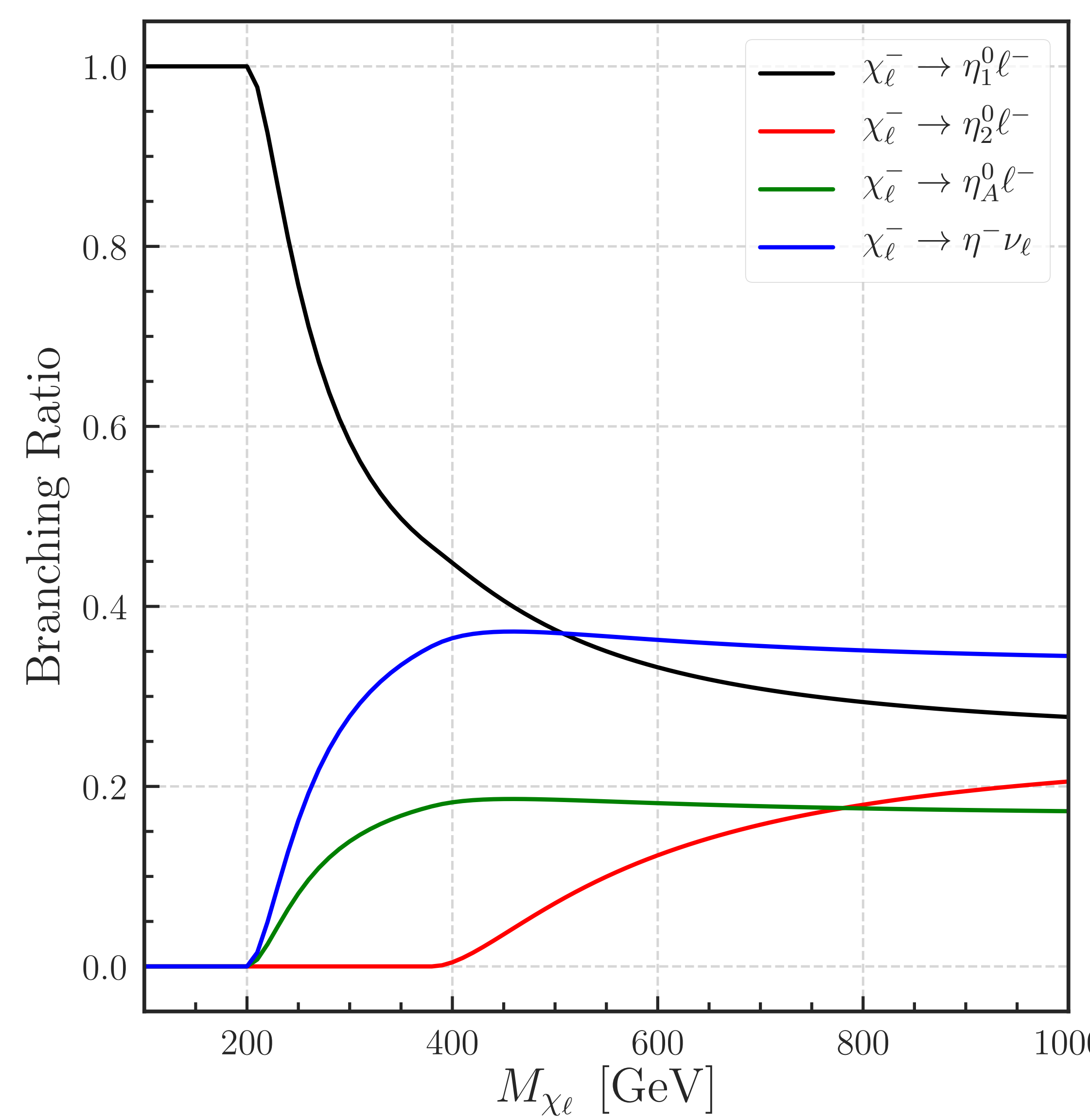
General Comments

- In our model, all the new particles are $\mathbb{Z}_2$-odd and would only be produced in pairs at colliders.
- Due to the new Yukawa interactions for μ and e, the decays of $\mathbb{Z}_2$-odd particles typically include a μ or e in association with missing energy carried away by the DM.
- Our model can be tested by looking for an excess of events with multiple charged leptons + missing energy, which is identical to the signatures of slepton or chargino production in supersymmetric models.

$Y_D = 1$ Scenario

- Drell-Yan production and decay of $\chi_\ell^\pm$:





cross section calculated at LO using `MadGraph_aMC@NLO` with the PDFs `NNPDF23_lo_as_0130_qed`

decay pattern of $\chi_\ell^\pm$ assuming the spectrum $(m_{\eta_1}, m_{\eta_A}, m_{\eta^\pm}, m_{\eta_2}) = (80, 200, 200, 380)$ GeV and $\theta = \pi/4$

ALTAS Constraint

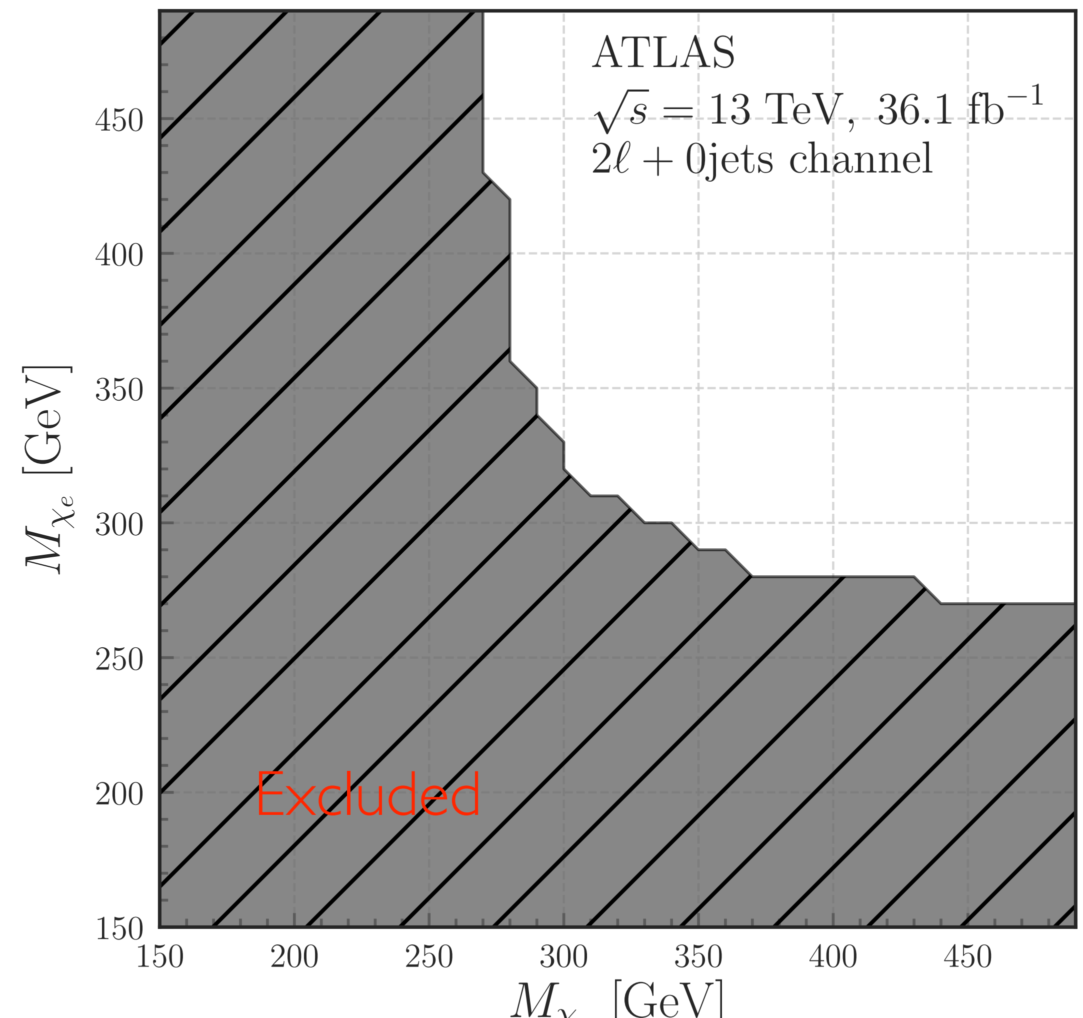
- With our parameter choice, $M_{\chi_\ell} \lesssim 270$ GeV is excluded.
- Note that such lower bounds on M_{χ_ℓ} depend on the mass spectrum of the $\mathbb{Z}_2$-odd scalars, and are usually lower than the bounds extracted in the literature.

ATLAS 2016, 2018

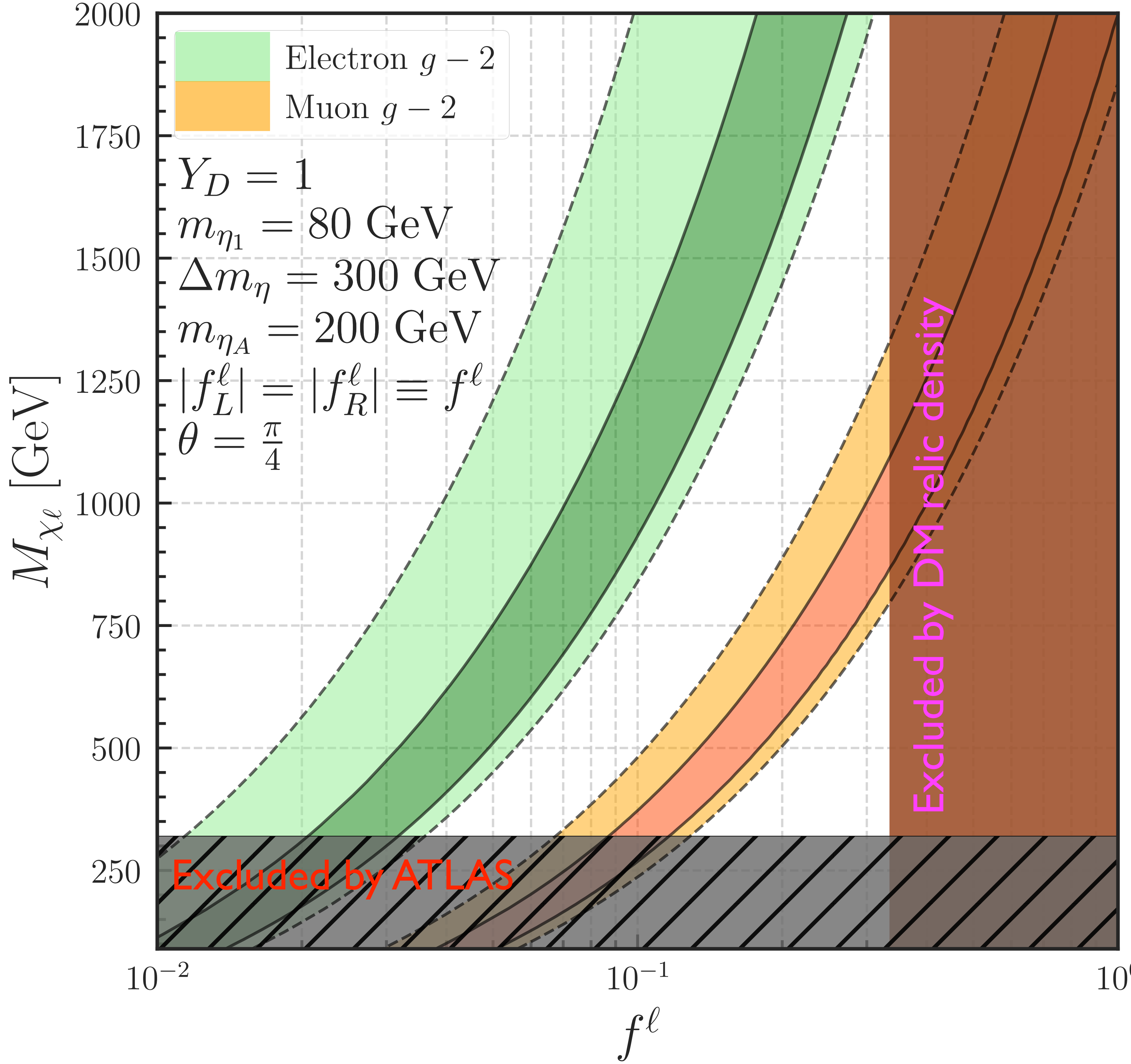
- For example, people usually assume $BR(\chi_\ell^\pm \to \eta_1 \ell^\pm) = 100\,\%$.

Calibbi, Ziegler, Zupan 2018

- We also take other decays into account and thus obtain a less stringent constraint.



Summary of $Y_D = 1$ Scenario



Bound on Inert Scalars

- In the case where the vector-like lepton masses are larger than the masses of the inert scalars, the signature of these scalars become quite similar to that in the IDM.
- Upper limit on the cross section of multi-lepton final states given by the LHC Run-II data is typically one or more orders of magnitude larger than that predicted in the IDM.

Dercks, Robens 2019

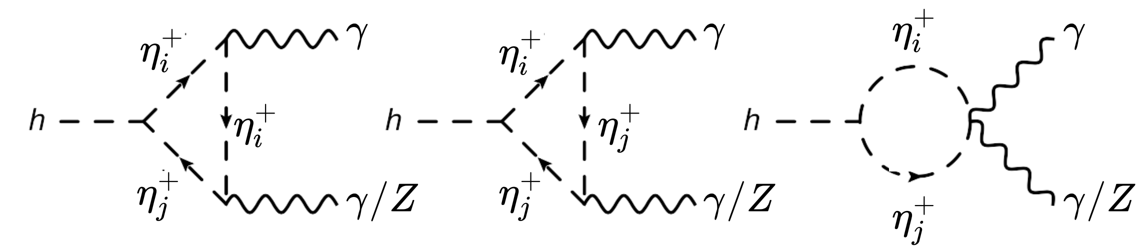
➠ no bound from direct searches at LHC for our inert scalar bosons

$Y_D = 0$ Scenario

- The vector-like lepton is electrically neutral.
  ➠ not produced in pair via the Drell-Yan process, but from decays of the inert scalar bosons, e.g., $\eta^{\pm}_{1,2} \to \ell^{\pm}\chi^0_{\ell}$ and $\eta^0_{H,A} \to \nu_{\ell}\chi^0_{\ell}$.
- The most promising process to test this scenario could then be a pair production of the charged inert scalars $pp \to \eta^{\pm}_i \eta^{\mp}_j$ $(i, j = 1,2)$.
- We find that the production cross sections of $\eta^{\pm}_{1,2}$ are roughly one order of magnitude smaller than those of vector-like lepton pairs.
  ➠ more weakly constrained by current LHC data as compared with that in the scenario with $Y_D = 1$.

Higgs Couplings

- In our model, the Higgs boson couplings do not change from their SM values at tree level due to the $\mathbb{Z}_2$ symmetry.
- Loop-induced couplings are modified due to the Higgs boson couplings to the charged scalars.



- Production of the Higgs boson is the same as in the SM.
  ➠ signal strengths simply given by ratio of the BRs between our model and SM

$$\mu_{\gamma\gamma/Z\gamma} = \frac{\sigma_h \times \mathrm{BR}(h \to \gamma\gamma/Z\gamma)_{\mathrm{NP}}}{\sigma_h \times \mathrm{BR}(h \to \gamma\gamma/Z\gamma)_{\mathrm{SM}}}$$

- Currently, experimental data give

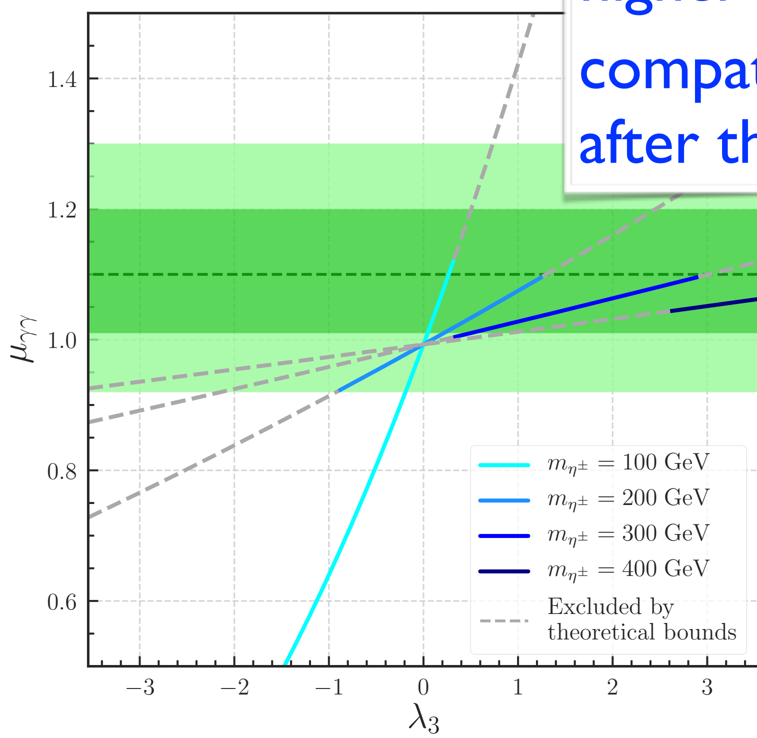
$$\begin{cases} \mu_{\gamma\gamma}^{\mathrm{Exp}} = 1.10^{+0.10}_{-0.09} \\ \mu_{Z\gamma}^{\mathrm{Exp}} \leq 6.6 \quad (95\%\ \mathrm{CL}) \end{cases}$$

PDG 2018
CMS 2018
ATLAS 2017

$\mu_{\gamma\gamma}$ AND $\mu_{Z\gamma}$

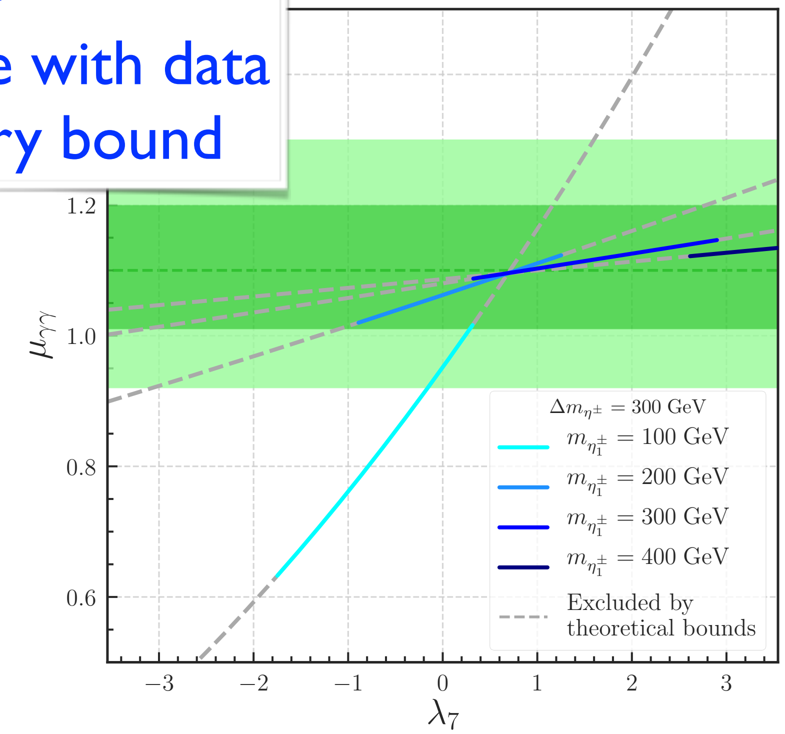
$(m_{\eta_H}, m_{\eta_A}, \theta) = (80\text{ GeV}, 200\text{ GeV}, \pi/4)$

$Y_D = 1$

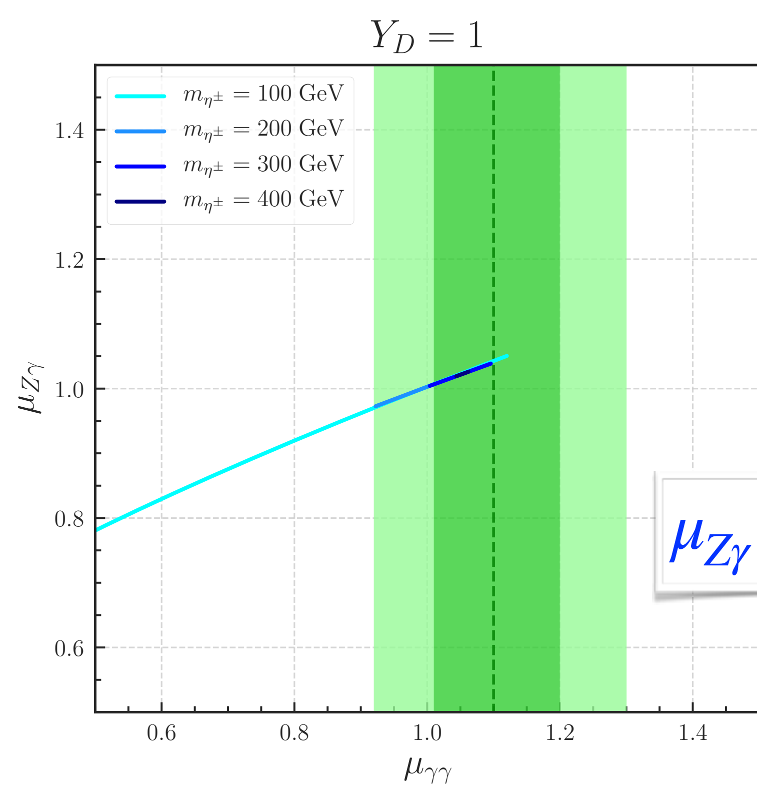


higher $m_{\eta^\pm}$ more compatible with data after theory bound

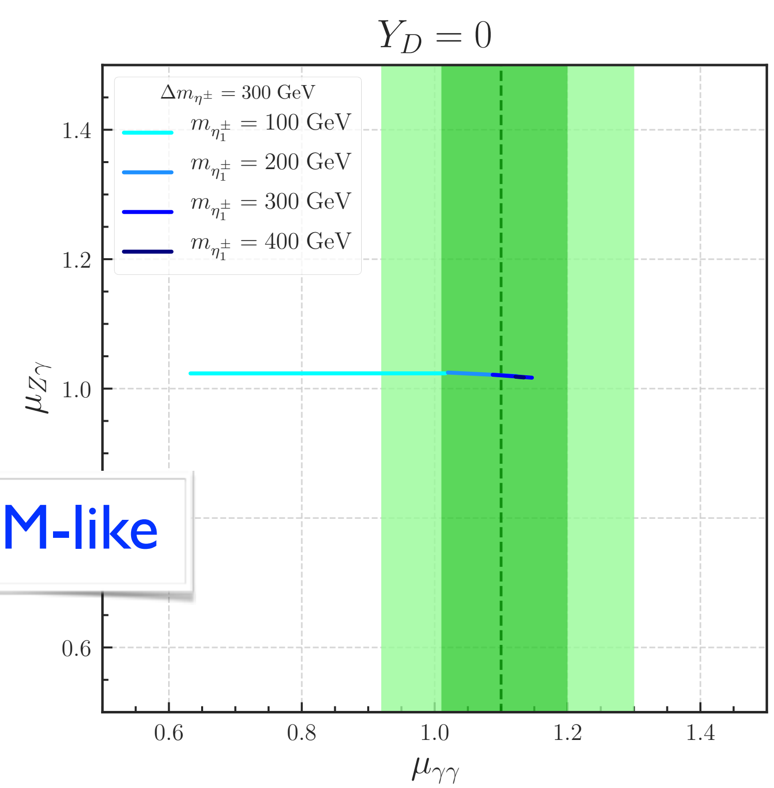
$Y_D = 0$



small or little correlation



$\mu_{Z\gamma}$ is SM-like



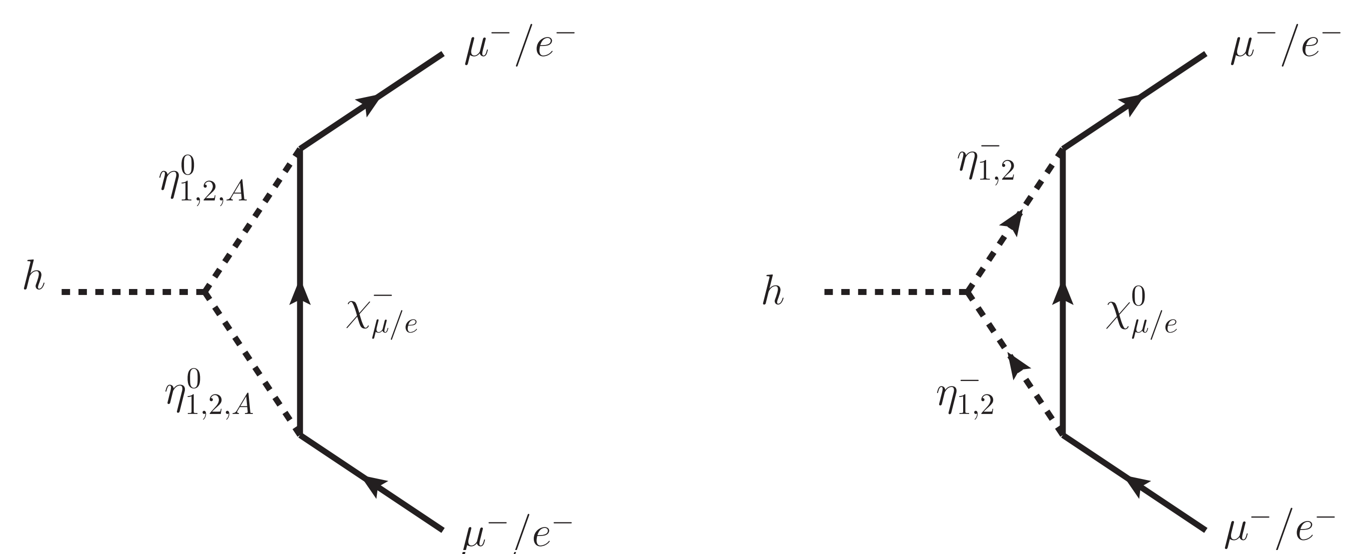
By scanning θ while imposing both theo. and exp. constraints, we find that $Y_D = 0$ scenario would predict an $\mu_{Z\gamma}$ at most +10% larger than SM.

Yukawa Corrections

- For the choice of $\theta = \pi/4$, $f_R^\ell = \sigma_\ell f_L^\ell$ and $|f_L^\ell| = |f_R^\ell| (= f^\ell)$ ($\sigma_\ell = +1$ for e and -1 for μ) , we have the Yukawa coupling corrections (assuming $M_{\chi_\ell} \gg m_{\eta^0}, m_{\eta^\pm}$ with $m_{\eta^0} \equiv m_{\eta_1} = m_{\eta_2}$ and $m_{\eta^\pm} \equiv m_{\eta_1^\pm} = m_{\eta_2^\pm}$.):

$$\Delta y_\ell \simeq \frac{(f^\ell)^2}{16\pi^2} \frac{\lambda_{h\eta_1^+\eta_1^-} + \sigma_\ell \lambda_{h\eta_2^+\eta_2^-}}{M_{\chi_\ell}} \left(1 - \ln \frac{M_{\chi_\ell}^2}{m_{\eta^\pm}^2}\right) \qquad (\text{for } Y_D = 0)$$

$$\Delta y_\ell \simeq \frac{(f^\ell)^2}{16\sqrt{2}\pi^2} \frac{\lambda_{h\eta_1^0\eta_1^0} + \sigma_\ell \lambda_{h\eta_2^0\eta_2^0}}{M_{\chi_\ell}} \left(1 - \ln \frac{M_{\chi_\ell}^2}{m_{\eta^0}^2}\right) \qquad (\text{for } Y_D = 1)$$



$Y_D = 1$ $\qquad$ $Y_D = 0$

Yukawa Corrections

- The diagrams are controlled by the new Yukawa coupling, f^ℓ, and the chirality flip happens via the intermediate vector-like lepton mass.
  ➠ no muon or electron mass suppression
- In spite of being one-loop, these contributions can be comparable or even larger than the tree-level one.
- As an example, taking $M_{\chi_\mu} = M_{\chi_e} = 1\ \mathrm{TeV}$, $m_{\eta_1} = 80\ \mathrm{GeV}$, $m_{\eta_2} = 380\ \mathrm{GeV}, f^\mu = 0.3$, $f^e = 0.1$, $\lambda_{h\eta_1^0\eta_1^0} = 2.6 \times 10^{-3} v$, and $\lambda_{h\eta_2^0\eta_2^0} = -1.095v$ for the $Y_D = 1$ scenario, we obtain

$$\Delta y_\mu \simeq 1.63 \times 10^{-4} \quad \text{and} \quad \Delta y_e \simeq -1.78 \times 10^{-5}$$

corresponding to about +38% and –858% corrections with respect to the SM tree-level predictions.

Perspective

- Such a large deviation in the $h\mu^+\mu^-$ coupling can possibly be detected in future collider experiments.
  ➠ at HL-LHC with an integrated luminosity of 3 /ab, the expected accuracy is about 14%
  ➠ further improved to about 5% through the combination of HL-LHC and 250-GeV ILC with 2 /ab. Fujii et al 2017
- Our model can be tested by precision measurement of the muon Yukawa coupling with the Higgs boson.

Summary

- We have proposed a new model whose symmetry is extended with a global $U(1)_\ell$ and a $\mathbb{Z}_2$ symmetries to simultaneously explain the DM data and the two g–2 anomalies.
- Depending on hypercharge charges of new fields, there are two scenarios with different phenomenologies.
- Lepton flavor-violating processes receive no new contributions.
- We have checked the constraints of LHC direct searches and Higgs signal strengths, and made predictions for $\mu_{Z\gamma}$.
- We have also predicted possible loop enhancements in the muon and electron Yukawa couplings, to be tested at HL-LHC and ILC.

Thank You!

Backup Slides

$Y_D = 1$ Scenario

- The t-channel process mediated by χ_ℓ is sensitive to the Yukawa couplings $f^\ell_{L,R}$, while weakly depending on the mass of the lighter vector-like lepton.
- We also take into account the contributions from DM co-annihilations with the heavier $\mathbb{Z}_2$-odd particles.

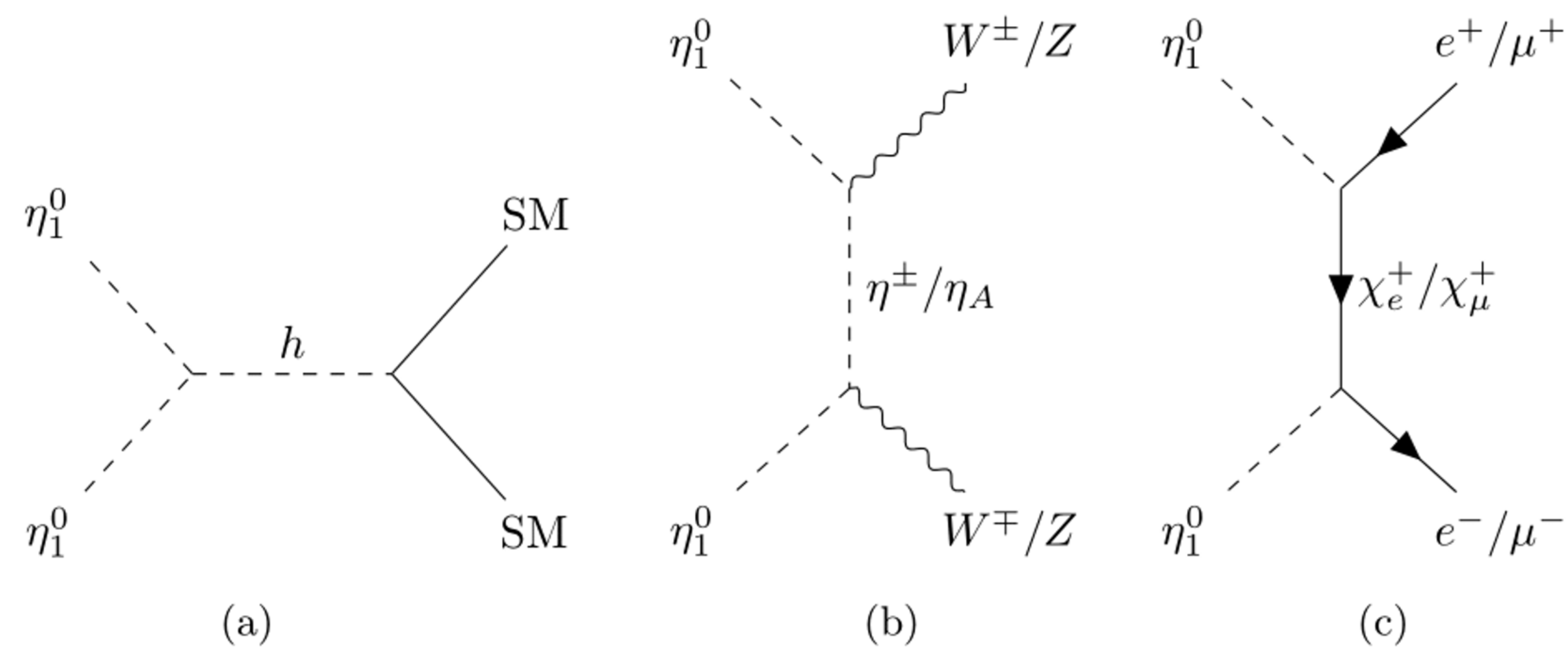


Figure 4. Important diagrams that contribute to the DM annihilation into the SM particles.

Comparison With IDM

- In the Inert Doublet Model, another solution of $m_{\rm DM}$ to satisfy the relic density may exist in a TeV region when the mass splitting among the $\mathbb{Z}_2$-odd scalars is small, typically <10 GeV. Lopez Honorez, Nezri, Oliver, Tytgat 2007
- In such a scenario, DM dominantly annihilates into a pair of weak gauge bosons whose annihilation cross section decreases by $\mathcal{O}(1/m_{\rm DM}^2)$, while the annihilation into H pairs is highly suppressed due to small Higgs-DM couplings.
- In our model, such a high mass solution cannot be realized, because the additional η_2^0 state preferably has a large mass splitting with η_1^0 for the g–2 anomalies.
- (Co)annihilation into a pair of the Higgs bosons is not suppressed in the high mass region.