Anomalous $U(1)'$

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- In search for new physics, one possibility is to extend the Standard Model (SM) with additional massive Z' gauge boson.
- They can be a possible mediator between the dark and visible sectors.
- U(1) extensions can also be a part of a unified framework.
- One can indeed study a more general type of Z' gauge boson which is “anomalous”.
- Anomalies present in these models are canceled by Green-Schwarz/Wess-Zumino mechanisms and additional Chern-Simons terms appear in low energies.
- Such low-energy anomalies are possible in QFT if there are scalars that give mass to anomalous subset of fermions or intersecting D-brane models [*JHEP* 11 (2006) 057, JHEP02(2023)051].
- Nevertheless, compared to the non-anomalous U(1) models, there exists anomalous three boson couplings a low energies.
- This is a strong hint towards an underlying String theory or a field theory with very heavy chiral fermions

- Apart from direct detections, there has been efforts also to evaluate the contribution of such anomalous three boson couplings in muon g-2. [Pascal Anastasopoulos, Kunio Kaneta, Elias Kiritsis, and Yann Mambrini, JHEP02(2023)051]

$$
\begin{aligned}
A^\mu &\to A^\mu+\partial^\mu\varepsilon, & Y^\mu &\to Y^\mu+\partial^\mu\zeta,\\
a &\to a-M\varepsilon, & &\\
\psi &\to e^{ig_A q^{\psi-A}\varepsilon}\psi, & \psi &\to e^{ig_Y q^{\psi-Y}\zeta}\psi,\\
H &\to e^{ig_A q^{H-A}\varepsilon}H, & H &\to e^{ig_Y q^{H-Y}\zeta}H,
\end{aligned}
$$

		SU(3)	SU(2)	$U(1)_Y$	$U(1)_A$
Q_L^i	:	$\mathbf{3}$	$\mathbf{2}$	1/6	q_i^{Q-A}
$u_R^{i,c}$	:	$\bar{\mathbf{3}}$	$\mathbf{1}$	−2/3	q_i^{u-A}
$d_R^{i,c}$	:	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	q_i^{d-A}
L_L^i	:	$\mathbf{1}$	$\mathbf{2}$	−1/2	q_i^{L-A}
$l_R^{i,c}$	:	$\mathbf{1}$	$\mathbf{1}$	1	q_i^{l-A}
H	:	$\mathbf{1}$	$\mathbf{2}$	1/2	q^{H-A}

$$
\begin{aligned}
&Tr[q_Y] &&= Tr[q_Y q_Y q_Y] = Tr[q_Y T^a_{\mathrm{SU}(2/3)} T^a_{\mathrm{SU}(2/3)}] &&= 0\\
&Tr[q_A q_Y q_Y] &&= \sum_i \frac{q_i^{Q-A}}{6}+\frac{4q_i^{u-A}}{3}+\frac{q_i^{d-A}}{3}+\frac{q_i^{L-A}}{2}+q_i^{l-A} &&= t_{AYY}\\
&Tr[q_Y q_A q_A] &&= \sum_i (q_i^{Q-A})^2-2(q_i^{u-A})^2+(q_i^{d-A})^2-(q_i^{L-A})^2+(q_i^{l-A})^2 &&= t_{YAA}\\
&Tr[q_A q_A q_A] &&= \sum_i 6(q_i^{Q-A})^3+3(q_i^{u-A})^3+3(q_i^{d-A})^3+2(q_i^{L-A})^3+(q_i^{l-A})^3 &&= t_{AAA}\\
&Tr[q_A T^a_{\mathrm{SU}(2)} T^a_{\mathrm{SU}(2)}] &&= \sum_i 3q_i^{Q-A}+q_i^{L-A} &&= T_{A,2}\\
&Tr[q_A T^a_{\mathrm{SU}(3)} T^a_{\mathrm{SU}(3)}] &&= \sum_i 2q_i^{Q-A}+q_i^{u-A}+q_i^{d-A} &&= T_{A,3}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\text{extra fields}} =& -\frac{1}{4}F^A_{\mu\nu}F_A^{\mu\nu}+\frac{1}{2}(\partial_\mu a+MA_\mu)^2+g_A q^{\psi-A}A_\mu\bar{\psi}\gamma^\mu\psi\\
&+2ig_A q^{H-A}A^\mu H^\dagger\Big(\partial_\mu-ig_2T^\alpha W^\alpha_\mu-ig_Y q^{H-Y}Y_\mu-\frac{i}{2}g_A q^{H-A}A_\mu\Big)H\\
&+\frac{1}{24\pi^2}a\Big(C_{YY}F_Y\wedge F_Y+C_{YA}\,F_Y\wedge F_A+C_{AA}\,F_A\wedge F_A+\sum_{i=2,3}D_i\,Tr_i[G\wedge G]\Big)\\
&+\frac{1}{24\pi^2}A\wedge Y\wedge\Big(E_{AY,A}F_A+E_{AY,Y}F_Y\Big)\\
&+\frac{1}{24\pi^2}\sum_{i=2,3}Z_i\,A\wedge Tr_i\Big[A\wedge\Big(dA-\frac{2}{3}A\wedge A\Big)\Big]
\end{aligned}
\tag{2.6}
$$

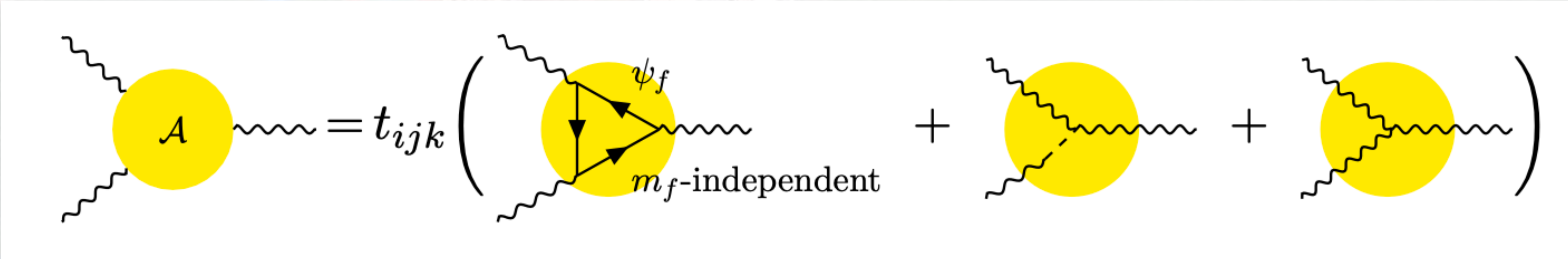
where

$$
F_i\wedge F_j=\frac{1}{4}\varepsilon_{\mu\nu\rho\sigma}F_i^{\mu\nu}F_j^{\rho\sigma},\quad A_i\wedge A_j\wedge F_k\equiv\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}A_i^\mu A_j^\nu F_k^{\rho\sigma}
\tag{2.7}
$$

- [Pascal Anastasopoulos, Kunio Kaneta, Elias Kiritsis, and Yann Mambrini, JHEP02(2023)051]

$$\delta S_{\text{one-loop}} = -\frac{1}{24\pi^2}\int \Big\{ \epsilon\Big(t_{AYY} F_Y \wedge F_Y + t_{YAA} F_A \wedge F_Y + t_{AAA} F_A \wedge F_A + T_{A,i} Tr[G_i \wedge G_i] \Big) + \zeta\Big(t_{YAA} F_A \wedge F_A + t_{AYY} F_A \wedge F_Y \Big) \Big\} \tag{2.8}$$

$$\delta S_{\text{one-loop}} + \delta S_{\text{extra fields}} = 0 \;\rightarrow\; \begin{cases} MC_{YY} = -2 g_A g_Y^2 t_{AYY} & MC_{YA} = -2 g_A^2 g_Y t_{YAA} \\ MC_{AA} = -g_A^3 t_{AAA} & 2MD_i = -3Z_i = -6 g_A g_i^2 T_{A,i} \\ E_{AY,A} = g_A^2 g_Y t_{YAA} & E_{AY,Y} = g_A g_Y^2 t_{AYY} \end{cases}$$



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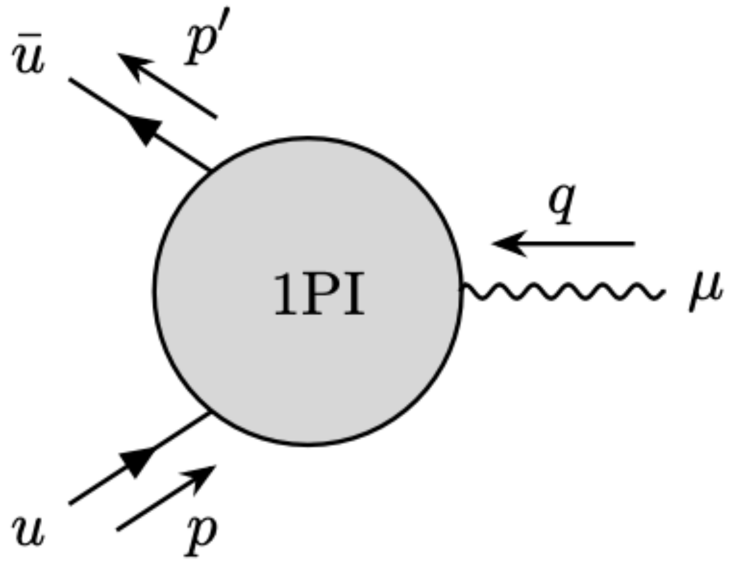
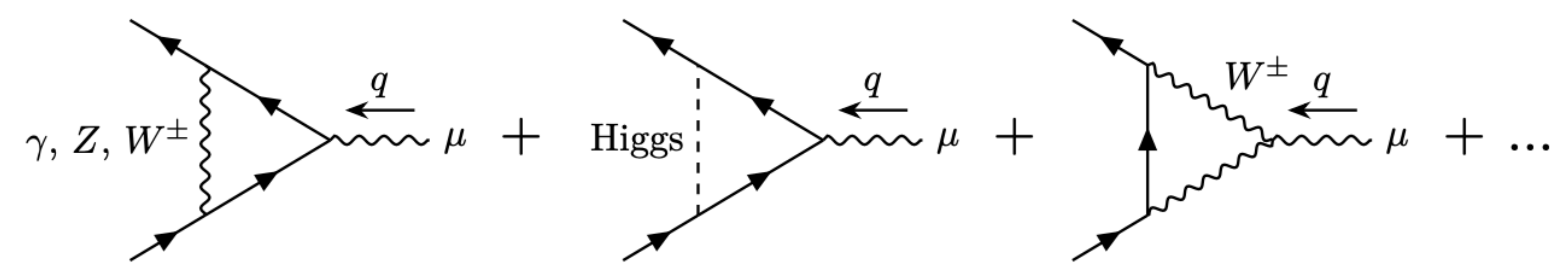
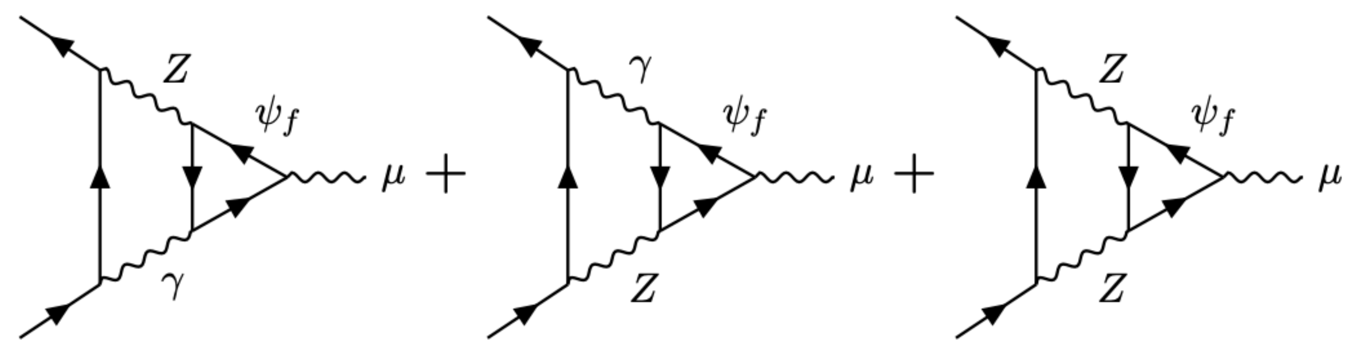
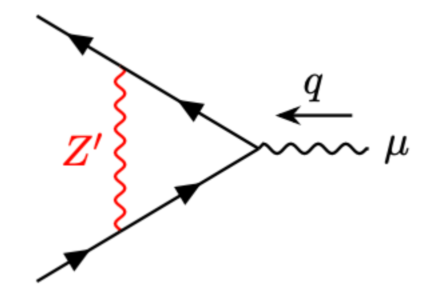
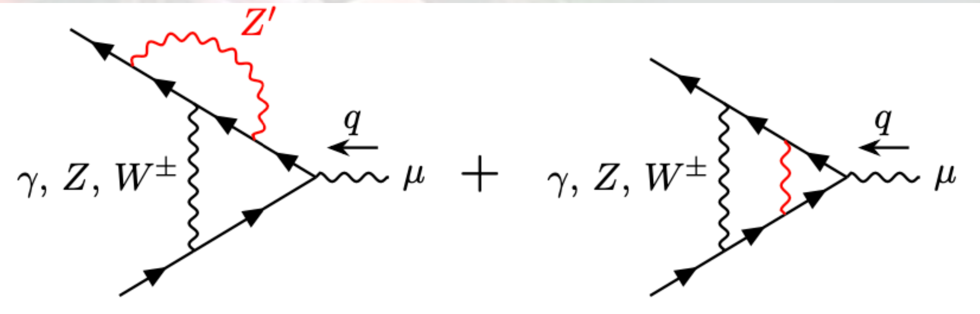


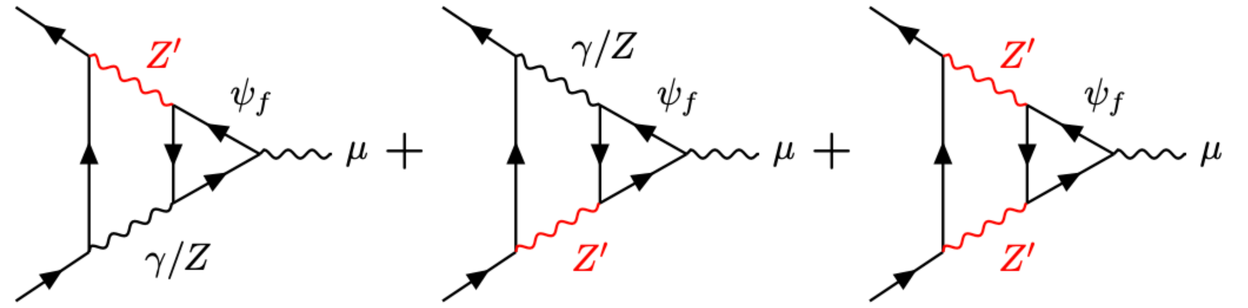
$$= (-ie)\bar{u}(p')\Big(\gamma^\mu F_1(q) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\ell}F_2(q) + \gamma^5\frac{\sigma^{\mu\nu}q_\nu}{2m_\ell}F_3(q) + \gamma^5(q^2\gamma^\mu - \not{q}q^\mu)F_4(q)\Big)u(p)$$

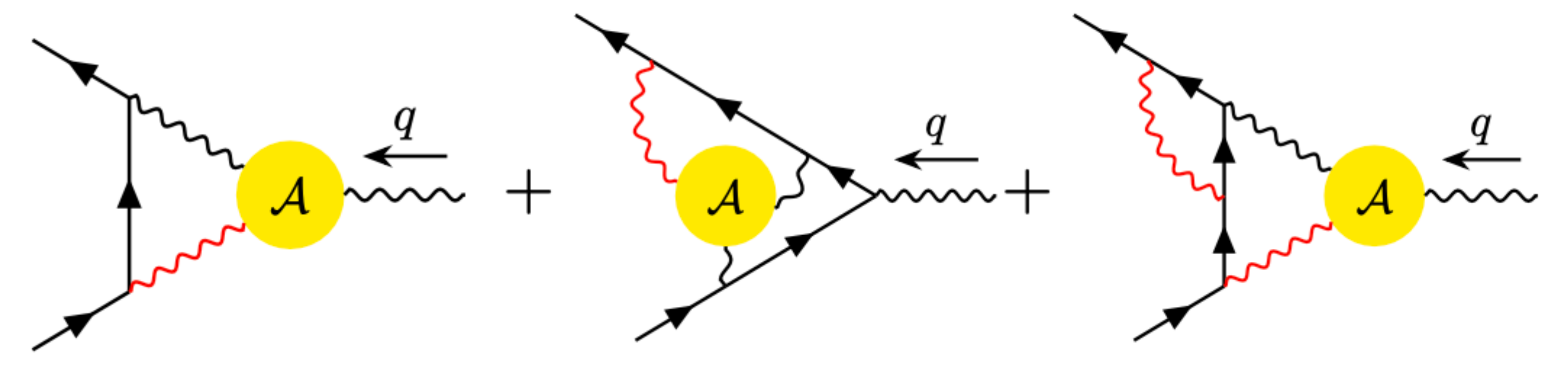












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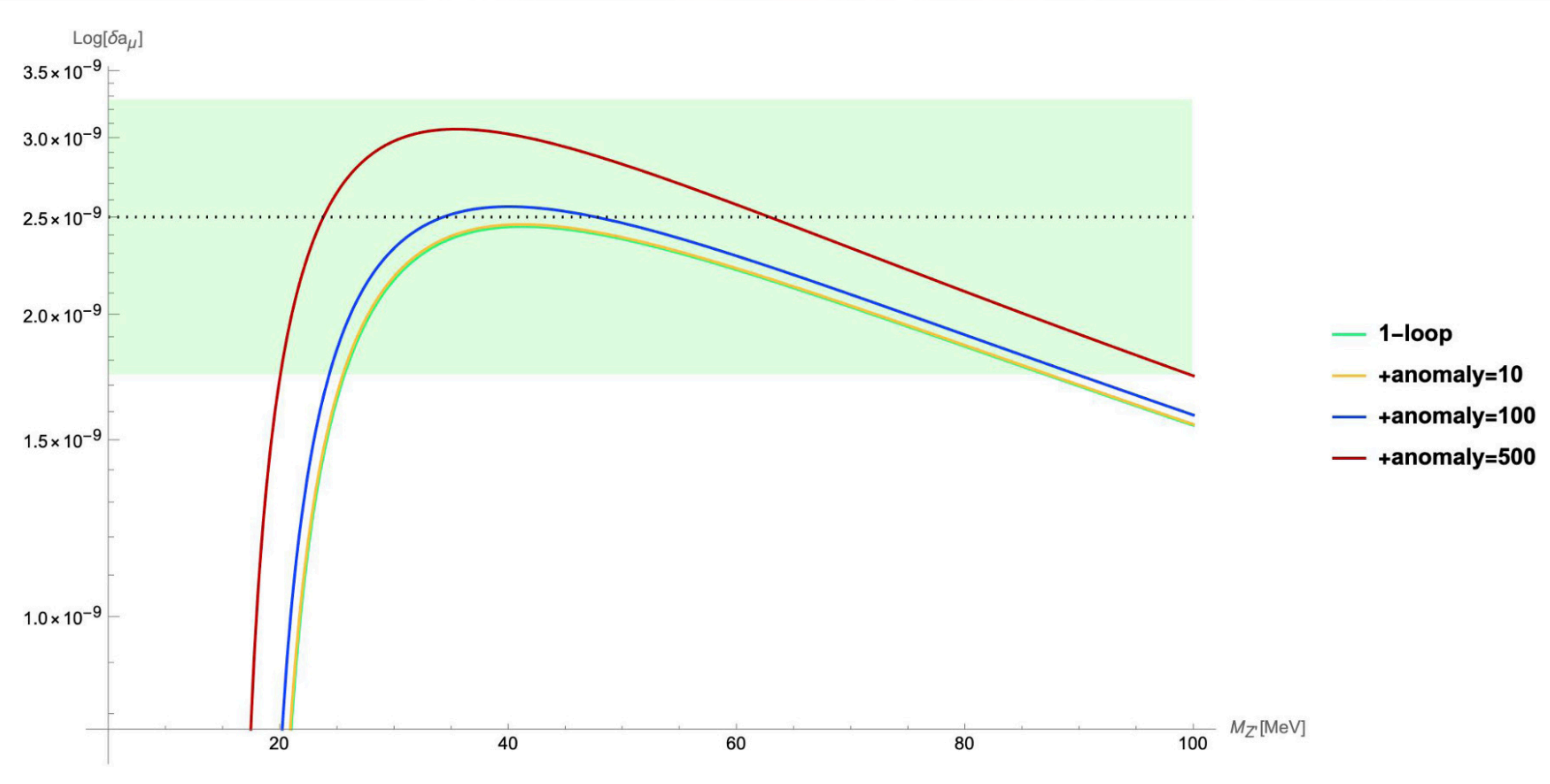


- Leptophilic Z' with mass $\sim$ 5 MeV - 200 MeV with coupling only to muon and tau.

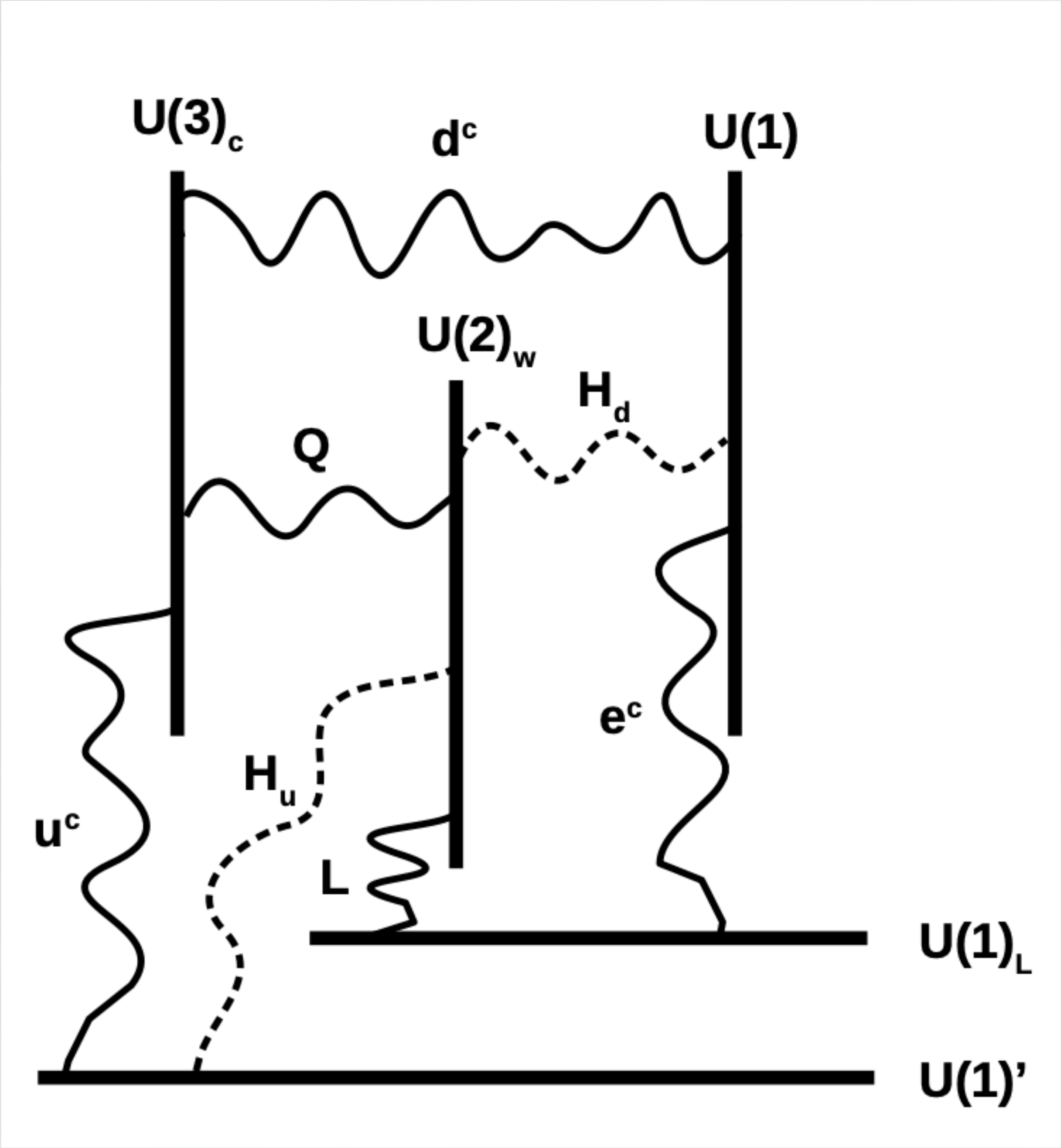
- [Pascal Anastasopoulos, Kunio Kaneta, Elias Kiritsis, and Yann Mambrini, JHEP02(2023)051]

- Realisation of Leptophilic Z' in D-brane models

- Anomalous $U(1)'$ are common in TeV scale string theory with intersecting D-branes

- Strings with both ends on a stack of N parallel D-branes forms SU(N) × U(1).

- Strings with one end on N stack and the other on a stack of M D-branes transform as $(N,1;\bar{M},-1)$ under the gauge group.



- Anomaly free hypercharge, and a Lepton number can be realized in a 5 stack model, where linear combinations of 4 $U(1)$s form the hypercharge and the fifth D-brane giving rise to Lepton number. [Antoniadis and Rondeau, Eur. Phys. J. C 82, 701 (2022)]

Axi-Higgs portal Dark Matter via Wess-Zumino mechanism

[**Akshay Anilkumar, MTA, and Arjun S. Nair, arXiv:2405.04680v1**]

- We study the axion portal between the visible and the dark sector, where the Dark Matter is charged under an anomalous abelian extension of the Standard Model.

- Since irreducible anomalies are absent in this anomalous $U(1)'$ extension, the gauge invariance can be restored by the WZ anomaly cancellation mechanism by including a Stükelberg axion that couples to Chern Simmons term.

- We also extend the Standard Model matter sector to include a fermionic dark matter candidate and a complex scalar, both charged under the $U(1)'$.

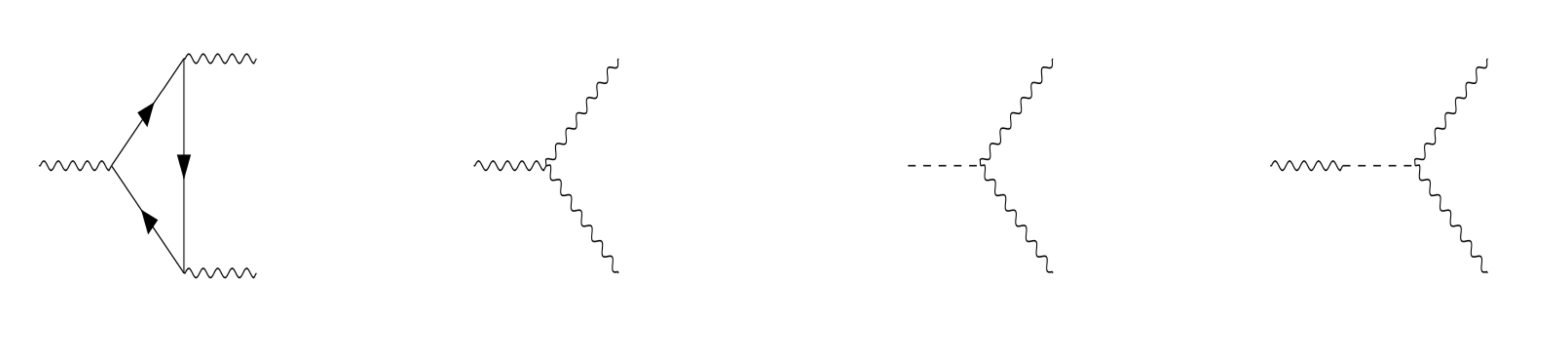
- It might seem that the Stükelberg axion in the WZ mechanism is eaten away by the new Z' boson, in the presence of a complex scalar field, the Stükelberg axion mixes with the complex scalar field to produce a physical pseudo-Goldstone field.

- We will, here, show that these physical, pseudo-Goldstone bosons (namely axi-Higgs), mediate an efficient portal between the dark and the visible sectors to generate the observed dark matter relic density in the universe. In fact, the most dominant channels include DM + DM → W^+W^-, γZ, γγ and ZZ, for heavier Dark Matter masses, generated by the Wess-Zumino term.

- Let's consider a single fermion field that transforms under two abelian gauge fields.

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \bar{\psi}i\gamma^{\mu}(\partial_{\mu} + ieA_{\mu} + ig\gamma^{5}Z'_{\mu})\psi \\ & + \frac{g^{3}C^{BAA}}{48\pi^{2}f_{b}}\; b\; F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g^{3}C^{BBB}}{48\pi^{2}f_{b}}\; b\; Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} \\ & + \frac{1}{2}(\partial_{\mu}b + f_{b}Z'_{\mu})^{2} + L_{R_{\xi}}\;.\end{aligned}$$

- This axion, in the St*ü*kelberg term, is eaten away to become the longitudinal component of the new gauge boson.



- On the other hand, in the presence of other scalars in the model, the St*ü*kelberg axion mixes with them, and integrating out the axion becomes non-trivial.

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$$\mathcal{L}_{scalar} = (D_{\mu}\phi)^{\dagger}(D^{\mu}\phi) - m_{\phi}^{2}\phi^{\dagger}\phi + \frac{1}{2}(\partial_{\mu}b + f_{b}Z'_{\mu})^{2}$$

- Assuming that the new scalar field has a non-zero vacuum expectation value

$$\phi = \frac{1}{\sqrt{2}}(v + \phi_1)e^{i\frac{\phi_2}{v}}$$

- Then the Lagrangian becomes,

$$\begin{aligned}\mathcal{L}_{scalar} &= \frac{1}{2}(\partial_\mu\phi_1)^2 - \frac{1}{2}m_\phi^2\phi_1^2 \\ &+\frac{1}{2}(\partial_\mu\phi_2)^2 + \frac{1}{2}(\partial_\mu b)^2 + \frac{1}{2}(f_b^2 + (e_\phi g_{Z'}v)^2)Z'_\mu Z'^\mu + Z'_\mu\partial^\mu(f_b b + e_\phi g_{Z'}v\phi_2)\end{aligned}$$

- Upon diagonalizing,

$$\begin{aligned}G_1 &= \frac{1}{m_{Z'}}(-f_b\phi_2 + e_\phi g_{Z'}vb)\ , \\ G_2 &= \frac{1}{m_{Z'}}(e_\phi g_{Z'}v\phi_2 + f_b b)\ .\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{scalar} &= \frac{1}{2}(\partial_\mu\phi_1)^2 - \frac{1}{2}m_\phi^2\phi_1^2 \\ &+\frac{1}{2}(\partial_\mu G_1)^2 + \frac{1}{2}(\partial_\mu G_2)^2 + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu + m_{Z'}Z'_\mu\partial^\mu G_2\end{aligned}$$

- In this basis, note that G_1, namely the axi-Higgs, is massless, and the mixing term between Z_μ and G_2 gets cancelled on using the generalised R_ξ gauge

$$\mathcal{L}_{R_\xi} = \frac{1}{\sqrt{\xi}}(\partial_\mu Z'^\mu - \xi m_{Z'}G_2).$$

- Upon including the U(1) breaking terms in the scalar Lagrangian,

$$V_{\not{U}} = b_1(\phi e^{-ie_\phi g_{Z'}\frac{b}{f_b}}) + \lambda_1(\phi e^{-ie_\phi g_{Z'}\frac{b}{f_b}})^2 + 2\lambda_2(\phi^*\phi)(\phi e^{-ie_\phi g_{Z'}\frac{b}{f_b}}) + c.c.$$

- This Goldstone field becomes massive. The mass of the pseudo-Goldstone boson G_1 now becomes,

$$m_{G_1}^2 = -\frac{1}{2}c_{G_1}v^2(1 + (e_\phi g_{Z'}v)^2/f_b^2) = -\frac{1}{2}c_{G_1}v^2\frac{m_{Z'}^2}{f_b^2}$$

$$c_{G_1} = 4(\frac{b_1}{v^3} + 4\frac{\lambda_1}{v^2} + 2\frac{\lambda_2}{v})$$

- Now, the field in the un-rotated and the rotated basis are related as,

$$\begin{aligned} \phi_2 &= \frac{1}{m_{Z'}}(-f_b G_1 + e_\phi g_{Z'} v G_2) \ , \\ b &= \frac{1}{m_{Z'}}(e_\phi g_{Z'} v G_1 + f_b G_2) \ . \end{aligned}$$

Field	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)'$
Q_L^i	3	2	1/3	$e_{q_L}^i = (e_{q_L}^1, e_{q_L}^2, e_{q_L}^3)$
u_R^i	3	1	4/3	$e_{u_R}^i = (e_{u_R}, e_{c_R}, e_{t_R})$
d_R^i	3	1	-2/3	$e_{d_R}^i = (e_{d_R}, e_{s_R}, e_{b_R})$
L_L^i	1	2	-1	$e_{\ell_L}^i = (e_{\ell_L}^1, e_{\ell_L}^2, e_{\ell_L}^3)$
e_R^i	1	1	-2	$e_{\ell_R}^i = (e_{e_R}, e_{\mu_R}, e_{\tau_R})$
χ_L	1	1	0	e_{χ_L}
χ_R	1	1	0	e_{χ_R}
ϕ	1	1	0	e_ϕ
H	1	2	1	0

$$U(1)' - U(1)' - U(1)' \quad : \quad \mathcal{A}^{(0)} = \sum_f Q_f^3 \ ,$$

$$U(1)' - U(1)' - U(1)_Y \quad : \quad \mathcal{A}^{(1)} = \sum_f Q_f^2 Y_f \ ,$$

$$U(1)' - U(1)_Y - U(1)_Y \quad : \quad \mathcal{A}^{(2)} = \sum_f Q_f Y_f^2 \ ,$$

$$U(1)' - SU(2)_W - SU(2)_W \quad : \quad \mathcal{A}^{(3)} = \sum_f Q_f Tr[T_k T_k] \ ,$$

$$U(1)' - SU(3)_c - SU(3)_c \quad : \quad \mathcal{A}^{(4)} = \sum_f Q_f Tr[\tau_k \tau_k] \ ,$$

- On including the Stükelberg axion interaction,

$$\mathcal{L}_b = \frac{1}{48\pi^2}\frac{g_{Z'}}{f_b}b(x)\Big(C_1 g_{Z'}^2 Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} + C_2 g_Y g_{Z'} Y_{\mu\nu}\tilde{Z}'^{\mu\nu} + C_3 g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C_4 g_W^2 W_{\mu\nu}\tilde{W}^{\mu\nu} + C_5 g_G^2 G_{\mu\nu}\tilde{G}^{\mu\nu}\Big)$$

- Anomaly cancellation condition demands,

$$\begin{aligned}
C_1 &= 6e_q^3 - 3e_u^3 - 3e_d^3 + 6e_l^3 - 3e_e^3 + e_{\chi_L}^3 - e_{\chi_R}^3 \ , \\
C_2 &= 2e_q^2 - 4e_u^2 + 2e_d^2 - 6e_l^2 + 6e_e^2 \ , \\
C_3 &= 2/3e_q - 16/3e_u - 4/3e_d + 6e_l - 12e_e \ , \\
C_4 &= 6e_q + 6e_l \ , \\
C_5 &= 18e_q - 9e_u - 9e_d \ .
\end{aligned}$$

- After the Electro-weak symmetry breaking, $SU(2)_W \times U(1)_Y \rightarrow U(1)_{em}$, the W and Y bosons mix to give rise to massive Z_μ and the massless photon γ. The resultant interaction Lagrangian of the axion becomes,

.

$$\mathcal{L}_b = \frac{1}{12} g_{Z'} b(x) \Big(g_{b\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + g_{bZ\gamma} F_{\mu\nu} \tilde{Z}^{\mu\nu} + g_{bZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + g_{bWW} W^{+}_{\mu\nu} \tilde{W}^{-\mu\nu} + g_{bZ'Z'} Z'_{\mu\nu} \tilde{Z}'^{\mu\nu} + g_{b\gamma Z'} F_{\mu\nu} \tilde{Z}'^{\mu\nu} + g_{bZZ'} Z_{\mu\nu} \tilde{Z}'^{\mu\nu} + \frac{1}{4\pi^2 f_b} C_5 g_G^2 G_{\mu\nu} \tilde{G}^{\mu\nu} \Big) ,$$

$$g_{b\gamma\gamma} = \frac{C_3 g_Y^2 c_w^2 + C_4 g_W^2 s_w^2}{4\pi^2 f_b} , \qquad g_{bZ\gamma} = \frac{C_4 g_W^2 s_w c_w - C_3 g_Y^2 s_w c_w}{2\pi^2 f_b} ,$$

$$g_{bZZ} = \frac{C_3 g_y^2 s_w^2 + C_4 g_w^2 c_w^2}{4\pi^2 f_b} , \qquad g_{bWW} = \frac{C_4 g_w^2}{2\pi^2 f_b} ,$$

$$g_{bZ'Z'} = \frac{C_1 g_{Z'}^2}{4\pi^2 f_b} , \qquad g_{b\gamma Z'} = \frac{C_2 g_Y g_{Z'} c_w}{4\pi^2 f_b} ,$$

$$g_{bZZ'} = \frac{-C_2 g_Y g_{Z'} s_w}{4\pi^2 f_b} .$$

- With the extended Standard Model, the Lagrangian density of the matter content becomes,

$$\mathcal{L}_{fermion} = \sum_{i=1}^{3}\left(\overline{Q}_L^i i\not{D} Q_L^i + \overline{u}_R^i i\not{D} u_R^i + \overline{d}_R^i i\not{D} d_R^i + \overline{L}_L^i i\not{D} L_L^i + \overline{e}_R^i i\not{D} e_R^i\right) + \overline{\chi}_L i\not{D}\chi_L + \overline{\chi}_R i\not{D}\chi_R + \mathcal{L}_{Yukawa} \ ,$$

$$\mathcal{L}_{Yukawa} = -\lambda_u^{ij}(\frac{\phi^\dagger}{\Lambda})^{r_{uij}}\overline{Q}_L^i\tilde{H}u_R^j - \lambda_d^{ij}(\frac{\phi^\dagger}{\Lambda})^{r_{dij}}\overline{Q}_L^i H d_R^j - \lambda_\ell^{ij}(\frac{\phi^\dagger}{\Lambda})^{n_{ij}}\overline{L}_L^i H e_R^j - \lambda_\chi\phi^\dagger(\frac{\phi^\dagger}{\Lambda})^{n_4}\overline{\chi}_L\chi_R + \text{h.c.}$$

$r_{uij} = e_{q_L}^i - e_{u_R}^j$, $r_{dij} = e_{q_L}^i - e_{d_R}^j$, $n_{ij} = e_{\ell_L}^i - e_{\ell_R}^j$ and $n_4 = e_{\chi_L} - e_{\chi_R} + e_\phi$.

- Upon expanding about the vacuum expectation value of ϕ, the Goldstone boson appears as phase and can be rotated away from the Yukawa terms by redefining the fermions

.

$$\mathcal{L}_{Goldstone-fermion} = \frac{r_{uii}}{2v}(m_{u^i})(\phi_2\overline{u}^i\gamma^5 u^i) + \frac{r_{dii}}{2v}(m_{d^i})(\phi_2\overline{d}^i\gamma^5 d^i) + \frac{n_{ii}}{2v}(m_{e^i})(\phi_2\overline{e}^i\gamma^5 e^i) + \frac{n_4+1}{2v}(m_\chi)(\phi_2\overline{\chi}\gamma^5\chi)$$

- Since the scalar field, ϕ, transforms non-trivially under $U(1)'$, its Goldstone mode mix with the St*ü*kelberg axion as shown in the previous section. The SM Higgs field, on the other hand, do not mix with these axions since they are not charged under $U(1)'$.

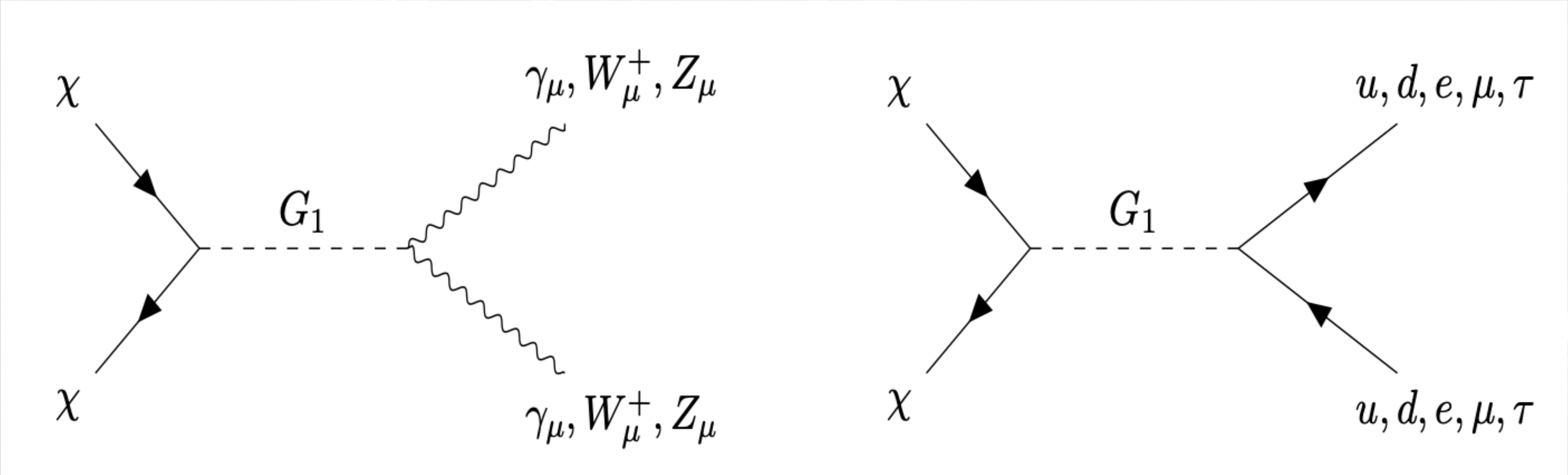
- With this mixing, the physical Goldstone boson becomes a mixture of the axion and the Goldstone. The interaction of the physical pseudo-Goldstone boson (axi-Higgs), could be found in the gauge ξ → ∞, we get,

$$\begin{aligned}\mathcal{L}_{G_1BB} &= \frac{1}{12}g_{Z'}\frac{e_\phi g_{Z'}v}{m_{Z'}}G_1\Big(g_{b\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}+g_{bZ\gamma}F_{\mu\nu}\tilde{Z}^{\mu\nu}+g_{bZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}+g_{bWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\\ &+g_{bZ'Z'}Z'_{\mu\nu}\tilde{Z}'^{\mu\nu}+g_{b\gamma Z'}F_{\mu\nu}\tilde{Z}'^{\mu\nu}+g_{bZZ'}Z_{\mu\nu}\tilde{Z}'^{\mu\nu}+\frac{1}{4\pi^2 f_b}C_5 g_G^2 G_{\mu\nu}\tilde{G}^{\mu\nu}\Big)\,,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{G_1 fermion} &= -\frac{r_{uii}}{2v}\frac{f_b m_{u^i}}{m_{Z'}}(G_1\overline{u}^i\gamma^5 u^i)-\frac{r_{dii}}{2v}\frac{f_b m_{d^i}}{m_{Z'}}(G_1\overline{d}^i\gamma^5 d^i)\\ &-\frac{n_{ii}}{2v}\frac{f_b m_{e^i}}{m_{Z'}}(G_1\overline{e}^i\gamma^5 e^i)-\frac{n_4+1}{2v}\frac{f_b m_\chi}{m_{Z'}}(G_1\overline{\chi}\gamma^5\chi)\,.\end{aligned}$$

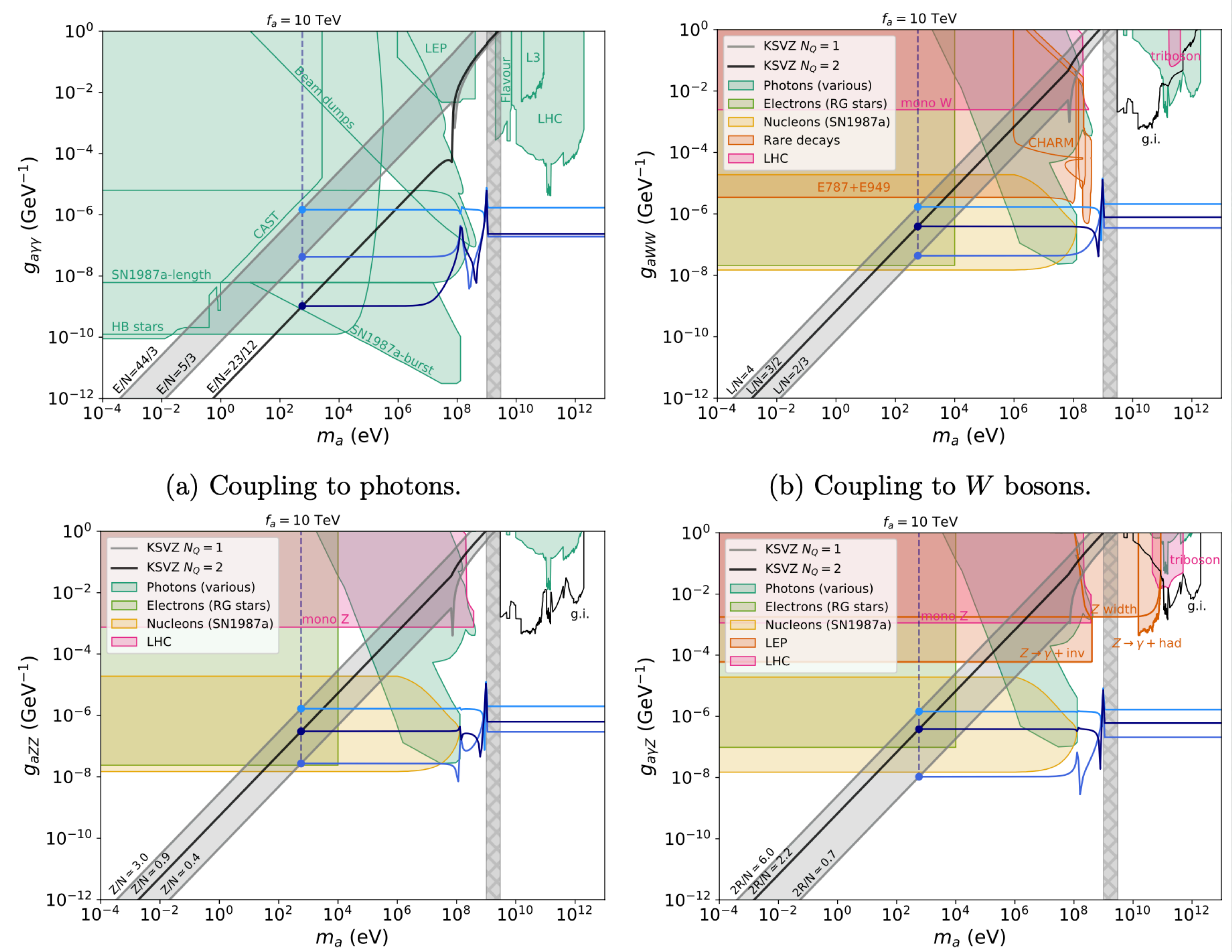
$$m_{G1}=\frac{m_{Z'}\sqrt{c_{G1}(m_{Z'}^2-f_b^2)}}{\sqrt{2}g_{Z'}f_b}.$$

$$c_{G_1}=4\left(\frac{b_1}{v^3}+4\frac{\lambda_1}{v^2}+2\frac{\lambda_2}{v}\right)$$



$$\begin{aligned}
\sigma(\chi\overline{\chi} \to W^+W^-) &= (\frac{-f_b m_\chi}{2v m_{Z'}})^2 \frac{g_{bWW}^2 \tilde{s}(\tilde{s} - 4m_W^2)}{16\pi\Big((m_{G_1}^2 - \tilde{s})^2 + m_{G_1}^2\Gamma_{G_1}^2\Big)} \\
\sigma(\chi\overline{\chi} \to ZZ) &= (\frac{-f_b m_\chi}{2v m_{Z'}})^2 \frac{g_{bZZ}^2 \tilde{s}(\tilde{s} - 4m_Z^2)}{16\pi\Big((m_{G_1}^2 - \tilde{s})^2 + m_{G_1}^2\Gamma_{G_1}^2\Big)} \\
\sigma(\chi\overline{\chi} \to \gamma\gamma) &= (\frac{-f_b m_\chi}{2v m_{Z'}})^2 \frac{g_{b\gamma\gamma}^2 \tilde{s}^2}{16\pi\Big((m_{G_1}^2 - \tilde{s})^2 + m_{G_1}^2\Gamma_{G_1}^2\Big)} \\
\sigma(\chi\overline{\chi} \to \gamma Z) &= (\frac{-f_b m_\chi}{2v m_{Z'}})^2 \frac{g_{b\gamma Z}^2 (\tilde{s} + m_Z^2)^2}{16\pi\Big((m_{G_1}^2 - \tilde{s})^2 + m_{G_1}^2\Gamma_{G_1}^2\Big)} \\
\sigma(\chi\overline{\chi} \to e^i\overline{e}^i) &= (\frac{-f_b m_\chi}{2v m_{Z'}})^2 (\frac{-f_b m_{e^i}}{v m_{Z'}})^2 \frac{\tilde{s}}{16\pi\Big((m_{G_1}^2 - \tilde{s})^2 + m_{G_1}^2\Gamma_{G_1}^2\Big)}
\end{aligned}$$

- [G. Alonso -Álvarez, M.B. Gavela, P. Quilez, *Eur.Phys.J.C* 79 (2019) 3, 223]



- Anomalous $U(1)'_{L_\mu - L_\tau}$

Field	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	χ_L	χ_R	ϕ	H
$U(1)'$ charge	0	0	0	$(0, e_\mu, -e_\tau)$	$(0, e_\mu, -e_\tau)$	1/2	-1/2	-1	0

$$C_1 = e_\mu^3 - e_\tau^3 + 1/4, \quad C_2 = 0, \quad C_3 = -2e_\mu + 2e_\tau, \quad C_4 = 2e_\mu - 2e_\tau, \quad C_5 = 0$$

$$\mathcal{L}_{Yukawa} = -\lambda_q \overline{Q}_L \tilde{H} u_R - \lambda_d \overline{Q}_L H d_R - \lambda_e \overline{L}_L^1 H e_R^1 - \lambda_\mu \overline{L}_L^2 H e_R^2 - \lambda_\tau \overline{L}_L^3 H e_R^3 - \lambda_{mix} \left(\frac{\phi^\dagger}{\Lambda}\right)^e \overline{L}_L^2 H e_R^3 - \phi^\dagger \overline{\chi_L} \chi_R + h.c.$$

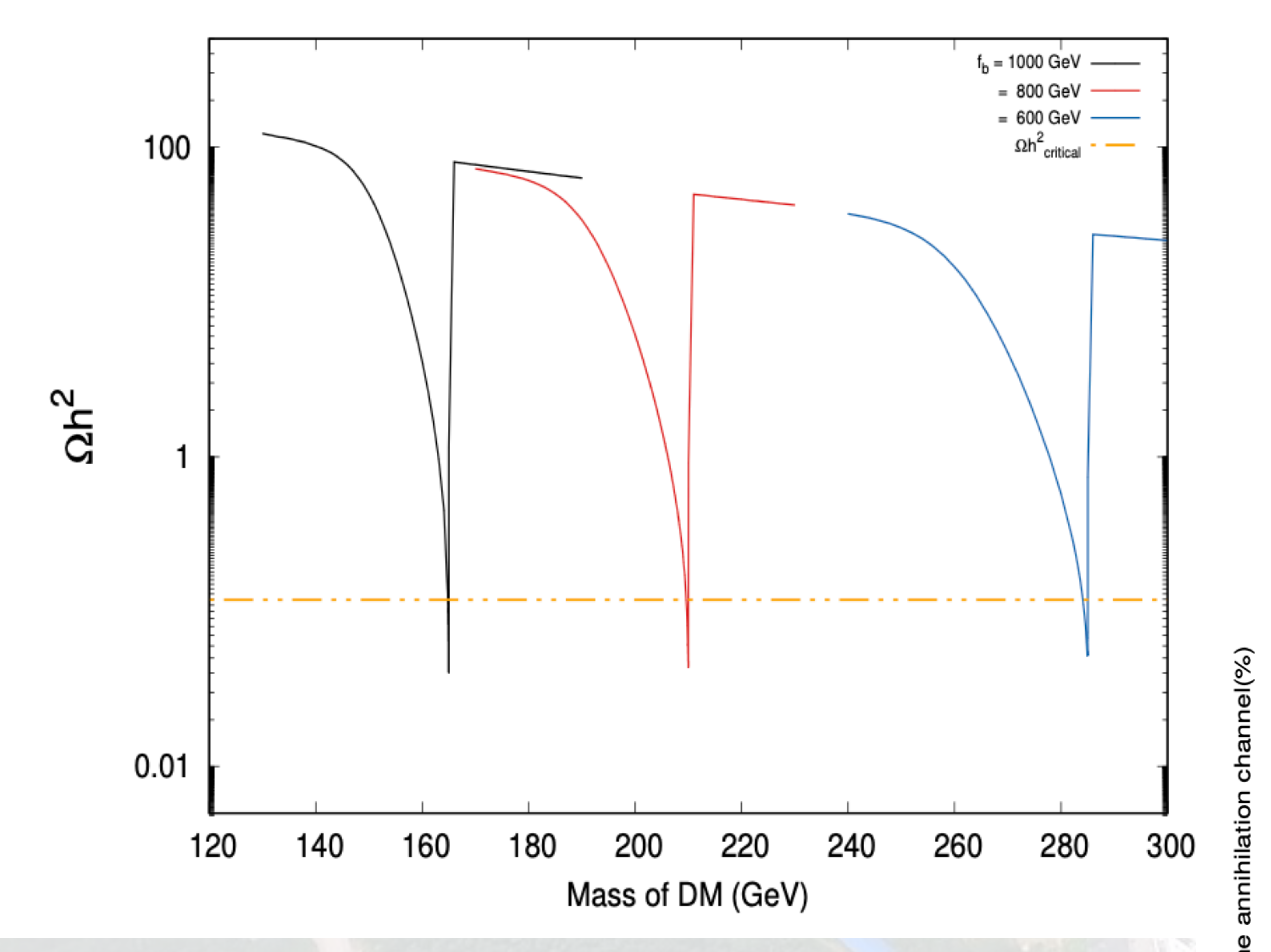
- In the above, we have the freedom to choose 'e', λ_{mix} and $\frac{\langle\phi\rangle}{\Lambda}$ such that the charged lepton mixing is suppressed, making the model free from charged lepton flavour violations. For completeness, here we take $e_\mu = 2$ and $e_\tau = 1$. In this scenario, $g_{a\gamma\gamma}$ vanishes

$$\mathcal{L}_{G_1 BB} = -\frac{1}{12} g_{Z'} \frac{g_{Z'} v}{m_{Z'}} G_1 \Big(g_{bZ\gamma} F_{\mu\nu} \tilde{Z}^{\mu\nu} + g_{bZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + g_{bWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} + g_{bZ'Z'} Z'_{\mu\nu} \tilde{Z}'^{\mu\nu} + g_{b\gamma Z'} F_{\mu\nu} \tilde{Z}'^{\mu\nu} + g_{bZZ'} Z_{\mu\nu} \tilde{Z}'^{\mu\nu} \Big),$$

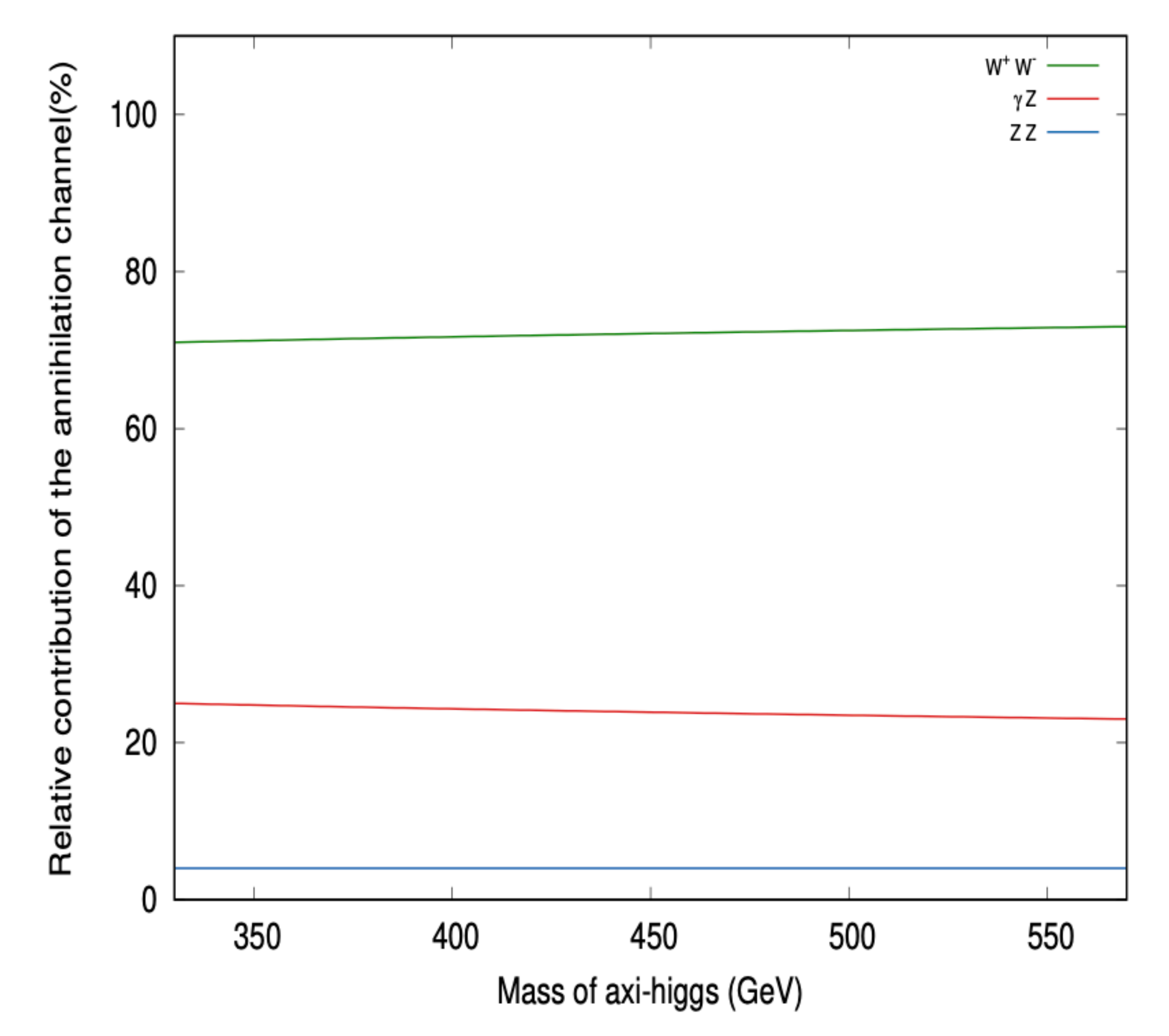
$$\mathcal{L}_{G_1 fermion} = -\frac{1}{2v} \frac{f_b m_\chi}{m_{Z'}} (G_1 \overline{\chi} \gamma^5 \chi).$$

- These interaction terms lead to annihilation channels for the Dark Matter $\chi\chi \to (WW, ZZ, Z\gamma)$.

- In the $U(1)_{L_\mu - L_\tau}$ model, since the charge distribution prohibits DM-fermion coupling, the dark matter can annihilate only to gauge bosons, for lower mass range ($m_{DM} \lesssim$ 45 GeV) dark matter relic density becomes higher than the observed critical value.



m_{G_1} (GeV)	m_{DM} (GeV)	**Annihilation channels**
330	164.9	71% $\chi\overline{\chi} \to W^+W^-$ 25% $\chi\overline{\chi} \to \gamma Z$ 4% $\chi\overline{\chi} \to ZZ$
420	209.6	72% $\chi\overline{\chi} \to W^+W^-$ 24% $\chi\overline{\chi} \to \gamma Z$ 4% $\chi\overline{\chi} \to ZZ$
570	284.1	73% $\chi\overline{\chi} \to W^+W^-$ 23% $\chi\overline{\chi} \to \gamma Z$ 4% $\chi\overline{\chi} \to ZZ$



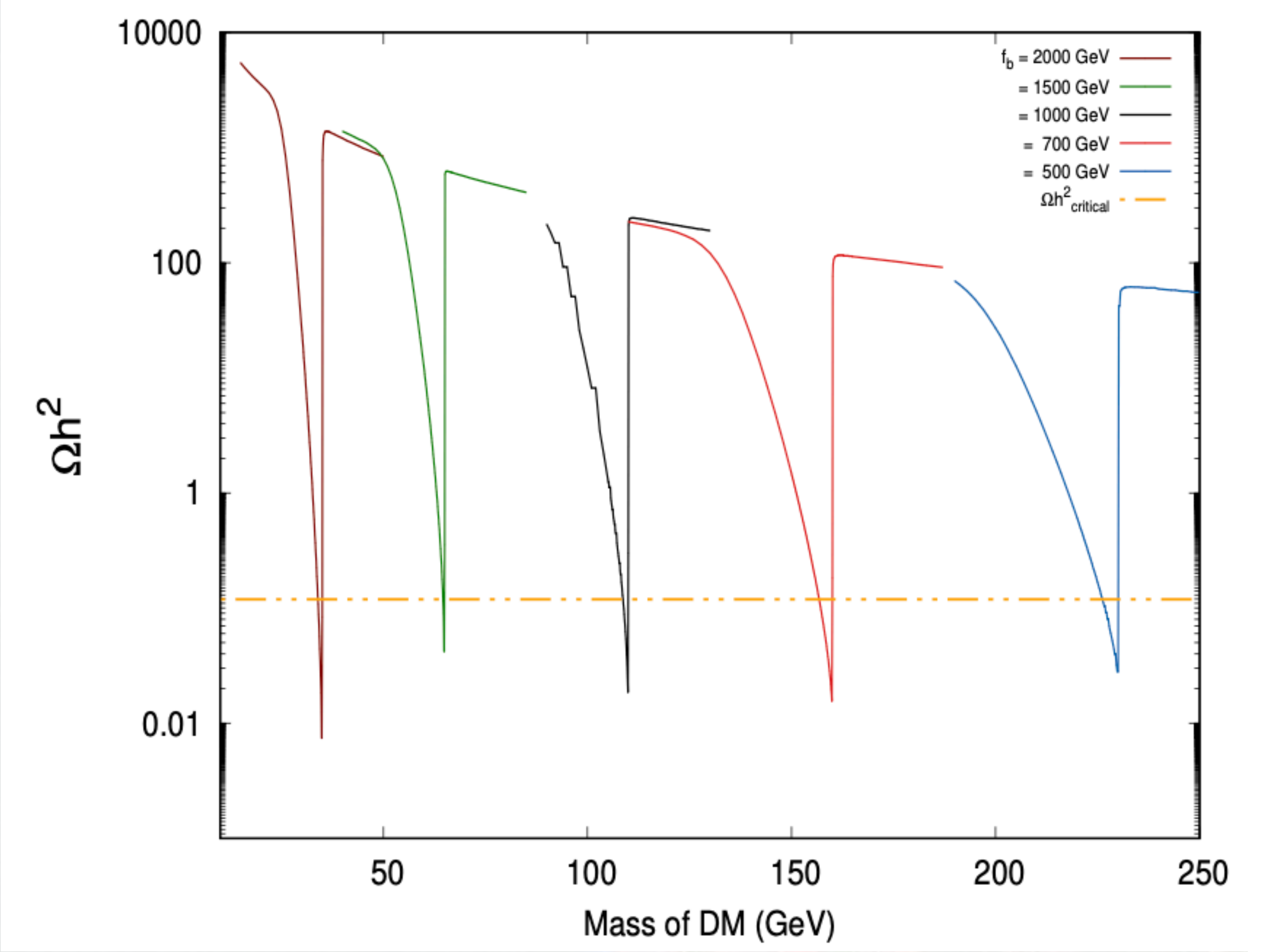
- Anomalous $U(1)'_{L_e+L_\mu+L_\tau}$

Field	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	χ_L	χ_R	ϕ	H
$U(1)'$ charge	0	0	0	(e,e,e)	(-e,-e,-e)	1/2	-1/2	-1	0

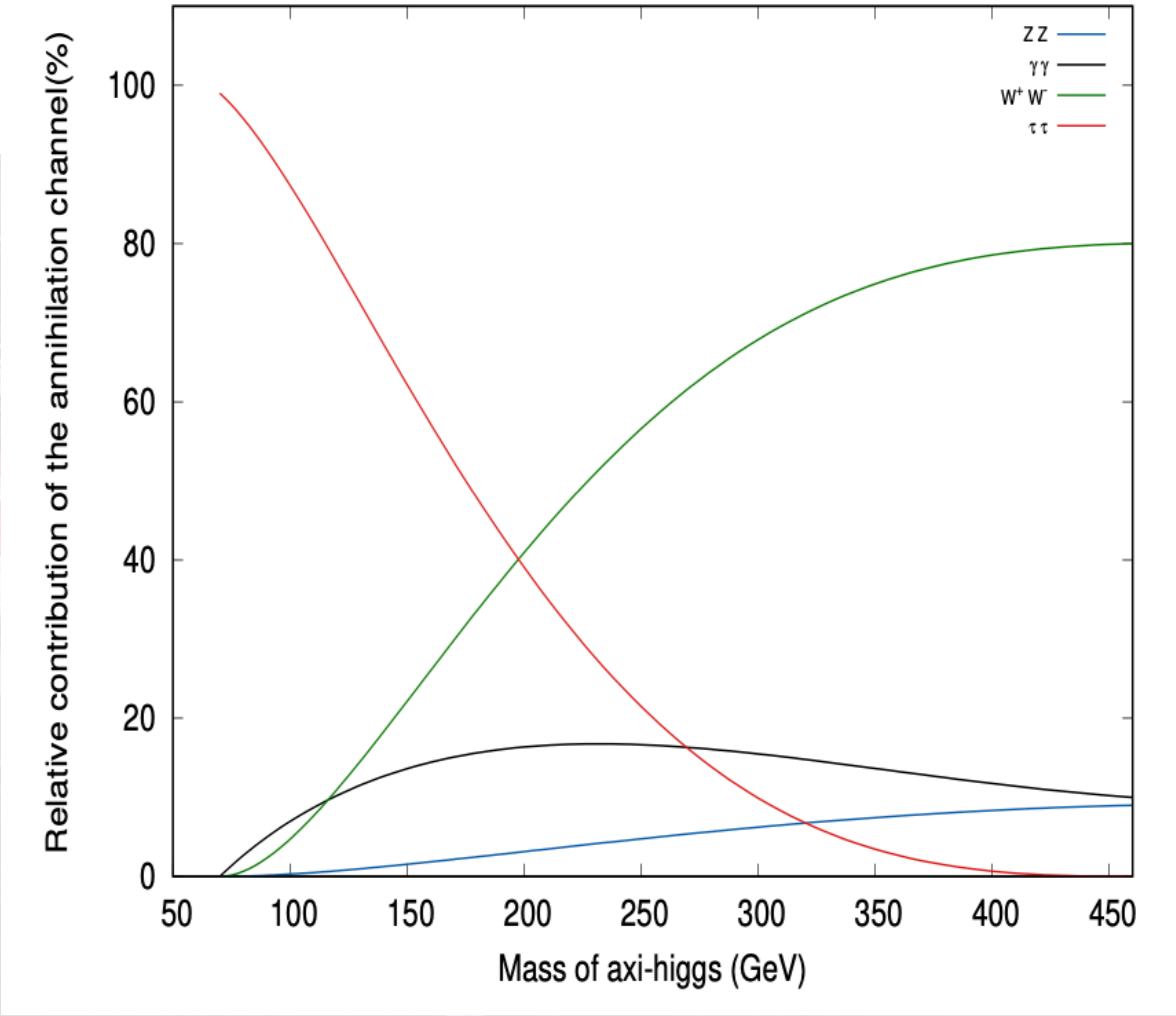
$$\mathcal{L}_{G_1BB} = -\frac{1}{12}g_{Z'}\frac{g_{Z'}v}{m_{Z'}}G_1\Big(g_{b\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{bZ\gamma}F_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{bZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{bWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu} + g_{bZ'Z'}Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} + g_{b\gamma Z'}F_{\mu\nu}\tilde{Z}'^{\mu\nu} + g_{bZZ'}Z_{\mu\nu}\tilde{Z}'^{\mu\nu}\Big) ,$$

$$\mathcal{L}_{G_1fermion} = -\frac{1}{v}\frac{f_b m_{e^i}}{m_{Z'}}(G_1\bar{e}^i\gamma^5 e^i) - \frac{1}{2v}\frac{f_b m_\chi}{m_{Z'}}(G_1\bar{\chi}\gamma^5\chi) .$$

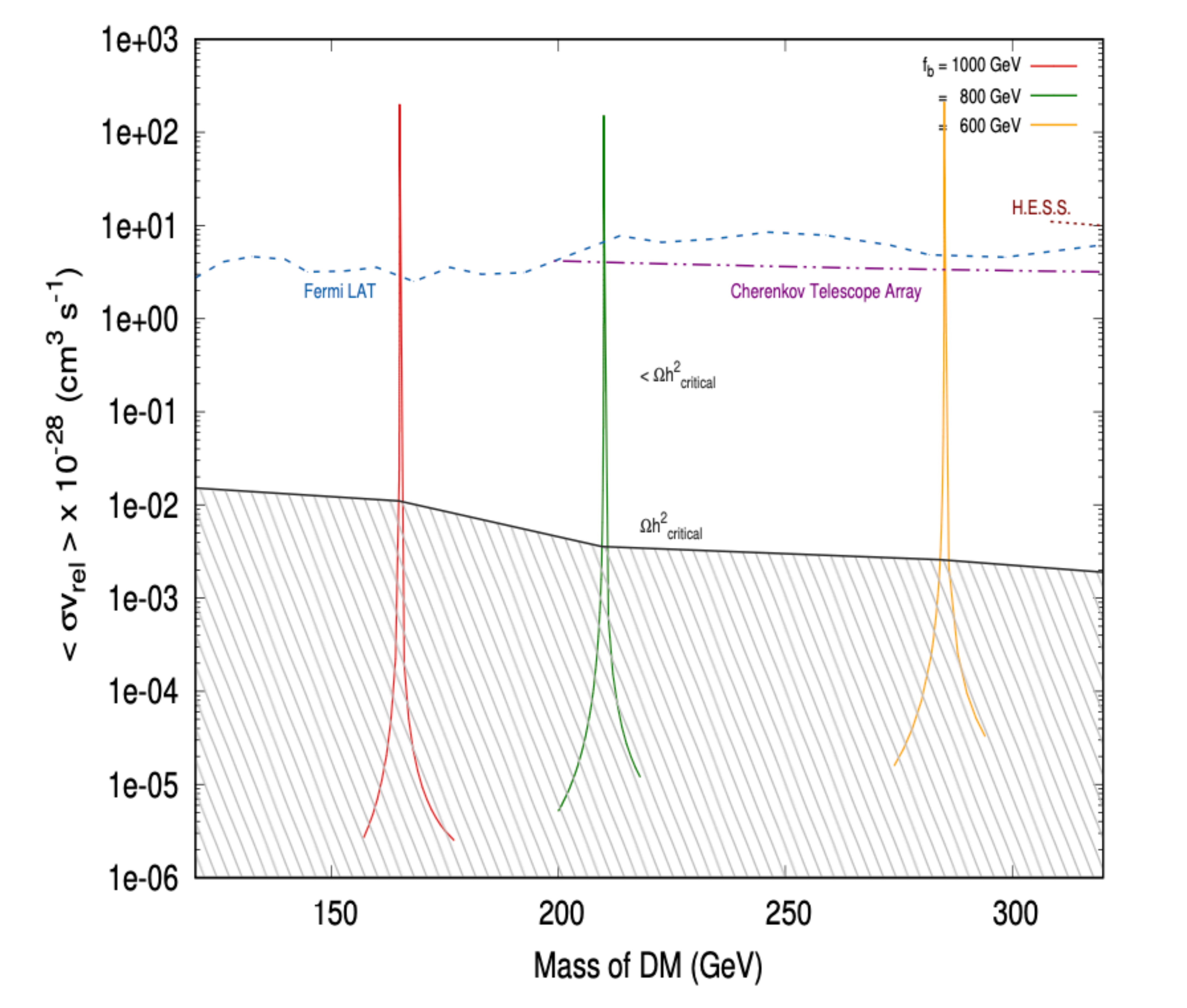
- These interaction terms lead to annihilation channels for the Dark Matter $\chi\chi \to (WW, ZZ, \gamma\gamma, e^i e^i)$

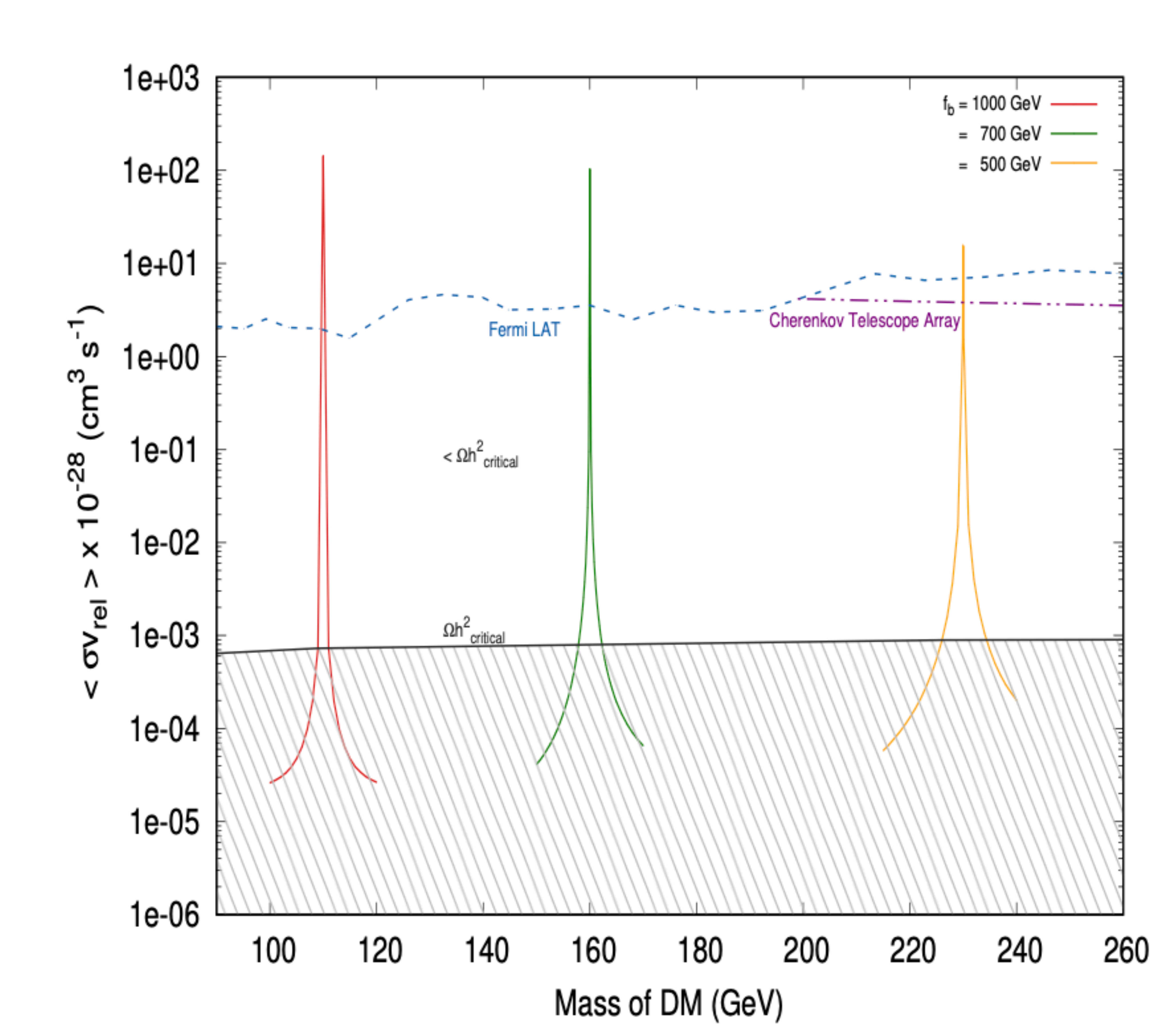


m_{G_1} (GeV)	m_{DM} (GeV)	**annihilation channels**
70	33.9	99% $\chi\bar{\chi} \to \tau\tau$
130	64.6	83% $\chi\bar{\chi} \to \tau\tau$ 17% $\chi\bar{\chi} \to \gamma\gamma$
220	108.7	68% $\chi\bar{\chi} \to W^+W^-$ 23% $\chi\bar{\chi} \to \gamma\gamma$ 4% $\chi\bar{\chi} \to \tau\tau$ 4% $\chi\bar{\chi} \to ZZ$
320	156.7	79% $\chi\bar{\chi} \to W^+W^-$ 13% $\chi\bar{\chi} \to \gamma\gamma$ 8% $\chi\bar{\chi} \to ZZ$
460	226.0	80% $\chi\bar{\chi} \to W^+W^-$ 10% $\chi\bar{\chi} \to \gamma\gamma$ 9% $\chi\bar{\chi} \to ZZ$



- Indirect detection





Conclusion

- Anomalous $U(1)'$ need focused study
- A distinguishing aspect of the resulting effective theory is the decay of X bosons into Standard Model gauge bosons, X → ZZ,WW,γZ .
- This can be studied by looking at pp → X → ZZ → 4l signal, and analyze the prospects of discovery [*Phys.Rev.D* 77 (2008) 066011]
- These studies of Green-Schwarz mechanism also can include physical Goldstone bosons emerging from the mixing of axions with other scalars in the model.