On Theories of Dark Matter

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CASE WESTERN RESERVE UNIVERSITY EST. 1826
think beyond the possible

GGI Lectures on the Theory of Fundamental Interactions
Galileo Galilei Institute for Theoretical Physics, Florence, Italy, Jan 24th, 2025

Main Goal

Discuss theories for physics beyond the Standard Model predicting a Dark Matter candidate !

Supersymmetry
and
Dark Matter

SUSY

MSSM $\longrightarrow$ $m_h^2 = M_Z^2 \cos^2 2\beta + \delta m_h^2(m_{\tilde{f}_i}, X_{\tilde{f}_i})$

$(m_h = 125 \text{ GeV})$

$$\mathcal{W} \supset Y_u \hat{Q} \hat{H}_u \hat{u}^c + Y_d \hat{Q} \hat{H}_d \hat{d}^c + Y_e \hat{L} \hat{H}_d \hat{e}^c + \mu \hat{H}_u \hat{H}_d$$

$$\mathcal{W} \supset \epsilon \hat{L} \hat{H}_u + \lambda \hat{L} \hat{L} \hat{e}^c + \lambda^{'} \hat{Q} \hat{L} \hat{d}^c + \lambda^{''} \hat{u}^c \hat{d}^c \hat{d}^c$$

(*Lepton and Baryon numbers are explicitly broken*) $\left(\lambda^{'} \lambda^{''} \leq 10^{-25} \text{ if } m_{\tilde{f}_i} \sim 1 \text{ TeV}\right)$

$M = (-1)^{3(B-L)}$ $\longrightarrow$ **DM**

RpV vs RpC: *V. Barger, P.F.P., S. Spinner, Phys. Rev. Lett.*

The Fate of R-Parity, P.F.P., S. Spinner, Phys. Rev. D

SUSY DM (WIMPS)

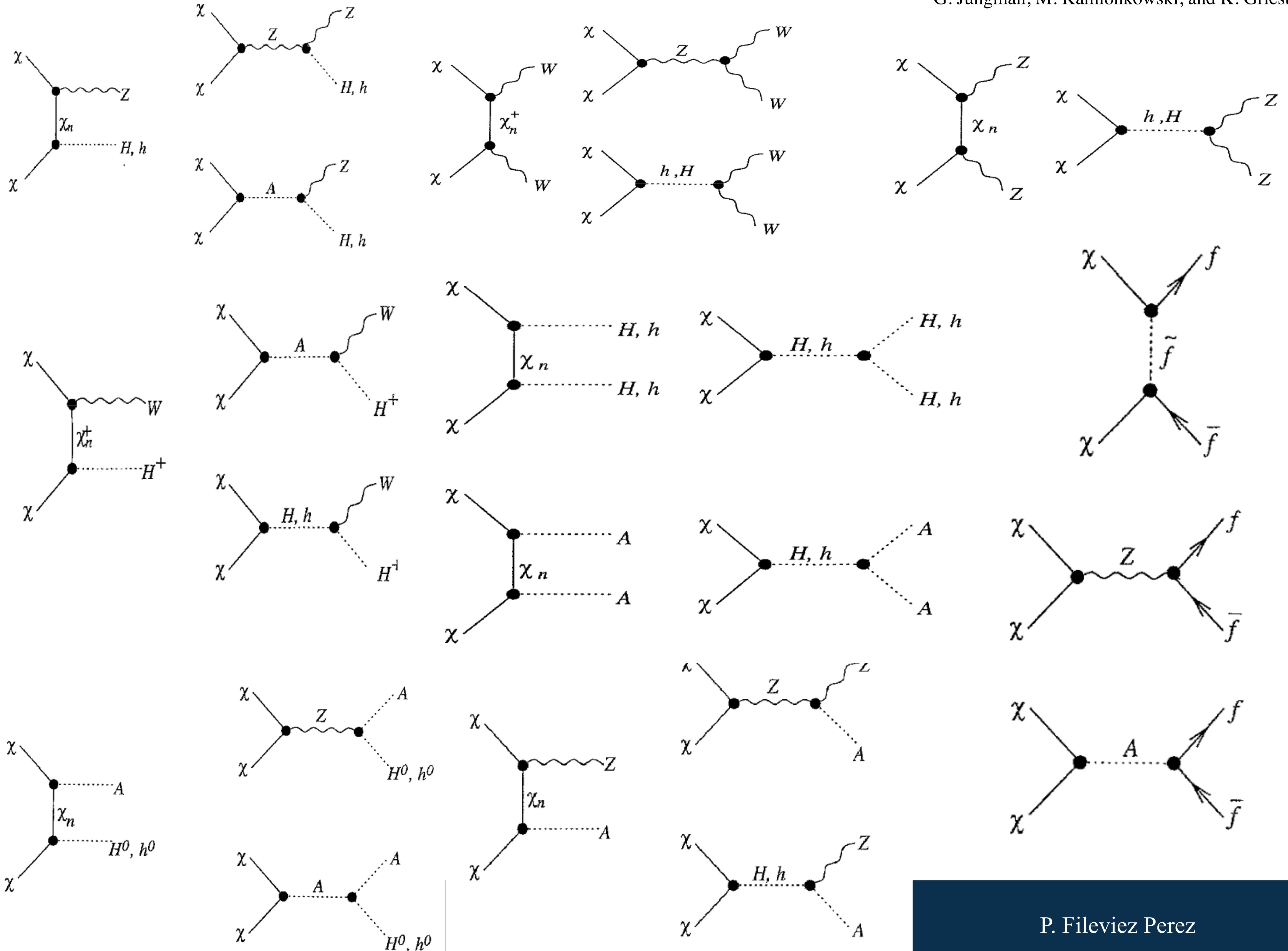
$B_\mu \to \tilde{B}$ $\quad W_\mu^3 \to \tilde{W}$ $\quad H_u^0 \to \tilde{H}_u^0$ $\quad H_d^0 \to \tilde{H}_d^0$

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W} + N_{i3}\tilde{H}_u^0 + N_{i4}\tilde{H}_d^0$$

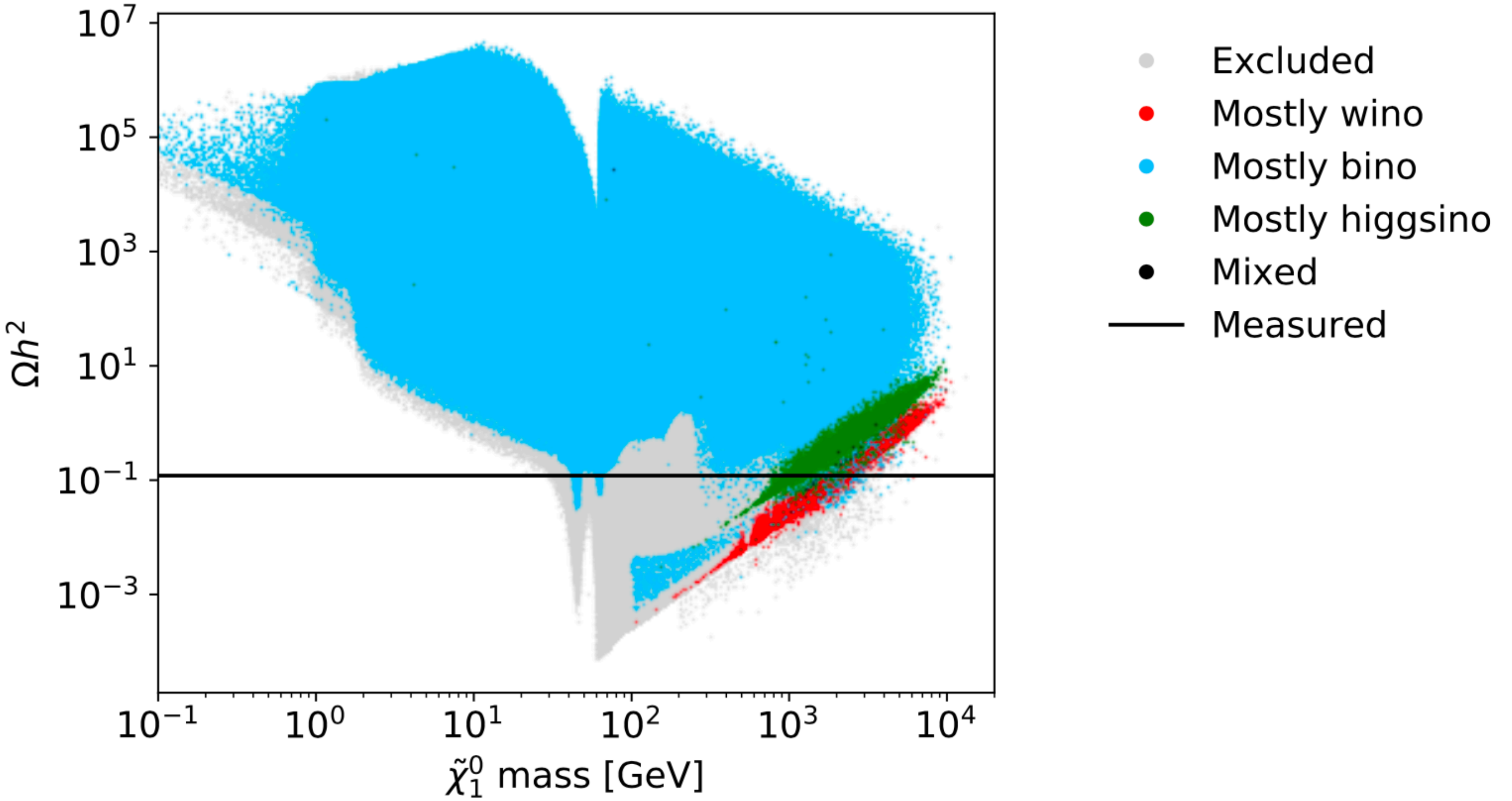
$\tilde{\chi}_1^0$ is the LSP and stable !

$M = (-1)^{3(B-L)}$ ⟹ Neutralino DM

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{SM SM}, \ldots$ ⟹ $\Omega_{\tilde{\chi}_1^0} h^2 \leq 0.12$


χ χ Z H, h χ_n
χ χ Z Z H, h
χ χ A Z H, h
χ χ W W χ_n^+
χ χ Z W W
χ χ h ,H W W
χ χ Z Z χ n
χ χ h ,H Z Z
χ χ W H^+ χ_n^+
χ χ A W H^+
χ χ H, h W H^+
χ χ H, h H, h χ n
χ χ A A χ n
χ χ H, h H, h H, h
χ χ H, h A A
χ χ f $\bar{f}$ $\tilde{f}$
χ χ Z f $\bar{f}$
χ χ A f $\bar{f}$
χ χ A H^0, h^0 χ_n
χ χ Z A H^0, h^0
χ χ A A H^0, h^0
χ χ Z A χ_n
χ Z Z A
χ χ H, h Z A

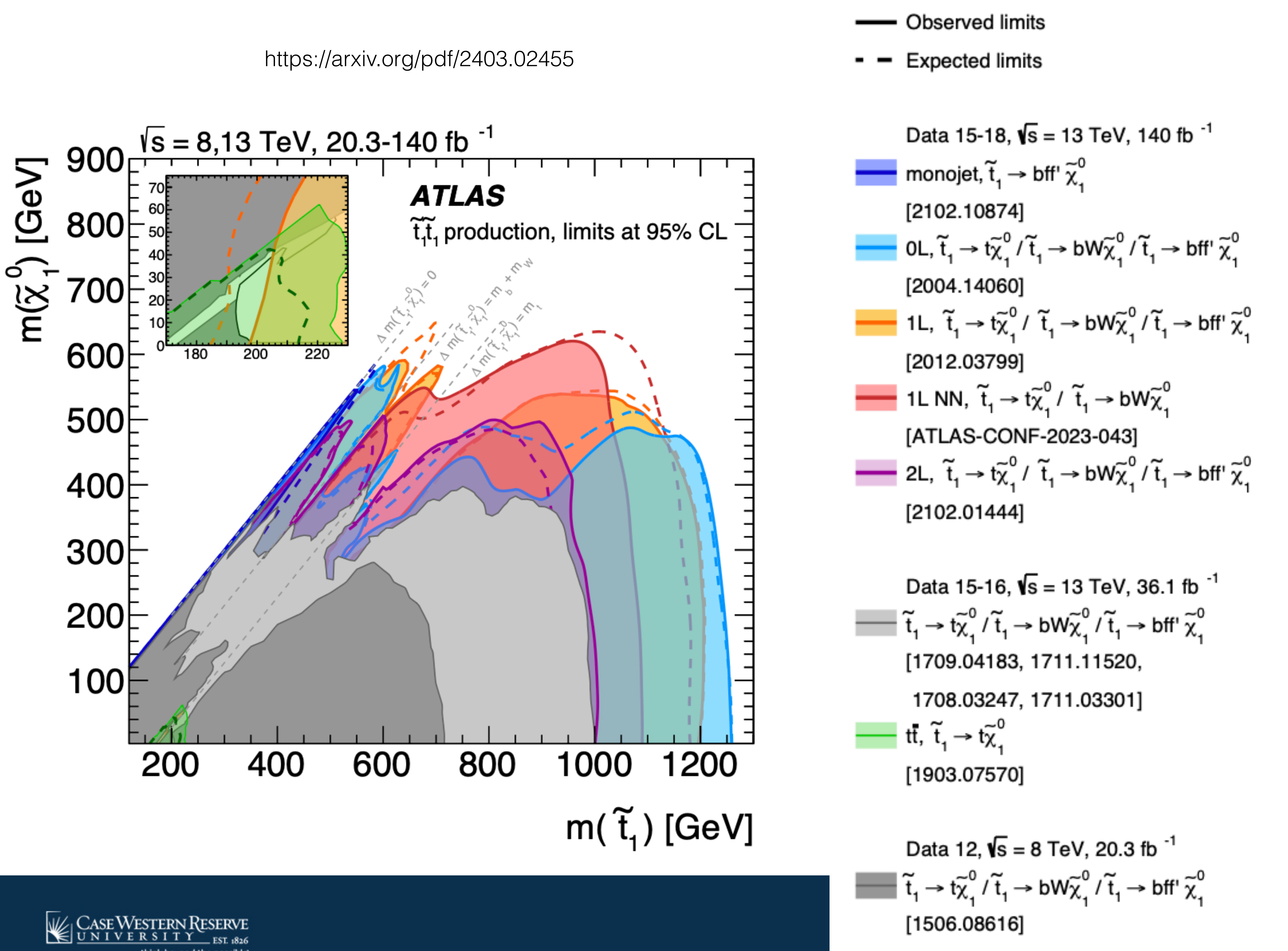
SUSY DM



Distribution of sampled pMSSM points as function of the DM relic density vs. DM candidate mass. Points excluded by existing measurements (as implemented in SModelS, HiggsBounds, and MicrOMEGAS) are shown in light gray. The remaining points are broken down by the electroweakino composition of the DM candidate. The DM candidate is considered mostly pure if a single electroweakino comprises > 80% of the admixture, and mixed otherwise.

https://arxiv.org/pdf/2207.05103

https://arxiv.org/pdf/2403.02455



Collaborators

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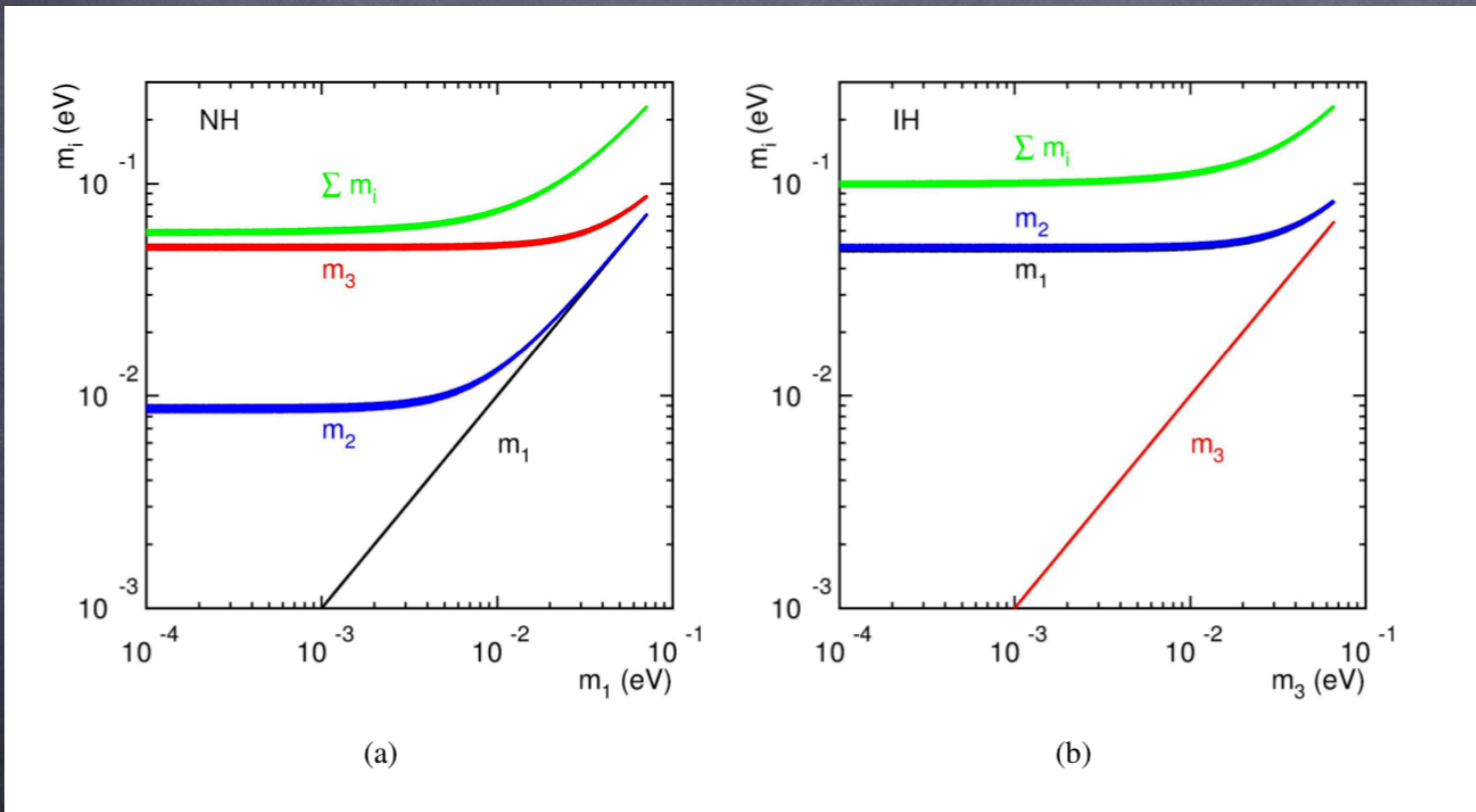
Kevin Gonzalez-Quesada
(CWRU)

Dark Matter and Neutrino Masses

Massive Neutrinos

Normal Hierarchy *Inverted Hierarchy*



Massive Neutrinos

- Majorana Fermions *(Lepton Number is broken by two units)*

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_M \nu_L$$

- Dirac Fermions *(Lepton Number is conserved or broken but not effective Majorana masses)*

$$\mathcal{L} \supset M_D \bar{\nu}_L \nu_R$$

Majorana Neutrino Masses

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_\nu \nu_L$$

Mechanics:

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Witten's Model

…

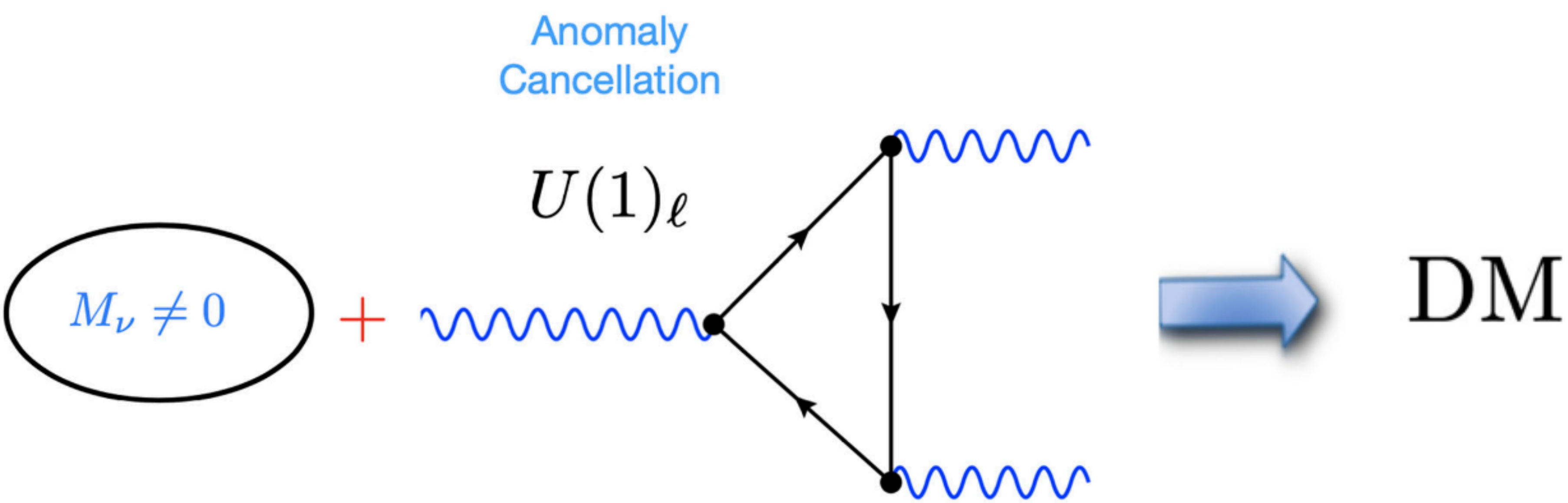
…

Theories:

- B-L
- Left-Right Symmetry
- Pati-Salam
- GUTs
- ….

P.F.P., M.B.Wise

Lepton Number as Local Gauge Symmetry



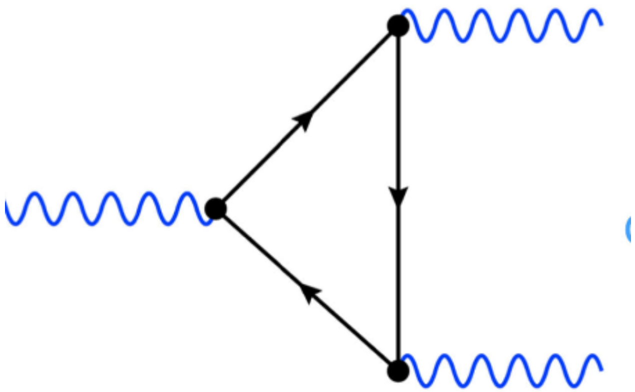
$\Omega_{DM} h^2 \leq 0.12$ → Low Scale Seesaw

Lepton Number as Local Gauge Symmetry

Anomaly Cancellation:

$$\ell_L \sim (\mathbf{2}, -1/2, 1) \quad \text{and} \quad e_R \sim (\mathbf{1}, -1, 1),$$

$$\mathcal{A}_1\left(SU(3)_C^2 U(1)_\ell\right) = 0,$$
$$\mathcal{A}_2\left(SU(2)_L^2 U(1)_\ell\right) = 3/2,$$
$$\mathcal{A}_3\left(U(1)_Y^2 U(1)_\ell\right) = -3/2,$$
$$\mathcal{A}_4\left(U(1)_Y U(1)_\ell^2\right) = 0,$$
$$\mathcal{A}_5\left(U(1)_\ell^3\right) = 3, \quad \text{and} \quad \mathcal{A}_6\left(U(1)_\ell\right) = 3.$$



Solutions:

- Vector-like leptons

  P. F. P., M. B. Wise, JHEP1108, 068

  M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110, 231801

- Four representations

  P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

- Minimal Model

  P. F. P., Physical Review D 110, 035018 (2024)

$$\ell_1 - \ell_2 = -3$$

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	ℓ_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	ℓ_2
η_R	$\mathbf{1}$	$\mathbf{1}$	-1	ℓ_1
η_L	$\mathbf{1}$	$\mathbf{1}$	-1	ℓ_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	ℓ_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	ℓ_2

$$\ell_1 = -\ell_2 = -3/2$$ (Majorana DM)

H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_\ell$$

$$\mathcal{L} \supset y_\Psi \bar{\Psi}_L \Psi_R S^* + y_\eta \bar{\eta}_R \eta_L S^*$$

$$+ y_\chi \bar{\chi}_R \chi_L S^* + \lambda_\chi \chi_L^T C \chi_L S^* + \lambda_\chi^{'} \chi_R^T C \chi_R S + h.c.$$

$$S \sim (\mathbf{1}, \mathbf{1}, 0, 3).$$

$$-\mathcal{L}_\nu \supset Y_\nu \, \bar{\ell}_L \tilde{H} \nu_R + \lambda_R \, \nu_R^T C \phi \nu_R \; + \; \text{h.c.}.$$

$$\phi \sim (\mathbf{1}, \mathbf{1}, 0, -2)$$

Neutrino Masses

$$M_\nu = \frac{v_0^2}{2} Y_\nu M_N^{-1} Y_\nu^T,$$

$$M_N = \sqrt{2}\lambda_R v_\phi = \frac{\lambda_R}{\sqrt{2}} \frac{M_{Z_\ell}}{g_\ell} \cos\beta.$$

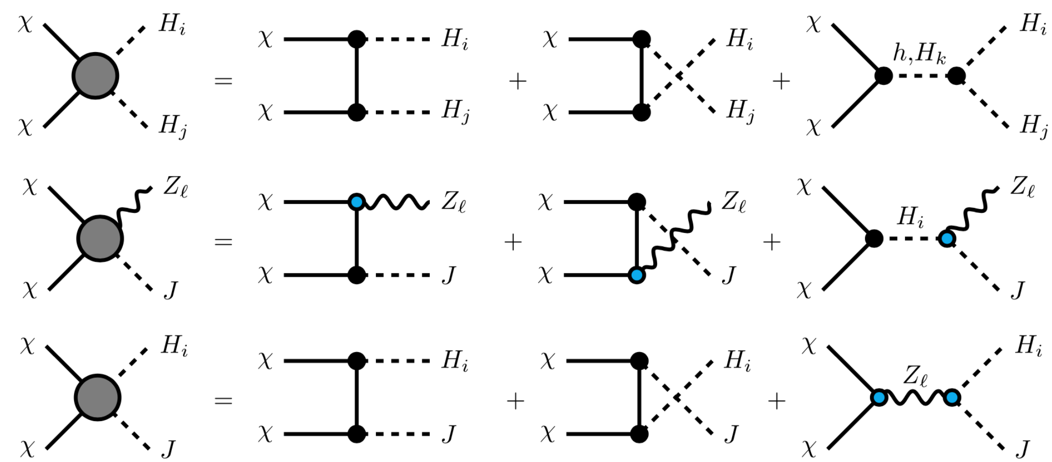
$$M_{Z_\ell}^2 = g_\ell^2 \left(9 v_s^2 \ + \ 4 v_\phi^2\right).$$

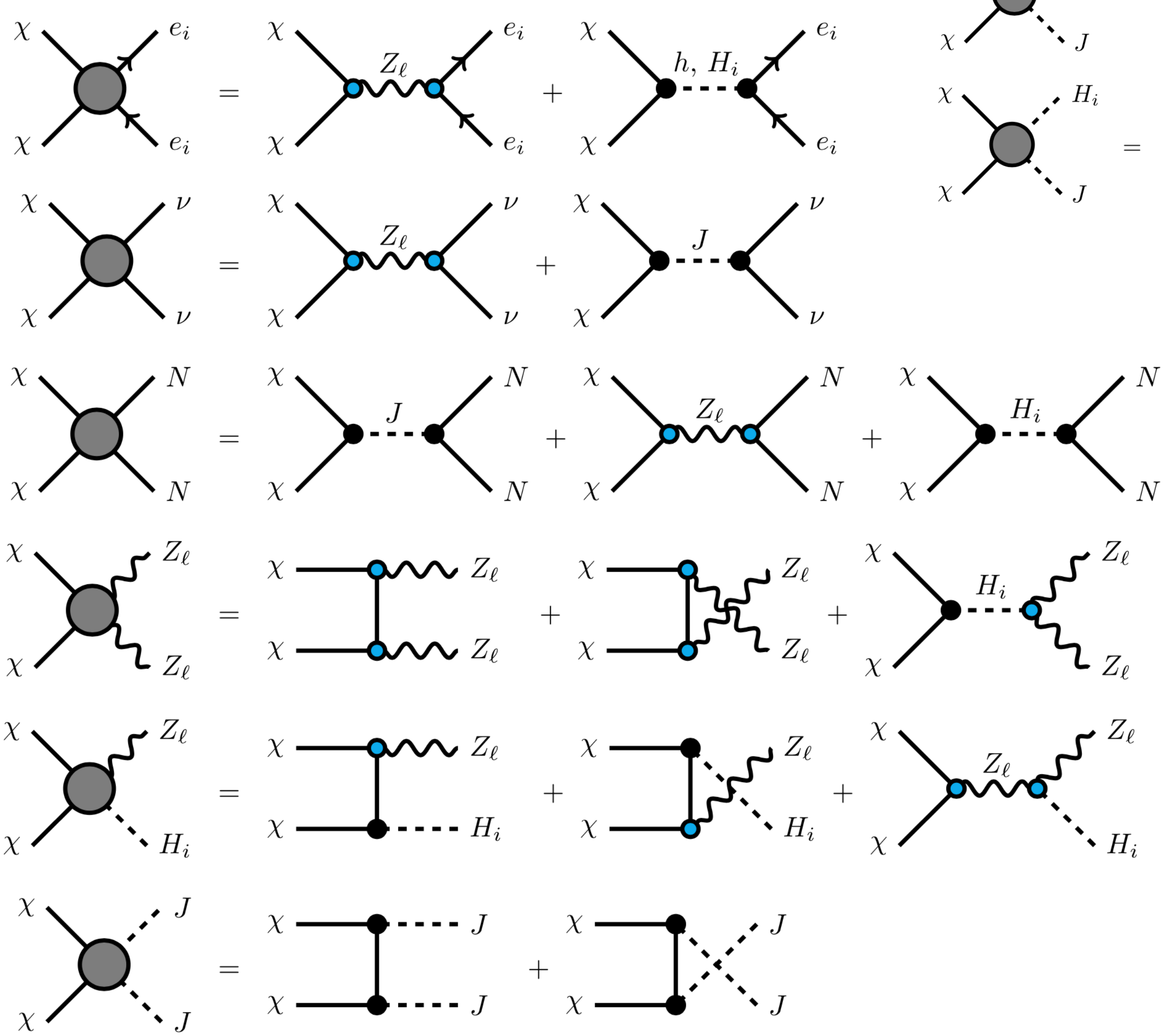
Since the scale for spontaneous L violation must be below the multi-TeV scale one has a **Low Scale Seesaw !**

H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

Dark Matter

$$\chi = \chi_L + (\chi_L)^C$$

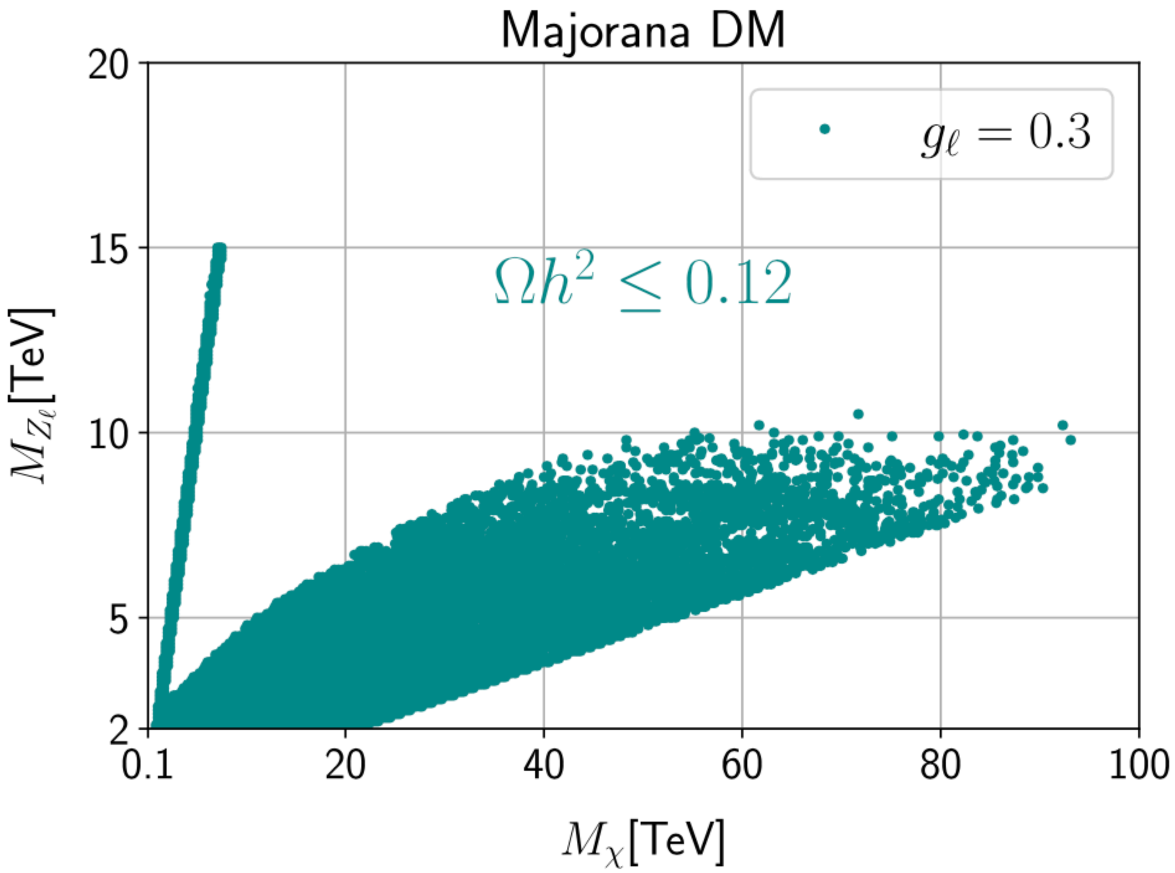




P. Fileviez Perez

H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

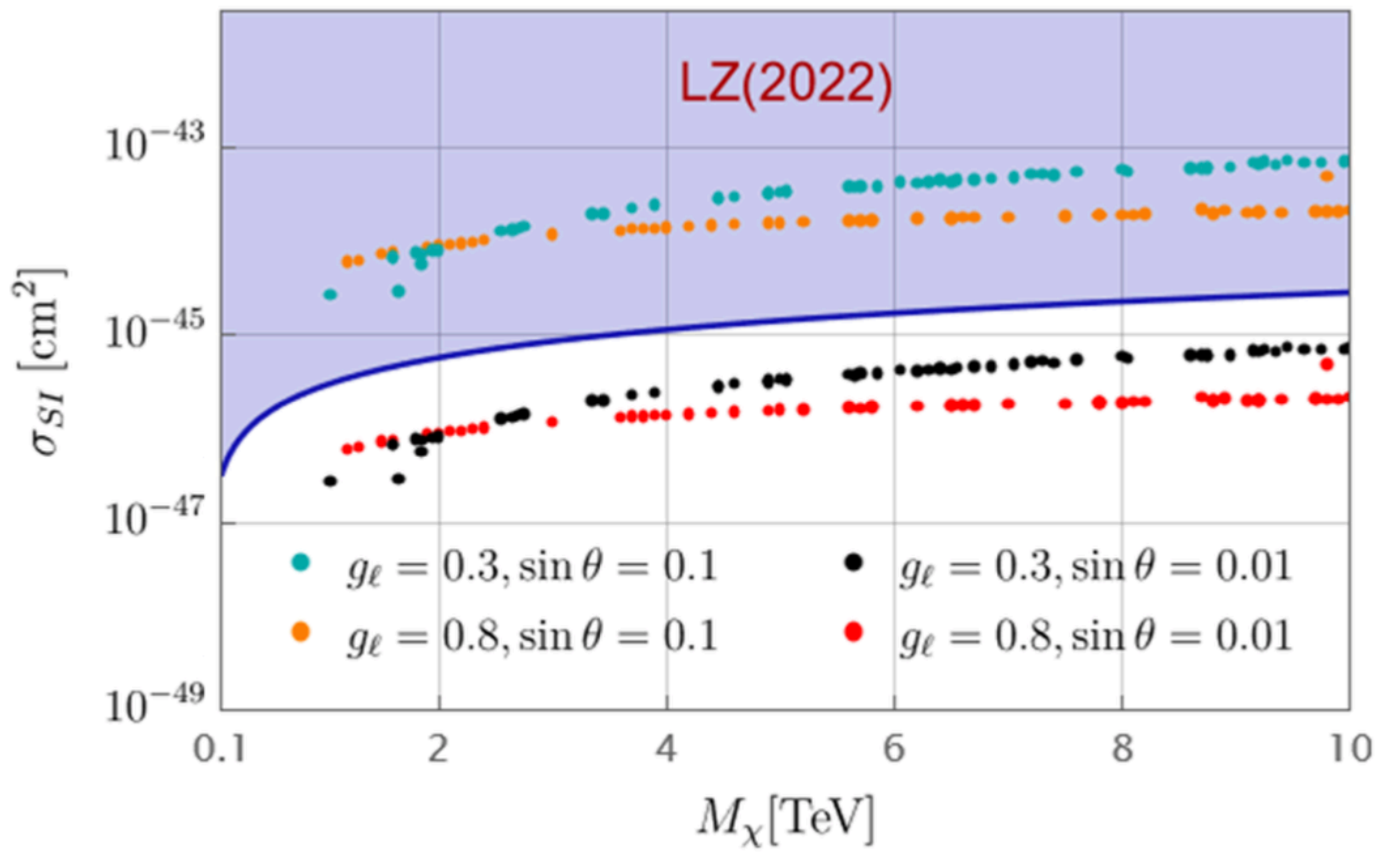
Dark Matter

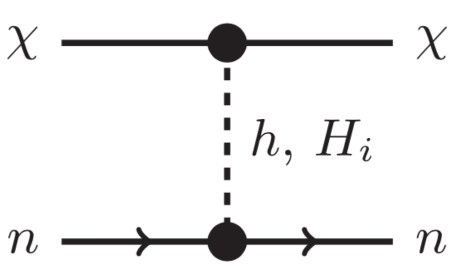


The scale for spontaneous L violation must be below the multi-TeV scale !

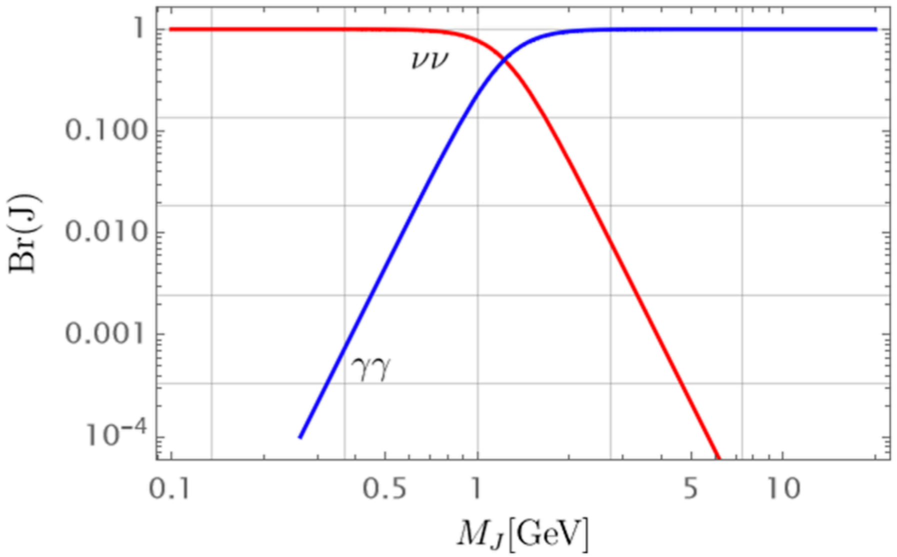
H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

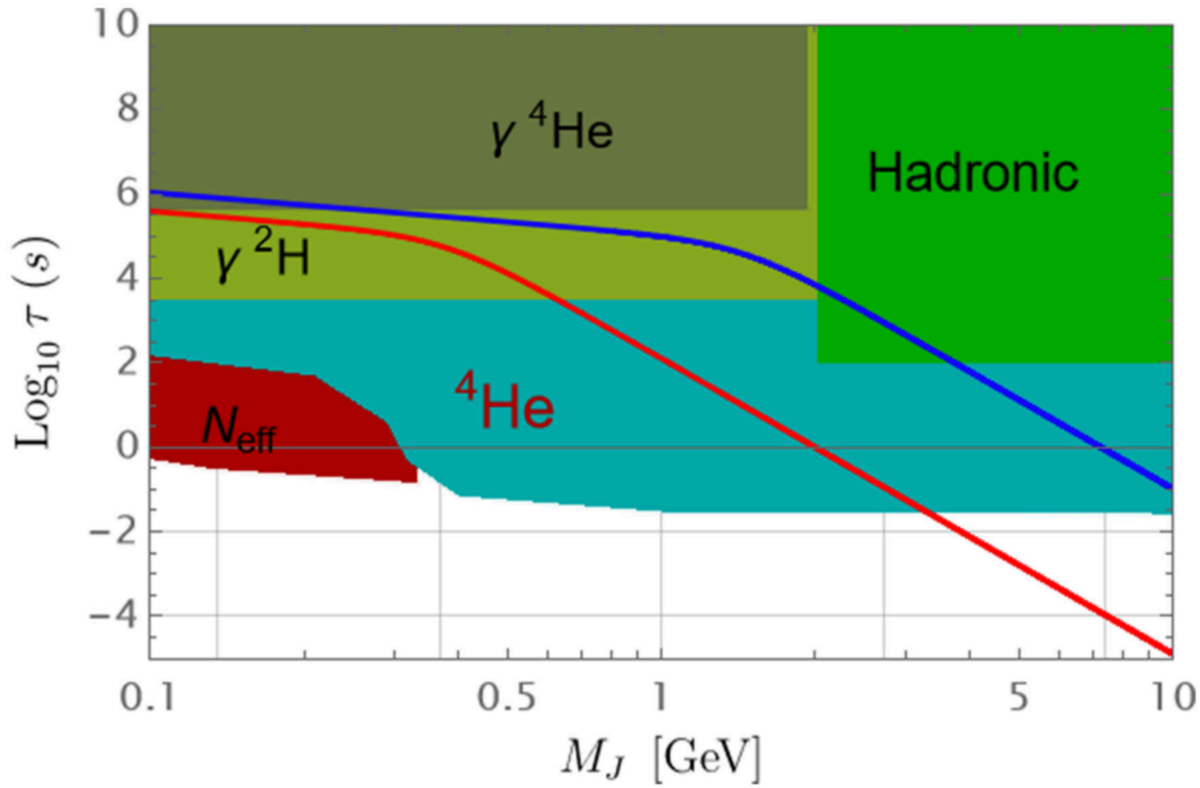
Direct detection:





H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)





Minimal Model

P. F. P., Physical Review D 110, 035018 (2024)

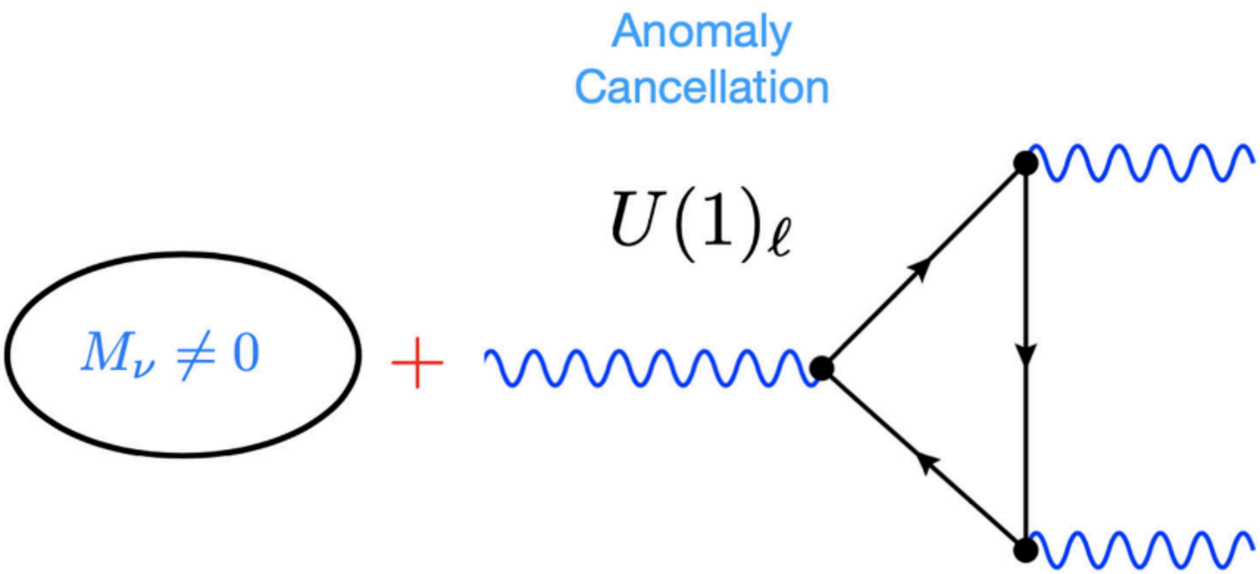
ν_R^i

$$\Psi_L \sim (\mathbf{1}, -1, 3/4), \qquad \Psi_R \sim (\mathbf{1}, -1, -3/4),$$
$$\chi_L \sim (\mathbf{1}, 0, 3/4), \quad \text{and} \quad \rho_L \sim (\mathbf{3}, 0, -3/4).$$

Minimal number of fields to cancel all leptonic and baryonic gauge anomalies

P.F.P., M.B.Wise

Lepton Number as Local Gauge Symmetry



DM

$\Omega_{DM} h^2 \leq 0.12$ → *Low Scale Seesaw*

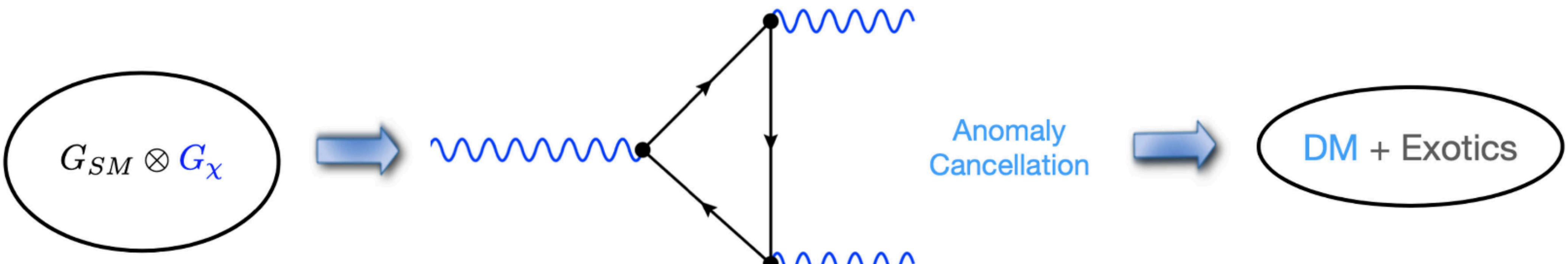
Dark Matter

and

Baryon Number

P.F.P., M.B.Wise

Baryon Number as Local Gauge Symmetry



$$G_\chi = U(1)_B$$

Relation between proton stability and DM !

The Proton is stable in these theories !

Baryon Number as Local Gauge Symmetry

$$
\begin{aligned}
\mathcal{A}(SU(3)_C^2 U(1)_B) \;&=\; 0,\; \mathcal{A}(SU(2)_L^2 U(1)_B) = 3/2,\\
\mathcal{A}(U(1)_Y^2 U(1)_B) \;&=\; -3/2,\; \mathcal{A}(U(1)_Y U(1)_B^2) = 0,\\
\mathcal{A}(U(1)_B^3) \;&=\; 0,\; \text{and } \mathcal{A}(U(1)_B) = 0.
\end{aligned}
$$

Solutions:

- Vector-like fermions

P. F. P., M. B. Wise, JHEP1108, 068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110, 231801

- Four representations

P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

- Minimal Model

P. F. P., Physical Review D 110, 035018 (2024)

P. F. P., Physical Review D 110, 035018 (2024)

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$$

Fields needed for anomaly cancellation !

$$\Longrightarrow \quad \begin{aligned} \Psi_L &\sim (\mathbf{1}, \mathbf{1}, -1, 3/4), \ \Psi_R \sim (\mathbf{1}, \mathbf{1}, -1, -3/4), \\ \chi_L &\sim (\mathbf{1}, \mathbf{1}, 0, 3/4), \ \text{and } \rho_L \sim (\mathbf{1}, \mathbf{3}, 0, -3/4). \end{aligned}$$

Yukawa interactions:

$$-\mathcal{L} \supset \lambda_\rho \mathrm{Tr}(\rho_L^T C \rho_L) S + \lambda_\Psi \bar{\Psi}_L \Psi_R S + \lambda_\chi \chi_L^T C \chi_L S^* \ + \ \mathrm{h.c.}.$$

$$\Longrightarrow \qquad S \sim (\mathbf{1}, \mathbf{1}, 0, 3/2),$$

$$\lambda_e \bar{\Psi}_L e_R \phi + h.c. \qquad \Longrightarrow \qquad \phi \sim (\mathbf{1}, \mathbf{1}, 0, 3/4)$$

The Proton is stable

P. F. P., Physical Review D 110, 035018 (2024)

Physical States:

– $M_{Z_B} = 3 g_B v_S / 2$

– $h = h_0 \cos\theta_B - h_S \sin\theta_B$

– $h_B = h_0 \sin\theta_B + h_S \cos\theta_B$

- ϕ is a complex scalar field

- Two Majorana fermionic fields: $\chi = \chi_L + (\chi_L)^C$ and $\rho^0 = \rho^0_L + (\rho^0_L)^C$ with masses

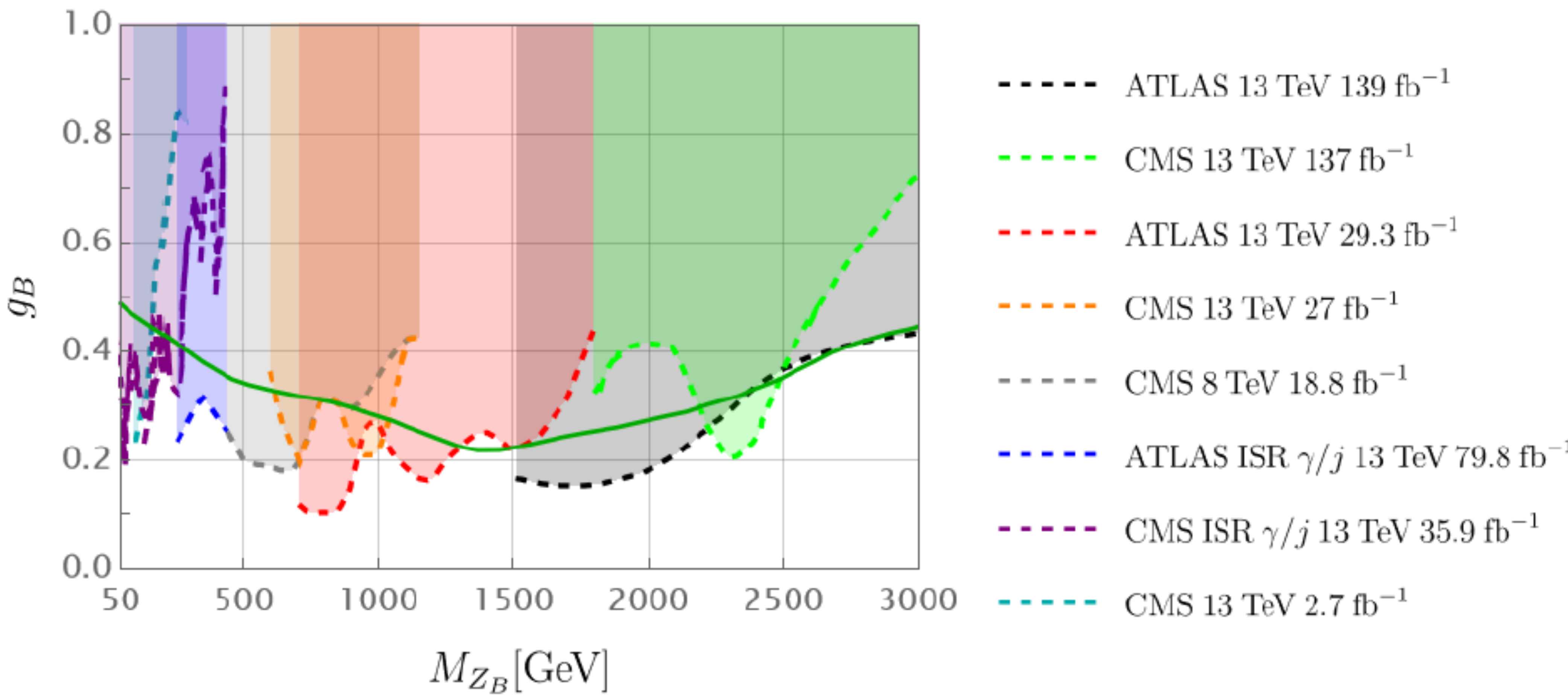
$$M_\chi = \sqrt{2}\lambda_\chi v_S \text{ and } M_{\rho^0} = \sqrt{2}\lambda_\rho v_S.$$

- Two charged fields: $\Psi^- = \Psi^-_L + \Psi^-_R$ and $\rho^- = \rho^-_L + (\rho^+_L)^C$ with masses given by

$$M_{\Psi^-} = \frac{1}{\sqrt{2}}\lambda_\Psi v_S \text{ and } M_{\rho^-} = M_{\rho^0} + \delta M,$$

- J. Butterworth, H. Debnath, P. F. P., Y. Yeh, Physical Review D110, 075001(2024)

Collider Bounds



"Cucuyo" Higgs

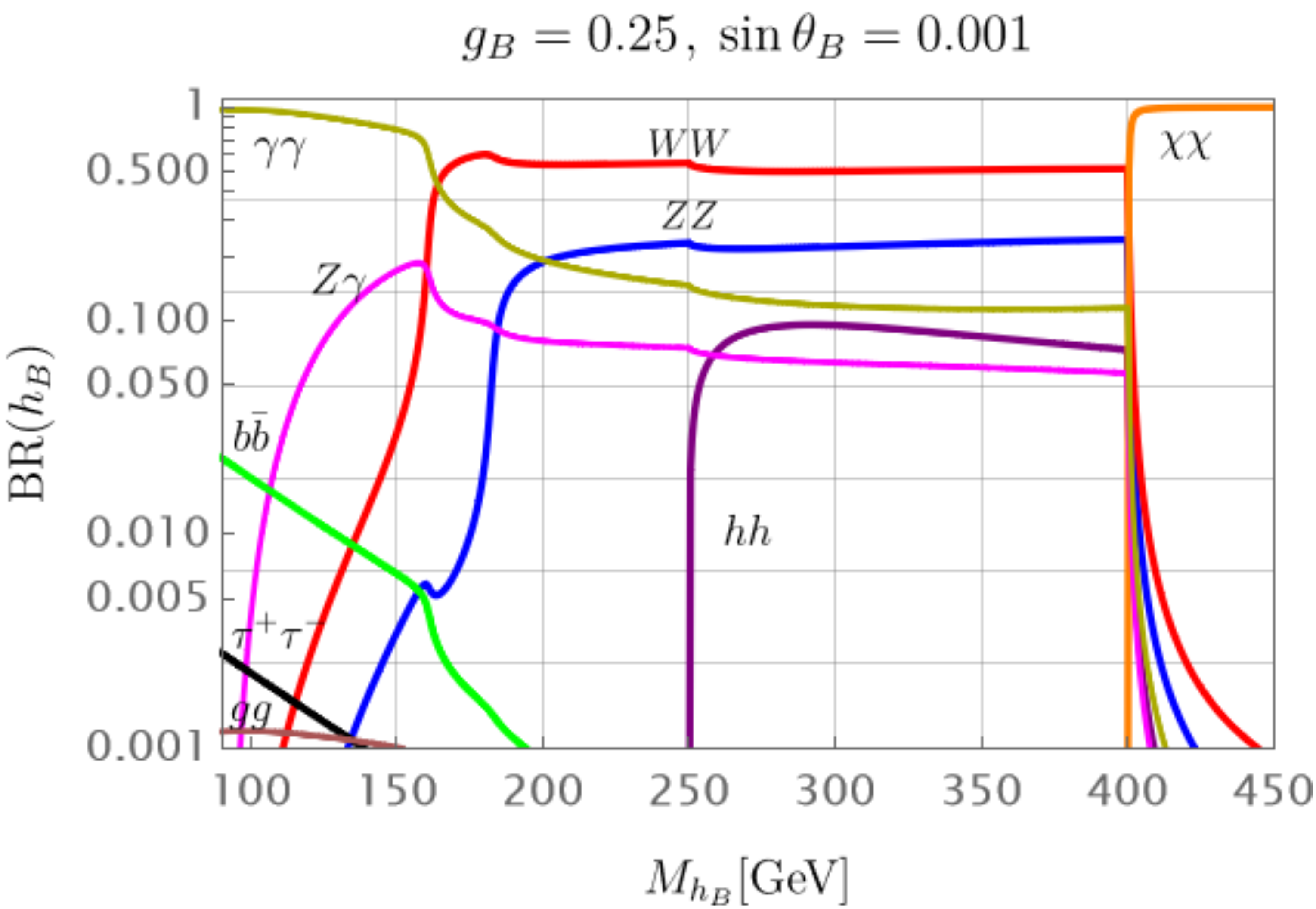
$$h_B$$

An insect very common in Cuba, Brazil, Guiana and Mexico. It may be seen at night in great numbers among the foliage of trees. They sometimes are so numerous that they light up the dark forest.

- J. Butterworth, H. Debnath, P. F. P., Y. Yeh, Physical Review D110, 075001(2024)

"Cucuyo" Higgs decays

$$h_B = h_0 \sin\theta_B + h_S \cos\theta_B .$$



Dark Matter

$$\chi = \chi_L + (\chi_L)^C$$

Neutral and Stable

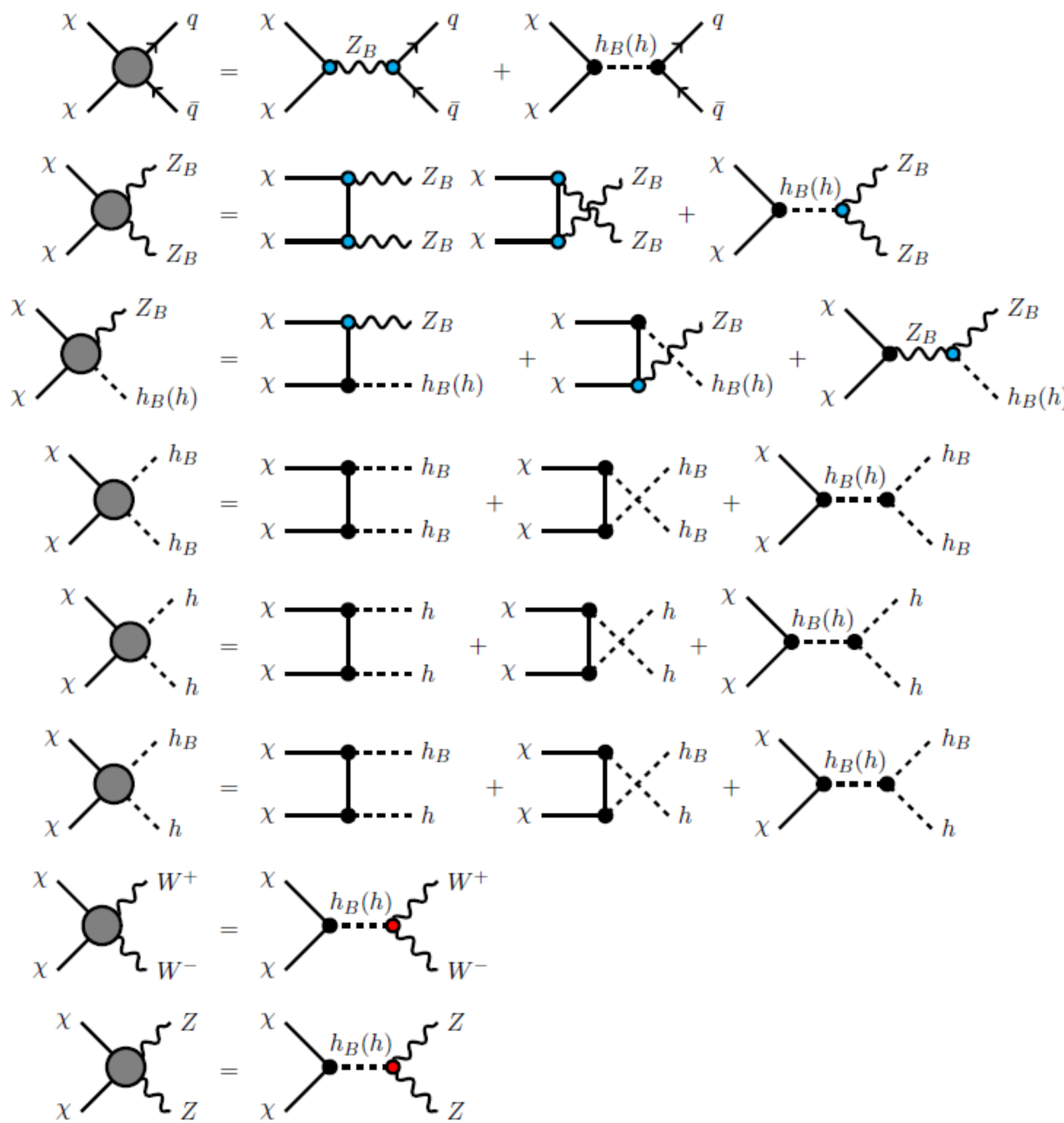
$$\mathcal{Z}_2 : \chi_L \to -\chi_L, \phi \to -\phi, \Psi_L \to -\Psi_L, \Psi_R \to -\Psi_R, \rho_L \to -\rho_L$$

More relevant free parameters of the theory:

g_B, M_χ, M_{z_B}, M_{h_B} *and* θ_B.

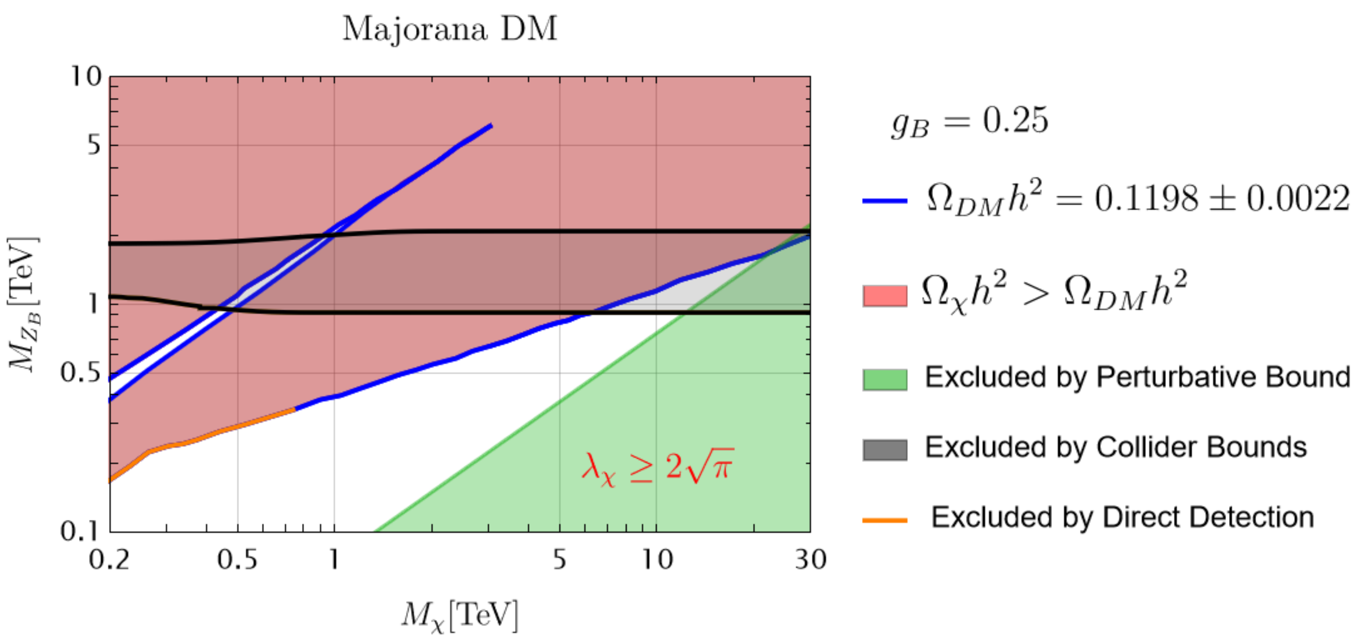
- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

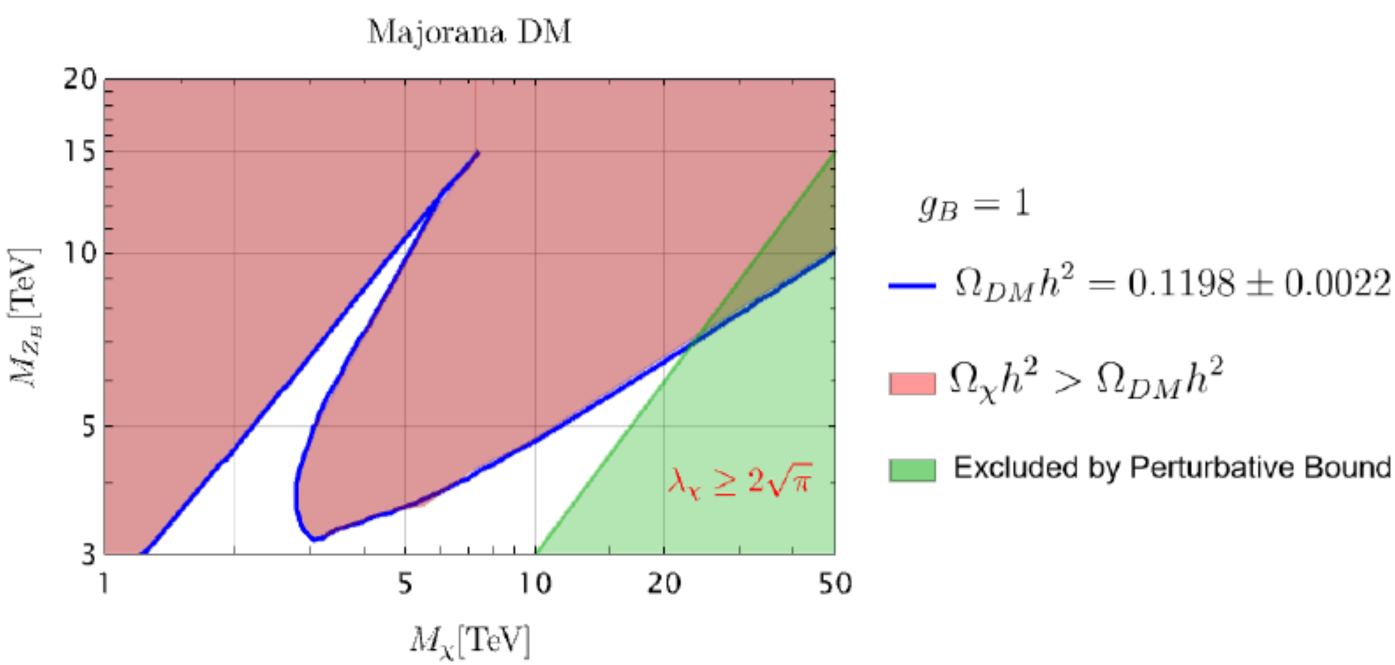
Relic Density



Relic Density

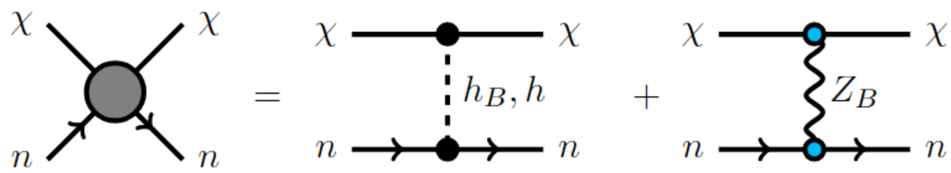
- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

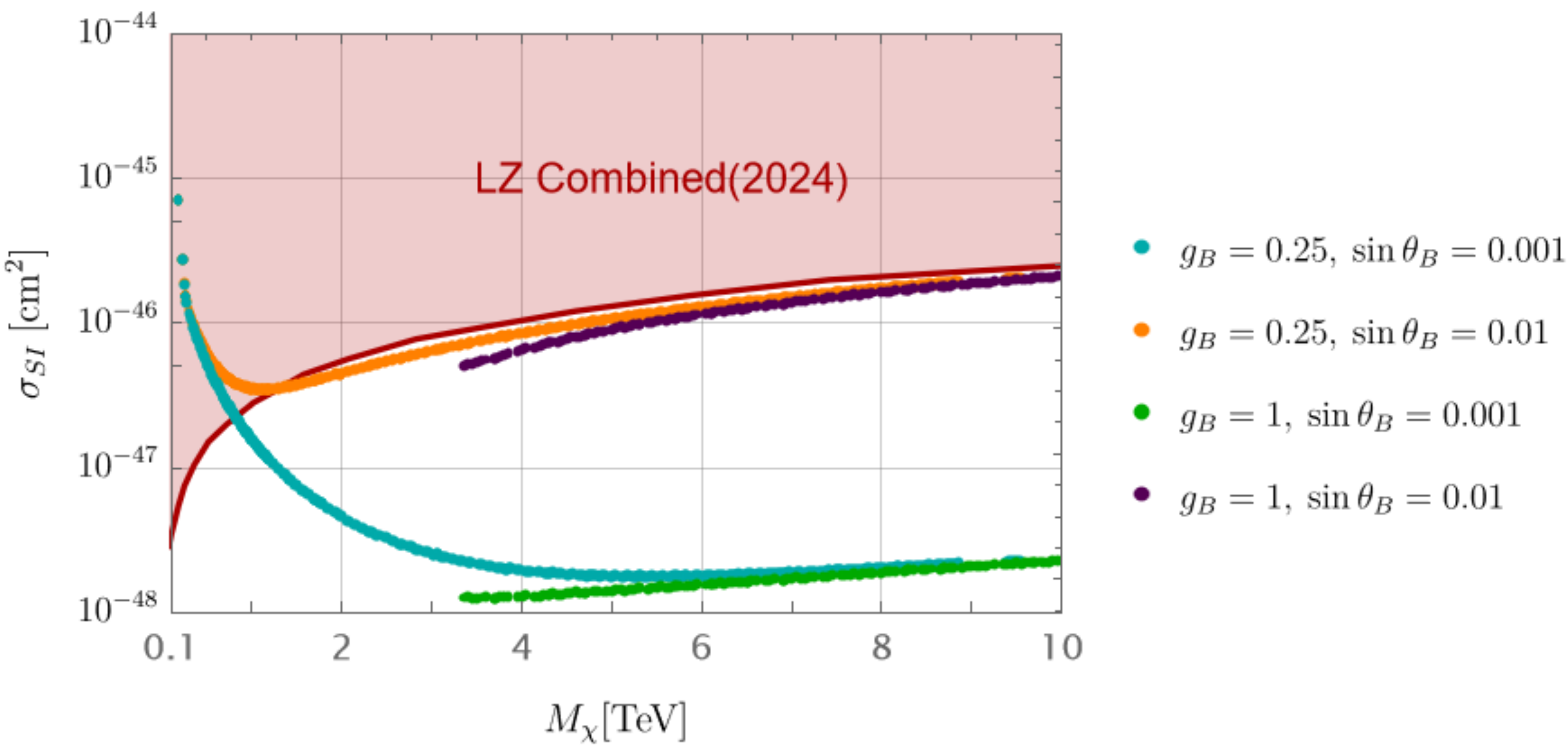




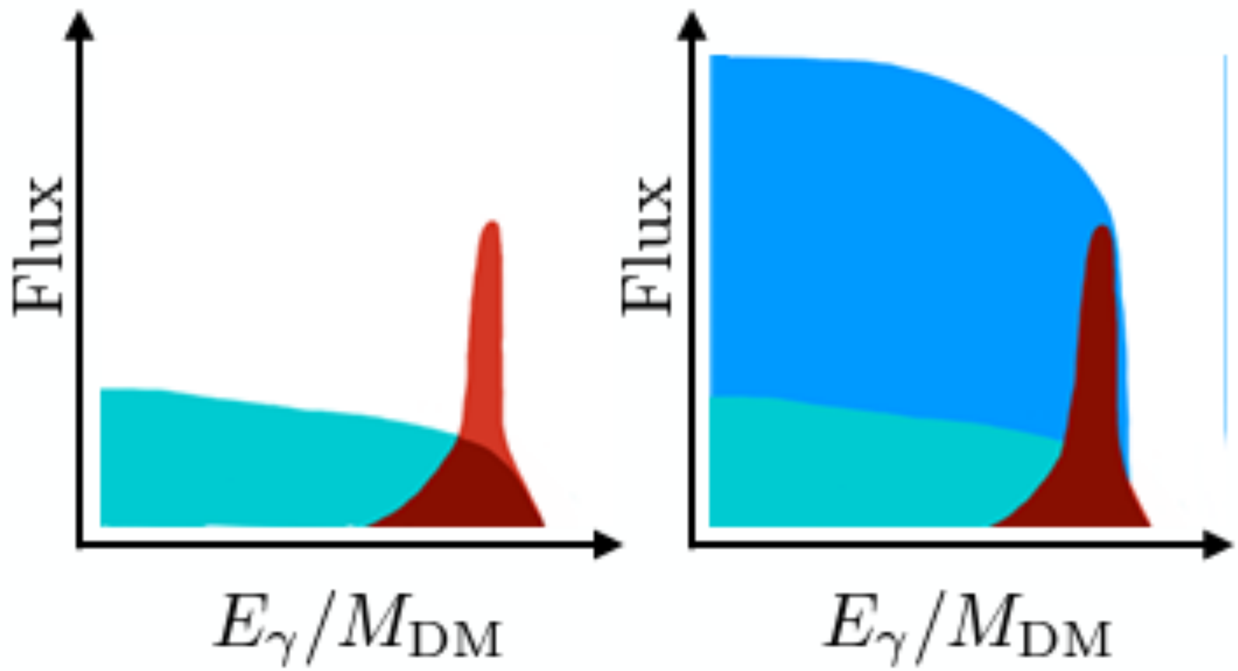
- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

Direct Detection





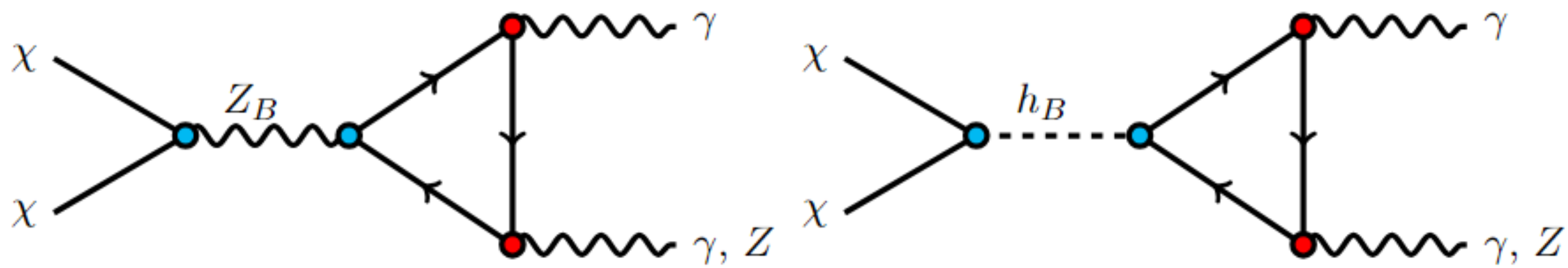
Gamma Lines



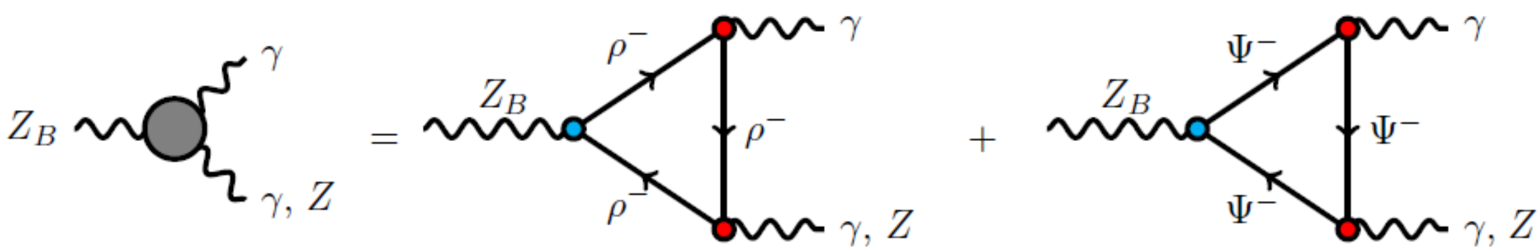
P.F.P., C. Murgui

- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

Gamma Lines

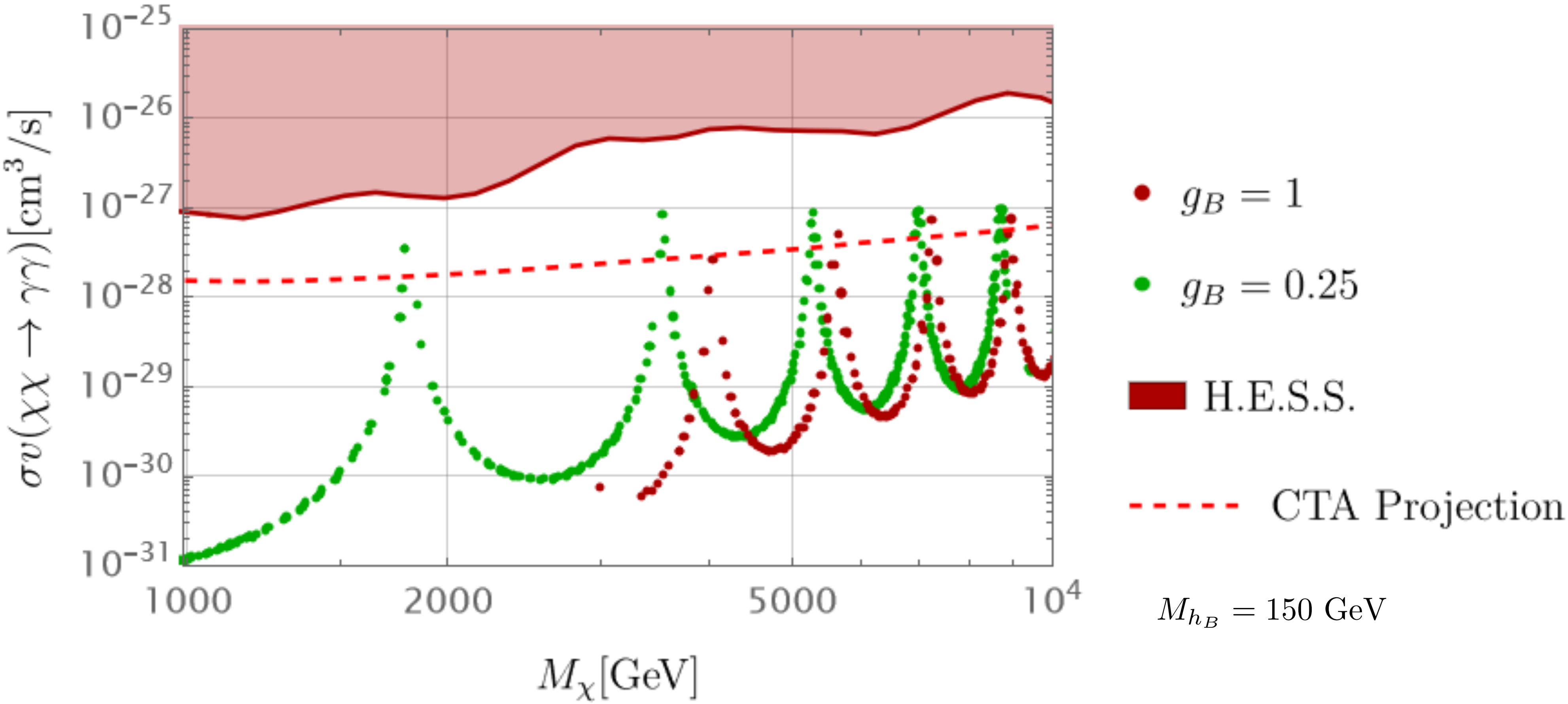


- Effective $Z_B\gamma\gamma$, $Z_B\gamma Z$ couplings:



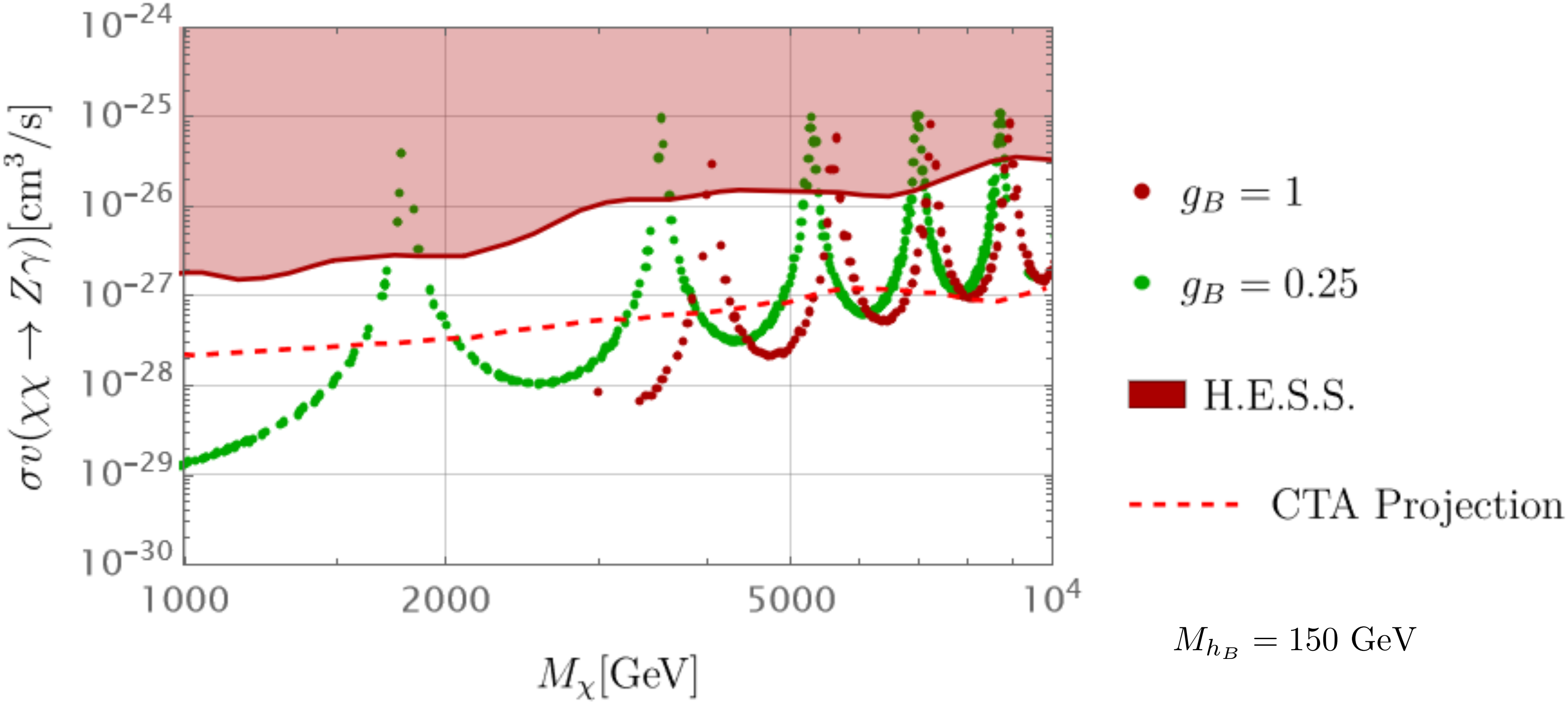
- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

$\chi\chi \to \gamma\gamma$



- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

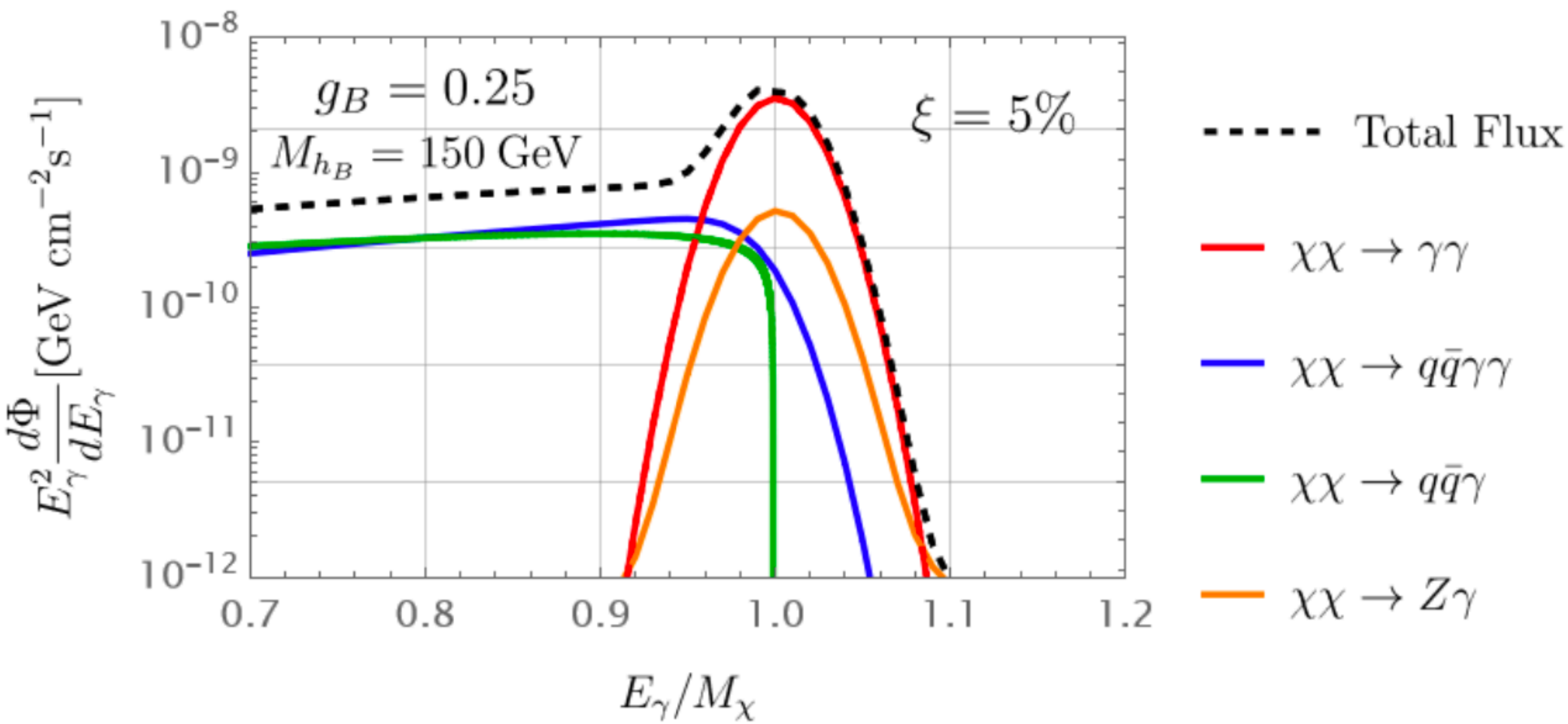
$\chi\chi \to \gamma Z$



$M_{h_B} = 150$ GeV

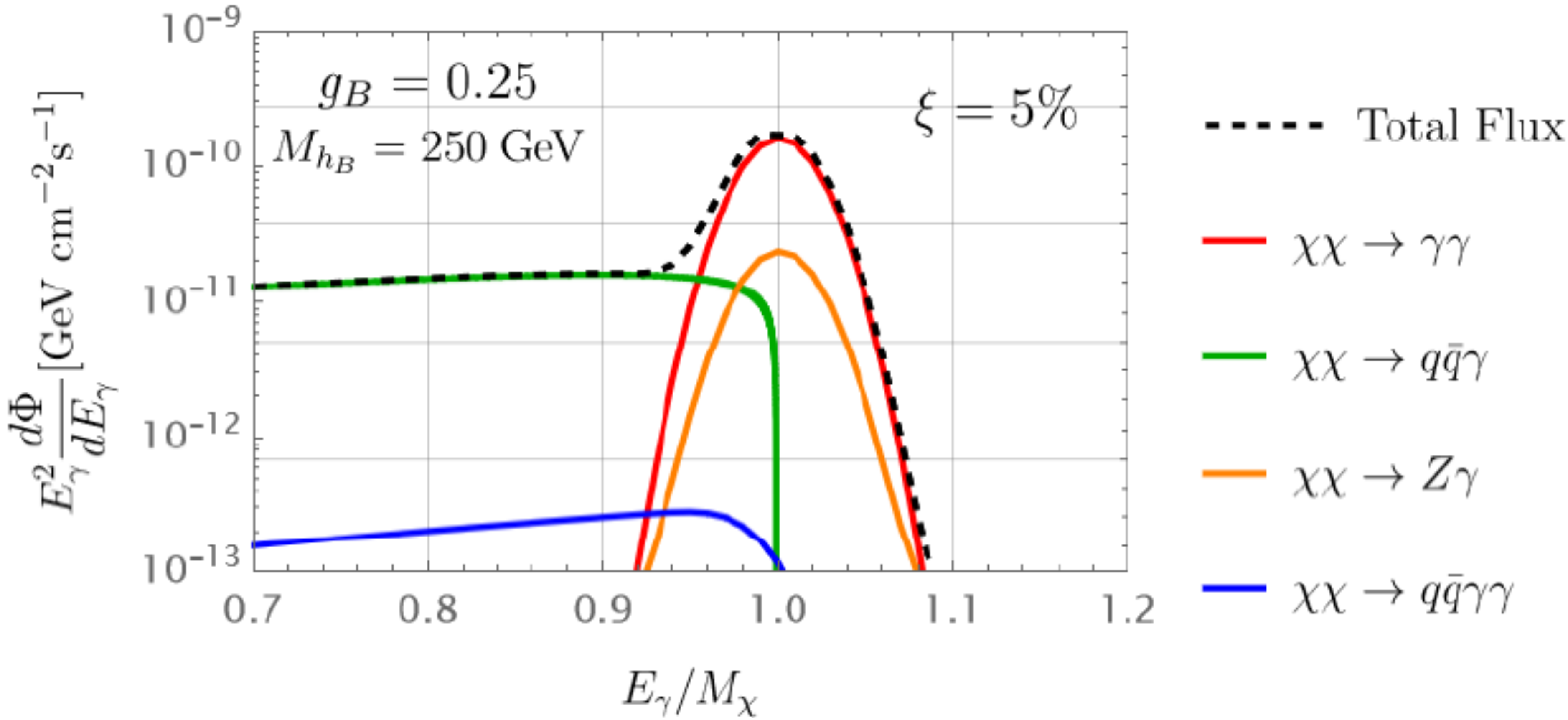
- H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976

Total Flux



- *H. Debnath, P. F. P., K. Gonzalez-Quesada, arXiv:2409.17976*

Total Flux



Collider Signatures

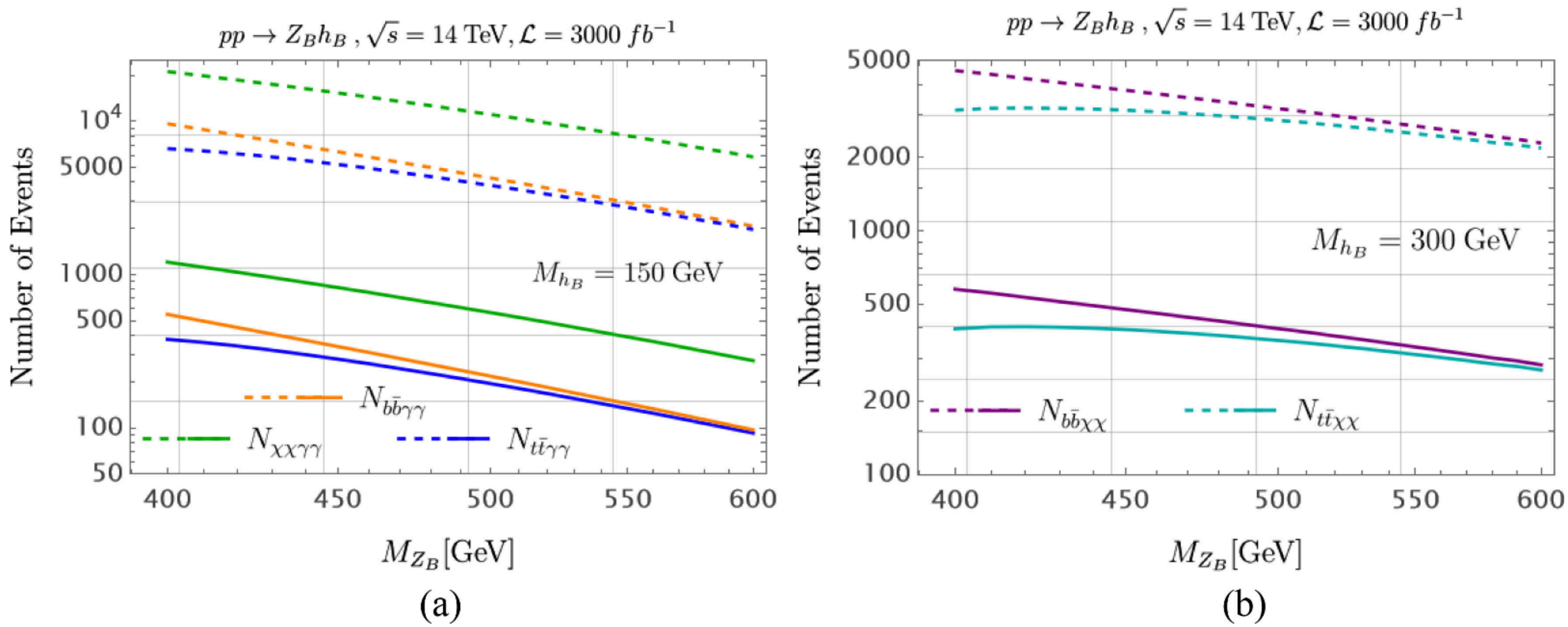


FIG. 12. (a) Number of events for different signatures as a function of Z_B mass when $M_{h_B} = 150$ GeV. (b) same as (a), but now $M_{h_B} = 300$ GeV. The solid and dashed lines represent the number of events for $g_B = 0.15$ and $g_B = 0.25$, respectively. Here, we assumed $M_\chi = 100$ GeV, $\sqrt{s} = 14$ TeV, the luminosity is $\mathcal{L} = 3000$ fb^{-1} and used MadGraph5 [68] to compute the cross section for $pp \to Z_B h_B$.

- J. Butterworth, H. Debnath, P. F. P., Y. Yeh, Physical Review D110, 075001(2024)

Summary

- We discussed theories for physics beyond the Standard Model predicting a dark matter candidate below the multi-TeV scale.

- We discussed theories where the baryon (or lepton) number is a local gauge symmetry broken at the low scale. These theories predict a dark matter candidate from anomaly cancellation. We have shown the constraints from the cosmological bounds on the dark matter relic density, direct detection and collider experiments.

- We have discussed in detail the predictions for gamma lines and show that the predictions could be tested in the near future at gamma-ray telescopes such as CTA.

- There is a hope to test these theories at colliders. In the first case, one has a theory for neutrino masses and dark matter. In the second case, one has a theory for proton stability and dark matter.