

On Theories of Dark Matter

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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

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

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

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

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

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

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

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)

$$B_\mu \rightarrow \tilde{B}$$

$$W_\mu^3 \rightarrow \tilde{W}$$

$$H_u^0 \rightarrow \tilde{H}_u^0$$

$$H_d^0 \rightarrow \tilde{H}_d^0$$

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

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

$$M = (-1)^{3(B-L)}$$

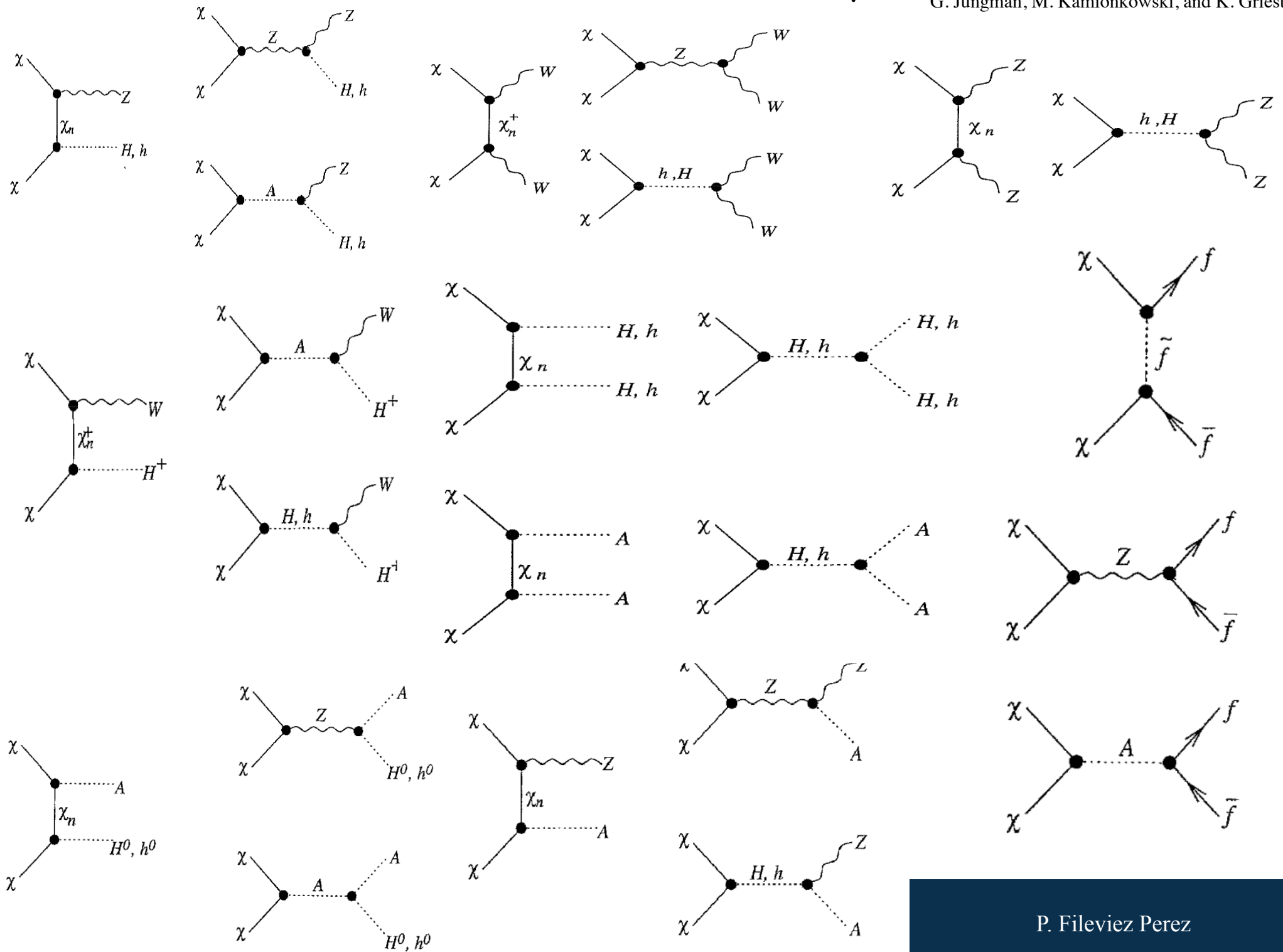


Neutralino DM

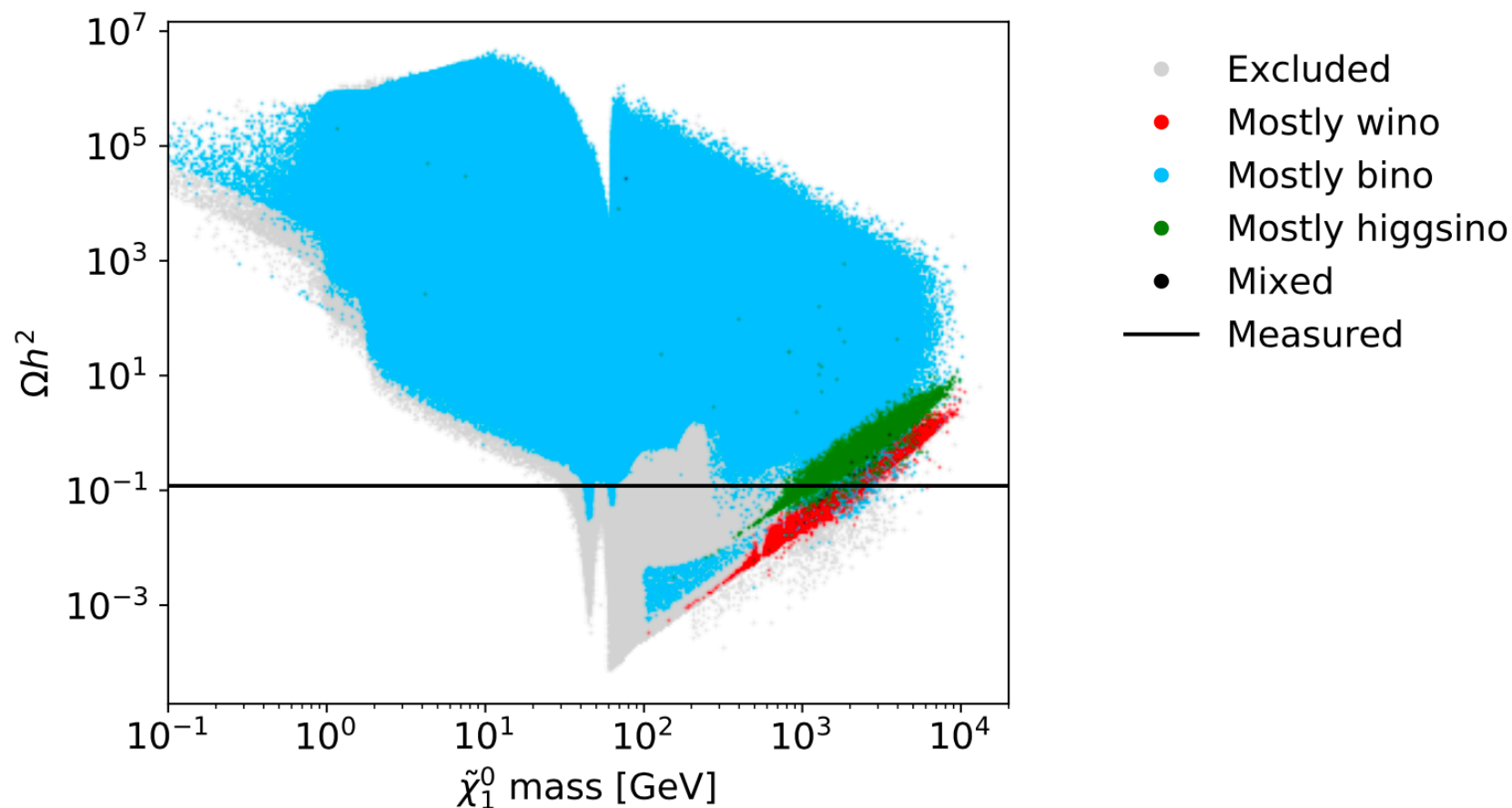
$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \text{SM SM}, \dots$$



$$\Omega_{\tilde{\chi}_1^0} h^2 \leq 0.12$$

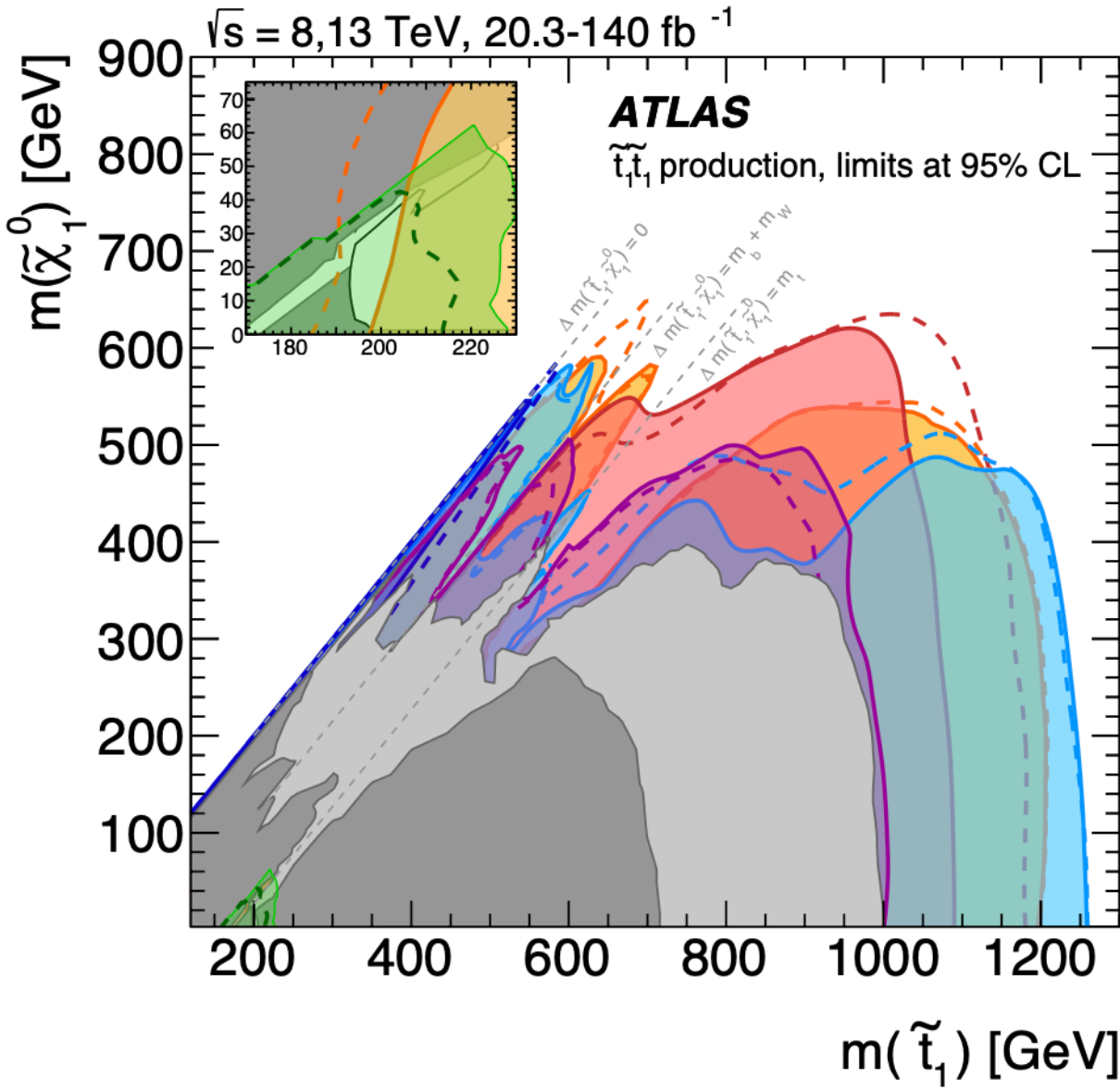


SUSY DM



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>



— Observed limits

- - Expected limits

Data 15-18, $\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$

monojet, $\tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[2102.10874]

0L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[2004.14060]

1L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[2012.03799]

1L NN, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$

[ATLAS-CONF-2023-043]

2L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[2102.01444]

Data 15-16, $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$

$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[1709.04183, 1711.11520,

1708.03247, 1711.03301]

$t\bar{t}, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

[1903.07570]

Data 12, $\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\bar{f}'\tilde{\chi}_1^0$

[1506.08616]

Collaborators



Mark B. Wise
(Caltech)



Clara Murgui
(CERN)



Hridoy Debnath
(CWRU)



Kevin Gonzalez-Quesada
(CWRU)



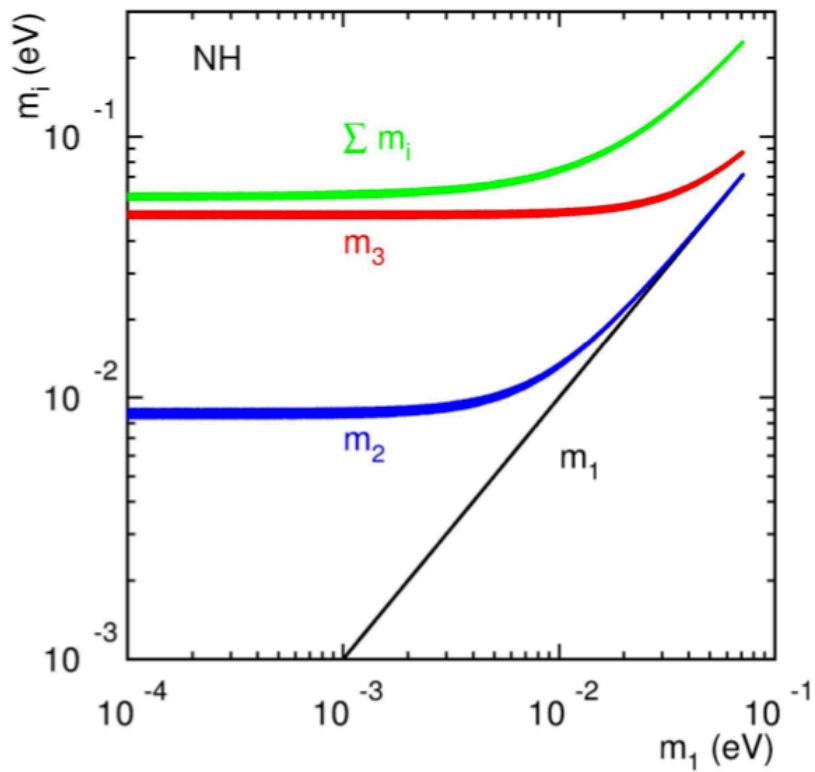
J. Butterworth
(UCL)

*Dark Matter
and
Neutrino Masses*

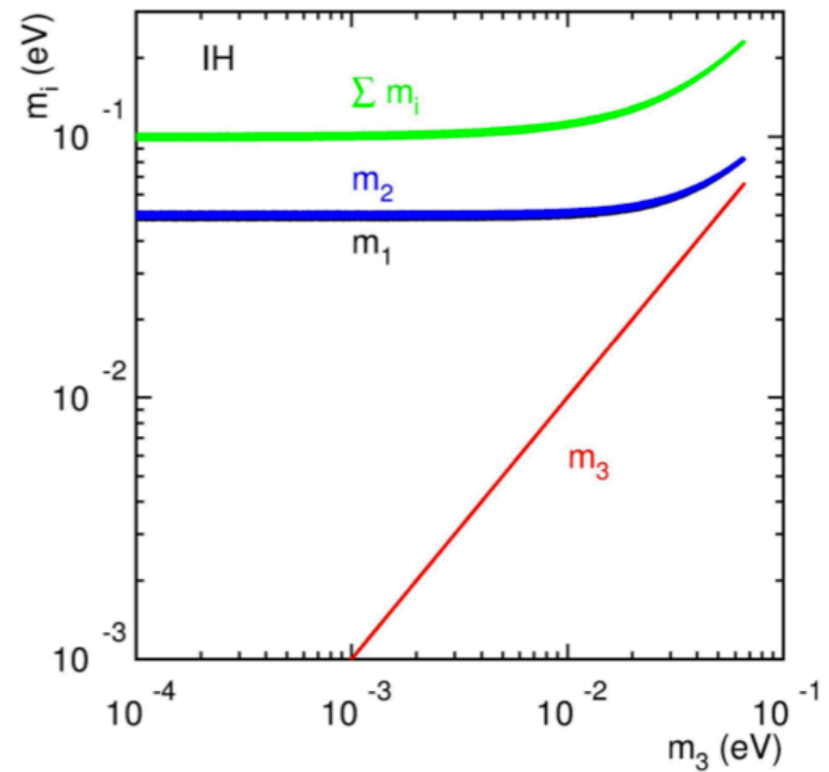
Massive Neutrinos

Normal Hierarchy

Inverted Hierarchy



(a)



(b)

Massive Neutrinos

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

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

- 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

$$\int d^3x \frac{1}{2} \bar{\nu}_L^T C M_M \nu_L$$

Mechanics:

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

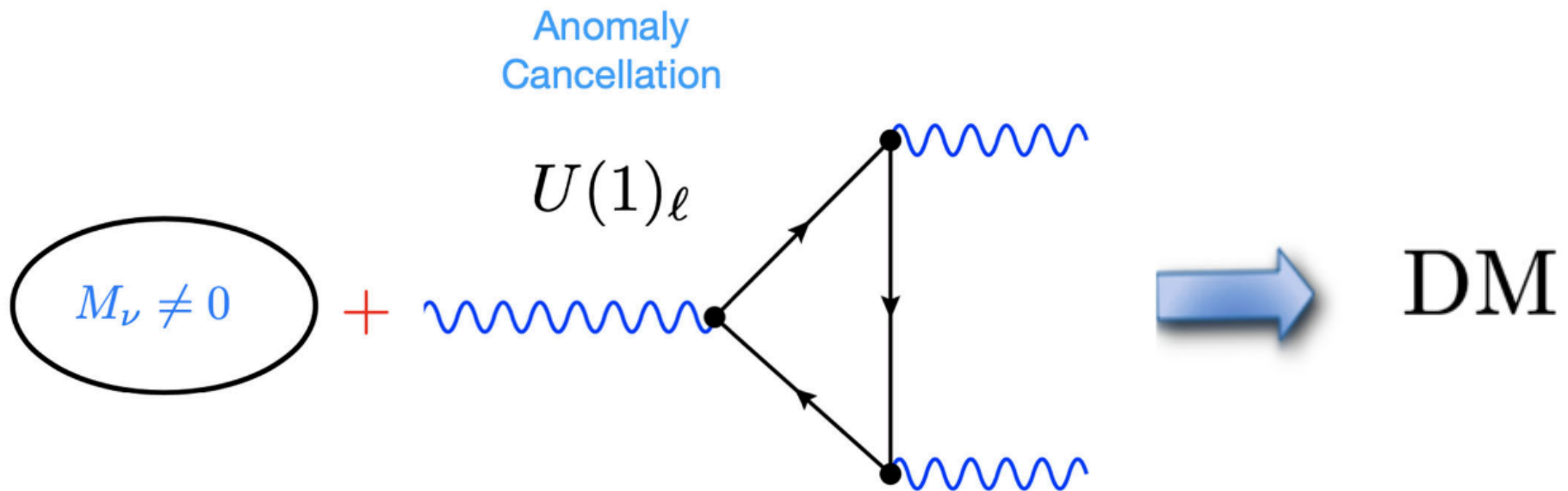
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Theories:

- B-L
- Left-Right Symmetry
- **Pati-Salam**
- GUTs
-

Lepton Number as Local Gauge Symmetry



$$\Omega_{DM} h^2 \leq 0.12$$



Low Scale Seesaw

Lepton Number as Local Gauge Symmetry

Anomaly Cancellation:

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

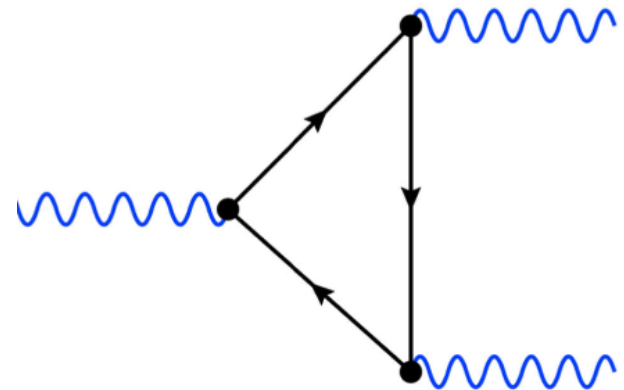
$$\mathcal{A}_1(SU(3)_C^2 U(1)_\ell) = 0,$$

$$\mathcal{A}_2(SU(2)_L^2 U(1)_\ell) = 3/2,$$

$$\mathcal{A}_3(U(1)_Y^2 U(1)_\ell) = -3/2,$$

$$\mathcal{A}_4(U(1)_Y U(1)_\ell^2) = 0,$$

$$\mathcal{A}_5(U(1)_\ell^3) = 3, \quad \text{and} \quad \mathcal{A}_6(U(1)_\ell) = 3.$$



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

$$\ell_1 = -\ell_2 = -3/2 \quad (\text{Majorana DM})$$

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



$$\begin{aligned} \mathcal{L} \supset & y_\Psi \bar{\Psi}_L \Psi_R S^* + y_\eta \bar{\eta}_R \eta_L S^* \\ & + y_\chi \bar{\chi}_R \chi_L S^* + \lambda_\chi \chi_L^T C \chi_L S^* + \lambda'_\chi \chi_R^T C \chi_R S + h.c. \end{aligned}$$

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



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

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

Neutrino Masses

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

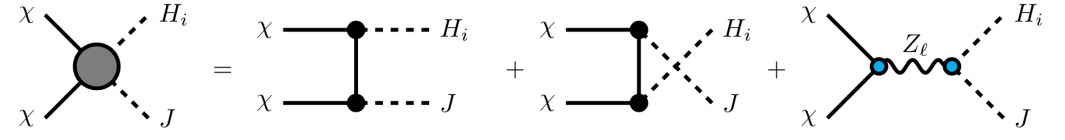
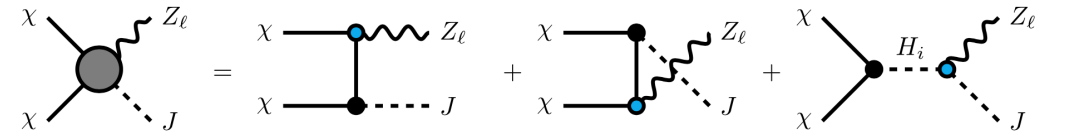
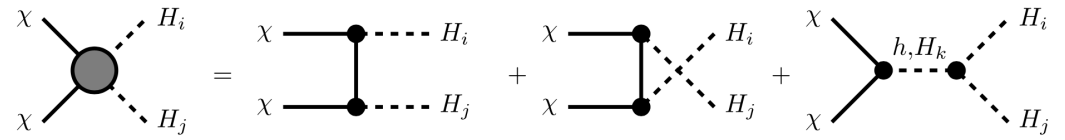
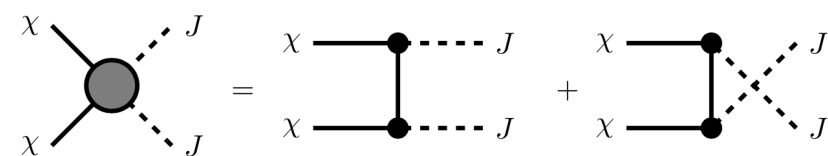
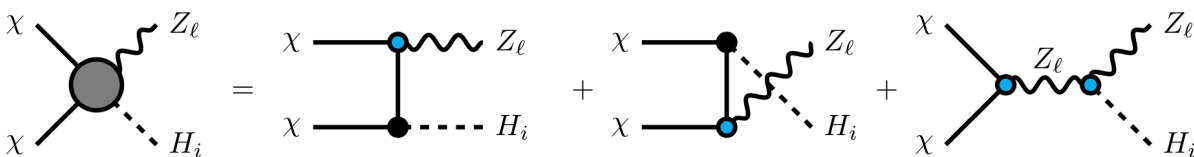
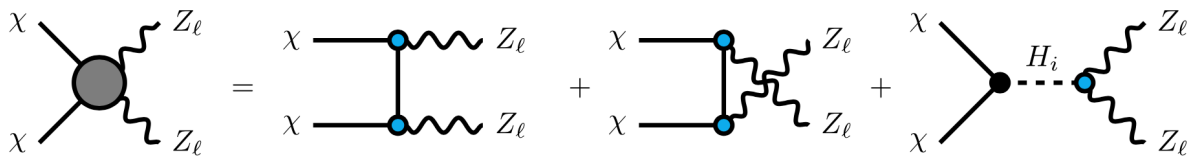
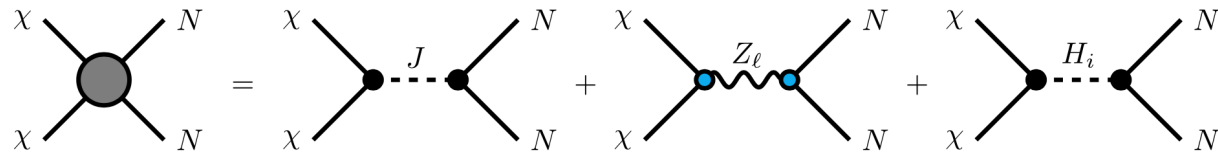
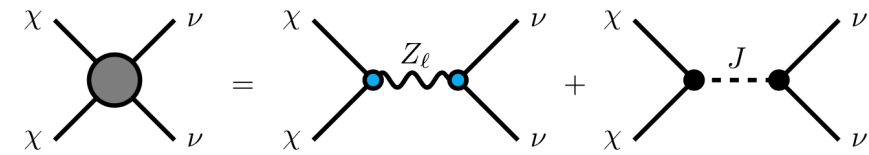
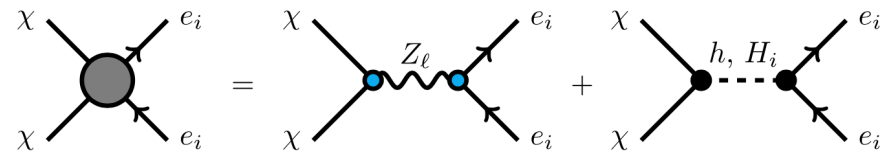
→
$$M_N = \sqrt{2} \lambda_R v_\phi = \frac{\lambda_R}{\sqrt{2}} \frac{M_{Z_\ell}}{g_\ell} \cos \beta.$$

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

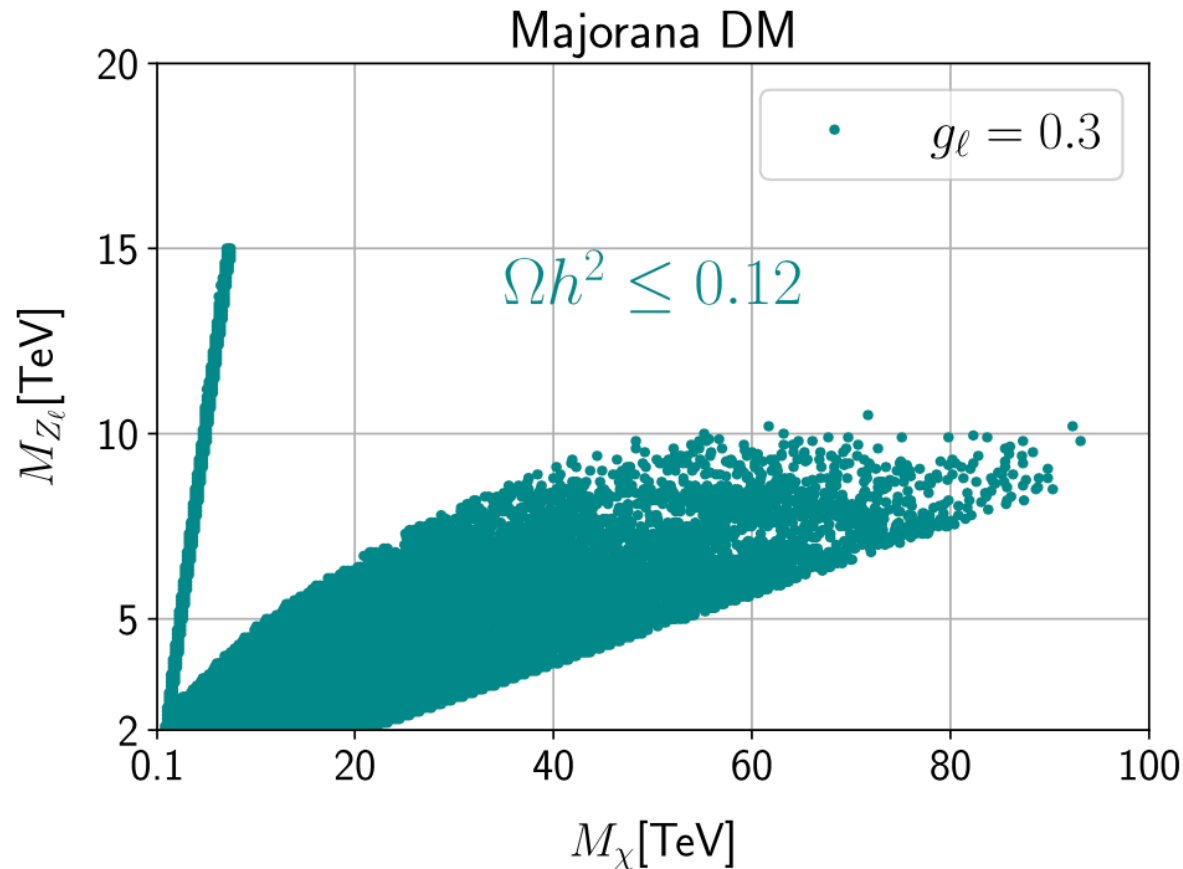
Since the scale for spontaneous L violation must be below the multi-TeV scale one has a **Low Scale Seesaw** !

Dark Matter

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

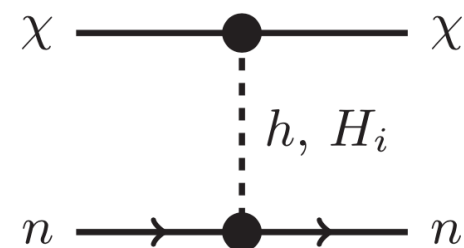
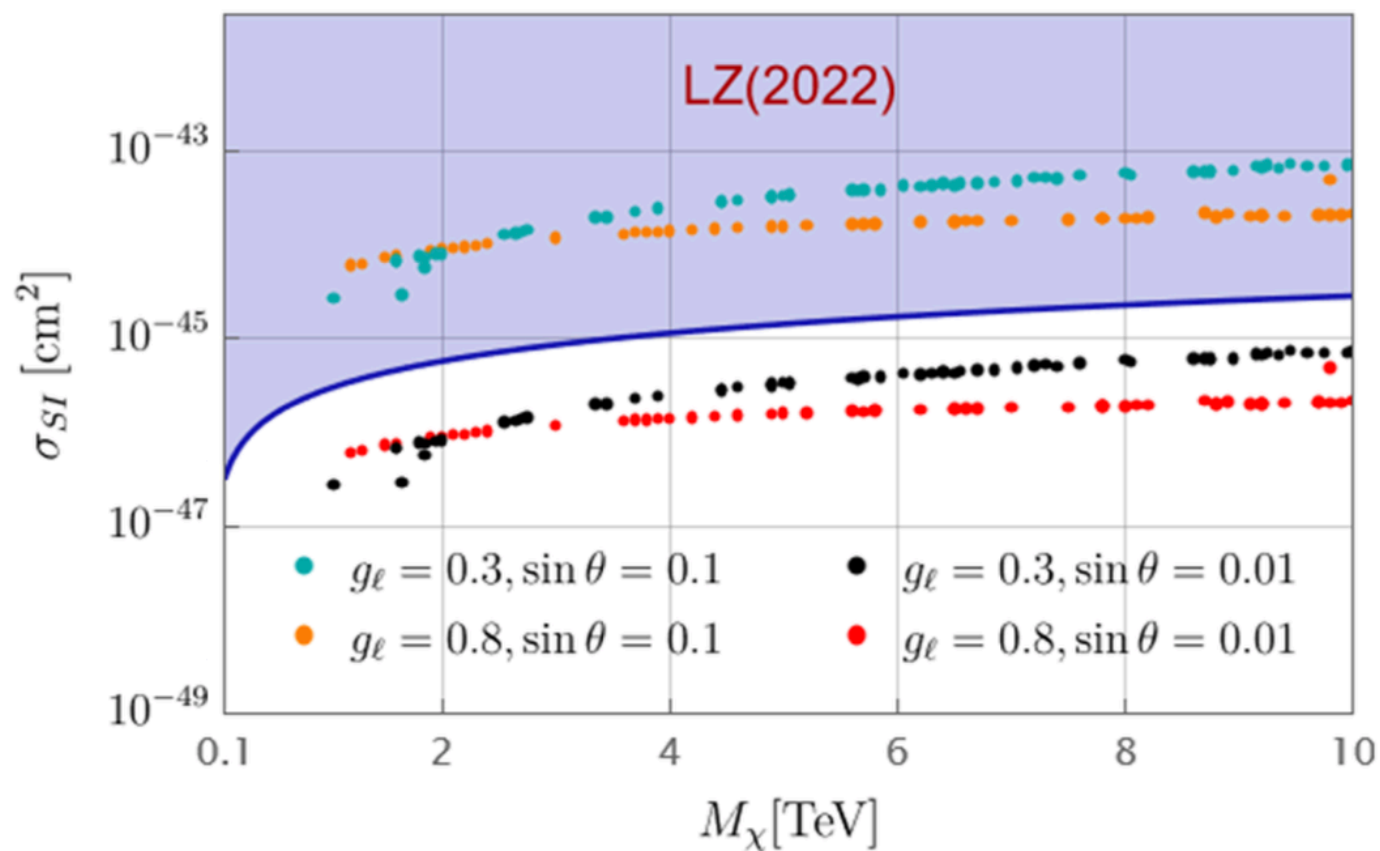


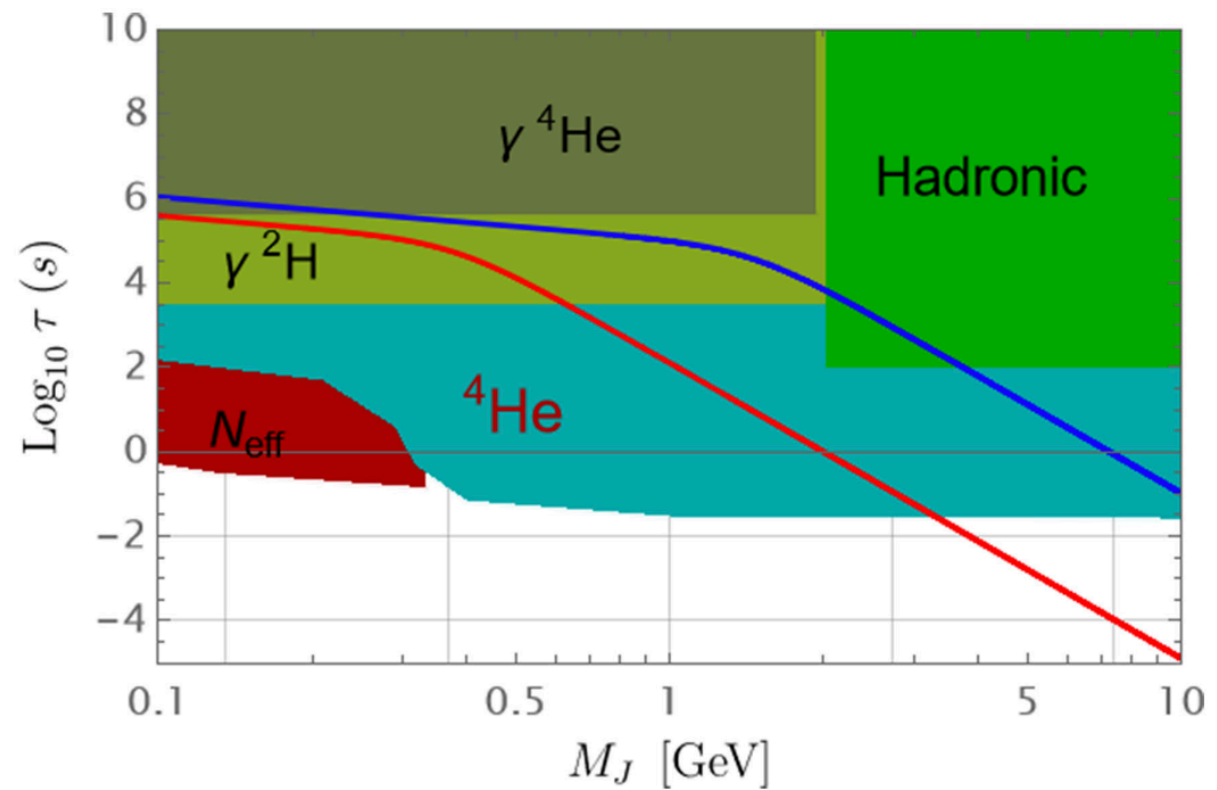
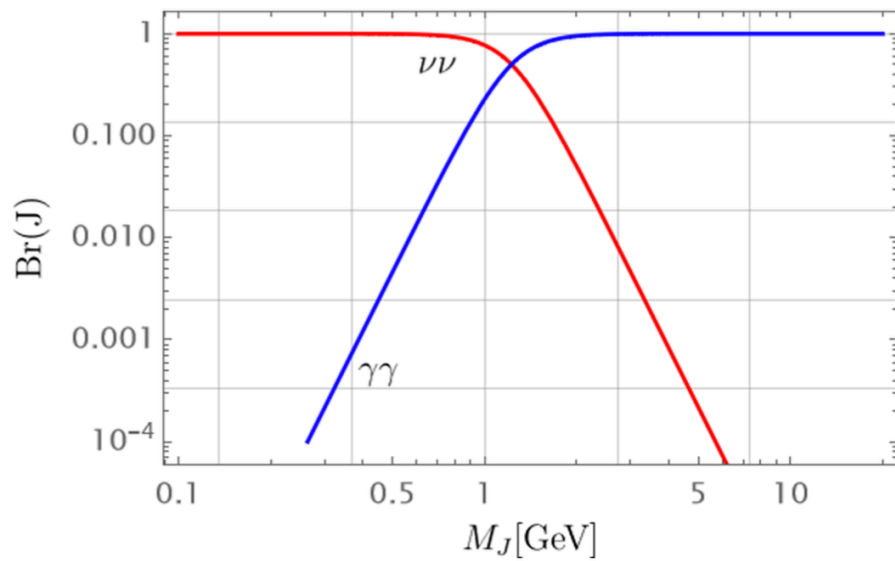
Dark Matter



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

Direct detection:





Minimal Model

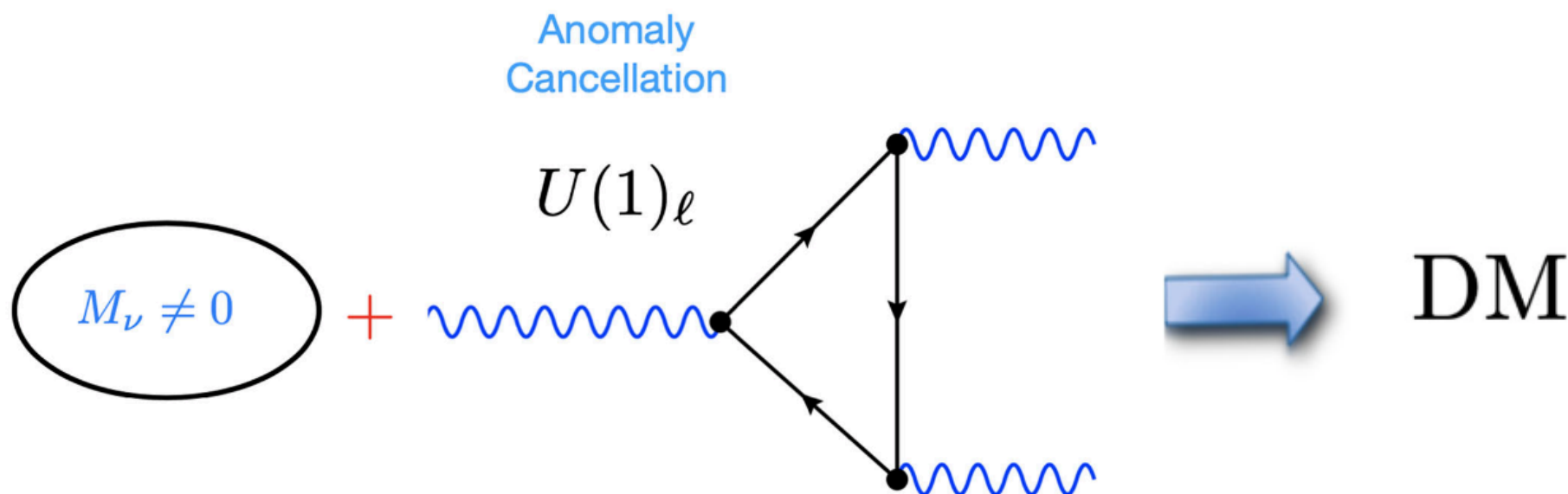
P. F. P., Physical Review D 110, 035018 (2024)

ν_R^i

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

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

Lepton Number as Local Gauge Symmetry



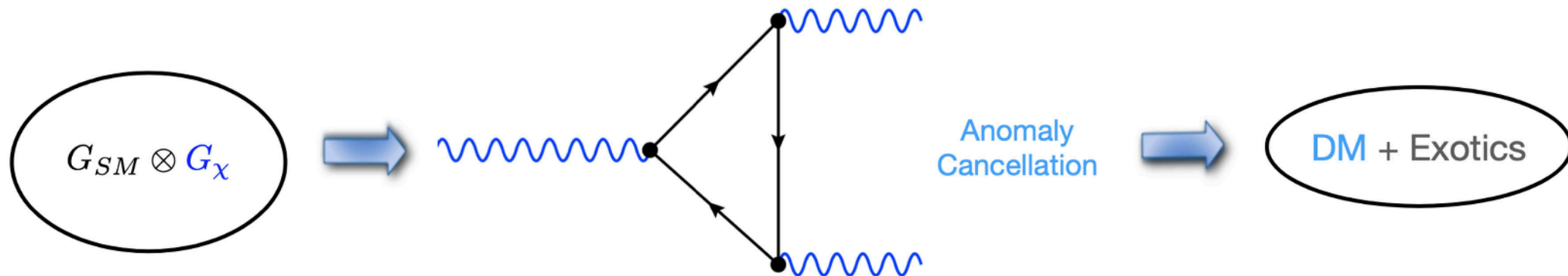
$$\Omega_{DM} h^2 \leq 0.12$$



Low Scale Seesaw

*Dark Matter
and
Baryon Number*

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

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

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

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- 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 !

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

Yukawa interactions:

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

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

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

The Proton is stable

Physical States:

$$\begin{aligned} - M_{Z_B} &= 3g_B v_S / 2 \\ - h &= h_0 \cos \theta_B - h_S \sin \theta_B \\ - h_B &= h_0 \sin \theta_B + h_S \cos \theta_B \end{aligned}$$

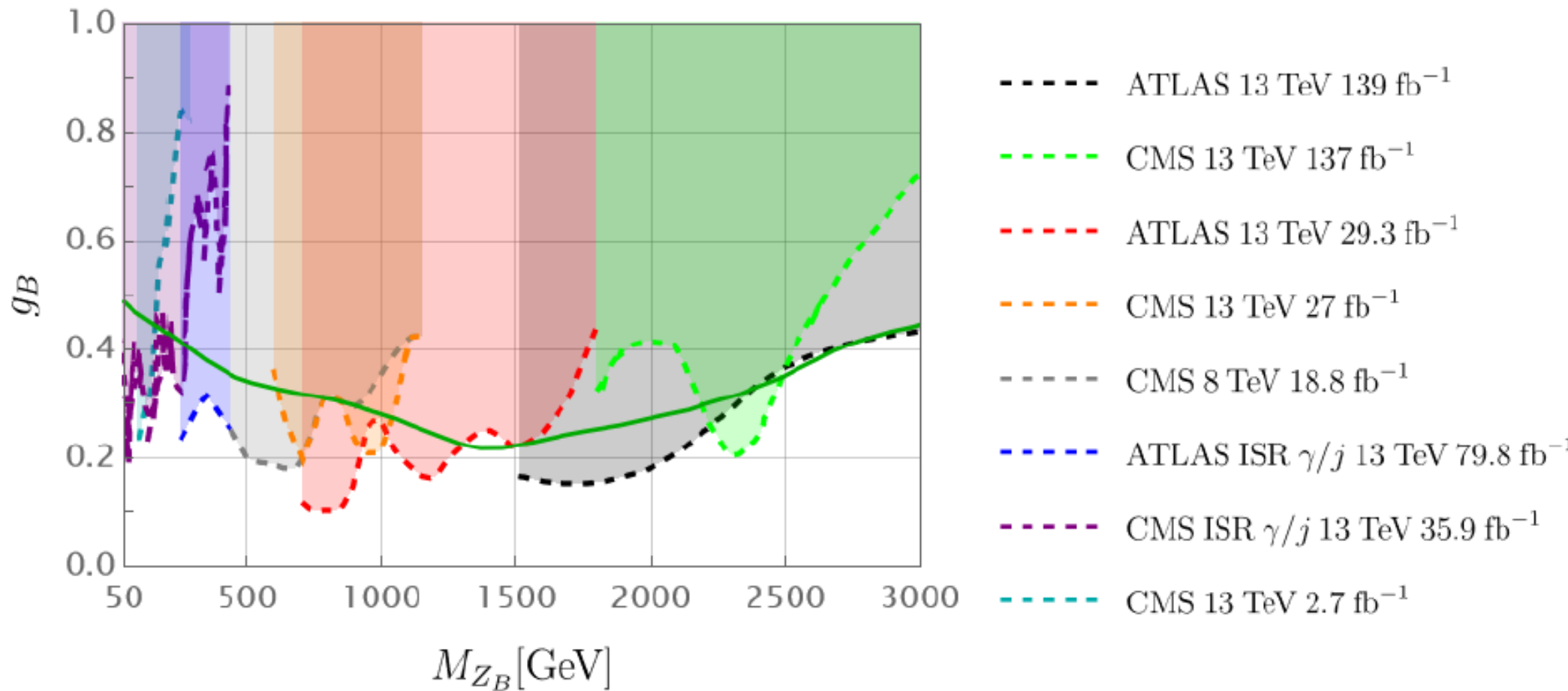
- ϕ is a complex scalar field
- Two Majorana fermionic fields: $\chi = \chi_L + (\chi_L)^C$ and $\rho^0 = \rho_L^0 + (\rho_L^0)^C$ with masses

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

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

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

Collider Bounds



“Cucuyo” Higgs

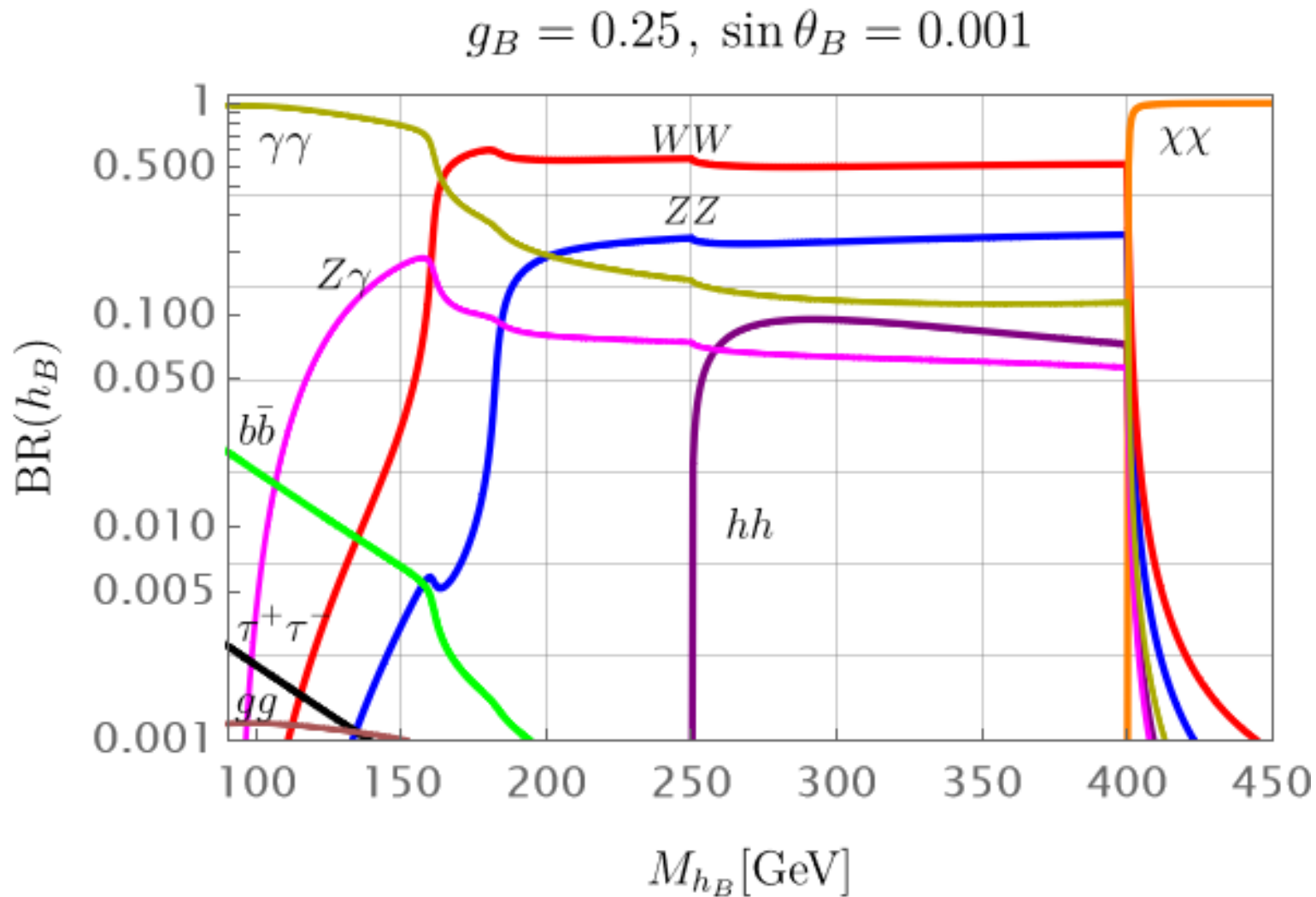
h_B



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.

“Cucuyo” Higgs decays

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



Dark Matter

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

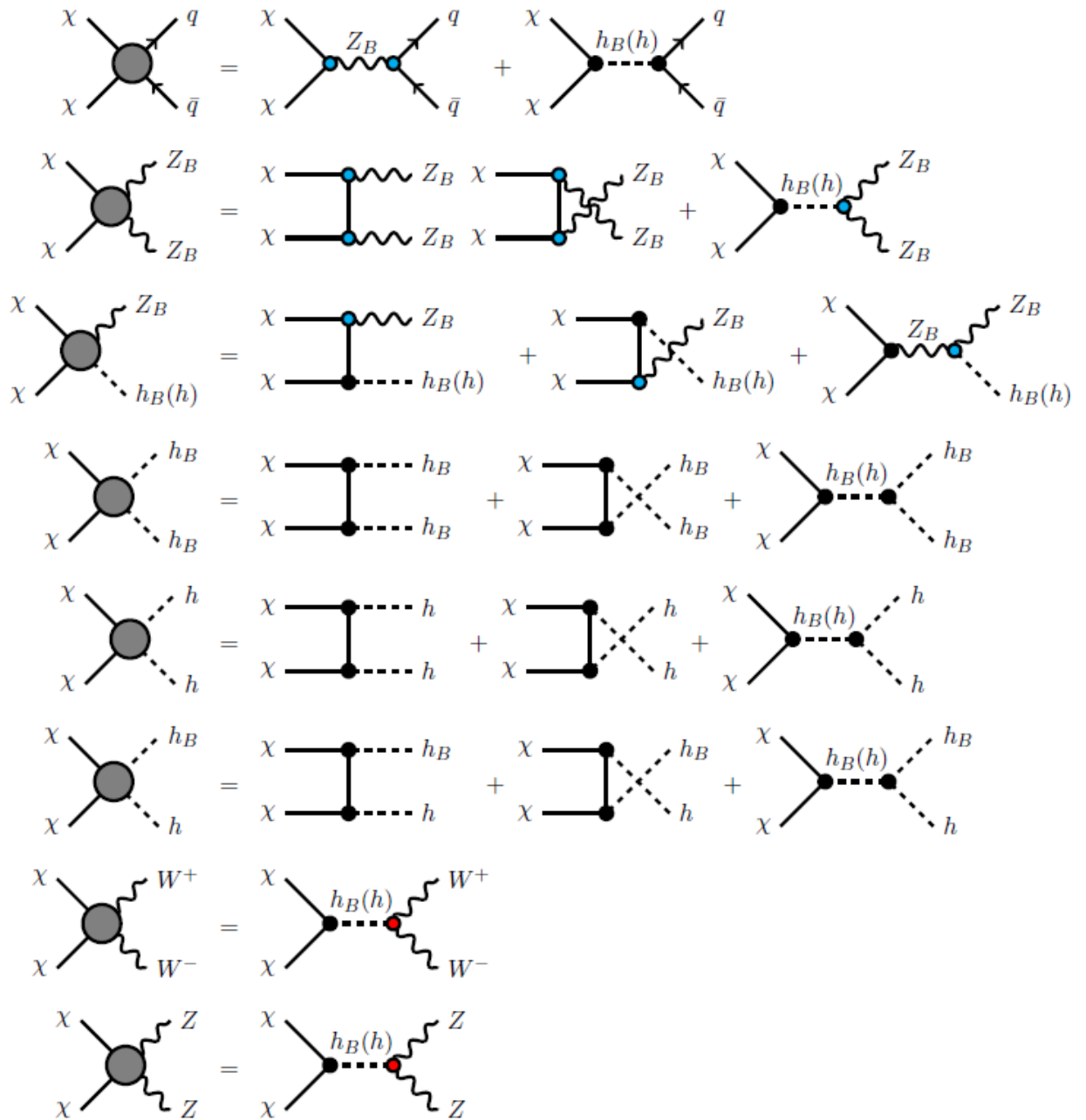
Neutral and Stable

$$\mathbb{Z}_2 : \chi_L \rightarrow -\chi_L, \phi \rightarrow -\phi, \Psi_L \rightarrow -\Psi_L, \Psi_R \rightarrow -\Psi_R, \rho_L \rightarrow -\rho_L$$

More relevant free parameters of the theory:

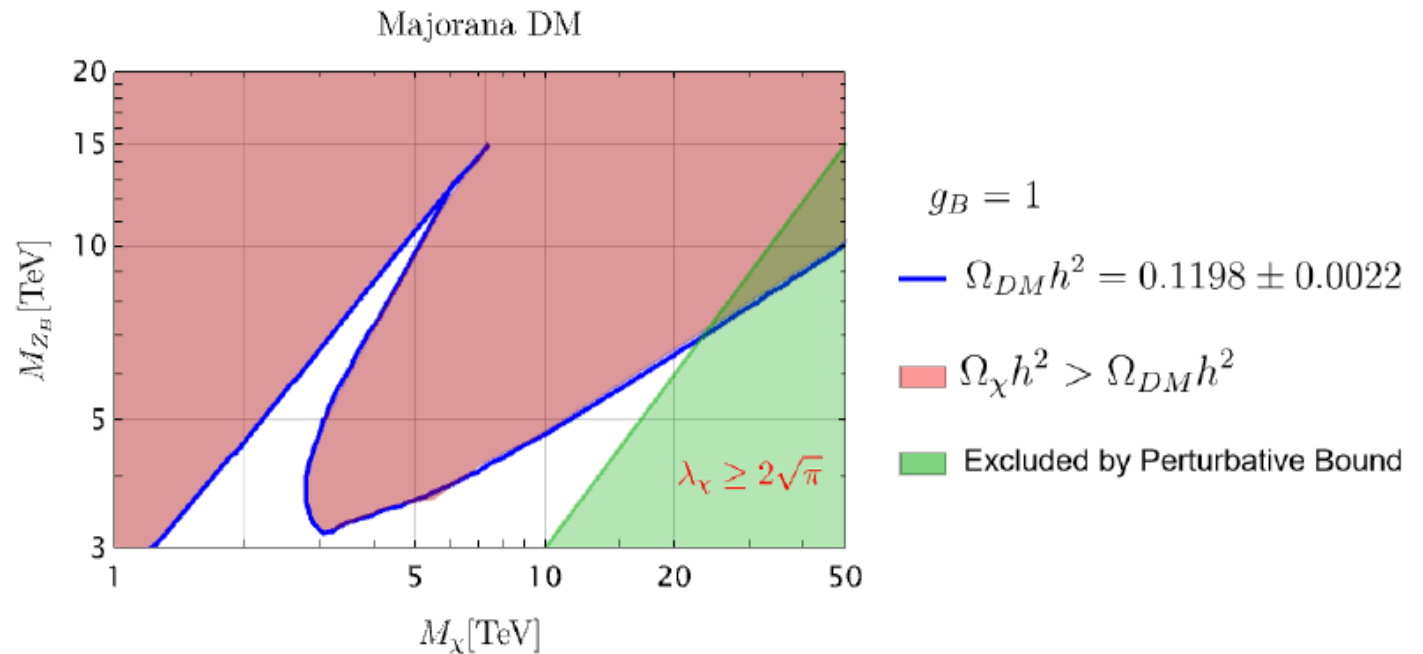
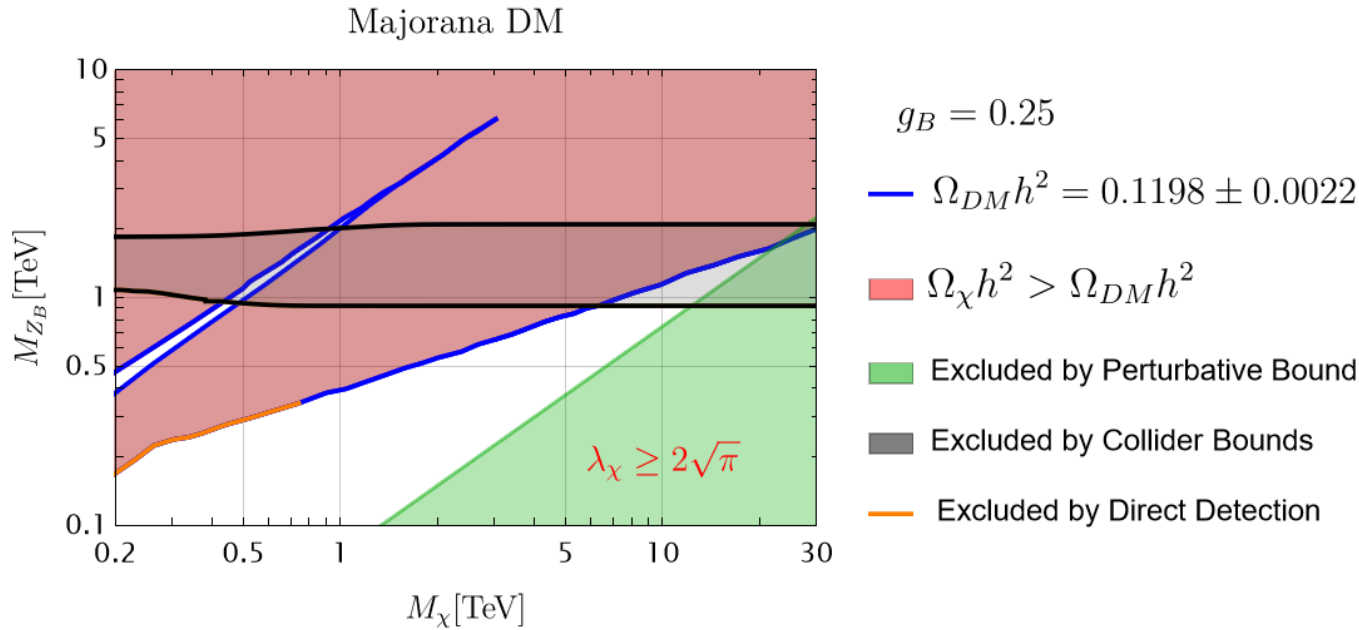
$$g_B, M_\chi, M_{z_B}, M_{h_B} \text{ and } \theta_B.$$

Relic Density

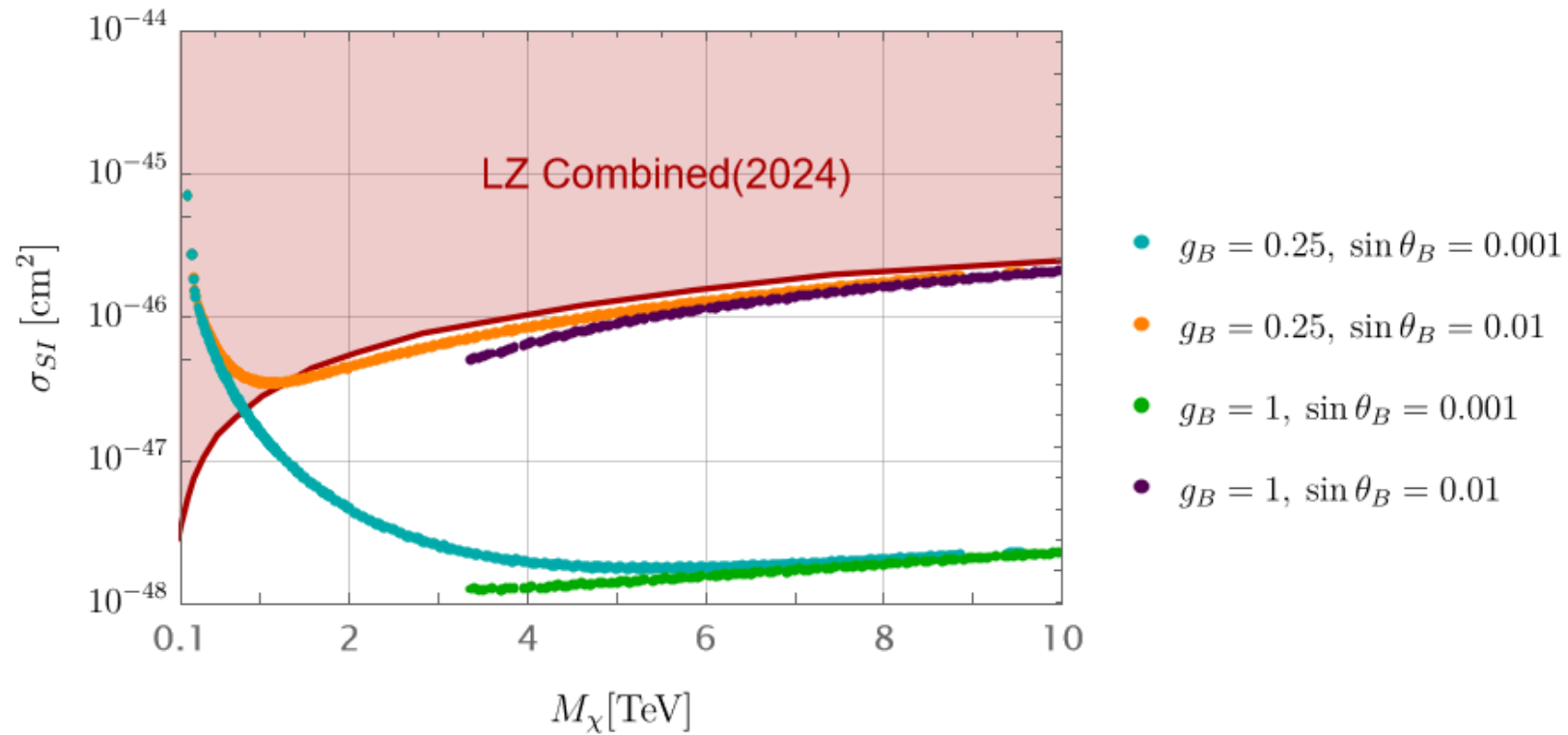
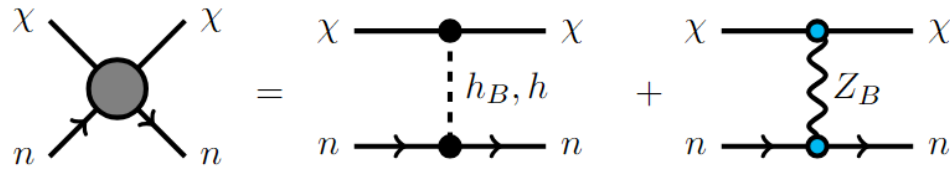


Relic Density

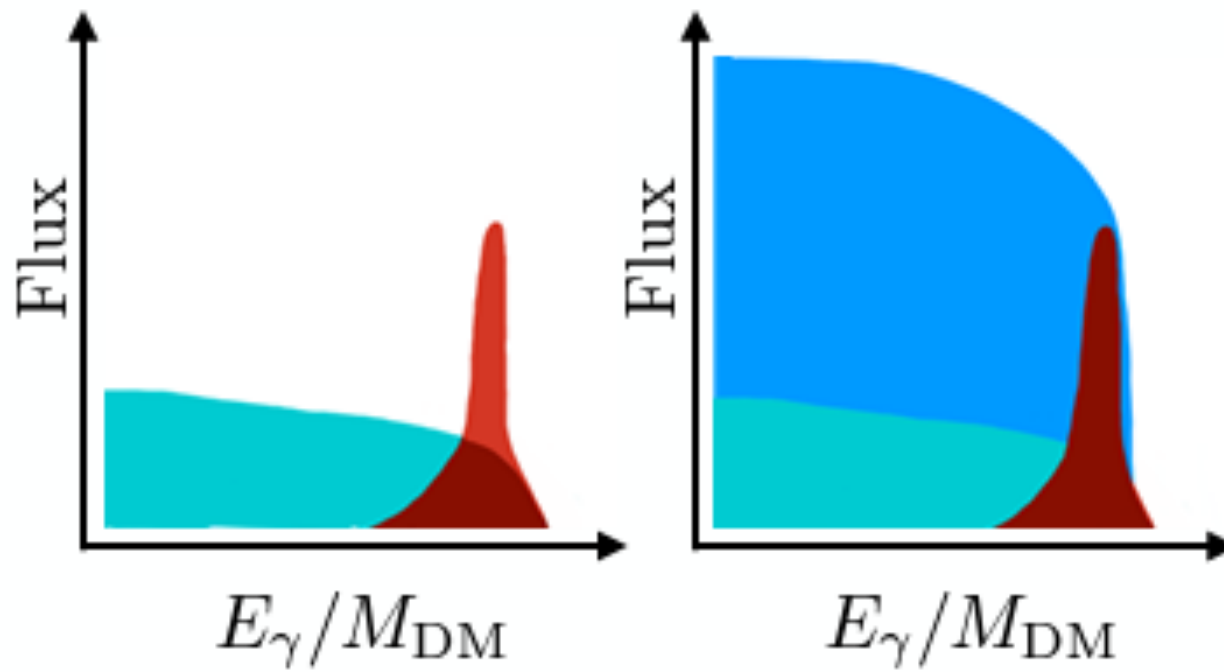
- H. Debnath, P. F. P., K. González-Quesada, [arXiv:2409.17976](#)



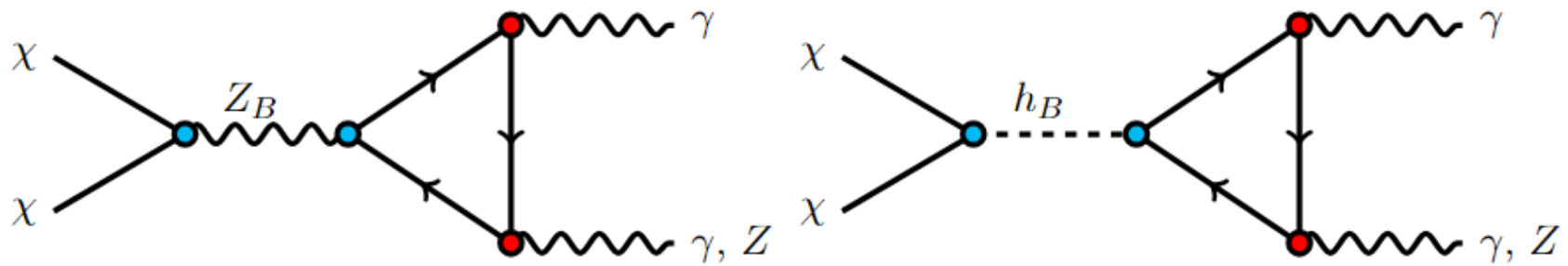
Direct Detection



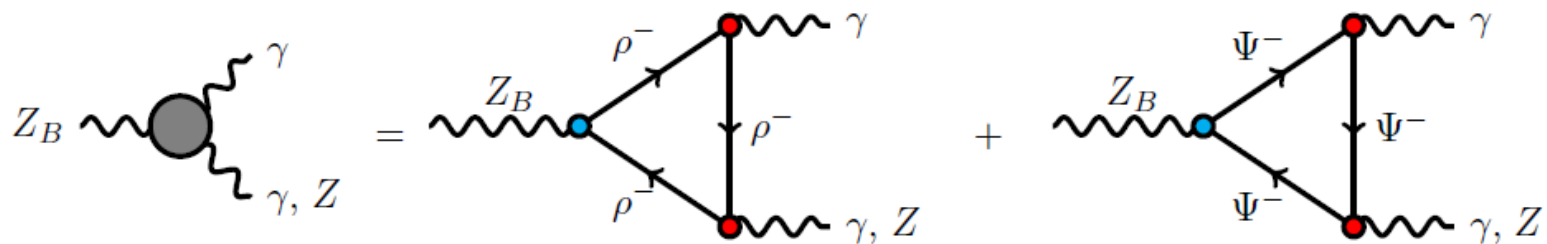
Gamma Lines



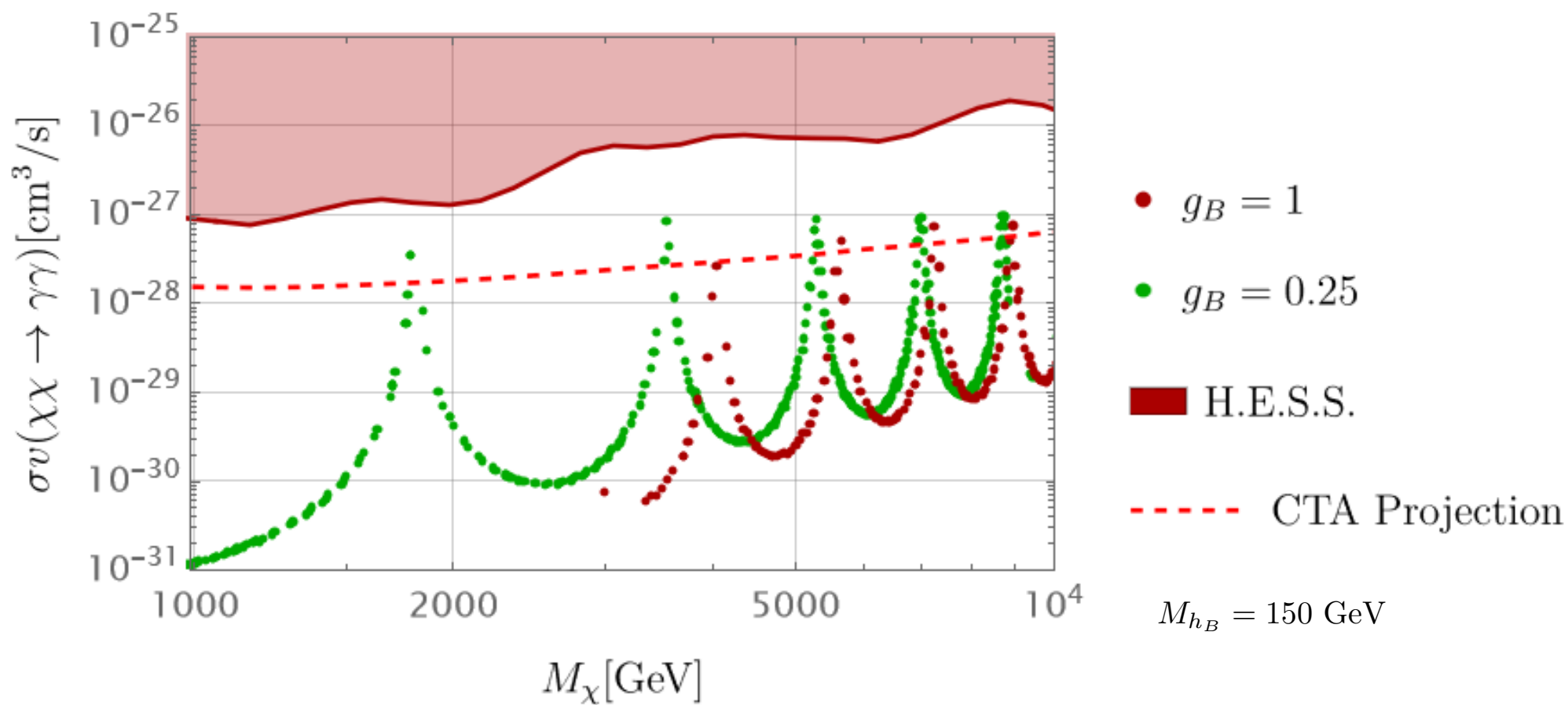
Gamma Lines



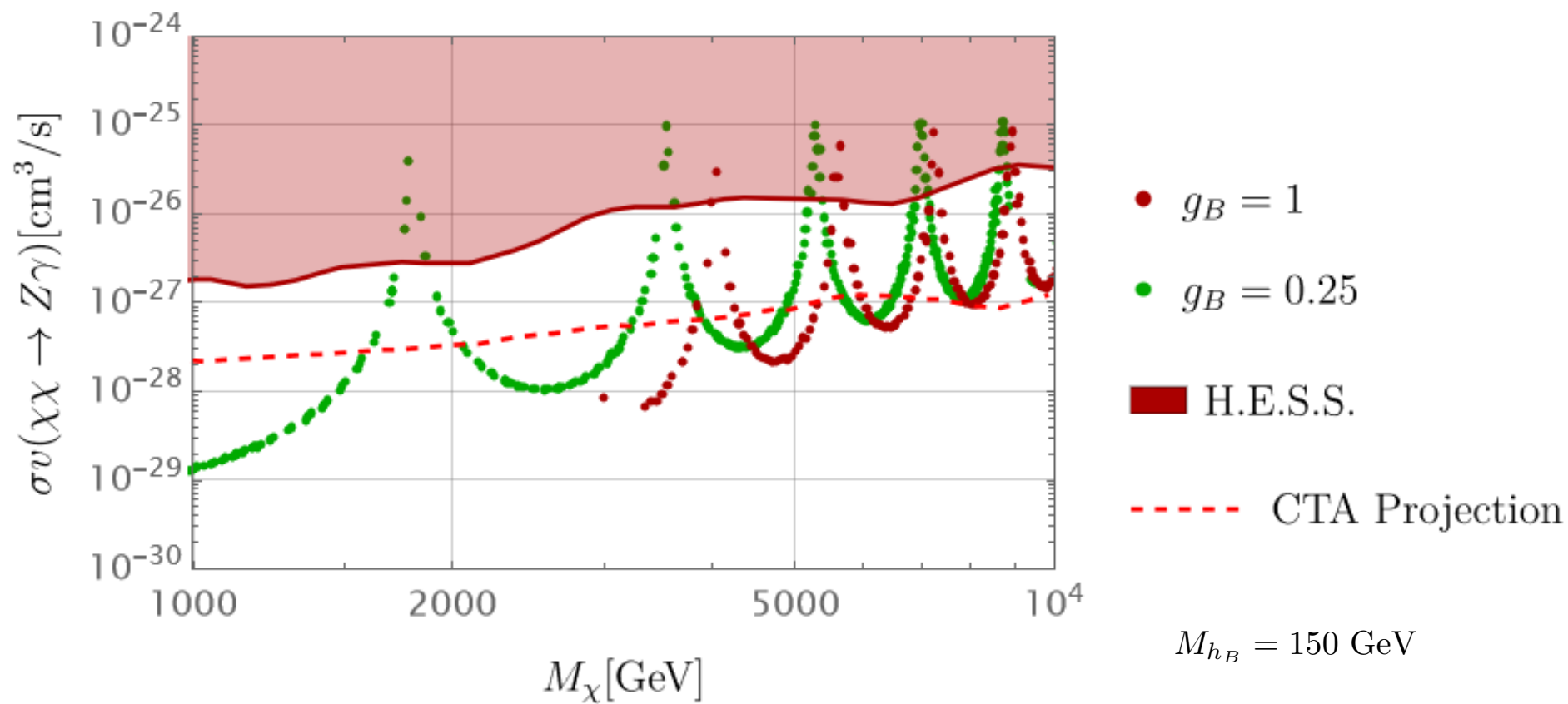
- Effective $Z_B\gamma\gamma$, $Z_B\gamma Z$ couplings:



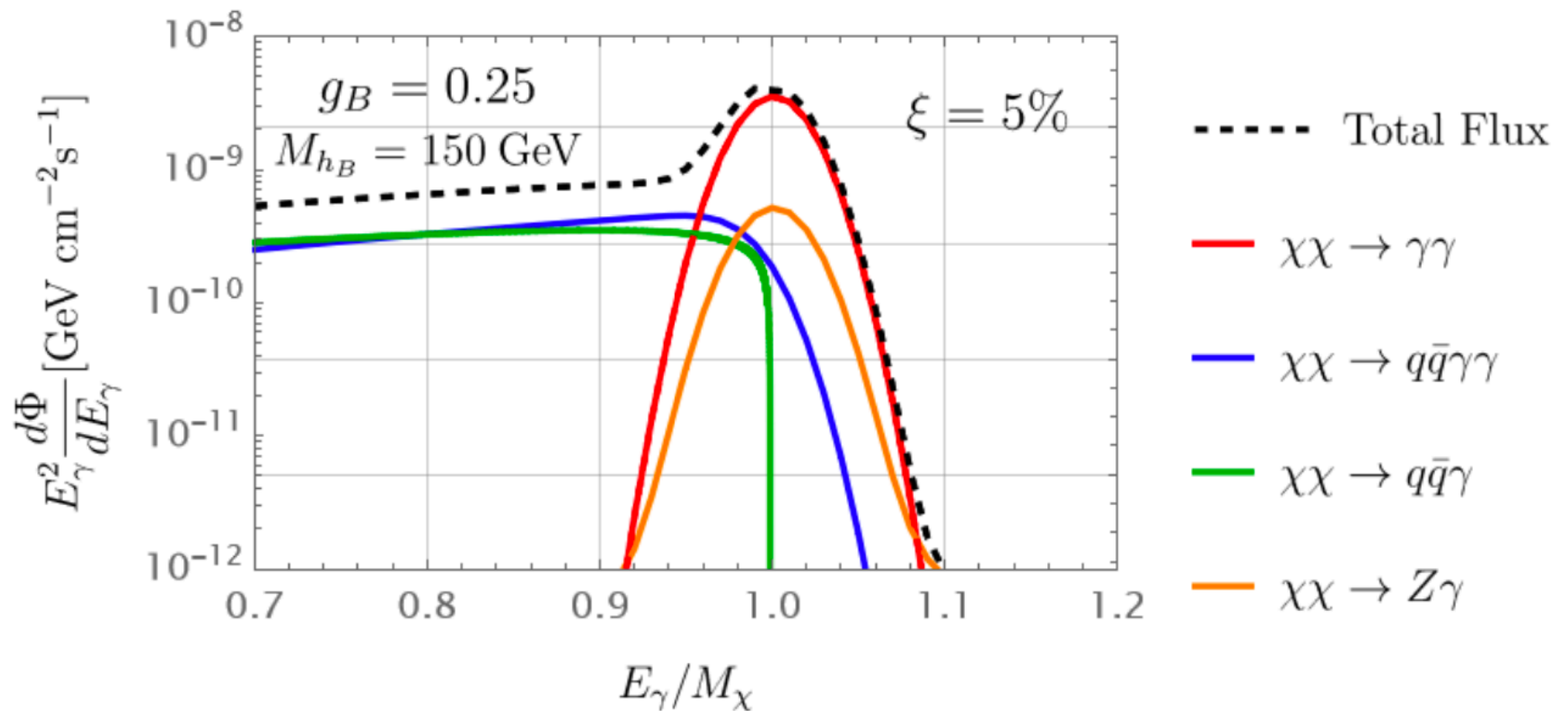
$$\chi\chi \rightarrow \gamma\gamma$$



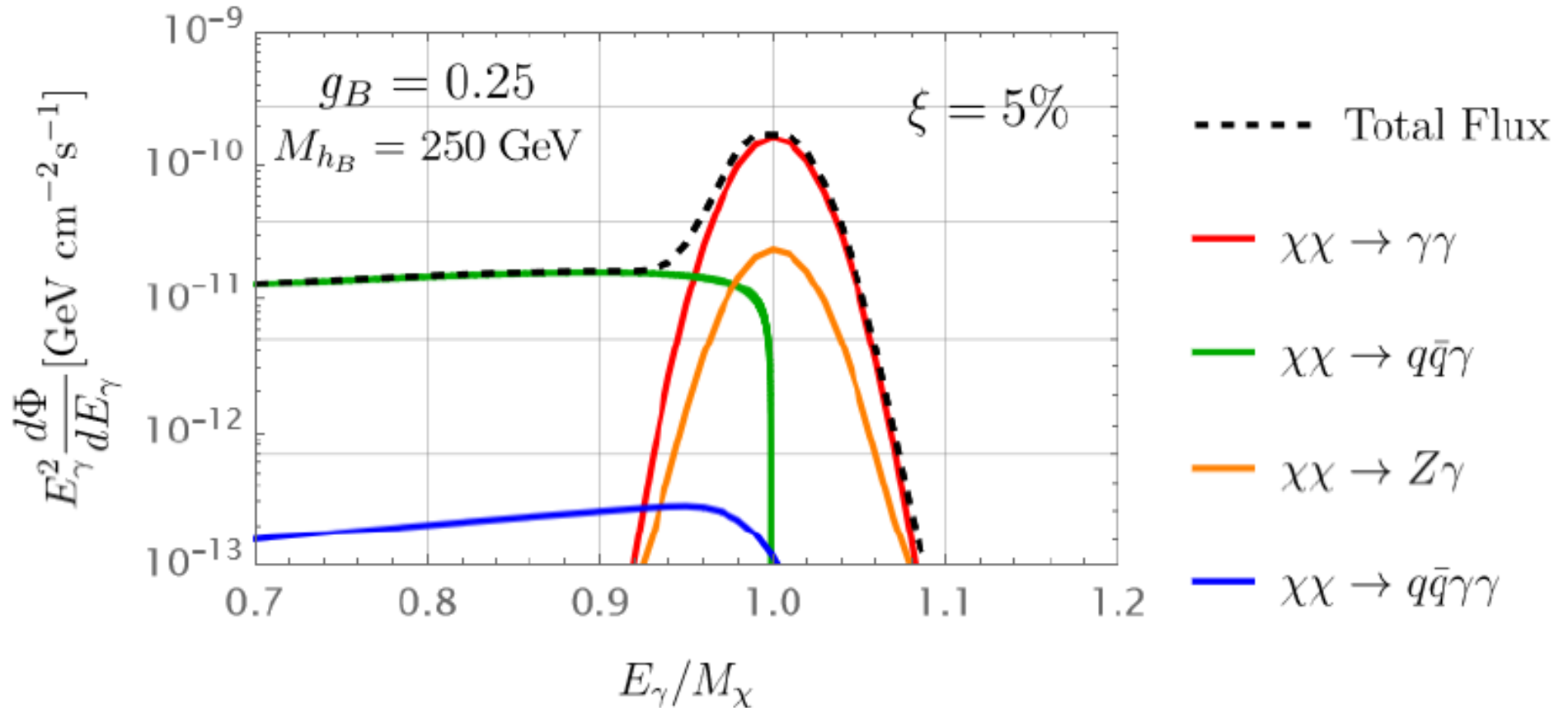
$$\chi\chi \rightarrow \gamma Z$$



Total Flux



Total Flux



Collider Signatures

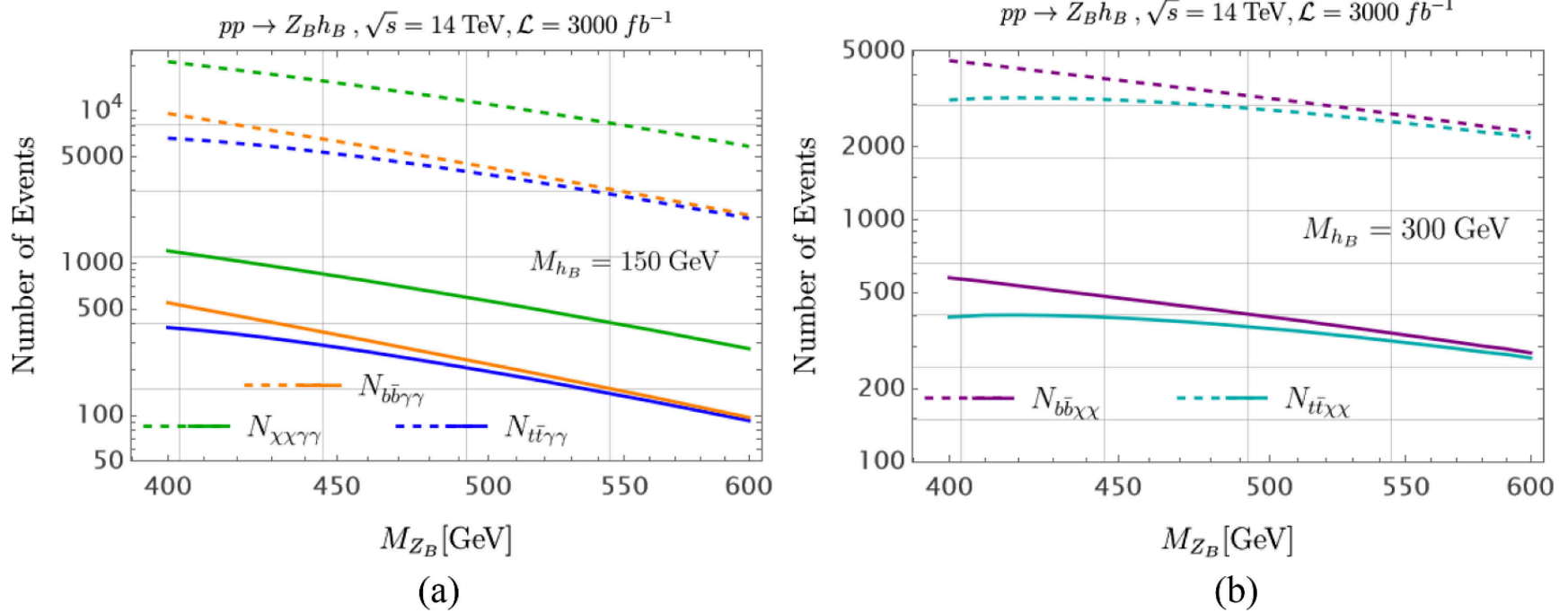


FIG. 12. (a) Number of events for different signatures as a function of Z_B mass when $M_{h_B} = 150$ GeV. (b) same as (a), but now $M_{h_B} = 300$ GeV. The solid and dashed lines represent the number of events for $g_B = 0.15$ and $g_B = 0.25$, respectively. Here, we assumed $M_\chi = 100$ GeV, $\sqrt{s}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

- J. Butterworth, H. Debnath, P. F. P., Y. Yeh, *Physical Review D* 110, 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*.