Scotogenic models: neutrinos, dark matter and more

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NOW 2022
Ostuni

There are MANY
Majorana neutrino mass models...

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

There are MANY Majorana neutrino mass models...

Review: [Cai, Herrero-García, Schmidt, AV, Volkas, 2017]

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Loop suppression

Dark matter candidate

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

Outline

Introduction

Finished already!

The Scotogenic model

A quick review of the well-known Scotogenic model

Beyond the Scotogenic model

Two examples of variants of the Scotogenic model

The Scotogenic model

Also known as...

The inert doublet model

The radiative seesaw

Ma's model

The Scotogenic model

[Ma, 2006]

σκότος

skotos = darkness

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
η	1	$\mathbf{2}$	$1/2$	$-$
N	3	$\mathbf{1}$	0	$-$

Inert (or dark) doublet

Dark Matter!

$$\mathcal{L}_N = \overline{N_i} \not{\partial} N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

$$\begin{aligned} \mathcal{V} = \quad & m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(H^\dagger H\right) \left(\eta^\dagger \eta\right) \\ & + \lambda_4 \left(H^\dagger \eta\right) \left(\eta^\dagger H\right) + \frac{\lambda_5}{2} \left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right] \end{aligned}$$

The Scotogenic model

[Ma, 2006]

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(H^\dagger H\right) \left(\eta^\dagger \eta\right) + \lambda_4 \left(H^\dagger \eta\right) \left(\eta^\dagger H\right) + \frac{\lambda_5}{2} \left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

Inert scalar sector: $\eta^\pm$ $\eta^0 = (\eta_R + i \eta_I)/\sqrt{2}$

$$\begin{aligned} m_{\eta^+}^2 &= m_\eta^2 + \lambda_3 \langle H^0 \rangle^2 \\ m_R^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5) \langle H^0 \rangle^2 \\ m_I^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5) \langle H^0 \rangle^2 \end{aligned} \Rightarrow \mathrm{m}_R^2 - m_I^2 = 2\, \lambda_5 \langle H^0 \rangle^2$$

Radiative neutrino masses

[Ma, 2006]

Tree-level:

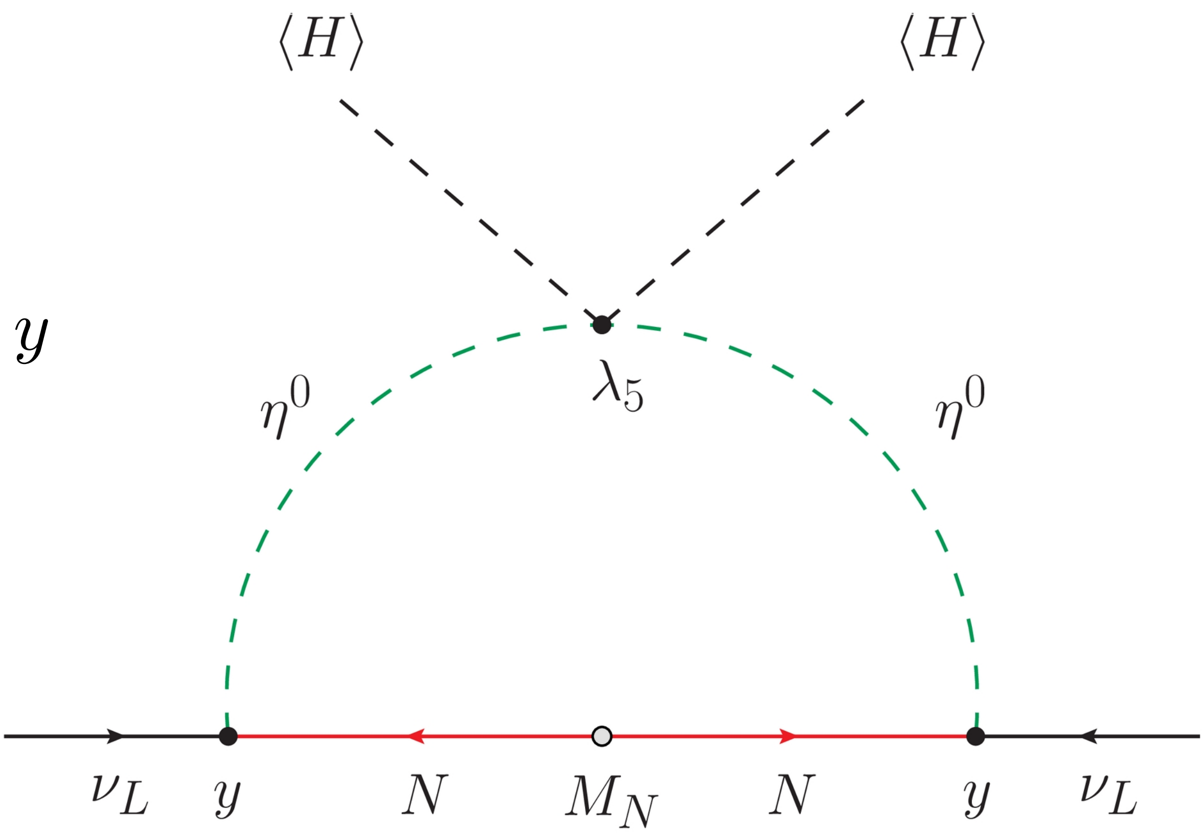
Forbidden by the $\mathbb{Z}_2$ symmetry

Radiative generation of neutrino masses

$$m_\nu = \frac{\lambda_5 v^2}{32\pi^2} \, y^T \, M_R^{-1} f_{\text{loop}} \, y$$

Dark particles in the loop

1-loop neutrino masses



Dark matter

The lightest particle charged under $\mathbb{Z}_2$ is stable: dark matter candidate

Fermion Dark Matter: N_1

- It can only be produced via Yukawa interactions
- Potential problems with lepton flavor violation: is it compatible with the current bounds?

Scalar Dark Matter: the lightest neutral η scalar, η_R or η_I

- It also has gauge interactions
- Not correlated to lepton flavor violation

Beyond the Scotogenic model

Chuck Norris fact of the day

Chuck Norris counted to infinity. Twice.

Beyond the Scotogenic model

From “model” to “paradigm”

There are multiple Scotogenic paths to explore:

- Number of generations of each Scotogenic state
- Representations under the gauge group
- Additional Scotogenic states
- Spontaneous violation of lepton number
- ...

A “charged” Scotogenic model

Work in collaboration with

Valentina De Romeri and **Miguel Puerta**

[arXiv:2106.00481]

A charged Scotogenic model

[Aoki, Kanemura, Yagyu, 2011]

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
η	1	$\mathbf{2}$	$1/2$	$-$
Φ	1	$\mathbf{2}$	$3/2$	$-$
$\psi_{L,R}$	2	$\mathbf{1}$	-1	$-$

Vector-like $\longrightarrow$ ($\psi_{L,R}$)

$$\Phi = \begin{pmatrix} \Phi^{++} \\ \Phi^{+} \end{pmatrix}$$

$$\mathcal{L}_Y = M_\psi \, \overline{\psi}_L \, \psi_R + Y^L \, \overline{\ell^c_L} \, \Phi \, \psi_L + Y^R \, \overline{\ell_L} \, \eta \, \psi_R + \text{h.c.}$$

$$\begin{aligned}\mathcal{V} = & \, \mu_1^2 \, H^2 + \mu_2^2 \, \eta^2 + \mu_\Phi^2 \, \Phi^2 + \frac{1}{2} \lambda_1 \, H^4 + \frac{1}{2} \lambda_2 \, \eta^4 + \frac{1}{2} \lambda_\Phi \, \Phi^4 \\ & + \lambda_3 \, H^2 \, \eta^2 + \lambda_4 \, H^\dagger \eta^2 + \rho_1 \, H^2 \, \Phi^2 + \rho_2 \, \eta^2 \, \Phi^2 + \sigma_1 \, H^\dagger \Phi^2 + \sigma_2 \, \eta^\dagger \Phi^2 \\ & + \frac{1}{2} \left[\lambda_5 \, (H^\dagger \eta)^2 + \text{h.c.} \right] + \left[\kappa \, (\Phi^\dagger H)(\eta H) + \text{h.c.} \right] ,\end{aligned}$$

Neutrino masses

Tree-level:

Forbidden by the $\mathbb{Z}_2$ symmetry

1-loop neutrino masses

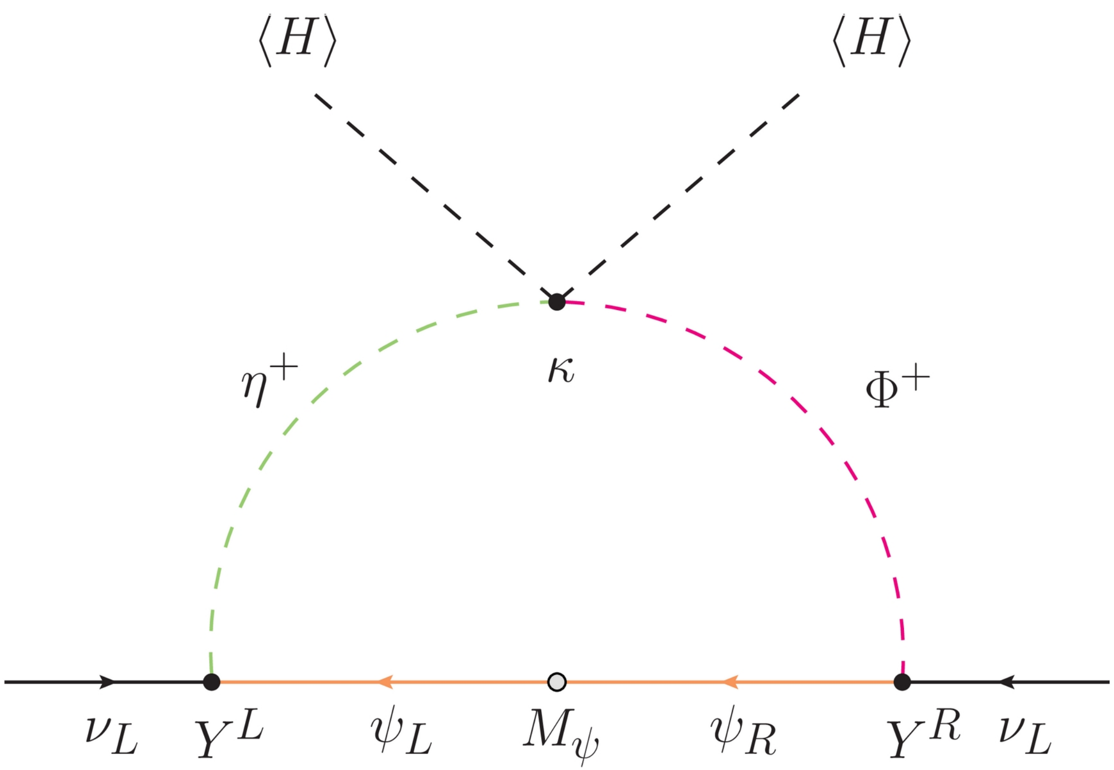
Electrically charged states in the loop

Two <u>independent</u> Yukawa matrices

$$Y^L \qquad Y^R$$

Master parametrization

[Cordero-Carrión, Hirsch, AV, 2018, 2019]



$$(m_\nu)_{\alpha\beta} = \sum_{b=1}^{2} \frac{{Y^L}_{\alpha b}\, {Y^R}_{\beta b} + {Y^R}_{\alpha b}\, {Y^L}_{\beta b}}{32\,\pi^2\, m_{\psi^a}} \frac{\kappa\, v^2}{m^2_{H_2^\pm} - m^2_{H_1^\pm}} \left(m^2_{H_2^\pm} \log \frac{m^2_{\psi^b}}{m^2_{H_2^\pm}} - m^2_{H_1^\pm} \log \frac{m^2_{\psi^b}}{m^2_{H_1^\pm}} \right)$$

Dark matter

The lightest particle charged under $\mathbb{Z}_2$ is stable: dark matter candidate

Fermion Dark Matter: ψ_1

- Electrically charged!

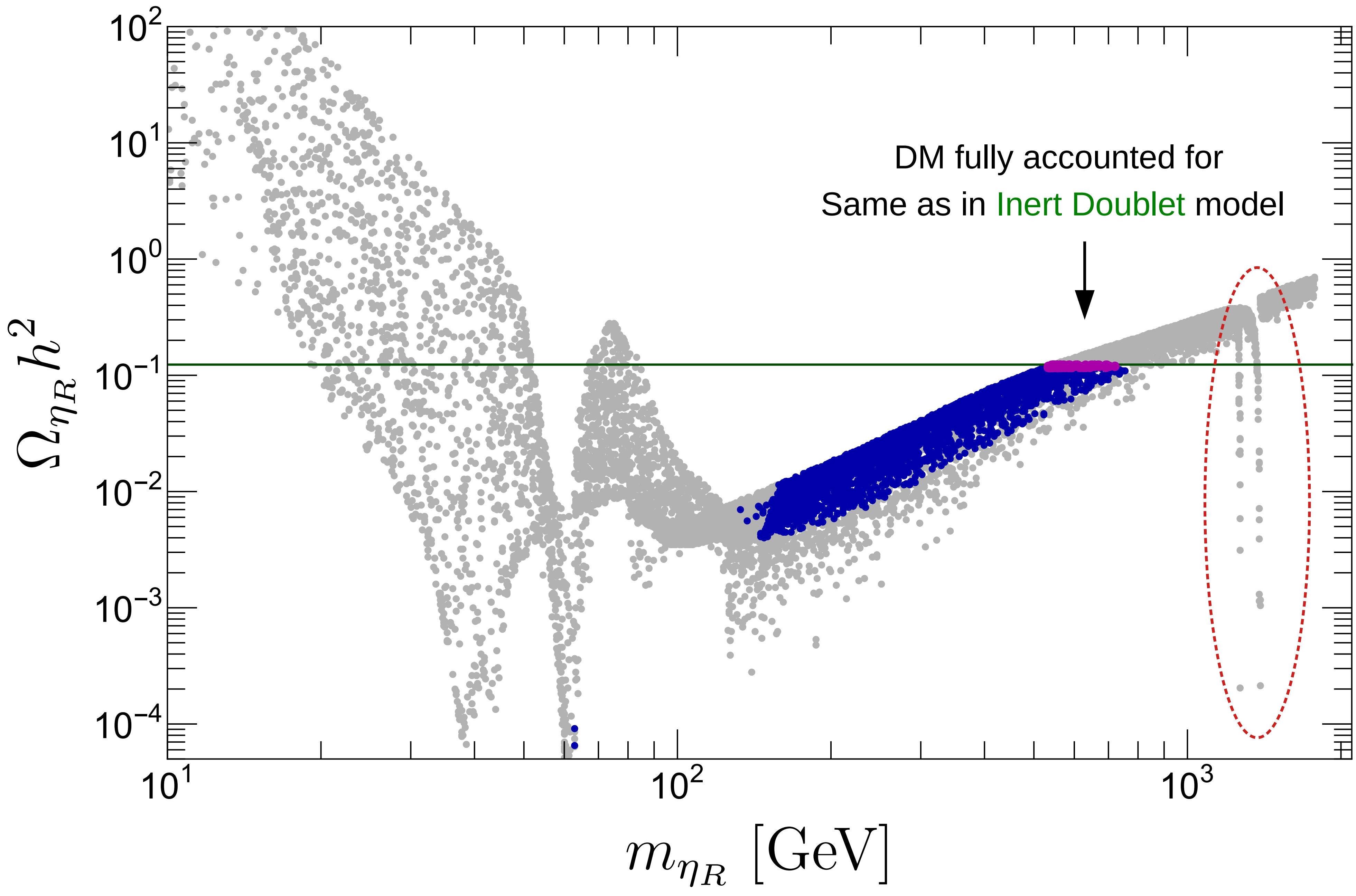
Scalar Dark Matter:

A: the lightest Φ scalar

- Electrically charged!

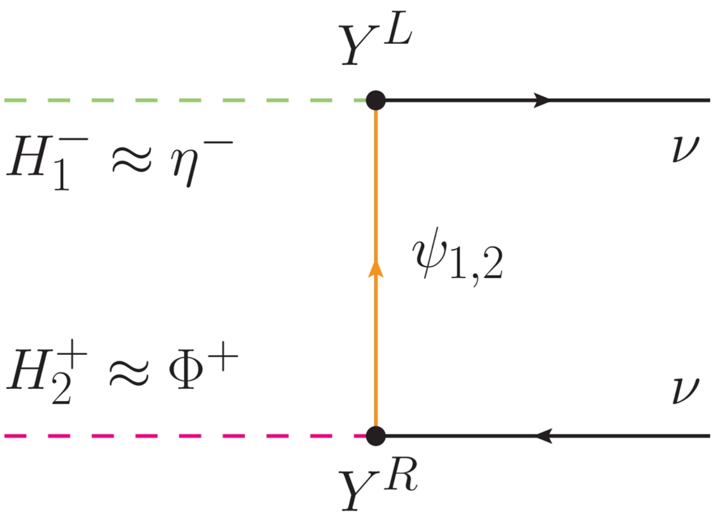
B: the lightest neutral η scalar, η_R or η_I

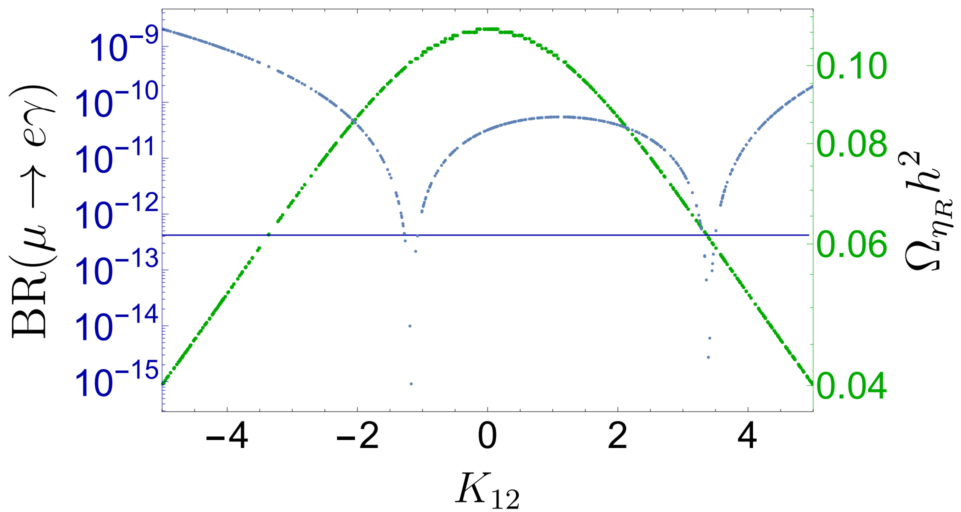
- It also has gauge interactions
- Not correlated to lepton flavor violation
- Any new phenomenology due to electrically charged states?

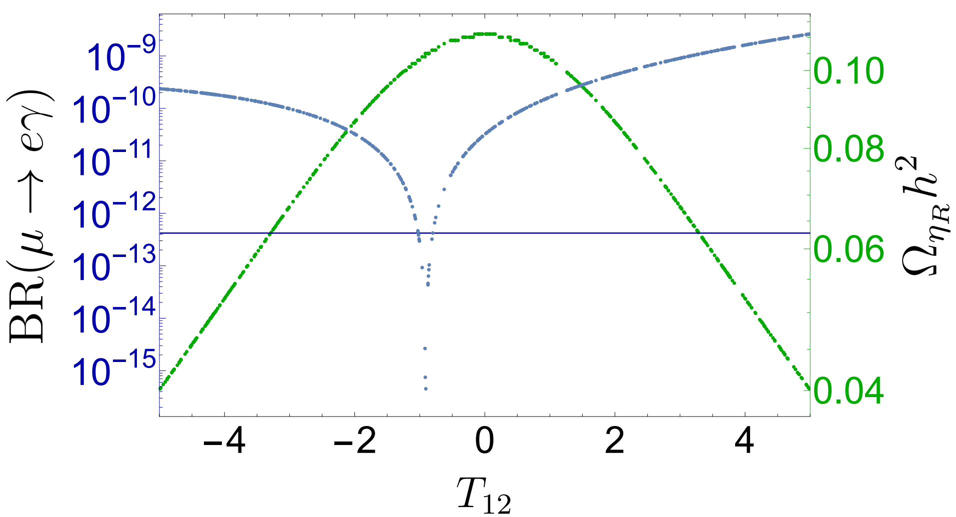


DM fully accounted for
Same as in Inert Doublet model
$\Omega_{\eta_R} h^2$
m_{η_R} [GeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}

Dark matter phenomenology







Novel annihilation channel due to charged states

However, some fine-tuning is required to avoid the bounds from LFV

A Scotogenic model “for everything”

Work in collaboration with

Ricardo Cepedello and **Pablo Escribano**

[arXiv:2209.02730]

A novel Scotogenic model

[Cepedello, Escribano, AV, 2022]

Leptoquark →

$$S = \begin{pmatrix} S_{\frac{2}{3}} \\ S_{-\frac{1}{3}} \end{pmatrix}$$

	gen	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
η	2	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$-$
S	1	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$-$
ϕ	1	$\mathbf{1}$	$\mathbf{1}$	-1	$-$
N	1	$\mathbf{1}$	$\mathbf{1}$	0	$-$

$$-\mathcal{L}_{\mathrm{Y}} = Y_N \, \overline{N} \, \ell_L \, \eta + Y_S \, \overline{q}_L \, S \, N + \kappa \, \overline{N^c} \, e_R \, \phi^\dagger + \frac{1}{2} \, M_N \, \overline{N^c} \, N + \mathrm{h.c.}$$

$$\mathcal{V} \supset \frac{\lambda_5}{2} \left(H^\dagger \, \eta \right)^2 + \mu \, H \, \eta \, \phi + \mathrm{h.c.}$$

Neutrino masses

Tree-level:

Forbidden by the $\mathbb{Z}_2$ symmetry

1-loop neutrino masses

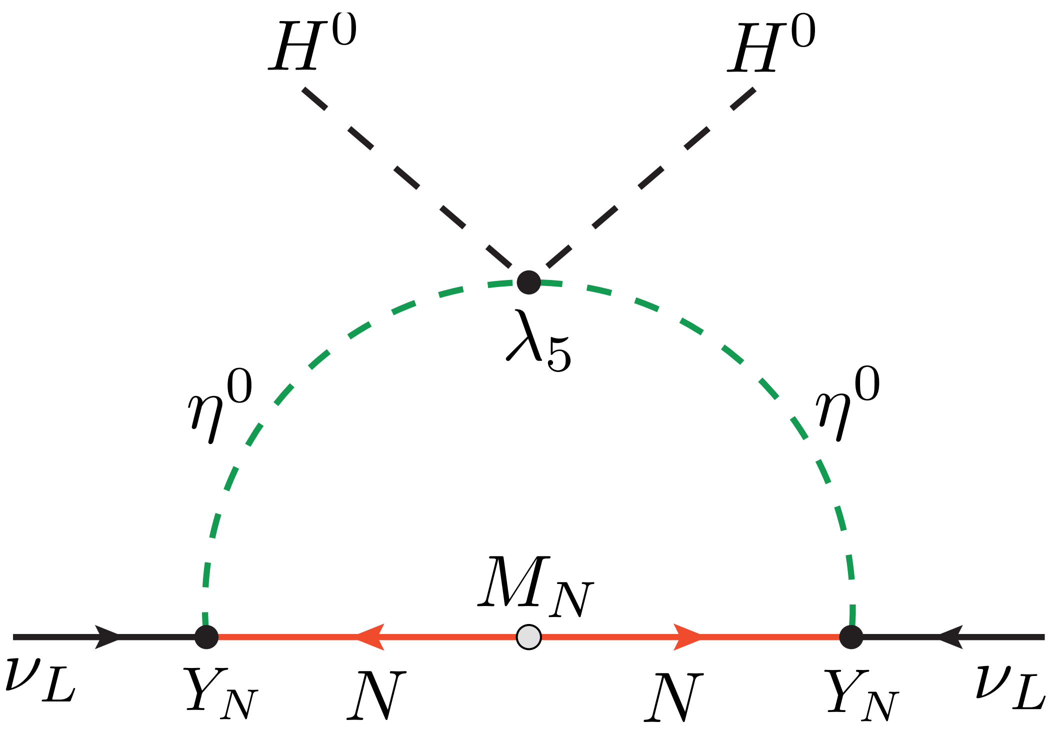
Scotogenic mechanism

<u>However</u>:

unusual generation numbers

$$n_N = 1 \qquad n_\eta = 2$$

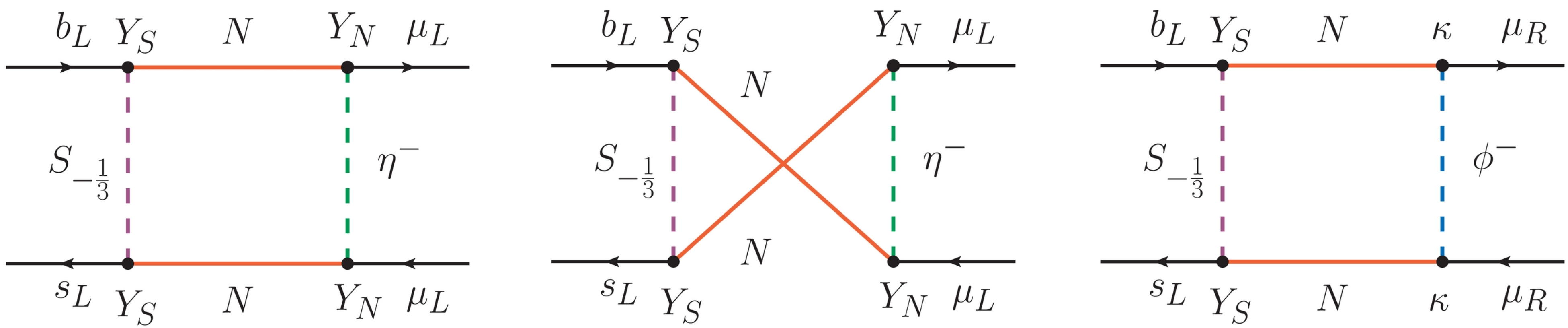
[Escribano, Reig, AV, 2020]

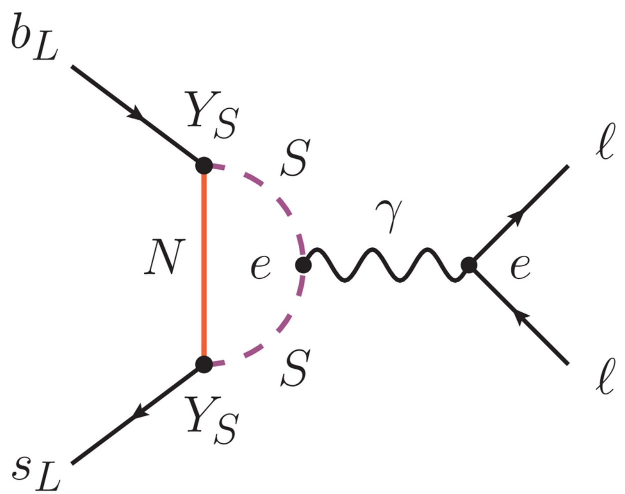


$$(m_\nu)_{\alpha\beta} \approx \frac{1}{32\pi^2} v^2 \sum_{a,b} (Y_N)_{\alpha a} (Y_N)_{\beta b}\, {\lambda_5}^{ab} \frac{M_N}{m_b^2 - M_N^2} \left[\frac{m_b^2}{m_a^2 - m_b^2} \log \frac{m_a^2}{m_b^2} - \frac{M_N^2}{m_a^2 - M_N^2} \log \frac{m_a^2}{M_N^2} \right]$$

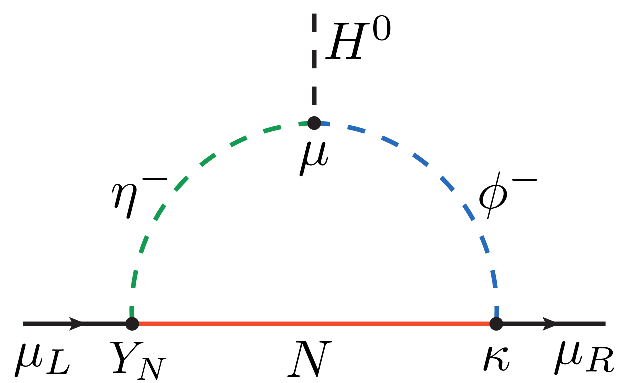
Dark loops

Flavor non-universal $b \to s\ell\ell$





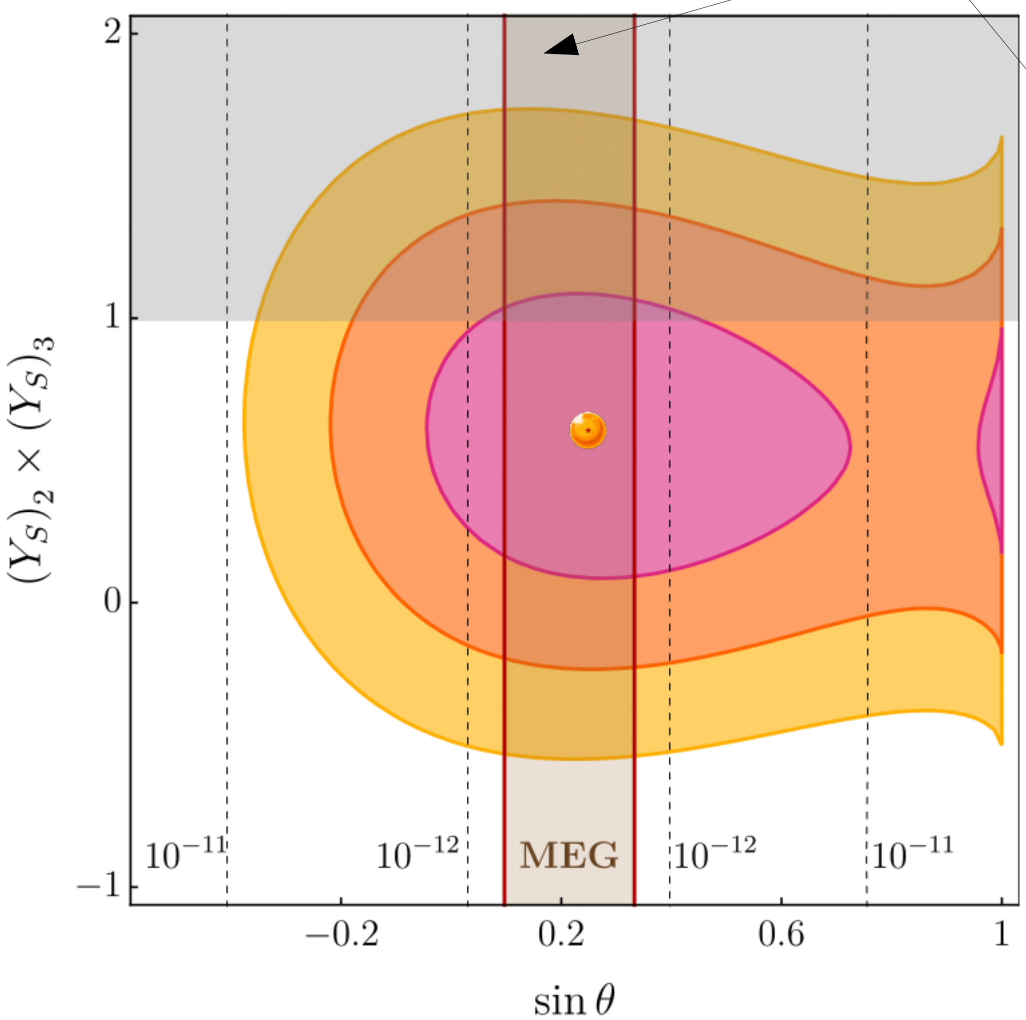
Flavor universal $b \to s\ell\ell$

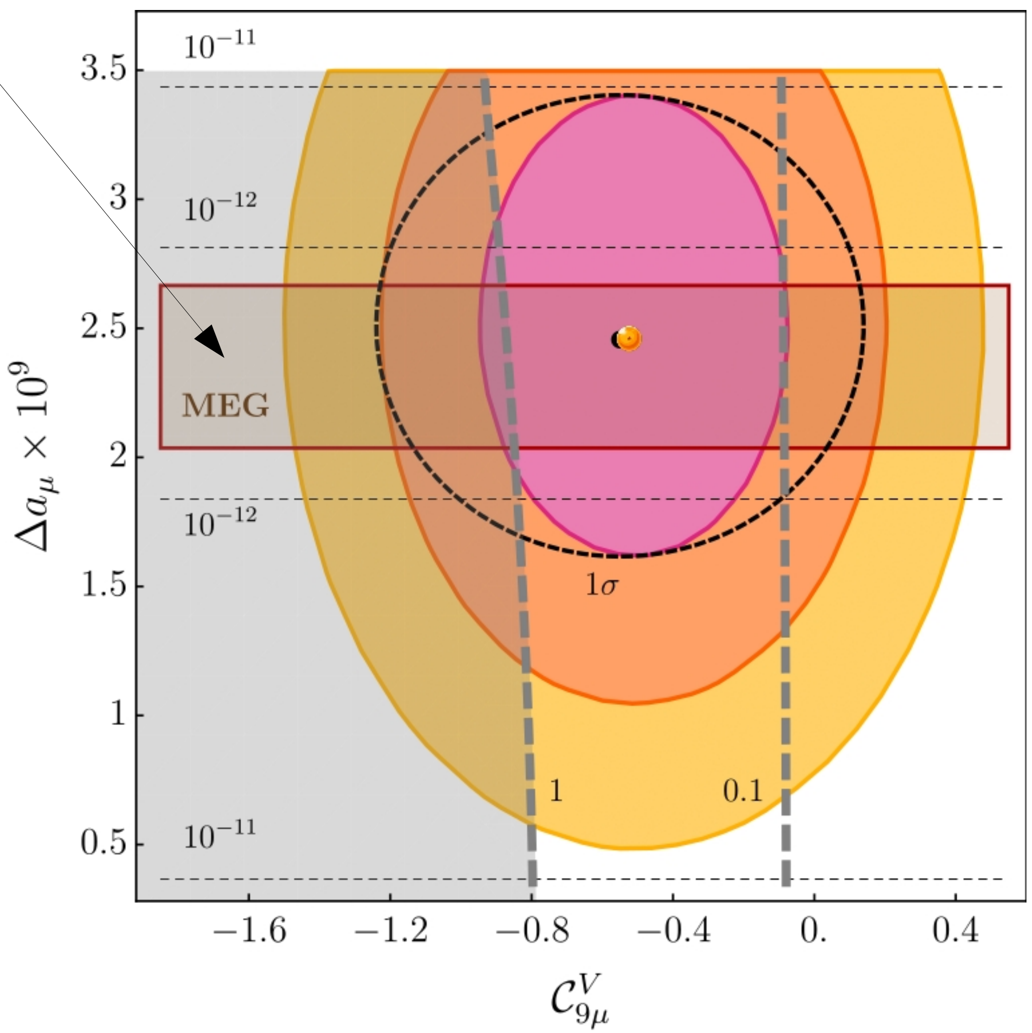


Muon $g - 2$

Dark loops

$\text{BR}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$





A free parameter in Y_N

For experts: the *R* matrix angle

Coefficient of $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

$b \to s\ell\ell$

Final discussion

Final discussion

Scotogenic neutrino mass models constitute an **economical class of models**, including a dark matter candidate. There are plenty of ways to go beyond the minimal model

Two examples:

A variant of the Scotogenic model with electrically charged states. **Novel annihilation processes**, but some fine-tuning is required to escape the lepton flavor violating bounds

A model featuring some additional Scotogenic states, capable of explaning the $b \to s\ell\ell$ and muon $g-2$ **anomalies**, in addition to neutrino masses and dark matter

Thanks for your attention!

And congratulations to the organizers for an awesome NOW 2022

Backup slides

The master parametrization

[Cordero-Carrión, Hirsch, AV, 2018, 2019]

$$\boxed{m = f \, \left(y_1^T \, M \, y_2 + y_2^T \, M^T \, y_1 \right)}$$

$$y_1 = \frac{1}{\sqrt{2\,f}} \, V_1^\dagger \begin{pmatrix} \Sigma^{-1/2} \, W \, A \\ X_1 \\ X_2 \end{pmatrix} \bar{D}_{\sqrt{m}} \, U^\dagger$$

$$y_2 = \frac{1}{\sqrt{2\,f}} \, V_2^\dagger \begin{pmatrix} \Sigma^{-1/2} \, \widehat{W}^* \, \widehat{B} \\ X_3 \end{pmatrix} \bar{D}_{\sqrt{m}} \, U^\dagger$$

A charged Scotogenic model

$\mathbb{Z}_2$ -odd scalars

$$\eta^0 \longrightarrow \eta_R \, , \eta_I \qquad \mathrm{m}_R^2 - m_I^2 = 2 \, \lambda_5 \, \langle H^0 \rangle^2$$

$$\left.\begin{matrix} \eta^+ \\ \\ \Phi^+ \end{matrix}\right\} \longrightarrow \begin{pmatrix} H_1^+ \\ H_2^+ \end{pmatrix} = \begin{pmatrix} c_\chi & s_\chi \\ -s_\chi & c_\chi \end{pmatrix} \begin{pmatrix} \eta^+ \\ \Phi^+ \end{pmatrix}$$

$$c_\chi \, s_\chi \approx \frac{\kappa \, v^2}{2 \left(m^2_{H_1^\pm} - m^2_{H_2^\pm} \right)}$$

Small mixing for $\kappa \ll 1$

$\Phi^{++} \longrightarrow$ Doubly-charged scalar

Analysis

Tools

SARAH-4.11.0

SPheno-4.0.2

micrOmegas-5.0.9

$\lambda_1 = 0.26$	$m_{\psi^1} = 2.1 \text{ TeV}$
$\lambda_2 = 0.5$	$m_{\psi^2} = 2.3 \text{ TeV}$
$\lambda_3 = 10^{-2}$	$\rho_1 = 0.5$
$\lambda_4 \in \left[-0.5, -10^{-4}\right]$	$\rho_2 = 0.7$
$\lambda_5 \in [-0.32, -0.003]$	$\sigma_1 \in \left[10^{-5}, 0.16\right]$
$\lambda_\Phi = 3 \times 10^{-3}$	$\sigma_2 = 10^{-2}$
$\mu_\Phi^2 \in \left[100, 4.4 \times 10^6\right] \text{ GeV}^2$	$\kappa = 10^{-8}$
$\mu_2^2 = \mu_\Phi^2$ except if $m_{\eta_R} \in [50, 100]$ GeV	

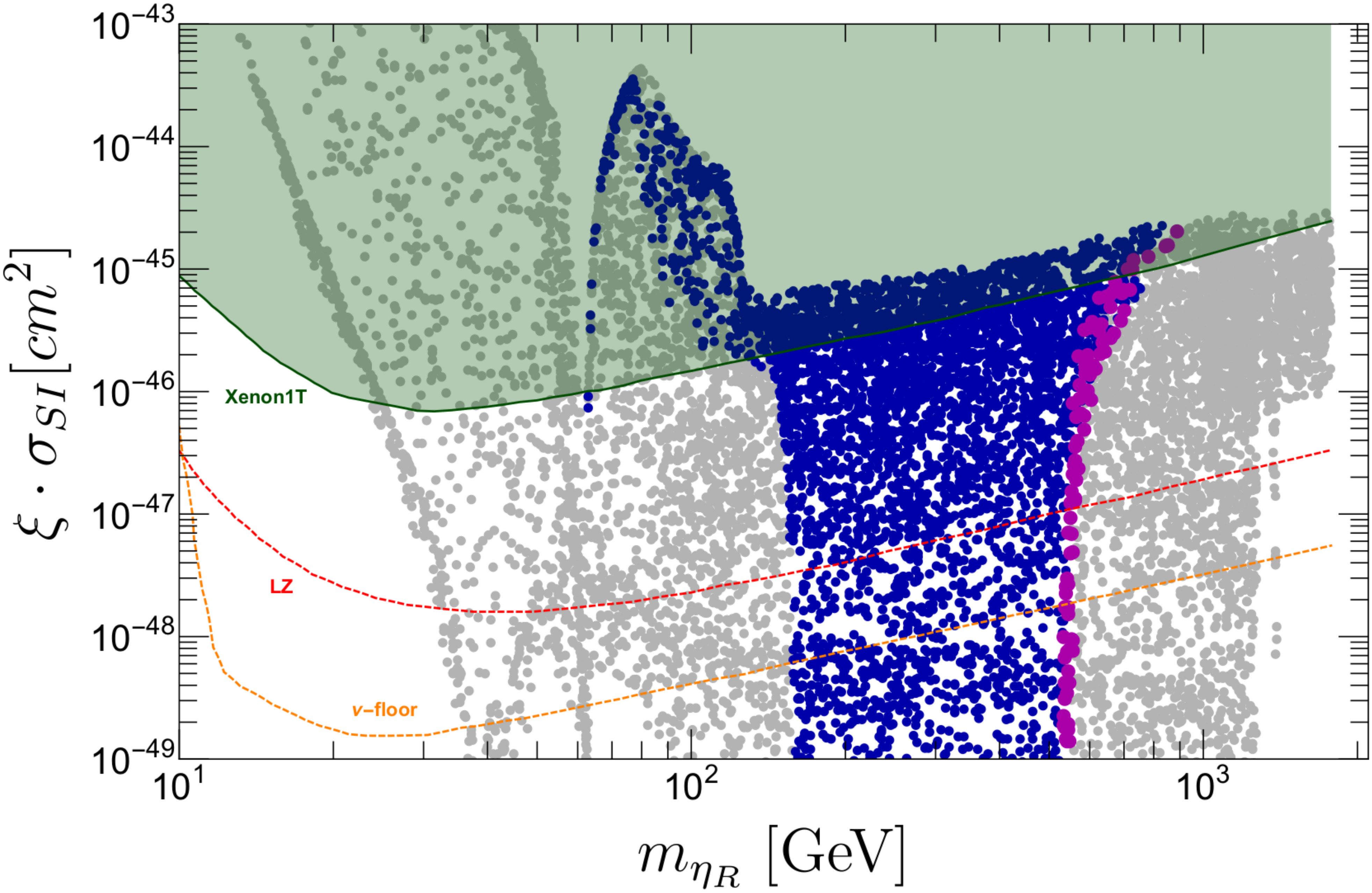
Constraints:

- Neutrino oscillation data
- Lepton flavor violation
- Electroweak precision data ($\Delta\rho$)
- Dark matter searches
- LHC searches
- Higgs decays (invisible & diphoton)
- Lifetime of the next-to-lightest $\mathbb{Z}_2$-odd state

Analysis

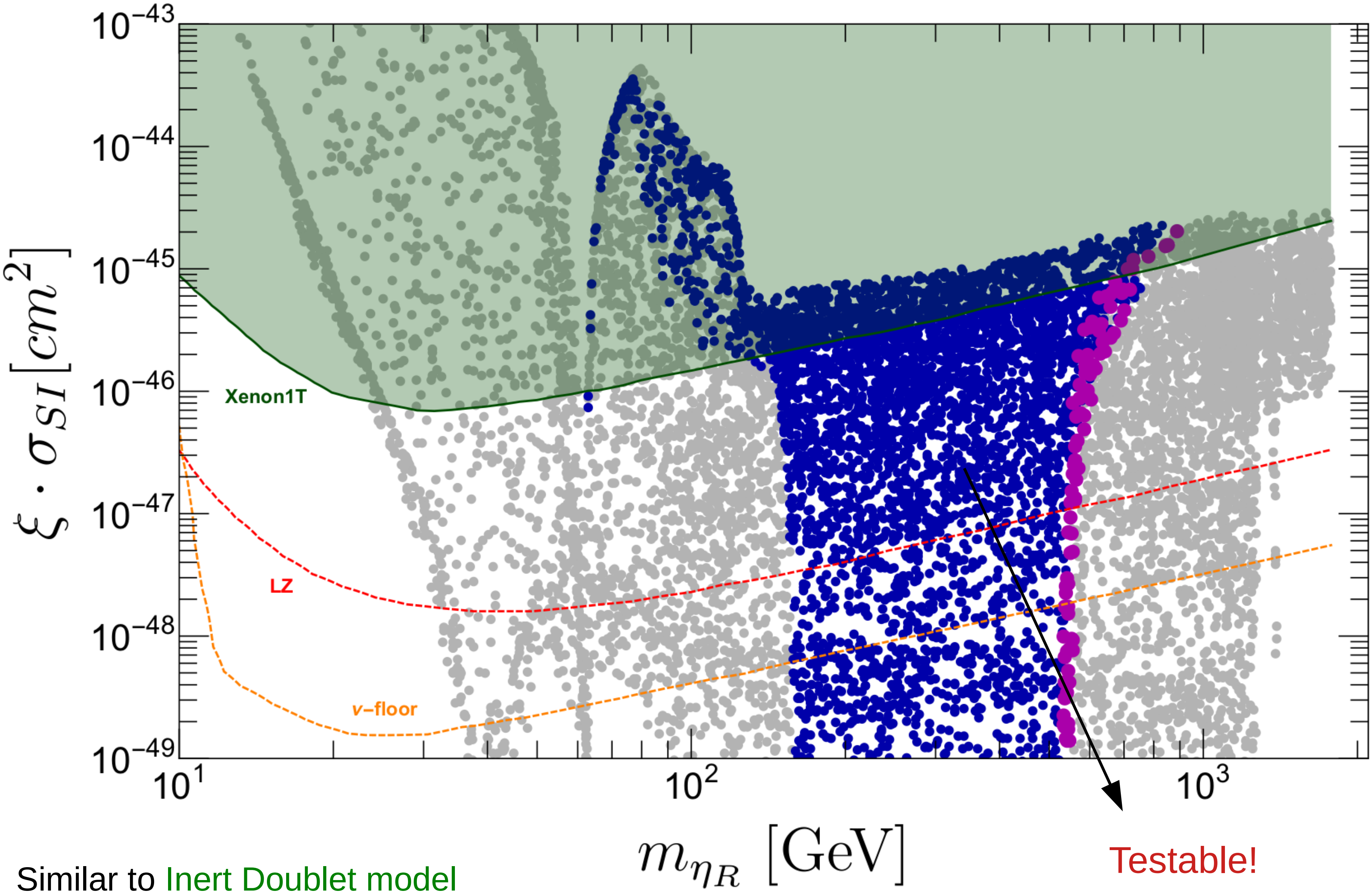
Some of the constraints applied in the numerical scan

$\mathrm{BR}(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\mu \to eee)$	$< 1. \times 10^{-12}$
$\mathrm{CR}(\mu^-, \mathrm{Au} \to e^-, \mathrm{Au})$	$< 7 \times 10^{-13}$
$\frac{\mathrm{BR}(h\to\gamma\gamma)}{\mathrm{BR}(h\to\gamma\gamma)_{\mathrm{SM}}}$	$[0.84, 1.41]$
$\mathrm{BR}(h \to \gamma\gamma)_{\mathrm{SM}}$	$(0.227 \pm 0.011) \times 10^{-2}$
$\mathrm{BR}(h \to \mathrm{inv})$	0.19
$\delta\rho$	$[-0.00022, 0.00098]$
$\Omega_{\eta_R} h^2$	$[0.1164, 0.1236]$



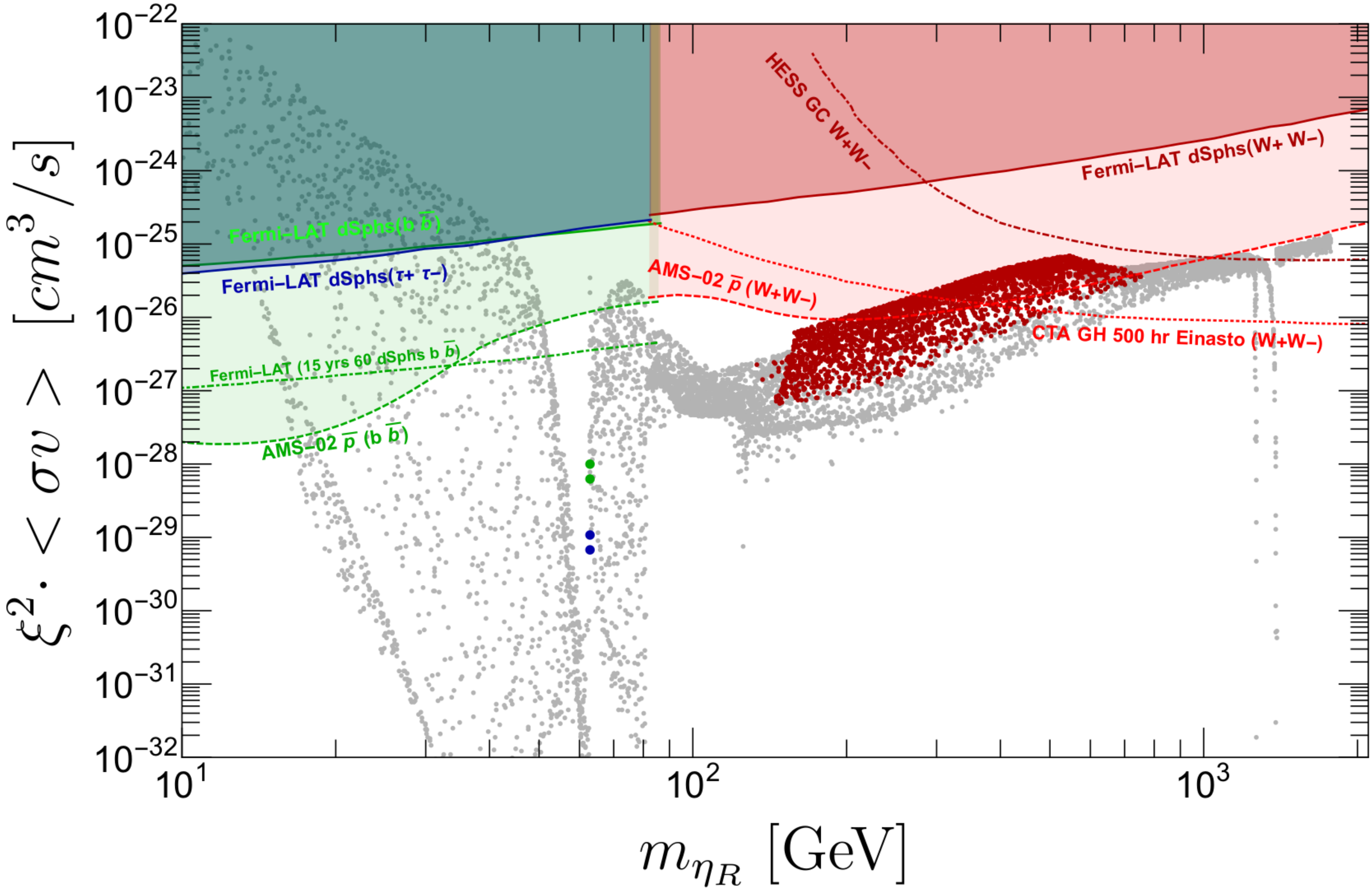
$\xi \cdot \sigma_{SI}\,[cm^2]$
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
Xenon1T
LZ
ν–floor
10^{1}
10^{2}
10^{3}
m_{η_R} [GeV]

Z-boson mediated scattering suppressed due to sizable λ_5

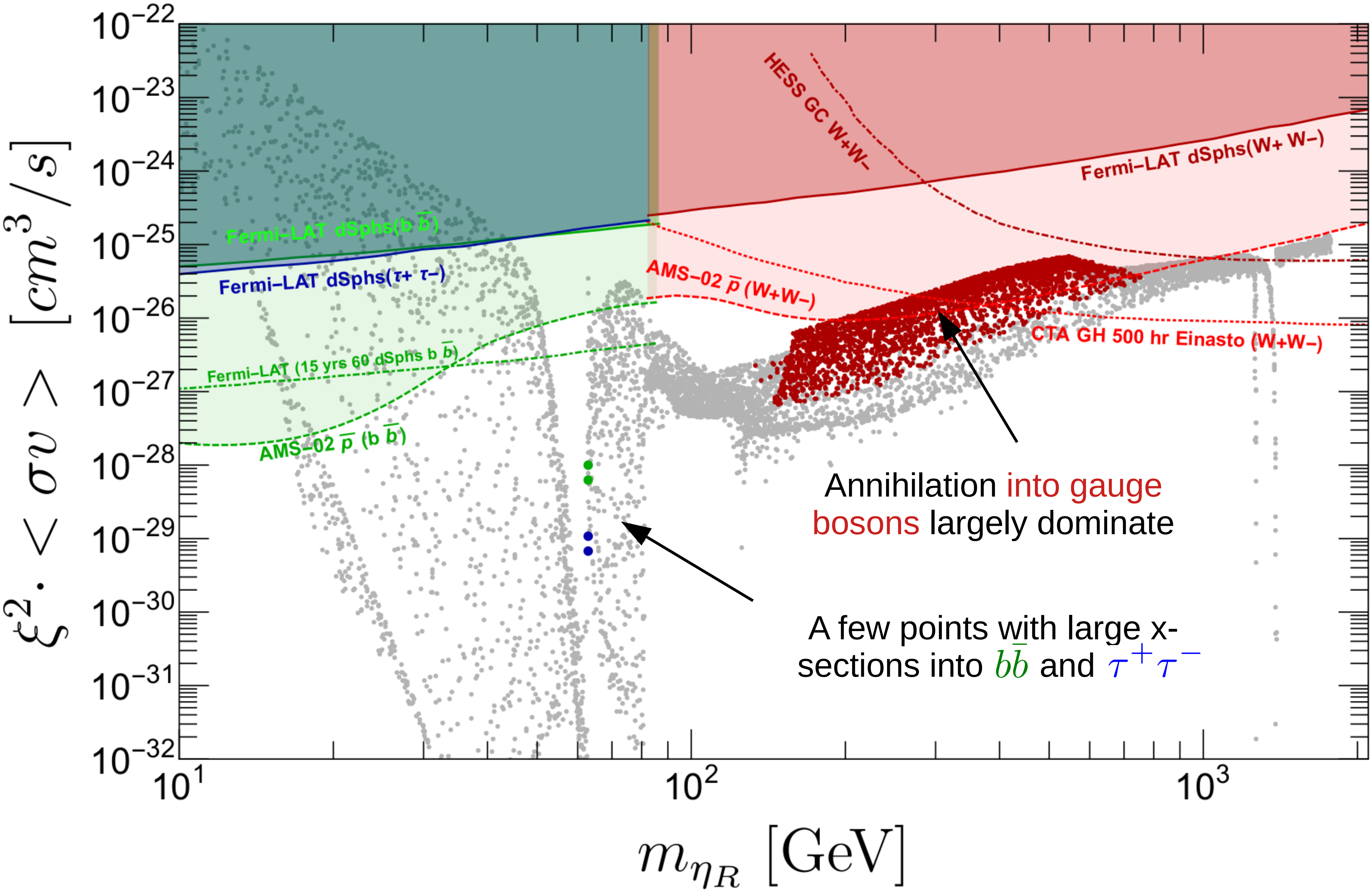


Testable!

Similar to Inert Doublet model


HESS GC W+W−
Fermi−LAT dSphs(W+ W−)
Fermi−LAT dSphs(b $\bar{b}$)
Fermi−LAT dSphs(τ+ τ−)
AMS−02 $\bar{p}$ (W+W−)
CTA GH 500 hr Einasto (W+W−)
Fermi−LAT (15 yrs 60 dSphs b $\bar{b}$)
AMS−02 $\bar{p}$ (b $\bar{b}$)
$\xi^2 \cdot <\sigma v>$ $[cm^3/s]$
m_{η_R} [GeV]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^1
10^2
10^3

Our predictions lie well below the current limits from **γ-rays**

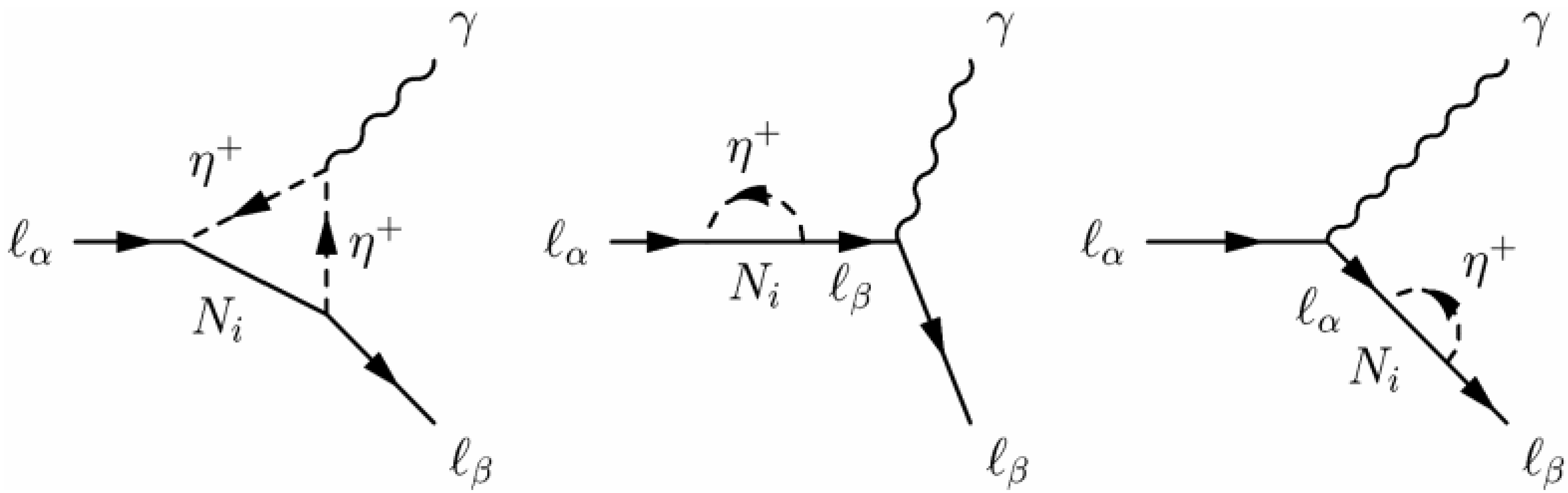


Annihilation into gauge bosons largely dominate

A few points with large x-sections into $b\bar{b}$ and $\tau^+\tau^-$

$\ell_\alpha \to \ell_\beta \gamma$

[Kubo et al, 2006]
[Ma, Raidal, 2001]



$$\mathcal{L}_{\text{eff}} = \left(\frac{\mu_{\beta\alpha}}{2}\right) \overline{\ell_\beta} \sigma^{\mu\nu} \ell_\alpha F_{\mu\nu}$$

$$\mu_{\beta\alpha} = e m_\alpha A_D / 2$$

Transition magnetic moment

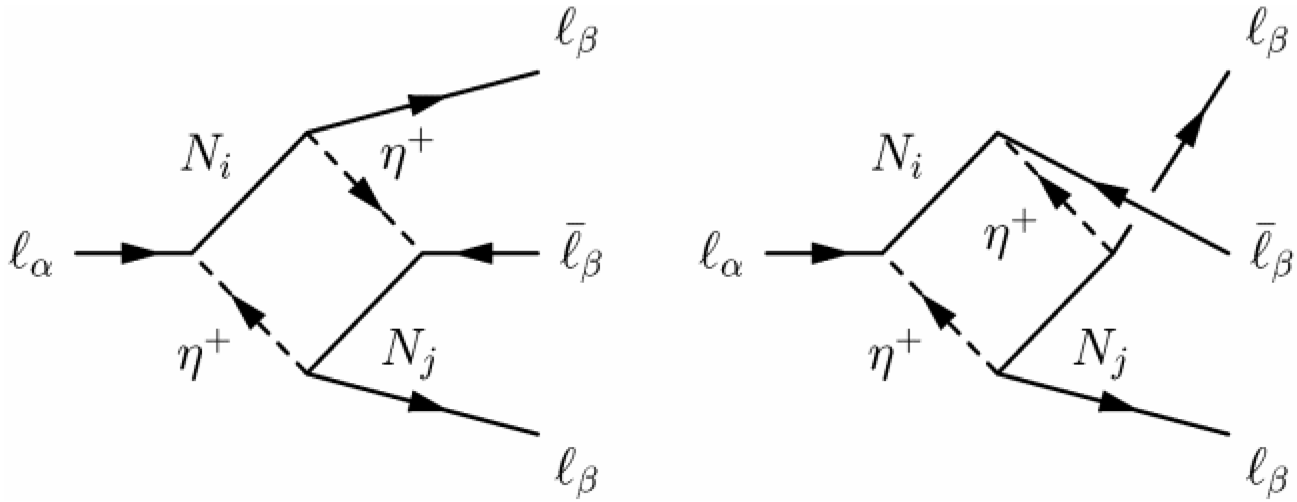
$$A_D = \sum_{i=1}^{3} \frac{y_{i\beta}^* y_{i\alpha}}{2(4\pi)^2} \frac{1}{m_{\eta^+}^2} F_2\left(\xi_i\right)$$

$(\xi_i \equiv m_{N_i}^2 / m_{\eta^+}^2)$

$\ell_\alpha \to 3\,\ell_\beta$

$$\ell_\alpha(p) \to \ell_\beta(k_1)\bar{\ell}_\beta(k_2)\ell_\beta(k_3)$$

[Toma, Vicente, 2013]



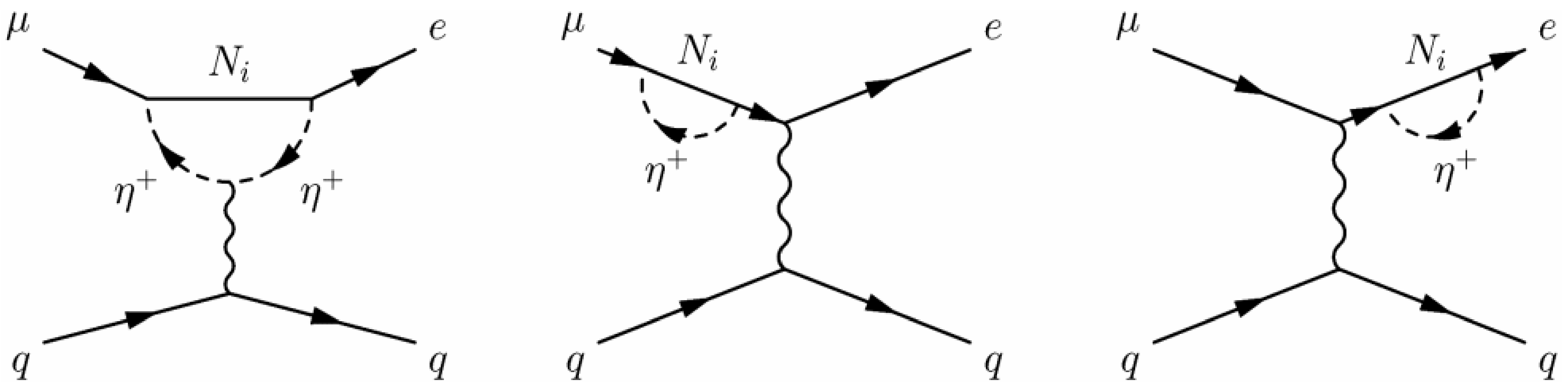
Boxes

$$i\mathcal{M}_{\rm box} = ie^2\, B\, \left[\bar{u}(k_3)\gamma^\mu P_L v(k_2)\right]\left[\bar{u}(k_1)\gamma_\mu P_L u(p)\right]$$

$$e^2 B = \frac{1}{(4\pi)^2 m_{\eta^+}^2} \sum_{i,\,j=1}^{3} \left[\frac{1}{2} D_1(\xi_i,\xi_j) y_{j\beta}^* y_{j\beta} y_{i\beta}^* y_{i\alpha} + \sqrt{\xi_i \xi_j}\, D_2(\xi_i,\xi_j) y_{j\beta}^* y_{j\beta}^* y_{i\beta} y_{i\alpha}\right]$$

$\mu - e$ conversion in nuclei

[Toma, Vicente, 2013]



- No box contributions from the inert doublet (they do not couple to the quark sector)

- The phenomenology is determined by photon penguin diagrams (Z penguins are negligible)

A philosophical moment

Occam’s razor:

The simplest explanation is the correct one

Occam’s laser:

The most awesome explanation is the correct one

Occam’s hammer:

My explanation is the correct one

All credit goes to
Alberto Aparici