Model building for dark matter

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Jornadas científicas del IFIC

Línea L4

Model building boils down to (properly) choosing...

Symmetry + Representations

DM stability **DM candidate**

In the process of making a DM model one should consider...

- Is the model compatible with the current constraints?
- Does the model address any other problem of the SM?
- Would a variation of the model lead to a different phenomenology?

This talk ⇨ **The Scotogenic model**

Other (non-Scotogenic) works

DM from flavor
S. Centelles Chulia, R. Cepedello, O. Medina, 2204.12517

DM from a dark CP symmetry
L. Coito, C. Faubel, J. Herrero-Garcia, A. Santamaria, 2106.05289 → Juan's talk

DM in supersymmetric scenarios
J. S. Kim, D. E. Lopez-Fogliani, A. D. Perez, R. Ruiz de Austri, 2107.02285
D. E. Lopez-Fogliani, A. D. Perez, R. Ruiz de Austri, 2102.08986 → Roberto's talk

DM and lepton number
S. Bhattacharya, A. Sil, R. Roshan, D. Vatsyayan, 2105.06189

DM in extra-dimensions
F. J. de Anda, O. Medina, J. W. F. Valle, C. A. Vaquera-Araujo, 2212.09174
N. Bernal, A. Donini, M. G. Folgado, N. Rius, 2004.14403

Disclaimer

I will focus on (some) recent works (mostly of mine). Apologies for missing your paper!

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!

$$\mathcal{L}_N = \overline{N_i} \partial\!\!\!/ N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

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

Radiative neutrino masses

[Ma, 2006]

Tree-level:

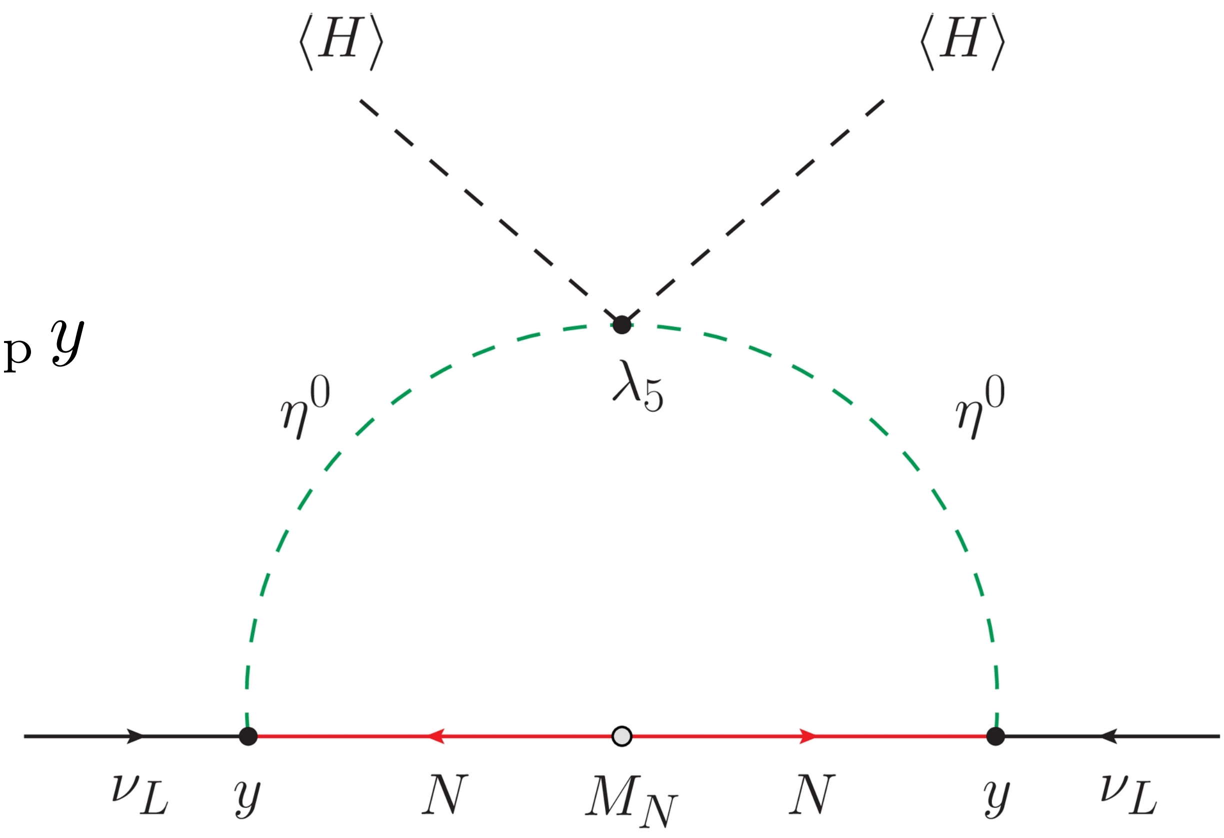
Forbidden by the $\mathbb{Z}_2$ symmetry

1-loop neutrino masses

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



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
- Similar to the inert doublet model

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 (or non-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 → $\psi_{L,R}$

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

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

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

Neutrino masses

Tree-level:

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

1-loop neutrino masses

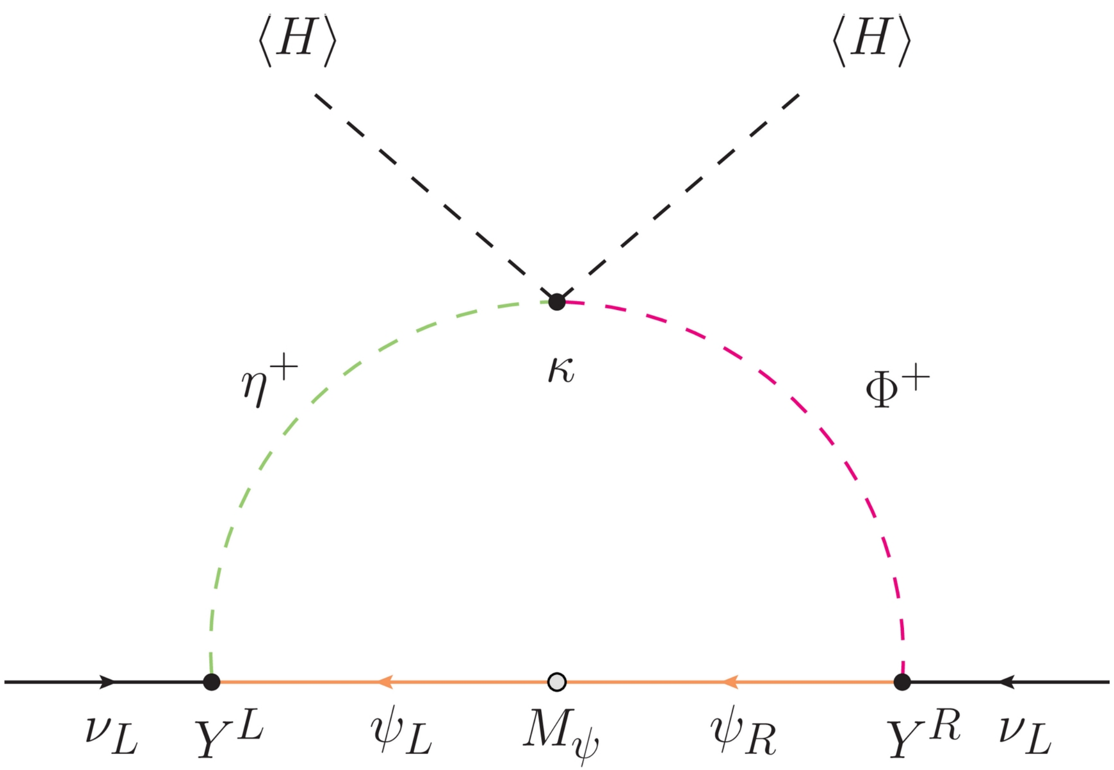
Electrically charged states in the loop

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!

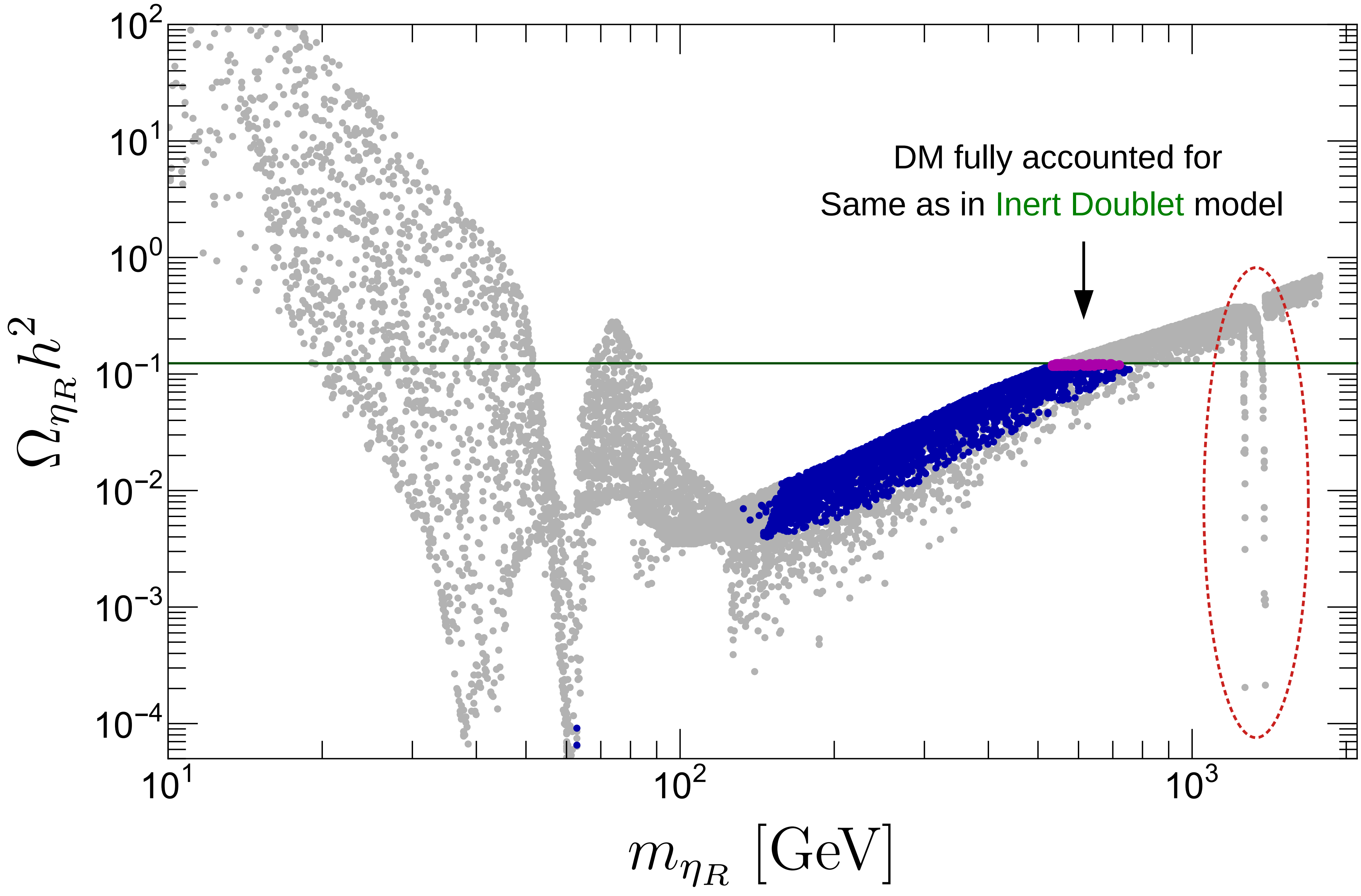
Scalar Dark Matter:

A: the lightest Φ scalar

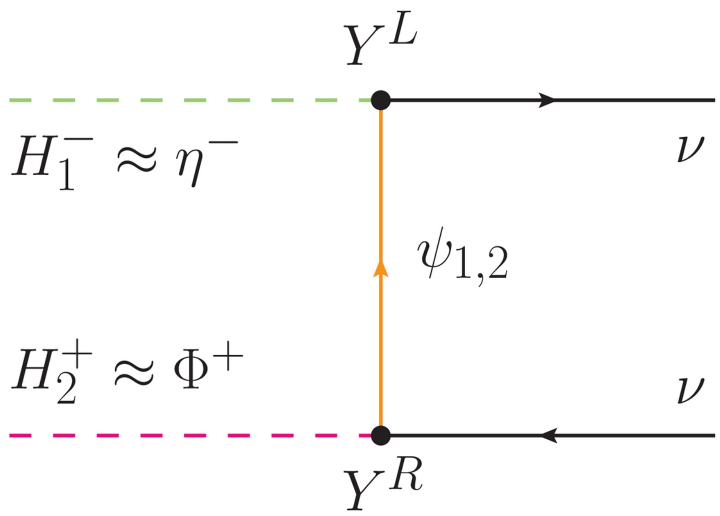
- Electrically charged!

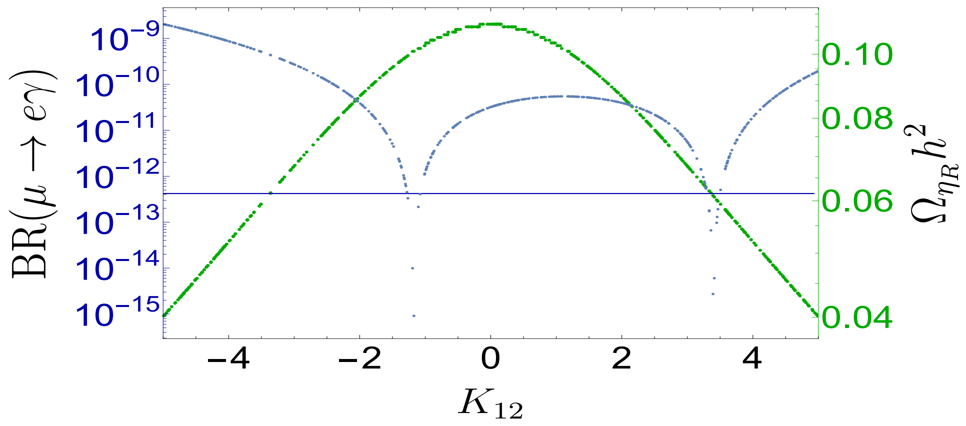
B: the lightest neutral η scalar, η_R or η_I

- 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

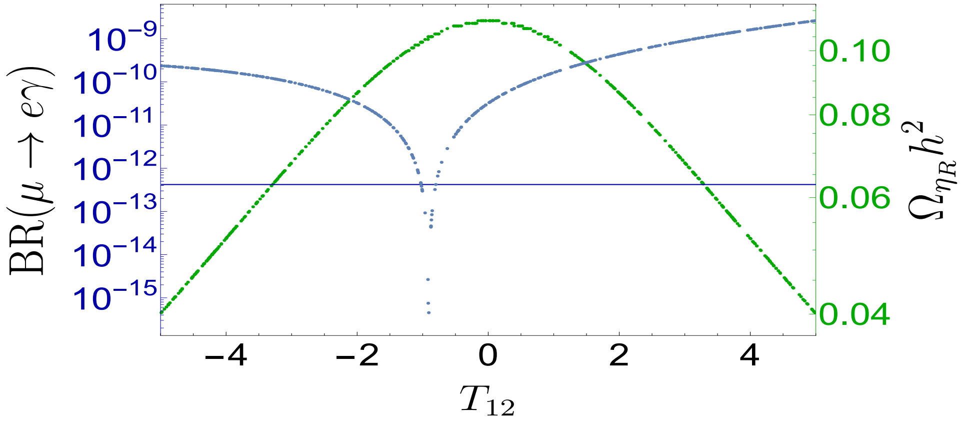
Dark matter phenomenology





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]

	gen	$\text{SU}(3)_c$	$\text{SU}(2)_L$	$\text{U}(1)_Y$	$\mathbb{Z}_2$
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	$-$

Leptoquark → S

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

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

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

Neutrino masses

Tree-level:

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

1-loop neutrino masses

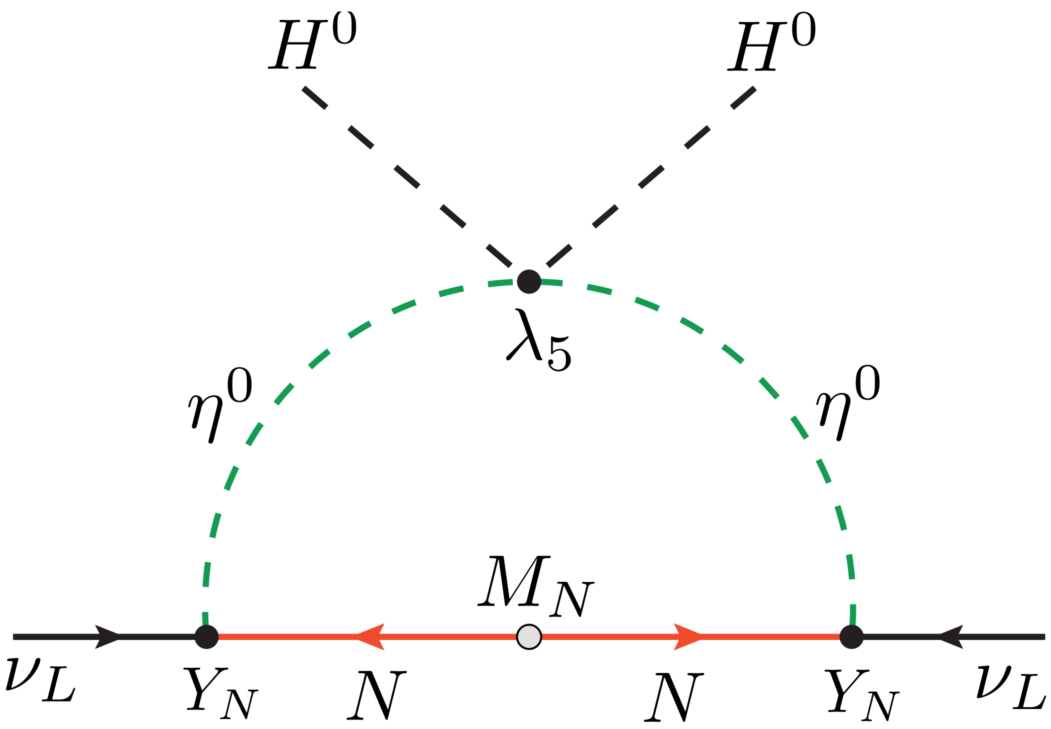
Scotogenic mechanism

<u>However</u>:

unusual generation numbers

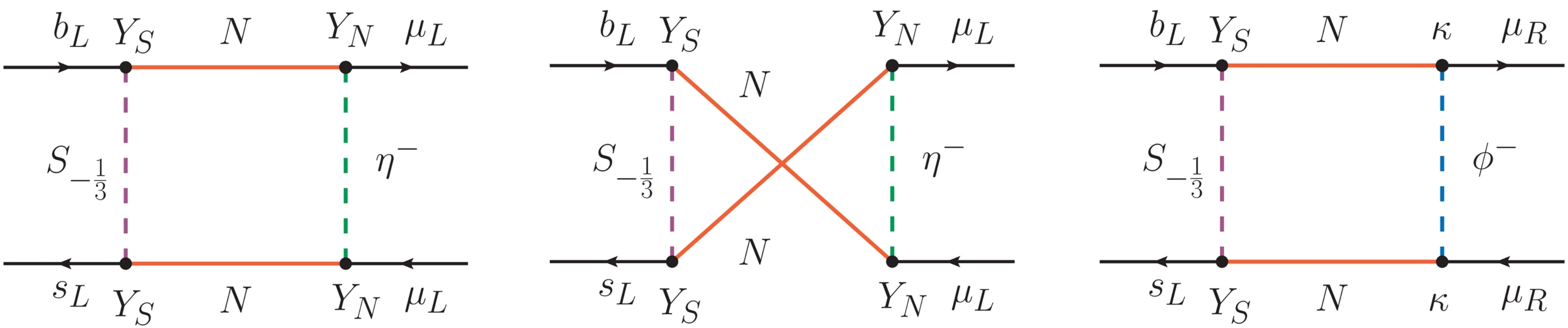
$$n_N = 1 \qquad n_\eta = 2$$

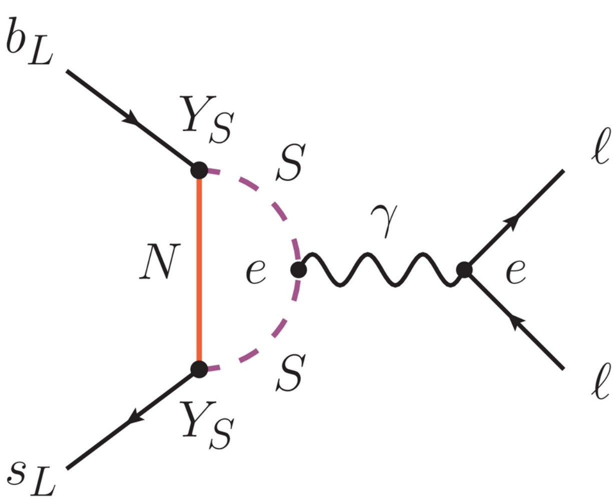
[Escribano, Reig, AV, 2020]



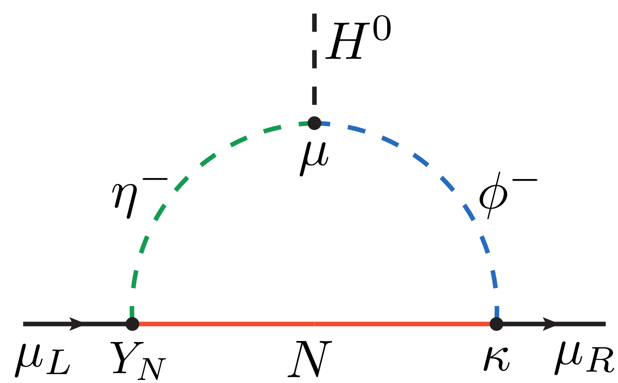
$$(m_\nu)_{\alpha\beta} \approx \frac{1}{32\pi^2} v^2 \sum_{a,b} (Y_N)_{\alpha a} (Y_N)_{\beta b} \, {\lambda_5}^{ab} \, \frac{M_N}{m_b^2 - M_N^2} \left[\frac{m_b^2}{m_a^2 - m_b^2} \log \frac{m_a^2}{m_b^2} - \frac{M_N^2}{m_a^2 - M_N^2} \log \frac{m_a^2}{M_N^2} \right]$$

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



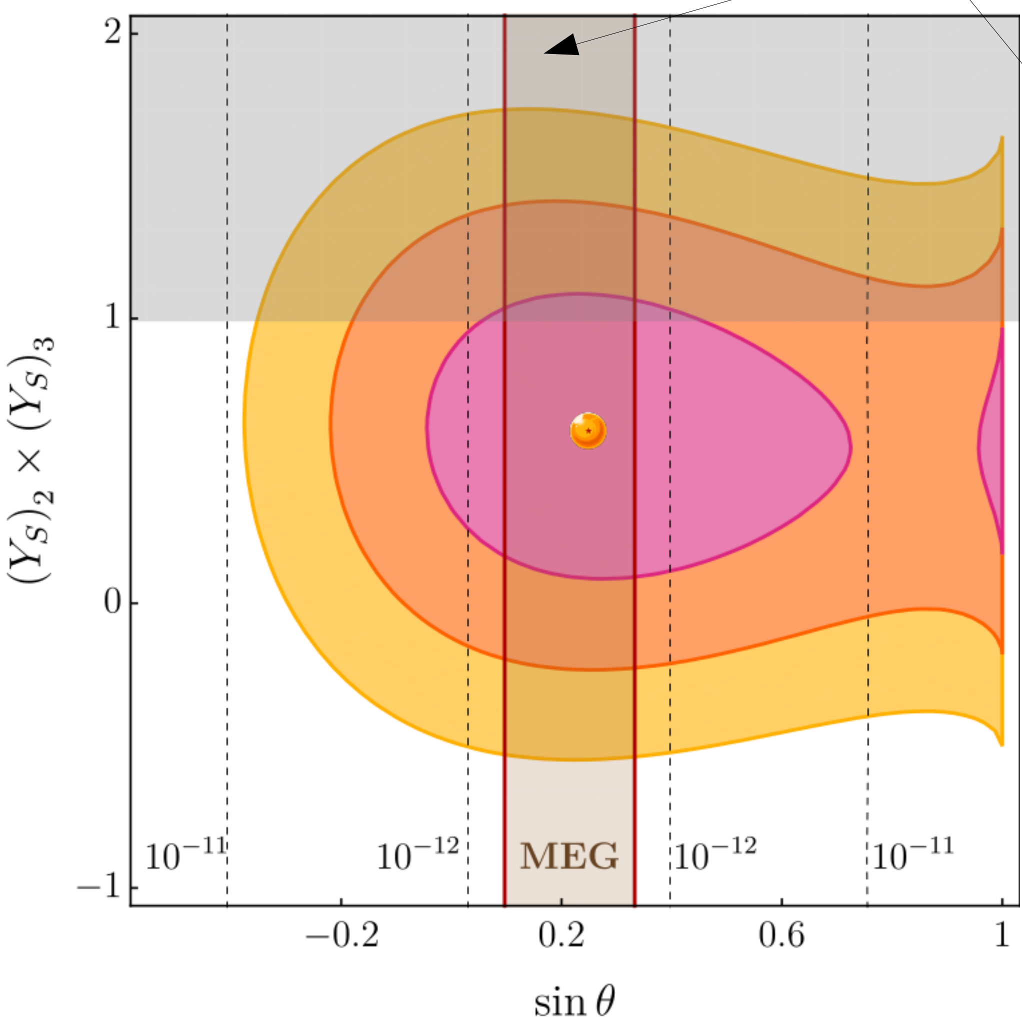


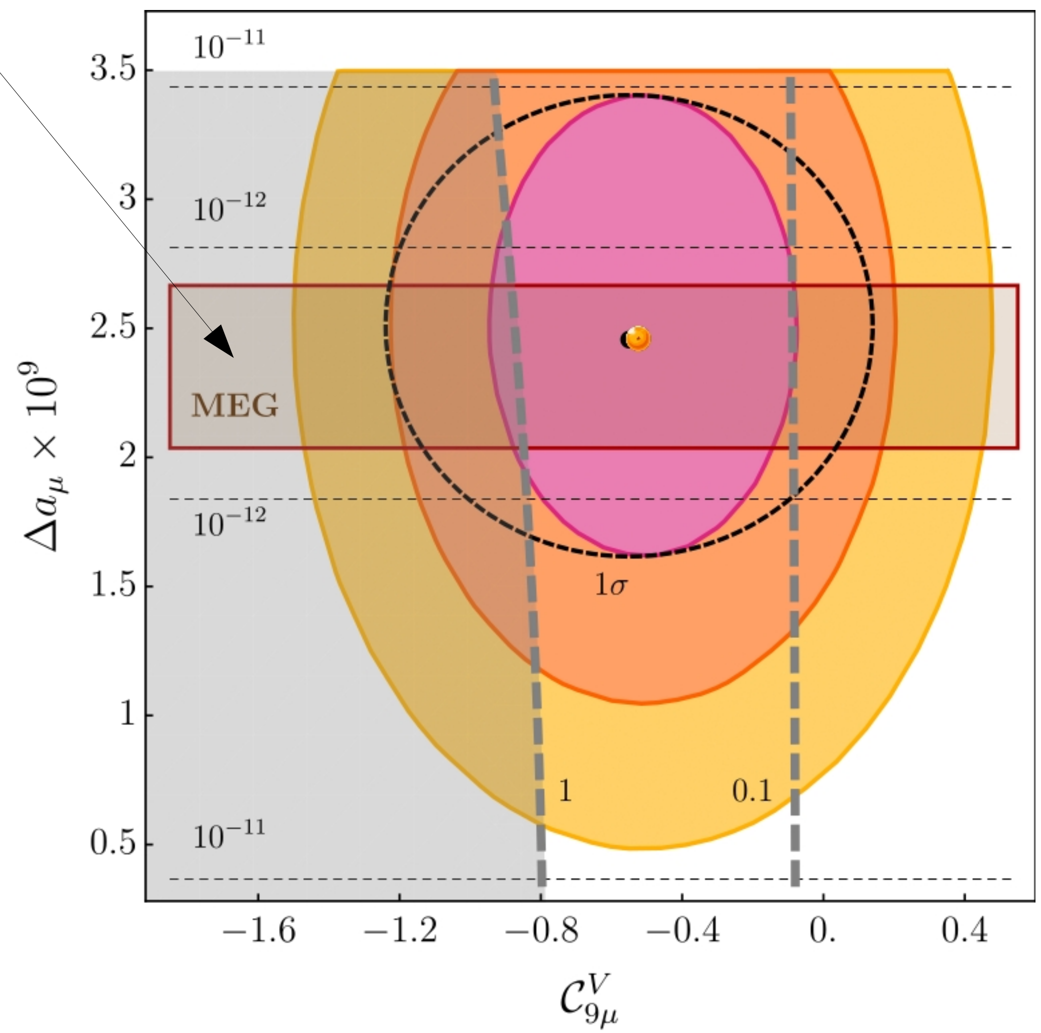
Flavor universal $b \to s\ell\ell$



Muon $g-2$

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





A free parameter in Y_N

For experts: the *R* matrix angle

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

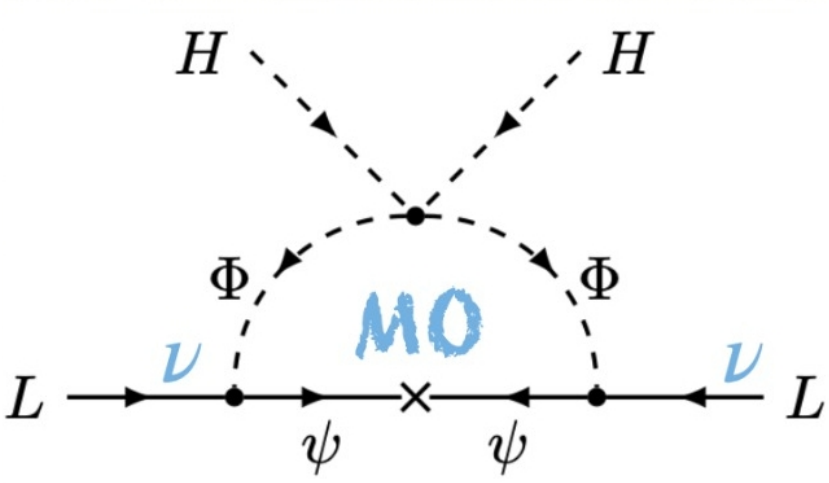
$b \to s\ell\ell$

Other Scotogenic variations

C. Hagedorn, J. Herrero-Garcia,
E. Molinaro, M. A. Schmidt
1804.04117

$\mathrm{U}(1)_{\mathrm{DM}}$ global symmetry

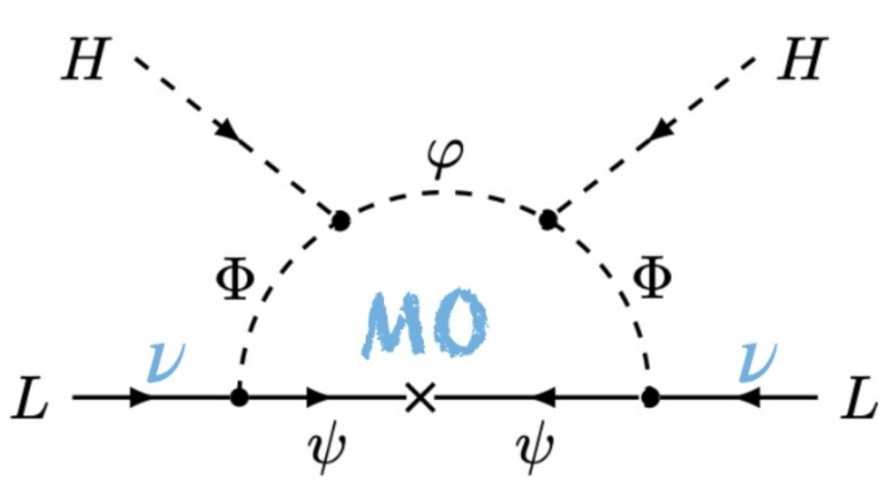
Dirac fermions



Other variants also discussed: gauge version, $\mathbb{Z}_N$ symmetry and triplet fermions

A. Beniwal, J. Herrero-Garcia,
N. Leerdam, M. White, A. G. Williams
2010.05937

Additional scalar singlet



Modified neutrino mass generation and scalar DM phenomenology

Other (Scotogenic) works

D. Sánchez-Portillo, P. Escribano, A. Vicente, 2301.05249

V. De Romeri, J. Nava, M. Puerta, A. Vicente, 2210.07706

A. E. Cárcamo Hernández, C. Hati, S. Kovalenko, J. W. F. Valle, C. A. Vaquera-Araujo, 2109.05029

P. Escribano, A. Vicente, 2107.10265

E. Ma, V. De Romeri, 2105.00552

S. Mandal, R. Srivastava, J. W. F. Valle, 2104.13401

C. Alvarado, C. Bonilla, J. Leite, J. W. F. Valle, 2102.07216

D. M. Barreiros, F. R. Joaquim, R. Srivastava, J. W. F. Valle, 2012.05189

Disclaimer (again)

Apologies for missing your paper!

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!

Backup slides

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

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

⇒

$$\mathrm{m}_R^2 - m_I^2 = 2\,\lambda_5 \, \langle H^0 \rangle^2$$

A charged Scotogenic model

$\mathbb{Z}_2$ -odd scalars

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

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

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

Small mixing for $\kappa \ll 1$

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

The master parametrization

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

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

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

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

Analysis

Tools

SARAH-4.11.0

SPheno-4.0.2

micrOmegas-5.0.9

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

Constraints:

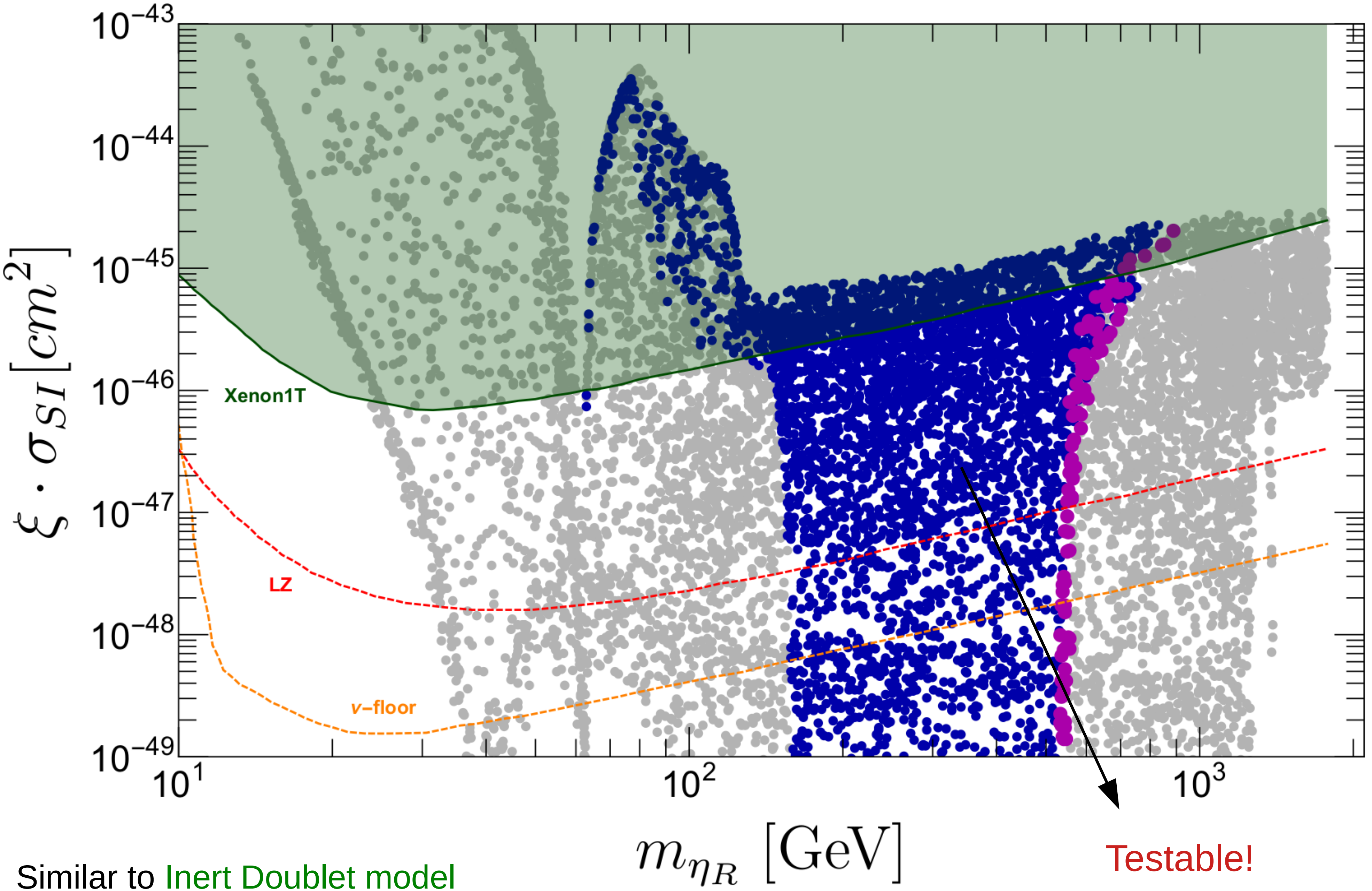
- Neutrino oscillation data
- Lepton flavor violation
- Electroweak precision data ($\Delta\rho$)
- Dark matter searches
- LHC searches
- Higgs decays (invisible & diphoton)
- Lifetime of the next-to-lightest $\mathbb{Z}_2$-odd state

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
$\delta\rho$	$[-0.00022, 0.00098]$
$\Omega_{\eta_R} h^2$	$[0.1164, 0.1236]$

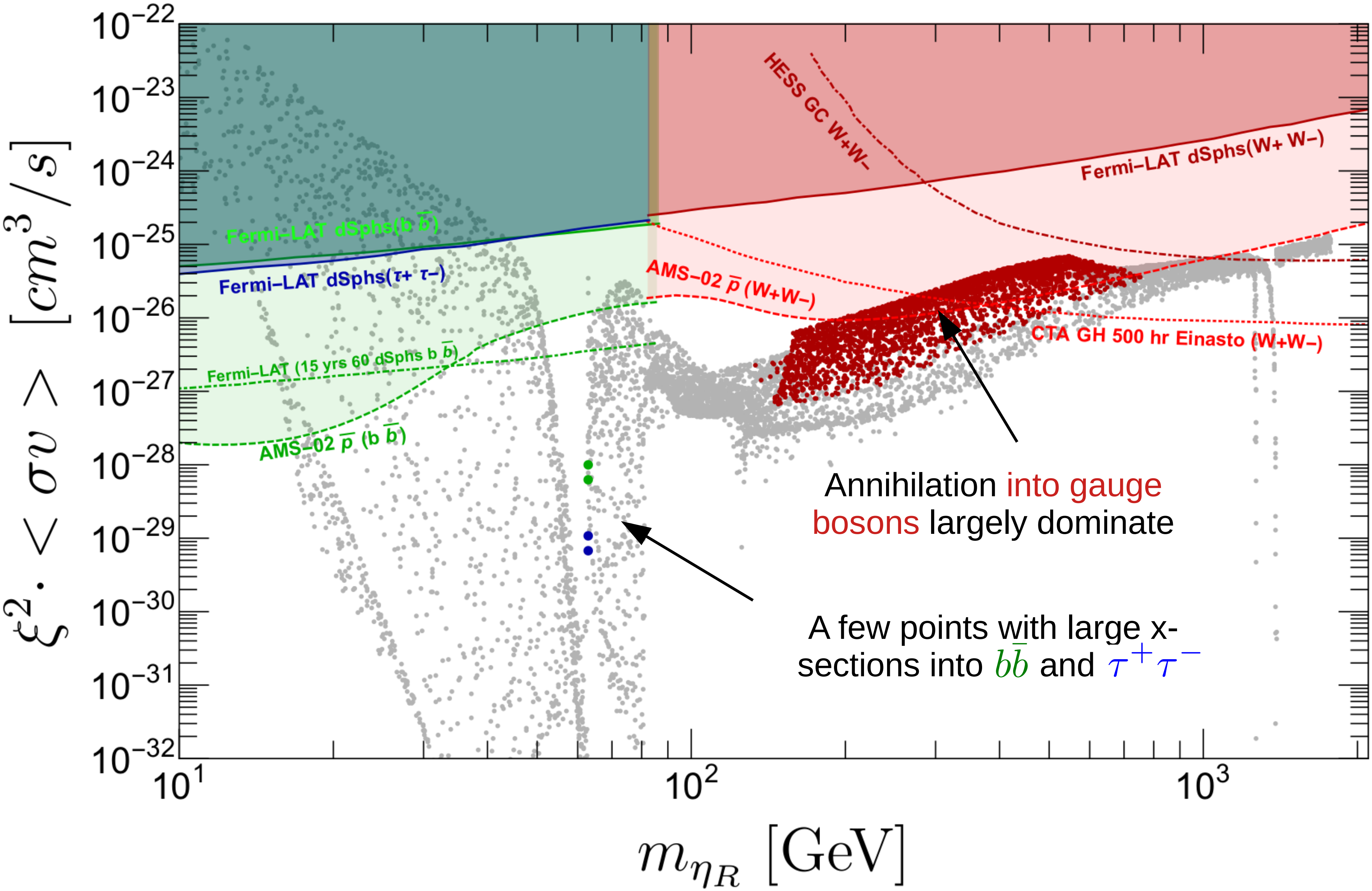
Z-boson mediated scattering suppressed due to sizable λ_5



Testable!

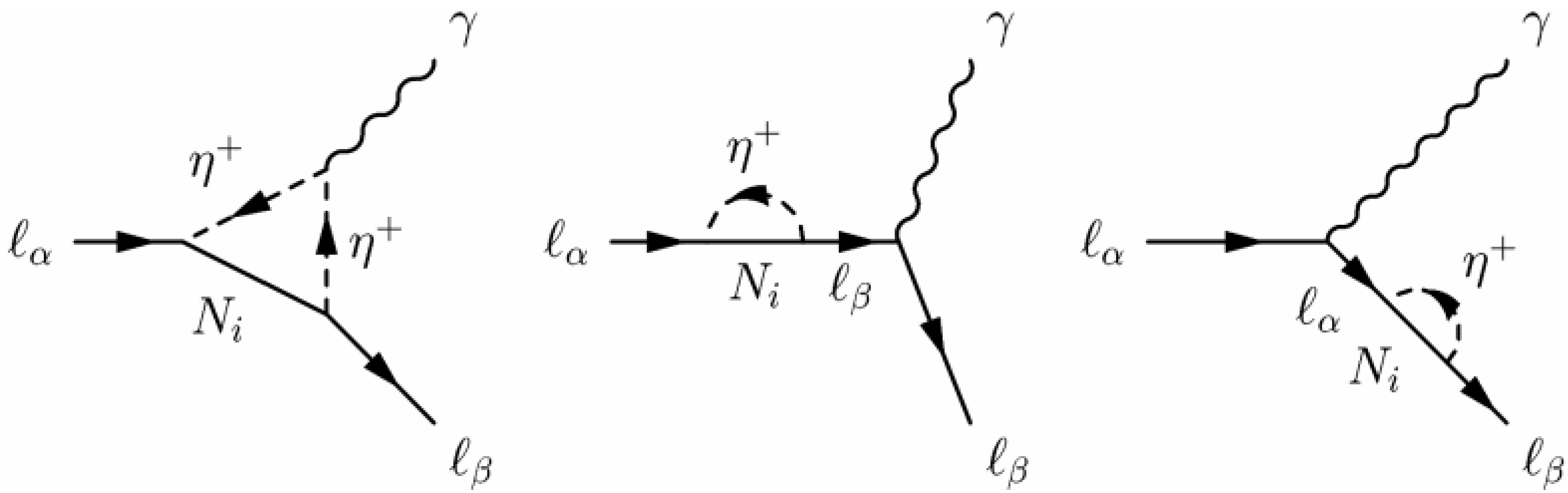
Similar to Inert Doublet model

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



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

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



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

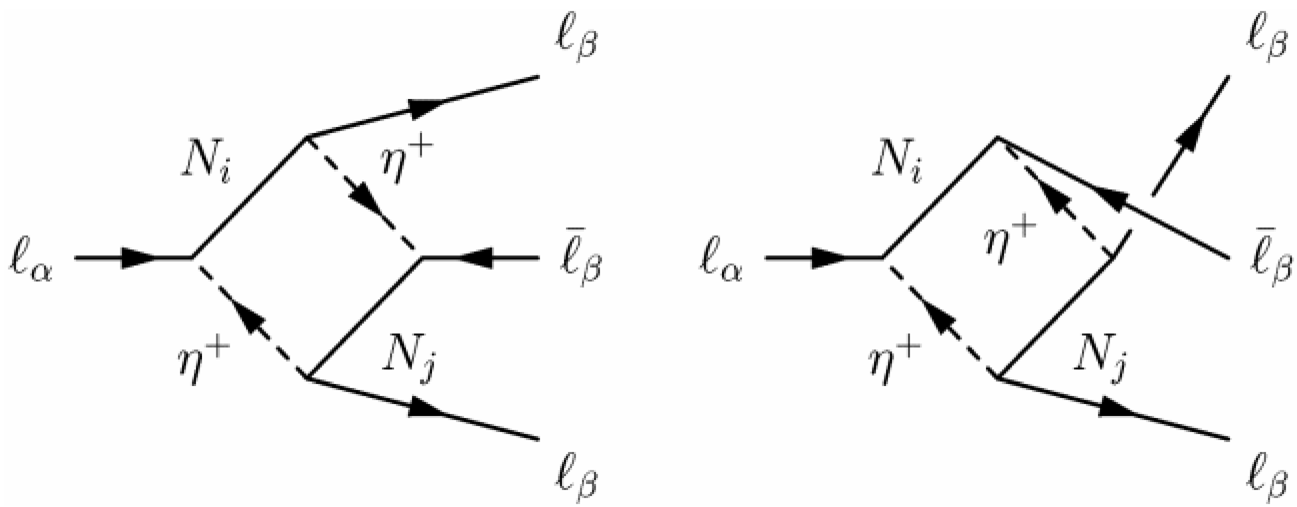
$$\mu_{\beta\alpha} = e m_\alpha A_D / 2$$

Transition magnetic moment

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

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

$\ell_\alpha(p) \to \ell_\beta(k_1)\bar{\ell}_\beta(k_2)\ell_\beta(k_3)$ [Toma, Vicente, 2013]



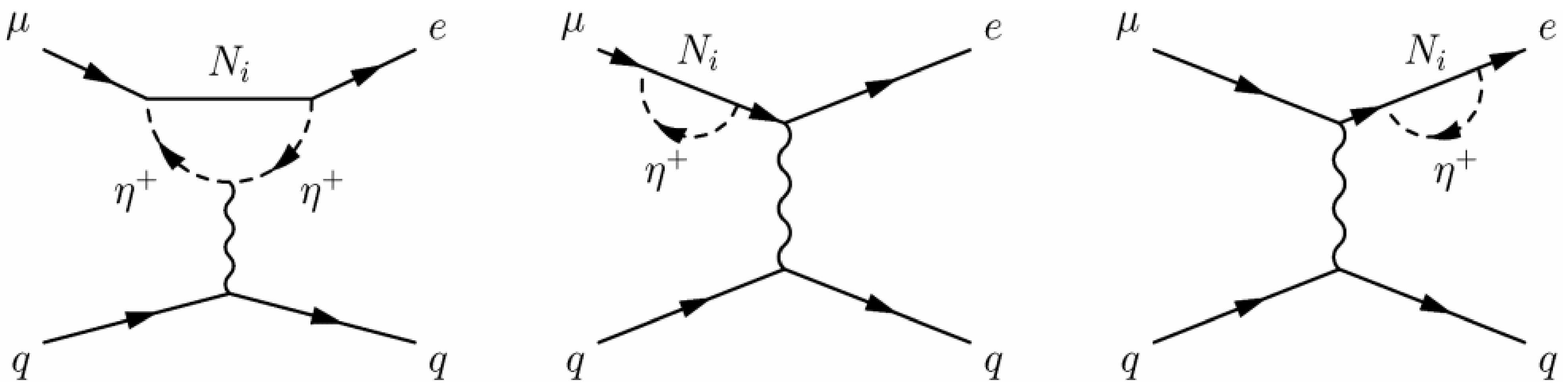
Boxes

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

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

$\mu - e$ 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