PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

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An extensive study of dark matter in the Singlet + Triplet Scotogenic Model

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ABOUT NEUTRINOS AND DARK MATTER

- Neutrinos are particles with a mass different from zero [1]. The actual Standard Model cannot explain these results by itself

  → Many theoretical models try to explain it

- 85% of the Universe's matter is dark [2]

  → A particle DM: observations of its gravitational effects on baryonic matter.
  The most recent measured of DM abundance by Planck satellite yields that

$$\Omega_{DM} h^2 = 0.1196 \pm 0.0031$$

There are different scenarios about how the abundance was generated and different DM candidates.

[1] Fukuda, Y.; et al. Phys. Rev.Let. 81 (8): 1562–1567 (1998)
[2] Planck Collaboration, 1502.01589

BORN FROM THE DARK

- To generate neutrino masses at tree level, a dim-5 operator can be introduced via the seesaw mechanism [1] [2] [3]. Neutrino masses can be generated at loop level.
- The idea of the Scotogenic Model was proposed by Ernest Ma [4]
  - His model introduced the possibility of giving mass to neutrinos at One-Loop
  - Also a WIMP-like Dark Matter (DM) candidate appears which can be either scalar or fermionic.

    → The stability of the DM particle is ensured by the same Z_2 symmetry that leads to the radiative origin of neutrino masses.

The Scotogenic Model has been generalized in different ways [5][6]

[1] R. N. Mohapatra et al Phys. Rev. Lett. 44 (1980) 912.

[2] J. Schechter, José W. F. Valle (1980). Phys. Rev. 22 (9): 2227–2235

[3] B. Bajc and G. Senjanovic, JHEP 0708 (2007) 014

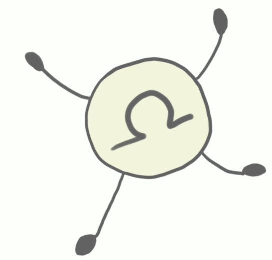
[4] E. Ma, Phys.Rev. D73, 077301 (2006), hep-ph/0601225.

[5] R. Foot et al., Z.Phys. C44 (1989) 441.

[6] M. Hirsch et al., JHEP 1310, 149 (2013), 1307.8134.

SINGLET+TRIPLET SCOTOGENIC: "A NEW SCOTOGENIC MODEL"

The full particle content of the model is given by the following table



	Standard Model			new fermions		new scalars	
	L	e	ϕ	Σ	F	η	Ω
Generations	3	3	1	1	1	1	1
$\mathrm{SU}(3)_{\mathrm{C}}$	1	1	1	1	1	1	1
$\mathrm{SU}(2)_{\mathrm{L}}$	2	1	2	3	1	2	3
$\mathrm{U}(1)_{\mathrm{Y}}$	-1	-2	1	0	0	1	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$	$-$	$+$
L	1	1	0	0	0	-1	0

The new interactions included in the Lagrangian are

$$\mathcal{L} \subset -Y^{\alpha\beta} L_\alpha e_\beta \phi - Y_F^\alpha (\bar{L}_\alpha \tilde{\eta}) F - \frac{M_F}{2} \overline{F^c} F$$

$$- Y_\Sigma^\alpha \bar{L}_\alpha^c \Sigma^\dagger \tilde{\eta} - \frac{1}{4} M_\Sigma \mathrm{Tr}\left(\overline{\Sigma}^c \Sigma\right) - Y_\Omega \mathrm{Tr}\left[\bar{\Sigma}\Omega\right] F + h.c.$$

Simple Scotogenic

Triplet Scotogenic

Singlet +Triplet Scotogenic

where $\tilde{\eta} = i\sigma\eta^*$

The corresponding scalar potential is

Singlet +Triplet Scotogenic

$$
\begin{aligned}
\mathcal{V} = & -m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta - \frac{m_\Omega^2}{2} \mathrm{Tr}\left(\Omega^\dagger \Omega\right) \\
& + \frac{\lambda_1}{2}\left(\phi^\dagger \phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger \eta\right)^2 + \frac{\lambda_3}{2}\left(\phi^\dagger \phi\right)\left(\eta^\dagger \eta\right) + \lambda_4\left(\phi^\dagger \eta\right)\left(\eta^\dagger \phi\right) + \frac{\lambda_5}{2}\left[\left(\phi^\dagger \eta\right)^2 + \left(\eta^\dagger \phi\right)^2\right] \\
& + \mu_1 \phi^\dagger \Omega \phi + \mu_2 \eta^\dagger \Omega \eta \\
& + \frac{\lambda_1^\Omega}{2}\left(\phi^\dagger \phi\right) \mathrm{Tr}\left(\Omega^\dagger \Omega\right) + \frac{\lambda_2^\Omega}{4}\left[\mathrm{Tr}\left(\Omega^\dagger \Omega\right)\right]^2 + \frac{\lambda_\eta^\Omega}{2}\left(\eta^\dagger \eta\right) \mathrm{Tr}\left(\Omega^\dagger \Omega\right)
\end{aligned}
$$

The conditions for the parameters in the scalar potential are

$$
\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2^\Omega \geq 0,
$$

$$
\lambda_3 + \sqrt{\lambda_1 \lambda_2} \geq 0, \quad \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1 \lambda_2} \geq 0,
$$

$$
\lambda_1^\Omega + \sqrt{2\lambda_1 \lambda_2^\Omega} \geq 0, \quad \lambda_\eta^\Omega + \sqrt{2\lambda_2 \lambda_2^\Omega} \geq 0,
$$

$$
\sqrt{2\lambda_1 \lambda_2 \lambda_2^\Omega} + \lambda_3 \sqrt{2\lambda_2^\Omega} + \lambda_1^\Omega \sqrt{\lambda_2} + \lambda_\eta^\Omega \sqrt{\lambda_1} + \sqrt{\left(\lambda_3 + \sqrt{\lambda_1 \lambda_2}\right)\left(\lambda_1^\Omega + 2\sqrt{\lambda_1 \lambda_2^\Omega}\right)\left(\lambda_\eta^\Omega + \sqrt{\lambda_2 \lambda_2^\Omega}\right)} \geq 0.
$$

Scalar sector

The scalar fields presented in the model can be written as follows

$$\eta = \begin{pmatrix} \eta^+ \\ (\eta_R + i\eta_I)/\sqrt{2} \end{pmatrix} \qquad \phi = \begin{pmatrix} \varphi^+ \\ (h_0 + v_\phi + i\psi)/\sqrt{2} \end{pmatrix}$$

$$\Omega = \begin{pmatrix} (\Omega_0 + v_\Omega)/\sqrt{2} & \Omega^+ \\ \Omega^- & -(\Omega_0 + v_\Omega)/\sqrt{2} \end{pmatrix}$$

The masses for the neutral scalar are

$$m^2_{H^\pm} = 2\mu_1 \frac{(v_\phi^2 + v_\Omega^2)}{v_\Omega},$$

$$m^2_{\eta^\pm} = m^2_\eta + \frac{1}{2}\lambda_3 v_\phi^2 + \frac{1}{\sqrt{2}}\mu_2 v_\Omega + \frac{1}{2}\lambda_\eta^\Omega v_\Omega^2,$$

$$m^2_{\eta_R} = m^2_{\eta^\pm} + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v_\phi^2 + \frac{1}{2}\lambda_\eta^\Omega v_\phi^2 - \frac{1}{\sqrt{2}}\mu_2 v_\Omega,$$

DM candidate

$$m^2_{\eta_I} = m^2_{\eta^\pm} + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v_\phi^2 + \frac{1}{2}\lambda_\eta^\Omega v_\phi^2 - \frac{1}{\sqrt{2}}\mu_2 v_\Omega.$$

Fermionic sector

$$\Sigma = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} \end{pmatrix}$$

The DM candidate will be the lightest mass eigenstate of the mass matrix

$$\mathcal{M}_\chi = \begin{pmatrix} M_\Sigma & \frac{1}{\sqrt{2}} Y_\Omega v_\Omega \\ \frac{1}{\sqrt{2}} Y_\Omega v_\Omega & M_F \end{pmatrix}$$

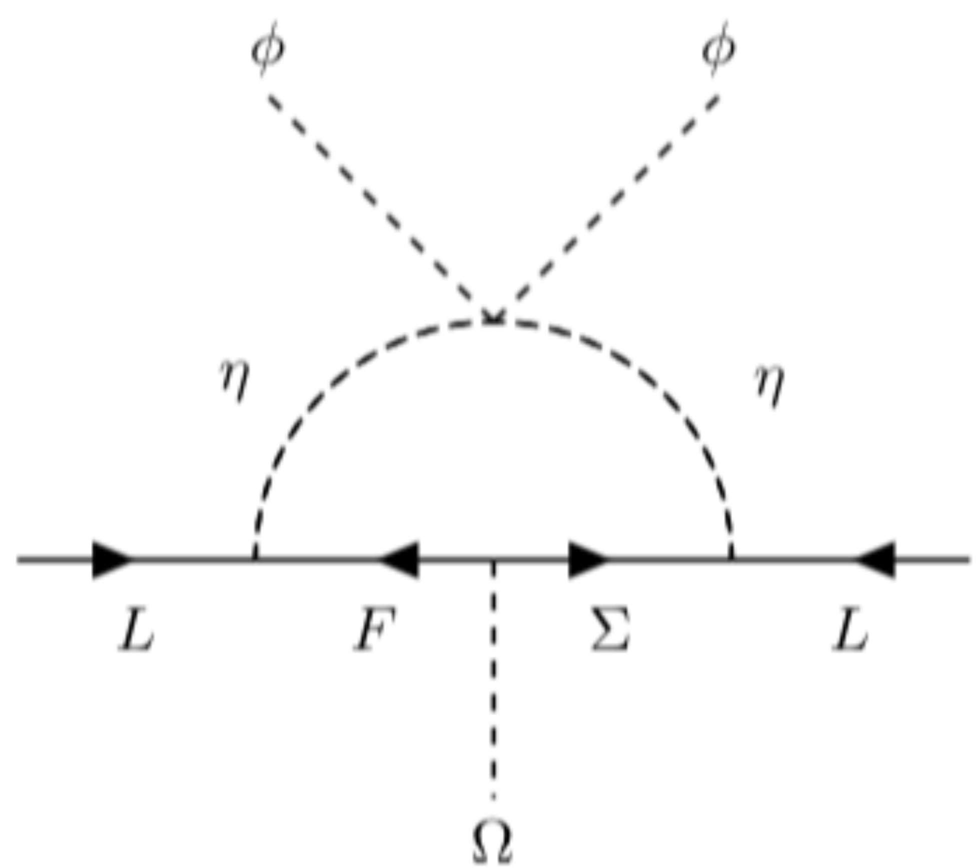
The fermion masses generated at tree level

$$\begin{aligned} m_\chi^\pm &= M_\Sigma, \\ m_{\chi_1^0} &= \frac{1}{2}\left(M_\Sigma + M_F - \sqrt{(M_\Sigma - M_F)^2 + 4(2Y_\Omega v_\Omega)^2}\right) \\ m_{\chi_2^0} &= \frac{1}{2}\left(M_\Sigma + M_F + \sqrt{(M_\Sigma - M_F)^2 + 4(2Y_\Omega v_\Omega)^2}\right) \\ \tan(2\theta) &= \frac{4Y_\Omega v_\Omega}{M_\Sigma - M_F} \end{aligned}$$

NEUTRINO MASS GENERATION

$$\mathcal{M}^{\nu}_{\alpha\beta} = \sum_{\sigma=1,2} \frac{Y^{\nu}_{\alpha\sigma} Y^{\nu}_{\beta\sigma}}{32\pi^2} m_{\chi_\sigma} \left(\frac{m^2_{\eta_R}}{m^2_{\eta_R} - m^2_{\chi_\sigma}} \ln\left(\frac{m^2_{\eta_R}}{m^2_{\chi_\sigma}}\right) - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - m^2_{\chi_\sigma}} \ln\left(\frac{m^2_{\eta_I}}{m^2_{\chi_\sigma}}\right)\right)$$

$$Y^{\nu} = \begin{pmatrix} Y^1_{\Sigma} & Y^1_F \\ Y^2_{\Sigma} & Y^2_F \\ Y^3_{\Sigma} & Y^3_F \end{pmatrix} \cdot V(\theta)\,.$$



$$Y^{\nu}_{\alpha\beta} = U_{\nu}\sqrt{m_{\nu}}\rho\sqrt{\mathcal{F}}^{-1},$$

[J. A. CASAS AND A. IBARRA, NUCL. PHYS. B618, 171 (2001), HEP-PH/0103065]

One neutrino will be massless

Constraints

For our analysis the following constraints have been considered

- Lepton Flavor Violation $\mu \to e\gamma < 4.2 \times 10^{-13}$ [Baldini+ (MEG), EPJC 2016]

  $\mu \to 3e < 1.0 \times 10^{-12}$ [Bellgardt+ (SINDRUM), NPB 1988] [Rocha-Morán+ arxiv:1605.01915]

  $CR(\mu - e, Au) < 7.10^{-13}$ [Bertl+ (SINDRUM II), EPJC 2006]

- Neutrino oscillation parameters [de Salas+ PLB, 2018]
- Electroweak precision tests $-0.00018 \leq \delta\rho \leq 0.00096 (3\sigma)$
- DM and cosmological observations
- Invisible Higgs decay of the Higgs boson $BR(h^0 \to inv) \leq 24\%$

  $0.62 \leq BR(h^0 \to \gamma\gamma)/BR(h^0 \to \gamma\gamma)_{SM} \leq 1.7$

- Colliders $80GeV \leq m_{H^\pm} \leq 1TeV$ $122GeV \leq m_{h^0} \leq 128GeV$

  $m_H \leq 1TeV$

Tools

For the montecarlo simulation we develop our own python code.

For our analysis we use numerical tools.

- SARAH: model implementation, computation off all the vertices, mass matrices, one loop correction for tadpole and self-energies.
- SPHENO: computation of the physical particle spectrum and low energy observables
- MicrOMEGAs: computation of the thermal component to the DM relic abundance and the DM-nucleon scattering cross section.
- MadGraph: computation of the cross section.
- Checkmate: test our results with the last results given by the LHC.

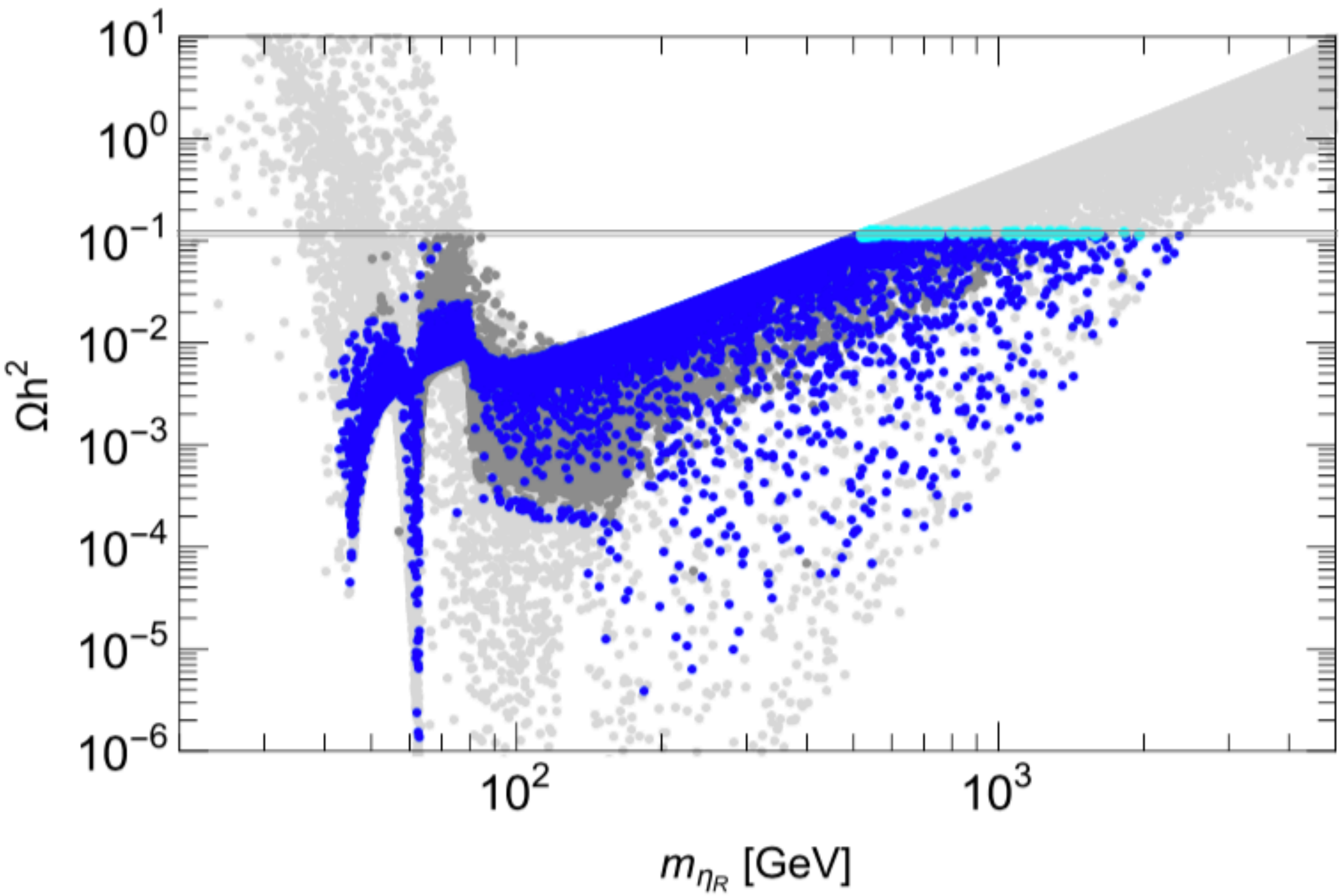
Numerical scan

The values for the main parameter considered in the analysis are

Parameter	**Range**
M_N	$[5 \cdot 10^3, 10^4]$ (GeV)
M_Σ	$[5 \cdot 10^3, 10^4]$ (GeV)
m_η^2	$[100, 5000]$ (GeV^2)
$\mu_{1,2}$	$[10^{-8}, 5 \cdot 10^3]$ (GeV)
v_Ω	$[10^{-5}, 5]$ (GeV)
$\lvert\lambda_i\rvert$, $i = 1...4$	$[10^{-8}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_{1,2}^\Omega\rvert$	$[10^{-8}, 1]$
$\lvert\lambda_\eta^\Omega\rvert$	$[10^{-8}, 1]$
$\lvert Y_\Omega\rvert$	$[10^{-8}, 1]$

RELIC DENSITY

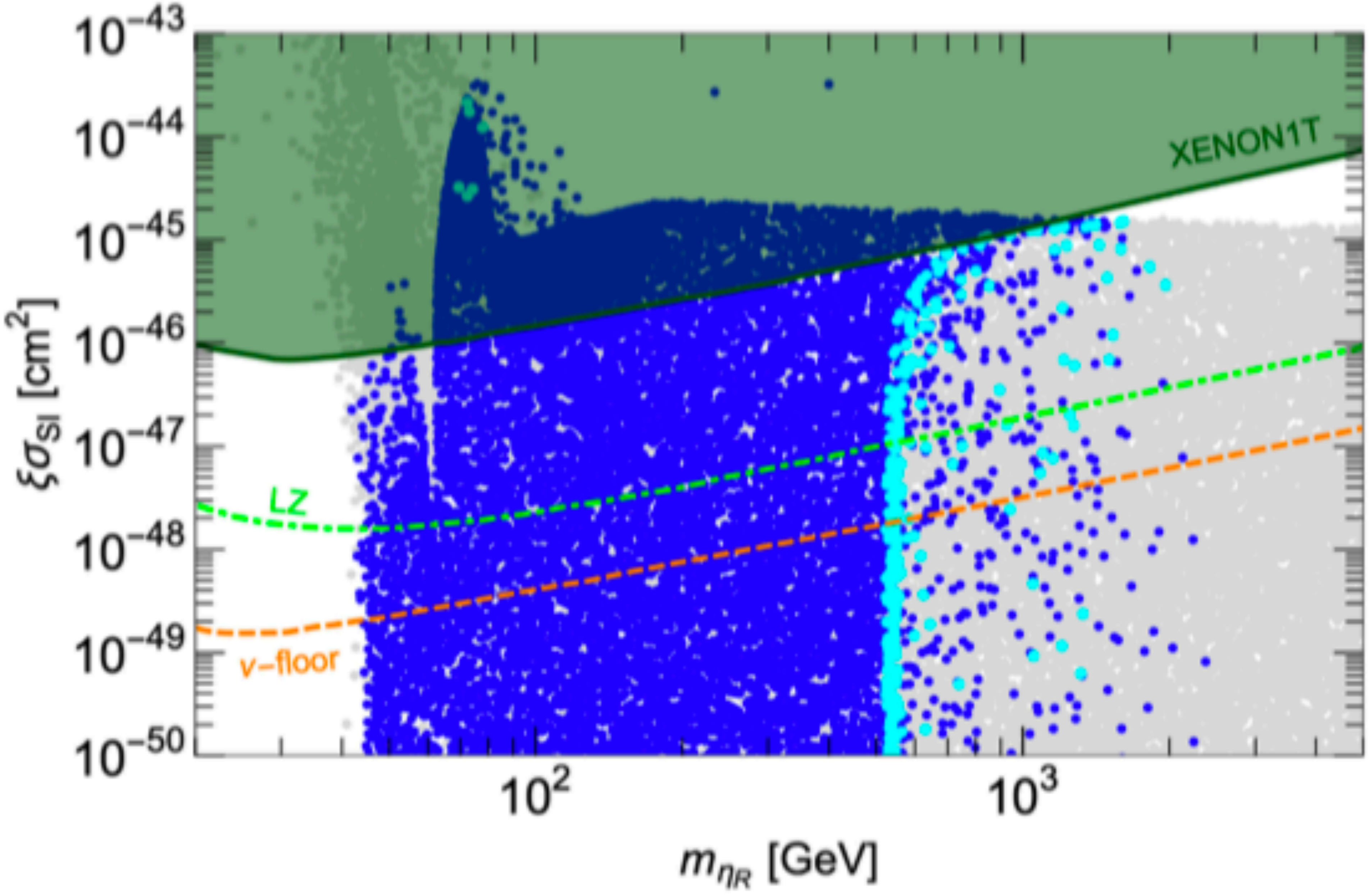
[arXiv:1910.08422]



Relic abundance $\Omega_{\eta_R} h^2$ as a function of the η_R mass. Cyan points are solutions that fall exactly within the 3σ C.L. cold DM measurement by the Planck collaboration. Dark grey points are solutions in conflict with the current limit on WIMP-nucleon SI elastic scattering cross section set by XENON1T

[Planck Collaboration, 1502.01589]
[Xenon1T collaboration arXiv:1805.12562v2 [astro-ph.CO]]

[arXiv:1910.08422]

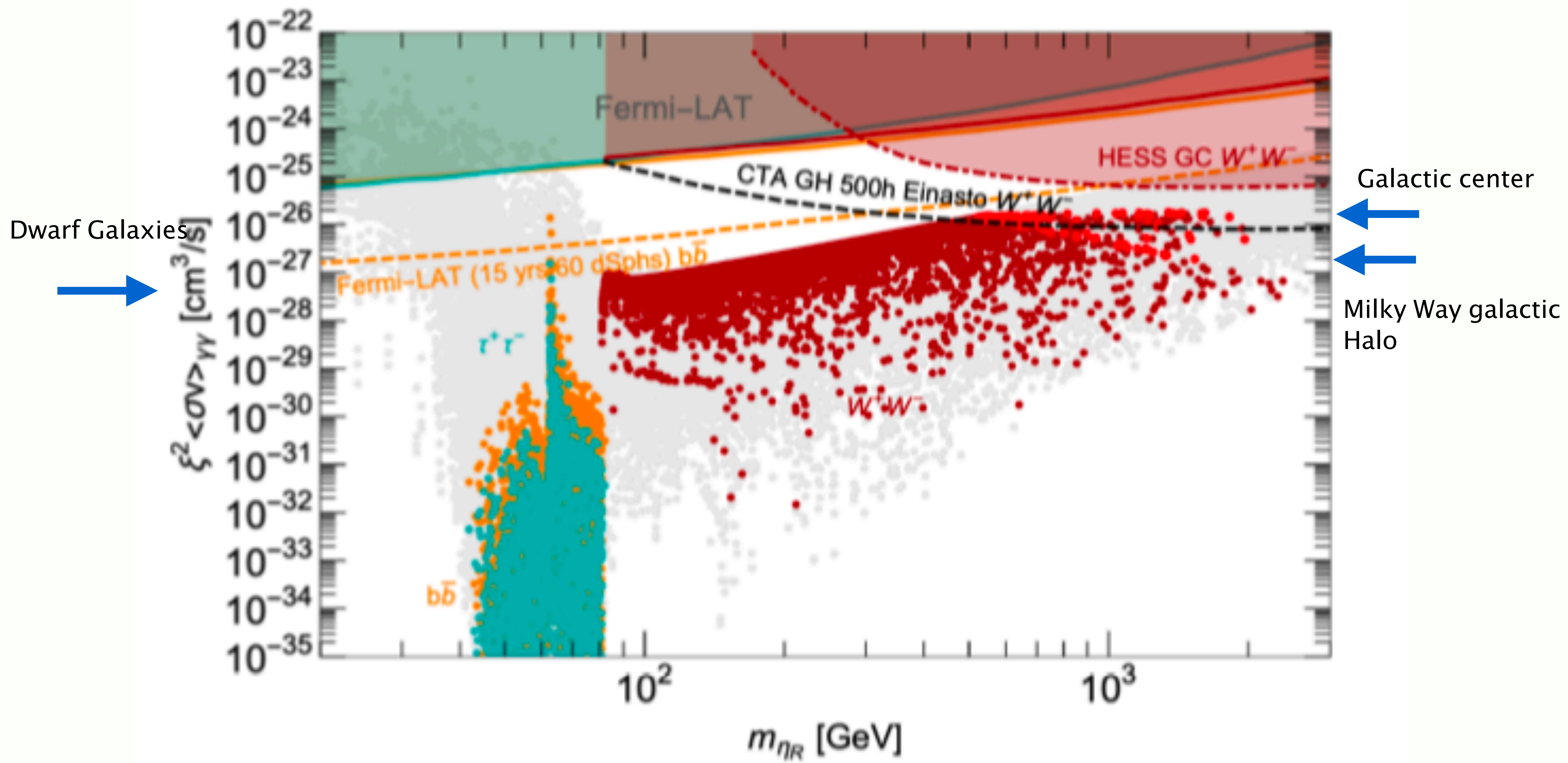


Spin-independent η_R-nucleon elastic scattering cross section versus the η_R mass.The dark green line denotes the most recent upper bound from XENON1T.The dashed orange line correspond to the neutrino floor limit from coherent elastic neutrino nucleus scattering.

[Xenon1T collaboration arXiv:1805.12562v2 [astro-ph.CO]]

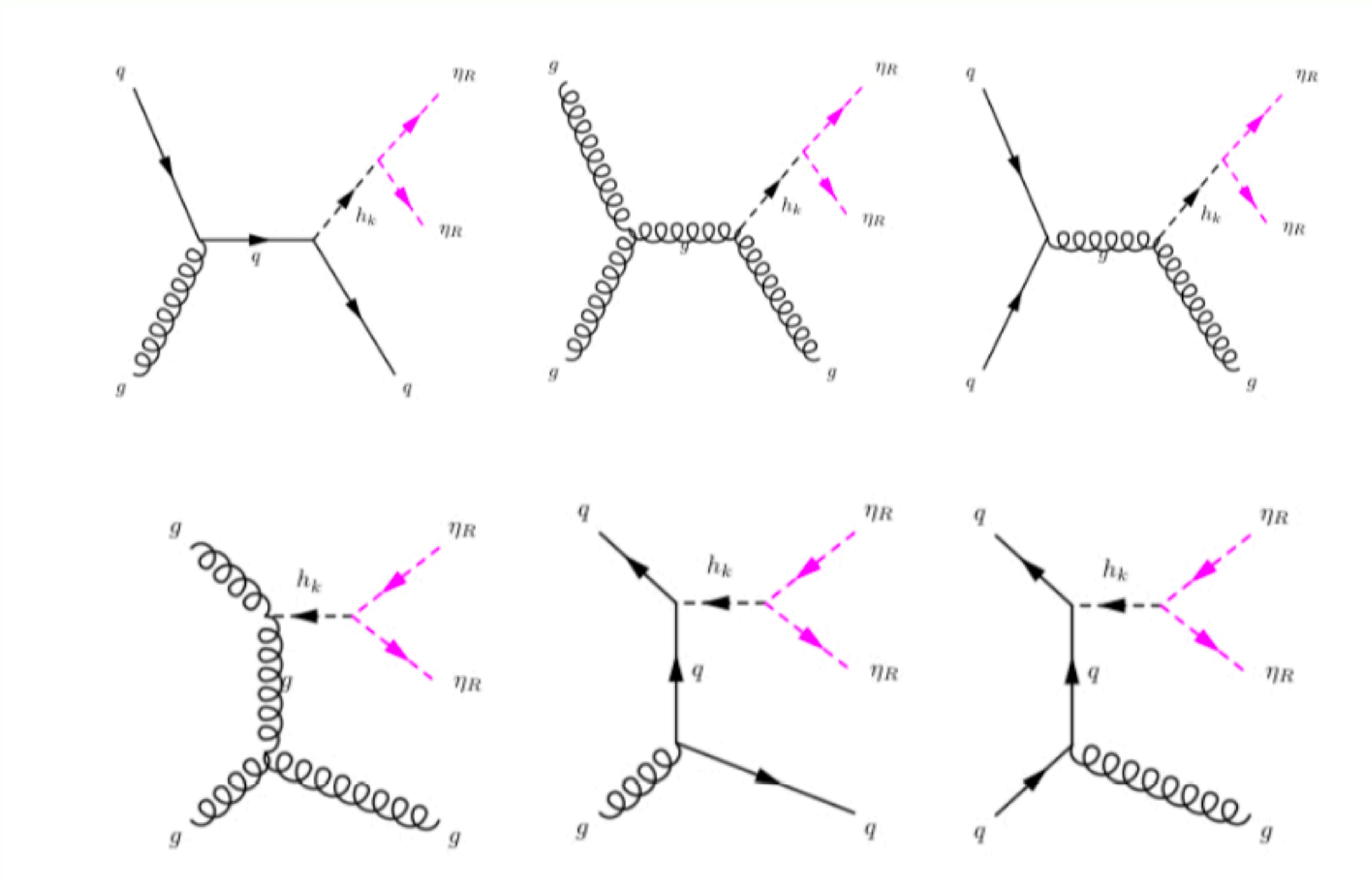
INDIRECT DETECTION

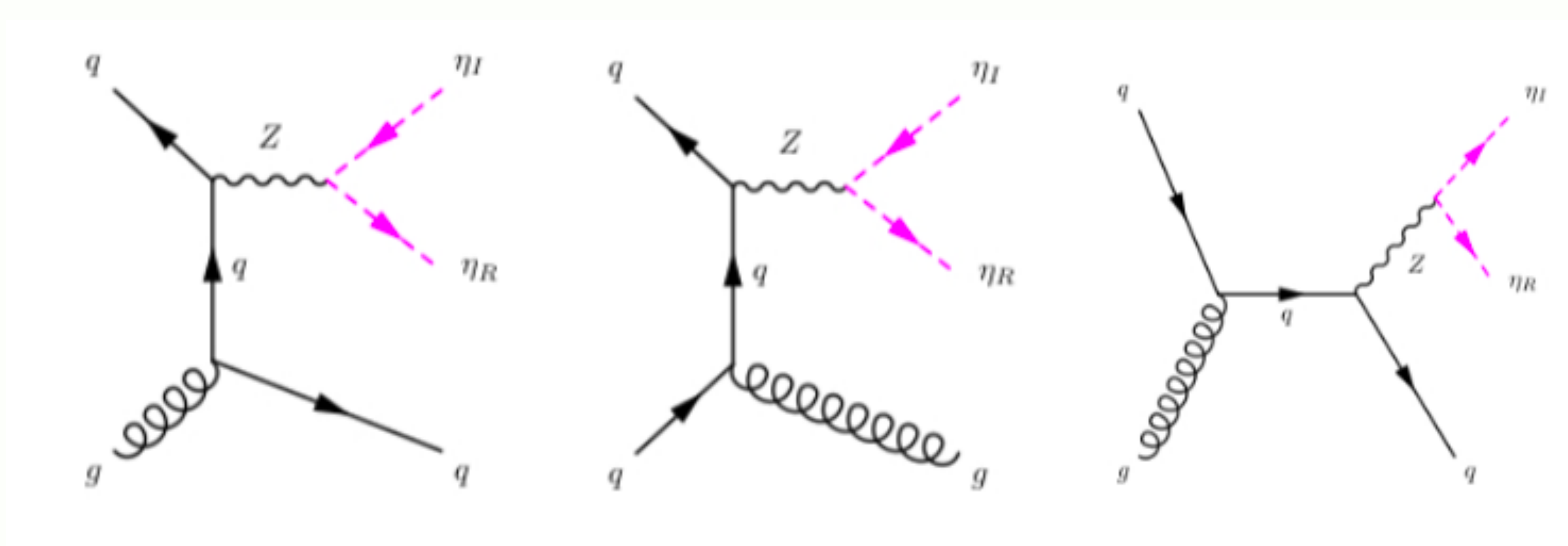
[arXiv:1910.08422]



Predicted DM annihilation cross section into γ rays (weighted by the relative abundance) for annihilations to $b\bar{b}$ (orange), $\tau^+\tau^-$ (dark cyan) and W^+W^- (dark and light red) final states (left panel). The dark cyan, red and orange lines are the current limit set by Fermi-LAT satellite. The dot dashed red line is the current limit for HESS telescope. Current limits lie a couple of orders of magnitude above the predicted signals but future data offer promising prospects.

$\not{E}_T$ + jet signal (mono-jet)



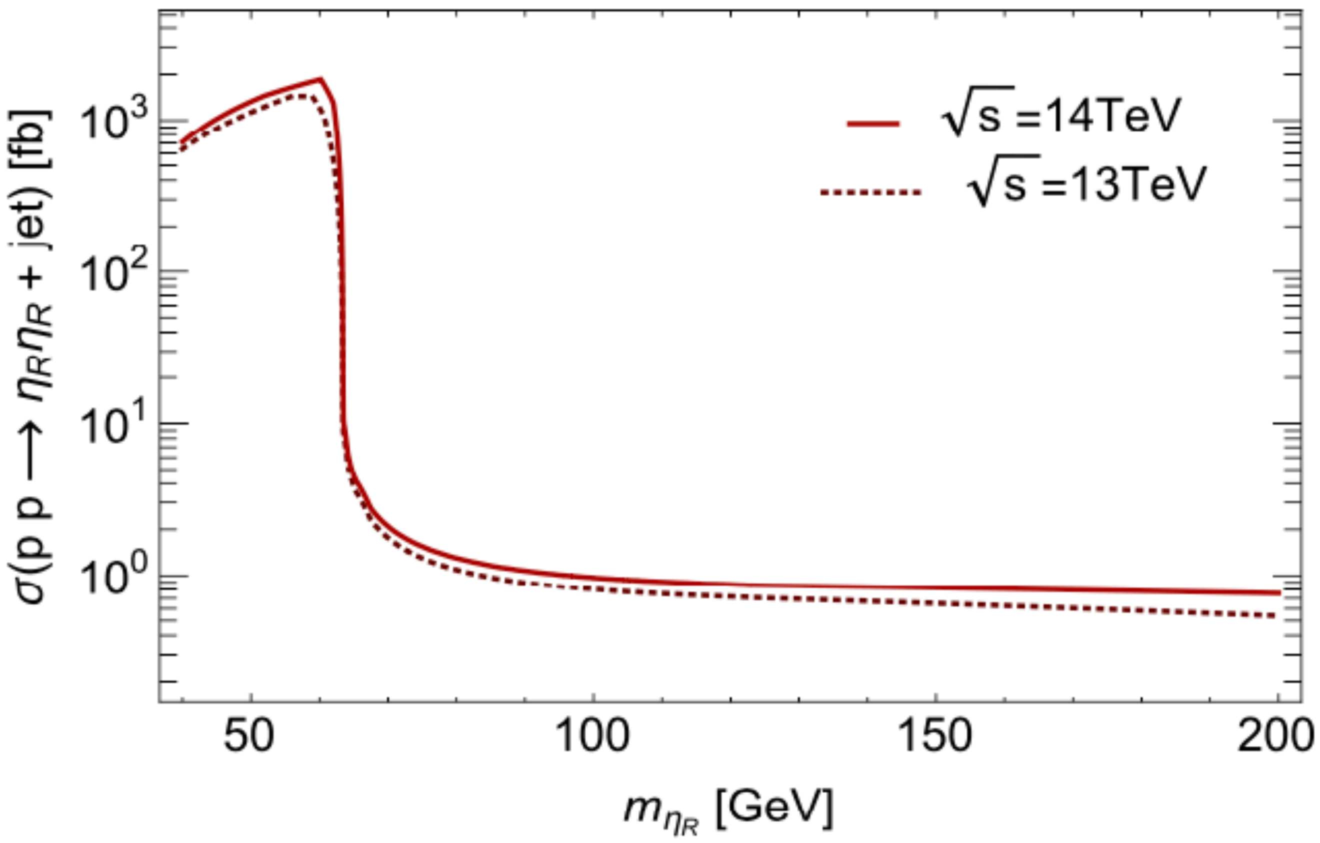


Parameters	Benchmark 1	Benchmark 2	Units
λ_3	3.64×10^{-5}	-1.64×10^{-5}	-
λ_4	7.02×10^{-7}	-3.29×10^{-7}	-
λ_5	-1.8×10^{-2}	-1.45×10^{-2}	-
λ_η^Ω	-1.32×10^{-5}	-7.11×10^{-6}	
μ_2	-4.57×10^{-8}	-1.59×10^{-1}	[GeV]
v_Ω	2.43×10^{-4}	9.21×10^{-1}	[GeV]
m_η^2	3678.17	2851.39	$[\mathrm{GeV}]^2$
Scalar masses			
m_{η_R}	55.92	49.09	[GeV]
m_{η_I}	65.04	57.38	[GeV]
m_{h^0}	124.68	125.54	[GeV]
m_H	425.9	834.45	[GeV]
Constraints			
Ωh^2	0.0107	0.0129	-
$\mathrm{BR}(h^0 \to inv.)$	0.155489	0.12939	-
$\mathrm{BR}(\mu \to e\gamma)$	7.33×10^{-29}	8.55×10^{-32}	-
$\mathrm{BR}(\mu \to eee)$	3.75×10^{-30}	1.01×10^{-30}	-
$\mathrm{CR}(\mu^-, Au \to e^-, Au)$	3.88×10^{-29}	1.40×10^{-29}	-
$\mathrm{BR}(h^0 \to \gamma\gamma)$	0.00226748	0.00212008	-
Δa_μ	2.18×10^{-14}	2.15×10^{-14}	-
σ_{SI}	5.953×10^{-10}	4.862×10^{-10}	cm^2

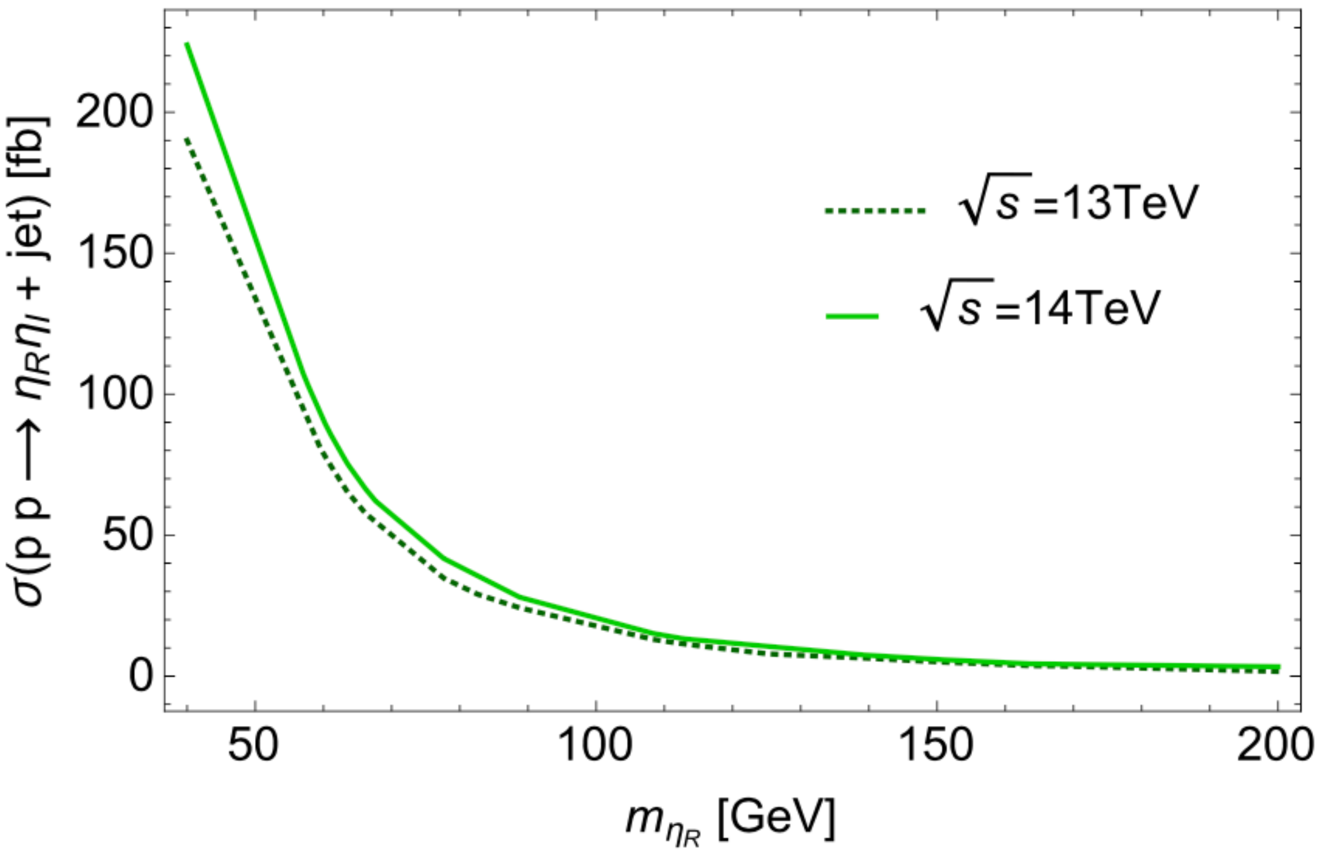
Quantity	Benchmark 1
$\sigma \perp d\sigma$ [fb]	787.791
Norm. Events $(\mathcal{L} \times \sigma)$	28439.2
Cuts Eff. $(\mathcal{A} \times \epsilon)$	0.00574
$S \pm dS$	163.241 ± 6.814
$B + dB$	4680.0 ± 160.0
r	0.220
Signal Region	**IM6**

$$r_{\mathrm{BSP}_1} = 0.220$$

λ_{345} =[-0.2,0.9]



Cross section of $pp \to \eta_R\eta_R$ + jet at LHC $\sqrt{s} = 13(14)$ TeV. The maximum value of the cross section is ~ 1400 (1800) fb for 13 (14) TeV respectively, both values are below those in the last analysis presented by ATLAS.

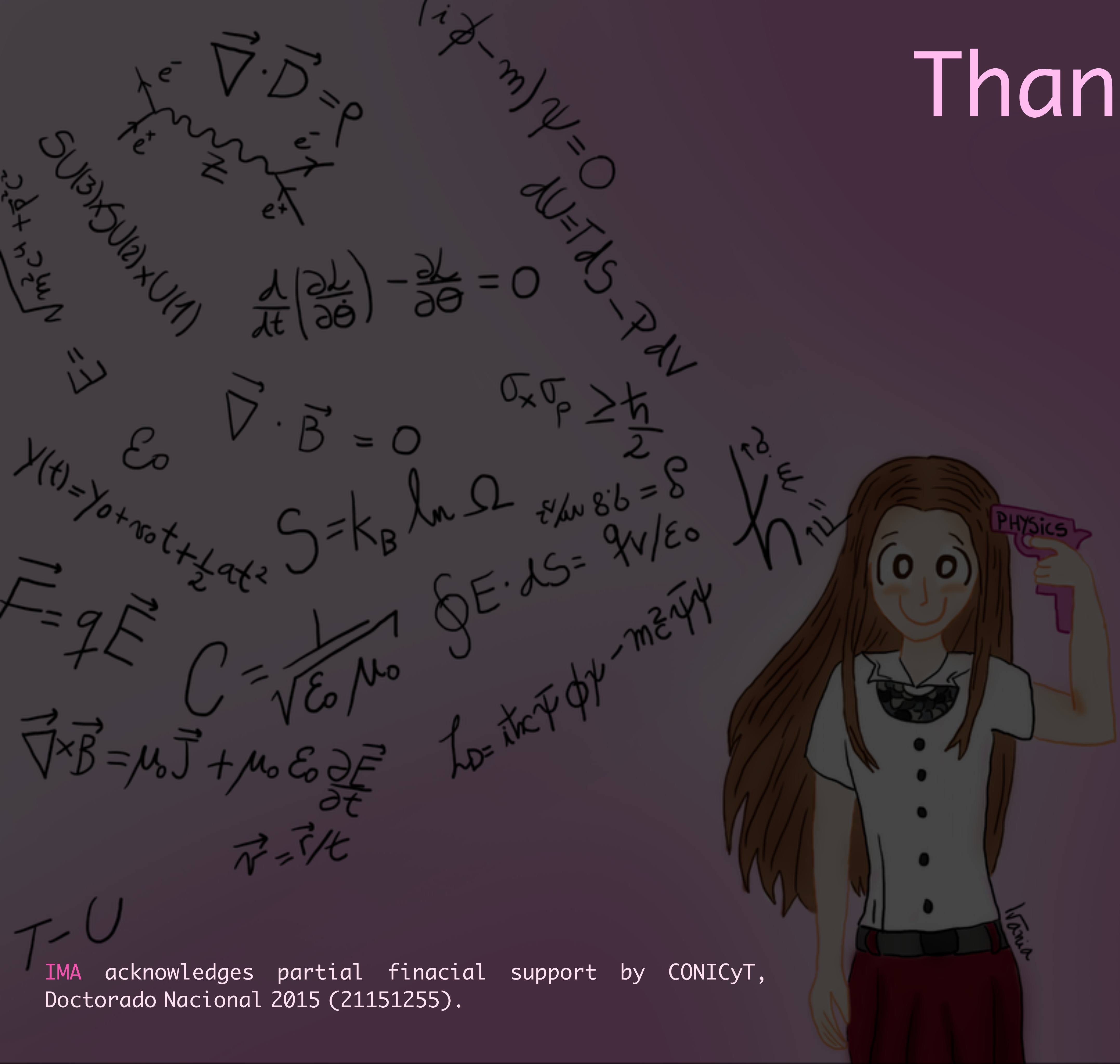


Cross section for the $pp \to \eta_R\eta_I$ jet production at LHC $\sqrt{s} = 13(14)$ TeV.

[arXiv:1910.08422]

SUMMARY AND OUTLOOK

Thanks!



IMA acknowledges partial finacial support by CONICyT, Doctorado Nacional 2015 (21151255).

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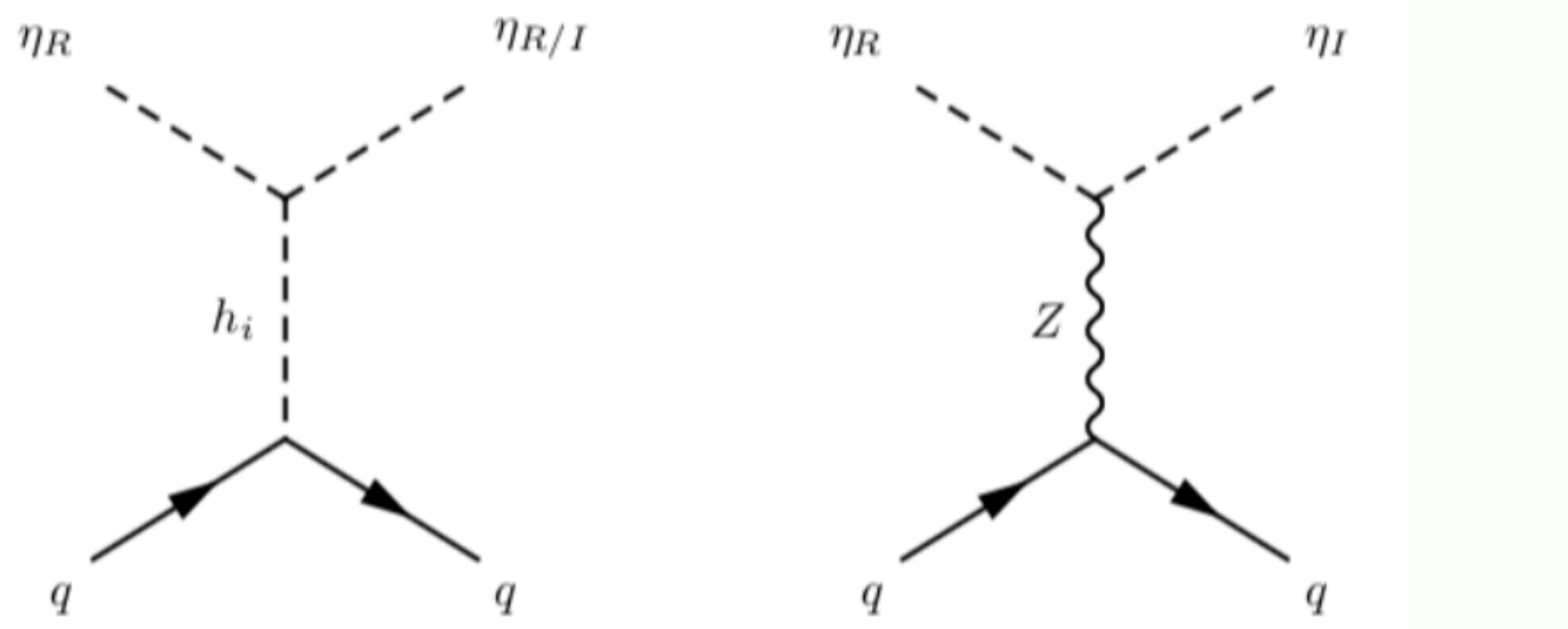
DIRECT DETECTION



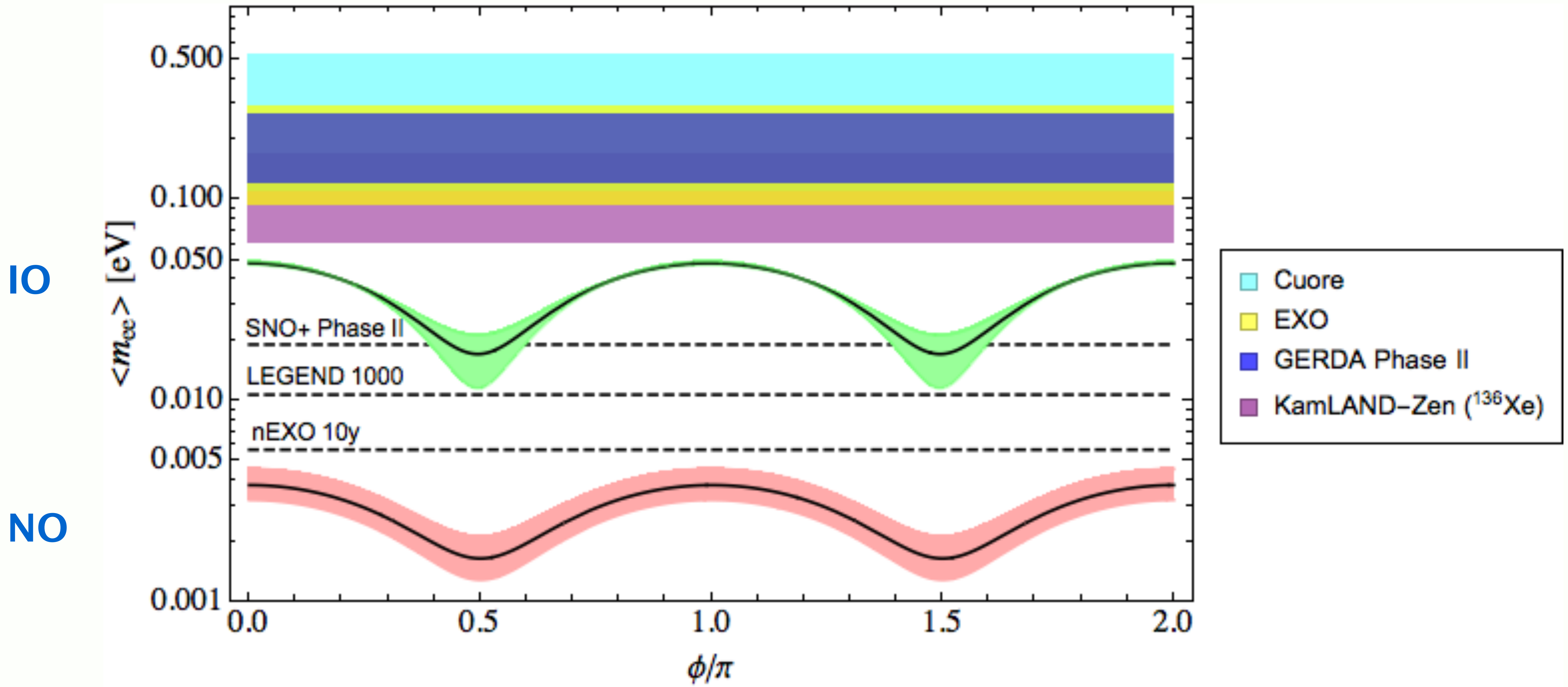
The tree-level spin independent DM nucleon interaction is through the Higgs and Z portals. If the mass difference of mass between the CP-odd particle and the DM is small, the interaction through the Z boson appear.

0v2B

[arXiv:1910.08422]

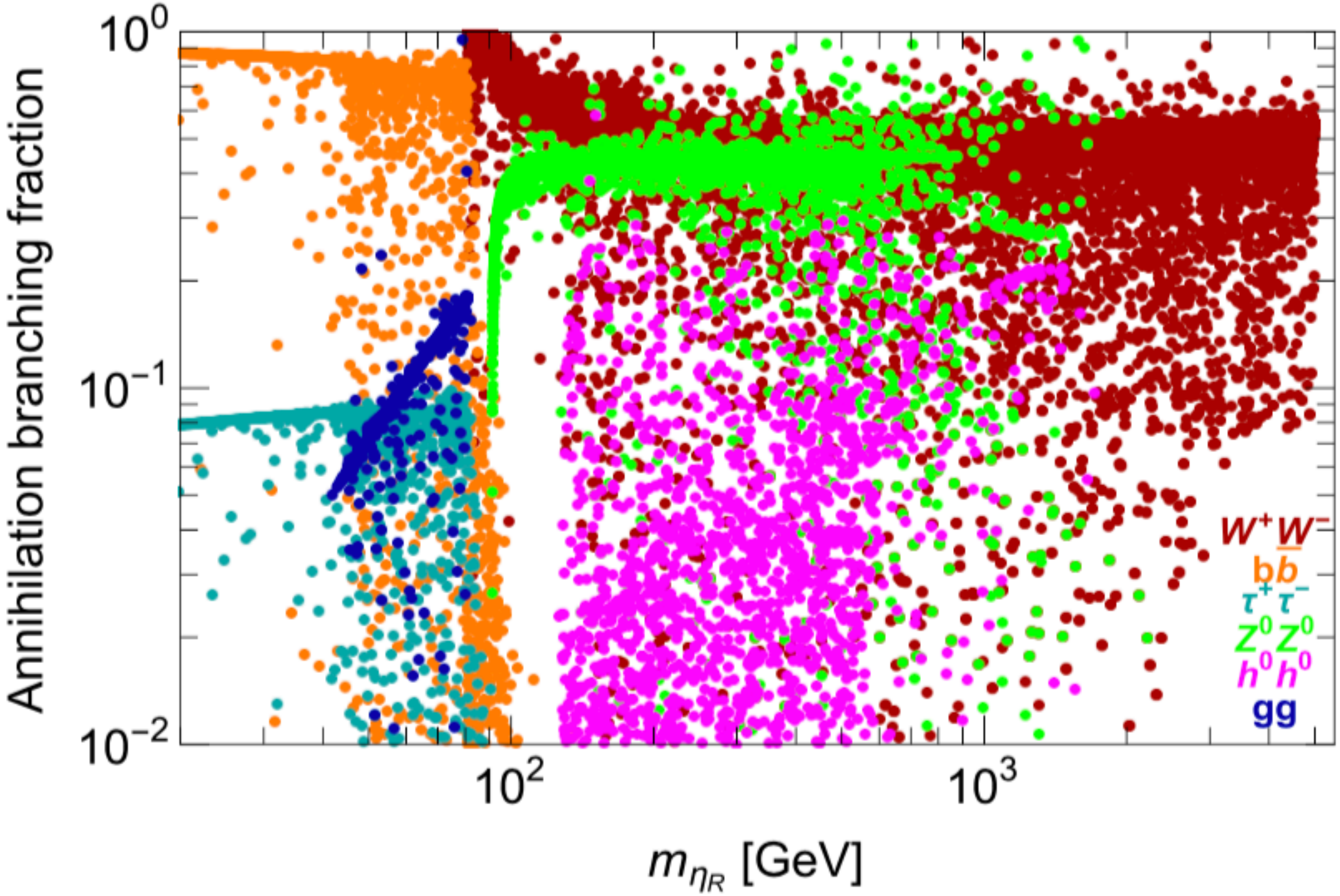
The Effective 0ν2β Majorana mass parameter expression is

$$\langle m_{ee}\rangle = \left|\sum_j U^2_{\nu,ej} m_j\right| = \left|\cos\theta^2_{12}\cos\theta^2_{13} m_1 + \sin\theta^2_{12}\cos\theta^2_{13} m_2 e^{2i\phi_{12}} + \sin\theta^2_{13} m_3 e^{2i\phi_{13}}\right|$$



The effective mass parameter characterizing the amplitude for neutrinoless double beta (0ν2β) decay has a lower limit

[arXiv:1910.08422]



Main branching fractions of the annihilation cross section of η_R into SM final states versus the mass of η_R.

CHECKMATE

This code allows to determine whether our model is excluded or not at 95% C.L. by comparing to recent experimental analyses in the same final states.

- First, we generate Monte Carlo events for our model with Madgraph.

- CheckMATE 2 determines whether the model is excluded or not at 95% C.L. by comparing to many recent experimental analyses.

signal events

signal error

$$r \equiv \frac{S - 1.96\Delta S}{S^{95}_{exp}}$$

According the algorithm definitions

a result is excluded $r \geq 1.5$

a result is compatible $r \leq 0.67$

a result is "potentially excluded" $0.67 < r < 1.5$

[arXiv:1812.05186]

Integrate luminosity of $36.1\,\mathrm{fb}^{-1}$

between the missing transverse momentum direction and each selected jet

Leading jet with $p_T > 250$ GeV and $|\eta| < 2.4$

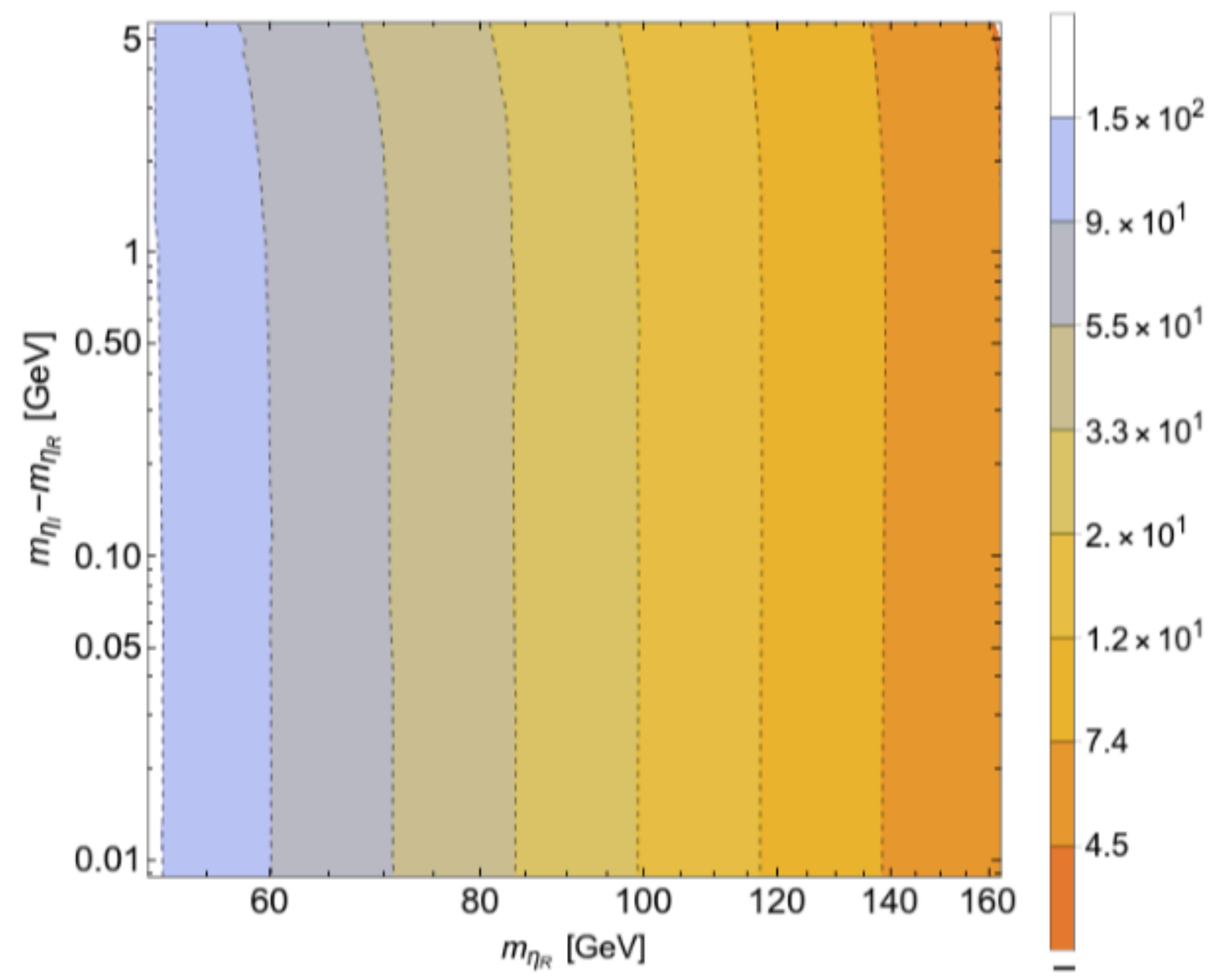
Separation in the azimuthal plane of $\Lambda\phi(\mathrm{jet}, pT^{\mathrm{miss}}) > 0.4$

Events with identify muons with $p_T > 10$ GeV or electrons with $p_T > 20$ GeV ✗

Quantity	**Benchmark 1**	**Benchmark 2**
$\sigma \perp d\sigma$ [fb]	787.791	1074.62
Norm. Events ($\mathcal{L} \times \sigma$)	28439.2	38793.7
Cuts Eff. ($\mathcal{A} \times \epsilon$)	0.00574	0.01086
$S \pm dS$	163.241 ± 6.814	421.3 ± 12.784
$B + dB$	4680.0 ± 160.0	12720.0 ± 340.0
r	0.220	0.263
Signal Region	**IM6**	**IM5**

Outline

- INTRODUCTION
- SCOTOGENIC MODELS
  - ✳SIMPLEST SCOTOGENIC MODEL
  - ✳TRIPLET SCOTOGENIC MODEL
  - ✳SINGLET + TRIPLET SCOTOGENIC
- CONSTRAINTS
- NUMERICAL SCAN
- RESULTS
- SUMMARY



Mass difference $m\eta I - m\eta R$ as a function of $m_{\eta R}$ in mono-jet events mediated by the Z boson, $pp \rightarrow \eta_R \eta_I$ + jet. The color shades represent values of the cross section in fb.

[arXiv:1910.08422]