Dark matter direct detection at one loop and in two-component scenarios

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Windows on the Universe

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Outline

1 **Introduction**

2 **Part I:** Dark matter direct detection at one loop

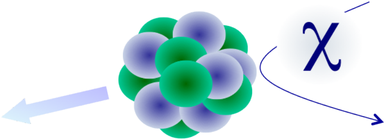
$\rightarrow$ Possible connection to neutrino masses

3 **Part II:** Two-component dark matter

$\rightarrow$ Reproducing DAMA's annual modulation signal

4 **Conclusions**

Introduction to dark matter (DM) direct detection (DD)



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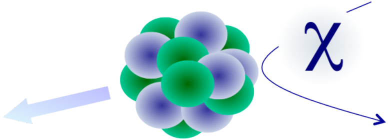

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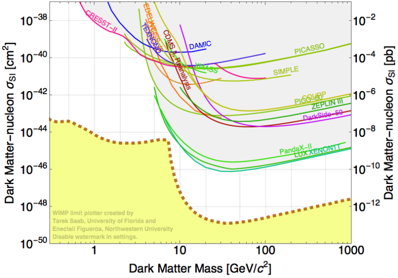
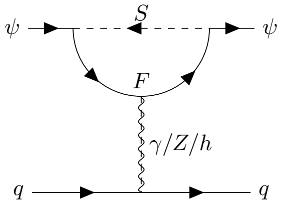


However, so far there is no DM positive signal in DD...

- What if DD is suppressed because it occurs at **one loop**?
- A **fermionic singlet** DM ψ (e.g. bino) is a natural example.



Dark sector	Field	SU(3)$_{\rm C}$	SU(2)$_{\rm L}$	U(1)$_{\rm Y}$	$G_{\rm dm}$
Dark matter	ψ	1	1	0	$I_{\rm dm}^{\psi}$
Dark scalar	S	1	$I_{\rm L}^S$	Y^S	$I_{\rm dm}^S$
Dark fermion	F	1	$I_{\rm L}^S$	Y^S	$I_{\rm dm}^{\psi} \otimes I_{\rm dm}^S$

$$\mathcal{L}_\psi = i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi + i\,\overline{F}\,D\!\!\!\!/\,F - m_F\,\overline{F}\,F + (D_\mu S)^\dagger\,D^\mu S$$
$$- \left(y_1\,\overline{F_{\rm R}}\,S\,\psi_{\rm L} + y_2\,\overline{F_{\rm L}}\,S\,\psi_{\rm R} + \text{h.c.}\right) - \lambda_{HS}\,v\,h\,S^\dagger S + \ldots$$

Simplified models with Standard Model (SM) fields

F or S being a SM field:

1. $F \to L_L/e_R \, [\nu_{\rm R}]$: ψ or S have $L=1$ LFV, EDM/AMMs [ν-portal]
2. $S \to$ Higgs: mixing $\psi - F_0$, thus tree-level h/Z exchange.

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Specially interesting models of type 1:

- No problems with charged stable particles.
- m_ν may also be generated if $\Delta L = 2$.
- $F \to L_L$: the [Generalized] Scotogenic model with dark [U(1)] Z_2.

(Relevant) direct detection effective operators

Dirac DM

- Electric and magnetic dipoles: $\mathcal{L} = \mu_\psi \mathcal{O}_{\rm mag} + d_\psi \mathcal{O}_{\rm edm}$ [long range]

$$\mathcal{O}_{\rm mag} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}\psi)F_{\mu\nu}, \qquad \mathcal{O}_{\rm edm} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}i\gamma_5\psi)F_{\mu\nu}$$

- Vector interactions from γ/Z penguins:

$$\mathcal{O}^q_{VV} = (\overline{\psi}\gamma^\mu\psi)(\overline{q}\gamma_\mu q) \qquad \mathcal{O}^q_{AA} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu\gamma_5 q)$$

- Scalar and gluonic interactions (induced by heavy quarks):

$$\mathcal{O}^q_{SS} = m_q(\overline{\psi}\psi)(\overline{q}q) \qquad \mathcal{O}_g = \frac{\alpha_s}{8\pi}(\overline{\psi}\psi)G^{a\mu\nu}G^a_{\mu\nu}$$

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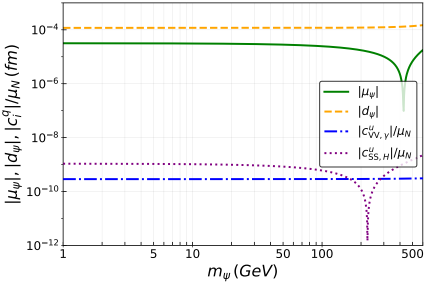
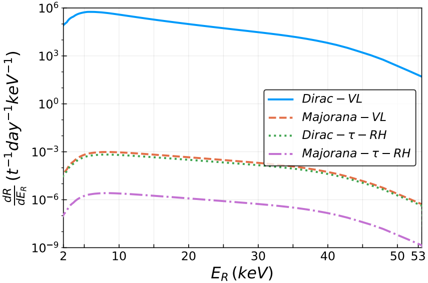
Majorana DM

- No dipole/vector, but momentum suppressed $\mathcal{O}^q_{AV} = (\overline{\psi}\gamma^\mu\gamma_5\psi)\,(\overline{q}\gamma_\mu q)$

Wilson coefficients and event rates [with LikeDM]

- $m_F = 600$ GeV, $m_S = 500$ GeV, $y_V = 1$, $y_A = 1.3\, e^{i\,1.4}$, $\lambda_{HS} = 3$.
- For Majorana DM, Higgs and photon penguin dominate.

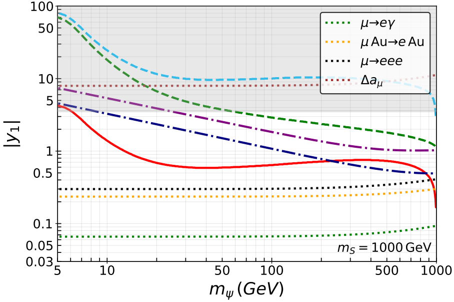




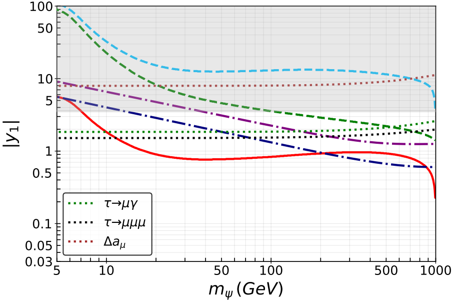
Flavor-dependent upper limits, $m_S = 1000$ GeV

- DD: Dirac (solid), Majorana $\lambda_{HS} = 0.1\,(3)$ dashed.
- Relic abundance from $\psi\psi \to \ell\ell$: Dirac, Majorana dot-dashed.

$y_e = y_\mu = y_\tau$



$y_e = 0$



Connection to neutrino masses

[C. Hagedorn, JHG, E. Molinaro, M. Schmidt, arXiv:1804.04117]

- The Generalized Scotogenic Model (GScM): dark global U(1)

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{DM}$
Φ	1	2	1/2	q
Φ'	1	2	-1/2	q
DM ψ	1	1	0	q

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- The new terms are (H is the SM Higgs doublet)

$$\Delta\mathcal{L} \supset i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi - \left(y_\Phi^\alpha\,\overline{\psi}\,\tilde{\Phi}^\dagger\,L_L^\alpha + (y_{\Phi'}^\alpha)^*\,\overline{\psi}\,\tilde{\Phi}'^\dagger\,\tilde{L}_L^\alpha + \text{H.c.}\right).$$

$$\Delta V \supset \lambda_{H\Phi\Phi'}\left[(H^\dagger\tilde{\Phi}')(H^\dagger\Phi) + \text{H.c.}\right].$$

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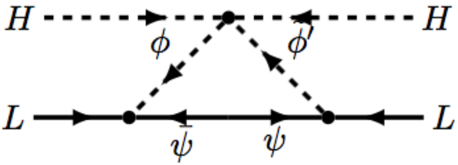
$$\Delta V \supset \lambda_{H\Phi\Phi'}\left[(H^\dagger\tilde{\Phi}')(H^\dagger\Phi) + \text{H.c.}\right].$$

- $\Delta L = 2$ by the combination $y_\Phi\,y'_\Phi\,\lambda_{H\Phi\Phi'}\,m_\Psi$.

Majorana ν masses at one loop



- Majorana neutrino masses are generated at 1 loop:

$$\mathcal{M}_\nu^{\alpha\beta} = \frac{\sin 2\theta \, m_\psi}{32\,\pi^2} \left(y_\Phi^\alpha \, y_{\Phi'}^\beta + y_{\Phi'}^\alpha y_\Phi^\beta \right) \left[\frac{m_{\eta_0}^2}{m_{\eta_0}^2 - m_\psi^2} \log \frac{m_{\eta_0}^2}{m_\psi^2} - (\eta_0 \leftrightarrow \eta_0') \right]$$

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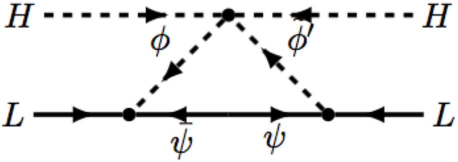

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- One massless ν and two massive (rank 2)

$$m_\nu^\pm \quad \propto \quad |\mathbf{y}_\Phi|\;|\mathbf{y}_{\Phi'}| \pm |\mathbf{y}_\Phi{}^* \cdot \mathbf{y}_{\Phi'}|\,.$$

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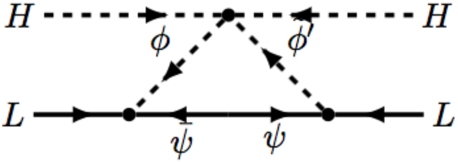

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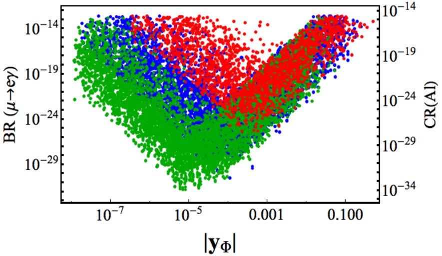
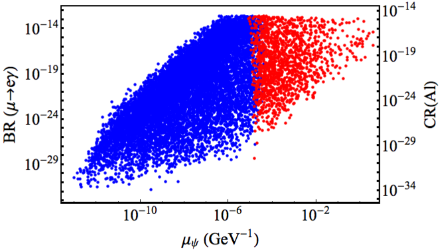
- Yukawa flavour structure determined by $\nu-$data: correlations in LFV.

Interplay lepton flavor violation (LFV) – direct detection

Left plot) $10^{-8} \leq \lambda_{H\Phi\Phi'} \leq 0.01$, $0.01 \leq \lambda_{H\Phi\Phi'} \leq 0.5$, $0.5 \leq \lambda_{H\Phi\Phi'} \leq 4\pi$

Right plot) DD limits: blue allowed, red excluded





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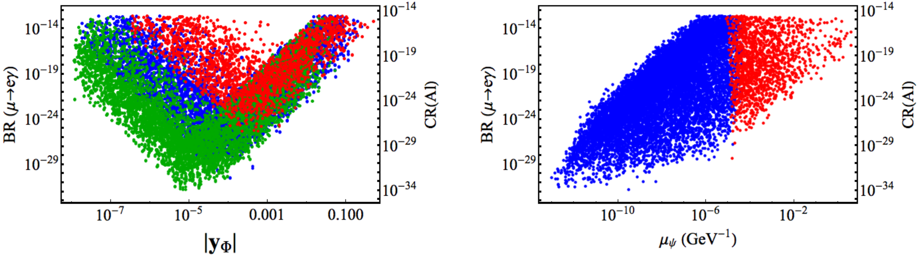

Strong LFV limits imply that annihilations are small:

DM would be overproduced: need coannihilations ψ/S for relic abundance.

Review of radiative neutrino mass models [arXiv: 1706.08524]
Different classifications and models

Y. Cai, JHG, M. Schmidt, A. Vicente, R. Volkas


frontiers in Physics

REVIEW
published: 04 December 2017
doi: 10.3389/fphy.2017.00063

From the Trees to the Forest: A Review of Radiative Neutrino Mass Models

Yi Cai[1,2], Juan Herrero García[3], Michael A. Schmidt[4*], Avelino Vicente[5] and Raymond R. Volkas[2]*

Part II: Direct detection of two-component dark matter

[JHG, A. Scaffidi, M. White, A. Williams, JCAP 1711 (2017) no.11, 021, arXiv:1709.01945]

- DM can be multi-component. For 2DM:

$$\rho_{\rm tot} = \rho_1 + \rho_2$$

and

$$R_{\rm tot}(E_{\rm R}, t) = R_1(E_{\rm R}, t) + R_2(E_{\rm R}, t)\,.$$

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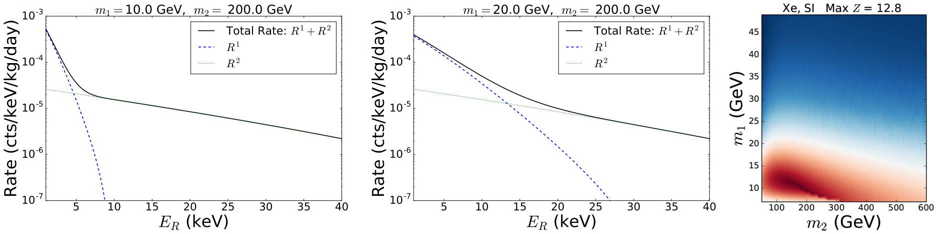
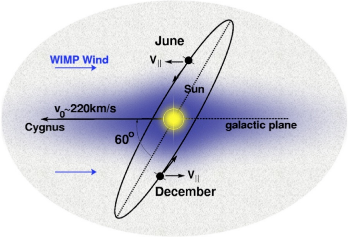
- Smoking gun of 2DM in average rate ($\bar{R}_{\rm tot}$): a *kink* in the spectrum.



DAMA/LIBRA phase-2 annual modulation results

[JHG, A. Scaffidi, M. White, A. Williams, arXiv:1804.08437]



Annual modulation

The DM flux varies due to the motion of the Earth around the Sun:

$$R(E_{\rm R},t) \equiv \bar{R} + M\cos[2\pi(t-t_0)]$$

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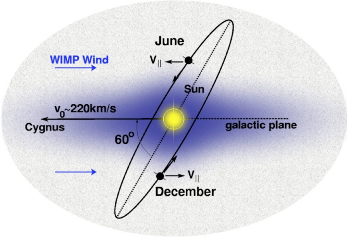

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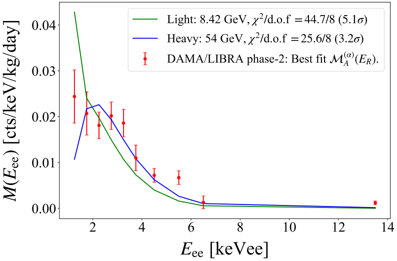
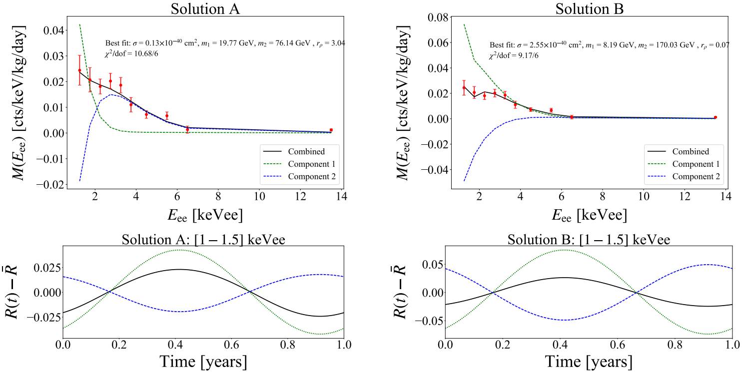


DAMA new results at lower E_{R}:

Not consistent with a 1DM spin-independent interpretation [Kahlhoefer, Baum, us].

2DM fits [assuming sinusoidal, as no DAMA data available in (E_R, t)]

- Two solutions ($\sigma_1^p = \sigma_2^p \equiv \sigma$; $r_\rho \equiv \rho_2/\rho_1$):



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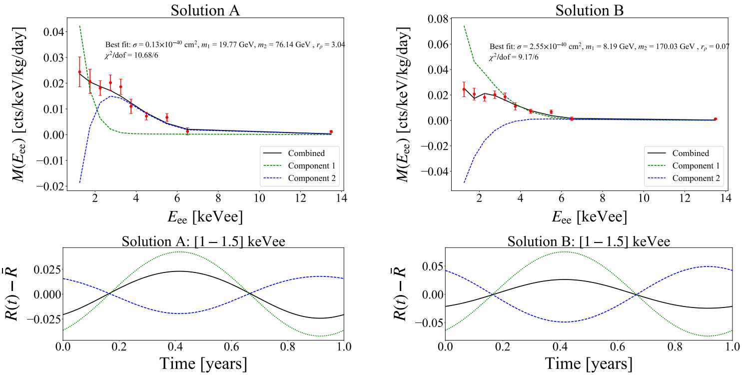
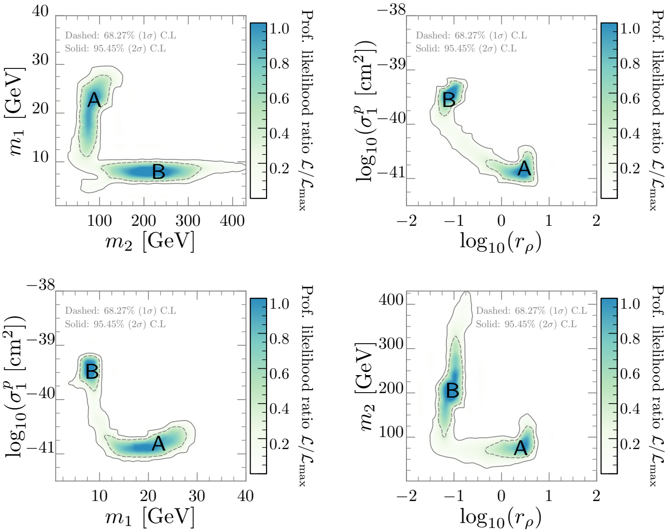


Smoking guns of 2DM in the time-dependent rate:

- Partial cancellation at low E_R (for DAMA below 2 keVee).
- Non-sinusoidal at low E_R (Sun's gravitational focusing: $t_1 \neq t_2$).

2D parameter space



Conclusions

- **Part I. DD at 1 loop.**
- Motivation: no large DD signals, natural for fermion singlet.
- Dirac (Majorana) DM: magnetic/electric dipoles (Higgs/photon).
- Interesting if SM leptons in the loop, connection to neutrino masses?
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- A *kink* for average rates. Mass splitting is critical.
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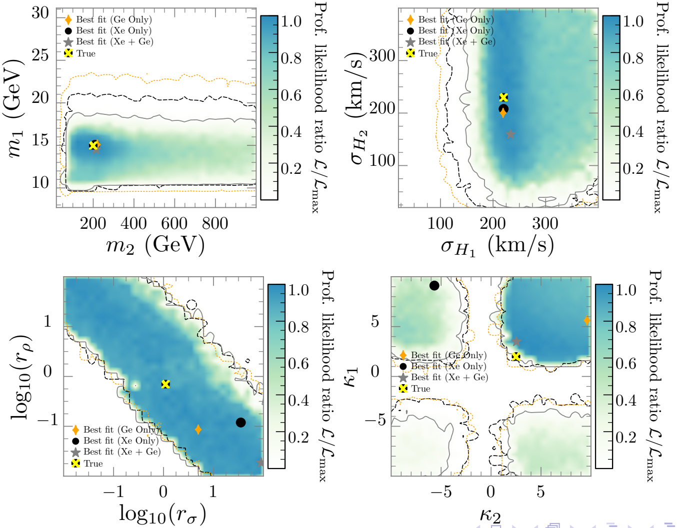
THANK YOU!

Back-up slides

Parameter estimation. Profile Likelihood Ratio

Definitions: $r_\rho \equiv \frac{\rho_2}{\rho_1}$, $r_\sigma \equiv \frac{\sigma_2^p}{\sigma_1^p}$, $\kappa_\alpha \equiv \frac{f_n^\alpha}{f_p^\alpha}$, $\sigma_{H_\alpha} \equiv$ velocity dispersion.



Interactions in the dark sector for a discrete symmetry

- For dark discrete Z_2 symmetry ($\psi \to -\psi$), ψ can also have a Majorana mass (also F if it is an SU(2) singlet with $Y = 0$).
- We can identify $\psi_L \to \psi_R^c$ and $S \to \tilde{S} \equiv i\sigma_2 S^*$.
- In this case, $y_1 = y_2 \equiv y$:

$$\mathcal{L}_\psi \;=\; i\,\overline{\psi}\,\partial\!\!\!/\,\psi \,-\, \frac{1}{2}\,m_\psi\,\overline{\psi^c}\,\psi \,-\, \frac{1}{2}\,m_F\,\overline{F^c}\,F \,-\, \left(y\,\overline{F}\,S\,\psi \,+\text{H.c.}\right).$$

Stability of the dark sector

- For global $G_{\rm dm}$, DM may decay via EFT $\bar{\psi}\tilde{H}^\dagger(\not{D}L)$ [Mambrini], depending on m_ψ and UV completion. We assume DM is stable.
- In principle two of the three new states can be stable: ψ, and S or F.
- In the case of F being lighter (e.g. $m_S \geq m_F + m_\psi$):
  1. If F is neutral under the SM group, it also contributes to the DM.
  2. If F is charged (and uncharged) under the SM (dark) group, they must decay, mixing SM leptons [Dissauer] or via EFT.
  3. If F is a SM lepton, these are stable (e, ν_1), into which S decays.
  4. Also if F is a RH neutrino, it will mix with SM neutrinos and decay.
- Similar discussion for S being lighter (can also be the SM Higgs).

Dominant interactions: electric/magnetic dipole moments

- For Dirac ψ, in the limit $m_\psi \ll m_F < m_S$, dipoles:

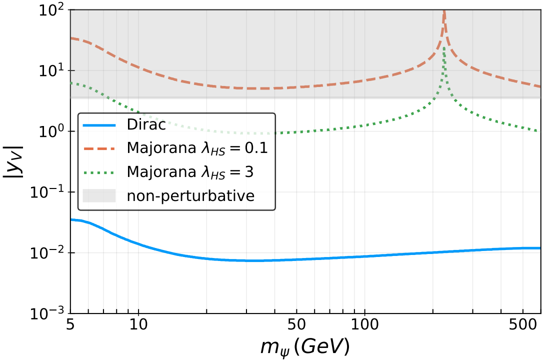
$$
\begin{aligned}
\mu_\psi &\approx -\frac{Q_F}{4\,m_S}\left(|y_V|^2 - |y_A|^2\right) x_F\,\frac{1 - x_F^2 + 2\,\ln x_F}{(1-x_F^2)^2}\,,\\
d_\psi &\approx -\frac{Q_F}{2\,m_S}\,\mathrm{Im}[y_V^*\,y_A]\,x_F\,\frac{1 - x_F^2 + 2\,\ln x_F}{(1-x_F^2)^2}\,.
\end{aligned}
$$

where

$$
x_F \equiv \frac{m_F}{m_S} \qquad \text{and} \qquad y_{V\,(A)} = \frac{y_2 + (-)y_1}{2}\,.
$$

- All general expressions provided in the paper.
- Similar results in literature [Chang, Agrawal, Schmidt, Kopp, Ibarra...]

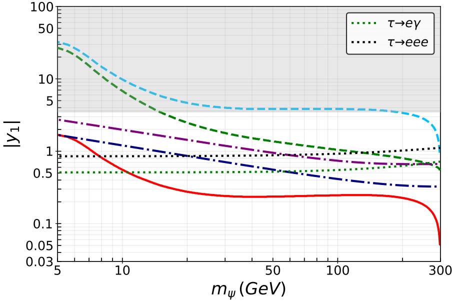
Upper limits for vector-like leptons

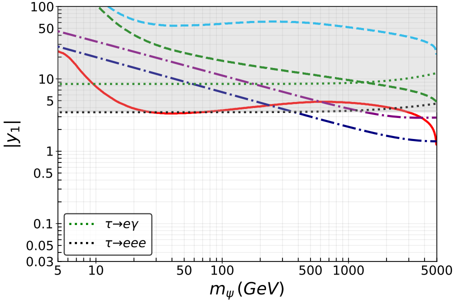


Upper limits for different m_S. $y_\mu = 0$.

Left) $m_S = 300$ GeV.

Right) $m_S = 5000$ GeV.





The potential

The most general scalar potential invariant under $\mathrm{U}(1)_{\mathrm{DM}}$ is

$$\begin{aligned}\mathcal{V} = & - m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + m_{\Phi'}^2 \Phi'^\dagger \Phi' \\ & + \lambda_{H\Phi} (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_{H\Phi'} (H^\dagger H)(\Phi'^\dagger \Phi') + \lambda_{\Phi\Phi'} (\Phi^\dagger \Phi)(\Phi'^\dagger \Phi') \\ & + \lambda_{H\Phi,2} (H^\dagger \Phi)(\Phi^\dagger H) + \lambda_{H\Phi',2} (H^\dagger \tilde{\Phi}')(\tilde{\Phi}'^\dagger H) + \lambda_{\Phi\Phi',2} (\Phi^\dagger \tilde{\Phi}')(\tilde{\Phi}'^\dagger \Phi) \\ & + \lambda_{\Phi'} (\Phi'^\dagger \Phi')^2 + \lambda_{H\Phi\Phi'} \left[(H^\dagger \tilde{\Phi}')(H^\dagger \Phi) + \mathrm{H.c.} \right] ,\end{aligned}$$

with $H \equiv (h^+, \ (h+v)\sqrt{2})^T$ being the SM Higgs doublet after EWSB.

The physical scalars

- The SM Higgs boson h.
- Two (complex) neutral scalars η_0 and η_0', combinations of ϕ_0 and ϕ_0':

$$\eta_0 = \sin\theta\,\phi_0 + \cos\theta\,\phi_0'\,, \qquad \eta_0' = -\cos\theta\,\phi_0 + \sin\theta\,\phi_0'\,,$$

with $\tan 2\theta = 2\,c/(b - a)$, where $c = -1/2\,\lambda_{H\Phi\Phi'}\,v^2$ and

$$a = m_\Phi^2 + \frac{1}{2}\,v^2\,(\lambda_{H\Phi} + \lambda_{H\Phi,2})\ , \quad b = {m_\Phi'}^2 + \frac{1}{2}\,v^2\left(\lambda_{H\Phi'} + \lambda_{H\Phi',2}\right)\ ,$$

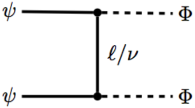
with masses

$$m^2_{\eta_0\,(\eta_0')} = \frac{1}{2}\left(a + b + (-)\sqrt{(a - b)^2 + 4\,c^2}\right)\ .$$

- Two charged scalars $\eta^\pm \equiv \phi^\pm$ and $\eta'^\pm \equiv \phi'^\pm$, for $\lambda_{H\Phi\Phi'} \ll \lambda_i$:

$$m^2_{\eta_0} \simeq m^2_{\eta^\pm} + \frac{1}{2}\lambda_{H\Phi,2}\,v^2, \qquad m^2_{\eta_0'} \simeq m^2_{\eta'^\pm} + \frac{1}{2}\lambda_{H\Phi',2}\,v^2\,.$$

DM s-wave annihilations into leptons and LFV limits



$$\simeq \frac{1}{32\pi m_\psi^2}\left| y_\Phi^i y_\Phi^{j*}\frac{m_\psi^2}{m_{\eta^\pm}^2+m_\psi^2} - y_{\Phi'}^{i*} y_{\Phi'}^{j}\frac{m_\psi^2}{m_{\eta'^\pm}^2+m_\psi^2}\right|^2$$

- $\eta^{(\prime)\pm}$ also generate $\ell_\alpha \to \ell_\beta\,\gamma$ at one loop $\propto |y_\Phi^{\beta *}\, y_\Phi^\alpha / m_{\eta^\pm}^2|^2$.
- Using the weakest LFV limit, $\tau \to \mu\,\gamma$:

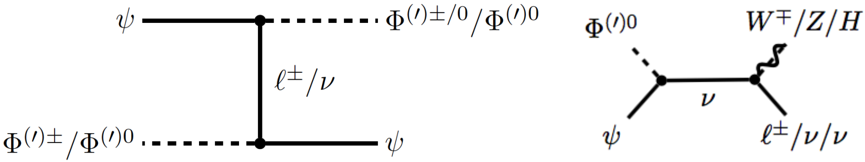
$$\left\langle v\sigma_{\psi\bar\psi\to\tau^-\mu^+}\right\rangle \lesssim 7\cdot 10^{-2}\left(\frac{B(\tau\to\mu\,\gamma)}{4.4\cdot 10^{-8}}\right)\left(\frac{3\cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle v\sigma\rangle_{\mathrm{th}}}\right)\left(\frac{m_\psi}{100\,\mathrm{GeV}}\right)^2$$

Annihilations into leptons are not large enough:

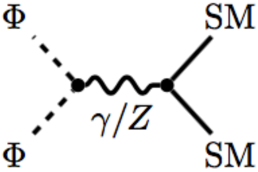
DM overproduced $\to$ need another mechanism for the relic abundance.

Coannihilations with scalars

- If $(m_\psi - m_{\Phi^{(\prime)}})/m_{\Phi^{(\prime)}} \ll 1$, $\Phi^{(\prime)}/\psi$ in equilibrium, coannihilations:



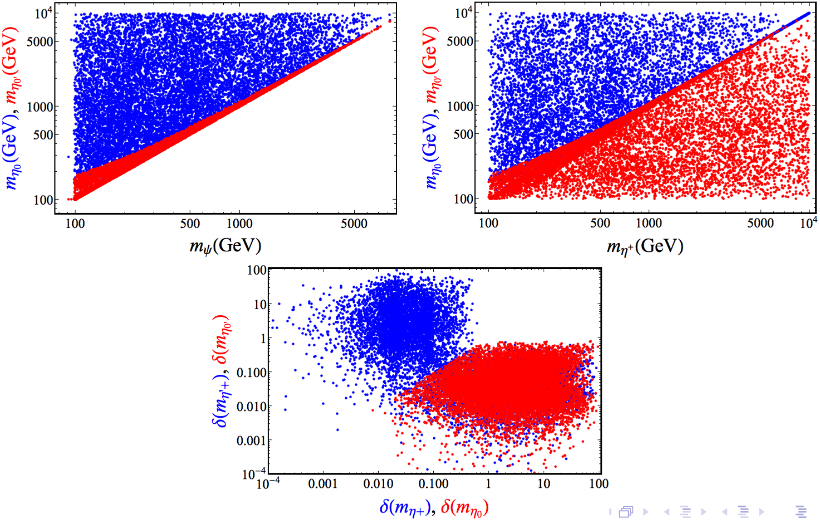
- For smaller $y_{\Phi^{(\prime)}}$, annihilations of the scalar partners dominate:



$$\sigma_{eff} = r_\psi^2\, \sigma_{\psi\psi} + r_\psi r_\Phi\, \sigma_{\psi\Phi} + r_\Phi^2\, \sigma_{\Phi\Phi}$$ [Griest]

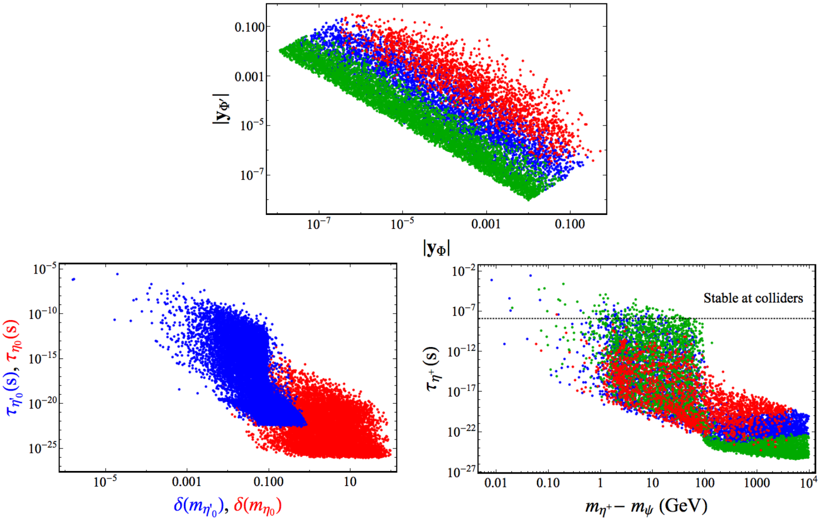
Masses for coannihilations

Using MicroOMEGAs. All points obey V stability, LFV, 3σ of ν masses and mixings, $\Omega_{\rm DM}$ and EWPT. Similar results for IO and NO.



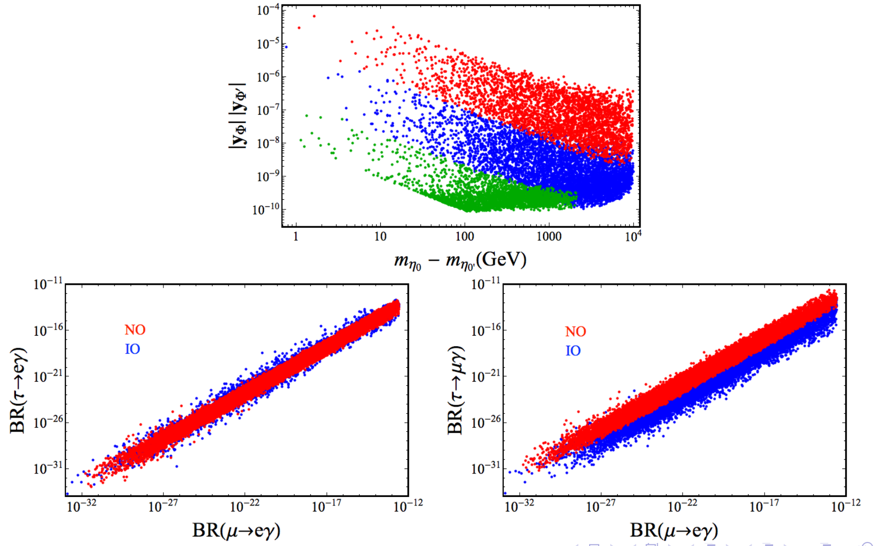
Yukawas and lifetime of the scalars

$10^{-8} \leq \lambda_{H\Phi\Phi'} \leq 0.01$, $0.01 \leq \lambda_{H\Phi\Phi'} \leq 0.5$, $0.5 \leq \lambda_{H\Phi\Phi'} \leq 4\pi$



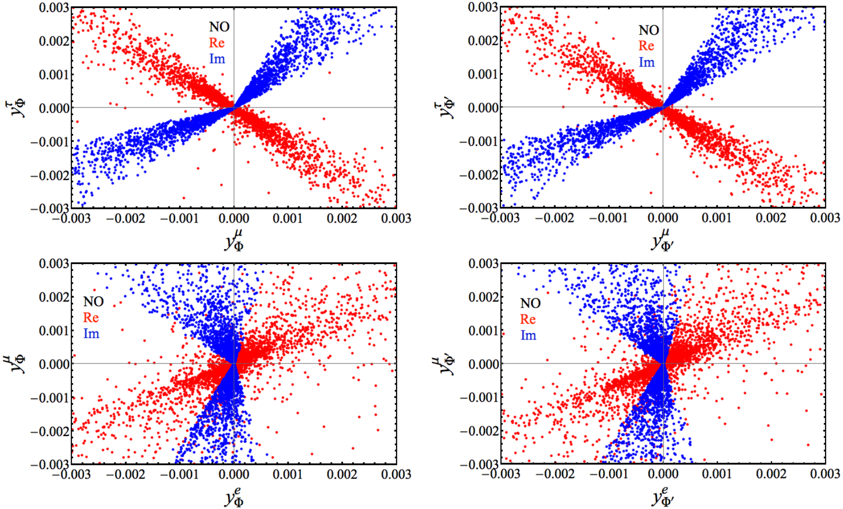
Yukawas, correlations LFV

$10^{-5} \leq |\sin(2\theta)| \leq 0.001$, $0.001 \leq |\sin(2\theta)| \leq 0.05$, $0.05 \leq |\sin(2\theta)| \leq 1$



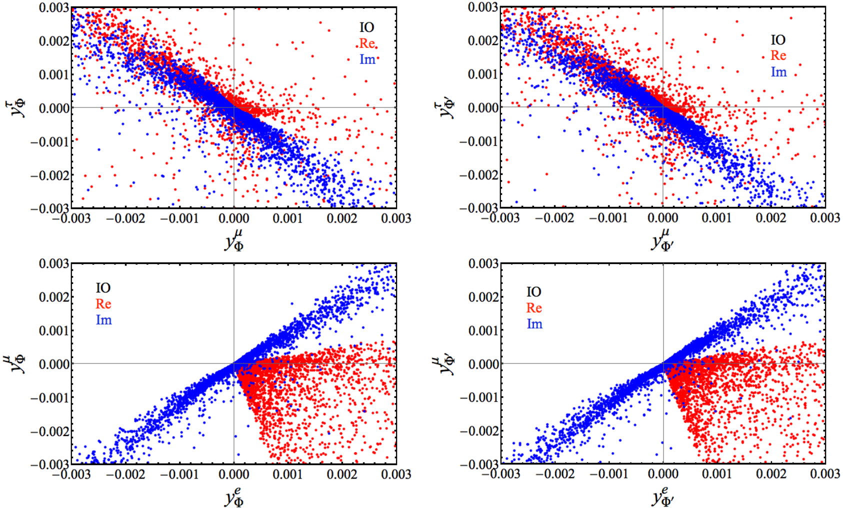
Flavor structure NO

NO: pattern $y_\tau^{(\prime)} \approx y_\mu^{(\prime)}$.



Flavor structure IO

IO: pattern $y_\tau^{(\prime)} \approx -y_\mu^{(\prime)}$.



Can the relic abundance be set by annihilations?

- Need to break the proportionality $\ell_\alpha \to \ell_\beta \, \gamma \propto \langle v\sigma \rangle_{\rm th}$.
- $\langle v\sigma \rangle_{\nu_i \bar{\nu}_j} \gg \langle v\sigma \rangle_{\ell_i \bar{\ell}_j}$, with small LFV [Boehm, Hambye, Farzan, Arhrib].

$$\left\langle v\sigma_{\nu_i \bar{\nu}_j} \right\rangle \simeq \frac{1}{64\pi m_\psi^2 (1+\delta_{ij})} \left| y_\Phi^i y_\Phi^{j*} \left(\frac{m_\psi^2 s_\theta^2}{m_{\eta^0}^2 + m_\psi^2} + \frac{m_\psi^2 c_\theta^2}{m_{\eta'^0}^2 + m_\psi^2} \right) \right.$$
$$\left. - y_{\Phi'}^{i*} y_{\Phi'}^{j} \left(\frac{m_\psi^2 c_\theta^2}{m_{\eta^0}^2 + m_\psi^2} + \frac{m_\psi^2 s_\theta^2}{m_{\eta'^0}^2 + m_\psi^2} \right) \right|^2$$

- Need large hierarchy in masses:

$$\mathcal{O}(1)\,\text{MeV} \simeq m_\psi \lesssim m_{\eta'^0} \ll m_{\eta^0},\, m_{\eta'^\pm},\, m_{\eta^\pm} \sim \mathcal{O}(0.1-10)\,\text{TeV}.$$

Can the relic abundance be set by annihilations?

- To suppress $Z \to \eta_0' \eta_0'^*$ need $\cos(2\theta) \approx 0$. But then need $y \ll y'$ to suppress m_ν, which makes LFV too large...
- Also too large T parameter, which grows with the scalar splittings:

$$T = \frac{1}{16\pi^2 \alpha v^2} \Big\{ 2\, s_\varphi^2 \mathcal{F}(m_{\eta^+}^2, m_{\eta^0}^2) + 2\, c_\varphi^2 \mathcal{F}(m_{\eta^+}^2, m_{\eta'^0}^2) +$$

$$+ 2\, c_\varphi^2 \mathcal{F}(m_{\eta'^+}^2, m_{\eta^0}^2) + 2\, s_\varphi^2 \mathcal{F}(m_{\eta'^+}^2, m_{\eta'^0}^2) \Big\} .$$

- MeV DM into ν, if possible, is extremely fine-tuned.

Can the $U(1)_{\rm DM}$ symmetry be gauged?

Z' options:

1. Massless: radiation and large self-interactions. Strong limits.
2. Mass from a Stueckelberg mechanism.
3. Spontaneously broken by scalar σ, which mixes with H: strong bounds from DD and invisible decays. Remnant Z_2.

Even if kinetic mixing induced $\epsilon(\Lambda_{\rm UV}) = 0$, it is induced at one loop:

$$|\epsilon| \gtrsim \frac{\sqrt{\alpha_Y \alpha_D}}{4\pi} \left| \ln\left(\frac{m_\Phi}{m_{\Phi'}}\right)\right| \sim 10^{-4}\,.$$

Strong limits on the kinetic mixing.
$\longrightarrow$ **We will focus on the global symmetry case.**

Boltzmann equations for coannihilations

$$\frac{dn_\psi}{dt} = -3Hn_\psi - \langle\sigma_{eff} v\rangle \left(n_\psi^2 - n_{\psi,eq}^2\right) \quad \text{with:}$$

$$\sigma_{eff} = r_\psi^2\, \sigma_{\psi\psi} + r_\psi r_\Phi\, \sigma_{\psi\Phi} + r_\Phi^2\, \sigma_{\Phi\Phi}\ ,$$

$$r_\psi = \frac{4}{g_{eff}},\ \ r_\Phi = \frac{g_{eff}^\Phi}{g_{eff}},\ \ g_{eff} = 4 + g_{eff}^\Phi,\ \ g_{eff}^\Phi = g_\Phi \left(\frac{m_\Phi}{m_\psi}\right)^{3/2} e^{-\frac{m_\Phi - m_\psi}{T}}\ .$$

Comparison to the Scotogenic Model: the Z_2 case

- Instead of a $\mathrm{U}(1)_{\mathrm{DM}}$, it has a Z_2. We can identify $\psi \leftrightarrow \psi^c$ and $\Phi' \leftrightarrow \tilde{\Phi}$. It works with one Majorana ψ and one scalar doublet Φ:

$$\mathcal{L}_\psi = i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi^c}\,\psi - \left(y^\alpha\,\overline{\psi}\,\tilde{\Phi}^\dagger L_\alpha + \text{H.c.}\right).$$

- The scalar potential becomes

$$\mathcal{V} = -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \\ + \lambda_{H\Phi}(H^\dagger H)(\Phi^\dagger \Phi) + \lambda_{H\Phi,2}(H^\dagger \Phi)(\Phi^\dagger H) + \frac{\lambda_{H\Phi,3}}{2}\left[(H^\dagger \Phi)^2 + \text{H.c.}\right]$$

- Many studies: [Ma, Restrepo, Ibarra, Molinaro, Schwetz, Toma...].
- For scalar DM [Re(Φ)/ Im(Φ)], DD by the Z is inelastic [Hambye...].
- For fermionic DM ψ, strong constraints from LFV. Some options are coannihilation [Schmidt, Toma...], freeze-in [Molinaro...]... DD at one loop.

The Scotogenic Model: neutrino masses

- The mass matrix is given by:

$$(\mathcal{M}_\nu)_{\alpha\beta} \;=\; \sum_k \frac{y_{\alpha k}\, y_{\beta k}\, m_{\psi_k}}{16\,\pi^2}\; F_{\rm ScM}(m_{\phi_0^R}, m_{\phi_0^I}, m_{\psi_k})\,,$$

where

$$F_{\rm ScM}(m_{\phi_0^R}, m_{\phi_0^I}, m_{\psi_k}) \;\equiv\; \left(\frac{m_{\phi_0^R}}{m_{\phi_0^R} - m_{\psi_k}^2}\log\frac{m_{\phi_0^R}^2}{m_{\psi_k}^2} - (\phi_0^R \leftrightarrow \phi_0^I)\right)$$

- In the limit $m_{\phi_0^R}^2 - m_{\phi_0^I}^2 = \lambda_{H\Phi,3} v^2 \ll m_0^2 = (m_{\phi_0^R}^2 + m_{\phi_0^I}^2)/2$, we get:

$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda_{H\Phi,3} v^2}{16\,\pi^2}\sum_k \frac{y_{\alpha k}\, y_{\beta k}\, m_{\psi_k}}{m_0^2 - m_{\psi_k}^2}\left[1 - \frac{m_{\psi_k}^2}{m_0^2 - m_{\psi_k}^2}\log\frac{m_0^2}{m_{\psi_k}^2}\right].$$

- It needs two $\psi_{1,2}$ (and one Φ) in order to generate at least two ν masses, while the Generalized version needs only one ψ (but two Φ).

Hypothesis testing: 1DM vs. 2DM

- Discrimination between $H_{1\mathrm{DM}}$ and $H_{2\mathrm{DM}}$ $\longleftrightarrow$ detect *kink*.
- Frequentist approach, with test-statistic $\mathcal{T}$:

$$\mathcal{T} = \min_{\theta_{H_{1\mathrm{DM}}}} \chi^2(\theta_{H_{1\mathrm{DM}}}) - \min_{\theta_{H_{2\mathrm{DM}}}} \chi^2(\theta_{H_{2\mathrm{DM}}}) \, ,$$

where

$$\chi^2(\theta_\alpha) = \sum_i^N \frac{[x_i - \mu_i(\theta_\alpha)]^2}{\sigma_i^2} \, , \quad \alpha = [H_{1\mathrm{DM}}, H_{2\mathrm{DM}}] \, .$$

- x_i = observed number of events in bin i.
- $\mu_i(\theta_\alpha)$ expected events as a function of model parameters θ.
- $\sigma_i = \sqrt{x_i}$ = uncertainty.

Hypothesis testing: distribution of $\mathcal{T}$

Null hypothesis $H_{1\mathrm{DM}}$ true:

- $H_{1\mathrm{DM}} \subset H_{2\mathrm{DM}} \Rightarrow$ Nested hypotheses:
  - Can see this by setting $r_\rho = 0$.
- Wilk's theorem: $\mathcal{T}$ follows a χ^2-distribution with $n(\theta_2) - n(\theta_1)$ dof.

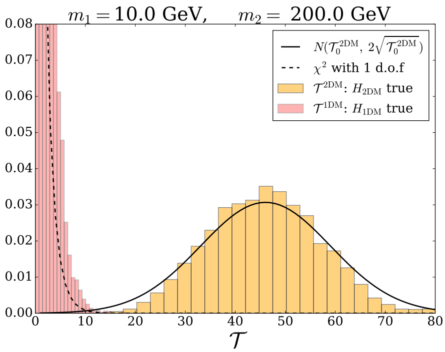
Alternative hypothesis $H_{2\mathrm{DM}}$ true:

- $\mathcal{T}$ is Gaussian with $\mu = \mathcal{T}_0^{2\mathrm{DM}}$ and $\sigma = 2\sqrt{\mathcal{T}_0^{2\mathrm{DM}}}$:

$$\mathcal{T}_0^{2\mathrm{DM}} \equiv \mathcal{T}(x_i = \mu_i(\theta^{\mathrm{true}}_{H_{2\mathrm{DM}}})) = \min_{\theta_{H_{1\mathrm{DM}}}} \sum_i^n \left(\frac{\mu_i(\theta^{\mathrm{true}}_{H_{2\mathrm{DM}}}) - \mu_i(\theta_{H_{1\mathrm{DM}}})}{\sqrt{\mu_i(\theta^{\mathrm{true}}_{H_{2\mathrm{DM}}})}} \right)^2$$

- $\mathcal{T}_0^{2\mathrm{DM}}$ has no statistical fluctuations from data: *'Asimov likelihood'*. Approximation of the *median value* of $\mathcal{T}$, see Cowan for details.

Example



- True in general as long as $H_{1DM} \subset H_{2DM}$.
- $T_0^{2DM} \simeq 46$ is the experiment's *average capability* to observe H_{2DM}.