Dark matter direct detection at one loop

Michael A. Schmidt

12 December 2017

CosPA 2017

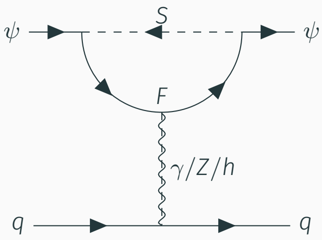
based on
C. Hagedorn, J. Herrero-García, E. Molinaro, MS [1712.xxxxx]
J. Herrero-García, E. Molinaro, MS [1712.xxxxx]

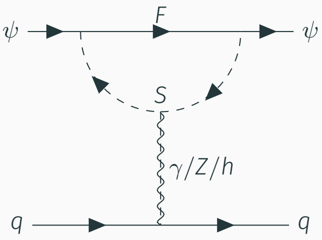
THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Motivation

- No clear evidence for DM in direct/indirect detection or at LHC
- Only hints from DAM.*
- Option: DM is not directly coupled to quarks
- Examples: fermionic singlet DM ψ such as bino, fermionic DM in scotogenic model, or models explaining the DAMPE result
- Direct detection occurs at one loop
- Next generation (liquid noble gas) experiments could probe it



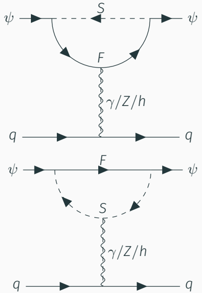


Simplified fermionic DM model

Dark sector	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{dm}$
Dark matter	ψ	1	1	0	1
Dark scalar	S	1	d_F	Y_F	q_s
Dark fermion	F	1	d_F	Y_F	$q_s + 1$

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

- Higgs portal coupling may arise in different ways
- Easy to generalise to larger dark symmetry groups

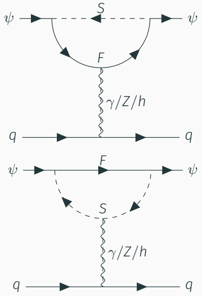


Simplified fermionic DM model

Dark sector	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{dm}$
Dark matter	ψ	1	1	0	1
Dark scalar	S	1	d_F	Y_F	q_s
Dark fermion	F	1	d_F	Y_F	$q_s + 1$

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

- Higgs portal coupling may arise in different ways
- Easy to generalise to larger dark symmetry groups



SM fields in loop

1. $F \to L_L/e_R$: ψ or S have $L = 1$ LFV, EDM/AMMs, LNV
2. $F \to \nu_R$: ν_R and ψ or S have $L = 1$ Gonzalez-Macias, Escudero, ...
3. $S \to H$: mixing $\psi - F_0$, thus tree-level H/Z exchange

(Relevant) effective interactions for direct detection

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 induced by Z/γ-penguins [anapole $(\overline{\psi}\gamma^\mu\psi)(\partial^\nu F_{\mu\nu}) \equiv \mathcal{O}^V_{\rm SI}$ by EOM]

$$\mathcal{O}^V_{\rm SI} = (\overline{\psi}\gamma^\mu\psi)(\overline{q}\gamma_\mu q) \qquad \mathcal{O}^{AV}_{\rm SD} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu\gamma_5 q),$$

- Scalar interactions [and gluon interaction induced by heavy quarks]

$$\mathcal{O}^S_{\rm SI} = m_q(\overline{\psi}\psi)(\overline{q}q) \qquad \mathcal{O}^G_{\rm SI} = \frac{\alpha_s}{8\pi}(\overline{\psi}\psi)G^{a\mu\nu}G^a_{\mu\nu}$$

(Relevant) effective interactions for direct detection

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 induced by Z/γ-penguins [anapole $(\overline{\psi}\gamma^\mu\psi)(\partial^\nu F_{\mu\nu}) \equiv \mathcal{O}^V_{\rm SI}$ by EOM]

$$\mathcal{O}^V_{\rm SI} = (\overline{\psi}\gamma^\mu\psi)(\overline{q}\gamma_\mu q) \qquad \mathcal{O}^{AV}_{\rm SD} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu\gamma_5 q),$$

- Scalar interactions [and gluon interaction induced by heavy quarks]

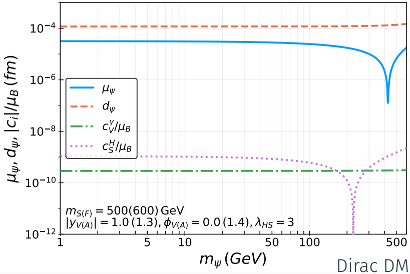
$$\mathcal{O}^S_{\rm SI} = m_q(\overline{\psi}\psi)(\overline{q}q) \qquad \mathcal{O}^G_{\rm SI} = \frac{\alpha_s}{8\pi}(\overline{\psi}\psi)G^{a\mu\nu}G^a_{\mu\nu}$$

Majorana DM

- no dipole and vector interactions
- P-violating vector interaction [momentum suppressed]

$$\mathcal{O}^{AV} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu q)$$

Dominant interactions: electric/magnetic dipole moments



For Dirac DM ψ $[m_\psi \ll m_F < m_S]$

$$\mu_\psi \approx -\frac{Q_F}{4\,m_S}\left(|y_V|^2 - |y_A|^2\right) x_F\, \frac{1 - x_F^2 + 2\,\ln x_F}{(1 - x_F^2)^2}$$

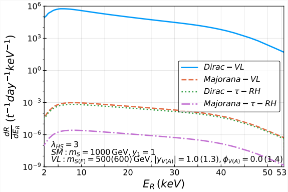
$$d_\psi \approx -\frac{Q_F}{2\,m_S}\,\mathrm{Im}[y_V^*\, y_A]\, x_F\, \frac{1 - x_F^2 + 2\,\ln x_F}{(1 - x_F^2)^2}$$

where

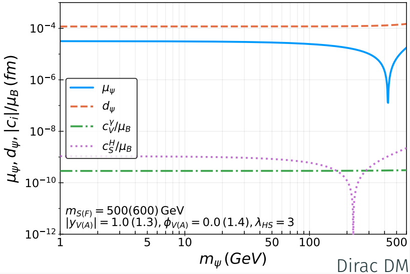
$$x_F \equiv \frac{m_F}{m_S} \quad \text{and} \quad y_{V,A} = \frac{y_2 \pm y_1}{2}\,.$$

Dominant contribution:

- Dirac DM: magnetic and electric dipole moments
- Majorana DM: Higgs, but also photon penguin.



Dominant interactions: electric/magnetic dipole moments



For Dirac DM ψ $[m_\psi \ll m_F < m_S]$

$$\mu_\psi \approx -\frac{Q_F}{4\,m_S}\left(|y_V|^2 - |y_A|^2\right) x_F\,\frac{1 - x_F^2 + 2\,\ln x_F}{(1-x_F^2)^2}$$

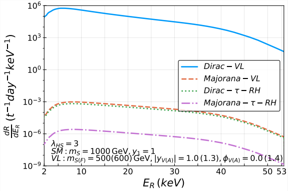
$$d_\psi \approx -\frac{Q_F}{2\,m_S}\,\mathrm{Im}[y_V^*\,y_A]\,x_F\,\frac{1 - x_F^2 + 2\,\ln x_F}{(1-x_F^2)^2}$$

where

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

Dominant contribution:

- Dirac DM: magnetic and electric dipole moments
- Majorana DM: Higgs, but also photon penguin.

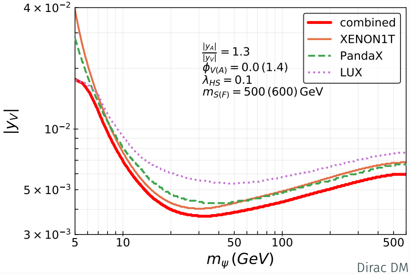


All contributions have to be considered simultaneously

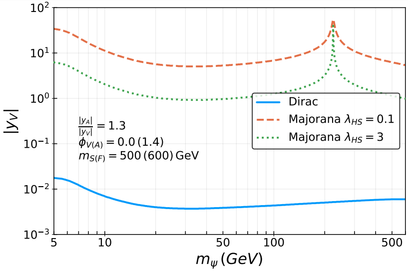
- Analytical expressions valid for general models provided in paper and compared to existing results Berlin, Chang, Agrawal, Kumar, Schmidt, Kopp, Ibarra...
- Implemented with DirectDM 1708.02678 and LikeDM 1708.04630

Direct detection limits

Vector-like fermions

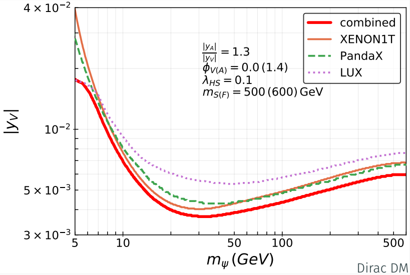


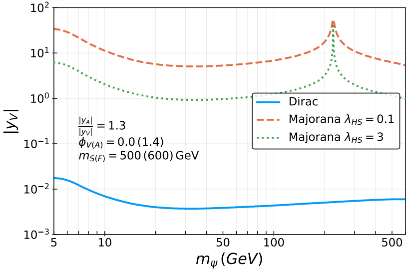
Dirac DM



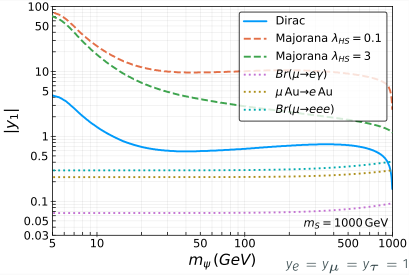
Direct detection limits

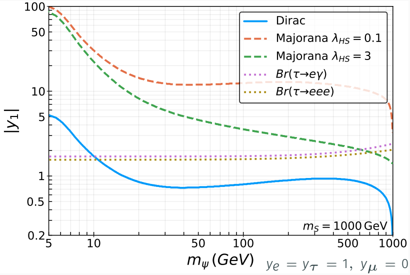
Vector-like fermions





Right-handed charged leptons





Connection to neutrino masses: scotogenic model with Dirac fermion

Scotogenic model with Dirac DM

Simple example of loopy DD with radiative ν masses:

Dirac DM ψ, $F \equiv L_L$, $S = \Phi, \Phi'$. Dark global (anomaly-free) $U(1)_{\rm DM}$

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

Just **one fermionic singlet** ψ needed. $\mathbf{y}_{\Phi^{(\prime)}}$ are 3-component vectors

$$\mathcal{L}_\psi \supset i\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi - \left(y^\alpha_\Phi\,\overline{\psi}\,\tilde{\Phi}^\dagger\,L^\alpha_L + (y^\alpha_{\Phi'})^*\,\overline{\psi}\,\tilde{\Phi}'^\dagger\tilde{L}^\alpha_L + \text{H.c.}\right).$$

Two neutral scalars $\eta_0^{(\prime)}$ (mixing angle θ),
two charged scalars $\eta^{(\prime)\pm}$ (no mixing)

$$V \supset \lambda_{H\Phi\Phi'}\left[(H^\dagger\tilde{\Phi}')(H^\dagger\Phi) + \mathrm{H.c.}\right] \quad\longrightarrow\quad \sin 2\theta \propto \lambda_{H\Phi\Phi'}\,.$$

Y. Cai, J. Herrero-Garcia, MS, A. Vicente, R. Volkas [1706.08524]

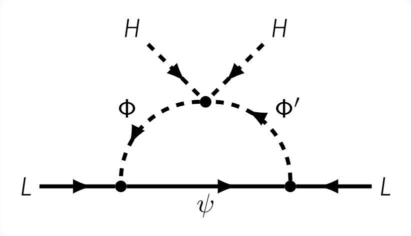

frontiers in Physics

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]

Majorana ν mass



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

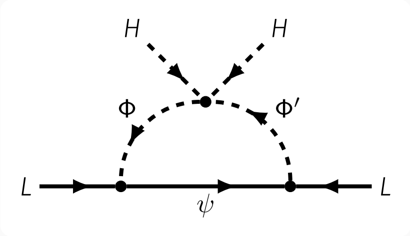
Lepton number L violated by combination of $\mathbf{y}_\Phi$, $\mathbf{y}'_\Phi$, $\lambda_{H\Phi\Phi'}(\sin 2\theta)$, m_Ψ, and $m_{\eta_0'} - m_{\eta_0}$

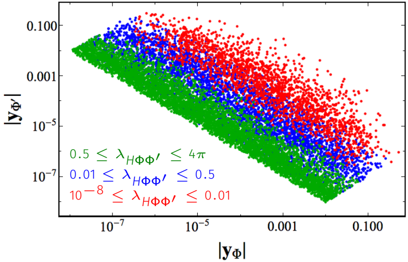
$\mathcal{M}_\nu$ is rank 2, so one massless ν and two massive

$$m_\nu^\pm \propto \left(|\mathbf{y}_\Phi|\,|\mathbf{y}_{\Phi'}| \pm |\mathbf{y}_\Phi \cdot \mathbf{y}_{\Phi'}^\dagger|\right).$$

Yukawa vectors $\mathbf{y}_\Phi^{(\prime)}$ determined by low-energy data up to one parameter ζ which determines relative size

Majorana ν mass





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

Lepton number L violated by combination of $\mathbf{y}_\Phi$, $\mathbf{y}'_\Phi$, $\lambda_{H\Phi\Phi'}(\sin 2\theta)$, m_Ψ, and $m_{\eta_0'} - m_{\eta_0}$

$\mathcal{M}_\nu$ is rank 2, so one massless ν and two massive

$$m_\nu^\pm \propto \left(|\mathbf{y}_\Phi|\ |\mathbf{y}_{\Phi'}| \pm |\mathbf{y}_\Phi \cdot \mathbf{y}_{\Phi'}^\dagger|\right)\,.$$

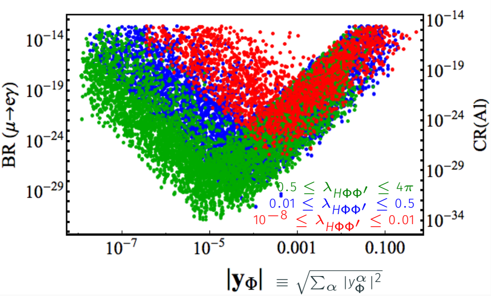
Yukawa vectors $\mathbf{y}_\Phi^{(\prime)}$ determined by low-energy data up to one parameter ζ which determines relative size

Lepton flavour violation: $\mu \to e$ transition

$$\mathrm{BR}(\mu \to e\,\gamma) = \frac{3\,\alpha_{\rm em}}{64\pi G_F^2} \left| \frac{y_\Phi^{\beta *}\, y_\Phi^{\alpha}}{m_{\eta^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta^\pm}^2}\right) + \frac{y_{\Phi'}^{\beta *}\, y_{\Phi'}^{\alpha}}{m_{\eta'^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta'^\pm}^2}\right) \right|^2$$

$$\mathrm{CR(Al)} \simeq [0.0077, 0.011] \times \mathrm{BR}(\mu \to e\gamma)$$ Dipole dominance

Only free parameters: masses m_ψ, $m_{\eta^\pm}$, and ζ



Lepton flavour violation: $\mu \to e$ transition

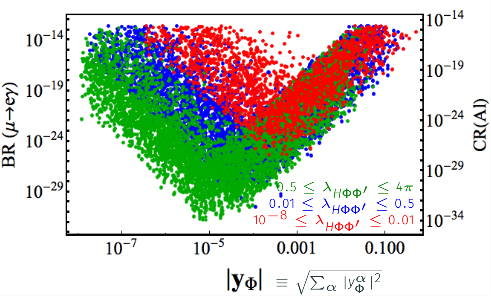
$$\mathrm{BR}(\mu \to e\,\gamma) = \frac{3\,\alpha_{\rm em}}{64\pi G_F^2} \left| \frac{y_\Phi^{\beta *}\, y_\Phi^{\alpha}}{m^2_{\eta^\pm}} f\left(\frac{m_\psi^2}{m^2_{\eta^\pm}}\right) + \frac{y_{\Phi'}^{\beta *}\, y_{\Phi'}^{\alpha}}{m^2_{\eta'^\pm}} f\left(\frac{m_\psi^2}{m^2_{\eta'^\pm}}\right) \right|^2$$

$$\mathrm{CR(Al)} \simeq [0.0077, 0.011] \times \mathrm{BR}(\mu \to e\gamma)$$ Dipole dominance

Only free parameters: masses m_ψ, $m_{\eta^\pm}$, and ζ

$$\mathrm{NO}: \quad \mathbf{y}_\Phi = \frac{\zeta}{\sqrt{2}}\left(\sqrt{m_{sol}}\,u_2^* \pm i\sqrt{m_{atm}}\,u_3^*\right) \qquad \mathbf{y}_{\Phi'} = \frac{1}{\zeta\sqrt{2}}\left(\sqrt{m_{sol}}\,u_2^* \mp i\sqrt{m_{atm}}\,u_3^*\right)$$

$$\mathrm{IO}: \quad \mathbf{y}_\Phi = \frac{\zeta}{\sqrt{2}}\left(\sqrt{m_{sol}}\,u_1^* \pm i\sqrt{m_{atm}}\,u_2^*\right) \qquad \mathbf{y}_{\Phi'} = \frac{1}{\zeta\sqrt{2}}\left(\sqrt{m_{sol}}\,u_1^* \mp i\sqrt{m_{atm}}\,u_2^*\right)$$



with u_i being the columns of the PMNS matrix

Using $f\left(m^2_{\eta^\pm}/m^2_\psi\right) \xrightarrow{m_{\eta^\pm}\to m_\psi} \frac{1}{12}$

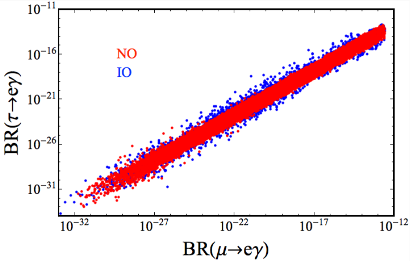
$$\mathrm{NO}: \quad 0.0003\,\frac{100\ \mathrm{GeV}}{m_{\eta'^\pm}} \lesssim \zeta \lesssim 4000\,\frac{m_{\eta^\pm}}{100\ \mathrm{GeV}}$$

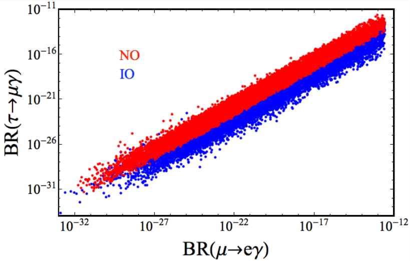
$$\mathrm{IO}: \quad 0.0004\,\frac{100\ \mathrm{GeV}}{m_{\eta'^\pm}} \lesssim \zeta \lesssim 3000\,\frac{m_{\eta^\pm}}{100\ \mathrm{GeV}}$$

Correlation between different LFV rates

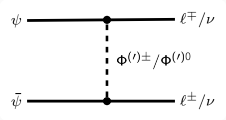
$$\mathrm{NO}: \frac{\mathrm{BR}(\tau \to e\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 0.2 \quad \text{and} \quad \frac{\mathrm{BR}(\tau \to \mu\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 5$$

$$\mathrm{IO}: \frac{\mathrm{BR}(\tau \to e\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx \frac{\mathrm{BR}(\tau \to \mu\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 0.2\,,$$





DM s-wave annihilations into leptons and LFV



$$\xrightarrow{ch.lep.} \langle v\sigma_{\ell\ell}\rangle = \frac{1}{32\pi m_\psi^2}\left| y_\Phi^\alpha y_\Phi^{\beta *}\frac{m_\psi^2}{m_{\eta^\pm}^2 + m_\psi^2} - y_{\Phi'}^\alpha y_{\Phi'}^{\beta *}\frac{m_\psi^2}{m_{\eta'^\pm}^2 + m_\psi^2}\right|^2$$

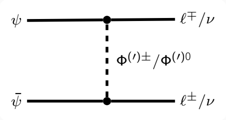
Only depends on masses and ζ and thus strongly constrained by LFV

A conservative estimate

$$\frac{\sum_{\alpha,\beta}\left\langle v\sigma(\psi\bar{\psi}\to \ell_\alpha^-\ell_\beta^+, \nu_\alpha\nu_\beta)\right\rangle}{\langle v\sigma\rangle_{\mathrm{th}}} \lesssim 1\,(0.3)\times 10^{-6}\left(\frac{3\times 10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle v\sigma\rangle_{\mathrm{th}}}\right)\left(\frac{m_\psi}{100\,\mathrm{GeV}}\right)^2$$

for $m_{\eta'_0} \simeq m_{\eta^\pm} \simeq m_\psi$. Larger scalar masses lead to a further suppression. This is confirmed by numerical scan with micrOMEGAs.

DM s-wave annihilations into leptons and LFV



$$\xrightarrow{\text{ch.lep.}} \langle v\sigma_{\ell\ell}\rangle = \frac{1}{32\pi m_\psi^2}\left| y_\Phi^\alpha y_\Phi^{\beta*}\frac{m_\psi^2}{m_{\eta^\pm}^2+m_\psi^2} - y_{\Phi'}^\alpha y_{\Phi'}^{\beta*}\frac{m_\psi^2}{m_{\eta'^\pm}^2+m_\psi^2}\right|^2$$

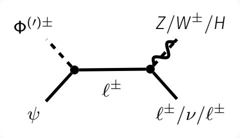
Only depends on masses and ζ and thus strongly constrained by LFV

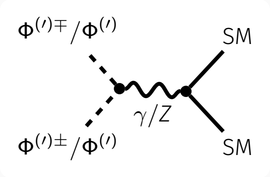
A conservative estimate

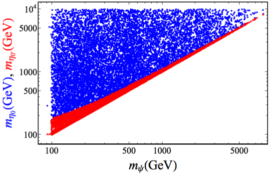
$$\frac{\sum_{\alpha,\beta}\langle v\sigma(\psi\bar{\psi}\to\ell_\alpha^-\ell_\beta^+,\nu_\alpha\nu_\beta)\rangle}{\langle v\sigma\rangle_{\rm th}} \lesssim 1\,(0.3)\times 10^{-6}\left(\frac{3\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle v\sigma\rangle_{\rm th}}\right)\left(\frac{m_\psi}{100\,{\rm GeV}}\right)^2$$

for $m_{\eta_0'} \simeq m_{\eta^\pm} \simeq m_\psi$. Larger scalar masses lead to a further suppression. This is confirmed by numerical scan with micrOMEGAs.

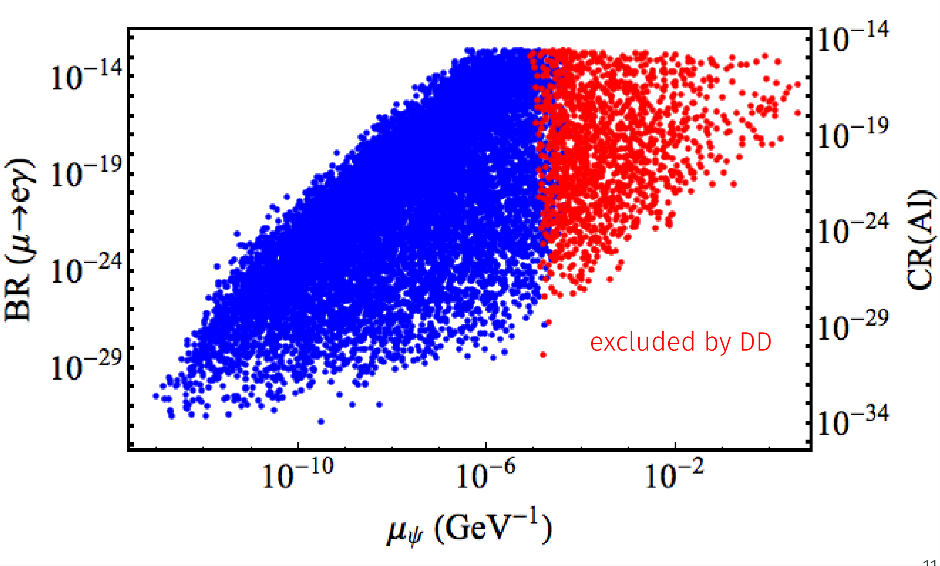
Annihilations into leptons too small: need coannihilation with scalars $\Phi^{(\prime)}$







Complementarity of LFV and DM direct detection



Conclusions

Conclusions

DM may not couple directly to quarks

DM - nucleus scattering only at 1-loop order (or higher)

Discussion of simplifed fermionic DM model

magnetic and electric dipole moment dominate
Higgs penguins are important for Majorana DM

Scotogenic model with Dirac fermion

fermionic DM requires coannihilation
interplay between LFV and direct detection

Conclusions

DM may not couple directly to quarks

DM - nucleus scattering only at 1-loop order (or higher)

Discussion of simplifed fermionic DM model

magnetic and electric dipole moment dominate
Higgs penguins are important for Majorana DM

Scotogenic model with Dirac fermion

fermionic DM requires coannihilation
interplay between LFV and direct detection

Thank you!