Testing Effective Interactions of Dark Matter at Colliders and Direct Detection Experiments

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DESY Theory Workshop
"Particle Cosmology after PLANCK"

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Motivation

- Fundamental theory of dark matter unknown
  $\rightarrow$ use **effective theory** to describe interactions
  Bai, Fox, Harnik (2010), Fox, Harnik, Kopp, Tsai (2011), Beltran, Hooper, Kolb, Krusberg (2009), Agrawal, Chacko, Kilic, Mishra (2010), Zheng, Yu, Shao, Bi, Li (2012), Goodman, Ibe, Rajaraman, Shepherd, Tait (2011) , Buckley (2013), ...
- Study of **UV-completions** of effective interactions
  $\rightarrow$ relevant for collider phenomenology
  e.g., Dreiner, Huck, Krämer, Schmeier, Tattersall (2012), Lopez-Honorez, Schwetz, Zupan (2012)
- No conclusive evidence for DM in direct detection
  $\rightarrow$ suppression of DM interactions
  $\rightarrow$ direct detection interactions generated by **higher-dimensional operators**

Effective Operators

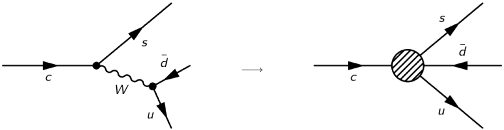
- BSM physics can be parameterized as **tower of effective operators**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}}^{d=5} + \mathcal{L}_{\mathrm{eff}}^{d=6} + \cdots , \quad \text{with} \quad \mathcal{L}_{\mathrm{eff}}^{d} \propto \frac{1}{\Lambda_{\mathrm{NP}}^{d-4}} \mathcal{O}^d$$

  suppressed by powers of the new physics scale $\Lambda_{\mathrm{NP}}^{d-4}$
- Describing **low energy effects** of a fundamental theory at **high energies**
- Obtained by **integrating out** heavy fields
- Good **approximation** below heavy mass scale

Examples

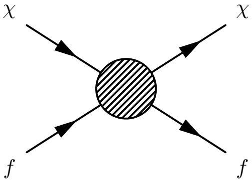
- Fermi theory
- Seesaw mechanism
- ...

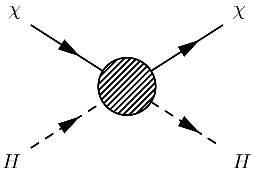


Dark matter interactions with SM particles

- Dark matter particle χ: fermionic gauge singlet
- Leading order interactions with SM particles:

$$\mathcal{O}_1 = \frac{1}{\Lambda^2}\chi\chi ff \qquad \text{and} \qquad \mathcal{O}_H = \frac{1}{\Lambda}\chi\chi H^\dagger H$$

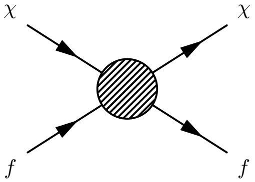


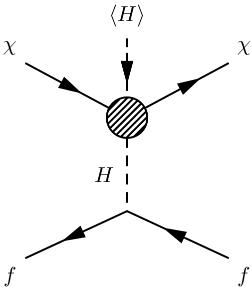


Dark matter interactions with SM particles

- Dark matter particle χ: fermionic gauge singlet
- Leading order interactions with SM particles:

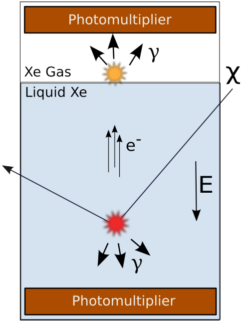
$$\mathcal{O}_1 = \frac{1}{\Lambda^2}\chi\chi\, ff \qquad \text{and} \qquad \mathcal{O}_2 = \frac{1}{\Lambda m_H^2}\,\chi\chi ff\,\langle H\rangle$$

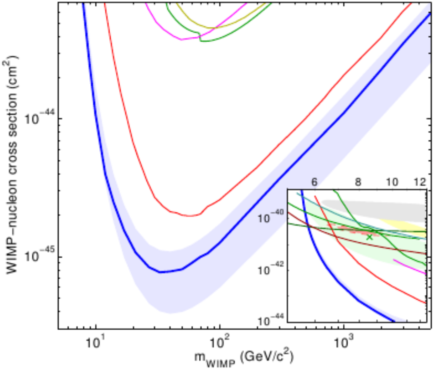




Direct detection:

interactions of DM with SM particles in nuclei





LUX collaboration; arXiv:1310.8214

Structure functions

Higgs portal interactions

Form factor of the Higgs to a nucleon is theoretically known
(depends on quark Yukawa couplings and parton distribution function)

$$f_N^H = \sum_q f_{Tq} + \frac{2}{9} f_{TG} \,,$$

m_N nucleon mass, f_{Tq} and f_{TG} form-factors for quarks and gluons

Direct interaction with SM fermions

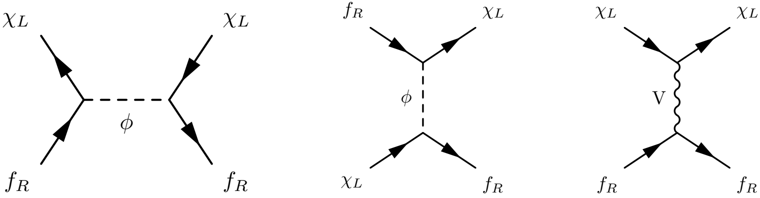
Assume couplings flavor blind and order one $\rightarrow$ form factor is then
(corresponding form factor for neutralino DM)

$$f_N^{\mathcal{O}_1} = m_N \left(\sum_{q=u,d,s} \frac{f_{Tq}}{m_q} + \frac{2}{27} f_{TG} \sum_{q=c,b,t} \frac{1}{m_q} \right) \,.$$

In our scenario $\rightarrow$ both operators have roughly equal contributions

Operators of the class $\chi\chi ff$

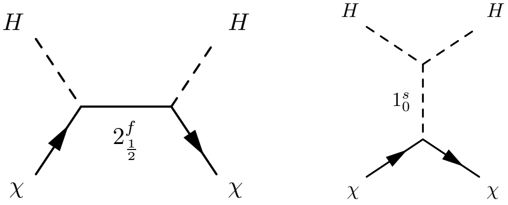
- Both contributions are of similar order
- Decompositions of $\chi\chi ff$ can be invariant under discret symmetries



- Avoid mediators with the $(SU(3)_c, SU(2)_L, U(1)_Y; \mathbb{Z}_2)$ quantum numbers

$$(3, *, *; -)\ ,$$
$$\left(1, 2, -\frac{1}{2}; -\right)\ ,$$
$$(1, 1, -1; -)\ ,$$

- Decompositions of $\chi\chi H^\dagger H$



- Mediators $((SU(3)_c, SU(2)_L, U(1)_Y; \mathbb{Z}_2))$:

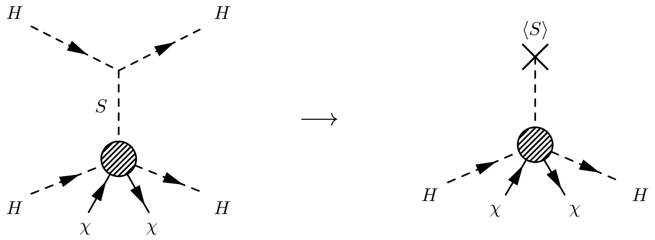
$$\left(1, 2, \pm\frac{1}{2}; -\right) \,,$$
$$(1, 1, 0; +) \,,$$

Higher order contributions I

	(a)	(b)
$d = 5$	—	$\chi\chi H^\dagger H$
$d = 6$	$\chi\chi f f$	$\chi\chi H^\dagger H S$
$d = 7$	$\chi\chi f f S$	$\chi\chi (H^\dagger H)^2$
	$\chi\chi f f H$	$\chi\chi H^\dagger H S^2$

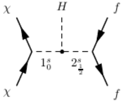
- Leading order direct and Higgs-portal interactions forbidden
- Systematic study of operators up to $d = 7$
- Consider also scalar singlets S as external fields

Higher order contributions II



- UV completions can have scalar singlet mediator S
- Coupling $H^\dagger HS$ induces VEV of S
  $\rightarrow$ additional contribution to interaction

Systematic study of decompositions



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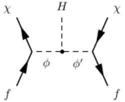

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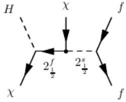

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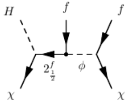

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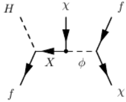

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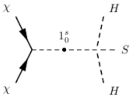

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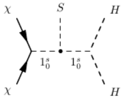

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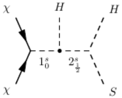

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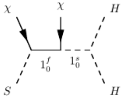

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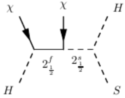

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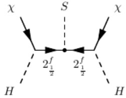

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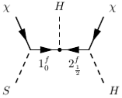
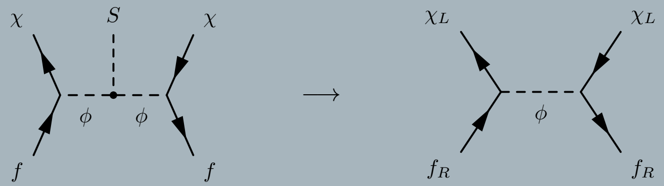


Operators of the class $\chi\chi ffS$

- Obtained by inserting S in leading order decompositions
- Mediators will always generate leading order operator $\chi\chi ff$

Example

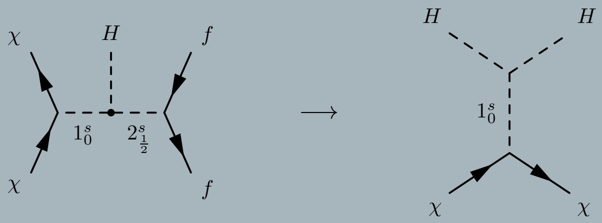


$$\mathcal{L}_{\#S1} = \mathcal{L}_{SM} + \lambda_{\chi f \phi}\, \chi f \cdot \phi + \lambda_{S\phi\phi}\, S^\dagger \phi \cdot \phi + m_\phi\, \phi^\dagger \phi + m_\chi\, \chi\chi + \cdots + \text{h.c.}\,,$$

Operators of the class $\chi\chi ffH$

- Some operators contain again mediators that generate leading order interactions
- Others contain scalar SU(2) doublet that can be identified as Higgs field
  $\rightarrow$ leading order Higgs portal interaction

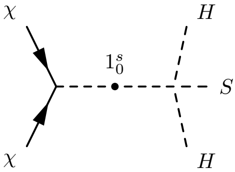
Example



$\Rightarrow$ No leading order interaction from $\chi\chi ffH$

Operators of the class $\chi\chi H^\dagger HS$

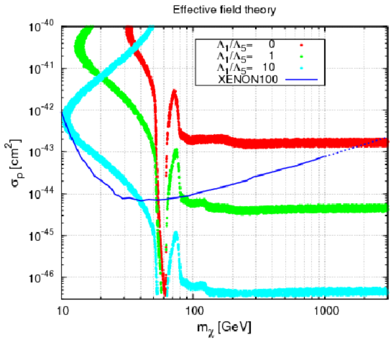
- Need additional symmetry to avoid generation of leading order Higgs-portal
- Generate DM mass via $\lambda S\chi\chi$
- The terms $m_S S^\dagger S$ and $S^\dagger S H^\dagger H$ are always present and will lead to the following interaction:



- Decompositions with singlet fermion mediator
  $\rightarrow$ will mix with dark matter
  $\rightarrow$ generates leading order operator

Leptophilic DM

- Not all $d = 6$ operators forbidden
- Leading order interactions with leptons
- Higher order interactions with quarks
- Supressed direct detection **but** observed DM abundance

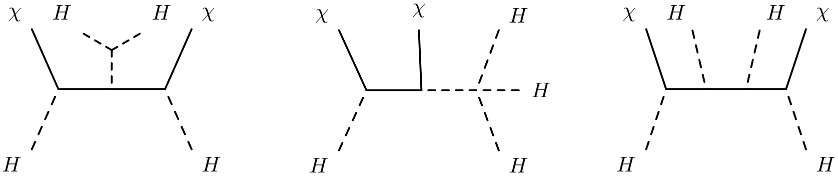


Lopez-Honorez, Schwetz, Zupan; *Phys. Lett.* **B716** (2012) 179

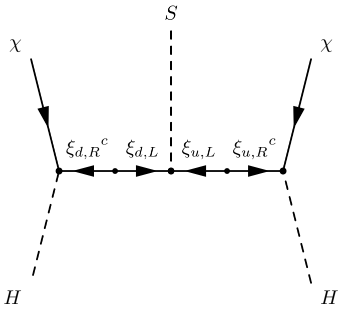
Operators of the class $\chi\chi(H^\dagger H)^2$

- Next to leading order operator when no S present
- None of them is consistent with leading order contribution to dark matter interactions:
  - Mediators obtain a VEV
  - Mediator can be identified as Higgs field
  - Mediator appears in leading order operator

$\Rightarrow$ Induces leading order interaction



UV-complete example I



Fields:	SM	Fermions					Scalars
		$\xi_{d,L}$	$\xi_{u,L}$	$(\xi_{u,R})^c$	$(\xi_{d,R})^c$	χ	S
$SU(2)$		2	2	2	2	1	1
$U(1)_Y$		$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0
$\mathbb{Z}_3$	1	ω	ω	ω^2	ω^2	ω	ω
$\mathbb{Z}_2$	$+$	-	-	-	-	-	$+$

UV-complete example II

$$\mathcal{L}_{\#\mathrm{C6}} = \mathcal{L}_{\mathrm{SM}} + \Big[\lambda_{\xi_u}\, H \cdot (\xi_{u,R})^c\, \chi + \lambda_{\xi_d}\, H^\dagger \cdot (\xi_{d,R})^c\, \chi + \lambda_{\xi\xi S}\, S\, \xi_{u,L} \cdot \xi_{d,L}$$
$$+ \lambda'_{\xi\xi S}\, S^* \, (\xi_{u,R})^c \cdot (\xi_{d,R})^c + m_u\, \xi_{u,L} \cdot (\xi_{u,R})^c + m_d\, (\xi_{d,R})^c \cdot \xi_{d,L}$$
$$+ \lambda_{S\chi\chi} S\chi\chi + \kappa_S S^3 + \mathrm{h.c.}\Big]$$
$$+ \lambda_{SSHH}(S^* S)(H^\dagger H) + m_S S^* S + \lambda_S (S^* S)^2 \,.$$

The doublets can explicitly be expressed as

$$\xi_{d,L} = \begin{pmatrix} \xi^0_{d,L} \\ \xi^-_{d,L} \end{pmatrix} \quad \xi_{u,L} = \begin{pmatrix} \xi^+_{u,L} \\ \xi^0_{u,L} \end{pmatrix} \quad {\xi_{u,R}}^c = \begin{pmatrix} {\xi^0_{u,R}}^c \\ ({\xi_{u,R}}^c)^- \end{pmatrix} \quad {\xi_{d,R}}^c = \begin{pmatrix} ({\xi_{d,R}}^c)^+ \\ {\xi^0_{d,R}}^c \end{pmatrix} \,.$$

LHC phenomenology I

Mass eigenstates of new particles

- 2 charged fermions $X^{\pm}$
- 5 neutral fermions X_i^0
- Singlet-like pseudoscalar P^0

  Decay width $\Gamma_{P^0 \to \gamma\gamma}$ of $\mathcal{O}$(keV) 4 $\to$ decays before big bang nucleosynthesis
- Two higgs-bosons $h_{1/2}$, one of them the SM Higgs

Contribtuions to mass matrix from explicit mass terms

$$m_{\xi u} \text{ and } m_{\xi d}$$

and masses induced by VEV of S

$$\lambda_{\xi\xi S} \frac{v_S}{\sqrt{2}}, \lambda'_{\xi\xi S} \frac{v_S}{\sqrt{2}}$$

LHC phenomenology II

Case A ($m_{\xi_d,\xi_u} \gg \lambda_{\xi\xi S}\frac{v_S}{\sqrt{2}}, \lambda'_{\xi\xi S}\frac{v_S}{\sqrt{2}}$)

- Pseudo-Dirac fermions with masses close to $m_{\xi u}$ and $m_{\xi d}$
- Bound on $\lambda_{\xi\xi S}$ and $\lambda'_{\xi\xi S}$ from pseudoscalar life-time
- Dominant decays for $m_{\xi_d} \simeq m_{\xi_u}$

$$X^+_{1/2} \rightarrow W^+ X^0_1$$
$$X^0_{2-5} \rightarrow ZX^0_1 \,,\; h_i X^0_1 \,,\; PX^0_1$$

else also

$$X^+_2 \rightarrow ZX^+_1 \,,\; h_i X^+_1 \,,\; PX^+_1 \,,\; W^+ X^0_{2/3}$$
$$X^0_{4/5} \rightarrow ZX^0_{2/3} \,,\; h_i X^0_{2/3} \,,\; PX^0_{2/3} \,,\; W^\pm X^\mp_1$$

- Possibly displaced vertices

Case B ($m_{\xi_d,\xi_u} \ll \lambda_{\xi\xi S}\frac{v_S}{\sqrt{2}}, \lambda'_{\xi\xi S}\frac{v_S}{\sqrt{2}}$)

- Pseudo-Dirac fermions with masses close to $\lambda_{\xi\xi S}\frac{v_S}{\sqrt{2}}$
- Lower limit on m_ξ guarantees large couplings $\rightarrow$ short pseudo-scalar lifetime
- Similar decays as for $m_{\xi_d} \simeq m_{\xi_u}$ above

Summary and Conclusion

- Detailed understanding of DM interactions important for understanding direct detection experiments
- DM interactions can be generated by higher-dimensional operators $\rightarrow$ additional suppression
- Systematic study of decompositions $\rightarrow$ constrain consistent models
- Testable at colliders such as the LHC

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Thank you!