Self-consistent Dark Matter Simplified Models with an s-channel scalar mediator

1612.03475

G. Busoni

CoEPP
University of Melbourne

30 Jan 17

Outline

1. Introduction
   - Generation I model
   - Assumptions and Implications
   - A possible Gauge invariant version
   - Consequences of Gauge Invariance
2. Going Beyond: 2HDM
   - Adding a second doublet
   - DD constraints: Type I and II
   - DD constraints: Type III and FCNC
   - Relic Density and Collider
3. Conclusions
   - Summary

Outline

Just one additional scalar coupled with generic couplings $g_q y_i$, y_χ

$$\mathcal{L}_{new} = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}M^2 S^2 - \frac{g_q}{\sqrt{2}} S \sum_q y_i \bar{q}_i q_i - y_{DM} S \bar{\chi}\chi$$

The interaction term of S with quarks is not gauge invariant, as

$$\bar{q}_i q_i = \bar{q}^i_L q^i_R + \bar{q}^i_R q^i_L$$

is not SM singlet

Outline

Assumptions

- S is a scalar, and is a portal to DM
- χ is a SM singlet
- S is exchanged in the s-channel
- Structure of SM yukawa lagrangian is not modified
- There is only one Higgs doublet

Implications

- S is a SM singlet
- S has to mix with SM higgs, as a quark scalar bilinear can only couple to a particle that has the same quantum numbers as an Higgs doublet

Outline

1. Introduction
   - Generation I model
   - Assumptions and Implications
   - A possible Gauge invariant version
   - Consequences of Gauge Invariance
2. Going Beyond: 2HDM
   - Adding a second doublet
   - DD constraints: Type I and II
   - DD constraints: Type III and FCNC
   - Relic Density and Collider
3. Conclusions
   - Summary

A Gauge invariant version of this model could be obtained by the following lagrangian (Z_2 on S)

$$\mathcal{L}_{new} = \frac{1}{2}\partial^\mu S \partial_\mu S + \frac{1}{2} M_{SS}^2 S^2 - \frac{1}{2}\lambda_{HS}\phi^\dagger \phi S^2 - \frac{1}{4!}\lambda_S S^4 - y_{DM} S \bar{\chi}\chi$$

EW symmetry breaking mixes the SM higgs with the new scalar

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\epsilon & \sin\epsilon \\ -\sin\epsilon & \cos\epsilon \end{pmatrix} \begin{pmatrix} h' \\ S \end{pmatrix}$$

The mixing angle ϵ has to be small, so that higgs and EW phenomenology does not get affected much (all SM signal strengths involving the higgs get a $\cos^2\epsilon$ factor)

Consequently, $\cos\epsilon \sim 1$

Introduction

A possible Gauge invariant version

The $h - s$ mixing gives s a coupling to Standard Model fermions:

$$\mathcal{L}_{int} = -y_i \bar{Q}^i_L u^i_R \widetilde{\phi} = -m_i \bar{u}^i_L u^i_R (1 + \cos\epsilon \frac{h}{v} - \sin\epsilon \frac{s}{v})$$

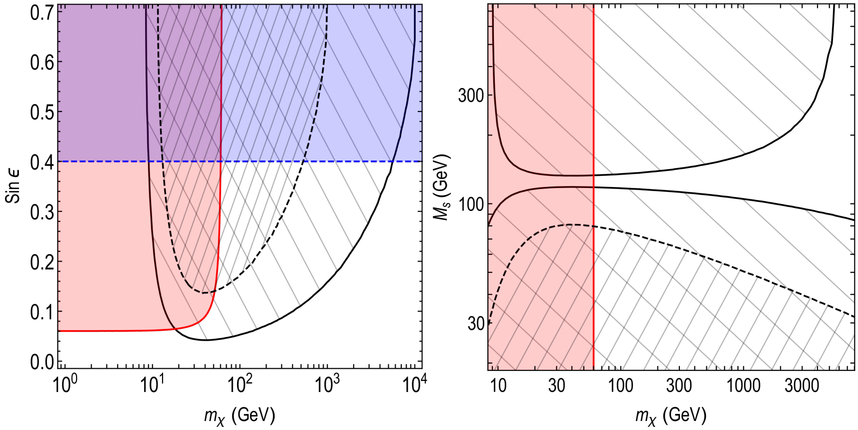
The coupling of s to quarks is indeed proportional to yukawas

$$g_q = -\sin\epsilon$$

Both mediators therefore contribute to all cross sections:

$$\sigma_{\bar{q}q\to\bar{\chi}\chi+X} \propto (y_\chi y_q \sin\epsilon\cos\epsilon)^2 \left(\frac{1}{s - M_h^2} - \frac{1}{s - M_s^2}\right)^2$$

The mixing requires also the Higgs to couple to DM, and the product of the couplings for h and s is equal and opposite


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Sin ϵ
10^0
10^1
10^2
10^3
10^4
m_χ (GeV)
300
100
30
M_S (GeV)
10
30
100
300
1000
3000
m_χ (GeV)

Outline

- $g_q = \sin\epsilon \leq 1$ means low to moderate sensitivity
- Higgs couples to DM
- Stringent DD constraints on ϵ, even $M_s \to \infty$ (but not for $M_s \sim M_h$)
- DD blind window at $M_s \sim M_h$ [1509.05771]
- Too weak signal at LHC unless at least one of the 2 mediators can go on shell
- Bounds on h invisible give stringent constraints for $m_\chi \lesssim M_h/2$
- VBF operator arises

$$L_{int,VBF} = -\sin\epsilon\left(2\frac{M_W^2}{v}W_\mu^+ W^{-\mu} + \frac{M_z^2}{v}Z_\mu Z^\mu\right)s$$

Outline

Going Beyond: 2HDM

Adding a second doublet

- Conclusions of the previous slides are quite general
  - A more complex scalar sector would still lead to similar conclusions
- To get more freedom with couplings to quarks, the only way is to add an additional Higgs doublet
- New Lagrangian will contain the singlet S as well, for a total of 3 scalars

$$\begin{aligned} V(\Phi_1,\Phi_2,S) &= M_{11}^2\Phi_1^\dagger\Phi_1 + M_{22}^2\Phi_2^\dagger\Phi_2 + (M_{12}^2\Phi_2^\dagger\Phi_1 + h.c.) \\ &+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{1}{2}\left(\lambda_5(\Phi_2^\dagger\Phi_1)^2 + h.c.\right), \\ &+ \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{3}\mu_S S^3 + \frac{1}{4}\lambda_S S^4 \\ &+ \frac{\lambda_{11S}}{2}(\Phi_1^\dagger\Phi_1)S^2 + \frac{\lambda_{22S}}{2}(\Phi_2^\dagger\Phi_2)S^2 + \frac{1}{2}(\lambda_{12S}\Phi_2^\dagger\Phi_1 S^2 + h.c.) \end{aligned}$$

- The 3 scalars will in general mix with arbitrary mixing angles
  - There is always a region of the parameter space where one can decouple the first doublet and make it SM-like $\cos(\beta - \alpha) = 0$
  - This region may rise up naturally in presence of some simmetries of the full UV model
  - In that case S mixes only with the scalar of the second doublet, and there is no constraints on the mixing angle
  - SM phenomenology doesn't get affected in this limit, and no VBF operator arises

- In 2HDM, natural alignment arises in presence of the symmetry
$$\lambda_1 = \lambda_2 = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$
- Under such symmetry, rotating the doublets of an angle β leave the couplings $\lambda_{1,\ldots,5}$ invariant
- Rotating in the higgs basis, where $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ and $\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ one gets the mass matrix

$$M^\rho = \begin{pmatrix} M^\rho_{hh} & 0 & M^\rho_{hS} \\ 0 & M^\rho_{HH} & M^\rho_{HS} \\ M^\rho_{hS} & M^\rho_{HS} & M^\rho_{SS} \end{pmatrix} \quad (1)$$

- To avoid the SM higgs to mix with the singlet state, one needs to require that in the new basis $\lambda_{11S} = 0$

Outline

Going Beyond: 2HDM

Type I and II

In the alignment limit $(\beta - \alpha = \pi/2)$, ones gets (neglecting scalar interactions))

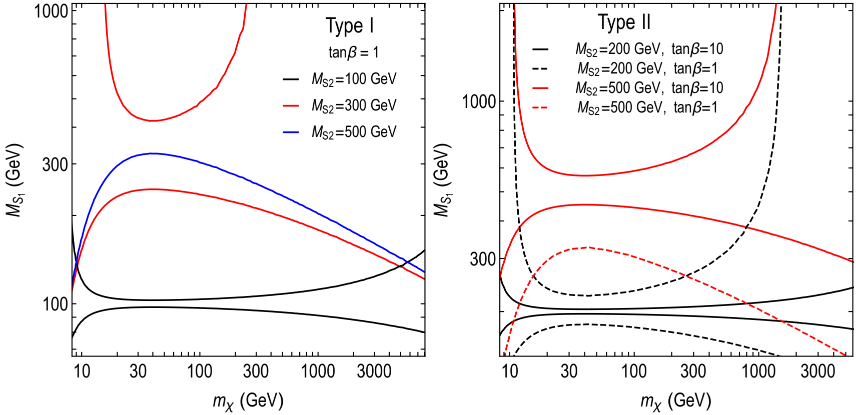
$$\begin{aligned} L &= L_{SM} + \frac{1}{2}\partial^\mu S_i \partial_\mu S_i - \frac{1}{2} M_i^2 S_i^2 (i = 1,2) + \bar{\chi}(i\not{\partial} - m_\chi)\chi \\ &- y_{DM}(\cos\theta S_2 + \sin\theta S_1)\bar{\chi}\chi - \frac{y_f \xi^f}{\sqrt{2}}(\cos\theta S_1 - \sin\theta S_2)\bar{f} f \end{aligned}$$

	Type I	Type II
ξ^u	$\cot\beta$	$\cot\beta$
ξ^d	$\cot\beta$	$-\tan\beta$
ξ^ℓ	$\cot\beta$	$-\tan\beta$

- Type II can allow an enhanced coupling to down quarks, for large values of $\tan\beta$
- u, d quarks have same-sign couplings in Type I and opposite sign couplings in Type II

Going Beyond: 2HDM

Direct Detection Constraints



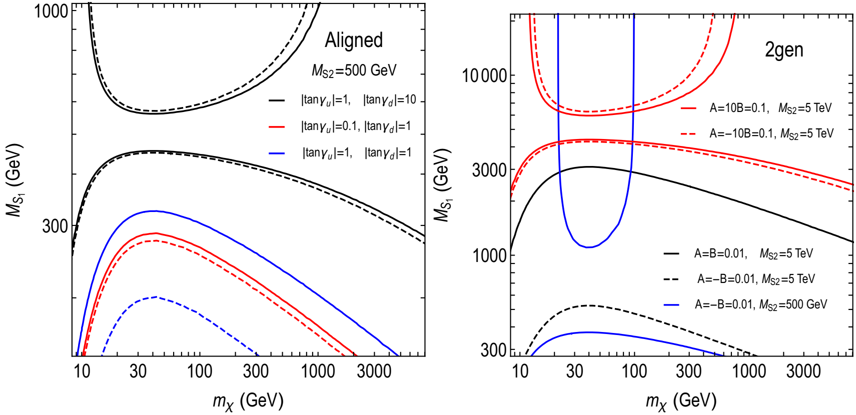
Not only interference between the 2 mediators, but also interference between different flavours (Type II)

Outline

- The most general case is Type III
  - In this case, FCNC generally appear at tree level
- To get rid of them at tree level, one needs flavour-diagonal couplings (in mass eigenstates basis)
- In absence of symmetry, loop level FCNC will appear
- Examples of Yukawa patterns that are ”protected” against loop level FNCN:
  - Aligned yukawas: $y_H^U = \tan\gamma_u y_h^U, y_H^D = \tan\gamma_d y_h^D, y_H^l = \tan\gamma_l y_h^l$
  - Coupling only to first 2 generations: $y_H^{u,c} = A, y_H^{d,s} = B, y_H^{b,t,l} = 0$

Going Beyond: 2HDM

Direct Detection Constraints



Interference between flavours only happens for a certain ratio between the yukawa couplings

Outline

Going Beyond: 2HDM

Relic Density and Collider

- Rich phenomenology and highly dependent on the mass spectrum
- Relic Density: can be obtained with
  - Scalar/gauge only annihilations ($\chi\bar{\chi} \to S_i S_i, S_i Z, S_i h, H^+ W^-$)
  - Fermion-only annihilations ($\chi\bar{\chi} \to f\bar{f}$) (might require ”large” couplings or resonant enhancement)
  - Mixture of the two
- Collider: other than monojet, certain mass spectrums allow resonant production and decay to get large mono-higgs/mono-Z signals

Outline

Conclusions

Models Summary

Model	Singlet	Type I	Type II	Type III
2 Mediators	Yes	Yes	Yes	Yes
MAX g_q	$\sin\epsilon \lesssim 0.4$	$\sqrt{4\pi}$	$g_u < \sqrt{4\pi}$ $g_d < \frac{m_t}{m_b}\sqrt{4\pi}$	$\frac{m_t}{m_q}\sqrt{4\pi}$
VBF	Yes	No	No	No
SM constr.	Yes	No	No	No
Num. Par.	$4(+1\Gamma)$	$6(+2\Gamma)$	$6(+2\Gamma)$	$14(+2\Gamma)$
NFC	N/D	Yes	Yes	No
MFV	Yes	Yes	Yes	Yes
Flavour constr.	No	Moderate	Moderate	Depends

- Single scalar mediator
  - not gauge invariant wrt SM symmetries
- Singlet mixed with SM Higgs
  - Simple model, can be studied in details without ”simplifying” it
  - Many constrains from SM physics
  - Negative interference in DD for degenerate mediators
- Singlet plus 2 Higgs doublets
  - Necessary to go beyond the above
  - Interesting case in the alignment limit
  - S mixes with 2nd Higgs, thus no Higgs mixing constraints
  - Negative interference in DD also from flavour interference
  - Flavour diagonal (*but not necessarily Yukawa suppressed*) couplings forbid tree-level FCNC
  - Arbitrary diagonal couplings allow large LHC signals
  - Large parameter space for Type III can be ”simplified” with flavor constrains