



Consistent scalar mediators for dark matter: the 2HDM case

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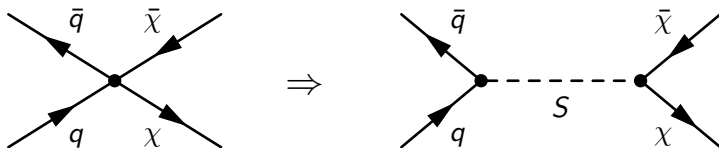
Brief outline

- ▶ Naive scalar mediator (S)
- ▶ Simplest consistent scalar mediator ($H + S$)
- ▶ NSimplest consistent scalar mediator ($2HDM + S$)

Earlier studies in 1612.03475 (Bell, Busoni, Sanderson),
1705.03913 (Buckley, Feld), ...

Simplified scalar mediators

In Simplified Model paradigm we go step further than EFT by adding an explicit mediator S :



Motivation is to avoid applying EFT to regime where Taylor expansion of propagator fails to converge:

$$\frac{1}{p^2 - M^2} \approx -\frac{1}{M^2} (1 + \mathcal{O}(p^2/M^2)) \quad (1)$$

Simplified scalar mediators

Naive implementation in broken phase:

$$\mathcal{L}_S \supset -g_q S \sum_q \frac{y_q}{\sqrt{2}} \bar{q}q - y_\chi S \bar{\chi}\chi \quad (2)$$

But:

- ▶ if $\chi \sim (\mathbf{1}, \mathbf{1}, 0)_{\mathcal{G}_{SM}}$, then $S \sim (\mathbf{1}, \mathbf{1}, 0)_{\mathcal{G}_{SM}}$
- ▶ but $Q_L \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_{\mathcal{G}_{SM}}$, $u_R \sim (\mathbf{3}, \mathbf{1}, \frac{2}{3})_{\mathcal{G}_{SM}}$

\Rightarrow this model is not $SU(2)_L \times U(1)_Y$ invariant!

$$H + S$$

There's a convenient dimension-2 singlet operator in the Standard Model: $H^\dagger H$

$$V(H, S) \supset \lambda_{sh} H^\dagger H S^2 + \lambda_h (H^\dagger H)^2 + \lambda_s S^4 \quad (3)$$

Expanding around the vevs $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$, $S = s + x$, we get mixing between h and s :¹

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} \quad (4)$$

¹Here θ is a function of $v, x, \lambda_s/h/sh$.

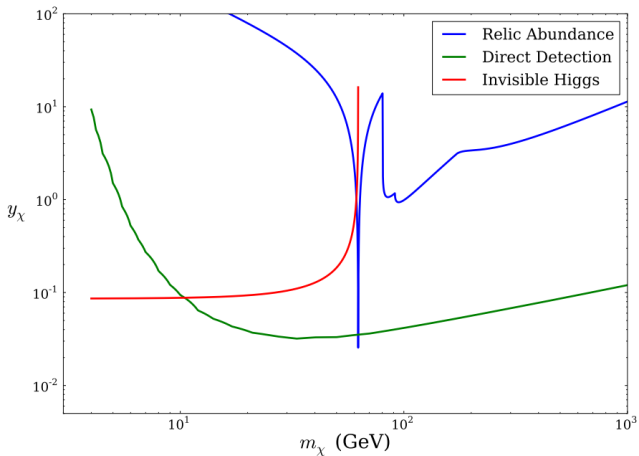
Both mass eigenstates now couple to both the visible and dark sectors with strengths modified by θ :

$$\mathcal{L}_{h_{1/2}} \supset - \left(\sum_f \frac{y_f}{\sqrt{2}} \bar{f} f + \sum_V g_V V_\mu V^\mu \right) \times (\cos \theta h_1 - \sin \theta h_2) \\ - y_\chi \bar{\chi} \chi \times (\cos \theta h_2 + \sin \theta h_1) \quad (5)$$

This is a consequence of requiring the model to be consistent!

'Unfortunately' also introduces massive sensitivity to direct detection experiments through the 125 GeV state.

$H + S$



Taken from 1705.03913 (Buckley, Feld).

2HDM + S

Can decouple 125 GeV state from mixing by enlarging visible scalar sector. Taking 2HDM with Z_2 which mixes with S again:

$$\begin{aligned} V(H_1, H_2, S) = & \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 \\ & + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ & + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + (\lambda_5 (H_1^\dagger H_2)^2 + \text{h.c.}) \\ & + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 + \frac{\lambda_{2S}}{2} H_2^\dagger H_2 S^2 \end{aligned} \quad (6)$$

Here:

$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i + h_i + i\phi_i^0}{\sqrt{2}} \end{pmatrix}, \quad S = x + s \quad (7)$$

2HDM + S

Useful to work in Higgs basis where ($\tan \beta = v_2/v_1$)

$$H_h = \cos \beta H_1 + \sin \beta H_2 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix} \quad (8)$$

$$H_H = -\sin \beta H_1 + \cos \beta H_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix} \quad (9)$$

- ▶ The pseudoscalar and charged scalar sectors are similar to standard 2HDM²
- ▶ The scalar sector now mixes h, H, s

We want to remove any sensitivity of the 125 GeV state to direct detection \rightarrow avoid h, H and h, s mixing.

²See Patrick Tunney's talk for a similar model mixing in a pseudoscalar mediator with A .

Mixing matrix:

$$\begin{pmatrix} h & H & s \end{pmatrix} \begin{pmatrix} \mathcal{M}_{hh} & \mathcal{M}_{hH}/2 & \mathcal{M}_{hs}/2 \\ \mathcal{M}_{hH}/2 & \mathcal{M}_{HH} & \mathcal{M}_{Hs}/2 \\ \mathcal{M}_{hs}/2 & \mathcal{M}_{Hs}/2 & \mathcal{M}_{ss} \end{pmatrix} \begin{pmatrix} h \\ H \\ s \end{pmatrix} \quad (10)$$

In usual 2HDM, only top left 2×2 part present and we can introduce single mixing angle α :

$$\begin{pmatrix} h' \\ H' \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} \quad (11)$$

We can remove mixing by hand using e.g. λ_1 :

$$\mathcal{M}_{hH} = \frac{1}{8} \left(2x^2 s_{2\beta} (\lambda_{2S} - \lambda_{1S}) + 3v^2 ((\lambda_3 + \lambda_4 + 2\lambda_5) s_{4\beta} - 8\lambda_1 s_{\beta} c_{\beta}^3 + 8\lambda_2 s_{\beta}^3 c_{\beta}) \right) \rightarrow 0 \quad (12)$$

We also need to remove the mixing between h, s using e.g. λ_{1S} :

$$\mathcal{M}_{hs} = vx (c_{\beta}^2 \lambda_{1S} + s_{\beta}^2 \lambda_{2S}) \rightarrow 0 \quad (13)$$

2HDM + S

We have fixed $\alpha = 0$ here \neq alignment! Alignment in this case additionally requires that $\sin \beta = 0 \Rightarrow \tan \beta = 0$.

In other words, we have $H_h = H_1$ and this doublet behaves exactly like the SM Higgs doublet, and has to generate all masses (since $v_2 = 0$).

\Rightarrow We are forced to use a type-I Yukawa structure, and by default H does not couple to fermions/weak bosons at all.

\Rightarrow Need to abandon usual Natural Flavor Conservation approach of only coupling one doublet to each type of fermion.

Consequence of requiring h to be in alignment while also completely insensitive to direct detection!

2HDM + S

In the end we have Standard Model-like h and two heavier mass eigenstates s_1, s_2 which couple to both sectors again, dependent on a new mixing angle η :

$$\mathcal{L}_{s_{1/2}} \supset - \sum_f \xi^f \frac{y_f}{\sqrt{2}} \bar{f} f (\cos \eta s_1 - \sin \eta s_2) \\ - y_\chi \bar{\chi} \chi (\cos \eta s_2 + \sin \eta s_1) \quad (14)$$

ξ^f depends on how we couple H_2 to $u/d/l$, here assumed to be \propto normal Yukawas for MFV, however flavour constraints still possible since not protected from quantum corrections.

Can now make the lightest mass eigenstate heavy enough to be able to satisfy both direct detection and relic density constraints!

Conclusions

- ▶ Demanding simplified models to be theoretically consistent can make a big difference to predicted signatures³
- ▶ The $2HDM + S$ model is quite subtle and can not use the standard Natural Flavour Conservation assumption to avoid FCNCs

³See also 1704.03850 (Ellis, Fairbairn, Tunney) for a discussion of anomalies in Z' models.