Self-consistent DM Simplified Models with an s-channel scalar mediator

(2HDMs as UV completions to dark matter interactions)

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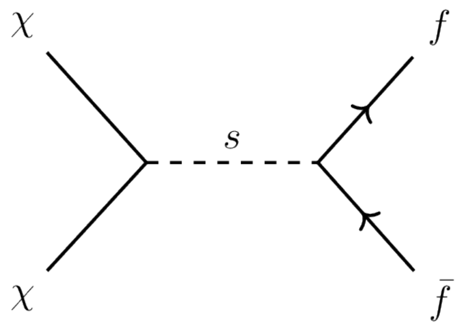
Outline

- Introduction
- Mixing of a scalar singlet with the SM Higgs (H+S)
  A two mediator scenario motivated by gauge invariance
- Mixing of a scalar singlet with an additional Higgs (2HDM+S)
  Scalar spectrum and Yukawa structure
- Interesting parameter space and constraints
- Conclusions

Basic scalar-mediator interaction



$$L_{int} = -g_q S \sum_q \frac{y_i}{\sqrt{2}} \bar{q}_i q_i - y_\chi S \bar{\chi} \chi$$

- This Simplified Model is not $SU(2)_L$ gauge invariant
- We should generalise to a minimal self-consistent model (especially if we consider complementary signals from different channels).

- Need to mix the singlet scalar with $SU(2)_L$ doublet scalar(s)
  → will have minimum of two scalar mediators
  → important phenomenology of this multi-mediator scenario not captured by single-mediator version.

Singlet scalar + SM Higgs (H+S)

$$V = V_{Higgs,SM} - \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \frac{1}{2}\lambda_{HS}\Phi^\dagger\Phi S^2$$

After symmetry breaking, $\langle\phi\rangle = v$, $\langle S\rangle = w$, we have mixing of the mass eigenstate scalars, h and s, with mixing angle

$$\tan\epsilon \simeq \frac{\lambda_{HS} v w}{m_h^2 - m_s^2}$$

Both h and s, mediate $q - \chi$ interactions:

$$L_{int,s-h} = -(h\cos\epsilon - s\sin\epsilon)\sum_f \frac{m_i}{v}\bar{f}_i f_i - y_{DM}(s\cos\epsilon + h\sin\epsilon)\bar{\chi}\chi$$

Note: universal proportionality constant for fermion$-s$ interactions: $\sin\epsilon$

If $m_\chi < m_h/2$, the mixing angle is tightly constrained by Higgs invisible width:

$$\Gamma(h \to \bar{\chi}\chi) = \frac{y_\chi^2 \sin^2\epsilon}{8\pi} M_h \left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{3/2}$$

e.g. $\sin\epsilon < 0.06$ for $y_\chi = 1,\ m_\chi \ll m_h/2$

In addition to the Yukawa terms, other terms 1st order in $\sin\epsilon$ include:

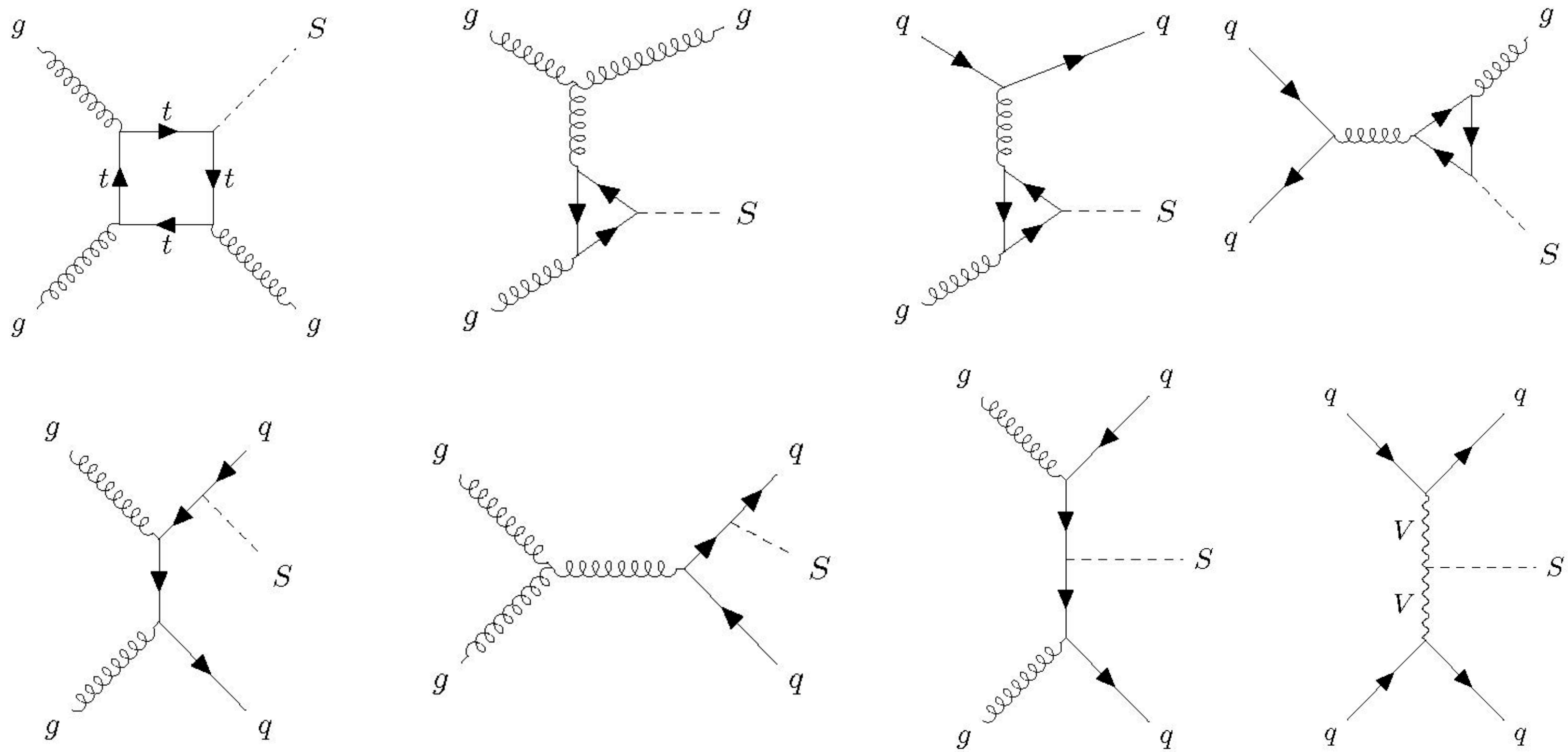
$$L_{int,sWZ} = -\sin\epsilon \left(2\frac{M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu\right) s$$

Precision electroweak constraints imply:

$$|\sin\epsilon| < 0.4 \quad \text{if} \quad m_s \sim 200\ \text{GeV}$$

$$|\sin\epsilon| < 0.2 \quad \text{if} \quad m_s \sim 1000\ \text{GeV}$$

Mono-jets $+ET_{miss}$



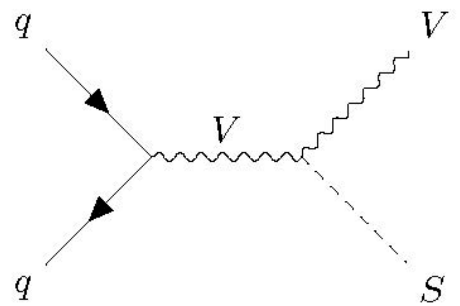
All diagrams contribute to jets/monojets$+ET_{miss}$

Diagrams in lower row also contribute to $t\bar{t} + ET_{miss}$

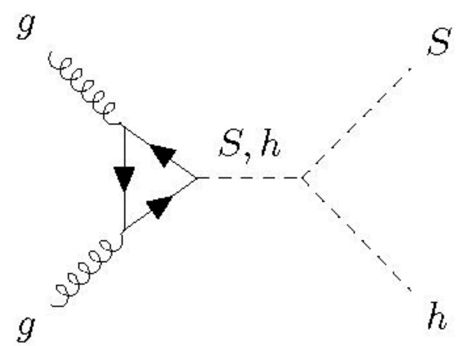
VBF diagram occurs in H+S, 2HDM+S (but not in 1-mediator model)

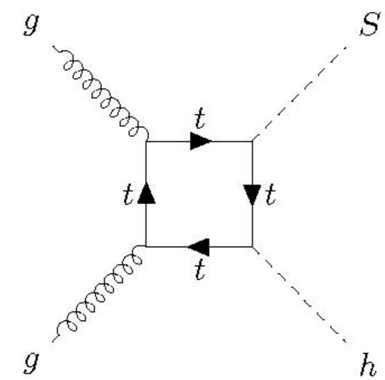
Complementary processes

Mono-W+ET_{miss}



Mono-Higgs+ET_{miss}





Mono-jets sensitivity

Can we rescale the limits on the single-mediator Simplified Model?
→In general no, because:

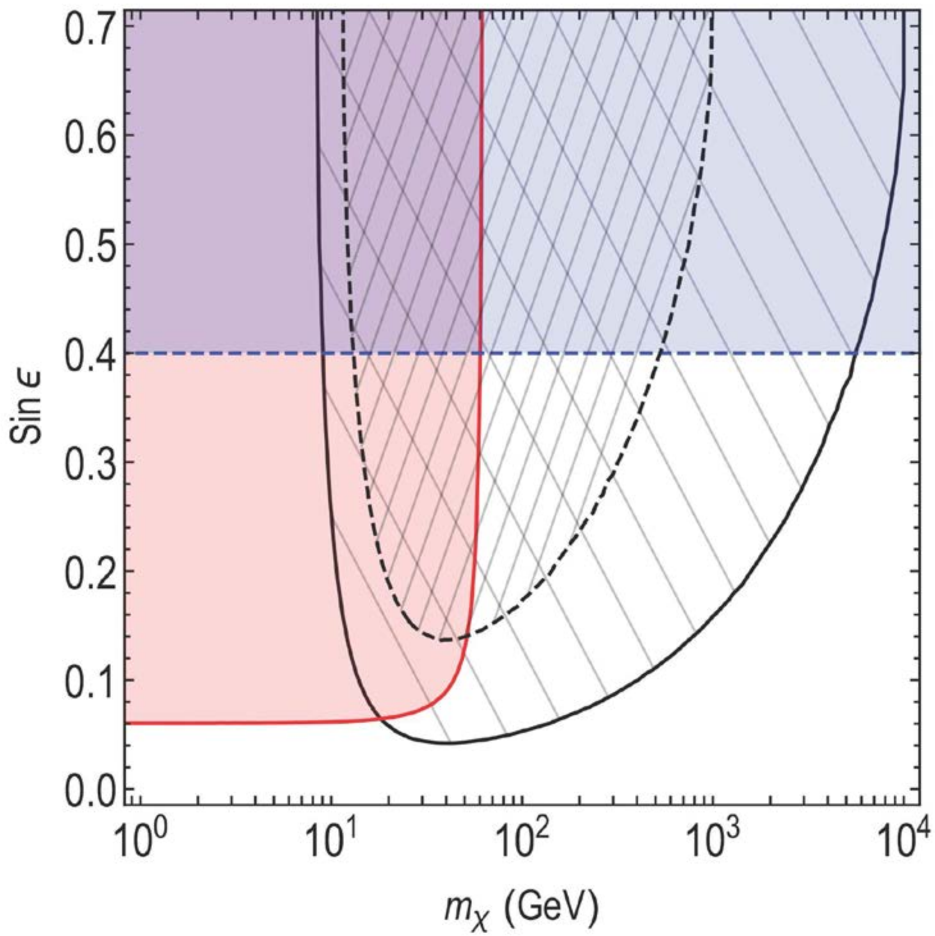
- neglects interference of h and s
- neglects vector boson fusion operators

Nonetheless, if we make a naïve rescaling:

$$\frac{\sigma_{S+H}}{\sigma_S} \sim \frac{\sin^2 \epsilon}{g_q^2} \leq \frac{0.16}{g_q^2}$$

- Current CMS sensitivity is close to $g_q = 1$ (for low mass mediators)
- H+S model harder to exclude due to mixing angle suppression.
- 2HDM+S version will not suffer this suppression (can instead be enhanced by $\tan \beta$ (or other factors that scale the Yukawas)

Direct detection bounds on H+S model



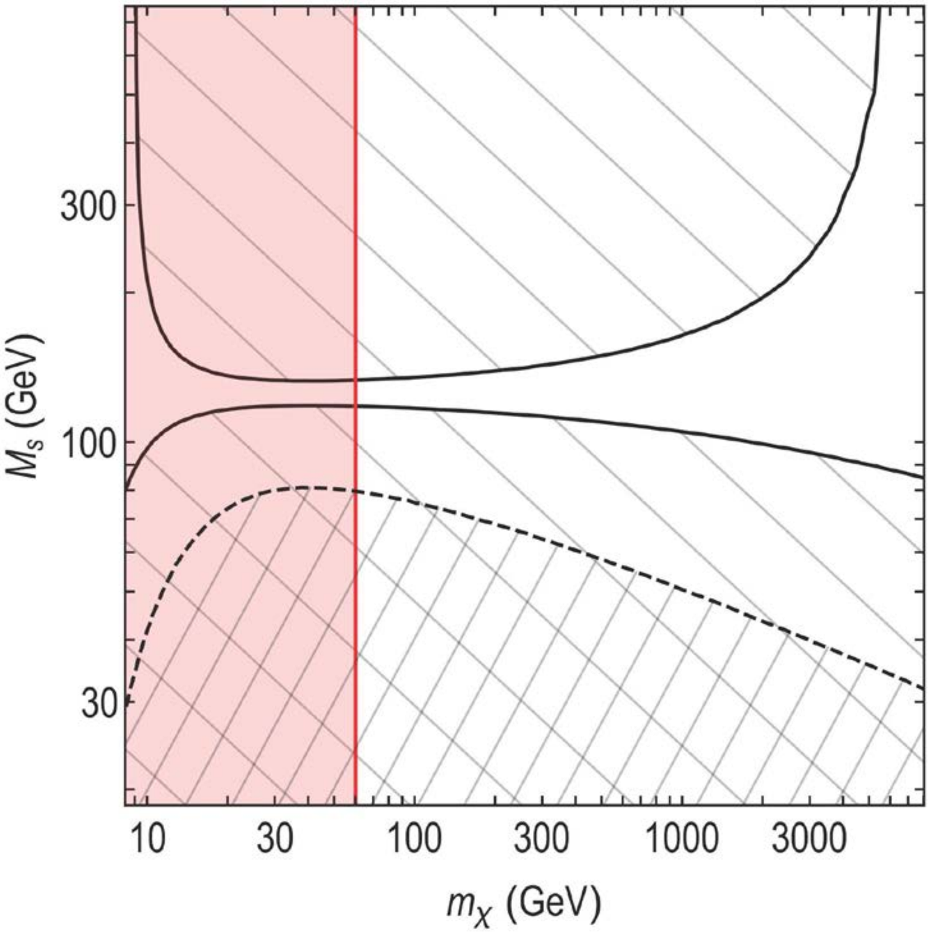
Scalar mediator interactions result in spin-independent (SI) DM-nucleon scattering

→ strongly constrained

—— m_S = 1 TeV
- - - - $m_s = 150$ GeV

Red – excluded by Higgs invisible width
Blue – excluded by EW constraints

Direct detection bounds on H+S model



Destructive interference of h and s occurs when $m_s \sim m_h$
→ Results in a blind spot for direct detection

—— $\sin\epsilon = 0.4$
- - - - $\sin\epsilon = 0.03$

Red – For $\sin\epsilon = 0.4$, this region excluded by Higgs invisible width.
No corresponding bound for $\sin\epsilon = 0.03$.

Singlet + two Higgs doublets (2HDM+S)

Introduce an additional Higgs doublet

- We will want one doublet to be SM-like (alignment limit)
- Mix the additional doublet with a singlet to mediate DM interactions

Use the well-established framework of 2HDMs, and expand to include the additional scalar singlet

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1} \qquad v_1^2 + v_2^2 = v^2$$

Plus the singlet scalar: $S = v_s + S'$

Scalar mixing in 2HDM+S

Work in the Higgs basis where only one doublet obtains a vev:

$$\Phi_h = \cos\beta\Phi_1 + \sin\beta\,\Phi_2 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

$$\Phi_H = -\sin\beta\Phi_1 + \cos\beta\,\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

In general, all 3 scalars will mix after symmetry breaking:

$$M = \begin{pmatrix} M_{hh} & m_{hH} & m_{hs} \\ m_{hH} & m_{HH} & m_{Hs} \\ m_{hs} & m_{Hs} & m_{ss} \end{pmatrix}$$

Note that a pseudoscalar analogue of this setup has only 2x2 mixing, since only one physical pseudoscalar in a 2HDM.

$$M = \begin{pmatrix} M_{hh} & m_{hH} & m_{hs} \\ m_{hH} & m_{HH} & m_{Hs} \\ m_{hs} & m_{Hs} & m_{ss} \end{pmatrix}$$

Enforce generalised “alignment limit”, in which h is SM-like, by requiring

$$\Rightarrow \quad M_{hH} = 0, \qquad M_{hs} = 0$$

(could relax this assumption somewhat and look at 3-state mixing…)

Reduces to 2x2 mixing of $\{H, S\}$, with mass eigenstates $\{S_1, S_2\}$:

$$H = \cos\theta S_1 - \sin\theta S_2$$
$$s = \sin\theta S_1 + \cos\theta S_2$$

2HDM+S Lagrangian

$$L_{int} = -y_\chi(\sin\theta\, S_1 + \cos\theta S_2)\bar{\chi}\chi$$

$$-\sum_{f=u,d,l}\epsilon_f \sum_{i\in f}\frac{y_i}{\sqrt{2}}(\cos\theta\, S_1 + \sin\theta S_2)\bar{f}_i f_i$$

+ charged scalar terms + scalar mixing terms + ….

where the parameters ϵ_f depend on choice of Yukawa structure

Coupling of DM and SM fermions to S_1, S_2 of similar form to H+S model, but

- not subject to Higgs invisible width constraints on the mixing angle
- interference effects possible for m_{S_1}, m_{S_2} very different to m_h^{SM}=125 GeV
- Significantly more freedom in Yukawa couplings

Price we pay is introduction of flavour changing interactions.

2HDM+S Yukawa structure

$$L_{Yukawa} = -\sum_{n=h,H} Y^U_{n,ij}\bar{Q}^i_L u^j_R \tilde{\Phi}_n + Y^D_{n,ij}\bar{Q}^i_L d^j_R \Phi_n + Y^L_{n,ij}\bar{L}^i_L l^j_R \Phi_n + h.c.$$

Type I, II, X and Y, with Natural Flavour Conservation (NFC):

- symmetry which permits each fermion type (u,d,l) to couple to only one of the doublets Φ_1, Φ_2.
- FCNCs suppressed, but still arise from charged scalars in loops

Model	ϵ_d	ϵ_u	ϵ_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Couplings of S_1 and S_2 to fermions proportional to ϵ_f.

e.g. Suppress or enhance couplings to top-quarks with choice of $\tan\beta$

Type III models, with Minimal Flavour Violation (MFV):

- Type III model have no symmetry to prevent coupling to both doublets and hence potential FCNC issues
- Important to implement MFV

MFV, with no tree level FCNCs, can be achieved by requiring that the Yukawa couplings to the two doublets are *simultaneously diagonalizable:*

Couplings to h

$$Y_h^U = V_{CKM}^\dagger D(y_u, y_c, y_t)$$
$$Y_h^D = D(y_d, y_s, y_b)$$
$$Y_h^L = D(y_e, y_\mu, y_\tau)$$

Couplings to H

$$Y_H^U = V_{CKM}^\dagger D(\lambda_u, \lambda_c, \lambda_t)$$
$$Y_H^D = D(\lambda_d, \lambda_s, \lambda_b)$$
$$Y_H^L = D(\lambda_e, \lambda_\mu, \lambda_\tau)$$

Yukawa Aligned model (Type III):

$$Y_h^U \equiv Y_{SM}^U$$
$$Y_H^U = \tan\gamma_u \, Y_{SM}^U$$ and similarly for d, l

where $\{\gamma_u, \gamma_d, \gamma_l\}$ are arbitrary

- Satisfies the simultaneously diagonalizable requirement for MFV.
- Allows coupling for the u,d,l sectors to be scaled independently
- Flavour constraints well studied (e.g. 1511.05066).
- $\tan\gamma_{u,l}$ < O(few); $\tan\gamma_d$ can be much larger (e.g. $\tan\gamma_d > O(100)$ if $\gamma_{u,d} \sim 0$)

2-generation model (Type III):

$$Y_H^U = A\, V_{CKM}^\dagger P_{12} \qquad Y_h^U = y_t V_{CKM}^\dagger P_3 + O(\frac{m_c}{m_t})$$
$$Y_H^D = B P_{12} \qquad Y_h^D = y_b P_3 + O(\frac{m_s}{m_t})$$

$$P_{12} = \begin{pmatrix} 1 & & \\ & 1 & \\ & & 0 \end{pmatrix} \qquad P_3 = \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}$$

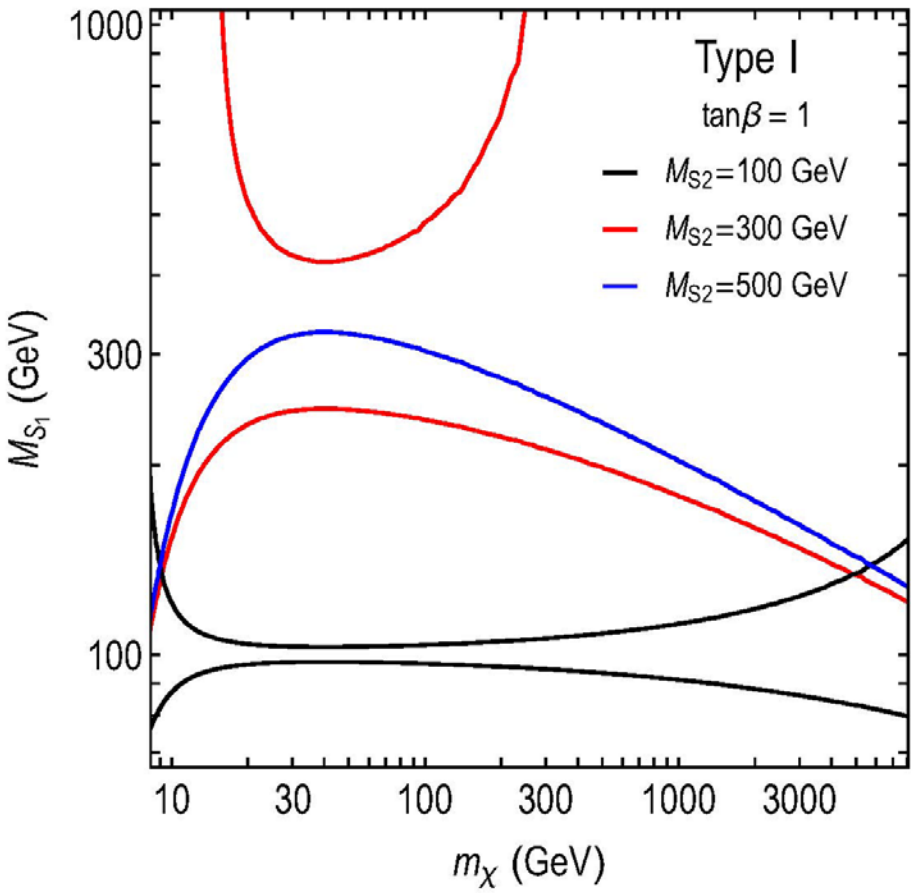
SM-like Higgs couples 3rd gen

New doublet couples to 1st,2nd gen with equal strength

Example parameters:
B<0.01, A<0.1

Direct detection bounds on 2HDM+S

Type I, $\tan\beta = 1$ (the "plain vanilla" case)

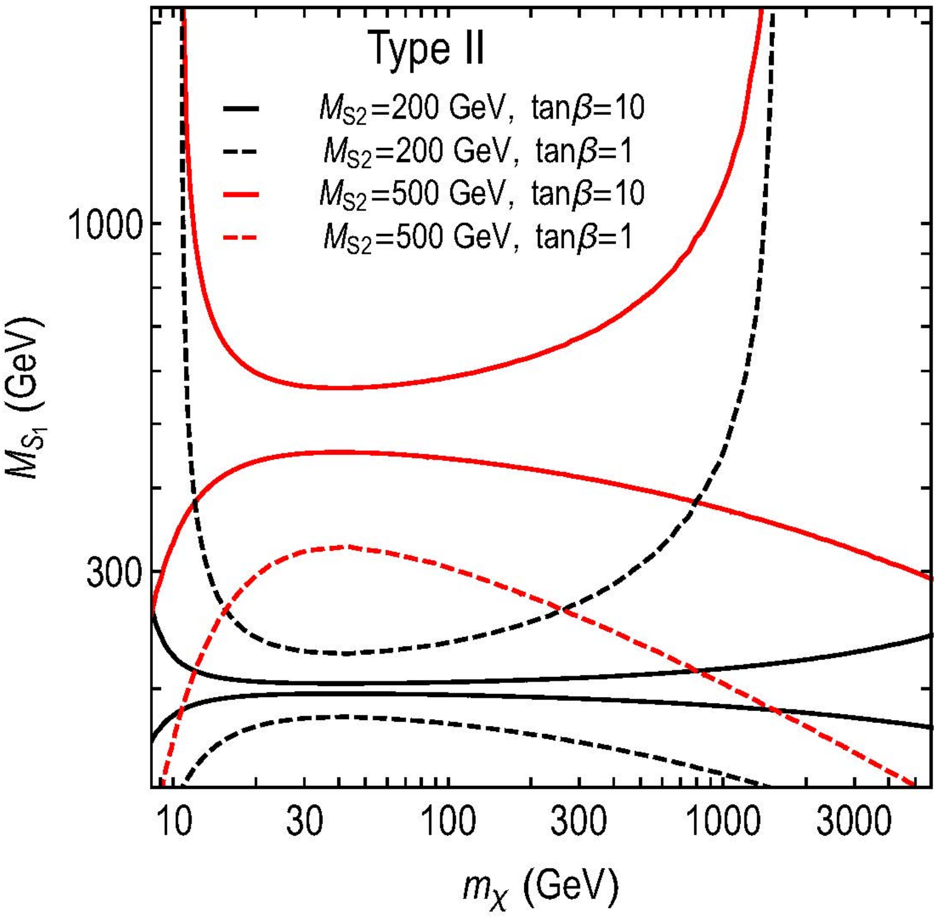


As in H+S model, interference where the two scalar mediators are approx degenerate.

When one of the scalars is >500 GeV, the other one can be arbitrarily heavy
(i.e. cross section small enough even without destructive interference)

Direct detection bounds on 2HDM+S

Type II, $tan\,\beta = 1, 10$

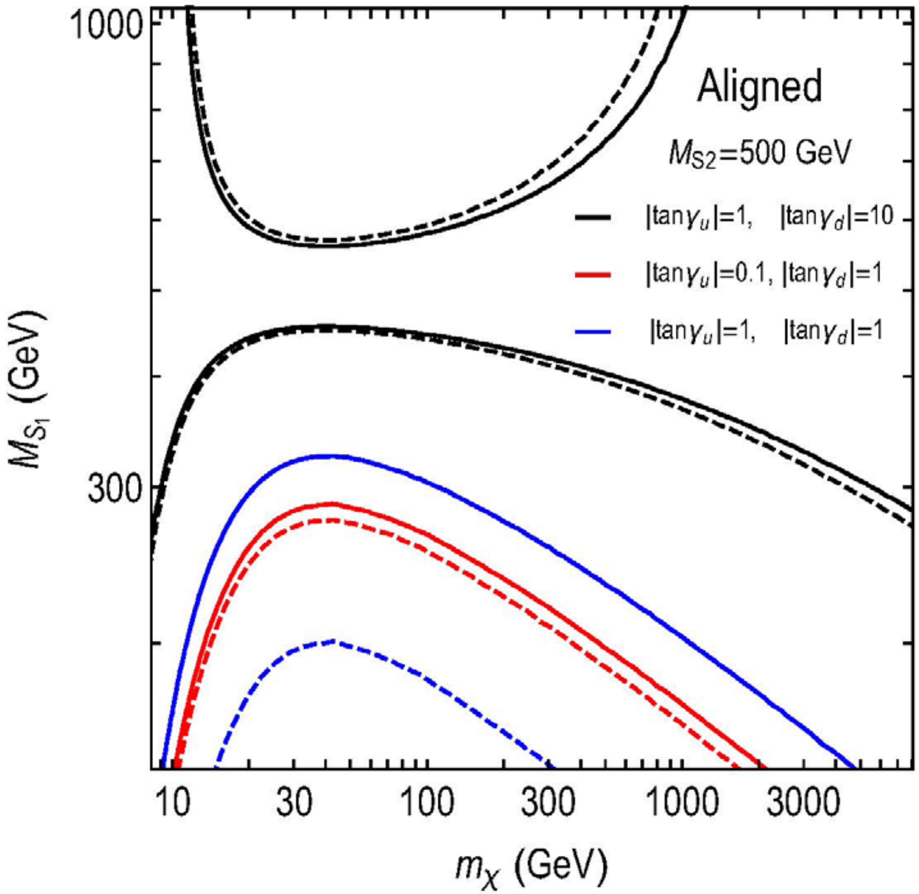


For type II, $\tan\beta \simeq 1$ implies u and d quarks have opposite sign contributions of similar size – which is an additional interference effect.

For large $\tan\beta$, d-quarks dominate

Direct detection bounds on 2HDM+S

Yukawa Aligned

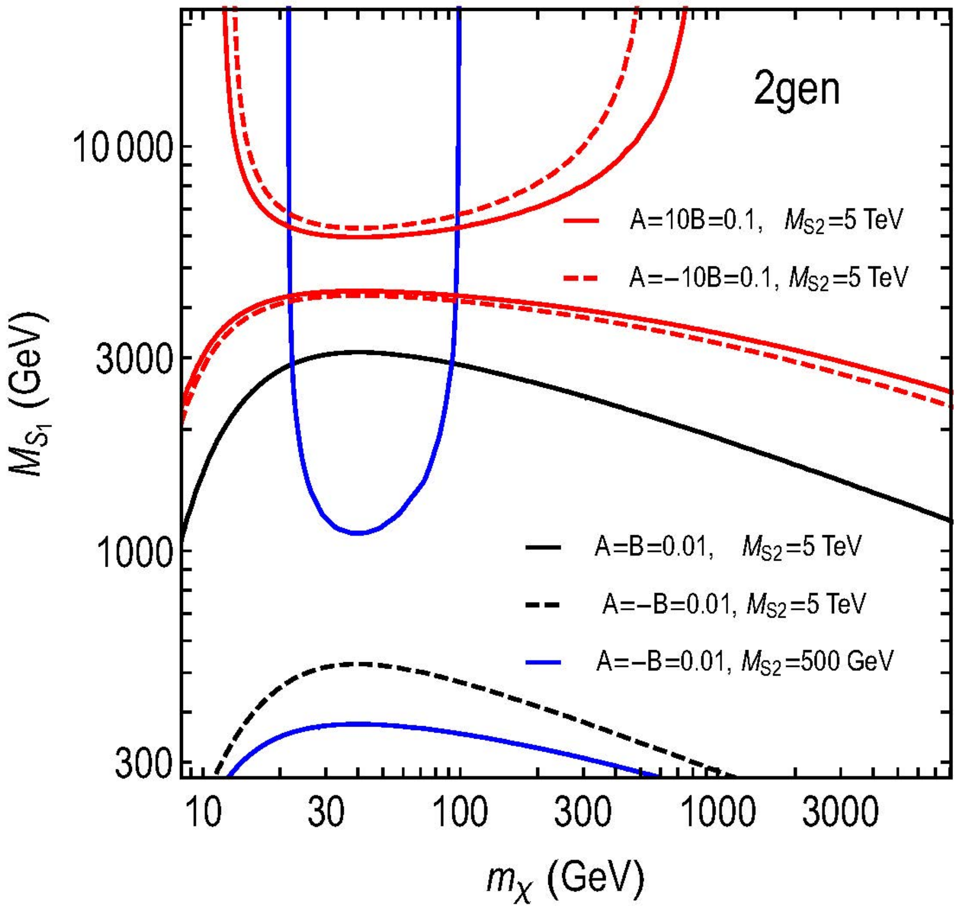


Again, interference of *u* and *d* quarks when their Yukawas are scaled by factors of similar size but opposite sign.

(blue dashed vs blue solid)

Direct detection bounds on 2HDM+S

2-generation model



- No coupling to t,b.
- Couplings to light quarks significantly enhanced.

- Interference effects again relevant

Summary

- s-channel scalar mediator ***must*** be analysed in ***multi-mediator*** framework
- SM Higgs +singlet (H+S)
  - All couplings proportional to SM Yukawa couplings
  - Strong Higgs and precision EW constraints
  - Largely excluded by direct detection unless H & S degenerate

  (of course, usual caveats about comparing DD and collider apply)
- Additional Higgs +singlet (2HDM+S)
  - Sector or even flavour dependent couplings
  - Higgs alignment limit allows more freedom for the two mixed scalars, while allowing SM Higgs to decouple
  - Direct detection suppressed by two interference effects
    - interference of scalar mediators
    - interference of opposite sign u and d quark contributions

    → important for colliders to probe parameters where DD is blind

Outlook

- Any model beyond the minimal H+S will involve a non-minimal Higgs sector
  → new charged scalars
  → flavour constraints

  (inevitable consequence of scalar s-channel + SU(2) invariance)

- Relative importance of different collider channels will strongly depend on Yukawa structure assumed. In 2HDM+S model, signals can be enhanced/suppressed by $\tan\beta$ and other Yukawa-sector scaling factors, e.g:
  - Suppress ttbar signals in Type-II model with $1/\tan\beta$
  - Suppress dilepton resonances in Type-Y with $1/\tan\beta$, or eliminate dilepton signals altogether in a leptophobic Yukawa-aligned case

→ Important to do searches in all complementary channels