Second Generation of Simplified Models

Implications of Gauge invariant for the Scalar S-channel model

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Outline

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Introduction

Generation I model

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

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

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

$$\bar{q}_i q_i = \bar{q}_L^i q_R^i + \bar{q}_R^i q_L^i$$

is not SM singlet

Getting a Gauge Invariant version of this model could tell us some additional constraints on the mass of the additional scalar, on the size of the couplings

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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

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A possible Gauge invariant version

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)

Already discussed in ”Dark matter model with two s-channel mediators” [1606.07609], more on Summary of [1607.06680]

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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

$$g_q = -\frac{1}{\sqrt{2}} \sin\epsilon$$

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

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

The gauge-invariant version of this simplified model is therefore

$$\begin{aligned} L &= L_{SM}|_{h\to\cos\epsilon h-\sin\epsilon s} + \frac{1}{2}\partial^\mu S\partial_\mu S - \frac{1}{2}M_s^2 S^2 \\ &+ \bar{\chi}(i\partial - m_\chi)\chi - y_{DM}(\cos\epsilon S + \sin\epsilon h)\bar{\chi}\chi \end{aligned}$$

So the interactions relevant for monojet are

$$L_{int,s-h} = -(\cos\epsilon h - \sin\epsilon S)\sum_q \frac{m_i}{v}\bar{q}_i q_i - y_{DM}(\cos\epsilon S + \sin\epsilon h)\bar{\chi}\chi$$

However there are also other interactions that are first order in ϵ

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

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Consequences of Gauge Invariance

- $g_q = \sin\epsilon/\sqrt{2} \leq 1$ 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 $m_\chi \lesssim M_h/2$
- Well approximated by Gen I if only one of the 2 mediators can go on shell
- Any case where both mediators can go on shell is not well described by Gen I model

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   - Consequences of Gauge Invariance

2. Going Beyond: 2HDM
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   - Type I II
   - Type III and FCNC

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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
- 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 $\cos(\beta - \alpha) = 0$
  - 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

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

$$\begin{aligned} L &= L_{SM} + \frac{1}{2}\partial^\mu S_i \partial_\mu S_i - \frac{1}{2} M_i^2 S_i^2 (i = 1, 2) \\ &+ \bar{\chi}(i\partial - m_\chi)\chi - y_{DM}(\cos\theta S_2 + \sin\theta S_1)\bar{\chi}\chi \\ &- \frac{y_f \xi^f}{\sqrt{2}}(\cos\theta S_1 - \sin\theta S_2)\bar{f} f \end{aligned}$$

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

- β is unconstrained, however if we want the top coupling to be perturbative ones needs $\cot\beta < \sqrt{4\pi} \rightarrow \tan\beta > 0.28$
- Type II can allow an enhanced coupling to down quarks, for large values of $\tan\beta$

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Going Beyond: 2HDM

Adding a second doublet

Choosing the SM Yukawa matrices to be (before digonalizing)

$$V^\dagger y_h^u, y_h^d, y_h^l \qquad (y_h^f{}_{ij} = \sqrt{2}\frac{m_{f_i}}{v}\delta_{ij})$$

we can choose the yukawa matrices for the second doublet to be instead some new arbitrary diagonal matrices y_H

$$V^\dagger y_H^u, y_H^d, y_H^l$$

- This yukawa structure means the fermion mass matrices and yukawa matrices for both doublets are simultaneously diagonalizable
- Flavor loop constrains have to be taken into account
- Large parameter space
- The only model that can decouple leptons (or quarks, or a specific particle)
- Simple flavour-protected case $y_H^u = \tan\gamma_u y_h^u$, $y_H^d = \tan\gamma_d y_h^d, Y_H^l = \tan\gamma_l y_h^l$ (Aligned Yukawa [1001.0293])

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Model	Singlet	Type I	Type II	Type III
2 Mediators	Yes	Yes	Yes	Yes
MAX g_q	$\frac{sin\epsilon}{\sqrt{2}}$	$\sqrt{4\pi}$	$g_u < \sqrt{4\pi}$ $g_d < \frac{m_t}{m_b}\sqrt{4\pi}$	$\frac{m_t}{m_q}\sqrt{4\pi}$
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/A	Yes	Yes	No
MFV	Yes	Yes	Yes	Yes
Flavour constr.	No	Moderate	Moderate	Depends

Conclusions

Summary

- 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
- 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
  - 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