Gauge invariant Simplified Models

Implications for the Scalar S-channel model

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Outline

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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 constrains on the mass of the additional scalar, on the size of the couplings

Outline

1. Introduction
   - The current model
   - Necessary Implications
   - A possible Gauge invariant version
   - Consequences of Gauge Invariance

2. Going Beyond: 2HDM
   - Adding a second doublet
   - FCNC

3. Conclusions
   - Summary

Assumptions

- S is a scalar, and is a portal to DM
- χ is a SM singlet
- S is exchanged in the s-channel
- There is only one Higgs doublet

Implications

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

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

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

After EW symmetry breaking, the following mass matrix gets generated

$$M^2 = \begin{pmatrix} 2\lambda v^2 & \lambda_{SH} v w \\ \lambda_{SH} v w & \frac{1}{3}\lambda_S w^2 \end{pmatrix}$$

If λ_{SH} is small, the mass (and also the SM phenomenology) of the higgs does not get affected

$$\begin{aligned} m_h^2 &= 2\lambda v^2 + O(\lambda_{SH}^2) \\ m_s^2 &= \frac{1}{3}\lambda_s w^2 + O(\lambda_{SH}^2) \end{aligned}$$

Introduction

A possible Gauge invariant version

The mixing angle is

$$\tan\epsilon \sim \frac{\lambda_{SH} v w}{M_h^2 - M_s^2} \sim \sin\epsilon \sim \epsilon$$

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

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

The coupling of s to quarks is indeed proportional to yukawas

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

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

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

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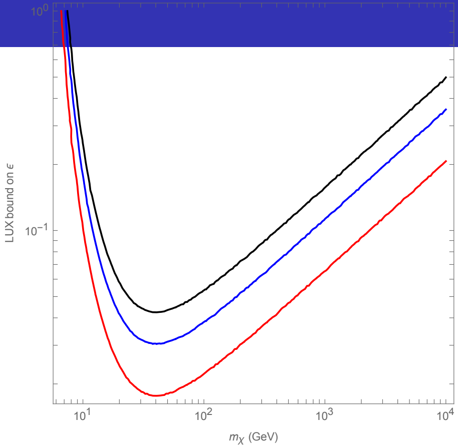
Introduction

Consequences of Gauge Invariance

- $g_q = \sin\epsilon/\sqrt{2} \leq 1$
- Higgs couples to DM
- Stringent DD constrains
- Too weak signal at LHC unless $m_\chi \lesssim M_h/2$
- Bounds on h invisible can constrain $m_\chi \lesssim M_h/2$



- Only one mediator$\rightarrow M_s \gg M_h$ and the only relevant mediator is the higgs
- Models with only a generic mediator s, different from the higgs, coupling to both quarks and DM cannot be obtained in this way

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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 $\langle \phi_1 \rangle = v/\sqrt{2}$
  - In that case S mixes only with the scalar of the second doublet, and there is no constrain on the mixing angle
- The full lagrangian is too long to report it here, but once the mass spectrum and the mixing angles are obtained, once can derive the relative "simplified model" by neglecting all the scalar interaction terms

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- In general, the yukawa couplings of the second doublet may generate FCNC
  - Anyway, is always possible to choose the second yukawa matrix to be diagonalised by the same transformation that diagonalises the first one
  - This will forbid tree level FCNC, but in general will not at loop level
- To forbid them also at loop level, one needs to impose a symmetry
  - This kind of symmetries might not be evident at the level of the simplified model, where one is neglecting part of the lagrangian to simplify the framework
  - Additionally, there are multiple ways to suppress FCNC both at tree and loop level
- On the other hand, choosing arbitrary diagonal couplings (especially for the first generation quarks) can lead to new signatures

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Conclusions

Summary

- Single scalar mediator
  - not gauge invariant wrt SM symmetries
- S mixed with SM Higgs
  - FCNS controlled (MFV)
  - Yukawa and mixing angle suppressions
  - LHC signals very small
- S plus 2 Higgs doublets
  - necessary to go beyond the above
  - interesting case is where 1st Higgs is SM-like
  - 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.
  - For some parameters, a scalar mass hierarchy will effectively decouple the heavier scalars, resulting in a single mediator scenario