Gauge invariant Simplified Models

Implications for the Scalar S-channel model

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Outline

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Simplified Models the next step beyond EFT to analyse collider DM search

- Renormalizable models
- Just one Mediator
- Simplified Coupling structure
- No Gauge invariance or Anomaly cancellation
  - Gauge invariance violation might lead to non-physical cross sections
  - Enforcing gauge invariance might lead to additional features required by the model, constrains on couplings and new signatures
- Scalar Mediator Models have low sensitivity due to yukawa suppression of couplings

Outline

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

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

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

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

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

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

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

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

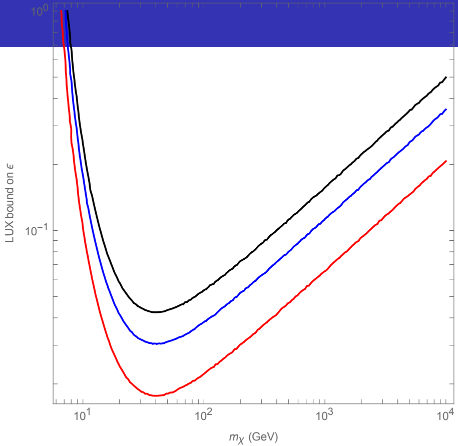
The mixing requires also the Higgs to couple to DM, and the product of the couplings for h and s is equal and opposite

Outline

Introduction

Consequences of Gauge Invariance

- $g_q = \sin\epsilon/\sqrt{2} \leq 1(\ll 1)$
- 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

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
- 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
  - In that case S mixes only with the scalar of the second doublet, and there is no constrain on the mixing angle

Outline

Going Beyond: 2HDM

Type I, II THDM

- Alignment limit $\beta - \alpha = \pi/2$
  - SM couplings are not affected
- Type I leads to $g_q = \cot\beta \sin\theta/\sqrt{2}, \cot\beta \lesssim 1 \to g_q \lesssim 1$
  - Similar to SM+Singlet
- Type II gives up and down quarks different ratios to SM yukawas
  - $g_u = \cot\beta \sin\theta/\sqrt{2} \lesssim 1 \to g_u \lesssim 1$
  - $g_d = \tan\beta \sin\theta/\sqrt{2}$
  - Couplings to down quarks could be enhanced
- In both cases $g_\chi = y_\chi \cos\theta$ and there are 2 mediators between DM and SM sectors
- If one of the 2 mediators is very heavy the model can be reduced to a "True Simplified Model", but one would expect a small mixing angle to come along with the large mass difference

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Going Beyond: 2HDM

Type III THDM and FCNC

- 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
  - FCNC might not be forbidden but just suppressed, 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

Outline

Conclusions

Summary

- Single scalar mediator
  - not gauge invariant wrt SM symmetries
- S mixed with SM Higgs
  - FCNC 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