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Scalar singlet model with mixing

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Abstract: This note describes the scalar singlet model with mixing and its implementation into the UFO framework. Although all possible care was taken to ensure the correctness of the provided information, no warranty can be accepted regarding the correctness, accuracy, uptodateness, reliability and completeness of the content of this note and the corresponding UFO implementation.

Contents

1 Lagrangian

The simplest extension of the scalar Dark Matter Forum (DMF) model, called scalar singlet model with mixing or simply SMM hereafter, has the following Lagrangian

$$\mathcal{L}_{\rm SMM} = -\frac{1}{2} m_S^2 S^2 - \mu_S S H^\dagger H - \lambda_S S^2 H^\dagger H + \bar\chi \left(i\partial\!\!\!/ - m_\chi\right) \chi - y_S S \bar\chi \chi \,, \tag{1.1}$$

where S is a real scalar field, H denotes the usual Standard Model (SM) Higgs doublet and χ is a Dirac dark matter (DM) particle. The mass of S (χ) is denoted by m_S (m_χ) whereas μ_S, λ_S and y_S couple the field S to the SM and the dark sector, respectively.

2 Input parameters

As a result of the portal coupling μ_S, the Higgs field h and the real scalar field S mix, giving rise to mass eigenstates h_1 and h_2 with mass m_{h_1} and m_{h_2}. The state h_1 plays the role of the observed Higgs boson, while h_2 is an extra scalar mediator. In terms of the masses $m_{h_1} \simeq 125\,{\rm GeV}$, m_{h_2} and the mixing angle θ the coupling μ_S can be written as

$$\mu_S = \frac{m_{h_2}^2 - m_{h_1}^2}{2v}\, s_{2\theta} \,, \tag{2.1}$$

where $v \simeq 246\,{\rm GeV}$ is the Higgs vacuum expectation value and we have introduced the shorthand notation $s_{2\theta} = \sin\left(2\theta\right)$.

The quartic coupling λ_S entering (1.1) can be eliminated in favour of one of the four physical trilinear scalar couplings. In terms of the trilinear coupling $\lambda_{h_1 h_2^2}$ between a SM Higgs h_1 and two extra scalars h_2, one has

$$\lambda_S = \frac{2}{(3c_{2\theta} - 1)c_\theta}\, \lambda_{h_1 h_2^2} - \frac{s_\theta^2}{3c_{2\theta} - 1} \frac{m_{h_1}^2 + 2m_{h_2}^2}{v^2} \,, \tag{2.2}$$

where $s_\theta = \sin\theta$, $c_\theta = \cos\theta$ and $c_{2\theta} = \cos(2\theta)$.

Any observable in the SMM model can thus be described in terms of the following four parameters: (i) the mass m_{h_2} of the extra scalar state, (ii) the sine $\sin\theta$ of the mixing angle, (iii) the trilinear coupling $\lambda_{h_1 h_2^2}$ between a SM Higgs h_1 and two h_2 and (iv) the dark sector Yukawa coupling y_S.

3 Parameter restrictions

An important feature of the SMM model is that all SM Higgs boson couplings receive a universal suppression factor of $\cos\theta$. The mixing angle is therefore subject to the constraints that arise from the ATLAS and CMS measurements of the signal strengths in Higgs production and decay. The LHC Run I combination of the two experiments yields the following signal strength relative to the SM expectation

$$\mu_h = 1.09^{+0.11}_{-0.10}\,. \tag{3.1}$$

This limit translates into the following 95% confidence level (CL) bound on the sine of the mixing angle

$$\sin\theta < 0.32\,. \tag{3.2}$$

In the SMM model not only the coupling between the Higgs and gauge boson and fermions is modified, but also the Higgs self coupling λ is altered with respect to the SM. The latest ATLAS measurements of $pp \to 2h \to 2b2\bar{b}$ constrains such modifications to the range

$$\mu_\lambda \in [-8.4, 12.4]\,, \tag{3.3}$$

at 95% CL. This bound together with (3.2) puts a non-trivial constraint on the mass m_{h_2} of the extra scalar state. Expanding in small mixing angles, one obtains

$$m_{h_2} \lesssim \sqrt{-\frac{m_{h_1}^2}{2s_\theta^4}\,(\mu_\lambda - 1) + \frac{1}{s_\theta^2}\left[\left(\frac{5\mu_\lambda}{4} - 2\right) m_{h_1}^2 + \lambda_{h_1 h_2^2}\, v^2\right]}\,. \tag{3.4}$$

For $\sin\theta = 0.3$ and $\lambda_{h_1 h_2^2} = 0$ this inequality implies for instance $m_{h_2} \lesssim 2.6\,\text{TeV}$. The latter constraint has to be kept in mind when studying the mono-Higgs signal that arises in the SMM model, because this process receives a contribution from a diagrams with a h_1^3 vertex.

4 UFO implementation

The SMM model as described above has been implemented into the UFO framework. The implementation can be used in MadGraph to calculate all relevant missing transverse energy ($\not{E}_{T,\text{miss}}$) signals including 1-loop QCD corrections. For instance a mono-jet signal can be generated via

```
import model SMM
generate p p > xd xd~ j [QCD]
```

These commands will produce 1-loop diagrams with massive top and bottom quarks that lead to a production of a DM pair and a single jet. At leading order a $t\bar{t} + \not{E}_{T,\text{miss}}$ signal can be generated via

```
generate p p > xd xd~ t t~
```

while the command

```
generate p p > xd xd~ t t~ [QCD]
```

includes the next-to-leading order QCD corrections to $t\bar{t} + \not{E}_{T,\text{miss}}$.

As usual the parameters for the Monte Carlo generation in MadGraph can be set in the file `param_card.dat`. The relevant parameters are

```
⋮

###################################
## INFORMATION FOR DMINPUTS
###################################
Block dminputs
    1 1.000000e+00 # yS
    2 2.000000e-01 # sinmix
    3 1.000000e+00 # la

⋮

###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.720000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118760e+01 # MZ
   25 1.250000e+02 # mh1
   52 1.000000e+01 # MXd
   54 3.000000e+02 # mh2

⋮

###################################
## INFORMATION FOR DECAY
###################################
DECAY   6 1.508336e+00 # WT
DECAY  23 2.495200e+00 # WZ
DECAY  24 2.085000e+00 # WW
DECAY  25 4.070000e-03 # Wh1
DECAY  54 1.000000e+00 # Wh2
```

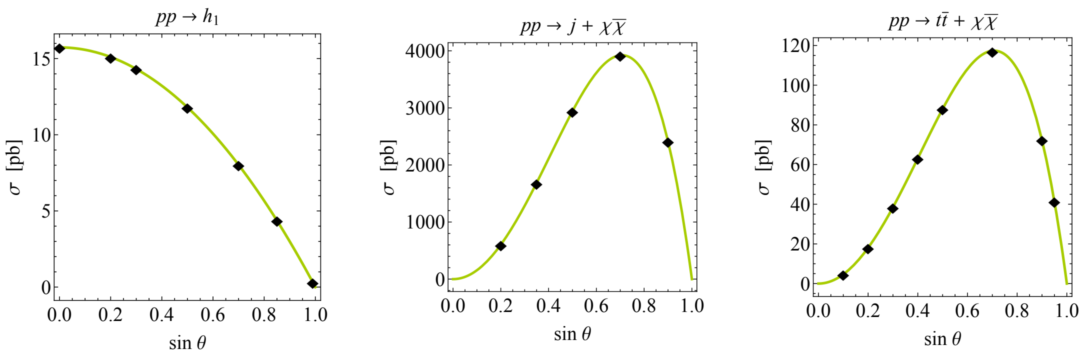

Figure 1. Prediction for the Higgs production (left), mono-jet (center) and $t\bar{t} + \not{E}_{T,\text{miss}}$ (right) cross section as a function of the sine of the mixing angle. The black diamonds correspond to the results of the MadGraph simulation, while the green curves represent fits to the expected functional dependencies of the cross sections. See text for further details.

⋮

Here `yS`, `sinmix` and `la` denote the dark sector Yukawa coupling y_S, the sine $\sin\theta$ of the mixing angle and the trilinear $h_1 h_2^2$ coupling $\lambda_{h_1 h_2^2}$, respectively. The masses and widths of the scalar states are set by `mh1`, `mh2`, `Wh1` and `Wh2`. The parameter `MXd` corresponds to the mass of DM. The PDG codes of the extra scalar and DM are 54 and 52, respectively.

5 Validation

In order to validate the UFO implementation signals for $pp \to h_1$, $pp \to j + \not{E}_{T,\text{miss}}$ and $pp \to t\bar{t} + \not{E}_{T,\text{miss}}$ have been generated with MadGraph for different values of $\sin\theta$ but fixed values of m_{h_1}, m_{h_2}, y_S, $\lambda_{h_1 h_2^2}$, Γ_{h_1} and Γ_{h_2}. In such a case the dependence on θ factorises and one expects to find the following dependencies on the mixing angle:

$$\sigma(pp \to h_1) \propto \sin^2\theta\,, \qquad \sigma(pp \to j/t\bar{t} + \not{E}_{T,\text{miss}}) \propto \sin^2(2\theta)\,. \tag{5.1}$$

In the three panels of Figure 1 these expectations (green curves) are compared to the results for the cross sections as calculated by MadGraph (black diamonds). No significant deviations from the expected $\sin\theta$ dependencies are found which provides a sanity-check of the UFO implementation. In the case of the $pp \to h_1$ cross section we furthermore verified that for $\sin\theta = 0$ the SM cross section for Higgs production is reproduced.

6 Feedback

Please send feedback, fan mail, etc. to `ulrich.haisch@physics.ox.ac.uk`.