Higgs Singlet Model

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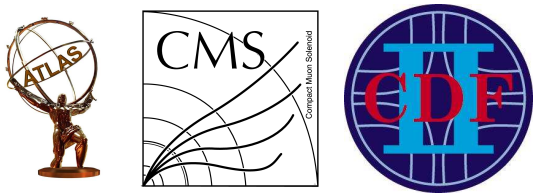
Index

Introduction

August 2012: Higgs discovery, close to the SM Higgs!!!



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- dark matter
- baryon asymmetry
- neutrino masses
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$\Longrightarrow$ several BSM theories have been proposed

- SUSY
- SM extensions
- Higgs sector extensions

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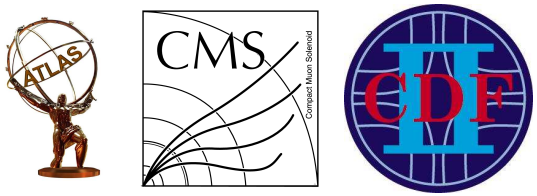

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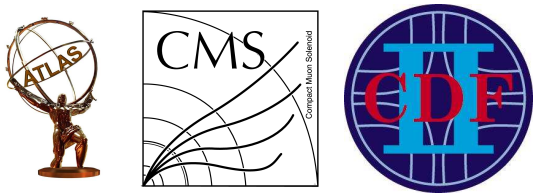

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we already know

$$\mathcal{L}^{SM}_{Higgs} = (D_\mu \Phi)^\dagger D^\mu \Phi + \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{4}(\Phi^\dagger \Phi)^2$$

$$\mathcal{L}_{Higgs} = \mathcal{L}^{SM}_{Higgs} + ???$$

Higgs sector extensions

constrained by

- gauge invariance
- renormalizability
- custodial symmetry
- no FCNCs

on the experimental side

run II is starting @ LHC

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accurate predictions will be tested against experimental outcomes

higgstools

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higgstools

The model

extra singlet used in the literature for

- dark matter

  [V. Silveira, A Zee, 1985]

  [J. McDonald, 1994]

  [C.P. Burgess, M. Pospelov and T. Veldhuis, 2001]

  [H. Davoudiasl, R. Kitano, T. Li and H. Murayama, 2005]

  [V. Barger et al., 2008]

  [O. Fischer, J.J. van der Bij, 2014]

- hidden sector SB

  [A. Datta and A. Raychaudhuri, 1997]

  [B. Patt and F. Wilczek, 2008]

  [G. M. Pruna and T. Robens, 2013]

- baryon asymmetry

  [S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, 2007]

  [V. Barger et al., 2007]

The model

$$SU(2) \text{ doublet } \Phi + \text{singlet } \sigma$$

the most general scalar Lagrangian is

$$\mathcal{L}_{Higgs} = \mathcal{L}^{SM}_{Higgs} + \partial_\mu \sigma \partial^\mu \sigma - \eta_{12} \sigma \Phi^\dagger \Phi - \lambda_{12} \sigma^2 \Phi^\dagger \Phi - \xi_1 \sigma + \mu_1^2 \sigma^2 - \eta_1 \sigma^3 - \lambda_1 \sigma^4$$

optional requirements

- extra $\mathbb{Z}_2$ symmetry

$$\eta_{12} = \xi_1 = \eta_1 = 0$$

- vanishing VEV

$$\langle \sigma \rangle = 0$$

	$\mathbb{Z}_2$	$\langle \sigma \rangle = 0$
Dark matter	✓	✓
Hidden sector	✓	
Higgs mixing		✓

The model

$SU(2)$ doublet Φ + singlet σ

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The model

generally, EWSB on both scalar fields

$$\sigma = \frac{v_1 + h'}{\sqrt{2}}, \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}[v_2 + \tilde{h} + i\phi^0] \end{pmatrix}$$

$\ldots h'$ and $\tilde{h}$ do not correspond to mass eigenstates, thus

Higgs mass diagonalization

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}$$

"doublet-like" Higgs h + "singlet-like" Higgs H

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"Dark" singlet extension

additional singlet provides stable dark matter candidate

$$\updownarrow$$

H-number conserved

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- extra symmetry
  $\sigma \to -\sigma$
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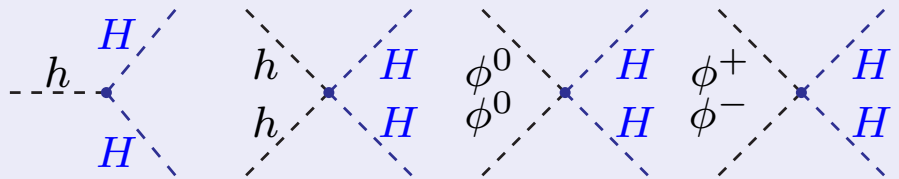
$$\Downarrow$$

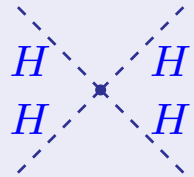
$$\alpha = 0, \quad (h, H) = (\tilde{h}, h')$$

BSM vertices have even H num.

- λ_{12} vertices



- λ_1 vertex



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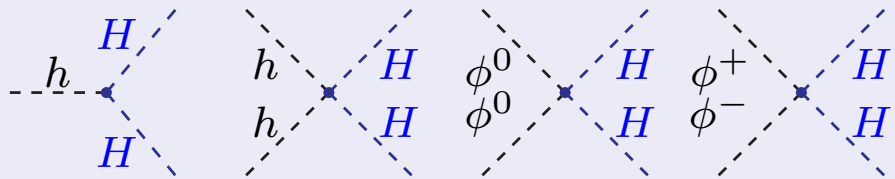

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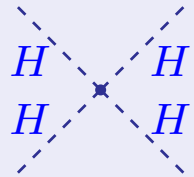

$M_H, \lambda_1, \lambda_{12}$ free parameters, simple phenomenology!!!

“Hidden sector” singlet extension

additional singlet responsible for SB in an hidden sector

"Hidden sector" singlet extension

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- extra symmetry
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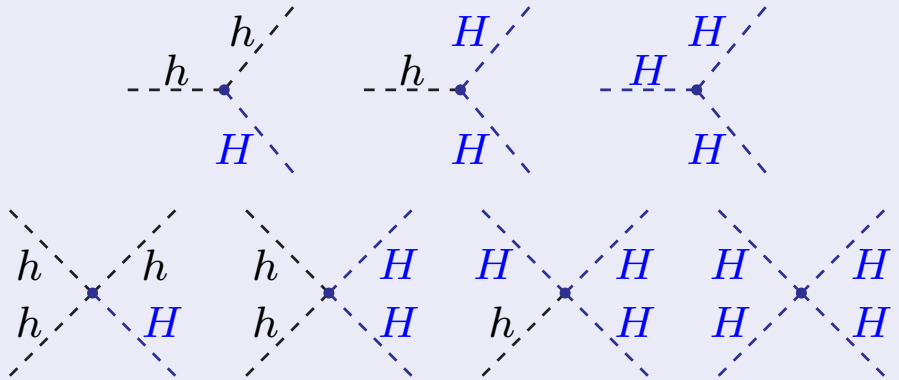
- $\langle \sigma \rangle = v_1 \neq 0$

$$\Downarrow$$

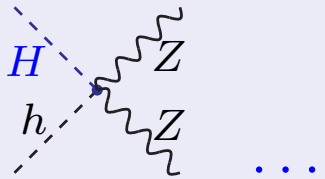
h, H couple to SM particles, couplings rescaled by $\cos\alpha$, $\sin\alpha$

more BSM vertices

- Higgs vertices



- Higgs-SM vertices



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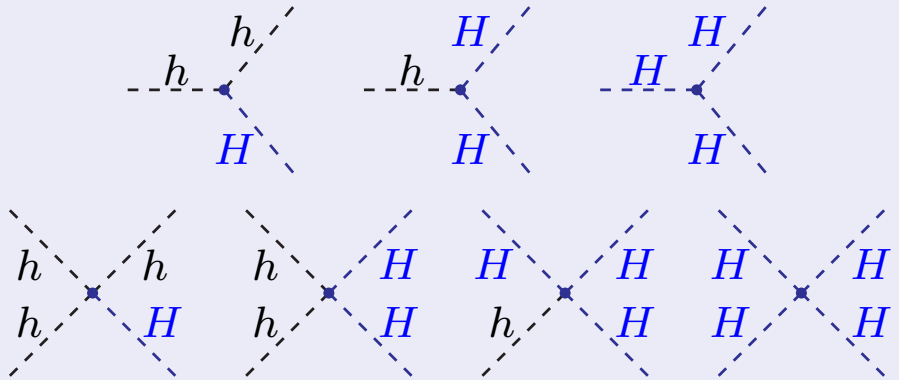

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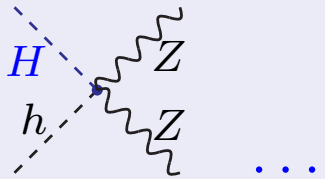

M_H, α, v_1 free parameters

“Higgs mixing” singlet extension

additional singlet as a second Higgs boson, with the same coupling structure

- no $\mathbb{Z}_2$ symmetry

$$\eta_{12}, \xi_1, \eta_1 \neq 0$$

- $\langle \sigma \rangle = 0$ without loss of generality

$$\Downarrow$$

- h, H couple to SM particles as HS case
- 2 more free parameters

$M_H, \alpha, \lambda_{12}, \eta_1, \lambda_1$ free parameters

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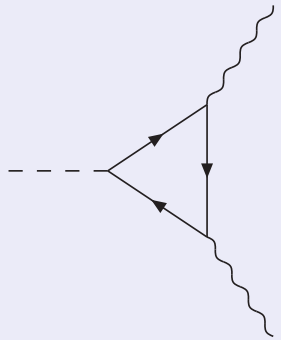
Objectives

- development of singlet extension tools
- NLO evaluation for Higgs decays in the Higgs singlet model
- further applications to Higgs processes (VBF, $h \to VV \to 4f$)

Automation

FeynRules	Feynman rules generation
FeynArts	diagram generation
FormCalc	algebraic simplification + numerical evaluation
LoopTools	implementation of the integrals

$\mathcal{L}^{HSM}$ $\xrightarrow{\text{FeynRules}}$ `HSM.gen` `HSM.mod` $\xrightarrow{\text{FeynArts}}$  $\longrightarrow$ FormCalc

NLO checks

using FeynRules

FeynArts model files have been generated for the 3 cases

- LO rules
- 1 loop counterterms

using FeynArts + FormCalc + LoopTools, at 1 loop EW

- on-shell renorm. scheme
- UV finiteness for self-energies, 3- and 4-leg vertices
- SM limit for the on-shell decay $h \to VV$, $h \to q\bar{q}$
- IR structure for charged final states

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Further developments and applications

- $\overline{\text{MS}}$ renorm. scheme
- further predictions for Higgs processes
  (e.g. VBF Higgs production, $h \to ZZ/WW \to 4f$ in PROPHECY4f)
- analysis of the parameter space in the different singlet models

Summary

- the Higgs singlet model has been studied in the 3 different "flavours" found in the literature
- for each model, a FeynRules model file has been written
- renorm. conditions have been included in the files
- FeynArts can be used to generate amplitudes in the considered model, at 1 loop
- the developed tools could be used for specific processes