Constraints on coloured scalars from global fits

O. Eberhardt, **V. Miralles** and A. Pich

Instituto de Física Corpuscular (Universitat de València and CSIC)

Portugal, September 8th, 2021

PANIC 2021

Based on: [2106.12235]

Introduction

- The Standard Model succeed but it has some deficiencies $\Rightarrow$ Not the definitive theory
- Why just one Higgs boson?
- Processes involving flavour changing neutral are strongly constrained
- In order to avoid those processes some assumption can be made
- Minimal Flavour Violation (MFV) $\Rightarrow$ the dynamics of flavour violation is completely determined by the structure of the ordinary Yukawa couplings
- A. V. Manohar & M. B. Wise $\Rightarrow$ only $(\mathbf{1},\mathbf{2})_{1/2}$ and $(\mathbf{8},\mathbf{2})_{1/2}$ satisfy MFV

Our Work

- Many works studying extensions with more $(\mathbf{1,2})_{1/2}$ scalars
- We focussed on the $(\mathbf{8,2})_{1/2}$ scalar extensions
- For the first time a global fit of this model is performed
- We use the public HEPfit package
- We study both theoretical and experimental constraints

The Manohar-Wise Model

- Scalar sector

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad S^A = \begin{pmatrix} S^{+A} \\ S^{0A} \end{pmatrix}$$

- Different quantum numbers than the SM Higgs doublet $\Rightarrow$ No mixture
- Conservation of colour $\Rightarrow$ Cannot acquire a vev

$$\langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \mathrm{e}^{i\theta} \end{pmatrix} \qquad \langle 0|S^A|0\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Most general potential build with these scalars ($S = S^A T^A$)

$$\begin{aligned} V = {} & \frac{\lambda}{4}\left(\phi^{\dagger i}\phi_i - \frac{v^2}{2}\right)^2 + 2{m_S}^2 \operatorname{Tr} S^{\dagger i} S_i + \nu_1 \phi^{\dagger i}\phi_i \operatorname{Tr} S^{\dagger j} S_j + \nu_2 \phi^{\dagger i}\phi_j \operatorname{Tr} S^{\dagger j} S_i \\ & + \left[\nu_3 \phi^{\dagger i}\phi^{\dagger j} \operatorname{Tr} S_i S_j + \nu_4 \phi^{\dagger i} \operatorname{Tr} S^{\dagger j} S_j S_i + \nu_5 \phi^{\dagger i} \operatorname{Tr} S^{\dagger j} S_i S_j + \text{h. c.}\right] \\ & + \mu_1 \operatorname{Tr} S^{\dagger i} S_i S^{\dagger j} S_j + \mu_2 \operatorname{Tr} S^{\dagger i} S_j S^{\dagger j} S_i + \mu_3 \operatorname{Tr} S^{\dagger i} S_i \operatorname{Tr} S^{\dagger j} S_j \\ & + \mu_4 \operatorname{Tr} S^{\dagger i} S_j \operatorname{Tr} S^{\dagger j} S_i + \mu_5 \operatorname{Tr} S_i S_j \operatorname{Tr} S^{\dagger i} S^{\dagger j} + \mu_6 \operatorname{Tr} S_i S_j S^{\dagger j} S^{\dagger i} \end{aligned}$$

The Manohar-Wise Model

- The vev produces a splitting of the masses

$$m_H^2 = \frac{\lambda}{2} v^2 \qquad m_{S_R^0}^2 = m_S^2 + (\nu_1 + \nu_2 + 2\nu_3)\frac{v^2}{4}$$

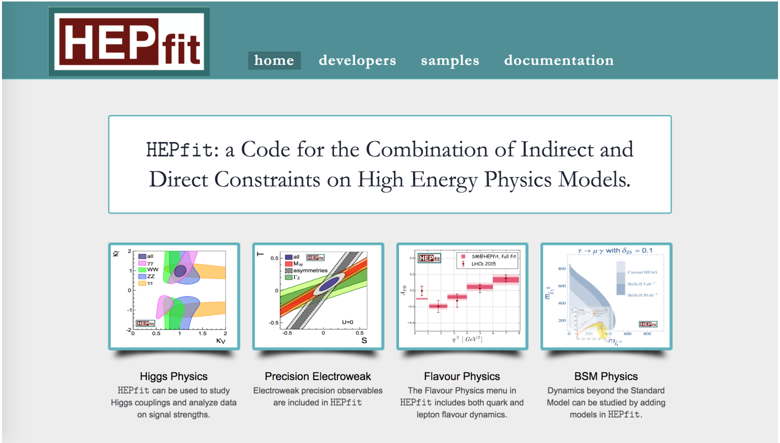
$$m_{S^\pm}^2 = m_S^2 + \nu_1 \frac{v^2}{4} \qquad m_{S_I^0}^2 = m_S^2 + (\nu_1 + \nu_2 - 2\nu_3)\frac{v^2}{4}$$

- The kinetic term of the colour octet is

$$\mathcal{L}_{S\text{Kin}} = 2\,\mathrm{Tr}[(D_\mu S)^\dagger D^\mu S], \text{ with } D_\mu S = \partial_\mu S + i g_s [G_\mu, S] + i g \widetilde{W}_\mu S + i y_S g' B_\mu$$

- The Yukawa term takes the form:

$$\mathcal{L}_{SY} = -\sum_{i,j=1}^{3} \left[\eta_D Y_{ij}^d \overline{Q}_{L_i} S d_{R_j} + \eta_U Y_{ij}^u \overline{Q}_{L_i} \widetilde{S} u_{R_j} + \text{h. c.} \right]$$



http://hepfit.roma1.infn.it/

The MW Constraints

Parameters	m_S^2	ν_n	μ_n	η_U	η_D
Priors	$(0.4^2, 1.5^2)$ TeV^2	(-10, 10)	(-10, 10)	(-5, 5)	(-20, 20)

Positivity
Unitarity
} Theoretical constraints

Higgs Signal Strengths
Direct Searches
Flavour
Electroweak Precision
} Experimental constraints

The MW Constraints: Theoretical

- Renormalisation group stability → Absence of Landau poles and bounded from below [arXiv:1808.05824]
- Perturbative unitarity: scattering of two to two scalars must not have a probability largen than 1
- Expressions at LO available for large s approximation → we only apply them for scales higher than $\mu_u = 1.5$ TeV [arXiv:1303.4848]
- Using RGEs we obtain approximately the NLO(+) perturbative unitarity condition [arXiv:1702.08511]

$$\text{LO:} \quad \left(a_j^{(0)}\right)^2 \leq \frac{1}{4}$$

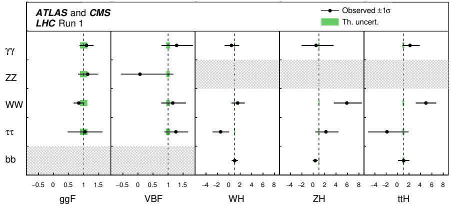
$$\text{NLO:} \quad 0 \leq \left(a_j^{(0)}\right)^2 + 2\left(a_j^{(0)}\right) \mathrm{Re}\left(a_j^{(1)}\right) \leq \frac{1}{4}$$

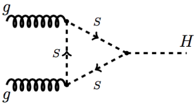
$$\text{NLO+:} \quad \left[\left(a_j^{(0)}\right) + \mathrm{Re}\left(a_j^{(1)}\right)\right]^2 \leq \frac{1}{4}$$

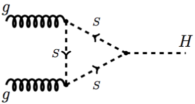
- Perturbative behaviour of quantum corrections

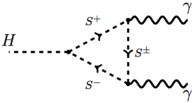
The MW Constraints: Higgs Signal Strengths

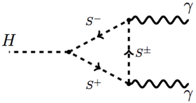
$$\mu^X = \frac{\sigma(pp \to h)\Gamma(h \to X)}{\sigma(pp \to h)_{SM}\Gamma(h \to X)_{SM}}$$

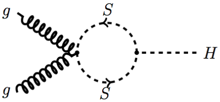


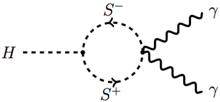












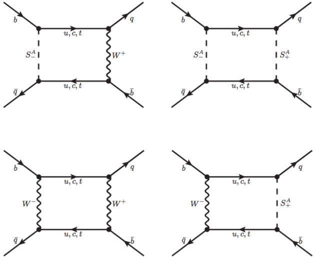
The MW Constraints: Direct Searches

- We use MadGraph for producing the theoretical prediction
- We compare the result with data of ATLAS and CMS

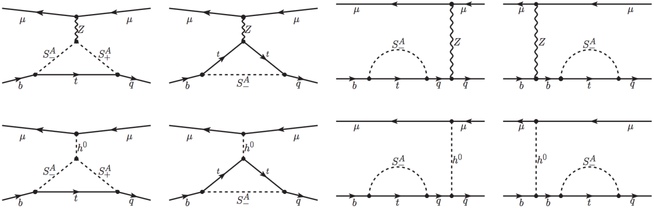
Channel	**Experiment**	**Mass range [TeV]**	$\mathcal{L}$ **[fb^{-1}]**
$pp \to S_{R,I} \to tt$	ATLAS	[0.4;3]	36.1
$bb \to S_{R,I} \to tt$	ATLAS	[0.4;1]	13.2
$pp \to S_{R,I}tt \to (tt)(tt)$	ATLAS	[0.4,1]	36.1
$pp \to S^{+}b\bar{t} \to t\bar{b}b\bar{t}$	ATLAS	[0.2;2]	139.1
$bb \to S_{R,I} \to bb$	CMS8	[0.1;0.9]	19.7
$gg \to S_{R,I} \to bb$	CMS8	[0.325;1.2]	19.7
$pp \to S_{R,I} \to bb$	CMS	[0.55;1.2]	2.69
$bb \to S_{R,I} \to bb$	CMS	[0.3;1.3]	35.7
$pp \to S_{R,I} \to gg$	CMS	[0.5,8]	27 & 36
$pp \to S_{R,I}S_{R,I} \to (gg)(gg)$	ATLAS	[0.5,1.75]	36.7

The MW Constraints: Flavour

- $B_s - \bar{B}_s$ mixing [arXiv:1504.00839]

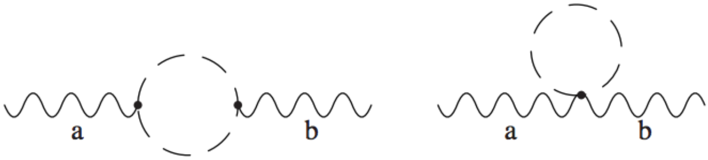


- $B_s \to \mu^+\mu^-$ decay [arXiv:1504.00839]

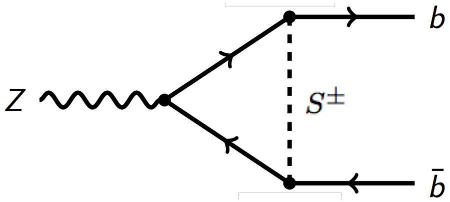


The MW Constraints: Electroweak Precision Observables

- Contribution to the oblique parameters (S, T and U) [arXiv:1002.1071]

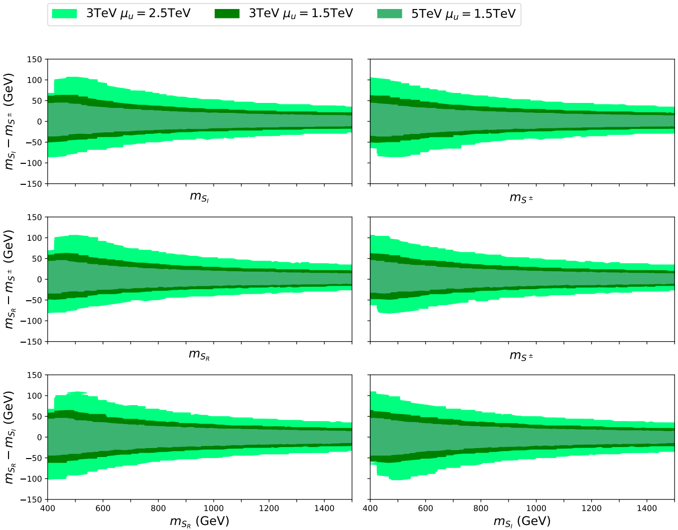


- Contribution to the $R_b = \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to \text{hadrons})}$ [arXiv:0907.2696]



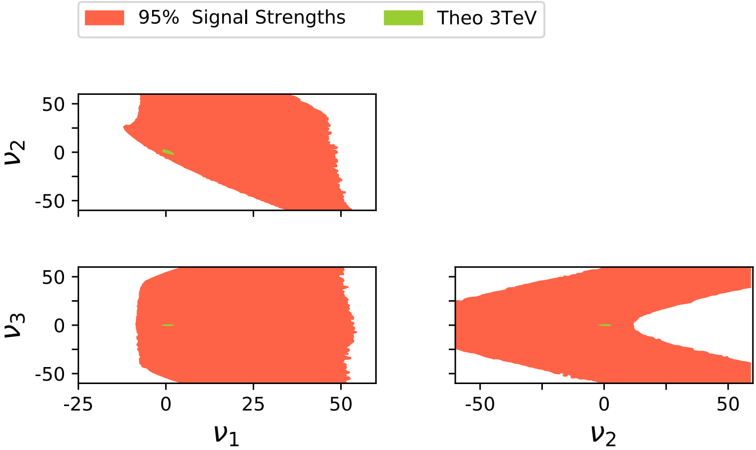
Theoretical constraints

Constrain the parameters of the potential → Constraints on the mass splitting



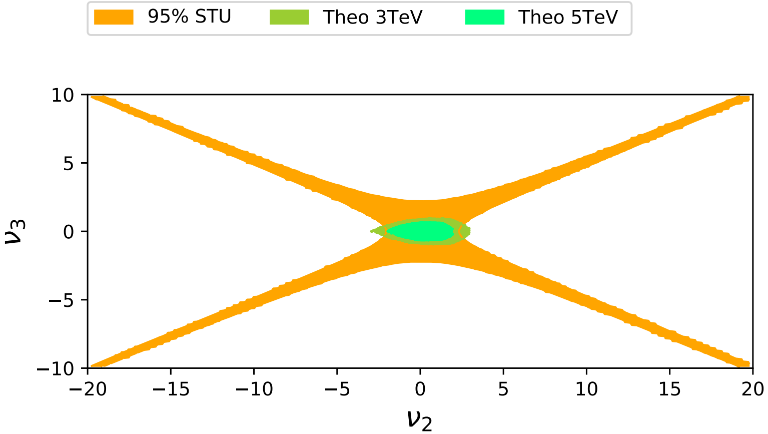
Higgs Signal Stregths

No constraints from Higgs Signal Stregths alone



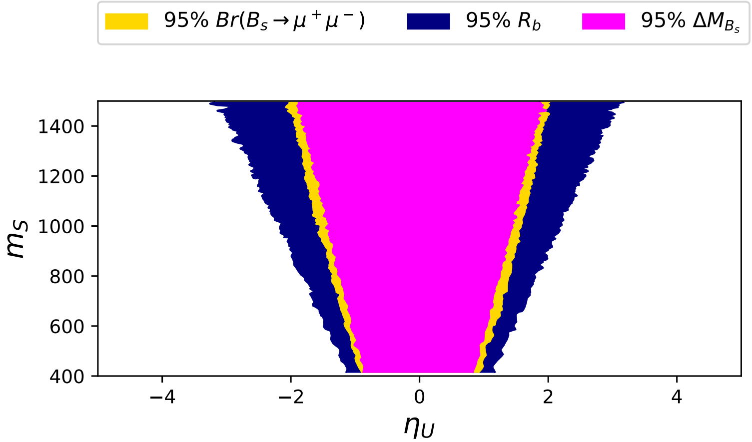
Oblique Parameters

Important constraints on $\nu_2 - \nu_3$ plane



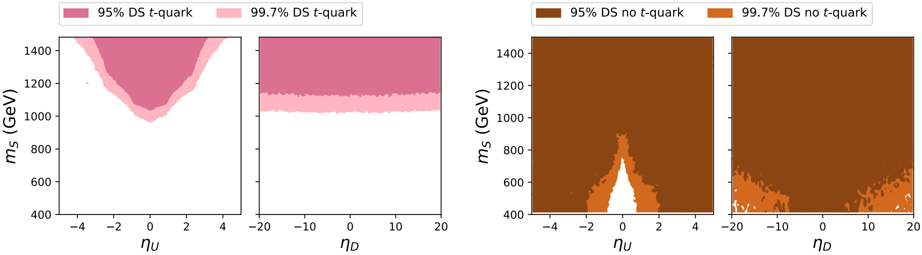
Flavour and R_b

Important constraints on $\eta_U - m_S$ plane, ΔM_{B_s} dominant

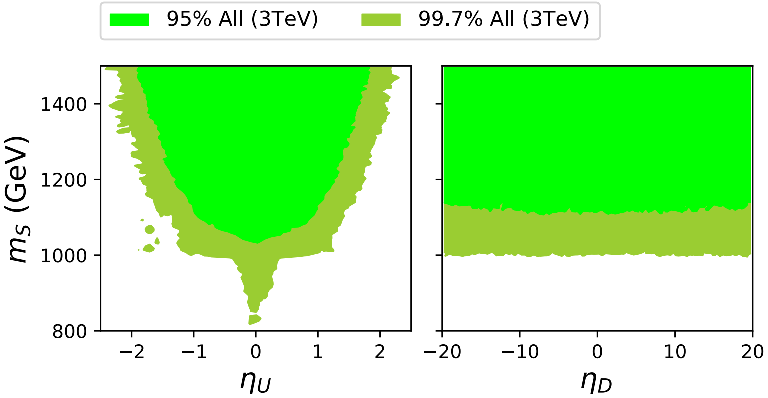


Direct Searches (DS)

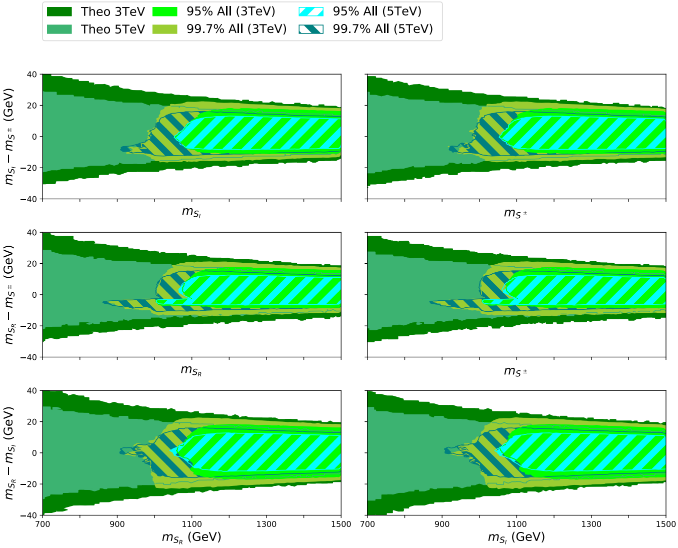
Dominant constraints come from processes with t-quarks produced

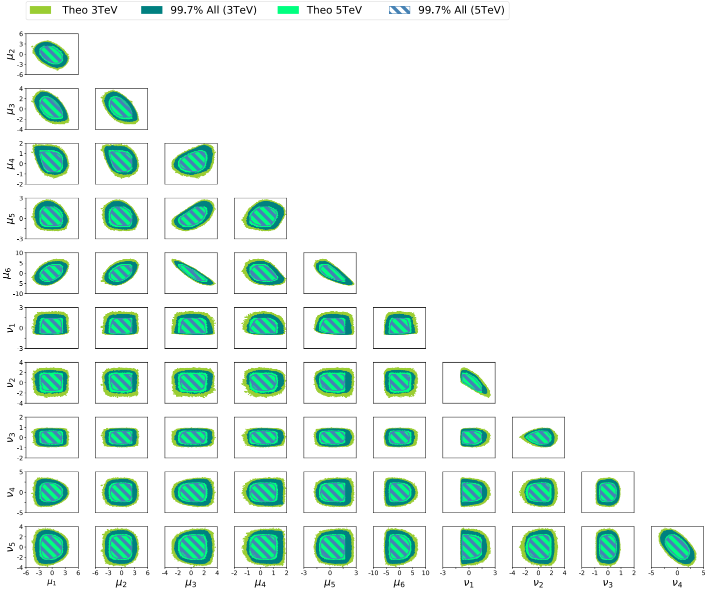


All Observables



All Observables





Theo 3TeV
99.7% All (3TeV)
Theo 5TeV
99.7% All (5TeV)
μ_1 μ_2 μ_3 μ_4 μ_5 μ_6 ν_1 ν_2 ν_3 ν_4 ν_5

Summary

- For the first time a global fit of the MW is performed
- The theoretical constraints are dominant for the parameters of the potential
- DS with t-quark production $\rightarrow m_S >$ 1.05 TeV with 95% probability
- Flavour $\rightarrow |\eta_U| <$ 1.8
- No constraints of η_D in the range (-20, 20)