Title: Light Octet Scalars, a Heavy Higgs and Minimal Flavour Violation

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Abstract: TBA

Light Octet Scalars, a Heavy Higgs and Minimal Flavour Violation

Saba Zuberi
University of Toronto

Based on arXiv:**0907.2696** with C.P Burgess and M. Trott

Outline

Motivation: Why octet scalars?

- General scalar sector consistent with MFV and ~ $SU(2)_C$ symmetry.

Constraints: How light can octet scalars be?

- Our EW precision data fit STUVWX relevant for light states.
  → Constraints on Octet masses
- Direct production at LEP
- Implications for the Higgs mass?
  → Joint fits of the Higgs and Octets to EWPD
- Tevatron: dijet limits, decays to leptons, $\gamma\gamma$.

Conclusions

Early new physics: General Scalar Sector?

Consider a **general scalar sector** which has potential for early detection:

- couples to quarks and/or gluons.
- light
- naturally suppresses FCNC
- satisfies precision electroweak measurements.

Early new physics: Why Octet Scalars?

Consider a **general scalar sector** which has potential for *early* detection:

- couples to quarks and/or gluons.
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- naturally suppresses FCNC
- satisfies precision electroweak measurements.

The Approach:

Scalars low energy EFT degrees of freedom

Obeys approximate symmetries :

- Minimal Flavour Violation ⟶ naturally suppresses FCNC
- Custodial SU(2)c ⟶ precision EW measurements.

Early new physics: Why Octet Scalars?

Chivukula & Geor
d'Ambrosio, Giudice, Isidori & Strumi

Minimal Flavour Violation (MFV):

Restore SM flavour symmetry $SU_Q(3) \times SU_U(3) \times SU_D(3)$
by promoting Yukawas to spurions $y_U \sim (\underline{3}, 3, 1)$ $y_D \sim (\underline{3}, 1, 3)$

Construct theory invariant under full flavour group.

MFV says any NP Yukawas $\lambda_{ij}^{U,D} \propto y_{ij}^{U,D}$

→ Yukawas are diagonal in same basis as mass matrices.

FCNC naturally not present

Since then:

- neutral scalar couplings are diagonal when masses are.
- charged scalar couplings in loops are GIM suppressed.

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Construct theory

MFV says any NP

Manohar Wise show MFV **only** possible for following representations:

$$H \sim (1, 2)_{1/2} \text{ or } S \sim (8, 2)_{1/2}$$

under

$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

FCNC naturall

Since then:

- neutral scalar
- charged scalar couplings in loops are GIM suppressed.

Manohar-Wise Model

hep-ph/0606172

Low energy EFT scalar sector: SM Higgs + a $(\mathbf{8},\mathbf{2})_{1/2}$ Octet scalar

$$S^A = \begin{pmatrix} S^{A+} \\ S^{A0} \end{pmatrix}$$

Yukawa sector:

$$\begin{aligned}\mathcal{L} \; = \; & -\sqrt{2}\,\eta_U\,\bar{u}^i_R\,\frac{m^i_U}{v}T^A\,u^i_L\,S^{A0} + \sqrt{2}\,\eta_U\,\bar{u}^i_R\,\frac{m^i_U}{v}T^A\,V_{ij}\,d^j_L\,S^{A+} + h.c. \\ & -\sqrt{2}\,\eta_D\,\bar{d}^i_R\,\frac{m^i_D}{v}T^A\,d^i_L\,S^{A0\,\dagger} - \sqrt{2}\,\eta_D\,\bar{d}^i_R\,\frac{m^i_D}{v}T^A\,V^\dagger_{ij}\,u^j_L\,S^{A-} + h.c.\end{aligned}$$

overall complex coefficients $\eta_U,\ \eta_D$

Note there are no new parameters in the coupling of octet to electroweak gauge bosons (use to bound masses with EWPD) or gluons.

Manohar-Wise Model

hep-ph/0606172

The potential:

$$\begin{aligned}
V &= \frac{\lambda}{4}\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_S^2\,\mathrm{Tr}\,(S^{\dagger i}S_i) + \lambda_1 H^{\dagger i}H_i\,\mathrm{Tr}\,(S^{\dagger j}S_j) + \lambda_2 H^{\dagger i}H_j\,\mathrm{Tr}\,(S^{\dagger j}S_i) \\
&+ \left[\lambda_3 H^{\dagger i}H^{\dagger j}\,\mathrm{Tr}\,(S_iS_j) + \lambda_4 H^{\dagger i}\,\mathrm{Tr}\,(S^{\dagger j}S_jS_i) + \lambda_5 H^{\dagger i}\,\mathrm{Tr}\,(S^{\dagger j}S_iS_j) + h.c.\right] \\
&+ \lambda_6\mathrm{Tr}\,(S^{\dagger i}S_iS^{\dagger j}S_j) + \lambda_7\mathrm{Tr}\,(S^{\dagger i}S_jS^{\dagger j}S_i) + \lambda_8\mathrm{Tr}\,(S^{\dagger i}S_i)\,\mathrm{Tr}\,(S^{\dagger j}S_j) \\
&+ \lambda_9\mathrm{Tr}\,(S^{\dagger i}S_j)\,\mathrm{Tr}\,(S^{\dagger j}S_i) + \lambda_{10}\mathrm{Tr}\,(S_iS_j)\,\mathrm{Tr}\,(S^{\dagger i}S^{\dagger j}) + \lambda_{11}\mathrm{Tr}\,(S_iS_j\,S^{\dagger j}S^{\dagger i})\,,
\end{aligned}$$

What's the mass spectrum?

$$S^{A0} = \frac{S_R^{A0} + iS_I^{A0}}{\sqrt{2}}$$

$$\begin{aligned}
M_\pm^2 &= M_S^2 + \lambda_1\frac{v^2}{4} \\
M_R^2 &= M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3)\,\frac{v^2}{4} \\
M_I^2 &= M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3)\,\frac{v^2}{4}.
\end{aligned}$$

Manohar-Wise Model

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$$\begin{aligned} M_\pm^2 &= M_S^2 + \lambda_1\frac{v^2}{4} \\ M_R^2 &= M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3)\,\frac{v^2}{4} \\ M_I^2 &= M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3)\,\frac{v^2}{4}. \end{aligned}$$

In the $SU(2)_C$ case : 14 real parameters $\longrightarrow$ 9 parameters

$$\begin{aligned} 2\,\lambda_3 &= \lambda_2, \\ 2\,\lambda_6 &= 2\,\lambda_7 = \lambda_{11}, \\ \lambda_9 &= \lambda_{10} \end{aligned}$$

and $\lambda_4 = \lambda_5^\star$.

arXiv:0907.2696

$$M_\pm^2 = M_I^2$$

hep-ph/0606172

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What has been done.....

Initial Work: Manohar & Wise: hep-ph/0606172

Early studies: Gresham & Wise: arXiv:0706.0909; (*R_b vertex corrections*)
Dobrescu, Kong & Mahbubani: arXiv:0709.2378;
Gerbash et al: arXiv:0710.3133;
Perez, Iminniyaz & Rodrigo: arXiv:0803.4156

More detailed phenomenology:
Perez, Gavin, McElmurry & Petriello: arXiv:0809.2106; (*LHC discovery*)
Kim & Mehen: arXiv:0812.0307; (*Octetonia*)
Idilbi, Kim & Mehen, arXiv:0903.3668; (*SCET resummation*)
Perez & Wise: arXiv:0906.2950;
Burgess, Trott & SZ: arXiv:0907.2696

Fit to Electroweak Precision Data

Electroweak Precision Fits

New scalars contribute to EW precision measurements through 'oblique' corrections

$$\Pi_{ab}(q^2) = \Pi_{ab}^{SM}(q^2) + \delta\Pi_{ab}(q^2)$$

$$ab = (WW, ZZ, \gamma\gamma, \gamma Z)$$

Standard approach 3 parameter fit, STU:

- Expand $\delta\Pi_{ab}(q^2) = A_{ab} + B_{ab}\, q^2$
- Ignoring corrections of order $\frac{M_Z^2}{M^2}$

Holdom & Terning; Peskin & Takeuchi; Altarelli & Barbier

But new scalars could potentially be light ~ 100 GeV...

Electroweak Precision Fits

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But new scala .

Don't expand $\delta\Pi_{ab}(q^2)$

Instead require 6 parameter extended fit: S T U V W X

Burgess, London & Maksymyk

Electroweak Precision Fits

Standard EW precision view:

- For STU to be inadequate new particles must be extremely light & V W X generally too small to matter.

- Adding additional parameters will make fit less constraining, so STU is more conservative anyway.

→ V W X not really needed

Electroweak Precision Fits

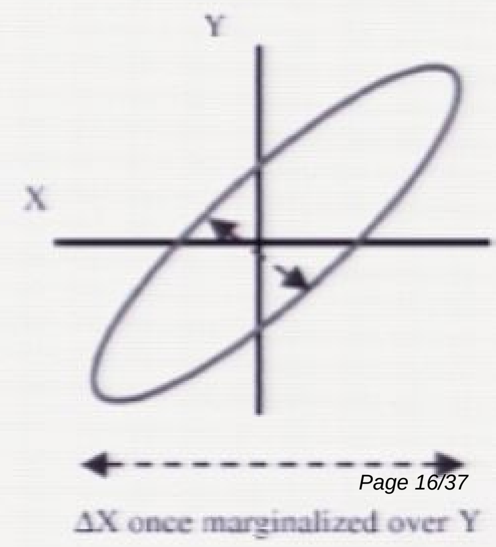
Standard EW precision lore:

- New particles must be extremely light to make STU inadequate, even then V W X too small to matter.

  We find V and X matter even for masses in few hundred GeV range.

- Adding additional parameters will make fit less constraining, so STU is more conservative anyway.

  STUVWX gives stronger constraint because correlations are strong.



→ V W X not really needed

Electroweak Precision Fits

- Updated S T U V W X using:

PDG 2008 & Erler, Langacker, Munir, Pena
arXiv: 0906.2435

Observable	Data Used	Theory Prediction
M_W [GeV]	80.428 ± 0.039	80.380 ± 0.015
	80.376 ± 0.033	80.380 ± 0.015
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954 ± 0.0009
Γ_{had} [GeV]	1.7444 ± 0.0020	1.7419 ± 0.0009
Γ_{inv} [MeV	499.0 ± 1.5	501.68 ± 0.07
$\Gamma_{l^+l^-}$ [MeV]	83.984 ± 0.086	84.002 ± 0.016
σ_{had} [nb]	41.541 ± 0.037	41.483 ± 0.008
R_e	20.804 ± 0.050	20.736 ± 0.010
R_μ	20.785 ± 0.033	20.736 ± 0.010
R_τ	20.764 ± 0.045	20.736 ± 0.010
R_b	0.21629 ± 0.00066	0.21578 ± 0.00005
R_c	0.1721 ± 0.0030	0.17224 ± 0.00003
A^e_{FB}	0.0145 ± 0.0025	0.01627 ± 0.00023
A^μ_{FB}	0.0169 ± 0.0013	0.01627 ± 0.00023
A^τ_{FB}	0.0188 ± 0.0017	0.01627 ± 0.00023
A^b_{FB}	0.0992 ± 0.0016	0.1033 ± 0.0007
A^c_{FB}	0.0707 ± 0.0035	0.0738 ± 0.0006
$\bar{s}^2_l(A^q_{FB})$	0.2316 ± 0.0018	0.2315 ± 0.0001
A_e	0.15138 ± 0.00216	0.1473 ± 0.0010
	0.1544 ± 0.0060	0.1473 ± 0.0010
	0.1498 ± 0.0049	0.1473 ± 0.0010
A_μ	0.142 ± 0.015	0.1473 ± 0.0010
A_τ	0.136 ± 0.015	0.1473 ± 0.0010
	0.1439 ± 0.0043	0.1473 ± 0.0010
A_b	0.923 ± 0.020	0.9347 ± 0.0001
A_c	0.670 ± 0.027	0.6679 ± 0.0004
g_L^2	0.3010 ± 0.0015	0.3039 ± 0.0002
g_R^2	0.0308 ± 0.0011	0.03000 ± 0.00003
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0003
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001
$Q_W(Cs)$	-73.16 ± 0.35	-73.16 ± 0.03
$Q_W(Tl)$	-116.4 ± 3.6	-116.8 ± 0.04
Γ_W [GeV]	2.141 ± 0.041	2.0902 ± 0.0009

EWPD fit results

- Updated S T U V W X.

Oblique	STUVWX Fit ($\chi^2/v = 0.91$)	STU Fit ($\chi^2/v = 0.99$)	ST Fit ($\chi^2/v = 0.98$)
S	0.07 ± 0.41	-0.02 ± 0.08	$-9.9 \times 10^{-3} \pm 0.08$
T	-0.40 ± 0.28	-0.02 ± 0.08	$1.1 \times 10^{-2} \pm 0.07$
U	0.65 ± 0.33	0.06 ± 0.10	-
V	0.43 ± 0.29	-	-
W	3.0 ± 2.5	-	-
X	-0.17 ± 0.15	-	-

Consistent with previous results.

- Correlation coefficient matrix.

$$M_{STUVWX} = \begin{pmatrix} 1 & 0.60 & 0.38 & -0.57 & 0 & -0.86 \\ 0.60 & 1 & -0.49 & -0.95 & 0 & -0.13 \\ 0.38 & -0.49 & 1 & 0.46 & -0.01 & -0.76 \\ -0.57 & -0.95 & 0.46 & 1 & 0 & 0.13 \\ 0 & 0 & -0.01 & 0 & 1 & 0 \\ -0.86 & -0.13 & -0.76 & 0.13 & 0 & 1 \end{pmatrix}.$$

$$M_{STU} = \begin{pmatrix} 1 & 0.84 & -0.20 \\ 0.84 & 1 & -0.49 \\ -0.20 & -0.49 & 1 \end{pmatrix}$$

$$M_{ST} = \begin{pmatrix} 1 & 0.87 \\ 0.87 & 1 \end{pmatrix}.$$

EWPD fit results

- Updated S T U V W X.

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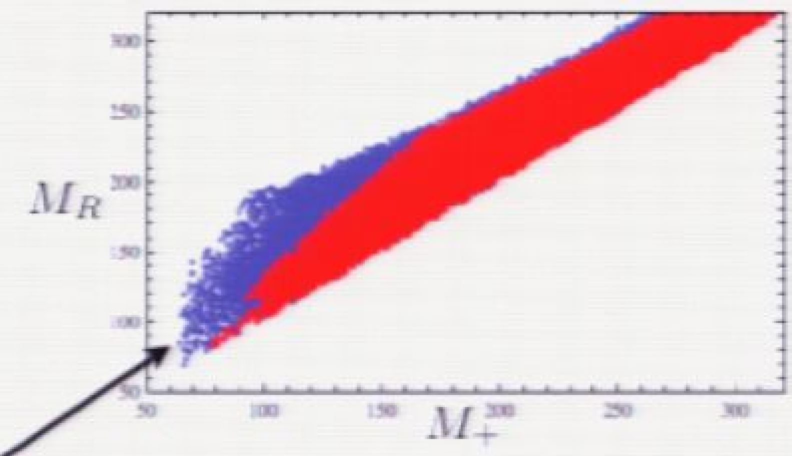
$$M_{STU} = \begin{pmatrix} 1 & 0.84 & -0.20 \\ 0.84 & 1 & -0.49 \\ -0.20 & -0.49 & 1 \end{pmatrix}$$

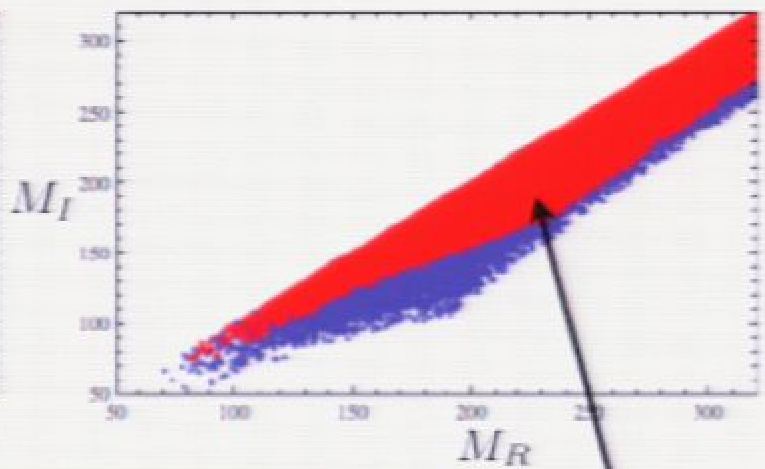
$$M_{ST} = \begin{pmatrix} 1 & 0.87 \\ 0.87 & 1 \end{pmatrix}.$$

See strong correlation for (S,X), (T,V) (U,X) in addition to usual (S,T).

EWPD fit results

- Compare STU vs STUVWX. Scan couplings $0 < \lambda_i < 1$.

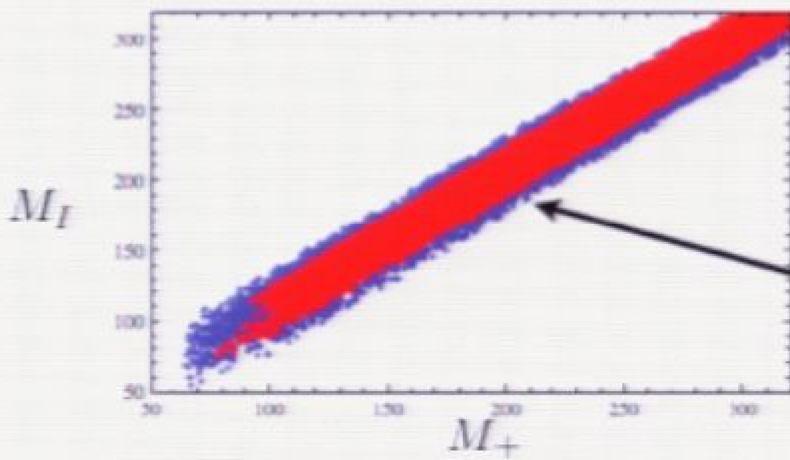




68% region STU blue

68% region STUVWX red

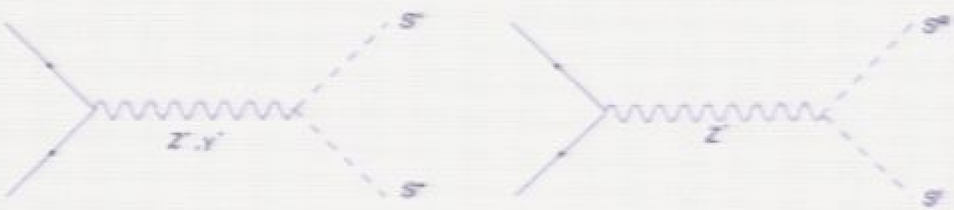
$$
\begin{aligned}
M_{\pm}^2 &= M_S^2 + \lambda_1 \frac{v^2}{4} \\
M_R^2 &= M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3)\frac{v^2}{4} \\
M_I^2 &= M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3)\frac{v^2}{4}
\end{aligned}
$$

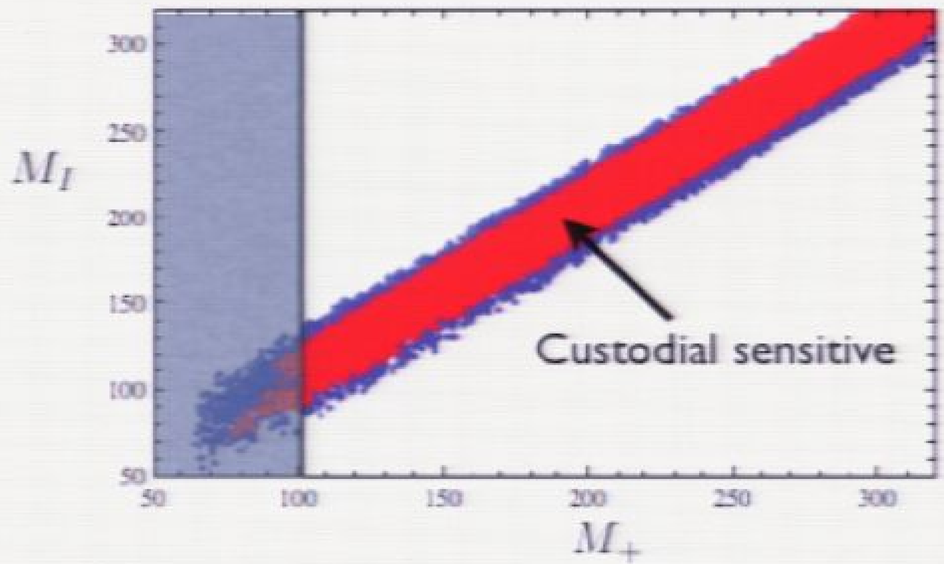


Approximate $SU(2)_c$

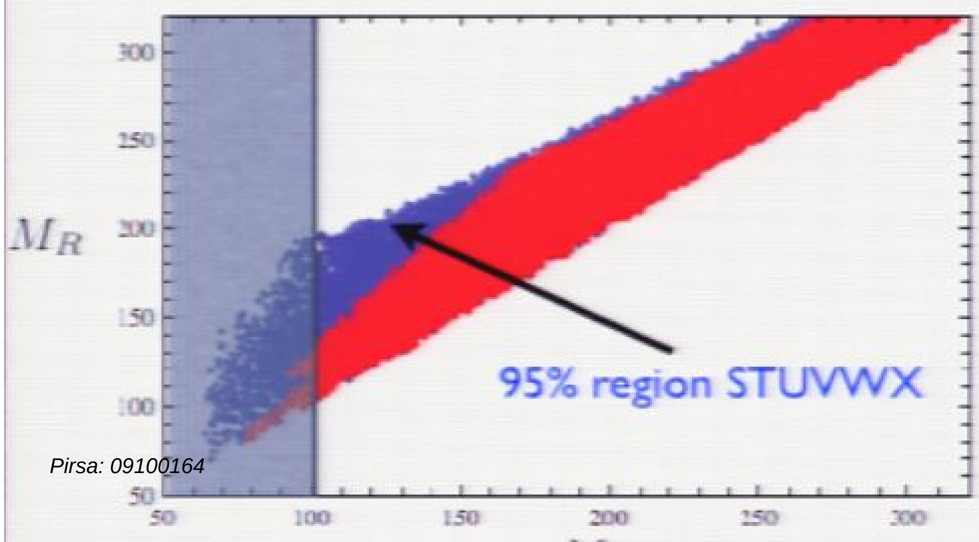
Direct Production: LEP

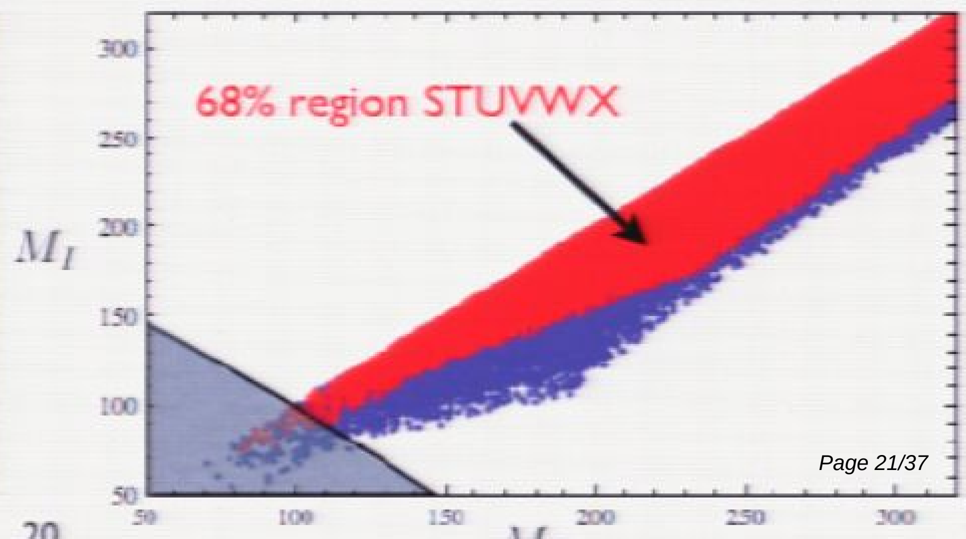
- If octet scalars were light enough, they would have been directly produced at LEP2 : $e^+e^- \to S^+S^-$ and $e^+e^- \to S_I^0\, S_R^0$





Place limit based on 10 events with no cuts $\sigma \times \int \mathcal{L}\mathrm{d}t < 10$





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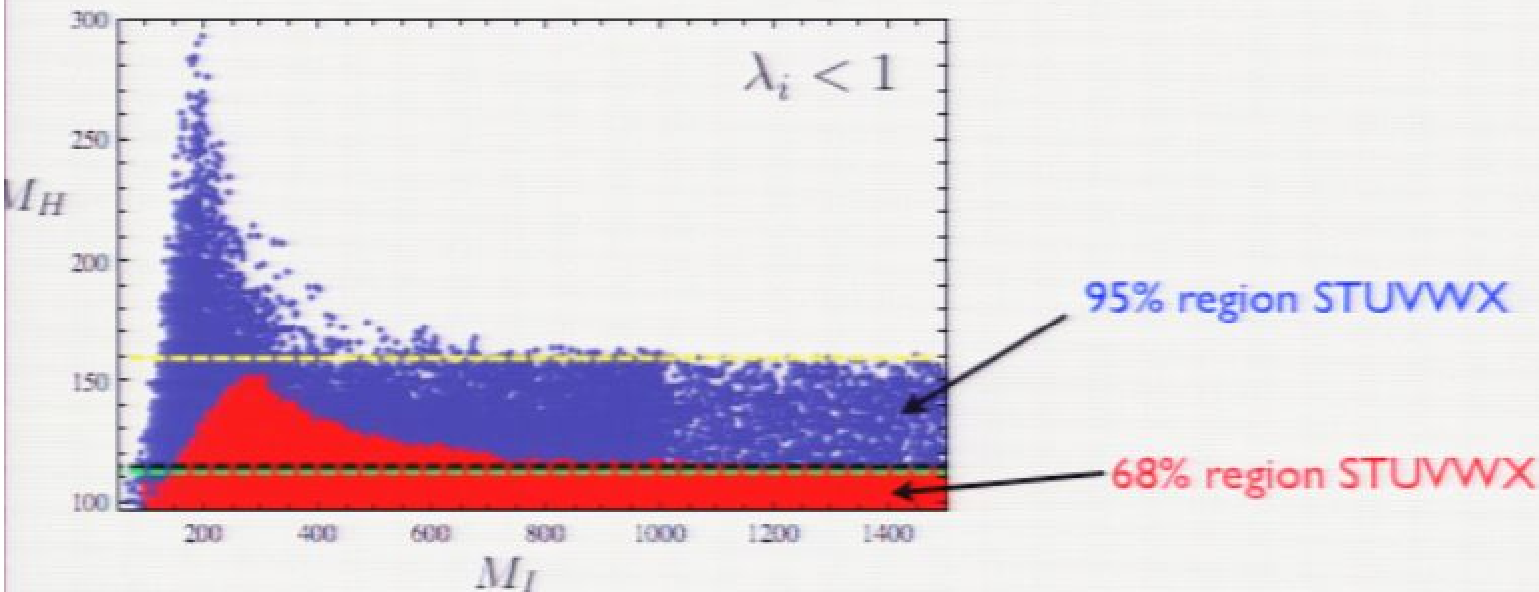
Joint fit: Influence on the Higgs Mass

- What happens to the best-fit value of the Higgs mass from EW fit?



Direct production bound 114 GeV

68% confidence level Higgs alone 112 GeV

95% confidence level Higgs alone 160 GeV

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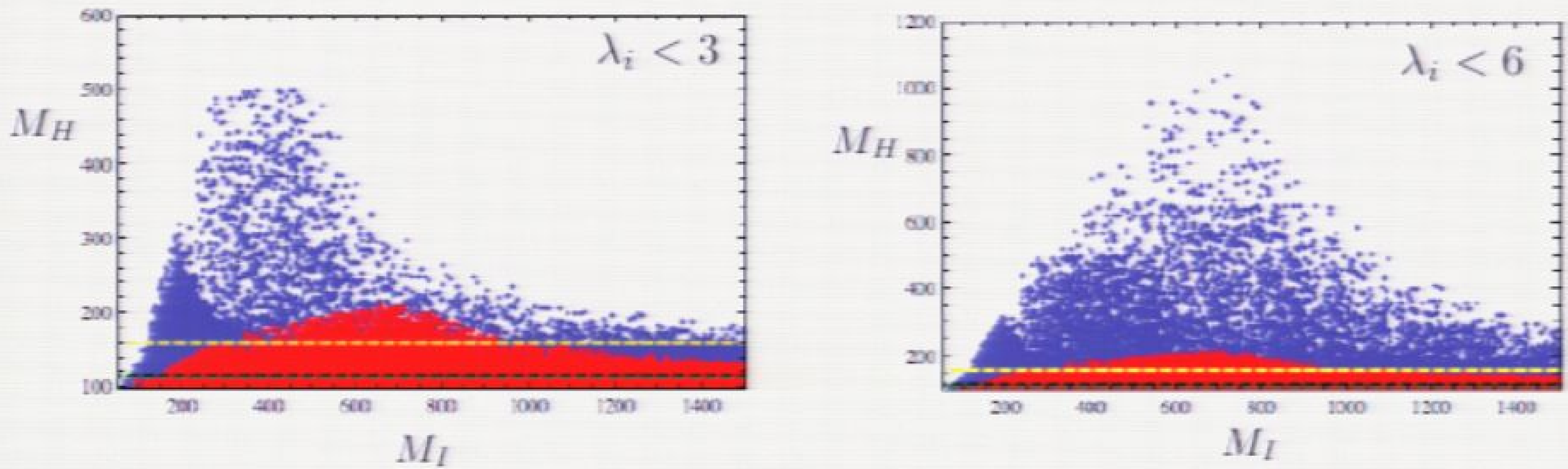


$$(\Delta T) \simeq -\frac{3\,\alpha}{16\,\pi}\log\left(\frac{M_H^2}{\hat{M}_H^2}\right)+\frac{v^4}{96\,\pi^2 M_S^2 s_W^2 M_W^2}(\lambda_2^2-(2\,\lambda_3)^2)$$

measure of octet mass splitting

$$(M_R^2 - M_\pm^2)(M_I^2 - M_\pm^2)$$

Octets give positive ΔT contribution, allowing M_H to go up.

→ TeV scale NP can mask a heavy Higgs in EW precision data

Tevatron Constraints

Decays of Octets

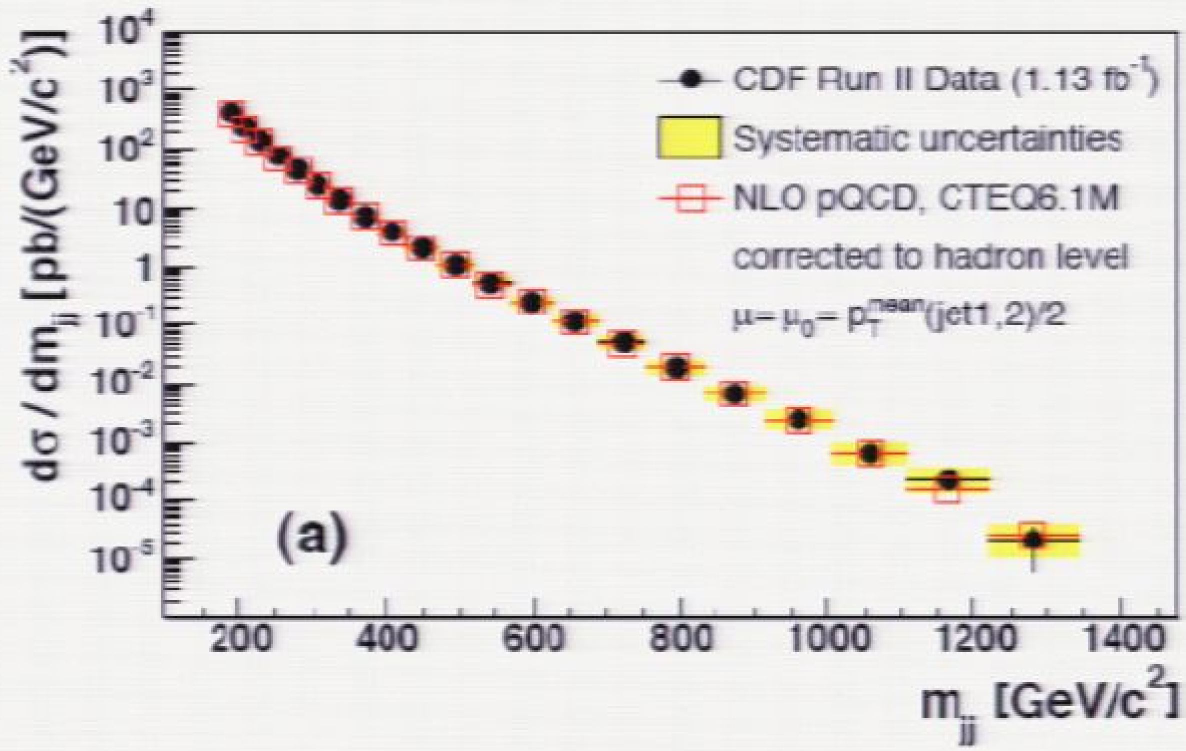
Let's consider how you might look for these *light* states at the Tevatron (since previous studies for heavy Octets)

- Depend on mass splittings, parameters of scalar potential.
- Heavy Octets cascade decay to lighter one, emitting gauge boson. $S_{\pm} \to W^{\pm} S_{R,I}$
- Octets can decay to quarks: decay preferentially to heavy states, lighter states suppressed by small Yukawas.

$$S^+ \to t\bar{b} \qquad S_R \to t\bar{t} \qquad S_R \to b\bar{b}$$

Dijets at Tevatron

- Most model independent constraint on Octets from Tevatron is non-standard dijet search. CDF **arXiv:0812.4036.**

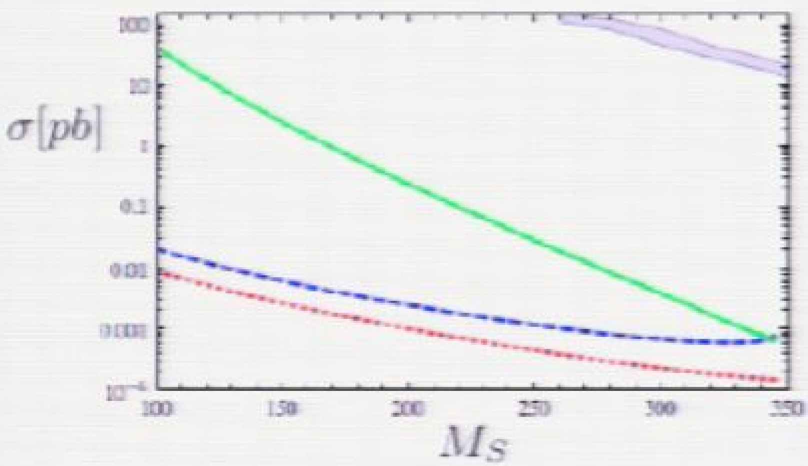


- Can use the lack of any deviation from the SM prediction to bound NP dijet signals if they are big enough.

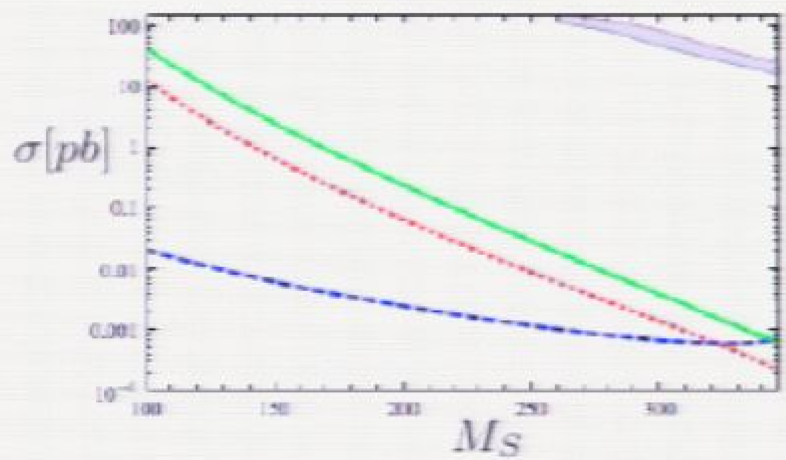
Dijets at Tevatron

- Dijet rates from Octets too small to get interesting constraint.
- Tevatron constraints are generally weak since octets couple to light quark with small Yukawas.

$(\lambda_4, \lambda_5) = (0, 0)$



$(\lambda_4, \lambda_5) = (1, 1)$



CDF **arXiv:0812.4036**

——— $\sigma(g\,g \to S_R\,S_R)$

– – – $\sigma(g\,g \to S_I)$

- - - - $\sigma(g\,g \to S_R)$

$\sigma(g\,g \to S_+\,S_-) = 2\sigma(g\,g \to S_R\,S_R)$

▭ 95% confidence limit on new particle $\sigma(X) \times B(X \to jj) \times A(|y| < 1)$

there is shape dependence

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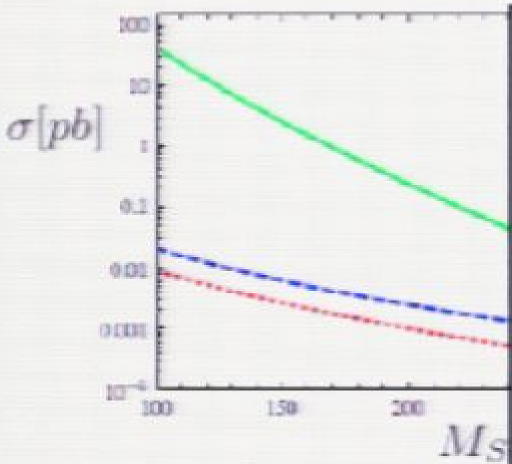
$(\lambda_4, \lambda_5) = (0,0)$ $(\lambda_4, \lambda_5) = (1,1)$



Same for decay to $S^0 \to t\bar{t}$

Dominant for $M_S > 350\text{GeV}$

Tevatron search for resonance in $t\bar{t}$: not ruled out

D0 search with 0.9 fb^{-1} data **arXiv:0804.3664**

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$\sigma(gg \to S_R$

$\sigma(gg \to S_I)$

$\sigma(gg \to S_R)$

$\sigma(gg \to S_+ S_-) = 2\sigma(gg \to S_R S_R)$

95% confidence limit on new particle
$\sigma(X) \times B(X \to jj) \times A(|y| < 1)$
there is shape dependence

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Dijets at Tevatron

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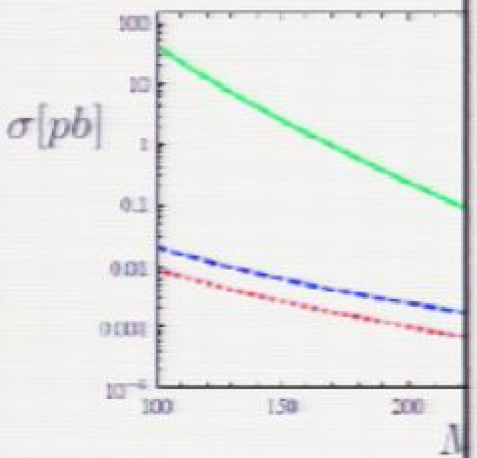
$(\lambda_4, \lambda_5) =$



For $M_S < 350\text{GeV}$

What about decays $S^0 \to b\bar{b}$?

Assume branching ~1 and use CDF bound on $b\bar{b}b\bar{b}$
get bound : $S_R \gtrsim 200\text{GeV}$

Gerbush et al.
arXiv:0710.3133v2

This is evaded for much of parameter space.

$\frac{|\eta_U|}{|\eta_D|} \gtrsim 3$ or branching <<1

$\sigma(g\,g \to S$

$\sigma(g\,g \to S$

$\sigma(g\,g \to S$

$\sigma(g\,g \to S_+ S_-) = 2\sigma(g\,g \to S_R S_R)$

Decays to Leptons?

- Octets can cascade decay via gauge boson $S_R \to W^+ S^-$

  Small mass splitting, Δ, favoured by EWPD, decays likely through virtual W, Z.

  Consider: $S_R \to S^- l^+ \nu$ $\quad \Gamma_l = \dfrac{\alpha^2 \Delta^5}{60\pi s_W^4 M_W^4}$

- Compare to decay to quarks: $M_R < 350\text{GeV}$

$$\frac{\Gamma_l}{\Gamma_{S_R^0 \to b\bar{b}}} = \frac{8\text{GeV}}{M_R |\eta_D|^2} \left(\frac{\Delta}{50\text{GeV}} \right)^5 \qquad \frac{\Gamma_l}{\Gamma_{S_R^0 \to c\bar{c}}} = \frac{82\text{GeV}}{M_R |\eta_U|^2} \left(\frac{\Delta}{50\text{GeV}} \right)^5$$

→ For light scalars can have significant branching to leptons + jets signals!

Eg. $M_R = 200\text{GeV}$ Decay to leptons dominates $b\bar{b}$ for $|\eta_D| \lesssim 0.2$

Decay to leptons dominates $c\bar{c}$ for $|\eta_U| \lesssim 0.6$

From Rb $|\eta_U| < 0.33$ for which $B \to X_s \gamma$ gives $|\eta_D| \lesssim 0.5$

(Gresham Wise) (Manohar Wise)

Needs closer look to constrain.

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Octet Bound States to $\gamma\gamma$

A promising signal $gg \to S^+S^- \to \gamma\gamma$

Mehen and Kim detailed study **arXiv:0812** showed bound states can form for $\eta_U < 1$

- D0 search for resonance in $\gamma\gamma$ signal, set 95% CL on $\sigma(h) \times Br(h \to \gamma\gamma)$

- Rules out $M_S < 75\,\mathrm{GeV}$. Already ruled out by EWPD, but extending mass region in search would give strong constraint.

Conclusions

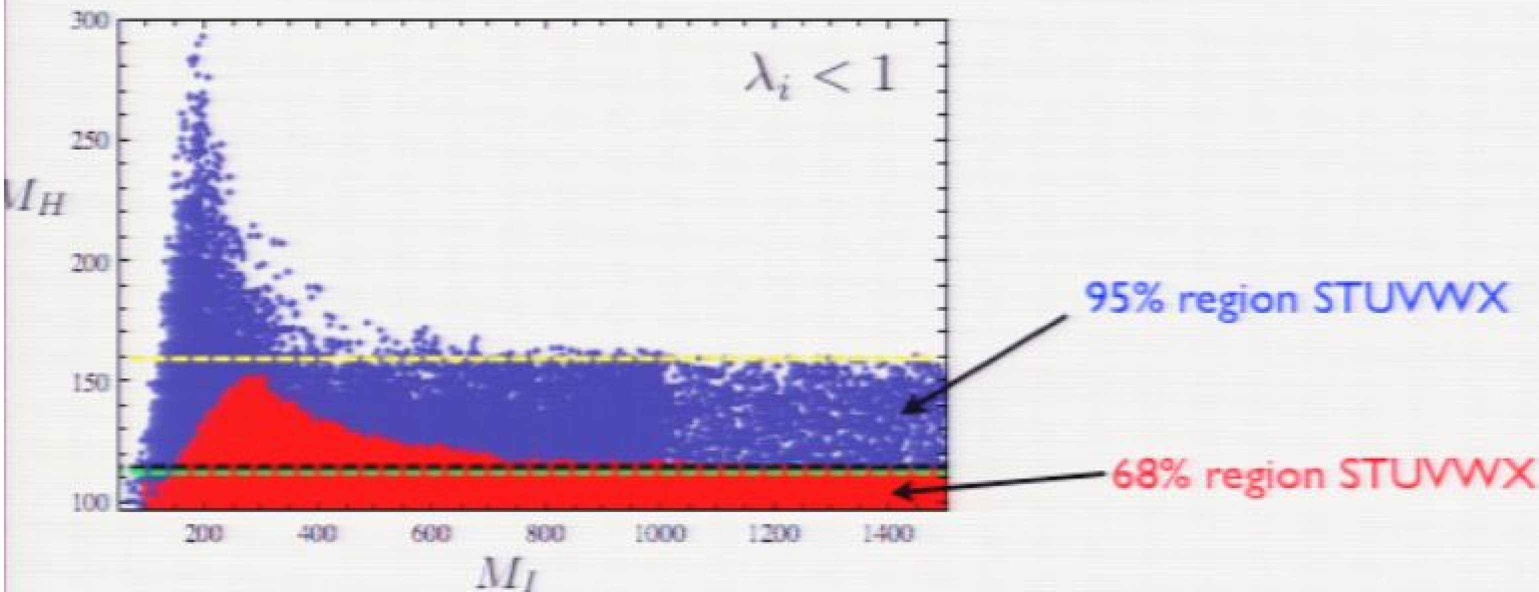
- Light coloured scalar could be found at LHC, and be consistent with results from Tevatron, in EWPD & flavour constraints.
- Such scalars can remove preference of EWPD for light Higgs.
- Promising signals:
  - leptons + jets + missing energy
  - Octet bound states giving $\gamma\gamma$

Acknowlegements:
Brian Batell

Tevatron Constraints

Joint fit: Influence on the Higgs Mass

- What happens to the best-fit value of the Higgs mass from EW fit?



Direct production bound 114 GeV

68% confidence level Higgs alone 112 GeV

95% confidence level Higgs alone 160 GeV

What has been done.....

Initial Work: Manohar & Wise: hep-ph/0606172

Early studies: Gresham & Wise: arXiv:0706.0909; (*R_b vertex corrections*)
Dobrescu, Kong & Mahbubani: arXiv:0709.2378;
Gerbash et al: arXiv:0710.3133;
Perez, Iminniyaz & Rodrigo: arXiv:0803.4156

More detailed phenomenology:
Perez, Gavin, McElmurry & Petriello: arXiv:0809.2106; (*LHC discovery*)
Kim & Mehen: arXiv:0812.0307; (*Octetonia*)
Idilbi, Kim & Mehen, arXiv:0903.3668; (*SCET resummation*)
Perez & Wise: arXiv:0906.2950;
Burgess, Trott & SZ: arXiv:0907.2696

Manohar-Wise Model

hep-ph/0606172

The potential:

$$
\begin{aligned}
V &= \frac{\lambda}{4}\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_S^2\,\mathrm{Tr}\,(S^{\dagger i}S_i) + \lambda_1 H^{\dagger i}H_i\,\mathrm{Tr}\,(S^{\dagger j}S_j) + \lambda_2 H^{\dagger i}H_j\,\mathrm{Tr}\,(S^{\dagger j}S_i)\\
&+ \left[\lambda_3 H^{\dagger i}H^{\dagger j}\,\mathrm{Tr}\,(S_iS_j) + \lambda_4 H^{\dagger i}\,\mathrm{Tr}\,(S^{\dagger j}S_jS_i) + \lambda_5 H^{\dagger i}\,\mathrm{Tr}\,(S^{\dagger j}S_iS_j) + h.c.\right]\\
&+ \lambda_6\mathrm{Tr}\,(S^{\dagger i}S_iS^{\dagger j}S_j) + \lambda_7\mathrm{Tr}\,(S^{\dagger i}S_jS^{\dagger j}S_i) + \lambda_8\mathrm{Tr}\,(S^{\dagger i}S_i)\;\mathrm{Tr}\,(S^{\dagger j}S_j)\\
&+ \lambda_9\mathrm{Tr}\,(S^{\dagger i}S_j)\;\mathrm{Tr}\,(S^{\dagger j}S_i) + \lambda_{10}\mathrm{Tr}\,(S_iS_j)\;\mathrm{Tr}\,(S^{\dagger i}S^{\dagger j}) + \lambda_{11}\mathrm{Tr}\,(S_iS_j\,S^{\dagger j}S^{\dagger i})\;.
\end{aligned}
$$

What's the mass spectrum?

$$
S^{A0} = \frac{S_R^{A0} + iS_I^{A0}}{\sqrt{2}}
$$

$$
\begin{aligned}
M_\pm^2 &= M_S^2 + \lambda_1\frac{v^2}{4}\\
M_R^2 &= M_S^2 + (\lambda_1+\lambda_2+2\lambda_3)\,\frac{v^2}{4}\\
M_I^2 &= M_S^2 + (\lambda_1+\lambda_2-2\lambda_3)\,\frac{v^2}{4}.
\end{aligned}
$$

In the $SU(2)_C$ case : 14 real parameters $\longrightarrow$ 9 parameters

$$
\begin{aligned}
2\,\lambda_3 &= \lambda_2,\\
2\,\lambda_6 &= 2\,\lambda_7 = \lambda_{11},\\
\lambda_9 &= \lambda_{10}
\end{aligned}
$$

and $\lambda_4 = \lambda_5^\star.$

arXiv:0907.2696

$$
M_\pm^2 = M_I^2
$$

hep-ph/0606172

9

Early new physics: Why Octet Scalars?

Chivukula & Geor
d'Ambrosio, Giudice, Isidori & Strumi

Minimal Flavour Violation (MFV):

Restore SM flavour symmetry $SU_Q(3) \times SU_U(3) \times SU_D(3)$
by promoting Yukawas to spurions $y_U \sim (\underline{3}, 3, 1)$ $y_D \sim (\underline{3}, 1, 3)$

Construct theory

MFV says any NP

FCNC naturall

Since then:

- neutral scalar
- charged scalar couplings in loops are GIM suppressed.

Manohar Wise show MFV **only** possible for following representations:

$$H \sim (1, 2)_{1/2} \text{ or } S \sim (8, 2)_{1/2}$$

under

$$SU_c(3)xSU_L(2)xU_Y(1)$$