

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

Date: Oct 30, 2009 04:10 PM

URL: <http://pirsa.org/09100164>

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 $\sim SU(2)_C$ symmetry.

Constraints: How light can octet scalars be?

- Our EW precision data fit STUUVWX 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:

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The Approach:

Scalars low energy EFT degrees of freedom

Obeys approximate symmetries :

- Minimal Flavour Violation \longrightarrow naturally suppresses FCNC
- Custodial $SU(2)_c \longrightarrow$ precision EW measurements.

Early new physics: Why Octet Scalars?

*Chivukula & Georgi
d'Ambrosio, Giudice, Isidori & Strumia*

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.

Early new physics: Why Octet Scalars?

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Construct theory

MFV says any NP

FCNC natural

Since then:

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- 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

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

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:

$$\begin{aligned} \mathcal{L} = & -\sqrt{2}\eta_U \bar{u}_R^i \frac{m_U^i}{v} T^A u_L^i S^{A0} + \sqrt{2}\eta_U \bar{u}_R^i \frac{m_U^i}{v} T^A V_{ij} d_L^j S^{A+} + h.c. \\ & -\sqrt{2}\eta_D \bar{d}_R^i \frac{m_D^i}{v} T^A d_L^i S^{A0\dagger} - \sqrt{2}\eta_D \bar{d}_R^i \frac{m_D^i}{v} T^A V_{ij}^\dagger u_L^j S^{A-} + h.c. \end{aligned}$$

overall complex coefficients
 η_U, η_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:

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

What's the mass spectrum?

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

$$M_{\pm}^2 = M_S^2 + \lambda_1 \frac{v^2}{4}$$

$$M_R^2 = M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4}$$

$$M_I^2 = M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4}.$$

Manohar-Wise Model

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$$M_R^2 = M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4}$$

$$M_I^2 = M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4}$$

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

$$2\lambda_3 = \lambda_2,$$

and $\lambda_4 = \lambda_5^*$.

$$2\lambda_6 = 2\lambda_7 = \lambda_{11},$$

$$\lambda_9 = \lambda_{10}$$

arXiv:0907.2696

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

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 scalars

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

Instead require 6 parameter
extended fit: STUVWX

*Burgess, London &
Maksymyk*

Electroweak Precision Fits

Standard EW precision view:

- For STU to be inadequate new particles must be extremely light & $VW X$ generally too small to matter.
- Adding additional parameters will make fit less constraining, so STU is more conservative anyway.

→ $VW X$ not really needed

Electroweak Precision Fits

Standard EW precision lore:

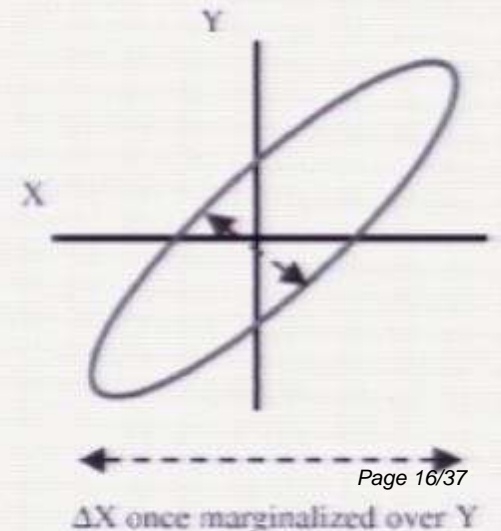
- New particles must be extremely light to make STU inadequate, even then $V W X$ too small to matter.

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 ST UVW 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 |
| Γ_{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_{FB}^e | 0.0145 ± 0.0025 | 0.01627 ± 0.00023 |
| A_{FB}^μ | 0.0169 ± 0.0013 | 0.01627 ± 0.00023 |
| A_{FB}^τ | 0.0188 ± 0.0017 | 0.01627 ± 0.00023 |
| A_{FB}^b | 0.0992 ± 0.0016 | 0.1033 ± 0.0007 |
| A_{FB}^c | 0.0707 ± 0.0035 | 0.0738 ± 0.0006 |
| $s_1^2(A_{FB}^q)$ | 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 |
| $g_V^{e^+e^-}$ | -0.040 ± 0.015 | -0.0397 ± 0.0003 |
| $g_A^{e^+e^-}$ | -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 STUVWX.

| 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

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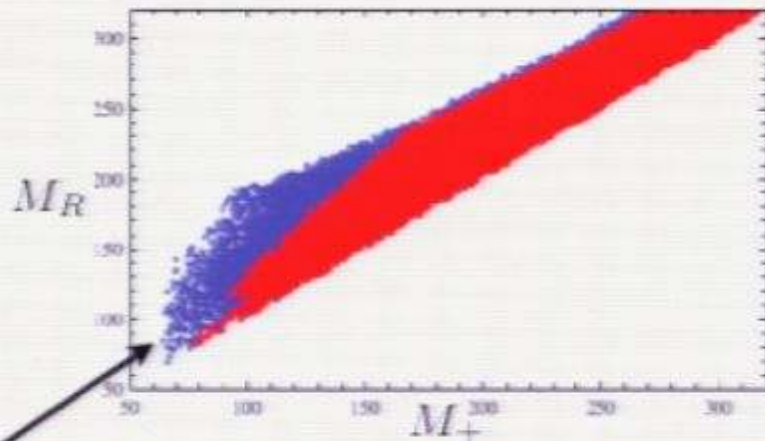
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$$M_{ST} = \begin{pmatrix} 1 & 0.87 \\ 0.87 & 1 \end{pmatrix}$$

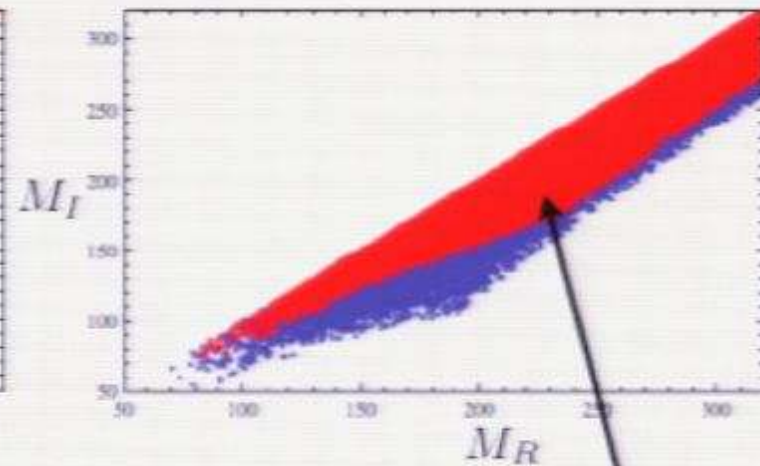
See strong correlation for (S,X), (T,V) (U,X) in addition to usual (S,T).

EWPD fit results

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



68% region STU blue

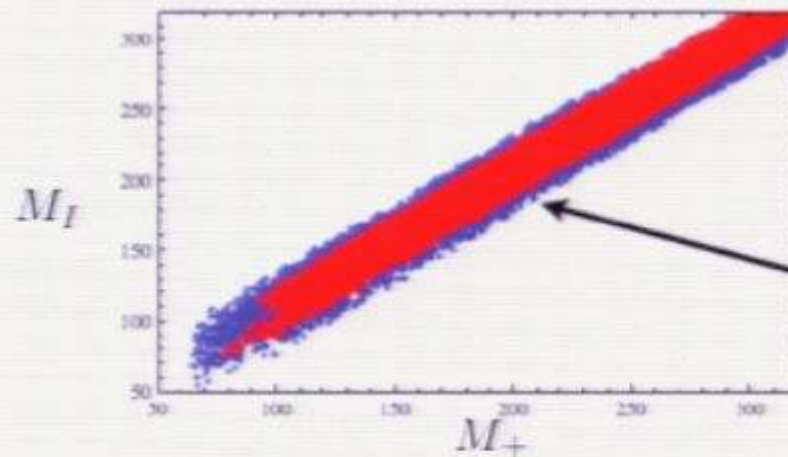


68% region STUVWX red

$$M_{\pm}^2 = M_S^2 + \lambda_1 \frac{v^2}{4}$$

$$M_R^2 = M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4}$$

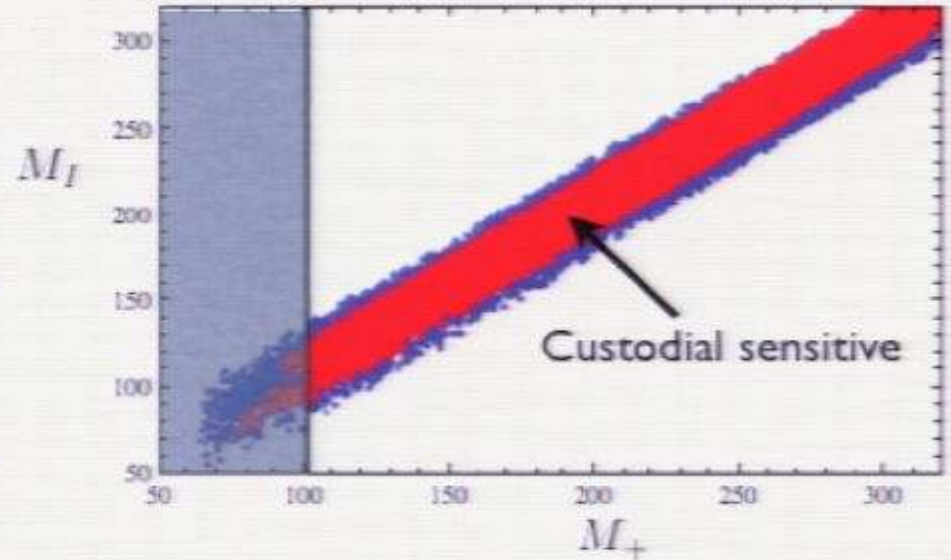
$$M_I^2 = M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4}$$



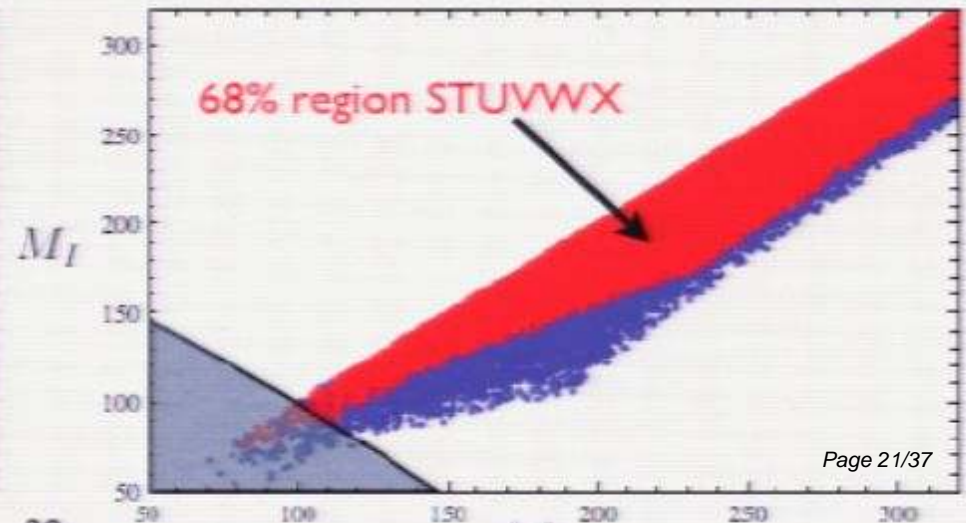
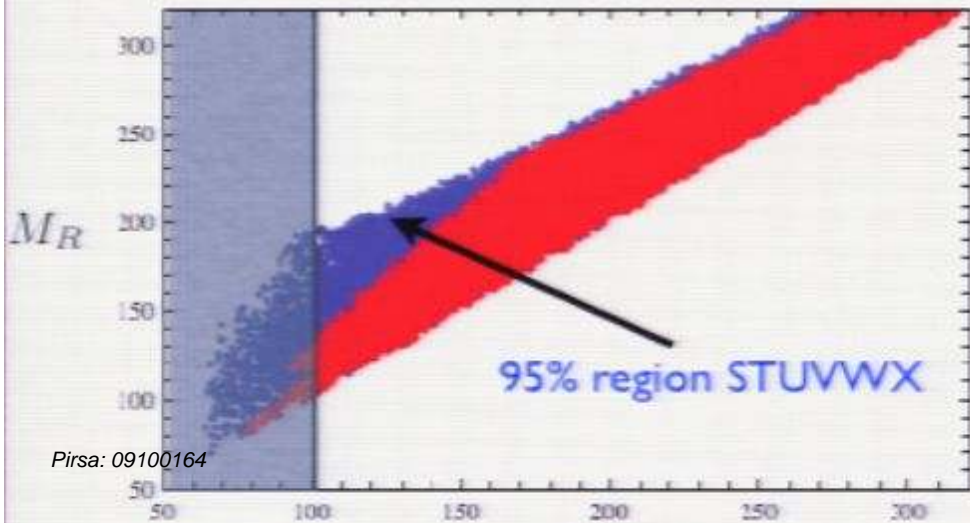
Approximate $SU(2)_c$

Direct Production: LEP

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

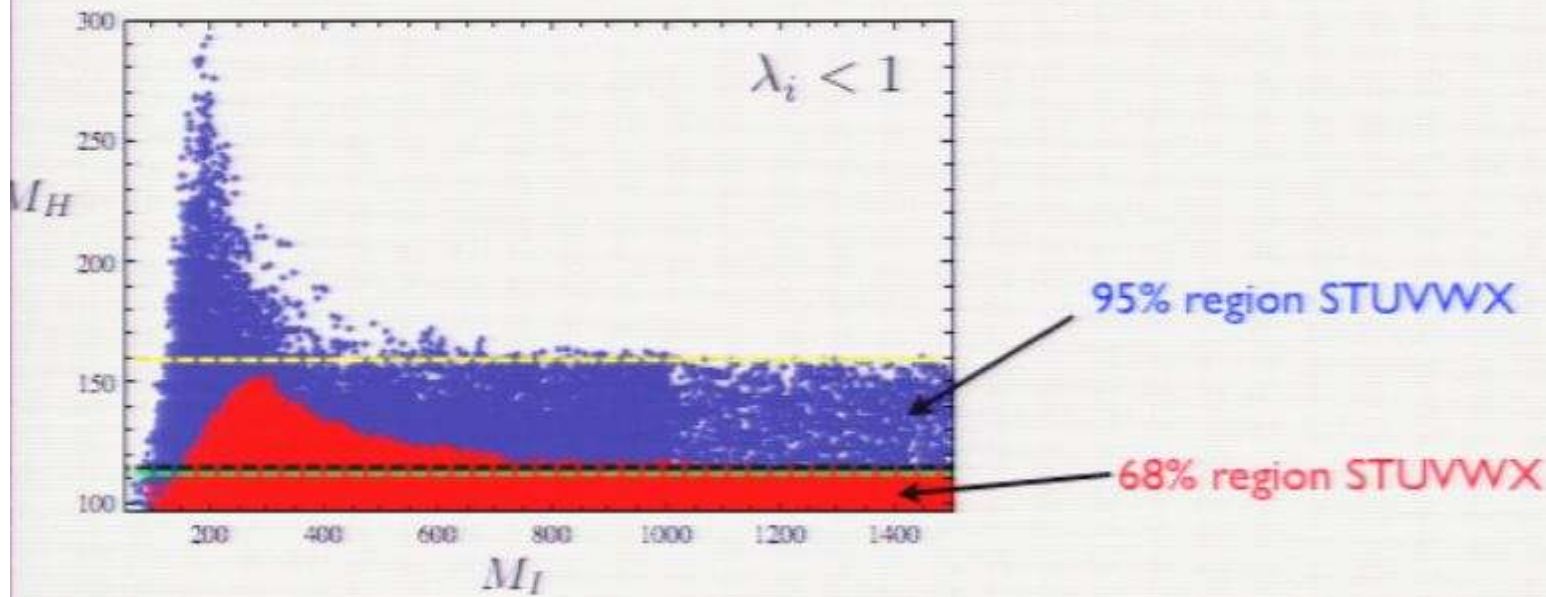


Place limit based on 10 events with no cuts $\sigma \times \int \mathcal{L} dt < 10$



Joint fit: Influence on the Higgs Mass

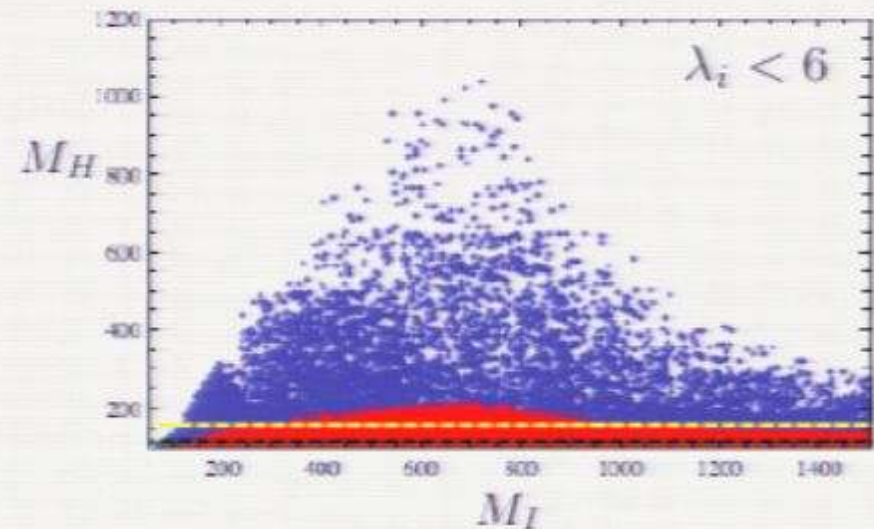
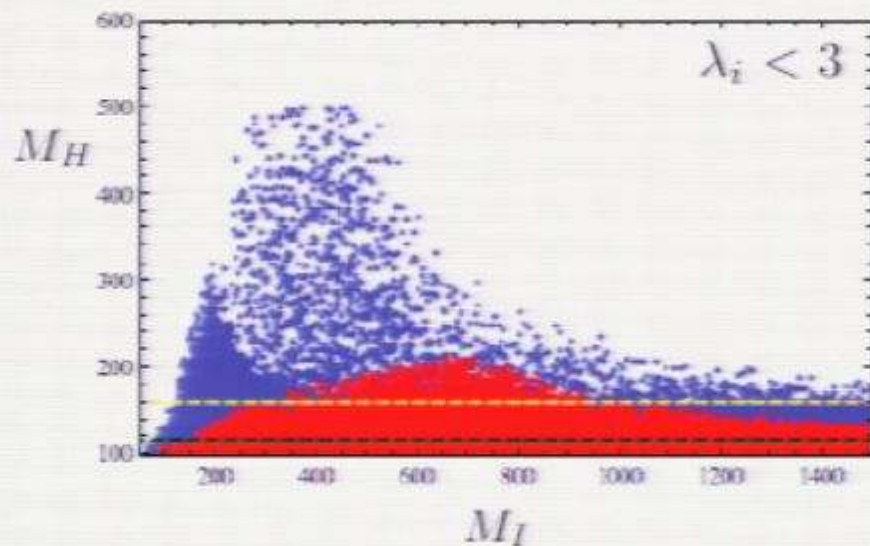
- What happens to the best-fit value of the Higgs mass from EW fit?



- - - - Direct production bound 114 GeV
- - - - 68% confidence level Higgs alone 112 GeV
- - - - 95% confidence level Higgs alone 160 GeV

Joint fit: Influence on the Higgs Mass

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



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

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.

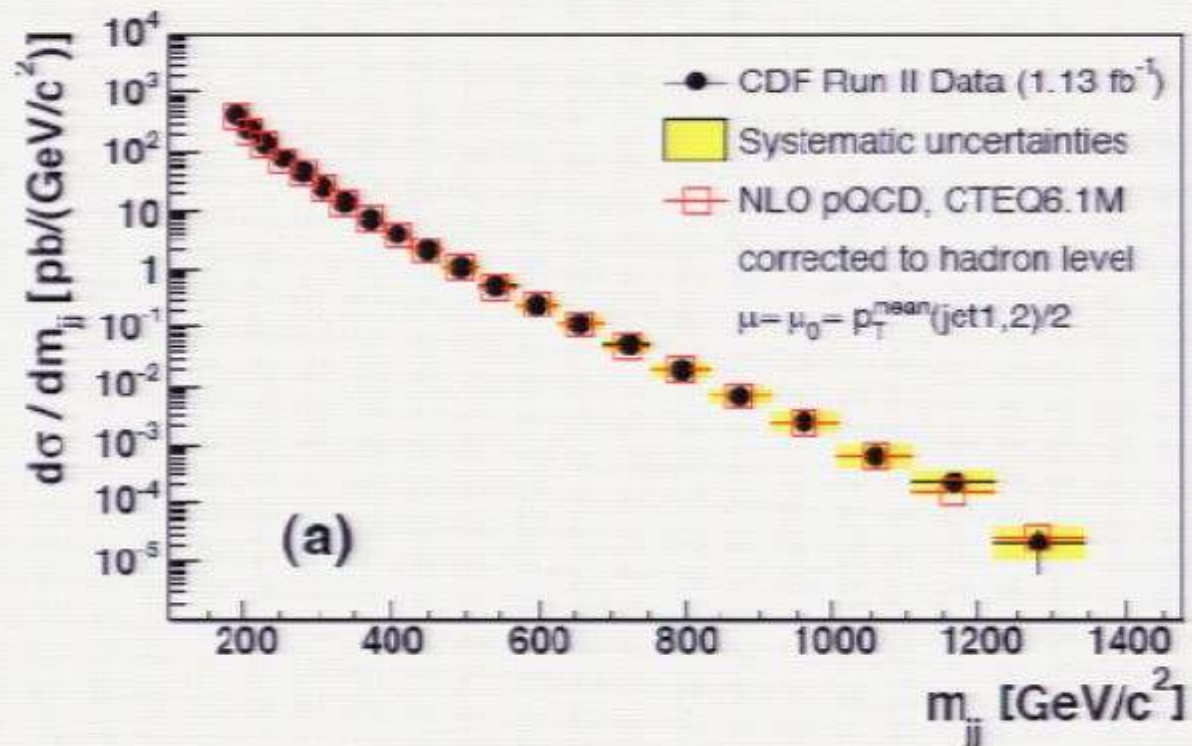
$$S_{\pm} \rightarrow W^{\pm} S_{R,I}$$

- Octets can decay to quarks: decay preferentially to heavy states, lighter states suppressed by small Yukawas.

$$S^{+} \rightarrow t\bar{b} \quad S_{R} \rightarrow t\bar{t} \quad S_{R} \rightarrow b\bar{b}$$

Dijets at Tevatron

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

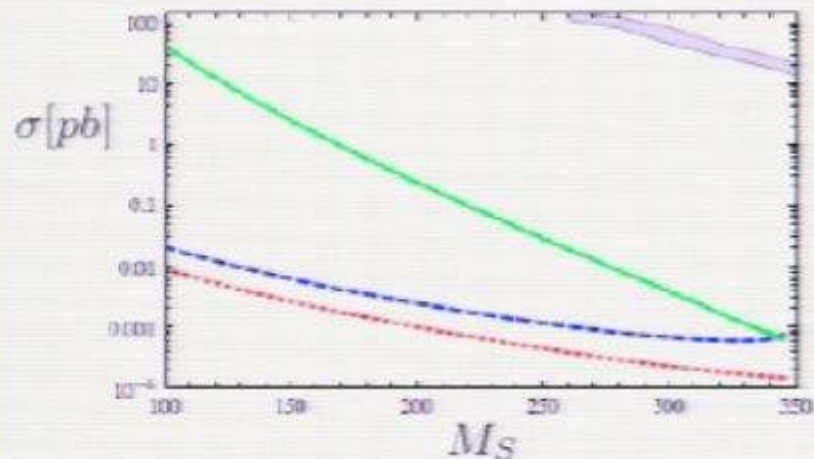


- Can use the lack of any deviation from the SM prediction to bound NP dijet signals if they are big enough.

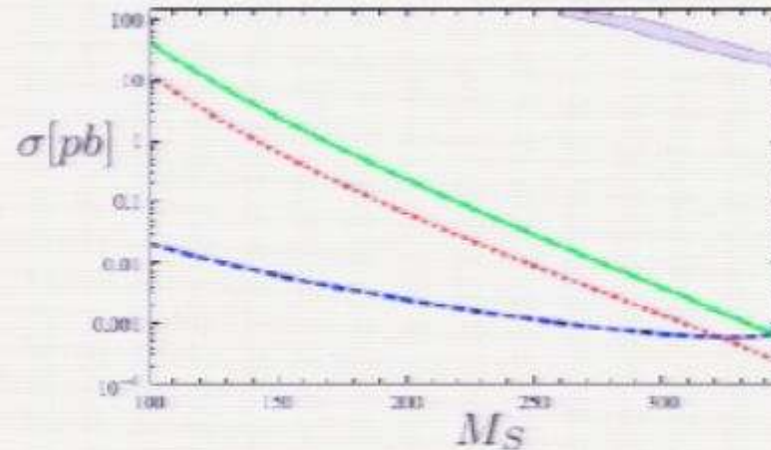
Dijets at Tevatron

- 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

— $\sigma(gg \rightarrow S_R S_R)$

- - - $\sigma(gg \rightarrow S_I)$

- - - $\sigma(gg \rightarrow S_R)$

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

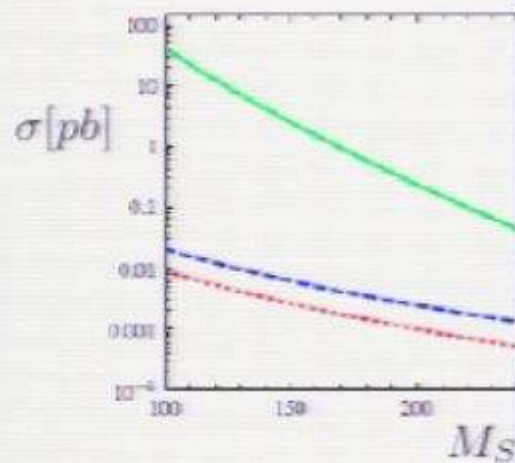
Pirsa: 09100164 $\sigma(gg \rightarrow S_+ S_-) = 2\sigma(gg \rightarrow S_R S_R)$

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

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



- $\sigma(gg \rightarrow S_R)$
- - - $\sigma(gg \rightarrow S_I)$
- - - $\sigma(gg \rightarrow S_0)$

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

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

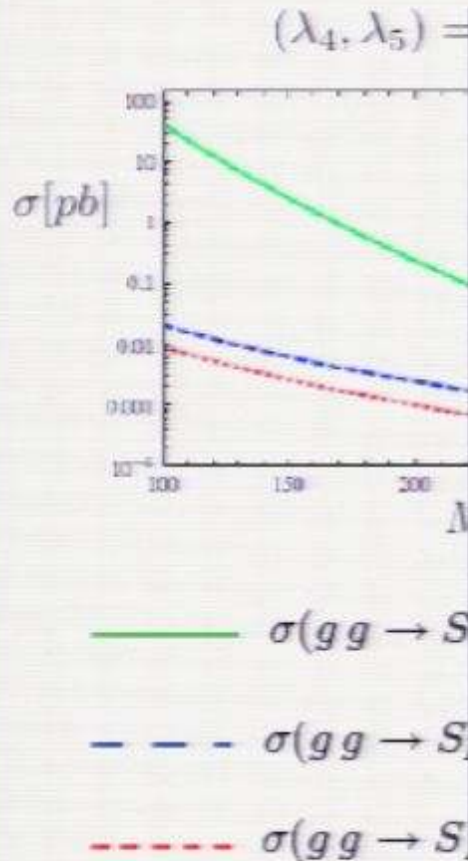
Tevatron search for resonance in $t\bar{t}$: not ruled out
 D0 search with 0.9 fb^{-1} data [arXiv:0804.3664](https://arxiv.org/abs/0804.3664)

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

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

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.



For $M_S < 350\text{GeV}$

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

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.

$$\frac{|\eta_U|}{|\eta_D|} \gtrsim 3 \quad \text{or} \quad \text{branching} \ll 1$$

Decays to Leptons?

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

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

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

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

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

→ 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 $B \rightarrow X_s \gamma$ gives $|\eta_D| \lesssim 0.5$
 (Gresham Wise) (Manohar Wise)

Octet Bound States to $\gamma\gamma$

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

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 $\sigma(h) \times Br(h \rightarrow \gamma\gamma)$
- Rules out $M_S < 75 \text{ GeV}$. Already ruled out by EWPD, but extending mass region in search would give strong constraint.

Conclusions

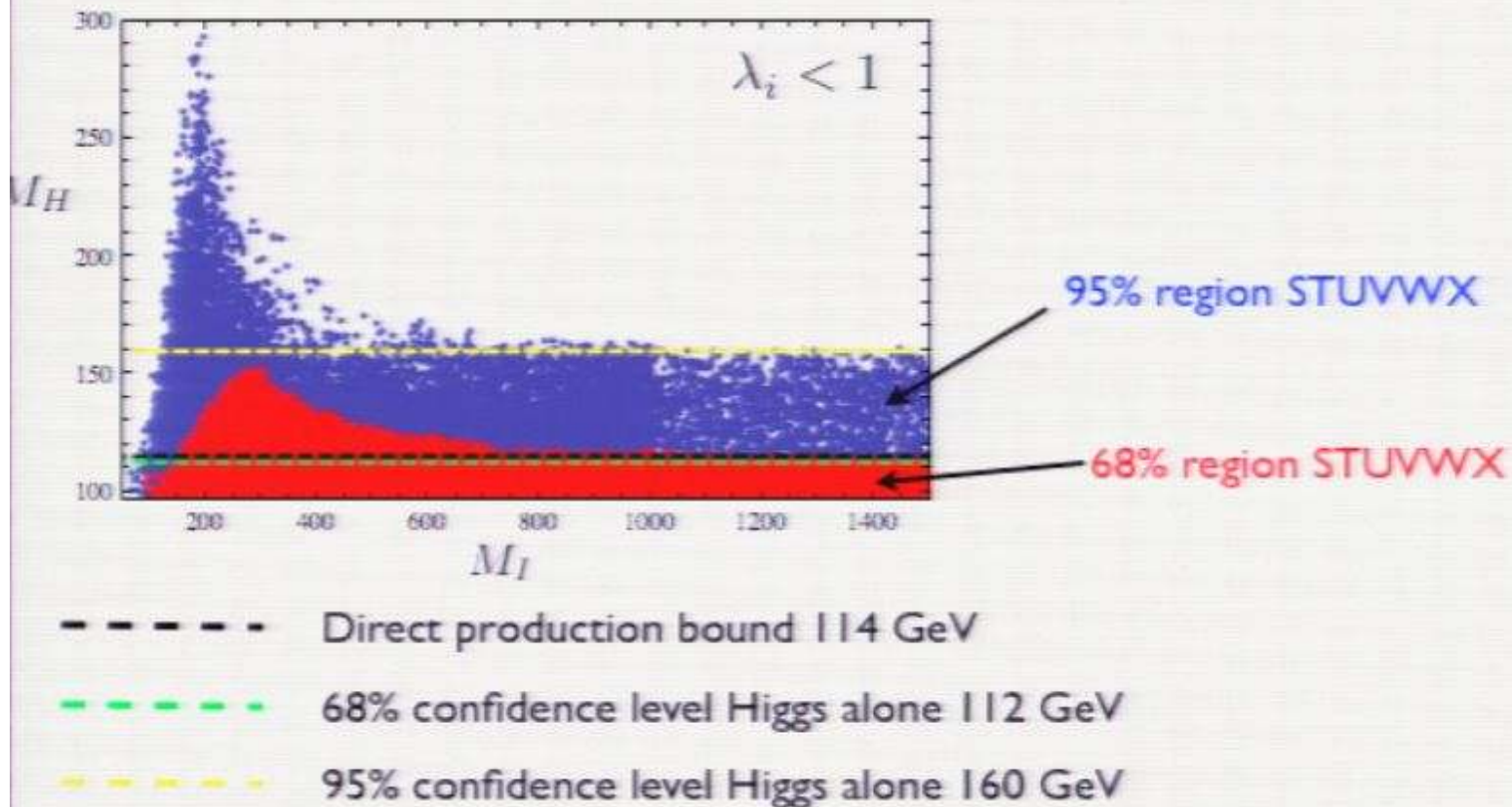
- Light coloured scalar could be found at LHC, and be consistent with results from Tevatron, in EWPD & flavour constraints.
- Such scalars can remove preference of EWPD for light Higgs.
- Promising signals:
 - leptons + jets + missing energy
 - Octet bound states giving $\gamma\gamma$

Acknowledgements:
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?



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:

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

What's the mass spectrum?

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

$$M_{\pm}^2 = M_S^2 + \lambda_1 \frac{v^2}{4}$$

$$M_R^2 = M_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4}$$

$$M_I^2 = M_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4}$$

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

$$2\lambda_3 = \lambda_2,$$

$$2\lambda_6 = 2\lambda_7 = \lambda_{11},$$

$$\lambda_9 = \lambda_{10}$$

and $\lambda_4 = \lambda_5^*$.

arXiv:0907.2696

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

Early new physics: Why Octet Scalars?

Chivukula & Georgi
d'Ambrosio, Giudice, Isidori & Strumia

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 natural

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

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