The plan

1. The Standard Model: the “indirect” informations
2. “Higgsless”
3. The Higgs boson as a PGB
4. Beyond mSUGRA

The Higgs boson from an extended symmetry

The Higgs boson made light by an <u>approximate</u> symmetry

$\Rightarrow$ Global symmetry

$$h \longrightarrow h + \alpha \;\Rightarrow\; \cancel{m^2 h^2}$$

$\Rightarrow$ Gauge symmetry

$$A_\mu \longrightarrow A_\mu + d_\mu \alpha \;\Rightarrow\; \cancel{m^2 A_\mu^2}$$

$$h = A_5$$

$\Rightarrow$ Supersymmetry

($\Rightarrow$ By accident: not an explanation)

A minimal model: SO(5)/SO(4)

$\Rightarrow$ Preliminaries

1. Standard Model: $\phi_{i=1,\ldots,4} \Rightarrow SO(4)/SO(3)$

with $\phi^2 = v^2$ and $<\phi_i>= (0,0,0,v)$

$\Rightarrow$ Three massless bosons produced

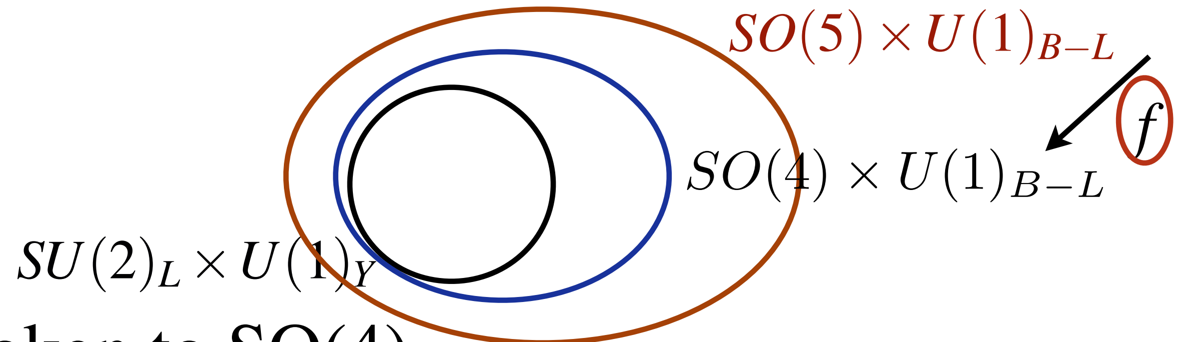
Since Adj[SO(4)] = Adj[SO(3)] + 3 ⇒ 3 GB's

$\Rightarrow$ Gauged standard SU(2)xU(1) inside SO(4)

broken down to $U(1)_{em}$

and the 3 GBs "eaten up" by the $W^{\pm}$ and the Z

A minimal model: SO(5)/SO(4)



1. Extend to SO(5) broken to SO(4)
   by a strong dynamics at $\Lambda \approx \frac{4\pi f}{\sqrt{N_g}},\ N_g = 4$

2. Introduce $\hat{\phi}_{i=1,\ldots,5} \Rightarrow SO(5)/SO(4)$ with $\hat{\phi}^2 = f^2$

3. Gauge standard SU(2)xU(1) inside SO(4)
   acting on first 4 $\phi_{i=1,\ldots,4}$

Since Adj[SO(5)] = Adj[SO(4)] + 4 ⇒ a PGB Higgs

4. For ElectroWeak Symmetry Breaking
   what matters is relative orientation:

$< \hat{\phi}_i >= (0,0,0,0,f)$ ⇒ no EWSB

$< \phi^2 >= f^2$ ⇒ maximal EWSB at v=f

EWSB continued

explicit SO(5)-breaking
(where from?)

Study $V = V_0 f^2 \delta(\hat{\phi}^2 - f^2) - A f^2 \phi^2 + B f^3 \phi_5$

A > 0

$$< \phi^2 > \equiv 2v^2 = f^2[1 - (\frac{B}{2A})^2] \qquad m_h = 2\sqrt{A}v \qquad v = 175\ GeV$$

Take f = 500 GeV as benchmark $\Rightarrow \Lambda \approx 3$ TeV

1. v << f requires tuning B/2A to 1:

$$\Delta = \frac{A}{v^2}\frac{\partial v^2}{\partial A} \approx \frac{f^2}{v^2} \quad \Rightarrow \; 1/\Delta \approx 10 \div 20\%$$

EWSB continued

2. The Higgs boson has reduced couplings to W and Z

$$(\partial_\mu \hat{\phi})^2 = (\partial_\mu (f^2 - \phi^2)^{1/2})^2 \approx \frac{1}{4f^2}(\partial_\mu \phi^2)^2$$

and, after symmetry breaking, from $\phi \longrightarrow v + h$

$$(\partial_\mu \hat{\phi})^2 \approx \frac{v^2}{f^2}(\partial_\mu h)^2$$

requiring a field redefinition

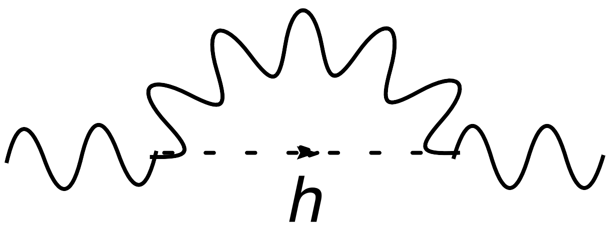
$$h \rightarrow \frac{h}{(1 + v^2/f^2)^{1/2}} \approx (1 - v^2/f^2)^{1/2} h$$

$$\Rightarrow \quad \mathcal{A}(W_L W_L \rightarrow W_L W_L) = -\frac{Gs}{\sqrt{2}} \sin^2 \alpha (1 + \cos\theta)$$

$$\sin\alpha = \frac{\sqrt{2}v}{f} \qquad \Lambda_{unit} = \frac{\Lambda_{unit}^{SM}}{\sin\alpha} \approx 2.4\ TeV\ f_{500}$$

How about the EWPTs? (the usual story)

1. loop effects



$$\widehat{S},\widehat{T}|_{SM} = a_{S,T}\log m_H + b_{S,T}$$

$$\widehat{S},\widehat{T}|_{this-model} = a_{S,T}[(\cos\alpha)^2\log m_h + (\sin\alpha)^2\log\Lambda] + b_{S,T}$$

$$= (\hat{T},\hat{S})|_{SM}(m_{EWPT,eff})$$

$$m_{EWPT,eff} = m_h(\Lambda/m_h)^{\sin^2\alpha}$$

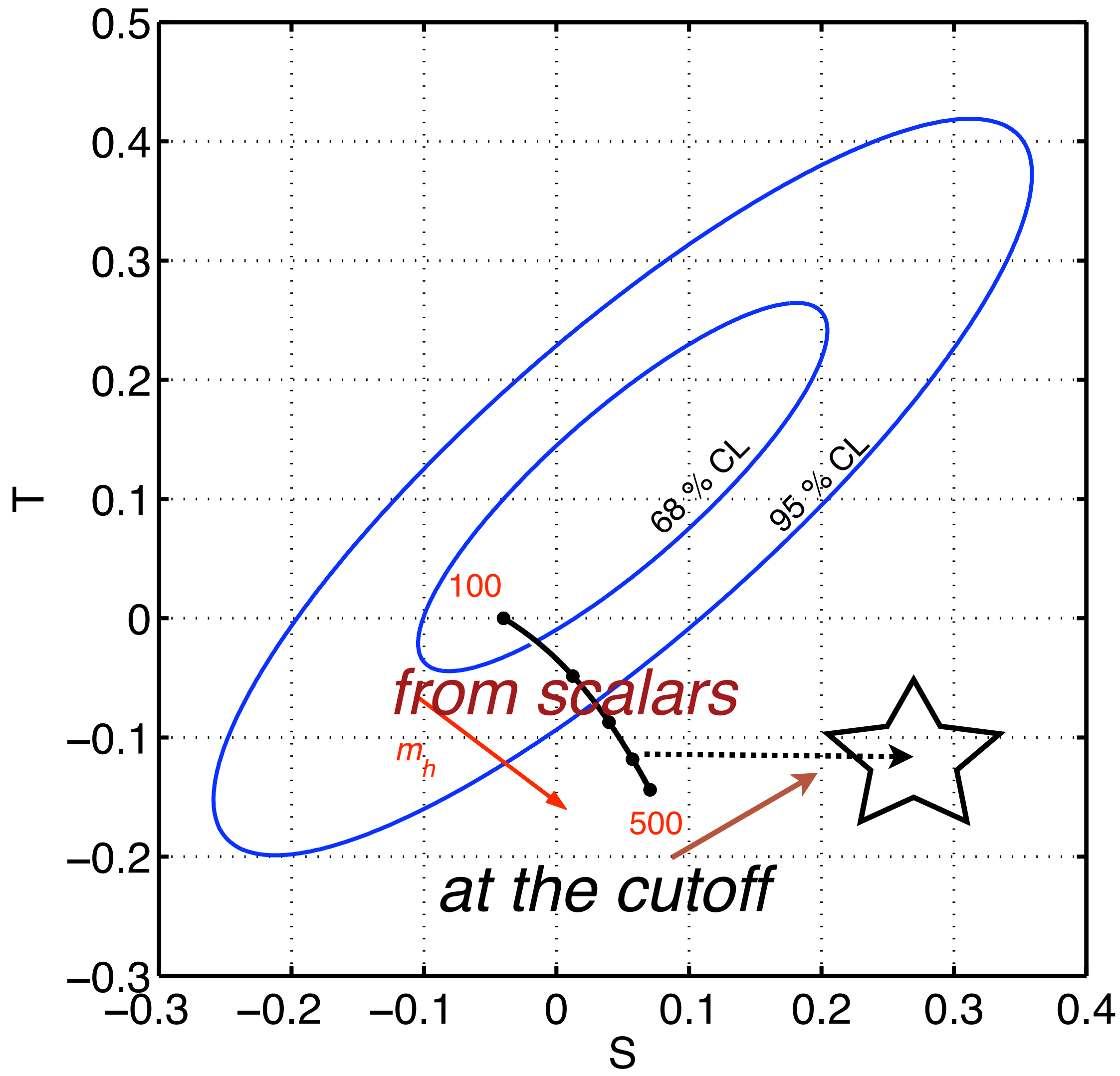
$$(\sin\alpha)^2 \approx 0.25$$

2. At the cutoff

$$\Delta\hat{S} = \frac{g^2v^2}{\Lambda^2} \qquad \Delta S = 0.25\left(\frac{2\ TeV}{\Lambda}\right)^2$$

(can be defended in some "UV-completions"?)

This model (continued)



LEPEWWG

Better than Higgless, although still not defendable as it stands so far (for small finetuning)

$$f.t. \approx 10 \div 20\% \ \frac{1}{f_{500}^2}$$

$$S \approx 0.2 \frac{1}{f_{500}^2}$$

$$E_0(W_L W_L) \approx 2.4 \ TeV \ \ f_{500}$$

More than 1 Higgs doublet PGB

Pomarol et al

G	H	PGB	
SO(5)	SO(4)	4=(2,2)	⇐ 1 Doublet
SO(6)	SO(5)	5=(2,2)+(1,1)	⇐ 1 Doublet+ 1 Singlet
	SO(4)xSO(2)	8=(2,2)+(2,2)	⇐ 2 Doublets
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)	
	G_2	7=(1,3)+(2,2)	
...	...	...	

⇑

SU(2)xSU(2)

Some vectors (ρ-like) might be there as well

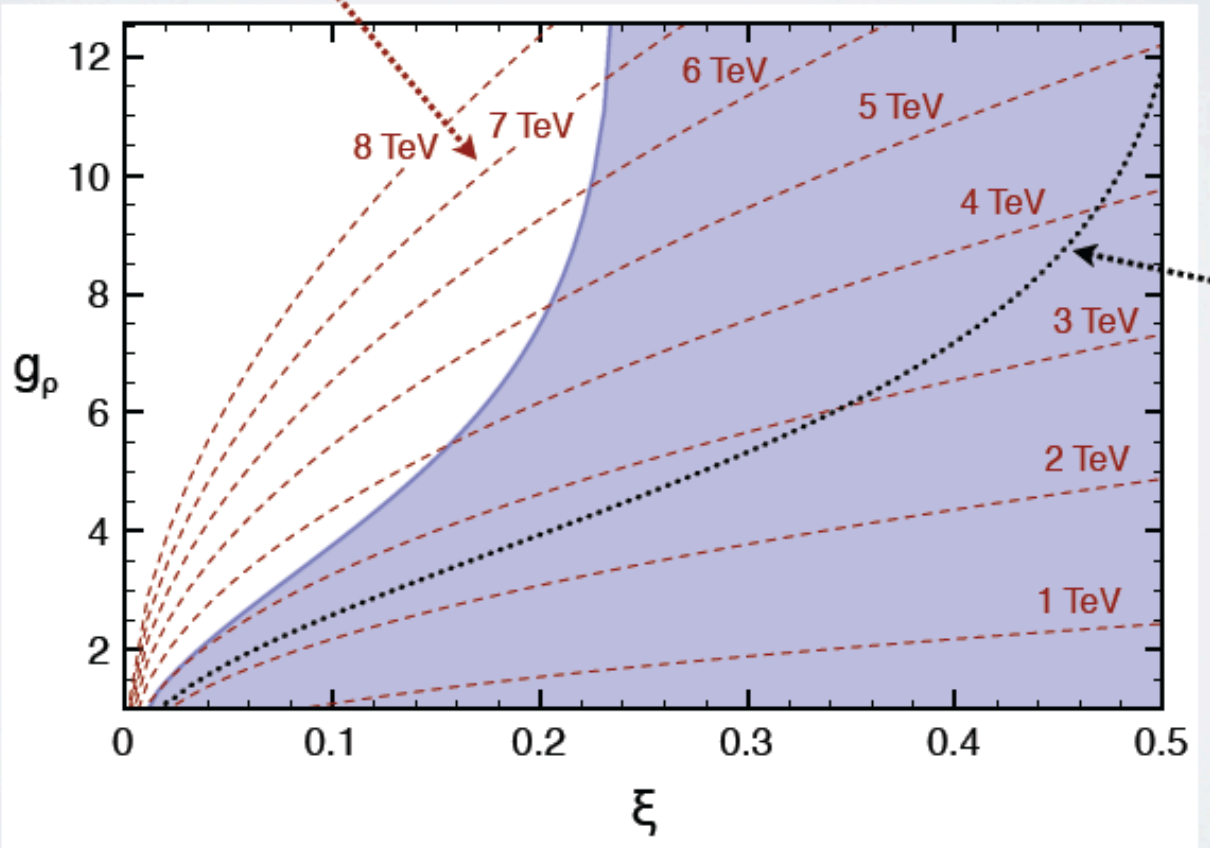
Ex: SO(5) → SO(4)

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

$$m_\rho = \frac{3}{8\pi}\frac{g_\rho v}{\sqrt{\xi}} \qquad a = \sqrt{\xi - 1}$$

$$\xi = (\tfrac{v}{f})^2$$

isocurves of constant m_ρ



adding an extra

$\Delta\rho = +2\times 10^{-3}$

What cuts off the top loop?

Extend SO(5) to the top

$\Psi_L \equiv (q, X, T)_L$ = 5 of SO(5) (=2+2+1 of SU(2))

$$\Psi_L \equiv (q, X, T)_L;\ u_R, d_R, X_R, T_R$$

$SO(5) \supset SU(2)_L \times SU(2)_R \qquad Y = T_R^3 + 2B$

$\Rightarrow$ 3 more quarks than normal

$X = (X_{5/3}, X_{2/3}) \qquad U_{2/3} \qquad$ "composite" quarks

$$\mathcal{L}_Y^{top} = \lambda_1 \bar{\Psi}_L \widehat{\phi} u_R + \lambda_2 f \bar{U}_L U_R + \lambda_3 f \bar{X}_L X_R + \lambda_4 f \bar{U}_L u_R$$

(Other choices possible, sometimes with more extra states)

mass eigenstates and their composition

state	mass	composition
b	0	standard
t	$m_t \simeq \lambda_t v(1 - \frac{1}{2}\epsilon_L^2 - \frac{1}{2}\epsilon_R^2)$	$t_L \simeq t_L^0 - \epsilon_L T_L^0,$ $t_R \simeq t_R^0 - \epsilon_R X_R^0$
T	$m_T = \sqrt{\lambda_1'^2 + \lambda_2^2} f$	$T_L \simeq T_L^0 + \epsilon_L t_L^0$
$X_{5/3}$	m_X	unchanged
$X_{2/3}$	$m_X(1 + \frac{1}{2}\epsilon_R^2)$	$X_R \simeq X_R^0 + \epsilon_R t_R^0$

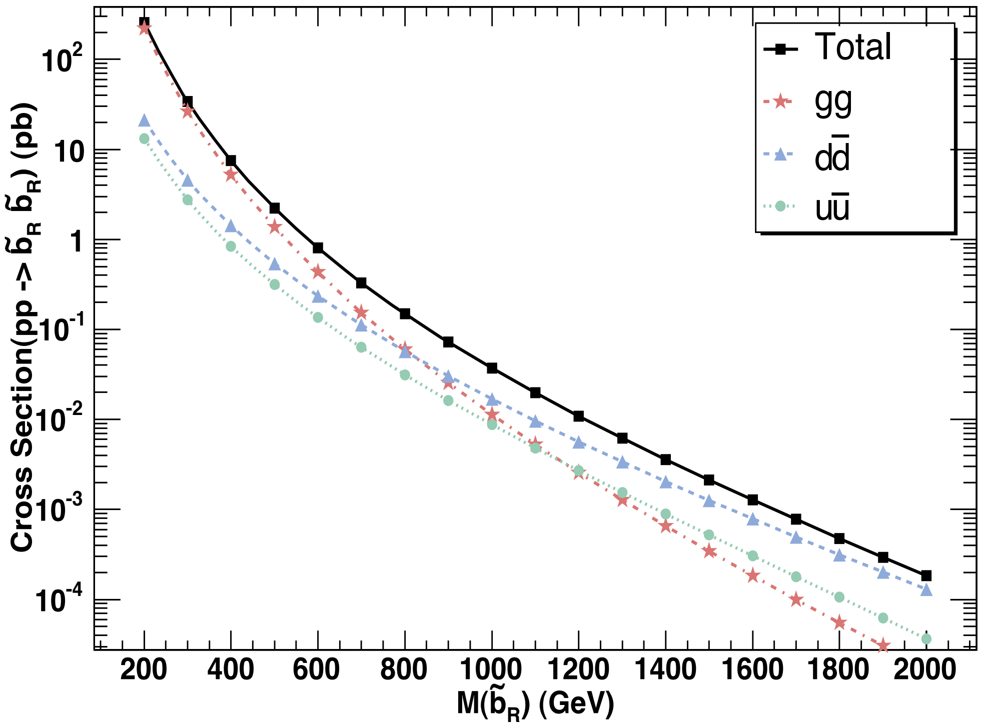
$$t_R = -\sin\chi U_R + \cos\chi u_R, \quad T_R = \cos\chi U_R + \sin\chi u_R, \quad \tan\chi = \frac{\lambda_1}{\lambda_2}.$$

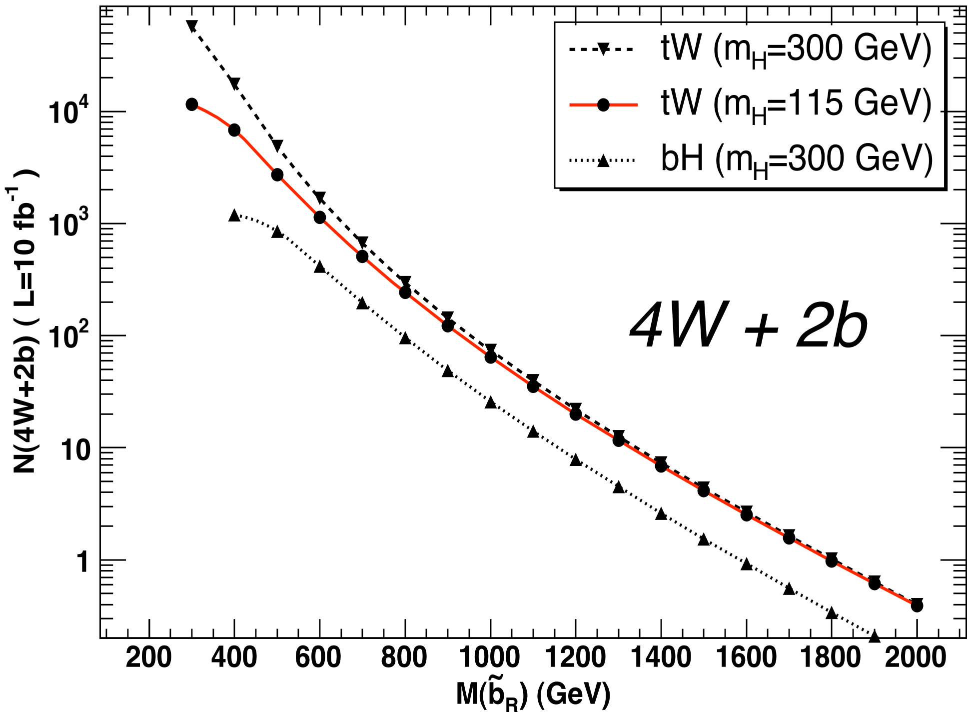
$$\varepsilon_R = \frac{m_t}{m_X} \qquad \varepsilon_L = \frac{\lambda_T v}{m_T}$$

b-quark is normal (because there is no state to mix with)!

Composite quark production

$$pp \to BB$$





Γ(bZ)~ Γ(tW)~ Γ(bh)~ 5÷20 GeV

and similar (mutatis mutandis) for T, X

Significant production/ no $\not{E}_T$

Composite quark signals

$$Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$$

$$qq \to Q\bar{Q}$$

$$Q \to tV,\ th$$

(t or b, depending on the charge)

If they exist, easier to catch than KK-vectors

(like squarks, but without $\not{E}_T$)

$$pp \to X\bar{X} + B\bar{B} \to l^{\pm}l^{\pm} + jets + \not{E}_T$$

$$T(1\ TeV) \to Z\,t \to l^{+}l^{-}l^{\pm}\nu b$$

Single production also possible