Models of EW Symmetry Breaking:

String-Inspired Deformations of Higgs Sector and LHC Implications

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SM Higgs Boson

EWSB accomplished by a single Higgs boson.

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h+v) + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \quad \text{where } v = 246\,\text{GeV}$$

$$\{W_T^\pm, Z_T^0\} + \{\phi_1, \phi_2, \phi_3\} \Rightarrow \{W_T^\pm, W_L^\pm, Z_T^0, Z_L^0\}$$

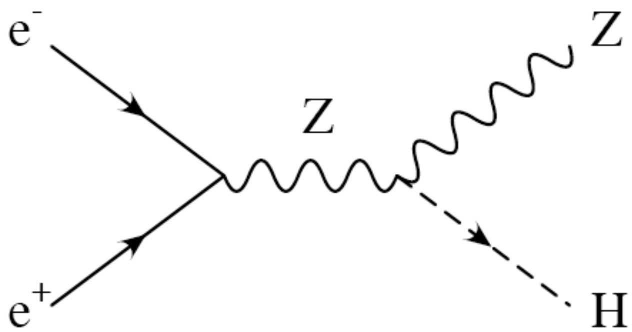
$$L = \left[m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right] \cdot \left(1 + \frac{h}{v}\right)^2 - m_f \bar{f}_L f_R \left(1 + \frac{h}{v}\right) + h.c.$$

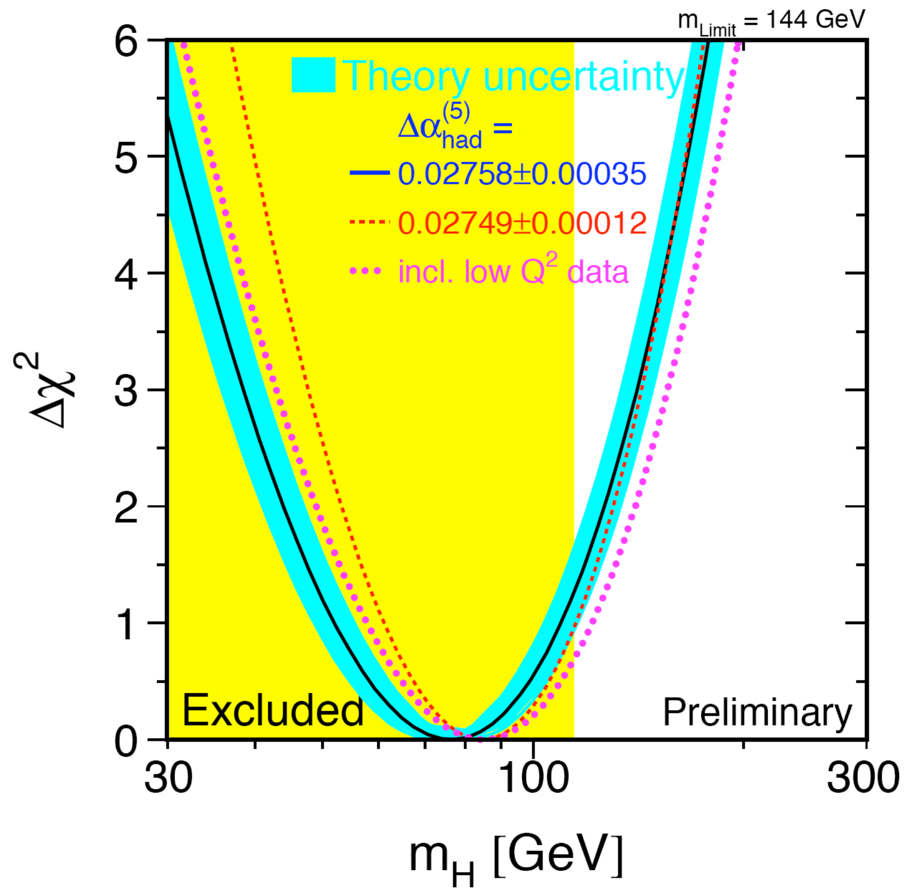
Higgs mass is only free parameter.

Higgs mass limits

Higgs boson mass upper limit (95% CL) from precision Electroweak is less than 182 GeV.

Lower limit from lack of direct signal at LEP 2 is about 115 GeV.





LEPEWWG

Experiment: 115 GeV < m_h < 180 GeV

String-Inspired Deformations

Most important string-inspired result: Supersymmetry

Two Higgs doublets:

H_u gives mass to up quarks
H_d gives mass to down quarks and leptons

Example of “Type II” Higgs model.

Phenomenology is very SM-like over much of parameter space.

Coupling of the neutral scalar Higgses

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Table from
Haber et al. '01

Heavy Higgs

$$HVV: \quad \cos(\beta-\alpha) \to 0 + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \to \frac{1}{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \to \tan\beta + \mathcal{O}(m_Z^2/m_A^2)$$

Light Higgs

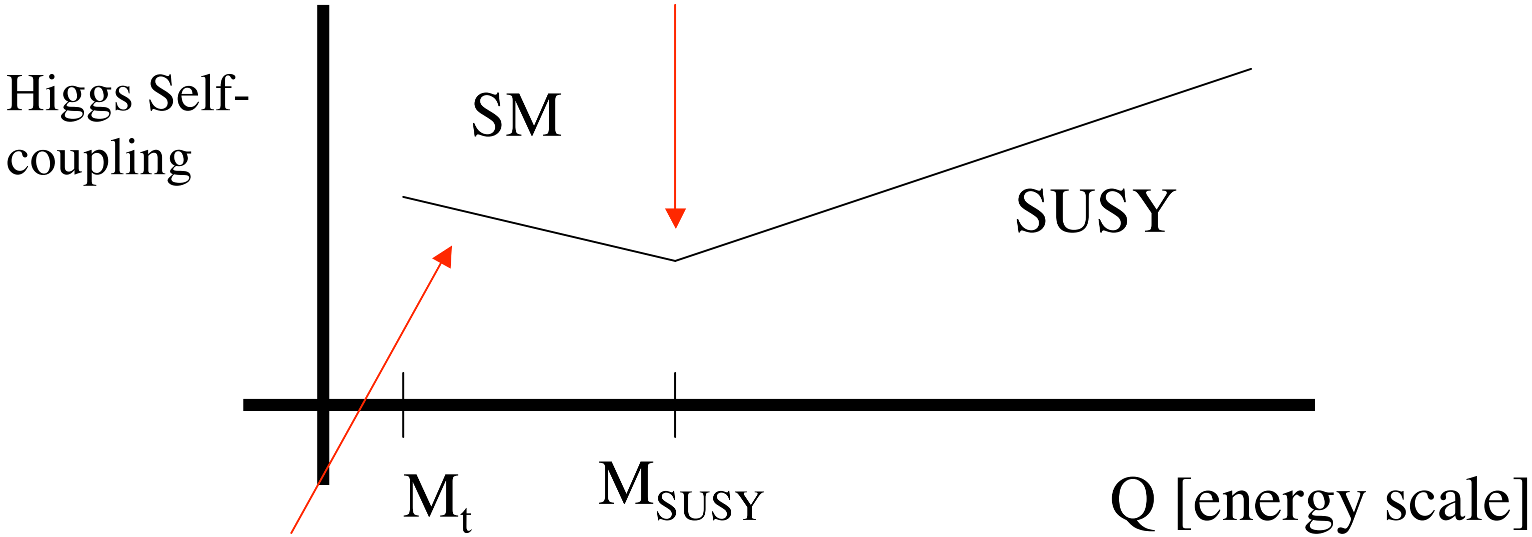
$$hVV: \quad \sin(\beta-\alpha) \to 1$$

$$htt: \quad \frac{\cos\alpha}{\sin\beta} \to 1$$

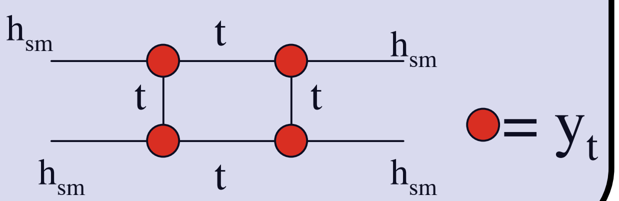
$$hbb: \quad \frac{-\sin\alpha}{\cos\beta} \to 1$$

Lightest Higgs Mass Computation

$$\lambda(M_{SUSY}) = \frac{1}{8}(g^2 + g'^2)\cos^2 2\beta$$



$$\frac{d\lambda}{d\log Q} = -\frac{3}{4\pi^2}y_t^4 + \cdots$$



$$\begin{aligned} m_h^2 &= 2\lambda v^2 = 2\left(\lambda(M_{SUSY}) + \frac{3}{4\pi^2}y_t^4 \log\frac{M_{SUSY}}{M_t}\right)v^2 \\ &= M_Z^2\cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2}\log\frac{M_{SUSY}}{M_t} \end{aligned}$$

Multi-Higgs Pairs

Higgses are vector-like pairs and their proliferation is acceptable to some approaches in string model building.

“Branes at singularities”: bifundamental states come from the same quivers, and multiplicities of Higgs pairs are generic just like multiplicities of other reps.

“Intersecting D-brane models”: chiral content constrained by intersection numbers, but vector-like states can be many-fold.

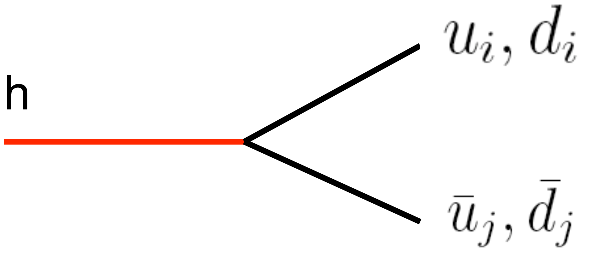
“Heterotic orbifold models”: exotics are generic. Restriction to 3 families rarely restricts Higgs bosons to one pair.

Example:
Ambroso, Braun, Ovrut, “Two Higgs Pair Heterotic Vacua and Flavor-Changing Neutral Currents,” 0807.3319

Pheno Consideration: Number of Higgs boson pairs is a free parameter.
Study: What are the challenges facing multiple Higgs boson theories, and what are the discovery opportunities?

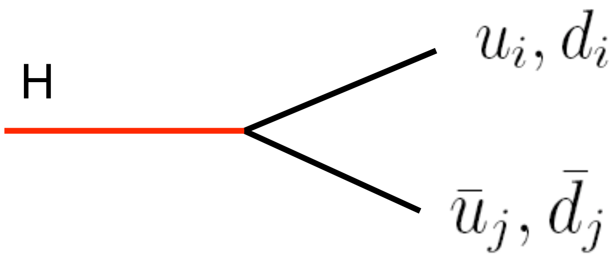
FCNC Challenges of Multi-Doublets

Rotating from the $\{h_{vev}, \phi\}$ basis, where fermion masses are diagonal couplings to h_{vev}, to the $\{h, H\}$ basis, where Higgs masses are diagonalized, one finds the Feynman rules:



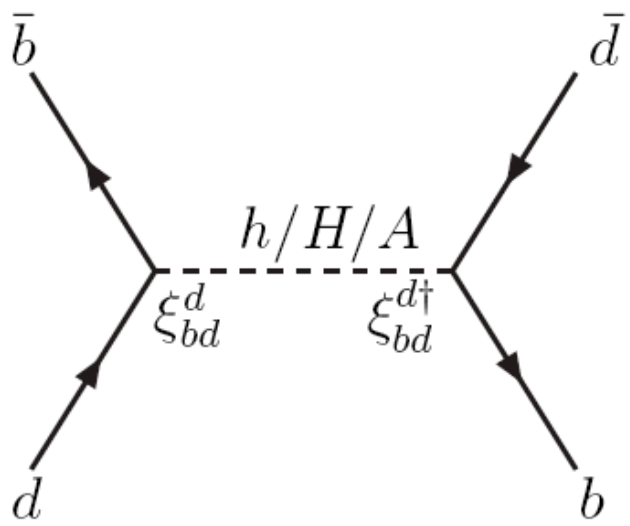
$$c_\alpha \frac{m_i^{u,d}}{v} \delta_{ij} - s_\alpha \lambda_{ij}^{u,d}$$

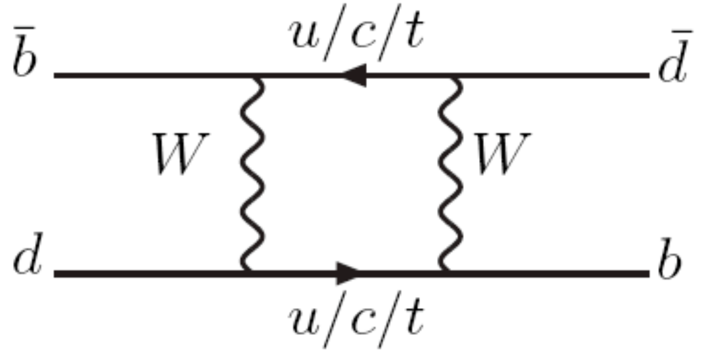
Tree-level FCNCs!



$$s_\alpha \frac{m_i^{u,d}}{v} \delta_{ij} + c_\alpha \lambda_{ij}^{u,d}$$

Flavor Constraint: $B_d^0 - \bar{B}_d^0$ mixing





Defining $\tilde{\xi}^f_{ij} \equiv \xi^f_{ij} \left(\frac{120\,\mathrm{GeV}}{m_{\mathrm{Higgs}}}\right)^2$ implies limit of $\tilde{\xi}^d_{db} \lesssim 10^{-4}$

Expect a principle to be involved to suppress this FCNC coupling

Solution to FCNC Problem

No FCNC theorem: Tree-level FCNCs do not arise if Higgs boson interactions with the fermions take the form

$$y^d_{ij}\bar{Q}\,F_u(\{\Phi_k\})\,d_R + y^u_{ij}\bar{Q}\,F_d(\{\Phi_k\})\,u_R + y^e_{ij}\bar{L}\,F_e(\{\Phi_k\})\,e_R + h.c.$$

where $F_{u,d,e}(\{\Phi_k\})$ are arbitrary functions of Higgs fields $\{\Phi_k\}$.

Noting the obvious: Higgs fields that do not show up in F-functions can be present and contribute to W,Z masses but do not induce FCNCs.

Example Possibilities

Standard Model: F_u=H_{sm} and F_d=F_e=H_{sm}*

Type II 2HDM and SUSY: F_u=H_u and F_d=F_d=H_d

Type I 2HDM: F_u=H and F_d=F_e=H*, and additional φ that does not couple to fermions.

Multi-Pair SUSY: F_u=H_u and F_d=F_d=H_d and additional φ_u and φ_d copies that do not couple to fermions.

ABO model is of this last type. Protected by $\varphi_u \rightarrow -\varphi_u$ and $\varphi_d \rightarrow -\varphi_d$. Toy model is simplified 'Type I model'.

Minimal Type I = ABO Toy Model

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ v + \phi_R + i\phi_I \end{pmatrix} \qquad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi'^+ \\ v' + \phi'_R + i\phi'_I \end{pmatrix}$$

Impose Z_2 symmetry on Φ_2 to forbid couplings with fermions:

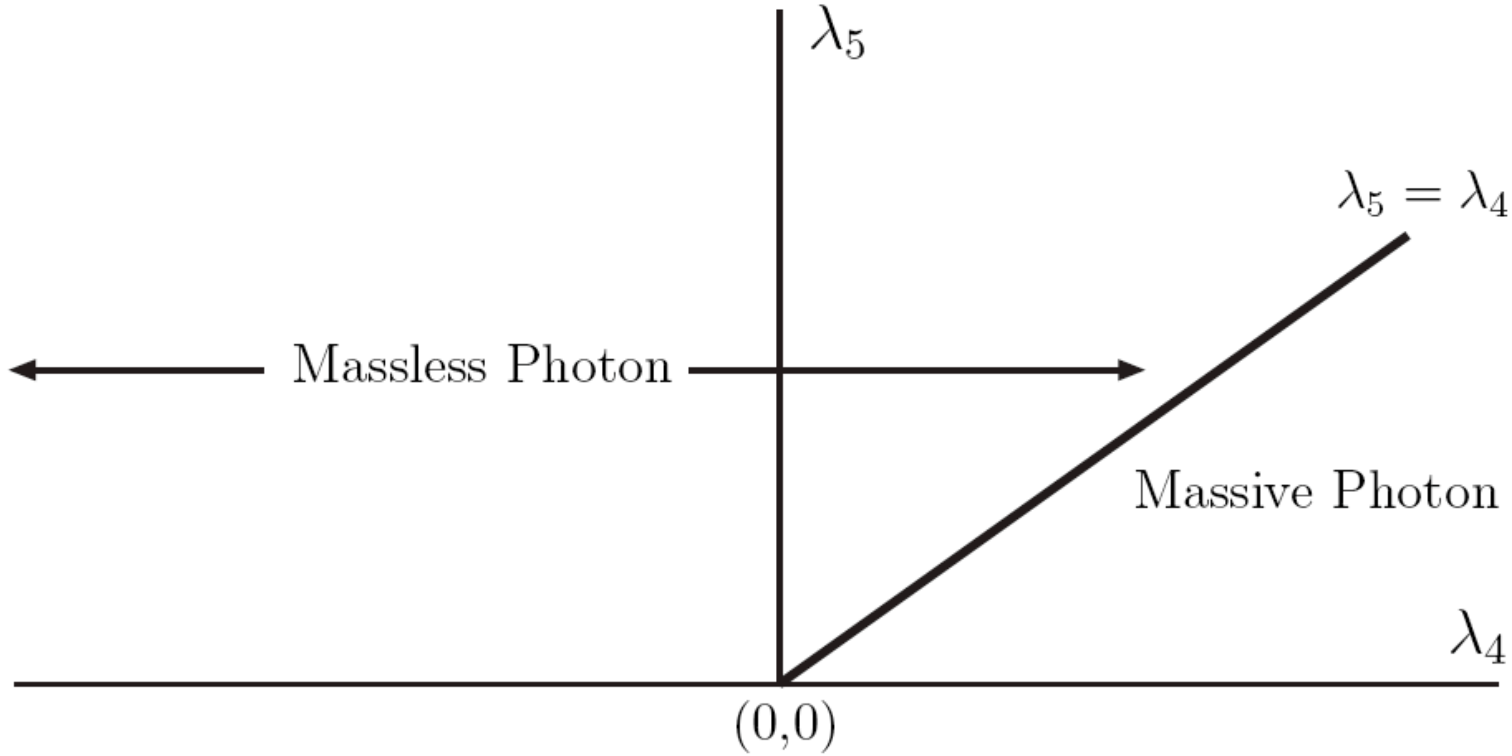
$\Phi_2 \to -\Phi_2$ Ratio of vevs is tanβ: $\tan\ \beta = v'/v$

$$\begin{aligned} V(\Phi_1, \Phi_2) \ &= \ \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \\ &\lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.\right) \end{aligned}$$

Potential is bounded from below if these conditions satisfied:

$$\lambda_1 > 0 \quad \lambda_2 > 0 \quad \lambda_3 + \lambda_4 + \lambda_5 > -2\sqrt{\lambda_1\lambda_2} \quad \lambda_4 + \lambda_5 < 0$$

Proper Electroweak Vacuum



Symmetric about λ_5=0 axis.

JW'09; Diaz-Cruz, Mendez,'92

Masses and Mixings

$$\begin{pmatrix} \phi_I \\ \phi'_I \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G \\ A \end{pmatrix} \qquad m_A^2 = -\lambda_5(v^2 + v'^{\,2})$$

$$\begin{pmatrix} \phi^+ \\ \phi'^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} \qquad m_+^2 = -(\lambda_4 + \lambda_5)(v^2 + v'^2)/2$$

$$\begin{pmatrix} \phi_R \\ \phi'_R \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \qquad \tan(2\alpha) = \frac{\kappa v v'}{\lambda_2 v'^2 - \lambda_1 v^2}$$

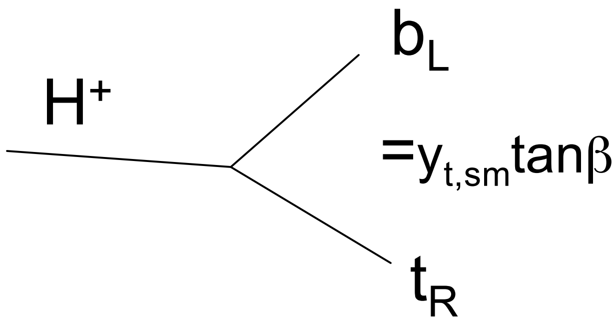
$$m_{h,H}^2 = (\lambda_1 v^2 + \lambda_2 v'^2) \pm \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \kappa^2 v'^2 v^2}$$

where $\kappa \equiv \lambda_3 + \lambda_4 + \lambda_5$

B decay Constraint

The interaction of the charged Higgs with top-bottom is enhanced by a factor of tanβ over the SM top quark Yukawa coupling.

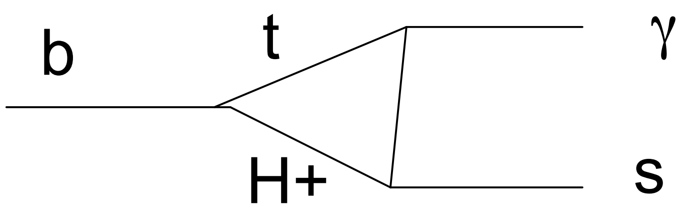
$$y_t Q \Phi_1 t_R \Longrightarrow m_t = y_t v \cos\beta$$



$$y_t Q \Phi_1^+ t_R \rightarrow \frac{m_t}{v\cos\beta} Q(-\sin\beta H^+) t_R = -\tan\beta \left(\frac{m_t}{v}\right)_{SM} Q H^+ t_R$$

B decay constraint continued

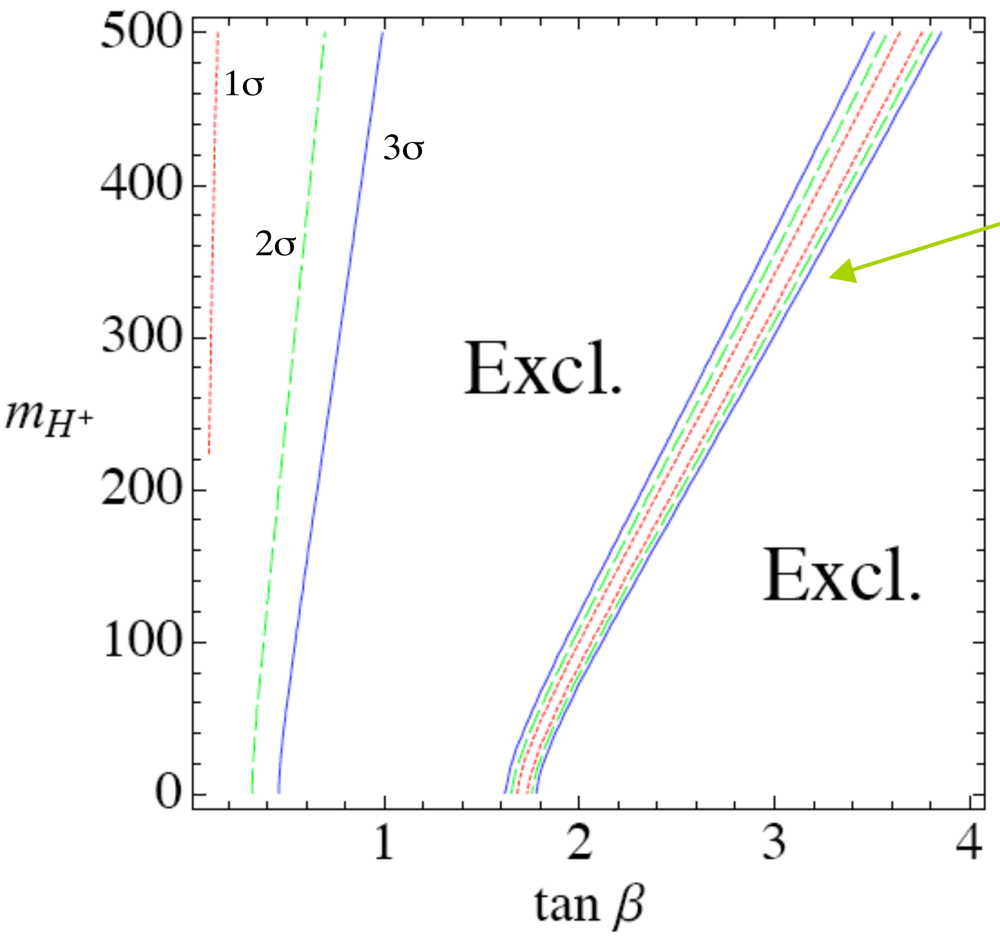
B decays to strange quark plus photon constrained:



$$\Gamma_{b\to s\gamma} = \frac{\alpha G_F^2 m_b^2}{128\pi^4} \left| A_W + \tan^2\beta A_H(m_+) \right|^2$$

Experiment: $\Gamma_{b\to s\gamma} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$

Constraints on tanβ



De Visscher et al., '09

A = -A_W

Generally safe if tanβ < 0.3, or v' < 70 GeV.

Spectrum with small v'

Higgs Masses are

$$m_H^2 = 2\lambda_1 v^2$$

(Part of EW Multiplet)

$$m_h^2 = 2\lambda_2 v'^2 - \frac{\kappa^2}{2\lambda_1} v'^2$$

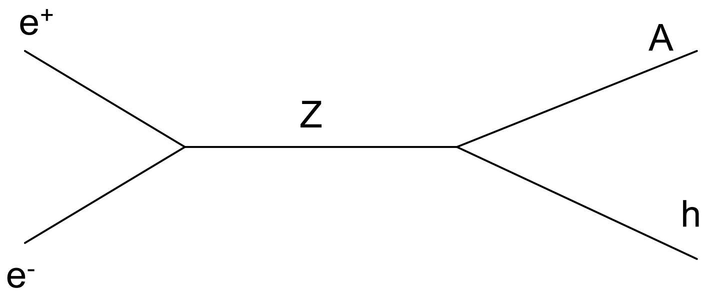
$$m_A^2 = -\lambda_5 (v^2 + v'^{\,2})$$

With Mixing angle: $\alpha = -\frac{\kappa}{2\lambda_1}\frac{v'}{v}$ $\quad \begin{pmatrix} \phi_R \\ \phi'_R \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$

Basically, H is SM-like, v'<<v and β and α << 1, h is exotic and light (~ v'), A is exotic but heavier (~ v).

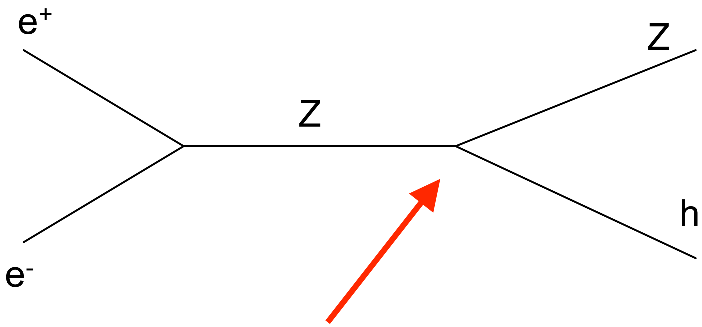
hA production

hA couples with O(1) strength to Z [$\cos(\beta - \alpha) \sim 1$]



Limits at LEP2 imply that $m_A + m_h > 200$ GeV.

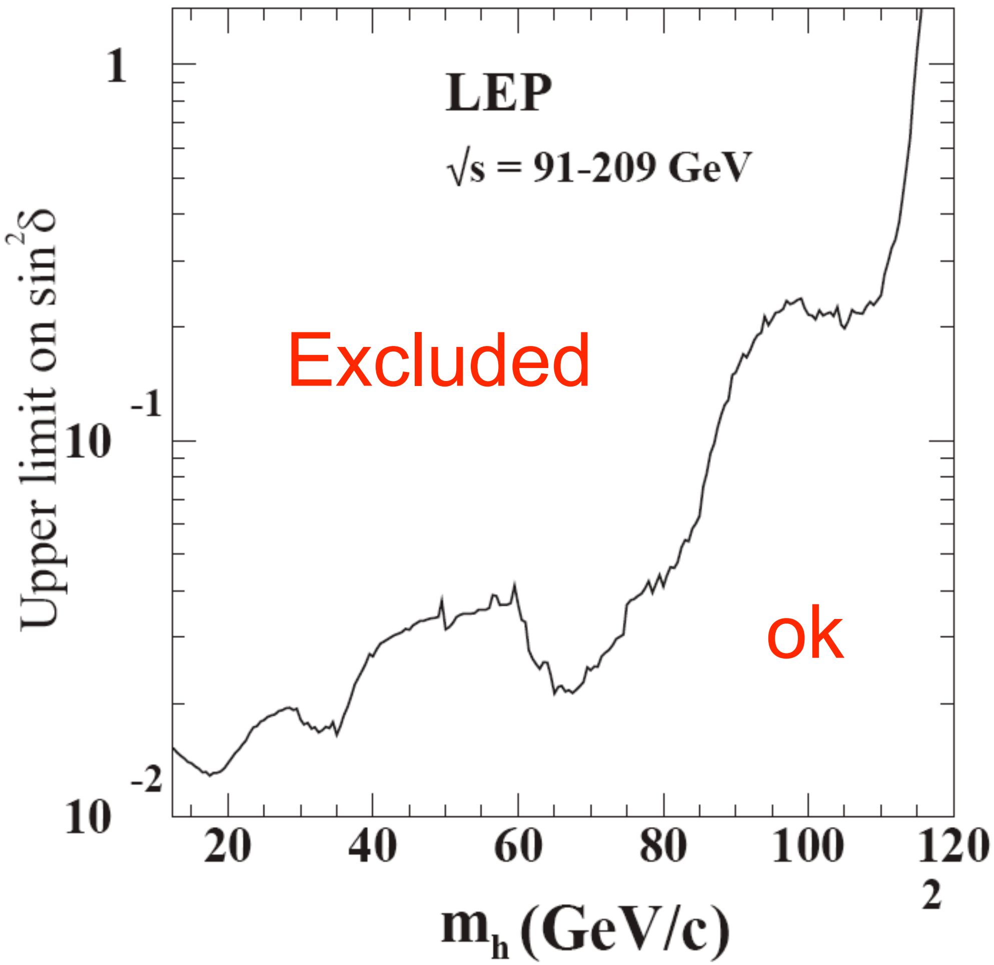
Light h at LEP2



$g_{sm} \sin\delta = g_{sm} \sin(\beta - \alpha)$

$\delta = \beta - \alpha \ll 1$

Easily satisfied if $\delta < 0.1$



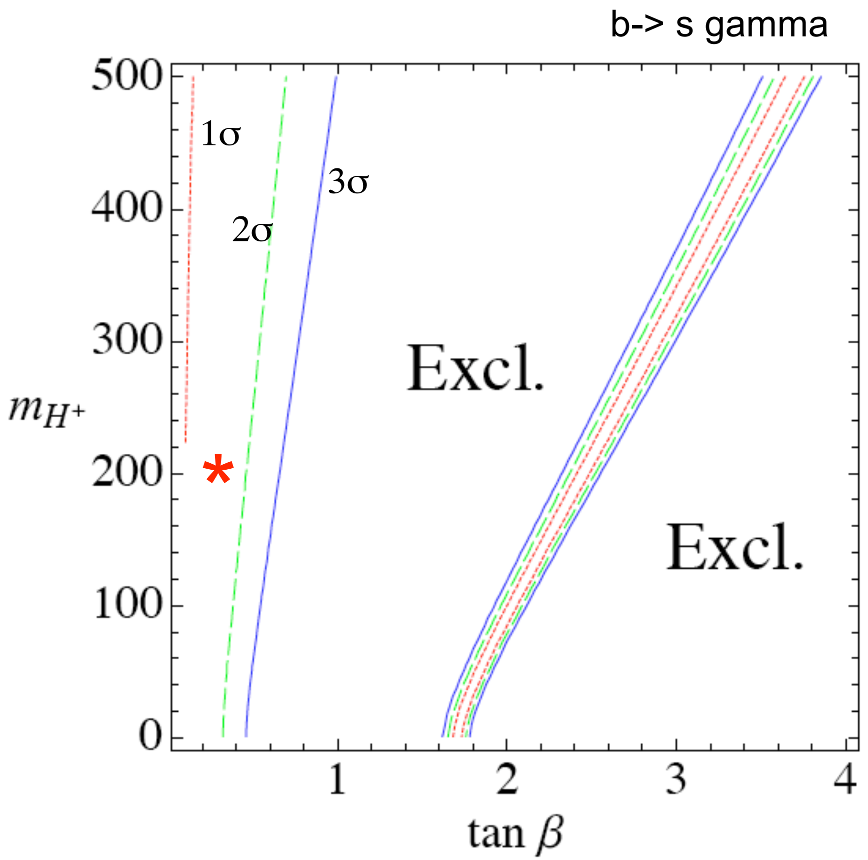
LEP, hep-ex/0602042

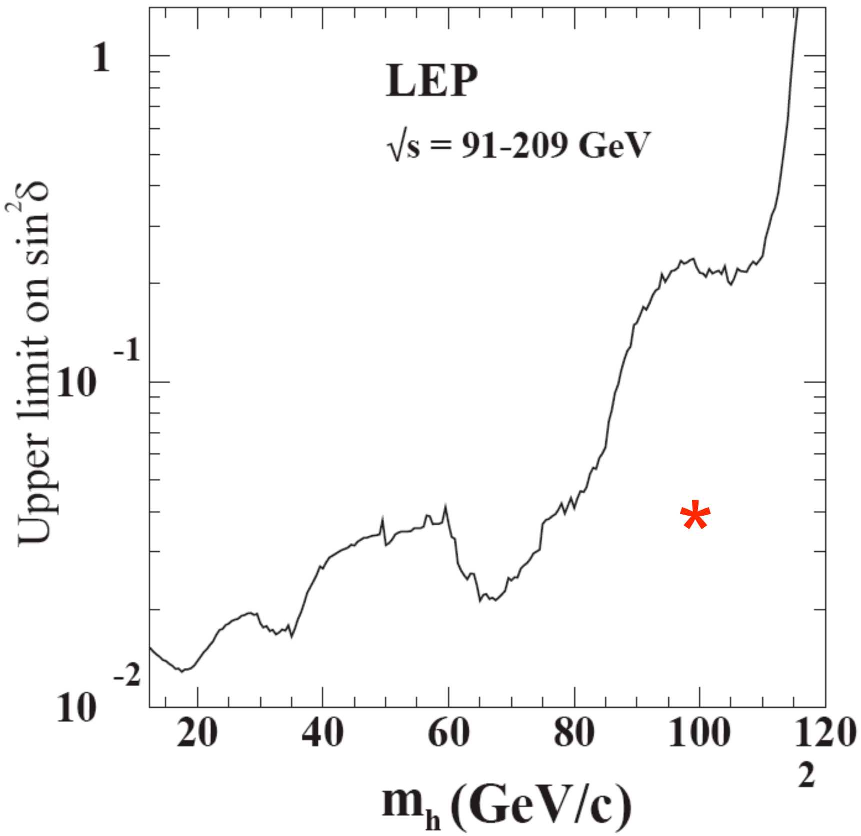
Example Points

Set	Input Parameters
A	$m_H = 120$ GeV, $m_h = 50$ GeV, $m_A = 150$ GeV, $m_+ = 200$ GeV,$s_\beta = 0.1$, $s_\alpha = 0.2$ ($\sin\delta = 0.10$)
B	$m_H = 120$ GeV, $m_h = 70$ GeV, $m_A = 180$ GeV, $m_+ = 200$ GeV,$s_\beta = 0.1$, $s_\alpha = 0.2$ ($\sin\delta = 0.10$)
C	$m_H = 120$ GeV, $m_h = 100$ GeV, $m_A = 200$ GeV, $m_+ = 200$ GeV,$s_\beta = 0.1$, $s_\alpha = 0.3$ ($\sin\delta = 0.20$)

Let's demonstrate with Set C.

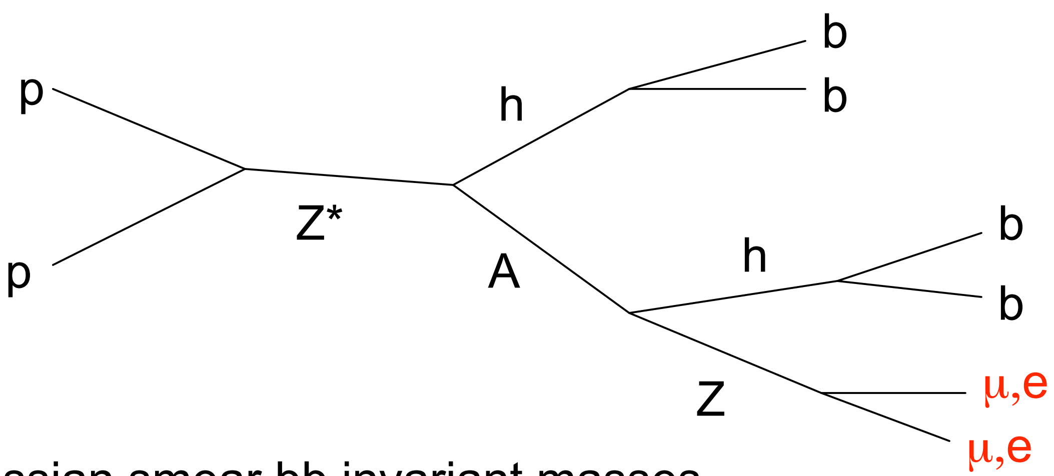
Compatible with Experiment





Find at LHC?

Look for Z (decaying to leptons) plus 4 b quarks from



$$p_{Tb,l} > 15\ GeV$$
$$|\eta_{b,l}| < 2.5$$
$$R_{bb,bl} > 0.4.$$
$$|M_{bb1} - M_{bb2}| < 0.2\ M_{bb}$$

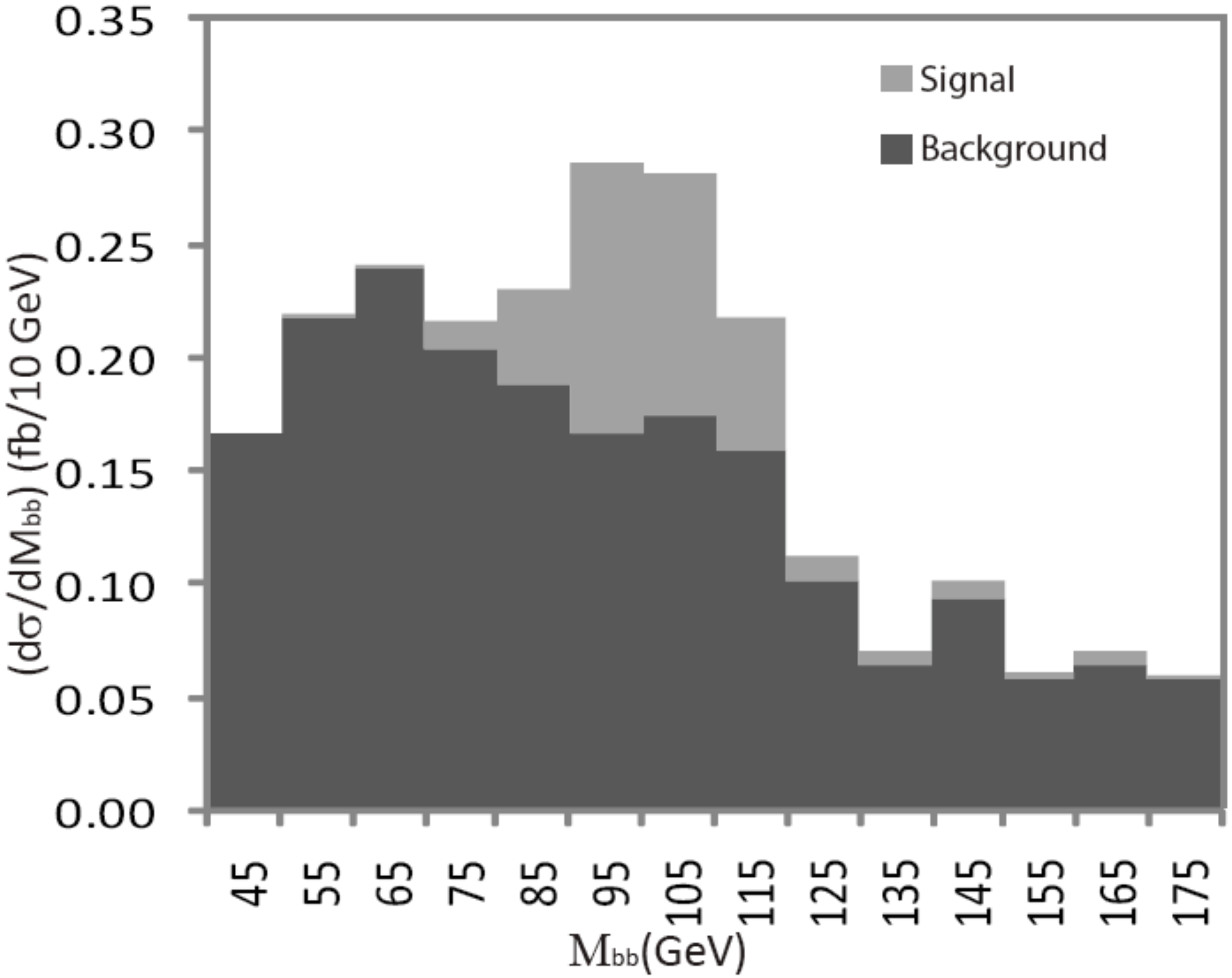
Gaussian smear bb invariant masses such that 85% of events are within 20% of the true value.

Require at least 3 b-quark tags at ε_b=50% efficiency.

Apply id eff'cs (~0.8 lepton, ~0.9 jet)

SM Background rate after all cuts:
σ_{sm} ~ 0.4 fb, and signal rate ~ 0.1 fb.

bb invariant mass spectrum



Multiply by ~1/6 for efficiencies. Discovery possible with ~100 fb^{-1}.

Prel., Gupta, JW

Conclusions

Naively, it is unlikely that Higgs sector is simple SM Higgs.

Supersymmetry overlays a type II structure on Higgs sector that we know well.

Additional Higgs bosons must satisfy the 'no-FCNC theorem' exactly or approximately. This usually means overlaying an additional type I structure on the Higgs sector.

FCNC constraints nonetheless ($b \rightarrow s\gamma$) at loop level, and additional collider constraints. Easiest to satisfy if extra vevs are small.

Only non-SM signature may be, e.g., challenging 4b+Z signature at the LHC.