Lecture 2

Weakly Interacting Higgs Physics Beyond the SM

Why to expect New Physics?

To explain dark matter, baryogenesis, dynamical origin of fermion properties, tiny neutrino masses…

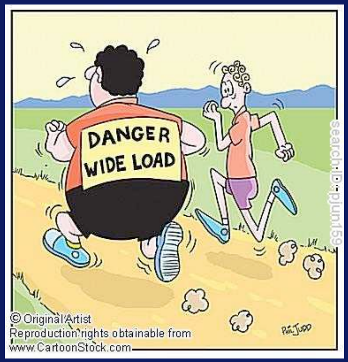
None of the above demands NP at the electroweak scale

- **The Higgs restores the calculability power of the SM**
- **The Higgs is special : it is a scalar**

Scalar masses are not protected by gauge symmetries and at quantum level have quadratic sensitivity to the UV physics

$$\mathcal{L} \propto m^2 |\phi|^2 \qquad \delta \mathbf{m^2} = \sum_{\mathbf{B,F}} \mathbf{g_{B,F}} (-\mathbf{1})^{\mathbf{2S}} \frac{\lambda^{\mathbf{2}}_{\mathbf{B,F}} \mathbf{m}^{\mathbf{2}}_{\mathbf{B,F}}}{\mathbf{32}\pi^{\mathbf{2}}} \log(\frac{\mathbf{Q^2}}{\mu^{\mathbf{2}}})$$

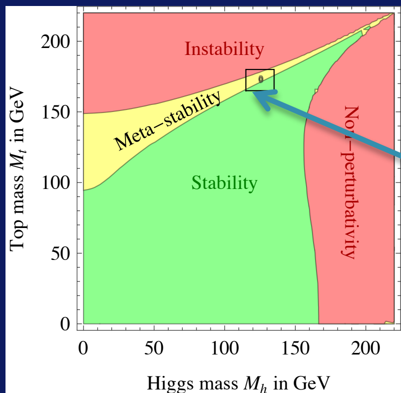
Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales

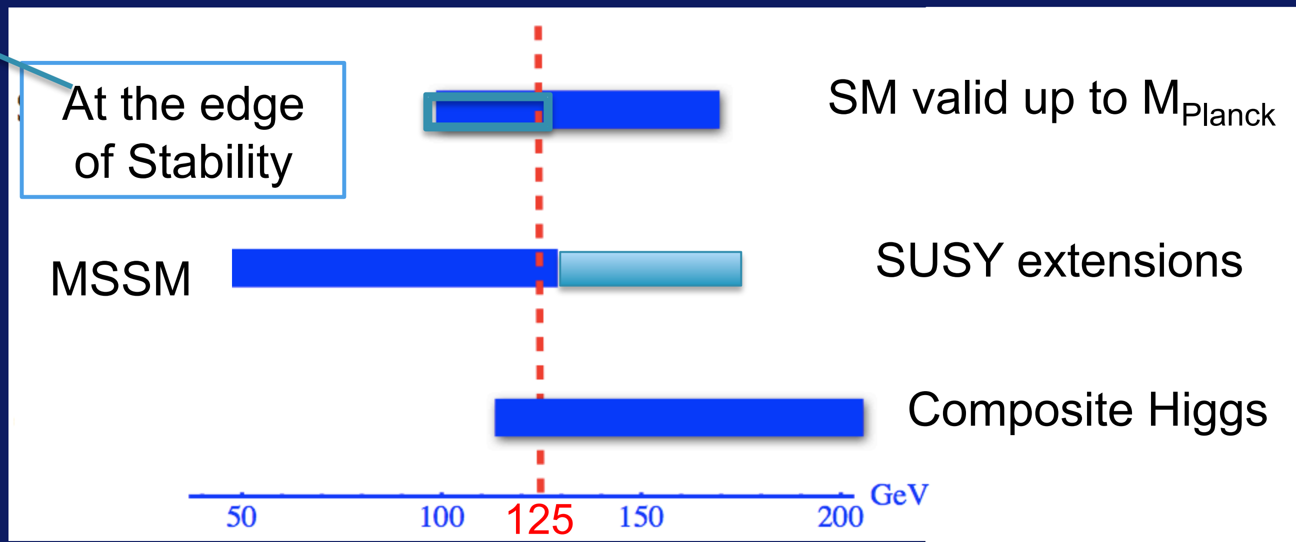


Fine tuning ⟷ **Naturalness problem**

Looking under the Higgs lamp-post:

What type of Higgs have we seen?





Also, back in fashion:
Twin Higgs and Mirror Worlds

125 GeV is suspiciously light for a composite Higgs boson but it is suspiciously heavy for minimal SUSY

Additional option: Higgs as part of an extended sector (e.g. 2HDM) to explain flavor from the electroweak scale (a la Frogatt Nielsen)

Supersymmetry:

a fermion-boson symmetry :

The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

Composite Higgs Models

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place

➔ dynamical origin of EWSB

New strong resonance masses constrained by Precision Electroweak data and direct searches

Higgs ➔ scalar resonance much lighter that other ones

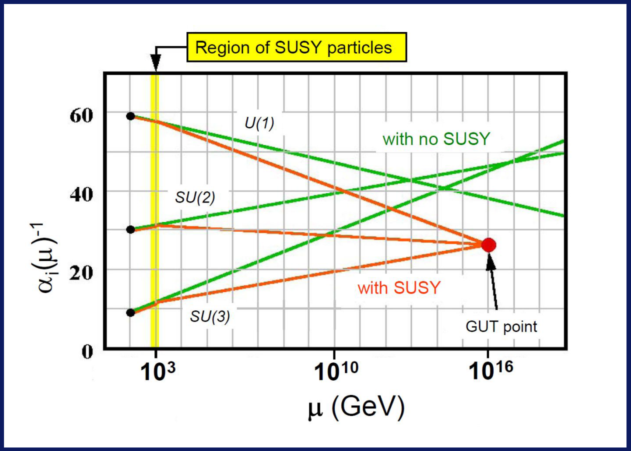
2HDM's or Higgs Triplet models may induce EWSB and be well motivated from flavor or neutrino physics. Require a UV completion (a more fundamental theory)

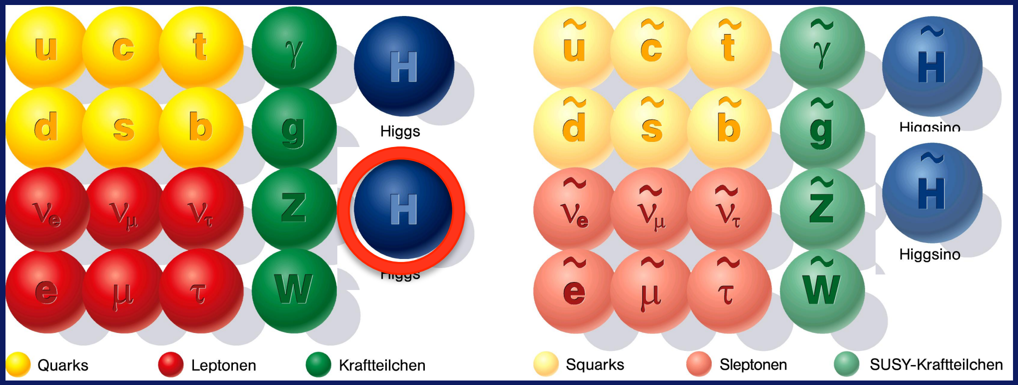
All options imply changes in the Higgs phenomenology and beyond

SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**
- **Generates EWSB automatically from radiative corrections to the Higgs potential**
- Allows gauge coupling unification at ~10^{16} GeV
- Provides a good dark matter candidate:

  The Lightest SUSY Particle (LSP)
- Allows the possibility of electroweak baryogenesis
- String friendly





For every fermion there is a boson with equal mass & couplings

Extended Higgs sector at least a 2HDM (type II)

SUSY and Naturalness

• Higgs mass parameter protected by the fermion-boson symmetry: $\delta m^2 = 0$

In practice, no SUSY particles seen yet ➔ SUSY broken in nature:

$$\delta m^2 \propto M^2_{SUSY}$$

If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

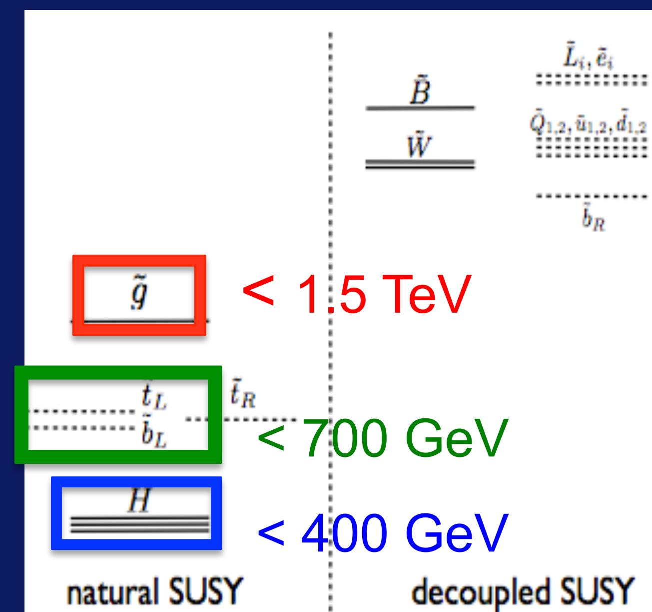
If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy problem solved

Where are the superpartners?

- **Not all SUSY particles play a role in the Higgs Naturalness issue**

Higgsinos, stops (sbottoms) and gluinos are special

- So why didn't we discover any SUSY particle already at LEP, Tevatron, or LHC8?

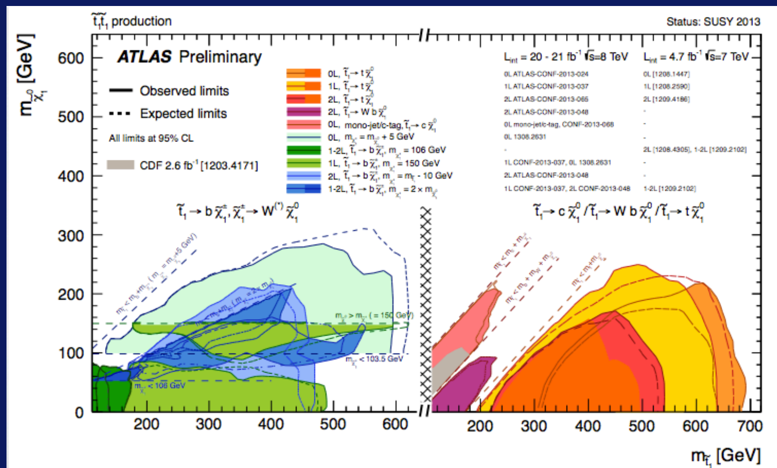


Papucci, Rudermann, Weiler '11

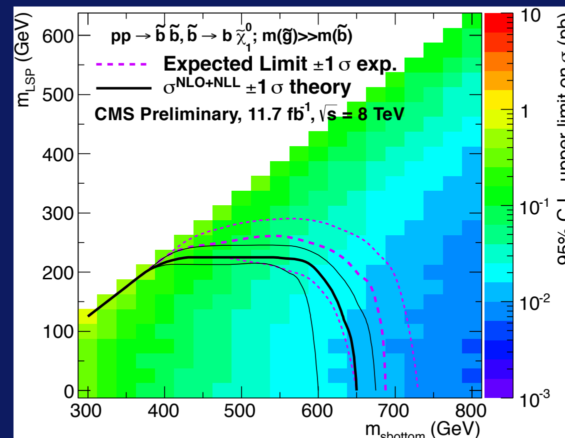
SUSY Weltschmerz*?

ATLAS/CMS are aggressively pursuing the signatures of "naturalness".

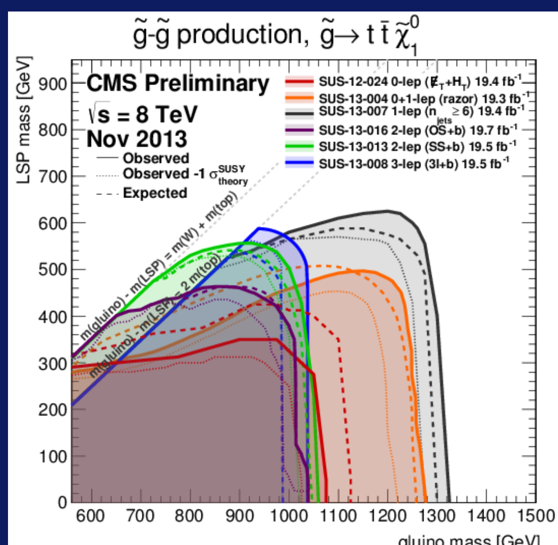
stops



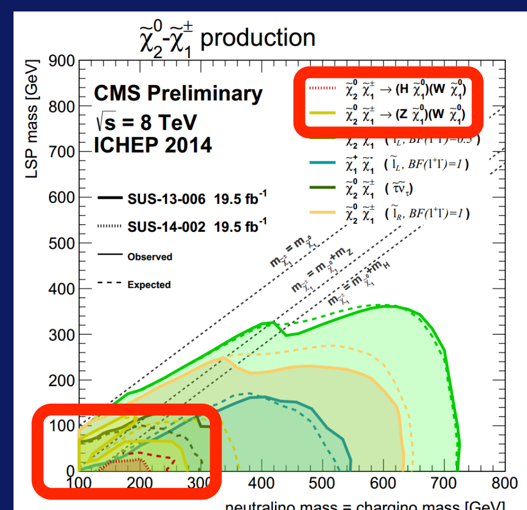
sbottoms



gluinos



Higgsinos



**The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind*

Is SUSY hiding?

It is possible to have SUSY models with super-partners well within LHC8 kinematic reach, but with ***degraded*** missing energy signatures or event activity

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass

M.C., Freitas, Wagner '08

- Stealth SUSY: long decay chains soften the spectrum of observed particles from SUSY decays
- The LSP is not the dark matter, but decays

ATLAS/CMS closing the gaps

Still many opportunities for non-minimal "Natural" SUSY models, not yet badly threaten by LHC:

- address flavor as part of the SUSY breaking mechanism

connect lightness of 3rd generation sfermions to heaviness of 3rd generation fermions

- alleviate the tension of a Higgs mass that needs sizeable radiative corrections from stop contributions, by raising its tree level value

additional SM singlets or triplets or models with enhanced weak gauge symmetries

General Features of 2HDM's (e.g. minimal SUSY)

The simplest extension of the SM is to add one Higgs doublet, with the same quantum numbers as the SM one.

Now, we will have contributions to the gauge boson masses coming from the vacuum expectation value of both fields

$$(\mathcal{D}\phi_i)^\dagger \mathcal{D}\phi_i \to g^2 \phi_i^\dagger T^a T^b \phi_i A_\mu^a A^{\mu,b}$$

Therefore, the gauge boson masses are obtained from the SM expressions by simply replacing

$$v^2 \to v_1^2 \ + \ v_2^2$$

There is then a free parameter, that is the ratio of the two vacuum expectation values, and this is usually denoted by

$$\tan\beta = \frac{v_2}{v_1}$$

The number of would-be Goldstone modes are the same as in the SM, namely 3. Therefore, there are still 5 physical degrees of freedom in the scalar sector which are a charged Higgs, a CP-odd Higgs and two CP-even Higgs bosons.

Goldstone Modes and Physical States

Since both Higgs fields carry the same quantum numbers, one can always define the combinations

$$\frac{H_2 v_2 + H_1 v_1}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \sin\beta + H_1 \cos\beta = H_v$$

$$\frac{H_2 v_1 - H_1 v_2}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \cos\beta - H_1 \sin\beta = H_{NS}$$

The first combination acquires vacuum expectation value v. The second does not acquire a vacuum expectation value.

Then, it is clear that the Goldstone modes will be the charged and the imaginary part of the neutral components of H_v

The charged and imaginary part of the neutral components of H_{NS} will be the physical charged and CP-odd Higgs bosons respectively.

$$G^{\pm} = H_2^{\pm} \sin\beta + H_1^{\pm} \cos\beta$$

$$H^{\pm} = -H_2^{\pm} \cos\beta + H_1^{\pm} \sin\beta$$

$$\sqrt{2}\ G^0 = \mathrm{Im} H_2^0 \sin\beta + \mathrm{Im} H_1^0 \cos\beta$$

$$\sqrt{2}\ A = -\mathrm{Im} H_2^0 \cos\beta + \mathrm{Im} H_1^0 \sin\beta$$

What about the CP-even states ? There is no symmetry argument and in principle both states could mix.

CP-even Higgs Bosons

There is no symmetry argument and in general these two Higgs boson states w
mix. The mass eigenvalues, in increasing order of mass, will be

$$\sqrt{2}\ h = -\sin\alpha\ \mathrm{Re}H_1^0 + \cos\alpha\ \mathrm{Re}H_2^0$$
$$\sqrt{2}\ H = \cos\alpha\ \mathrm{Re}H_1^0 + \sin\alpha\ \mathrm{Re}H_2^0$$

From here one can easily obtain the coupling to the gauge bosons. This is simpl
given by replacing in the mass contributions

$$v_i \rightarrow v_i + ReH_i^0$$

This leads to a coupling proportional to

$$v_i\ \mathrm{Re}H_i^0$$

Hence, the effective coupling of h is given by

$$hVV = (hVV)^{\mathrm{SM}}(-\cos\beta\sin\alpha + \sin\beta\cos\alpha) = (hVV)^{\mathrm{SM}}\sin(\beta-\alpha)$$
$$HVV = (hVV)^{\mathrm{SM}}(\cos\beta\cos\alpha + \sin\beta\sin\alpha) = (hVV)^{\mathrm{SM}}\cos(\beta-\alpha)$$

These proportionality factors are nothing but the projection of the Higgs mass
eigenstates into the one acquiring a vacuum expectation value.

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Fermion Masses and Flavor

Similarly to the gauge boson masses, the fermion masses are obtain from the sum of the contributions of both Higgs fields.

For instance, the down-quark mass matrix is given by

$$M_d^{ij} = h_{d,1}^{ij} \frac{v_1}{\sqrt{2}} + h_{d,2}^{ij} \frac{v_2}{\sqrt{2}}$$

The interaction of the two CP-even scalars with fermions is given, instead, by

$$g_{hd_id_j} \propto h_{d,1}^{ij}(-\sin\alpha) + h_{d,2}^{ij}(\cos\alpha)$$
$$g_{Hd_id_j} \propto h_{d,1}^{ij}(\cos\alpha) + h_{d,2}^{ij}(\sin\alpha)$$

So, contrary to the SM, the rotation that diagonalizes the mass matrix does not diagonalize the couplings. This in general leads to large Higgs mediated Flavor changing processes, that are in conflict with experiment.

One solution is to make the non-standard Higgs bosons very heavy, going close to the SM. Another natural solution is to restrict the couplings of each fermion sector to only one of the two Higgs doublets. This is what happens to a good approximation in supersymmetry.

Fermion-Higgs Couplings and Different Types of 2HDM's

Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

Add Symmetry transformations that determine the allowed Higgs boson couplings to up, down and charged lepton-type $SU(2)_L$ singlet fermions in four discrete types of 2HDM models

Low Energy Supersymmetry: 2HDM Type II

In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\text{diag}}}{v}\frac{(-\sin\alpha)}{\cos\beta}, \quad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\text{diag}}}{v}\frac{\cos\alpha}{\cos\beta} \quad g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\text{diag}}^{\text{dd}}}{v}\tan\beta$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\text{diag}}}{v}\frac{(\cos\alpha)}{\sin\beta}, \quad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\text{diag}}}{v}\frac{\sin\alpha}{\sin\beta} \quad g_{Aff}^{uu} = \frac{\mathcal{M}_{\text{diag}}^{\text{uu}}}{v\tan\beta}$$

If the mixing is such that $\cos(\beta-\alpha)=0$ → **Decoupling limit obtained for large masses of non-standard Higgs bosons**

$$\sin\alpha = -\cos\beta,$$
$$\cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

The Higgs Potential

The most generic two Higgs doublet potential is given by

$$
\begin{aligned}
V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
&\quad + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&\quad + \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)]\Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right\} ,
\end{aligned}
$$

One can minimize this potential and use the minimization conditions to derive the CP-odd and charged Higgs masses as a function of one mass parameter and the quartic couplings

$$m_A^2 = \frac{2m_{12}^2}{s_{2\beta}} - \frac{1}{2} v^2 (2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta) \qquad m_H^{\pm} = m_A^2 + \frac{v^2}{2}(\lambda_5 - \lambda_4)$$

Using the minimization conditions one can also derive the masses in the CP-even sector, in terms of m_A and the quartic couplings

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

$$
\begin{aligned}
L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 , \\
L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \\
L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 .
\end{aligned}
$$

For large mA and perturbative quartics we can ignore the second term in the right hand side and one obtains that $m_H \sim m_A$, while m_h is of order an effective quartic coupling times v^2

Alignment without Decoupling

The eigenstate equation may be rewritten in the following way

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

For large values of the CP-odd Higgs mass we obtain

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} \approx 0 \qquad \cos(\beta - \alpha) = 0$$

Now, the idea would be to obtain this condition for lower CP-odd Higgs masses, independently of m_A

$$v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = m_h^2 \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

Valid for any 2HDM

$$m_h^2 = v^2 L_{11} + t_\beta v^2 L_{12} = v^2 \left(\lambda_1 c_\beta^2 + 3\lambda_6 s_\beta c_\beta + \tilde{\lambda}_3 s_\beta^2 + \lambda_7 t_\beta s_\beta^2 \right) ,$$

$$m_h^2 = v^2 L_{22} + \frac{1}{t_\beta} v^2 L_{12} = v^2 \left(\lambda_2 s_\beta^2 + 3\lambda_7 s_\beta c_\beta + \tilde{\lambda}_3 c_\beta^2 + \lambda_6 t_\beta^{-1} c_\beta^2 \right)$$

Alignment without Decoupling → other light Higgs Bosons

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$
$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

Alignment conditions

If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- Case of $\lambda_{6,7} = 0$ (SUSY at tree level)

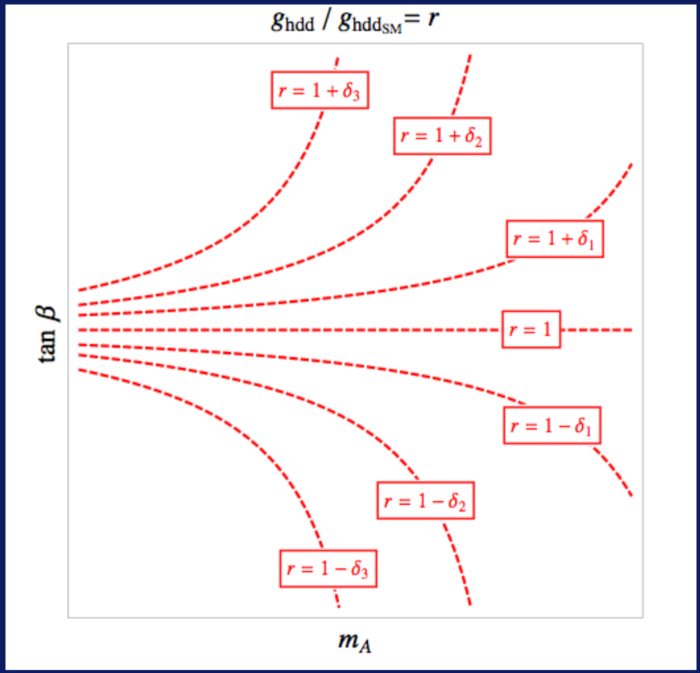
The additional condition is $\tan^2\beta = \dfrac{\lambda_1 - \lambda_{\rm SM}}{\lambda_{SM} - \tilde{\lambda}_3}$ and should be positive.

In the MSSM, this ratio tends to be negative, but tends to be positive in the NMSSM.

- Case of $\lambda_{6,7} \neq 0$

Alignment may occur at sizable tan beta

e.g in the MSSM $t_\beta^{(1)} = \dfrac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}$



Down-quark coupling behavior for the lightest Higgs boson in the proximity of alignment

The Minimal SUSY Higgs Sector

2 Higgs doublets necessary to give mass to both up and down quarks and leptons in gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.

$$V_{SUSY}(H_u, H_d) = |\mu|^2(H_u^\dagger H_u + H_d^\dagger H_d) + \frac{(g_1^2 + g_2^2)}{8}((H_u^\dagger H_u)^2 + (H_d^\dagger H_d)^2) + \frac{(g_1^2 - g_2^2)}{4} H_u^\dagger H_u H_d^\dagger H_d - \frac{g_2^2}{2}|H_d^T i\tau_2 H_u|^2$$

$$H_1 = \begin{pmatrix} \mathrm{v}_1 + (H_1^0 + iA_1)/\sqrt{2} \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ \mathrm{v}_2 + (H_2^0 + iA_2)/\sqrt{2} \end{pmatrix}$$

$H_1 \equiv H_d$
$H_2 \equiv H_u$

The supersymmetric parameter μ defines the higgsino masses and plays a relevant role in Higgs physics

SM-like Higgs boson mass in the Minimal SUSY SM extension

depends on: **CP-odd mass m_A, tanβ, M_t** **and Stop masses & mixing**

$$M^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

For large m_A

$$m_h^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{< (91\ \mathrm{GeV})^2} + \Delta m_h^2$$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

m_h depends logarithmically on the averaged stop mass scale $\mathbf{M_{SUSY} \sim m_Q \sim m_U}$

$$t = \log(M^2_{SUSY}/m_t^2)$$

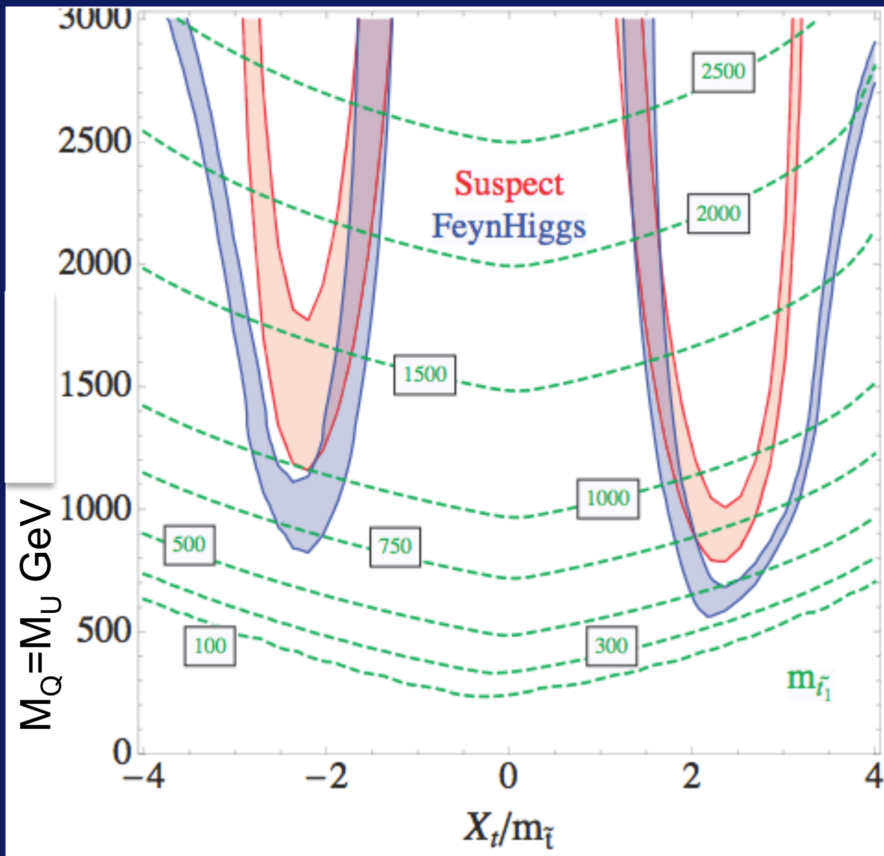
and has a quadratic and quartic dep. on the stop mixing parameter $X_t = A_t - \mu/\tan\beta$

$$\tilde{X}_t = \frac{2X_t^2}{M^2_{SUSY}}\left(1 - \frac{X_t^2}{12 M^2_{SUSY}}\right)$$

Also dependence on sbottoms/staus for large tanβ

Two-loop computations: Brignole, M.C, Degrassi, Diaz, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, Wagner,Weiglein, Zhang, Zwirner

Stop Spectra and the Higgs Mass in the MSSM



Hall, Pinner, Ruderman'11

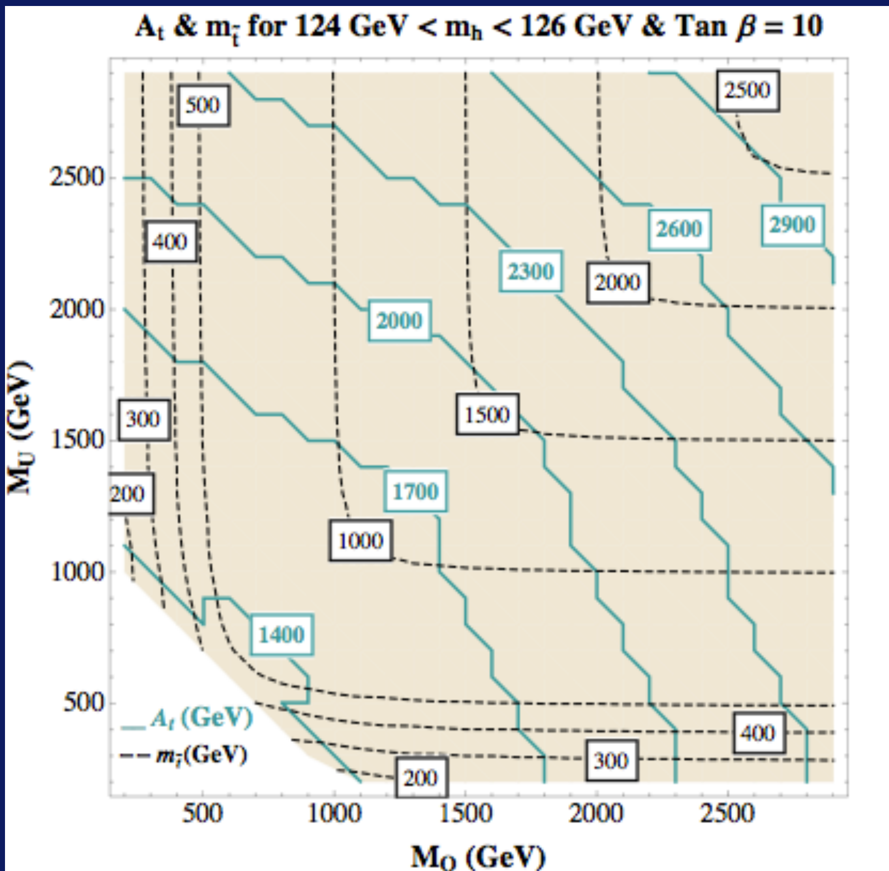
Large mixing in the stop sector
A_t > 1 TeV
[Unless stop very heavy (5-10 TeV)]

In the case of similar stop soft masses both stops should be > 500 GeV

Large mixing also constrains SUSY breaking model building

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon; Draper Meade, Reece, Shih
Heinemeyer, Stal, Weiglein'11; Ellwanger'11; Shirman et al.

Stop Spectra and the Higgs Mass in the MSSM



M. C., S. Gori, N. Shah, C. Wagner '11
+L.T.Wang '12

Large mixing in the stop sector
A_t > 1 TeV
[Unless stop very heavy (5-10 TeV)]

In the case of similar stop soft masses both stops should be > 500 GeV

For hierarchical stop soft masses, one stop can be light (~ few 100 GeV) and the other heavy (> 1 TeV)

Direct Stop searches at LHC are probing these mass regime

Similar results from
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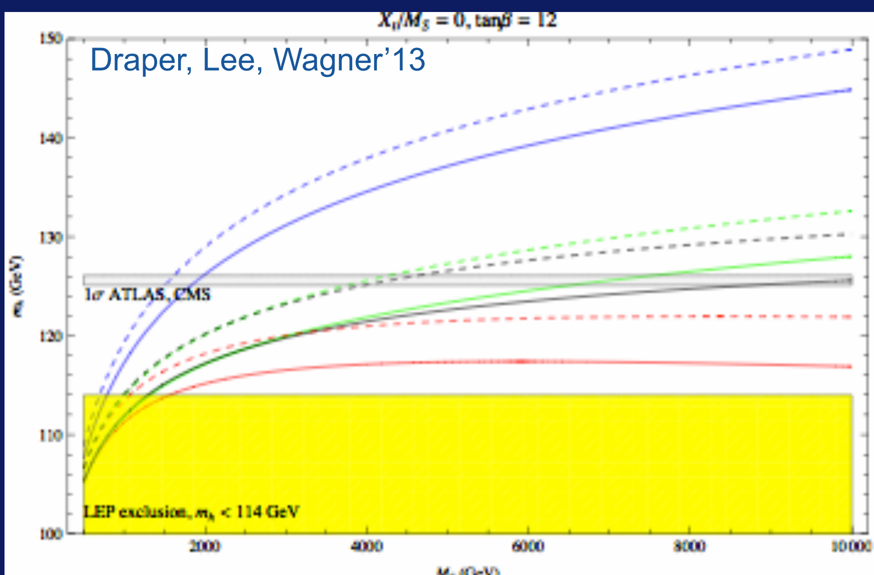
• A 125 GeV Higgs and light stops

Light stop coupling to the Higgs $$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

Lightest stop coupling to the Higgs approximately vanishes for Xt ~m_Q
Higgs mass pushes us in that direction
Modification of the gluon fusion rate mild due to this reason.

• A 125 GeV Higgs and very heavy stops

An upper bound on the SUSY scale [stop masses < 10 TeV]
if tanβ moderate or large (> 5-10)]



Recalculation of RG prediction with 4 loops in RG expansion:

The importance of higher order loop computations

See also: Martin'07; Strumia et al; Kant et al; *Feng, et al.;* G. Kane et al.: A.Arvanitaki et al.

Extensions of the MSSM

- MSSM with explicit CP violation (radiatively induced): no effect on m_h

Pilaftsis, Wagner '99

- Add new degrees of freedom that contribute at tree level to mh (new quartics)

new F term contributions ➔ e.g. additional SM singlets or triplets

Possible additional CP violation at tree level ➔ relevant for EW baryogenesis

and/or additional D terms ➔ models with enhanced weak gauge symmetries

New gauge bosons (~ a few TeV) at LHC reach?

- A more model-independent approach: (SUSY breaking as a perturbation)

SUSY 2HDM effective field theory with higher dimensional operators

Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou; M.C, Kong, Ponton, Zurita

look at specific examples singlet, triplets with Y =0 ; 1, and extra gauge bosons

Effects most relevant for small tanβ; for $M_A > 400$ GeV pheno very close to MSSM

Otherwise, new decay channels: H to AA/AZ, and H^+ to W^+A may be open (alignment?)

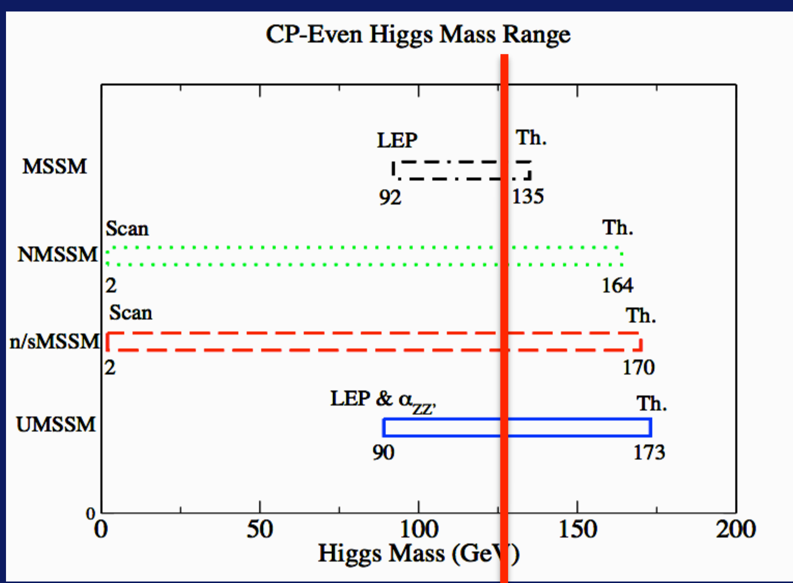
Singlet extensions of the MSSM

A solution to the μ problem: Superpotential ⊃ $\lambda_s S H_u H_d$ → $\mu_{eff} = \lambda_s \langle S \rangle$

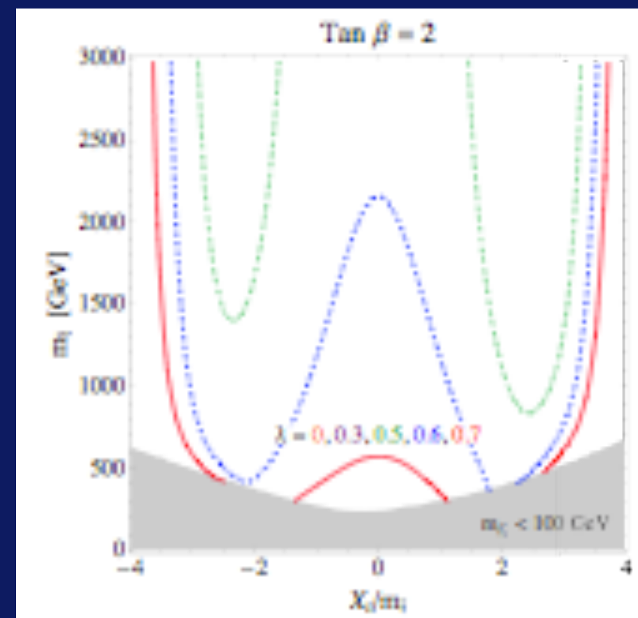
$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda_S^2 v^2 \sin^2 2\beta + \text{rad. corrections}$$

Main one-loop level contributions common with the MSSM

Model	MSSM	NMSSM	nMSSM	UMSSM
Symmetry	-	Z_3	Z_5^R, Z_7^R	$U(1)'$
Superpotential	$\mu \Phi_2 \cdot \Phi_1$	$\lambda_S S \Phi_2 \cdot \Phi_1 + \frac{\kappa}{3} S^3$	$\lambda_S S \Phi_2 \cdot \Phi_1 + t_F S$	$\lambda_S S \Phi_2 \cdot \Phi_1$
H_i^0	2	3	3	3
A_i^0	1	2	2	1



m_{H1} =125 GeV



Hall, Pinner, Ruderman'11

At low tan beta, trade requirement on large stop mixing by sizeable trilinear Higgs-Higgs singlet coupling λ_S

- more freedom on gluon fusion production -

SUSY with extended Gauge Sectors

TeV scale new gauge interactions, and MSSM Higgs bosons charged under them :

D term lifting of m_h^{tree}

requires extended gauge and Higgs sectors are integrated out in a non-SUSY way

Simplest example: extended $SU(2)_1 \times SU(2)_2$ sector spontaneously broken to $SU(2)_L$

bi-doublet Σ under the two SU(2) gauge groups acquires $\langle\Sigma\rangle = u$

Heavy gauge boson: $M_{W'}^2 = (g_1^2 + g_2^2)\, u^2/2$ $SU(2)_L$: $g^2 = g_1^2 g_2^2/(g_1^2 + g_2^2)$

Flavor option: 3rd gen. fermions and Higgs doublets charged under $SU(2)_1$, while the 2nd and 1st gen. are charged under $SU(2)_2$.

$$m_h^2\big|_{tree} = \frac{g^2\Delta + g'^2}{4} v^2 \cos^2 2\beta$$

with $\Delta = \left(1 + \frac{4m_\Sigma^2}{g_2^2 u^2}\right)\left(1 + \frac{4m_\Sigma^2}{(g_1^2 + g_2^2)u^2}\right)^{-1}$ m_Σ ~~SUSY~~ mass

For $m_\Sigma \to 0$ one recovers the MSSM; for $m_\Sigma \gg M_{W'}$ the D term is that of $SU(2)_1$

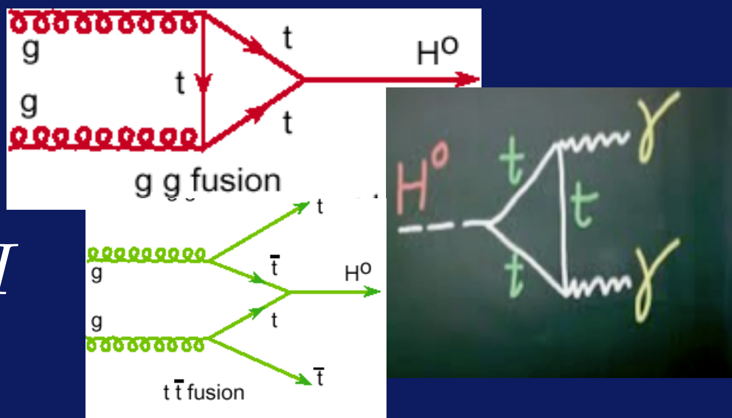
For $m_\Sigma \sim M_{W'}$ and $g_1 \sim g_2 \sim O(1)$ ➔ $m_h \sim 125$ GeV without heavy stops or large stop mixing

- In addition, in gauge extensions m_h can be increased due to RG evolution of the Higgs quartic couplings at low energies, in the presence of light strongly coupled gauginos

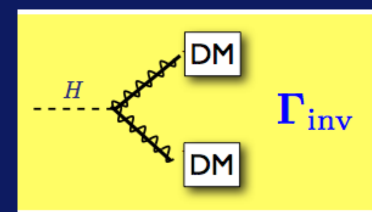
What do the Higgs Production and Decay rates tell us?

Many different pieces of information: $B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h)\frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$

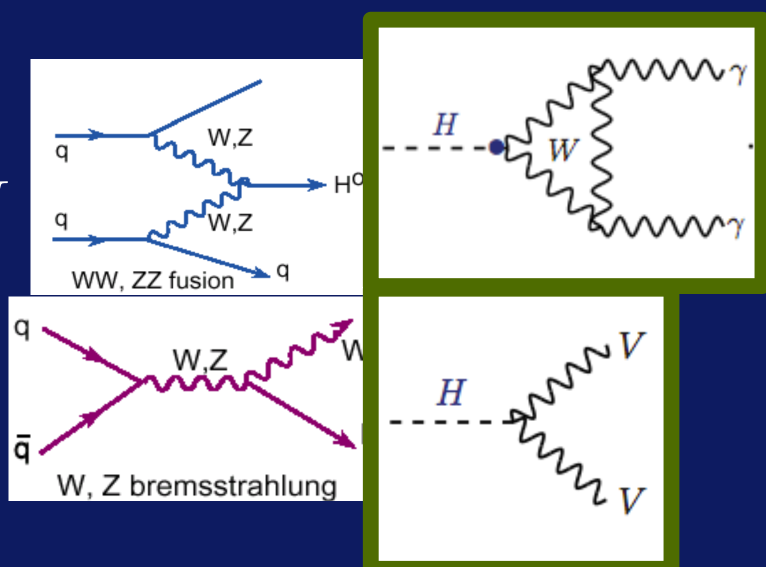
$t\bar{t}H$



also $H \to b\bar{b}, \tau^+\tau^-$



VVH



Different patterns of deviations from SM couplings if:

- New light charged or colored particles in loop-induced processes
- Modification of tree level couplings due to mixing effects
- Decays to new or invisible particles

crucial info on NP from Higgs precision measurements

Loop induced Couplings of the Higgs to Gauge Boson Pairs

Low energy effective theorems

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos'76, Shifman,Vainshtein,Voloshin, Zakharov'79, Kniehl and Spira '95
M. C, Low, Wagner '12

Similarly for the Higgs-gluon gluon coupling

Hence, W (gauge bosons) contribute negatively to Hγγ,
while top quarks (matter particles) contribute positively to Hgg and Hγγ

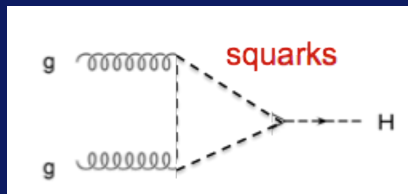
- New chiral fermions will enhance Hgg and suppress hγγ
- To reverse this behavior matter particles need to have negative values for

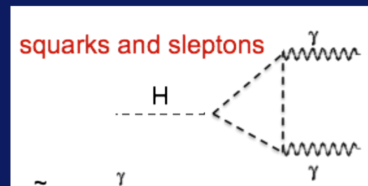
$$\frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) \qquad \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)$$

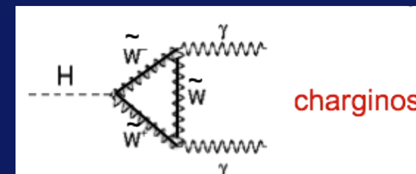
For a study considering CP violating effects and connection with EDM's and MDM's see
Voloshin'12; Altmannshofer, Bauer, MC'13, Brod et al.; Primulando et al.

Possible departures in the production and decay rates at the LHC

- **Through SUSY particle effects in loop induced processes**







$$\delta A^{\tilde{f}}_{\gamma\gamma,gg} \propto \frac{m_f^2}{m^2_{\tilde{f}_1}\, m^2_{\tilde{f}_2}}\left[m^2_{\tilde{f}_1} + m^2_{\tilde{f}_2} - X_f^2\right]$$

$$\delta A^{\tilde{\chi}^\pm}_{\gamma\gamma} \propto -\frac{g^2 v^2 \sin 2\beta}{M_2\mu - \frac{1}{2} g^2 v^2 \sin 2\beta}$$

If a particle's mass is proportional to the Higgs vev, contributes with the same sign of the top loop. But mixing can alter the sign

- Light stops and gluon fusion production

MSSM➔ increase the gluon fusion rate but, for large stop mixing X_t required by m_h~125 GeV, mostly leads to moderate suppression

Singlet extensions at low tanβ ➔ no need for large X_t, hence more freedom in gluon fusion

- MSSM Light staus with large mixing (sizeable μ and tanβ) can enhance Higgs to di-photons without changing any other rates.

- Singlet extensions with light charginos, depending on sign of $M_2\mu$, can enhance Higgs to di-photon rate for small tanβ

- Gauge extensions with light charginos, enhance Higgs to di-photons for strong coupling

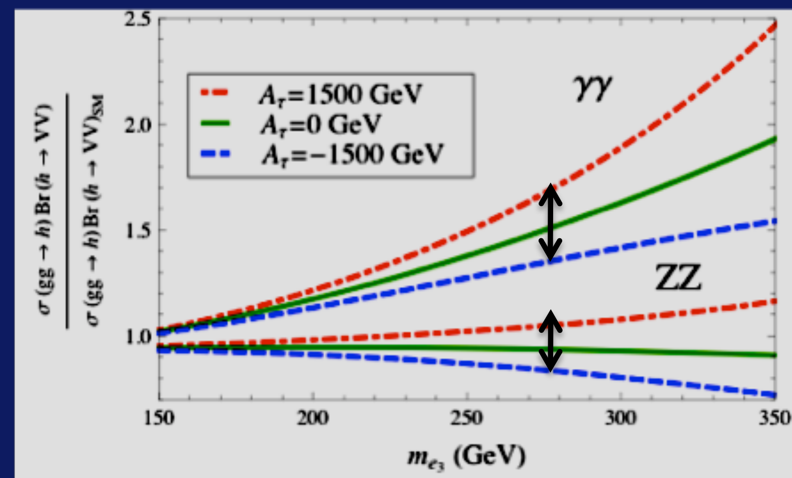
Possible departures in the production and decay rates at the LHC cont'd

•Through enhancement/suppression of the Hbb and Hττ coupling strength via mixing in the scalar sector

This affects in similar manner BR's into all other particles

MSSM: Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

NMSSM : Wide range of WW/ZZ and γγ rates due to Higgs-singlet mixing (λ_S)



pMSSM/MSSM fits: Arbey, Battagllia, Djouadi,Mahmoudi '12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weiglein, Zeune'12

•Through vertex corrections to Yukawa couplings: different for bottoms and taus

This destroys the SM relation BR(h→bb)/BR(h→ττ) ~ m_b^2/m_τ^2

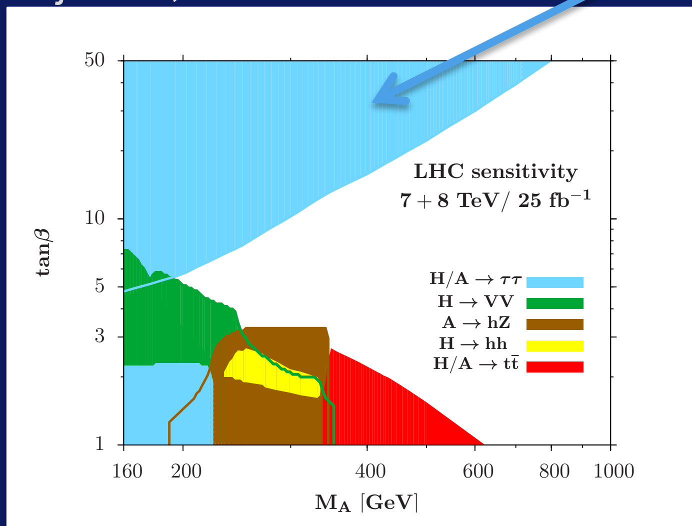
•Through decays to new particles (including invisible decays)

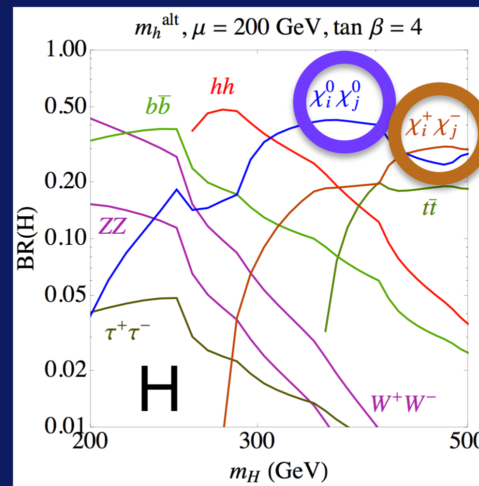
This affects in similar manner BR's to all SM particles

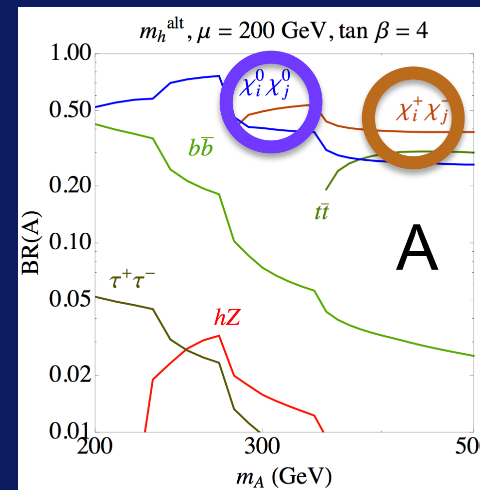
Additional Higgs boson Searches at the LHC

ATLAS/CMS strong limits in A/H → τ τ via gluon fusion and bbA/H production

Djouadi, Quevillon'13





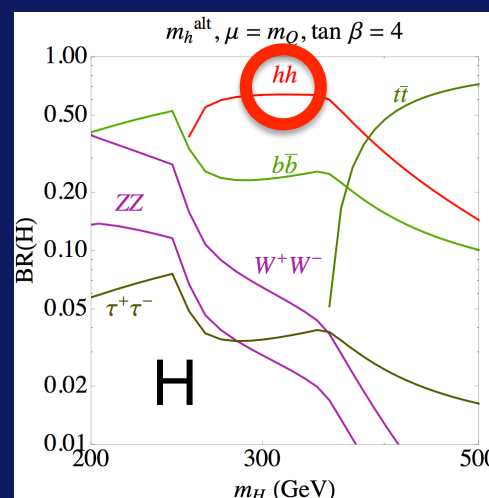


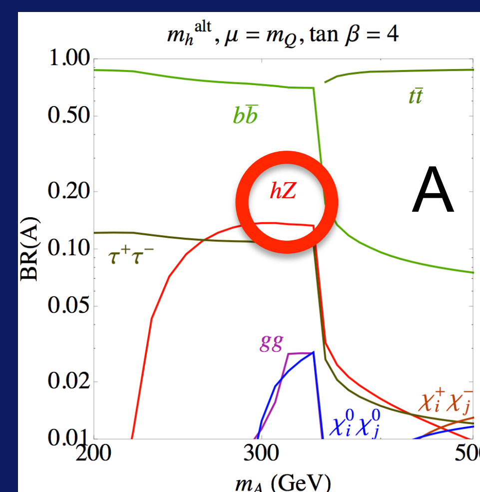
At low tanβ, it is important to search for

H → WW+ ZZ, hh, tt ; A → Zh, tt

If low mu, then chargino and neutralino channels open up

(stop masses > 10 TeV if tanb < 4)





M.C, Low, Shah, Wagner'13 + Haber'14

Alignment and Complementarity for A/H Searches

Haber, Gunion '03
MC, Low, Shah, Wagner '13

sinα = - cosβ ➔ h has SM like properties

Alignment Conditions:

Independent of m_A

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \; ,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

$$\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$$

also

$$m_h^2 = \lambda_{SM} v^2$$

$$\lambda_{SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + +\lambda_2 \sin^4\beta$$

Alignment solutions for → **MSSM: sizeable μ and intermediate tanβ**
→ **NMSSM: small μ and tanβ**

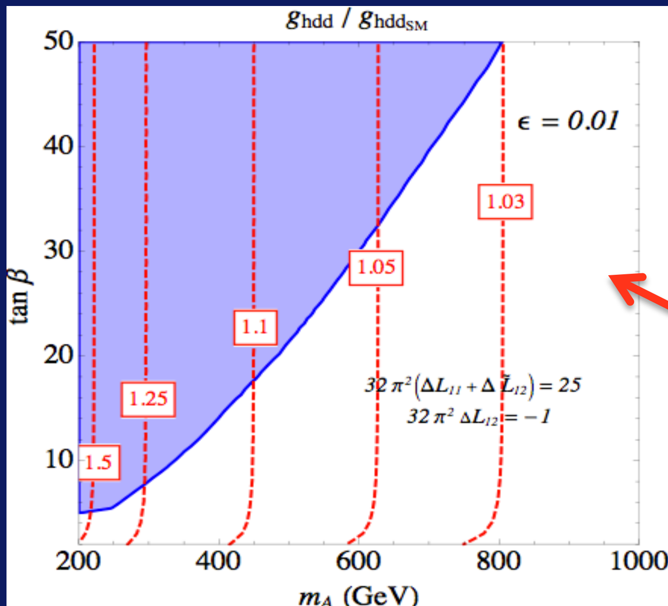
Is it more important to measure Higgs couplings with the highest precision possible

Or

Find new ways of searching for additional Higgs states?

Alignment and Complementarity for A/H Searches

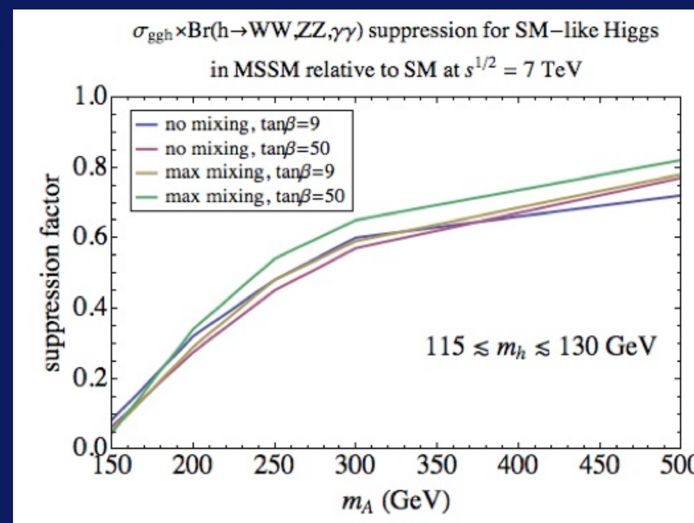
MC, Low, Shah, Wagner '13

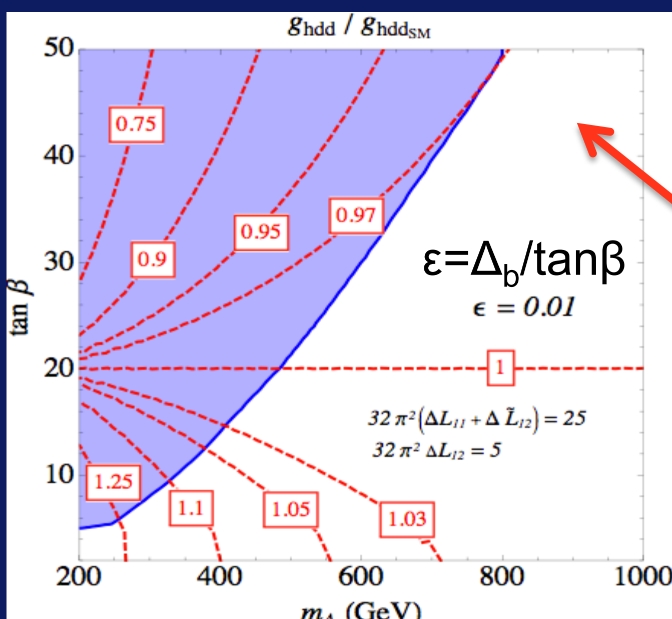


No alignment for small μ

Strong lower bounds on m_A from BR($h \to WW/ZZ$) variations due to enhancement in hbb coupling

All vector boson BRs suppressed indep. of tanβ





Alignment for large μ and tanβ ~O(10)

Weaker lower bounds on m_A, with strong tanβ dependence

e.g. Tauphobic Benchmark

MC, Heinemayer, Stal, Wagner, Weiglein'14

The new era of precision Higgs Physics (cont'd)

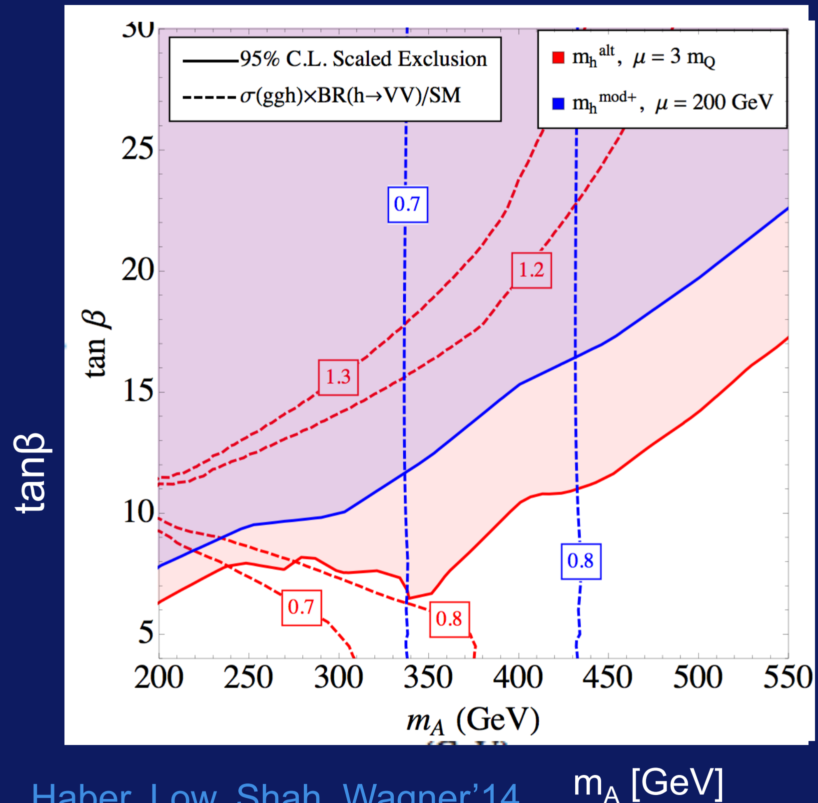
All other 3 Higgs bosons may be heavy ~ TeV range ~ (Decoupling)
Or as light as a few hundred GeV (Alignment)

Additional Higgs Bosons Searches:
A/H → ττ (shaded)
Vs Precision Higgs Physics:
h → WW/ZZ (dashed lines)

Complementarity crucial to probe SUSY Higgs sector

Correlations between deviations may reveal underlying physics

At low tanβ: important to look for
H → WW+ ZZ, hh, tt ; A → Zh, tt



M.C., Haber, Low, Shah, Wagner'14

Similar effects in Extensions of the MSSM

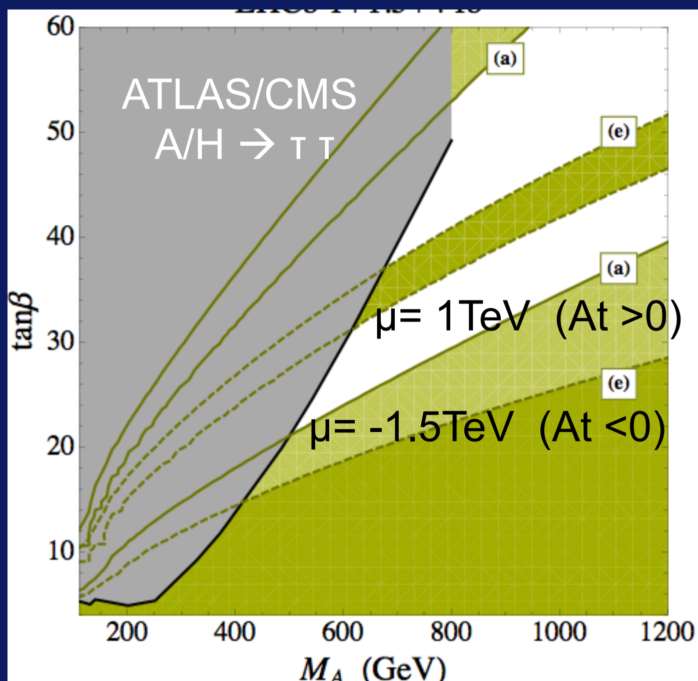
~ Add new degrees of freedom that contribute at tree level to m_h ~

e.g. additional SM singlets or triplets or models with enhanced weak gauge symmetries

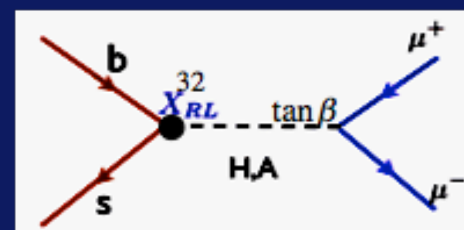
Indirect limits on the SUSY spectrum from rare processes

The Higgs-flavor connection in the MSSM with Minimal Flavor Violation

Altmannshofer, MC, Shah, Yu ’13



$B_s \to \mu^+\mu^-$



$$\propto \frac{y_t^2}{16\pi^2}\frac{\mu A_t}{m_{\tilde{t}}^2}\frac{\tan\beta^3}{M_A^2}$$

mu = 1TeV (At >0)

LHCb Projections: 1 (7 TeV) +1.5 (8 TeV)+4 (13 TeV) fb^{-1}

SM central value with 30% effects of NP allowed

SUSY effects intimately connected to the structure of the squark mass matrices

Two Higgs Doublet models and a Theory of Flavor

- The Froggatt Nielsen mechanism: Effective Yukawa coupling

$$\mathcal{L}_{\rm Yuk} = y_t \bar{Q}_L \tilde{H} t_R + y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R + \cdots$$

$$\mathbf{m_t = y_t \frac{v}{\sqrt{2}}} \qquad \mathbf{m_b = y_b \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda}\right)^{n_b}}$$

$$\mathbf{y_{eff} = \epsilon^n y} \qquad \epsilon = \mathbf{f/\Lambda}$$

- New scalar singlet S obtains a vev: <S> =f
  - Quarks & scalars are charged under a global $U(1)_F$ flavor symmetry
- Lighter quarks, more S insertions

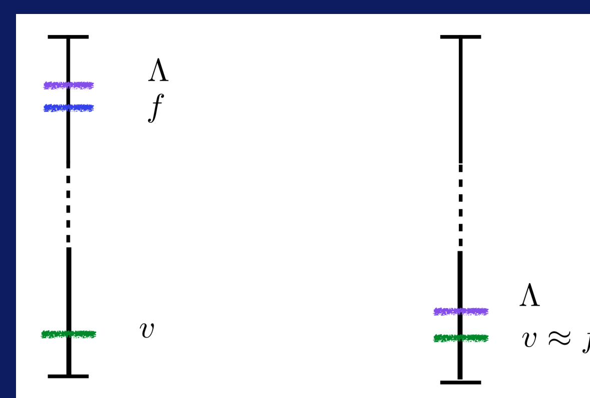
Issue: Scales undetermined

- How to define the scales? Can the Higgs play the role of the Flavon?

Babu ‘03, Giudice-Lebedev ‘08

$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \rightarrow y_b \left(\frac{H^\dagger H}{\Lambda^2}\right)^{n_b} \bar{Q}_L H b_R$$

$$\epsilon = \mathbf{v^2/2\Lambda^2 \equiv m_b/m_t \rightarrow \Lambda \approx (5-6)v}$$



Two Main Problems

- **The flavon is a flavor singlet**
- **The Higgs coupling to Bottom quarks is too large**

$$\mathbf{g_{hbb} \propto 3\, m_b/v}$$

Two Higgs Doublet models and a Theory of Flavor (cont'd)

- Type II 2HDM with different flavor charges for H_u and H_d

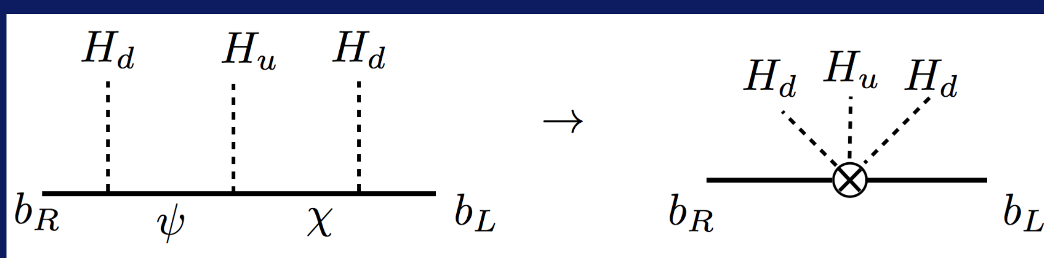
$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R \to y_b \left(\frac{H_u H_d}{\Lambda^2}\right)^{n_b} \bar{Q}_L H_d\, b_R$$

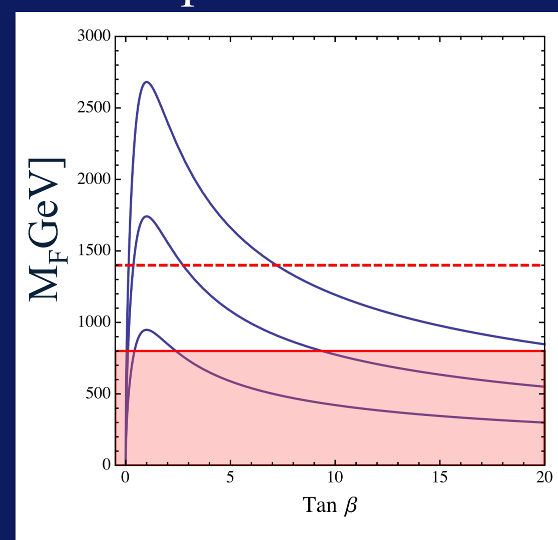
Bauer, MC, Gemmler '15

With effective Yukawa coupling suppression factor

$$\epsilon = \mathbf{v_u v_d/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v} \left(\frac{\tan\beta}{1+\tan^2\beta}\right)^{1/2}$$

The value of $\Lambda \sim 4$ v ~ 1TeV (maximizes for tan β = 1)
and can be slightly larger depending on the specific UV completion





Flavor from the Electroweak Scale

- Flavor Structure by fixing flavor charges

$$m_t \approx \frac{v_u}{\sqrt{2}}, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1, \quad \frac{m_s}{m_t} \approx \varepsilon^2, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

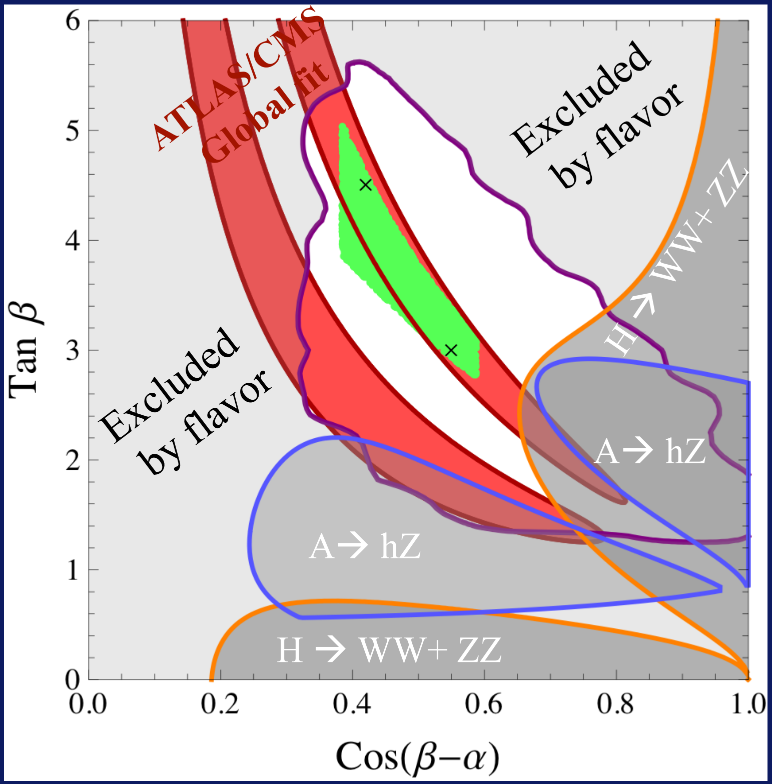
$$(V_{\rm CKM})_{12} \approx \varepsilon^0, \qquad (V_{\rm CKM})_{13} \approx (V_{\rm CKM})_{23} \approx \varepsilon^1$$

- Higgs couplings to gauge bosons and top quark as in 2HDM
- Light quark coupling to Higgs special!

~ in particular Higgs-bottom coupling ~

A predictive model with new Physics at LHC reach (shaded green)

- Interplay of flavor phyiscs with precision Higgs global fit {ATLAS/CMS)
- Great possibilities for direct collider searches for additional Higgs bosons
- New particles in the few TeV range



SM Higgs

- Resolves the problem of consistency within the SM
- Is a scalar, sensitive to new physics at high scales
- **All current data is well compatible with SM expectations but there is room for small deviations**
- **Still many open questions that demand new physics**

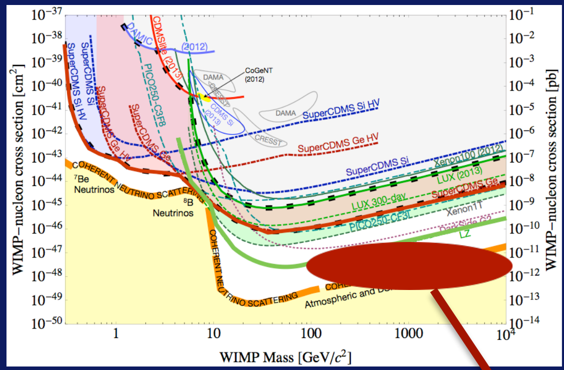
Extended Higgs and Natural SUSY models

- Being cornered by LHC data but still many places to hide

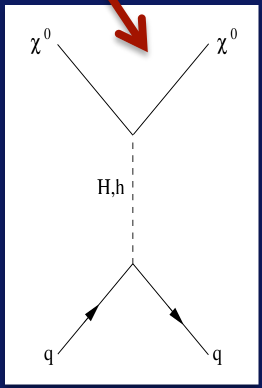
  (searches moving in those directions)

- Direct searches for additional Higgs bosons as important as precise measurements of Higgs properties
- Correlations among deviations in different Higgs signals may reveal underlying physics

We are exploring the Higgs connections



- In there a Higgs portal to dark matter and/or other dark sectors?



- Is Baryogenesis generated at the EWSB scale?
- How does the Higgs talk to neutrinos ?
- What are the implications of the Higgs sector for flavor?
- Is the Higgs a portal to new particles and new energy scales?
- Is the Higgs related to inflation or dark energy?
- What is the dynamical origin of the electroweak scale?