## Higgs Boson a la Carte?



## Marcela Carena

Fermilab and U. of Chicago
PITT PACC Workshop: Higgs and Beyond
University of Pittsburgh, December 5, 2015

## Higgs Boson a la Carte?



Discovering additional Higgs bosons may be our next window to a new world.
Nobody can anticipate how many sweet treats may be available in the new run of the LHC, but we will soon find out.


Fermilab Today; March 15 th 2015
Work done in collaboration with
Howard Haber, Ian Low, Nausheen Shah and Carlos Wagner
JHEP 1404 (2014) 015 ; Phys. Rev. D 91, 035003, 2015 and Arxiv:1510.09137

## What kind of Higgs?

- Is it THE STANDARD MODEL HIGGS ?
- Or does it have non-SM properties?
- Could be a mixture from more than one Higgs Field
- Could be a mixture of CP even and CP odd
- Could be a composite particle
- Could be partly a singlet or a triplet instead of an SU(2) doublet
- Could have enhanced/suppressed coupling to photons or gluons if there are exotic heavy charged or colored particles
- Could decay to exotic particles, e.g. dark matter
- May not couple to matter particles proportional to their masses

How to quantify its SM-likeness and use it in the search for other Higgs bosons

## Looking under the Higgs lamp-post:

What type of Higgs have we seen?


SM valid up to $\mathrm{M}_{\text {Planck }}$

SUSY extensions

Composite Higgs

Also, back in fashion: Twin Higgs and Mirror Worlds

Interesting option: Flavor from the EW scale Higgs as part of a 2HDM to explain flavor from the electroweak scale (a la Frogatt Nielsen)


This talk: explore 2HDMs, MSSM, NMSSM Higgs phenomenology

## Going Beyond the SM: Two Higgs Doublet Models

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

$$
\left(\mathcal{D} \phi_{i}\right)^{\dagger} \mathcal{D} \phi_{i} \rightarrow g^{2} \phi_{i}^{\dagger} T^{a} T^{b} \phi_{i} A_{\mu}^{a} A^{\mu, b}
$$

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

$$
v^{2} \rightarrow v_{1}^{2}+v_{2}^{2} \quad \tan \beta=\mathrm{v}_{2} / \mathrm{v}_{1}
$$

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

$$
\begin{aligned}
\frac{H_{2} v_{2}+H_{1} v_{1}}{\sqrt{v_{1}^{2}+v_{2}^{2}}} \equiv H_{2} \sin \beta+H_{1} \cos \beta=H_{\mathrm{SM}} & <\mathrm{H}_{\mathrm{SM}}>=\mathrm{v} \\
\frac{H_{2} v_{1}-H_{1} v_{2}}{\sqrt{v_{1}^{2}+v_{2}^{2}}} \equiv H_{2} \cos \beta-H_{1} \sin \beta=H_{\mathrm{NSM}} & <\mathrm{H}_{\mathrm{NSM}}>=0
\end{aligned}
$$

Then, it is clear that the Goldstone modes will be the charged and the imaginary part of the neutral components of $H_{S M}$

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

$$
\begin{array}{rr}
G^{ \pm}=H_{2}^{ \pm} \sin \beta+H_{1}^{ \pm} \cos \beta & \sqrt{2} G^{0}=\operatorname{Im} H_{2}^{0} \sin \beta+\operatorname{Im} H_{1}^{0} \cos \beta \\
H^{ \pm}=-H_{2}^{ \pm} \cos \beta+H_{1}^{ \pm} \sin \beta & \sqrt{2} A=-\operatorname{Im} H_{2}^{0} \cos \beta+\operatorname{Im} H_{1}^{0} \sin \beta \\
\hline
\end{array}
$$

## CP-even Higgs Bosons

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

$$
\begin{gathered}
\sqrt{2} h=-\sin \alpha \operatorname{Re} H_{1}^{0}+\cos \alpha \operatorname{Re} H_{2}^{0} \\
\sqrt{2} H=\cos \alpha \operatorname{Re} H_{1}^{0}+\sin \alpha \operatorname{Re} H_{2}^{0}
\end{gathered}
$$

Then the couplings of $h / H$ to the gauge bosons are given by

$$
\begin{gathered}
h V V=(h V V)^{\mathrm{SM}}(-\cos \beta \sin \alpha+\sin \beta \cos \alpha)=(h V V)^{\mathrm{SM}} \sin (\beta-\alpha) \\
H V V=(h V V)^{\mathrm{SM}}(\cos \beta \cos \alpha+\sin \beta \sin \alpha)=(h V V)^{\mathrm{SM}} \cos (\beta-\alpha)
\end{gathered}
$$

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

## Fermion Masses and Flavor

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

For instance, for the down quark mass matrix:

$$
M_{d}^{i j}=h_{d, 1}^{i j} \frac{v_{1}}{\sqrt{2}}+h_{d, 2}^{i j} \frac{v_{2}}{\sqrt{2}}
$$

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

$$
\begin{aligned}
g_{h d_{i} d_{j}} & \propto h_{d, 1}^{i j}(-\sin \alpha)+h_{d, 2}^{i j}(\cos \alpha) \\
g_{H d_{i} d_{j}} & \propto h_{d, 1}^{i j}(\cos \alpha)+h_{d, 2}^{i j}(\sin \alpha)
\end{aligned}
$$

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 | $\Phi_{2}$ | $\Phi_{2}$ | $\Phi_{2}$ | $\Phi_{2}$ |
| d | $\Phi_{2}$ | $\Phi_{1}$ | $\Phi_{2}$ | $\Phi_{1}$ |
| e | $\Phi_{2}$ | $\Phi_{1}$ | $\Phi_{1}$ | $\Phi_{2}$ |

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

## e.g. 2HDM Type II

$$
\begin{array}{ll}
g_{h f f}^{d d, l l}=\frac{\mathcal{M}_{d d, l l}^{\text {diag }}}{v} \frac{(-\sin \alpha)}{\cos \beta}, \quad g_{H f f}^{d d, l l}=\frac{\mathcal{M}_{d d, l l}^{\text {diag }}}{v} \frac{\cos \alpha}{\cos \beta} & g_{A f f}^{d d, l l}=\frac{\mathcal{M}_{\text {diag }}^{\text {dd }}}{v} \tan \beta \\
g_{h f f}^{u u}=\frac{\mathcal{M}_{u u}^{\text {diag }}}{v} \frac{(\cos \alpha)}{\sin \beta}, \quad g_{H f f}^{u u}=\frac{\mathcal{M}_{u u}^{\text {diag }}}{v} \frac{\sin \alpha}{\sin \beta} & g_{A f f}^{u u}=\frac{\mathcal{M}_{\text {diag }}^{\text {uu }}}{v \tan \beta}
\end{array}
$$

If the mixing is such that $\cos (\beta-\alpha)=0 \quad$ (hence $\sin \alpha=-\cos \beta \quad \cos \alpha=\sin \beta$ )
The coupling of the lightest Higgs to fermions and gauge bosons is SM-like.

## This situation is called ALIGNMENT

## The Higgs Potential

The most generic two Higgs doublet potential is given by

$$
\begin{aligned}
V= & m_{11}^{2} \Phi_{1}^{\dagger} \Phi_{1}+m_{22}^{2} \Phi_{2}^{\dagger} \Phi_{2}-m_{12}^{2}\left(\Phi_{1}^{\dagger} \Phi_{2}+\text { h.c. }\right)+\frac{1}{2} \lambda_{1}\left(\Phi_{1}^{\dagger} \Phi_{1}\right)^{2}+\frac{1}{2} \lambda_{2}\left(\Phi_{2}^{\dagger} \Phi_{2}\right)^{2} \\
& +\lambda_{3}\left(\Phi_{1}^{\dagger} \Phi_{1}\right)\left(\Phi_{2}^{\dagger} \Phi_{2}\right)+\lambda_{4}\left(\Phi_{1}^{\dagger} \Phi_{2}\right)\left(\Phi_{2}^{\dagger} \Phi_{1}\right) \\
& +\left\{\frac{1}{2} \lambda_{5}\left(\Phi_{1}^{\dagger} \Phi_{2}\right)^{2}+\left[\lambda_{6}\left(\Phi_{1}^{\dagger} \Phi_{1}\right)+\lambda_{7}\left(\Phi_{2}^{\dagger} \Phi_{2}\right)\right] \Phi_{1}^{\dagger} \Phi_{2}+\text { h.c. }\right\}
\end{aligned}
$$

## Minimization conditions $\Rightarrow \mathrm{CP}$-odd and charged Higgs masses as a function

 of one mass parameter and the quartic couplings$$
m_{A}^{2}=\frac{2 m_{12}^{2}}{s_{2 \beta}}-\frac{1}{2} v^{2}\left(2 \lambda_{5}+\lambda_{6} t_{\beta}^{-1}+\lambda_{7} t_{\beta}\right) \quad m_{H}^{ \pm}=m_{A}^{2}+\frac{v^{2}}{2}\left(\lambda_{5}-\lambda_{4}\right)
$$

## masses in the CP-even sector, in terms of $\mathrm{m}_{\mathrm{A}}$ and the quartic couplings

$$
\mathcal{M}=\left(\begin{array}{ll}
\mathcal{M}_{11} & \mathcal{M}_{12} \\
\mathcal{M}_{12} & \mathcal{M}_{22}
\end{array}\right) \equiv m_{A}^{2}\left(\begin{array}{cc}
s_{\beta}^{2} & -s_{\beta} c_{\beta} \\
-s_{\beta} c_{\beta} & c_{\beta}^{2}
\end{array}\right)+v^{2}\left(\begin{array}{ll}
L_{11} & L_{12} \\
L_{12} & L_{22}
\end{array}\right)
$$

$$
\begin{aligned}
L_{11} & =\lambda_{1} c_{\beta}^{2}+2 \lambda_{6} s_{\beta} c_{\beta}+\lambda_{5} s_{\beta}^{2} \\
L_{12} & =\left(\lambda_{3}+\lambda_{4}\right) s_{\beta} c_{\beta}+\lambda_{6} c_{\beta}^{2}+\lambda_{7} s_{\beta}^{2} \\
L_{22} & =\lambda_{2} s_{\beta}^{2}+2 \lambda_{7} s_{\beta} c_{\beta}+\lambda_{5} c_{\beta}^{2}
\end{aligned}
$$

For large $\mathrm{m}_{\mathrm{A}}$ and perturbative quartics:
one obtains that $\mathrm{m}_{\mathrm{H}} \sim \mathrm{m}_{\mathrm{A}}$, while $\mathrm{m}_{\mathrm{h}}$ is of order an effective quartic coupling times $\mathrm{v}^{2}$

## Alignment in 2HDMs

Consider the eigenstate equation:

$$
\left(\begin{array}{cc}
s_{\beta}^{2} & -s_{\beta} c_{\beta} \\
-s_{\beta} c_{\beta} & c_{\beta}^{2}
\end{array}\right)\binom{-s_{\alpha}}{c_{\alpha}}=-\frac{v^{2}}{m_{A}^{2}}\left(\begin{array}{cc}
L_{11} & L_{12} \\
L_{12} & L_{22}
\end{array}\right)\binom{-s_{\alpha}}{c_{\alpha}}+\frac{m_{h}^{2}}{m_{A}^{2}}\binom{-s_{\alpha}}{c_{\alpha}}
$$

For large values of the CP-odd Higgs mass, it follows:

$$
\left(\begin{array}{cc}
s_{\beta}^{2} & -s_{\beta} c_{\beta} \\
-s_{\beta} c_{\beta} & c_{\beta}^{2}
\end{array}\right)\binom{-s_{\alpha}}{c_{\alpha}} \approx 0 \quad \cos (\beta-\alpha)=0 \quad \text { Decoupling }
$$

Is it possible to obtain alignment independent of the value of $\mathrm{m}_{\mathrm{A}}$ ? We shall call this situation ALIGNMENT without decoupling

$$
\begin{gathered}
v^{2}\left(\begin{array}{cc}
L_{11} & L_{12} \\
L_{12} & L_{22}
\end{array}\right)\binom{-s_{\alpha}}{c_{\alpha}}=m_{h}^{2}\binom{-s_{\alpha}}{c_{\alpha}} \\
m_{h}^{2}=v^{2} L_{11}+t_{\beta} v^{2} L_{12}=v^{2}\left(\lambda_{1} c_{\beta}^{2}+3 \lambda_{6} s_{\beta} c_{\beta}+\tilde{\lambda}_{3} s_{\beta}^{2}+\lambda_{7} t_{\beta} s_{\beta}^{2}\right), \quad \text { and 2do } \\
m_{h}^{2}=v^{2} L_{22}+\frac{1}{t_{\beta}} v^{2} L_{12}=v^{2}\left(\lambda_{2} s_{\beta}^{2}+3 \lambda_{7} s_{\beta} c_{\beta}+\tilde{\lambda}_{3} c_{\beta}^{2}+\lambda_{6} t_{\beta}^{1} c_{\beta}^{2}\right)
\end{gathered}
$$

## Alignment without Decoupling $\stackrel{>}{ }$ other light Higgs Bosons

$$
\begin{aligned}
& \left(m_{h}^{2}-\lambda_{1} v^{2}\right)+\left(m_{h}^{2}-\tilde{\lambda}_{3} v^{2}\right) t_{\beta}^{2}=v^{2}\left(3 \lambda_{6} t_{\beta}+\lambda_{7} t_{\beta}^{3}\right), \\
& \left(m_{h}^{2}-\lambda_{2} v^{2}\right)+\left(m_{h}^{2}-\tilde{\lambda}_{3} v^{2}\right) t_{\beta}^{-2}=v^{2}\left(3 \lambda_{7} t_{\beta}^{-1}+\lambda_{6} t_{\beta}^{-3}\right)
\end{aligned}
$$

## Alignment conditions

- If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_{h}^{2}=\lambda_{\mathrm{SM}} v^{2}$, with $\lambda_{\mathrm{SM}} \simeq 0.26$ and $\lambda_{3}+\lambda_{4}+\lambda_{5}=\tilde{\lambda}_{3}$

$$
\lambda_{\mathrm{SM}}=\lambda_{1} \cos ^{4} \beta+4 \lambda_{6} \cos ^{3} \beta \sin \beta+2 \tilde{\lambda}_{3} \sin ^{2} \beta \cos ^{2} \beta+4 \lambda_{7} \sin ^{3} \beta \cos \beta+\lambda_{2} \sin ^{4} \beta
$$

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

$$
\tan ^{2} \beta=\frac{\lambda_{1}-\lambda_{\mathrm{SM}}}{\lambda_{\mathrm{SM}}-\tilde{\lambda}_{\mathbf{3}}}=\frac{\lambda_{\mathrm{SM}}-\tilde{\lambda}_{3}}{\lambda_{2}-\lambda_{\mathrm{SM}}}
$$

$\tan \beta$ should be positive, hence $\lambda_{\mathbf{1 , 2}} \leq \lambda_{\mathbf{S M}} \leq \tilde{\lambda}_{\mathbf{3}}$ or $\lambda_{1,2} \geq \lambda_{\mathrm{SM}} \geq \tilde{\lambda}_{3}$
In the MSSM both $\lambda_{1}, \tilde{\lambda}_{3}<\lambda_{\mathbf{S M}}$
However, in the MSSM, radiative corrections needed for $\mathbf{m h} \sim 125 \mathrm{GeV} \Rightarrow \lambda_{6,7} \neq 0$

- Case of $\lambda_{6,7} \neq 0$, additional solution $\tan \beta \simeq \frac{\lambda_{\mathrm{SM}}-\tilde{\lambda}_{\mathbf{3}}}{\lambda_{7}}$
$\Rightarrow$ Alignment may occur at sizable $\tan \beta$, e.g in the MSSM


## Departures from Alignment

- Alignment might only be partially realized, useful to study the effects of small departures
- It is customary to parametrize departures from alignment by a Taylor exp. in $\cos (\beta-\alpha)$ which defines deviations from Higgs-WW/ZZ couplings BUT Higg -bottom coupling is controlled by $\eta$

$$
c_{\beta-\alpha}=t_{\beta}^{-1} \eta, \quad s_{\beta-\alpha}=\sqrt{1-t_{\beta}^{-2} \eta^{2}}
$$

At leading order in $\eta$

$$
\begin{aligned}
& g_{h V V} \approx\left(1-\frac{1}{2} t_{\beta}^{-2} \eta^{2}\right) g_{V}, \quad g_{H V V} \approx t_{\beta}^{-1} \eta g_{V}, \\
& g_{h d d} \approx(1-\eta) g_{f}, \quad \quad g_{H d d} \approx t_{\beta}\left(1+t_{\beta}^{-2} \eta\right) g_{f} \\
& g_{\text {huu }} \approx\left(1+t_{\beta}^{-2} \eta\right) g_{f}, \quad \quad g_{\text {Huu }} \approx-t_{\beta}^{-1}(1-\eta) g_{f}
\end{aligned}
$$

The couplings to down fermions are not only the ones that dominate the Higgs width but also tend to be the ones that differ at most from the SM ones

For small departures from alignment, $\eta$ can be determined as a function of the quartic couplings and the Higgs masses

## Conditions of Alignment in the Higgs Basis

$$
\begin{aligned}
& \mathbf{H}_{\mathrm{SM}}=\sin \beta \boldsymbol{\Phi}_{1}+\cos \beta \boldsymbol{\Phi}_{\mathbf{2}} \\
& \mathbf{H}_{\mathrm{NSM}}=-\cos \beta \boldsymbol{\Phi}_{1}+\sin \beta \boldsymbol{\Phi}_{2}
\end{aligned}
$$

$$
\begin{gathered}
<\mathrm{H}_{\mathrm{SM}}>=\mathrm{v} \\
<\mathrm{H}_{\mathrm{NSM}}>=0
\end{gathered}
$$

The CP-even mass matrix in the Higgs basis:
$\Rightarrow Z_{6}$ governs the mixing and yields non-alignement of the mass eigenstates $h, H$ with the real part of the neutral eigenstates in the Higgs Basis

$$
\mathcal{M}_{H}^{2}=\left(\begin{array}{cc}
Z_{1} v^{2} & Z_{6} v^{2} \\
Z_{6} v^{2} & m_{A}^{2}+Z_{5} v^{2}
\end{array}\right)
$$

$$
\mathrm{m}_{\mathrm{h}}^{2} \leq \mathrm{Z}_{1} \mathrm{v}^{2}
$$

$$
\mathrm{Z}_{6}=0 \rightarrow \quad m_{Z}^{2} c_{2 \beta}=\frac{3 v^{2} s_{\beta}^{2} h_{t}^{4}}{16 \pi^{2}}\left[\ln \left(\frac{M_{S}^{2}}{m_{t}^{2}}\right)+\frac{X_{t}\left(X_{t}+Y_{t}\right)}{2 M_{S}^{2}}-\frac{X_{t}^{3} Y_{t}}{12 M_{S}^{4}}\right]
$$

## MSSM


$\mathrm{H}_{\mathrm{SM}}$ and $\mathrm{H}_{\mathrm{NSM}}$
couplings to stops


At moderate to large $\tan \beta$

$$
t_{\beta}=\frac{m_{Z}^{2}+\frac{3 v^{2} h_{t}^{4}}{16 \pi^{2}}\left[\ln \left(\frac{M_{S}^{2}}{m_{t}^{2}}\right)+\frac{2 A_{t}^{2}-\mu^{2}}{2 M_{S}^{2}}-\frac{A_{t}^{2}\left(A_{t}^{2}-3 \mu^{2}\right)}{12 M_{S}^{4}}\right]}{\frac{3 v^{2} h_{t}^{4} \mu A_{t}}{32 \pi^{2} M_{S}^{2}}\left(\frac{A_{t}^{2}}{6 M_{S}^{2}}-1\right)}
$$

Alignment difficult for small $\mu$ or close to maximal mixing

## Impact of Precision Higgs measurements on A/H searches

1) No alignment for small $\mu$ (in this regime $\lambda_{6,7} \propto \mu A_{t} \simeq 0$ )


$$
\begin{array}{r}
\eta=\mathrm{t}_{\beta} \mathbf{c}_{\beta-\alpha}=-\mathbf{t}_{\beta} \mathbf{Z}_{6} \mathrm{v}^{2} /\left(\mathrm{m}_{\mathrm{H}}^{2}-\mathrm{m}_{\mathrm{h}}^{2}\right) \\
t_{\beta} c_{\beta-\alpha} \simeq \frac{-1}{m_{H}^{2}-m_{h}^{2}}\left[m_{h}^{2}+m_{Z}^{2}+\frac{3 m_{t}^{4}}{4 \pi^{2} v^{2} M_{S}^{2}}\left\{A_{t} \mu t_{\beta}\left(1-\frac{A_{t}^{2}}{6 M_{S}^{2}}\right)-\mu^{2}\left(1-\frac{A_{t}^{2}}{2 M_{S}^{2}}\right)\right\}\right]
\end{array}
$$

For moderate to large $\tan \beta$ and small $\mu$
$\Rightarrow$ no dependence on $\tan \beta$ or on the stop mixing
$\rightarrow$ All vector boson BR's suppressed by enhancement of bottom decay width

## Impact of Precision Higgs measurements on A/H searches

2) Alignment for large $\mu$ and $\tan \beta \sim O(10)$


Weaker lower bounds on $\mathrm{m}_{\mathrm{A}}$, with strong $\tan \beta$ dependence
e.g. Tauphobic Benchmark MC, Heinemayer, Stal, Wagner, Weiglein'14


Mostly determined by the change of width


$$
\mu / M_{\mathrm{SUSY}}=2, \quad A_{t} / M_{\mathrm{SUSY}} \simeq 3
$$

## Heavy Higgs Bosons: A variety of decay Branching Ratios

Depending on the values of $\mu$ and $\tan \beta$ different search strategies must be applied
Large $\mu$ : depending on $\tan \beta$ could be close to alignment or not



Large $\tan \beta \Rightarrow$ close to alignment, usual bottom and tau decay channels, hh suppressed production mainly via large bottom couplings: bbH
Small $\tan \beta \rightarrow$ away from alignment, $\mathrm{H} \rightarrow \mathrm{hh}, \mathrm{WW}$ and ZZ become relevant production mainly via top loops in gluon fussion

## Additional Higgs boson Searches at the LHC

ATLAS/CMS strong limits in $\mathrm{A} / \mathrm{H} \rightarrow$ т т via gluon fusion and bbA/H production

Djouadi, Quevillon'13


Away from alignment (low tan $\beta$ ) it is important to search for $\mathrm{H} \rightarrow \mathrm{WW}+\mathrm{ZZ}, \mathrm{hh}, \mathrm{tt} ; \mathrm{A} \rightarrow \mathrm{Zh}, \mathrm{tt}$ If low $\mu$, then chargino and $\qquad$ neutralino channels open up
(stop masses > 10 TeV if tanb <4)



## Effects of Light Chargino/Neutralinos on A/H searches

$$
\sum_{\phi_{i}=A, H} \mathrm{bb}\left(\phi_{i} \rightarrow \tau \tau\right)+\operatorname{gg}\left(\phi_{i} \rightarrow \tau \tau\right)
$$



Reach improved for large $\mu$ due to the enhanced Higgs to taus BR

## Complementarity between Higgs precision and A/H Searches

## All other 3 Higgs bosons may be heavy $\sim \mathrm{TeV}$ range $\sim$ (Decoupling) Or as light as a few hundred GeV (Alignment)

Additional Higgs Bosons Searches:

$$
\mathbf{A} / \mathbf{H} \rightarrow \boldsymbol{\tau} \tau \text { (shaded) }
$$

Vs Precision Higgs Physics: $\mathbf{h} \rightarrow \mathbf{W W} / \mathbf{Z Z}$ (dashed lines)

Complementarity crucial to probe
SUSY Higgs sector
Correlations between deviations may reveal underlying physics

Away from precise alignment

- either small $\mu$ or not the right $\tan \beta$ look for $\mathrm{H} \rightarrow \mathrm{WW}+\mathrm{ZZ}$, hh, tt ; $\mathrm{A} \rightarrow \mathrm{Zh}$, tt or $\mathrm{A} / \mathrm{H}$ into chargino/ neutralino pairs

$\mathrm{m}_{\mathrm{A}}[\mathrm{GeV}]$

Similar effects in Extensions of the MSSM
$\sim$ Add new degrees of freedom that contribute at tree level to $m_{h} \sim$
e.g. additional SM singlets or triplets or models with enhanced weak gauge symmetries

## Extending the Analysis to the NMSSM

$\mathbf{W}=\lambda S \Phi_{1} \Phi_{2}+\frac{\kappa}{3} \mathbf{S}^{3}$ $-\mathcal{L}_{\text {soft }}=\lambda \bigwedge_{\mathrm{A}_{\mathrm{A}}} \mathrm{S} \Phi_{1} \Phi_{2}+\frac{1}{3} \kappa \underset{\mathrm{~m}_{\mathrm{a}} / \mathrm{m}_{\text {hs }}}{\mathrm{E}_{\mathrm{h}} \mathrm{S}^{3}}$
2 Doublets $\Phi_{1}$ and $\Phi_{2}$ and a singlet S
Interaction basis: $\left(\Phi_{1}, \Phi_{2}, \mathrm{~S}\right)$
$\Phi_{2}$ : Couples only to up-type fermions $\quad \rightarrow\left\langle\Phi_{2}\right\rangle=v_{u} \quad \tan \beta=\mathrm{v}_{\mathrm{u}} / \mathrm{v}_{\mathrm{d}}$
$\Phi_{1}$ : Couples only to down-type fermions
$\Rightarrow\left\langle\Phi_{1}\right\rangle=v_{d}$
S: Only couples to Higgs sector
$\rightarrow\langle S\rangle=v_{S}=\mu / \lambda$
"Extended" Higgs basis: $\left(\mathrm{H}_{\mathrm{NSM}}, \mathrm{H}_{\mathrm{SM}}, \mathrm{S}\right)$
$\mathrm{H}_{\text {NSM }}$ : $($ down, up, V$)=\left(\mathrm{y}_{\mathrm{d}} \mathrm{t}_{\beta}, \mathrm{y}_{\mathrm{u}} / \mathrm{t}_{\beta}, 0\right)$

$$
\begin{aligned}
& <\mathrm{H}_{\mathrm{NSM}}>=0 \\
& <\mathrm{H}_{\mathrm{SM}}>=\mathrm{V}
\end{aligned}
$$

Mass basis: $\left.\left(\mathrm{H}^{3}, \mathrm{H}^{2}, \mathrm{H}^{1}\right)\right) \rightarrow\left(\mathrm{H}, \mathrm{h} 125, \mathrm{~h}_{\mathrm{S}}\right)$

$$
H^{i}=\kappa^{i}{ }_{N S M} H_{N S M}+\kappa_{S M}^{i} H_{S M}+\kappa_{S}^{i} S
$$

Alignment Condition $\Rightarrow \mathrm{k}^{\mathrm{h} 125}{ }_{\mathrm{NSM}}=0$ and $\mathrm{k}^{\mathrm{h} 125} \mathrm{~s}^{=0}$

## Naturalness and the Alignment conditions in the NMSSM

- Well known additional contributions to $\mathrm{m}_{\mathrm{h}}$

$$
m_{h}^{2} \simeq \lambda^{2} \frac{v^{2}}{2} \sin ^{2} 2 \beta+M_{Z}^{2} \cos ^{2} 2 \beta+\Delta_{\tilde{t}}
$$

- Less well known: sizeable contributions to the mixing between MSSM CP-even eigenstates

$$
M_{S}^{2}(1,2) \simeq \frac{1}{\tan \beta}\left(m_{h}^{2}-M_{Z}^{2} \cos 2 \beta-\lambda^{2} v^{2} \sin ^{2} \beta+\delta_{\tilde{t}}\right)
$$

Last term from MSSM; small for moderate/small $\mu \mathrm{A}_{\mathrm{t}}$ and small $\tan \beta$

Alignment leads to $\lambda$ in the restricted range 0.65 to 0.7 , in agreement with perturbativity up to the GUT scale


$$
\lambda_{\mathrm{alt}}^{2}=\frac{m_{h}^{2}-M_{Z}^{2} \cos 2 \beta}{v^{2} \sin ^{2} \beta}
$$



## Naturalness and the Alignment conditions in the NMSSM

Given that $\lambda_{\text {alt }} \sim 0.65 \rightarrow$ stops can be light, inducing only moderate corrections to $m_{h}$
After some algebra it follows: (replacing $\lambda_{\text {alt }}$ expression in mh)

$$
\Delta_{\tilde{t}}=-\cos 2 \beta\left(m_{h}^{2}-M_{Z}^{2}\right)
$$



For moderate mixing, It is clear that low values of $\tan \beta<3$ require low $\mathrm{M}_{\mathrm{S}}$
$\Rightarrow$ small stop corrections to the Higgs mass parameter at the alignment values

## Aligning the Singlet

Previously was assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states

The mixing mass matrix element between the singlets and the SM-like Higgs is $M_{S}^{2}(1,3) \simeq 2 \lambda v \mu\left(1-\frac{m_{A}^{2} \sin ^{2} 2 \beta}{4 \mu^{2}}-\frac{\kappa \sin 2 \beta}{2 \lambda}\right)$

Needs to vanish in alignment

For $\tan \beta<3$ and $\lambda \sim 0.65$, plus k in the perturbative regime, one concludes that in order to get small mixing in the Higgs sector $\mathrm{m}_{\mathrm{A}}$ and $\mu$ are correlated

$$
\mathrm{m}_{\mathrm{A}} \approx \frac{2|\mu|}{\sin 2 \beta}
$$

Since both $m_{A}$ and $\mu$ should be small, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

Moreover, this ensures also that all parameters are small and the CPeven and CP-odd singlets (and singlino) become self consistently light

## Singlet, Higgsino and Singlino Masses




For values of $k$ at the edge of perturbativity, the singlino mass is equal to the Higgsino mass.

$$
m_{\tilde{S}}=2 \mu \frac{\kappa}{\lambda}
$$

The whole Higgs and Higgsino spectrum remains light

## Singlet Spectra



Heavier CP-even Higgs can decay to lighter ones

Anticorralation between singlet -like CP-even and CP-odd masses

$$
\cdot \tan \beta=2 \cdot \tan \beta=2.5 \cdot \tan \beta=3
$$

Scan of over parameter space with allowed misalignment from precision Higgs measurements and searches (e.g. $\Phi \rightarrow$ WW)

NMSSMTools + HiggsBounds/Signals

## MSSM-like A and H decays into top pairs




Significant decays into top pairs, BR's depend on $\tan \beta$
May be somewhat suppressed by decays involving to non-SM particles

MSSM-like A and H decay into lighter Higgs bosons and Z's


$\mathrm{H} \Rightarrow \mathrm{hh}$ and $\mathrm{A} \Rightarrow \mathrm{hZ}$ decays strongly suppressed due to alignment
Others: $\mathrm{H} \rightarrow$ hs hs; $\mathrm{H} \rightarrow$ As $\mathrm{Z} ; \mathrm{A} \rightarrow$ As hs; $\mathrm{A} \rightarrow$ As h of order $10 \%$ or below

## MSSM-like A and H decay charginos and Neutralinos

 are relevant, even above the top threshold

$\mathrm{H} \Rightarrow \mathrm{hh}$ and $\mathrm{A} \Rightarrow \mathrm{hZ}$ decays strongly suppressed due to alignment
Others: $\mathrm{H} \rightarrow$ hs hs; $\mathrm{H} \rightarrow$ As $\mathrm{Z} ; \mathrm{A} \rightarrow$ As hs; $\mathrm{A} \rightarrow$ As h of order 10\% or below

## Singlet-like $h_{S}$ decays



Singlet mainly decays to bb and WW

## Complementarity between $\mathrm{gg} \rightarrow \mathrm{A} \rightarrow \mathrm{Z} \mathrm{h}_{\mathrm{S}} \rightarrow \| \mathrm{llb}$

 and $\mathrm{gg} \rightarrow \mathrm{h}_{\mathrm{S}} \rightarrow \mathrm{WW}$ search channels @ 8 TeV

## Promising $\mathrm{H} \rightarrow \mathrm{h} \mathrm{h}_{\mathrm{S}}$ channels:



Complementarity between the $\mathrm{hs} \rightarrow \mathrm{bb}$ and the hs $\rightarrow$ WW decay modes


- < 10 fb
$10-50 f b$
- $50-100 \mathrm{fb}$
- $100-150 \mathrm{fb}$
- $150-200 \mathrm{fb}$
- 200-250 fb
- 250-300 fb


## Outlook

Precision measurements of Higgs signal strengths strongly constrain departures from alignment in extended Higgs Sectors

This in turn has important implications for the searches for additional Higgs bosons
Alignment in the MSSM appears for large values of $\mu$, suppressing decays into electro-weakinos and making bounds from decays into SM particles stronger.

Bounds on $\mathrm{A} / \mathrm{H}$ are model dependent and should be interpreted with care .
Away from alignment decays of $\mathrm{A} / \mathrm{H}$ into gauge bosons, the light Higgs and electro-weakinos become relevant.

Complementarity between precision measurements and direct searches will allow to probe efficiently the MSSM Higgs sector

In the NMSSM, alignment occurs in regions of parameter space in which the naturalness conditions are fulfilled, with $\lambda \sim 0.65$. Stops can be light. Allowed misalignment opens up interesting search channels

