Lecture 3:

Examples of Non-Standard Higgs Physics:

- CP Violating phases in the MSSM
- SUSY models with extra gauge Singlets

Other BSM ideas for the Higgs hierarchy problem:
- Flat Extra Dimensions, Warped Extra Dimensions (Dobrescu)
- Little Higgs Models (Kaplan)
CP Violation in the MSSM

- In low energy SUSY, there are extra CP-violating phases beyond the CKM ones, associated with complex SUSY breaking parameters

- One of the most important consequences of CP-violation is its possible impact on the explanation of the matter-antimatter asymmetry.

  Electroweak baryogenesis may be realized even in the simplest SUSY extension of the SM, but demands new sources of CP-violation associated with the third generation sector and/or the gaugino-Higgsino sector.

- These CP-violating phases may induce effects on observables such as
  - new contributions to the e.d.m. of the electron and the neutron.
  - Higgs mediated FCNC in the K and B -meson systems

  Effects on observables can be small/sizeable depending on the SUSY parameter space

- In the Higgs sector at tree-level, all CP-violating phases, if present, may be absorbed into a redefinition of the fields.

- CP-violation in the Higgs sector appears at the loop-level, associated with third generation scalars and/or the gaugino/Higgsino sector, but can still have important consequences for Higgs and flavour physics

- After radiative corrections: CP violation induced through loop effect:
  via 3. generation sfermion and gaugino mass parameters

- Many possible relevant phases to Higgs sector
  \( m_{\tilde{g}} \) (one phase if Univ. gaugino masses) \( A_f, \mu \) and \( m_{12}^2 \)

Due to U(1) symm.of the conformal inv. sector:
  → one can redefine fields and absorb two phases

rephasing inv. combinations
  if \( \text{Im} ((m_{12}^2) A_f \mu) \neq 0 \) and/or \( \text{Im} ((m_{12}^2) \mu \tilde{g}) \neq 0 \)

⇒ CP violating effects will be present in the MSSM
  in practice, take \( m_{12}^2 \) and \( \mu \) real and leave phases in \( A_f \) and \( m_{\tilde{g}} \)
Higgs Potential → Quantum Corrections

Minimization should be performed with respect to real and imaginary parts of Higgs fluctuations \( H_1^0 = \phi_1 + iA_1 \quad H_2^0 = \phi_2 + iA_2 \)

Performing a rotation: \( A_1, A_2 \rightarrow A, G^0 \) (Goldstone)

Main Effect of CP-Violation is the mixing between the three neutral Higgs boson states

\[
\begin{pmatrix}
A \\
\Phi_1 \\
\Phi_2
\end{pmatrix} = \mathcal{O}
\begin{pmatrix}
H_1 \\
H_2 \\
H_3
\end{pmatrix}
\]

In the base \((A, \phi_1, \phi_2)\):

\[
\mathcal{M}_N^2 = \begin{bmatrix}
m_A^2 & (M_{SP}^2)^T \\
M_{SP}^2 & M_{SS}^2
\end{bmatrix}
\]

\( M_{SS}^2 \) is similar to the mass matrix in the CP conserving case, and \( M_A^2 \) is the mass of the would-be CP-odd Higgs.

\( M_{SP}^2 \) gives the mixing between would-be CP-odd and CP-even states, predominantly governed by stop induced loop effects

\[
M_{SP}^2 \propto \frac{m_t^4}{16\pi^2 v^2} \text{Im} \left( \frac{\mu A_t}{M_S^2} \right)
\]

Gluino phase relevant at two-loop level. Guagino effects may be enhanced for large tan \( \beta \).

Comments on Higgs Boson Mixing

- \( m_A \) no longer a physical parameter, but the charged Higgs mass \( m_{H^\pm} \) can be used as a physical parameter, together with
  
  \[
  M_S, |\mu|, |A_t|, |m_\tilde{g}|, \arg(A_t), \arg(m_\tilde{g})
  \]

- Elements of matrix \( \mathcal{O} \) are similar to \( \cos \alpha \) and \( \sin \alpha \) in the CP-conserving case. But third row and column are zero in the non-diagonal elements in such a case.

- Three neutral Higgs bosons can now couple to the vector bosons in a way similar to the SM Higgs.

- Similar to the decoupling limit in the CP-conserving case, for large values of the charged Higgs mass, light Higgs boson with Standard Model properties.
Interaction Lagrangian of W,Z bosons with mixtures of CP even and CP odd Higgs bosons

\[ g_{H^+ VV} = \cos \beta O_{1i} + \sin \beta O_{2i} \]
\[ g_{H^+ H_j Z} = O_{3i} (\cos \beta O_{2j} - \sin \beta O_{1j}) - O_{3j} (\cos \beta O_{2i} - \sin \beta O_{1i}) \]
\[ g_{H^+ H^- W^+} = \cos \beta O_{2i} - \sin \beta O_{1i} + i O_{3i} \]
\[ (V = W, Z) \]
\[ O_{ij} \rightarrow \text{analogous to } \sin \alpha \text{ and } \cos \alpha \]

→ All couplings as a function of two: \[ g_{H^+ VV} = \epsilon_{ijk} g_{H^+ H_j Z} \]

and sum rules:
\[ \sum_{i=1}^{3} g_{H_i ZZ}^2 = 1 \]
\[ \sum_{i=1}^{3} g_{H_i ZZ}^2 m_{H_i}^2 = m_{H_1}^{2,\text{max}} \lesssim 135 \text{ GeV} \]

(equiv. to CP-conserv. case)

upper bound remains the same

Pilaftsis, Wagner

Decoupling limit: \( m_{H^+} \gg M_Z \)

- Effective mixing between the lightest Higgs and the heavy ones is zero
→ \( H_1 \) is SM-like

- Mixing in the heavy sector still relevant!
  (Due to the high degeneracy between the would be \( m_A \) and \( m_H \))

\[ \rightarrow \begin{pmatrix} m_A^2 & \Delta \\ \Delta & \Delta' + m_A^2 \end{pmatrix} \]

w/ \[ \Delta \sim O(\Delta') \ll m_A^2 \]

Higgs boson-quark Lagrangian

- taking into account both CP-violating self-energy and vertex effects

\[ \mathcal{L}_{H_i \bar{f} f} = - \sum_{f=u,d,l} \frac{g_{m f}}{2 M_W} \sum_{i=1}^{3} H_i \bar{f} \left( g_{H_i \bar{f} f}^S + i g_{H_i \bar{f} f}^P \gamma_5 \right) f \]

All neutral Higgs bosons couple to fermion with both scalar and pseudoscalar couplings

\[ g_{H_i dd}^S = \frac{1}{h_b + \Delta_b} \left\{ Re(h_b) O_{1i}^\beta \cos \beta + Re(\Delta h_b) O_{2i}^\beta \cos \beta - [Im(h_b) \tan \beta - Im(\Delta h_b)] O_{13} \right\} \]
\[ g_{H_i dd}^P = \frac{1}{h_b + \Delta_b} \left\{ [Re(\Delta h_b) - Re(h_b) \tan \beta] O_{3i} - Im(h_b) \frac{O_{1i}^\beta}{\cos \beta} - Im(\Delta h_b) \frac{O_{2i}^\beta}{\cos \beta} \right\} \]

- The one loop effects to the Yukawa couplings introduce CP-violating effects which are independent of the Higgs mixing

\[ \frac{\Delta h_b}{h_b} \sim \frac{2 \alpha_s}{3 \pi} \frac{m_{\tilde{g} \mu \mu}^*}{\max (Q_{\tilde{g}}, |m_{\tilde{\beta}}|^2)} + \frac{|h_b|^2}{16 \pi^2} \frac{A_{\mu}^*}{\max (Q_{\mu}, |\mu|^2)} \]

\[ \Delta_b \equiv \Delta h_b \tan \beta \]
- Decoupling limit: $M_{H^+} \gg M_Z$
- CP violation effects in the Higgs-fermion couplings
  
  $$O_{11} \rightarrow \cos \beta \quad O_{21} \rightarrow \sin \beta \quad O_{31} \rightarrow 0$$

- $H_1 b \bar{b}$ and $H_1 u \bar{u}$ pseudoscalar couplings tend to zero while their scalar couplings tend to SM-like

- Heaviest Higgs Scalar and Pseudoscalar couplings to up and down quarks do not vanish

$\Rightarrow$ non decoupling of CP-violating vertex effects as well as self energy ones

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**CP-Violating Phases affect relevantly masses and couplings**

$M_{H_1}$

$M_{H_1} = 120 \text{ GeV}$

$M_{H_1} = 160 \text{ GeV}$

$M_{H_1} = 250 \text{ GeV}$

**CPX scenario**

$M_{\Phi_1} = M_{\Phi_2} = M_{\Phi_3} = M_{\Phi_4} = M_{\Phi_5} = M_{\text{SUSY}}$,  
$|\mu| = 4 M_{\text{SUSY}}$,  
$|\lambda_{123}| = 2 M_{\text{SUSY}}$,  
$|M_3| = 1 \text{ TeV}$.

two physical phases to vary:  
$\Phi_A$ and $\Phi_3 = \text{Arg}(M_3)$.

This figures: CPX scenario with  
$\tan \beta = 4$, $\Phi_3 = 0^\circ$,  
$M_{\text{SUSY}} = 0.5 \text{ TeV}$.  

Higgs boson decay patterns for MSSM with CP phases

CPX with zero phases
decay channels
\[ H_2 \rightarrow H_1 H_1, WW, ZZ \]
and
\[ H_3 \rightarrow H_1 Z ; \]
are forbidden

with \( \Phi_A = \Phi_3 = 90^\circ \).

\( H_2 \) dominantly decays into \( H_1 \)
for \( H_2 \) close to LEP threshold

\( H_1 \) is mainly CP-odd

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LEP Results for CPX with maximal CP phases

\[ m_{H_2} \approx 105 \text{ GeV} \text{ and } m_{H_1} < 40 \text{ GeV} \]

intermediate \( \tan \beta \)

\[ g_{H_1 ZZ} \] too small to detect \( H_1 \)

\( H_2 \) is produced via Higgs-strahlung but,
it has sizeable decay rate into \( H_1 H_1 \)

New search mode opens up:
\[ ZH_2 \rightarrow ZH_1 \]
\[ H_1 \rightarrow Z b\bar{b} b\bar{b} \]
(also \( H_1 \rightarrow 4 \) taus, or 2 taus 2 b's)

The above exact unexcluded range depends on exact \( M_{\text{top}} \) mass and CP phases

LEP data shows large unexcluded domains down at the smallest masses

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\[ \Rightarrow \text{no absolute limit on } H_1 \text{ mass can be set} \]
Can LHC discover the SM-like Higgs in the MSSM with explicit CP violation?

**CPX scenario**

- $m_{H_1} < 70$ GeV
- $m_{H_2} : 105$ to $120$ GeV
- $m_{H_3} : 140$ to $180$ GeV

- $H_2/H_3$ channels: VBF and ttHi

**Present limitations:**
- VBF only for mass > 110 GeV
- No study for $H_1$ below 70 GeV

- Encourage the study of $gg \rightarrow H_2$, $t\bar{t}H_2$, $W/Z H_2$ and $WW/ZZ H_2$
  with subsequent decay $H_2 \rightarrow H_1 H_1$, using the extra leptons from $W/Z$'s.
  Also $t\bar{t} \rightarrow WbH^\pm b$ with $H^\pm \rightarrow WH_1 \rightarrow Wb\bar{b}$

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MSSM Extensions with an additional singlet
Electroweak Symmetry Breaking and the $\mu$ Problem

- Negative values of the soft supersymmetry breaking mass parameter induce electroweak symmetry breaking. The total Higgs masses receive a SUSY contribution

$$\mu^2 + m^2_{H_i}$$

- Electroweak symmetry breaking therefore demands the relation

$$\mu^2 + \frac{M_Z^2}{2} = \frac{m^2_{H_u} - \tan^2 \beta m^2_{H_d}}{\tan^2 \beta - 1}, \quad \tan \beta = \frac{v_u}{v_d}$$

- Therefore, $\mu$ must be of the order of the SUSY breaking parameters.

- Also, the mixing term $-(B_\mu H_u H_d + h.c.)$ appearing in the potential

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m^2_{H_u} + m^2_{H_d}}$$

must be of the same order.

Is there a natural framework to solve the flavor problem, inducing weak scale values for $\mu$ and $B_\mu$?

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Singlet Mechanism for the generation of $\mu$ in the NMSSM

- Break PQ symmetry by self interactions of the singlet

$$W = \lambda S H_u H_d - \frac{\kappa}{3} S^3 + h_u Q U H_u + \ldots$$

- No dimensionful parameters in the superpotential due to $Z_3$ symmetry, $\phi \rightarrow exp(i2\pi/3)\phi$

- This discrete symmetry would be broken by the singlet v.e.v. Discrete symmetries are dangerous since they could lead to the formation of domain walls: Different volumes of the Universe with different v.e.v's separated by massive wall $\Rightarrow$ ruled out by cosmology observations.

- One could assume a small explicit breakdown of the $Z_3$ symmetry, by higher order operators, which would lead to the preference of one of the three vacuum states. Solve the problem without changing the phenomenology of the model.

- BUT ....
Singlet Mechanism for the generation of $\mu$

- A natural solution would be possible by introducing a singlet
  \[ W = \lambda S H_u H_d + h_u Q U H_u + \ldots \]

- This allows to replace the $\mu$ term by the vacuum expectation value of the singlet field $S$,
  \[ \mu = \lambda \nu S \]

- This model, however, preserves a Peccei Quinn (PQ) symmetry
  \[ Q : -1, \quad \tilde{Q}^C : 0, \quad \tilde{D}^C : 0, \quad \tilde{L} : -1, \quad \tilde{E}^C : 0, \quad \tilde{H}_u : 1, \quad \tilde{H}_d : 1, \quad \tilde{S} : -2, \]

- Once the Higgs acquire v.e.v.'s, PQ symmetry spontaneously broken
  \[ \implies \text{an unacceptable massless Goldstone (axion) in the spectrum.} \]

- Solution: break the PQ symmetry explicitly

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Tadpoles in the NMSSM

- The NMSSM construction assumes the existence of small $Z_3$ breaking terms to solve the domain wall problem.

- One possible construction in supergravity theories is to break the $Z_3$ symmetry by the same sector that breaks supersymmetry.

- However, in general this also leads to the generation of tadpole terms for the singlet, \[ \mathcal{L}_{\text{soft}} \supset t_S S \sim \frac{1}{(16\pi^2)^n} M_P M_{\text{SUSY}}^2 S \], where $n$ is the number of loops at which it is generated.

- If a large tadpole is generated, it combines with \[ \sim M_{\text{SUSY}}^2 S S \] soft mass term and shift the v.e.v. of $S$ to \[ \langle S \rangle \sim \frac{t_S}{M_{\text{SUSY}}^2} \sim \frac{1}{(16\pi^2)^n} M_P \] reintroducing the mu problem. Therefore, $n$ should be larger than 5.

- Imagine that the operators present do not lead to large tadpoles or find a way of eliminating them and keep the NMSSM.

- Three natural solutions: Gauge the PQ symmetry (UMSSM) or find alternative symmetries that ensure large $n$ (MNSSM or nMSSM) or break SUSY at lower energies.
Higgs Bosons in the NMSSM

- Assume the tadpole problem is absent and analyze the NMSSM. The singlet introduces a complex degree of freedom.

- Five physical neutral Higgs bosons: three CP-even and two CP-odd Higgs bosons (if no CP violation)

- Mass of the singlet scalar depends on the soft supersymmetry breaking terms
  \[ m_S^2 |S|^2 + A_\lambda \lambda S H_u H_d - A_\kappa \frac{\kappa}{3} S^3 + A_u h_u Q U H_u + \cdots \]

- For \( \kappa = 0 \) there would be a massless Goldstone from the spontaneous PQ breakdown. The explicit breaking yields a pseudo-Goldstone boson with a mass proportional to \( \kappa \)

- The two pseudoscalar and the three CP-even scalars mix, respectively.

Parameters specifying the Higgs Sector:
\[ \lambda, \ \kappa, \ \lambda_\lambda, \ \lambda_\kappa, \ \mu = \mu_{\text{eff}}, \ \tan \beta. \]

Higgs Spectrum in the NMSSM

Analytic expressions in the large \( \tan \beta \) large charged Higgs mass limit

- The charged Higgs mass is given by
  \[ M_{H^\pm}^2 = \frac{2\mu_{\text{eff}}}{\sin 2\beta} \left( A_\lambda + \frac{\kappa \mu_{\text{eff}}}{\lambda} \right) + M_W^2 - \frac{1}{2} \lambda^2 v^2 \]
  \[ \mu \equiv \mu_{\text{eff}} = \lambda v_S \]

and, contrary to the MSSM, could be lower than the CP-odd masses at tree-level

- \( M_{A_1}^2 \approx -3 \frac{\kappa \mu_{\text{eff}}}{\lambda} A_\kappa, \)

- \( M_{A_2}^2 \approx \frac{2\mu_{\text{eff}}}{\sin 2\beta} \left( A_\lambda + \frac{\kappa \mu_{\text{eff}}}{\lambda} \right) \left( 1 + \frac{\lambda^2 v^2}{8 \mu_{\text{eff}}^2 \sin^2 2\beta} \right). \)

- \( A_1 \) is the pseudo-Goldstone boson associated with the PQ symmetry, with mass proportional to \( \kappa \).
- \( A_2 \) has mass of the order of the charged Higgs mass.
**CP-even Scalars**

- The three CP-even Higgs bosons mix and the mass eigenstates masses acquire somewhat complicated expressions. At tree-level,

\[
M_{H_{1/2}}^2 \approx \frac{1}{2} \left[ M_2^2 \cos^2 2\beta + \frac{K_{\mu\text{eff}}}{\lambda} \left( A_\kappa + 4 \frac{K_{\mu\text{eff}}}{\lambda} \right) + \left( \frac{K_{\mu\text{eff}}}{\lambda} \left( A_\kappa + 4 \frac{K_{\mu\text{eff}}}{\lambda} \right) \right)^2 \right. \\
+ 2\lambda^2 v^2 \left( 2\mu_{\text{eff}} - \left( A_\lambda + 2 \frac{K_{\mu\text{eff}}}{\lambda} \sin 2\beta \right) \right)^2 \left. \right]^{1/2},
\]

\[
M_{H_3}^2 \approx \frac{2\mu_{\text{eff}}}{\sin 2\beta} \left( A_\lambda + \frac{K_{\mu\text{eff}}}{\lambda} \right) \left( 1 + \lambda^2 \frac{v^2}{8\mu_{\text{eff}}^2} \sin^2 2\beta \right).
\]

- \( M_{H_3} \) becomes similar to one of the CP-odd scalar masses (analogous to the MSSM).
- The other two reduce to simple expressions only in certain limits.
- For instance, when

\[
A_\lambda = 2\mu_{\text{eff}} / \sin 2\beta - 2\kappa \mu_{\text{eff}} / \lambda, \quad M_{H_1}^2 \approx \frac{K_{\mu\text{eff}}}{\lambda} \left( A_\kappa + 4 \frac{K_{\mu\text{eff}}}{\lambda} \right), \quad M_{H_2}^2 \approx M_2^2 \cos^2 2\beta.
\]

- In this limit \( H_1 \) would be mostly singlet, \( H_3 \) would be mostly coming from a non-standard doublet component, while \( H_2 \) would be SM-like.

**The nMSSM**

As said above, in the nMSSM symmetries are introduced to prevent the appearance of large singlet tadpole terms.

The symmetries necessary to minimize tadpole terms, also demand \( \kappa \) to be zero.

Tadpole terms still appear both in the superpotential and in the potential, of the order of the weak scale.

The Peccei Quinn is now explicitly broken by the tadpole terms and the CP-odd masses are naturally large, like in the MSSM.
Minimal Extension of the MSSM (nMSSM)

- Superpotential restricted by $Z_5^R$ or $Z_7^R$ symmetries
  $$ W = \lambda S H_1 H_2 + \frac{m_{12}^2}{\lambda} S + y_t Q H_2 U $$

- No cubic term. Tadpole of order of the weak scale, instead

- Discrete symmetries broken by tadpole term, induced at the sixth loop level. Scale stability preserve

and:
  $$ V_{\text{soft}} = m_1^2 H_1^2 + m_2^2 H_2^2 + m_S^2 S^2 + \left( t, S + \text{h.c.} \right) $$
  $$ + \left( a_\lambda S H_1 H_2 + \text{h.c.} \right) $$

Tadpole term $t S$ and soft SUSY breaking mass term $m_S^2 S^* S$

yield vev for $S$, $v_S$ of order $m_{\text{weak}}$

Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controled by $m_S^2$ )

- They mix with standard CP-even and CP-odd states in a way proportional to $\lambda$ and $a_\lambda$

- Values of $\lambda$ restricted to be lower than 0.8 in order to avoid Landau-pole at energies below the GUT scale
  $$ \Rightarrow \text{light LSP} < 70 \text{ GeV} $$

- Similar to MSSM, upper bound on Higgs that couples to weak bosons

- Extra tree-level term helps in avoiding LEP bounds.
  $$ m_h^2 \leq M_Z^2 \cos^2 \beta + \lambda^2 \, v^2 \sin^2 2\beta + \text{loop corrections} $$

Espinosa,Quiros '98; Kane et al. '98
CP-even Higgs Mass Matrix in the nMSSM

For large values of the charged Higgs mass, one heavy state $S_3$ decouples and

$$M_{S_{1,2}}^2 = \begin{pmatrix} M_Z^2 \cos 2\beta + \lambda^2 v^2 \sin^2 2\beta & v(a_\lambda \sin 2\beta + 2\lambda^2 v_\beta) \\ v(a_\lambda \sin 2\beta + 2\lambda^2 v_\beta) & m_s^2 + \lambda^2 v^2 \end{pmatrix} + \Delta M_{S_{1,2}}^2$$

$$\Delta M_{S_{1,2}}^2 \equiv \begin{pmatrix} \Delta s_{11} & \Delta s_{12} \\ \Delta s_{21} & \Delta s_{22} \end{pmatrix} \approx \begin{pmatrix} \Delta s_{11} & 0 \\ 0 & 0 \end{pmatrix}, \quad \text{with} \quad \Delta s_{11} \approx \frac{3}{8\pi^2} \frac{m_t^4}{m_s^2} \log \frac{m_t^2}{m_s^2}.$$ 

CP-odd Higgs Mass Matrix

$$M_p^2 = \begin{pmatrix} M_A^2 & -a_\lambda v \\ -a_\lambda v & m_s^2 + \lambda^2 v^2 \end{pmatrix},$$

$$M_A^2 = -\frac{2}{s_{2\beta}} (m_{12}^2 + a_\lambda v_\beta),$$

Comparison of Different extra Singlet Extensions

- Quite generally, the tree-level potential of all extensions have the form:

$$V_F = |\lambda H_u \cdot H_d + t_F + \kappa S|^2 + |\lambda S|^2 \left( |H_d|^2 + |H_u|^2 \right)$$

$$V_D = \frac{G_F^2}{8} \left( |H_d|^2 - |H_u|^2 \right)^2 + \frac{g_1^2}{2} \left( |H_d|^4 + |H_u|^4 - 2 |H_d|^2 |H_u|^2 \right)$$

$$\quad + \frac{g_{1Y}^2}{2} \left( Q_{H_d} |H_d|^2 + Q_{H_u} |H_u|^2 + Q_S |S|^2 \right)^2$$

$$V_{soft} = m^2_{H_d} |H_d|^2 + m^2_{H_u} |H_u|^2 + m^2_S |S|^2 \left( A_\lambda \lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + t_{S,S} + h.c. \right)$$

- The parameters should be chosen in the following form:

<table>
<thead>
<tr>
<th>Model</th>
<th>Symmetry</th>
<th>Superpotential</th>
<th>CP-even</th>
<th>CP-odd</th>
<th>Charged</th>
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</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>-</td>
<td>$\mu H_u \cdot H_d$</td>
<td>$H_1, H_2$</td>
<td>$A_1$</td>
<td>$H^\pm$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$Z_3$</td>
<td>$\lambda S H_u \cdot H_d + \frac{3}{2} S^3$</td>
<td>$H_1, H_2, H_3$</td>
<td>$A_1, A_2$</td>
<td>$H^\pm$</td>
</tr>
<tr>
<td>MNSSM</td>
<td>$Z_3^b, Z_3^b$</td>
<td>$\lambda S H_u \cdot H_d + t_{S} S$</td>
<td>$H_1, H_2, H_3$</td>
<td>$A_1, A_2$</td>
<td>$H^\pm$</td>
</tr>
<tr>
<td>UMSSM</td>
<td>$U(1)$</td>
<td>$\lambda S H_u \cdot H_d$</td>
<td>$H_1, H_2, H_3$</td>
<td>$A_1$</td>
<td>$H^\pm$</td>
</tr>
<tr>
<td>sMSSM</td>
<td>$U(1)$</td>
<td>$\lambda S H_u \cdot H_d + \lambda_s S H_1 S_2 S_3$</td>
<td>$H_1, \ldots, H_6$</td>
<td>$A_1, \ldots, A_4$</td>
<td>$H^\pm$</td>
</tr>
</tbody>
</table>
Upper bounds on the lightest CP-even Higgs Boson Mass

- The upper bound on the lightest CP-even Higgs mass depends on the model:

  \[ M_{H_1}^2 \leq M_Z^2 \cos^2 2\beta + \tilde{M}(1) \]

  \[ M_{H_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + \tilde{M}(1) \]

  \[ M_{H_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + g_1^2 v^2 (Q_{H_2} \cos^2 \beta + Q_{H_2} \sin^2 \beta)^2 + \tilde{M}(1) \]

- The tree-level masses may be much larger than in the MSSM, particularly at low values of \( \tan \beta \).

- In the UMSSM, the tree-level mass may be pushed to larger values even for large values of \( \tan \beta \).

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Challenging New Higgs search modes in MSSM models with one extra singlet

* Higgs Decay into two lighter scalars

In the presence of light scalar modes LEP SM-like Higgs bound must be revised and Tevatron/LHC studies may be promising:

\[ W/ZH^2 \rightarrow W/ZH_1H_1 \] with \( H_1H_1 \rightarrow 4b's, 2b's2\tau's, 4\tau's \)

* Invisible Higgs decays

Decay into LSP pairs kinematically allowed, becomes dominant naturally in the nMSSM with LSP \( \sim 35 \) GeV for DM/baryogenesis

Detection seems possible at LHC via Vector Boson Fusion
Higgs Decay into light scalars

- Light scalar particles appear in many models that extend the SM description at the weak scale.

- In most of the models of this kind studied in the literature, these light particles are singlets under the SM gauge group and therefore easily avoid the collider constraints.

- The advantage of singlet scalars is that they couple in a renormalizable way only to the Higgs sector of the theory (ignoring the possibility of light right handed neutrinos)

\[ \mathcal{L}_{\text{int}} = -c_1 S^* S H^\dagger H - (c_2 S H^\dagger H + \text{h.c.}) \]

- One could eliminate \( c_2 \) by imposing a parity symmetry. Once \( H \) acquires a v.e.v. \( c_1 \) induces decays of \( H \) to two \( S \)'s, and \( c_2 \) induces a mixing between \( S \) and \( H \).
**Higgs Couplings to Gauge Bosons**

- In general, in the presence of an extended sector having extra singlets and doublets, the CP-even and CP-odd Higgs mass eigenstates will not coincide with the weak eigenstates.

- The \( VVH \) coupling will be proportional to the projection of the Higgs components into the one acquiring a v.e.v.

- For instance, in two Higgs doublet models

\[
\frac{g_{VVH_i}^{SM}}{g_{VVH}^{SM}} = O_{i1} \cos \beta + O_{i2} \sin \beta;
\]

where \( O_{i1} \) and \( O_{i2} \) are the components of the i-Higgs on the real neutral components of the Higgs doublets, \( H_1 \) and \( H_2 \), which acquire a v.e.v.

\[
\sum_i g_{VVH_i}^2 = 1
\]

---

**Standard Higgs Search Channels at LEP**

Figure 1: Higgs boson production processes at LEP.

- Bjorken process
- Pair production
- Yukawa process

**SM-like Higgs**

**Extended Higgs Doublets**
Exotic Higgs Decays into two Scalars.

Non-SM-like Higgs h  
Non-Singlet A. Easiest realization:  
h and A are real and imaginary  
components of the charged zero  
component of a “doublet” of SU(2)

SM-like Higgs h  
Appears in both singlet and non-singlet  
A cases

LEP Higgs “Excess” at 100 GeV

LEP experiments saw an excess of Higgs events at around 100 GeV.  
Not consistent with SM-Higgs production and decay rates

\[
\frac{g_{HVV}^2 BR(H \rightarrow b\bar{b})}{[g_{HVV}^2 BR(H \rightarrow b\bar{b})]_{SM}} \approx 0.1
\]

This excess could be explained by a Higgs with either reduced  
coupling to the Higgs or reduced branching ratio (via, for instance,  
additional decay channels)  
Gunion and Dermisek’07

A SM-like Higgs boson of mass 100 GeV, decaying into two lighter  
scalars is an attractive possibility, since it would improve the  
agreement with precision measurements.

It would also reduce necessity of radiative corrections (fine tuning)

Alternatively, Higgs bosons with reduced couplings may be present  
in the CPX model  
M. Carena, J. Ellis, A. Pilaftsis and C.W. ’00, Drees’05
Higgs Decays into two lighter Higgs bosons
Signatures at Hadron Colliders

We will concentrate on the production of Higgs bosons associated with weak gauge bosons

<table>
<thead>
<tr>
<th>parameters</th>
<th>representative value</th>
<th>considered range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{h}$</td>
<td>120</td>
<td>90–130</td>
</tr>
<tr>
<td>$m_{a}$</td>
<td>30</td>
<td>20–60</td>
</tr>
<tr>
<td>$\kappa^h_{VV}$</td>
<td>0.7</td>
<td>0.5–1.0</td>
</tr>
<tr>
<td>$\kappa^a_{VV}$</td>
<td>0.95</td>
<td>0.8–1.0</td>
</tr>
<tr>
<td>$\kappa^{\tau \tau}_{VV}$</td>
<td>0.08</td>
<td>0.05–0.50</td>
</tr>
</tbody>
</table>

$Wh \rightarrow l\nu_l, aa \rightarrow \{l\nu_l, b\bar{b}, \tau^{+}\tau^{-}\}$

$Zh \rightarrow l^{+}l^{-}, aa \rightarrow \{l^{+}l^{-}, b\bar{b}, \tau^{+}\tau^{-}\}$

$\sigma(Vh) = \kappa^{2}_{hVV} \sigma^{SM}(Vh)$

$C_{2b2\tau}^{2} \equiv 2\kappa^{2}_{hVV} BR(h \rightarrow aa)BR(a \rightarrow b\bar{b})BR(a \rightarrow \tau^{+}\tau^{-})$

$C_{4b}^{2} \equiv \kappa^{2}_{hVV} BR(h \rightarrow aa)BR(a \rightarrow b\bar{b})^{2}$

Higgs Production Cross Section in the 2b 2$\tau$ channel

$p_T(j) > 10$ GeV, $|\eta(j)| < 3.0$,

$p_T > 10, 8, 5$ GeV for $\tau_h, \tau_e, \tau_{\mu}$, $|\eta| < 1.5$.

$\varepsilon_b = 50\%$ for $E_T^{jet} > 15$ GeV and $|\eta_{jet}| < 1.0$.

$\varepsilon_{\tau} = 40\%$ for $E_{vis} > 20$ GeV and $|\eta| < 1.5$.

Isolation cut: $\Delta R > 0.4$

We tag one b-jet and one tau
Higgs Cross Section in the 4b channel

Three b-tags are required

Small Higgs masses and large branching ratios excluded by LEP

Higgs Bosons Invariant Mass Reconstruction at the Tevatron

Irreducible and Reducible Backgrounds are small after applying cuts. Evidence of Higgs production may be observed at the Tevatron. But production cross section too small to expect a discovery at the Tevatron in these decay channels.
Higgs Signal Cross Section at the LHC

\[ p_T(l) > 20 \text{ GeV, } |\eta(l)| < 2.5, \quad E_T > 20 \text{ GeV}. \]
\[ \epsilon_b = 50\% \text{ for } E_T^{\text{jet}} > 15 \text{ GeV and } |\eta_{\text{jet}}| < 2.0, \]
\[ \epsilon_r = 40\% \text{ for } E_{\text{vis}} > 15 \text{ GeV and } |\eta| < 2.5. \]

Wh \to lvb\bar{b}r^*\tau^- \text{ at LHC}

Wh \to lvbbb\bar{b} at LHC

Production Cross Section much larger at the LHC. We demand one b-tau and one tau tag, for the first, and 3 b-tags for the second.

But backgrounds also increase in a significant way.

Background for the 2 b 2 tau channel

- Irreducible background from
  \[ W bb (Z/\gamma^* \rightarrow \tau\tau) \]
  very small.

- But reducible background from, for instance
  \[ W bb 2j \]
  leads, considering a jet rejection rate of about 1/150, to a background of around 92 fb, compared with a signal of order 1 fb.

- We will therefore concentrate on the 4b channel where, demanding at least three b-taggings, the signal to background ratio increases to more reasonable levels.
Backgrounds for the 4b channel

- The signal, for the representative point is about 6fb
- Irreducible background from 4 b's + lepton + Miss. Energy is of about 25 fb
- Reducible background from W 2b 2j (mostly from top quark production) is of about 80 fb
- Since the 2b 2j system in the background events that come from top quark production contain all the decay products of a top quark, it can be reduced by imposing the constraint

\[ m(4b) \leq 160 \text{ GeV} \]

Reconstruction of Higgs Bosons Invariant Mass

Selecting Invariant Mass Windows:

- \( 10 \text{ GeV} < m(2b) < 70 \text{ GeV} \),
- \( 60 \text{ GeV} < m(4b) < 160 \text{ GeV} \).

A significance of about 3.5 \( \sigma \) is obtained for 10 fb\(^{-1}\). Higgs Boson(s) may be discovered with 30 fb\(^{-1}\).
The origin of electroweak symmetry breaking mechanism remains a mystery.

For a light Higgs, dominant decay mode is into the relatively light bottom quark. If other light degrees of freedom are present, they can easily provide the dominant decay mode.

Searches for several new modes have been performed at LEP.

If the Higgs decays into lighter Higgs bosons, the Tevatron and the LHC will still have a chance of finding it.

It is quite important to analyze Higgs searches in alternative decay channels to fully test the mechanism of electroweak symmetry breaking.
Another interesting example within the CPX Scenario:

1. \( m_{H^+} = 160 \text{ GeV} \quad \tan \beta = 4 \)
2. \( m_{H^+} = 150 \text{ GeV} \quad \tan \beta = 5 \)
3. \( m_{H^+} = 140 \text{ GeV} \quad \tan \beta = 6 \)

\[ \arg(A_{t,b}) = 110^\circ \text{ and case (3)} \]

\[ \Rightarrow m_{H^2} = 112 \text{ GeV} \quad \text{and} \quad m_{H_1} = 40 \text{ GeV} \]

\( g_{H_1ZZ} \) too small to detect \( H_1 \)

\( H_2 \) is produced via Higgs-strahlung but, it has sizeable decay rate into \( H_1H_1 \)

**New search mode opens up:**

\[ ZH_2 \to ZH_1H_1 \to Zb\bar{b}b \]

---

**Generation of \( \mu \): Giudice-Masiero mechanism**

- Assume exact Peccei-Quinn symmetry forbidding \( \mu \)
- Then, introduce higher dimensional operators in Kahler function

\[ \Delta \mathcal{L} = \int d^4 \theta \ H_u H_d \left( c_1 \frac{X}{M} + c_2 \frac{X^\dagger X}{M^2} \right) + h.c. \]

- where \( X = X + F_X \theta^2 \) is the SUSY breaking chiral superfield. Then,

\[ \mu = \frac{c_1 F_X}{M}, \quad B_\mu = \frac{c_2 F_X^2}{M^2} \]

- But in theories of gauge mediation, as we have seen

\[ \frac{B_\mu}{\mu} \approx \frac{F_X}{M} \approx 100 \text{ TeV} \]

- It is therefore required that \( c_2 \) is suppressed. Different alternatives have been proposed to make it work. I will concentrate on a slightly different strategy.
Neutralino Mass Matrix

For large values of the gaugino masses, masses are proportional to the Higgs vacuum expectation values, and naturally of the weak scale

In the nMSSM, $\kappa = 0$.

$$M_{\tilde{\chi}^0} = \begin{pmatrix}
M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z & 0 \\
0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z & 0 \\
-c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & \lambda v_s & \lambda v_2 \\
s_\beta s_W M_Z & -s_\beta c_W M_Z & \lambda v_s & 0 & \lambda v_1 \\
0 & 0 & \lambda v_2 & \lambda v_1 & 2\kappa v_s
\end{pmatrix},$$

Five Neutralinos in the Spectrum, the new states being a singlino that mixes with the standard Higgsinos

---

Upper bound on Neutralino Masses

$$m_1 = \frac{2\lambda v \sin \beta \ x}{(1 + \tan^2 \beta + x^2)} \quad \text{with} \quad x = \frac{v_s}{v_1}$$

Values of neutralino masses below dotted line consistent with perturbativity constraints.
Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are imposed.
Z-boson and Higgs boson contributions shown to guide the eye.

\[
\Omega h^2
\]

\[
\text{Z-width constraint}
\]

CP-even Masses

- For large values of the singlet v.e.v. compared to the weak scale, \( M_C \simeq v, \, v_s/v = \epsilon \), we get

NMSSM (with an additional assumption of \( \kappa \sim \epsilon \)):

\[
M_{h_1}^2 \approx \frac{1}{2} v_s \kappa (4 v_s \kappa + \sqrt{2} A_s)
\]

\[
M_{h_2,3}^2 \approx \frac{1}{2} M_Z^2 + \left( A_\lambda + \frac{v_s \kappa}{\sqrt{2}} \right) \mu_{\text{eff}} \csc 2\beta
\]

\[+ \sqrt{\left( \frac{1}{2} M_Z^2 - \left( A_\lambda + \frac{v_s \kappa}{\sqrt{2}} \right) \mu_{\text{eff}} \csc 2\beta \right)^2 + 2 M_Z^2 \left( A_\lambda + \frac{v_s \kappa}{\sqrt{2}} \right) \mu_{\text{eff}} \sin 2\beta} \]

NMSSM/AMSSM (with an additional assumption of \( t_s/M_C^2 \sim \epsilon \)):

\[
M_{h_1}^2 \approx \frac{1}{2} \frac{\mu_{\text{eff}} \sec^2 2\beta}{v_s^2} \left( 32 \mu_{\text{eff}}^2 \sin 2\beta A_\lambda^2 - G_\lambda v^2 \sin^3 2\beta (4 \mu_{\text{eff}}^2 + A_\lambda^2) 
\right.
\]

\[+ 2 \mu_{\text{eff}} A_\lambda (G_\lambda v^2 - 16 \mu_{\text{eff}}^2 - 2 A_\lambda^2 + \cos 4\beta (-G_\lambda v^2 + 2 A_\lambda^2)) - \frac{\sqrt{2} t_s}{v_s} \]

\[
M_{h_2,3}^2 \approx \frac{1}{2} M_Z^2 + A_\lambda \mu_{\text{eff}} \csc 2\beta \pm \sqrt{\left( \frac{1}{2} M_Z^2 - A_\lambda \mu_{\text{eff}} \csc 2\beta \right)^2 + 2 M_Z^2 A_\lambda \mu_{\text{eff}} \sin 2\beta}
\]

UMSSM:

\[
M_{h_1}^2 \approx \frac{1}{2} M_Z^2 + A_\lambda \mu_{\text{eff}} \csc 2\beta \pm \sqrt{\left( \frac{1}{2} M_Z^2 - A_\lambda \mu_{\text{eff}} \csc 2\beta \right)^2 + 2 M_Z^2 A_\lambda \mu_{\text{eff}} \sin 2\beta}
\]

\[
M_{h_2,3}^2 \approx M_Z^2 \quad (\text{with Z' mass given by} \; M_{Z'}^2 = g_{\gamma Z'}^2 (Q_{h_2,3}^2 v_s^2 + Q_{h_2,3}^2 v_s^2 + Q_{h_2,3}^2 v_s^2))
\]
CP-even Higgs Boson Searches

- Invisibly decaying Higgs may be searched for at the LHC in the Weak Boson Fusion production channel.

- Defining

\[ \eta = \frac{\text{BR}(H \rightarrow \text{inv.})}{\sigma(WBF)} \frac{\sigma(WBF)}{\sigma(WBF)_{SM}} \]

- The value of \( \eta \) varies between 0.5 and 0.9 for the lightest CP-even Higgs boson.

- Minimal luminosity required to exclude (discover) such a Higgs boson, with mass lower than 130 GeV:

\[ L_{95\%} = \frac{1.2 \text{ fb}^{-1}}{\eta^2}, \quad L_{5\sigma} = \frac{8 \text{ fb}^{-1}}{\eta^2} \]

---

Higgs Working Group, Les Houches'01

- Lightest CP-odd and heavier CP-even has much larger singlet component. More difficult to determine