Determination of the Discovery Potential for Higgs Bosons in MSSM

Dorian Kcira
University of Louvain
Center for Particle Physics and Phenomenology

On behalf of the CMS and ATLAS collaborations

The 15th International Conference on Supersymmetry and the Unification of Fundamental Interactions
Karlsruhe, Germany, July 26 - August 1, 2007
Outline

• The MSSM Higgs Sector

• Discovery Potential
  ➢ CP-Conserving scenarios
  ➢ CP-Violating scenarios

• Summary
The Standard Model does a great job in description of physics at the weak scale (100 GeV)

- But: hierarchy problem in the Higgs sector

- SUSY at the TeV scale provides elegant solution to the hierarchy problem
  - Introduces superpartners of SM particles and cancels problematic loop corrections out
  - Allows light Higgs in the context of GUT without fine tuning
Minimal SuperSymmetric Model

- Thorough intro: Abdelhak Djouadi, SUSY07
  - [http://indico.cern.ch/materialDisplay.py?contribId=78&amp;sessionId=143&amp;materialId=slides&amp;confId=6210](http://indico.cern.ch/materialDisplay.py?contribId=78&amp;sessionId=143&amp;materialId=slides&amp;confId=6210)

- 2HDM - two isospin Higgs doublets
  - $\Phi_1$ couples to down-, $\Phi_2$ to up-type fermions

- Higgs sector described by 4 masses and 2 mixing angles
  - 3 of 8 degrees of freedom absorbed by $Z$, $W^\pm$ after EW symmetry breaking, 5 physical higgses
  - $h$, $H$ (scalar, CP-even),
  - $A$ (pseudoscalar, CP-odd),
  - $H^\pm$ (charged)
  - $\beta$ (VEVs), $\alpha$ (mixing of neutral CP-even)
    - $\tan \beta = v_2/v_1$, $v_1^2 + v_2^2 = 1$
Minimal SyperSymmetric Model

- Assuming CP conservation, at tree level
  - Only 2 independent params.: choose $M_A$ and $\tan \beta$
  - Mass hierarchies: $M_h < M_Z$, $M_A < M_H$ & $M_{W^\pm} < M_{H^\pm}$

- Radiative corrections increase upper bound on $M_h \sim 135$ GeV
  - Upper bound reached at large $M_A$ => SM-like $h$

Graph showing the relationship between $m_A$ (GeV) and Higgs mass (GeV). The graph includes lines for maximal mixing, $\mu = -200$ GeV, $M_{susy} = 1$ TeV, $H^*$, $H$, $h$, and $\tan \beta = 3$. The upper bound on $M_h$ is indicated as approximately 135 GeV.
Unconstrained MSSM has large number of free parameters. Choose specific parameter points: benchmark scenarios

- $M_h^{\text{max}}$ scenario
  - maximal $M_h < 133 \text{GeV}$
  - Conservative exclusion bounds on $\tan \beta$ and $M_A$
  - Used at LEP, $M_{\text{SUSY}} = 1 \text{TeV}$

- No-mixing scenario
  - Small $M_h < 116 \text{GeV}$
  - No stop mixing, $X_t = 0$, $M_{\text{SUSY}} = 2 \text{TeV}$

- Gluophobic scenario
  - small $g_{h,\text{gluon}}$
    - main production channel $gg \rightarrow h$
    - strongly suppressed
  - $M_h < 119 \text{ GeV}$, $M_{\text{SUSY}} = 350 \text{GeV}$

- Small-$\alpha$ scenario
  - small $g_{hbb}$ and $g_{h\tau\tau}$
  - $M_h < 123 \text{ GeV}, M_{\text{SUSY}} = 800 \text{GeV}$
Neutral Higgs Production Mechanisms

**gg fusion:** dominant at small & moderate $\tan \beta$;
Mediated by t/b loops (also stop/sbottom loops $M < 400 \text{ GeV}/c^2$)

Associated production: $tt\Phi$ only important for $h$; $bb\Phi$ dominant process for large $\tan \beta$

**VBF:** important when $h$ at upper mass limit “SM-like” and $H$ at lower mass bound. (No VBF for $A$ at tree level)

Not important for MSSM neutral Higgs production
Light Neutral Higgs - Low Luminosity

- Light neutral scalar Higgs constrained to be “SM-like”
- Use SM Higgs search results to determine SUSY discovery potential
- \( M_{h_{\text{max}}} \) scenario, low luminosity
  - Production: VBF, decay: \( \gamma\gamma, WW, \tau\tau, \mu\mu \)
  - CMS: 30/60 fb\(^{-1}\) (heavier H included in plot), ATLAS: 30 fb\(^{-1}\)
- 5\sigma discovery regions

\[
\begin{align*}
\text{CMS} & \\
\text{m}_{h_{\text{max}}} & \\
M_{\text{SUSY}} = 1 \text{ TeV}/c^2 & \\
M_{\phi} = 200 \text{ GeV}/c^2 & \\
\mu = 200 \text{ GeV}/c^2 & \\
m_{\text{gluino}} = 800 \text{ GeV}/c^2 & \\
\text{Stop mix: } \chi_t = 2 M_{\text{SUSY}} & \\
\end{align*}
\]

\[
\begin{align*}
\text{ATLAS Preliminary 30fb}^{-1} & \\
\text{MHMAX Scenario} & \\
\end{align*}
\]
Light Neutral Higgs - Other Scenarios

- Difference mainly due to different $m_h$ in same $(\tan\beta, M_A)$ (up to 17 GeV difference)
- $H \to \tau\tau$ main discovery channel. Assoc. production important at moderate $\tan\beta$ and small $M_A$
- "Hole" in small-\(\alpha\) scenario due to $H \to \tau\tau$ branching ratio closed by enhanced BR to gauge bosons
- Complementarity of search channels (almost) guarantees observation of $h$

Gluophobic scenario

Small $\alpha$ scenario
Light Neutral Higgs – High Luminosity

- L = 300 fb⁻¹ (only VBF at 30 fb⁻¹)
  - includes h → γγ, h → Z → 4 l, tth → bb
- Small area uncovered mh = 90 ÷ 100 GeV
- h → γγ sensitive in gluophobic scenario due to Wh, tth production

- Large area covered by several channels
- Sure discovery and parameter determination possible
Heavy Neutral Higgs Production

- Measure large $\tan\beta$, unexplored at LEP
- Associated production: $gg/qq \rightarrow bb\Phi$
- Decays: $gg/qq \rightarrow bb\Phi, \Phi \rightarrow bb, \tau\tau, \mu\mu$
  - Leptonic decays smaller branching ratio but much cleaner signature

Width measurement possible
- large $\tan\beta \Rightarrow \Phi$ width comparable to / dominates experimental mass resolution
- $\mu\mu$ decay gives best mass and width measurement for $\Phi = H/A$

CMS

<table>
<thead>
<tr>
<th>events / 1 GeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS, 30 fb⁻¹</td>
</tr>
</tbody>
</table>

$M_{\mu\mu}$ (GeV/c²)

- $M_h^{\text{max}}$ - scenario
  - $M_A = 150$ GeV/c²
  - $\tan\beta = 40$
Heavy Neutral Higgs production

3 different regimes

- **Low** $M_A$: $M_A < M_{h_{\text{MAX}}}$
  - $M_A \sim M_h$

- **Intensive coupling:**
  - $M_A \sim M_h \sim M_H$

- **Decoupling:**
  - $M_A \gg M_h$, $M_A \sim M_H \sim M_{H^+}$, $M_h \sim M_{h_{\text{MAX}}}$

- Coverage in the $M_{h_{\text{MAX}}}$ scenario.
- Coverage in other scenarios similar.
Neutral Higgs production: Constrain $\tan\beta$

$\Phi$ width sensitive to $\tan\beta$

$\Gamma_\Phi \sim \tan^2 \beta$

imperfect A-H degeneracy gives contribution to width

- Uncertainty on $\tan\beta$ measurement using the width-angle relation
- 15% theoretical uncertainty included
- Further constraints can be applied using the relation $\sigma \times Br \sim \tan^2 \beta_{\text{eff}}$
Neutral Higgs production: Access to low tan\(\beta\)

Search for \(gg(qq)\rightarrow A\rightarrow Zh\)

- decays: \(Z\rightarrow l^+l^-\), \(h\rightarrow bb\)
- detect \(A\) and \(h\) simultaneously
- Largest \(\text{Br}(A\rightarrow Zh)\) for low tan\(\beta\) and \(M_Z+M_h<M_A<2M_{\text{top}}\)

- Measure low tan\(\beta\) region not completely excluded by LEP
- 5\(\sigma\) discovery contours for 30 and 60 fb\(^{-1}\)
  - For 30 fb\(^{-1}\), tested systematic uncertainty
Charged Higgs Production

- No charged Higgs in SM
  - tree level: $M_{H^\pm}^2 = M_A^2 + M_W^2$
  - Radiat. corr. can push mass below the $m_{top}$

Production mechanisms:
- High mass, $M_{H^\pm} > M_{top}$: $gb \rightarrow tH^\pm$
- Low mass, $M_{H^\pm} < M_{top}$: $gg \rightarrow tbH^\pm$
- Two main decay channels:
  - $H^\pm \rightarrow \tau \nu$ clean, good reach
  - $H^\pm \rightarrow tb$ multi-jet background

$\tan \beta$ vs. $M_A$ (GeV)
- $pp \rightarrow tbH^\pm$, $H^\pm \rightarrow \tau \nu$
- $m_t = 175$ GeV/$c^2$
- $m_{max}$ scenario
  - $M_{SUSY} = 1$ TeV/$c^2$
  - $M_2 = 200$ GeV/$c^2$
  - $\mu = 200$ GeV/$c^2$
  - $m_{gluino} = 800$ GeV/$c^2$
  - Stop mix: $X_t = 2 M_{SUSY}$

$N_{exp} / 10$ fb$^{-1}$
- $tt \rightarrow bH^+ bW^-$, $H^+ \rightarrow \tau \nu$, $W^- l\nu$
- $tt \rightarrow bH^+ bW^-$, $H^+ \rightarrow \tau \nu$, $W^- qq$
- $30$ fb$^{-1}$

Excluded by LEP (prelim.)
Charged Higgs Production

- NLO includes $t\bar{t}$ prod. for $M_{\text{top}} > M_{H^\pm}$
  - Careful handling of predictions in transition region
  - Avoid double counting of different processes
- Decay channels $H^\pm \rightarrow \tau \nu\tau$, $t \rightarrow b jj$ studied with matched production $gg \rightarrow tbH$, $gb \rightarrow tH$
- MATCHIG (J. Alwall hep-ph/0503124)

- @ 30fb$^{-1}$: discover $H^\pm < 160$GeV for all $\tan \beta$, all mass region for $\tan \beta > 40$
- Decrease of cross section vs. $M_{H^\pm}$ explains shape of discovery contour in $(M_{H^\pm}, \sigma)$
- First results using properly-handled theory to look at full mass range
**Overall Discovery Potential CP-Conserving MSSM**

- **Discovery potential**
  - CMS: 30/60fb$^{-1}$, only associated neutral higgs here, others in previous slides
  - ATLAS: 300 fb$^{-1}$ $M_h^{\text{max}}$, VBF channels, H/A$\rightarrow$tt only with 30fb$^{-1}$

- At least one Higgs boson observable for all parameters in all four scenarios

- Only $h$ for significant part of phase space

- Can this MSSM $h$ be discriminated from the SM Higgs?
SM or Extended Higgs Sector?

- estimate sensitivity from rate measurements in VBF (30fb⁻¹)
  - Only stat errors, assume \( M_h \) exactly known

\[
R = \frac{BR(h \rightarrow \tau\tau)}{BR(h \rightarrow WW)}
\]

- Compare MSSM (expected) measurement with SM prediction

\[
\Delta = \frac{R_{MSSM} - R_{SM}}{\sigma_{exp}}
\]

- Potential for discrimination
  - Seems promising, further studies will include syst. errors

ATLAS Preliminary

\( > 1 \) Higgs boson

\( \Delta > 2 \)
\( \Delta > 1 \)

excluded by LEP (prel.)
Distinguish Between MSSM & SM Couplings

- Perform $\chi^2$ analysis of couplings.
- Exclusion of SM
- Plot at $3\sigma$ discrepancy from standard model

For $2*300$ fb$^{-1}$:

- $3\sigma \rightarrow M_A < 450$GeV
- $5\sigma \rightarrow M_A < 350$GeV

M. Duhrssen et al. hep-ph/0406323
The CP violating CPX scenario

- CP conserving at Born level but CP violation via complex trilinear couplings $A_{t,b}$
- CP eigenstates $h, A, H$ mix to mass eigenstates $H_1, H_2, H_3$
  - $M_{H_1} < M_{H_2} < M_{H_3}$
- No more well defined $M_A$, the only remaining well defined mass parameter is $M_{H^+}$
- CPX scenario: maximize effect
  - $\arg(A_{t,b}) = \arg(M_{\text{gluino}}) = 90^\circ$
- Carena et al.
  - hep-ph/0202167
  - hep-ph/0009212
The CPX Scenario

- $H_1, H_2, H_3$ couple to $W, Z$
  - No $g_{AVV}$ coupling in CPC
  - $H_1$ decouples from boson for $m_{H^+} < 150$GeV
- No absolute limit on $H_1$ from LEP
  - Loss of sensitivity for $\tan\beta = 3 \div 10$ due to complexity of final states
  - Insensitivity to low Higgs mass
  - Exclusion region strongly depends on $M_{\text{top}}$
- LHC: $H_1$ relevant channels
  - VBF: $H_1 \rightarrow WW$, $H_1 \rightarrow \tau\tau$
  - bbh: $H_1 \rightarrow \mu\mu$
  - tth: $H_1 \rightarrow bb$

$M_{\text{top}} = 174.3$GeV
• Discovery potential with 300fb⁻¹
• Almost whole parameter space covered by observation of at least one Higgs boson
• Only H1 observable in intermediate \( \tan \beta \)
• Small uncovered region not yet excluded by LEP
  ➢ Calculations for uncovered region strongly depend on the top quark mass
    ▪ FeynHiggs2.1, \( M_{\text{top}}=175 \text{ GeV} \), gives: \( M_{H1}<50, 105<M_{H2}<115, 140<M_{H3}<180, 130<M_{H^\pm}<170 \text{ GeV} \)
  ➢ Studying possibility to cover this area with top pair production using the decay chain
    ▪ \( t \rightarrow bH^+ \rightarrow bWH_1 \rightarrow bqqbb \)
    ▪ \( t \rightarrow bW \)
Summary

- For the CP-Conserving MSSM Higgs all of the parameter space is potentially covered (30 fb\(^{-1}\)) by discovery of at least one Higgs boson
- Coverage seen on all 4 benchmark scenarios reflects probably most of MSSM phase space
- In large regions of the phase space only the SM-like MSSM Higgs boson might be observed. Working on strategies to distinguish between SM and MSSM origin in this case

- For the CP-Violating MSSM, almost all parameter space covered by observation of at least one Higgs in the CPX scenario.
- Studies ongoing on small uncovered space (\(M_{H_1}<50\text{GeV}\)) not excluded by LEP searches