SUSY after the Higgs
Implications of LHC Higgs results for supersymmetry

HEFTI Higgs Signal Workshop, UC Davis, 22-26 April 2013
Introduction

- The 2012 Higgs discovery at ~125 GeV is a tremendous first success of the LHC program.

- Completes the Standard Model (SM) of electroweak and strong interactions.

- However, this should not be regarded as the closing of a chapter but the opening of a new one.

- Most pressing issue: to explain the value of the electroweak (EW) scale itself. Why is the Higgs boson so light when it is predicted to be driven to the GUT or Planck scale by radiative corrections?

\[
\text{new physics at the TeV scale (or extreme fine-tuning)}
\]
Beyond the SM?

- While the SM provides a good fit to the data, the situation not yet conclusive. E.g. some new physics contributions to the effective couplings to gluons and photons are quite possible.

- Supersymmetry is a very attractive framework to explain the ‘smallness’ of the Higgs mass.

- With the absence of any sign of new physics, the Higgs results may become our main guide for where to look for SUSY (or other BSM).

- This talk is about what the Higgs can tell us (and cannot tell us) about supersymmetry.

Fit to ATLAS, CMS and Tevatron data for SM-like Higgs couplings to fermions and gauge bosons.
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Two parts:
1. GUT-scale boundary conditions
2. phenomenological MSSM

Fit to ATLAS, CMS and Tevatron data for SM-like Higgs couplings to fermions and gauge bosons.

Two parts:
1. GUT-scale boundary conditions
2. phenomenological MSSM
Disclaimer

This talk has been done on very short notice.

Plots got ready yesterday,
thanks to Suchita Kulkarni and Sezen Sekmen.

Preliminary results,
be kind to me ;-)
MSSM Higgs mass

- Three level prediction for the light Higgs mass in the MSSM: $m_h \leq m_Z$!
- Need $\sim100\%$ radiative corrections to achieve $m_h$ around 125-126 GeV

\[
m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2
\]

\[
(126 \text{ GeV})^2 = (91 \text{ GeV})^2 + (87 \text{ GeV})^2
\]

\[
\Delta m_h^2 = \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left( \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right)
\]

- $\Delta m_h^2$ is maximized for $|X_t/M_S| \simeq \sqrt{6}$ .... “maximal mixing”

\[
X_t = A_t - \mu \cot \beta, \quad M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}
\]

Brummer, Kulkarni, SK, arXiv:1204.5977
GUT-scale boundary conditions:
Non-universal Higgs mass (NUHM) model

parameters to scan over:

\[ m_0, M_{1/2}, A_0 \bigg|_{M_{\text{GUT}}} \mu, m_A, \tan \beta \bigg|_{M_{\text{EW}}} \]

based on

“Anatomy of maximal mixing”
F. Brümmer, SK, S. Kulkarni, arXiv:1204.5977
Constraints

- **B-physics:**
  \[ 2.87 < BR(b \rightarrow s\gamma) \times 10^4 < 4.23 \]
  \[ 0.015 < BR(B_s \rightarrow \mu\mu) \times 10^9 < 6.35 \]

- **SUSY mass limits from LEP; LHC: \( m(\text{gluino}) > 1\text{ TeV} \)**

- **Higgs mass:** \( m_h^{\text{MSSM}} = [123, 128] \text{ GeV} \) assuming \( \sim 2 \text{ GeV} \) theory uncertainty

- For Higgs signal strengths \( R \), require consistency with 95% CL ellipses (orange):

  Combined ATLAS+CMS+Tevatron signal strength ellipses, cf. Beranger Dumont’s talk on Monday
Higgs versus stop mass

color code shows amount of stop mixing
Higgs versus stop mass

color code shows amount of stop mixing

small mixing requires heavy stops
Higgs versus stop mass

color code shows amount of stop mixing
Higgs versus stop mass

color code shows amount of stop mixing

light stops require large mixing
small mixing requires heavy stops
Higgs versus stop mass

The color code shows the amount of stop mixing:
- Small mixing requires heavy stops.
- Light stops require large mixing.

95% CL Higgs signal strength requirement has marginal effect, excludes only <1% of points.
Higgs versus stop mass

Color code shows amount of stop mixing

Stop below 1 TeV requires $|X_t/M_S| \gtrsim 1.8$.
Higgs versus stop mass

color code shows amount of stop mixing

stop below 1 TeV requires $|X_t/M_S| \gtrsim 1.8$
A terms

with universal $m_0$:

\[ m_h \approx 125 \text{ GeV from maximal mixing (light stops)} \]

requires very large negative $A_0$

\[ A_0 \approx (-2 \text{ to } -3) \times \max(m_0, M_{1/2}) \]

\[
X_t^4 \approx 9.4 M_{1/2}^4 - 7.5 A_0 M_{1/2}^3 + 2.2 A_0^2 M_{1/2}^2 - 0.3 A_0^3 M_{1/2} \\
+ 1.1 M_{1/2} \hat{\mu} - 0.7 A_0 M_{1/2} \hat{\mu}.
\]

\[
M_S = m^2_{U_3} m^2_{Q_3} |_{M_S} \approx 8.7 M_{1/2}^4 + 2.5 M_{1/2}^2 \hat{m}_{U_3}^2 + 1.7 M_{1/2} \hat{m}_{Q_3}^2 + 1.2 A_0 M_{1/2}^3 \\
- 0.4 A_0^2 M_{1/2} - 0.9 M_{1/2} \hat{m}_{H_u}^2 + 0.8 \hat{m}_{U_3}^2 \hat{m}_{Q_3}^2.
\]
A terms

with universal $m_0$:

$m_h \sim 125$ GeV from maximal mixing (light stops)

requires very large negative $A_0$

$$A_0 \approx (-2 \text{ to } -3) \times \max(m_0, M_{1/2})$$

$$X_1^4 \approx 9.4 M_{1/2}^4 - 7.5 A_0 M_{1/2}^3 + 2.2 A_0^2 M_{1/2}^2 - 0.3 A_0^3 M_{1/2}$$

$$+ 1.1 M_{1/2}^3 \tilde{\mu} - 0.7 A_0 M_{1/2} \tilde{\mu}.$$

$$M_S^4 = m_{U_3}^2 m_{Q_3}^2 \big|_{M_S} \approx 8.7 M_{1/2}^4 + 2.5 M_{1/2}^2 \tilde{m}_{U_3}^2 + 1.7 M_{1/2} \tilde{m}_{Q_3}^2 + 1.2 A_0 M_{1/2}$$

$$- 0.4 A_0^2 M_{1/2}^2 - 0.9 M_{1/2} \tilde{m}_{H_u}^2 + 0.8 \tilde{m}_{U_3}^2 \tilde{m}_{Q_3}^2.$$
NUHM with 10 TeV squarks

2-loop effects in the RGE running drive $M_S$ down.

Light stops, near-maximal mixing and $m_h \sim 125$ GeV even for moderate $A_0$

Howie Baer's talk tomorrow
SUSY particles

- **stop**
- **gluino**
- **chargino**
- **neutralino**
- **bino LSP**
- **higgsino LSP**
- **$\Omega h^2$**
- **$\mu$**

**Diagram Elements**

- **HEFTI LHC Higgs Signal Workshop, UC Davis, 22-26 Apr 2013**
- **S. Kraml**
SUSY particles

stop

gluino

s. Kraml

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neutralino

μ

Ω h^2

bino LSP

higgsino LSP

higgsino LSP branch
SUSY particles

Don't worry about $\Omega h^2 \gg 0.1$; e.g. additional entropy production or neutralino decaying into axinos.
Signal strengths

\[ R(\text{X} \rightarrow \text{h} \rightarrow \text{Y}) = \frac{\Gamma(\text{h} \rightarrow \text{X}) \, \text{BR}(\text{h} \rightarrow \text{Y})}{\Gamma(H_{\text{SM}} \rightarrow \text{X}) \, \text{BR}(H_{\text{SM}} \rightarrow \text{Y})} \]
Signal strengths, $m(\text{stop1}) < 1 \text{ TeV}$

\[
R(X \rightarrow h \rightarrow Y) = \frac{\Gamma(h \rightarrow X) \text{ BR}(h \rightarrow Y)}{\Gamma(H_{\text{SM}} \rightarrow X) \text{ BR}(H_{\text{SM}} \rightarrow Y)}
\]
Phenomenological MSSM
(19-parameter realization of general MSSM)

parameters defined at the weak scale,
no SUSY breaking prejudices, no RGE running

Markov Chain Monte Carlo analysis
based on work with
Sezen Sekmen, JFG, et al.

CMS analysis not approved yet!
MCMC

• Markov Chain Monte Carlo (MCMC): random walk through parameter space guided by the likelihood function

• Sampling of parameter space with flat prior

\[-3 \text{ TeV} \leq M_1, M_2 \leq 3 \text{ TeV}\]
\[0 \leq M_3 \leq 3 \text{ TeV}\]
\[-3 \text{ TeV} \leq \mu \leq 3 \text{ TeV}\]
\[0 \leq m_A \leq 3 \text{ TeV}\]
\[2 \leq \tan \beta \leq 60\]
\[0 \leq \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \leq 3 \text{ TeV}\]
\[-7 \text{ TeV} \leq A_t, A_b, A_{\tau} \leq 7 \text{ TeV}\]

• Minimal assumptions: R-parity, neutralino LSP, flavor-diagonal mass-matrices and A terms, 1st/2nd gen. degenerate, no new CP phases

• Results are probability distributions of parameters, masses, etc; advantage: it gives rigorous Bayesian statistics interpretation
### Constraints: “preHiggs”

<table>
<thead>
<tr>
<th>i</th>
<th>Observable</th>
<th>Constraint</th>
<th>Likelihood function</th>
<th>MCMC / post-MCMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$BR(b \to s\gamma)$</td>
<td>$\left(3.55 \pm 0.23^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.09^{\text{sys}}\right) \times 10^{-4}$</td>
<td>Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>2a</td>
<td>$BR(B_s \to \mu\mu)$</td>
<td>observed CLs curve from [29]</td>
<td>$d(1 - \text{CLs})/dx$</td>
<td>MCMC</td>
</tr>
<tr>
<td>2b</td>
<td>$BR(B_s \to \mu\mu)$</td>
<td>$3.2^{+1.5}_{-1.2} \times 10^{-9}$</td>
<td>2-sided Gaussian</td>
<td>post-MCMC</td>
</tr>
<tr>
<td>3</td>
<td>$R(B_u \to \tau\nu)$</td>
<td>$1.63 \pm 0.54$</td>
<td>Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>4</td>
<td>$\Delta a_\mu$</td>
<td>$(26.1 \pm 8.0^{\text{exp}} \pm 10.0^{\text{th}}) \times 10^{-10}$</td>
<td>Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>5</td>
<td>$m_t$</td>
<td>$173.3 \pm 0.5^{\text{stat}} \pm 1.3^{\text{sys}} \text{ (GeV)}$</td>
<td>Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>6</td>
<td>$m_h(m_h)$</td>
<td>$4.19^{+0.18}_{-0.06} \text{ (GeV)}$</td>
<td>Two-sided Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>7</td>
<td>$\alpha_s(M_Z)$</td>
<td>$0.1184 \pm 0.0007$</td>
<td>Gaussian</td>
<td>MCMC</td>
</tr>
<tr>
<td>8a</td>
<td>$m_h$</td>
<td>pre-LHC: $m_h^{\text{low}} = 112$</td>
<td></td>
<td>MCMC</td>
</tr>
</tbody>
</table>
| 8b | $m_h$ | LHC: $m_h^{\text{low}} = m_h^{\text{up}}$ | 1 if $m_h \geq m_h^{\text{low}}$  
0 if $m_h < m_h^{\text{low}}$  
1 if $m_h^{\text{low}} \leq m_h \leq m_h^{\text{up}}$  
0 if $m_h^{\text{low}} < m_h$ or $m_h > m_h^{\text{up}}$ | MCMC              |
| 9  | sparticle masses | LEP [34], (via micrOMEGAs [23]) | 1 if allowed, 0 if excluded | MCMC              |
| 10 | prompt $\tilde{\chi}_1^+$ | $cr(\tilde{\chi}_1^+) < 10 \text{ mm}$ | 1 if allowed, 0 if excluded | post-MCMC         |

1-7, 8a, 9, 10: “pre-Higgs” constraints used in MCMC sampling
Constraints: Higgs

• Higgs mass: in MCMC sampling: $m_h > 112$ GeV, afterwards hard cut requiring $m_h = [123, 128]$ GeV

• Higgs signal strengths: likelihood computed as $L = \exp(-\chi^2/2)$ from fit to experimental Higgs results

• $L(\text{Higgs})$ multiplied a posteriori on top of $L(\text{preHiggs})$ → see how this affects the probability distributions

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cf. Beranger Dumont’s talk on Monday
Results

- **Probability density**

  - \( p_\theta^{(0)} \)
  - \( p(\theta | \text{prompt } \not\chi) \)
  - \( p(\theta | \text{prompt } \overline{\chi}, \text{preHiggs}) \)
  - \( p(\theta | \text{prompt } \overline{\chi}, \text{preHiggs}, 123 < m_h < 128) \)

- **Effects of “preHiggs” and Higgs mass constraints**

- **Effect of Higgs signal strengths**

\[ \mu \text{ [GeV]} \]

\[ \mu \text{ [GeV]} \]
Masses

\begin{align*}
\text{Probability density} \quad \theta(0, \pm 1, \chi | \text{prompt}) \\
\text{mass [GeV]} \\
\begin{array}{cccc}
\bar{\chi}_1^0 & \bar{\chi}_1^1 & \bar{\chi}_1 & \bar{\chi}_1 & \bar{\chi}_1 & \bar{\chi}_1 \\
0 & 500 & 1000 & 1500 & 2000 & 2500 \text{[GeV]} \\
\end{array} \\
\begin{array}{cccc}
\bar{h} & \bar{A} & \bar{t} & \bar{t} & \bar{t} & \bar{t} \\
0 & 500 & 1000 & 1500 & 2000 & 2500 \text{[GeV]} \\
\end{array} \\
\begin{array}{cccc}
\bar{b}_1 & \bar{b}_1 & \bar{t}_1 & \bar{t}_1 & \bar{t}_1 & \bar{t}_1 \\
0 & 500 & 1000 & 1500 & 2000 & 2500 \text{[GeV]} \\
\end{array} \
\end{align*}
Masses

$\bar{\chi}_1^0$ mass [GeV]

$\chi$ mass [GeV]

$h$ mass [GeV]

$A$ mass [GeV]

$\tilde{b}_1$ mass [GeV]

$\tilde{t}_1$ mass [GeV]

$\tilde{t}_2$ mass [GeV]
Masses

Study how CMS SUSY searches impact these distributions is done but stuck in CMS.
S. Kraml

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Light Higgs signal

\[ \gamma \gamma \rightarrow h \rightarrow R(gg) \]

\[ \tau \tau \rightarrow h \rightarrow R(gg) \]

\[ ZZ \rightarrow h \rightarrow R(gg) \]

\[ VBF \rightarrow h \rightarrow \gamma \gamma \]

\[ VBF \rightarrow h \rightarrow ZZ \]

\[ VBF \rightarrow h \rightarrow bb \]

Probability density

\[ p(0 \rightarrow h, 123 < m_h < 128) \]

\[ p(0 \rightarrow h, 123 < m_h < 128, lhHiggs) \]

\[ p(0 \rightarrow h, 123 < m_h < 128, lhHiggs) \]

\[ p(0 \rightarrow h, 123 < m_h < 128, lhHiggs) \]

\[ p(0 \rightarrow h, 123 < m_h < 128, lhHiggs) \]
Higgs decays into SUSY
Dark matter

\[
\chi \sim (p_{SI} \sigma \xi \log(\cdot)) \\
\theta(p_{\pm 1})
\]

\[
\chi \sim |\text{prompt}_\theta(p_{\pm 1})|_{\text{preHiggs}}
\]

\[
\chi \sim |\text{prompt}_\theta(p_{\pm 1})|_{\text{lhHiggs}}
\]

\[
\log(\Omega_{\chi}h^2)
\]

\[
\log(\xi \sigma^{SI}(p\chi^0_{1}) [pb])
\]
Conclusions

• We have a SM-like Higgs with ~125 GeV mass.

• In the absence, so far, of any sign of new physics, it is interesting to use the Higgs mass and couplings (signal strength measurements) for constraining BSM theories.

➤ Use the Higgs as a guide to where to look for new physics.

• In the MSSM case, it turns out that the strongest effect still comes from the Higgs mass itself; fitting Higgs signal strengths so far has little impact. reason: the Higgs is too SM-like :-(

• Stay tuned for NMSSM results
SUSY particles

**Stop**

**Chargino**

**Bino LSP**

**Higgsino LSP**

**Neutralino**

**Gluino**
Signal strengths

\[ R(X \rightarrow h \rightarrow Y) = \frac{\Gamma(h \rightarrow X) \cdot \text{BR}(h \rightarrow Y)}{\Gamma(H_{\text{SM}} \rightarrow X) \cdot \text{BR}(H_{\text{SM}} \rightarrow Y)} \]
Signal strengths
Signal strengths, $m(\text{stop1}) < 1$ TeV
NUHM with inverted mass hierarchy
(splits generations, very heavy 1st/2nd gen. squarks)