Two Higgs at LEP, Tevatron and the LHC?

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Introduction

• Higgs discovery at LHC raises many questions
  – Is the new boson the SM Higgs
  – Deviations from SM couplings?
  – A probe of BSM
  – Is it lightest Higgs in MSSM? fine tuning problem
  – Are there more light Higgeses?

• Here consider two possibilities
  – 125GeV Higgs is the heavy Higgs - another one at 100GeV
  – LHC/Tevatron might not have seen the same Higgs: 125-135GeV

• No sign (yet) of supersymmetry at LHC

• Supersymmetry offers a good DM candidate, strong evidence for DM - motivation for beyond standard model
Outline

• Higgs at LHC and LEP
• Higgs in the NMSSM
• Two light Higgses
  – implications for LHC, DM ...
• Two Higgses at Tevatron and LHC
Higgs at LHC

- July 4th 2012: ATLAS and CMS reported a signal consistent with a Higgs boson with mass
  - \( m_h = 125.3^{+/-0.4+/-0.5}\text{GeV} \) (CMS)
  - \( = 126.0^{+/-0.4+/-0.4}\text{GeV} \) (ATLAS)
- Such a mass can be reached in MSSM require large mixing in stop sector, fine-tuning
- Also measure the signal strength in various production/decay channels: give indication whether the new particle is a SM Higgs
- Results not precise enough yet: indications that signal strength is larger than expected in two-photon mode
- If this result is confirmed: precious information/constraints on physics beyond the standard model, e.g. challenge for MSSM
CMS - Higgs results

m_H = 125 GeV

CMS Preliminary
\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

H \rightarrow bb (VH tag)
H \rightarrow bb (ttH tag)
H \rightarrow \tau\tau (0/1 jet)
H \rightarrow \tau\tau (VBF tag)
H \rightarrow \tau\tau (VH tag)
H \rightarrow \gamma\gamma \text{ (untagged)}
H \rightarrow \gamma\gamma \text{ (VBF tag)}
H \rightarrow WW (0/1 jet)
H \rightarrow WW (VBF tag)
H \rightarrow WW (VH tag)
H \rightarrow ZZ

Best fit \( \sigma/\sigma_{SM} \)

123 124 125 126 127 128 129
m_x (GeV)

\( \sigma/\sigma_{SM} \)

\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

Combined
H \rightarrow \gamma\gamma \text{ (untagged)}
H \rightarrow \gamma\gamma \text{ (VBF tag)}
H \rightarrow ZZ

gg fusion ; vector boson fusion

lundi 19 novembre 2012
ATLAS - Higgs results

- Also has an excess in two-photon mode
- Results for signal strength relative SM combining all production modes

![ATLAS 2011 - 2012 Higgs Results Diagram](attachment:image.jpg)
LEP results

- Small excess in $e^+e^- \rightarrow Zbb$ ($\sim 2\sigma$) at LEP with $M_h \sim 98\text{GeV}$.
- How can it be consistent with bound $M_h > 114 \text{GeV}$? coupling to $ZZ$ must be much weaker than in SM, only 0.1-0.25 SM
- Could that be a second Higgs $h'$?
- $h'$ can mix with $h$ and shift its properties, e.g. mixing with $h'$ can suppress $hbb$, $\text{Br}(h\rightarrow \gamma\gamma)$ can be modified because total width is suppressed
  - $\text{Br}(h\rightarrow \gamma\gamma) \sim \Gamma(h\rightarrow \gamma\gamma)/\Gamma(h\rightarrow bb)$
SUSY Higgs at LEP

- Characteristics of the LEP ‘signal’ at 100GeV
  - e.g. Drees (hep-ph/0502075) the light Higgs of MSSM with suppressed couplings to ZZ (MSSM in non-decoupling limit)

- Is the LHC Higgs the lightest Higgs?
  - This question was addressed in framework of MSSM
    - Heinemeyer et al, 1112.3026
    - Hagiwara et al, 1207.0802
    - Drees, 1210.6507

- As an example of a model that can be consistent with both LEP and LHC observations (including enhanced two-photon) here we will consider NMSSM
NMSSM

- MSSM with additional singlet superfield

\[ W_{\text{NMSSM}} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3} \kappa \hat{S}^3, \]

\[ V_{\text{NMSSM}}^{\text{soft}} = \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + (A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3} \kappa S^3 + h.c.). \]

- \( \mu \) parameter is related to vev of singlet
  - naturally of order of weak scale

- Higgs sector: 3 CP-even, 2 CP-odd + charged Higgs
  - much richer phenomenology than in MSSM
  - one singlet CP-even scalar + one singlet CP-odd scalar

- Also extra neutralino \( \rightarrow \) singlino
  - can impact dark matter properties
Higgs mass in NMSSM

- Light Higgs mass: new contribution at tree level
- Increase in Higgs mass \( m_h^2 < M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \)
- largest increase is for low values of \( \tan\beta \)
- Easier to reach 125GeV even without very large stop corrections (Ellwanger et al JHEP1109.105; Hall et al 1112.2703)

- Fine tuning:
  \[
  m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_i^2} + \frac{X_t^2}{m_i^2} \left( 1 - \frac{X_t^2}{12m_i^2} \right) \right].
  \]
  \[
  M_Z^2 \approx -2\mu^2 + \frac{2(m^2_{H_u} - \tan^2 \beta m^2_{H_u})}{\tan^2 \beta - 1}.
  \]
  \[
  \delta m^2_{H_u} = -\frac{3y_t^2}{8\pi^2} \left( m_Q^2 + m_{u_3}^2 + |A_t|^2 \right) \ln \left( \frac{\Lambda}{m_t} \right)
  \]
  - in NMSSM with lambda~1 stop mass/mixing not so large
  - fine-tuning reduced in CNMSSM (Ellwanger et al 1107.2472)

- Doublet singlet mixing - the lightest Higgs scalar can be very light escape LEP bounds
• Mixing can lead to reduce hbb, reduced total width--> increased branching ratios

\[ H_1 = S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S \]

\[ c_{D_i} = \frac{S_{i,d}}{\cos \beta}, \quad c_{U_i} = \frac{S_{i,u}}{\sin \beta}, \quad c_{V_i} = \cos \beta S_{i,d} + \sin \beta S_{i,u} \]

• Possible to increase branching ratios in two photons.
  – Ellwanger, 1012.1201,1112.3548
  – Does not require light sparticles

\[ R_{gg}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow gg) \ BR(h_i \rightarrow X)}{\Gamma(h_{SM} \rightarrow gg) \ BR(h_{SM} \rightarrow X)}, \quad R_{VBF}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow WW) \ BR(h_i \rightarrow X)}{\Gamma(h_{SM} \rightarrow WW) \ BR(h_{SM} \rightarrow X)} \]

• \( R_{gg}(\gamma \gamma) > 1 \) for \( m_H = 125 \text{GeV} \), when \( \lambda \) large (determines singlet-doublet mixing), \( \tan \beta \) small
• $R_{gg\gamma\gamma}>1$ - associated with small $\mu$, light charginos because singlet mass light

$$m_S^2 = \kappa \mu / \lambda (A_\kappa + 4\kappa \mu / \lambda)$$

• Signal strength for Higgs in different channels

• Complete independent set of $R^h$

$$R^h_{gg}(WW), \ R^h_{gg}(bb), \ R^h_{gg}(\gamma\gamma), \ R^h_{VBF}(WW), \ R^h_{VBF}(bb), \ R^h_{VBF}(\gamma\gamma).$$

• Note for LEP : $R_{VBF}(bb)$
• Can one explain $M_{h1} \sim 100 + M_{h2} \sim 125$ with $R_{gg\gamma\gamma} > 1$ in NMSSM?

• Framework: NMSSM with semi-unified GUT scale soft SUSY breaking
  – $m_{1/2}, m_0, A_0, m_{2_{Hu}}, m_{2_{Hd}}, m_S, A_\lambda, A_\kappa, \tan\beta$

• Take into account Higgs constraints in NMSSMTools + B physics, DM (WMAP upper bound and Xenon100), g-2

• Note that g-2 does not explain discrepancy with SM
Higgs signal strength

- Two Higgses at 98GeV+125GeV

- For discovery of light Higgs in bb channel need to increase current LHC sensitivity (R~1) by a factor 4-10 -> higher luminosity LHC run

- $h_1$ in two-photon very small R~0.02
Other NMSSM particles

- Other particles below TeV scale: pseudoscalars, neutralino, chargino, stop

![Graphs showing mass distributions for different particles](image_url)
Dark matter issues

- 5 neutralinos
  - LSP either higgsino or singlino
    - higgsino annihilate into W pairs -\(\Omega h^2 \sim 0.1\) because just below threshold
    - Singlino component annihilate via singlet Higgs exchange
Direct detection

- Searches for DM scattering with nuclei in large detectors - best limits from Xenon100 (2012)

- DM direct detection: from just below Xenon to quite a bit suppressed

This division is clearly seen in Figlv. We note that to a reasonable approximation the singlino fraction of the \(\chi_0^1\) is given by minus the Higgsino fraction plotted in the left-hand window of the figure. Dark matter eDMf properties for the surviving NMSSM parameter points are summarized in Figlv. Referring to the figure, we see a mixture of blue circle points (those with \(\Omega h^2 < n_x^f\)) and orange diamond points (those with \(n_x^f < \Omega h^2 < n_x^f\)), i.e. in the WMAP window. The main mechanism at work to make \(\Omega h^2\) too small for many points is rapid \(\chi_0^1\) annihilation to \(W^+W^-\) due to a substantial Higgsino component of the \(\chi_0^1\). Indeed, the relic density of a Higgsino LSP is typically of order \(\Omega h^2 \approx 10^{-4}\) - 10^{-5}\.

As the Higgsino component declines, \(\Omega h^2\) increases and except for the strongly overlapping points with \(m_{\chi_0}^1 < m_W\) for which \(\chi_0^1\) annihilation is below threshold, it is the points for which the LSP is dominantly singlino that...
Indirect detection

- Annihilation of pairs of DM into SM particles: decay products observed
- FermiLAT: Photons from Dwarf Spheroidal Galaxies probe typical DM annihilation cross section at freeze-out for light DM
  \[ < \sigma v > = 3 \times 10^{-26} \text{cm}^3/\text{sec} \]
- Gamma-ray line at 130GeV
  - Weniger, arXiv:1204.2797

\[ \langle \sigma v \rangle (\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \gamma) \sim 10^{-27} \text{cm}^3/\text{sec} \]
Photons

- In general NMSSM (no GUT scale unification) gamma-ray line possible (Das, Ellwanger, Mitropoulos, 1206.2639)
  \[ \langle \sigma v \rangle (\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow a_1 \rightarrow \gamma \gamma) \]

- If \( 2m_{\text{LSP}} \sim m_A \) (extremely fine tuned) can have resonance enhancement at \( v \sim 0.001c \)
  \[
  \nu \sigma(v) \propto \frac{1}{(s - m_A^2)^2 + \Gamma_A^2 m_A^2} = \frac{1}{16 m_\chi^4 (v^2/4 + \Delta)^2 + \Gamma_A^2 (1 - \Delta)/4 m_\chi^2}
  \]

- In semi-unified NMSSM with 98+125GeV Higgs and enhanced two-photon width: gamma-ray line much suppressed and limits from Fermi dSPh’s easily satisfied
Apart from possible signals in future ton-scale direct detection experiments, for the moment no constraints on this scenario from DM observables other than relic density.

**How to probe further this scenario?**
How to probe further this scenario?

• LHC:
  – $h_1$ (bb) with high luminosity
  – $a_1$: light but mostly singlet - low rates
  – $a_2$: mainly doublet better prospect (no dedicate study yet)
    • $gg \rightarrow a_2 \rightarrow tt$ ( ~0.01pb for mass 500 GeV)
    • or $a_2 \rightarrow a_1 h_1 \rightarrow 4b$
    • $gg \rightarrow a_2, h_3 \rightarrow \tau\tau$
    • Current limit at 200GeV ~8
      – need high luminosity
• Charged Higgs
  – 20% branching ratio into $h_1W$
  – possible detection of $h_1$ with high luminosity

• Higgses from neutralino decays
  – several channels have BR
  ~10% for decay into $h_1$
... at future colliders

- **ILC**
  - Large rate for Zh$_1$
  - In some cases can detect all 5 neutral Higgses

![Graph showing cross sections for Higgs production at an e$^+$e$^-$ collider as functions of the center of mass energy $\sqrt{s}$ for three illustrative mass spectra as tabulated in Table 1](image.png)

scenario I

For low Higgs masses, the required electron collider could have energy of order $m_{\text{Higgs}}/v$. In the present context, it is of interest to assess the extent to which a $\gamma\gamma$ collider would be able to study the neutral NMSSM Higgs bosons. This is determined by the ratio of the $\gamma\gamma$ coupling squared of the given Higgs boson to that of the SM Higgs. In Figure we present plots of $\sigma_{\gamma\gamma}$ as a function of $m_h$ for $h = h_1, h_2, h_3, a_1, a_2$ for masses below $\sim 5$ TeV. The fairly SM-like $h_2$ at $\sim 5$ GeV can be studied easily at such a collider since its $\gamma\gamma$ coupling is close to SM strength. For example, at an $e^+e^-$ collider with the optimal $E_{ee} = 6$ GeV, a 5 GeV SM Higgs has a cross section of $\sim 10^{-1}$ fb. After two years of operation, equivalent to $L = 5$ fb$^{-1}$, one can measure the $b\bar{b}, W^+W^-$, $\gamma\gamma$...
... at future colliders(2)

• Photon collider
  – $h_2$ - SM-like coupling to two-photons: large cross section can measure also $b\bar{b}$/$WW$ partial widths
  – $h_1$, $a_1$ - suppressed because singlet but important contribution from light chargino loop
• Possibility of having a Higgs at 98 GeV hidden in LEP data - fits in the NMSSM with distinctive signatures

• LHC can look for it in some standard search channels, and remains to be seen how well new channel can be exploited to search for $h_1, a_1$

• Note that in NMSSM light singlet can have any mass
Two Higgses at LHC and Tevatron
Could it be that Tevatron and LHC have seen two Higgs bosons?

- At Tevatron enhanced signal in VH,H->bb between 110-140GeV best value, M_H~135GeV,
- \(\tau\tau\) mode: CMS has deficit at 125GeV for VBF-tag mode, excess at 132 GeV
- Can all these small deviations be compatible with two lightest Higgses in NMSSM?
• Signal strength for 125 GeV

\[ R_1^{\gamma\gamma}(ggF) \simeq 1.66 \pm 0.36 \quad R_1^{ZZ(*)}(ggF) \simeq 1.02 \pm 0.38 . \]

• Signal strength for 135 GeV

\[ R_2^{\gamma\gamma}(ggF) \simeq 0.45 \pm 0.3 \quad R_2^{ZZ(*)}(ggF) \lesssim 0.2 \]

\[ R_2^{\tau\tau}(VBF) < 1.81 \quad R_{135}^{bb}(VH) \simeq 3.53 + 1.26 - 1.16 \]
• ‘Fit’ CMS+Tevatron Higgs signal
• Here ignore DM requirement

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<th>$A_{\kappa}$</th>
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- At Tevatron - poor mass resolution in $bb$ + production $H_1 > H_2$
- $R^{bb}(VH) \simeq R^{bb}_{1}(VH) + 1.3 \times R^{bb}_{2}(VH) \sim 1.3$
- Below central value of Tevatron
- More data at LHC ($\gamma\gamma$) will confirm/rule out this possibility
- Search for $H_3$ - look at decays into light Higgs/ neutralino pairs
CONCLUSION

• Higgs searches at LHC could still provide exciting news

• Important to look for light Higgses - in particular mainly singlet Higgs at 100GeV

• NMSSM is extension of MSSM that provide a Higgs 125 GeV with possibly enhanced di-photon rate and some extra light Higgs state