Exotic Higgs Searches in CMS

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on behalf of the CMS Collaboration

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Outline

• Introduction:
  ✓ Overview of the newly discovered boson

• BSM Higgs models:
  ✓ Introduction to Minimal Supersymmetric Standard Model (MSSM)
  ✓ MSSM searches in CMS
  ✓ Introduction to Next-to-Minimal Supersymmetric Standard Model
  ✓ NMSSM searches in CMS
  ✓ Double Charged Higgs searches in CMS

• Summary and Perspectives
The discovery of a new boson

✓ In 2012 CMS and ATLAS experiments reported the discovery of a new boson with a mass of \(\sim 126\) GeV

✓ The measured properties indicate a consistency with the predicted SM Higgs Boson

\[H \rightarrow \gamma\gamma\quad \quad H \rightarrow ZZ\]

What is next?

• Precision particle measurements with more data (2015 and beyond)

• Understand if this particle correspond to the SM prediction or an extended theory (MSSM, NMSSM, 2HDM, etc.)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
Minimal Supersymmetric Standard Model (MSSM)

- So far SM describing successfully known phenomena
- The experimental frontier has advance into the TeV scale
- SM has to be modified in order to describe phenomena between the Electroweak and the Planck Scale

Unstable quantum corrections to Higgs mass

The electrically neutral part of the SM Higgs

\[ V = m_H^2 |H|^2 + \lambda |H|^4 \]

Heavy particles may interact with the Higgs field, leading to corrections on the squared Higgs mass

\[ \Delta m_H^2 = - \frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + ... \]  (1)

\[ \Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + ... \right] \]  (2)

\( \Lambda_{UV} \) scale at which new physics alter the high energy behavior

\( \Lambda_{UV} \) scale at which new physics alter the high energy behavior.
Minimal Supersymmetric Standard Model (MSSM)

- If $\Lambda_{\text{UV}}$ is of order $M_P$, quantum correction is 30 order magnitude larger than the required $m_H^2 \sim (100\text{GeV})^2$

- By renormalization and fine tuning those large corrections are controlled but it would be desirable that the solution comes in a natural way

- Looking into (1) and (2) is clear that by introducing a new symmetry relating fermions and bosons the large quantum corrections are canceled, such symmetry is the so-called Supersymmetry (SUSY)

- A supersymmetry transformation turns a bosonic state into a fermionic state and viceversa
Phenomenology of the MSSM Higgs sector can be effectively described using only two parameters:

- \( m_A \) mass of the CP odd Higgs boson
- \( \tan \beta \) ratio of the vacuum expectation values of the two Higgs doublets

Experimental searches in CMS MSSM (Neutral Higgs Boson \( \phi \))

- \( \phi \rightarrow bb \) \((Br=90\%)\)
- \( \phi \rightarrow \tau \tau \) \((Br=10\%)\)
- \( \phi \rightarrow \mu^+\mu^- \) \((Br=10\%)\)

**Minimal Supersymmetric Standard Model (MSSM)**

<table>
<thead>
<tr>
<th>Field Content of the MSSM</th>
<th>Super-Multiplets</th>
<th>Boson Fields</th>
<th>Fermionic Partners</th>
<th>SU(3)</th>
<th>SU(2)</th>
<th>U(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon/gluino</td>
<td>( g ), ( W^\pm, W^0 ), ( B )</td>
<td>( \tilde{g} ), ( \tilde{W}^\pm, \tilde{W}^0 ), ( \tilde{B} )</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>gauge/gaugino</td>
<td>( (\tilde{\nu}, \tilde{e}^-)_L ), ( \tilde{e}_R )</td>
<td>( (\nu, e^-)_L ), ( e_R )</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>slepton/lepton</td>
<td>( (\tilde{\nu}_L, \tilde{d}_L) ), ( \tilde{d}_R )</td>
<td>( (u, d)_L ), ( u_R ), ( d_R )</td>
<td>3</td>
<td>2</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>squark/quark</td>
<td>( (\tilde{u}_L, \tilde{u}_R) ), ( \tilde{u}_R ), ( \tilde{\nu}_L ), ( \tilde{\nu}_R )</td>
<td>( (H_u^0, H_d^0) ), ( H_u^0 ), ( H_d^0 )</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>Higgs/higgsino</td>
<td>( (H_u^+, H_d^-) ), ( H_u^- ), ( H_d^+ )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Five physical states:** \( h^0, H^0, A^0, H^+/^- \)

**Three neutral Higgs bosons** \( \phi \)

- For large \( \tan(\beta) \) the Higgs boson decays to tau and b-quarks play a more important role than in the SM
• Search for a Higgs boson decaying into b-quark pair and produced in association with at least one b-quark

• All hadronic signature
  • 3 leading b-tagged jets
  • Dominant background comes from QCD multi-jet production

• Semi-leptonic signature
  • Events with 3 leading b-jets
  • One muon from semi-leptonic b-decay
  • Dominant background QCD multi-jet events
  • Other background such as tt+jets, Z->bb+jets are predicted by MC to be less than 1%

Both analysis search for an excess of events in the invariant mass of the two leading jets

QCD estimation from data

A pure QCD sample selecting events with only 2 b-tag jets, 5 bkg templates
• Clean signature by requiring a muon from semi-leptonic b-decay

• Possibility of lowering thresholds at the cost of losing some signal acceptance

• No visible excess of events is observed neither in all-hadronic or semi-leptonic channels

• 95% CL limits are set on $\tan(\beta)$ as a function of $M_A$ for the combined all-hadronic and semi-leptonic analysis

• Results are compared with previous limits from LEP and Tevatron experiments
Three independent tau pair final states $e\tau_h, \mu\tau_h, e\mu$

For each of the lepton candidates isolation is required

To enhance sensitivity the events were divided into several categories based on jet multiplicity and b-jet content

Analysis sensitive to both SM and MSSM searches

Non $b$-tagged

b-tagged

No visible excess of events, limits are set in the $m_A, \tan(\beta)$ plane.

Results are compared with previous limits from LEP.
Search for the Neutral MSSM Higgs Boson in the $\mu^+ \mu^-$ final state

Sensitive search for SUSY higgs boson production in association with $b\bar{b}$ and via gluon-gluon fusion processes

Three non overlapping categories:
- **categ1**: at least one $b$-tagged jet
- **categ2**: No $b$-jet but additional third muon as a signature of semileptonic $b$-decay
- **categ3**: Events that do not belong to first two categories

Main background is due to Drell-Yan process
- Other less important source of backgrounds are: $t\bar{t}$, $W^+/-W^+/-\phi$
• Data driven approach for limit setting
• Background contribution determined from a fit to data
• Signal shape for various $m_A$ and $\tan(\beta)$ determined by a fit to the invariant mass distribution of the simulated signal events

Excluded Regions
Above the curves
Some reasons to take into account NMSSM

- Naturally solves in an elegant way the so-called $\mu$ problem
- Reduce the fine tuning in MSSM theory

Higgs sector is highly restricted in MSSM (lightest Higgs is always SM like). An extended Higgs sector may relax this restriction and lower experimental bounds (In NMSSM the lightest Higgs boson can be as light as 1 GeV)

3 CP even Higgs Bosons
2 CP odd Higgs Bosons
2 charged Higgs Bosons

<table>
<thead>
<tr>
<th>chiral supermultiplets</th>
<th>spin-0</th>
<th>spin-1/2</th>
<th>$SU_C(3)$</th>
<th>$SU_L(2)$</th>
<th>$U_Y(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark–squark</td>
<td>$Q$</td>
<td>$(\tilde{u}_L, \tilde{d}_L)^T$</td>
<td>$Q = (u_L, d_L)^T$</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$\tilde{u}$</td>
<td>$\tilde{u}_R^*$</td>
<td>$\tilde{u}_R^*$</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{d}$</td>
<td>$\tilde{d}_R^*$</td>
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<tr>
<td>lepton–slepton</td>
<td>$L$</td>
<td>$(\tilde{e}_L, \tilde{\nu}_L)^T$</td>
<td>$L = (\nu_L, e_L)^T$</td>
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<td>2</td>
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<tr>
<td></td>
<td>$\tilde{\nu}$</td>
<td>$\tilde{\nu}_R^*$</td>
<td>$\tilde{\nu}_R^*$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Higgs–Higgsino</td>
<td>$H_u$</td>
<td>$(H_u^+, H_u^0)^T$</td>
<td>$H_u = (H_u^+, H_u^0)^T$</td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>$\tilde{H}_u$</td>
<td>$\tilde{H}_u^0$</td>
<td>$\tilde{H}_u^0$</td>
<td>1</td>
<td>2</td>
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<tr>
<td></td>
<td>$H_d$</td>
<td>$(H_d^-, H_d^0)^T$</td>
<td>$H_d = (H_d^-, H_d^0)^T$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{H}_d$</td>
<td>$\tilde{H}_d^0$</td>
<td>$\tilde{H}_d^0$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>gauge supermultiplets</td>
<td>spin-1/2</td>
<td>spin-1</td>
<td>$SU_C(3)$</td>
<td>$SU_L(2)$</td>
<td>$U_Y(1)$</td>
</tr>
<tr>
<td>gluon–gluino</td>
<td>$g$</td>
<td>$\tilde{g}$</td>
<td>$g$</td>
<td>8</td>
<td>1</td>
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<tr>
<td>W-boson–wino</td>
<td>$\tilde{W}^\pm, \tilde{W}^0$</td>
<td>$W^\pm, W^0$</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>B-boson–bino</td>
<td>$\tilde{B}^0$</td>
<td>$B^0$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Experimental searches in CMS**

$\alpha \rightarrow \mu^+ \mu^-$

$h \rightarrow 2\alpha \rightarrow 4\mu$
• Search for light pseudo-scalar Higgs boson $a$
• $a$ is a superposition of the MSSM doublet pseudo-scalar and the additional single pseudo-scalar of the NMSSM
• Large cross section for $gg \rightarrow a \rightarrow \mu^+ \mu^-$ event though $B(a \rightarrow \mu^+ \mu^-)$ is small

- Main background from QCD processes
- Background shape extracted from DATA and use of simulation as a cross check
- Search exclusively between 5.5 and 8.8 GeV and between 11.5 and 14 GeV, to avoid the range where the abundant contribution of bottomonium resonances
\[ \alpha \rightarrow \mu^+ \mu^- \]

- No visible excess of events
- Limit on cross section times branching ratio as a function of \( m_{\mu\mu} \)
- The region between 11.5 and 14 GeV not included due to the overwhelming contribution of bottomonium processes
Non SM Higgs Boson decay to pairs of new light bosons predicted in the context of NMSSM

- Each light boson decays to a pair of muons
- Final topology: pair of di-muons with compatible mass
- Main backgrounds for this search are bbbar and double jpsi production

**Bkg estimation from data**

- bbbar estimation directly from data
- bbbar background enriched sample by selecting events with one di-muon + one “orphan” muon
- No isolation is required to the di-muon
- Background template is validated in events with two dimuons

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13010TWiki
\[ h \rightarrow 2a \rightarrow 4\mu \]

- One event surviving all the selection and located inside the mass corridor (signal region)

- The intensity of the shading indicates the background expectation which is the sum of \( b\bar{b} \) and double jpsi contribution

- Double jpsi estimated using MC expectation corrected with cross section measurements in data

- No excess of events over SM expectation

- 95% CL limit on the production cross section (of the two light bosons) x the BR (to muons) as a function of \( m_{h_1} \)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13010TWiki
Search for the double charged Higgs boson

Charge Higgs boson is a member of SU(2)L scalar triplet $\Phi$ in extension of the SM which include the seesaw mechanism of type II

Inclusive search in events with three or more leptons originated from the decay of pair produced triplet components $\Phi^{++}\Phi^{--}$ and $\Phi^{++}\Phi^{-}$

**Associated production**

**Pair production**

**Invariant mass distribution from three lepton final state**

**Invariant mass distribution from four lepton final state**
Double Charged Higgs

- Observed $\Phi^{++}$ mass limits at 95% CL for 100% Branching fraction to $ee$ channel

- Summary of results for all lepton combinations

- Results are compared for different CMS luminosities and ATLAS and Tevatron limits
The recent discovery of a new boson with mass of 126 GeV has fired the question whether it corresponds to the SM Higgs boson or a new particle from an extended theory.

There is an extensive number of BSM Higgs models, in this talk the latest experimental constrains for MSSM, NMSSM and the double charged Higgs results in CMS were reviewed.

There is no visible excess of events over SM expectations in all the channels explored, exclusion limits are set as a function of the parameters of each extended theory.

We are looking forward to analyze more data (2015 and beyond) and reveal "true" identity of the new
Backup
H→WW and H→tautau SM CMS searches

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

m_\parallel distribution in the emu channel

tautau invariant mass
Triggers for H-\(\rightarrow\)bb

Higgs boson decaying to a pair of b-quarks in association with at least another b-quark

- Triggers adjusted according to the increasing luminosity

<table>
<thead>
<tr>
<th>all hadronic channel</th>
<th>semi-leptonic channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>category I: di-jet trigger (46,38) GeV</td>
<td>category I: muon with pT&gt;12 GeV, one or two jets ((</td>
</tr>
<tr>
<td>category II: di-jet trigger (60,53) GeV</td>
<td>category II: Same as I but jet threshold raised from 20 to 30 GeV</td>
</tr>
<tr>
<td>category 3: same as I but requiring a third jet with pT&gt;20 GeV</td>
<td></td>
</tr>
</tbody>
</table>
## H->tautau

### etau

<table>
<thead>
<tr>
<th>Process</th>
<th>SM 0/1-Jet</th>
<th>Boosted</th>
<th>VBF</th>
<th>MSSM Non b-Tag</th>
<th>MSSM b-Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z to tt</td>
<td>13438 ± 977</td>
<td>190 ± 14</td>
<td>19 ± 1</td>
<td>14259 ± 1037</td>
<td>135 ± 9</td>
</tr>
<tr>
<td>Multijets</td>
<td>6365 ± 299</td>
<td>27 ± 3</td>
<td>15 ± 2</td>
<td>6404 ± 301</td>
<td>100 ± 7</td>
</tr>
<tr>
<td>W+jets</td>
<td>2983 ± 216</td>
<td>62 ± 4</td>
<td>4.2 ± 0.4</td>
<td>5432 ± 377</td>
<td>39 ± 3</td>
</tr>
<tr>
<td>Z to ll</td>
<td>5170 ± 464</td>
<td>28 ± 4</td>
<td>5 ± 1</td>
<td>6146 ± 502</td>
<td>28 ± 4</td>
</tr>
<tr>
<td>tt</td>
<td>63 ± 7</td>
<td>42 ± 6</td>
<td>2 ± 1</td>
<td>47 ± 7</td>
<td>75 ± 11</td>
</tr>
<tr>
<td>Dibosons</td>
<td>68 ± 21</td>
<td>5 ± 2</td>
<td>0.1 ± 0.1</td>
<td>105 ± 22</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>Total Background</td>
<td>28087 ± 1142</td>
<td>354 ± 17</td>
<td>45 ± 2.9</td>
<td>32392 ± 1249</td>
<td>378 ± 17</td>
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<tr>
<td>H to tt</td>
<td>53 ± 9</td>
<td>2.7 ± 0.6</td>
<td>2.0 ± 0.2</td>
<td>279 ± 29</td>
<td>26 ± 4</td>
</tr>
<tr>
<td>Data</td>
<td>27727</td>
<td>318</td>
<td>43</td>
<td>32051</td>
<td>391</td>
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</tbody>
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### mutau

<table>
<thead>
<tr>
<th>Process</th>
<th>SM 0/1-Jet</th>
<th>Boosted</th>
<th>VBF</th>
<th>MSSM Non b-Tag</th>
<th>MSSM b-Tag</th>
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</thead>
<tbody>
<tr>
<td>Z to tt</td>
<td>28955 ± 2054</td>
<td>295 ± 22</td>
<td>36 ± 2</td>
<td>29795 ± 2114</td>
<td>259 ± 18</td>
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<tr>
<td>Multijets</td>
<td>7841 ± 141</td>
<td>36 ± 2</td>
<td>9 ± 1</td>
<td>6387 ± 115</td>
<td>160 ± 9</td>
</tr>
<tr>
<td>W+jets</td>
<td>5827 ± 392</td>
<td>65 ± 4</td>
<td>9 ± 1</td>
<td>9563 ± 628</td>
<td>110 ± 9</td>
</tr>
<tr>
<td>Z to ll</td>
<td>777 ± 70</td>
<td>9 ± 1</td>
<td>10 ± 0.2</td>
<td>924 ± 115</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>tt</td>
<td>147 ± 15</td>
<td>94 ± 12</td>
<td>4 ± 1</td>
<td>101 ± 15</td>
<td>145 ± 20</td>
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<tr>
<td>Dibosons</td>
<td>178 ± 55</td>
<td>9 ± 4</td>
<td>0.4 ± 0.4</td>
<td>217 ± 46</td>
<td>5 ± 2</td>
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<tr>
<td>Total Background</td>
<td>43725 ± 2097</td>
<td>504 ± 26</td>
<td>73 ± 3.9</td>
<td>46987 ± 2211</td>
<td>681 ± 30</td>
</tr>
<tr>
<td>H to tt</td>
<td>96 ± 17</td>
<td>3.9 ± 0.8</td>
<td>3.0 ± 0.5</td>
<td>502 ± 52</td>
<td>45 ± 6</td>
</tr>
<tr>
<td>Data</td>
<td>43612</td>
<td>500</td>
<td>76</td>
<td>47178</td>
<td>680</td>
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</table>

### emu

<table>
<thead>
<tr>
<th>Process</th>
<th>SM 0/1-Jet</th>
<th>Boosted</th>
<th>VBF</th>
<th>MSSM Non b-Tag</th>
<th>MSSM b-Tag</th>
</tr>
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<tbody>
<tr>
<td>Z to tt</td>
<td>11787 ± 790</td>
<td>98 ± 11</td>
<td>16 ± 4</td>
<td>11718 ± 797</td>
<td>112 ± 11</td>
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<tr>
<td>Multijet and W+jets</td>
<td>483 ± 145</td>
<td>9 ± 3</td>
<td>2 ± 1</td>
<td>474 ± 147</td>
<td>15 ± 5</td>
</tr>
<tr>
<td>tt</td>
<td>427 ± 41</td>
<td>70 ± 8</td>
<td>14 ± 3</td>
<td>161 ± 15</td>
<td>289 ± 35</td>
</tr>
<tr>
<td>Dibosons</td>
<td>570 ± 91</td>
<td>21 ± 4</td>
<td>2.0 ± 0.6</td>
<td>527 ± 84</td>
<td>55 ± 10</td>
</tr>
<tr>
<td>Total Background</td>
<td>13267 ± 809</td>
<td>197 ± 14</td>
<td>34 ± 5</td>
<td>12881 ± 815</td>
<td>471 ± 38</td>
</tr>
<tr>
<td>H to tt</td>
<td>36 ± 6</td>
<td>1.0 ± 0.3</td>
<td>1.0 ± 0.2</td>
<td>161 ± 10</td>
<td>17 ± 1.6</td>
</tr>
<tr>
<td>Data</td>
<td>13152</td>
<td>189</td>
<td>26</td>
<td>12761</td>
<td>468</td>
</tr>
</tbody>
</table>
MSSM \[ \alpha \rightarrow \mu^+ \mu^- \]

- Cross section for \( gg \rightarrow \alpha \) for \( \tan(\beta) = 1, 2, 3, 10, 30, 50 \)
- Including all available higher order corrections (HIGLU)
MSSM $a \rightarrow \mu^+ \mu^-$
**NMSSM** $h \rightarrow 2a \rightarrow 4\mu$

- Limit as a function of $m_h$ for the dark-SUSY scenario
- The limit is compared with the predicted rate (solid line) using a simplified SM scenario

CMS Prelim. 2012 \( \sqrt{s} = 8 \text{ TeV} \) \( L_{\text{int}} = 20.65 \text{ fb}^{-1} \)

Dark SUSY 95% CL Limit:
- \( m_{\gamma} = 10 \text{ GeV/c}^2 \), \( m_{\nu} = 1 \text{ GeV/c}^2 \)
  and \( m_{\nu} = 0.4 \text{ GeV/c}^2 \)
- Prediction with \( \sigma(pp \rightarrow h) = \sigma_{\text{SM}}(m_h) \),\( B(h \rightarrow 2\nu) = 0.25\% \),
  \( B(\nu \rightarrow \gamma_D + n_D) = 50\% \),
  and \( B(\gamma_D \rightarrow 2\mu) = 45\% \)