Search for a light Higgs boson decaying to a pair of taus in the Next-to-Minimal Supersymmetric Standard Model at the CMS detector

R. Aggleton (Bristol/Southampton/RAL) on behalf of the CMS Collaboration
MSSM - Minimal Supersymmetric Standard Model

- Supersymmetric partner particle for each SM particle
- Stop squark avoids divergent $m_h$ ( + other benefits )

Simple, but theoretical issues:

- Mu problem
- Little fine-tuning problem

Experimental issue - MSSM increasingly constrained from data
NMSSM

- **Next-to-Minimal Supersymmetric Standard Model**

- NMSSM = MSSM + extra Singlet + parameter $\lambda$ – parameter $\mu$

- ✔ **Mu problem solved**: $\lambda$ scale invariant

- ✔ **Little fine tuning problem solved**: extra correction term for $m_h$

- More Higgs bosons: 3 CP-even ($h_{1,2,3}$), 2 CP-odd ($a_{1,2}$), 2 charged ($h^{\pm}$)
  - Discovered $h$ (125) can be $h_1$ or $h_2$
Theoretical motivation

Scenario where $a_1$ or $h_1$ (denote by $\phi_1$) is light: $2m_{\tau} < m_\phi < 2m_b$

$h (125) = h_1$ or $h_2$, produced via gluon-gluon fusion

$\phi_1 = h_1$ or $a_1$

- If $\phi_1 = h_1$: $h_2 \to 2h_1$

- If $\phi_1 = a_1$: $h_2 \to 2a_1$ or $h_1 \to 2a_1$

BR ($\phi_1 \to \ell^-\ell^+$) $\sim m_\ell^2$

Dominant decay: $\phi_1 \to 2 \tau$
Theoretical motivation

Overall: $h(125) \rightarrow 2\phi_1 \rightarrow 4\tau$

- No strong theory limit on $\sigma \times BR$, but expect $\sim pb$

Limits already placed on $m_\phi < 2m_\tau$, but $2m_\tau \rightarrow 2m_b$ new region for LHC
How CMS detects objects

Key:
- **Muon**
- **Electron**
- **Charged Hadron (e.g. Pion)**
- **Neutral Hadron (e.g. Neutron)**
- **Photon**

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

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Signal Characteristics

• \( m_h \gg m_\phi \rightarrow \phi_1 \) will be boosted, tau pair collimated
  ‣ Identifying 2 pairs of overlapping taus not trivial

• Instead use simple, clean objects: **2 muons + 2 tracks**
  ‣ One tau in each pair decays to muon
  ‣ Other decays to 1 charged particle
Signal Characteristics

Muon-track “pair” or “system”, randomly assign label “1” or “2”

Same-charge muons to remove backgrounds ($\ell\ell$, ttbar)

$\mu^\pm$ track$^\mp$

$h (125)$ has low $p_T \rightarrow$ require large separation between muons

Look for 1 opposite-charge track close to $\mu$

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Background Estimate

- Backgrounds dominated by QCD events
  - b/c hadron decay in $b\bar{b}$ events, SS muons emerge from
    \[
    b \rightarrow c + \mu^- \bar{\nu}_\mu
    \]
    \[
    \bar{b} \rightarrow \bar{c} \rightarrow \bar{s} + \mu^- \bar{\nu}_\mu
    \]
- E.g. example same-charge $\mu\mu$ event from $gg \rightarrow b\bar{b}$ event in PYTHIA

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Background Estimate

- MC statistics insufficient - require data driven estimate

- Use **muon-track invariant masses** $m_i$ as discriminating variable
  - Use 2D distribution of $m_1 \times m_2$
  - Background distribution from sideband region

![Graphs showing the signal simulation and background distributions with $m_\Phi = 8$ GeV.](image)

- Work in progress

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Background Estimate

- Sideband region must be QCD-rich, little signal contamination

- **Sideband region**: allow 1 or 2 additional tracks around one muon

- QCD events have muon amongst jet particles → several tracks around muon

- Muon-track invariant mass good discriminator for $m_\phi = 8$ GeV

- Shapes more similar at $m_\phi = 4$ GeV
Background Estimate

- Method relies on same mass distribution shape for signal & sideband regions
  - Shape *uncorrelated* with track multiplicity around one muon
  - Confirmed with dedicated MC made using PYTHIA, no detector effects

![Graph showing mass distribution](image)

- Red: shape in signal region
- Blue: shape in sideband region
- Consistent shapes for both regions

*Work in progress*
Signal Extraction

- Put bins from 2D plot of $m_1$ V $m_2$ into 1D plot
- Fit signal & background shapes to data
  - Allow normalisations of background and signal to float freely

![Graph showing data and fitted shapes](image)

**CMS**

Data

Bkg(+uncertainty)

Signal, $m(\psi) = 4$ GeV

Signal, $m(\psi) = 8$ GeV

Work in progress
No significant excess seen in data → set upper limits on $\sigma \times \text{BR}$
No significant excess seen in data → set upper limits on $\sigma \times \text{BR}$

Expected quantifies sensitivity of search

Work in progress
No significant excess seen in data → set upper limits on $\sigma \times \text{BR}$

![Graph showing upper 95% C.L. limit on $\sigma \times \text{BR}$ vs. $m_{\phi_1}$ (GeV). The observed limit is shown as a black line, while the expected limits are shown in green (1σ) and yellow (2σ). The graph indicates that work is in progress and excludes $\sigma \times \text{BR}$ at 95% C.L. above the black line.]
Summary

- No significant excess seen above SM backgrounds

- Placed upper limits on $\sigma \times \text{BR}$ for $gg \rightarrow h \ (125) \rightarrow 2\phi_1 \rightarrow 4 \tau$:
  - $m_\phi = 5 \text{ GeV}$: 9.7 pb observed (10.1 pb expected)
  - $m_\phi = 8 \text{ GeV}$: 4.4 pb observed (2.6 pb expected)

- First limit from the LHC in the mass range $2m_\tau < m_\phi < 2m_b$
Backup
Table 1: The number of observed data events, expected background and signal yields and signal acceptances after final selection. The computed signal acceptances include a branching ratio factor, $BR^2(\tau \rightarrow \mu \nu \bar{\nu}) \times (2 \cdot BR(\tau \rightarrow 1 - \text{prong}) - BR(\tau \rightarrow \mu \nu \bar{\nu}))^2 \approx 7\%$, as well as a factor of 1/2 due to the selection of same-sign muon pairs. The electroweak background includes the Drell-Yan process, $W + \text{jets}$ events, and diboson production of $WW, WZ, \text{and } ZZ$. The numbers of signal events are reported for the value of the signal production cross section times branching ratio of 5 pb. The expected background and signal yields and signal acceptances are obtained from simulation. The quoted uncertainties on predictions from simulation include only MC statistical errors.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>873</td>
</tr>
<tr>
<td>Expected background events</td>
<td></td>
</tr>
<tr>
<td>QCD multijets</td>
<td>820±320</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1.2±0.2</td>
</tr>
<tr>
<td>Electroweak</td>
<td>5.0±4.7</td>
</tr>
<tr>
<td>Signal acceptance, $\mathcal{A}(gg \rightarrow H(125) \rightarrow \phi_1 \phi_1 \rightarrow 4\tau)$</td>
<td></td>
</tr>
<tr>
<td>$m_{\phi_1} = 4 \text{ GeV}$</td>
<td>$(5.38\pm0.23)\cdot10^{-4}$</td>
</tr>
<tr>
<td>$m_{\phi_1} = 5 \text{ GeV}$</td>
<td>$(4.36\pm0.21)\cdot10^{-4}$</td>
</tr>
<tr>
<td>$m_{\phi_1} = 6 \text{ GeV}$</td>
<td>$(4.00\pm0.23)\cdot10^{-4}$</td>
</tr>
<tr>
<td>$m_{\phi_1} = 7 \text{ GeV}$</td>
<td>$(4.04\pm0.20)\cdot10^{-4}$</td>
</tr>
<tr>
<td>$m_{\phi_1} = 8 \text{ GeV}$</td>
<td>$(3.13\pm0.18)\cdot10^{-4}$</td>
</tr>
<tr>
<td>Number of signal events for $(\sigma \times BR)^{\text{sig}} = 5 \text{ pb}$</td>
<td></td>
</tr>
<tr>
<td>$m_{\phi_1} = 4 \text{ GeV}$</td>
<td>53.0±2.3</td>
</tr>
<tr>
<td>$m_{\phi_1} = 5 \text{ GeV}$</td>
<td>43.0±2.0</td>
</tr>
<tr>
<td>$m_{\phi_1} = 6 \text{ GeV}$</td>
<td>39.5±2.0</td>
</tr>
<tr>
<td>$m_{\phi_1} = 7 \text{ GeV}$</td>
<td>39.9±2.0</td>
</tr>
<tr>
<td>$m_{\phi_1} = 8 \text{ GeV}$</td>
<td>30.8±1.8</td>
</tr>
</tbody>
</table>

Work in progress
Table 3: The number of observed data events, the predicted background yields, and expected signal yields, for different masses of the $\phi_1$ boson in individual bins of the $(m_1, m_2)$ distribution. The background yields are obtained from the maximum-likelihood fit under the background-only hypothesis. The signal yields are obtained from simulation and normalized to the signal cross section times branching ratio of 5 pb. Errors on signal estimate include systematic and MC statistical uncertainties. Notation of bins follows the definition presented in Figure 4.

<table>
<thead>
<tr>
<th>Bin</th>
<th>Data</th>
<th>Bkg.</th>
<th>$m_{\phi_1}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>(1,1)</td>
<td>124</td>
<td>115±5</td>
<td>9.7±1.5</td>
</tr>
<tr>
<td>(1,2)</td>
<td>231</td>
<td>251±10</td>
<td>21.6±2.9</td>
</tr>
<tr>
<td>(1,3)</td>
<td>91</td>
<td>97±7</td>
<td>3.8±0.8</td>
</tr>
<tr>
<td>(1,4)</td>
<td>64</td>
<td>59±4</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td>(2,2)</td>
<td>137</td>
<td>142±7</td>
<td>14.2±2.0</td>
</tr>
<tr>
<td>(2,3)</td>
<td>112</td>
<td>104±6</td>
<td>3.7±0.7</td>
</tr>
<tr>
<td>(2,4)</td>
<td>61</td>
<td>57±4</td>
<td>0</td>
</tr>
<tr>
<td>(3,3)</td>
<td>16</td>
<td>20±2</td>
<td>0</td>
</tr>
<tr>
<td>(3,4)</td>
<td>29</td>
<td>21±2</td>
<td>0</td>
</tr>
<tr>
<td>(4,4)</td>
<td>8</td>
<td>6±1</td>
<td>0</td>
</tr>
</tbody>
</table>

Work in progress
Yields

Table 4: The observed upper limit at a 95% confidence level on $(\sigma \times BR)_{\text{sig}}$ in pb, together with the expected limit, obtained in the background-only hypothesis, as a function of $m_{\phi_1}$. Also reported are 68% ($\pm 1\sigma$) and 95% ($\pm 2\sigma$) probability intervals around the expected limit.

<table>
<thead>
<tr>
<th>$m_{\phi_1}$ [GeV]</th>
<th>observed</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.2</td>
<td>5.2</td>
<td>7.0</td>
<td>9.7</td>
<td>13.8</td>
<td>18.9</td>
</tr>
<tr>
<td>5</td>
<td>9.7</td>
<td>5.3</td>
<td>7.1</td>
<td>10.1</td>
<td>14.6</td>
<td>20.6</td>
</tr>
<tr>
<td>6</td>
<td>8.3</td>
<td>2.5</td>
<td>3.4</td>
<td>4.9</td>
<td>7.2</td>
<td>10.2</td>
</tr>
<tr>
<td>7</td>
<td>4.8</td>
<td>1.4</td>
<td>1.9</td>
<td>2.8</td>
<td>4.1</td>
<td>5.9</td>
</tr>
<tr>
<td>8</td>
<td>4.4</td>
<td>1.3</td>
<td>1.8</td>
<td>2.6</td>
<td>3.9</td>
<td>5.7</td>
</tr>
</tbody>
</table>
Table 2: List of systematics uncertainties and their effect on estimates of the QCD multijet background and signal.

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Affected sample</th>
<th>Type</th>
<th>Effect on normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.5%</td>
<td>signal</td>
<td>norm.</td>
<td>2.5%</td>
</tr>
<tr>
<td>Track selection and isolation efficiency</td>
<td>5% per track</td>
<td>signal</td>
<td>norm.</td>
<td>10%</td>
</tr>
<tr>
<td>Muon ID and trigger efficiency</td>
<td>2% per muon</td>
<td>signal</td>
<td>norm.</td>
<td>4%</td>
</tr>
<tr>
<td>Bin-by-bin statistical uncertainties on $C(i,j)$</td>
<td>2-15%</td>
<td>bkg.</td>
<td>shape</td>
<td>–</td>
</tr>
<tr>
<td>QCD background shape</td>
<td>–</td>
<td>bkg.</td>
<td>shape</td>
<td>–</td>
</tr>
<tr>
<td>Bin-by-bin MC statistical uncertainties</td>
<td>7-100%</td>
<td>signal</td>
<td>norm./shape</td>
<td>4-6%</td>
</tr>
</tbody>
</table>

**Theory uncertainties on the signal acceptance**

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Affected sample</th>
<th>Type</th>
<th>Effect on normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale variation</td>
<td>1%</td>
<td>signal</td>
<td>norm.</td>
<td>1%</td>
</tr>
<tr>
<td>PDF</td>
<td>1%</td>
<td>signal</td>
<td>norm.</td>
<td>1%</td>
</tr>
<tr>
<td>Effect of b-loop contribution to $gg \rightarrow H(125)$</td>
<td>3%</td>
<td>signal</td>
<td>norm.</td>
<td>3%</td>
</tr>
</tbody>
</table>
Theory scans

Private study by D. Barducci/S. Moretti/A. Belyaev

1 dot per point in parameter space
Correlations

- Are $m_1$ and $m_2$ actually uncorrelated? Carried out tests.

- Look in two different BG-rich control regions
  - Region A: Each muon has 1 or 2 extra nearby tracks with $1 < p_T < 2.5$ GeV
  - Region B: Each muon has 1 or 2 extra nearby tracks with $2.5 < p_T < 6$ GeV which fail 1-prong criteria

- Calculate correlation coefficients, $C(i,j)$, for each bin in 2D distribution:
  \[
  C(i,j) = \frac{f^{CR,\text{sym}}_{2D}(i,j)}{(f^{CR}_{1D}(i) \times f^{CR}_{1D}(j))^{\text{sym}}}. 
  \]

- If $= 1$, then uncorrelated
Correlations

Figure 5: The \((m_1, m_2)\) correlation coefficients \(C(i, j)\) derived in control regions A (left plot) and B (right plot). Notation of bins in the two-dimensional \((m_1, m_2)\) distribution follows definition presented in Figure 4.
Signal Selection

- 2 tight muons, non-isolated:
  - $|d0| < 0.03 \text{ cm}, |dz| < 0.1 \text{ cm}$ to PV [heavy flavour QCD more displaced]
  - Leading (sub-leading) $p_T > 17 \ (10) \text{ GeV}, |\eta| < 2.1$ for both
  - Same charge [reduces $VV, DY, ttbar$ bkg]
  - $\Delta R(\mu-\mu) > 2$ [h(125) has low $p_T \therefore \phi_1$ are well separated]

- Around each muon, within $\Delta R < 0.5$:
  - Require $== 1$ track with $p_T > 1 \text{ GeV}, |d0| < 1 \text{ cm}, |dz| < 1 \text{ cm}$ to PV [QCD has high track multiplicity]
  - Track $p_T > 2.5 \text{ GeV}, |\eta| < 2.4, |d0| < 0.02 \text{ cm}, |dz| < 0.04 \text{ cm}$ to PV [1-prong candidate]
  - Track and muon have opposite charge
Work in progress
Previous Searches

- **LEP**: used Zh channel, but limited by $m_h$ range (OPAL: 45-86 GeV, ALEPH: 114 GeV)

- **Tevatron (D0)**:
  - Search for $2\tau 2\mu$ & $4\mu$, sharp dimuon resonance at $m_a$. “For $m_a > 2m_\tau$, the limits [on $\sigma xBR$] set are a factor of $\approx 1-4$ larger than the expected production cross section”

- **LHC**:
  - **HIG-13-010**: Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-$\mu$ final states - looked for 2 dimuon resonances.
    - Only valid for $m_a = 0.25$ - 3.55 GeV, $m_a > 2m_\tau$ not covered. Nothing found.
  - Interpretation of multi-lepton searches from CMS & ATLAS:
    - “Below 15 GeV, quarkonium vetoes begin to make all of the searches very inefficient ... isolation cuts also have a major impact...this leaves fully open the interesting NMSSM-motivated region with $m_a < \sim m_\Upsilon$”