Search for Higgs boson in models beyond SM at CMS

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Overview

- Higgs boson in MSSM
  - Neutral Higgs boson: \( h/H/A \rightarrow bb, \tau\tau \)
  - Charged Higgs boson: \( H^\pm \rightarrow \tau \nu \)

- Higgs boson in Next-to-MSSM
  - A very light CP odd scalar boson: \( h \rightarrow 2a \rightarrow 4\mu, \quad (m_a < 2m_\tau) \)
MSSM Higgs production at LHC

- MSSM Higgs Sector:
  - Two Higgs doublet $\Rightarrow$ 5 physical bosons: $h, H$ (CP even), $A$ (CP odd) and $H^\pm$
  - Controlled by two parameters at tree level: $m_A$ and $\tan\beta$

- Neutral Higgs production and decay:
  - Dominant decay mode: $bb$ and $\tau\tau$

- Charged Higgs production and decay:
  - For $M_{H^+} \leq m_{top}$:
    - $pp \rightarrow t\bar{t} \rightarrow bH^{\pm}\bar{b}W^{\mp}$ with $t \rightarrow bH^+$
  - For $M_{H^+} \geq m_{top}$:
    - $pp \rightarrow tbH^+$
  - For large $\tan\beta$, $\text{Br}(H^+ \rightarrow \tau\nu) \approx 1$
MSSM Higgs search channels

• $pp \rightarrow \phi b, \phi \rightarrow bb$
  • Semileptonic $b$ decays (jet containing a muon)
  • Hadronic $b$ decays

• $pp \rightarrow \phi, \phi \rightarrow \tau\tau$
  • $e+\mu$ (very clean channel, low statistics)
  • $e+\tau_{\text{had}}$ (larger background, high statistics)
  • $\mu+\tau_{\text{had}}$ (smaller background, high statistics)
  • $\mu+\mu$ (low sensitivity)

• $pp \rightarrow tt, t \rightarrow H^+b, H^+ \rightarrow \tau\nu$

  (1) $H^\pm \rightarrow \tau_h\nu, W^\mp \rightarrow q\bar{q}_j$
  (2) $H^\pm \rightarrow \tau_h\nu, W^\mp \rightarrow \ell\nu$
  (3) $H^\pm \rightarrow \tau\nu, \tau \rightarrow e(\mu)\nu, W^\mp \rightarrow \mu(e)\nu$

$\phi : h, H, A$

$\tau_{\text{had}}$: hadronic $\tau$ decay

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MSSM Higgs $\rightarrow bb$

Analysis divided in two sub-categories

- Semileptonic $b$ decays (jet containing a muon)
- Hadronic $b$ decays

Event Selection:

Trigger:
- diJet OR muon+jet triggers, with one or more $b$-tagged jets

Offline:
- $\geq 3$ $b$-tagged jets (Thresholds vary according to analysis)

One of the jet contains a muon in semi-leptonic analysis.

Backgrounds:
- Major background: qcd $b\bar{b}$
- Measured from data

$pp \rightarrow \varphi b, \varphi \rightarrow bb$, $\varphi : h, H, A$

di-Jet mass in semi-leptonic final state

Data in Agreement with background prediction

$M_{12}$ Resolution $\sim 15\%$
Upper Limit on $pp \rightarrow \phi b, \phi \rightarrow bb$ production by fitting observed $M_{12}$ distribution. Non-observation of $\phi \rightarrow bb$ Signal excludes region of large $\tan\beta$ in MSSM Parameter space.
MSSM Higgs $\rightarrow \tau\tau$

Analysis performed in 4 final states:
\[ e^+\mu, e^+\tau_{\text{had}}, \mu^+\tau_{\text{had}}, \mu^+\mu \]

Event Selection
- Events triggered by $e^+\mu$, $e^+\tau_{\text{had}}$ and $\mu^+\tau_{\text{had}}$ Triggers
- Opposite Charged isolated Lepton Pair ($\mu\tau_h, e\tau_h, e\mu, \mu\mu$)
- Veto Events with additional isolated Leptons

- Selected Events analyzed in 2 Categories: non-b-Tag and b-Tag
  - **b-Tag**: $\leq 1$ jet with $p_T > 30$ GeV, $\geq 1$ b-Tagged Jet with $p_T > 20$ GeV (enhance bbH signal)
  - **Non b-Tag**: $\leq 1$ jet with $p_T > 30$ GeV, No b-Tagged Jet with $p_T > 20$ GeV

Backgrounds:
- $Z \rightarrow \tau\tau, Z \rightarrow ee, \mu\mu$, QCD, W+Jets, ttbar, diboson.
- $Z \rightarrow \tau\tau$ is estimated using $Z \rightarrow \mu\mu$ events, where muon is replaced by a simulated tau.
- W+jets and ttbar is suppressed by requiring $m_\tau < 20$ GeV
- W+jets estimated from high $m_\tau$ $(m_\tau > 70)$ sideband.
- QCD is estimated from data using same-sign lepton pairs.

$pp \rightarrow \phi, \phi \rightarrow \tau\tau$, $\phi : h, H, A$
Mass of τ Lepton pair reconstructed via Likelihood technique, based on:
- τ decay Kinematics
- Compatibility of reconstructed $E_T^{\text{miss}}$ with Neutrino hypothesis

$m_{\tau\tau}$ Resolution $\sim 20\%$ (almost Gaussian)

Distribution observed in Data in agreement with background expectation

More details on tau-ID and di-tau mass reconstruction is in SM H→ $\tau\tau$ talk.
$\phi \rightarrow \tau \tau$ Exclusion Limit

- Limit obtained by scanning $\tan\beta$ for each mass hypothesis $M_A$:
- Cross-section $\times$ BR for $gg \rightarrow \phi$ and $bb \rightarrow \phi$ computed as function of $M_A$, $\tan(\beta)$
- Dependence of $M_h$ and $M_H$ on $\tan\beta$ taken into account
Charged Higgs

Search for a charged Higgs in top quark decay

\[ pp \to tt, \ t \to H^+ b, \ H^+ \to \tau \nu \]

4 final states analysed (e\(\mu\), e\(\tau_h\), \(\mu\tau_h\), \(\tau_h+jets\))

Shape based analysis using \(m_T (\tau + E_T^{miss})\) or \(p_T(leading\ track)/p_T(\tau)\)

Upper limit on \(BR(t \to H^+ b)\) excludes region of large \(\tan \beta\) in MSSM Parameter space for \(M_{H^+}/M_A \leq M_{top}\) (arXiv:1307.1347)
Search for \( h \rightarrow 2a \rightarrow 4\mu \)

- Generic search for non-SM decay of Higgs boson to a pair of new light bosons (a), which subsequently decay to boosted pairs of oppositely charged muons.

- Predicted in several models (NMSSM, dark SUSY)

**Benchmark Scenarios:**

- **NMSSM Higgs Sector:** 3 CP-even: \( h_{1,2,3}, 2 \) CP-odd: \( a_{1,2} \)
- Possible Signature at LHC: \( h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu \)
- Typical Higgs masses: \( 90 \lesssim m_{h1} \lesssim 120-135 \text{ GeV} \)
- Search assumption: \( 0.25 < m_{a1} < 3.55 \text{ GeV} \)
  
  \[ 2m_\mu \leq m_{a1} \leq 2m_\tau \]

- **Dark Susy:** New light dark boson \( \gamma_D \)
- Possible Signature at LHC: 
  
  \( h 1 \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu \)
- Search assumption: \( 0.25 < m_{\gamma D} < 3.55 \text{ GeV} \)
Analysis Strategy

**Event Selection**

- di-muon trigger ($p_T > 17$ GeV, 8 GeV)
- Exactly two distinct, opposite charged, muon pairs ($m_{\mu\mu} < 5$ GeV)
- Di-muons are required to be isolated to suppress qcd $bb$ background.
- No limit on no. of unpaired muons.

- Search for di-muon resonance peaks on diagonal of 2D distribution of the di-muons mass

**Signal Region :**

$m_{\mu\mu_1}-m_{\mu\mu_2}<5\sigma=0.13+0.065\cdot(m_{\mu\mu_1}+m_{\mu\mu_2})/2$

(detector resolution)

**Backgrounds :**

- $bb\bar{b}$ : Measured from data using orthogonal sample of $bb\bar{b}$ events with exactly one di-muon and one unpaired muon.
- $J/\psi$ : Estimated using simulation
- Total background in the signal region : $3.8 \pm 2.1$

(background expectation shown as the intensity of the shading)

8 events outside signal region

One event in Signal region
Exclusion Limits

Model independent 95% CL upper limit on
\[ \sigma(pp \rightarrow 2a + X) \times Br^2(a \rightarrow 2\mu) \times \alpha_{gen} \]

- where \( \alpha_{gen} \) is geometric and kinematic acceptance calculated using generated information.

- The efficiency of detector and analysis selection requirements have very weak dependence on the model, Thus allowing to set limit on any arbitrary new physics model predicting similar signature.

Model Independent Exclusion Limit

Exclusion Limits on Higgs boson in NMSSM
Exclusion Limits (II)

95% CL upper limit as functions of $m_h$

**NMSSM**

- $m_{h_1} = 3.55$ GeV/c$^2$
- $m_{a_1} = 2$ GeV/c$^2$
- $m_{a_1} = 0.25$ GeV/c$^2$

Prediction with $\sigma(pp \rightarrow h_1) = \sigma_{SM}(m_h)$:

- $\sigma(pp \rightarrow h_1) \times B(h_1 \rightarrow 2a_1) = 0$,
- $B(h_1 \rightarrow 2a_1) = 0.8\%$,
- and $B(a_1 \rightarrow 2\mu) = 7.7\%$

**dark-SUSY**

- $m_h = 10$ GeV/c$^2$, $m_{\tau_1} = 1$ GeV/c$^2$
- and $m_{\tau_2} = 0.4$ GeV/c$^2$

Prediction with $\sigma(pp \rightarrow h) = \sigma_{SM}(m_h)$:

- $B(h \rightarrow 2\tau_1) = 0.25\%$,
- $B(\tau_1 \rightarrow \gamma_D + n_D) = 50\%$,
- and $B(\gamma_D \rightarrow 2\mu) = 45\%$
Summary

- CMS explored the search for Higgs boson in many promising models beyond SM.

- Results are presented for the search of Higgs boson in MSSM, NMSSM and other exotic models.

- No evidence of any excess above Standard Model backgrounds.

- Stringent limit set on the production of Higgs boson in most of the models beyond SM.

- An update on the MSSM Higgs results with full 7TeV+8TeV data is expected soon.
Higgs boson in MSSM

- Two Higgs doublet => 5 physical bosons
  - Three neutrals: \( h, H \) (CP even), \( A \) (CP odd)
  - Two charged: \( H^\pm \)
- Controlled by two parameters at tree level
  - \( m_A \) and \( \tan \beta \)

\[
\begin{align*}
\Phi_1 &= \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix} \\
\Phi_2 &= \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix}
\end{align*}
\]

\[
\tan \beta = \frac{v_2}{v_1}
\]

\[
\begin{align*}
M_{H^+}^2 &= M_A^2 + M_W^2 \\
M_{h/H}^2 &= \frac{1}{2} \left( M_A^2 + M_Z^2 + \sqrt{(M_A^2 + M_Z^2)^2 - 4 M_A^2 M_Z^2 \cos^2 2\beta} \right)
\end{align*}
\]

Other SUSY parameters are important at higher order corrections
### \( \phi \rightarrow bb \) Event Selection

<table>
<thead>
<tr>
<th><strong>Semileptonic</strong></th>
<th><strong>Hadronic</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger:</strong></td>
<td></td>
</tr>
<tr>
<td>Muon+1/2 Jets</td>
<td>2/3 Jets</td>
</tr>
<tr>
<td>( \geq 1/2 ) b-tagged</td>
<td>( \geq 2 ) b-tagged</td>
</tr>
<tr>
<td><strong>Offline:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td></td>
</tr>
<tr>
<td>( P_T &gt; 15 ) GeV (no Isolation applied)</td>
<td></td>
</tr>
<tr>
<td><strong>Jets</strong></td>
<td></td>
</tr>
<tr>
<td>( \geq 2 ) Jets of ( P_T &gt; 30 ) GeV</td>
<td>( \geq 3 ) Jets:</td>
</tr>
<tr>
<td>+ 3rd Jet of ( P_T &gt; 20 ) GeV</td>
<td>( P_T ) 1st &gt; 46 (60) GeV</td>
</tr>
<tr>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>all 3 b-tagged</td>
<td>( P_T ) 3rd &gt; 20 GeV</td>
</tr>
<tr>
<td>Muon is within one of two leading jets</td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>all 3 b-tagged</td>
</tr>
</tbody>
</table>

Jet \( P_T \) Threshold depends on Higgs Mass hypothesis: lower (higher) Thresholds used for \( M_\phi < 180 \) GeV (\( M_\phi > 180 \) GeV), driven by Trigger Thresholds.

The major background, QCD, is estimated from data. The other minor backgrounds, ttbar and Z(bb)+jets Is taken from MC.

19/07/2013
$\varphi \rightarrow \tau\tau$ Analysis

Event Selection

- **Trigger**
  Events triggered by $e^+\mu$, $e^+\tau_{\text{had}}$ and $\mu^+\tau_{\text{had}}$ Triggers, $P_T$ thresholds $10-20$ GeV/c

- **Lepton Selection**
  - **Electrons**
    - $P_T > 10-20$ GeV
    - $|\eta| < 2.1$ (2.3 for $e + \mu$)
    - isolated
  - **Muons**
    - $P_T > 10-20$ GeV
    - $|\eta| < 2.1$
    - isolated
  - **$\tau_{\text{had}}$**
    - $P_T > 20$ GeV
    - $|\eta| < 2.3$
  - **Tau Identification**
    - Veto against $e/\mu$

- **Opposite Charge Lepton Pair**

- **Veto Events with additional isolated Leptons**

- **Selected Events analyzed in 2 Categories: non-b-Tag and b-Tag**
  - **b-Tag**: $\leq 1$ jet with $p_T > 30$ GeV, $\geq 1$ b-Tagged Jet with $p_T > 20$ GeV
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BSM Higgs @ CMS, A. Nayak
Hadron + Strips Algorithm

\( \pi^+/K^+ , \rho^+ \rightarrow \pi^+\pi^0 \) and \( a_1 \rightarrow \pi^+\pi^+\pi^-\pi^0\pi^0 \)

Ring-Based Isolation:
- Isolation \( p_T \) summed in \( \Delta R \) rings around tau
- BDT trained against jet \( \rightarrow \tau \) fakes
b-Jet Tagging

Many algorithms developed at CMS, based on track impact parameter and secondary vertex of B hadron decay.
Algorithm used for most Higgs searches in 2011: TCHE

TCHE: Simple method.
Tracks are ordered according to the impact parameter significance (IP/\sigma_{IP}). The IP significance of 2^{nd} track is used as discriminator.
Small Branching ratio (few times $10^{-4}$), However, Muons are reconstructed very efficiently in CMS and with very good Mass Resolution (almost comparable to Higgs width)

**Event Selection**

Single Muon trigger
2 Muons $P_T$ 1st $> 30$ GeV $P_T$ 2nd $> 20$ GeV
$|\eta| < 2.1$, isolated

Opposite Charge Muon Pair
Suppression of $t\bar{t}$ Background $E_T^{miss} < 30$ GeV

Selected Events analyzed in 3 Categories: b-Tag, 3rd Muon and neither

> Observed diMuon mass spectrum is well in agreement with background expectations.
The signal is defined as the excess of $t\bar{t}$ event yields in presence of $H^+$:

$$N_{\text{excess}} = N_{\text{tt}}^{\text{MSSM}} - N_{\text{tt}}^{\text{SM}} = N_{\text{WH}} \, 2(1-x)x + N_{HH} x^2 + N_{tt}^{\text{SM}} \, (1-x)^2 - 1$$

$x = \text{BR}(t \rightarrow H^+ b)$

No Excess of events observed. Data is agrees well with SM backgrounds.

Major backgrounds are estimated from data.
Doubly charged Higgs boson ($\Phi^{++}$)

- Standard model extension by a scalar triplet adding three new particles
  - $\Phi^{++}, \Phi^+, \Phi^0$ (e.g. Type-|| seesaw model)
- The triplet is responsible for neutrino masses, the couplings being directly linked to the mass matrix
  - $M_{ij} = k \, Y_{ij}$
- Unknown neutrino mass matrix $\rightarrow$ unknown branching ratios
- Assume branching ratios to leptons only

- Six standard searches covered, where $\text{BR}(\Phi^{++} \rightarrow l^+ l^+) = 100\%$
- Four additional model dependent points to describe the neutrino sector

$\Phi^{++}$ and $\Phi^+$ are assumed to be degenerate in mass
**Φ^{±±} Exclusion Limits**

Signatures: **3 or 4 leptons** in the final state, dilepton made by same sign lepton

arXiv:1207.2666

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**CMS √s = 7 TeV, \( \int L dt = 4.9 \text{ fb}^{-1} \)**

![Graph showing exclusion limits for Φ^{±±}](image)

**Pre-selection**
- \( \sum p_T \)
- Z veto
- \( \Delta \varphi(\ell\ell) \)
- Mass window

**Events**
- Data
- Drell-Yan
- Diboson
- \( tt \)
- Single top
- Signal (350 GeV)
- \( \times \times \times \) MC stat. uncert.

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BSM Higgs @ CMS, A. Nayak
NMSSM: $a_1 \rightarrow \mu^+ \mu^-$

- Add a scalar singlet to MSSM Higgs family
  - 3 CP even ($h_1, h_2, h_3$), 2 CP odd ($a_1, a_2$), and $H^\pm$
  - One of the CP odd Higgs boson can be very light
    \[ a_1 = a_{\text{mssm}} \cos \theta_A + a_s \sin \theta_A \]
    (superposition of MSSM CP odd doublet scalar
     And the additional CP odd singlet scalar)
- At CMS: search above and below the Upsilon family
  - Larger production rate relative to Tevatron
  - Extended search relative to BaBar.

Event Selection

- Trigger (Prescaled):
  - OS dimuon, $p_T^\mu > 3.5$ GeV, $p_T^{\mu\mu} > 6.0$ GeV
  - $5.5 < m_{\mu\mu} < 14$ GeV
  - Impact parameter compatible with prompt muon
- Offline Muon Selection: $p_T^\mu > 5.5$ GeV, $|\eta| < 2.4$, isolated

Search mass ranges 5.5-8.8 GeV and 11.5-14 GeV
Search Strategy

- **Signal extraction**
  - Binned ML fit over 5.5 – 14 GeV
  - Mass scan in 30 MeV steps

- **Background model**
  - QCD: 1st-order polynomial
  - Y(NS): double crystal ball

- **Signal model**
  - Single Gaussian
  - Mean fixed to center of step
  - Width fixed to detector resolution (by fitting the inv. mass spectrum with two CB functions)
    - Barrel: 50 – 120 MeV
    - Endcap: 90 – 190 MeV
No significant excess of events observed in 1.3fb-1 @ 7 TeV, exclusion limits set at the level of 2 – 6 pb for $\sigma \times B$
production of $a_1$