Search for MSSM and NMSSM Higgs bosons with the CMS detector

Christian Veelken
for the CMS Collaboration

ICHEP Conference, July 4th 2014
A SM-like Higgs boson has been discovered at the LHC
A SM-like Higgs boson has been discovered at the LHC

It looks like the SM Higgs boson, sounds like the SM Higgs boson and smells like the SM Higgs boson... but: **Is it really the SM Higgs boson?**

– or just one of multiple Higgs bosons in a supersymmetric world?
A SM-like Higgs boson has been discovered at the LHC

It looks like the SM Higgs boson, sounds like the SM Higgs boson and smells like the SM Higgs boson... but: **Is it really the SM Higgs boson?**
- or just one of multiple Higgs bosons in a supersymmetric world?

**Two (complementary) ways to find-out:**

- Precision measurements of BRs
  (good sensitivity already with 7+8 TeV LHC data ➔ see next BEH session)
- Find more Higgs bosons!

➔ Subject of this Presentation: Results of CMS searches for Higgs bosons in the context of MSSM and NMSSM
MSSM

2 Higgs doublets [*]

\[ H_u = \left( \begin{array}{c} H_u^+ \\ H_u^0 \end{array} \right), \quad H_d = \left( \begin{array}{c} H_d^0 \\ H_d^- \end{array} \right) \]

2 scalars: \( h, H \)
1 pseudo-scalar: \( A \)
2 charged Higgs bosons: \( H^+, H^- \)

Higgs mass \( > m_Z \) due to radiative corrections: large stop mass and/or large stop mixing required to reach \( m_h = 125 \text{ GeV} \)

NMSSM

2 Higgs doublets [*]
+ complex Higgs singlet

\[ H_u = \left( \begin{array}{c} H_u^+ \\ H_u^0 \end{array} \right), \quad H_d = \left( \begin{array}{c} H_d^0 \\ H_d^- \end{array} \right), \quad S \]

3 scalars: \( h_1, h_2, h_3 \)
2 pseudo-scalars: \( a_1, a_2 \)
2 charged Higgs bosons: \( H^+, H^- \)

\( m_h = 125 \text{ GeV} \) for Higgs with SM-like couplings can be achieve by mixing between doublet and singlet fields; much less constraints on radiative corrections

Simplicity

Naturalness

NB.: \( m_h = 125 \text{ GeV} \) is right where SUSY predicted the Higgs boson to be!
Search for light NMSSM Higgs bosons
Model independent search for events containing 2 muon pairs of same mass

Event selection

Exactly 2 muon pairs of:

- zero charge
- mass $m_{\mu\mu} < 5$ GeV
- same mass (within 5 times detector resolution)
Background Estimation

Main backgrounds:

- $b\bar{b}$ decays to muons
- Direct di-$J/\Psi$ production

estimated from sideband in data

8 Events observed in $m_{\mu\mu_1} \neq m_{\mu\mu_2}$ sideband

→ Background estimate in signal region = $3.8 \pm 2.1$
Results

1 event observed in signal region, compatible with background prediction of $3.8 \pm 2.1$

No evidence for a signal

$\Rightarrow$ Set limit on cross-section x BR
Model independent Limit

Effect of the 1 event observed in signal region
Searches for charged MSSM Higgs bosons
$H^+ \rightarrow c\bar{s}$ \((m_{H^+} < m_{top})\)

**Event selection**

\[ \geq 2 \text{ b-tagged jets of } P_T > 30 \text{ GeV} \& |\eta| < 2.4 \]
H^{+} \rightarrow c \bar{s} \ (m_{H^{+}} < m_{\text{top}})

Event selection

≥ 2 b-tagged jets of $P_{T} > 30 \text{ GeV} \& |\eta| < 2.4$

≥ 2 further jets of $P_{T} > 30 \text{ GeV} \& |\eta| < 2.4$
$H^+ \rightarrow c\bar{s} \ (m_{H^+} < m_{top})$

Event selection

- $\geq 2$ b-tagged jets of $P_T > 30$ GeV & $|\eta| < 2.4$
- $\geq 2$ further jets of $P_T > 30$ GeV & $|\eta| < 2.4$
- $E_T^{miss} > 20$ GeV
- 1 isolated muon of $P_T > 25$ GeV & $|\eta| < 2.1$
Separation of $H^+$ Signal from Backgrounds

Main background: SM $t\bar{t}$
Minor background: single top

Difference between signal and background: $t \rightarrow H^+b$ instead of $t \rightarrow Wb$ decay

$\Rightarrow$ Distinguish signal from background by looking at mass of jets without $b$-tag
Dijet Mass Reconstruction

**Analysis strategy:** Shape analysis of dijet mass distribution

Dijet mass reconstructed by **constrained kinematic fit**, using measured momenta + constraints

- muon
- b-tagged and non-b-tagged jets
- $E_T^{\text{miss}}$

plus their respective resolutions

Choose fit solution with lowest $\chi^2$:

- For deciding which of the 2 b-tagged jets to pair with the non-b-tagged jets
- In case there are > 4 jets in the event

---

**Shape analysis of dijet mass distribution**

CMS Simulation, $\sqrt{s} = 8$ TeV

- $m(b + q\bar{q}') = m_t$
- $m(b + \mu\nu) = m_t$
- $m(\mu + v) = m_W$
Signal Extraction

In the case of a $t \rightarrow H^+b$ signal:

- a deficit of events at $m_W$ [*]
- an excess of events at $m_{H^+}$ is expected in the dijet mass distribution.

[*] due to reduction of the number of $t \rightarrow Wb \rightarrow qa'b$ decays (total number of $t\bar{t}$ events does not change)

The yields of the $t \rightarrow H^+b$ signal and of the backgrounds (SM $t\bar{t}$ and other) is determined via a fit of the dijet mass spectrum observed in data.

No evidence for a signal

$\Rightarrow$ Set limits on $\text{BR}(t \rightarrow H^+b)$
Limit on $t \rightarrow H^+ b$ computed assuming all charged Higgs bosons to decay into dijets.
Searches for neutral MSSM Higgs bosons
Events are analyzed in 2 Categories, targeting different MSSM neutral Higgs production mechanisms:

1. **No-B-tag:** Events without b-tagged jets
   
   \[ pp \rightarrow \phi \]  
   gluon-gluon Fusion  
   dominates cross-section in case \( \tan \beta \) is **small**

2. **B-tag:** Events containing \( \geq 1 \) b-tagged jet of \( P_T > 20 \) GeV & \( |\eta| < 2.4 \)
   
   \[ pp \rightarrow \phi b \]  
   b-associated Production  
   dominates cross-section in case \( \tan \beta \) is **large**
Events are analyzed in 2 Categories, targeting different MSSM neutral Higgs production mechanisms:

1. **No-B-tag:** Events without b-tagged jets

   \[ pp \rightarrow \phi \text{ gluon-gluon Fusion} \]
   
   dominates cross-section in case \( \tan \beta \) is small

2. **B-tag:** Events containing \( \geq 1 \) b-tagged jet of \( P_T > 20 \) GeV \& \( |\eta| < 2.4 \)

   \[ pp \rightarrow \phi b \text{ b-associated Production} \]
   
   dominates cross-section in case \( \tan \beta \) is large

Presence of b-jet helps to reduce background (one b-jet usually outside acceptance)
Decay Channels

Signal events selected in 5 out of 6 channels:

- $\tau_{h}\tau_{h}$: 42.0%
- $e\tau_{h}$: 23.1%
- $\mu\tau_{h}$: 22.6%
- $e\mu$: 6.2%
- $\mu\mu$: 3.0%

96.9% of possible signal included in analysis
(not yet included in analysis: ee, BR = 3.1%)
**Higgs Mass Reconstruction**

**Analysis strategy:**  Search for peak in ditau mass distribution

Reconstruction of ditau mass based on **Likelihood method**, using as input:

- Measured $e$, $\mu$, $\tau_h$-jet momenta
- Reconstructed $E_T^{\text{miss}}$ and event-by-event estimate of $E_T^{\text{miss}}$ resolution ($E_T^{\text{miss}}$ reconstructed by a multivariate regression technique)

Resolution on $m_{\tau\tau}$ is $O(20\%)$, improves separation of signal from backgrounds

![Histogram of $m_{\tau\tau}$](image)

*J.Phys.Conf.Ser. 513 (2014) 022035*
No evidence for a signal beyond 125 GeV

Set upper limits on cross-section x BR for the 2 production processes $pp \rightarrow \phi$ and $pp \rightarrow \phi b$

Compute region in $m_A$-$\tan\beta$ parameter space excluded by non-observation of a signal
m_{\tau\tau} Distributions for all Channels

![Graphs showing m_{\tau\tau} distributions for different channels with and without B-tagging.](image-url)
Model independent Limits on $\phi$

$m_{\tau\tau}$ spectra observed in B-tag and No-B-tag category are fitted simultaneously, with shape templates for $\phi \to \tau\tau$ signal and for background processes.

$pp \to \phi b$ ($pp \to \phi$) cross-section treated as nuisance parameter when computing limit on $pp \to \phi$ ($pp \to \phi b$)

red line: limit expected in case no SM Higgs production is present in the data
blue line: limit expected in the presence of $H \to \tau\tau$ with SM cross-section x BR
**Exclusion contour in $m_A$-$\tan\beta$ plane**

Interpretation of results on new MSSM benchmark scenarios in preparation

- **red** line: limit expected in case no SM Higgs production is present in the data
- **grey** line: limit expected in the presence of Higgs $\rightarrow \tau\tau$ with SM cross-section $\times$ BR

Fit for sum of $A+H+h$,
taking dependency of cross-section,
BR and mass of each Higgs on
$m_A$ and $\tan\beta$ into account

Excluded

red line:
limit expected in case no SM Higgs production is present in the data

grey line: limit expected in the presence of Higgs $\rightarrow \tau\tau$ with SM cross-section $\times$ BR

Christian Veelken

Search for MSSM and NMSSM Higgs bosons
Summary & Outlook
Summary

CMS has searched for:

• Light NMSSM Higgs bosons
• Charged MSSM Higgs bosons
• Neutral MSSM Higgs bosons

No evidence for a supersymmetric Higgs signal observed in CMS data so far

→ Stringent limits on cross-section x BR have been set
Outlook

CMS is about to restart taking data in 2015, with:

• Higher center-of-mass energy $\sqrt{s} = 13$ TeV
• Higher luminosity
• New, more powerful, experimental techniques

⇒ Greatly enhanced sensitivity, in particular for signals of high mass

⇒ Stay tuned!
CMS Searches for SUSY Higgs bosons

Presented at ICHEP 2014
Presented at Conferences previously


CMS PAS HIG-12-052
$H^+ \rightarrow \tau\nu$

CMS PAS HIG-13-035
$H^+ \rightarrow c\bar{s}$


CMS PAS HIG-13-010
$a_1 \rightarrow 2\mu$

100pb

CMS PAS HIG-13-021
$\phi \rightarrow \tau\tau$

CMS PAS HIG-13-024
$\phi \rightarrow \mu\mu$

CMS PAS HIG-13-010
$h \rightarrow 2a_1 \rightarrow 4\mu$

10 pb

$m_H [\text{GeV}]$
The CMS Detector

Silicon tracking detector

ECAL

HCAL

Muon system


Christian Veelken

Search for MSSM and NMSSM Higgs bosons
Signal cross-section dropping rather steeply with Higgs mass

Parton luminosity increases by $O(10)$ in run 2 compared to run 1

http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

ratios of LHC parton luminosities: 14 TeV / 8 TeV and 33 TeV / 8 TeV
Width of MSSM neutral Higgs boson 
\[ \leq 3\% \text{ of Higgs mass} \]

Higgs width relevant for \( \phi \rightarrow \mu \mu \) analysis only
(experimental resolution on reconstructed Higgs mass
\( O(15\%) \) in \( \phi \rightarrow bb \) and \( O(20\%) \) in \( \phi \rightarrow \tau \tau \) decays)
$m_h^\text{max}$ scenario disfavored by observation of SM-like Higgs boson of mass $125 \pm 3$ GeV

New MSSM benchmark scenarios compatible with 125 GeV in most of parameter space
$pp \rightarrow a_1 \rightarrow 2\mu$

Search for peak in dimuon mass distribution

No evidence for signal

$\Rightarrow$ Set limits


Christian Veelken
Search for MSSM and NMSSM Higgs bosons

37
Fraction $R$ of energy carried by highest $P_T$ ("leading") track of hadronic tau is sensitive to $\tau$-lepton polarization, which is opposite for taus originating from $t \rightarrow Wb \rightarrow \tau b$ and taus produced in $H^+ \rightarrow \tau v$ decays.

Data in agreement with background expectation

Set limits
$\phi b \rightarrow 3b$

Search for peak in dijet mass distribution

Sizeable signal, but also large backgrounds

No evidence for signal

$\Rightarrow$ Set limits


Christian Veelken

Search for MSSM and NMSSM Higgs bosons
Search for peak in dimuon mass distribution

No evidence for signal peak in dimuon mass spectrum observed in data

$\phi \rightarrow \mu\mu$

Dimuon mass Resolution $\sim 3\%$

Set Limit

CMS PAS HIG-12-011

Search for MSSM and NMSSM Higgs bosons
Backgrounds to $\phi \rightarrow \tau \tau$

$Z/\gamma^* \rightarrow \tau \tau$
Obtained using Embedding technique:
$Z \rightarrow \mu \mu$ events selected in data, reconstructed muons replaced by simulated taus

Electroweak ($W+$jets, diboson, $Z \rightarrow ee/\mu\mu$)
Shapes from MC simulation
 Normalization of $W+$jets obtained by extrapolation from high $m_\tau$ control region in data, others from MC simulation

QCD
Fully data driven: Normalization (shape) obtained from same-sign events with isolated (non-isolated) muons

$t\bar{t}$, single top
Shape from MC simulation, normalization from data

Christian Veelken
Search for MSSM and NMSSM Higgs bosons
Hadronic tau Reconstruction

Mass $m_\tau = 1.78$ GeV

Lifetime $c \cdot \tau = 87 \, \mu$m

→ Taus typically decay before reaching first detector layer

Charged and neutral pions reconstructed by Particle Flow algorithm

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>17.36</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau$</td>
<td>17.85</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \nu_\tau$</td>
<td>11.6</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>26.0</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$</td>
<td>9.5</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$</td>
<td>9.8</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$</td>
<td>4.8</td>
</tr>
<tr>
<td>others</td>
<td>3.1</td>
</tr>
</tbody>
</table>
**Tau Decay Mode reconstruction**

![Diagram showing decay modes](image)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Resonance</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau$</td>
<td>$\pi(140)$</td>
<td>11.6</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>$\rho(770)$</td>
<td>26.0</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$</td>
<td>$a_1(1260)$</td>
<td>10.8</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$</td>
<td>$a_1(1260)$</td>
<td>9.8</td>
</tr>
<tr>
<td>Other hadronic modes</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td>All hadronic modes</td>
<td></td>
<td>64.8</td>
</tr>
</tbody>
</table>

Approach works well up to high pile-up
CMS Tau ID performed well during run 1
Data well modeled by Monte Carlo simulation

See also poster by Rosamaria Venditti