Non-SM Higgs searches at the LHC

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on behalf of the ATLAS and CMS Collaborations

MSSM Higgs Sector / Neutral Higgs: $Φ \rightarrow ττ$, $Φ \rightarrow \mu\mu$ / Charged Higgs: $m_{H^±} < m_{t_{top}}$, $m_{H^±} > m_{t_{top}}$ / Summary
Most non-SM Higgs searches at the LHC are performed within MSSM.

- Several benchmark scenarios, selecting most interesting regions of parameter space. 
  \( m_h^{\text{max}} \)-scenario is used for most of the results presented here.)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( M_{\text{SUSY}} ) (GeV)</th>
<th>( X_t ) (GeV)</th>
<th>( \mu ) (GeV)</th>
<th>( M_2 ) (GeV)</th>
<th>( M_{\tilde{g}} ) (GeV)</th>
<th>Upper bound on ( m_h ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_h^{\text{max}} )</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
<td>200</td>
<td>800</td>
<td>133</td>
</tr>
<tr>
<td>no mixing</td>
<td>2000</td>
<td>0</td>
<td>200</td>
<td>200</td>
<td>800</td>
<td>116</td>
</tr>
<tr>
<td>gluophobic</td>
<td>350</td>
<td>-750</td>
<td>300</td>
<td>300</td>
<td>500</td>
<td>119</td>
</tr>
<tr>
<td>small-( \alpha )</td>
<td>800</td>
<td>-1100</td>
<td>2000</td>
<td>500</td>
<td>500</td>
<td>123</td>
</tr>
</tbody>
</table>

The Higgs sector of the MSSM

- Two Higgs doublets, resulting in 5 physical Higgs bosons: \( h^0, H^0, A^0 \) and \( H^\pm \).
- At the tree-level, the Higgs sector is determined by only two parameters: 
  \( m_A, \tan \beta = \frac{v_u}{v_d} \).
- In the \( m_h^{\text{max}} \)-scenario, the lightest neutral Higgs is constrained by \( m_h < 133 \) GeV.
- Mass degeneration at large \( \tan \beta \): \( h^0 & A^0 \) \( (m_A < 130 \) GeV) or \( H^0 & A^0 \) \( (m_A > 130 \) GeV).
  \( \Rightarrow \) observed signal is given by the sum of all degenerate states.
Neutral MSSM Higgs Bosons

Dominant production modes:

- **Direct production**
  \[ g \rightarrow \Phi (h, H, A) \]

- **Associated production with b−quarks**
  Dominating production at large \( \tan \beta \)
  \[ g \rightarrow b \Phi \]

Higgs boson decays:

- **\( \Phi \rightarrow \tau^+ \tau^- \)**
  Large BR, clear final state.

- **\( \Phi \rightarrow \mu^+ \mu^- \)**
  Very low branching fraction, but excellent mass resolution.

- **\( \Phi \rightarrow b\bar{b} \)**
  Dominant decay, but large QCD background.
Charged MSSM Higgs Bosons

**Dominant production modes, depend on the mass \( m_{H^\pm} \):**

**Light \( H^\pm (m_{H^\pm} < m_{\text{top}}) \):**

\[
\text{gg} \rightarrow t\bar{t} \rightarrow \bar{t}H^+b
\]

**Heavy \( H^\pm (m_{H^\pm} > m_{\text{top}}) \):**

\[
g\bar{b} \rightarrow \bar{t}H^+ \text{ and } \text{gg} \rightarrow \bar{t}bH^+
\]

**\( H^\pm \) decay modes:**

- For \( m_{H^\pm} < m_{\text{top}} \):
  \[
  H^\pm \rightarrow \tau^\pm \nu
  \]
- For \( m_{H^\pm} > m_{\text{top}} \):
  \[
  H^\pm \rightarrow tb \text{ and } H^\pm \rightarrow \tau^\pm \nu
  \]

Two dominant decays:
MSSM Higgs Searches at the LHC

Search for the neutral MSSM Higgs bosons:

- \( h/H/A \to \tau^+\tau^- \to \ell\ell + 4\nu \) (ATLAS and CMS)
  - \( \to \ell\tau_{jet} + 3\nu \) (CMS; currently under study in ATLAS)
  - \( \to \tau_{jet}\tau_{jet} + 2\nu \) (CMS; currently under study in ATLAS)

- \( h/H/A \to \mu^+\mu^- \) (ATLAS and CMS)

Search for the charged MSSM Higgs bosons:

- **Light \( H^\pm \):**
  \[
  \begin{align*}
  tt & \to (H^\pm b)(W^\mp b) \to (\tau\nu b)(\ell^\mp \nu b) \to (\tau_{jet}\nu\nu b)(\ell^\mp \nu b) \quad \text{(ATLAS and CMS)} \\
  tt & \to (H^\pm b)(W^\mp b) \to (\tau\nu b)(qqb) \to (\tau_{jet}\nu\nu b)(qqb) \quad \text{(only ATLAS)} \\
  tt & \to (H^\pm b)(W^\mp b) \to (\tau\nu b)(qqb) \to (\ell\nu\nu\nu b)(qqb) \quad \text{(only ATLAS)}
  \end{align*}
  \]

- **Heavy \( H^\pm \):**
  \[
  \begin{align*}
  gg, gb & \to t[b]H^\pm \to (Wb)[b](\tau\nu) \to (bqq)[b](\tau_{jet}\nu\nu) \quad \text{(ATLAS and CMS)} \\
  gg, gb & \to t[b]H^\pm \to (Wb)[b](tb) \to (b\ell\nu)[b](bqqb) \quad \text{(ATLAS and CMS)}
  \end{align*}
  \]

Additional searches not presented in this talk:

\( h \to bb, A/H \to \chi_2^0\chi_2^0 \), non-MSSM models (Randall-Sundrum, Little Higgs), etc.
All presented results are obtained for the center of mass energy $\sqrt{s}=14$ TeV and an integrated luminosity of 1-30 fb$^{-1}$.

- Most recent theoretical calculations and Monte Carlo generators.
- Detailed detector simulation.
- Pile-up effects simulated for CMS ($L=2\times10^{33}$ cm$^{-2}$s$^{-1}$).

ATLAS results shown without the pile-up and cavern background. These effects are currently under study by ATLAS, and are shown/expected to be small at the luminosity $L=10^{33}$ cm$^{-1}$s$^{-1}$.

- Detailed consideration of systematic uncertainties in each channel.
- Methods for the background estimation from control data samples.
\( b\bar{b} \left( h/H/A \rightarrow \tau^+\tau^- \right) \)

Main background processes: \( Z/\gamma^*(+jets) \), \( t\bar{t} \), \( W + jets \), \( QCD \) multijets.

<table>
<thead>
<tr>
<th></th>
<th>2(\ell4\nu)</th>
<th>(\ell_{Tjet}3\nu)</th>
<th>2(\tau_{jets}2\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>single- or di-lepton</td>
<td>single-lep or lepton+(\tau_{jet})</td>
<td>single- or di-(\tau_{jet})</td>
</tr>
<tr>
<td>Higgs decay</td>
<td>2 isolated leptons</td>
<td>1 isol. lepton + 1 (\tau_{jet})</td>
<td>2 (\tau_{jets})</td>
</tr>
<tr>
<td>(b)-tagging</td>
<td>CMS: = 1 (b)-jet. ATLAS: ≥ 1 (b)-jet. (Not exactly two (b)-jets, due to the soft (p_T^b)-spectrum for the signal.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central jet veto</td>
<td>CMS: No additional jets in the central region (except (b)- and (\tau)-jets). ATLAS: Not more than two jets (including the (b)-tagged jets).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse mass</td>
<td>Collinear approximation: (\tau) decay products emitted in (\tau)-direction. No back-to-back decays, momentum fractions of (\nu)-s should be positive.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos (p_T^\ell, E_T^{miss}))}\)

Mass resolution: \(\sim 20\%\) in \(H \rightarrow \tau\tau \rightarrow 2\ell4\nu\)

\(\sim 25\%\) in \(H \rightarrow \tau\tau \rightarrow e\tau_{jet}3\nu\)
Dominant systematic uncertainty: $E_T^{miss}$ and jet energy scale, additional uncertainty from fake $\tau$-jets due to the tracker misalignment.

⇒ Background contributions need to be estimated from control data.

- $t\bar{t}$ (from MC)  Uncertainty: 5-10%.
- $Z \rightarrow \tau\tau$ from $Z \rightarrow \mu\mu$ or $Z \rightarrow ee$ control data:
  Shape: replacing the real $e/\mu$ by a simulated $\tau$-decay.
  Normalization: $\left[ \frac{(Z \rightarrow \ell\ell)_{Data}}{(Z \rightarrow \ell\ell)_{MC}} \right]_{control} = \left[ \frac{(Z \rightarrow \tau\tau)_{Data}}{(Z \rightarrow \tau\tau)_{MC}} \right]_{signal \ region}$
  Expected systematic uncertainty: 3%.
- QCD multijets from data:
  Selecting same-sign $\tau$-pairs (signal free sample).
  Expected systematic uncertainty: 5-20%.
Leptonic decay mode (2l4ν): mass region up to 450 GeV.
Semi-leptonic decays (lτjet3ν): intermediate masses, 200-500 GeV.
Hadronic decay mode (2τjet2ν): for high masses, above 400 GeV.

Wide region of the (mA,tan β)-plane covered with L = 30 fb⁻¹.
Motivation

- Branching ratio into $\mu\mu$-pairs is about 300 times smaller than $\text{BR}(\Phi \rightarrow \tau\tau)$.

- However, muons provide for a very clean signature with an excellent mass resolution. (3\% for $m_{\mu\mu}$, compared to 20\% for the $\tau\tau$-channel.)

Event selection:

Main background processes: $Z/\gamma^* (+\text{jets})$, $t\bar{t}$ ($ZZ$, $WW$ negligible).

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Higgs decay</th>
<th>$E_T^{\text{miss}}$ (against $t\bar{t}$)</th>
<th>single high-$p_T$ muon, $p_T &gt; 20$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\geq 1$ $b$-jet (CMS and ATLAS)</td>
<td>2 isolated muons of opposite charge $&lt;40$ GeV</td>
</tr>
</tbody>
</table>

- In ATLAS, the two independent analyses (final states with 0 and $\geq 1$ $b$-jet) are finally combined.

In ATLAS, the two independent analyses (final states with 0 and $\geq 1$ $b$-jet) are finally combined.
Systematic uncertainties mostly related to the jet energy scale and $b$-tagging; $\sim$5-10%.

**Background estimation from data:**

- Side-band fit,
- combined with additional information from the $e^+e^-$ and $e^\pm\mu^\mp$ control samples. (Signal-free samples with the same shape as for the $\mu^+\mu^-$ background.)
Comparison with the discovery reach from $h/H/A \to \tau\tau$:

- $\mu\mu$ is a competitive channel.
- Combination of $\mu\mu$ and $\tau\tau$ can improve the discovery reach.
- $\mu\mu$ allows for the precise mass measurement.
Main background processes: $t\bar{t}$, single top, $W +$ jets, QCD multijets.

$$t\bar{t} \rightarrow (bH^\pm)(bW) \rightarrow (b\tau\nu)(bqq)$$

<table>
<thead>
<tr>
<th>Trigger</th>
<th>$(b\tau_{\text{jet}}\nu\nu)(bqq)$</th>
<th>$(bl\nu\nu)(bqq)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline</td>
<td>$\tau_{\text{jet}} + E_T^{\text{miss}}$</td>
<td>lepton$+E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>Offline</td>
<td>$\tau_{\text{jet}}$, large $E_T^{\text{miss}}$, lepton veto</td>
<td>isolated lepton, large(r) $E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$W$ &amp; $top$</td>
<td>by means of jet pairing; 2 $b$-jets, $\geq 2$ non-tagged jets</td>
<td>angular and charge correlation; 100$&lt; m_t^{\text{had}} &lt;$ 300 GeV</td>
</tr>
<tr>
<td>$W$ &amp; $top$</td>
<td>cuts on $p_T^{t_1}/p_T^{t_2}$, $\Delta \phi(t_1, t_2)$</td>
<td>$\cos \psi = 2m_{tb}^2/(m_T^2 - m_W^2) - 1$ against leptons from $W$</td>
</tr>
<tr>
<td>Further $t\bar{t}$</td>
<td>likelihood discriminant, 7 kinematics variables</td>
<td></td>
</tr>
<tr>
<td>$W$ &amp; $top$</td>
<td>suppression</td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>From Likelihood discriminant and $H^\pm$ transverse mass.</td>
<td>From transverse masses$^\ast$ of $H^\pm$ and $W$.</td>
</tr>
<tr>
<td>Significance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Light Charged Higgs, $m_{H^\pm} < m_{top}$ (II)

\[ t\bar{t} \rightarrow (bH^\pm)(bW) \rightarrow (b\tau_{jet}\nu\nu)(b\ell\nu) \]

Complete event reconstruction is difficult due to $3\nu$, originating from both top-decays. ⇒ Signal is observed as an excess of $\tau$-leptons in $t\bar{t}$, since $\text{BR}(H^\pm \rightarrow \tau^\pm\nu) > \text{BR}(W^\pm \rightarrow \tau^\pm\nu)$.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>lepton+$E_T^{miss}$ (+3jets)(+\tau_{jet})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline</td>
<td>≥3 jets, ≥1 $b$-jets, ≥1 isolated lepton</td>
</tr>
<tr>
<td>Kinematics</td>
<td>$p_T^\tau &gt; 40$ GeV, $Q_\ell + Q_{\tau} = 0$</td>
</tr>
</tbody>
</table>

ATLAS

MSSM Higgs Sector / Neutral Higgs: $\Phi \rightarrow \tau\tau$, $\Phi \rightarrow \mu\mu$ / Charged Higgs: $m_{H^\pm} < m_{top}$, $m_{H^\pm} > m_{top}$ / Summary 14/18
Heavy Charged Higgs, $m_{H^\pm} > m_{top}$

The search in $H^\pm \to \tau_{jet}\nu\nu$ decay mode is similar to the one for light charged Higgs.

$$ gg, gb \to t[b] H^\pm \to b\nu[b] tb \to b\nu[b] bqqb $$

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Offline</th>
<th>$E_T^{miss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline</td>
<td>$=1$ isolated lepton, $\geq 5$ jets, out of those $\geq 3$ $b$-jets</td>
<td>$=1$ isolated lepton, $\geq 5$ jets, out of those $\geq 3$ $b$-jets</td>
</tr>
<tr>
<td>$W$ &amp; $top$</td>
<td>kinematic constraint on $W$-mass,</td>
<td>kinematic constraint on $W$-mass,</td>
</tr>
<tr>
<td>reconstr.</td>
<td>jet association by combinatorial likelihood</td>
<td>jet association by combinatorial likelihood</td>
</tr>
<tr>
<td>Further $t\bar{t}$ suppression</td>
<td>likelihood discriminant, with several $b$-kinematics variables</td>
<td>likelihood discriminant, with several $b$-kinematics variables</td>
</tr>
</tbody>
</table>

This channel is extremely sensitive to systematic uncertainties. $\Rightarrow$ Current analyses show a very low sensitivity in the MSSM parameter space.
The dominant background for all $H^\pm$ searches is the $t\bar{t}$ process.

- Theoretical scale uncertainty on the $t\bar{t}$ cross-section (NNLO): $\sim 10\%$.
- Experimental uncertainty: 10-40\%.
  Mostly affected by the jet energy scale and the $b$-tagging.

Need a reliable method for background estimation from control data.

- Control data samples: $t\bar{t} \rightarrow WbWb \rightarrow (\mu\nu b)(\mu\nu b)$, $t\bar{t} \rightarrow WbWb \rightarrow (\mu\nu b)(qqb)$.
- Replace the real muon(s) by an emulated $\tau$-decay.
- The method can be used for all $H^\pm$ searches with $\tau$-s in the final state.

$t\bar{t} \rightarrow (b\tau_{jet}\nu\nu)(bqq)$

Experimental uncertainty on $t\bar{t}$ can be reduced down to less than 10\%. 

MSSM Higgs Sector / Neutral Higgs: $\Phi \rightarrow \tau\tau$, $\Phi \rightarrow \mu\mu$ / Charged Higgs: $m_{H^\pm} < m_{top}$, $m_{H^\pm} > m_{top}$ / Summary
$H^\pm$: Combined Discovery

$m_h^{\text{max} - \text{scenario}}$

With 30 fb$^{-1}$:
- Light charged Higgs, $m_{H^\pm} < m_{\text{top}}$: Covered for nearly all $\tan \beta$.
- Heavy charged Higgs, $m_{H^\pm} > m_{\text{top}}$: Sensitivity only for large $\tan \beta$.
Summary

Discovery reach for MSSM Higgs bosons, explored by ATLAS and CMS:
- Most recent theoretical calculations and Monte Carlo generators.
- Detailed detector simulation.
- Detailed consideration of systematic uncertainties.
- Methods for the background estimation from the control data samples.

Neutral MSSM Higgs Bosons, $h/H/A$:

$h/H/A \rightarrow \tau\tau$ channel provides a good coverage of the $(m_A, \tan \beta)$-plane.
- With 30 $fb^{-1}$:
  $\tan \beta$-values above 15/20/50 are covered for $m_A=120/300/600$ GeV respectively.

$h/H/A \rightarrow \mu\mu$ is a competitive channel.
- Helps to increase the discovery reach. Allows for a precise mass reconstruction.

Charged MSSM Higgs Bosons, $H^\pm$:

Decay modes with $H^\pm \rightarrow \tau_{jet}\nu\nu$ provide the highest discovery reach.

Combining all channels, after 1 $fb^{-1}$ of well understood data:
- Current Tevatron limits can be exceeded.

Combining all channels, after 30 $fb^{-1}$:
- $m_{H^\pm} < m_{\text{top}}$: Almost the whole parameter space is covered.
- $m_{H^\pm} > m_{\text{top}}$: Sensitive only for larger $\tan \beta$ values.