Searches for Higgs Bosons beyond the SM

On behalf of the CMS Collaboration

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Higgs sector in SUSY

SUSY requires at least 2 Higgs doublets (2HDM type-II) → **five Higgs bosons:**

\[ \phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u : \text{VEV}_u \]

\[ \phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}, \quad Y_{\phi_d} = -1, \quad v_d : \text{VEV}_d \]

\[ N_{\text{ndof}} = 8 - 3 = 5 \]

\[ W, Z, H^\pm, H, h, A \]

- Strict mass requirements imposed by symmetry
- At tree level two free parameters: \( m_A, \tan \beta = v_u/v_d \).

\[ m_{H^\pm}^2 = m_A^2 + m_W^2 \]

\[ m_{H, h}^2 = \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2m_Z^2\cos^22\beta} \right) \]

\[ \tan \alpha = \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2m_Z^2\cos^22\beta}} \]

\( \alpha \) : angle between \( H \) and \( h \) in mass matrix

**NB:** w/o CP-violation in the SUSY Higgs sector.
$m_h^2 \approx m_Z^2 \cos^2 2\beta + \Delta_{\text{rad}}$

$$\Delta_{\text{rad}} = \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left( \ln \left( \frac{m_t^2}{m_{\tilde{t}}^2} \right) + \frac{X_t^2}{m_{\tilde{t}}^2} \left( 1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right)$$

- +30% of $m_h$ due to higher order corrections.
- Large values of $m_{\tilde{t}}$ for $|X_t| = \sqrt{6}m_{\tilde{t}}$ help to increase $m_h$.

$\tan \alpha = \frac{-(m_A^2 + m_Z^2) \sin 2\beta}{(m_Z^2 - m_A^2) \cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2m_Z^2 \cos^2 2\beta}}$

$\alpha$: angle between $H$ and $h$ in mass matrix
Down-type fermions in the MSSM

<table>
<thead>
<tr>
<th>$gVV$</th>
<th>$g_{uu}$</th>
<th>$g_{dd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$\gamma_5 \cot \beta$</td>
<td>$\gamma_5 \tan \beta$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha) \rightarrow 0$</td>
<td>$\sin \alpha / \sin \beta \rightarrow \cot \beta$</td>
</tr>
<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha) \rightarrow 1$</td>
<td>$\cos \alpha / \sin \beta \rightarrow 1$</td>
</tr>
</tbody>
</table>

For $m_A \gg m_Z$: $\alpha \rightarrow \beta - \pi/2$ (coupling $A/H$ to down-type fermions enhanced by $\tan \beta$).

**Production modes:**

- $gg \rightarrow \phi$ ("$gg\phi$")
- $gg \rightarrow \phi b\bar{b}$ ("$bb\phi$")

**Decay channels:** $m_h^{mod+}$

<table>
<thead>
<tr>
<th>$A \rightarrow $</th>
<th>$b\bar{b}$</th>
<th>$\tau\tau$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_h^{180 \text{ GeV}}$</td>
<td>(10^{-4})</td>
<td>(10^{-3})</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>$m_h^{300 \text{ GeV}}$</td>
<td>(10^{-3})</td>
<td>(10^{-2})</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>$m_h^{500 \text{ GeV}}$</td>
<td>(10^{-2})</td>
<td>(10^{-1})</td>
<td>(1)</td>
</tr>
</tbody>
</table>

NB: w/o CP-violation in the SUSY Higgs sector.
Harvest of LHC Run-2 (so far)

- Huge parameter space in MSSM systematically explored.

- Large values of $\tan \beta$ constrained by $H/A$ searches in down type fermion final states.

- Summary plot (status 03/2020) only exploits only $\frac{1}{4}$ of Run-2 dataset.
Di-τ final state

- Search for 2 isolated high $p_T$ leptons ($e$, $\mu$, $\tau_h$).
- Reduce obvious backgrounds, control what can’t be reduced.
- Reconstruct discriminating variable, related to di-τ final state.
**Di-$\tau$ final state**

- Search for **2 isolated high** $p_T$ leptons ($e$, $\mu$, $\tau_h$).
- Reduce obvious backgrounds, control what can’t be reduced.
- Reconstruct discriminating variable, related to di-$\tau$ final state.

- Usually large fraction of BGs ($\rightarrow$ Jet $\rightarrow$ $\tau_h$ and $Z \rightarrow \tau\tau$ modeled from data).
- Simple event categories enhance sensitivity.
FF method

\[ F_F = \sum_i w_i F_F^i \]

\[ w_i = \frac{\text{N}_{\text{AR}}^i}{\sum_j \text{N}_{\text{AR}}^j} \]

\[ i, j \in \{ \text{QCD, W+jets, } t\bar{t} \} \]

\[ F_F = \frac{\text{tight } \tau\text{-ID}}{\text{loose } \land \neg \text{tight } \tau\text{-ID}} \]

\[ \text{DR}_{t\bar{t}} \]

\[ \text{Taken from simulation} \]
$\tau$-embedding

$Z \rightarrow \tau\tau$ Simulation

Simulate $\tau$ leptons with same kinematic properties as muons.

$Z \rightarrow \mu\mu$ Selection

$Z \rightarrow \mu\mu$ Cleaning

Remove energy deposits from muons.

$Z \rightarrow \tau\tau$ Hybrid

Merge simulated and cleaned event.
Reach & challenges

- Sensitivity reach up to $m_A \approx 2 \text{ TeV}$ for LHC@13TeV.

- Take $A/H/h$ into account when comparing to benchmark models.

- Models have to cope with the properties we observe for $h$.

- Will become especially challenging for $\tan \beta \lesssim 10$.

- In addition dedicated analyses explicitly target low $\tan \beta$.

Projection of simple $A/H \rightarrow \tau\tau$ analysis to 3000/fb.
Low $\tan \beta$ and $m_h$

- Already after Run-1 LHC Higgs WG addressed low $\tan \beta$ region taking knowledge of $m_h$ into account with two dedicated benchmark models: “hMSSM” and “low-tb-high”.

- “low-tb-high”:
  - Benchmark parameters adapted to match $m_h \approx 125$ GeV for each value of $\tan \beta$.
  - Required values of $m_t$ up to 100 TeV.

$$\Delta_{\text{rad}} = \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left( \ln \left( \frac{m_t^2}{m_t^2} \right) + 3 \right)$$

- $m_h$ estimate required consideration of large log’s of $\tan(m_t/m_t)$.

- In the meantime a model exploiting an EFT approach to resum such log’s has been provided by EPJ C (2019) 79 ($M_{h, \text{EFT}}^{125}$).
$A \rightarrow Z(\ell\ell) h(\tau\tau)$

- A more recent analysis explicitly targeting low $\tan\beta$.
- A production via gluon fusion and in association with b-quarks:
- Exploiting kinematic fit of $\ell\ell + \tau\tau$ as discriminating observable.
LHC Higgs WG-2 has also provided translation tables between MSSM parameters and EFT Wilson coefficients (in the SILH basis) in LHC-HXSWG-2019-006.

Here an example is shown for the marginalisation of large degenerate “stop” masses.
Conclusions

- MSSM searches (as an important example of UV theories) → integral part of CMS search programme.

- Experimental results challenge MSSM models and will even more with full Run-2 and Run-3 data.

- Kinematic reach at LHC is up to 2 TeV. Low values of $m_h$ require large values of $m_{\tilde{t}}$ to match $m_h \approx 125$ GeV, which will be one of the strongest challenges to the MSSM.

- EFT based models have been developed to address low $\tan \beta$ region. Translation tables between MSSM parameters and Wilson coefficients have been provided by LHC Higgs WG.
MSSM $H/A \rightarrow bb$

- Largest coupling and branching fraction to $b$ quarks.
- Main challenge: background from QCD multijet production

**Reduce input rate:**
- Strict trigger requirements already at trigger level.$(1)$
- Monitor efficiency w.r.t. to offline selection using tag & probe method.

**Concentrate on $b$-associated production:**
- Use $b$ jets and invariant mass to distinguish signal from background

**Model remaining background:**
- Signal region (SR): three $b$-tagged high $p_T$ jets (100, 100, 40 GeV).
- Control region (CR): invert $b$-tag requirement on third leading jet.

- Fit analytic model to data in SR.

$N_j(p_T > 100 \text{ GeV}) \geq 2$
$\eta_j > 2.4$; \ $\Delta\eta_j < 1.6$
Signal and background model

- Discriminating variable: invariant mass of two leading jets after b-tagging requirement ($M_{12}$).
- Different shapes of signal and background motivate separation into three (overlapping) categories in $M_{12}$.

Signal shapes (from simulation):

Background shapes (from CR):

Priv. Doz. Dr. Roger Wolf
http://ekpwww.physik.uni-karlsruhe.de/~rwolf/
Results

- Most important systematic uncertainties:
  - Potential bias due to choice of analytic functions.
  - b-tagging efficiency.
- Sensitivity significantly improved w.r.t. Run-1 analysis (Run-1 analysis reached further down in $m_A$).

- No deviations observed from SM expectation.
  $\rightarrow$ limits on $\sigma \times \text{BR}$. 

http://ekpwww.physik.uni-karlsruhe.de/~rwolf/
Before:
After:
**τ-embedding**

Control particle flux close to μ to level of 140 MeV

Muon direction $ΔR$

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Signal modeling

Test MSSM vs SM hypothesis: allows for well defined statistical problem, even when reaching sensitivity to the 125 GeV Higgs boson.

- Typical scan to determine exclusion contours in specific models.
- Determine CLs in each point in parameter space to obtain limit at significance level $\alpha$. 
Signal modeling

- $p_T(A, H, h)@ \text{NLO QCD + PS} \rightarrow \text{multiscale problem.}$
- Plus: b contribution varies as a function of $\tan \beta$. 

$\tan \beta = 5$
Signal modeling

- $p_T(A, H, h)@$ NLO QCD + PS $\rightarrow$ multiscale problem.
- Plus: $b$ contribution varies as a function of $\tan \beta$. 

![Graph showing $\tan \beta$ vs. $p_T$ for different scenarios.](image)
Signal modeling

- \( p_T(A, H, h) @ \) NLO QCD + PS → multiscale problem.
- Plus: \( b \) contribution varies as a function of \( \tan \beta \).

Change in \( p_T(A, H, h) \) implies change in signal acceptance.
Signal modeling

- \( p_T(A, H, h) @ \text{NLO QCD + PS} \rightarrow \text{multiscale problem} \).
- Plus: \( b \) contribution varies as a function of \( \tan \beta \).
- Taking into account all \( \tan \beta \) enhanced SUSY corrections and non-trivial \( \tan \alpha \) dependency for \( H/h \).
- Developed with S. Liebler (KIT) and E. Bagnashi (DESY).

Check ETP-KA/2018-07 for more details.