“LHC Run 1 Results: Beyond Standard Model Scalar Boson”

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On behalf of the ATLAS and CMS Collaborations

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With the discovery of a Higgs boson, the SM could be completed and it looks very much like "the SM Higgs Boson."
Is the SM Minimal? (2HDM/MSSM, NMSSM Models, Multi-Higgs Cascades)

Tool for Discovery - Portal to DM (invisible decays), hidden sectors

Higgs: A Portal to BSM

Rare Higgs Modes, FCNC, LFV Higgs Decays, Long-Lived Higgs

Higgs Boson Pair Production, resonant searches, etc…
Effective theory; extension of SM by adding a second complex Higgs doublet

- **5 Higgs Bosons**: 2 CP-even neutral bosons: $h$ (light) & $H$ (heavy),
  1 CP-odd neutral boson ($A$) and 2 charged bosons ($H^\pm$)
- **6 Parameters**: $m_h$, $m_H$, $m_A$, $m_{H^\pm}$; $\alpha =$ mixing between $h$ and $H$;
  $\tan \beta = \langle vev \rangle_u / \langle vev \rangle_d$ satisfying $\langle vev \rangle_u^2 + \langle vev \rangle_d^2 = (246 \text{ GeV})^2$

Flavor conservation can be enforced via symmetries

Four types of 2HDM, depending on the way the Higgs doublets couple

- **Type I**: one doublet couples only with vector bosons [Fermiophobic], other only with fermions
- **Type II**: one doublet couples with up-type quarks, other with down-type quarks and leptons [MSSM-like]
- **Type III**: one doublet couples with quarks as in Type I, other with leptons as in Type II [lepton-specific]
- **Type IV**: one doublet couples with quarks as in Type II, other with leptons as in Type I [Flipped]

2HDM with natural flavor conservation:

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_V$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$\kappa_u$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
</tr>
<tr>
<td>$\kappa_d$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$-\sin(\alpha) / \cos(\beta)$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$-\sin(\alpha) / \cos(\beta)$</td>
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<tr>
<td>$\kappa_l$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
<td>$-\sin(\alpha) / \cos(\beta)$</td>
<td>$-\sin(\alpha) / \cos(\beta)$</td>
<td>$\cos(\alpha) / \sin(\beta)$</td>
</tr>
</tbody>
</table>

- **MSSM**: 2HDM Type II + SUSY sector
- **NMSSM**: MSSM+1 additional singlet
  - 7 Higgs bosons:
    5 neutral $h_1, h_2, h_3$ (CP even), $a_1, a_2$ (CP odd), 2 charged ($H^\pm$)
- **Flavor-changing Yukawa couplings are in principle possible (Type III models)**

Pseudoscalars in Extended Higgs Sector:

<table>
<thead>
<tr>
<th>Model</th>
<th>Higgs sector</th>
<th>CP-odd</th>
<th>SUSY partners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2HDM:</strong> Two-Higgs-Doublet-Model</td>
<td>Two doublets ( \rightarrow 5 ) Higgs bosons ((h, H, H^+, H^-, A))</td>
<td>A (heavy)</td>
<td>None</td>
</tr>
<tr>
<td><strong>MSSM:</strong> Minimal Supersymmetric Standard Model</td>
<td>Two doublets ( \rightarrow 5 ) Higgs bosons ((h, H, H^+, H^-, A))</td>
<td>A (heavy)</td>
<td>+ sparticles</td>
</tr>
<tr>
<td><strong>NMSSM:</strong> Next-to-minimal Supersymmetric Standard Model</td>
<td>Two doublets, one singlet ( \rightarrow 7 ) Higgs bosons ((h_1, h_2, h_3, H^+, H^-, a_1, a_2))</td>
<td>(a_2) (light)</td>
<td>+ sparticles</td>
</tr>
</tbody>
</table>

Next-to-MSSM Prospects (NMSSM)
# Summary of 2 HDM / MSSM and NMSSM Searches

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(fb⁻¹)</td>
<td>Result</td>
</tr>
<tr>
<td>---</td>
<td>--------------</td>
</tr>
<tr>
<td>2 HDM Neutral and Charged Higgs:</td>
<td></td>
</tr>
<tr>
<td>φ → bb</td>
<td>5</td>
</tr>
<tr>
<td>H⁺ → τν⁺ lep/τν +jet</td>
<td>5</td>
</tr>
<tr>
<td>H⁺ → cs</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 HDM Higgs Cascade and Indirect Limits:</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→W±H±→W=W±h(bb)</td>
</tr>
<tr>
<td>H→hh, A→Zh</td>
</tr>
<tr>
<td>Indirect limits gγ,VV,ττ,bb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NMSSM Neutral Bosons; Doubly Charged Higgs:</th>
</tr>
</thead>
<tbody>
<tr>
<td>h₁→2a₁→4μ</td>
</tr>
<tr>
<td>h₁→a₁→2μ</td>
</tr>
<tr>
<td>h₁→2a₁→4γ</td>
</tr>
<tr>
<td>Doubly charg  Φ⁺⁺→l⁺l⁺</td>
</tr>
</tbody>
</table>

*Results discussed in the talk (marked in magenta)
Five Higgs Boson in MSSM:
→ CP-even (h, H); CP-odd (A), H^+/−: assume 125 GeV is light CP-even Higgs in 2HDM?

6 New MSSM Benchmark Scenarios:
- Each addressing certain phenomenology

- High tan β: φ→ττ, φ→μμ; H^+→τν, tb
  - A. Djouadi et al., arXiv: 1307.5205

- Intermediate tan β:
  - H/A→χ_i^0χ_j^0, χ_i^+χ_j^−; H^+→χ_i^+χ_j^0

- Low tan β:
  - A→Zh; H→hh, tt;
  - H^+→cs, cb, τν, tb, Wh
Production via gluon fusion (b-, t-loops) and associated b-quark annihilation

- 2 HDM and Fermions: enhanced coupling to b-quarks and τ-leptons
  \[ g_{\tilde{b}H}^{MSSM} = \tan^2 \beta \cdot g_{bH}^{SM} \] production rate enhanced \( \times \tan^2 \beta \); associated production dominant
  - small-moderate \( \tan \beta \): gluon-fusion production is dominant
  - high \( \tan \beta \): b-associated production is enhanced

- Decay Modes: \( b\bar{b} \) (90%), \( \tau \tau \) (10%), \( \mu \mu \) (0.04%)
Neutral MSSM Higgs Boson $\varphi(h, H, A)$ Searches

- Cover five of six possible $\tau\tau$ decay patterns: $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$
- Split events into $b$-tag and no-$b$-tag categories

### Table

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channels</strong></td>
<td><strong>Channels</strong></td>
</tr>
<tr>
<td>$\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$ (94%)</td>
<td>$\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$ (97%)</td>
</tr>
<tr>
<td><strong>Categories</strong></td>
<td><strong>Categories</strong></td>
</tr>
<tr>
<td>$ll$, $lh$: $b$-tag / $b$-veto</td>
<td>all channels: $b$-tag / no $b$-tag</td>
</tr>
<tr>
<td>$lh$ high-mass: incl.</td>
<td></td>
</tr>
<tr>
<td>$hh$: single-/$di$-tau trigger</td>
<td></td>
</tr>
<tr>
<td><strong>Discriminant</strong></td>
<td><strong>Discriminant</strong></td>
</tr>
<tr>
<td>$ll$, $lh$: di-tau mass taking missing energy into account (MMC)</td>
<td>all channels: di-tau mass taking missing energy into account (SVFit)</td>
</tr>
<tr>
<td>$hh$: total transverse mass</td>
<td></td>
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</tbody>
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### Diagrams

**SIGNAL:**
- Use lepton+MET to suppress $W/Z+$jets (e.g. transverse mass)
- 2 OS tau decays

**BACKGROUND:**
- Estimated using $Z\rightarrow\mu\mu$ embedding
- Estimated using tau ID fake-factor
- Estimated using MC + data norm.

**Exploit enhanced $b$-quark associated production in MSSM**
Di-tau mass reconstruction (SVFit) based on likelihood method using e/\mu/\tau momenta and \Eslash_{\text{miss}} information

Analysis is similar to SM H → ττ but optimized for different production mechanisms and Higgs boson masses

Missing Mass Calculation (MMC) method based on lepton/tau momenta and \Eslash_{\text{miss}} information

Separate optimizations in \tau_{\text{lep}}\tau_{\text{had}} channel for the high- and low- mass → best sensitivity at high mass

- \tau_{\text{lep}}\tau_{\text{lep}} and \tau_{\text{lep}}\tau_{\text{had}} channels combined for \mA < 200 \text{ GeV}

- \tau_{\text{had}}\tau_{\text{had}} and \tau_{\text{had}}\tau_{\text{had}} channels combined for \mA ≥ 200 \text{ GeV}
No evidence of signal beyond the SM found

Separate for gluon-fusion and $b$-associate production mechanisms

→ Calculate $\sigma \times BR$ limit on one process while the other is left floating freely

Excluded $\sigma \times BR$ ranges from $>29\, pb$ ($>6.4 pb$) at $m_\phi = 90\, GeV$ to $>7.4\, pb$ ($>7.2\, pb$) at $m_\phi = 1000\, GeV$ for $ggF$ ($b$-associated) mechanisms

Model-independent $\sigma \times BR$ limits achieve limits down to $\sim10 fb$ at high mass

arXiv: 1408.3316

ATLAS-CONF-2014-049
Old Approach:
- Test MSSM vs background only (h+H+A+BG) vs (BG)
- New discovered particle was not taken into account

New Approach:
- Take into account the discovered Higgs boson at 125 GeV
- Hypothesis test of MSSM vs SM: (h+H+A+BG) vs (h_{SM}+BG)
- Presence of h(125) weakens the MSSM limits

Incompatible with 125 + 3 GeV mass constraint

m_{h}^{\text{max}} \text{ scenario is in agreement with the Higgs-like state only in a relatively small strip in the } M_A-\tan \beta \text{ plane at low } \tan \beta
- Very low tan $\beta$ upper limits ($\tan \beta < 5$ for $m_A < 250$ GeV → touching the LEP constraint at low $m_A$

- $m_A$-$\tan \beta$ exclusions in new benchmark scenarios (arXiv:1302.7033)

- $m_{h_{\text{mod}^+}}$ scenario much better suited for mass of $h(125)$, than $m_{h_{\text{max}^+}}$ scenario

ATLAS Preliminary, $\sqrt{s}=8$ TeV, $h/H/A \to \tau\tau$

<table>
<thead>
<tr>
<th>$m_A$ [GeV]</th>
<th>$\tan \beta$</th>
</tr>
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<tbody>
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</table>

ATLAS CONF-2014-049
Relation between $m_{\text{top}}$ and $M_{H^{\pm}}$ dictates both production mode and decay channels

- Decay via $H^+ \rightarrow \tau \nu / c\bar{s} / t\bar{b}$, depending on $m(H^+)$ and $\tan \beta$
- $\tau / b / \text{top}$ reconstruction play a central role in the searches

**Low mass $H^{\pm}$ ($M_{H^{\pm}} < m_{\text{top}}$):**
Final state: $H^{\pm} bWb$

Dominant Decays:
1. $\tan \beta > 3$: $B(H^+ \rightarrow \tau \nu) \sim 90\%$
2. $\tan \beta < 1$: $B(H^+ \rightarrow c\bar{s}) \sim 70\%$

**Heavy ($M_{H^{\pm}} > m_{\text{top}}$):**
Final state: $tH^{\pm}$

- $H^{\pm} \rightarrow t\bar{b}$ dominant
- $H^{\pm} \rightarrow \tau \nu$ can be sizeable

<table>
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<tr>
<th>Coll.</th>
<th>Channel</th>
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<th>Cite</th>
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</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$\tau \nu + $jets</td>
<td>20fb-1(8TeV)</td>
<td>ATLAS-CONF-2013-090</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$\tau \nu + $leptons</td>
<td>5fb-1(7TeV)</td>
<td>JHEP 03(2013)076</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$c\bar{s}$</td>
<td>5fb-1(7TeV)</td>
<td>EPJC 73 6 (2013) 2465</td>
</tr>
<tr>
<td>CMS</td>
<td>$\tau \nu + $leptons/jets</td>
<td>5fb-1(7TeV)</td>
<td>CMS-PAS-HIG-12-052</td>
</tr>
<tr>
<td>CDF</td>
<td>$c\bar{s}$</td>
<td>2fb-1(2TeV)</td>
<td>PRL 103, 101803 (2009)</td>
</tr>
<tr>
<td>D0</td>
<td>$t\bar{b}$</td>
<td>1fb-1(2TeV)</td>
<td>PRL 102, 191802 (2009)</td>
</tr>
</tbody>
</table>
Charged Higgs Boson Searches ($H^+ \rightarrow cs$)

$H^+ \rightarrow cs$ dominant decay mode for $\tan \beta < 1$ and $m(H^+) < m_{top}$

- Kinematic fit of both top candidates
  - $m=172.5$ GeV
  - Improves mass resolution of $cs$ candidate (WH separation)

- Bkgs.: $tt\bar{t}$, $W/Z+\text{jets}$, di-bosons, QCD

- Mjj (invariant mass of non-b-tagged jets)
  - Distribution after kinematic fit
  - No signal

Light charged Higgs search $mH^+ < m_{top}$:

- Determine $\text{BR}(t \rightarrow bH^+)$ assuming $\text{BR}(H^+ \rightarrow cs) = 100\%$

<table>
<thead>
<tr>
<th>CMS Preliminary, $\sqrt{s} = 8$ TeV, 19.7 $fb^{-1}$</th>
<th>CMS-PAS-HIG-13-035</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL:</td>
<td></td>
</tr>
<tr>
<td>$\text{BR} &lt; 1.7 - 7.0%$</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td></td>
</tr>
<tr>
<td>$\text{BR} &lt; 1.5 - 5.0%$ expected</td>
<td></td>
</tr>
</tbody>
</table>

Applies to any BSM resonance with the corresponding production & decay topology
Charged Higgs Boson Searches ($H^+ \to \tau \nu + \text{jets}$)

- $1\tau, \geq 4$ jets ($\geq 1$ b-jet), no leptons, large MET;
- Look for excess in $\tau$-MET transverse mass distribution
- SM ttbar dominant background

Model-independent limits:

- **Light H+:**
  
  BR ($t \to H+b$) = 0.24–2.1% for $90< m_{H^+} < 160$ GeV

- **Heavy H+:**
  
  $\sigma(H^+)$ = 0.017–0.9 pb for $180 < m_{H^+} < 600$ GeV

Results interpreted in MSSM mhmax scenario

- ongoing searches: heavy $H^+ \to tb$

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ATLAS-CONF-2013-090
2 HDM phenomenology allow for cascade decays: \( H \rightarrow W^\pm H^\mp \rightarrow W^\pm W^\mp \) \( h \rightarrow W^\pm W^\mp \) \( bb \)

- No particular model assumed
- CP-odd \( (A) \) too heavy to participate in decay chain
- Only consider gluon fusion production

- \( h_0 (125 \text{ GeV}) \) is the SM Higgs Boson
- \( \rightarrow \) exploit \( h \rightarrow bb \) decay to gain statistics
- Drawback: same final state as \( tt \) semileptonic (l+jets) \( \rightarrow \) use MVA to discriminate against bkg.
- Produce limits in the \((m_H,m_{H^\pm})\) plane

Upper limits: larger than theoretical (SM-like) \( H^0 \) Cross-section

Approaching SM pred. in high-mass region

BDT output trained at 36 \((m_{H_0}; m_{H^+})\) mass points \( \rightarrow \) kinematic difference between Higgs cascade and top-pair production

- \( m_{H_0} \) trained
- \( m_{H^+} \) from W mass constraint
- Reconstruct leptonic W, MET + \( p_T \) from W mass constraint
- Reconstruct hadronic W
- Reconstruct \( H^\pm \) from \( h^0 + W \) that gives highest mass
- Reconstruct \( h^0 \)

\[ \begin{align*}
\text{Events} & \quad \text{ATLAS} \quad \sqrt{s} = 8 \text{ TeV} \\
\text{Data} & \quad \int L = 20.3 \text{ fb}^{-1} \\
\text{Signal} & \quad (1.00 \text{ pb}) \\
\text{Other} & \\
& \quad \text{BDT threshold} \\
m_{h_0} = 625 \text{ GeV} \\
m_{H^+} = 325 \text{ GeV} \\
\text{Signal} & \quad \text{Data - SM} \\
\text{Uncertainty} & \\
\text{Trained for} & \quad m_{h_0}, m_{H^+} = 625, 325 \text{ GeV} \\
\end{align*} \]
h (126) is the SM-like Higgs boson:

- **H→hh** dominant in $2m_h < m_H < 2m_{top}$
- **A→Zh** dominant in $m_h + m_z < m_H < 2m_{top}$

Exclusive search in various final states:

- **Multileptons**: ≥ 3 leptons; 0 or 1 τ had
- **Diphotons**: = 2 photons; at least one lepton

Use SuShi + 2HDMC to calculate cross sections and BRs from theory

Translate limits on $\sigma \cdot BR$ in limits on $\alpha$ and $\beta$ (determine cross-section and BRs for H and A production/decays)

$\cos(\beta - \alpha) = 0$: Decoupling limit: h behaves like in SM

**H→hh**:  

<table>
<thead>
<tr>
<th></th>
<th>$h \rightarrow WW^*$</th>
<th>$h \rightarrow ZZ^*$</th>
<th>$h \rightarrow \tau\tau$</th>
<th>$h \rightarrow bb$</th>
<th>$h \rightarrow \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow WW^*$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
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<tr>
<td>$h \rightarrow ZZ^*$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>$h \rightarrow \tau\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$h \rightarrow bb$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>✓</td>
<td>✓</td>
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**H→Zh**:

<table>
<thead>
<tr>
<th></th>
<th>$h \rightarrow WW^*$</th>
<th>$h \rightarrow ZZ^*$</th>
<th>$h \rightarrow \tau\tau$</th>
<th>$h \rightarrow \gamma\gamma$</th>
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<td>$Z \rightarrow ll$</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>$Z \rightarrow qq$</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

**Direct Constraints: on 2 HDM (Type I and Type II) Models**

EXCLUDED

EXCLUDED

EXCLUDED

EXCLUDED
Parameterize difference in Higgs couplings w.r.t. SM (production/decay rates in $\gamma\gamma, ZZ, WW, \tau\tau, bb$ interpret in each type of 2HDM).

Assume Higgs decay kinematics not significantly altered and $h(126)$ - light CP-even neutral Higgs.

Rescaling rates according to $k_i$ for the SM production modes ($bbH$ included as correction scaling with the square of $b$-quark coupling).

Extracting from $k_i$ information on $\tan\beta$ and $\cos(\beta-\alpha)$.

Fermiophobic

MSSM-like

Lepton-specific

Flipped
Higgs Sector in NMSSM

NMSSM: additional gauge singlet w. r. t. MSSM → further extend Higgs sector: 1 additional CP-even and 1 additional CP-odd wrt MSSM

Larger phenomenology: additional particles can be very light (neutral scalars with $m_h < 125$ not excluded in NMSSM)

Motivated by two model interpretations:

- NMSSM:
  - $h_{1,2}$ (SM-like Higgs) decays to $2a_1$ ($CP$-odd)
  - BR($a_1 \rightarrow \mu\mu$) sizeable, if $2m_{\mu} < m_{a_1} < 2m_\tau$

- Dark SUSY:
  - $h \rightarrow 2n_1 \rightarrow 2n_D 2\gamma_D \rightarrow 2n_D 4\mu$
  - $n_1$ - lightest neutralino, $n_D$ - dark neutralino, $\gamma_D$ - dark photon
  - BR($\gamma_D \rightarrow \mu\mu$) up to 45% depending on $\gamma_D$ mass

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_a$ range (GeV)</th>
<th>Dataset</th>
<th>Cite</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>$h \rightarrow 2a \rightarrow 4\mu$</td>
<td>0.25 - 3.55</td>
<td>21fb-1(8TeV)</td>
</tr>
<tr>
<td>D0</td>
<td>$h \rightarrow 2a \rightarrow 4\mu/2\mu 2\tau$</td>
<td>0.2 - 20</td>
<td>4fb-1(2TeV)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$h \rightarrow 2a \rightarrow 4\gamma$</td>
<td>0.1 - 0.4</td>
<td>5fb-1(7TeV)</td>
</tr>
<tr>
<td>CMS</td>
<td>$a \rightarrow 2\mu$</td>
<td>5.5 - 14</td>
<td>1fb-1(7TeV)</td>
</tr>
<tr>
<td>CDF</td>
<td>$t \rightarrow H + b \rightarrow Wa(\rightarrow \tau\tau)b$</td>
<td>4 - 9</td>
<td>3fb-1(2TeV)</td>
</tr>
</tbody>
</table>

- $2m_\mu < m_{h_1} < 2m_\tau$: $h_1 \rightarrow a_1 a_1 \rightarrow 4\mu + X$
- $2m_\tau < m_{h_1} < 2m_b$: $h_2 \rightarrow h_1 h_1 \rightarrow 4\tau + X$
- $2m_b < m_{h_1} < 125/2$ GeV: $h_2 \rightarrow h_1 h_1 \rightarrow t\tau b b + X$
- $Wh_2 \rightarrow h_1 h_1 \rightarrow b b b b$
- $125/2$ GeV $< m_{h_1} < 125$ GeV: $h_3 \rightarrow h_2 h_1 \rightarrow WW bb$
Search for pair production of a new light boson from the decay of a SM-like Higgs boson:

- NMSSM: substantial BR $a \rightarrow \mu \mu$ if $2m_\mu < m_a < 2m_\tau$
  $h \rightarrow 4\mu +X$ final state is explored
- Background dominated by $b\bar{b}$ and $J/\psi$ pair production
- 1 event observed in signal region, compatible with bkg.
prediction $3.8 \pm 2.1$
- Limit obtained for $0.25 < m_a < 3.55$ GeV, $m_h > 86$ GeV
- Search interpreted for NMSSM, dark-SUSY models as well as model-independent

Model - Independent Limit:

nMSSM Interpretation:

Dark SUSY Interpretation:
Searches for particles with long lived signatures at colliders \(\rightarrow\) see talk Rachel Christine Rosten

Comparison of collider and non-collider DM results \(\rightarrow\) see talk Phat Srimanobhas

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(fb^{-1})</td>
<td>Result</td>
</tr>
<tr>
<td>h \rightarrow \mu\mu</td>
<td>25</td>
</tr>
<tr>
<td>h \rightarrow Z\gamma</td>
<td>25</td>
</tr>
<tr>
<td>h \rightarrow \gamma* \rightarrow \mu\mu\gamma</td>
<td>20</td>
</tr>
</tbody>
</table>

**Rare SM Higgs Decays:**

**FCNC, Lepton Flavour Violating and Exotic Higgs Decays:**

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
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<tbody>
<tr>
<td>t \rightarrow cH</td>
<td>20</td>
</tr>
<tr>
<td>H \rightarrow \tau\mu</td>
<td>20</td>
</tr>
<tr>
<td>\Phi \rightarrow \pi_{V}\pi_{V} (long-lived)</td>
<td>-</td>
</tr>
</tbody>
</table>

**Invisible Higgs Decays:**

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(ll) \rightarrow H(\text{inv})</td>
<td>25</td>
</tr>
<tr>
<td>Z(bb) \rightarrow H(\text{inv})</td>
<td>-</td>
</tr>
<tr>
<td>VBF \rightarrow H(\text{inv})</td>
<td>-</td>
</tr>
</tbody>
</table>
Rare Higgs decays as probes of new couplings and SM extensions (may enhance SM branching ratios)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Limit (σ/σ_{SM})@125 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>ATLAS</td>
</tr>
<tr>
<td>h→γ*γ→μμγ</td>
<td>&lt;10</td>
</tr>
<tr>
<td>h→Zγ</td>
<td>&lt;10</td>
</tr>
<tr>
<td>h→μμ</td>
<td>&lt;7.4</td>
</tr>
</tbody>
</table>

- Clean signature - μμ resonance
- Main backgrounds: Z/γ*, tt, WW

- Categorization of events
  - mass resolution
  - production ggF/VBF mechanism

- tan β can be extracted from the signal mass $M_{A0} = M_{μ+μ-}$ and its width ($Γ_{μ+μ-}$)

CMS-PAS-HIG-13-007

H→μμ
- SM BR @125 GeV ≈ 2x10^{-4}
- probes directly 2nd generation Higgs fermion coupling

H→Zγ/γ*γ
- SM BR @125 GeV ≈ 1x10^{-4} (Z→ee,μμ)
- constrains new particle contributions in loops

arXiv: 1406.7663

CMS-PAS-HIG-13-007
**Rare SM Higgs Decays**

- **h→Zγ Final State:** sensitive to BSM contributions in loops → e.g. composite Higgs

  - μμγ and eeγ final states
  - Main backgrounds: Zγ EWK production, FSR in Z→ll decays, jets (mis)identified as photon in Z+jets events
  - m(llγ) use to extract limits

  ![Graphical representation of h→Zγ](image)

- **h→γ*γ→μμγ** Final State: Sensitive to BSM loop/tree level processes → e.g. new resonances

  - "Dalitz decay": internal conversion of γ* into μμ
  - m_{μμ} < 20 GeV to separate γ*γ from Zγ
  - Similar sensitivity as in H → Z(→μμ)γ

  ![Graphical representation of h→γ*γ→μμγ](image)
FCNC: $t \rightarrow cH$ Decays

Searches done using $t\bar{t}$ topology:
- Reinterpretation of searches:
  - Diphoton: CMS-PAS-HIG-13-025 ($H \rightarrow hh$, $A \rightarrow Zh$)
  - Multilepton: CMS-PAS-SUS-13-002

$B(t \rightarrow Hc) < 0.56\%$ (0.65\%)

Used to place limit on coupling

$g_{tHc} < 0.14$ (observed)

Study of Top-Higgs Coupling ($tHq$): $tHq \rightarrow bW \rightarrow l\nu q(H \rightarrow \gamma\gamma)$

FCNC highly suppressed in SM due to GIM mechanism $\rightarrow$ can be relaxed in BSM

LHC: Large $t\bar{t}$ cross section and large top-coupling to Higgs: for $t \rightarrow cH$ possible new physics rate higher than SM by $\sim 10^{10}$-$10^{12}$

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow u\gamma$</td>
<td>$3.7 \cdot 10^{-16}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uZ$</td>
<td>$8 \cdot 10^{-17}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uH$</td>
<td>$2 \cdot 10^{-17}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$5.5 \cdot 10^{-6}$</td>
<td>—</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow c\gamma$</td>
<td>$4.6 \cdot 10^{-14}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cZ$</td>
<td>$1 \cdot 10^{-14}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cH$</td>
<td>$3 \cdot 10^{-15}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>$\sim 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>

Combine most sensitive categories for stat. interpretation:
- Multileptons: 3 leptons (no hadronic tau), no opposite-sign same-flavour pair (OSSF) or an OSSF and a b-tag
- Sensitivity improved by diphoton channel b-tag

Study of Top-Higgs Coupling ($tHq$): $tHq \rightarrow bW \rightarrow l\nu q(H \rightarrow \gamma\gamma)$
In 2 HDM Type III model (without flavor conservation) The c(u)H coupling is present at tree level

Search for FCNC \( t \to qH \) done in top-pair events: \( tt \to b(W\to ff)q(H\to\gamma\gamma) \)

FCNC: \( t\to qH \), where \( H\to\gamma\gamma \)

Other \( t\to bW \), both leptonic & hadronic \( W \) decays used

CLs as a function of the FCNC branching ratio

Limit on \( \text{Br}(t\to cH) \): \( B(t\to Hc)< 0.83\% \) (0.53\%)

Equally sensitive to tuH and tcH:

Limit on Higgs Yukawa coupling

\[
\frac{\lambda_{tcH}}{\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2}} < 0.17 \quad (0.14)
\]

arXiv: 1403.6293
Forbidden in the SM; naturally occur in 2HDM, composite Higgs, and Randall-Sundrum models

Previous best limit from indirect searches: $B(H \rightarrow \mu \tau) < 10\% \rightarrow$ reinterpretation of ATLAS $H \rightarrow \tau \tau$ searches and from $\tau \rightarrow \mu \gamma$ (arXiv:1209.1397)

Can do better with the first dedicated search: $H \rightarrow \mu \tau_e$ and $H \rightarrow \mu \tau_{\text{had}}$ (within current LHC reach)

Similar strategy as for $H \rightarrow \tau \tau$ (but kinematics differ)

- Exploit collinearity between tau and MET
- Signal variable: "collinear mass", reconstructed from visible decay products

Harder muon $p_T$ spectrum

Search for $H \rightarrow \tau_{\text{had}}\mu$

Search for $H \rightarrow \tau_e\mu$
LFV Couplings: Search for $H \rightarrow \tau \mu$

- **Selection:** isolated muon + isolated electron ($\mu \tau_e$) or hadronic tau candidate ($\mu \tau_{\text{had}}$)
- **Categorize according to number of jets**

**0 Jet**

**1 Jet**

**2 Jet (VBF)**
Constraint on $\text{B}(H \rightarrow \mu\tau)$ interpreted in terms of LFV Higgs Yukawa couplings

- $\text{BR}(H \rightarrow \tau\mu) < 1.57\%$ @ 95 CL observed (expected $\text{B}(H \rightarrow \mu\tau) < (0.75 \pm 0.38)\%$)

- Best fit: $\text{B}(H \rightarrow \mu\tau) = (0.89 \pm 0.40)\%$

Mild excess in data at the level of $2.5\sigma$ $\rightarrow$ still compatible with the SM

Promising future in the LFV Yukawa sector

- Significant improvement (4.4x) wrt. indirect measurements
  - Previous best limit from $\tau \rightarrow \mu\gamma$: $\sqrt{|y_{\mu\tau}|^2 + |y_{\mu\tau}^\ast|^2} < 0.016$
  - Observed limit: $\sqrt{|y_{\mu\tau}|^2 + |y_{\mu\tau}^\ast|^2} < 0.0036$

Best limits on $\tau$ anomalous Yukawa couplings to date

CMS-PAS-HIG-14-005
### Alternative models

<table>
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<tbody>
<tr>
<td>L(fb⁻¹)</td>
<td>Result</td>
</tr>
<tr>
<td><strong>Higgs Boson Pair Production (resonant, non-resonant)</strong></td>
<td></td>
</tr>
<tr>
<td>hh → bbbb</td>
<td>18</td>
</tr>
</tbody>
</table>

| Resonant Searches (Extended Higgs sector): |
|-----|-------|
| | |
SM: rate of Higgs pair production is very small

BSM (rate of resonant hh production enhanced):

- Heavy(N)MSSM Higgs: $H \rightarrow h(125)h(125)$
- Radion or Kaluza-Klein excitation of graviton (Warped Extra Dimensions)

**Model Independent Analysis** → results interpreted in terms of spin-0 (radion) or spin-2 (KK graviton):

- $hh \rightarrow \gamma\gamma bb$: large BR($H \rightarrow b\bar{b}$), low bkg., good mass resolution ($H \rightarrow \gamma\gamma$)

**ATLAS (260-550 GeV):**
- Non resonant: fit to inbunned $m_{\gamma\gamma}$
- Resonant production: counting experiemnt

**CMS (260-1100 GeV):**
- Low mass ($m_X<400$ GeV) → fit to $m_{\gamma\gamma}$ spectrum
- High mass ($m_X<400$ GeV) → fit to the $m_{\gamma\gamma jj}$

- $hh \rightarrow bbbb$: Increased sensitive at high mass

**ATLAS/CMS:** 4b-tagged jets, veto $t\bar{t}b\bar{b}$ events
ATLAS: non-resonant and resonant (2 HDM model)

Spin-0 benchmark, $260 < m_\chi < 500$ GeV

- Resonant: $2.1 \sigma$ max. deviation (incl. LEE)
- Non-resonant (assuming SM Br(h)): $\sigma < 2.2$ pb obs. (1.0 exp.)

 CMS: resonant search (KK-graviton and radion)

Spin-0 (2) benchmarks $260 < m_\chi < 1100$ GeV

Exclude:
- Radions: $m_\chi < 970$ GeV; radion scale $\Lambda_R = 1$ TeV
- RS1 KK-graviton: mass range $340 < m_\chi < 400$ GeV.
Search for $X \rightarrow hh \rightarrow (bb)(bb)$ Final State

ATLAS searches:

- TeV resonance decaying into pair of SM Higgs bosons
- KK Graviton Excluded: $590 < m_X < 710$ GeV

CMS Searches → see Conference Poster Caterina Vernieri

$\sigma$ vs $m_X$ for a KK excitation of graviton

95% CL on $\sigma \times$ BR vs. $m_X$ for a KK excitation of graviton

Signal region (m_{4j}) mass (90% bkg. From multijet +10% ttbar)

CMS-PAS-HIG-14-013

Spin 0 interpretation +20-30% signal efficiency
Run I ATLAS/CMS searches covered a large range of BSM Higgs boson signatures narrowing the phase space for the (N)MSSM models.

LHC is the discovery machine the adventure in the TeV energy regime has just begun.

Run II will open new horizons for an exciting future Higgs Physics program.
... Preparing for the LHC Restart ... « Dreaming for the BSM Future ... »