Status and prospects for BSM ( (N)MSSM ) Higgs searches at the LHC

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Run I legacy on Higgs discovery

ATLAS-CONF-2015-044/
CMS-PAS-HIG-15-002

ATLAS & CMS combined mass:
PRL 114, 191803 (2015)

ATLAS & CMS combined couplings:

CMS J^CP: Phys. Rev. D 92, 012004

ATLAS dσ/dx: arXiv:1508.02507
CMS dσ/dx: CMS-PAS-HIG-14-028

\[ m_H = 125.09 \pm 0.24 \text{ GeV} \]
\[ = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV} \]

- Looks very much like SM-Higgs boson. So where will we find new physics?
There is no theoretical reason to have only one Higgs boson.

- It is an open question whether the observed Higgs is responsible for the generation of all fermion masses (arXiv: 1508.01501)
- Many theories include extra Higgs boson(s), as SUSY, models with axions, baryogenesis, neutrino masses, ...

So far, no physics observed beyond the SM.

Reasons to extend SM:

- Hierarchy problem
- Dark matter
- ...
Strategies that use Higgs to find new physics

- Direct search for BSM Higgs boson
  - Most models include Two Higgs Double Model (2HDM)
- Higgs boson \( \rightarrow \) invisible and dark sector analyses
- Higgs decays not allowed in SM
- New physics in Higgs boson pair production
- Discrepancies in couplings
- Discrepancies in kinematics
<table>
<thead>
<tr>
<th>SM Higgs field</th>
<th>2HDM Higgs field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SM Higgs field:</strong> Complex scalar doublet</td>
<td><strong>2HDM Higgs field:</strong> Two complex scalar doublets</td>
</tr>
<tr>
<td>4 degrees of freedom of which:</td>
<td>More degrees of freedom than SM. For Higgs sector:</td>
</tr>
<tr>
<td>– 3 provide longitudinal components of $W^\pm$, $Z$</td>
<td>– 2 CP-even Higgs bosons ($h,H$), one of which is the observed 125 GeV resonance</td>
</tr>
<tr>
<td>– 1 CP-even Higgs boson ($h$)</td>
<td>– 1 CP-odd pseudoscalar ($A$)</td>
</tr>
<tr>
<td>– Two charged Higgs bosons ($H^\pm$)</td>
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</table>
Contents

• MSSM and NMSSM.
• Physics analysis:

  • MSSM Higgs searches
    - $h/H/A \rightarrow \tau\tau$
    - $h/H/A \rightarrow bb$
    - $H+ \rightarrow \tau\nu/tb$
    - $A \rightarrow Zh$
    - $hh$ decays
    - $H \rightarrow WW/ZZ$

  • NMSSM motivated searches for a light Higgs:
    - $a \rightarrow \mu\mu$
    - $h \rightarrow aa$
    - NMSSM inspired cascades

High tan$\beta$

Low tan$\beta$
Common parameters of 2HDM

- Four Higgs masses \((m_H, m_h, m_A, m_{H^\pm})\)
  - \(m_H\) or \(m_h = 125\) GeV
- Ratio of the vacuum expectation values of the two doubles, \(\tan\beta = v_2/v_1\).
- Mixing angle between \(H\) and \(h\), \(\alpha\).

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MSSM and NMSSM

- MSSM (Minimal Supersymmetric Standard Model) is the simplest extension of SM with Type II 2HDM for Higgs sector.
- NMSSM (Next-to MSSM) is an extension of MSSM with an extra gauge singlet
  - Solves $\mu$-problem (fine-tuning) of MSSM
  - Gain extra CP-even and CP-odd Higgs bosons

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MSSM Neutral Higgses at LHC

• Neutral Higgs production at the LHC

  gluon-fusion

  “b-associated” production

• Preferred decays at large $\tan\beta$:
  $h/H/A \rightarrow \tau\tau$ and $bb$
  – $BR(h/H/A \rightarrow \tau\tau) \sim 10\%$ at high $\tan\beta$.
  – “$\tau\tau$” modes have usually better sensitivity

  $h/H/A \rightarrow \tau\tau$: arXiv:1409.6064 (ATLAS),
arXiv:1408.3316 (CMS), arXiv:1304.2591 (LHC-b)

  $h/H/A \rightarrow bb$: arXiv:1302.2892 (CMS),
arXiv:1506.08329 (CMS)
Searches for $h/H/A \rightarrow \tau\tau$

- Categorization based on the following event properties
  - $\tau\tau$ pair decay: $\tau(e)\tau(\mu)$, $\tau(\text{lep})\tau(\text{had})$, $\tau(\text{had})\tau(\text{had})$
  - “b-tag” and “b-veto” to take advantage of the b-associated production
- Most important backgrounds
  - All channels:
    - $Z/\gamma^* + \text{jets}$ (estimated with embedding)
    - multi-jet production (estimated from data)
    - top background (estimated from simulation)
  - $\tau(\text{lep})\tau(\text{had}) + \tau(\text{had})\tau(\text{had})$ only:
    - $W + \text{jets}$ (estimated from simulation)
    - Dibosons (estimated from simulation)
Searches for $h/H/A \rightarrow \tau\tau$

- Cross section limits

- “Traditional” cross section limits for a single scalar produced either via gluon-fusion or b-associated production from ATLAS

- 2D limit for a scalar particle that is produced by both gluon-fusion and b-associated production for a very fine grid of mass points from CMS
Searches for $h/H/A \rightarrow \tau\tau$

- Interpretation of the search in the $m_h^{\text{mod}}$ benchmark scenario
ATLAS and CMS search for $H^\pm$

- 2HDM/MSSM (NMSSM) predict the existence of $H^\pm$
- The $\text{BR}(H^\pm)$ is presented for $m_{h_{\text{max}}}^\text{max}$ model of the MSSM
- $H^\pm \rightarrow \tau \nu$ is relevant in a large parameter range, specially for low $m_{H^\pm}$ (below $m_{\text{top}}$)
- For $m_{H^\pm}$ above $m_{\text{top}}$, $H^\pm \rightarrow t \bar{b}$ is the predominant decay
- $H^\pm \rightarrow W^\pm Z$ also searched in the context of Higgs triplet model (not MSSM)  
  arXiv: 1503.04233 (ATLAS)
Search for $H^{\pm} \rightarrow \tau\nu$

- Similar strategies in both ATLAS and CMS at the search for a light and heavy $H^{\pm} \rightarrow \tau\nu$

- In the ATLAS search:
  - “tau+jets” channel: one hadronic tau decay and jets from the full hadronic top decays
  - tau+Missing $E_T$ trigger: very involved
  - High and low mass categories are separated

- Example from the final discriminating distribution from the high mass category

95% CL exclusion limits on $\tan\beta$ as a function of $m_{H^+}$ in the context of $m_h^{\max}$ benchmark scenario of the MSSM, for $m_{H^+} < m_{\text{top}}$ search.

For CMS: arXiv:1508.07774
Search for $H^{\pm} \rightarrow tb$

- Most predominant decay at high mass.
- First results from LHC already available.

- Recent paper from CMS combining searches in $\tau\nu$ and $tb$ channels: arXiv:1508.07774 (CMS)
Remaining parameter space in the MSSM

- The low $\tan\beta$ regime in the MSSM has a very rich decay spectrum of MSSM Higgs bosons
  - However, the discovery of a light CP-even Higgs boson at 125 GeV has imposed very strong constraints: SUSY scale should be very high.
  - Examples:
    - $A \rightarrow Zh$:
    - $hh$ decays:
    - $H \rightarrow WW/ZZ$:
A→ Zh -> llττ/llbb/ννbb in ATLAS and CMS

- Look for decays of new, heavy Higgs bosons to 125 GeV Higgs + Z boson
- Take advantage of Z→ll / Z →νν decays
- Use highest branching ratio of Higgs boson decays (bbbar/ττ).
- Typically use knowledge of masses of Z/h to select events, constrain the system and improve 4-object mass resolution.

This type of search constrains parameter region in (tanβ, cos(β−α)) plane. The figure shows the 95% CL allowed region of parameter space for type II 2HDMs from ATLAS Run 1 measurements.
ATLAS search for $A \rightarrow Zh \rightarrow ll\tau\tau/lb\nu\nu$ 

- $h \rightarrow \tau\tau$, $Z \rightarrow ll$ 
  - Categorized based on $\tau$ decays 
  - Shape of hadronic tau fakes from SS events plus taus failing ID criteria. Normalization from sidebands.

- $h \rightarrow bb$, $Z \rightarrow ll$ and $\nu\nu$ 
  - For $Z \rightarrow \nu\nu$ use track MET and transverse mass. 
  - Multijet backgrounds: 
    - $\mu\mu bb$ negligible 
    - ee $bb$ estimated by fitting $m_{ll}$ to templates with inverted isolation 
    - $\nu\nu bb$ estimated by inverting cuts on track versus calo MET. 
  - V+HF constrained with V+0/1 btag versus number of jets.
ATLAS search for $A \rightarrow Zh \rightarrow ll\tau\tau/lb

- Constraints for a gluon-fusion and b-associated produced heavy CP-odd Higgs boson A
- No evidence for new physics

Cross-section times BR limits use gluon-fusion only, while plots on the right also use b-associated production.
CMS search for $A \rightarrow Zh \rightarrow llbb$

- Use loose and tight b-tagging
- Study 0/1/2 btag regions but $m_{bb}$ far from $m_h$
- Kinematic fit to improve mass resolution
- Multivariate BDT trained separately for different $m_A$ values
- Results from fit to 2D distributions of BDT and $m_{llbb}$
CMS search for $A \rightarrow Zh \rightarrow llbb$

- BDT adding significant additional information:
  - Using 1D fit only worsens limits by 10-20%

Figures show CMS results for $A \rightarrow Zh \rightarrow llbb$ with $L = 19.7 \text{ fb}^{-1}$ (8 TeV). The plots illustrate Type-I and Type-II 2HDM with $m_A = 300 \text{ GeV}$.
Search for \( hh' \rightarrow bb\gamma\gamma/bbbbb/bb\tau\tau/WW\gamma\gamma \)

- Search for both resonant and nonresonant Higgs boson pair production

New

Nonresonant background fits in \( m_{\gamma\gamma} \) for one of the categories (medium purity) for the resonance mass hypothesis of 270 GeV.
Search for $hh\rightarrow bb\gamma\gamma/bbbb/bb\tau\tau/WW\gamma\gamma$

Results combining all channels. The improvement above 500 GeV is due to the sensitivity of the $hh\rightarrow bbbb$ channel.

Observed and expected 95% CL exclusion regions in $(\tan\beta,m_A)$ plane for the low-$\tan\beta$-high MSSM scenario. The observed exclusion region in this plane is smaller than the expectation, reflecting a small excess observed in data.
Search for $H \to WW/ZZ$

- In this search the Higgs is either produced by gluon fusion, VBF or VH processes
  - Mass range from 140-400 GeV up to 1 TeV.

Distribution used in a likelihood fit of the four-lepton invariant mass ($m_{llll}$) for $H \to ZZ \to llll$ search in the gluon-fusion production mode. No events are observed beyond the upper limit of the plot.

Upper limits at 95% CL for each of the contributing final states and their combination. The theoretical cross section, $\sigma_{SM}$, is computed in arXiv:1307.1347.

Next-to-MSSM (NMSSM)

- NMSSM: next to minimal supersymmetric Standard Model
  - Addition of a singlet in the Higgs sector
  - 2 more Higgses and one more neutralino with respect to MSSM; more freedom with respect to the MSSM
    - Higgs sector not necessarily CP conserving at lowest order (although usually CP-conservation is assumed)
    - Tree level MSSM relation “$m_h < m_Z$” is not valid any more
  - Typical signatures involve a light CP-odd Higgs
    - $a \rightarrow \mu\mu$ arXiv: 1206.6326 (CMS)
    - $h \rightarrow aa \rightarrow \mu\mu\tau/\mu\mu\mu$ arXiv:1506.00424 (CMS), 1505.01609 (ATLAS)
    - $h_1 \rightarrow bb$ in cascades CMS-PAS-HIG-14-030
    - …
Search for $a \rightarrow \mu \mu$

- Search for a gluon-fusion produced, light CP-odd Higgs boson decaying to $\mu \mu$

arXiv: 1206.6326 (CMS)
Search for $h \rightarrow aa \rightarrow \mu\mu\tau\tau / \mu\mu\mu\mu$

- Search for this decay in multi-lepton events, with several resonances involved.

$H \rightarrow a a \rightarrow \tau\tau \rightarrow \mu / e + \nu\nu$

arXiv:1506.00424 (CMS), 1505.01609 (ATLAS)
Conclusions

• No evidence for BSM Higgs yet.
• Current searches constrain large parts of parameter space
  – There are still many things to do be done, and many
    searches that are still starting up.
  – Expect that this will continue to be a hot area in Run-II.
• For the coming months expect early results in high mass
  searches.
• For Moriond, search of intermediate-high mass Higgs
  bosons with full 2015 dataset.
• For summer, update with searches sensitive to additional
  data collected in 2016.
Backup
Production modes in MSSM

\[ \tan \beta = 5 \]

\[ \tan \beta = 30 \]
Branching ratios in MSSM

Branching ratios for different mass scenarios and values of $\tan\beta$.
Searches for h/H/A \rightarrow bb

- Trigger selection: 2 high \( p_T \) b-jets inclusive. Offline selection: 3 tight b-tag inclusive.
- Most important background: QCD, estimated from data with control samples.
- Categorize the events according to flavor of jets: 2b, 1b, 2c, 1c, LF jets.
- Use different templates for each category and merge according to weight from simulation.

**High \( \tan\beta \)**

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Projection of the dijet mass \( M_{12} \) in the triple-b-tag sample, together with the corresponding projections of the fitted background templates.

Expected and observed upper limits at 95\%CL for the MSSM parameter \( \tan\beta \) versus \( m_A \) in the \( m_h^{\text{mod+}} \) benchmark scenario with \( \mu = +200 \) GeV. Regions where the mass of neither of the CP-even MSSM Higgs bosons h or H is compatible with the discovered Higgs boson of 125 GeV within a range of 3 GeV are marked by the hatched areas.
Search for $H^{\pm} \to W^{\pm}Z$

- Higgs triplet model (not MSSM).
- Require two forward separated jets in $\eta$ with large dijet mass

arXiv: 1503.04233 (ATLAS)
Search for $H^{±} \rightarrow W^{±}Z$

- Set limits as a function of $m_{H^{±}}$
- $(s_H)^2$ is the fraction of vector boson mass squared ($m_W^2/m_Z^2$) generated by triplet vev (free parameter) in Georgi-Machacek Higgs Triplet Model.
Search for $h_1 \rightarrow bb$ in cascades

- A light boson produced in a SUSY-inspired cascade: hard jets, MET and b-jets from Higgs decay

CMS-PAS-HIG-14-030

- The shown prediction from an NMSSM benchmark is taken from arXiv:0801.4321
Tau CP / Flavour tagging

(Left) Inverse background efficiency versus signal efficiency for the offline tau identification.
(Right) b-tagging efficiency as a function of the discriminator for the CSV algorithm.

arXiv:1412.7086 (ATLAS)