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

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Run I legacy on Higgs discovery

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

ATLAS & CMS combined couplings:
ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002

ATLAS J\textsuperscript{CP}: arXiv:1506.05669
CMS J\textsuperscript{CP}: Phys. Rev. D 92, 012004

ATLAS d\sigma/dx: arXiv:1508.02507
CMS d\sigma/dx: CMS-PAS-HIG-14-028

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

- Looks very much like SM-Higgs boson. So where will we find new physics?
Reasons for Beyond Standard Model (BSM) Higgs

• 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
SM Higgs field vs 2HDM

SM Higgs field: Complex scalar doublet
4 degrees of freedom of which:
– 3 provide longitudinal components of $W^\pm, Z$
– 1 CP-even Higgs boson ($h$)

2HDM Higgs field: Two complex scalar doublets
More degrees of freedom than SM. For Higgs sector:
– 2 CP-even Higgs bosons ($h, H$), one of which is the observed 125 GeV resonance
– 1 CP-odd pseudoscalar ($A$)
– Two charged Higgs bosons ($H^\pm$)
Contents

• MSSM and NMSSM.
• Physics analysis:
  • MSSM Higgs searches
    - h/H/A \rightarrow \tau\tau
    - h/H/A \rightarrow bb
    - H^{\pm} \rightarrow \tau\nu/tb
  • NMSSM Higgs searches
    - A \rightarrow Z\ell
    - hh decays
    - H \rightarrow WW/ZZ
  • NMSSM motivated searches for a light Higgs:
    - a \rightarrow \mu\mu
    - h \rightarrow aa
    - NMSSM inspired cascades
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 \(h\), \(\alpha\).

| 2HDM Type       | Doublet coupled to up-type quarks | Doublet coupled to down-type quarks | Doublet coupled to leptons |
|-----------------|-----------------------------------|-------------------------------------|--------------------------|
| Type I          | \(\Phi_2\)                        | \(\Phi_2\)                          | \(\Phi_2\)               |
| Type II         | \(\Phi_2\)                        | \(\Phi_1\)                          | \(\Phi_1\)               |
| Lepton-specific | \(\Phi_2\)                        | \(\Phi_2\)                          | \(\Phi_1\)               |
| Flipped         | \(\Phi_2\)                        | \(\Phi_1\)                          | \(\Phi_2\)               |
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

| 2HDM Type     | Doublet coupled to up-type quarks | Doublet coupled to down-type quarks | Doublet coupled to leptons |
|---------------|-----------------------------------|------------------------------------|---------------------------|
| Type I        | $\Phi_2$                          | $\Phi_2$                           | $\Phi_2$                  |
| Type II       | $\Phi_2$                          | $\Phi_1$                           | $\Phi_1$                  |
| Lepton-specific | $\Phi_2$                         | $\Phi_2$                           | $\Phi_1$                  |
| Flipped       | $\Phi_2$                          | $\Phi_1$                           | $\Phi_2$                  |
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 $bb$
    - $\text{BR}(h/H/A \rightarrow \tau\tau) \sim 10\%$ 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 BR($H^{\pm}$) is presented for $m_h^{\text{max}}$ 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 $m_{h_{\text{max}}}$ 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:
    – \(A \rightarrow Zh\):
      • Phys. Lett. B 744 (2015) 163-183 (ATLAS), arXiv:1504.04710 (CMS)
    – hh decays:
      • arXiv:1509.04670 (ATLAS), CMS-PAS-HIG-13-032
    – \(H \rightarrow WW/ZZ\):
      • arXiv:1504.00936 (CMS), arXiv:1507.05930 (ATLAS), arXiv: 1509.00389 (ATLAS)
**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.

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*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 $A \rightarrow Zh \rightarrow \ell\ell\tau\tau/\ell\ell bb/\nu\nu bb$

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

- $h \rightarrow bb$, $Z \rightarrow \ell\ell$ 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 $m_{\ell\ell}$ 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 $A \rightarrow Zh \rightarrow ll\tau\tau/llbb/\nu\nu bb$

- 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 $A \rightarrow Z h \rightarrow llbb$

- Use loose and tight $b$-tagging
- Study 0/1/2 $b$tag 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 $m_{llbb}$

arXiv:1504.04710 (CMS)
CMS search for $A \rightarrow Zh \rightarrow llbb$

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

See arXiv:1504.04710 for more details.
Search for $hh\rightarrow bb\gamma\gamma/bbbb/bb\tau\tau/WW\gamma\gamma$

- 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 $hh\rightarrow bb\gamma\gamma/bbbbb/bb\tau\tau/WW\gamma\gamma$

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→ 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 ($m_{\text{llll}}$) for H→ZZ→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, $\sigma_{\text{SM}}$, 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 $a\to\mu\mu$

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

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

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

\[ \text{H} \rightarrow a \ a \ \mu / e + \nu \nu \]

\[ \text{H} \rightarrow a \ a \ \mu \mu \]

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

$\tan\beta=5$

$\tan\beta=30$

$M_A$ [GeV]

$BR(A)$

$BR(h)$

$BR(H)$
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 $\tan\beta$**

Expected and observed upper limits at 95%CL for the MSSM parameter $\tan\beta$ versus $m_A$ in the $m_h^{mod+}$ 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 $H^\pm \rightarrow W^\pm Z$

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

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

- Set limits as a function of $m_{H^{\pm}}$
- $(s_H)^2$ 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.

arXiv: 1503.04233 (ATLAS)
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

- 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)