BSM Higgs searches

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BSM Models

- **2HDM** (Two Higgs Doublet Model) is the extension of Standard Model: second Higgs doublet is added to SM leads to 5 physical states, 3 neutral, 2 charged: CP-even $h$ and $H$, CP-odd pseudoscalar $A$, charged $H^+$, $H^-$
  - model has 6 free parameters: Higgs masses $m_h$, $m_H$, $m_A$, $m_{H^\pm}$ and the ratio of doublet vacuum expectation values $\tan \beta = v_1/v_2$ and a mixing angle $\alpha$
  - between the CP-even Higgs bosons
- **MSSM** (Minimal Supersymmetric Standard Model): simple extension of SM and particular case of 2HDM (5 physical states)
- **NMSSM**: Higgs singlet is added to MSSM→7 physics states, 5 neutral, 2 charged: CP-even $H_1$, $H_2$, $H_3$, CP-odd $A_1$, $A_2$, charged $H^+$, $H^-$
- **HTM**: (Higgs Triplet Model): simple extension of SM, Higgs triplet is added, lead to 7 physical states: $H^{\pm\pm}$, $H^\pm$, $A$, $H$ and $h$
- **MLRSM**: (Minimal Left Right Symmetric models) extension of SM, several variations: e.g. addition of triplet + two doublets (bi-doublet) ....
- ... and more ...
The page contains a slide titled "Searches by ATLAS & CMS" and lists several types of Higgs boson decays:

- **Neutral Heavy Higgs**: \( h/H/A \rightarrow \tau \tau, H \rightarrow WW \rightarrow l\nu l\nu, \) \( A \rightarrow Zh(Z \rightarrow ll, h \rightarrow b\bar{b} (\tau \tau)), h/H/A \rightarrow t\bar{t} \ldots \)

- **Neutral Higgs decaying to di-Higgs**: \( H \rightarrow hh \rightarrow b\bar{b} \tau \tau, hh \rightarrow b\bar{b}b\bar{b}, hh \rightarrow bb\gamma\gamma, hh \rightarrow WW\gamma\gamma, hh \rightarrow WWbb, hh \rightarrow WWWW \)

- **Charged Higgs**: \( H^\pm \rightarrow \tau \nu, H^+ \rightarrow tb, H^+ \rightarrow WZ \rightarrow 3l+\nu_\ell, H^+ \rightarrow WZ \rightarrow 2l+2j \) \( H^+ \rightarrow \mu \nu, H^+ \rightarrow Wh/WA/W\gamma, \) light \( H^+ \rightarrow cs, cb \)

- **Double charged Higgs boson**: \( H^{\pm \pm} \rightarrow l^\pm \ell^\pm, H^{++} \rightarrow WW \)

- **... and more ...**
Neutral Heavy Higgs
**MSSM h/H/A→ττ: ATLAS@13TeV**

**gg-fusion**

- 2 channels: \(\tau_{\text{lep}}\tau_{\text{had}}\) and \(\tau_{\text{had}}\tau_{\text{had}}\)
- Discriminating variable:
  
  \[
  m_T^{\text{tot}} = \sqrt{m_T^2(E_{T\text{miss}}^1, \tau_1) + m_T^2(E_{T\text{miss}}^2, \tau_2) + m_T^2(\tau_1, \tau_2)}.
  \]
  
  \[
  m_T(a, b) = \sqrt{2p_T(a)p_T(b)[1 - \cos \Delta \phi(a, b)]}
  \]

**b-associated production**

Events category:
- b-veto: no b-jets in the event
- b-tag: at least one b-jet
MSSM $h/H/A \rightarrow \tau\tau$: ATLAS@13TeV

Limits on cross-section $\times$ BR

$gg$-fusion

$b$-associated production

Limits on $\tan\beta$

$m_h^{mod+}$ MSSM

hmMSSM

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The are two production mechanisms: VBF and ggF.

- only different-flavor lepton pairs in the final state are considered.
- two oppositely-charged leptons and no additional lepton with $p_T > 15$ GeV in order to suppress diboson backgrounds.

**Discriminating variable:**

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |p_T^{\ell\ell} + E_T^{miss}|^2},$$

$$E_T^{\ell\ell} = \sqrt{|p_T^{\ell\ell}|^2 + m_T^{\ell\ell}}.$$
Two different hypotheses are tested:
- a narrow width approximation (NWA), where the width of the heavy Higgs boson is smaller than the experimental resolution
- large width assumption (LWA), where widths of 5%, 10%, and 15% of the heavy Higgs boson mass are considered.
Event selection:
- only different-flavour lepton pairs in the final state are considered
- The event is required to have two oppositely-charged isolated leptons with $p_T > 20$ GeV
- no additional identified and isolated lepton with $p_T > 10$ GeV
- 0,1 jets and VBF events
- Discriminating variable: $m_{T,i} = \sqrt{(p_{T,i} + E_{miss}^T)^2 - (p_{T,i} + p_{Tmiss}^T)^2}$
• ggF + VBF
• 4 different signal width
  $\Gamma = 0.09 \times \Gamma_{SM}$,
  $\Gamma = 0.25 \times \Gamma_{SM}$,
  $\Gamma = 0.49 \times \Gamma_{SM}$,
  $\Gamma = \Gamma_{SM}$
  have been used for the interpretation
• The black dotted line corresponds to the central value
A→Zh→ℓℓb̄b (ννbb): ATLAS@13TeV

- Search for A CP-odd (pseudoscalar) Higgs boson
- Leptonic decay of Z-boson
- Analysis was done separately for the events categories: 0 or 2 – leptons and 1 or 2 of b-tagged jets
- Resolved or merged jets are considered
- In the case of “2” leptons the invariant mass is reconstructed, in the case of “0” leptons the discriminating variable used:

\[ m_T^{Zh} = \sqrt{(E_T^h + E_T^{miss})^2 - (p_T^h + E_T^{miss})^2}. \]

\[ 95\% \text{ C.L. limit on } \sigma(A \rightarrow Zh) BR(h \rightarrow b \bar{b}) \text{ [pb]} \]

\[ 95\% \text{ C.L. limit on } \sigma(A \rightarrow Zb) \text{ [pb]} \]

Results are interpreted in the context of 2HDM

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2HDM Type I and Type II. 
The width of the A boson is assumed in simulation to be narrow, but is corrected to the width ($\Gamma_A$) predicted by the 2HDM for each point in the parameter space using a relativistic Breit-Wigner function. 
Only points in parameter space where $\Gamma_A/m_A < 5\%$ are considered.
Di-Higgs
$H \rightarrow hh \rightarrow bb\tau\tau$: CMS@13TeV

- $H \rightarrow hh \rightarrow bb\tau\tau$
  - $bb \rightarrow 2\text{jet}(1\ b\text{-tag}, 2\ b\text{-tag})$
  - $\tau\tau \rightarrow (\mu\tau_h, e\tau_h, \tau_h\tau_h)$ OS final states
  - ($\tau_h$ visible products of a hadronically decaying $\tau$)
- discriminant variable – inv mass

CMS Preliminary

CMS PAS HIG-17-002
H→hh: ATLAS@13 TeV

H→hh→b̅bb̅
Simplified models

H→hh(→WWγγ)

ATLAS-CONF-2016-071

H→hh(→b̅bγγ)

ATLAS-CONF-2016-004

ATLAS
1s=13 TeV, 3.2 fb⁻¹

Resolved
Boosterd

σ(pp→H→hh→b̅b̅bb)[fb]

m_{H}[GeV]

σ(pp→H→hh→b̅b̅bb)[fb]

m_{X}[GeV]

σ(gg→X×BR(X→hh))[pb]

m_{X}[GeV]

σ(gg→X×BR(X→hh))[pb]

m_{X}[GeV]

Obs. limit
Exp. limit
Exp. limit ±1σ
Exp. limit ±2σ

H→hh→b̅b̅bb

Charged Higgs
Interpretation in MSSM model

Fully hadronic final state is considered.

The signal extraction is performed with the transverse mass variable ($m_T$), reconstructed from the hadronic tau and $\slash ET$, and defined as:

$$m_T^2 = 2 \cdot p_T^h |\slash E_T| \left(1 - \cos \Delta \phi (\slash E_T, \tau^h)\right)$$
$H^{+/−} \rightarrow \tau^{±} \nu_τ$: CMS@13TeV

$pp \rightarrow tbH^{±}$

$m_{H^{±}} < m_{t} - m_{b}$

$pp \rightarrow H^{±}W^{±}bb$

$m_{H^{±}} > m_{t} - m_{b}$
H^{±} → τν: ATLAS@13TeV

hadronically decaying top quark discriminant variable:

\[ m_T = \sqrt{2p_T^\tau E_T^{miss} (1 - \cos \Delta \phi_\tau, E_T^{miss})} \]
(pp → btH±) × BR(H± → tb) Event selection ≥ 1 lepton, ≥ 4 jets (≥ 2 b − tagger jets) Discrimination variable: BDT

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ATLAS-CONF-2016-089
**Higgs Triplet Model used for interpretation**

- VBF production mechanism is assumed
- Events with 2 jets are selected
- Lepontic decay (e,µ) W,Z bosons
- Discriminating variable:

$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (p_T(W) + p_T(Z))^2}$$

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**CMS PAS HIG-16-027**
Double Charged Higgs
Interpretation: LRSM
Events with:
same-charge, isolated, high-p_T electrons

$H^{\pm\pm} \rightarrow e^\pm e^\pm$

The observed(expected)
lower mass limits at 95%
C.L. are:
(100% BR)
420 (460) GeV for: $H_R^{\pm\pm}$
570 (580) GeV for: $H_L^{\pm\pm}$
(50% BR)
380 (400) GeV for: $H_R^{\pm\pm}$
530 (530) GeV for: $H_L^{\pm\pm}$
Double charged Higgs: CMS@13TeV

- Interpretation: LRSM
- 100% decay to $ee$, $\mu\mu$, $tt$, $e\tau$, $\mu\tau$, and $\tau\tau$
- 3(4) lepton candidates with charge configuration: $(++-),(-++)$ and $(++++)$

The shaded region represents the excluded mass points and the thick solid line represents the expected exclusion with the hashed region indicating the direction.
• The recent results on wide range searches of BSM Higgs boson obtained by the ATLAS and CMS collaborations are presented
• The results are based on the data collected in Run I at $\sqrt{s} = 8$ TeV and Run II at $\sqrt{s} = 13$ TeV
• The results have been interpreted in the context of 2HDM, MSSM and LRSM models
• No excess over SM was observed for all the channels $\Rightarrow$ the exclusion limits for cross-sections and some of the model’s parameters are given
• There are a lot of searches still are in the progress $\Rightarrow$ hope to obtain the positive results!
Back Up
A → Zh → llττ: CMS@8TeV

- 2HDM used for interpretation
- A → Zh → llττ:
  $$ll \rightarrow (\mu\mu \text{ or } ee)$$
  $$h \rightarrow (\mu\tau_{\text{had}} e\tau_{\text{had}} \tau\tau_{\text{had}} e\mu)$$
- 8 final states were analyzed
- Discriminant variable – inv mass (Zh)

Higgs Triplet Model used for interpretation
VBF production mechanism is assumed
The VBF process reconstructed with two jets, with high $|\eta|$ moving in opposite directions.
- $Z \rightarrow e^+e^- / \mu^+\mu^-$ two OS leptons
- $W^\pm \rightarrow q\bar{q}'$ reconstructed from two high $p_T$ central jets
- Discriminating variable: invariant mass $m_{\ell\ell jj}$
The limit falls off rapidly as $m_A$ approaches 350 GeV because decays of the A to two top quarks are becoming kinematically allowed.

The areas highlighted in blue bounded by the black curves mark the observed exclusion

H→hh: ATLAS

\[ \sqrt{s} = 8 \text{TeV} \]

\[ \sqrt{s} = 13 \text{TeV} \]

H→hh→bbττ
H→hh→WWγγ
H→hh→bbγγ
H→hh→bbbb

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