Searches for neutral BSM Higgs bosons in fermionic decays in CMS

Antonio Vagnerini
DESY
for the CMS collaboration

Charged2018 Workshop
Uppsala, 25-28 Sep. 2018
This talk: **neutral** BSM Higgs searches **in fermionic decays**

**Heavy Higgs** resonances:
- $h/A/H \to \tau\tau$  JHEP09(2018)007
- $b\bar{b}(A/H \to b\bar{b})$  JHEP08(2018)113
- $t\bar{t}(A/H \to t\bar{t})$  EPJC(2017)77:578

**Light Higgs** resonances:
- $h_{125} \to aa \to 4\mu$  CMS PAS-HIG-18-003
- $h_{125} \to aa \to 2b2\tau$  Phys. Lett. B 785 (2018) 462
- $h_{125} \to aa \to 2\mu2\tau$  arXiv:1805.04865

Related talks on searches for **BSM Higgs bosons**: 
- in bosonic decays in CMS by Roberto Covarelli
- in dark matter searches in ATLAS and CMS by Michele Gallinaro
Motivation for BSM Higgs

- Standard model most successful theory of physics **but we need BSM physics**
- To explain **hierarchy problem**, **dark matter**, ...

- The discovery of h(125) could be a **portal** to BSM

- Several theoretical models with **extra Higgs doublets**
  - **2HDM** → including **MSSM**
  - **add gauge Singlet S** → special case **NMSSM**

- Combined searches of H→inv at 13 TeV in CMS constrain **BR(H→BSM)<0.26** at 95% CL

- **Direct BSM searches**
  - probe large range of m_χ since no **golden channel**
  - complement **indirect constraints** on **2HDM**
  - from **h(125) couplings** and **rare B-decays**

arXiv:1809.05937
The Two-Higgs-Doublet Model (2HDM) is an effective theory with extra $SU(2)_L$ doublet

- 7 parameters: 5 Higgs masses, $\tan \beta$ and mixing angle $\alpha$ between $h$ and $H$

Neutral $\Phi$
- CP-even

Charged
- CP-odd

→ 5 physical Higgs states after EWSB

In this talk focus on neutral $h/H/A$!

- 4 flavour and CP-conserving scenarios based on how the Higgs doublets couple to SM particles

Type I
- $\Phi_2$
- $\Phi_1$
- All fermions couple to one Higgs boson

Type II
- $\Phi_2$
- $\Phi_1$
- Up vs. down

Lepton Specific
- $\Phi_2$
- $\Phi_1$
- Quark vs. lepton

Flipped
- $u$ - (u,c,t)
- $d$ - (d,s,b)
- $\ell$ - (e,\mu,\tau)

MSSM-like
The **Minimal Supersymmetric Standard Model** has the same structure as 2HDM Type II:

- **2** parameters at tree level: \( \tan \beta \) and \( m_a \)

Several benchmark scenarios for different phase space properties, e.g. **MSSM** \( m_h^{\text{mod+}} \)

- theory predictions **unstable** for \( \tan \beta > 60 \)
H/A → fermionic decays
Heavy Higgs Searches

- Searches for $H/A \to$ fermionic decays
  - events categories based on number of $b$-tagged jets
  - main production modes: gluon fusion $ggF$ and $b$-associate $bbH$

- Couplings to fermions of pseudoscalar $A$ enhanced at large $\tan\beta$ with respect to $h_{SM}$

<table>
<thead>
<tr>
<th></th>
<th>Type-1</th>
<th>Type-2</th>
<th>Type-3 (lepton-specific)</th>
<th>Type-4 (flipped)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Up-type quarks</strong></td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
</tr>
<tr>
<td><strong>Down-type quarks</strong></td>
<td>$-\cot \beta$</td>
<td>$\tan \beta$</td>
<td>$-\cot \beta$</td>
<td>$\tan \beta$</td>
</tr>
<tr>
<td><strong>Charged leptons</strong></td>
<td>$-\cot \beta$</td>
<td>$\tan \beta$</td>
<td>$\tan \beta$</td>
<td>$-\cot \beta$</td>
</tr>
</tbody>
</table>

- Cross-section of $\sigma(A/H \to ff)$ enhanced for:
  - $tt$ final state at $\tan\beta < 1$ in 2HDM Type II
  - $bb$ up to $2\tan\beta^2$ in Type II and flipped model
  - $\tau\tau$ for large $\tan\beta$ in Type II and lepton-specific model
MSSM searches for $h/H/A \rightarrow \tau\tau$ in four di-tau final states: $\tau_h \tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$

- $e\mu$ discarded due to large DY background

- Dominates at low $\tan\beta$

- Dominates at high $\tan\beta$

- 2 event categories per final state:
  - b-tagged ($gg\Phi$) vs non b-tagged jets ($bb\Phi$)

- Main backgrounds: $Z/\gamma^* \rightarrow \tau\tau$, QCD, $tt$, $W+\text{jets}$
  - Largely data-driven background estimation
  - Clean final state

- Several discriminating variables:
  - e.g. di-tau total transverse mass

\[ m_T^{\text{tot}} = \sqrt{m_T^2(p_T^1, p_T^2) + m_T^2(p_T^1, p_T^{\text{miss}}) + m_T^2(p_T^2, p_T^{\text{miss}})}, \]

\[ m_T = \sqrt{2 p_T p_T' [1 - \cos(\Delta \phi)]}. \]
h/H/A → ττ - results

- Model independent limits for $gg\Phi$ and $bb\Phi$ production modes
  - combined maximum likelihood fit for all final states
  - no significant excess over SM background

- Large $m_{\Phi}$ range probed → sensitivity reach extended from 1 TeV in Run I to 2.3 TeV!
**Exclusion limits in the tanβ-\(m_A\) plane in the context of MSSM \(m_h^{\text{mod+}}\) and hMSSM scenarios**

**MSSM Higgs boson** excluded up to \(m_A \leq 250\) GeV for \(\tan\beta > 6\)
$b\bar{b}$ ($H/A \rightarrow b\bar{b}$)

- Cross section enhanced up to $2\tan\beta^2$ in 2HDM Type II and flipped model

- Dedicated trigger selection
  - triple $b$-tag signal region and $3^{rd}$ $b$-tag veto in control region

- Signal extraction from $m_{12}$: invariant mass of 2 leading $b$-jets

- Data-driven parametric approach
  - 3 subranges to reduce bias

JHEP08(2018)113
$b\bar{b}$ (H/A $\rightarrow$ b$\bar{b}$) - results

✶ Model independent exclusion limits for $b\bar{b}(H/A \rightarrow b\bar{b})$ cover $m_{A/H}$ up to 1300 GeV

✶ Translated into exclusion contours in the MSSM parameter space - $m_A$ and $\tan\beta$

✶ Significant improvement for MSSM $m_h^{mod+}$ scenario wrt Run I analysis beyond 300 GeV
**Exclusion limits** on $\tan\beta$ vs $m_A$ and $\cos(\beta-\alpha)$ for 2HDM flipped model

**h(125) couplings** allow only narrow $|\cos(\beta-\alpha)|$ region

**Unique sensitivity** at LHC of this analysis in the flipped model!
$(\bar{t}t, tW, tq) \ (H/A \rightarrow \bar{t}t)$

- Search for $H/A \rightarrow \bar{t}t$ in 2HDM type II model

- Baseline selection with dilepton and $H_t$ trigger:
  - 2 same-sign leptons (SS)
    - very rare process in SM!

- Background sources:
  - Prompt SS dileptons - mostly $WZ$, $ttZ$
  - Non-prompt leptons for low $m_T$ and $H_t$ region
  - Charge-misidentified events with electrons

EPJ C (2017) 77:578
(t\bar{t},tW,tq) (H/A\rightarrow t\bar{t}) - results

* Upper Limits on $\sigma(pp\rightarrow (t\bar{t},tW,tq)+H)BR(H\rightarrow t\bar{t})$ in 2HDM type II interpretation

* Cross section in pseudo(scalar) model

- Observed limit excludes scalar (pseudo)scalar masses up to 360 (410) GeV
h → aa → 4 fermions
The **2HDM** can be extended by addition of EWK singlet \( S \)

The **Next-to-MSSM (NMSSM)** is the approximate *R*-symmetric limit of 2HDM+S Type II

- 7 physical Higgs states after EWSB
  - one extra **light pseudoscalar** \( a_1 \) and one extra **light scalar** \( h_1 \)

**CP-odd**

\[ a_1, a_2 \]

- can be very light

**CP-even**

\[ h_1, h_2, h_3 \]

- one of these is SM-like

**Charged**

\[ H^\pm \]

In the **NMSSM**, the \( a_1 \) boson identified as the **lightest Higgs state**

- exotic \( h(125) \rightarrow aa \) decays allowed!
  - narrow width of \( h_{SM} \) yields \( \text{BR}(h \rightarrow aa) \) at percent level even for small coupling
**NMSSM** interpretation of search \( h \rightarrow a_1a_1 \rightarrow 4\mu \)

**narrow mass range probed** \( 2m_\mu < m_a < 2m_\tau \)

**Dedicated trigger selection** of dimuon events

- **Two isolated** \( \mu^+\mu^- \) **systems per event with common primary vertex** PV

**Main SM background is** \( b\bar{b} \) **production**

**Resonant and semileptonic** \( b \) **decays**

**Smaller contributions from**

- **Prompt double** \( J/\Psi \) **emission**
  - irreducible bkg from SPS and DPS from MC

- **Electroweak** \( qq\rightarrow ZZ\rightarrow 4\mu \) and \( qq\rightarrow Z\rightarrow 2\mu \)
**Signal region** (SR) defined as $m_{(\mu\mu)1} \approx m_{(\mu\mu)2}$

- **13 events** $\Delta$ in SR and $9.90 \pm 1.24 \text{ (stat)} \pm 1.84 \text{ (syst)}$ from SM background
  - no significant excess observed over **SM background**

- **Observed Upper Limits** on $\sigma(pp \rightarrow h_{1,2} \rightarrow 2a_1)B^2(a_1 \rightarrow 2\mu)$ vs masses of $a_1$ and $h_{1,2}$
Two 2HDM+S $h \rightarrow aa \rightarrow (2\mu, 2b)2\tau$ searches with 4(3) final states: $2\mu$ ($2b$) x $e\mu e\tau_h \mu\tau_h \{\tau_h, \tau_h\}$.

- Non-boosted $\tau$ pair restricts search region in $15 < m_a < 62.5$ GeV.

**Dimuon invariant $m_{\mu\mu}$**

$2\mu 2\tau$

**Visible invariant $m_{b\tau\tau}$**

$2b 2\tau$

---

**Visualizations:**

- CMS Preliminary
- Observed $h \rightarrow aa \rightarrow 2\mu 2\tau$
- Bkg. model
- Signal model

---

**Obs./Exp.:**

- $m_{\mu\mu}$ (GeV)
- $m_{b\tau\tau}$ (GeV)

---

**References:**

- arXiv:1805.04865

---

**Additional Information:**

- BSM neutral Higgs in fermionic decays
- Charged2018 Workshop
- Antonio Vagnerini
**Combined** maximum likelihood **unbinned fit** for all final states:

- **Fit observable:** \( m_{\mu\mu} \)
  - 2\(\mu\)2\(\tau\)

- **Fit observable:** \( m_{\tau\tau} \)
  - 2b2\(\tau\)

- Improvement of limits of several factors in \( h \rightarrow a a \rightarrow 2\mu2\tau \) wrt 8TeV!

- First time decay channel \( h \rightarrow a a \rightarrow 2b2\tau \) probed!
h→aa - 2HDM+S limits

Type III

Type IV
Improvement in **Exclusion Limits** in all **2HDM+S Types**

- In **NMSSM**, \( \text{BR}(h \rightarrow aa) > 23\% \) excluded at 95% CL for \( m_a \sim 35 \text{ GeV} \)

  ◊ most sensitive result at LHC!

In **Type III**, upper limits on \( \text{BR}(h \rightarrow aa \rightarrow 2\mu 2\tau) \) as low as 1% for \( m_a \sim 60 \text{ GeV} \)
Summary & Outlook

- Observed **Higgs boson** at mass **125 GeV** could be a portal to **BSM physics**

- Searches for **additional neutral Higgs** bosons in **fermionic** decays presented in
  - **heavy A/H** resonances searches
  - **exotic h_{125}** decays

- **Model interpretation** of **2HDM** and **extensions** has become more **systematic**

- **No signs of BSM Higgs sector yet...**

- Many **more Higgs analyses** targeting both **low and high-mass** search regions are **ongoing** at CMS in Run II will benefit from
  - **3x more** integrated **luminosity!**
Exclusion contours on 2HDM parameter space imposed by \textit{h(125) coupling measurements} assuming

In the \textbf{alignment limit} i.e. when \(\cos(\beta-\alpha) \approx 0\)

\textbf{In the alignment limit} i.e. when \(\cos(\beta-\alpha) \approx 0\)

\textbf{In the alignment limit} i.e. when \(\cos(\beta-\alpha) \approx 0\)

\textbf{In the alignment limit} i.e. when \(\cos(\beta-\alpha) \approx 0\)

\textbf{In the alignment limit} i.e. when \(\cos(\beta-\alpha) \approx 0\)

the light \textbf{h decouples} from the rest of the Higgs sector and SM couplings obtained

results show \textbf{good agreement of h(125) with the SM Higgs}!

\textbf{CMS PAS-HIG-16-007}

\textbf{Type I}

\textbf{Type II}

BSM neutral Higgs in fermionic decays

Charged2018 Workshop

Antonio Vagnerini

26
2HDM - Direct searches @RunI

* 2HDM exclusion contours driven by the $H \rightarrow WW/ZZ$ search and $h(125)$ constraints

**Type I**

**Type II**

*Exclusion of high-mass Higgs boson for $M_A < 380$ GeV and for $\tan\beta > 2.5$ in type II*
MSSM interpretation @RunI

- The **Minimally-Supersymmetric** model has the same Higgs sector structure as in Type II
- 2 parameters at tree level: \(\tan\beta\) and \(m_A\)

- The **MSSM** provides a solution to the **hierarchy problem** and **DM candidates**
- Several benchmark scenarios for different phase space properties, e.g. **MSSM** \(m_{h_{\text{mod}}}\), **hMSSM**
- Theory predictions **unstable** for \(\tan\beta > 60\)

---

**Figure:**
- CMS Preliminary: \(\leq 5.1 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.7 \text{ fb}^{-1} (8 \text{ TeV})\)
- Plots showing the relationship between \(m_A\) and \(\tan\beta\) with various excluded regions and theoretical predictions.
Light Higgs searches @RunI

**Combined upper limits** for $h \rightarrow aa \rightarrow 4\text{fermions}$ searches at 8 TeV in 2HDM+S

Type 2

2HDM+S type-2
\(\tan \beta = 2.0\)

![Graph for Type 2](image1)

\(\sigma(h) \times B(h \rightarrow aa)\)

Type 3

2HDM+S type-3
\(\tan \beta = 5.0\)

![Graph for Type 3](image2)

\(\sigma(h) \times B(h \rightarrow aa)\)

https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/SummaryResultsHIG
**Observed Exclusion limit** in range \(90 < m(h_{1,2}) < 150 \text{ GeV}\)

---

**Improvement with respect to 8TeV analysis up to factor 3 for \(m_{a_1} \sim 0.25 \text{ GeV} \)**
The CMS collaboration has performed a search for Higgs boson decays into four leptons, specifically $h \rightarrow aa \rightarrow 2\mu 2\tau$. The analysis uses a $2HDM+S$ framework with four final states: $2\mu x (e\mu, e\tau, \mu\tau, \tau\tau)$. The events are characterized by four well-reconstructed and isolated leptons, with a non-boosted $\tau$ pair topology restricting the mass range to $15 < m_A < 62.5$ GeV.

**Redducible background:**
- $Z$+jets and $WZ$+jets
- A jet is misidentified as a fake $\tau$ or lepton
- The shape from data in signal- and ZZ-free control regions with same-sign $\tau_h$
- The yield is estimated from data events with $Z \rightarrow \mu\mu$+jets ($\geq$1 non-isolated lepton)

**Main observable:**
- Di-muon mass $m_{\mu\mu}$
- Loose mass constraint di-tau pair
  - The search is sensitive to different pseudoscalars!
**2HDM+S** $h \rightarrow aa$ search with 3 final states: $e\mu, e\tau_h, \mu\tau_h$

- $\tau_h\tau_h$ discarded because of lower signal acceptance
- $ee$, $\mu\mu$ not included due to lower BR and large Drell-Yan bkg
- Mass range probed $15 < m_a < 60$ GeV

Leptons **isolated** and **well-separated**

- Requirement of a least **one soft b-jet**
- **90%** signal events 1 jet $p_T > 20$ GeV due to typically soft b-jets spectra

Final observable: **visible invariant** $m_{b\tau\tau}$

- Of highest $p_T$ b-jet and the **ditau pair** defines 4 **mass categories**
- Low $m_{b\tau\tau} < 65$ GeV category with best **sensitivity**
- High $m_{b\tau\tau} > 95$ GeV maximum bkg
- Used as **CR**


![Graph showing signal and background distributions](image-url)

- $35.9$ fb$^{-1}$ (13 TeV)
- CMS
- Events / 10 GeV
- $\mu\tau_h$
- $m_a = 40$ GeV
- Observed
- Expected
- $h \rightarrow aa \rightarrow bb\tau\tau$
- $\sigma(h) B(h \rightarrow aa \rightarrow bb\tau\tau) = 10 \sigma_{SM}$

- $m_{b\tau\tau}^{vis}$ (GeV)
- Obs./Exp.
- $1, 2, 3, 4$