Beyond the Standard Model Higgs Searches

49th SLAC Summer Institute - The Higgs State Fair
Jan Steggemann
20 August 2021
The BSM Higgs Landscape

**SM-like**
- $h_{125}$ measurements
- Rare $h_{125}$ decays

**BSM-like**
- $h_{125}$ BSM decays
- Additional Higgs bosons

Marumi’s lectures
*TH: Stefania, Bernhard*

This lecture!
*TH: Nausheen, Jessie*
The BSM Higgs Landscape

**SM-like**

- $h_{125}$ measurements: Is it really SM-like?
  - E.g. coupling deviations, EFT
- Rare $h_{125}$ decays: Rate much higher than in SM?

**BSM-like**

- $h_{125}$ BSM decays
- Additional Higgs bosons

It’s all BSM!
The BSM Higgs Landscape

**SM-like**
- $h_{125}$ measurements
- Rare $h_{125}$ decays

**BSM-like**
- Additional Higgs bosons:
  - Scalar $h/H$
  - Pseudoscalar $a/A$
  - Charged scalar $H^\pm$
  - Doubly charged scalar $H^{\pm\pm}$

**$h_{125}$ BSM decays:**
- $h_{125} \rightarrow aa/hh$
- $h_{125} \rightarrow$ invisible
- $h_{125} \rightarrow$ long-lived
- LFV decays

_Higgs as a tool_ - e.g. other new particles decaying to Higgs
ADDITIONAL HIGGS BOSONS

Main part of the lecture - will go through different extended Higgs sectors and discuss how we look for them
Extended Higgs sectors - 1-slide reminder

_Slightly simplified view_

**Additional singlets, doublets, triplets, …, and combinations** of them in addition to SM doublet

<table>
<thead>
<tr>
<th>Singlet</th>
<th>Doublet</th>
<th>Triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional scalar $H$ (or $h/a$)</td>
<td>Two additional scalars $A/H$ (*), Charged scalar $H^\pm$</td>
<td>Fermiophobic scalars $H_3$ and $H^{\pm}$, Doubly charged scalar $H^{\pm\pm}$</td>
</tr>
</tbody>
</table>

Generally **mixing with SM doublet**, modifying the $h_{125}$ couplings ➔ $h_{125}$ is SM-like so mixing must be small

\[
\sum_i \left( k_i \frac{h_i}{V} \right)^2 = 1
\]

(*) *we most often look at CP eigenstates, but there can also be models with CP admixtures (not covered)*
How to look for additional Higgs bosons

“Heavy” neutral scalars (<~ 100 GeV to ~ TeV):

Produced like $h_{125}$:

**gluon fusion**, vector boson fusion, or t- or b-associated

⇒ Need the LHC (or future high-energy collider) and multi-purpose experiment (currently ATLAS or CMS)

⇒ Cross sections typically smaller than $h_{125}$: Searches $\text{Lint-limited}$

![Diagram showing process of Higgs boson production](image)

![Diagram showing LHC setup](image)
How to look for additional Higgs bosons

“Heavy” neutral scalars (<~ 100 GeV to ~ TeV):

Produced like $h_{125}$:
- gluon fusion, vector boson fusion, or t- or b-associated
  ➭ Need the LHC (or future high-energy collider) and multi-purpose experiment (currently ATLAS or CMS)
  ➭ Cross sections typically smaller than $h_{125}$: Searches $L_{\text{int}}$-limited

Decays:
Either into SM like $h_{125}$ ($ZZ$, $WW$, $\gamma\gamma$; $\tau\tau$, $bb$, …) or heavier ($tt$)

Or into boson pairs $H \rightarrow h_{125}h_{125}/hh/h_{125}h/aa/ZA/…$
$A \rightarrow Zh_{125}/ZH/ha/…$

x 3
How to look for additional Higgs bosons

“Heavy” neutral scalars (<~ 100 GeV to ~ TeV):

Produced like $h_{125}$:
- gluon fusion, vector boson fusion, or $t$- or $b$-associated

➡ Need the LHC (or future high-energy collider) and multi-purpose experiment (currently ATLAS or CMS)

➡ Cross sections typically smaller than $h_{125}$: Searches L-integrated

Decays:
- Either into SM like $h_{125}$ ($ZZ$, $WW$, $gg; \tau\tau$, $bb$, …)
- Or into boson pairs $H \rightarrow h_{125}h_{125}/hh/h_{125}h/aa/Z/…$
- $A \rightarrow Zh_{125}/ZH/ha/…$

A plethora of interesting final states and searches, experimentally very rich!

Nowadays, most of the searches aren’t “simple” bump hunts anymore, but increase the sensitivity by using multiple event categories or multivariate classifiers (BDTs, DNNs)
Search for $H \rightarrow ZZ \rightarrow 4$ leptons

Kinematics of the 4 leptons and a possible jet

DNN classifier discriminates gluon fusion against SM ZZ production

“Bump hunt” with 4-lepton mass distribution

Search for $H \to ZZ$

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$

ATLAS-MVA-high

$H \to ZZ \to l^+l^-l^+l^- + l^+l^-\nu\bar{\nu}$

NWA, ggF production

95% CL limits on $\sigma_{ggF} \times B(H \to ZZ)$ [pb]

- Observed CL$_s$ limit
- Expected CL$_s$ limit
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

$\sigma_{ggF}$ 

$B(H \to ZZ)$ [pb]
Connecting it to the simplest extended Higgs model: Additional real scalar singlet

Three parameters:

• $m_H$

• **Mixing angle $\alpha$:**
  - $h_{125}$ couplings universally suppressed by $\cos(\alpha)$
  - $H$ couplings same as $h_{125}$ but scale with $\sin(\alpha)$

• **Ratio of v.e.v.s $\tan(\beta)$**
  - Only important for $m_H > 250$ GeV, where $H \rightarrow h_{125}h_{125}$ mode opens (subsensitive but reduces branching fractions to WW/ZZ, up to 30% effect on limits)

adapted from T.Robens PoS(LHCP2019)138
The MSSM Higgs sector: a 2HDM of type II

- A/H/H± couplings to down-type quarks & leptons scale ~ with tan β
- A/H/H± couplings to up-type quarks scale ~ with 1/tan β

Decoupling: $h_{125}$ naturally SM-like, $\cos(\beta - \alpha) \rightarrow 0$

<table>
<thead>
<tr>
<th>$m_A$ (GeV)</th>
<th>125</th>
<th>170</th>
<th>350</th>
</tr>
</thead>
</table>

**Yukawa sector**

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\phi_2}^\Phi$</th>
<th>$g_{\phi_1}^\Phi$</th>
<th>$g_{VV}^\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{SM}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$h$</td>
<td>$\cos \alpha / \sin \beta$</td>
<td>$- \sin \alpha / \cos \beta$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\sin \alpha / \sin \beta$</td>
<td>$\cos \alpha / \cos \beta$</td>
<td>$\cos(\beta - \alpha)$</td>
</tr>
<tr>
<td>$A$</td>
<td>$\pm 1 / \tan \beta$</td>
<td>$\tan \beta$</td>
<td>0</td>
</tr>
</tbody>
</table>

**2HDM (Two-Higgs-Doublet Model)**

<table>
<thead>
<tr>
<th>Model</th>
<th>$u_R$</th>
<th>$d_R$</th>
<th>$\ell_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>$\phi_2$</td>
<td>$\phi_2$</td>
<td>$\phi_2$</td>
</tr>
<tr>
<td>Type II</td>
<td>$\phi_2$</td>
<td>$\phi_1$</td>
<td>$\phi_1$</td>
</tr>
<tr>
<td>Lepton-specific</td>
<td>$\phi_2$</td>
<td>$\phi_2$</td>
<td>$\phi_1$</td>
</tr>
<tr>
<td>Flipped</td>
<td>$\phi_2$</td>
<td>$\phi_1$</td>
<td>$\phi_2$</td>
</tr>
</tbody>
</table>

**MSSM: Minimal Supersymmetric Standard Model**

- 2 free parameters at tree level: $m_A$, \(\tan \beta\)
Production

b-associated production, b-loop in gluon fusion

t loop dominates

\[ \tan \beta \]

125 170 350

\[ m_A \text{ (GeV)} \]
Most important decays

Decoupling: $h_{125}$ naturally SM-like, $\cos(\beta - \alpha) \to 0$,
implies $B(H \to VV, H \to h_{125}h_{125}) \to 0$

- $A/H \to \tau\tau$
  - $A/H \to b\bar{b}$: Higher branching fraction but more background $\to$ less sensitive than $A/H \to \tau\tau$

- $H \to h_{125}h_{125}$
- $A \to Zh_{125}$
- $H \to WW$
- $H^\pm \to t\bar{b}$
- $A/H \to \tau\tau$
- $A/H \to b\bar{b}$

$tan \beta$

$m_A$ (GeV)
**A/H \rightarrow \tau\tau:** Experimental approach

**\(\tau\) decays:**
65% hadrons + \(\nu\) (\(\tau_h\))
35% e/\(\mu\) + 2\(\nu\)

3 (4) interesting final states: \(\mu\tau_h\), e\(\tau_h\), \(\tau_h\tau_h\) (e\(\mu\))

**Challenges:**
\(\tau_h\) reconstruction/ID/trigger, \(p_T^{\text{miss}}\), related background

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**ATLAS**\(\sqrt{s} = 13\) TeV, 139 fb\(^{-1}\)
\(\tau_{\text{had}}\tau_{\text{had}}\) b-veto

**ATLAS**\(\sqrt{s} = 13\) TeV, 139 fb\(^{-1}\)
\(\tau_{\text{had}}\tau_{\text{had}}\) b-tag

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A/H \rightarrow \tau\tau: Experimental challenges

Multijet background:
Jets misidentified as $\tau_h$

Measure jet $\rightarrow \tau_h$ misID rate in data control region & apply in data sideband

Irreducible $Z/\gamma^* \rightarrow \tau\tau$ background:
Estimated from simulation (ATLAS) or from $\tau$ embedding (CMS): replacing reconstructed $\mu$ in data (typically from $Z/\gamma^* \rightarrow \mu\mu$) by simulated $\tau$

$m_{T^{tot}}$: Square sum of $m_T$ of three $\tau_h/\tau_h/p_T^{miss}$ combinations

Worse resolution for signal but shifts background to lower values
A/H\rightarrow\tau\tau: \text{Limits extend to 2 TeV at high tan } \beta

Observed limits a bit weaker than expected around 400-500 GeV

hMSSM
Assume m_h = 125 GeV and make a few simplifying assumptions
- only 2 free parameters
- low tan \beta open (at expense of high SUSY scale)

More benchmarks exist

**A/H → t¯t:**

**Tackling low tan β**

Beyond t¯t production threshold of around 350 GeV:
A/H decays nearly 100% to t¯t

Lineshape depends on coupling (~ 1/tan β)

**Interference leads to complicated lineshape**

A/H\rightarrow\ttbar

Three ttbar final states:
\begin{itemize}
  \item $\mu + p_{T\text{miss}} + \text{bbjj}$
  \item $e + p_{T\text{miss}} + \text{bbjj}$
  \item $\mu\mu/e\mu/ee + p_{T\text{miss}} + \text{bb}$
\end{itemize}

Reconstruct $m(\ttbar)$ using W mass constraint
Irreducible $t\bar{t}$ background from simulation: Requires very careful evaluation of all experimental & theoretical/modelling uncertainties

Need to be able to resolve < 1% level deviations in lineshape
Systematic uncertainties do luckily not give rise to shapes like the ones we expect for signal: not systematically limited

CMS JHEP 04 (2020) 171
A/H\rightarrow\ttbar

Sensitivity at low $\tan\beta$ beyond 400 GeV
$H^\pm \rightarrow tb$

ttbb$\rightarrow \mu/e + p_T^{miss} + 4b + 2j$ final state (lepton + jets)
Categorise in n(jets) and n(b-tagged jets)

Reach extends to higher $m_{H^\pm} \sim m_A$
MSSM Summary

Complementarity between direct searches and $h_{125}$ coupling measurements

code on github

A brief note on MSSM with other mass hierarchy

Heavier of the two neutral scalars takes role of $h_{125}$:

Mostly excluded, important role of $H^\pm \to \tau \nu$ searches in top quark decays

*Large $H^\pm \to W^\pm h$ branching fraction in (small) allowed phase space, with $h \to \tau \tau$ or $h \to b \bar{b}$*
General 2HDMs

Compared to MSSM:

- Alignment not natural - but $h_{125}$ couplings imply small $|\cos(\beta-\alpha)|$
  (still slightly higher $H\to WW/ZZ/h_{125}h_{125}$ and $A\to Zh_{125}$ rates possible)

- A priori no mass degeneracy (*): $A\to ZH/ H\to ZA$ can be possible and are not suppressed by alignment

Type I: Decoupled at high $\tan\beta$

Flipped: high $\tan\beta$ probed by $A/H\to bb$

Lepton-specific: difficult to probe at high $\tan\beta$

(*) but EWK precision constraints imply that 2 out of 3 additional Higgs bosons are close in mass
**H→ZA/A→ZH**

**H→ZA** unsuppressed in alignment limit

dominates over wide tanβ range
(very high tanβ covered by ττ)

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**Type-II 2HDM**

- ZA
- bb
- hh
- WW
- ZZ
- ττ
- ττ
- γγ
- gg

**BR(H→XX)**

- m_H = 300 GeV, m_A = 200 GeV, tanβ = 1.5
- m_H = 300 GeV, m_A = 200 GeV, cos(β - α) = 0.01

- Conventional
- Twisted

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**m [GeV]**

<table>
<thead>
<tr>
<th>A,H⁺</th>
<th>A,H⁺</th>
<th>H,H⁺</th>
<th>H,H⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>h</td>
<td>h</td>
<td>h</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

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**BR(A→XX)**

- cos(β - α) from -1.0 to 1.0

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**BR(A→XX)**

- tanβ from 10^-3 to 10^1
H→ZA/A→ZH: Z→ll, A/H→b¯b

m(ll) required to be compatible with nominal Z boson mass

\[ m_H = 500 \text{ GeV} \]
\[ m_A = 300 \text{ GeV} \]
H→ZA/A→ZH: Z→ll, A/H→b¯b

data from CMS/μμ + ee

35.9 fb⁻¹ (13 TeV)

ΔM < mZ

tt̄ background estimated from eμ events

decays to tt̄ become important

CMS JHEP 03 (2020) 055
2HDM+S/NMSSM

Compared to 2HDM/MSSM:
Two additional singlet-like scalars, which can be light

Signatures:
• Lower-mass $a/h \rightarrow \text{SM}$ searches
• Higgs-to-Higgs decays - have received a lot of attention lately since they lead to many interesting signatures
  $\rightarrow h_{125} \rightarrow aa/hh$
  $\rightarrow H \rightarrow h_{125} h, A \rightarrow h_{125} a$
  $\rightarrow H \rightarrow hh, A \rightarrow Zh, h_{125} \rightarrow Za, …$

Aside: Higgs-to-Higgs signatures can appear in models as simple as two additional singlets, and additional decays like $h_{125} \rightarrow H h$ might be interesting
There can also be cascade decays with 3 or 4 Higgs bosons in the final state  Robens, Stefaniak, Wittbrodt
A search for $H \rightarrow \gamma\gamma$ with $70 < m_H < 110$ GeV

Fit $m(\gamma\gamma)$ spectrum in three categories defined by BDT that separates photon pairs from Higgs decays from those from the continuum

*Excess has spurred some interest in theory community, though accounting for look-elsewhere-effect leads to significance of only $1.5\sigma$*
h_{125} \rightarrow aa

**Summary**

Excellent reach for h_{125} \rightarrow 4\mu analyses

Higher masses will become more interesting with more data

Experimentally very interesting/diverse

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2HDM+S type II, tan \beta = 2

- h_{125} \rightarrow undetected (CMS)
- h_{125} \rightarrow aa \rightarrow \mu\mu\mu\mu (ATLAS)
- h_{125} \rightarrow aa \rightarrow \mu\mu\mu (CMS)
- h_{125} \rightarrow aa \rightarrow bb\tau\tau (CMS)
- h_{125} \rightarrow aa \rightarrow \mu\mu bb (ATLAS)
- h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau (CMS)
- h_{125} \rightarrow aa \rightarrow \tau\tau\tau (CMS)
**h_{125} \rightarrow aa**

**Summary**

Excellent reach for $h_{125} \rightarrow 4\mu$ analyses

Higher masses will become more interesting with more data

Experimentally very interesting/diverse

**boosted regime:**
- $a$ boson decay products nearby, requiring dedicated isolation or reconstruction criteria

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**standard resolved analyses**

- $h_{125} \rightarrow aa \rightarrow \mu\mu\mu\mu$ (ATLAS)
- $h_{125} \rightarrow aa \rightarrow b\bar{b}tt$ (CMS)
- $h_{125} \rightarrow aa \rightarrow \mu\mu bb$ (ATLAS)
- $h_{125} \rightarrow aa \rightarrow \mu\mu tt$ (ATLAS)
- $h_{125} \rightarrow aa \rightarrow \tau\tau\tau$ (CMS)

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First H→h_{125}h result (ττbb)

Separate DNNs trained for several sets of nearby mass hypotheses

Many pairs of mass hypotheses to consider

CMS 2106.10361
First $H \rightarrow h_{125}h$ result ($\tau\tau bb$)

Separate DNNs trained for several sets of nearby mass hypotheses

CMS 2106.10361
Higgs triplet: striking signatures

Vector boson fusion production: 2 forward jets + $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$: either same-sign leptons
$H^{\pm} \rightarrow WZ$: or a three-lepton final state

Signal extracted from 2D fit to $(m_{jj}, m_T)$ + control regions

CMS HIG-20-017 (acc. by EPJC)
Higgs triplet: Constraint on Georgi-Machacek model

$s_H$: sets fraction of gauge boson mass generated by the triplet Higgs fields

$H_5$: Mass of (degenerate) additional fermiophobic heavy Higgs bosons ($H, H^\pm, H^{\mp}$)

Comparably high mass reach

CMS HIG-20-017 (acc. by EPJC)
EXOTIC DECAYS

A vast field!
Will briefly discuss a few interesting signatures if time allows (also already covered by Marumi)

(Lepton-) flavour violation (LFV): Very active field in light of LHCb anomalies - connection to Higgs sector would be very exciting!

Invisible decays: Higgs as portal to dark matter - one of the big questions of (particle?) physics

There are also many well-motivated searches for $h_{125} \to$ long-lived, semi-invisible, mesonic final states, and others (axion-like particles, dark photons, …)
LFV decays

$h_{125}\rightarrow e\mu$
Fit to $m(e\mu)$ in 8 categories

$h_{125}\rightarrow \mu\tau$
Fit to BDT discr. in 4 categories x 2 final states ($\mu\tau_h, \mu e$)

$h_{125}\rightarrow e\tau$
Fit to BDT discr. in 4 categories x 2 final states ($e\tau_h, e\mu$)
LFV decays - constraints

Limits set on off-diagonal Yukawa coupling terms
Higgs as flavour-changing neutral current

Fit to $m(\gamma\gamma)$ distribution in 14 BDT categories

CMS Preliminary

$137 \text{ fb}^{-1} (13 \text{ TeV})$

- All Categories
- S/(S+B) weighted
- Data
- S+B model (exp.)
- B component
- $\pm 1 \sigma$
- $\pm 2 \sigma$

$H \rightarrow \gamma\gamma$
$m_H = 125.38 \text{ GeV}$
$BF(t \rightarrow H\text{c}) = 0.051\%$

$B(t \rightarrow Hu) < 1.9 \times 10^{-4}$
$B(t \rightarrow H\text{c}) < 7.3 \times 10^{-4}$
h_{125} \rightarrow \text{invisible}

Experimentally challenging: Insufficient discrimination with $p_T^{\text{miss}}$ alone

**Best sensitivity with vector boson fusion production:**

- Distinct tag
- Reasonably high cross section
  (but other channels studied as well)

Rely on $p_T^{\text{miss}}$ trigger
h_{125}\rightarrow\text{invisible}

Involved background estimation with multiple control regions

\[ \text{B}(h_{125}\rightarrow\text{inv}) < 0.13 \text{ (0.13 exp.)} \]
h_{125} \rightarrow \text{invisible}

VBF channel main contributor to current best limits

*May crack the 10% barrier soon*

**Combined:**
\[ B(h_{125} \rightarrow \text{inv}) < 0.11 \ (0.11 \ 	ext{exp.}) \]
$h_{125}\rightarrow$invisible

VBF channel main contributor to current best limits

May crack the 10% barrier soon

Combined:
$B(h_{125}\rightarrow\text{inv}) < 0.11$ (0.11 exp.)

Provides sensitivity to dark matter candidates with mass up to $\sim60$ GeV

ATLAS Preliminary
\[ \sqrt{s} = 7\text{ TeV}, 4.7\text{ fb}^{-1} \]
\[ \sqrt{s} = 8\text{ TeV}, 20.3\text{ fb}^{-1} \]
\[ \sqrt{s} = 13\text{ TeV}, 139\text{ fb}^{-1} \]
Summary

This lecture covered

- **Searches for additional Higgs bosons**, motivated by extended scalar sectors
- **Exotic Higgs boson decays**, in particular lepton-flavour violating decays and decays to invisible

Various other BSM Higgs possibilities, e.g. CP violation, decays to BSM/long-lived

**A very active field of research:**
- Well more than 5% of ATLAS and CMS publications
- Searches limited by integrated luminosity - essential for HL-LHC programme and future colliders
- A few interesting hints: a great time to be or get involved!

Experimental results and related information:
- ATLAS results [HDBS](#) [Higgs](#)
- CMS results [HIG](#)
- LHCb results [Exotica](#)
- LHC Higgs WG 3: [LHCHWG3](#)