Introduction

Additional electroweak singlet

\[ H \rightarrow ZZ \rightarrow 4l \]

Two Higgs doublet Model (2HDM)

\[ \phi \rightarrow \mu \mu \]
\[ A \rightarrow Zh \rightarrow llb \bar{b} \]
\[ H \rightarrow ZZ \rightarrow 4l \]

Indirect search

Summary
In the Standard model:

- Higgs sector is minimal
- Include only one complex doublet: one CP-even Higgs boson

2012: Discovery of a Higgs-like boson with $m_A = 125.5$ GeV and $J^P = 0^+$

Combined coupling fits of the measured production and decay rates: no significant deviation from SM
Important question: Higgs sector minimal or extended, as predict in many beyond-SM theories

Upgrade of LHC: better study of the higgs sector and search for new physics

- 2011/12: 25 fb$^{-1}$ at $\sqrt{s} = 7$-8 TeV
- till 2022: 300 fb$^{-1}$ at $\sqrt{s} = 13$-14 TeV
- till 2030: 3000 fb$^{-1}$

Current studies:
- What can be done with this Data?
- Which new physics can be observed?
Introduction

Indirect search:

- Measuring the signal strength in different channels
- Combined coupling fits: determine couplings of higgs to fermions and vector bosons
- Search for deviation from SM

Channels:

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow Z\gamma$, $Z \rightarrow ll$
- $H \rightarrow WW^* \rightarrow l\nu l\nu$
- $H \rightarrow \tau^+\tau^-$
- $H \rightarrow \mu\mu$

Direct search:

- Search for new particles in different decay channels:
  - $H, A \rightarrow \mu\mu$
  - $A \rightarrow Zh \rightarrow llb\bar{b}$
  - $H \rightarrow ZZ \rightarrow 4l$
Additional electroweak singlet

- Simplest extension of the SM Higgs sector: Addition of an electroweak singlet
- Both: Non-zero vacuum expectation values
- Spontaneous symmetry breaking $\Rightarrow$ two CP-even Higgs bosons: $h, H$
  - Non-degenerate
  - Coupling to fermions and vector bosons similar to the SM Higgs boson
  - Strength reduced by a scale factor: $\kappa_h, \kappa_H$, with $\kappa_h^2 + \kappa_H^2 = 1$
- For the lighter Higgs boson $h$ (identical decay modes SM Higgs):

\[
\begin{align*}
\sigma_h &= \kappa_h^2 \cdot \sigma_{h,SM}, \\
\Gamma_h &= \kappa_h^2 \cdot \Gamma_{h,SM}, \\
\text{BR}_{h,i} &= \text{BR}_{SM,i}
\end{align*}
\]
**Additional electroweak singlet**

- For $H$: new decay modes possible ($H \to hh$):

\[ \sigma_H = \kappa_H^2 \cdot \sigma_{H,SM}, \quad \Gamma_H = \frac{\kappa_H^2}{1 - BR_{H,\text{new}}} \cdot \Gamma_{H,SM}, \quad \text{BR}_{H,i} = (1 - BR_{H,\text{new}}) \cdot BR_{H,SM,i} \]

- Indirect searches for deviations in the fit of the Higgs boson couplings

- Expected 95 % CL upper limit on $\kappa_H$ at $\sqrt{s} = 14$ TeV:

<table>
<thead>
<tr>
<th>Coupling $\kappa_H$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All unc.</td>
<td>0.35</td>
<td>0.31</td>
</tr>
<tr>
<td>No theory unc.</td>
<td>0.31</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Selection:

- Electron $p_T > 10 \text{ GeV}$ and muon $p_T > 5 \text{ GeV}$, $|\eta| < 2.5$
- Lepton isolation
- Ensure trigger efficiency: Leading lepton with $p_T > 30 \text{ GeV}$ or leading with $p_T > 20 \text{ GeV}$ and sub-leading with $p_T > 10 \text{ GeV}$

$Z$ candidates:

- Same flavor, opposite sign
- $60 < m_{ll} < 100 \text{GeV}$
- Require two candidates
- One with $80 < m_{ll} < 100 \text{GeV}$

One $H \to ZZ$ candidate with $m_{ZZ} > 150 \text{GeV}$
Contents
Introduction  Additional electroweak singlet  Two Higgs doublet Model (2HDM)  Summary

CMS PAS FTR-13-024

$H \rightarrow ZZ \rightarrow 4l$ (CMS)

Configuration 3 with $<N_{PU}> = 140$

Background: B, Bj, Bjj-vbf, BB, BBB
tj, tt, tB, ttB

Verena Walbrecht | Prospects for Higgs boson physics beyond the Standard Model at the Large Hadron Collider (LHC)
The 2HDM

SM Higgs sector is extended by an additional doublet

Vacuum expectation values: $v_1 = \langle \phi_1 \rangle$ and $v_2 = \langle \phi_2 \rangle$:

$v_1^2 + v_2^2 = v^2 = (246 \text{ GeV})^2$

Predict five Higgs bosons: two neutral CP-even bosons $h$ and $H$

two charges bosons $H^\pm$ and one CP-odd boson $A$

Parameters (no CP violation):

- $m_h$, $m_H$, $m_A$ and $m_{H^\pm}$
- $\tan \beta = v_2 / v_1$
- mixing angle $\alpha$ of the two neutral CP-even Higgs states
- Scalar coupling: $\lambda_5$, $\lambda_6$ und $\lambda_7$

(Minimal Supersymmetric Standard Model (MSSM) $\lambda_5 = \lambda_6 = \lambda_7 = 0$)
The 2HDM - Types

ATL-PHYS-PUB-2013-015

- Couplings to the light Higgs boson $h$:

<table>
<thead>
<tr>
<th>Coupling strength</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_V$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$\kappa_u$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
</tr>
<tr>
<td>$\kappa_d$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
</tr>
<tr>
<td>$\kappa_l$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$-\cos(\alpha)/\sin(\beta)$</td>
</tr>
<tr>
<td>Type</td>
<td>Name</td>
<td>Doublet $\phi_1$</td>
<td>Doublet $\phi_2$</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------------</td>
<td>------------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>fermiophobic</td>
<td></td>
<td>$u\ d\ l$</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>MSSM-like</td>
<td>$d\ l$</td>
<td>$u$</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>lepton-specific</td>
<td>$l$</td>
<td>$u\ d$</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>flipped</td>
<td>$d$</td>
<td>$u\ l$</td>
<td></td>
</tr>
</tbody>
</table>
Higgs bosons \((A, H)\) produced by gluon fusion and/or association with b-quark pair

Selection: Event contains exactly two muons (opposite charge)

Two categories:

- \(b\)-tag: At least one \(b\)-tagged jet
- \(b\)-veto: No \(b\)-tagged jet

Background:

- \(Z/\gamma^* + \text{jets}\)
- \(Z/\gamma^* + bb\)
- \(t\bar{t}\)
Di-muon invariant mass distribution:
• Expected significance:
Selection:

- Electrons: $E_T > 25$ GeV and $|\eta| < 2.57$ (without $1.37 < |\eta| < 1.52$)
- Muons: $p_T > 25$ GeV and $|\eta| < 2.5$
- At least two with same flavor and opposite sign ($80 < m_{ll} < 100$ GeV)
- At least 2 b-jets ($90 < m_{bb} < 140$ GeV)
- $1.4 - 0.001m_A < \Delta R(bb) < 1.8 - 0.001m_A$

Clean signature and fully reconstructible $m_A$

$$m_A^{rec} = m_{llbb} - m_{ll} - m_{bb} + m_Z^0 + m_h^0$$
Background: \( \bar{t}t \)
\( Z + \text{jets} \)
\( Zbb \)
\( ZZ \)
Limits on the 2HDM parameter space:
This decay channel also possible in the 2HDM

Limits on the 2HDM parameter space:
Indirect measurement possible by setting constrains on the parameter:
Discovery of the Higgs boson in 2012

Question: Higgs sector minimal?

New physics is observable in direct and indirect measurements

Studies of expected limits on an additional electroweak singlet and electroweak doublet has been done

New data at 13-14 TeV allow for the exploration of a wide range of Higgs sectors beyond the Standard Model, both via direct searches for new Higgs bosons and indirectly via fit of the Higgs boson couplings to the measured data
Expected upper limits ($200 < m_H < 1000$ GeV):

<table>
<thead>
<tr>
<th>Production Mode</th>
<th>Expected Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>$0.01 - 0.1$ fb</td>
</tr>
<tr>
<td>$VBF$</td>
<td>$0.008 - 0.04$ fb</td>
</tr>
</tbody>
</table>
Same selections for Leptons as for $H \rightarrow ZZ$

- One $Z$ candidate (opposite sign and same flavor lepton pair with $60 < m_{ll} < 100$ GeV)

Selections for jets:

- $p_T > 10$ GeV and $|\eta| > 2.5$
- One $h$ candidate with $90 < m_{bb} < 150$ GeV

- $|\Delta \phi(l_1 l_2)| < 1.9$ rad
- $p_T(Z) > 40$ GeV
- $0.4 < p_T(Z)/p_T(h) < 2.75$
**CMS PAS FTR-13-024**

**Configuration 3 with \(<N_{pu}> = 140\)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sel. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, Bj, Bjj-vbf, BB, BBB</td>
<td>5.8 (\cdot) 10^4</td>
</tr>
<tr>
<td>tj, tt, tB, ttB</td>
<td>6.6 (\cdot) 10^4</td>
</tr>
<tr>
<td>h</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Total Background</td>
<td>1.2 (\cdot) 10^5</td>
</tr>
</tbody>
</table>

**Source**  
**Sel. events**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sel. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow Zh) ((m_A = 300\text{GeV}))</td>
<td>1.2 (\cdot) 10^4</td>
</tr>
<tr>
<td>(H \rightarrow Zh) ((m_A = 500\text{GeV}))</td>
<td>210</td>
</tr>
<tr>
<td>(H \rightarrow Zh) ((m_A = 800\text{GeV}))</td>
<td>85</td>
</tr>
</tbody>
</table>

**Verena Walbrecht | Prospects for Higgs boson physics beyond the Standard Model at the Large Hadron Collider (LHC)**
• Limits on the 2HDM parameter space:
$A \rightarrow Zh \rightarrow llb\bar{b}$ (ATLAS)

ATLAS-PHYS-PUB-2013-016
$A \rightarrow Zh \rightarrow llb\bar{b}$ (ATLAS)

ATLAS-PHYS-PUB-2013-016
$A \rightarrow Zh \rightarrow llb\bar{b}$ (ATLAS)

ATLAS-PHYS-PUB-2013-016
$A \rightarrow Zh \rightarrow llb\bar{b}$ (ATLAS)

ATLAS-PHYS-PUB-2013-016
Electroweak (EW) theory is non-abelian → self-interaction of gauge bosons

Scattering of vector bosons: Triple and quartic boson couplings (TGC and QGC)

Each of these processes violates unitarity at high energies

In Standard Model (SM): Higgs maintain unitarity → probe SM nature of EWSB

Scattering topology: Sensitive to new physics in EWSB sector (anomalous QGC)

Addition to the scattering process → change the cross section
- In $pp$-collisions: VBS in $pp \rightarrow VVjj$

- Experimental signature: two jets with large pseudorapidity difference plus leptons (from W and Z decays)

- SM Lagrangian: dimension-4 operators

- New physics: higher dimension operators in an effective field theory

- Multi-boson production: dimension-6 and dimension-8 operators (contain Higgs and/or gauge boson fields)

- New physics which is $SU(2)_L \times U(1)_Y$ gauge invariant and CP-even operators
Small cross section

Final state: Fully reconstructible

Operator (6-dimensional):

\[ \mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \text{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger \phi \]

where \( \Lambda \): mass-dimensional parameter

Selection:

- 4 Leptons with \( p_T > 25 \text{ GeV} \), two with opposite sign
- 1 Lepton over detector threshold
- 2 jets with \( p_T > 50 \text{ GeV} \)
- \( m_{jj} > 1 \text{ TeV} \)
- $5\sigma$ discovery potential:

$$\frac{c_{\phi W}/\Lambda^2}{300 \text{ fb}^{-1}} = \frac{34 \text{ TeV}^{-2}}{3000 \text{ fb}^{-1}} = \frac{16 \text{ TeV}^{-2}}{16 \text{ TeV}^{-2}}$$

**ATLAS** Simulation Preliminary

$L = 3000 \text{ fb}^{-1}$

- VBS ZZ (SM)
- SM VBS ZZ + $C_{\phi W} = 15/\text{TeV}^2$
- SM ZZ QCD

**Significance [c]**

- $3000 \text{ fb}^{-1}$
- $300 \text{ fb}^{-1}$

**ZZjj $\rightarrow lllljj$ (ATLAS)**

- **ATLAS-PHYS-PUP-2013-006**
Larger cross section

Final state: Reconstruction with neutrino $p_z$

Operator (8-dimensional):

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$$

Selection:

- 3 Leptons with $p_T > 25\text{ GeV}$: opposite sign, same flavor pair + additional single lepton
- 1 Lepton over detector threshold
- 2 jets with $p_T > 50\text{ GeV}$
- $m_{jj} > 1\text{ TeV}$
\( WZjj \rightarrow l\nu lljj \) (ATLAS)

**5σ discovery potential:**

\[
\frac{f_{T_1}/\Lambda^4}{1.3 \text{ TeV}^{-4}} \quad \frac{300 \text{ fb}^{-1}}{3000 \text{ fb}^{-1}} \quad \frac{0.6 \text{ TeV}^{-4}}{3.6 \text{ TeV}^{-4}}
\]
Calculated cross sections [fb] (14 TeV \( pp \)-collision):

<table>
<thead>
<tr>
<th></th>
<th>WZ EWK</th>
<th>WZ QCD</th>
<th>ZZ</th>
<th>( L_{T_1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>7.7</td>
<td>210</td>
<td>16</td>
<td>3.1</td>
</tr>
<tr>
<td>Fiducial</td>
<td>0.69</td>
<td>0.96</td>
<td>0.038</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Selection:

- 3 Electrons/muons with \( p_T >20 \text{ GeV} \) and \( |\eta| < 2.4 \):
  - same flavor pair and opposite charge
  - one Z candidate with \( m_\ell > 20 \text{ GeV} \)
  - no additional lepton with \( p_T >10 \text{ GeV} \)
- 2 jets with \( p_T >50 \text{ GeV} \) and \( |\eta| < 4.7 \)
  - \( \Delta \eta_{jj} > 4.0 \)
  - \( m_{jj} >600 \text{ GeV} \)
- no overlap: \( \Delta R(ll') > 0.04 \) and \( \Delta R(lj') > 0.4 \)
Anomalous coupling signal for $f_{t_1}/\Lambda^4 = 1.0 \text{ TeV}^{-4}$

Expected sensitivity to aGQC:

<table>
<thead>
<tr>
<th></th>
<th>$3\sigma$</th>
<th>$5\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T1}/\Lambda^4$ at 300 fb$^{-1}$</td>
<td>$0.8 \text{ TeV}^{-4}$</td>
<td>$1.0 \text{ TeV}^{-4}$</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$ at 3000 fb$^{-1}$</td>
<td>$0.45 \text{ TeV}^{-4}$</td>
<td>$0.55 \text{ TeV}^{-4}$</td>
</tr>
</tbody>
</table>
$W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$ (ATLAS)

Operator (8-dimensional):

$$\mathcal{L}_{T,0} = \frac{f_{S0}}{\Lambda^4} \left( (D_\mu \phi)^\dagger D_\nu \phi \right) \times \left[ (D^{\mu} \phi)^\dagger D^{n} \nu \phi \right]$$

Selection:

- 2 Leptons with $p_T > 25$ GeV: same charge
- 1 Lepton over detector threshold
- 2 jets with $p_T > 50$ GeV
- $m_{jj} > 1$ TeV
$W^\pm W^\pm jj \rightarrow l^\pm \nu l'^\pm \nu jj$ (ATLAS)

$\int L = 3000 \text{ fb}^{-1}$

$5\sigma$ discovery potential:

\[
\begin{array}{c|c|c}
\frac{f_{S_0}}{\Lambda^4} & 300 \text{ fb}^{-1} & 3000 \text{ fb}^{-1} \\
10 \text{ TeV}^{-4} & 4.5 \text{ TeV}^{-4} \\
\end{array}
\]
Sensitive to BSM triboson contributions

Operators (8-dimensional):

\[ \mathcal{L}_{T,8} = \frac{f_{T,8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \]

\[ \mathcal{L}_{T,9} = \frac{f_{T,9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} \]

Selection:

- Lepton and $\gamma$: $p_T > 25$ GeV, $|\eta| < 2.0$
- At least one lepton and $\gamma$: $p_T > 160$ GeV
- $|m_{ll} - 91 \text{GeV}| < 10$ GeV
- $\Delta(\gamma, \gamma) > 0.4$; $\Delta(l, \gamma) > 0.4$; $\Delta(l, l) > 0.4$;
Zγγ in dilepton plus diphoton channel (ATLAS)

ATLAS-PHYS-PUP-2013-006

- 5σ discovery potential:

<table>
<thead>
<tr>
<th>$f_T$/$\Lambda^4$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T8}/\Lambda^4$</td>
<td>0.9 TeV$^{-4}$</td>
<td>0.4 TeV$^{-4}$</td>
</tr>
<tr>
<td>$f_{T9}/\Lambda^4$</td>
<td>2.0 TeV$^{-4}$</td>
<td>0.7 TeV$^{-4}$</td>
</tr>
</tbody>
</table>