Prospects for light Higgs measurements at the 250 GeV ILC

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

The 2023 International Workshop on Future Linear Colliders (LCWS2023)

Track 1: Physics at e^+e^- colliders
May 18, 2023
Prospects for light Higgs measurements...

Outline

1. Motivation
2. Analysis setup
3. Tau reconstruction
4. First results
5. Tau tagging
6. Conclusions

All presented results are preliminary
Motivation
Motivation

Experimental hints... arXiv:2203.13180

Mounting evidence for a 95 GeV Higgs boson

T. Biekötter*, S. Heinemeyer† and G. Weiglein‡

1Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
2Instituto de Física Teórica UAM-CSIC, Cantoblanco, 28049, Madrid, Spain
3II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Abstract

In 2018 CMS reported an excess in the light Higgs-boson search in the diphoton decay mode at about 95 GeV based on Run 1 and first year Run 2 data. The combined local significance of the excess was $2.8\sigma$. The excess is compatible with the limits obtained in the ATLAS searches from the diphoton search channel. Recently, CMS reported another local excess with a significance of $3.1\sigma$ in the light Higgs-boson search in the di-tau final state, which is compatible with the interpretation of a Higgs boson with a mass of about 95 GeV. We show that the observed results can be interpreted as manifestations of a Higgs boson in the Two-Higgs Doublet Model with an additional real singlet (N2HDM). We find that the lightest Higgs boson of the N2HDM can fit both excesses simultaneously, while the second-lightest state is such that it satisfies the Higgs-boson measurements at 125 GeV, and the full Higgs-boson sector is compatible with all Higgs exclusion bounds from the searches at LEP, the Tevatron and the LHC as well as with other theoretical and experimental constraints.
N2HDM type IV: fitting all three excesses: [T. Biekötter, S.H., G. Weiglein '22]

\[ pp \rightarrow h_{95} \rightarrow \gamma\gamma \quad \text{gg} \rightarrow h_{95} \rightarrow \tau^+\tau^- \quad e^+e^- \rightarrow Zh_{95} \rightarrow Zb\bar{b} \]

gray lines: central values of excesses

\[ \Rightarrow \text{type IV can fit the } \gamma\gamma, \tau\tau \text{ and } bb \text{ excesses very well} \]
Motivation

**N2HDM model**  

Parameters of the best-fit point (minimal value of $\chi^2$) ⇒ **BP1**

<table>
<thead>
<tr>
<th>$m_{h_1}$</th>
<th>$m_{h_2}$</th>
<th>$m_{h_3}$</th>
<th>$m_A$</th>
<th>$m_{H^\pm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.68</td>
<td>125.09</td>
<td>713.24</td>
<td>811.20</td>
<td>677.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\tan \beta$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$m_{12}$</th>
<th>$v_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.26</td>
<td>1.57</td>
<td>1.22</td>
<td>1.49</td>
<td>221.12</td>
<td>1333</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{BR}_{h_1}^{bb}$</th>
<th>$\text{BR}_{h_1}^{gg}$</th>
<th>$\text{BR}_{h_1}^{cc}$</th>
<th>$\text{BR}_{h_1}^{\tau\tau}$</th>
<th>$\text{BR}_{h_1}^{\gamma\gamma}$</th>
<th>$\text{BR}_{h_1}^{WW}$</th>
<th>$\text{BR}_{h_1}^{ZZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.348</td>
<td>0.198</td>
<td>0.412</td>
<td>6.630 · $10^{-3}$</td>
<td>0.025</td>
<td>3.382 · $10^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{BR}_{h_2}^{bb}$</th>
<th>$\text{BR}_{h_2}^{gg}$</th>
<th>$\text{BR}_{h_2}^{cc}$</th>
<th>$\text{BR}_{h_2}^{\tau\tau}$</th>
<th>$\text{BR}_{h_2}^{\gamma\gamma}$</th>
<th>$\text{BR}_{h_2}^{WW}$</th>
<th>$\text{BR}_{h_2}^{ZZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.553</td>
<td>0.085</td>
<td>0.032</td>
<td>0.069</td>
<td>2.537 · $10^{-3}$</td>
<td>0.228</td>
<td>0.028</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{BR}_{h_3}^{tt}$</th>
<th>$\text{BR}_{h_3}^{bb}$</th>
<th>$\text{BR}_{h_3}^{\tau\tau}$</th>
<th>$\text{BR}_{h_3}^{h_1h_1}$</th>
<th>$\text{BR}_{h_3}^{h_1h_2}$</th>
<th>$\text{BR}_{h_3}^{h_2h_2}$</th>
<th>$\text{BR}_{h_3}^{WW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.123</td>
<td>0.739</td>
<td>0.000</td>
<td>0.002</td>
<td>0.072</td>
<td>0.030</td>
<td>0.022</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{BR}_{A}^{tt}$</th>
<th>$\text{BR}_{A}^{bb}$</th>
<th>$\text{BR}_{A}^{\tau\tau}$</th>
<th>$\text{BR}_{A}^{Zh_1}$</th>
<th>$\text{BR}_{A}^{Zh_2}$</th>
<th>$\text{BR}_{A}^{Zh_3}$</th>
<th>$\text{BR}_{A}^{WH^\pm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.053</td>
<td>0.173</td>
<td>0.000</td>
<td>0.024</td>
<td>0.001</td>
<td>0.015</td>
<td>0.734</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{BR}_{H^\pm}^{bb}$</th>
<th>$\text{BR}_{H^\pm}^{\tau\tau}$</th>
<th>$\text{BR}_{H^\pm}^{Vh_1}$</th>
<th>$\text{BR}_{H^\pm}^{Vh_2}$</th>
<th>$\text{BR}_{H^\pm}^{Vh_3}$</th>
<th>$\text{BR}_{H^\pm}^{WH^\pm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.922</td>
<td>0.000</td>
<td>0.073</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Parameters of the best-fit point for which the minimal value of $\chi^2$ is found ($\chi^2 = 88.07$, $\chi^2_{125} = 86.24$) and branching ratios of the scalar particles in the type IV scenario. Dimensionful parameters are given in GeV, and the angles are given in radian.

Interesting pattern for light Higgs: no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...
Analysis setup
Signal model  

many thanks to Thomas Biektor	

UFO file for Singlet-extended Two Higgs doublet model (S2HDM)


Difference with N2HDM: complex instead of a real singlet field.
Equivalent to N2HDM, when the additional dark-matter candidate heavy.

Modified by Thomas Biektor for type IV couplings.

BP1

\( h_1 \) production cross section at 250 GeV: \( \sim 11\% \) of the SM cross section for \( m_{h_{SM}} = 95.68 \) GeV

Scalar branching ratios from arXiv:2203.13180 used.

Problem with UFO interface in Whizard \( \Rightarrow \) fixed in 3.1.1 release!
Event samples

Generated using Whizard 3.1.1

Signal sample: with S2HDM UFO model

Four-fermion background samples: built-in SM_CKM model
  with restriction set to remove SM Higgs boson contribution
  SM-like $h_2$ contribution included using S2HDM UFO model

Consider ILC running at 250 GeV with \(-80\%/ + 30\%\) beam polarisation
  Integrated luminosity of $900 \text{ fb}^{-1}$

Fast detector simulation with Delphes ILCgen model
Tau reconstruction
Collinear approximation 

Used in the study of Higgs boson decaying into tau pairs at the ILC:

\[ e^+ e^- \rightarrow q\bar{q} h, \sqrt{s} = 250\text{GeV}, \mathcal{L} = 250\text{fb}^{-1}, P(e^-, e^+) = (-80\%, +30\%) \]
Collinear approximation

Example signal events, with hadronic tau decays (four jets).
**Collinear approximation**

Example signal events, with hadronic tau decays (four jets).
Collinear approximation

Example signal events, with hadronic tau decays (four jets).

Tau leptons are very boosted.

Assume neutrinos from tau decays emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

\[ \vec{p}_T = E_{\nu_1} \cdot \vec{n}_1 + E_{\nu_2} \cdot \vec{n}_2 \]

where \( \vec{n}_1 \) and \( \vec{n}_2 \) are directions of the two tau-tagged jets (!).

Unique solution
Collinear approximation

Distribution of the raw and corrected mass of the tau candidate pair.

Hadronic tau decays (two jets with tau-tag)

5.0 GeV mass resolution
Collinear approximation

Distribution of the raw and corrected mass of the tau candidate pair.

Semi-leptonic tau decays (one lepton + one jet with tau-tag)

5.4 GeV mass resolution
Collinear approximation

Distribution of the raw and corrected mass of the tau candidate pair.

Leptonic tau decays (two isolated leptons)

6.1 GeV mass resolution
First results
Event kinematics

Signal in hadronic tau decay channel
no leptons, clustering into four jets, two jets with tau-tag

- apply simple window cuts on:
  - $Z$ (jj) and $h_1$ ($\tau\tau$) invariant masses
  - corrected $h_1$ mass and recoil mass

Right plot: after left plot box cut
Event kinematics

Background from $qq\tau\tau$ in hadronic tau decay channel
no leptons, clustering into four jets, two jets with tau-tag

Dominated by $e^+e^- \rightarrow ZZ$ contribution
distribution very similar to signal events...
First results

Event kinematics

Background from $qqqq$ in hadronic tau decay channel
no leptons, clustering into four jets, two jets with tau-tag

Dominated by $e^+e^- \rightarrow W^+W^-$ contribution
suppressed by tau-tag requirement...

Right plot: after left plot box cut
Event kinematics

Signal in semi-leptonic tau decay channel
one leptons, clustering into three jets, one jet with tau-tag

\[ m_{\tau\tau} \text{[GeV]} \]

\[ m_{jj} \text{[GeV]} \]

\[ m_{\text{corr}} \text{[GeV]} \]

\[ m_{\text{recoil}} \text{[GeV]} \]

⇒ apply simple window cuts on:

- \( Z \) (jj) and \( h_1 \) (\( \tau\tau \)) invariant masses
- corrected \( h_1 \) mass and recoil mass

Right plot: after left plot box cut
First results

Results from cut-based analysis  
900 fb^{-1} (−80% / + 30%)

Hadronic tau decay selection

<table>
<thead>
<tr>
<th>Sample</th>
<th>Events expected after Presel.</th>
<th>Z mass</th>
<th>$h_1 + \text{rec}$</th>
<th>Final eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1234.69</td>
<td>711.957</td>
<td>423.921</td>
<td>3.179</td>
</tr>
<tr>
<td>$qqqq$</td>
<td>38636</td>
<td>4980.42</td>
<td>603.688</td>
<td>0.004</td>
</tr>
<tr>
<td>$qql\nu$</td>
<td>4793.66</td>
<td>104.21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$qq\tau\nu$</td>
<td>98069.7</td>
<td>296.134</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$qqll$</td>
<td>929.392</td>
<td>29.5045</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$qq\tau\tau$</td>
<td>10283.6</td>
<td>4360.07</td>
<td>2107.54</td>
<td>1.41</td>
</tr>
<tr>
<td>$qq\nu\nu$</td>
<td>1426.37</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$h_2$</td>
<td>1889.55</td>
<td>486.201</td>
<td>22.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>156028</td>
<td>10256.5</td>
<td>2733.33</td>
<td></td>
</tr>
<tr>
<td>Significance</td>
<td></td>
<td></td>
<td></td>
<td>7.54</td>
</tr>
</tbody>
</table>
First results

Results from cut-based analysis

900 fb\(^{-1}\) \((-80\% / + 30\%)\)

Semi-leptonic final state selection

<table>
<thead>
<tr>
<th>Sample</th>
<th>Events expected after Presel.</th>
<th>Z mass</th>
<th>(h_1 + \text{rec})</th>
<th>Final eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1738.75</td>
<td>1168.28</td>
<td>702.356</td>
<td>5.267</td>
</tr>
<tr>
<td>(qqqq)</td>
<td>150.922</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(qq\nu)</td>
<td>491142</td>
<td>2917.88</td>
<td>208.42</td>
<td>0.002</td>
</tr>
<tr>
<td>(qq\tau\nu)</td>
<td>70134.4</td>
<td>444.201</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(qql)</td>
<td>17053.6</td>
<td>678.604</td>
<td>44.2568</td>
<td>0.003</td>
</tr>
<tr>
<td>(qq\tau\tau)</td>
<td>13011.5</td>
<td>7503.45</td>
<td>3219.61</td>
<td>2.154</td>
</tr>
<tr>
<td>(qq\nu\nu)</td>
<td>34.3705</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(h_2)</td>
<td>2552.55</td>
<td>895.052</td>
<td>22.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>594079</td>
<td>12439.2</td>
<td>3494.39</td>
<td></td>
</tr>
<tr>
<td>Significance</td>
<td></td>
<td></td>
<td>10.84</td>
<td></td>
</tr>
</tbody>
</table>
Tau tagging
**Tau tagging in Delphes**

Tau tagging efficiency and miss-tagging probabilities in ILCgen Delphes model taken from ILD full simulation studies.

July 2020 results (Daniel Jeans) based on TaJet Finder by Taikan Suehara

**Tagging efficiency**

**Miss-tagging probability**

\[ e^+ e^- \rightarrow W^+ W^- \rightarrow qql\nu \text{ events} \]
**New tau-tagging approach** in ILCgen detector model

Old tagging: miss-tagging probability depends on the jet energy only.
**New**: miss-tagging probability depends on the jet mass and energy

**Miss-tagging vs jet energy**

**Miss-tagging vs jet mass**

same dependence reproduced
globally new dependence!
New tau-tagging approach

Background from $qqll$ in semi-leptonic tau decay channel

This channel turned out to be most sensitive to tau tagging change.
Low mass jet from “lost” lepton has much higher probability to be tau-tagged...
**Results from cut-based selection**  
\[ 900 \text{ fb}^{-1} \ (−80\% / + 30\%) \]

After all selection cuts, tau tagging description has surprisingly little impact on the final analysis result.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Tau tagging</th>
<th>Events expected</th>
<th>Signal</th>
<th>Total bg.</th>
<th>Signal significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic</td>
<td>old</td>
<td>423.9</td>
<td>2733.3</td>
<td>7.544</td>
<td></td>
</tr>
<tr>
<td></td>
<td>new</td>
<td>435.0</td>
<td>3042.9</td>
<td>7.376</td>
<td></td>
</tr>
<tr>
<td>Semi-leptonic</td>
<td>old</td>
<td>702.4</td>
<td>3494.4</td>
<td>10.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>new</td>
<td>692.9</td>
<td>3475.1</td>
<td>10.73</td>
<td></td>
</tr>
<tr>
<td>Leptonic</td>
<td>old</td>
<td>260.0</td>
<td>1353.0</td>
<td>6.474</td>
<td></td>
</tr>
<tr>
<td></td>
<td>new</td>
<td>276.0</td>
<td>1376.4</td>
<td>6.791</td>
<td></td>
</tr>
</tbody>
</table>

Background dominated by \(qq\tau\tau\), which is affected by tagging changes in the same way as the signal.
BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can be combined with non-standard decay patterns...

Decays to tau pairs for scalars with mass close to $M_Z$ seem a challenging scenario and a good testing ground for our detector and analysis methods.
Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can be combined with non-standard decay patterns...

Decays to tau pairs for scalars with mass close to $M_Z$ seem a challenging scenario and a good testing ground for our detector and analysis methods

Fast simulation indicates that measurement with high significance possible.

The study will continue to get better understand of signal and background

Experimental sensitivity should significantly increase when more advanced analysis methods (MVA) are used
Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can be combined with non-standard decay patterns...

Decays to tau pairs for scalars with mass close to $M_Z$ seem a challenging scenario and a good testing ground for our detector and analysis methods.

Fast simulation indicates that measurement with high significance possible.

The study will continue to get better understand of signal and background

Experimental sensitivity should significantly increase when more advanced analysis methods (MVA) are used

Full simulation is a must to get reliable quantitative result.
Thank you!
N2HDM model

Production cross section for $h_1$ is about 11% of the SM cross section for this mass (for the considered best-fit point, BP1)
**Collinear approximation**

Distribution of the *neutrino energies* from transverse momentum balance.

**Hadronic tau decays (two jets with tau-tag)**

Negative values ignored in event reconstruction
Collinear approximation

Distribution of the raw and corrected energy of the event.

Hadronic tau decays (two jets with tau-tag)
Event kinematics

Background from $qq\tau\tau$ in semi-leptonic tau decay channel
one leptons, clustering into three jets, one jet with tau-tag

Dominated by $e^+e^- \rightarrow ZZ$ contribution
distribution very similar to signal events...
Event kinematics

Background from $qq\nu$ in semi-leptonic tau decay channel
one lepton, clustering into three jets, one jet with tau-tag

Dominated by $e^+e^- \rightarrow W^+W^-$ contribution
Two-jet final state clustered into three jets...
Event kinematics

Background from $qqll$ in semi-leptonic tau decay channel
one leptons, clustering into three jets, one jet with tau-tag

Dominated by $e^+e^- \rightarrow ZZ$ contribution
one lepton has to be “lost”...
New tau-tagging approach

Weak point of the current Delphes model:
miss-tagging probability depends on the jet energy only.

However, tau jets and quark jets are very different!

Tau jets

<table>
<thead>
<tr>
<th>$E_{\text{jet}}$ [GeV]</th>
<th>$M_{\text{jet}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

Quark jets

<table>
<thead>
<tr>
<th>$E_{\text{jet}}$ [GeV]</th>
<th>$M_{\text{jet}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>
New tau-tagging approach

Fraction of quark jets with mass above 2 GeV, 3 GeV, 4 GeV and 5 GeV, compared with miss-tagging probability (black).

⇒ implement miss-tagging as energy dependent mass cut