Production of heavy Higgs bosons and decay into top quarks at the LHC

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in collaboration with
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→ at least 1 type of scalar elementary particle exists in nature

Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet → 2HDM, SUSY

Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons

high mass and Yukawa coupling $\sim m_f$ → study resonance in the $t\bar{t}$ decay channel
Motivation

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- Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet → 2HDM, SUSY
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- high mass and Yukawa coupling $\sim m_f$ → study resonance in the $t\bar{t}$ decay channel
2-Higgs-Doublet Model (2HDM) in a nutshell

\[
\begin{align*}
\Phi_1 &= \left( \frac{1}{\sqrt{2}} (v_1 + \phi_1 + i \chi_1) \right), & \Phi_2 &= \left( \frac{1}{\sqrt{2}} (v_2 + \phi_2 + i \chi_2) \right) \\
\end{align*}
\]

\text{CP conserving case}

\begin{align*}
h &= -\phi_1 \sin \alpha + \phi_2 \cos \alpha \\
H &= \phi_1 \cos \alpha + \phi_2 \sin \alpha \\
A &= -\chi_1 \sin \beta + \chi_2 \cos \beta \\
H^+ &= -\xi_1^+ \sin \beta + \xi_2^+ \cos \beta
\end{align*}

\text{CP violating case}

\[
\begin{pmatrix}
\phi_1 \\
\phi_2 \\
\phi_3
\end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3)
\begin{pmatrix}
\phi_1 \\
\phi_2 \\
A
\end{pmatrix}
\]

\[
\tan \beta = \frac{v_2}{v_1}
\]

\text{top-Yukawa coupling: } L_{Yuk,t} = -\frac{m_t}{\sqrt{2}} \sum_j \bar{t} \left( a_{jt} t - i b_{jt} \gamma_5 \right) t \phi_j

\text{reduced Yukawa couplings } a_t, b_t \text{ depend on } \alpha \text{ or } \alpha_1, \alpha_2, \alpha_3 \text{ and } \beta

\text{use flavour conserving type-II 2HDM (}d_R, \ell_R \text{ couple to } \Phi_1, u_R \text{ couple to } \Phi_2\text{) because of strong exp. constraints on FCNC}

for details see, e.g.: [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, arXiv:1106.0034]
### 2HDM-Type-II Scenarios

#### CP-conserving scenario I and II study: \( \tan \beta = 0.7, \ \alpha = \beta - \frac{\pi}{2} \)

<table>
<thead>
<tr>
<th></th>
<th>( h )</th>
<th>( H )</th>
<th>( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_t )</td>
<td>1</td>
<td>1.43</td>
<td>0</td>
</tr>
<tr>
<td>( b_t )</td>
<td>0</td>
<td>0</td>
<td>1.43</td>
</tr>
<tr>
<td>( f_{VV} )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( m(I) ) [GeV]</td>
<td>125</td>
<td>550</td>
<td>510</td>
</tr>
<tr>
<td>( \Gamma(I) ) [GeV]</td>
<td>0.004</td>
<td>34.56</td>
<td>49.28</td>
</tr>
<tr>
<td>( m(II) ) [GeV]</td>
<td>125</td>
<td>550</td>
<td>700</td>
</tr>
<tr>
<td>( \Gamma(II) ) [GeV]</td>
<td>0.004</td>
<td>34.49</td>
<td>75.28</td>
</tr>
</tbody>
</table>

#### CP-violating scenario III study: \( \tan \beta = 0.7, \alpha_1 = \beta, \alpha_2 = \frac{\pi}{15}, \alpha_3 = \frac{\pi}{4} \)

<table>
<thead>
<tr>
<th></th>
<th>( \phi_1 )</th>
<th>( \phi_2 )</th>
<th>( \phi_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_t )</td>
<td>0.98</td>
<td>0.86</td>
<td>-1.16</td>
</tr>
<tr>
<td>( b_t )</td>
<td>0.30</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>( f_{VV} )</td>
<td>0.98</td>
<td>-0.15</td>
<td>-0.15</td>
</tr>
<tr>
<td>( m(III) ) [GeV]</td>
<td>125</td>
<td>500</td>
<td>800</td>
</tr>
<tr>
<td>( \Gamma(III) ) [GeV]</td>
<td>0.004</td>
<td>36.55</td>
<td>128.16</td>
</tr>
</tbody>
</table>

- \( h, \phi_1 \) SM-like (by construction, so-called “alignment limit”)
- \( H,A \)-Yukawa coupling to \( t \) quark \( a_t, b_t = \cot \beta = 1.43 \) \( \Rightarrow \) enhanced
- \( H,A \)-Yukawa coupling to \( b \) quark \( a_b, b_b = \tan \beta \) \( \Rightarrow \) suppressed \( \rightarrow \) save to neglect
- \( f_{VV} \): coupling to vector bosons
- \( m \): free parameter; \( \Gamma \) fixed by mass and couplings
- CPC-case I: mass degenerate; CPC-case II: mass non-degenerate
Leading Order

QCD contribution

\[ A_{\text{QCD}} = \]

\( A_{\Phi_j} = \)

\( \frac{d\sigma}{dM_{t\bar{t}}} \) [pb/GeV]

Scenario 3
\( \sqrt{s} = 13\text{TeV} \)

QCD only
2HDM + QCD

\( \frac{\delta\sigma}{\sigma_{\text{QCD}}} \) [%]

\( \delta \sigma_{\text{QCD}} [\%] \)

2HDM + Interf.
effect of 2HDM most prominent in the resonant region

interference with QCD very important

interference effects between different CPV scalars negligible

How large are the contributions form the NLO QCD corrections?
LO is already a 1-loop calculation ⇒ NLO requires a 2-loop calculation

use effective $gg\phi$ vertex:

$$L_{\text{eff}} = (f_S G_{\mu\nu}^a G_{\mu\nu}^a + f_P \epsilon_{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a)\phi$$

effective theory: leading order in the $1/m_t$ expansion of the $gg\phi$ vertex

take higher orders of $1/m_t$ into account by using K-factor [Krämer, Laenen, Spira 1996]

$$\sigma_{\text{approx}}^{\text{NLO}} = \frac{\sigma_{\text{NLO}}^{\text{eff}}}{\sigma_{\text{LO}}^{\text{eff}}} \sigma_{\text{full}}$$

good approximation for $pp \rightarrow HX$

Assumption: also valid for $|pp \rightarrow \phi \rightarrow t\bar{t}|^2$

no K-factor for QCD-interference
LO: significant heavy Higgs contributions only in resonance region

NLO: restrict the calculation to the resonance region

⇒ extract resonance/pole contribution by applying soft gluon approximation

⇒ non-factorizing contributions from real and virtual corrections cancel exactly in soft gluon approximation [Fadin et al. '94, Melnikov et al. '96, Beenakker et al. '97, Dittmaier et al. 2014]
## NLO Results - Inclusive Cross Section

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_0$ [GeV]</td>
<td>265</td>
<td>312.5</td>
<td>325</td>
</tr>
<tr>
<td>$\sigma_{\text{QCDW}}$ [pb]</td>
<td>$643.22^{+81.23}_{-77.71}$</td>
<td>$624.25^{+80.98}_{-76.19}$</td>
<td>$619.56^{+81.05}_{-75.72}$</td>
</tr>
<tr>
<td>$\sigma_{\text{2HDM}}$ [pb]</td>
<td>$13.59^{+1.85}_{-1.64}$</td>
<td>$7.4^{+0.77}_{-0.78}$</td>
<td>$7.21^{+0.81}_{-0.77}$</td>
</tr>
<tr>
<td>$\sigma_{\text{2HDM}}/\sigma_{\text{QCDW}}$ [%]</td>
<td>2.1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

\[ \mu_0 = \mu_R = \mu_F = \frac{m_2 + m_3}{4} \]

\[ \mu \text{ variation: } \mu = \frac{\mu_0}{2}, \mu_0, 2\mu_0 \]

inclusive cross section shows only **little sensitivity** to heavy Higgs contribution (not yet constrained by measurement: $\delta \sigma_{t\bar{t}}^{\text{exp}} \sim 5\%$)

$\Rightarrow$ *study more sensitive observables*
- heavy Higgs NLO corrections small w.r.t. to QCD background
- heavy Higgs NLO corrections important w.r.t. the heavy Higgs LO
- strongest effect in the mass degenerate case where resonances overlap
scenario 1 cannot be excluded by this measurement because of background uncertainty
Comparison with CMS [arXiv:1309.2030]

How to avoid peak-dip cancellation and find resonance experimentally?

- use smaller $M_{t\bar{t}}$ bins: new ATLAS analysis (also incl. interference)
  - see talk by Danilo Enoque Ferreira De Lima on Saturday in BSM session
- here: use sliding $M_{t\bar{t}}$ window
estimate significance form \( N_s \) and \( N_b \) in different \( M_{t\bar{t}} \) windows

- smaller bin width → significance \( Z_{PL} \) larger
- smaller background uncertainty → significance \( Z_{PL} \) larger
- precision measurements crucial
Note: approximation valid only in resonance region

avoid peak-dip cancellation in other observables, e.g. $y_t$, $\cos \theta_{CS}$ by applying cuts below and above the resonance to estimate maximal effect
NLO slightly increases effect above the resonance in the central region
⇒ highest sensitivity in central region
NLO decreases effect below the resonance
θ_{CS} defined in $t\bar{t}$ ZMF (@LO same as scattering angle)

largest effects in central region: $\sim 7\%$ in lower $M_{t\bar{t}}$ bin
Results - Spin Dependent Observables

Try to increase signal/background ratio by analysing spin dependent observables, e.g. spin correlations

\[ C_{aa} = -4 \langle (S_t \cdot \hat{a}) (S_\bar{t} \cdot \hat{a}) \rangle \]

\( S_t \) and \( S_\bar{t} \) are the spin operators of \( t \) and \( \bar{t} \), respectively

choosing three different axes

\[ \hat{a} = \{ \hat{k}, \hat{n}, \hat{r} \} \]

\( \hat{k} \): direction of top quark in \( t\bar{t} \) ZMF, \( \hat{n}, \hat{r} \) directions perpendicular to \( \hat{k} \)

correlations have direct interpretation as expectation values of angular distributions, e.g. in the leptonic decay of \( t\bar{t} \)

\[ C_{kk} \sim \langle \cos \theta_+ \cos \theta_- \rangle \]

\( \theta_\pm \): angle between \( \ell^- \) and \( t(\bar{t}) \) in the \( t(\bar{t}) \) rest frame

Form \( C_{aa} \) construct opening angle correlation:

\[ D = \langle S_t \cdot S_\bar{t} \rangle = -\frac{1}{3} (C_{kk} + C_{nn} + C_{rr}) \]
model: scalar heavy Higgs boson, $m_H = 400$ GeV, SM Yukawa couplings

chosen $M_{t\bar{t}}$ cut to enhance signal/background ratio

$C_{rr}$ shows strongest effect (Sig./Bkg. ratio $\sim 15\%$

compare with Sig./Bkg. ratio of cross section in the same $M_{t\bar{t}}$ bin: $\sim 4\%$
Summary

- Heavy Higgs-QCD interference must be taken into account.
- NLO effect large w.r.t. Higgs-only cross section but small w.r.t. QCD background.
- NLO effects from heavy Higgs bosons can be enhanced by appropriate $M_{t\bar{t}}$ cuts.
- $m_{\Phi}$ unknown $\rightarrow$ scan $M_{t\bar{t}}$ to avoid cancellation from peak-dip structure.
- Strong significance in $d\sigma/dM_{t\bar{t}}$ only achievable by reducing background uncertainty.
- $\frac{d\sigma}{d\cos\theta_{CS}}$ is most sensitive observables among the spin independent observables studied so far.
- Spin correlations with an additional cut on $M_{t\bar{t}}$ have higher sensitivity than spin independent observables.
Thank you for your attention!
Additional Material
2-Higgs-Doublet Model (2HDM) – Yukawa Couplings

\[ \mathcal{L}_{\Phi,Yuk} \supset -\bar{Q}_L \left[ (\lambda_1^d \Phi_1 + \lambda_2^d \Phi_2) d_R + (\lambda_1^u \Phi_1 + \lambda_2^u \Phi_2) u_R \right] + \text{h.c.} \]

\[ \Phi_i = i\tau_2 \Phi_i^* \]

Flavour conserving 2HDMs:

<table>
<thead>
<tr>
<th>Type</th>
<th>( u_R )</th>
<th>( d_R )</th>
<th>( \ell_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
</tr>
<tr>
<td>II</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
<td>( \Phi_1 )</td>
</tr>
<tr>
<td>Lepton-specific (X)</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
</tr>
<tr>
<td>Flipped (Y)</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
<td>( \Phi_2 )</td>
</tr>
</tbody>
</table>

\( \mathcal{L}_{Yuk} \) in terms of Higgs mass eigenstates \( \phi_j \):

\[ \mathcal{L}_{Yuk} \supset -\sum_j \left[ \frac{m_u}{\nu} \bar{u}(a_{ju} - ib_{ju}\gamma_5)u + \frac{m_d}{\nu} \bar{d}(a_{jd} - ib_{jd}\gamma_5)d \right] \phi_j \]

\[ a_{ju} = \frac{R_{j2}}{\sin \beta}, \quad b_{ju} = R_{j3} \cot \beta, \quad a_{jd} = \frac{R_{j1}}{\cos \beta}, \quad b_{jd} = R_{j3} \tan \beta, \quad \nu = \sqrt{\nu_1^2 + \nu_2^2} \]
Higgs-Gauge couplings are derived from $L_{\Phi, \text{kin}}$

$$L_{\Phi, \text{kin}} = \left( D_\mu \Phi_1 \right)^\dagger \left( D^\mu \Phi_1 \right) + \left( D_\mu \Phi_2 \right)^\dagger \left( D^\mu \Phi_2 \right)$$

$$= L_{VV\Phi} + L_{VV\Phi\Phi} + L_{WZ\Phi\Phi} + L_{W\gamma\Phi\Phi} + L_{Z\Phi\Phi} + L_{W\Phi\Phi} + L_{\gamma\Phi\Phi}$$

relevant terms for decay width

$$L_{VV\Phi} = f_{VV\phi_i} \left( \frac{2m_W^2}{v} W^+ \mu W^- \mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) \phi_i$$

$$L_{Z\Phi\Phi} = \frac{m_Z}{\sqrt{v}} f_{Z\phi_j \phi_k} \left( \phi_j \partial_\mu \phi_k \right) Z^\mu$$

with

$$f_{VV\phi_i} = R_{i1} \cos \beta + R_{i2} \sin \beta$$

$$f_{Z\phi_j \phi_k} = \left( R_{i2} R_{j3} - R_{i3} R_{j2} \right) \cos \beta + \left( R_{i3} R_{j1} - R_{i1} R_{j3} \right) \sin \beta$$
Next-to-Leading Order – Effective $gg\phi$ Vertex

LO is already a 1-loop calculation
⇒ NLO is a 2-loop calculation
Use effective $gg\phi$ vertex:

$$L_{\text{eff}} = (f_S G^a_{\mu\nu} G^{a\mu\nu} + f_P \epsilon_{\mu\nu\rho\sigma} G^a_{\mu\nu} G_a^{\rho\sigma})\phi$$

Effective theory: leading order in the $1/m_t$ expansion of the $gg\phi$ vertex
→ take higher orders of $1/m_t$ into account by using K-factor

$$\sigma_{\text{approx}}^{\text{NLO}} = \frac{\sigma_{\text{eff}}^{\text{NLO}}}{\sigma_{\text{eff}}^{\text{LO}}} \sigma_{\text{full}}^{\text{LO}}$$

[Krämer, Laenen, Spira 1996]

Good approximation for Higgs production:

- major part of NLO QCD corrections originates from soft/collinear gluons which do not resolve the effective coupling
- here we assume that this is true for the process $pp \rightarrow \phi \rightarrow tt$ as well
Next-to-Leading Order – Soft Gluon Approximation

- Seen in LO: significant contributions form the extended Higgs sector to $t\bar{t}$ production only in resonance region
- at NLO: restrict the calculation to the resonance region

  a) factorizing contributions, e.g.

  b) non-factorizing contributions, e.g.

extract pole contribution by soft gluon approximation

\[ \ell \to 0 \quad \Rightarrow \quad \frac{1}{s - m^2 + i\Gamma m} \]

\( \Rightarrow \) non-factorizing contributions from real and virtual corrections cancel
\[
|\mathcal{M}_\phi|^2 = \frac{s^3 m_t^3}{2 C_F v^2} \left\{ (|\tilde{f}_{S_2}|^2 + 4|\tilde{f}_{P_2}|^2)\left(a_{2t}^2 \beta_t^2 + b_{2t}^2\right) + (|\tilde{f}_{S_3}|^2 + 4|\tilde{f}_{P_3}|^2)\left(a_{3t}^2 \beta_t^2 + b_{3t}^2\right) + 2(\text{Re}[\tilde{f}_{S_2}\tilde{f}_{S_3}^*] + \text{Re}[\tilde{f}_{P_2}\tilde{f}_{P_3}^*])(a_{2t} a_{3t} \beta_t^2 + b_{2t} b_{3t}) \right\}
\]

\[
2\text{Re}[\mathcal{A}_\phi \mathcal{A}_{QCD}^*] = -\frac{4\pi \alpha_s m_t^2 s}{C_A C_F v (1 - \beta^2 z^2)} \left\{ (a_{2t} \beta_t^2 \text{Re}[\tilde{f}_{S_2}] - 2b_{2t} \text{Re}[\tilde{f}_{P_2}]) + (a_{3t} \beta_t^2 \text{Re}[\tilde{f}_{S_3}] - 2b_{3t} \text{Re}[\tilde{f}_{P_3}]) \right\}
\]
The resonant contributions can be divided into

1. Factorizing Diagrams
   → scalar propagator as coefficient; divide into scalar prod. and decay
   (simpler to calculate, known from literature)

2. Non-Factorizing Diagrams
   → scalar propagator in loop; no division into scalar prod. and decay possible

How to extract pole contribution $\frac{1}{s-m_\phi^2+i\Gamma_\phi m_\phi}$?

$\Rightarrow$ soft-gluon approximation
Soft-Gluon Approximation

Example: Box Diagram

\[
\begin{align*}
\ell &+ k_1 \\
\ell + k_1 + k_2 &
\end{align*}
\]

\[
\ell \rightarrow 0 \quad \sim \quad \frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi} + \text{non-resonant terms}
\]
Soft-Gluon Approximation

Example for Virtual Correction:

\[ \left( \begin{array}{c} \text{example diagram} \\ \text{example diagram} \end{array} \right) \]

neglect loop momenta in the numerator \( \rightarrow \) scalar integral:

\[ \int \frac{d^4 \ell}{(2\pi)^4} \frac{1}{(\ell^2+i\epsilon)((\ell+k_1)^2+i\epsilon)((\ell+k_1+k_2)^2-m_\phi^2+i\Gamma_{\phi} m_\phi)((\ell+p_1)^2-m_t^2+i\epsilon)} \]

neglect \( \ell^2 \) terms in the denominator where possible

\[ \int \frac{d^4 \ell}{(2\pi)^4} \frac{1}{(\ell^2+i\epsilon)(2\ell k_1+i\epsilon)(2\ell (k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_{\phi} m_\phi)(2\ell p_1+i\epsilon)} \]

perform contour integration

\[ -i \int \frac{d^3 \ell}{(2\pi)^3} \frac{1}{2|\ell|} \left[ -2|\ell| k_1^0 + 2\ell k_1 + i\epsilon \right] \left[ -2|\ell| (k_1^0+k_2^0) + 2\ell (k_1+k_2) + \hat{s} - m_\phi^2 + i\Gamma_{\phi} m_\phi \right] \left[ -2|\ell| p_1^0 + 2\ell p_1 + i\epsilon \right] \]

\[ = +i \int \frac{d^3 \ell}{(2\pi)^3} \frac{1}{2\ell^0} \left[ -2\ell k_1 + i\epsilon \right] \left[ -2\ell (k_1+k_2) + \hat{s} - m_\phi^2 + i\Gamma_{\phi} m_\phi \right] \left[ 2\ell p_1 - i\epsilon \right] ; \quad \ell^0 = |\ell| \]
Example Real Correction:

\[
-\frac{1}{(2\pi)^3} \frac{d^3 q}{2q^0} \frac{1}{\left[ -2q k_1 + i\epsilon \right] \left[ -2q (k_1 + k_2) + \hat{s} - m^2_\phi + i\Gamma_\phi m_\phi \right] [2q p_1 - i\epsilon]} \]

\[ q^0 = |\vec{q}| \]
\[
\begin{align*}
\left( \begin{array}{c}
\end{array} \right) & \left( \begin{array}{c}
\end{array} \right)^* \\
\rightarrow & -i \int \frac{d^3 q}{(2\pi)^3 2q^0} \frac{1}{[-2q k_1 + i\varepsilon] \left[ -2q(k_1 + k_2) + s - m_\phi^2 + i\Gamma_\phi m_\phi \right] [2q p_1 - i\varepsilon]}
\end{align*}
\]

\[ q^0 = |q| \]

\[
\begin{align*}
\left( \begin{array}{c}
\end{array} \right) & \left( \begin{array}{c}
\end{array} \right)^* \\
\rightarrow & +i \int \frac{d^3 \ell}{(2\pi)^3 2\ell^0} \frac{1}{[-2\ell k_1 + i\varepsilon] \left[ -2\ell(k_1 + k_2) + s - m_\phi^2 + i\Gamma_\phi m_\phi \right] [2\ell p_1 - i\varepsilon]}
\end{align*}
\]

\[ \ell^0 = |\ell| \]
Soft-Gluon Approximation

Example: Box Diagram

\[ \ell + k_1 \quad \ell + p_1 \]

\[ k_2 \quad \ell + k_1 + k_2 \]

\[ p_1 \quad p_2 \]

\[ \ell \rightarrow 0 \quad \sim \frac{1}{\hat{s} - m_\phi^2 + i\Gamma_\phi m_\phi} + \text{non-resonant terms} \]

non-factorizing virtual corrections cancel with real corrections from initial and final state radiation in the soft-gluon approximation

(known effect from: [Beenakker, Chapovsky, Berends '97])

- only valid if observable is inclusive enough
## Results – Inclusive Cross Section (LO & NLO)

<table>
<thead>
<tr>
<th></th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o int</td>
<td>w int</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{LO}}$</td>
<td>$\sigma_{\text{NLO}}$</td>
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<tr>
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<td>1.88</td>
<td>8.92</td>
</tr>
</tbody>
</table>
### Heavy Higgs Widths

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_j \rightarrow tt$</td>
<td>$\Gamma_2$ [GeV]</td>
<td>$\Gamma_3$ [GeV]</td>
</tr>
<tr>
<td>$\phi_j \rightarrow VV$</td>
<td>34.48</td>
<td>49.15</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 Z$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_2 Z$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 \phi_1$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 \phi_2$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\phi_j \rightarrow gg$</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>34.56</strong></td>
<td><strong>49.28</strong></td>
</tr>
</tbody>
</table>