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

Peter Galler
Humboldt-Universität zu Berlin, Institut für Physik

in collaboration with
Werner Bernreuther, Clemens Mellein, Zong-Guo Si, Peter Uwer


LHCP 2016, 15.06.2016
Motivation

  - 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
→ 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
→ 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

  → 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
2-Higgs-Doublet Model (2HDM) in a nutshell

\[ \Phi_1 = \left( \frac{1}{\sqrt{2}} (v_1 + \varphi_1 + i\chi_1) \right), \quad \Phi_2 = \left( \frac{1}{\sqrt{2}} (v_2 + \varphi_2 + i\chi_2) \right) \]

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

top-Yukawa coupling: \[ \mathcal{L}_{\text{Yuk},t} = -\frac{m_t}{v} \sum_j \bar{t} (a_{jt} - i b_{jt} \gamma_5) t \phi_j \]

reduced Yukawa couplings \( a_t, b_t \) depend on \( \alpha \) or \( \alpha_1, \alpha_2, \alpha_3 \) and \( \beta \)

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

CP conserving case

- \( h = -\varphi_1 \sin \alpha + \varphi_2 \cos \alpha \)
- \( H = \varphi_1 \cos \alpha + \varphi_2 \sin \alpha \)
- \( A = -\chi_1 \sin \beta + \chi_2 \cos \beta \)

CP violating case

\[ \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ A \end{pmatrix} \]

\[ H^+ = -\xi_1^+ \sin \beta + \xi_2^+ \cos \beta \]

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

### CP-conserving scenario I and II

\[ \tan \beta = 0.7, \quad \alpha = \beta - \frac{\pi}{2} \]

<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

\[ \tan \beta = 0.7, \quad \alpha_1 = \beta, \quad \alpha_2 = \frac{\pi}{15}, \quad \alpha_3 = \frac{\pi}{4} \]

<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 (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

\[ \mathcal{A}_{\text{QCD}} = \]

\[
\begin{align*}
\mathcal{A}_{\phi_j} = & \quad \text{(pseudo-)scalar contribution} \\
\end{align*}
\]

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

Scenario 3
\[ \sqrt{s} = 13\text{TeV} \]

2HDM + QCD
QCD only
2HDM + Interf.
Different Contributions to the Leading Order

- effect of 2HDM most prominent in the resonant region
- interference with QCD important

interference effects between different CPV scalars negligible

How large are the contributions form the NLO QCD corrections?
Next-to-Leading Order – Heavy Top Quark Limit

- LO is already a 1-loop calculation
  \[ \Rightarrow \text{NLO is a 2-loop calculation} \]
- use effective \( gg\phi \) vertex:
  \[ L_{\text{eff}} = \left( f_S G_{\mu\nu}^a G_{\alpha}^{\mu\nu} + f_P \varepsilon_{\mu\nu\rho\sigma} G_{\alpha}^{\mu\nu} G_{\alpha}^{\rho\sigma} \right) \phi \]
  \[
  \begin{array}{c}
    \text{---} \quad m_t \rightarrow \infty \quad \text{---}
  \end{array}
  \]
- 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
  \[ [\text{Kr"{a}mer, Laenen, Spira 1996}] \]
- \( \sigma_{\text{approx}}^{\text{NLO}} = \frac{\sigma_{\text{eff}}^{\text{NLO}}}{\sigma_{\text{eff}}^{\text{LO}}} \sigma_{\text{full}}^{\text{LO}} \)
- good approximation for \( pp \rightarrow HX \)
  Assumption: good approx. for \( |pp \rightarrow \phi \rightarrow t\bar{t}|^2 \)
- no K-factor for QCD-interference
Next-to-Leading Order – Soft Gluon Approximation

- at LO: significant heavy Higgs contributions only in resonance region
- at 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></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>$\sigma_{QCDW}$ [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>$\sigma_{2HDM}$ [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>$\sigma_{2HDM}/\sigma_{QCDW}$ [%]</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 (also good because $\delta \sigma_{t\bar{t}}^{\exp} \sim 5\%$)
- 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
How to avoid peak-dip cancellation and find resonance experimentally? ⇒ sliding $M_{t\bar{t}}$ window
estimate significance form $N_s$ and $N_b$ in different $M_{t\bar{t}}$ windows

smaller bin width $\rightarrow Z_{PL}$ larger

smaller background uncertainty $\rightarrow Z_{PL}$ larger
strictly: approximation valid only in resonance region
want to avoid peak-dip cancellation in other observables, e.g. $y_t$, $\cos \theta_{CS}$
apply 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
$\theta_{\text{CS}}$ 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

$\geq 5\%$ for $-0.5 \leq \cos \theta_{\text{CS}} \leq 0.5$ (compare to: $\geq 5\%$ for $460\text{GeV} \leq M_{t\bar{t}} \leq 500\text{GeV}$)
Summary: Results on the Level of Stable Tops

- 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 corrections positive in resonance region
- NLO effects from heavy Higgs bosons can be enhanced by appropriate $M_{t\bar{t}}$ cuts (inclusive: 2% → with $M_{t\bar{t}}$-cut: $\sim 5\%$ for scenario 1)
- $m_\Phi$ unknown → scan $M_{t\bar{t}}$ to avoid cancellation from peak-dip structure
- strong significance only achievable by reducing background uncertainty
- $\frac{d\sigma}{d\cos\theta_{CS}}$ is most sensitive observables studied so far
- studied $p_t^\perp$ distribution as well: heavy Higgs effect well below 5%
Outlook: Decay of the $t\bar{t}$ Pair

Further investigation by including the decay of the tops

Answer questions:

1. What can be learned about the CP nature of the spin-0 resonance?
2. Is it possible to increase the signal/background ratio by analysing spin dependent observables?
3. Would a 750 GeV resonance be experimentally accessible in the $t\bar{t}$ channel?
expectation value of helicity correlation: \( \langle \cos \theta^+ \cos \theta^- \rangle \)

\[ \theta^\pm : \text{angle between } \ell^\pm \text{ and top (antitop) in top (antitop) rest frame} \]

preliminary result: considerable increase in sensitivity when considering spin dependent observables with additional \( M_{t\bar{t}} \) cuts
Thank you for your attention!
Additional Material
2-Higgs-Doublet Model (2HDM) – Yukawa Couplings

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

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

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>

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

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

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

$$\mathcal{L}_{\Phi,\text{kin}} = (D_{\mu} \Phi_1)^\dagger (D^\mu \Phi_1) + (D_{\mu} \Phi_2)^\dagger (D^\mu \Phi_2)$$

$$= \mathcal{L}_{VV\Phi} + \mathcal{L}_{V\gamma\Phi} + \mathcal{L}_{WZ\Phi\Phi} + \mathcal{L}_{W\gamma\Phi} + \mathcal{L}_{Z\Phi\Phi} + \mathcal{L}_{W\Phi\Phi} + \mathcal{L}_{\gamma\Phi\Phi}$$

relevant terms for decay width

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

$$\mathcal{L}_{Z\Phi\Phi} = \frac{m_Z}{v} f_{Z\phi_j\phi_k} (\phi_j \leftrightarrow \partial_{\mu} \phi_k) Z^\mu$$

with

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

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

LO is already a 1-loop calculation
$\Rightarrow$ NLO is a 2-loop calculation
Use effective $gg\phi$ vertex:
\[ L_{\text{eff}} = (f_S G^a_{\mu\nu} G^\mu_{a\nu} + f_P \epsilon_{\mu\nu\rho\sigma} G^\mu_{a\nu} G^\rho_{a\sigma})\phi \]

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

[Krämer, Laenen, Spira 1996]

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

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 $pp \rightarrow \phi \rightarrow t\bar{t}$ 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

\[ \ell \rightarrow 0 \quad \Rightarrow \quad \frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi} \]

⇒ non-factorizing contributions from real and virtual corrections cancel

\[ \left( \begin{array}{c}
\text{factorizing contributions, e.g.}
\end{array} \right) \left( \begin{array}{c}
\text{non-factorizing contributions, e.g.}
\end{array} \right)^* + \left( \begin{array}{c}
\text{soft-gluon approx.}
\end{array} \right) = 0 \]
\[ \overline{|M_\phi|^2} = \frac{s^3 m_t^3}{2C_F v^2} \left\{ \left( |\tilde{f}_S|^2 + 4|\tilde{f}_P|^2 \right) \left( a_{2t}^2 \beta_t^2 + b_{2t}^2 \right) + \left( |\tilde{f}_S|^2 + 4|\tilde{f}_P|^2 \right) \left( a_{3t}^2 \beta_t^2 + b_{3t}^2 \right) \right\} \\
\frac{2\text{Re}[A_\phi A_{QCD}^*]}{C_A C_F v (1 - \beta^2 z^2)} = -\frac{4\pi \alpha_s m_t^2 s}{C_A C_F v} \left\{ \left( a_{2t} \beta_t^2 \text{Re}[\tilde{f}_S] - 2b_{2t} \text{Re}[\tilde{f}_P] \right) \right\} \\
\ + \left( a_{3t} \beta_t^2 \text{Re}[\tilde{f}_S] - 2b_{3t} \text{Re}[\tilde{f}_P] \right) \} \]
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 \( \frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi} \)?

⇒ soft-gluon approximation
Soft-Gluon Approximation

Example: Box Diagram

\[
\begin{aligned}
&\ell + k_1 \\
&\ell + k_1 + k_2 \\
&\ell + p_1 \\
&\ell \to 0 \\
\end{aligned}
\sim \frac{1}{s-m_\phi^2+i\Gamma_\phi m_\phi} + \text{non-resonant terms}
\]
Soft-Gluon Approximation

Example for Virtual Correction:

\[
\begin{pmatrix}
\begin{array}{c}
\vdots \\
\end{array}
\end{pmatrix}
\begin{pmatrix}
\begin{array}{c}
\vdots \\
\end{array}
\end{pmatrix}
\]

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

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

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

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

perform contour integration

\[
- i \int \frac{d^3 \ell}{(2\pi)^3} \frac{1}{2|\ell| \left[-2|\ell| k_0^0 + 2\ell k_1^0 + i\epsilon\right] \left[-2|\ell|(k_1^0 + k_2^0) + 2\ell (\bar{k}_1 + \bar{k}_2) + \hat{s} - m_\phi^2 + i\Gamma m_\phi\right] \left[-2|\ell| p_1^0 + 2\ell \hat{p}_1 + i\epsilon\right]}
\]

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

$$\rightarrow -i \int \frac{d^3 q}{(2\pi)^3 2q^0} \frac{1}{\left[ -2qk_1 + i\epsilon \right] \left[ -2q(k_1 + k_2) + \hat{s} - m^2 + i\Gamma \phi m_\phi \right] \left[ 2qp_1 - i\epsilon \right]}$$

$q^0 = |\vec{q}|$
\[
\begin{align*}
&\rightarrow -i \int \frac{d^3 q}{(2\pi)^3 2q^0} \frac{1}{[-2q k_1 + i\epsilon][-2q(k_1 + k_2) + \hat{s} - m_\phi^2 + i\Gamma_\phi m_\phi][2q p_1 - i\epsilon]} \\
&q^0 = |\vec{q}| \\
&\rightarrow +i \int \frac{d^3 \ell}{(2\pi)^3 2\ell^0} \frac{1}{[-2\ell k_1 + i\epsilon][-2\ell(k_1 + k_2) + \hat{s} - m_\phi^2 + i\Gamma_\phi m_\phi][2\ell p_1 - i\epsilon]} \\
&\ell^0 = |\vec{\ell}| 
\end{align*}
\]
Soft-Gluon Approximation

Example: Box Diagram

\[
\begin{align*}
\ell + k_1 & \quad \ell + p_1 \\
\ell + k_2 & \quad \ell + k_1 + k_2 \\
p_1 & \quad p_2
\end{align*}
\]

\[
\left( \begin{array}{c}
\ell \\
k_1 \\
k_2 \\
\ell + k_1 + k_2
\end{array} \right) \left( \begin{array}{c}
\ell \\
p_1 \\
p_2 \\
\ell + k_1 + k_2
\end{array} \right)^* + \left( \begin{array}{c}
\ell \\
k_1 \\
k_2 \\
\ell + k_1 + k_2
\end{array} \right) \left( \begin{array}{c}
\ell \\
p_1 \\
p_2 \\
\ell + k_1 + k_2
\end{array} \right)^* = 0
\]

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>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I</strong></td>
<td></td>
</tr>
<tr>
<td>w/o int</td>
<td>2.03</td>
</tr>
<tr>
<td>w int</td>
<td>0.65</td>
</tr>
<tr>
<td>w/o int</td>
<td>7.34</td>
</tr>
<tr>
<td>w int</td>
<td>1.55</td>
</tr>
<tr>
<td><strong>II</strong></td>
<td></td>
</tr>
<tr>
<td>w/o int</td>
<td>0.79</td>
</tr>
<tr>
<td>w int</td>
<td>0.52</td>
</tr>
<tr>
<td>w/o int</td>
<td>3.05</td>
</tr>
<tr>
<td>w int</td>
<td>1.41</td>
</tr>
<tr>
<td><strong>III</strong></td>
<td></td>
</tr>
<tr>
<td>w/o int</td>
<td>1.30</td>
</tr>
<tr>
<td>w int</td>
<td>0.67</td>
</tr>
<tr>
<td>w/o int</td>
<td>4.74</td>
</tr>
<tr>
<td>w int</td>
<td>1.88</td>
</tr>
</tbody>
</table>
## Heavy Higgs Widths

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th></th>
<th>Scenario 2</th>
<th></th>
<th>Scenario 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Gamma_2$ [GeV]</td>
<td>$\Gamma_3$ [GeV]</td>
<td>$\Gamma_2$ [GeV]</td>
<td>$\Gamma_3$ [GeV]</td>
<td>$\Gamma_2$ [GeV]</td>
<td>$\Gamma_3$ [GeV]</td>
</tr>
<tr>
<td>$\phi_j \rightarrow tt$</td>
<td>34.48</td>
<td>49.15</td>
<td>34.41</td>
<td>71.97</td>
<td>32.31</td>
<td>85.05</td>
</tr>
<tr>
<td>$\phi_j \rightarrow VV$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.12</td>
<td>5.11</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 Z$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.65</td>
<td>3.24</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_2 Z$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.14</td>
<td>0</td>
<td>31.28</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 \phi_1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.38</td>
<td>3.00</td>
</tr>
<tr>
<td>$\phi_j \rightarrow \phi_1 \phi_2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.31</td>
</tr>
<tr>
<td>$\phi_j \rightarrow gg$</td>
<td>0.08</td>
<td>0.13</td>
<td>0.08</td>
<td>0.17</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>34.56</td>
<td>49.28</td>
<td>34.49</td>
<td>75.28</td>
<td>36.55</td>
<td>128.16</td>
</tr>
</tbody>
</table>