Revisiting the di-Higgs production processes at the FCC-hh

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Based on

Plan of my talk

- Motivation
- Status of the di-Higgs searches
- Di-Higgs in the EFT
- Non resonant di-Higgs production at the HL-LHC
- Di-Higgs + jet at FCC-hh
- $t\bar{t}hh$ at FCC-hh
- Summary and Outlook
Motivation

- Di-Higgs provides means to directly probe Higgs self coupling
- Indirect probe: Through radiative corrections of single Higgs productions [Goertz et al.; 2013, McCullough; 2013, Degrassi et al.; 2016]
- Challenging task: small di-Higgs cross-section in SM (39.56^{+7.32%}_{-8.38%} fb at NNLO + NNLL at 14 TeV with the exact top-quark mass dependence at NLO [deFlorian et al.; 2013, Borowka et al.; 2016]) ← partial cancellation of triangle and box diagram contributions
- LHC or 100 TeV colliders: self-coupling measurement at 10-50% precision possible → size of dataset, beam energy, control over systematics
- Assuming SM couplings, HL-LHC prediction: $-0.8 < \frac{\lambda}{\lambda_{SM}} < 7.7$ at 95% C.L. [ATL-PHYS-PUB-2017-001]
Motivation

- Enhancement of $\sigma_{hh} \rightarrow s$-channel heavy di-Higgs resonance \([\times SM \text{ models etc.}] \) \([\text{Mühlleitner et. al.; 2015; Ramsey-Musolf et. al.; 2016 etc.}]\), new coloured particles in loops \([\text{Kribs et. al.; 2012, Nakamura et. al.; 2017}]\) or HD operators \([\text{Nishiwaki et. al.; 2013}]\) \(\rightarrow\) kinematics altered \(\rightarrow\) requires different experimental search strategies

- Till date \(\rightarrow\) major focus on BSM di-Higgs sector \(\rightarrow\) enhancement in production

- New physics can affect Higgs decays \(\rightarrow\) exotic Higgs decays now actively studied \([\text{Curtin et. al.; 2015}]\)

- Worthwhile to consider exotic decays for di-Higgs \(\rightarrow\) present bounds on variety of Higgs decays: BR very weak (10-50%) \([\text{SB, Batell, Spannowsky; 2016}]\)
Di-Higgs production cross-sections as functions of $\sqrt{s}$

- Di-Higgs cross-sections [Baglio et. al.; 2015]

![Graph showing Di-Higgs production cross-sections as a function of $\sqrt{s}$]
### Status of the di-Higgs searches

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS (NR) $\times$ SM</th>
<th>CMS (R) [fb, (GeV)]</th>
<th>ATLAS (NR) $\times$ SM</th>
<th>ATLAS (R) [fb, (GeV)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>75</td>
<td>1500-45 (260-1200)</td>
<td>13</td>
<td>2000-2 (260-3000)</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>24</td>
<td>240-290 (250-900)</td>
<td>22</td>
<td>1100-120 (275-400)</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>30</td>
<td>3110-70 (250-900)</td>
<td>12.7</td>
<td>1780-100 (260-1000)</td>
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<tr>
<td>$\gamma\gamma WW^∗$</td>
<td></td>
<td></td>
<td>200</td>
<td>40000-6100 (260-500)</td>
</tr>
<tr>
<td>$(\gamma\gamma\ell\nu jj)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\bar{b}\ell\nu\ell\nu$</td>
<td>79</td>
<td>20500-800 (300-900)</td>
<td>300</td>
<td>6000-170 (500-3000)</td>
</tr>
<tr>
<td>$WW^∗ WW^∗$</td>
<td></td>
<td></td>
<td>160</td>
<td>9300-2800 (260-500)</td>
</tr>
</tbody>
</table>

**Table:** Non-resonant (NR) and resonant (R) double Higgs production. Numbers in brackets show the range of the heavy scalar mass.

NR: Non-resonant, R: Resonant
SMEFT motivation

- Many reasons to go beyond the SM, *viz.* gauge hierarchy, neutrino mass, dark matter, baryon asymmetry etc.
- Plethora of BSM theories to address these issues
- Two phenomenological approaches:
  - *Model dependent:* study the signatures of each model individually
  - *Model independent:* low energy effective theory formalism – analogous to Fermi’s theory of beta decay
- The SM here is a low energy effective theory *valid below a cut-off scale* $\Lambda$
- A bigger theory (either weakly or strongly coupled) is assumed to supersede the SM above the scale $\Lambda$
- At the perturbative level, all heavy ($> \Lambda$) DOF are decoupled from the low energy theory (*Appelquist-Carazzone theorem*)
- Appearance of HD operators in the effective Lagrangian valid below $\Lambda$

$$\mathcal{L} = \mathcal{L}_{SM}^{d=4} + \sum_{d \geq 5} \sum_i \frac{f_i}{\Lambda^{d-4}} \mathcal{O}_{i}^{d}$$
Relevant operators

- Dimension 6 operators which modify the Higgs self-interactions

\[ O_{\Phi,1} = (D_\mu \Phi^\dagger)\Phi \Phi^\dagger (D^\mu \Phi) \quad O_{\Phi,2} = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \]
\[ O_{\Phi,3} = \frac{1}{3} (\Phi^\dagger \Phi)^3 \quad O_{\Phi,4} = (D_\mu \Phi^\dagger)(D^\mu \Phi)\Phi^\dagger \Phi \quad O_{GG} = G^a_{\mu \nu} G^{a, \mu \nu} \Phi^\dagger \Phi \]

- \( O_{\Phi,2/3} \) only modify Higgs self-couplings but \( O_{\Phi,1/4} \) also modify \( HVV \) couplings and \( V \) masses

- \( O_{\Phi,1} \) contributes to \( m_Z \) and not to \( m_W \) \( \rightarrow \) Violates Custodial symmetry \( \rightarrow \) Strongly constrained by \( T \)-parameter \( \rightarrow \) Neglected for collider studies

- Redundancy amongst operators upon using EOMs \( \rightarrow \) \( O_{\Phi,2}, O_{\Phi,3} \) and \( O_{\Phi,4} \) are not independent

- Including SM Yukawa, the operator \( O_{\Phi,f} = (\Phi^\dagger \Phi)\bar{L} \Phi f_R + \text{h.c.} \), where \( L = (f^u_L, f^d_L)^T \) becomes relevant

- One can remove \( O_{\Phi,4} \) using EOMs \( \rightarrow \) Left with \( (O_{\Phi,2}, O_{\Phi,3}, O_{\Phi,f}, O_{GG}) \)
Non-linear EFT realisation

- Many popular BSM extensions which give rise to modification of Higgs interactions
- Composite Higgs models assume that the Higgs is a pNGB of a strongly coupled UV completion
- The electroweak chiral Lagrangian best describes the low-energy effects of a strongly-coupled embedding of the SM

\[ \mathcal{L}^{\text{ew}} \supset - V(h) + \frac{g_s^2}{48\pi^2} G^a_{\mu\nu} G^{a\mu\nu} \left( k_g \frac{h}{v} + \frac{1}{2} k_2 g \frac{h^2}{v^2} + \cdots \right) \]

\[ - \frac{v}{\sqrt{2}} (\bar{u}^i_L \bar{d}^i_L) \Sigma \left[ 1 + c \frac{h}{v} + c_2 \frac{h^2}{v^2} + \cdots \right] \left( y^u_{ij} u^j_R \right) \left( y^d_{ij} d^j_R \right) + \text{h.c.}, \]

with

\[ V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{m_h^2}{2v} h^3 + d_4 \frac{m_h^2}{8v^2} h^4 + \cdots . \]

- Here the $SU(2) \times U(1)$ symmetry is non-linearly realised $\Sigma(x) = \frac{e^{i\sigma^a \phi^a(x)/v}}{v}$

with the Goldstone bosons $\phi^a$ ($a=1,2,3$) and the Pauli matrices $\sigma^a$. 
Non-linear EFT realisation

- 5 vertices are of imminent importance, viz., $k_g, k_{2g}, c, c_2, d_3$ in the top-Higgs sector
- $k_g$ and $c \rightarrow$ can be constrained from gluon-fusion, VBF, $t\bar{t}h$ production
- $k_{2g}, c_2$ and $d_3 \rightarrow$ can be constrained at LO from double-Higgs processes
- To over-constrain the parameter space of $\mathcal{L}^{\text{ew}}$ it is necessary to access as many di-Higgs processes as possible, viz., $pp \rightarrow hh, hhj, hhjj, t\bar{t}hh$
- $t\bar{t}hh$ is the only process with appreciable cross-section that has the ability to constrain $c_2$ at tree-level
- Here however, we will discuss in terms of the following simplified Lagrangian

$$\mathcal{L}^{\text{simp}} = \mathcal{L}^{SM} + (1 - \kappa_{\lambda})\lambda_{SM} h^3 + \kappa_{t\bar{t}hh}(\bar{t}_L t_R h^2 + \text{h.c.}) - \frac{1}{8}\kappa_{gghh} G^a_{\mu\nu} G^a_{\mu\nu} h^2,$$

where $\lambda_{SM} = \lambda v = \frac{m_h^2}{2v}$ and $\kappa_{\lambda} = \lambda_{BSM}/\lambda_{SM}$
### Bases translations

[Giudice, Grojean, Pomarol, Rattazzi; 2007, Feruglio; 1993]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Non-linear EFT</th>
<th>Simplified Lagrangian</th>
<th>SILH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$hhh$</td>
<td>$d_3$</td>
<td>$\kappa_\lambda$</td>
<td>$1 + (c_6 - c_\tau/4 - 3c_H/2)\xi$</td>
</tr>
<tr>
<td>$t\bar{t}hh$</td>
<td>$c_2$</td>
<td>$-\frac{\sqrt{2}v}{y_t}\kappa_{t\bar{t}hh}$</td>
<td>$-(c_H + 3c_y + c_\tau/4)\xi/2$</td>
</tr>
<tr>
<td>$gghh$</td>
<td>$k_{2g}$</td>
<td>$-12\pi^2 v^2 \frac{g_s^2}{2g_{\rho}^2} \kappa_{gghh}$</td>
<td>$3c_g \left(\frac{y_t^2}{g_{\rho}^2}\right)\xi$</td>
</tr>
</tbody>
</table>

**Table:** Relationship between the $hhh$, $t\bar{t}hh$ and $gghh$ vertices in three different bases, where $\xi \equiv (v/f)^2$.

$$L_{SILH} = \frac{\bar{c}_H}{2v^2} \partial^\mu \left[\Phi^\dagger \Phi \right] \partial_\mu \left[\Phi^\dagger \Phi \right] + \frac{\bar{c}_T}{2v^2} \left[\Phi^\dagger \vec{D}^\mu \Phi \right] \left[\Phi^\dagger \vec{D}_\mu \Phi \right] - \frac{\bar{c}_6 \lambda}{v^2} \left[\Phi^\dagger \Phi \right]^3$$

$$- \left[ \frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \right] \Phi^\dagger \cdot Q_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \Phi Q_L d_R + \frac{\bar{c}_t}{v^2} y_t \Phi^\dagger \Phi \Phi L L e_R + h.c. \right]$$

$$+ \frac{ig}{m_W^2} \left[ \Phi^\dagger T_{2k} \vec{D}^\mu \Phi \right] D^\nu W_{\mu \nu}^k + \frac{ig'}{2m_{W'}^2} \left[ \Phi^\dagger \vec{D}^\mu \Phi \right] \partial' B_{\mu \nu}$$
Non resonant di-Higgs production at the HL-LHC

[A. Adhikary, SB, R. K. Barman, B. Bhattacherjee, S. Niyogi; 2017]

- We choose channels based on the rate and cleanliness
- Focus on final states with leptons and/or photons
- Focus on 11 channels, viz.
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}ll + \not{E}_T$, $b\bar{b}\ell\tau_h + \not{E}_T$, $b\bar{b}\tau_h\tau_h + \not{E}_T$
  - $b\bar{b}WW^* \rightarrow b\bar{b}ll + \not{E}_T$, $b\bar{b}\ell jj + \not{E}_T$
  - $WW^*\gamma\gamma \rightarrow \ell\ell\gamma\gamma + \not{E}_T$, $\ell jj\gamma\gamma + \not{E}_T$
  - $WW^*WW^* \rightarrow \ell^\pm\ell^\pm jjjj + \not{E}_T$, $\ell\ell jj + \not{E}_T$, $\ell\ell\ell\ell + \not{E}_T$
- $4\tau$, $WW^*\tau^+\tau^-$, $ZZ^*\tau^+\tau^-$, $4\gamma$, $ZZ^*\gamma\gamma$, $4Z$ may be important at 100 TeV colliders
- Follow CMS and ATLAS analyses (when available) and optimise upon them
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$

- $S/B = 0.19$ and $S/\sqrt{B} = 1.76\sigma$
- CMS (ATLAS) projection: $1.6\sigma$ ($1.05\sigma$)

![Histograms showing normalized distributions of $m_{bb}$, $p_{T\gamma\gamma}$, and $\Delta R_{bb}$ for signal and background processes.](image)
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW$

- Leptonic: $S/B = 0.01$ and $S/\sqrt{B} = 0.62$; CMS projection: $S/B = 0.009$ and $S/\sqrt{B} = 0.59$
Non resonant di-Higgs production at the HL-LHC:
Summary

[A. Adhikary, SB, R. K. Barman, B. Bhattacherjee, S. Niyogi; 2017]

- Bleak prospects for discovering SM non-resonant di-Higgs channel at HL-LHC with 3 ab$^{-1}$ data
- $b\bar{b}\gamma\gamma$ is the cleanest ($S/B \sim 0.19$) but suffers from small rate
- Combined significance $\sim 3\sigma$ from the aforementioned channels
- Purely leptonic case for $b\bar{b}WW^*$ shows promise but needs better handle over backgrounds $\rightarrow$ data driven backgrounds
- Both semi-leptonic and leptonic channels for $\gamma\gamma WW^*$ show excellent $S/B$ (0.11 and 0.4 respectively) $\rightarrow$ need larger luminosity (considering CMS and ATLAS datasets separately to form 6 ab$^{-1}$) or higher energy colliders
Di-Higgs + jet at FCC-hh

[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky; 2018]

- Observing the Higgs self-coupling at the HL-LHC seem difficult at the moment

- Di-Higgs cross-section increases by 39 times going from 14 TeV → 100 TeV

- Extra jet emission becomes significantly less suppressed: 77 times enhancement from 14 TeV → 100 TeV collider → extra handle

- Recoiling a collimated Higgs pair against a jet exhibits more sensitivity (decorrelates $p_{T,h}$ and $m_{hh}$) to $\lambda_{hhh}$ as compared to $pp \rightarrow hh$ → statistically limited at the LHC

- Study $hhj \rightarrow b\bar{b}\tau^+\tau^-j \rightarrow b\bar{b}\tau_h(\tau_\ell)\tau_\ell j$ and $hhj \rightarrow b\bar{b}b\bar{b}j$

- Use substructure technique: BDRS [Butterworth, et. al.; 2008] with mass drop and filtering
**Di-Higgs + jet at FCC-hh ($j b \bar{b} \tau^+ \tau^-$)**

- $R = 1.5$, $p_T^j > 110$ GeV, $\tau$-tag efficiency 70%, $b$-tag efficiency 70%, $b$-mistag rate 2%; Combined $\tau_h \tau_h$ and $\tau_h \tau_\ell$
- Backgrounds: EW (example: $HZ / \gamma^* +$ jet), QCD+EW (Example: $b\bar{b}Z / \gamma^* +$ jet), $t\bar{t} +$ jet

![Graphs showing cross-section and distributions](image)
Di-Higgs + jet at FCC-hh ($j b \bar{b} \tau^+ \tau^-$)
Di-Higgs + jet at FCC-hh ($j b \bar{b} \tau^+ \tau^-$)

<table>
<thead>
<tr>
<th>observable</th>
<th>reconstructed object</th>
</tr>
</thead>
</table>
| $p_T$      | 2 hardest filtered subjets  
|           | 2 visible $\tau$ objects ($\tau_\ell$ or $\tau_h$)  
|           | hardest non $b$, $\tau$-tagged jet  
|           | reconstructed Higgs from filtered jets  
|           | reconstructed Higgs from visible $\tau$ final states |
| $p_T$ ratios | 2 hardest filtered jets  
|           | 2 visible $\tau$ final state objects |
| $m_{T2}$   | described before |
| $\Delta R$ | two hardest filtered subjets  
|           | two visible $\tau$ objects ($\tau_\ell \tau_\ell$ or $\tau_\ell \tau_h$)  
|           | $b$-tagged jets and lepton or $\tau_h$  
|           | $b$-tagged jets and jet $j_1$  
|           | lepton or $\tau_h$ with jet $j_1$ |
| $M_{T\tau\tau}^{col}$ | collinear approximation of $h \rightarrow \tau \tau$ mass |
| $M_{filt}^{\tau\tau}$ | filtered $j_1$ and $j_2$ (and $j_3$ if present) |
| $M_{vis.\tau\tau}^{hh}$ | filtered jets and leptons (or lepton and $\tau_h$) |
| $E_T$     | reduce sub-leading backgrounds |
| $\Delta \phi$ | between visible $\tau$ final state objects and $E_T$  
|           | between filtered jets system and $\ell \ell$ (or $\ell \tau_h$) systems |
| $N_{jets}$ | number of anti-$k_T$ jets with $R = 0.4$ |
Di-Higgs + jet at FCC-hh ($j b \bar{b} \tau^+ \tau^-$)

[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky; 2018]

<table>
<thead>
<tr>
<th>$\kappa \lambda$</th>
<th>Signal [fb]</th>
<th>QCD+QED [fb]</th>
<th>QED [fb]</th>
<th>$t\bar{t}j$ [fb]</th>
<th>Total background [fb]</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$, 30/ab</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.428</td>
<td></td>
<td>0.95</td>
<td>0.27</td>
<td>2.31</td>
<td>0.121</td>
<td>39.44</td>
</tr>
<tr>
<td>1</td>
<td>0.363</td>
<td></td>
<td></td>
<td>0.27</td>
<td>2.31</td>
<td>0.103</td>
<td>33.44</td>
</tr>
<tr>
<td>2</td>
<td>0.264</td>
<td></td>
<td></td>
<td>0.27</td>
<td>2.31</td>
<td>0.075</td>
<td>24.31</td>
</tr>
</tbody>
</table>

$0.76 < \kappa \lambda < 1.28 \quad 3/\text{ab}$

$0.92 < \kappa \lambda < 1.08 \quad 30/\text{ab}$

at 68% confidence level using the CLs method.
Comparison with optimised cut-and-count analysis

<table>
<thead>
<tr>
<th>cut</th>
<th>$\kappa \lambda = 1$</th>
<th>$\kappa \lambda = 0.5$</th>
<th>$\kappa \lambda = 2$</th>
<th>QCD+EW</th>
<th>EW</th>
<th>$t\bar{t}j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>preselection</td>
<td>0.86</td>
<td>1.09</td>
<td>0.56</td>
<td>11.73</td>
<td>2.20</td>
<td>4090.29</td>
</tr>
<tr>
<td>$m_{T^2} &gt; 120$ GeV</td>
<td>0.65</td>
<td>0.78</td>
<td>0.45</td>
<td>4.65</td>
<td>1.10</td>
<td>300.68</td>
</tr>
<tr>
<td>$\Delta \Phi(\tau_{vis,2}, \not{E}_T) &lt; 1.5$</td>
<td>0.62</td>
<td>0.74</td>
<td>0.43</td>
<td>4.43</td>
<td>1.05</td>
<td>196.36</td>
</tr>
<tr>
<td>100 GeV $&lt; M_{\tau,\tau} &lt; 150$ GeV</td>
<td>0.48</td>
<td>0.57</td>
<td>0.33</td>
<td>0.96</td>
<td>0.26</td>
<td>28.05</td>
</tr>
<tr>
<td>$\Delta \Phi(\tau_{vis,1}, \not{E}_T) &lt; 1.5$</td>
<td>0.47</td>
<td>0.56</td>
<td>0.32</td>
<td>0.92</td>
<td>0.25</td>
<td>21.75</td>
</tr>
<tr>
<td>$\Delta R(b_1 \tau_{vis,1}) &gt; 0.8$</td>
<td>0.47</td>
<td>0.56</td>
<td>0.32</td>
<td>0.92</td>
<td>0.25</td>
<td>20.28</td>
</tr>
<tr>
<td>$p_T(H_{\tau_{vis,1}, \tau_{vis,2}}) &gt; 60.0$ GeV</td>
<td>0.45</td>
<td>0.53</td>
<td>0.31</td>
<td>0.88</td>
<td>0.24</td>
<td>19.02</td>
</tr>
<tr>
<td>$\Delta R(b_1 \tau_{vis,2}) &gt; 0.8$</td>
<td>0.44</td>
<td>0.52</td>
<td>0.31</td>
<td>0.87</td>
<td>0.24</td>
<td>18.91</td>
</tr>
<tr>
<td>100 GeV $&lt; M_{inv,filt} &lt; 150$ GeV</td>
<td>0.32</td>
<td>0.38</td>
<td>0.22</td>
<td>0.43</td>
<td>0.06</td>
<td>5.78</td>
</tr>
<tr>
<td>$\Delta R(b_1 b_2) &gt; 0.8$</td>
<td>0.32</td>
<td>0.38</td>
<td>0.22</td>
<td>0.43</td>
<td>0.06</td>
<td>5.46</td>
</tr>
<tr>
<td>$\Delta R(\tau_{vis,1} \tau_{vis,2}) &gt; 0.8$</td>
<td>0.31</td>
<td>0.37</td>
<td>0.22</td>
<td>0.42</td>
<td>0.06</td>
<td>5.15</td>
</tr>
<tr>
<td>BDT performance [fb]</td>
<td>0.36</td>
<td>0.44</td>
<td>0.26</td>
<td>0.95</td>
<td>0.27</td>
<td>2.31</td>
</tr>
</tbody>
</table>
Di-Higgs + jet at FCC-hh ($j b \bar{b} b \bar{b} b$)

- **Major background**: pure QCD: $g \rightarrow b \bar{b}$ (soft and collinear splittings →
  - Resulting fat jets ($R = 0.8$) are one-pronged.
- **Signal**: $H \rightarrow b \bar{b}$; clear two prongs
- **Require**: $\tau_{2,1} < 0.35$ and $100 \text{ GeV} < m_{SD} < 130 \text{ GeV}$

<table>
<thead>
<tr>
<th>$\kappa \lambda$</th>
<th>signal</th>
<th>QCD</th>
<th>QCD+EW</th>
<th>EW</th>
<th>tot. background</th>
<th>$S/B \times 10^3$</th>
<th>$S/\sqrt{B}, 30/ab$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.5$</td>
<td>0.094</td>
<td>4.3</td>
<td>0.1</td>
<td>0.003</td>
<td>4.4</td>
<td>20.8</td>
<td>7.67</td>
</tr>
<tr>
<td>$1$</td>
<td>0.085</td>
<td></td>
<td>0.003</td>
<td></td>
<td></td>
<td>19.1</td>
<td>6.61</td>
</tr>
<tr>
<td>$2$</td>
<td>0.071</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.2</td>
<td>5.85</td>
</tr>
</tbody>
</table>

\[
\kappa \lambda = 0.5
\]

Normalised

<table>
<thead>
<tr>
<th>$\tau_{2,1}$</th>
<th>$j_1^{(1)}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{SM}$</td>
<td>0.1</td>
</tr>
<tr>
<td>QCD</td>
<td>0.05</td>
</tr>
<tr>
<td>QCD+EWK</td>
<td>0.05</td>
</tr>
<tr>
<td>EWK</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Normalised

<table>
<thead>
<tr>
<th>$\tau_{2,1}$</th>
<th>$j_1^{(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{SM}$</td>
<td>0.04</td>
</tr>
<tr>
<td>QCD</td>
<td>0.03</td>
</tr>
<tr>
<td>QCD+EWK</td>
<td>0.03</td>
</tr>
<tr>
<td>EWK</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at 100 TeV

- Feynman diagrams showing the impact of the three effective vertices, viz., $hhh$, $t\bar{t}hh$ and $gghh$
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- $\sigma/\sigma_{SM}$ with respect to $\kappa_\lambda, \kappa_{t\bar{t}hh}, \kappa_{gghh}$
- First row shows $\sigma/\sigma_{SM}$ at 100 TeV and at 14 TeV [Frederix et. al.; 2014]
Unlike many di-Higgs processes, in $t\bar{t}hh$ cross-section increases with $\lambda > \lambda_{SM}$.

For $\kappa_\lambda$, growth of cross-section for $\lambda < 0$ has different features at 14 TeV and 100 TeV machines.

In linear EFT scenarios, the coupling modifying $ggh$ and $gghh$ are correlated.

→ In non-linear EFT they are uncorrelated.

We vary $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ to obtain bounds on these couplings.
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

[SB, F. Krauss, M. Spannowsky; 2019]

- For $\kappa_\lambda = 1$, $\sigma_{t\bar{t}hh}^{100 \text{ TeV}} / \sigma_{t\bar{t}hh}^{14 \text{ TeV}} \sim 75$
- 14 TeV study yields $\sim 13$ signal events and $\kappa_\lambda \lesssim 2.5$ at 95% CL [Englert et. al.; 2014]

- For the 100 TeV analysis, we consider final state with 6 $b$-tagged jets, 1 isolated lepton, at least 2 light jets and $E_T$

- Several backgrounds at play, viz., QCD processes: $t\bar{t}b\bar{b}b\bar{b}$, $t\bar{t}hb\bar{b}$, $t\bar{t}Zb\bar{b}$ and EW processes $t\bar{t}hZ$, $t\bar{t}ZZ$

- Fake backgrounds: $t\bar{t}b\bar{b}+$ jets, $t\bar{t}h+$ jets, $t\bar{t}Z+$ jets, $W^\pm b\bar{b}b\bar{b}+$ jet, $W^\pm c\bar{c}c\bar{c}+$ jets, $W^\pm b\bar{b}+$ jets, $t\bar{t}c\bar{c}c\bar{c}$, misidentifying $c$ or light jets as $b$-tagged jets

- We assume $b$-tagging efficiency of 80%, 10% (1%) mistagging efficiency for $c$-jets (light jets)
\( t\bar{t}hh \) Scale choices

<table>
<thead>
<tr>
<th>Process category</th>
<th>( \mu_T^2 )</th>
<th>( \mu_R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t}HH, t\bar{t}ZZ, t\bar{t}HZ ) ( t\bar{t}Hb\bar{b}, t\bar{t}Zb\bar{b} ) ( t\bar{t} + b's, c's or light jets ) ( W + b's, c's or light jets )</td>
<td>( \frac{1}{4} H_T^2 + 2m_t^2 + {2m_H^2, 2m_Z^2, m_H^2 + m_Z^2 } )</td>
<td>( \frac{1}{4} H_T^2 + 2m_t^2 )</td>
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<tr>
<td></td>
<td>( \frac{1}{4} H_T^2 + m_{H,Z}^2 + 2m_t^2 )</td>
<td>( \frac{1}{4} H_T^2 + 2m_t^2 )</td>
</tr>
<tr>
<td></td>
<td>( \frac{1}{4} H_T^2 + 2m_t^2 )</td>
<td>( \frac{1}{4} H_T^2 + 2m_t^2 )</td>
</tr>
<tr>
<td></td>
<td>( \frac{1}{4} H_T^2 + m_{W}^2 )</td>
<td>( \frac{1}{4} H_T^2 )</td>
</tr>
</tbody>
</table>

**Table:** Renormalisation and factorisation scales used for the various processes
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- For the $t\bar{t}Z/h+\text{ jets}$, we consider a merged sample, where additional jets ensue from QCD radiation including the $g \to b\bar{b}$ splitting.
- We ensure that the additional jets do not contain $>1$ $B$-mesons by requiring that the $B$-hadron closest to the jet axis satisfies $x_B = \frac{|\vec{p}_B|}{|\vec{p}_j|} \times \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_B||\vec{p}_j|} > 0.7$.
- Reflects $b$-quark fragmentation $\rightarrow$ Allows to suppress ”doubly-tagged” $b$-jets.
- We first reconstruct the two Higgs bosons by minimising the following $\chi^2$:

$$\chi^2_{HH} = \frac{(m_{b_i,b_j} - m_h)^2}{\Delta_h^2} + \frac{(m_{b_k,b_l} - m_h)^2}{\Delta_h^2},$$

$i \neq j \neq k \neq l$ run over all the $6$ $b$-tagged jets, $m_h = 120$ GeV taking into account invisible decays of $B$-mesons and $\Delta_h = 20$ GeV.
- We then require require $|m_{b_i,b_j} - m_h| < \Delta_h$ and $|m_{b_k,b_l} - m_h| < \Delta_h$.
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- Then we take the 2 remaining $b$-jets and minimise the following $\chi^2$

$$\chi^2_{t_h} = \frac{(m_{b_i,j_k,j_l} - m_t)^2}{\Delta_t^2},$$

$k \neq l$ and $\Delta_t = 40$ GeV We then require $|m_{b_i,j_k,j_l} - m_t| < \Delta_t$

- Finally we require $m_{t_{lep}}^{vis} < m_t$
Constraining $\kappa_\lambda$ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

[SB, F. Krauss, M. Spannowsky; 2019]

- At the design luminosity of 30 ab$^{-1}$, we expect $\sim 260$ signal events for $\kappa_\lambda = 1$ and $\sim 1900$ background events, with $S/B \sim 0.14$ and statistical significance of $S/\sqrt{B} \sim 5.9$.

- Upon taking $\kappa_{t\bar{t}hh} = 0$, one obtains (using the CLs method) at 68% CL with 5% (10%) systematic uncertainty

\[
-3.20 < \kappa_\lambda < 2.60 \quad (\sim 3.43 < \kappa_\lambda < 2.92) \quad 3/\text{ab}
\]
\[
-2.89 < \kappa_\lambda < 2.15 \quad (\sim 3.27 < \kappa_\lambda < 2.70) \quad 30/\text{ab}
\]

- Upon taking $\kappa_\lambda = 1$, one obtains (using the CLs method) at 68% CL with 5% (10%) systematic uncertainty

\[
-0.59 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.95 \text{ TeV}^{-1} \quad (\sim 0.71 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 1.07 \text{ TeV}^{-1}) \quad 3/\text{ab}
\]
\[
-0.43 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.78 \text{ TeV}^{-1} \quad (\sim 0.63 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.99 \text{ TeV}^{-1}) \quad 30/\text{ab}
\]

- Ultimate goal is to perform a global fit using the $pp \rightarrow hh$, $pp \rightarrow hhj$, $pp \rightarrow hhjj$ and $pp \rightarrow t\bar{t}hh$ with all these couplings to find correlated bounds.
Resonant di-Higgs at HL-LHC and FCC-hh

- Bounds on $\sigma(pp \to H \to hh)$ at HL-LHC (left) from various channels and at FCC-hh (right) from $b\bar{b}b\bar{b}$
  

- Right plot: isocontours of sensitivity on $\kappa^2 \times \text{BR}$ ($\kappa^2 \times \text{BR}$ is defined by $
abla \sigma \left( pp \to H_1 \to H_2 H_2 \to b\bar{b}b\bar{b} \right) = \hat{\sigma}_{H_1} \times \kappa^2 \times \text{BR}$ and $\hat{\sigma}_{H_1}$ is production of SM-like Higgs with mass $m_{H_1}$)

- FCC-hh can set stringent limit on $\kappa \times \text{BR}$ \rightarrow \text{factor } \sim 40 \text{ improvement with respect to HL-LHC}
Summary and Outlook

- Search for Higgs pair production is an important enterprise to understand the Higgs cubic coupling
- Non-resonant di-Higgs searches at the HL-LHC yields a significance of $\sim 3\sigma$
- 100 TeV collider studies show promise for di-Higgs + jet $\rightarrow \kappa\lambda$ can be constrained to $\sim 8\%$
- Possible to disentangle $\kappa_{t\bar{t}hh}$ and $\kappa_{\lambda}$ by combining $pp \rightarrow hh, pp \rightarrow hhj$ and $pp \rightarrow hhjj$ with $pp \rightarrow t\bar{t}hh$. Also other final states in $pp \rightarrow t\bar{t}hh$.
- Possible to constrain $\lambda_{hhhh}$ from one loop EW correction to $t\bar{t}hh$ at FCC-hh [SB, J. Lindert; ongoing]
- Systematic uncertainties need to be understood better in the future in order to make strong claims about these channels
- A global analysis with several di-Higgs channels will ultimately shed light on the couplings of the scalar sector and with the scalar and the top-quarks
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$

[A. Adhikary, SB, R. K. Barman, B. Bhattacharjee, S. Niyogi; 2017]

- **Cleanest channel** in spite of the low rate
- Major backgrounds: QCD-QED $b\bar{b}\gamma\gamma$, $hb\bar{b}$, $t\bar{t}h$, $Zh$
- Dominant fakes: $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}bj\gamma$, $c\bar{c}j\gamma$, $b\bar{b}jj$

### Selection cuts

<table>
<thead>
<tr>
<th>$N_j$ $&lt; 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.4 &lt; \Delta R_{\gamma\gamma} &lt; 2.0$, $0.4 &lt; \Delta R_{bb} &lt; 2.0$, $\Delta R_{bb} &gt; 0.4$</td>
</tr>
<tr>
<td>$100$ GeV $&lt; m_{bb} &lt; 150$ GeV</td>
</tr>
<tr>
<td>$122$ GeV $&lt; m_{\gamma\gamma} &lt; 128$ GeV</td>
</tr>
<tr>
<td>$p_T,bb &gt; 80$ GeV, $p_T,\gamma\gamma &gt; 80$ GeV</td>
</tr>
</tbody>
</table>

### Event rates with 3000 fb$^{-1}$ of integrated luminosity

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signal $hh \rightarrow 2b2\gamma$</th>
<th>Event rates</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>$hh \rightarrow hh$</td>
<td>$N_{bb}$</td>
<td>$t\bar{t}h$</td>
</tr>
<tr>
<td>$2b + 2\gamma$</td>
<td>31.63</td>
<td>21.20</td>
<td>324.91</td>
</tr>
<tr>
<td>lepton veto</td>
<td>31.63</td>
<td>21.20</td>
<td>255.66</td>
</tr>
<tr>
<td>$N_j &lt; 6$</td>
<td>31.04</td>
<td>21</td>
<td>192.05</td>
</tr>
<tr>
<td>$\Delta R$ cuts</td>
<td>22.19</td>
<td>7.75</td>
<td>38.71</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>12.71</td>
<td>1.53</td>
<td>13.80</td>
</tr>
<tr>
<td>$m_{\gamma\gamma}$</td>
<td>12.36</td>
<td>1.5</td>
<td>13.16</td>
</tr>
<tr>
<td>$p_T,bb,p_T,\gamma\gamma$</td>
<td>12.32</td>
<td>1.48</td>
<td>13.03</td>
</tr>
</tbody>
</table>

- **significance**: $S/B = 0.17$ and $S/\sqrt{B} = 1.46$
- With additional $E_T < 50$ GeV, $S/B = 0.19$ and $S/\sqrt{B} = 1.51$
- Changing to: $90$ GeV $< m_{bb} < 130$ GeV: $S/B = 0.19$ and $S/\sqrt{B} = 1.64$
- $b\bar{b}\gamma\gamma^* = b\bar{b}\gamma\gamma + c\bar{c}\gamma\gamma + jj\gamma\gamma$, Fake1 = $b\bar{b}j\gamma + c\bar{c}j\gamma$, Fake2 = $b\bar{b}jj$
• **Multivariate** technique employed to further optimise search

• **Boosted decision tree (BDT)** algorithms chosen

• **Overtaining** checked using the Kolmogorov-Smirnov test

• **Variables chosen** (according to the best discriminatory power):

\[
\begin{align*}
m_{bb}, \ p_{T,\gamma\gamma}, \ \Delta R_{\gamma\gamma}, \ p_{T,bb}, \ \Delta R_{b1\gamma1}, \ p_{T,\gamma1}, \ \Delta R_{bb}, \\
p_{T,\gamma2}, \ \Delta R_{b2\gamma1}, \ \Delta R_{b2\gamma2}, \ p_{T,b1}, \ \Delta R_{b1\gamma2}, \ p_{T,b2}, \ E_T
\end{align*}
\]

• \( S/B = 0.19 \) and \( S/\sqrt{B} = 1.76\sigma \) CMS (ATLAS) projection: 1.6\( \sigma \) (1.05\( \sigma \))
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW$

- Two scenarios considered: leptonic: $b\bar{b}\ell\ell + \slashed{E}_T$ and semi-leptonic: $b\bar{b}\ell jj + \slashed{E}_T$
- Major backgrounds: $t\bar{t}$: leptonic and semi-leptonic, $Wb\bar{b} +$ jets: semi-leptonic, $\ell\ell bb$: leptonic and semi-leptonic
- Subdominant backgrounds: $b\bar{b}h$, $t\bar{t}h$, $t\bar{t}V$, $Vh$, $Vb\bar{b}$, $VVV$: leptonic and semi-leptonic
- Variables for $b\bar{b}\ell\ell + \slashed{E}_T$

$$p_T, \ell_{1/2}, \slashed{E}_T, m_{\ell\ell}, m_{bb}, \Delta R_{\ell\ell}, \Delta R_{bb}, p_T, bb, p_T, \ell\ell, \Delta \phi_{bb \ell\ell},$$

- Variables for $b\bar{b}\ell jj + \slashed{E}_T$

$$p_T, \ell, \slashed{E}_T, m_{jj}, m_{bb}, \Delta R_{jj}, \Delta R_{bb}, p_T, bb, p_T, \ell jj, \Delta \phi_{bb \ell jj}, \Delta R_{\ell jj},$$
Limits on $\kappa\lambda$ from $hh \rightarrow b\bar{b}\gamma\gamma$: Various hypotheses

[A. Adhikary, SB, R. K. Barman, B. Bhattacherjee, S. Niyogi; 2017]

- Our results corroborate with ATLAS’ HL-LHC predictions
  
- $-0.86 < \kappa\lambda < 7.96$ CBA for $\kappa\lambda = 1$ optimisation; SM null hypothesis
- $-0.63 < \kappa\lambda < 8.07$ BDT analysis for $\kappa\lambda = 1$ optimisation; SM null hypothesis
- $-0.81 < \kappa\lambda < 6.06$ BDT analysis for $\kappa\lambda = 5$ optimisation; SM null hypothesis
- $-1.24 < \kappa\lambda < 6.49$ BDT analysis for $\kappa\lambda = 5$ optimisation; $\kappa = 5$ null hypothesis.
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}T^+ T^-$

- Major backgrounds: $t\bar{t}$ (hadronic, semi-leptonic and leptonic), $\ell\ell b\bar{b}$, $hb\bar{b}$, $Z\ell$, $t\bar{t}X$, $b\bar{b}jj$

- Variables for $\tau_h\tau_h$, $\tau_h\tau_\ell$ and $\tau_\ell\tau_\ell$:

$$p_T, bb, m_{bb}, \Delta R_{bb}, M_{\tau_h\tau_h}, m_{T2}, \Delta \phi_{\tau_h \tau_1} E_T, m_{\text{vis}}^{hh}, p_{T,hh}, \Delta R_{\text{vis}}^{hh}$$

$$p_T, bb, m_{bb}, \Delta R_{bb}, M_{\tau_h\tau_1}, m_{T2}, \Delta \phi_{\tau_h \tau_1} E_T, \Delta \phi_{\tau_\ell \tau_2} E_T, m_{\text{vis}}^{hh}, \Delta R_{\text{vis}}^{hh}$$

$$p_T, bb, m_{bb}, \Delta R_{bb}, M_{\tau_1\tau_1}, m_{T2}, \Delta \phi_{\tau_1 \tau_2} E_T, \Delta \phi_{\tau_\ell \tau_2} E_T, m_{\text{vis}}^{hh}$$

- $\tau_h\tau_h$: $S/B = 0.013$, $S/\sqrt{B} = 0.74$; $\tau_h\tau_\ell$: $S/\sqrt{B} = 0.49$; $\tau_\ell\tau_\ell$: $S/\sqrt{B} = 0.08$
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\tau^+\tau^-$

![Histograms showing di-Higgs production with $M_{\tau^+\tau^-}$ and $m_{\tau^+\tau^-}$ distributions.]

Shankha Banerjee (IPPP, Durham University)

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Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW^*$

Semi-leptonic: $S/B = 1.2 \times 10^{-4}$ and $S/\sqrt{B} = 0.13$
Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- We study fully leptonic: $\ell^+\ell^-\gamma\gamma + \slashed{E}_T$ and semi-leptonic: $\ell jj\gamma\gamma + \slashed{E}_T$ states
- Fully hadronic case entails an enormous background
- Backgrounds: $t\bar{t}h$, $Zh + \text{jets}$, $\ell\ell\gamma\gamma + \text{jets (leptonic)}$ and $Wh + \text{jets}$, $\ell\nu\gamma\gamma + \text{jets}$ (in addition for semi-leptonic case)
- In addition demand $b$-jet veto to control the $t\bar{t}h$ backgrounds
- Variables for $\ell^+\ell^-\gamma\gamma + \slashed{E}_T$
  
  \[ p_{T,\ell(1,2)}, \slashed{E}_T, m_{\ell\ell}, m_{\gamma\gamma}, \Delta R_{\gamma\gamma(\ell\ell)}, p_{T,\ell\ell}, p_{T,\gamma\gamma}, \Delta \phi_{\ell\ell\gamma\gamma} \]

- Variables for $\ell jj\gamma\gamma + \slashed{E}_T$
  
  \[ p_{T,\ell_1}, \slashed{E}_T, m_{\gamma\gamma}, \Delta R_{\gamma\gamma}, p_{T,\gamma\gamma}, p_{T,\ell_1}, \Delta \phi_{\ell_1\gamma\gamma}, \Delta R_{\ell_1}, m_T \]
Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- **Leptonic:** $S/B = 0.40$; Less than 1 signal event; Higher luminosity/energy
Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- Semi-leptonic: $S/B = 0.11$; Less than 5 signal events; Higher luminosity/energy: Perfect channel at 100 TeV colliders
Non resonant di-Higgs production at the HL-LHC: $4W$

- We consider $\ell^+\ell^- + 4j + \not{E}_T$ ($SS2\ell$), $3\ell + 2j + \not{E}_T$ ($3\ell$) and $4\ell + \not{E}_T$ ($4\ell$).
- Lose cleanliness (rate) upon including more jets (leptons).
- Major backgrounds for $SS2\ell$: $WZ$, $t\bar{t}$, $W^+W^-$, $Vh$, $t\bar{t}X$, $VVV$, $4\ell$.
- For $SS2\ell$, demand two same-sign leptons with $p_T > 25$ GeV and at least two jets with $p_T > 30$ GeV.
- Major backgrounds for $3\ell$: Same as before save for $W^+W^-$.
- For $3\ell$, $p_{T,\ell_{1/2/3}} > 25, 20, 15$ GeV and $|m_Z - m_{\ell\ell}| > 20$ GeV.
- Variables for $SS2\ell$
  
  $$m_{\ell^+\ell^-}, \Delta R_{\ell_ijk}, m_{jj}$$

- Variables for $3\ell$
  
  $$m_{\ell_i\ell_j}, \Delta R_{\ell_i\ell_j}, m_{\ell\ell\ell}, m_{\text{eff}}, \not{E}_T, p_{T,\ell_i}, n_{\text{jet}}$$
Non resonant di-Higgs production at the HL-LHC: $4W$

- $SS2\ell$: $S/B = 1 \times 10^{-3}$, $S/\sqrt{B} = 0.11$
Non resonant di-Higgs production at the HL-LHC: $4W$

3$\ell$: $S/B = 3 \times 10^{-3}$, $S/\sqrt{B} = 0.20$
Machinery in a nutshell

- Di-Higgs samples and backgrounds generated at LO with MG5_aMC@NLO
- Signal samples decayed using Pythia-6
- NN23LO parton distribution function employed
- Default factorisation and renormalisation scales used
- Shower + hadronisation using Pythia-6
- Delphes-3.4.1 used for detector simulation
- Jets: anti-$kT$ algorithm, $p_T > 20$ GeV, $R = 0.4$ (FastJet)
- Total energy around $e, \mu, \gamma$ required to be < 12%, 25%, 12% within $\Delta R = 0.5$
- $b$-tag efficiency: 70%, $j \rightarrow b$: 1%, $c \rightarrow b$: 30%
Dominant $t\bar{t}$ background can be greatly tackled with this variable

Designed for the case where a pair of equal mass particles ($A$ and $A'$) decay:

$$A \rightarrow B + C, \quad A' \rightarrow B' + C'$$

$B$ and $B'$ are visible particles and $C$ and $C'$ are not observed

$m_{T2}$ gives the maximal possible mass of parent particle $A$; provides greatest lower bound on $m_A = m_{A'}$

$$m_{T2}(m_B, m_{B'}, b_T, b_{T'}, p_T^\Sigma, m_C, m_{C'}) \equiv \min_{c_T+c_{T'}=p_T^\Sigma} \{\max(m_T, m_{T'})\}$$

$$m_T^2(b_T, c_T, m_b, m_c) \equiv m_b^2 + m_c^2 + 2(e_be_c - b_T \cdot c_T), \text{ with } e^2 = m^2 + p_T^2$$

Bounded above by top mass but unbounded below for the di-Higgs process
FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale $R$, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to $R_{\text{filt}}$ and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

Given a hard jet $j$, obtained with some radius $R$, we then use the following new iterative decomposition procedure to search for a generic boosted heavy-particle decay. It involves two dimensionless parameters, $\mu$ and $y_{\text{cut}}$:

1. Break the jet $j$ into two subjets by undoing its last stage of clustering. Label the two subjets $j_1, j_2$ such that $m_{j_1} > m_{j_2}$.

2. If there was a significant mass drop (MD), $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \frac{\min(p_{j_1}, p_{j_2})^2}{m_j^2} \Delta R_{j_1, j_2} > y_{\text{cut}}$, then deem $j$ to be the heavy-particle neighbourhood and exit the loop. Note that $y \simeq \min(p_{j_1}, p_{j_2}) / \max(p_{j_1}, p_{j_2})$.

3. Otherwise redefine $j$ to be equal to $j_1$ and go back to step 1.

The final jet $j$ is to be considered as the candidate Higgs boson if both $j_1$ and $j_2$ have $b$ tags. One can then identify $R_{bb}$ with $\Delta R_{j_1, j_2}$. The effective size of jet $j$ will thus be just sufficient to contain the QCD radiation from the Higgs decay products.

In practice the above procedure is not yet optimal for LHC at the transverse momenta of interest, $p_T \sim 200 - 300$ GeV because, from eq. (1), $R_{bb} \gtrsim 2m_b/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{bb}^4$ [9]. A second novel element of our analysis is to filter the Higgs neighbourhood. This involves resolving it on a finer angular scale, $R_{\text{filt}} < R_{bb}$, and taking the three hardest objects (subjets) that appear — thus one captures the dominant $O(\alpha_s)$ radiation from the Higgs decay, while eliminating much of the UE contamination. We find $R_{\text{filt}} = \min(0.3, R_{bb}/2)$ to be rather effective. We also require the two hardest of the subjets to have the $b$ tags.
Figure 1: Left: Schematic of the fully hadronic decay sequences in (a) $W^+W^-$ and (c) dijet QCD events. Whereas a $W$ jet is typically composed of two distinct lobes of energy, a QCD jet acquires invariant mass through multiple splittings. Right: Typical event displays for (b) $W$ jets and (d) QCD jets with invariant mass near $m_W$. The jets are clustered with the anti-$k_T$ jet algorithm [31] using $R = 0.6$, with the dashed line giving the approximate boundary of the jet. The marker size for each calorimeter cell is proportional to the logarithm of the particle energies in the cell. The cells are colored according to how the exclusive $k_T$ algorithm divides the cells into two candidate subjets. The open square indicates the total jet direction and the open circles indicate the two subjet directions. The discriminating variable $t_2/t_1$ measures the relative alignment of the jet energy along the open circles compared to the open square.
**Table:** Table shows the generation level cross-sections for the signal and background processes. We require the Higgs bosons to decay to a pair of $b/c$ quarks, the $Z$-bosons to all quarks. Furthermore, we require the $W^{\pm}$-bosons to decay leptonically. These branching ratios are included in these cross-sections. For the signals, $\kappa_\lambda$, is the ratio of the Higgs self-coupling to the SM value and $\kappa_{t\bar{t}hh}$ is the coupling of the four point $t\bar{t}hh$ interaction. The processes with $b/c$ quarks in the final state in the matrix element level have a further requirement of $m_{bb}/cc/bc > 50$ GeV, $p_T(b/c) > 25$ GeV, $D$-parameter $> 0.4$, $|y| < 4.0$.