# Standard Model Higgs boson pair production in the $(b\bar{b})(b\bar{b})$ final state


Danilo Enoque Ferreira de Lima


BOOST2014


Institute for Particle Physics Phenomenology - IPPP/Durham
University of Glasgow

*danilo.ferreiradelima@glasgow.ac.uk*

*dferreir@mail.cern.ch*


August 19, 2014

# Table of Contents

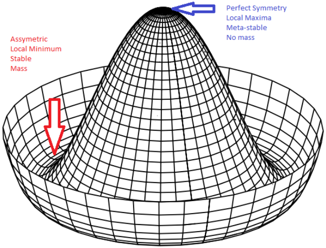
# Introduction

- The recently discovered Higgs particle is key to the Electroweak Symmetry Breaking mechanism.
- To find new physics or validate the SM, we need to study the Higgs potential.
- This can be done through the study of SM *HH* production.
- BSM *HH* searches (see Nikos' talk!) focus on new resonances.
- SM *HH* searches provide a way of measuring the shape of the Higgs potential itself $\rightarrow$ needs to be understood regardless of finding new resonances.

$$\begin{aligned} \mathcal{L}_{Higgs} &= D_\mu \phi^\dagger D^\mu \phi - V(\phi) \\ V(\phi) &= -\mu^2 \phi^\dagger \phi + \frac{\lambda}{2}(\phi^\dagger \phi)^2 \end{aligned}$$

# The Higgs potential

- The Higgs boson has a non-zero vaccuum expectation value due to the potential $|V(\phi)|$ and couples to other particles, giving them mass.
- The electroweak symmetry breaking mechanism is encoded in the Higgs potential in the Standard Model.
  - Measuring the $\phi^\dagger\phi$ coefficients helps validating the SM or finding new physics!



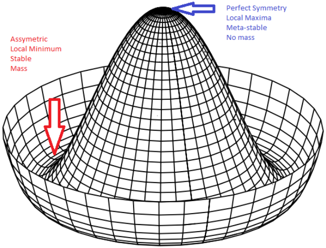

$$V(\phi) = -\mu^2\phi^\dagger\phi + \frac{\lambda}{2}(\phi^\dagger\phi)^2$$

# The Higgs potential after electroweak symmetry breaking

- The Higgs potential can be expanded after electroweak symmetry breaking as:

$$\mathcal{V} = \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4$$

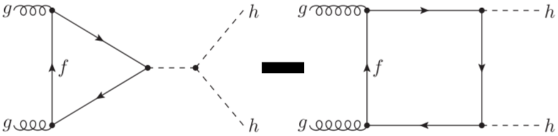
- We can try to measure the $h^3$ coefficient in the HL-LHC, but the $h^4$ might not work.
- SM expects $\lambda = \tilde{\lambda} = M_h^2 / 2v^2 \sim 0.13$, but we need to measure it.



# Higgs self-coupling in the Standard Model

- Di-Higgs produced with *box* and *triangle* diagrams.
- Higgs interaction with gluons through loops modelled in effective theory using $-\frac{\alpha_S}{12\pi} G^a_{\mu\nu} G^{a\ \mu\nu} \log(1 + h/v)$ term.

$$
\begin{aligned}
-\mathcal{L} \quad \supset \quad & \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4 \\
& - g m_V V^2 h - \frac{m_f}{v} \bar{f} f h \\
& - \frac{\alpha_S}{12\pi} G^a_{\mu\nu} G^{a\ \mu\nu} \log(1 + h/v)
\end{aligned}
$$



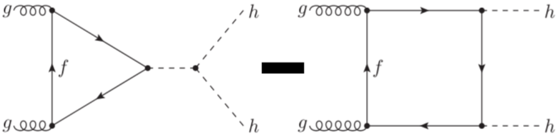

PRD **83** (2011) 094018, NPB **359** (1991) 283

PLB **264** (1991) 440, PRL **70** (1993) 1372, NPB **453** (1995) 17

# Higgs self-coupling in the Standard Model

- Di-Higgs produced with *box* and *triangle* diagrams.
- Higgs interaction with gluons through loops modelled in effective theory using $-\frac{\alpha_S}{12\pi} G^a_{\mu\nu} G^{a\ \mu\nu} \log(1 + h/v)$ term.

$$
\begin{aligned}
-\mathcal{L} \quad \supset \quad & \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4 \\
& - g m_V V^2 h - \frac{m_f}{v} \bar{f} f h \\
& - \frac{\alpha_S}{12\pi v} G^a_{\mu\nu} G^{a\ \mu\nu} h + \frac{\alpha_S}{24\pi v^2} G^a_{\mu\nu} G^{a\ \mu\nu} h^2 + \ldots
\end{aligned}
$$

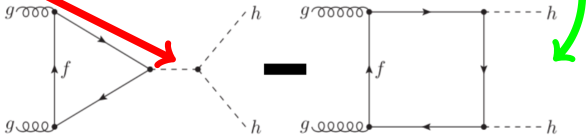



PRD **83** (2011) 094018, NPB **359** (1991) 283
PLB **264** (1991) 440, PRL **70** (1993) 1372, NPB **453** (1995) 17

# Higgs self-coupling in the Standard Model

- Di-Higgs produced with *box* and *triangle* diagrams.
- Higgs interaction with gluons through loops modelled in effective theory using $-\frac{\alpha_S}{12\pi} G^a_{\mu\nu} G^{a\ \mu\nu} \log(1 + h/v)$ term.

$$
\begin{aligned}
-\mathcal{L} \supset\ & \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4 \\
& - g m_V V^2 h - \frac{m_f}{v} \bar{f} f h \\
& - \frac{\alpha_S}{12\pi v} G^a_{\mu\nu} G^{a\ \mu\nu} h + \frac{\alpha_S}{24\pi v^2} G^a_{\mu\nu} G^{a\ \mu\nu} h^2 + \ldots
\end{aligned}
$$




PRD **83** (2011) 094018, NPB **359** (1991) 283

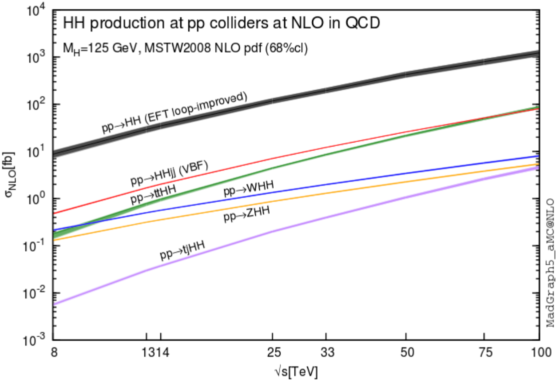
PLB **264** (1991) 440, PRL **70** (1993) 1372, NPB **453** (1995) 17

# Progress in $HH$ production cross section calculations

- **HH**
  - LO full $m_t$: Plehn, Spira, Zerwas (Nucl. Phys. B **479**) and many others.
  - NLO eff. $m_t$: Dawson, Dittmaier, Spira (Phys. Rev. D **58** (1998)) $\rightarrow$ http://people.web.psi.ch/spira/hpair/
  - NLO full $m_t$: Grigo, Hoff, Melnikov, Steinhauser (PoS RADCOR **2013** (2013) 006)
  - NNLO eff. $m_t$: De Florian, Mazzitelli (Phys. Rev. Lett. **111** (2013) 201801)
- **HH + 1 jet**
  - LO full $m_t$: Dolan, Englert, Spannowsky (JHEP **1210** (2012) 112); Li, Yan, Zhao (Phys. Rev. D **89** (2014) 033015); Maierhöfer, Papaefstathiou (JHEP **1403** (2014) 126).
- **HH + 2 jets**
  - LO full $m_t$: Dolan, Englert, Greiner, Spannowsky (Phys. Rev. Lett. **112** (2014) 101802).

# $HH$ production cross section in $pp$ colliders

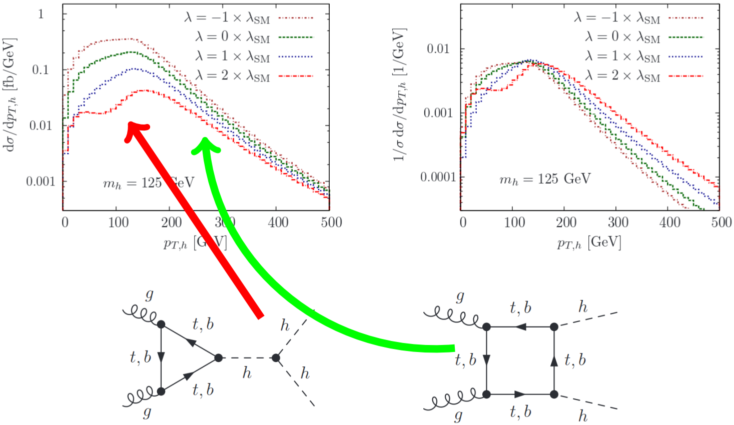
- $pp \to HH$ has the highest cross section.
- We will study this production at 14 TeV, in the LHC with 3 $ab^{-1}$ of luminosity.




PLB **732** (2014) 142

# Higgs self-coupling in *HH*

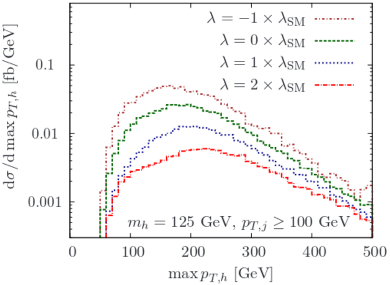
- Good sensitivity to the self-coupling $\lambda$ at low Higgs $p_T$.
- **But needs to boost due to huge backgrounds at low $p_{T,h}$ $\rightarrow$ looses sensitivity to $\lambda$.**

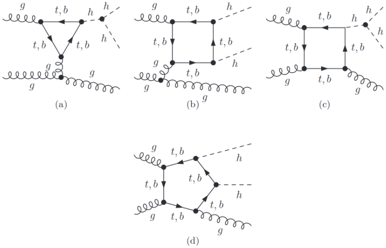



JHEP **1210** (2012) 112

# Keeping the boost and sesitivity

- Sensitivity is lost with the boost in *HH* production.
- But we can still retain sensitivity if extra jets are considered.
- No extra jets are used in the next slides.




JHEP **1210** (2012) 112

# The di-Higgs production decay channels

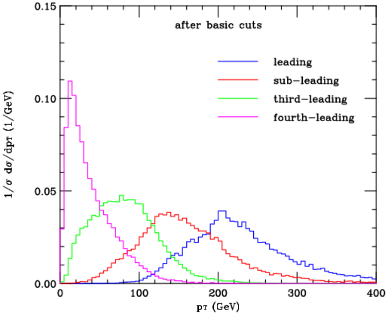
- Compromise between B.R. and clean signal.
  - $HH \to (b\bar{b})(W^+W^-) \to$ high contamination from $t\bar{t}$.
  - $HH \to (b\bar{b})(\tau^+\tau^-) \to$ lepton signature from $\tau$ decay and the $t\bar{t}$ background can be reduced in high boost.
  - $HH \to (b\bar{b})(\gamma\gamma) \to$ clean photon identification.
  - $HH \to (b\bar{b})(b\bar{b}) \to$ large signal, but large QCD multi-jet backgrounds.
- ATLAS has a public result on the (BSM) resonant $HH \to (b\bar{b})(b\bar{b})$ in ATLAS-CONF-2014-005.

| Channel | BR (%) | Events / 3 ab$^{-1}$ |
|---|---|---|
| $(b\bar{b})(W^+W^-)$ | 24.9 | 25300 |
| $(b\bar{b})(\tau^+\tau^-)$ | 7.3 | 7500 |
| $(b\bar{b})(\gamma\gamma)$ | 0.27 | 270 |
| $(b\bar{b})(b\bar{b})$ | 33.4 | 34000 |
| $(\gamma\gamma)(\gamma\gamma)$ | 0.001 | 1 |

PRD **69** (2004) 053004, JHEP **1210** (2012) 112; PLB **728** (2014) 308
PRD **87** (2013) 011301, ATLAS-CONF-2014-005, LHC Higgs XSWG, 1101.0593 [hep-ph]

# $HH \to (b\bar{b})(b\bar{b})$

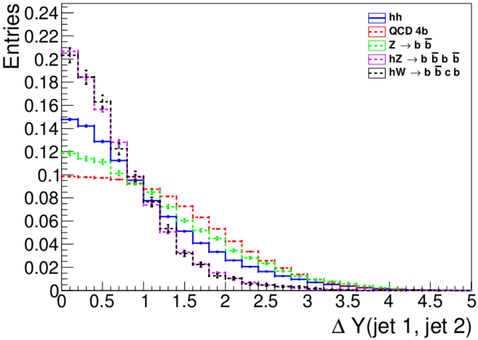
- The highest probability for a Higgs decay is the $H \to b\bar{b}$.
- There is a lot of QCD background to this at low energies.
- We will try to increase the signal-to-background ratio for Higgs bosons with a high boost.
- We will select 2 large-$R$ jets with $p_T > 200$ GeV and make small-$R$ jets inside of them with $p_T > 40$ GeV.




JHEP **08** (2014) 030

# Large-$R$ jet preselection

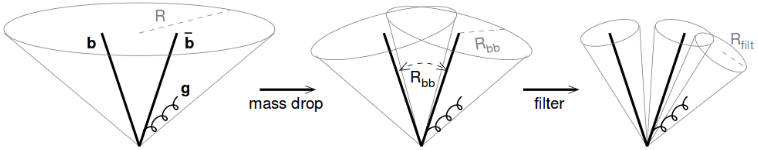
- We enforce that the 2 selected large-$R$ jets are central.
- The QCD background has a much higher cross section and it is less central.
- After applying this cut, we will try two procedures to detect the Higgs: apply the BDRS tagger and use the Shower Deconstruction technique.




JHEP **08** (2014) 030

# Detecting a Higgs with BDRS

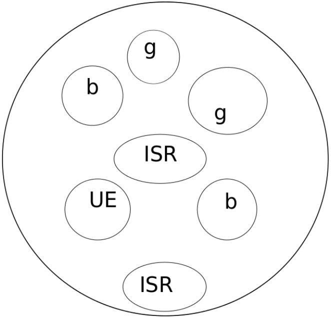
- Undo the large-$R$ jet clustering.
- Parameters: $\mu = 0.667$, $y_{cut} = 0.33$, $R_{filt} = 0.5 \times \Delta R(j_1, j_2)$ (or 0.3, if this value is too big).
- Take the three highest $p_T$ filtered jets as the Higgs.
- For the event to be accepted, the highest $p_T$ jets must be $b$-tagged.




Phys. Rev. Lett. **100** (2008) 242001

# Detecting a Higgs with Shower Deconstruction

- Use jet contituents to calculate sub-jets with smaller $R$ ($R_{sub} = 0.2$ in this analysis).
- For all possible (sub-jet $\to$ decay product/ISR/pile-up/UE) associations, calculate a *signal weight* and a *background weight*.
- The weights are related to the probability of the association to describe a signal or background shower history.

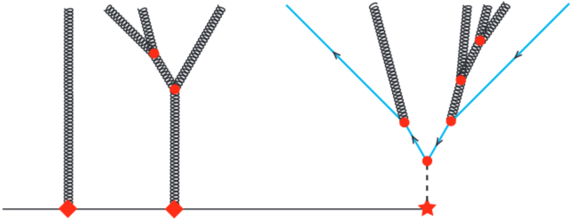



Example subjet association

PRD **84** (2011) 074002

# Detecting a Higgs with Shower Deconstruction

- Use jet contituents to calculate sub-jets with smaller $R$ ($R_{sub} = 0.2$ in this analysis).
- For all possible (sub-jet $\rightarrow$ decay product/ISR/pile-up/UE) associations, calculate a *signal weight* and a *background weight*.
- The weights are related to the probability of the association to describe a signal or background shower history.

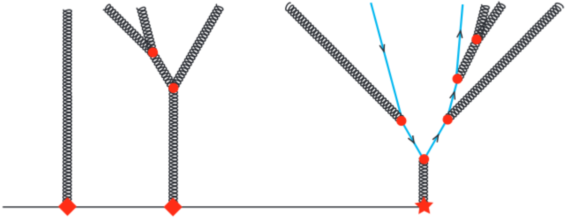


Higgs decay $\rightarrow$ SD associates sub-jets with final state elements

PRD **84** (2011) 074002

# Detecting a Higgs with Shower Deconstruction

- Use jet contituents to calculate sub-jets with smaller $R$ ($R_{sub} = 0.2$ in this analysis).
- For all possible (sub-jet $\rightarrow$ decay product/ISR/pile-up/UE) associations, calculate a *signal weight* and a *background weight*.
- The weights are related to the probability of the association to describe a signal or background shower history.



QCD splitting $\rightarrow$ SD associates sub-jets with final state elements

PRD **84** (2011) 074002

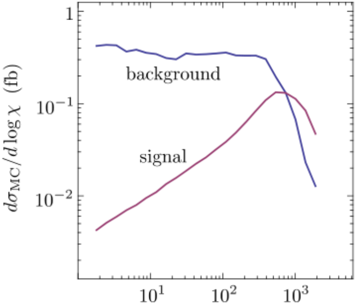
# Shower Deconstruction weight

- The ratio of the signal and background weights provide the discriminant variable ($\chi$).
- The conditional probabilities are calculated analytically. The full expression for the probabilities is studied in PRD **84** (2011) 074002.
- A cut in $\chi$ provides the discrimination power. It can be scanned for different rejection rates and efficiencies.

$$\chi(\mathrm{momenta}) \;=\; \frac{P(\mathrm{momenta}|\mathrm{signal})}{P(\mathrm{momenta}|\mathrm{background})}$$

# Shower Deconstruction weight

- The ratio of the signal and background weights provide the discriminant variable ($\chi$).
- The conditional probabilities are calculated analytically. The full expression for the probabilities is studied in PRD **84** (2011) 074002.
- A cut in $\chi$ provides the discrimination power. It can be scanned for different rejection rates and efficiencies.

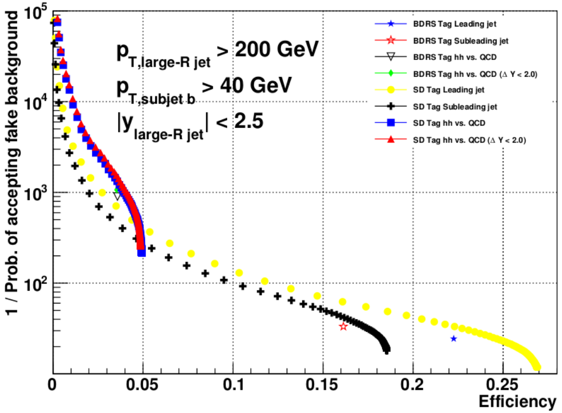



PRD **84** (2011) 0740

# Shower Deconstruction performance

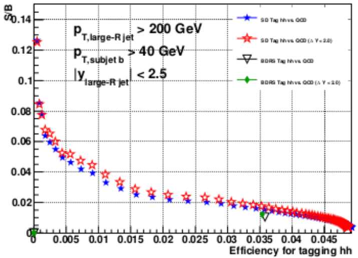
JHEP **08** (2014) 030

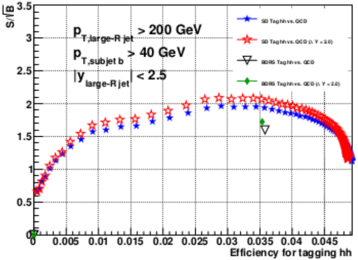
- We compare Shower Deconstruction with BDRS.
- It achieves, nevertheless, a much higher rejection.
- It could do even better with a lower transverse momentum selection requirement on sub-jets.



# *hh* detection performance

- The higher rejection of SD allows it to improve the signal-to-background ratio, holding a reasonable significance.
- This pushes the signal efficiency to low values: only acceptable because of the large $H \to b\bar{b}$ branching ratio.



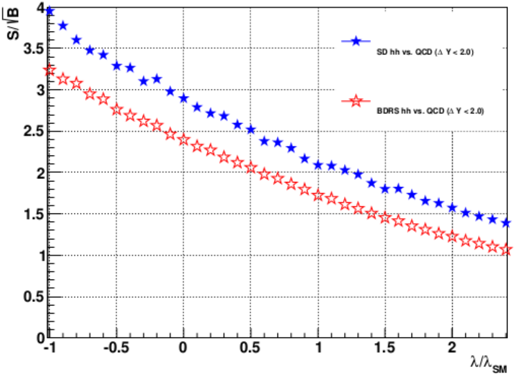




JHEP **08** (2014) 030

# A limit set on $\lambda$



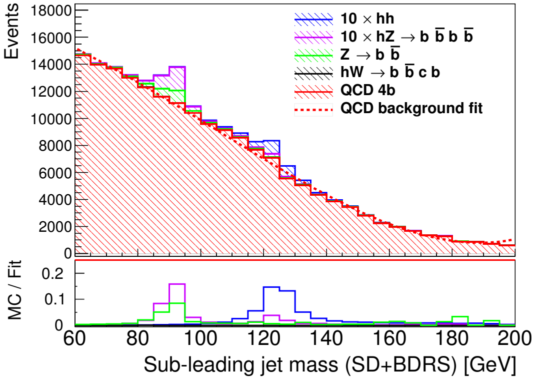
- This allows one to set a limit in the possible values of $\lambda$.
- The SM value ($\lambda = \lambda_{SM}$) can be probed with 95% ($2\sigma$) Confidence Level.
- Effect of the systematic uncertainties are not shown.



# A handle on the QCD background

JHEP **08** (2014) 030

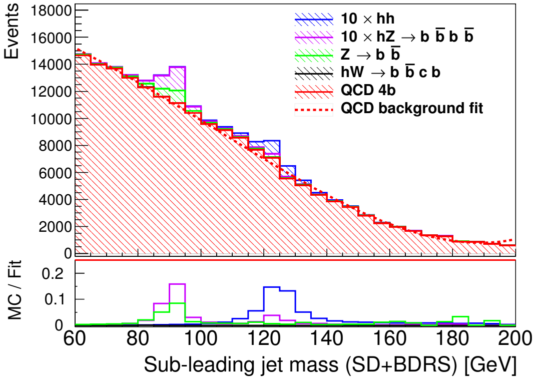
- Instead of using SD to identify both Higgses, one can loosen one SD tag and use BDRS for the second Higgs.
- No mass cut is applied on the BDRS-tagged Higgs.



# A handle on the QCD background



- This defines a side-band region → estimate the QCD background in the signal region by a fit extrapolation.
- The Higgs self-coupling can be compared to the $hZ$ coupling.



# Summary

- Higgs physics are at the core of electroweak symmetry breaking mechanism. Unraveling this mechanism is one of the main goals of the LHC Run II.
- New techniques can help analysing their properties. Shower Deconstruction is one of them and, amongst others it can be very useful in the analyses to come.
- The HL-LHC can be very good at detecting the Standard Model (or BSM) double Higgs production.
- Boosting the Higgs and using jet sub-structure techniques one can keep a reasonable signal-to-background ratio.
- If extra jets are produced, JHEP **1210** (2012) 112 shows that one can retain sensitivity to $\lambda$.

# The End

# Yields after cuts

| Selection | hh | QCD 4b | hW | Z $\rightarrow$ bb | hZ | $s/b$ | $s/\sqrt{b}$ |
|---|---|---|---|---|---|---|---|
| Event selection | 2.31 | 6941.860 | 4.854 | 266.472 | 3.787 | 0.000320 | 1.48 |
| Leading jet SD | 0.514 | 208.728 | 0.587 | 5.360 | 0.439912 | 0.00239 | 1.919 |
| Leading jet BDRS | 0.0982 | 54.223 | 0.0117 | 0.741 | 0.123 | 0.00178 | 0.724 |
| Both SD-tags | 0.0784 | 4.226 | $<$ 0.00096 | 0.0294 | 0.00605 | 0.0184 | 2.082 |
| Both BDRS-tags | 0.0817 | 6.671 | 0.000192 | 0.0593 | 0.00946 | 0.0121 | 1.723 |
| Loose SD and BDRS rec. | 0.621 | 592.145 | 0.686 | 17.228 | 0.627 | 0.00101 | 1.376 |
| Loose SD and BDRS | 0.0989 | 17.080 | 0.000612 | 0.129 | 0.0231 | 0.00574 | 1.305 |

Table : Expected cross sections after selection for $\lambda/\lambda_{SM} = 1$. The significance estimate, $s/\sqrt{b}$, is given for an integrated luminosity of 3000 fb$^{-1}$. The two final rows show the results obtained using Shower Deconstruction on the leading jet and the BDRS for the Higgs reconstruction on the sub-leading one. In the last row a final mass cut on the sub-leading Higgs mass is applied.