

# Note

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## 1 Signal and background

Signal events are 3 Higgs events in BSM. I use MadGraph to generate by following commands:

```
import model cxSM_VLF_EFT
generate g g > h h h
```

then pass the events through the Pythia and Delphes. In Pythia, I set the branching ratio of Higgs so that it only decays to b quarks.

Background events are 6b events in SM. I use MadGraph to generate by following commands:

```
generate p p > b b b b~ b~ b~
```

then pass the events through the Pythia and Delphes.

## 2 Transverse momentum and pseudorapidity distribution

In each event there are 6 b quarks. I order these b quarks by transverse momentum  $p_T$ , then plot  $p_T$  and pseudorapidity  $\eta$  distributions.

Figure 1 is the  $p_T$  and  $\eta$  distributions of b quarks for background.

Figure 2 is the  $p_T$  and  $\eta$  distributions of b quarks for signal.

## 3 Delta R and transverse momentum distribution

For signal, I plot the  $\Delta R(b,b)$  distribution of two b decays from the same Higgs. Then I plot  $\Delta R(b,b)$  against  $p_T(b,b)$ . The result is in Figure 3. As can be seen from the plot,  $\Delta R$  get smaller at higher  $p_T(b,b)$ .



Figure 1:  $p_T$  and  $\eta$  distributions of b partons for background events. They are ordered by  $p_T$ .



Figure 2:  $p_T$  and  $\eta$  distributions of b partons for signal events. They are ordered by  $p_T$ .



Figure 3:  $\Delta R(b,b)$  distribution and  $\Delta R(b,b)$  against  $p_T(b,b)$  plot

## 4 Cutflow table

I apply the  $\eta$  and  $p_T$  cuts sequentially and count how many event can pass the cuts. The results are in Table 1 and Table 2.

Table 1: 1000 background events. Those background events is generated in  $\sqrt{s} = 13$  TeV with the cut  $b$   $p_T > 10$  GeV in MadGraph.

| Cut                        | number of events pass |
|----------------------------|-----------------------|
| 6 b-partons $ \eta  < 2.5$ | 330                   |
| 6 b-partons $p_T < 25$ GeV | 11                    |
| 4 b-partons $p_T < 40$ GeV | 8                     |

Table 2: 1000 signal events.

| Cut                        | number of events pass |
|----------------------------|-----------------------|
| 6 b-partons $ \eta  < 2.5$ | 732                   |
| 6 b-partons $p_T < 25$ GeV | 534                   |
| 4 b-partons $p_T < 40$ GeV | 498                   |

## 5 Construction of bb-pairs

To construct the bb-pairs from the same Higgs, the typical strategy is to try all combinatoric and find the minimal mass difference between all pairs, i.e. minimize this

$$\chi^2 = [M(b_1b_2) - M(b_3b_4)]^2 + [M(b_1b_2) - M(b_5b_6)]^2 + [M(b_3b_4) - M(b_5b_6)]^2$$

where  $M(b_i b_j)$  means the invariant mass of b-parton  $i$  and b-parton  $j$ .

The other strategy is to minimize mass difference to the SM Higgs mass

$$\chi^2 = [M(b_1b_2) - M_H]^2 + [M(b_3b_4) - M_H]^2 + [M(b_5b_6) - M_H]^2$$

I implement these two methods to construct bb-pairs and test on the 10,000 signal events in parton level. The result is as follows:

- Method 1 (mass difference between all pairs): accuracy = 0.863
- Method 2 (mass difference to the SM Higgs mass): accuracy = 0.875

Method 2 is better for identifying the true Higgs pair.

## 6 Absolute cross section

Absolute cross section is defined as follow

$$\sigma_{\text{abs}} = \sigma \times \frac{\text{number of events pass the cut}}{\text{number of events}}$$

I have generated background events with different cuts in MadGraph, the detailed information of cuts is in Table 3. I calculate their absolute cross section and check if it is the same or not. The result is in Table 4.

From the Table 4, if the number of event is large enough the absolute cross section will be similar.

## 7 The problem for generating $pp \rightarrow 6b$ events

Failed to generate the requested number of events

Table 3: The cuts applied on the different run. Where  $p_T$  means the minimum transverse momentum of b and  $|\eta|$  means the range of b (-1 means no restriction).

| No. | $p_T$ (GeV) | $ \eta $ |
|-----|-------------|----------|
| 1   | 0           | -1       |
| 2   | 10          | 5        |
| 3   | 10          | 3        |
| 4   | 20          | 3        |
| 5   | 0           | -1       |
| 6   | 10          | -1       |

Table 4: Absolute cross section. Where the selection cut is  $p_T > 20$  GeV,  $|\eta| < 3$ .

| No. | total event | cross section | events pass selection | absolute cross section |
|-----|-------------|---------------|-----------------------|------------------------|
| 1   | 339         | 2731.9362     | 0                     | 0.0                    |
| 2   | 4761        | 71.316651     | 190                   | 2.846                  |
| 3   | 9054        | 35.225852     | 694                   | 2.700                  |
| 4   | 4207        | 2.7698473     | 4183                  | 2.754                  |
| 5   | 1000        | 2531.9304     | 0                     | 0.0                    |
| 6   | 1000        | 70.158431     | 27                    | 1.894                  |

## 8 $pp \rightarrow 4b$

I use MadGraph to generate 4b events by following commands:

```
generate p p > b b b~ b~
```

In MadGraph, I apply the cuts:  $p_T > 25$  GeV,  $|\eta| < 2.5$  for b. Pass those events through Pythia, then check how many events there are 6 b-hadrons final state.

In 100,000 events, there are 6,916 events having greater than or equal to 6 b-hadrons. The distribution of number of b-hadrons is in Figure 4.



Figure 4: Number of b-hadrons in Pythia final state.

Pass events through Delphes. In Delphes the b-tagging efficiency is set to 1.

Figure 5 is the number of jets and number of b-jets distributions. In 100,000 events, there are 173 events having greater than or equal to 6 b-jets.

## 9 Comparison for $pp \rightarrow 4b$ and $pp \rightarrow 6b$ event

To compare  $pp \rightarrow 4b$  and  $pp \rightarrow 6b$  events, I plot the  $p_T$ ,  $\eta$  and total invariant mass of 6 b-jets for both.

The number of events of 6 b-jets for  $pp \rightarrow 4b$  is 2051 and for  $pp \rightarrow 6b$  is 1408. I scaled the number of events for  $pp \rightarrow 4b$  to be the same as  $pp \rightarrow 6b$ .



Figure 5: Number of jets and number of b-jets.

Figure 6 is  $p_T$  and  $\eta$  distributions. Figure 7 is total invariant mass of 6 b-jets distributions. Their distributions look similar.

## 10 Cutflow table for b-jets

I apply following cut sequentially and count how many events can pass these cuts. Table 5 is the result for pp->4b events. Table 6 is the result for pp->6b events. Table 7 is the result for signal events.

- Cut 1: There are greater than or equal to 6 b-jets.
- Cut 2: There are greater than or equal to 6 b-jets satisfy  $|\eta| < 2.5$ .
- Cut 3: There are greater than or equal to 6 b-jets satisfy  $p_T > 25$  GeV.
- Cut 4: There are greater than or equal to 4 b-jets satisfy  $p_T > 40$  GeV.

Table 5: 1,000,000 pp->4b events. Those events are generated in  $\sqrt{s} = 14$  TeV with the cuts:  $p_T > 25$  GeV,  $|\eta| < 2.5$  for b in MadGraph.

| Cut | number of event pass |
|-----|----------------------|
| 1   | 1783                 |
| 2   | 1565                 |
| 3   | 1059                 |
| 4   | 735                  |





Figure 6:  $p_T$  and  $\eta$  distributions of b-jets for  $pp \rightarrow 4b$  and  $pp \rightarrow 6b$  events. They are ordered by  $p_T$ .



Figure 7: The distribution of total invariant mass of 6 b-jets for pp->4b and pp->6b events.

Table 6: 10,000 pp->6b events. Those events are generated in  $\sqrt{s} = 14$  TeV with the cuts:  $p_T > 25$  GeV,  $|\eta| < 2.5$  for b in MadGraph.

| Cut | number of event pass |
|-----|----------------------|
| 1   | 1408                 |
| 2   | 1322                 |
| 3   | 1052                 |
| 4   | 822                  |

Table 7: 100,000 signal events. Those events are generated in  $\sqrt{s} = 14$  TeV.

| Cut | number of event pass |
|-----|----------------------|
| 1   | 21,814               |
| 2   | 21,254               |
| 3   | 17,130               |
| 4   | 14,142               |

## 11 Signal

Generate resonant channel  $gg \rightarrow h_3$ ,  $h_3 \rightarrow h_2 h$ ,  $h_2 \rightarrow hh$  in MadGraph by following commands:

```
import model cxSM_VLF_EFT
generate g g > h3, (h3 > h2 h, h2 > h h)
```

then check this channel is dominated in signal ( $gg \rightarrow 3h$ ) or not.

I generate this channel and signal in  $\sqrt{s} = 14$  TeV, the cross sections are 2.094 pb and 4.067 pb, respectively.

Figure 8 is the total invariant mass of 6 b-jets for signal events. Figure 9 is the total invariant mass of 6 b-jets for this resonant channel. From the results, there is a peak around 400 GeV, because the mass of  $h_3$  is  $m_3 = 420$  GeV.

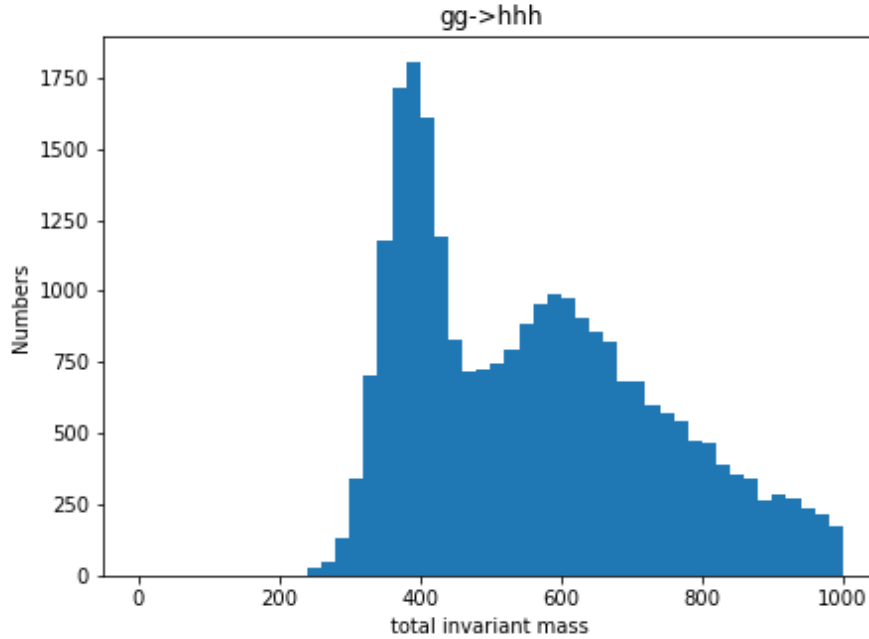


Figure 8: Total invariant mass of 6 b-jets for signal events.

A bump around 600 GeV in Figure 8? In run card, some parameters are not set correctly. After setting all parameters correctly and regenerating these event, the results are in Figure 10. There is no bump around 600 GeV.



Figure 9: Total invariant mass of 6 b-jets for resonant channel.



Figure 10: Total invariant mass of 6 b-jets for signal events and resonant channel (correct parameters).

## 12 The cross section in MadGraph

Table 8 is the cross sections calculated by MadGraph and in paper. They are different because in MadGraph we only consider LO. But in the paper, the numbers are quoted from the LHC Higgs Cross Section Working Group, and they have considered up to NNLO. The “k factor” is around 2.5, which accounts for the values in  $gg \rightarrow h3$ .

Table 8: Cross section from MadGraph and paper

| Process                               | $\sigma$ MadGraph (fb) | $\sigma$ in paper (fb) |
|---------------------------------------|------------------------|------------------------|
| $g g \rightarrow h3$                  | 21                     | 55                     |
| $gg \rightarrow h3 \rightarrow h h h$ | 4.0                    | 38.2                   |

The problem of cross section: If we use the default run card to generate the decay process, the value of cross section will be problematic.

Solution:

In madevent, use command `compute_widths` to compute decay widths of  $h_2, h_3$ , then replace the `run_card.dat` by `run_card_default.dat`.

Regenerate the signal and resonant event, the cross sections are 11.1 fb and 10.39 fb, respectively. This channel is indeed dominated in the signal.

## 13 Comparision for $pp \rightarrow hhh$ and $gg \rightarrow hhh$

Generate  $pp \rightarrow hhh$  in MadGraph by following commands:

```
import model cxSM_VLF_EFT
define p = p b b~
generate p p > h h h QCD<=8
```

Generate  $gg \rightarrow hhh$  in MadGraph by following commands:

```
import model cxSM_VLF_EFT
generate g g > h h h
```

These events are generated in 14 TeV and the sample size are 100k. The cross section for  $pp \rightarrow hhh$  and  $gg \rightarrow hhh$  are 11.22 fb and 11.11 fb, respectively. They only differ by 1%.

## 14 Comparision for $gg \rightarrow hhh$ and resonant channel

To compare  $gg \rightarrow hhh$  and resonant channel, I plot the  $p_T$ ,  $\eta$ , and total invariant mass of 6 b-jets for both.

These events are generated in 14 TeV and the sample size are 100k. The cross section for  $gg \rightarrow hhh$  and resonant channel are 11.11 fb and 10.38 fb, respectively.

The number of events of 6 b-jets for  $gg \rightarrow hhh$  is 21,814 and for the resonant channel is 21,475. The numbers are very close. I scaled the number of events for  $gg \rightarrow 3h$  to be the same as the resonant channel.

Figure 11 is  $p_T$  and  $\eta$  distributions. Figure 12 is total invariant mass of 6 b-jets distributions. Their distributions look similar.

I apply the cuts same in Sec.10 and count how many events can pass these cuts. Table 9 is the result. Those results for both events are similar.

Table 9: Number of events pass the selection cuts. Total number of events for  $gg \rightarrow hhh$  and resonant channel both are 100,000.

| Cut | $gg \rightarrow 3h$ | resonant channel |
|-----|---------------------|------------------|
| 1   | 21,814              | 21,475           |
| 2   | 21,254              | 20,898           |
| 3   | 17,130              | 16,828           |
| 4   | 14,142              | 13,730           |

## 15 Branching ratios and decay widths

The branching ratios and decay widths are calculated by MadGraph and Mathematica notebook. Mathematica notebook does not include  $uu$   $dd$   $ss$   $ee$  decay modes. Since the contribution of these modes is very small.

Table 10 is calculated by MadGraph. Table 11 is calculated by Mathematica notebook.

The exact values from both are slightly different because MG can not correctly expand the parameter  $\epsilon$  in the model.

Set the  $\epsilon$  to 0.001 and calculate again. The results are in Table 12 and Table 13.

This time, the decay widths and branching ratios calculated by MG and Mathematica notebook become close.



Figure 11:  $p_T$  and  $\eta$  distributions of b-jets for  $gg \rightarrow 3h$  and resonant channel. They are ordered by  $p_T$ .

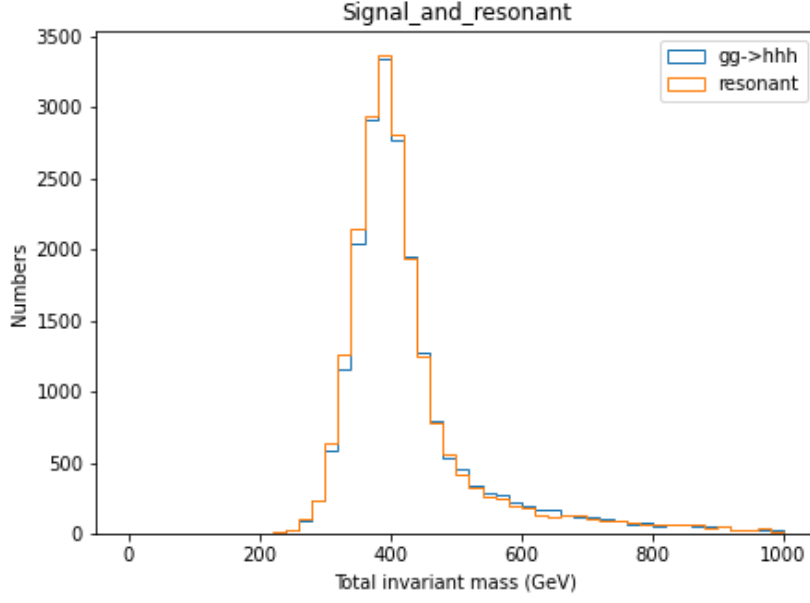


Figure 12: The distribution of total invariant mass of 6 b-jets for  $gg \rightarrow 3h$  and resonant channel.

Table 10: Decay widths and branching ratios calculated by MadGraph at BP1.

|                                | BR        | Width (GeV) |                                | BR        | Width (GeV) |
|--------------------------------|-----------|-------------|--------------------------------|-----------|-------------|
| $h_2 \rightarrow h_1 h_1$      | 0.7506    | 0.085616    | $h_3 \rightarrow h_1 h_2$      | 0.6795    | 0.8414      |
| $h_2 \rightarrow WW$           | 0.1734    | 0.019782    | $h_3 \rightarrow h_1 h_1$      | 0.1711    | 0.21183     |
| $h_2 \rightarrow ZZ$           | 0.07548   | 0.0086097   | $h_3 \rightarrow WW$           | 0.08756   | 0.10842     |
| $h_2 \rightarrow bb$           | 0.0004724 | 5.3887e-05  | $h_3 \rightarrow ZZ$           | 0.04102   | 0.050792    |
| $h_2 \rightarrow cc$           | 3.455e-05 | 3.9407e-06  | $h_3 \rightarrow tt$           | 0.02065   | 0.025569    |
| $h_2 \rightarrow \tau\tau$     | 2.254e-05 | 2.5714e-06  | $h_3 \rightarrow gg$           | 8.662e-05 | 0.00010725  |
| $h_2 \rightarrow ss$           | 2.185e-07 | 2.4927e-08  | $h_3 \rightarrow bb$           | 8.158e-05 | 0.00010102  |
| $h_2 \rightarrow gg$           | 1.561e-07 | 1.7811e-08  | $h_3 \rightarrow cc$           | 5.961e-06 | 7.3813e-06  |
| $h_2 \rightarrow \mu\mu$       | 7.972e-08 | 9.0933e-09  | $h_3 \rightarrow \tau\tau$     | 3.89e-06  | 4.8167e-06  |
| $h_2 \rightarrow \gamma\gamma$ | 6.495e-09 | 7.409e-10   | $h_3 \rightarrow \gamma\gamma$ | 3.852e-07 | 4.7697e-07  |
| $h_2 \rightarrow \gamma Z$     | 9.447e-10 | 1.0776e-10  | $h_3 \rightarrow \gamma Z$     | 4.937e-08 | 6.1131e-08  |
| $h_2 \rightarrow dd$           | 5.441e-10 | 6.207e-11   | $h_3 \rightarrow ss$           | 3.77e-08  | 4.6686e-08  |
| $h_2 \rightarrow uu$           | 1.393e-10 | 1.5889e-11  | $h_3 \rightarrow \mu\mu$       | 1.375e-08 | 1.7031e-08  |
| $h_2 \rightarrow ee$           | 1.865e-12 | 2.1269e-13  | $h_3 \rightarrow dd$           | 9.389e-11 | 1.1625e-10  |
|                                |           |             | $h_3 \rightarrow uu$           | 2.403e-11 | 2.976e-11   |
|                                |           |             | $h_3 \rightarrow ee$           | 3.217e-13 | 3.9835e-13  |



Table 11: Decay widths and branching ratios calculated by Mathematica at BP1.

|                                | BR        | Width (GeV) |                                | BR        | Width (GeV) |
|--------------------------------|-----------|-------------|--------------------------------|-----------|-------------|
| $h_2 \rightarrow h_1 h_1$      | 0.8321    | 0.1407      | $h_3 \rightarrow h_1 h_2$      | 0.8219    | 2.158       |
| $h_2 \rightarrow WW$           | 0.1166    | 0.019721    | $h_3 \rightarrow h_1 h_1$      | 0.1049    | 0.27543     |
| $h_2 \rightarrow ZZ$           | 0.05108   | 0.0086386   | $h_3 \rightarrow WW$           | 0.04131   | 0.10846     |
| $h_2 \rightarrow gg$           | 0.0001204 | 2.0359e-05  | $h_3 \rightarrow ZZ$           | 0.01941   | 0.050962    |
| $h_2 \rightarrow bb$           | 9.91e-05  | 1.6758e-05  | $h_3 \rightarrow tt$           | 0.01242   | 0.032613    |
| $h_2 \rightarrow \tau\tau$     | 1.526e-05 | 2.5802e-06  | $h_3 \rightarrow gg$           | 6.364e-05 | 0.00016711  |
| $h_2 \rightarrow cc$           | 4.59e-06  | 7.7613e-07  | $h_3 \rightarrow bb$           | 1.195e-05 | 3.1386e-05  |
| $h_2 \rightarrow \gamma\gamma$ | 3.161e-06 | 5.346e-07   | $h_3 \rightarrow \tau\tau$     | 1.841e-06 | 4.8326e-06  |
| $h_2 \rightarrow \gamma Z$     | 4.822e-07 | 8.154e-08   | $h_3 \rightarrow cc$           | 5.536e-07 | 1.4536e-06  |
| $h_2 \rightarrow \mu\mu$       | 5.43e-08  | 9.1826e-09  | $h_3 \rightarrow \gamma\gamma$ | 1.823e-07 | 4.7857e-07  |
| $h_2 \rightarrow tt$           | 4.355e-19 | 7.3649e-20  | $h_3 \rightarrow \gamma Z$     | 2.334e-08 | 6.1277e-08  |
|                                |           |             | $h_3 \rightarrow \mu\mu$       | 6.55e-09  | 1.7198e-08  |

Table 12: Decay widths and branching ratios calculated by MadGraph at BP1 with  $\epsilon = 0.001$ .

|                                | BR        | Width (GeV) |                                | BR        | Width (GeV) |
|--------------------------------|-----------|-------------|--------------------------------|-----------|-------------|
| $h_2 \rightarrow h_1 h_1$      | 0.8311    | 1.4041e-05  | $h_3 \rightarrow h_1 h_2$      | 1.0       | 2.1493      |
| $h_2 \rightarrow WW$           | 0.1174    | 1.9835e-06  | $h_3 \rightarrow h_1 h_1$      | 1.279e-05 | 2.748e-05   |
| $h_2 \rightarrow ZZ$           | 0.0511    | 8.6329e-07  | $h_3 \rightarrow WW$           | 5.058e-06 | 1.0871e-05  |
| $h_2 \rightarrow bb$           | 0.0003198 | 5.4032e-09  | $h_3 \rightarrow ZZ$           | 2.369e-06 | 5.0929e-06  |
| $h_2 \rightarrow cc$           | 2.339e-05 | 3.9513e-10  | $h_3 \rightarrow tt$           | 1.193e-06 | 2.5638e-06  |
| $h_2 \rightarrow \tau\tau$     | 1.526e-05 | 2.5783e-10  | $h_3 \rightarrow gg$           | 5.007e-09 | 1.0761e-08  |
| $h_2 \rightarrow ss$           | 1.479e-07 | 2.4994e-12  | $h_3 \rightarrow bb$           | 4.713e-09 | 1.0129e-08  |
| $h_2 \rightarrow \mu\mu$       | 5.397e-08 | 9.1178e-13  | $h_3 \rightarrow cc$           | 3.443e-10 | 7.4011e-10  |
| $h_2 \rightarrow dd$           | 3.684e-10 | 6.2237e-15  | $h_3 \rightarrow \tau\tau$     | 2.247e-10 | 4.8297e-10  |
| $h_2 \rightarrow uu$           | 9.431e-11 | 1.5932e-15  | $h_3 \rightarrow \gamma\gamma$ | 2.227e-11 | 4.7857e-11  |
| $h_2 \rightarrow gg$           | 1.056e-11 | 1.7841e-16  | $h_3 \rightarrow \gamma Z$     | 2.854e-12 | 6.1335e-12  |
| $h_2 \rightarrow ee$           | 1.262e-12 | 2.1326e-17  | $h_3 \rightarrow ss$           | 2.178e-12 | 4.6812e-12  |
| $h_2 \rightarrow \gamma\gamma$ | 4.393e-13 | 7.4213e-18  | $h_3 \rightarrow \mu\mu$       | 7.945e-13 | 1.7077e-12  |
| $h_2 \rightarrow \gamma Z$     | 6.389e-14 | 1.0794e-18  | $h_3 \rightarrow dd$           | 5.423e-15 | 1.1657e-14  |
|                                |           |             | $h_3 \rightarrow uu$           | 1.388e-15 | 2.984e-15   |
|                                |           |             | $h_3 \rightarrow ee$           | 1.858e-17 | 3.9942e-17  |

Table 13: Decay widths and branching ratios calculated by Mathematica at BP1 with  $\epsilon = 0.001$ .

|                                | BR        | Width (GeV) |                                | BR        | Width (GeV) |
|--------------------------------|-----------|-------------|--------------------------------|-----------|-------------|
| $h_2 \rightarrow h_1 h_1$      | 0.8321    | 1.407e-05   | $h_3 \rightarrow h_1 h_2$      | 1.0       | 2.158       |
| $h_2 \rightarrow WW$           | 0.1166    | 1.9721e-06  | $h_3 \rightarrow h_1 h_1$      | 1.276e-05 | 2.7543e-05  |
| $h_2 \rightarrow ZZ$           | 0.05108   | 8.6386e-07  | $h_3 \rightarrow WW$           | 5.026e-06 | 1.0846e-05  |
| $h_2 \rightarrow gg$           | 0.0001204 | 2.0359e-09  | $h_3 \rightarrow ZZ$           | 2.361e-06 | 5.0962e-06  |
| $h_2 \rightarrow bb$           | 9.91e-05  | 1.6758e-09  | $h_3 \rightarrow tt$           | 1.511e-06 | 3.2613e-06  |
| $h_2 \rightarrow \tau\tau$     | 1.526e-05 | 2.5802e-10  | $h_3 \rightarrow gg$           | 7.743e-09 | 1.6711e-08  |
| $h_2 \rightarrow cc$           | 4.59e-06  | 7.7613e-11  | $h_3 \rightarrow bb$           | 1.454e-09 | 3.1386e-09  |
| $h_2 \rightarrow \gamma\gamma$ | 3.161e-06 | 5.346e-11   | $h_3 \rightarrow \tau\tau$     | 2.239e-10 | 4.8326e-10  |
| $h_2 \rightarrow \gamma Z$     | 4.822e-07 | 8.154e-12   | $h_3 \rightarrow cc$           | 6.736e-11 | 1.4536e-10  |
| $h_2 \rightarrow \mu\mu$       | 5.43e-08  | 9.1826e-13  | $h_3 \rightarrow \gamma\gamma$ | 2.218e-11 | 4.7857e-11  |
| $h_2 \rightarrow tt$           | 4.355e-15 | 7.3649e-20  | $h_3 \rightarrow \gamma Z$     | 2.839e-12 | 6.1277e-12  |
|                                |           |             | $h_3 \rightarrow \mu\mu$       | 7.969e-13 | 1.7198e-12  |

For color channels, they are still doesn't look the same. The reason is that in MadGraph it only calculates to LO, but the numbers in Mathematica notebook are calculated to NLO.

## 16 SPANet

Code: [Symmetry Preserving Attention Networks](#)

Symmetry Preserving Attention NETWORKs (Spa-Net) is used to do the jet assignment task. The jet assignment task is the identification of the original particle which leads to a reconstructed jet.

### 16.1 Prepare training data

1. Defining the event topology in .ini file. The structure of the .ini file follows this format:

```
[SOURCE]
FEATURE_1 = FEATURE_OPTION
FEATURE_2 = FEATURE_OPTION
FEATURE_3 = FEATURE_OPTION
...
```

```
[EVENT]
particles = (PARTICLE_1, PARTICLE_2, ...)
permutations = EVENT_SYMMETRY_GROUP
```

```
[PARTICLE_1]
jets = (JET_1, JET_2, ...)
permutations = JET_SYMMETRY_GROUP
```

```
[PARTICLE_2]
jets = (JET_1, JET_2, ...)
permutations = JET_SYMMETRY_GROUP
```

```
...
```

2. Create training dataset in HDF5 format.
3. Write option-file in JSON format.

## 16.2 Training

Training:

```
python train.py -of <OPTIONS_FILE> --log_dir <LOG_DIR> --name <NAME> --gpus 1
```

<OPTIONS\_FILE>: JSON file with option overloads. <LOG\_DIR>: output directory. <NAME>: subdirectory for this run.

Evaluation:

```
python test.py <log_directory> --gpu
```

<log\_directory>: directory containing the checkpoint and options file.

```
python test.py <log_directory> -tf <TEST_FILE> --gpu
```

<TEST\_FILE> will replace the test file in option file.

## 17 SPANet for ttbar event

The training and testing datasets from here: [Link](#)

For full ttbar event:

- Training sample:
  - Total sample size: 10,009,520
  - 2t sample size: 2,967,955
- Testing sample size:
  - Total sample size: 358,946
  - 2t sample size: 116,342

Figure 13 is the training results for full ttbar events. The results are the same as the numbers given in the SPANet paper.

## 18 SPANet for di-Higgs event

Generate di-Higgs events in MadGraph by following commands:

```
import model 2HDMtII_NLO
generate p p > h2 [QCD] QED<=99 QCD<=99
```

then use the MadSpin let h2 decay to h1h1 and h1 decay to b $\bar{b}$ . The mass of h2 is 1000 GeV.

The .ini file for di-Higgs event (h > b  $\bar{b}$ )

```
[SOURCE]
mass = log_normalize
pt = log_normalize
eta = normalize
phi = normalize

[EVENT]
particles = (h1, h2)
permutations = [(h1, h2)]

[h1]
```

| Event Type: *t |                  |                |              |          |
|----------------|------------------|----------------|--------------|----------|
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | T Purity |
| = 6            | 0.812            | 0.308          | 0.640        | 0.694    |
| = 7            | 0.851            | 0.341          | 0.597        | 0.665    |
| >= 8           | 0.881            | 0.351          | 0.523        | 0.610    |
| Full           | 0.850            | 1.000          | 0.583        | 0.652    |
|                |                  |                |              |          |
| Event Type: 0t |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | T Purity |
| = 6            | 0.188            | 0.308          | 1.000        | N/A      |
| = 7            | 0.149            | 0.341          | 1.000        | N/A      |
| >= 8           | 0.119            | 0.351          | 1.000        | N/A      |
| Full           | 0.150            | 1.000          | 1.000        | N/A      |
|                |                  |                |              |          |
| Event Type: 1t |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | T Purity |
| = 6            | 0.566            | 0.308          | 0.567        | 0.567    |
| = 7            | 0.531            | 0.341          | 0.556        | 0.556    |
| >= 8           | 0.484            | 0.351          | 0.523        | 0.523    |
| Full           | 0.525            | 1.000          | 0.549        | 0.549    |
|                |                  |                |              |          |
| Event Type: 2t |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | T Purity |
| = 6            | 0.246            | 0.308          | 0.807        | 0.841    |
| = 7            | 0.320            | 0.341          | 0.666        | 0.755    |
| >= 8           | 0.397            | 0.351          | 0.523        | 0.663    |
| Full           | 0.324            | 1.000          | 0.637        | 0.735    |

Figure 13: The training result for full  $t\bar{t}$  events.

```
jets = (b1, b2)
permutations = [(b1, b2)]
```

```
[h2]
jets = (b1, b2)
permutations = [(b1, b2)]
```

There are three types of events, 0h, 1h, 2h. The number means how many identifiable Higgs in a event.

Definition of some parameters:

- Event proportion:

$$\text{Event proportion} \equiv \frac{\text{number of some type events with } i \text{ jets}}{\text{number of events with } i \text{ jets}} \quad (1)$$

- Jet proportion:

$$\text{Jet proportion} \equiv \frac{\text{number of events with } i \text{ jets}}{\text{total number of events}} \quad (2)$$

- Event purity:

$$\epsilon^{\text{event}} \equiv \frac{\text{number of some type events with and all Higgs are correctly identified}}{\text{number of some type events}} \quad (3)$$

- H purity:

$$\epsilon^{\text{h}} \equiv \frac{\text{number of correctly identified Higgs in some type events}}{\text{number of identifiable Higgs in some type events}} \quad (4)$$

## 18.1 Training sample for di-Higgs events

Di-Higgs events  $pp \rightarrow h2$ ,  $h2 \rightarrow hh$ ,  $h \rightarrow bb$  was generated at  $\sqrt{s} = 14$  TeV using MadGraph. Then pass these events to Pythia8 for showering and hadronization. Then pass to Delphes for detector simulation.

Jets are reconstructed by the anti-kT algorithm with radius  $R = 0.5$  and are required to have  $p_T \geq 20$  GeV.

Preselection requirements:  $\geq 4$  jets in  $|\eta| < 2.5$ .

Define the correct jet assignments by matching them to the simulated truth quarks within an angular distance of  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ .

## 18.2 Training result for di-Higgs event

For 100k di-Higgs event with  $m_{h_2} = 1000$  GeV:

- Training sample:
  - Total sample size: 78,785
  - 2h sample size: 36,765
  - 5% used on validation
- Testing sample:
  - Total sample size: 8,753
  - 2h sample size: 4,130

| Event Type: *h |                  |                |              |          |
|----------------|------------------|----------------|--------------|----------|
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.887            | 0.291          | 0.945        | 0.960    |
| = 5            | 0.925            | 0.331          | 0.908        | 0.940    |
| >= 6           | 0.947            | 0.378          | 0.792        | 0.865    |
| Full           | 0.922            | 1.000          | 0.874        | 0.914    |
| Event Type: 0h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.113            | 0.291          | 1.000        | N/A      |
| = 5            | 0.075            | 0.331          | 1.000        | N/A      |
| >= 6           | 0.053            | 0.378          | 1.000        | N/A      |
| Full           | 0.078            | 1.000          | 1.000        | N/A      |
| Event Type: 1h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.545            | 0.291          | 0.911        | 0.911    |
| = 5            | 0.442            | 0.331          | 0.888        | 0.888    |
| >= 6           | 0.385            | 0.378          | 0.827        | 0.827    |
| Full           | 0.450            | 1.000          | 0.876        | 0.876    |
| Event Type: 2h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.342            | 0.291          | 1.000        | 1.000    |
| = 5            | 0.483            | 0.331          | 0.926        | 0.963    |
| >= 6           | 0.562            | 0.378          | 0.769        | 0.878    |
| Full           | 0.472            | 1.000          | 0.871        | 0.933    |

Figure 14: The training result for 100k di-Higgs events.

Figure 14 is the training results for 100k di-Higgs events. For 2h events,  $\epsilon^{\text{event}} = 0.871$ ,  $\epsilon^{\text{h}} = 0.933$ .

For 1M di-Higgs event with  $m_{\text{h}_2} = 1000$  GeV:

- Training sample:
  - Total sample size: 788,160
  - 2h sample size: 364,773
  - 5% used on validation
- Testing sample:
  - Total sample size: 87,702
  - 2h sample size: 40,695

Figure 15 is the training results for 1M di-Higgs events. For 2h events,  $\epsilon^{\text{event}} = 0.914$ ,  $\epsilon^{\text{h}} = 0.955$ .

For di-Higgs event with  $m_{\text{h}_2} = 500$  GeV:

- Training sample:
  - Total sample size: 764,676
  - 2h sample size: 396,588
  - 5% used on validation
- Testing sample:
  - Total sample size: 84,687
  - 2h sample size: 43,818

Figure 16 is the training results for 500 GeV di-Higgs events. For 2h events,  $\epsilon^{\text{event}} = 0.779$ ,  $\epsilon^{\text{h}} = 0.871$ .

### 18.3 Apply the pre-trained model on different $m_{\text{h}_2}$ sample

The SPANet models in Sec.18.2 are trained on  $m_{\text{h}_2} = 500$  GeV and  $m_{\text{h}_2} = 1000$  GeV. Test these models on samples with  $m_{\text{h}_2} = 500$  GeV, 750 GeV, 1000 GeV.

The results are summarized in Table 14.



| Event Type: *h |                  |                |              |          |
|----------------|------------------|----------------|--------------|----------|
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.877            | 0.301          | 0.950        | 0.964    |
| = 5            | 0.920            | 0.326          | 0.919        | 0.946    |
| >= 6           | 0.944            | 0.372          | 0.831        | 0.891    |
| Full           | 0.916            | 1.000          | 0.894        | 0.928    |
| Event Type: 0h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.123            | 0.301          | 1.000        | N/A      |
| = 5            | 0.080            | 0.326          | 1.000        | N/A      |
| >= 6           | 0.056            | 0.372          | 1.000        | N/A      |
| Full           | 0.084            | 1.000          | 1.000        | N/A      |
| Event Type: 1h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.533            | 0.301          | 0.917        | 0.917    |
| = 5            | 0.445            | 0.326          | 0.885        | 0.885    |
| >= 6           | 0.394            | 0.372          | 0.813        | 0.813    |
| Full           | 0.452            | 1.000          | 0.873        | 0.873    |
| Event Type: 2h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.345            | 0.301          | 1.000        | 1.000    |
| = 5            | 0.475            | 0.326          | 0.950        | 0.975    |
| >= 6           | 0.551            | 0.372          | 0.844        | 0.918    |
| Full           | 0.464            | 1.000          | 0.914        | 0.955    |

Figure 15: The training result for 1M di-Higgs events.

Table 14: SPANet models test on different  $m_{h_2}$  samples.

| Training $m_{h_2}$ (GeV) | Testing $m_{h_2}$ (GeV) | Event purity | H purity |
|--------------------------|-------------------------|--------------|----------|
| 500                      | 500                     | 0.779        | 0.871    |
| 500                      | 750                     | 0.408        | 0.672    |
| 500                      | 1000                    | 0.390        | 0.665    |
| 1000                     | 500                     | 0.383        | 0.638    |
| 1000                     | 750                     | 0.731        | 0.860    |
| 1000                     | 1000                    | 0.914        | 0.955    |

| Event Type: *h |                  |                |              |          |
|----------------|------------------|----------------|--------------|----------|
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.872            | 0.319          | 0.879        | 0.914    |
| = 5            | 0.923            | 0.325          | 0.802        | 0.868    |
| >= 6           | 0.944            | 0.356          | 0.633        | 0.753    |
| Full           | 0.914            | 1.000          | 0.763        | 0.836    |
|                |                  |                |              |          |
| Event Type: 0h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.128            | 0.319          | 1.000        | N/A      |
| = 5            | 0.077            | 0.325          | 1.000        | N/A      |
| >= 6           | 0.056            | 0.356          | 1.000        | N/A      |
| Full           | 0.086            | 1.000          | 1.000        | N/A      |
|                |                  |                |              |          |
| Event Type: 1h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.497            | 0.319          | 0.793        | 0.793    |
| = 5            | 0.391            | 0.325          | 0.748        | 0.748    |
| >= 6           | 0.312            | 0.356          | 0.666        | 0.666    |
| Full           | 0.397            | 1.000          | 0.743        | 0.743    |
|                |                  |                |              |          |
| Event Type: 2h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 4            | 0.375            | 0.319          | 0.994        | 0.994    |
| = 5            | 0.532            | 0.325          | 0.841        | 0.912    |
| >= 6           | 0.632            | 0.356          | 0.617        | 0.775    |
| Full           | 0.517            | 1.000          | 0.779        | 0.871    |

Figure 16: The training result for di-Higgs events with  $m_{h_2} = 500$  GeV.

## 19 SPANet for tri-Higgs event

The tri-Higgs events are signal events ( $gg \rightarrow hhh$ ) generated in previous.

### 19.1 Training sample for tri-Higgs event

TriHiggs events  $gg \rightarrow hhh$  was generated at  $\sqrt{s} = 14$  TeV using MadGraph. Then pass these events to Pythia8 for showering and hadronization. In Pythia8, the Higgs are forced to decay to  $b\bar{b}$ . Then pass to Delphes for detector simulation.

Jets are reconstructed by the anti-kT algorithm with radius  $R = 0.5$  and are required to have  $p_T \geq 20$  GeV.

Preselection requirements:  $\geq 6$  jets in  $|\eta| < 2.5$ .

Define the correct jet assignments by matching them to the simulated truth quarks within an angular distance of  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ .

### 19.2 Training result for tri-Higgs event

For 1M tri-Higgs event:

- Training sample:
  - Total sample size: 542,681
  - 3h sample size: 104,467
  - 5% used on validation
- Testing sample:
  - Total sample size: 60,173
  - 3h sample size: 11,598

Figure 17 is the training results for 1M tri-Higgs events. For 3h events,  $\epsilon^{\text{event}} = 0.344$ ,  $\epsilon^h = 0.538$ .

| Event Type: 0h |                  |                |              |          |
|----------------|------------------|----------------|--------------|----------|
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 6            | 0.186            | 0.439          | 1.000        | N/A      |
| = 7            | 0.147            | 0.313          | 1.000        | N/A      |
| >= 8           | 0.119            | 0.248          | 1.000        | N/A      |
| Full           | 0.157            | 1.000          | 1.000        | N/A      |
|                |                  |                |              |          |
| Event Type: 1h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 6            | 0.386            | 0.439          | 0.452        | 0.452    |
| = 7            | 0.337            | 0.313          | 0.405        | 0.405    |
| >= 8           | 0.312            | 0.248          | 0.334        | 0.334    |
| Full           | 0.353            | 1.000          | 0.412        | 0.412    |
|                |                  |                |              |          |
| Event Type: 2h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 6            | 0.303            | 0.439          | 0.293        | 0.489    |
| = 7            | 0.298            | 0.313          | 0.228        | 0.429    |
| >= 8           | 0.285            | 0.248          | 0.152        | 0.343    |
| Full           | 0.297            | 1.000          | 0.239        | 0.435    |
|                |                  |                |              |          |
| Event Type: 3h |                  |                |              |          |
| Jet Limit      | Event Proportion | Jet Proportion | Event Purity | H Purity |
| = 6            | 0.124            | 0.439          | 0.603        | 0.705    |
| = 7            | 0.218            | 0.313          | 0.336        | 0.546    |
| >= 8           | 0.283            | 0.248          | 0.152        | 0.400    |
| Full           | 0.193            | 1.000          | 0.344        | 0.538    |

Figure 17: The training result for 1M tri-Higgs events.