Note

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1 Generate di-Higgs samples in SM

Generate the double Higgs events in the standard model by MadGraph with `loop_sm` model. Following are the MadGraph scripts for generating di-Higgs samples:

```
import model loop_sm
generate p p > h h [QCD] QED^2<=99 QCD^2<=99
output /home/r10222035/CPVDM/Di-Higgs-SM/di-Higgs-sm

launch /home/r10222035/CPVDM/Di-Higgs-SM/di-Higgs-sm

shower=OFF
detector=OFF
analysis=OFF
done

set run_card nevents 10000
set run_card ebeam1 6500.0
set run_card ebeam2 6500.0

done
```

1.1 Variation with κ_λ

Reference: How to change the trilinear Higgs coupling in Madgraph?

The definition of κ_λ

$$\kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{\text{SM}}} \tag{1}$$

Following the below steps, we can add a parameter κ_λ in the model

1. Go to the MadGraph model file directory. Copy `loop_sm` to `my_loop_sm`.

2. Go to `my_loop_sm` directory.

3. In `parameters.py`, add a new parameter for κ_λ by

   ```
   khhh = Parameter(name = 'khhh',
     nature = 'external',
     type = 'real',
     value = 1,
     texname = '\\text{khhh}',
     lhablock = 'SMINPUTS',
     lhacode = [ 10 ])
   ```

4. In `vertices.py`, we can find the coupling for three Higgs vertex in the form `GC_XX`.

5. In `couplings.py`, multiply the value for `GC_XX` found in step 4 by `khhh`.

6. In `restrict_default.dat`, add

   ```
   10 2.000000e+00 # khhh
   ```

   in Block SMINPUTS.

Finish the above setting we can use the following scripts to generate di-Higgs samples:

```
import model my_loop_sm
generate p p > h h [QCD] QED^2<=99 QCD^2<=99
output /home/r10222035/CPVDM/Di-Higgs-SM/di-Higgs-sm-kappa

launch /home/r10222035/CPVDM/Di-Higgs-SM/di-Higgs-sm-kappa

shower=OFF
detector=OFF
analysis=OFF
done

set param_card khhh 1

set run_card nevents 10000
```

```
set run_card ebeam1 6500.0
set run_card ebeam2 6500.0

done
```

1.2 Results

The cross sections of various κ_λ are showed in Table 1.

Table 1: The cross sections of various κ_λ. My data is the results from MadGraph. The reference data is from here.

	13 TeV			14 TeV			
	Cross section (fb)			Cross section (fb)			
κ_λ	Ref.	My data	Ref./My	Ref.	My data	Ref./My	Ref. K-factor
-1	116.71	74.62	1.564	136.91	87.93	1.56	1.86
0	62.51	41.96	1.490	73.64	49.45	1.49	1.79
1	27.84	20.27	1.373	32.88	24.05	1.37	1.66
2	12.42	9.56	1.299	14.75	11.34	1.30	1.56
2.4	11.65	8.33	1.399	13.79	9.90	1.39	1.65
3	16.28	9.81	1.660	19.07	11.55	1.65	1.90
5	81.74	43.55	1.877	95.22	50.68	1.88	2.14

The m_{HH} distribution with various κ_λ is presented in Figure 1. In the left plot, the data is the parton level data from MadGraph. The right plot comes from the ATLAS reference. Here, the $\sqrt{s} = 13$ TeV

Figure 2 and 3 are generated at $\sqrt{s} = 14$ TeV.

2 Non-resonant di-Higgs event selection

2.1 Sample

Non-resonant Higgs pair process is generated by MadGraph. Then pass to Pythia for showering and hadronization. Then pass to Delphes for detector simulation.

Jets are reconstructed using the anti-k_t algorithm with radius parameter $R = 0.4$.

The b-tagging part in the Delphes card is changed such that same as the DL1r b-tagger at 77% WP. The b-jet efficiency is set to 0.77. The c-jet missing rate is set to 0.204. The light jet missing rate is set to 0.0077.

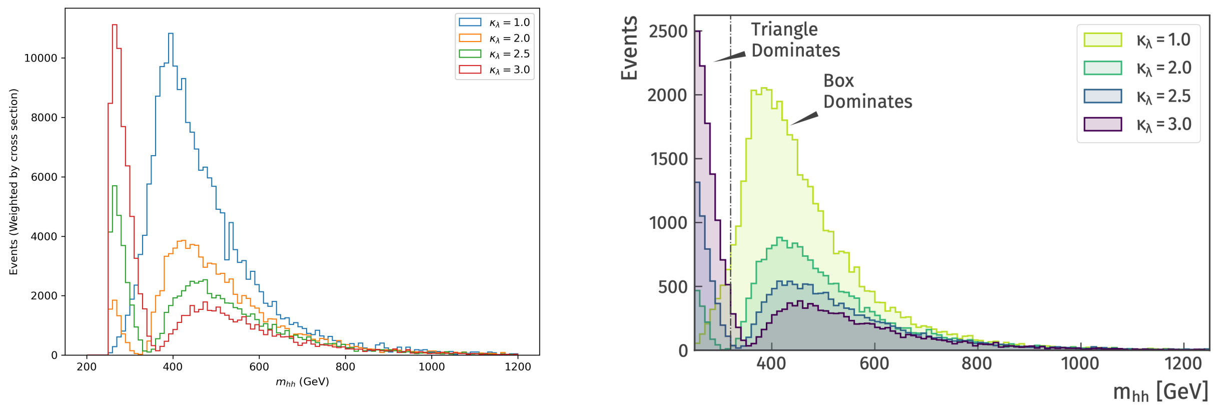

Figure 1: The m_{hh} distribution with various κ_λ. The bin height is weighted by the cross section.

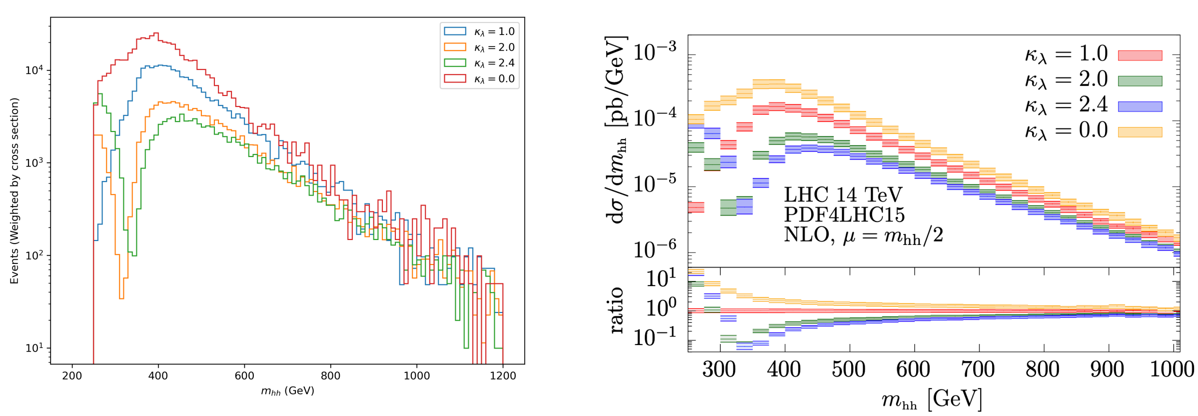

Figure 2: The m_{hh} distribution with various κ_λ. The bin height is weighted by the cross section.

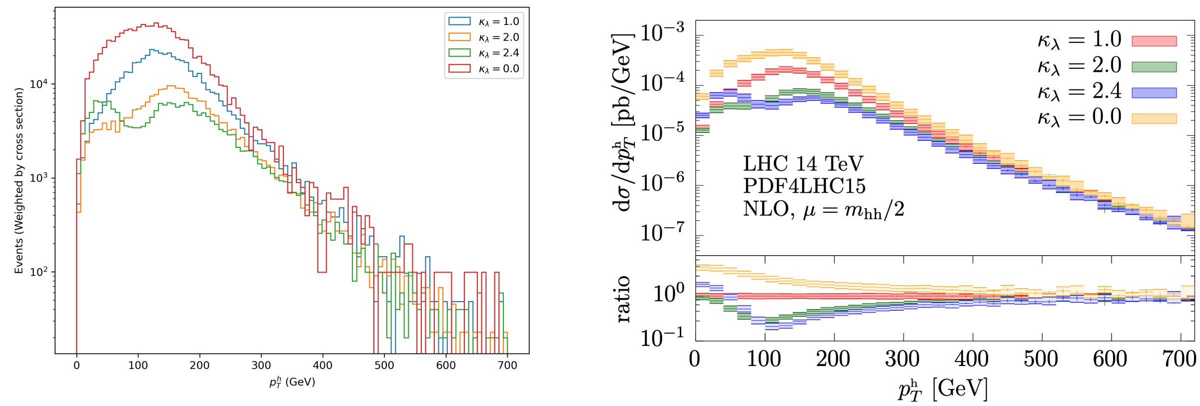

Figure 3: The p_{T}^{h} distribution with various κ_λ. The bin height is weighted by the cross section.

2.2 Event selection

Reference: ATLAS CONF Note CONF-HDBS-2022-35

The selection steps:

- Four tag: The event contains at least 4 b-tagged anti-k_t $R = 0.4$ jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.5$.
- The four jets with the highest p_{T} are paired to construct two Higgs boson candidates.
- min-ΔR pairing method: Choose the pairing in which the higher-p_{T} jet pair has the smallest ΔR separation.
- Higgs Eta:
$$|\Delta\eta_{HH}| < 1.5$$
- Top veto: Every possible pair of jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.5$, including those that were not selected for the H candidates, to form "W candidates". "Top quark candidates" are built by pairing W candidates with each remaining jet that was selected for H candidates. The quantity X_{Wt} is defined as
$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\ \mathrm{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5\ \mathrm{GeV}}{0.1 m_t}\right)^2}$$
Events with the smallest $X_{Wt} < 1.5$ are vetoed.

- Signal region:

$$X_{HH} = \sqrt{\left(\frac{m_{H_1} - 124\text{ GeV}}{0.1 m_{H_1}}\right)^2 + \left(\frac{m_{H_2} - 117\text{ GeV}}{0.1 m_{H_2}}\right)^2} < 1.6$$

Table 2: The selection passing rate and efficiency at each stage. The b-tagging part is the same as the DL1r 77% WP.

	ATLAS		My sample	
Cut	pass rate	efficiency	pass rate	efficiency
Four tag	0.0649	0.0649	0.0852	0.0852
Higgs Eta	0.0543	0.8360	0.0688	0.8074
Top veto	0.0456	0.8401	0.0553	0.8044
Signal region	0.0220	0.4818	0.0181	0.3283

Correct selection: Consider the events in which four jets can be matched one-to-one (within $\Delta R < 0.3$) to the four b-quarks decayed from the Higgs bosons. For the highest p_{T} there are 89% of simulated signal events reaching this selection.

Correct pairing: Consider the correct selection events, for min-ΔR pairing method there 85% of events are correctly paired.

Figure 4 shows the Higgs mass distribution. There is a deviation between the mass distribution peak and the signal region's center.

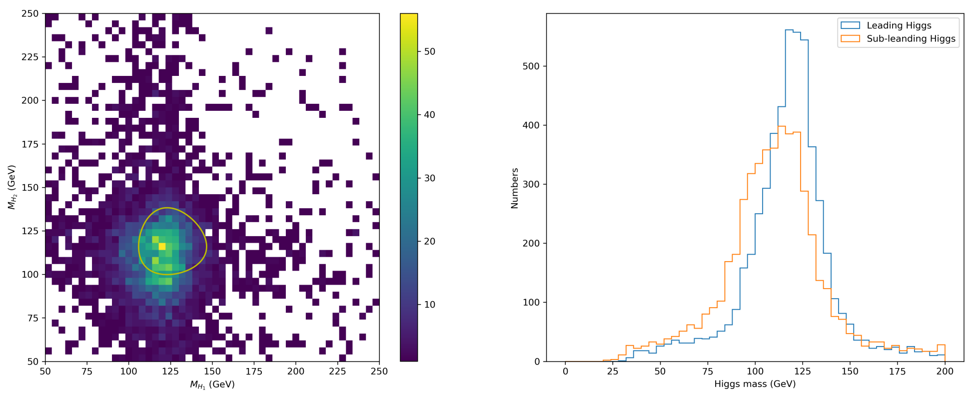

Figure 4: The mass plane and distribution for Higgs candidate.

2.2.1 Old method

Reference: Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The selection steps:

- Four tag: The event contains at least 4 b-tagged anti-kt small-R ($R = 0.4$) jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.5$. The four jets with the highest b-tagging score are paired to construct two Higgs boson candidates.

- The four jets with the highest p_{T} are paired to construct two Higgs boson candidates in my samples.

- Delta R: Pairing jets to Higgs boson candidate need to satisfy the following requirements:

$$\left.\begin{aligned} \frac{360\ \mathrm{GeV}}{m_{4\mathrm{j}}} - 0.5 < \Delta R_{jj,\mathrm{lead}} < \frac{653\ \mathrm{GeV}}{m_{4\mathrm{j}}} + 0.475 \\ \frac{235\ \mathrm{GeV}}{m_{4\mathrm{j}}} < \Delta R_{jj,\mathrm{subl}} < \frac{875\ \mathrm{GeV}}{m_{4\mathrm{j}}} + 0.35 \end{aligned}\right\} \text{ if } m_{4\mathrm{j}} < 1250\ \mathrm{GeV}$$

$$\left.\begin{aligned} 0 < \Delta R_{jj,\mathrm{lead}} < 1 \\ 0 < \Delta R_{jj,\mathrm{subl}} < 1 \end{aligned}\right\} \text{ if } m_{4\mathrm{j}} > 1250\ \mathrm{GeV}$$

- If there are more than 2 pairings satisfy the Delta R requirement. Calculate D_{HH}

$$D_{HH} = \frac{\left| m_{2\mathrm{j}}^{\mathrm{lead}} - \frac{120}{110} m_{2\mathrm{j}}^{\mathrm{subl}} \right|}{\sqrt{1 + \left(\frac{120}{110}\right)^2}}$$

  the pairing with the smallest value of D_{HH} is chosen.

- Higgs PT:

$$p_{\mathrm{T}}^{\mathrm{lead}} > m_{4\mathrm{j}} \times 0.5 - 103\ \mathrm{GeV}$$
$$p_{\mathrm{T}}^{\mathrm{subl}} > m_{4\mathrm{j}} \times 0.33 - 73\ \mathrm{GeV}$$

- Higgs Eta:

$$|\Delta\eta_{HH}| < 1.5$$

- Signal region:

$$X_{HH} = \sqrt{\left(\frac{m_{2\mathrm{j}}^{\mathrm{lead}} - 120\ \mathrm{GeV}}{0.1 m_{2\mathrm{j}}^{\mathrm{lead}}}\right)^2 + \left(\frac{m_{2\mathrm{j}}^{\mathrm{subl}} - 110\ \mathrm{GeV}}{0.1 m_{2\mathrm{j}}^{\mathrm{subl}}}\right)^2} < 1.6$$

- Top veto: Every possible pair of jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.5$, including those that were not selected for the H candidates, to form "W candidates". "Top quark candidates" are built by pairing W candidates with each remaining jet that was selected for H candidates

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80\text{ GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 173\text{ GeV}}{0.1 m_t}\right)^2}$$

  Events with the smallest $X_{Wt} < 1.5$ are vetoed.

The results are in Table 3.

Table 3: The selection passing rate and efficiency at each stage.

	ATLAS		My sample	
Cut	pass rate	efficiency	pass rate	efficiency
Four tag	0.0490	0.0490	0.0563	0.0563
Delta R	0.0448	0.9143	0.0471	0.8370
Higgs PT	0.0422	0.9420	0.0446	0.9480
Higgs Eta	0.0380	0.9005	0.0398	0.8911
Signal region	0.0193	0.5079	0.0170	0.4280
Top veto	0.0179	0.9275	0.0145	0.8537