

ATLAS: Higgs Pair Production

$bb' + \tau^+ \tau^-$ channel

Investigation of interference of Higgs Pair production via resonant and non-resonant production channels.

Looking at what it means to take non-resonant production into resonant production? How does it change signal?

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HYPOTHESIS

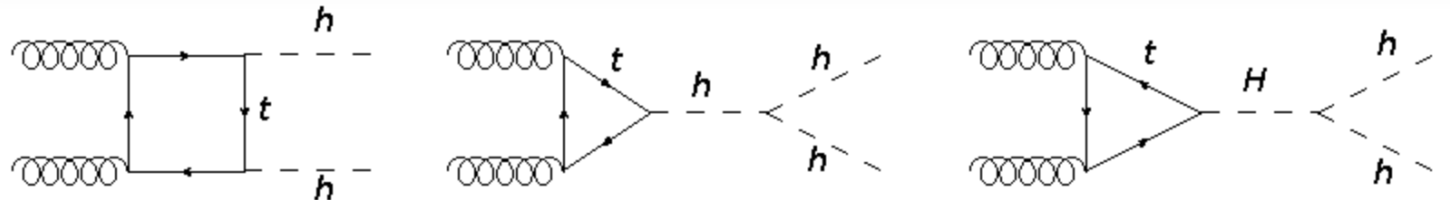
- Experimentalists have been using the narrow width approximation, ignoring the possible influence of the higher widths on heavy Higgs resonance.
- Is it safe to assume we can just use the narrow width approximation, or do variable widths have a significant influence on the interference between the heavy Higgs and the Standard Model?

METHODOLOGY

- All studies used MadGraph done at the Parton level. (Indicating No Parton Shower or Reconstruction)
- The multiple MadGraph job options carried varying point masses for the heavy Higgs (X in the ntuple TTree). We produce a ntuple with the following designated point masses for the heavy Higgs: 300, 500, 1000, 1500, and 2000 GeV.
- At each of the point masses, we generate at variable widths as follows: narrow(10 MeV), 1%, 2%, 3%, 5%, 10%, 15%, 20%, 30%. Generating diHiggs through Heavy Higgs resonance with MadGraph. We generate using the model

$$p p \rightarrow h h$$

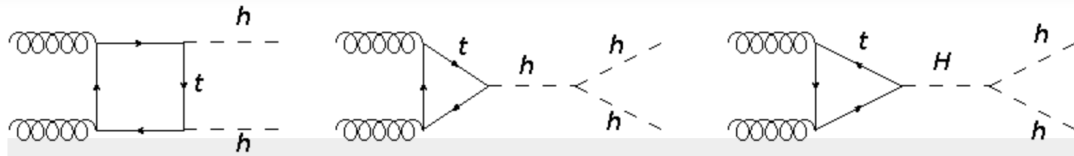
in order to include the following diagrams:



IMPLEMENTING MADGRAPH

<https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction#BSM:AdditionalHeavyScalarResonance>

Above you can find a link to further MadGraph documentation for Higgs Pair Production. Below you will find a reference to the leading order Feynman Diagrams and constants we are implementing in generated events



In this case we have considered the possibility of having a heavy scalar H (called hh in the MG files) as an intermediate state (so that we have the additional process $p p \rightarrow H \rightarrow h h$ that is taken into account). For this model in the param_card.dat the user has the freedom of modifying a wide range of parameters :

- the top yukawa coupling (via the parameter cy)
- the SM-Higgs trilinear coupling (ctr)
- the H coupling to the top (cyH)
- the H coupling to 2 SM-Higgs (ctrH)

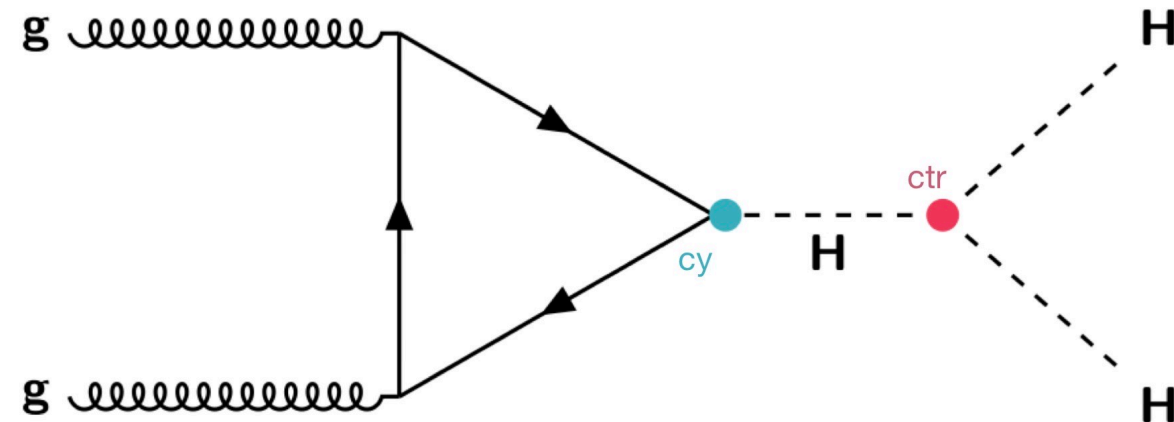
The parameters cy and ctr are just factors that multiply the SM couplings. The couplings for the heavy scalar are obtained similarly by multiplying the corresponding SM couplings with the parameters cyH and ctrH. By default they are all fixed to 1. Finally you can also modify :

- the H mass (MH)
- the H decay width (WH)

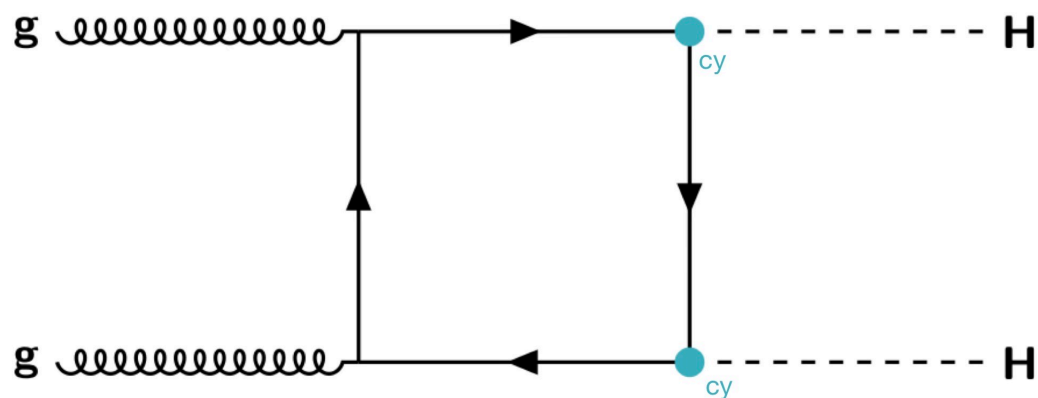
The corresponding code out of MG5 can be downloaded here: [HeavyScalar](#)

Note: Moving forward, we will refer to the Heavy Higgs as 'X' rather than 'H' and will refer to the Standard Model Higgs as 'H' rather than 'h'.

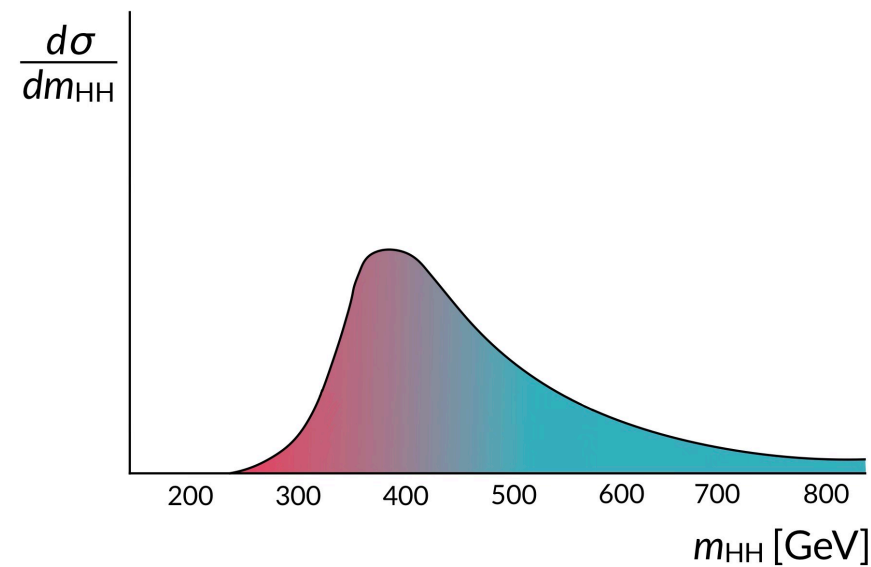
NON-RESONANT PRODUCTION



Triangle Diagram



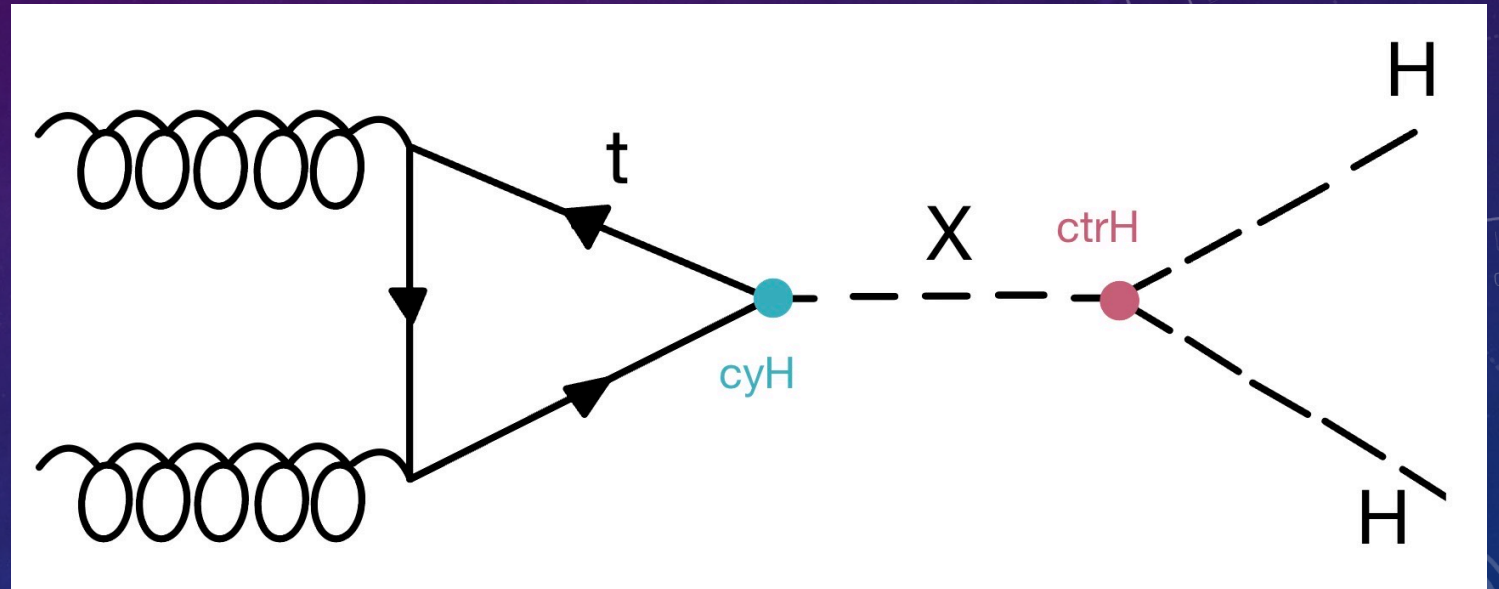
Box Diagram



SM Distribution

RESONANT PRODUCTION (BSM)

- BSM resonant HH signal production of Higgs Boson Pairs.
- The triangle and square diagrams interfere destructively, leading to a small SM ggF HH cross-section



Note: Beyond the Standard Model (BSM), is based on the indication that the Standard Model is not a complete model. The Standard Model (SM) predicts non-resonant HH production. However, an observation of SM non-resonant HH production is not expected with the currently available LHC data set. Significant non-resonant and resonant enhancements to the HH cross-section are predicted in many Beyond-the-SM theories.

SM, OSM, Nom

- We produced several sets with the varying point masses and varying widths. The sets are defined as follows:

- HH_OSM
- HH_SM
- HH_nom

Note: HH_OSM + HH_SM = no interference, and HH_nom includes interference

- HH_OSM stands for zero Standard Model, in which the trilinear coupling and top Yukawa coupling variables in MadGraph are set to zero. In which we produce events following the leading order resonant Feynman diagram in regard to BSM.
- HH_SM stands for Standard Model production, where the trilinear coupling is left to default value 1. As well as for the top Yukawa coupling. Then we set the Heavy Higgs (H) coupling to two Standard model Higgs (h) with a value of 0. As well as for the Heavy Higgs coupling to the top. Producing events from the leading order non-resonant Feynman diagrams, in regard to the SM.
- Lastly, we have HH_nom, standing for nominal. Here we set the trilinear coupling, top Yukawa coupling, Heavy Higgs coupling to the top, and H coupling to the two SM Higgs parameters to their default value of 1. Producing events with the leading order Feynman diagrams for both resonant and non-resonant production. An example of setting such parameters in MadGraph can be seen below:

```
5
6  #-----
7  # Setting mHH and WHH for param_card.dat
8  #-----
9  parameters={'1560':'300', #MHH
10             '1561':'3', #WHH
11             '188':'0.0', #ctr (trilinear coupling, default 1.0)
12             '189':'0.0', #cy (top Yukawa coupling, default 1.0)
13             '190':'1.0', #ctrH (hhH coupling, default 1.0)
14             '191':'1.0' #cyH (H Yukawa coupling, default 1.0)
15             }
16
```

} HH_OSM

PARAMETERS IN MADGRAPH

```
5
6 #-----
7 # Setting mHH and WHH for param_card.dat
8 #-----
9 parameters={'1560':'300', #MHH
10            '1561':'3', #WHH
11            '188':'0.0', #ctr (trilinear coupling, default 1.0)
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15            }
16
```

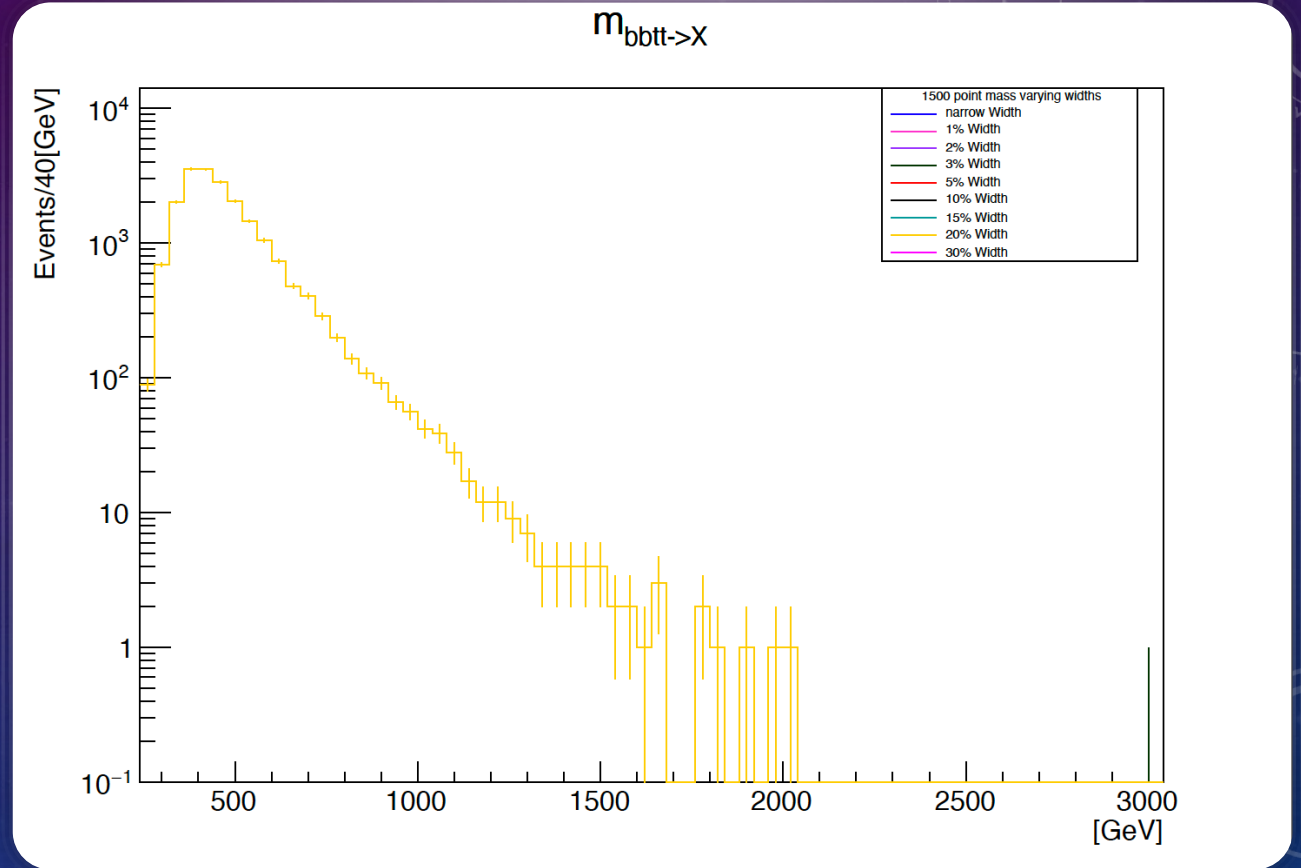
The Parameters are defined below:

- Top Yukawa coupling (via the parameter cy)
- The SM-Higgs trilinear coupling (ctr)
- The H coupling to the top (cyH)
- The H coupling to the 2 SM-Higgs (ctrH)
- The H mass (MHH)
 - In GeV
- The H decay width (WHH)
 - In GeV

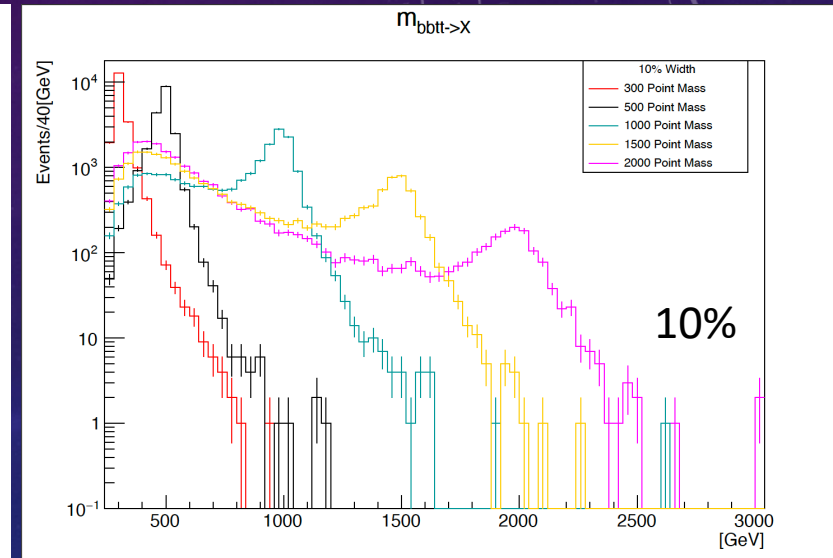
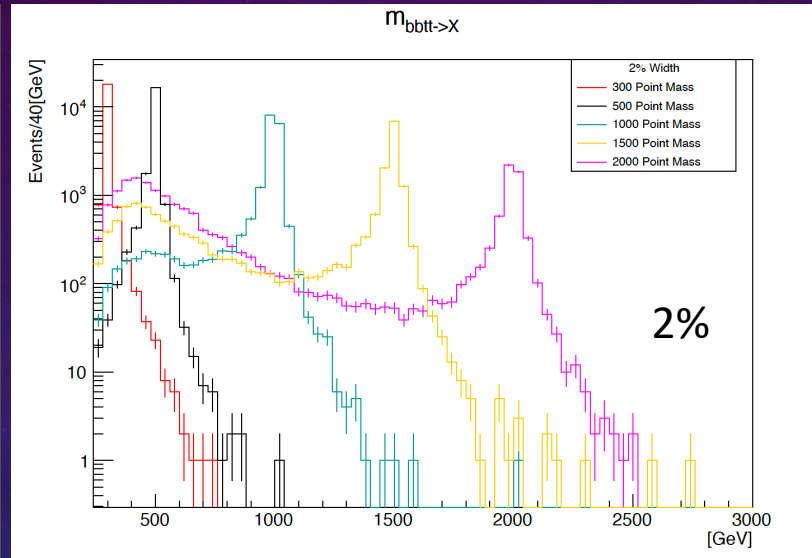
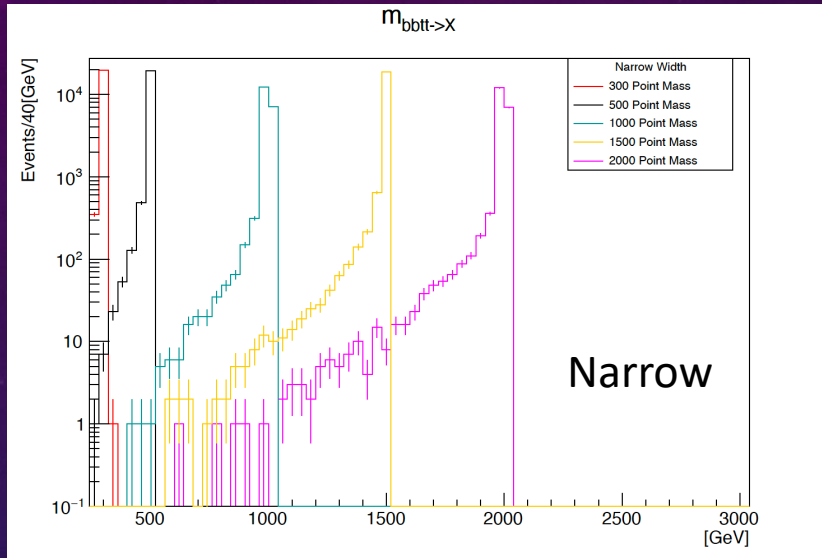
Note: The parameters cy and ctr are just factors that multiply the SM couplings. The couplings for the heavy scalar are obtained similarly by multiplying the corresponding SM couplings with the parameters cyH and ctrH.

SM

- Next, we will show the results of the SM, which predicts non-resonant HH production. Below is a $bb' + \tau\tau$ invariant mass plot produced via SM, a distribution that is the same at all masses and widths.



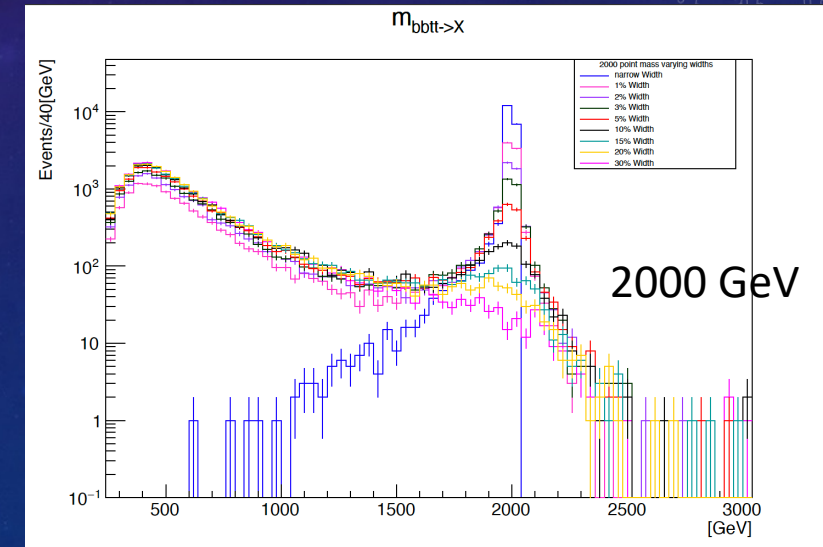
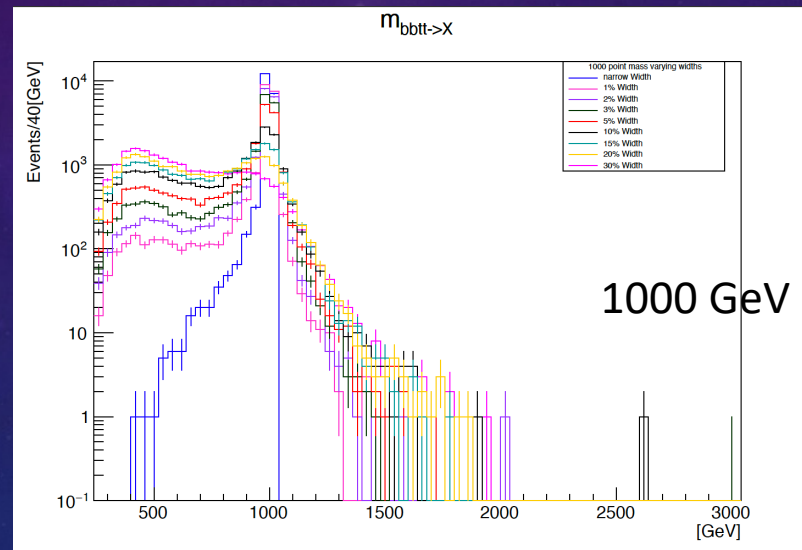
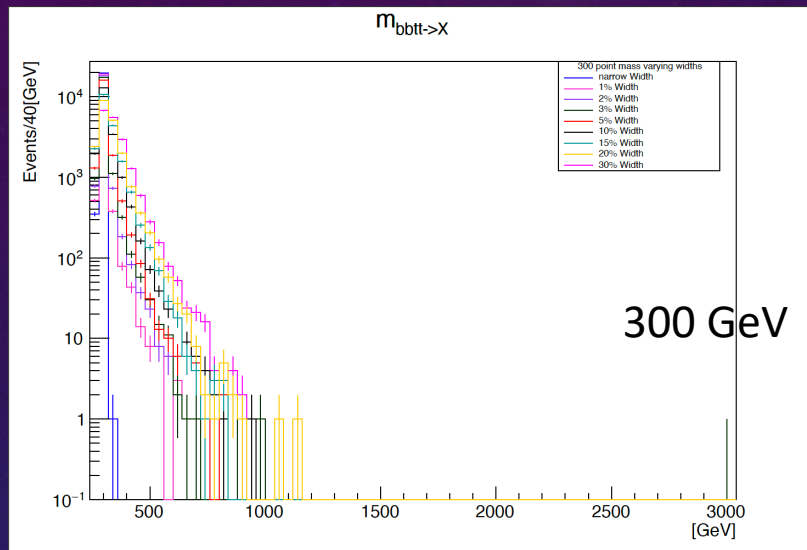
Varying widths at OSM aka BSM



- Here, looking at OSM, at the plots of varying widths, we see here that independent of interference between resonant and non-resonant production, that increasing widths yields more off-shell production giving narrower widths greater on-shell production. At lower masses, this effect is decreased in comparison to higher masses, where the effect is greatest.

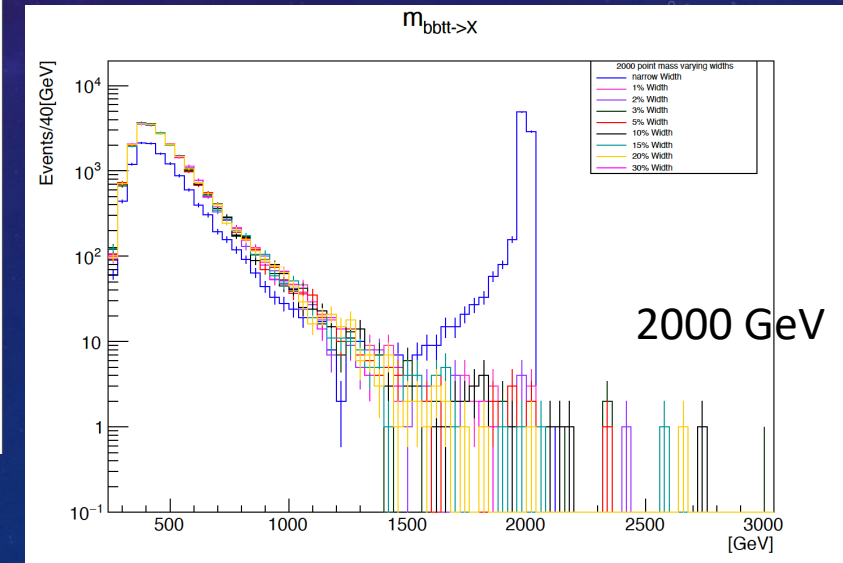
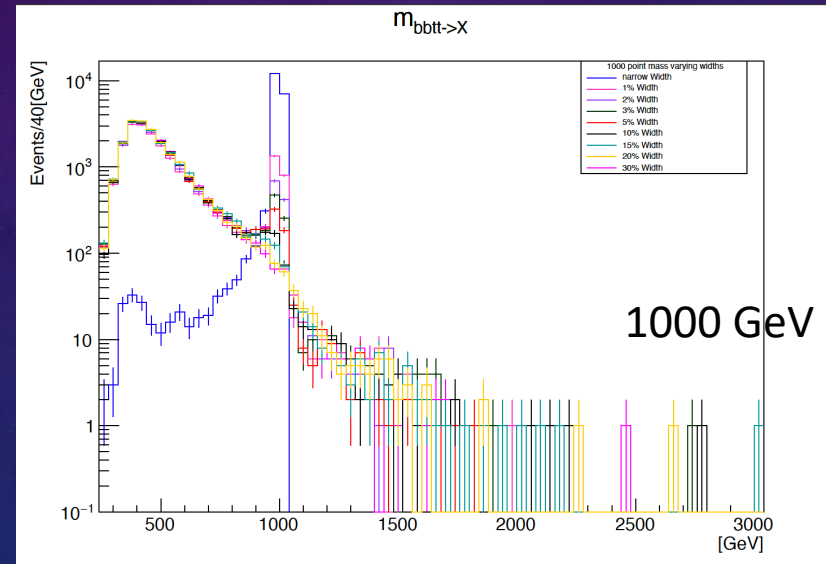
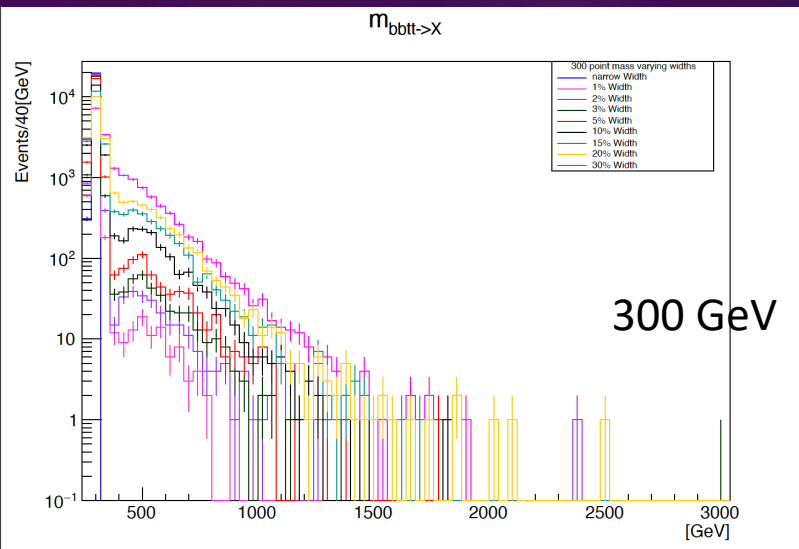
Varying Masses at OSM aka BSM

- Now looking at the varying masses of OSM, we see that independent of width and without interference between resonant and non-resonant production, we witness greater off-shell production occurs at higher point masses. It appears the enhancement at low mass looks the same for different high mass resonances, therefore further study may be needed. Could this allow us to access resonances with an on-shell mass beyond the reach of the LHC?



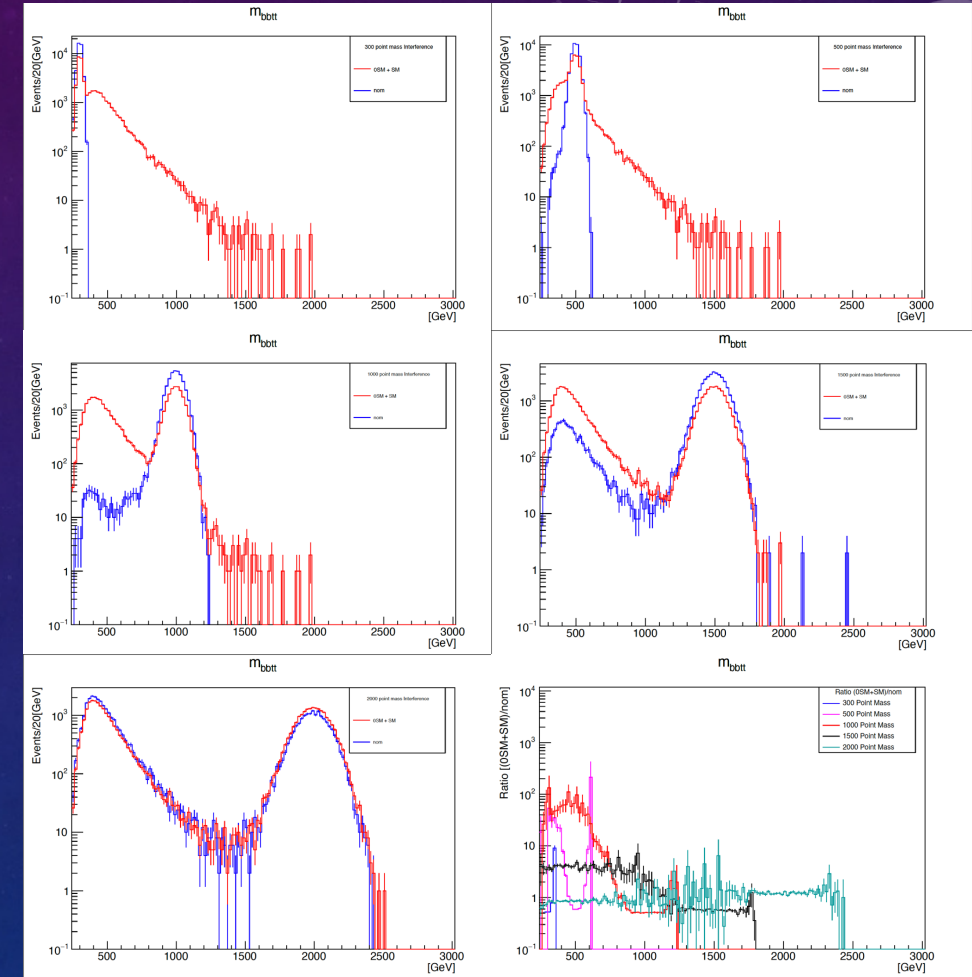
Varying Masses for Nom

- In comparison to the previous slide, we see SM contribution at the narrow width. At the other widths, the peak near 300 GeV is a combination of SM production and off-shell from resonant. As we go to higher masses and higher widths, we get more fraction of SM production in comparison to resonant production. Therefore, we should note that the off-shell from resonant could appear as an enhancement to the SM production. Thus, could lead to measuring a higher non-resonant cross section than without the presence of that resonance.



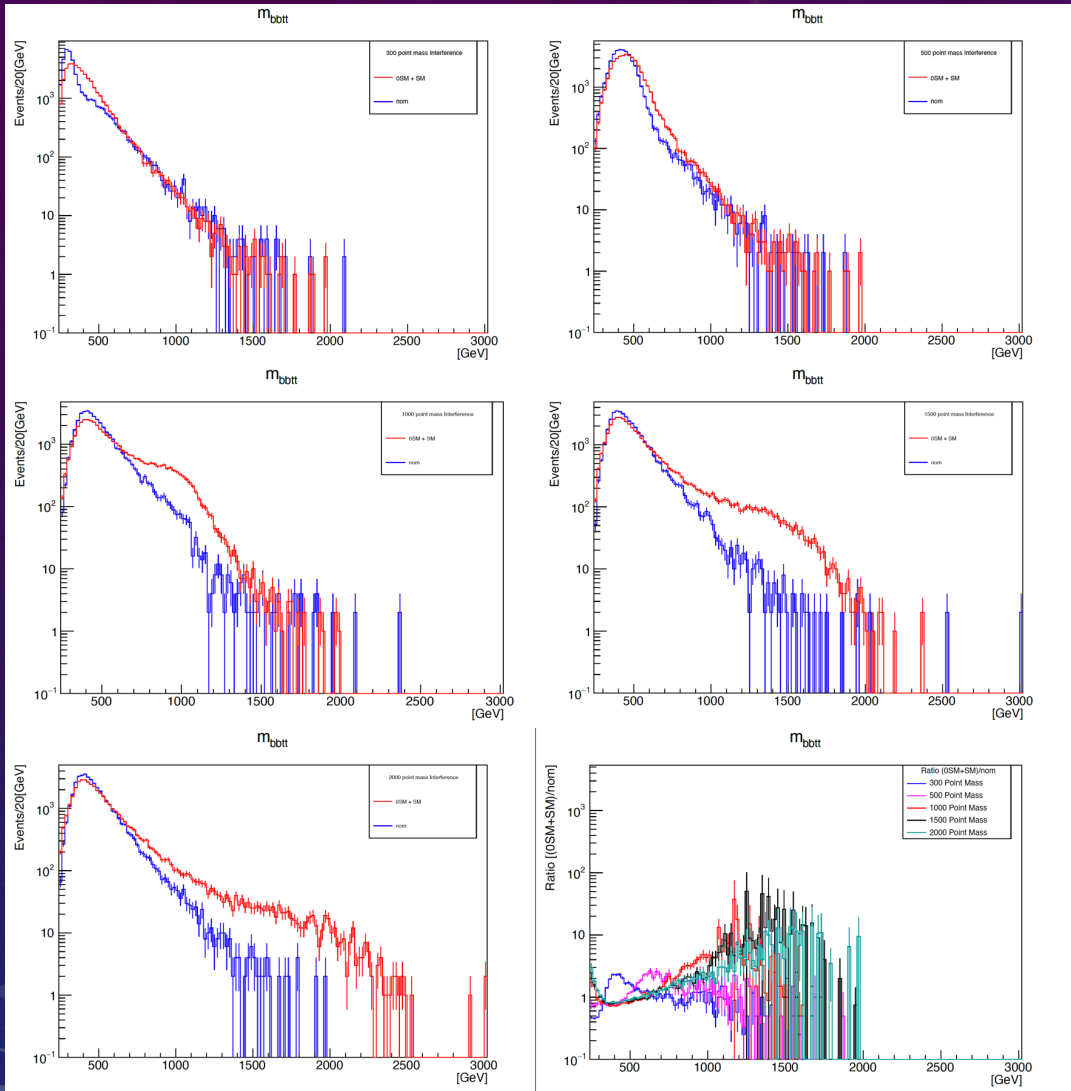
INTERFERENCE

- Now that we have identified the individual effects that occur within SM, OSM, and nominal, we can now begin to identify the interference that occurs between SM and OSM within nominal. We do this by plotting SM + OSM where we expect to see no interference because they were produced independently of one another then added together. Where nominal is SM and OSM are produced simultaneously and interference between them occurs. To aid us in maximizing identification if any effects that occur with this interference, we plot the SM+OSM against nominal for all point masses at the same width and then plot the ratio of interference $[(SM+OSM)/nom]$ for all point masses. Furthermore, we will produce this set of plots at each width.
- An example of a set of plots for a given width is shown here:



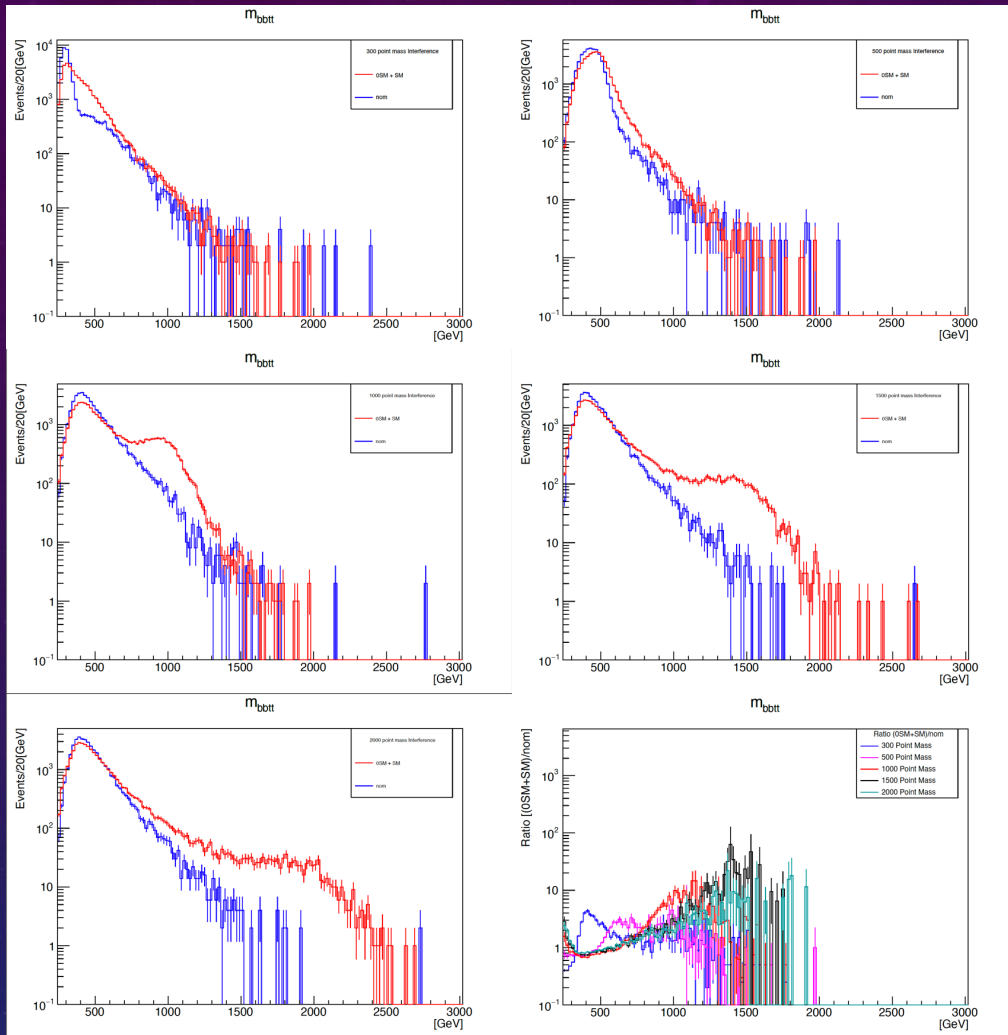
30% WIDTH INTERFERENCE

- At 30% width we see an increase in interference for increasing point masses. An effect depicted in the ratio graph for interference for all point masses. The last plot in our set.



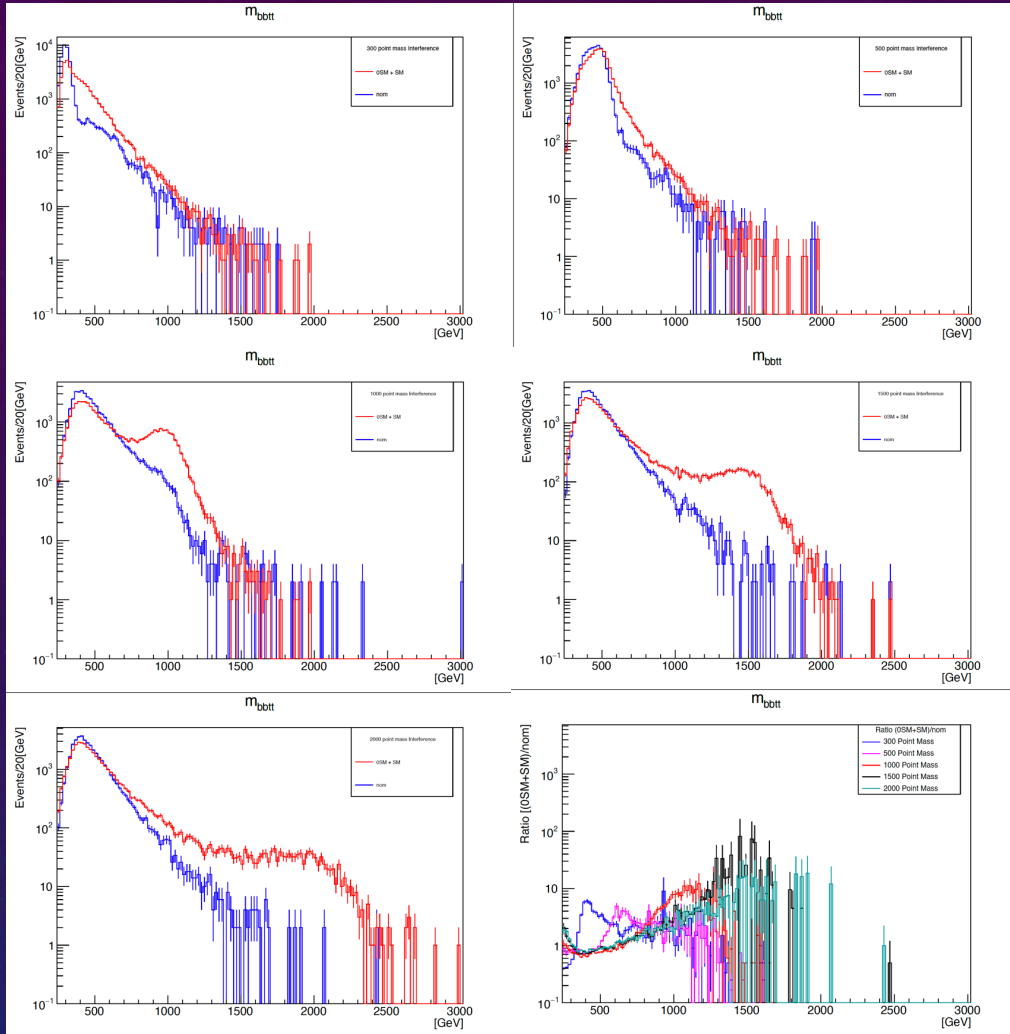
20% WIDTH INTERFERENCE

- At 20% width, an increase in interference for increasing point masses is observed. However, it appears to be in less effect in comparison to the 30% width set.

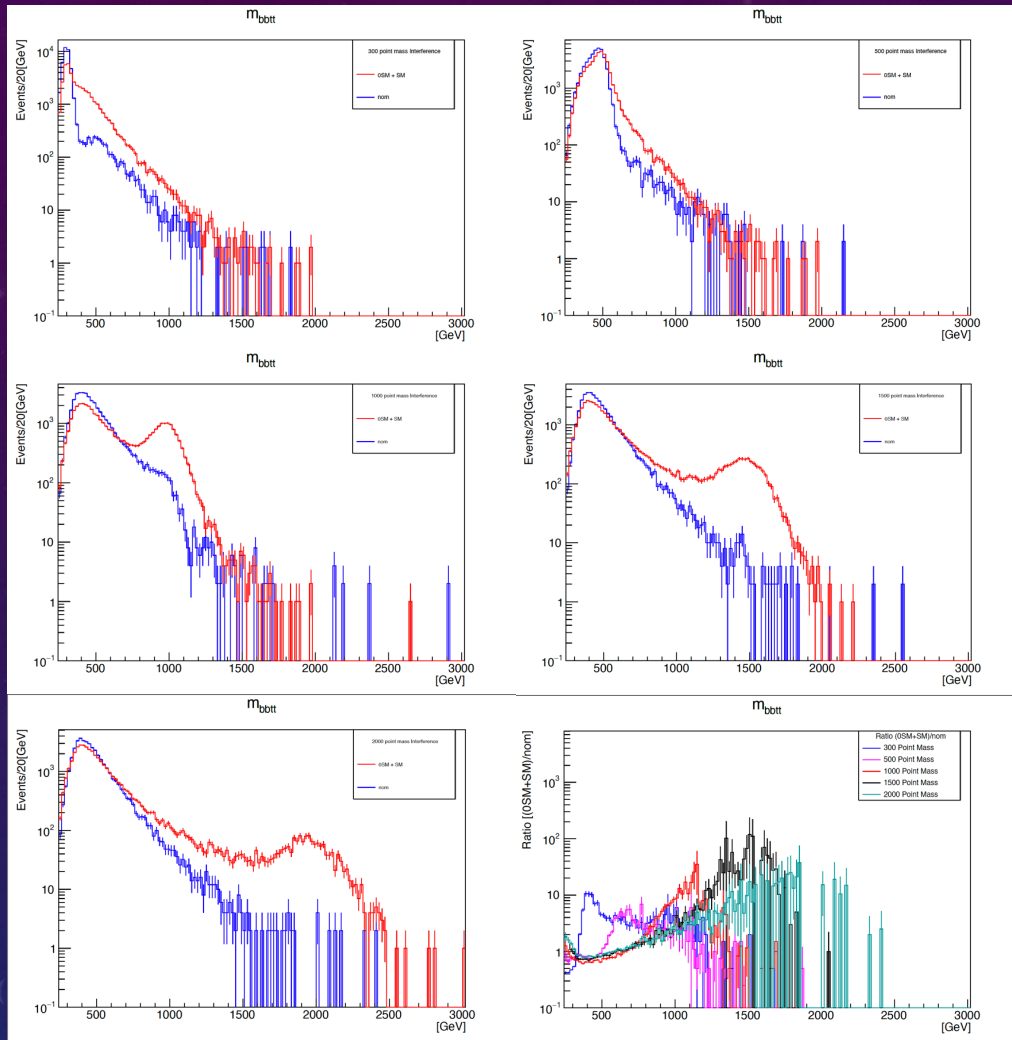


15% WIDTH INTERFERENCE

- Next, we have the 15% width set. We observe the same occurrence of an increase in interference for increasing point masses. Yet, similarly to what occurred between 20% and 30%, we observe it also occurs between 15% and 20%. Meaning we witness the affect of increased interference with increasing point mass to be less significant in 15% than the 20% width set.

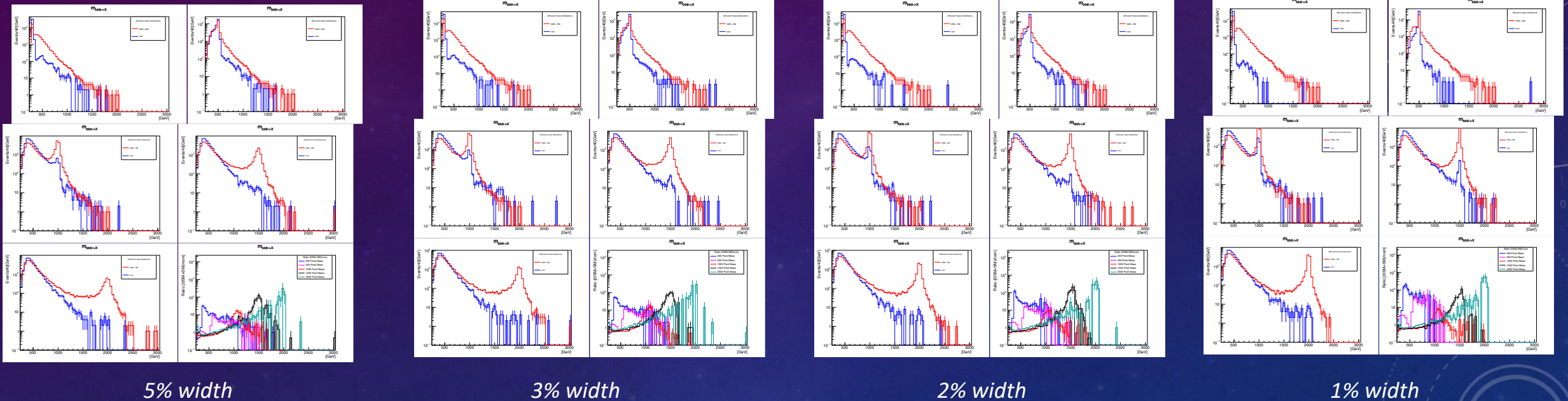


10% WIDTH INTERFERENCE

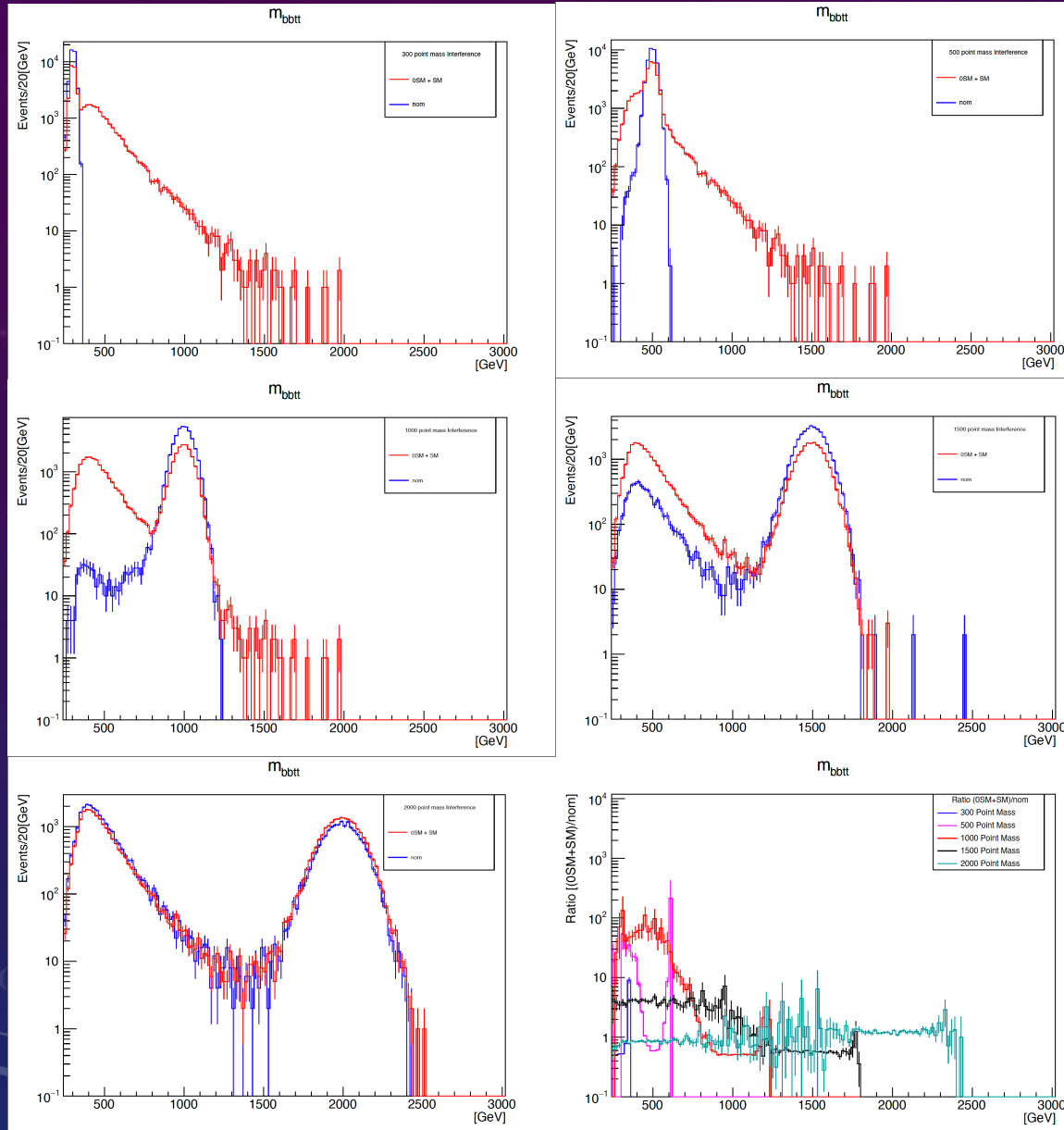


- Moving onto the 10% width set, where once again the interference grows with point mass. Although it is much less pronounced effect. So much so, that the interference peaks are equally high at the 1000 GeV point mass as the 300 GeV point mass.

5%, 3%, 2%, 1% WIDTH INTERFERENCE



Now at 5% width, once again we observe an increase in the severity of the interference for increasing point masses, but in far less affect in comparison to previous widths. In fact, as we see in decrease further in significance greater and greater as we go to lower widths. In fact, beginning at 3% width and down to 1%, the lower masses start to overtake the higher masses. Where we see eventually, that the interference decreases as we go to higher point masses, but then completely switches in effect and interference increase as we go to higher point masses. Acting as a parabola of sorts when it comes to the relationship between interference and increased point mass.



NARROW WIDTH INTERFERENCE

- Finally, at narrow width, the greatest interference occurs at low masses. And the higher masses have the least interference.

NOTABLE OBSERVATIONS

- The 300 GeV mass point sees the greatest interference effect at low widths.
- The interference of the 500 GeV point mass across all widths with some exception, has one of the lowest interferences. However, at narrow width this changes, and it has one of the greatest level of interferences.
- Vice versa, at point masses 1500 or 2000 GeV, we see the highest levels of interference, especially for for high widths. At narrow this changes and these high point masses have amongst the lowest level of interferences. In fact, at narrow, the 2000 GeV point mass appears to have nearly no interference across its distribution.

CONCLUSIONS

- There is an enhancement at the 300/400 GeV area in the SM non-resonant peak due to off-shell production from high mass resonances.
- We see an interference between the non-resonant and heavy Higgs resonant production. The interference is dependent on the mass point and width. For high masses, the interference is greatest at higher widths. For lower masses, the interference is greatest at lower widths.
- Thus, we should be testing at all widths rather than just narrow, especially when it comes to certain point masses.