# $hh \rightarrow b\bar{b}\gamma\gamma$: $p_T$ and $m_{jj}$ cuts

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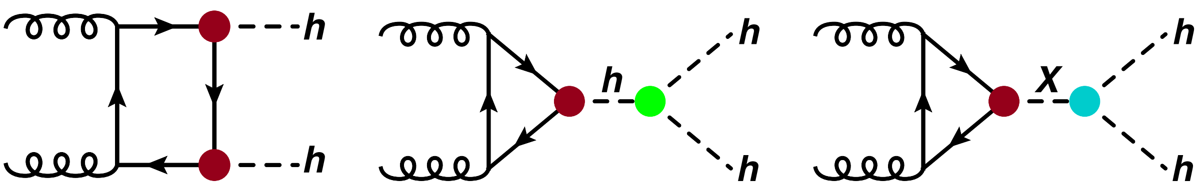
**Abstract**

Resonant and non-resonant production of pairs of Higgs bosons ( hh ) in the $b\bar{b}\gamma\gamma$ final state recorded by the ATLAS detector at the CERN Large Hadron Collider have been investigated in previous analyses. These used $\sqrt{s}$ = 8 TeV (2012) 20 fb$^{-1}$ [1] and $\sqrt{s}$ = 13 TeV (2015) 3.2 fb$^{-1}$ [2] data. The same analysis will be performed on the data that is currently accumulated and which will have considerably higher luminosity at $\sqrt{s}$ = 13 TeV. In order to get optimal results from the new data the significance for different cuts on $p_T$ and $m_{jj}$ has been investigated. It has been found that it is favorable to choose two sets of cuts, one for the low mass samples (BSM X275 hh, BSM X300 hh, BSM X325 hh, BSM X350 hh) and one for the high mass samples (BSM X400 hh, SM hh). The new cuts for the low mass samples were close to the cuts used before and were higher for the high mass samples. For all samples the new choices of cuts let to an improvement of the significance. The best JVT cut for all samples was found to be 0.59.

# Contents

# 1 Introduction

In 2012, both the ATLAS and CMS experiments at the Large Hadron Collider (LHC) have discovered a particle with properties that are in good agreement with those of the Standard Model (SM) Higgs boson (h). Since then many experiments are aimed at measuring its properties in more detail and investigating other properties that might outreach the predictions of the SM. This discovery opens up many new channels for possible beyond the Standard Model (BSM) physics. One of these possibilities is the production of Higgs boson pairs. In the SM the two leading order production modes are through a heavy quark loop and the Higgs self-coupling (figures 1 (a) and (b))which interfere destructively.




(a) (b) (c)

Figure 1: SM Leading order production diagrams through (a) a heavy quark loop, (b) Higgs self-coupling. (c) shows the decay through a resonance in BSM physics.

This leads to a cross section which is orders of magnitude smaller than the single Higgs cross section and therefore not expected to be observable using the present datasets. BSM models suggest among other things the existence of resonant decays or a value of the self-coupling $\lambda_{hhh}$ that differs from the value predicted by the SM. This would result in a higher cross section. Therefore the observation of Higgs boson pair production could be regarded as evidence for BSM physics. The decay channel $hh \rightarrow b\bar{b}\gamma\gamma$ seems to be very promising for this. It has a large branching ratio and a clean $m_{\gamma\gamma}$ signal.
In the analysis done in 2012 $pp$ collision data at $\sqrt{s}$ = 8 TeV and 20 fb$^{-1}$ were used and a modest excess was found with 2.4 standard deviations from the background-only hypothesis. This was repeated with the 2015 data at $\sqrt{s}$ = 13 TeV but only 3.2 fb$^{-1}$ and no excess was found since there was a deficit with regard to expected background. The luminosity in 2016 has already exceeded 22 fb$^{-1}$ and with such a large amount of data at this energy the analysis will be repeated again. In order to optimize the results that this future analysis will yield cuts on transverse momentum $p_T$ and on mass of the jets $m_{jj}$ are investigated in more detail.
The set of cuts chosen for the previous analyses were optimized for the 2012 data and reapplied in 2015 [2] in order to have comparable studies with the same methods. The aim of this study is to determine if these previous cuts are still optimal for the new data or if there is a set of cuts that lead to another improvement.

# 2 Methods

The cuts on the highest-$p_T$ b-jet ($p_{T,1}^{min}$) meaning that it must have $p_T > p_{T,1}^{min}$ and the next-highest-$p_T$ b-jet ($p_{T,2}^{min}$) are investigated in section 3.1.
The cuts on the invariant mass of the b-jet pair, $m_{jj}$, meaning that it must lie between $m_{jj}^{min}$ and $m_{jj}^{max}$ are investigated in section 3.2.

The optimization of the cuts was done with the following samples produced by the indicated Monte Carlo event generators:

- SM $hh \rightarrow \gamma\gamma b\bar{b}$ (NLO) aMC@NLO + Herwig++
- SM jet/photon bkg (LO) Sherpa
- $X275 \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ (LO) MadGraph+Pythia8
- $X300 \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ (LO) MadGraph+Pythia8
- $X325 \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ (LO) MadGraph+Pythia8
- $X350 \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ (LO) MadGraph+Pythia8
- $X400 \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ (LO) MadGraph+Pythia8

Standard HGam preselection cuts are applied which make sure that the number and quality of the photons are as needed for this analysis.
The cross section was chosen to be the maximum value that has not been ruled out by experiment yet. The luminosity applied is the value that is expected to be reached by the LHC.

- SM hh: $\sigma = 12.89$ fb
- BSM hh: $\sigma = 12.89$ fb
- L = 40 fb$^{-1}$

The cuts that were applied on the 2012 and 2015 data were: $p_{T,2}^{min} = 35$, $p_{T,1}^{min} = 55$ and $m_{jj}^{min} = 95$ GeV, $m_{jj}^{max} = 135$ GeV. In the following, it will be investigated whether these cuts are also optimal for future analysis. The significance was calculated for possible combinations of the cuts in the following ranges:

- $p_T$ cuts:
  - $p_{T,1}$ from 30 - 150
  - $p_{T,2}$ from 25 - ($p_{T,1}$ - 5) (meaning that $p_{T,2} < p_{T,1}$)
- $m_{jj}$ cuts:
  - $m_{jj,min}$ from 60 - 125GeV

- $m_{jj,max}$ from 130 - 160GeV

The significance shown in the following is calculated using the Asimov formula:

$$Z = \sqrt{(2 * ((S + B) * log(1 + S/B) - S))} \tag{1}$$

with S and B being the number of events between 120 - 130 GeV in the $M_{\gamma\gamma}$ histograms for the signal or background respectively as shown in fig 2.

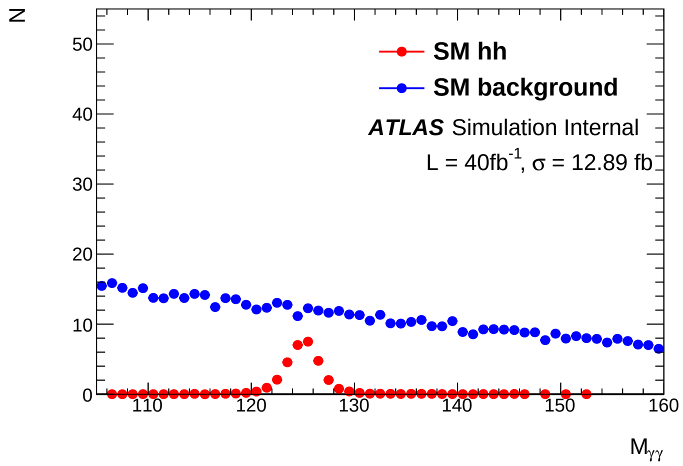



Figure 2: $M_{\gamma\gamma}$ histogram for SM sample with no cuts applied

Additionally it has also been investigated what the best JVT (jet vertex tagging) cut is for all samples. JVT is a parameter that separates pile up and hard-scatter jets. It ranges from 0 to 1 and peaks at 0 for pile up jets and at 1 for hard scatter jets. Recommended cuts by the ATLAS Jet/Etmiss group are 0.11, 0.59, 0.91. In the previously done analyses a JVT cut of 0.64 was used which was one of the recommended values at the time.

# 3 $p_T$ and $m_{jj}$ cuts

## 3.1 $p_T$ cuts

With no $m_{jj}$ cuts applied $p_{T,1}^{min}$ and $p_{T,2}^{min}$ have been varied in the ranges stated in section 2. The significance is visualized in two dimensional histograms as shown in figure 3. The value indicated in the plot shows the maximum significance. It was concluded that the cuts with this highest value were the best cuts.

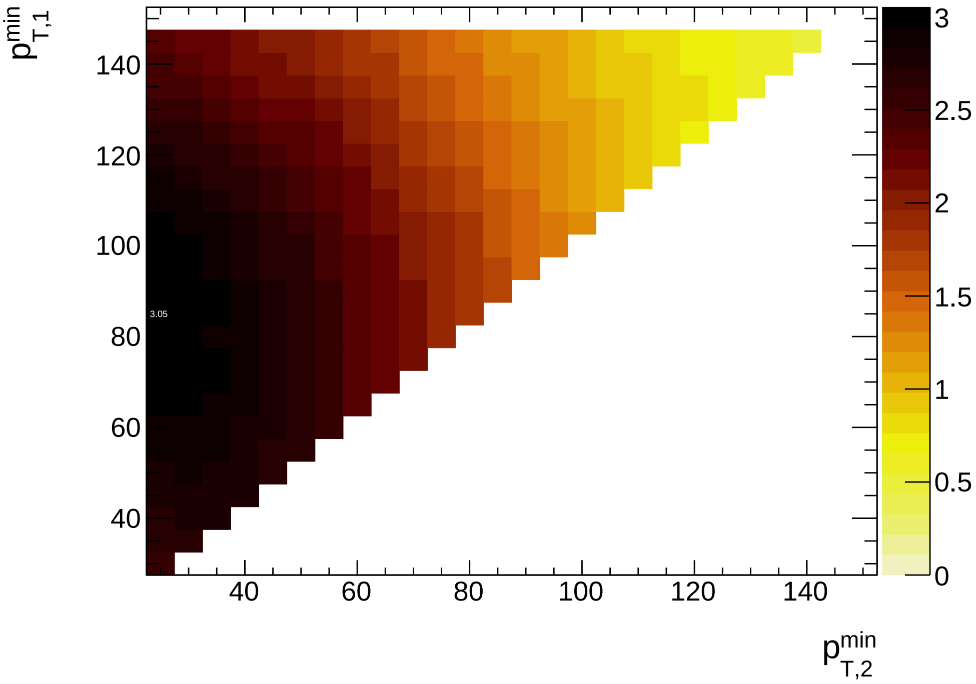



Figure 3: Significance histogram for SM sample with JVT = 0.59: $p_T$ cuts

Similar histograms were made for all samples and all JVT cuts. The results of the best cuts and the corresponding significance are shown in table 1.

| JVT cut | 0.11 | | | 0.59 | | | 0.91 | | |
|---|---|---|---|---|---|---|---|---|---|
| sample | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | Z | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | Z | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | Z |
| SM hh | 85 | 25 | 7.34 | 85 | 25 | 7.35 | 75 | 25 | 7.35 |
| BSM X275 hh | 40 | 25 | 4.24 | 40 | 25 | 4.20 | 40 | 25 | 4.16 |
| BSM X300 hh | 45 | 25 | 4.55 | 45 | 25 | 4.49 | 45 | 25 | 4.46 |
| BSM X325 hh | 50 | 25 | 4.87 | 50 | 25 | 4.82 | 50 | 25 | 4.79 |
| BSM X350 hh | 55 | 25 | 5.22 | 55 | 25 | 5.23 | 55 | 25 | 5.18 |
| BSM X400 hh | 70 | 25 | 6.13 | 70 | 25 | 6.19 | 70 | 25 | 6.15 |

Table 1: best $p_T$ cuts

From these results it seemed that $p_{T,2}^{min} = 25$ would be the best choice. For $p_{T,1}^{min}$ the options lay between 40 and 85. The best JVT cut was either 0.11 or 0.59. Since the best overall choice of $p_{T,1}^{min}$ was not clear the value of Z for various values of $p_{T,1}^{min}$ is shown in figure 4.

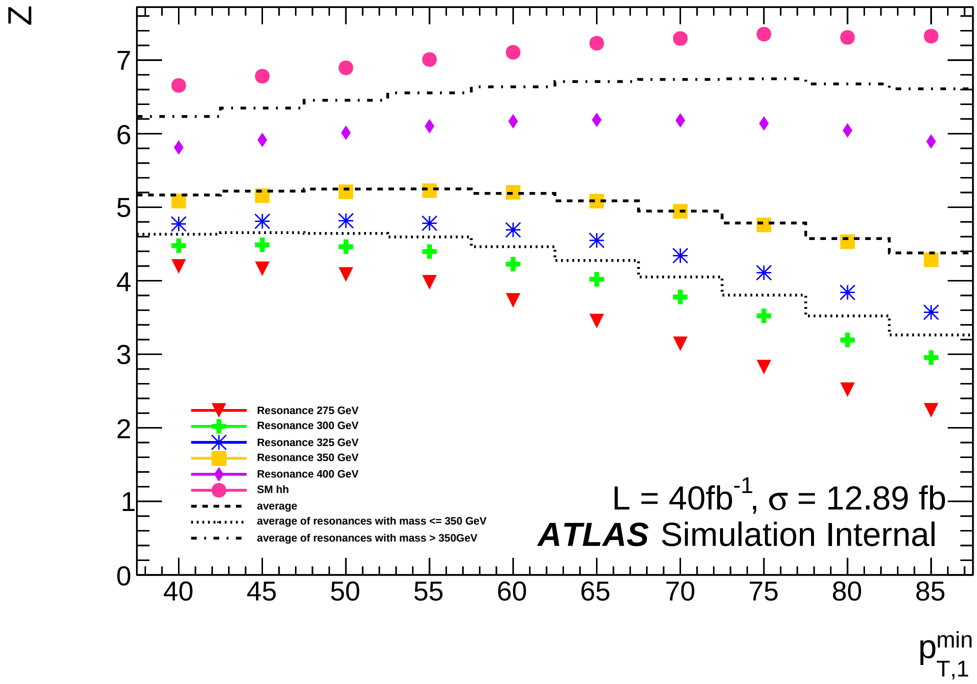



Figure 4: Cut options for $p_{T,1}^{min}$ with $p_{T,2}^{min} = 25$

This led to the conclusion that $p_{T,1}^{min} = 55$ is the best choice.

### 3.2 $m_{jj}$ cuts

With no $p_T$ cuts applied $m_{jj}^{min}$ and $m_{jj}^{max}$ have been varied in the ranges stated in section 2. Again, two dimensional histograms as shown in figure 5 were made and the maximum significance is shown.

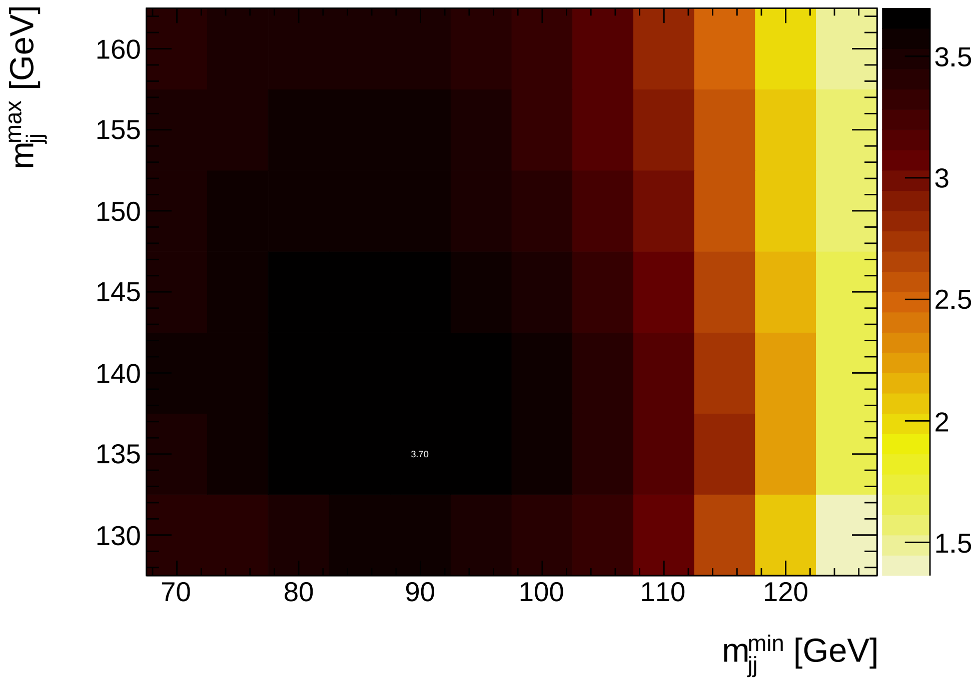



Figure 5: Significance histogram for SM sample with JVT = 0.59: $m_{jj}$ cuts

This was repeated for all samples and all JVT cuts. The results of the best cuts and the corresponding significance are shown in table 2.

| JVT cut | 0.11 | | | 0.59 | | | 0.91 | | |
|---|---|---|---|---|---|---|---|---|---|
| sample | $m_{jj}^{min}$ | $m_{jj}^{max}$ | Z | $m_{jj}^{min}$ | $m_{jj}^{max}$ | Z | $m_{jj}^{min}$ | $m_{jj}^{max}$ | Z |
| SM hh | 90 | 135 | 8.38 | 90 | 135 | 8.59 | 90 | 135 | 8.71 |
| BSM X275 hh | 90 | 140 | 5.37 | 90 | 140 | 5.32 | 90 | 145 | 5.30 |
| BSM X300 hh | 90 | 145 | 5.75 | 90 | 145 | 5.70 | 90 | 145 | 5.70 |
| BSM X325 hh | 90 | 140 | 6.15 | 90 | 140 | 6.15 | 90 | 140 | 6.14 |
| BSM X350 hh | 90 | 140 | 6.46 | 90 | 140 | 6.55 | 90 | 140 | 6.53 |
| BSM X400 hh | 90 | 140 | 7.30 | 90 | 140 | 7.50 | 90 | 140 | 7.54 |

Table 2: best $m_{jj}$ cuts

The best choice for the JVT cut was not clear. $m_{jj}^{min}$ = 90 GeV seemed to be the best cut whereas there were a few options for the best $m_{jj}^{max}$. Figure 6 shows Z for different values of $m_{jj}^{max}$.

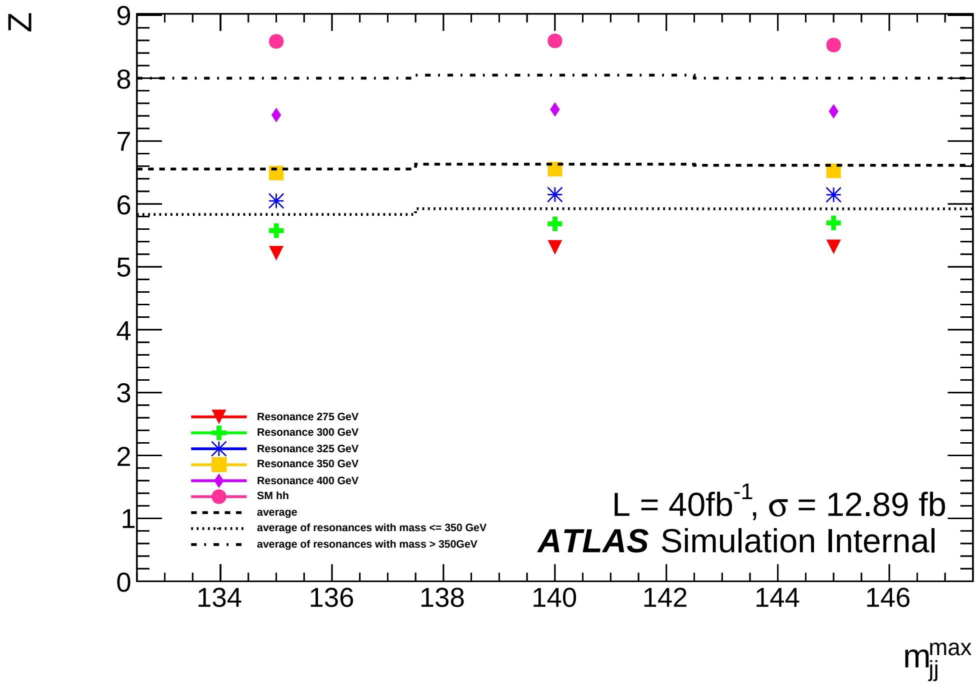



Figure 6: Cut options for $m_{jj}^{max}$ with $m_{jj}^{min} = 90$ GeV

This led to the conclusion that $m_{jj}^{max} = 140$ GeV is the best choice for all samples.

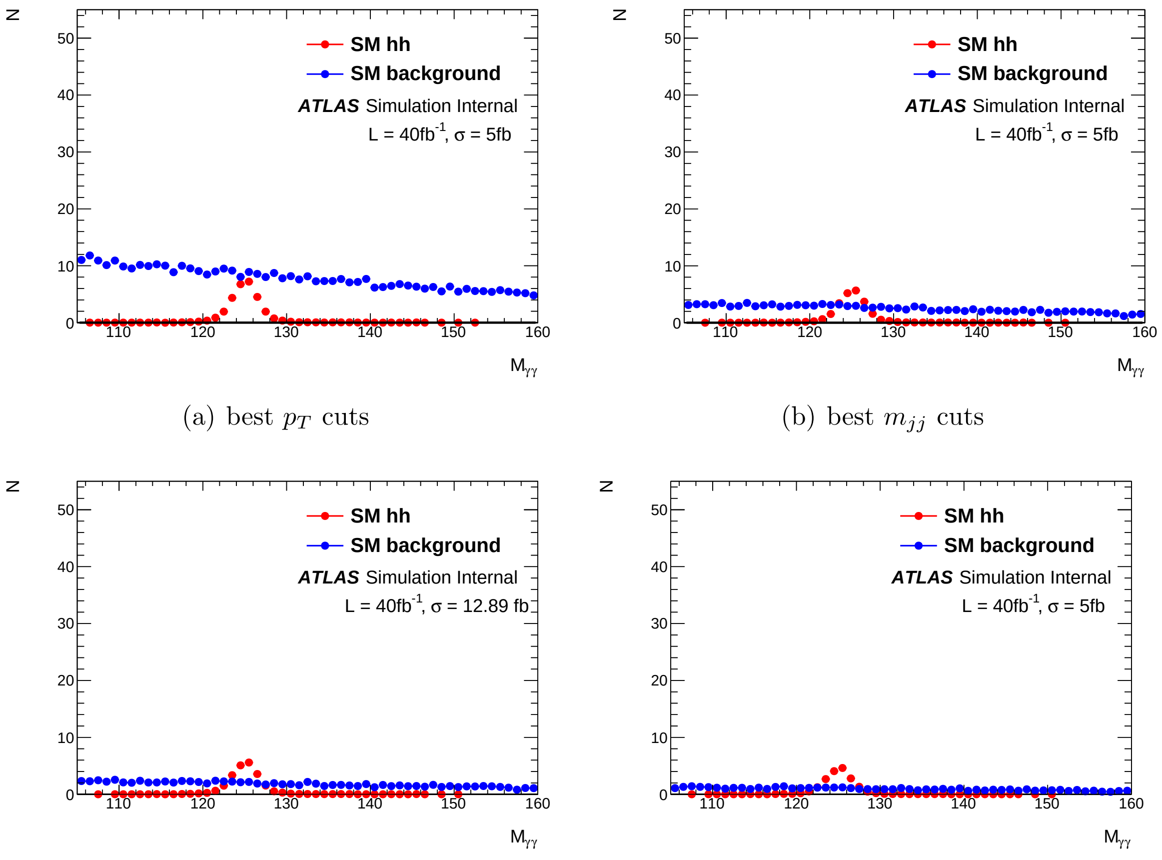
## 3.3 Comparison of old and new cuts

The best cuts found from this analysis and the old cuts are shown in table 3.

| cuts | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | $m_{jj}^{min}$ | $m_{jj}^{max}$ |
|---|---|---|---|---|
| old | 55 | 35 | 95 | 135 |
| new | 55 | 25 | 90 | 140 |

Table 3: Old and new best cuts

To show the improvement of the significance the $M_{\gamma\gamma}$ histograms are shown in figure 7.




(a) best $p_T$ cuts
(b) best $m_{jj}$ cuts
(c) best cuts new
(d) best cuts old

Figure 7: Comparison of $M_{\gamma\gamma}$ histograms

Compared to figure 7 (a) all cuts that were found show an enhanced significance. However when compared to the old cuts which were applied to the 2012 and 2015 data the new cuts seem to lead to a significance that was smaller than with the old cuts for some samples. This was especially the case for the SM sample and the BSM sample with a resonance mass of 400 GeV as can be seen in table 4.

| JVT cut | 0.11 | | 0.59 | | 0.91 | |
|---|---|---|---|---|---|---|
| sample | Z (old) | Z (new) | Z (old) | Z (new) | Z (old) | Z (new) |
| SM hh | 9.73 | 9.36 | 9.78 | 9.52 | 9.81 | 9.59 |
| BSM X275 hh | 4.99 | 5.34 | 4.90 | 5.28 | 4.83 | 5.22 |
| BSM X300 hh | 5.63 | 6.01 | 5.52 | 5.94 | 5.47 | 5.91 |
| BSM X325 hh | 11.02 | 11.82 | 10.83 | 11.69 | 10.75 | 11.60 |
| BSM X350 hh | 6.91 | 7.10 | 6.89 | 7.15 | 6.85 | 7.09 |
| BSM X400 hh | 8.18 | 8.14 | 8.25 | 8.31 | 8.24 | 8.30 |

Table 4: Comparison of the significance Z with the old and new best cuts applied

This means that the best cuts on $p_T$ and $m_{jj}$ stated in the previous sections are not the best choice for all samples when all four of these cuts are combined. Therefore, the significance was also investigated by varying all four variables.

## 3.4 Four dimensional analysis of both $p_T$ and $m_{jj}$ cuts

When varying all four parameters it is not possible anymore to show the results in form of plots. Therefore only the tables with the best cuts are shown. In order to minimize computing time the parameters were not varied over the complete range stated in section 2 but in the following ranges:

$p_T$ cuts:
$p_{T,1}$ from 40 - 120; $p_{T,2}$ from 25 - 55 (still $p_{T,1} < p_{T,2}$)
$m_{jj}$ cuts:
$m_{jj,min}$ from 85 - 110GeV; $m_{jj,max}$ from 130 - 150GeV

The best value was found when the cuts lay within the chosen interval and were not equal to a value at the border of the interval.

| sample | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | $m_{jj}^{min}$ | $m_{jj}^{max}$ | Z |
|---|---|---|---|---|---|
| SM hh | 100 | 45 | 100 | 140 | 11.72 |
| BSM X275 hh | 45 | 25 | 90 | 140 | 5.94 |
| BSM X300 hh | 50 | 25 | 90 | 140 | 6.51 |
| BSM X325 hh | 55 | 30 | 90 | 140 | 7.04 |
| BSM X350 hh | 65 | 30 | 90 | 140 | 7.52 |
| BSM X400 hh | 80 | 40 | 90 | 140 | 9.14 |

Table 5: Best cuts for JVT = 0.59

Since the best cuts differed especially for the high and low mass samples, different best cuts were chosen. Additionally also a set of best cuts for all samples is shown. The low mass samples are BSM X275 hh, BSM X300 hh, BSM X325 hh, BSM X350 hh and the high mass samples are BSM X400 hh, SM hh.

| samples | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | $m_{jj}^{min}$ | $m_{jj}^{max}$ | 0.11 | 0.59 | 0.91 |
|---|---|---|---|---|---|---|---|
| all samples | 55 | 30 | 90 | 140 | 7.41 | 7.51 | 7.49 |
| low mass | 55 | 25 | 90 | 140 | 6.59 | 6.69 | 6.67 |
| high mass | 85 | 35 | 90 | 140 | 10.19 | 10.23 | 10.23 |

Table 6: Best cuts for samples

Additionally to the best cuts for the different categories of samples also the performance of Z for different values of the JVT cut is shown in table 6. This led to the conclusion that a JVT cut of 0.59 is preferable.

A comparison of the value of the significance Z with the old cuts and the three pairs of cuts stated before is shown in table 7. A JVT cut of 0.59 is applied.

| samples | Z (old) | Z(all) | Z (low m) | Z (high m) |
|---|---|---|---|---|
| BSM X275 hh | 5.38 | 5.68 | 5.77 | 2.54 |
| BSM X300 hh | 6.01 | 6.37 | 6.48 | 3.94 |
| BSM X325 hh | 6.61 | 6.99 | 7.04 | 5.17 |
| BSM X350 hh | 7.19 | 7.48 | 7.45 | 6.40 |
| BSM X400 hh | 8.39 | 8.52 | 8.40 | 8.99 |
| SM hh | 9.89 | 9.83 | 9.53 | 11.40 |

Table 7: Z for best cuts

The enhancement of Z can be seen especially clearly for the SM sample. This also confirms that a different set of cuts for high and low mass samples improves the results. Therefore it can be concluded that the cuts found in the four dimensional analysis maximize the significance. These cuts are recommended for the future analysis of the $hh \rightarrow b\bar{b}\gamma\gamma$ channel.

# 4 Conclusion and outlook

Best cuts on $p_T$ and $m_{jj}$ i.e. the best choices for $p_{T,1}^{min}$, $p_{T,2}^{min}$, $m_{jj}^{min}$ and $m_{jj}^{max}$ for the decay channel $hh \rightarrow b\bar{b}\gamma\gamma$ for events with 2 b-tagged jets were investigated. In the SM the cross section for this channel is negligable compared to the single Higgs channel. Therefore a detected signal could give evidence for BSM physics. This analysis was done with 2012 and 2015 data and will be repeated with future data which will be at a higher energy and has a higher integrated luminosity. The cuts were optimized using Monte Carlo samples as stated in section 2.
Separate analysis of the best $p_T$ and $m_{jj}$ cut respectively led to the conclusion that these two parameters should not be optimized independently. The results can be found in section 3.1 and 3.2.
The cuts were then optimized all at once which let to three sets of best cuts:

| samples | $p_{T,1}^{min}$ | $p_{T,2}^{min}$ | $m_{jj}^{min}$ | $m_{jj}^{max}$ |
|---|---|---|---|---|
| all samples | 55 | 30 | 90 | 140 |
| low mass | 55 | 25 | 90 | 140 |
| high mass | 85 | 35 | 90 | 140 |

Table 8: Best cuts for samples

Since the best cuts were far apart for the samples with low mass (BSM X275 hh, BSM X300 hh, BSM X325 hh, BSM X350 hh) and high mass (BSM X400 hh, SM hh) different cuts were chosen. The influence on the value of the significance Z can be seen in table 7. These cuts should be applied in order to maximize the significance. The best overall JVT cut was found to be 0.59 which has already been used in the previous analyses.

Following this samples with other resonance masses that have not been covered yet will be investigated. Additionally the case with 1 b-tagged jet will be further investigated.

For future analysis of Higgs pair production in the $b\bar{b}\gamma\gamma$ channel in data collected by the ATLAS detector the cuts presented here could enhance the significance.

# References


[1] G. Aad *et al.* [ATLAS Collaboration], "Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using $pp$ Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector," Phys. Rev. Lett. **114** (2015) no.8, 081802 doi:10.1103/PhysRevLett.114.081802 [arXiv:1406.5053 [hep-ex]].

[2] ATLAS Collaboration, "Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using $pp$ Collision Data at $\sqrt{s} = 13$ TeV from the ATLAS Detector," ATLAS NOTE, ATLAS-CONF-2016-004.