Searches for heavy resonances in $HH \to \gamma\gamma\bar{b}b$ channel

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Introduction

In 2012, ATLAS and CMS collaborations at LHC have observed a massive[1], $J = 0$ particle consistent with SM Higgs boson [1]. Since then, next goal was to determine its' properties. One of the measurements that could be done is 2-Higgs production. Within the Standard Model, it happens in the same channels as single Higgs production, with gluon fusion dominating others by at least an order of magnitude [2].

[1]All data is given for Higgs boson mass $m_H = 125 GeV$

Introduction

Higgs scalar potential can be written as:

$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

Experimental measurement of λ_3 requires 2 Higgs production, and λ_4 requires 3 Higgs bosons. Within SM, expected cross sections are very small - can be sensitive to the New Physics [3].

Introduction

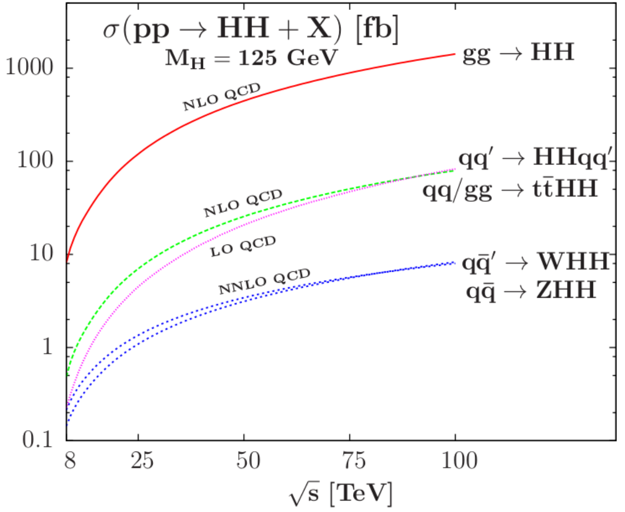

Figure: Fig.1 - cross-sections of SM 2-Higgs production. [2]

Introduction

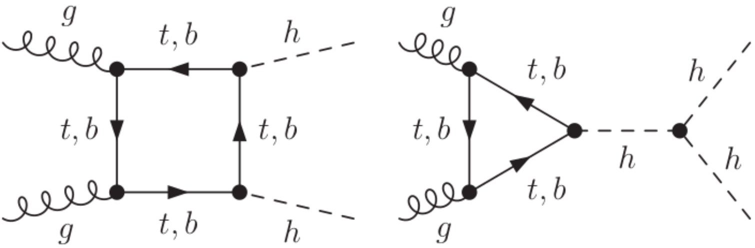

Figure: Fig.2 - gluon fusion - dominating mechanism of *HH* production in Standard Model. Box and triangle diagrams interfere destructively, resulting in very low cross-section.

Introduction

$\sqrt{s}$	$\sigma_{gg\to HH}$	$\sigma_{qq'\to qq'HH}$	$\sigma_{qq\to WHH}$	$\sigma_{qq\to ZHH}$	$\sigma_{qq\ gg\to HHt\bar{t}}$
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02

Table: Table 1 - SM predictions on 2-Higgs production in 4 dominant processes - gluon fusion, Higgs-strahlung, vector boson fusion, and associated top production at the energies of LHC. Energy is measured at TeV and cross-sections in fb [2]

$\sqrt{s}$	$\sigma_{gg\to H}[pb]$	σ_{WH}	σ_{ZH}	σ_{VBF}	$\sigma_{qq\ gg\to Ht\bar{t}}$
8	21.42	702.50	420.70	1650	133.0
13	48.57	1373	883.70	3925	507.1

Table: Table 2 - single Higgs production. Cross-sections are in fb, except gluon fusion [3].

Introduction

Comparison between Tables 1 and 2 gives a sense of scale - 2-Higgs production happens at the rate of $\approx 10^{-3}$ of single Higgs production. Next, let's have a look a the decay channels:

Introduction

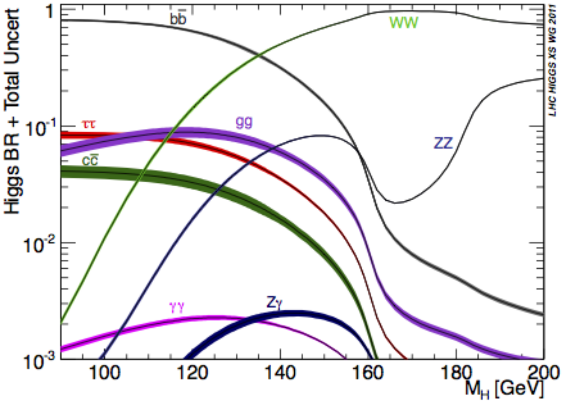

Figure: Fig.3 - Higgs SM cross-sections, from ATLAS website

Introduction

channel	BR	decay width [MeV]
$H \to b\bar{b}$	58.2%	2.38
$H \to WW$	21.4%	0.874
$H \to gg$	8.2%	0.335
$H \to \tau\bar{\tau}$	6.3%	0.256
$H \to c\bar{c}$	2.9%	0.118
$H \to ZZ$	2.6%	0.107
$H \to \gamma\gamma$	0.23%	$9.28 \cdot 10^{-3}$
other	$\leq 1\%$	

Table: Table 3 - branching ratios for Higgs boson of the mass $m_H = 125 GeV$ [3].

Why $HH \to b\bar{b}\gamma\gamma$?

We assume that each Higgs boson in 2-Higgs final state decays independently with branching ratios referred to in Table 3. While $\gamma\gamma$ channel is very clean, as evident from third column, requiring both Higgs bosons to undergo that decay suppresses an already rare process by an additional factor of $(2.27 \cdot 10^{-3})^2 \approx 5.15 \cdot 10^{-6}$. Therefore, we compromise and search for final states where one one Higgs decays into something with high BR, i.e $b\bar{b}$ or WW, despite the fact that jet channel is very dirty (QCD background, plus processes where single Higgs is produced together with 2 or more jets), and second Higgs in the pair to decay via clean $\gamma\gamma$ channel.

What we did

In analysis, I used Monte-Carlo simulated data,It had three main components:

- Standard Model background
- HH production consistent with the Standard Model
- $X \rightarrow HH$ samples for various m_H ranging from 260 to 1000 GeV.

Towards the end, we applied our analysis to a real LHC data sample (spoiler: we haven't seen anything surprising)

Event Selection

Two approaches to event selection were tried - a cut based analysis, and MVA, using TMVA Boosted Decision Tree (BDT) implementation.
First of all, we require candidate events to have at least 2 jets and 2 photons. Then, some generous low cuts were placed on jets' transverse momenta, to get rid of soft QCD background.
Two options:

- select highest p^T jets and photons are selected as candidates
- reconstruct masses of 2-jet 4-vectors.

We found out that for jets, selecting a pair that has reconstructed mass closest to $m_H = 125 GeV$ gives better results.

Event Selection

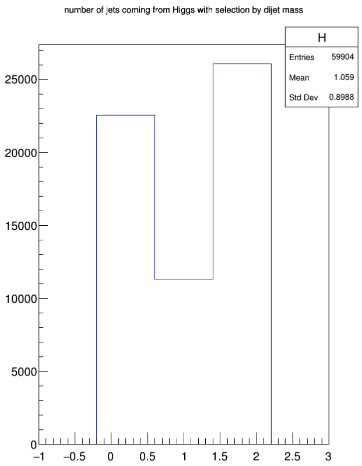

Figure: Fig.4 - Comparison between selection by p^T and reconstructed mass for $m_X = 300 GeV$ sample.

Event Selection

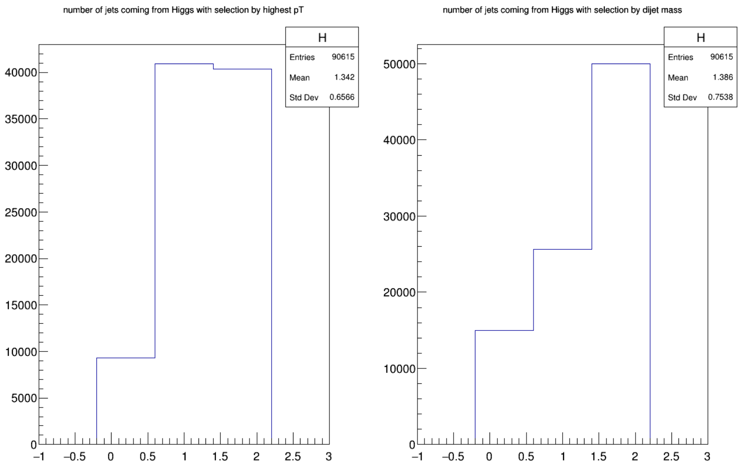

Figure: Fig.5 - Comparison between selection by p^T and reconstructed mass for MC SM 2-Higgs sample.

Event Selection

In the initial data samples, very loose cuts were already applied:

$$p^{T} \geq 20\ GeV$$

Signal is measured in $\gamma\gamma$ channel, where we expect a narrow peak around $m_H = 125 GeV$.

This is how things look without selection applied

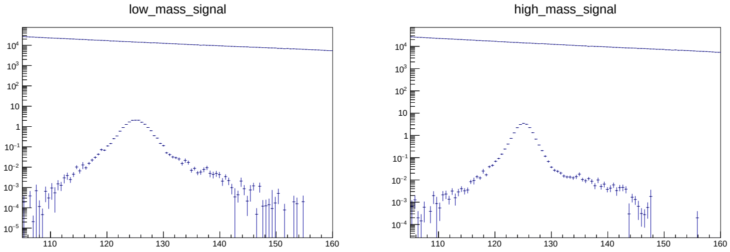

Figure: Fig.6 - $m_{\gamma\gamma}$ plots for $m_X = 300 GeV$ and $m_X = 1000 GeV$ samples. Signal significance is defined as $\frac{S}{\sqrt{B}}$, i.e ratio between areas under signal curve and background curve in signal region $(120 \leq m_{\gamma\gamma} \leq 130\,[GeV])$.

Signal on background in m_{jj}

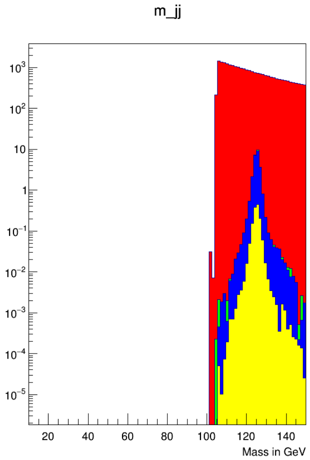

Figure: Fig.7 - several MC signals plotted on the same axis as background(red)

Event Selection

Following simple cuts are in place:

- $105 \leq m_{\gamma\gamma} \leq 160\,[GeV]$
- $n_\gamma \geq 2$
- $n_j \geq 2$

We then investigate if significance can be improved by placing additional cuts without throwing off significant part of the signal.

Event Selection

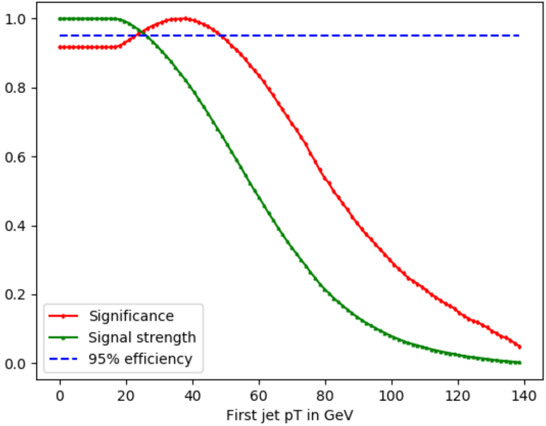

Figure: Fig.8 - plot of signal efficiency and significance, defined as $\frac{S}{\sqrt{B}}$, for different cut p^T_{jet1} cut placements.

Event Selection

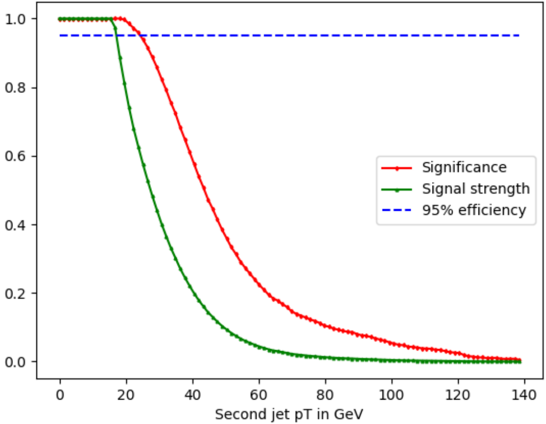

Figure: Fig.9 - plot of signal efficiency and significance, defined as $\frac{S}{\sqrt{B}}$, for different cut p^T_{jet2} cut placements.

Event Selection

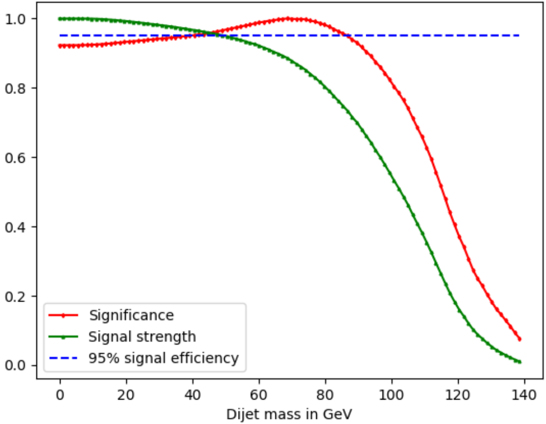

Figure: Fig.10 - plot of signal efficiency and significance for different m_{jj} cut placements

Event Selection

From the graphs above, we add following cuts, guided by the principle that 95% of signal should pass the cut:

- $p_2^T \geq 20\ GeV$
- $p_2^T \geq 25\ GeV$
- $m_{jj} \geq 50 GeV$

Those cuts are applied in all subsequent analyses.

Event Selection

For events that pass cuts described above, we select 2 photons with highest p^T and a pair of jets with invariant mass closest to $m_H = 125 GeV$. From those, we create lots of different variables to serve as MVA feature space - hoping that signal looks sufficiently different from background.

Boosted Decision Trees (BDT)

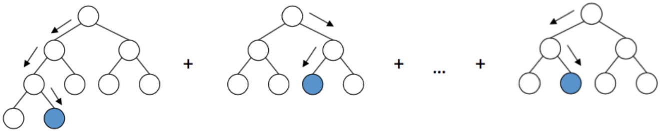

Figure: Fig.11 - schematic of a boosted decision tree, courtesy A. Rogozhnikov on github

Event Selection

In our analysis, we used $N = 800$ decision trees with $MaxDepth = 3$ working on input space of 83 variables initially. MC data was split into training and test samples randomly. After the first iteration, highly correlated ($\xi > 0.6$) variables were removed from feature space, with highest ranking surviving, to reduce overtraining.

Event Selection

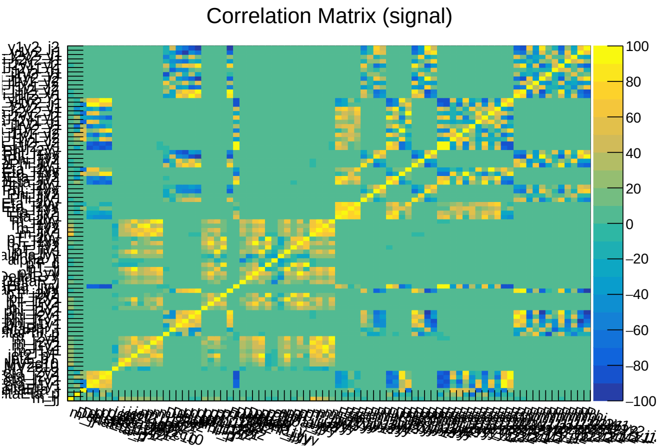

Figure: Fig.12 - Correlation matrix for our feature space.
Off-diagonal bright and cold spots are highly correlated variables

Event Selection

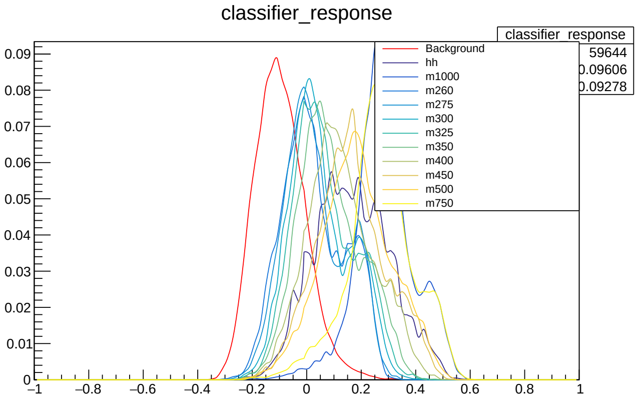

Figure: Fig.13 - Classifier response curves for single classifier. Significant overlap between signal and background events.

Event Selection

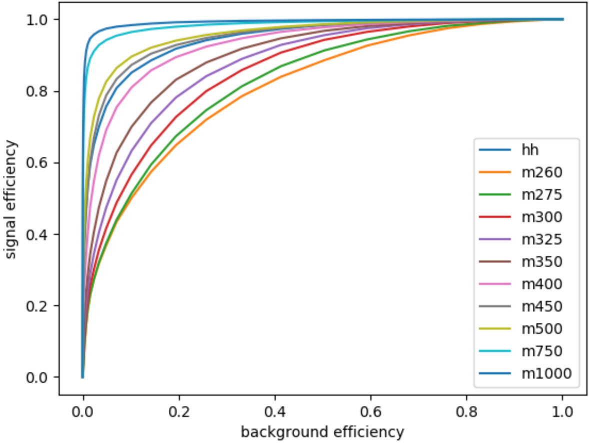

Figure: Fig. 14 - ROC for single classifier

Event Selection

In order to improve classification, we decided to split the samples into two classes. One class, for which classifier was shown to work quite well, incorporated SM di-Higgs simulated data as well as resonances with mass $m_X \geq 450\ GeV$. Another sample, for which classifier performed poorly, consisted of resonances with $m_X \leq 400\ GeV$.

Event Selection

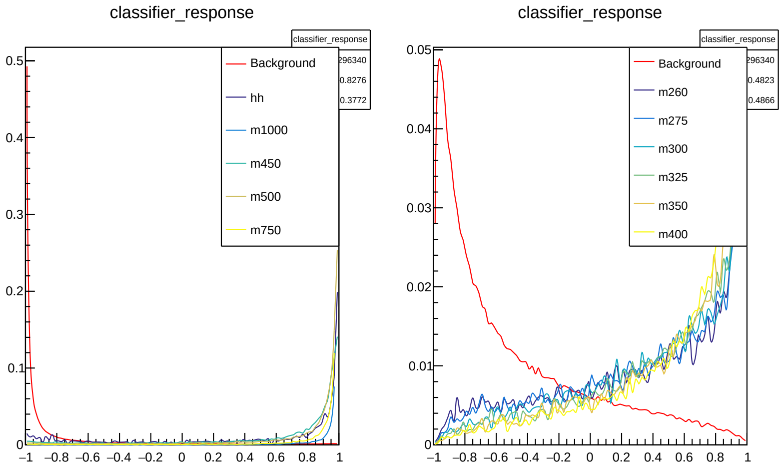

Figure: Fig.15 - classifier score plots for each subset.

Event Selection

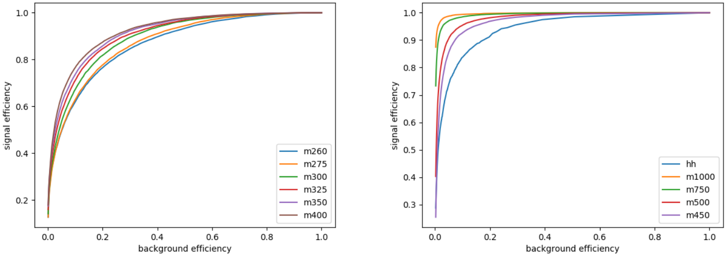

Figure: Fig.16 - ROC for 2 classifiers. On the left-hand side is the classifier for low-mass resonances, on the right-hand side is the classifier for high mass resonances and SM HH

Event Selection

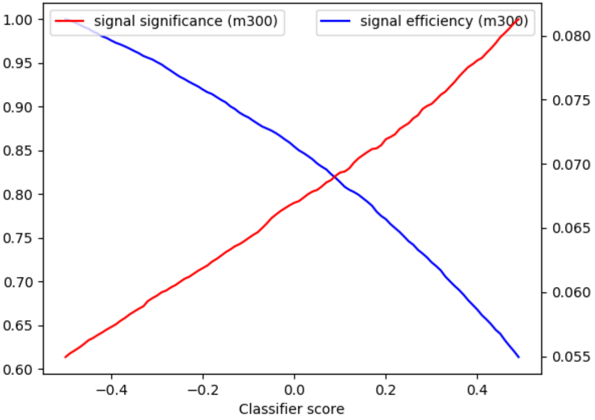

Figure: Fig.17 - plot of signal efficiency and significance for different cuts on MVA classifier score.

Results

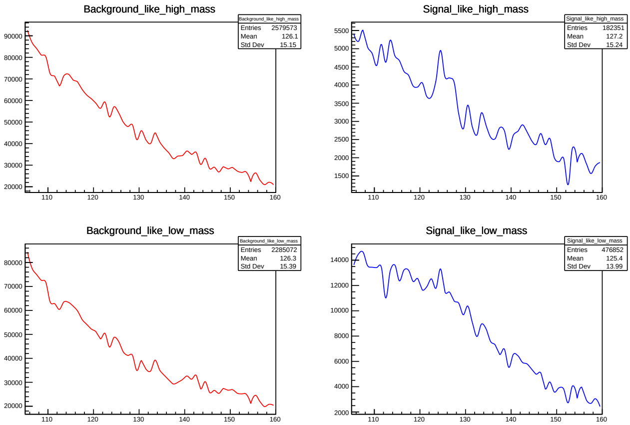

Figure: Fig.18 - data in $m_{\gamma\gamma}$ after classification applied, for both classifiers.

Results

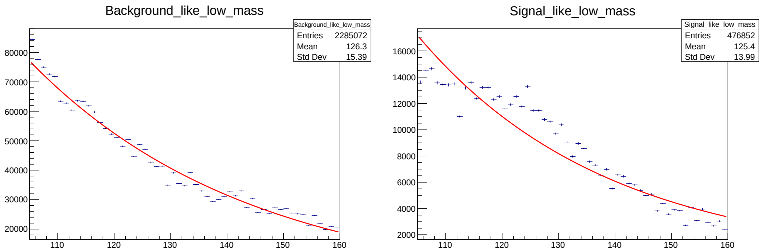

Figure: Fix.19 - signal- and background- candidates for low mass classifier, fitted with exponential to model SM $\gamma\gamma$ background

Results

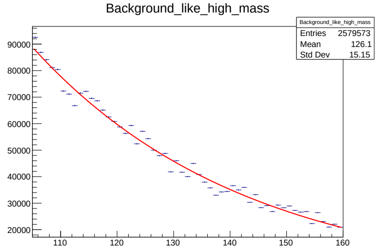

Figure: Fig.20 - signal- and background- candidates for high mass classifier, fitted with exponential to model SM $\gamma\gamma$ background.

Do we really see a signal?

We're looking for $b\bar{b}\gamma\gamma$ final states. Single H produced in association with two jets looks similarly. This warrants further work - model single-Higgs events we might wrongly classify as signal, and compare it to our results.

•Find a theoretical estimate for $Hb\bar{b}$ production, for example in [3].

•Use existing Higgs data to estimate how much $Hb\bar{b}$ or other states that we might mistake for that, such as $Ht\bar{t}$, must be in our data sample

•Use another MVA classifier to distinguish single-Higgs state with associated jets from true singal

Reference

- The ATLAS Collaboration, Phys. Lett. B716 (2012) 1 and ATLAS-CONF-2012-162;
  The CMS Collaboration, Phys. Lett. B716 (2012) 30 and CMS-PAS-HIG-12-045.
- J.Baglio et al. KA-TP-44-2012 SFB/CPP-12-102 LPT-ORSAY-12-124 PSI-PR-12-10
  The measurement of the Higgs self-coupling at the LHC: theoretical status
- D. de Florian, C. Grojean et al.
  Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector
  arXiv:1610.07922v2 [hep-ph] 15 May 2017