Summer Student Report:
Analysis and optimization of 16 GeV a-boson mass signal in search for Higgs boson decays in the $\bar{b}b\mu^+\mu^-$ final state

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Contents

1 Introduction

The search for exotic decays of the Higgs boson appears in theories and models that adopt an extension of the standard model, as an example we can cite Dark Matter (DM) models, models with a first-order electroweak phase transition and theories with an extended Higgs.

In this CERN summer project I will analyze data collected by the ATLAS project in the search for $H \to aa \to b\bar{b}\mu^+\mu^-$ decay for a a-boson mass equal to 16 GeV.

2 Theory and Motivation

2.1 Higgs Boson Production

In simplified form, the dominant process for producing Higgs bosons at the LHC consists of the fusion of two gluons from the collision of protons beams, which loop contain the Standard Model particles that can couple to the gluon and to Higgs bosons as well, Figure 1.

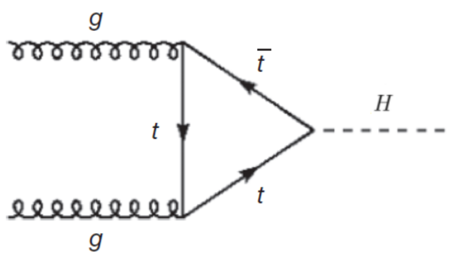

Figure 1: Feynman diagram for gluon fusion (ggF) process [3].

Another way to generate Higgs Boson is through vector-boson fusion (VBF), in this process a quark from each one LHC protons beam radiates from a heavy vector boson that interact to produce a particle, such as a Higgs boson. The quarks undergo a small deflection from their initial direction and are detected as jets of particles by the ATLAS detectors, Figure 2.

2.2 Detection of the Higgs Boson

The Higgs boson generated at the LHC is difficult to observe because its couplings are proportional to mass, therefore they are small for the light particles that are more commonly available in proton beam collision. Besides that, the mass of the Higgs boson is unknown in the Standard Model theory.

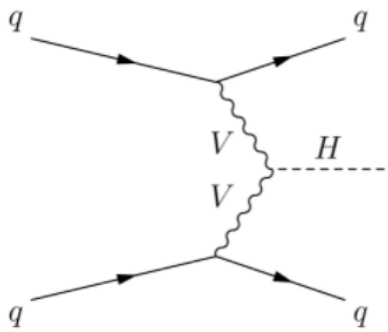

Figure 2: Feynman diagram for vector-boson fusion (VBF) process[4].

Since the Higgs mass was unknown, the searches had to be planned for different values, which is much more challenging than designing an experiment to look a specific mass value.

Different techniques was applied for different mass ranges in experiments at LEP searched for a Standard Model Higgs boson and would have observed one if it were lighter than about 114 GeV. The first run of the LHC, at 7 and 8 TeV, was sufficient to search for Higgs bosons up to several hundred GeV in mass, and only one candidate was found, at 125 GeV, which expanded the horizons beyond the Standard Model.

2.3 Higgs Boson Decay

Since the Higgs Boson interacts with all the massive particles of the Standard Model, there are several processes by which the Higgs boson can decay. One of the most common forms of decay is the appearance of a fermion-antifermion pair. For a Higss boson of mass 125GeV, the decays can generate a bottom-antibottom pair or a tau-antitheu pair, where the first is more common.

Another possibility, somewhat less common than the previous decay, is the emergence of a pair of W bosons or Z bosons. The pairs of bosons that arise can subsequently decay into a quark-antiquark pair or into leptons and neutrinos. Finally, decay into massless bosons, gluons, or photons is possible, of these processes the most common is decay into a pair of gluons. Decay into a pair of photons is very rare, it happens only twice every thousand decays.

Currently efforts are focused on the search for exotic decays, as it would corroborate extensions of the Standard Model. These include models addressing the baryon asymmetry of the universe, offering a solution to the naturalness problem, or providing insights into the nature of dark matter [1].

In this summer project we will issue the exotic decay in which a 125 GeV Higgs boson decays into two other unknown bosons, a-bosons, which subsequently decay into two muons and two b-quarks each, $H \to aa \to b\bar{b}\mu^+\mu^-$.

3 Project Activities

3.1 Objective

Using data from proton-proton collisions at a center-of-mass energy of $\sqrt{s} =$ 13TeV, collected by the ATLAS experiment between the years 2015 and 2018, this project aims to analyze the collected data and propose changes that improve the sensitivity of the signal corresponding to a supposed a-boson of mass 16 GeV.

3.2 Data Analysis and Optimization

The selection of the events was realized using five cuts through progressive selection criteria, both of which selected events with one or two muons. The first cut, cut 0, selects events with dimuon invariant mass, $m_{\mu\mu}$, between 15 GeV and 65 GeV. It also selects events with emissing transverse momentum, E_T^{miss}, smaller than 60 GeV, to reduce background events from $t\bar{t}$ events.

The second cut, cut 1, adds the kinematic-likelihood (KL) fit criterion to the previous cut, cut 0, which is defined as follows:

$$L = W(_{b1}, E_{b2}) \cdot W(_{b2}, E_{b2}) \cdot BW(m_{\mu\mu}, m_{bb})$$

Where W is the transfer function of the b-jets, responsible for constraining b-jet momenta within the resolution of the calorimeter and is described by a Gaussian probability with $\sqrt{E_b}$ width. The WB, on the other hand, is the function of Breit-Wigner function centered on $m_{\mu\mu}$ with a width of 0.5 GeV.

The purpose of this new criterion is to quantify how similar the event is from hypothesis $m_{\mu\mu} \simeq m_{bb}$, therefore the higher the value of L the better. The third cut, cut 2, adds a range for total mass, $m_{\mu\mu bb}$, in a way that it keeps in the Higg-mass window, which is between 110 GeV and 140 GeV.

The fourth and fifth cuts, cut 3 and cut 4, differ from the previous ones because now we will define the dimuon mass range, $m_{\mu\mu}$, between 15 GeV and 17 GeV in order to concentrate the search on m_a=16 GeV. For the fifth cut we add boosted decision tree (BDT) techniques to improve the separation of the signal of interest with the Standar Model background.

By applying the cuts described above to the collected data it is possible to select the events of interest, S, as well as the background events, $t\bar{t}$ and DY, Table 1. With this we can calculate the sensitivity of each filter by the expression:

$$Sensitivity = \frac{S}{\sqrt{t\bar{t} + DY}}$$

a16	S	$t\bar{t}$	DY	Sensitivity
Cut 0	123.266479	41949.88281	14472.08984	0.518945
Cut 1	35.232857	2191.474854	2469.571289	0.516067
Cut 2	30.628624	450.493103	890.052246	0.836541
Cut 3	30.541706	0.208927	9.913488	9.599569
Cut 4	29.842920	0.145188	6.458999	11.612672

Table 1: Selected events after applying the cuts.

The table 1 shows a drop in the sensitivity of the second cut, cut1, relative to the first cut, cut 0, which indicates that the kinematic-likelihood fit is not efficient and should be removed. To try to get around this problem, we remove the kinematic-likelihood fit and add new conditions to the cuts.

4 Results

Since the masses of the di-b-jets and the dimuon should be close, one of the new conditions imposed on the cut 1 to replace the kinematic-likelihood fit imposes that the modulus of the difference between the masses of the di-b-jet and the dimuont should be small for better selection of interesting events. We test the response of the cuts for different values of the modulus of difference of the masses until we arrive $|m_{\mu\mu} - m_{bb}| < 6.2$GeV.

In addition to the criterion described above, we imposed one more condition for the cuts that change the range of the Higg-mass window from 110 GeV $\leq$m$_{\mu\mu bb} \leq$ 140 GeV to 117 GeV $\leq$m$_{\mu\mu bb} \leq$ 143 GeV in such a way that we could keep at least two background events. Although reducing the range contributes to a decrease in events of interest, it also causes a curtailment in background events which results in improved sensitivity. The table 2 shows the selection of the new events after the application of the cuts as well as the increase in sensitivity.

a16	S	$t\bar{t}$	DY	Sensitivity
Cut0	123.266	41949.9	4477.7	0.518918
Cut1	40.2327	1489.9	1173.34	0.779603
Cut2	34.7627	141.886	315.285	1.625826
Cut3	28.1833	0.0231927	3.42153	15.184983
Cut4	27.0824	0.0231927	2.14629	18.386917

Table 2: Selected events after applying the cuts.

If we take the histograms of the events after applying the kinematic-likelihood fit, Figure 3, and compare them with the histograms after applying the new cri-

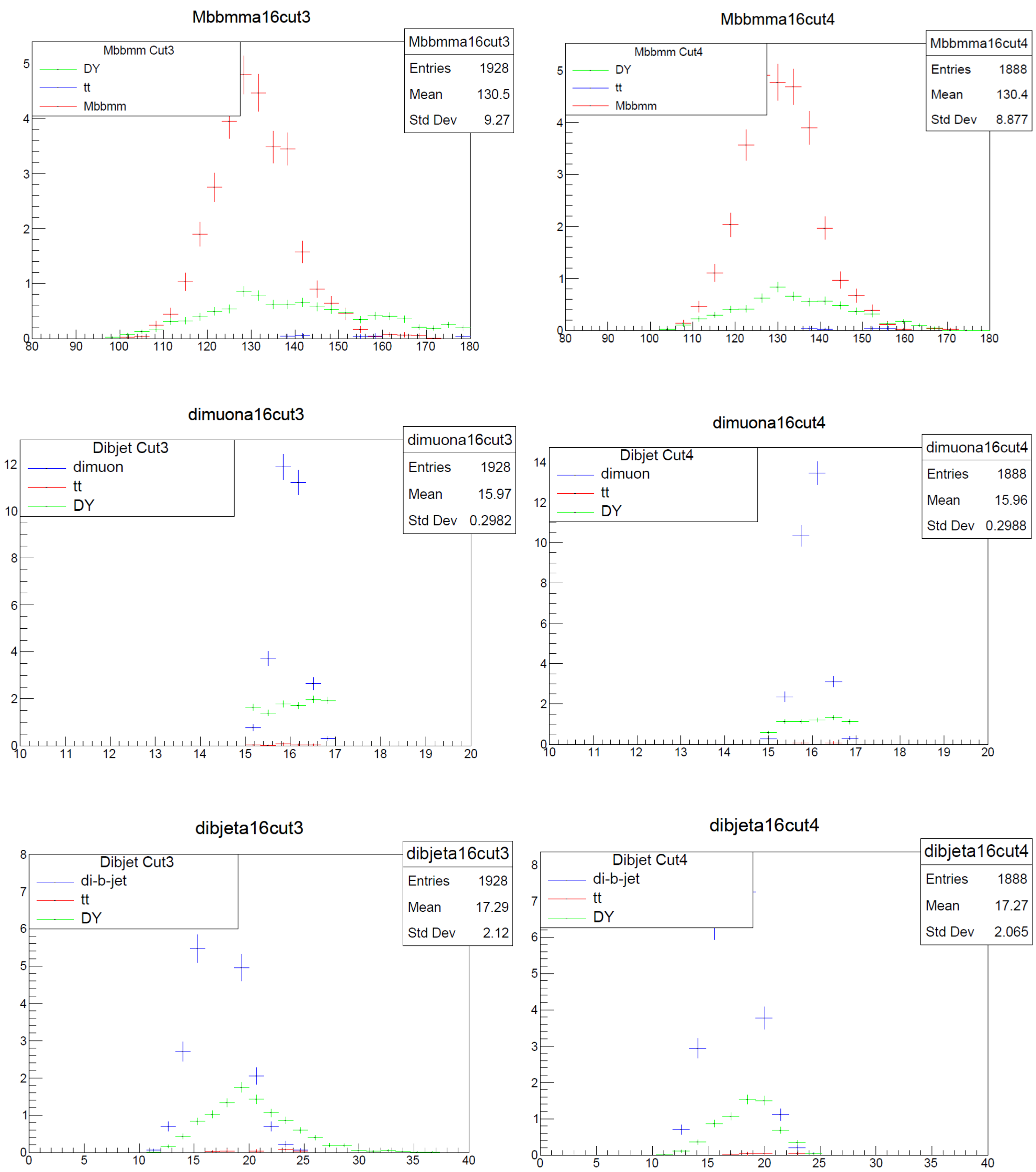

Figure 3: Histograms after applying cut 3 and cut 4 still using kinematic-likelihood fit for dimuon, di-b-jets and $M_{bb\mu\mu}$

teria, 4, we can observe a significant improvement in the signal of interest and a significant reduction in the background events.

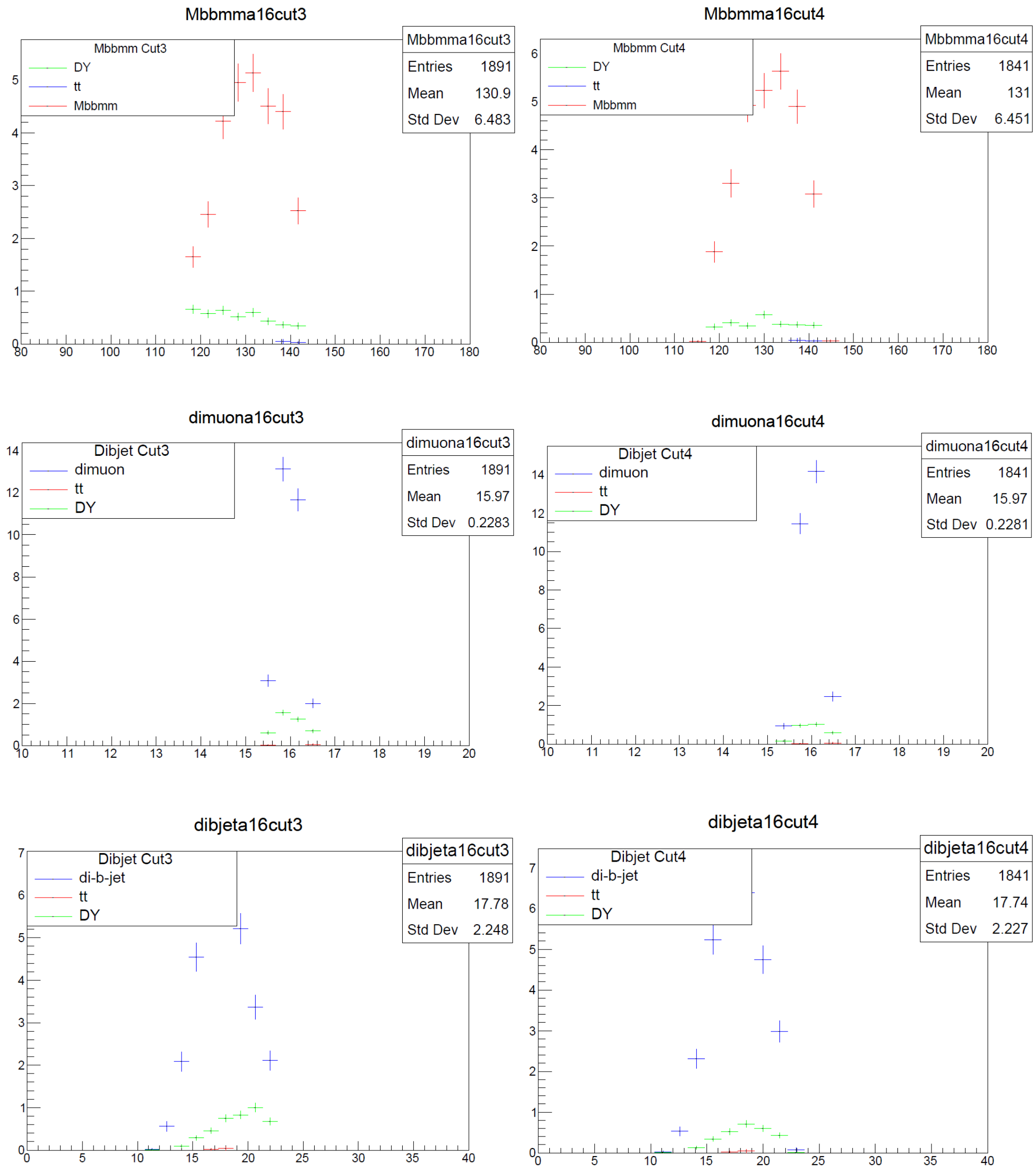

Figure 4: Histograms after applying cut 3 and cut 4 removing the kinematic-likelihood fit for dimuon, di-b-jets and $M_{bb\mu\mu}$

5 Conclusion

In this work it became evident that the kinematic-likelihood fit does not perform very well for *a*-boson masses of 16 GeV, although it is very efficient for values above 20 GeV. In this case, the replacement by a criterion based on the modulus of the difference in mass between the di-b-jet and the dimuon showed a significant increase in sensitivity.

Acknowledgments

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References

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