Optimising Higgs Decay events to Background events in the di-photon channel

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Abstract

A Higgs decay in to 2 photons ($H \rightarrow \gamma\gamma$) is optimised against a background of 2 photons simulated by python as gluon decay into 2 photons ($g \rightarrow \gamma\gamma$.) The signal was optimised via filtering the events based on their kinematic variables. A strong peak was found at $m = 123GeV/c^2$ with deviation from the modelled background of $\sigma =$ at the x % confidence limit.

1 Introduction

The aim of this project was to optimise a signal produced a program called Pythia of a decay of a Higgs boson (H) to 2 photons (γ.) This report will summarise the results of the project, justify the theoretical and experimental reasoning for the methods used to obtain these results and comment on the results obtained compared to current literature. [2] To begin a theoretical background is given first to illustrate the relevant theory being examined. The way in which the data is processed is then discussed in context of the physical processes being examined. The results are then presented in graph form, using both 3D scatter plots (for the optimisation plot) and 2D histogram plots (for the invariant mass plot). Comments on the results as well as comparison to current literature will then follow; the project's experimental (and theoretical) faults will be examined and improvements on these faults will be offered. The conclusion will summarise the results and comments in context of the literature as well as summarising the faults and possible improvements that could be made.

2 Theory

2.1 Higgs Mechanism

The Higgs mechanism, as proposed by Higgs, allowed for particles to keep their masses and keep the symmetry of the Standard Model Electroweak interaction

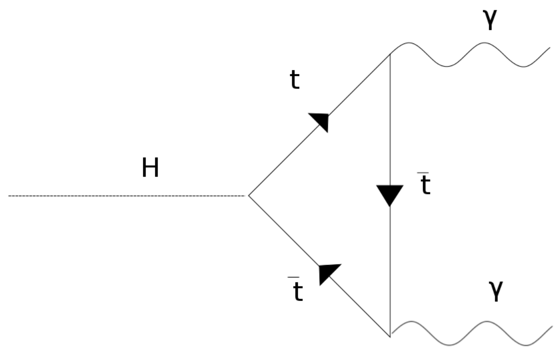

Figure 1: Feynman diagram for $H \to \gamma\gamma$ decay channel via a top quark loop

via symmetry breaking with a scalar field (called the 'Higgs' Field) that permeates all of space.[1, p. 1159] The details of the Higgs interaction (and electroweak theory) are not needed to optimise the signal, however the decay of the Higgs boson (that arises out of the introduction of the Higgs mechanism) affected by how the Higgs field 'couples' to other particles (in particular the photon and top quark.)

2.2 Higgs Decay

The Higgs boson has many possible decay modes, as it is estimated to have a relatively large mass in the window of $113 < m_H < 132 GeV/c^2$ at the 95% confidence limit. The most common decay for the Higgs boson is into a bottom, anti-bottom quark pair:

$$H \to b\bar{b} \tag{1}$$

The decay we are interested in is the Higgs boson to 2 photons (or the 'di-photon channel'):

$$H \to \gamma\gamma \tag{2}$$

[4] This decay has a very low chance of occurring, with a branching fraction of order 10^{-3} times per decay. [3, p. 5] The decay of the Higgs to the 2 photons is unlikely due to the nature of the decay, since the photon (having no mass) does not couple to the Higgs field, the only way to produce 2 photons from a Higgs is for the Higgs to decay into 2 particles (usually 2 top quarks [1]) which then annihilate to produce 2 photons. This decay is far less common than the decay to

[1] Other particle pairs can and are produced but at such low branching fractions that they are negligible

a bottom-anti bottom quark pair with a branching fraction of order 10^0 [3, p. 5]. It is reasonable to wonder why the botton-antibottom quark decay channel was not explored instead of the di-photon channel, it is for practical purposes that the di-photon channel is preferred. As quarks cannot be isolated, the decayed bottom-anti-bottom quark pair would manifest in a 'jet' of hadrons which would require a far more complex analysis of each event for possible candidate Higgs decays, contrast to a di-photon decay where 2 photons can be isolated and do not have associated jets, it is relatively simple to identify 2 candidate photons for Higgs decay than it is to do so for a bottom-anti bottom quark decay.

2.3 Significance

In order to test the effectiveness of the optimisation of the signal to background a quantitative measurement was needed, the statistical significance, Σ is given by the number of events S compared a background of number of events, B as

$$\Sigma = \frac{S}{\sqrt{S+B}} \tag{3}$$

Note that the significance is inversely proportional to the inverse square root of the total number of events, $N = S + B$, meaning that scaling to larger number of events would yield a lower significance at a relatively fast pace. Also note that reducing the number of background events, B to it's lowest ($B = 0$) would give a maximum value of $\Sigma = 1$, assuming that the signal is purely Higgs boson decays. On inspection of the signal data ('Higgs.txt') it is clear from the non-zero number of single photon events that the signal was not purely Higgs decays and needed filtering as well as the background.

2.4 Kinematics

As the Higgs is produced in our simulation at a LHC-like collider experiment, there are kinematic variables introduced to parameterise the Energy and momentum (4 - momenta) of the produced photons. These are given by the transverse momentum p_T, the azimuthal angle ϕ and the pseudo-rapidity η (in this case the pseudo-rapidity is the rapidity see appendix) related to the energy and 3 cartesian components of the momentum vector of the photon by

$$E = p_T \cosh\eta \tag{4}$$
$$p_x = p_T \cos\phi \tag{5}$$
$$p_y = p_T \sin\phi \tag{6}$$
$$p_z = p_T \sinh\eta \tag{7}$$

The reasoning behind using the transverse momentum is that it is Lorentz invariant as the particles are only moving relativistically along the beam line, perpendicular to the transverse momentum. The differences in ϕ and η are also Lorentz invariant and allow for a measure of the angular distance between photons. The difference in azimuthal angle, the angle in the plane perpendicular to the beam line, would test to see if the Higgs decays into 2 back to back photons (preserving transverse momentum) and the pseudo-rapidity difference allows for a measure of angle along the beam axis that is Lorentz invariant.

2.5 Higgs invariant mass

The way in which the Higgs signal will manifest is via an 'invariant mass plot' where the frequency of the an event of invariant mass m against the invariant mass. The Higgs to 2 photon decay event is relativistic and requires the conservation of the magnitude of the 4-momentum, p_H^μ, where $\mu = t, x, y, z$ for a 4-vector. Which leads to the relation

$$m_H^2 = 2E_{\gamma 1}E_{\gamma 2}(1 + \cos(\phi_1 - \phi_2)) \tag{8}$$

. This equation is used to obtain the expected parameters of the di-photon channel, therefore it is possible to distinguish background produced photons and Higgs produced photons. From (8), assuming that the transverse momenta and the energy are of the same order of magnitude and that $(1+cos(\phi_1-\phi_2)) \approx 1$ then it is expected that photons from a Higgs decay will have $p_T \approx m_H$.

2.6 Expectation

Since the current search for Higgs boson yielded a result of 5σ at mass $m_H = 126^{+U}_{-L}$GeV at ATLAS combined with the exclusion by the LEP and Tevatron in the range $113 < m_H < 132$ GeV respectively to the 95% confidence limit; we expect a peak in a invariant mass Histogram within the range described and near the 125 GeV from ATLAS.

3 Coding

3.1 Parsing

In order to begin to manipulate 4 momenta data, we needed that data to be in a usable format; this was done via a python script called 'parse.py.' The parsing program would proceed through both the 'Higgs.txt' file containing the photon event data for a Higgs signal and the 'background.txt' file which had the background photon events that the Higgs signal was optimised to. The script would take the following information from the text file for each 'event.':

1. The number of photons n for each event.
2. Each component of the 4-momentum, p_x, p_y, p_z for the x, y, z directions for each photon
3. The energy, E of each photon in the event

The format of this information was a python 'class' which allowed each event to treated as an object to be manipulated by further programs.

3.2 Filtering

The filtering functions work on the following algorithm

1. The photon has property x
2. x satisfies an inequality $I(x, X)$
3. Event with photon with x is kept.
4. Otherwise photon is discarded (not kept).
5. Events with fewer than 2 photons are discarded.

In the case where more than 2 photons survive the filtering process, another means is used to select 2 of the best photons that meet these criteria depending on the physical quantity being filtered.

3.3 Filters

3.3.1 Number

The number of photons in each event is calculated by iterating through the list of events and finding the number of photons in each event. The event is rejected if there are fewer photons than a threshold number n. In our case $n = 2$ since the Higgs cannot possibly decay into fewer than 2 photons, this means that the events are filtered by number both before filtering and after filtering to avoid non-Higgs candidates being present in the final array of events.

3.3.2 Transverse Momentum

The transverse momentum filter iterates through all of the events as stored by 'parse.py' in a list and keeps every event but removes all photons from that event that have a transverse momentum $p_T < P_T$ where P_T is obtained via optimising the filter with respect to the statistical significance of the Higgs signal Σ. In the case of more than 2 eligible photons, the photons with the highest p_T were chosen since these are more likely to be the result of a Higgs decay.

3.3.3 Energy

As with the transverse momenta filter, the energy filter will also remove every photon with Energy $E < E_{th}$, where E_{th} is some threshold energy also obtained by optimising the energy filter.

3.3.4 Azimuthal angle

The azimuthal angle filter considers each event and 2 photons in the event with 4-momenta p_i, p_j and proceeds to find the angle ϕ_{ij} between them. To avoid repeating the same operation only events with $i + j < 1$ are chosen so that the angle is taken between different photons a single time between them.

3.3.5 Pseudo-Rapidity

The pseudo rapidity was filtered in the same manner as the azimuthal angle, where 2 photon 4-momenta are considered and the pseudo rapidity is taken between them.

3.4 Optimisation

To optimise each of the filters, the Higgs events and background events are filtered several times and have the statistical significance, Σ recorded at each value of the threshold value of each filter. This means that the statistical significance Σ is a function of minimum transverse momenta p_{T1}, p_{T2}, minimum energy, E_1, E_2, minimum azimuthal angle ϕ and minimum pseudo rapidity η.

$$\Sigma = \Sigma(p_{T1}, p_{T2}, E_1, E_2, \phi, \eta) \tag{9}$$

To find the largest value of Σ, we find the largest value by changing each of the variables that Σ depends on. We do this by plotting Σ against a range of values of each variable and finding the maximum value of Σ from each one. Then the combination of all of these parameters are used to filter the events and produce an invariant mass plot.

3.5 Plotting

The invariant mass plot is used via the 'pyplot' library, creating a histogram of the invariant masses, calculated from the events using the summation of 4-momenta and taking the square as

$$m_{\gamma\gamma}^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 \tag{10}$$

4 Results

4.1 Optimisation

4.1.1 Transverse Momenta

Note that the significance plateaus starting at $p_{T1} = p_{T2} = 90$ GeV. It is noticeable that the significance has decreased before the

4.1.2 Energy

4.1.3 Azimuthal angle and Pseudo-rapidity

4.2 Invariant mass

As seen

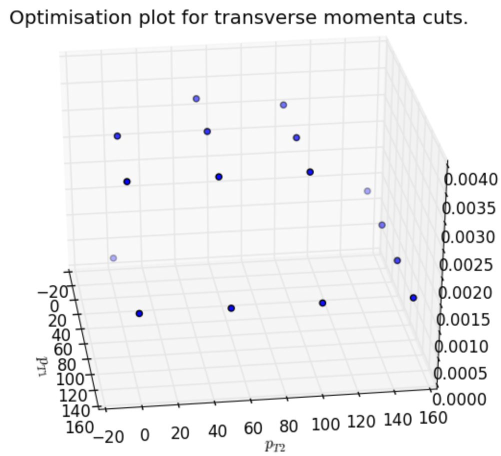

Figure 2: Statistical signifiance dependence on transverse momenta

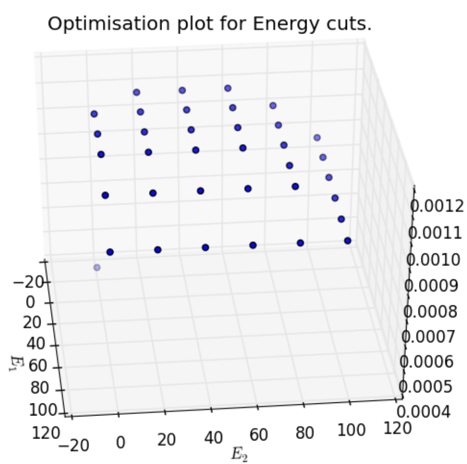

Figure 3: Energy dependence of significance

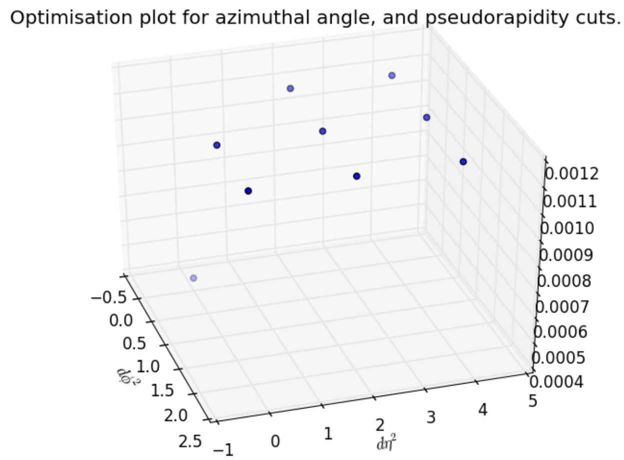

Figure 4: Azimuthal and pseudo-rapidity dependence on Σ

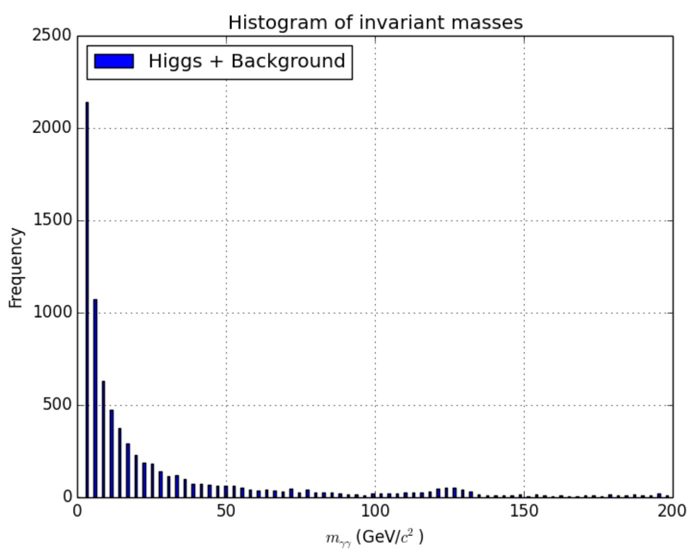

Figure 5: Invariant mass plot after optimisation

5 Conclusion

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References

[1]

[2] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys.Lett.*, B716:1–29, 2012.

[3] S Heinemeyer et al. Handbook of LHC Higgs Cross Sections: 3. Higgs Properties. 2013.

[4] K. Nielsen, N.˙ Higgs boson decay into two photons in an electromagnetic background field. *Phys. Rev. D*, 90:016010, Jul 2014.

A Derivation

A.1 Pseudo-rapidity

A.2 Derivation of invariant mass

B Code

B.1 Parse

B.2 Significance

B.3 Plot

C Plots

C.1 Optimisation

C.2 Invariant Mass